High Power Hadron Machines

Special Diagnostic I + II

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Outline

1) Needs for High Power Machine Diagnostic:
   - What is the goal of the instrumentation and diagnostic

2) Instruments: & Diagnostic methods:
   - Beam Current/Shape
   - Beam Position
   - Beam Profile
     - Emittance
     - Energy
     - Mismatch

Today

   - Beam Loss
     - Machine Protection Systems
     - Transversal and Longitudinal Halo
     - E-clouds

Monday

Needs for High Power Machine Diagnostic:

What is the goal of the instrumentation and diagnostic

The instruments have to be as minimal invasive as possible to survive the full beam.

- If, for any reason, this cannot be achieved the required diagnostics cannot be done with the full intensity of the beam and interpolations are necessary to calculate the parameters of the nominal beam. Such an interpolation might generate large error bars and might therefore not be suitable for precise beam diagnostics.

High Dynamic Range: Typically the instrument has to cover signals coming from low intensity beams during commissioning up to very high intensity beams after an upgrade of the accelerator (which often does not include an upgrade of the beam instrumentation).

- Sometimes tiny "pilot bunches" have to be diagnosed to ensure the right setup of the whole accelerator chain before injecting the full beam. Also variable operation modes, e.g. CW beam, various ion types, long and short pulsed beam have to be diagnosed.

Needs for High Power Machine Diagnostic:

What is the goal of the instrumentation, cont'd.

Large apertures are needed: Due to large beam size, especially for non-relativistic beams

Beam interlock or permit signal to protect the machine against damages from mis-steered or unmatched beams created by an instrument/system is an important feature.

- Therefore their high reliability and availability as well as their accurate and stable work are necessary to ensure a high productivity of the accelerator.

Needs for High Power Machine Diagnostic:

What is the goal of the instrumentation, cont'd.

In other words: Distinguish between three main periods within a machine cycle:

1) Tune up/Set up at the beginning and after each maintenances period (takes about 10% of the scheduled beam time).
   - If any single or even several diagnostics systems fail during this period, beam operation is still possible (also the instrumentation experts need to setup their devices).
   - The most important features during this period are accuracy of the data, ease of use (user friendliness), and speed of taking data. Operators should be able to perform the tune up procedures as quickly as possible, with as little support from diagnostics experts as possible.
   - Beam-destructive methods are possible.
   - Pilot beams with reduced intensity are possible/necessary.

Needs for High Power Machine Diagnostic:

Distinguish between three main periods within a machine cycle:

2) Machine study (about 10% of the scheduled beam).
   - All available diagnostics will possibly be used during this period.
   - If any single or several diagnostics systems fail, the beam operation is still possible.
   - The most important features during this period are accuracy and availability of the data. Measurements are usually done by machine-physicist, often with help from diagnostics experts. **DO NOT ANNOY THEM!** Some of the diagnostics systems for machine study can be of experimental nature or in a prototype stage of development.
   - Beam-destructive methods are possible.
   - Pilot beams with reduced intensity are possible/necessary.

Needs for High Power Machine Diagnostic:

Distinguish between three main periods within a machine cycle:

3) Physics (about 80% of the scheduled beam time).
- The most important performance is beam availability.
- Therefore only systems directly involved in the beam delivery are important –AND HAVE TO RUN!. All beam instrumentation systems connected to the Machine Protection System (MPS) are required. If any of the MPS significant systems fails the beam in the machine is inhibited.
- These systems have to operate at full rate. High availability and reliability of these systems are required.
- Only non-destructive methods are allowed
- Instrumentation have to deal with full beam power (without changing their main specs.)

=> The requirements for daily operation and commissioning are quite different and might not be reached with a small set of instruments!

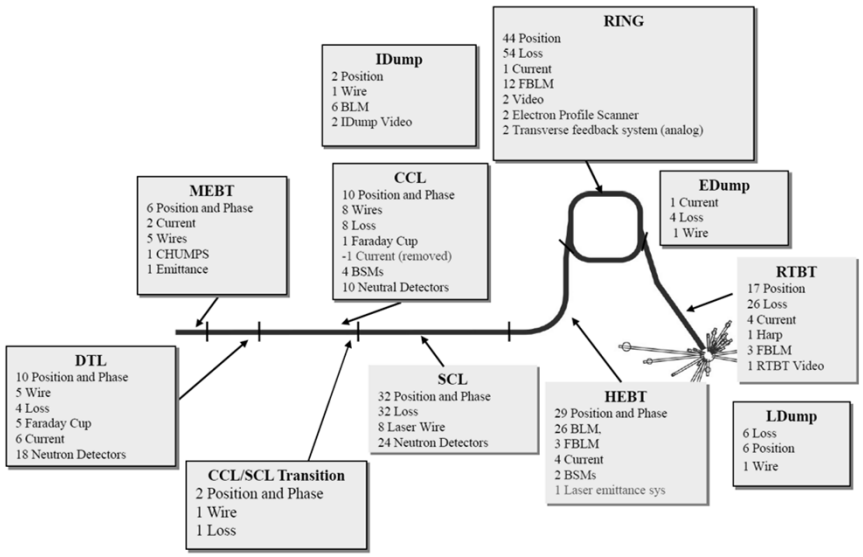
Needs for High Power Machine Diagnostic:

What is the goal of the instrumentation, cont'd.

An example for the main instruments in high intensity accelerators is given here; it summarizes the various beam diagnostic components of the J-Parc complex. [J-PARC11], [JPARC12], [JPARC13]

LINAC: MEBT, DTL/SDTL, A0BT, L3BT	103 Beam Position Monitors (BPM)
	98 Slow and fast current transformers SCT/FCT
	34 Profile Monitors (Wire Scanner (WS) and destructive Halo Monitors (Beam scraper, BSM))
	125 Beam Loss Monitors (BLM) (Scintillators and proportional chambers)
RCS	62 BPM
	9 Current Monitors (DCCT, SCT, FCT, Wall Current Monitor (WCM)), WCM used for bunch length meas.
	7 Secondary Emission Monitors (SEM)
	2 Ionization Profile Monitor (IPM), also for halo monitoring
	134 BLM (Scintillators, Proportional chambers, ionization chambers)
Beam Transfer Lines: 3-50 BT 3NBT	19 BPM
	5 FCT
	5 SEM
	53 BLM (Proportional and ionization chambers)
Main Ring (MR)	192 BPM
	11 Current Monitors (DCCT, FCT, WCM). WCM used for bunch length measurements.
	238 BLM (Proportional and ionization chambers)
	6 Screen Monitors (SEM, Luminescence Screens)
	3 Profile Monitors (WS, IPM)

SNS Beam Instrumentation Systems Map



Beam Current Monitors

Although the topic is high power accelerators, when starting your accelerator only (very) few particles may reach the end of a certain section. But you like to know how much beam survives.

What is the preferred instrument for this case?

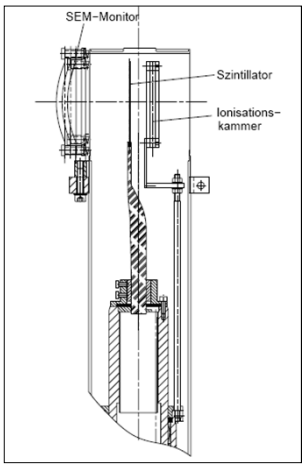
C

I

F

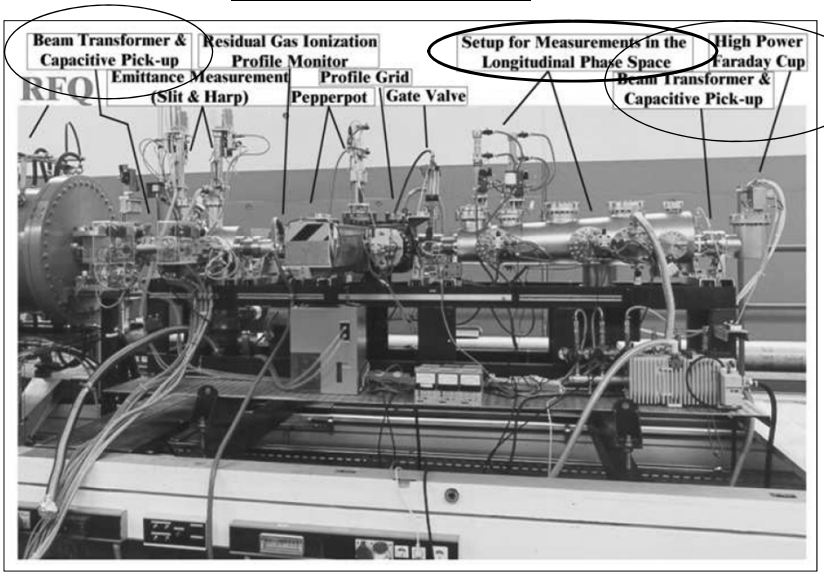
S

T



Detectors for Slowly Extracted Heavy Ions at the GSI Facility
P. Forck (GSI), T. Hoffmann (GSI), A. Peters (GSI), DIPAC 1997 in Frascati

Beam Current Monitors



P. Forck and P. Strehl, Measurements with a versatile test bench for the commissioning of the new GSI high current linac, Proc. DIPAC'99, Chester, UK, 1999

Beam Current Monitors

•Amount (charge) and distribution (bunch length)

1. Faraday cup
2. Wall Current Monitor
3. ACCT (Bunch charge)
4. DCCT (circulating charge, DC)
5. Bunch Shape Monitor (Feschenko type)

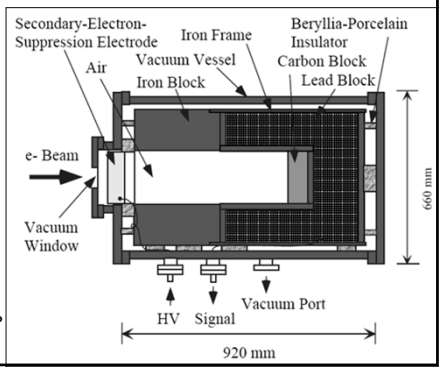
Emphasis on high power hadron beam problems!

Faraday cup for high intensities

•Amount (charge) and distribution (bunch length)

A Faraday Cup is typically a fully destructive device which can be driven into the beam and in which the beam is completely (!) absorbed. Since the Faraday cup has to collect the whole charge of the beam, no charges must escape the cup:

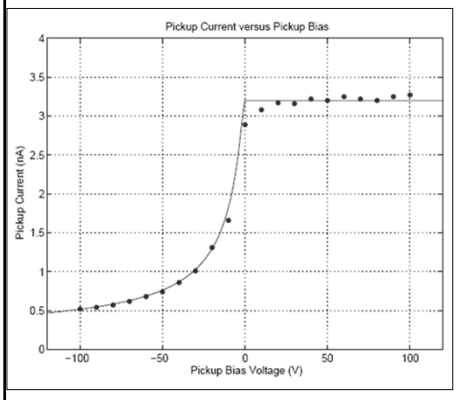
- It has to be large enough to avoid any leakage of shower and multiple scattered particles. Therefore its use is restricted to low energy beams, otherwise its dimension became very large.
- Hadron beam energy should be kept below about 150 MeV to stay below the π-production threshold.
- Backscattered particles have to be collected.
- Secondary and thermal electrons should not escape the FC.

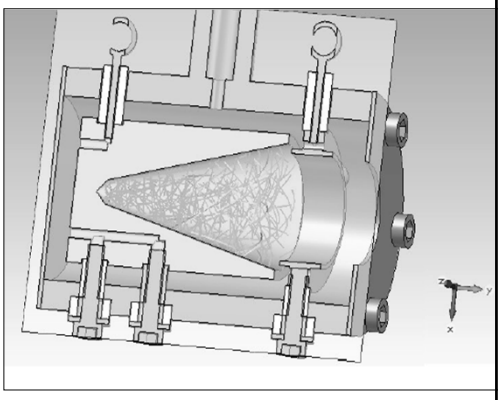


Proceedings of the 1999 Particle Accelerator Conference, New York, 1999
RECALIBRATION OF A WALL-CURRENT MONITOR USING A FARADAY CUP FOR THE KEKB INJECTOR LINAC
T. Suwada , S. Ohsawa, K. Furukawa, N. Akasaka, and K. Oide

Faraday cup for high intensities

The last two subjects are solved by additional negative voltage on a repeller electrode of about -100 V at the entrance of the cup, sometime in combination with a magnetic field perpendicular to the incoming beam.

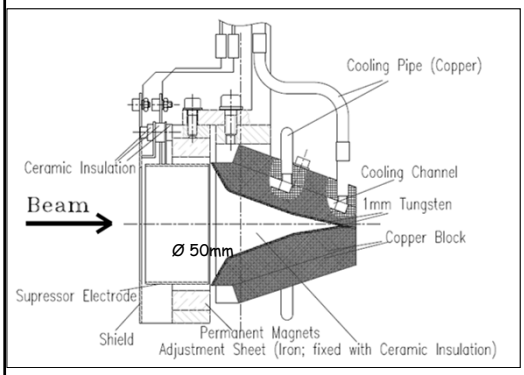


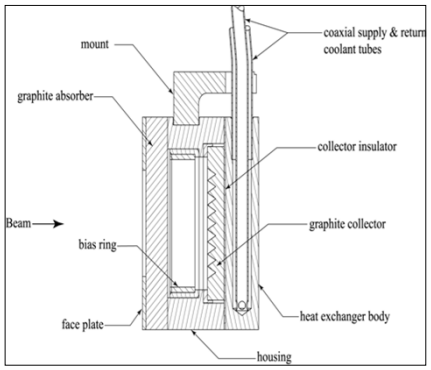


- INTENSITY BEAM MEASUREMENTS AT THE USR, J. Harasimowicz, C. P. Welsch, BIW10, May 2-6, 2010 ,Santa Fe, New Mexico USA
- The ISAC II Current Monitor System, M. Marchetto, et al.,LINAC10, Tsukuba, Japan,

Faraday cup for high intensities

FCs in high intense beams needs water cooling of the collector to take away the beam power of $P_{Beam} = E_{Beam} \times I_{Beam}$. Note that the water cooling only dissipates the average beam power. For pulsed beams the highest temperature is reached close to the penetration depth of the impact, which drives the design of the electrodes.

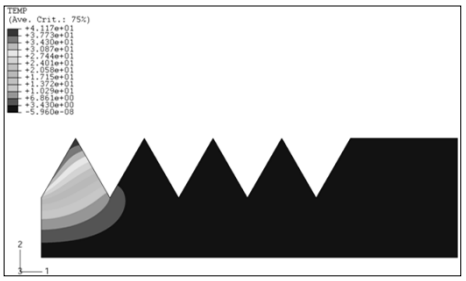


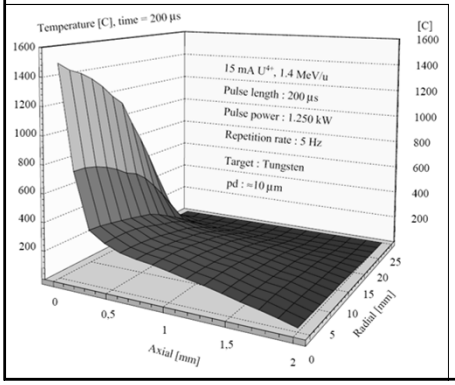


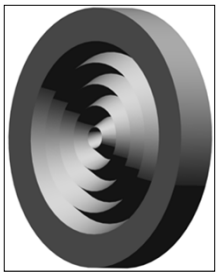
- Lecture Notes on Beam Instrumentation and Diagnostics, Peter Forck,Joint University Accelerator School January – March 2010
- SNS DTL Faraday Cup Engineering Review, Steve Ellis, SNS-03

Faraday cup for high intensities

Special shaped electrodes are necessary for intense low energy ion beams. These ions have a very short penetration depth in materials which lead to a very dense energy deposition. Therefore a V- or saw-tooth shaped electrode with a large inclination against the beam axis is needed to distribute the impact over a larger surface.





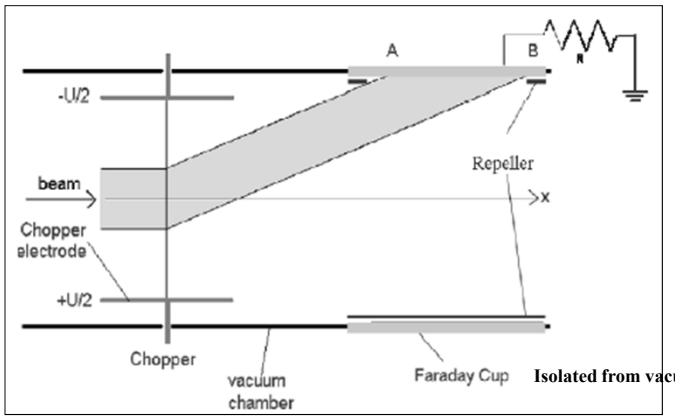


graphite collector

SNS DTL Faraday Cup Engineering Review
Steve Ellis
SNS-03

Peter Forck, JUAS2010

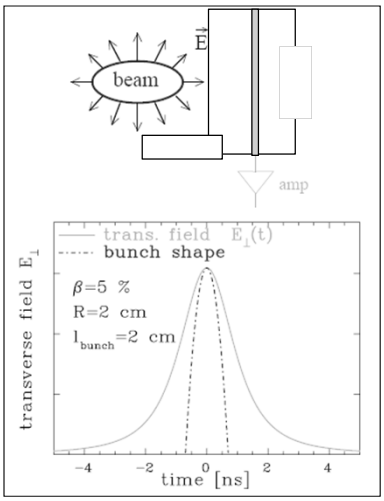
Another type, "non-interceptive" FC



Low energy
Fast chopper kick one bunch out of the train
Cooling necessary, 3.6 W at 0.15 mA C^{4+}

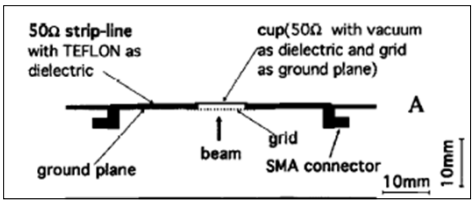
A "Not-Interceptive" Faraday Cup in the CNAO Low Energy Injection Lines
G. Balbinot, M. Caldara, L. Lanzavecchia, A. Parravicini, M. Pullia, J Bosser
CNAO Foundation, Milan ; CERN

Some important hints:

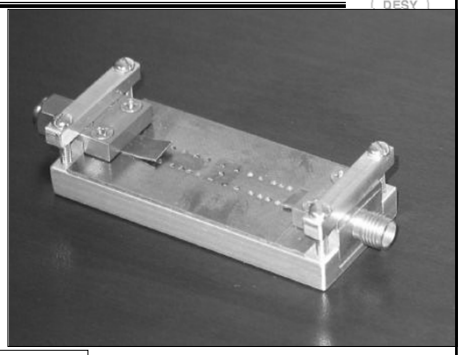


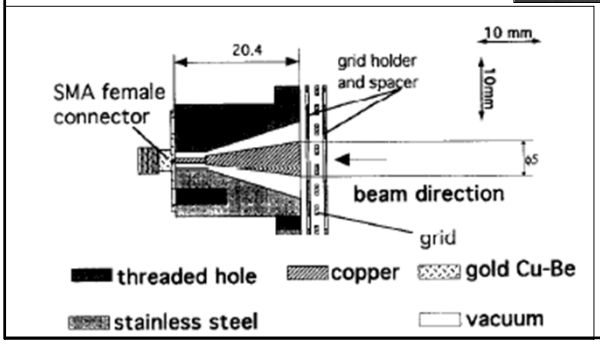
- A good isolation of several GΩ of the electrode offers a large dynamic range of beam charge measurements.
- Care has to be taken not to deteriorate the isolation (and the de-ionized water of the cooling) by radiation.
- A good vacuum is essential in the faraday cup to avoid extra accumulated charges due to ionization for the residual gas molecules.
- An absolute accuracy of better than 1 % can be reached.
- A high bandwidth FC enables a measurement of the longitudinal bunch shape also for low-β beams. A bandwidth of some GHz was measured with coaxial and stripline types of electrodes.
- In the case of low β-beams the advanced electrical field of the bunch has to be considered.

- Lecture Notes on Beam Instrumentation and Diagnostics, Peter Forck,Joint University Accelerator School January – March 2010



Design and tests for the fast Faraday cup of the ALPI post-accelerator
M. Bellato, et al; NIM A: 382





Non-destructive instruments for beam current and position measurements

- The electromagnetic field of the particle beam is used to determine its charge (current) and position.
- Its signal spectrum extends from the DC component of the beam to its frequency defined by bunch length (neglecting bunch sub-structures).
- All electric and most magnetic signals cannot reach the region outside the conducting and non-magnetic beam chamber due to its effective shielding.
- The interesting part of the spectrum lies at high frequencies and is therefore only accessible inside the chamber or by a "gap" in the beam pipe.
- A ceramic ring is soldered at both ends to the beam pipe to form such a non-conducting gap.
- Typical beam current monitors make use of a gap.
- Beam position monitors (BPMs) use antennas inside the chamber together with a small UHV feedthrough to access the signal on the outside of the chamber.

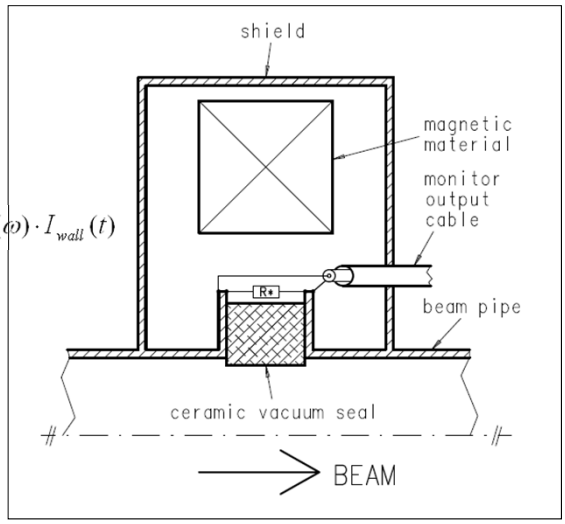
Resistive Wall Current Monitor (WCM)

The interruption in the beam pipe forces the image current to find a new path. Z_{gap} is defined by the instrument designer by clever designing the monitor the path and its impedance. The voltage across the gap V_{gap} is than

$$V_{gap}(\omega) = Z_{gap}(\omega) \cdot I_{beam}(t) = Z_{gap}(\omega) \cdot I_{wall}(t)$$

$$\frac{1}{Z_{gap}} = \frac{1}{R} + \frac{1}{i\omega L} + i\omega C$$

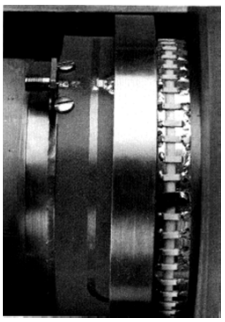
The resistance R is formed by a resistive network across the gap, the inductance L and the capacitance C depend on geometrical and mechanical issues. Z_{gap} is typically in the order of a few Ω.



Resistive Wall Current Monitor (WCM)

Some design hints

- Using a UHV compatible ceramic (with relative permittivity around 10) to form an equally spacing of the gap and a separation from the beam vacuum. The gap should be short compare to the bunch length to avoid beam shape integration. Since C depends on the gap width it shouldn't be too small to avoid high C and therefore a limit in the bandwidth. Typical values for C are about tens of pF.
- Equally spaced resistors of same value R* around a round gap and signal summation by combining the signals from four quadrants avoid beam position dependence.
- Well defined bypass for image current and avoiding resonances by adding material with high μ. This increases the inductance L at low frequencies and reduces the lower cutoff frequency. Typical values for L are around 100 nH.
- Reducing other, stray currents vagabonding along the pipe by careful shielding and grounding.
- Avoiding monitor positions close to beam pipe discontinuities, since higher order modes above cutoff can travel significant distances in the beam pipe. Even some absorbing material (e.g. ferrites) on both sides of the gap but inside the beam pipe might be useful to reduce high frequency background.



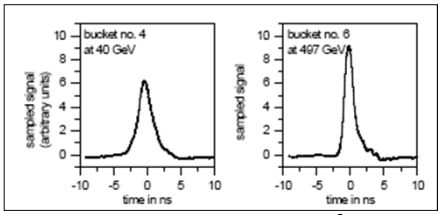
LONGITUDINAL EMITTANCE AN INTRODUCTION TO THE CONCEPT AND SURVEY OF MEASUREMENT TECHNIQUES INCLUDING DESIGN OF A WALL CURRENT MONITOR. Robert C. Webber, Fermi National Accelerator, Batavia, II. 60510, BIW 1989, Upton, NY, USA

Resistive Wall Current Monitor (WCM)

This type of monitor can have a broad frequency response from a few kHz up to a few GHz with flat impedance. A frequency response variation of less than 1 dB over the full range was reached. The bunch current or the number of particles in the bunch N_B can be determined by:

$$N_B = \frac{\int V_{gap} \cdot dt}{Z_{gap} \cdot e \cdot K}$$

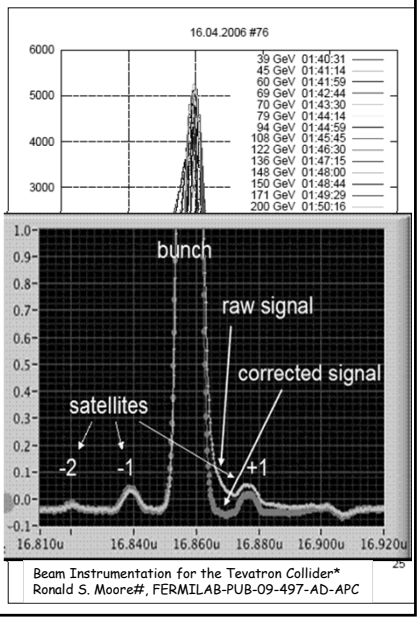
Real Time Measurements of Single Bunch Phase and Length in the HERA Proton Storage Ring and the Observation of Multi-Bunch Oscillations
E. Vogel; DESY-HERA-00-08, 2000



while K is a constant which takes into account various attenuation of cables, combiners and calibration constants. Note that the wall current does not contain information about the DC current component of the beam since this frequency component of the beam current penetrates the (non-magnetic) beam pipe unaffected. Therefore the baseline of the signal is shifted while the shift is proportional to the DC current. A careful baseline restoration is needed for precise bunch current measurements.

Resistive Wall Current Monitor (WCM)

Due to its broad frequency response the wall current monitor is often be used, beside bunch current determination, for measuring the longitudinal profile of the bunch, calculating its emittance and to diagnose longitudinal instabilities. Note that the ultimate bandwidth is limited by the spreading angle of the radial electrical field lines which have an opening angle of ≈1/γ. This limits the longitudinal resolution for non-relativistic beams. WCMs are also used for RF- and timing feedback issues (e.g. compensating beam loading) and time-of-flight measurements since they provide very fast and large signals.



Change of bunch length at acceleration in HERA-p. Note the population of neighbour buckets due to an improper switch from 52 MHz to 208 MHz accel. system.
HERA-p longitudinal; M. Hoffmann
DESY-HERA-06-03

Beam Instrumentation for the Tevatron Collider*
Ronald S. Moore#, FERMILAB-PUB-09-497-AD-APC

Resistive Wall Current Monitor (WCM)

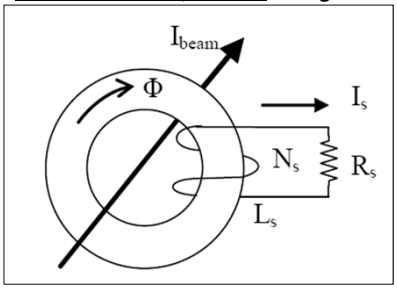
Some care has to be taken at high beam currents:

- The absorption of higher order modes (HOMs) in the magnetic material will increase its temperature. A good cooling is necessary. This is especially true for short bunches like in electron accelerators which induce strong HOMs.
- High beam currents may cause saturation in the magnetic material which changes the inductance L and therefore the lower cutoff frequency. As a result the droop rate will change.
- The power level in the monitor resistors R* can reach some ten Watts at $N_B=10^{11}$ particles/bunch which may lead to high thermal load of the resistors at high repetitive signals. Many distributed resistors around the gap will help but a change in resistance with temperature might occur which will change the calibration constant of the monitor. The signal level may reach 100 V or more.
- Since the signal level is quite high, a high dynamic readout can be achieved by various methods like switchable attenuators/amplifiers, logarithmic amplifiers or large bit ADCs. The last two options are limited in bandwidth, so that a compromise has to be found for each specific application.

Inductive alternating current transformers (ACT)

Need of Current Monitor independent on bunch length, => lower bandwidth

In contrast to the capacitive (electrical) coupling of a wall current monitor, the inductive current transformers are using the magnetic field of the beam to determine the beam current. A bunch crossing a (ceramic) gap in a beam pipe induces a magnetic flux in a high permeability toroid around the gap, like a primary single turn winding in a classical transformer. It induces a current in a secondary winding of N_s turns and an inductance L_s. This current can be measured by the voltage V_s across a resistor R_s. By applying the classical transformer equations one gets the typical transformer response

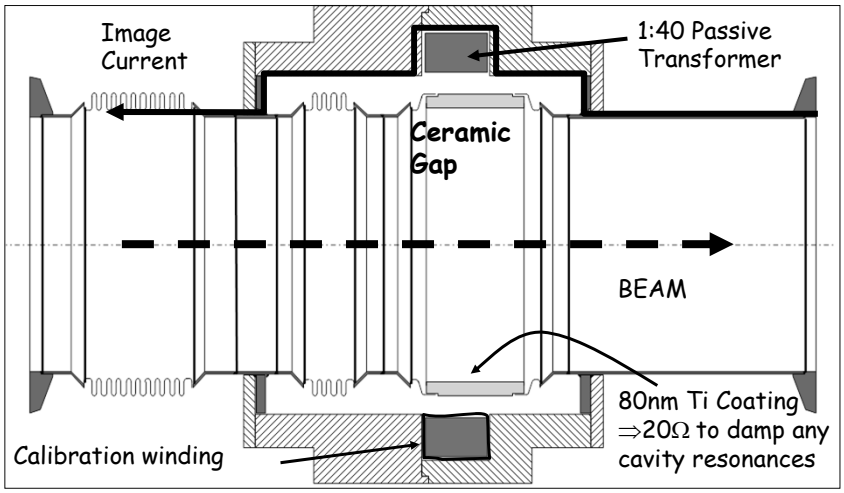


$$V_s(\omega) = \frac{i \cdot \omega \cdot \tau}{1 + i \cdot \omega \cdot \tau} \cdot R_s \cdot \frac{I_{Beam}}{N_s}$$

with $\tau = L_s/R_s$. t is the time constant of the secondary winding. For $\omega >> 1/\tau$ it results in a simple proportionality of

$$V_s = R_s \cdot \frac{I_{Beam}}{N_s}$$

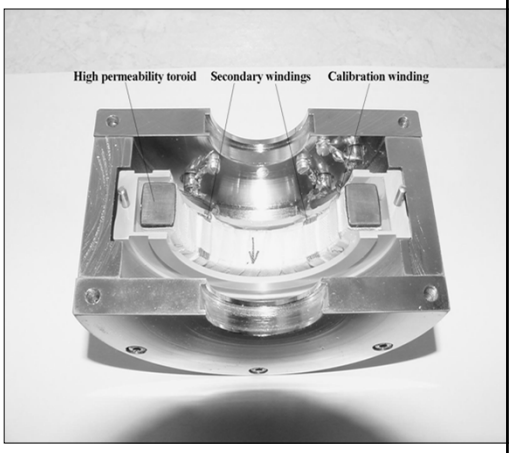
Fast Beam Current Transformer



- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

Inductive Alternating Current Transformers (ACT)

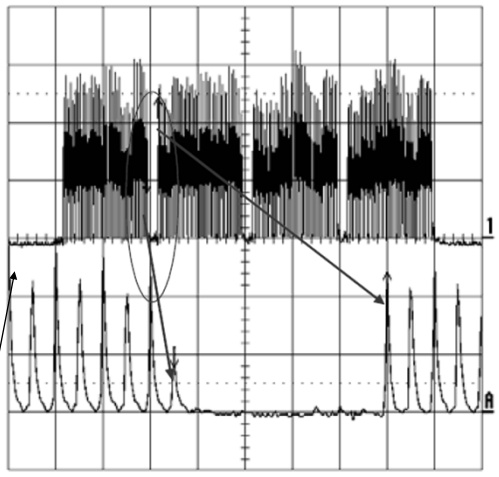
The inductance L_s depends on the permeability μ of the core material, the number of windings N_s^2 and its dimensions. Assuming typical values for L_s = 1 mH and a load resistor R_s of 50 Ω one gets the proportionality above for frequencies $\omega \gg 50$ kHz. The high frequency performance of such a classical current transformer is limited by stray capacitance between the windings and to ground as well as due to energy loss in the toroid material (~ ω^2). Typically the upper limit is in the some hundred MHz range. Proper impedance matching and low pass filters are essential to avoid resonances at higher frequencies in the readout loop. These limits make this simple AC transformer not suitable for the measurement of the longitudinal bunch shape but it is widely used for precise bunch current measurements.



An open inductive current transformer at DESY. The magnetic core is split into two half to allow easy mounting around a ceramic gap without opening the vacuum. Photo by N. Wentowski, DESY

Inductive Alternating Current Transformers (ACT)

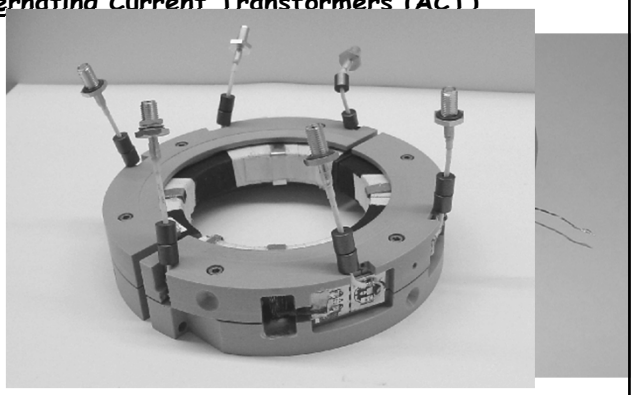
- Since this device is a classical transformer, it cannot transmit the DC component. Therefore a certain droop rate is indispensable ($t_{droop} \sim L_s / R_s$).
- An optimization between high frequency response and low droop rate becomes necessary. Fast current transformers with a droop rate of <1%/μs and an upper frequency of more than 800 MHz are commercial available.
- Accurate DC baseline restoring is necessary to avoid a measurement error in a train of successive bunches.
- In an accelerator/storage ring with an *infinitive long bunch train* an equilibrium is reached when the area below and above the zero line are equal.



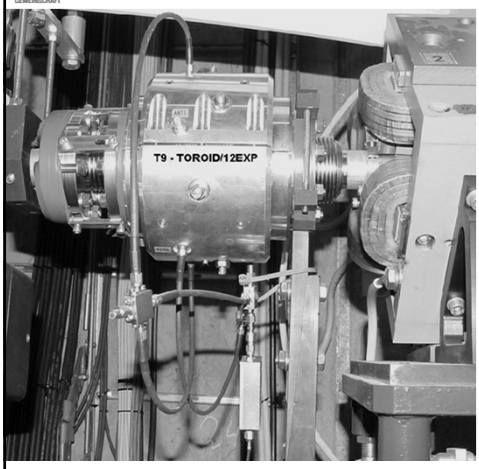
SPS low droop and fast FBCT; 400 MHz with droop rate < 0.1%/μs.
A 40MHZ BUNCH BY BUNCH INTENSITY MEASUREMENT FOR THE CERN SPS AND LHC. H. Jakob, et al, DIPAC 2003

Inductive Alternating Current Transformers (ACT)

An advantage of an inductive current transformer is its small dependence from the beam position.



- An absolute calibration of the measured value can be done by simply adding a calibration winding around the core. The response of a well defined short calibration pulse can be used to calibrate the device.
- Even drifts/droop can be compensated by sampling of the calibration signal just before or after the passage of the beam.
- Careful magnetic shielding of the core is very important as well as a good shielding of the signal windings to avoid contamination of external noise sources.



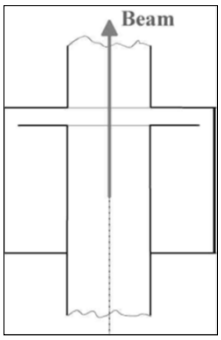
ACT in Flash

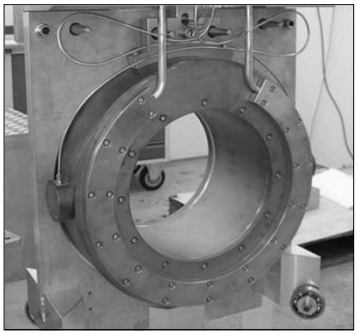
And installed in the SPS and LHC transfer lines. Capable of 40MHz bunch by bunch measurement. Dynamic range to cover 5×10^9 to 1.7×10^{11} cpb

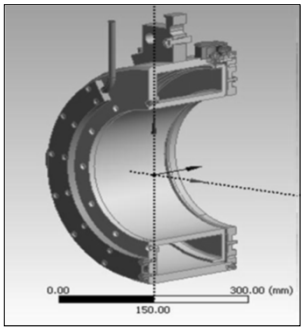
Inductive Alternating Current Transformers (ACT); high power issues

- High peak currents can cause magnetic core saturation which might result in non-linear behavior. Therefore the choice of the core material and the design of the monitor have to fit the required bunch charge range. A dynamic range of $\approx 10^3$ and a resolution of 10^{-4} of full scale can typically be reached.
- Since the voltage output is proportional to the bunch charge only the peak voltage is of interest.
- The acquisition rate is the bunch repetition rate; maybe twice the rate to get a value between two bunches for baseline restoration.
- High dynamic range (12-14 bit) and high bandwidth ADC are commercial available with sampling rates up to 100 MHz (> bunch rate).
- In circular machines the resolution can be improved by averaging the acquired bunch current over many turns, but taking into account the lifetime of the beam.

Another type at PSI







Resonating Re-entrant Cavity, 101 MHz

The magnetic field in the resonator is directly proportional to the beam current

Advantages

- Simple design
- Ruggedized
- Radiation resistant (useful near target, collimators)

Disadvantages

- No absolute measurements
- Temperature drifts
- Water cooling (water speed: up to 2m/s, 1kW cooling capacity)

Current and Transmission Measurement
Challenges for high Intensity Beams
P.-A. Duperrex, V. Gandel, D.C. Kiselev, Y. Lee, U. Müller
PSI, Villigen, HB2010

Direct current transformers (DCT)

The integration of any ACT monitor signal over an infinite period is always zero!

- Precise active baseline restoration may be used to get a DC value of the beam but due to the fact that the baseline slope and level depends on previous beam bunches (several transformer time constants), a precise measurement is difficult.

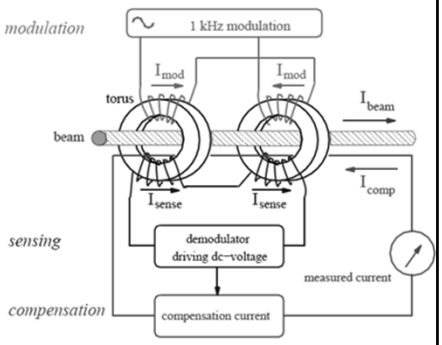
DCTs are used to measure the DC component of a bunched or unbunched beam with high precision and with a dynamic range of > 10^6.

- Sensitivities as low as 0.5 μA exist which is sufficient for low current commissioning.
- Obviously a DC beam current measurement doesn't make sense in short pulsed machines like Linacs (except CW Linacs) or transport lines.
- It is the only device that can measure the beam current of an unbunched or coasted beam in a circular machine.

K.Unser,
Beam current transformer with DC to 200MHz range
IEEE Trans.Nucl. SCI. NS-16, June 1969, pp. 934-938. PAC1969

Direct current transformers (DCT)

- The principle of a DCT (also called DCCT, PCT or zero-flux current transformer) relies on a pair of identical toroids with high permeability.
- They are exited in an opposite direction into saturation by a common AC current (or voltage) into individual windings. Careful matching of the toroids and the exciting current is necessary.
- A common sense winding picks up the resulting induced current which is zero in case of a perfect matching.
- A charged beam crossing the two coils drives one of the two out of saturation which led to a modulated current in the sense winding with a frequency of the second harmonic of the exiting frequency.
- This current is than proportional to the DC beam current.



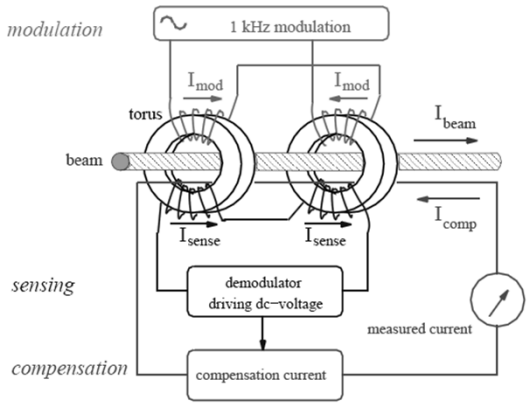
P. Forck, JUAS

GSI

Measurement of beam current

The dc-transformer

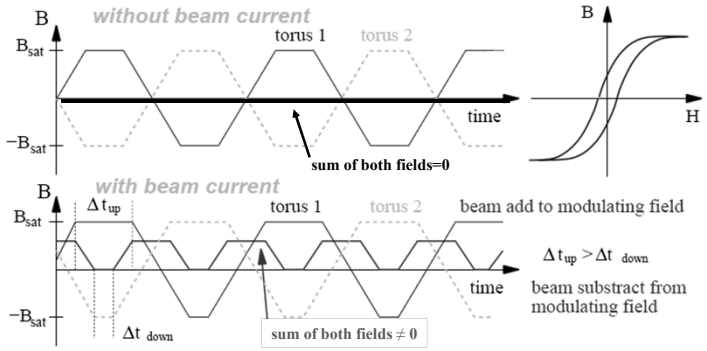
A dc beam can *not* be measured with an ac-transformer
$\Longrightarrow$ extension with two tori and three windings each.



Modulation winding with *opposite* orientation.
Sense winding with *same* orientation.

JUAS, Archamps — Peter Forck

The operation of a dc-transformer



Plot for triangular-modulation → smoother edges for realistic sine-modulation

- *Modulation* **without** *beam:* typical 1-10 kHz to saturation → no net flux
- *Modulation* **with** *beam:* saturation is reached at different times, → net flux
- *Net flux:* double frequency than modulation, rectified for feedback winding
- *Feedback:* comparator-technology for higher sensitivity
- *Two magnetic cores:* should be identical, zero-compensation necessary

Direct current transformers (DCT)

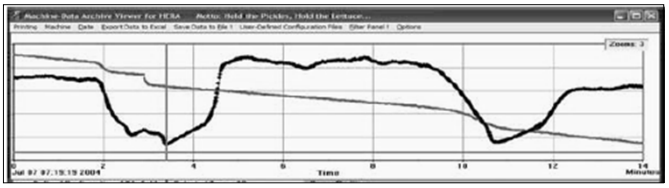
Some application issues of DCTs:

- The bandwidth of such a DCT is limited from DC to some tens of kHz. A further reduction in bandwidth is often useful to reduce the low frequency noise and to extend the resolution.
- If even more dynamic range (>>10^6) is needed the only (costly) solution is than to use two DCTs with different ranges.
- Temperature drifts induce a drift of the baseline. Good temperature stabilization and/or a frequent measurement of the offset in absence of the beam are recommended.
- HOMs in the gap induce heating; (water) cooling might be necessary.
- A calibration winding enables an absolute determination of the beam current.
- A DCT is quite sensitive to external noise and especially to external magnetic fields. Good electrical and magnetic shielding is essential.
- Keep away all external currents.
- Note that the DC component of a non-relativistic beam in a circular accelerator increases with the real acceleration of the beam particles while the bunch charge remains constant.

The HERA-p DCCT installation with heat sinks.

Current transformers, AC vs. DC

Beam lifetime determination in storage rings are often done by high precision DCTs but also with ACTs.



CARE-HHH-ABI Workshop on DC current transformers and Lifetime Calculations
eds. A. Peters, H. Schmickler, and K. Wittenburg
CARE-Conf-04-023-HHH (2004)
Lyon, France, 1-2 December 2004, Proceedings

Determination of coasting beam in a storage ring is provided by a comparison of the ACT and DCT monitors. In absents of coasting beam (e.g. during or immediately after acceleration) the sum of all individual bunch currents should be equal to the DC component of the beam. This can be used to calibrate the monitors. An increasing difference between the two monitors indicates an increase of coasting beam in the machine.
(more later in Halo session)

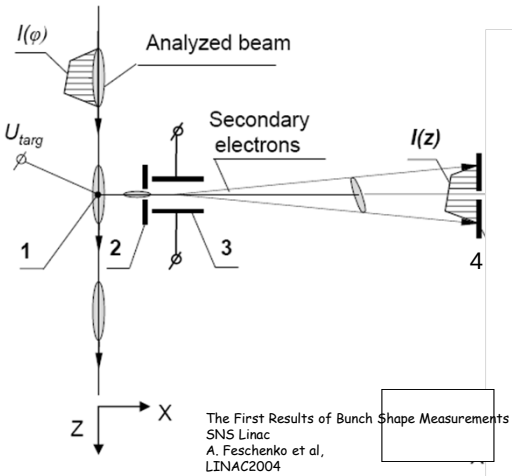
Bunch Shape Monitoring
(longitudinal charge distribution)

The longitudinal charge distribution of a highly relativistic bunch can be determined by a high bandwidth wall current monitor. For low β beams the electromagnetic field is not purely transversal and hence does not represent the charge distribution.

Proposals for a measurement?

Bunch Shape Monitoring (Feschenko Monitor)

• Parts of the beam hit a metal wire target (typ. Tungsten) in the beam pipe.
• The wire emits low energy secondary electrons of a few eV.
• Since this process does not have a significant delay, the temporal structure of the electrons now represents the one of the bunch.
• The electrons are accelerated radially away by a negative bias voltage ($U_{targ} \approx$ -10 kV) on the wire.
• A fraction of the electrons pass a collimator, an electrostatic lens and a varying Rf field of a deflector (U_{RF}= Acos(nωt+Φ).
• The RF is a multiple n of the acceleration frequency of the beam and is synchronized in time.
• Depending on the arrival of the electrons in respect on the phase Φ the electrons received transversal kick, so that their longitudinal distribution is transformed into a spatial one after some distance.



The First Results of Bunch Shape Measurements in SNS Linac
A. Feschenko et al,
LINAC2004

Configuration of Bunch Shape Monitor: 1 – target wire 2 - input collimator, 3 - rf deflector combined with electrostatic lens, 4 - output collimator or screen,

Bunch Shape Monitoring (Feschenko Monitor)

At that point the distribution can be measured by various detectors, e.g.:
•Phosphor screen + CCD
•Multichannel electron detector
•Scanning phase + stable slit (or stable phase + scanning slit) + collector

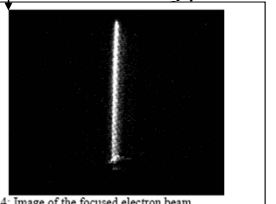


Figure 4: Image of the focused electron beam.

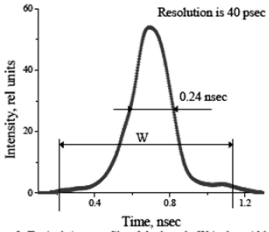
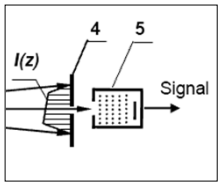
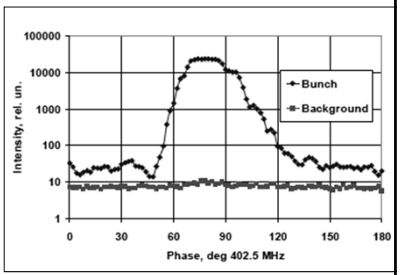
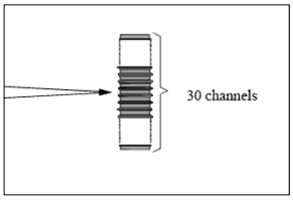


Figure 5: Typical time profile of the bunch. W is the width of the phosphor screen.

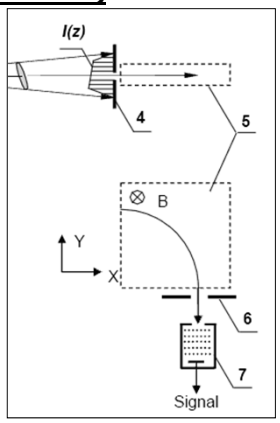


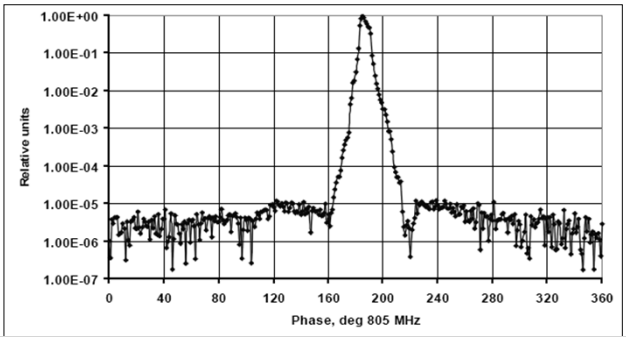




Bunch Shape Monitoring (Feschenko Monitor)

In the special case of an H- beam, the detached electrons originated by dissociation of the H- ions on the target wire (of initial energy of some keV) contribute to some background . Energy separation by an additional spectrometer behind the second slit (5) reduces the background down to better than 10^{-5} of the maximum. This enables measurements of longitudinal halo with a dynamic range of 10^5.





LONGITUDINAL BEAM PARAMETERS STUDY IN THE SNS LINAC
A. V. Feschenko et al,
Proceedings of PAC07, Albuquerque, New Mexico, USA

Longitudinal bunch profile combined from several measurements with gain ranging from 1 to 3500.

Bunch Shape Monitoring (Feschenko Monitor)

The resolution of a BSM is defined by some factors:

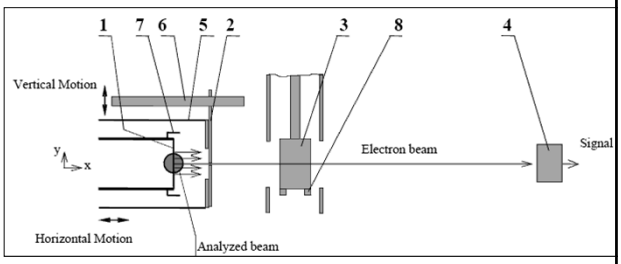
1. The time uncertainty of the secondary electron emission process is far below some ps,
2. The velocity and angular spread of the secondary electrons is minimized by a high bias voltage of -10 kV on the target and a short distance to the first collimator (≈1 ps),
3. The RF deflector might need a sufficient strength of up to some 1000 V/cm to get an image on the detector with a resolution of ≈1 ps ,
4. The slit size of the first collimator (the spot size on the detector without RF) should be small compared to the transversal dimension on the detector.
5. The phase stability of the RF and of the synchronization can be kept much below 1^0 of the RF phase.

Non linear effects like space charge and lens aberrations are assumed to be small.

Typical resolution achieved so far lies in the order of some 10 ps.

Bunch Shape Monitoring (Feschenko Monitor)

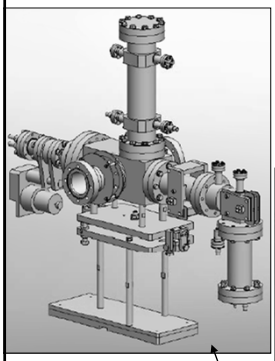
A BSM for measuring all three dimensions of the bunch.
Here additional the target wire is scanned across the beam and the slit of the first collimator is scanned along the wire. The intensity distributions versus the scanning positions give the two transversal distributions of the beam.

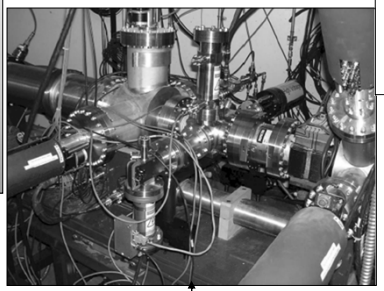


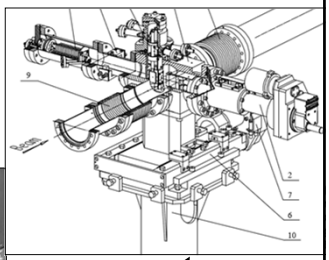
A Three Dimensional Bunch Shape Monitor for the CERN Proton Linac
Esin, S K ; et al. Linac '96, Geneva, Switzerland

The energy deposition of the beam in the target implies to problems, first the creation of thermal electrons and seconds the melting of the target. Thermal electrons blind the whole monitor. Therefore care has to be taken in positioning the target into the beam center; a measurement off-center increases the lifetime of the target.

Bunch Shape Monitoring (Feschenko Monitor)



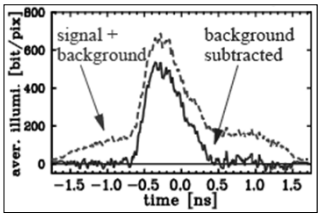


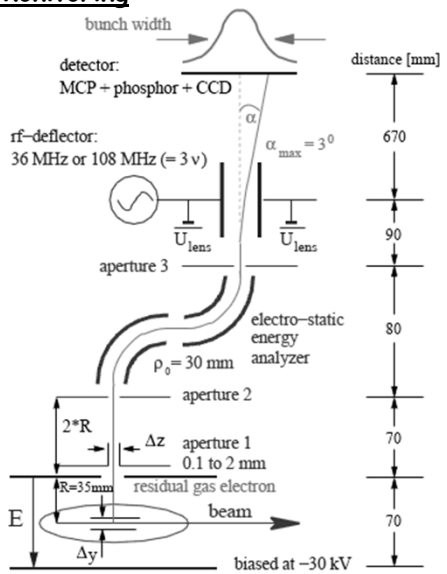


CERN: Linac 4 SNS DESY: Linac3

Bunch Shape Monitoring

To overcome this problem of wire heating in high intense beams the electrons created by the ionization of the residual gas can be used. Since the electrons have a broad spectrum of energies an electrostatic analyzer is located just after the first collimator to ensure a mono-energetic beam at the RF deflector.





MEASUREMENTS WITH A NOVEL NON-INTERCEPTING BUNCH SHAPE MONITOR AT THE HIGH CURRENT GSI-LINAC; P. Forck et al. DIPAC 2005

Bunch Shape Monitoring
(longitudinal charge distribution)

Others Types:

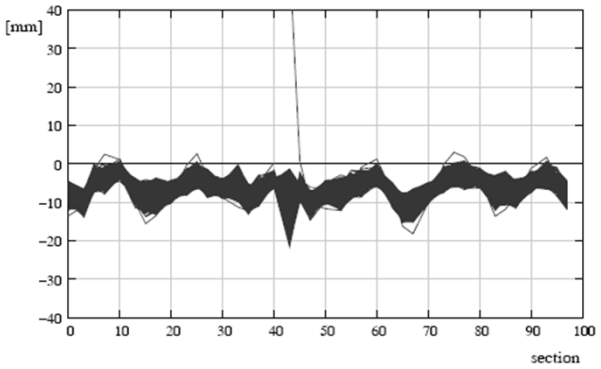
- Synchroton light detection with streak camera (only for very high energies)
- Laser wire scanner at H- beams (comes later at "Profile Monitors")
- OTR with streak camera might not create enough light for very fast detection even for high intense beams, especially not for ion beams and low energy proton beams ("Profile Monitors").

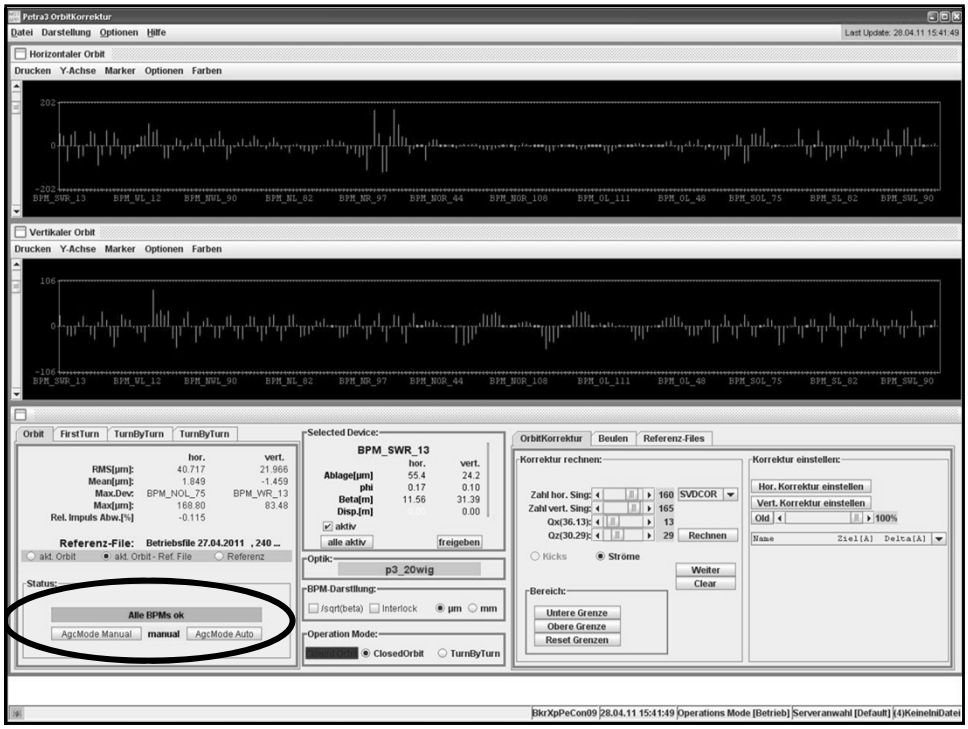
Beam Position Monitor (BPM)

Major tool for machine tuning
- Trajectory/Orbit correction
- Beam stabilization (transversal feedbacks)
- Centering at aperture limits, collimators, dumps, targets
- First turn steering (tune up)
- Injection optimization

A 1000-turn injection trajectory of a single-bunch p beam. The beam is injected in section 43. During the first few-hundred turns, it makes large excursions around its equilibrium orbit.

DIGITAL BPM SYSTEMS FOR HADRON ACCELERATORS; J. Belleman, DIPAC09





Beam Position Monitor (BPM)

The fundamental principle of a beam position monitor (BPM) is to measure the transversal center of the electromagnetic field of the beam in respect to the vacuum chamber wall.

- Inductive (coupling to magnetic field by loop)
- Capacitive (coupling to electric field by pick-up)

Nearly all modern hadron accelerators are using nowadays capacitive pick-ups.

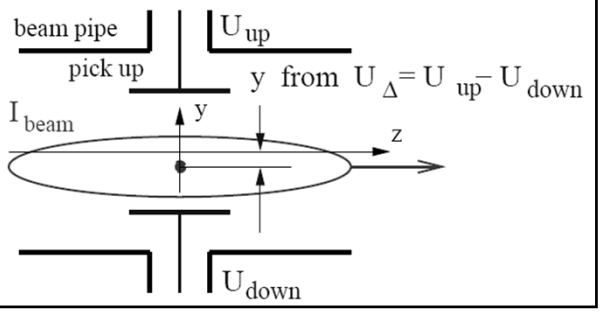
Principle:
The closer distance to one of the plates leads to a higher induced voltage.
Normalizing to the total signal (= beam current)
$U_{sum}=U_{up} + U_{down}$

gives the position

$Y = 1/C \cdot (U_{up}-U_{down})/U_{sum}$

C = monitor constant

Various electronic developments to measure this value very precisely.

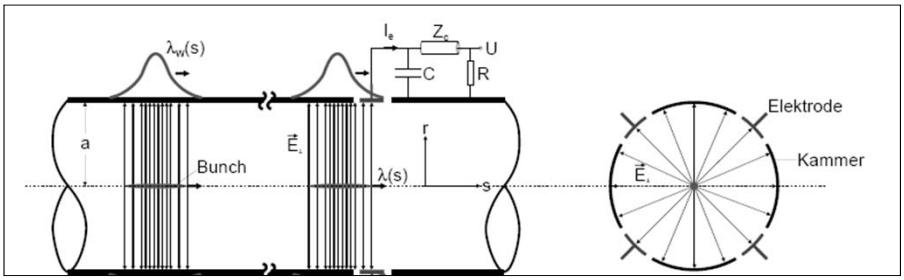


Beam Position Monitor (BPM)

The electromagnetic field of the beam induces an image charge on a metallic plate which is inside the vacuum chamber and insulated. Only one plate is considered here but it is true for all four plates of a BPM. Assuming a bunched beam, the image current $I_{im}(t)$ is driven by the beam charge Q(t):

$$I_{im}(t) = \frac{A}{2\pi dl} \cdot \frac{dQ(t)}{dt}$$

with $A=\pi r^2$ is the area of the electrode, d its distance to the beam center and l its length. dQ/dt depends on the beam current $I_{beam}(t)$:



Joachim Keil; Physikalisches Institut Universität Bonn, Bonn-IR-2000-09, PhD Thesis July 2000: Messung, Korrektur und Analyse der Gleichgewichtsbahn an der Elektronen – Stretcher - Anlage ELSA

Beam Position Monitor (BPM) –buttons-

$$\frac{dQ(t)}{dt} = \frac{1}{\beta c}\frac{dI_{beam}(t)}{dt} = \frac{1}{\beta c}\cdot i\omega I_{beam}(t) \quad with\ I_{beam}(t) = I_0 e^{i\omega t}$$

with β = beam velocity. To calculate the voltage drop U_{im} (ω,t) across a resistor R the capacity C between the plate and the grounded vacuum chamber has to be taken into account,

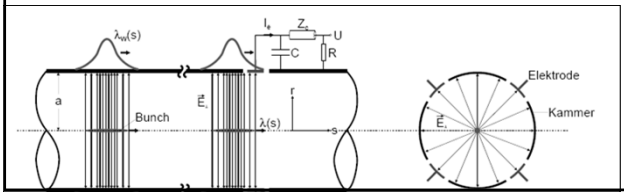
$$U_{im}(\omega,t) = Z_{plate}(\omega)\cdot I_{im}(t) = Z_t(\beta,\omega)\cdot I_{beam}(t)$$

The impedance Z_{plate} of the plate is:

$$Z_{plate} = \frac{R}{1+Ri\omega C}$$

And Z_t is the 'transfer impedance' derived from above:

$$Z_t(\omega) = \frac{A}{2\pi d}\cdot\frac{i\omega}{\beta c}\cdot\frac{R}{1+Ri\omega C}$$

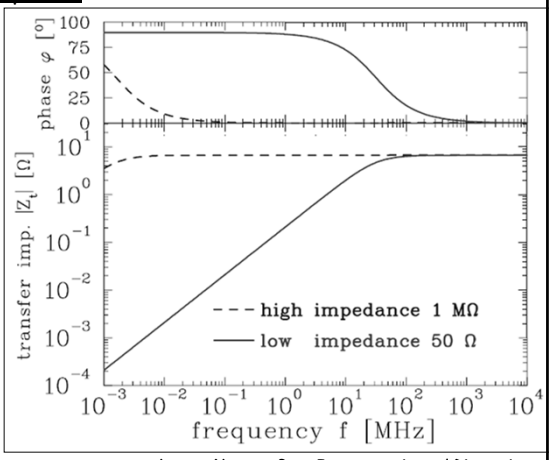


Beam Position Monitor (BPM) –buttons-

This impedance has a high pass characteristic which is shown in Fig. Since high frequency signals are typically transported via 50 Ω coaxial cables, a low input impedance of the first amplifier is often used.

The frequency ω depends on the bunch length, respectively on the RF frequency of the accelerator.

Therefore the coupling of a capacitive pick-up to the long bunches (e.g. in the beginning of a hadron accelerator chain) is very week.



Beam Position Monitor (BPM) –buttons-

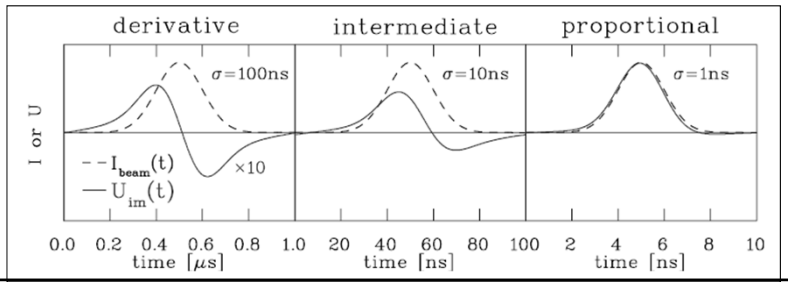
For frequencies $\omega \ll \omega/RC=\omega_{cut}$ the measured voltage $U_{im}(t)$ becomes

$$U_{im}(t) = \frac{R}{\beta c} \cdot \frac{A}{2\pi d} \cdot \frac{dI_{beam}(t)}{dt}$$

where $dI_{beam}(t)/dt = i\omega I_{beam}$ is the derivative of the bunch length.

For $\omega \gg \omega/RC=\omega_{cut}$ the voltage U_{im} follows the bunch length by

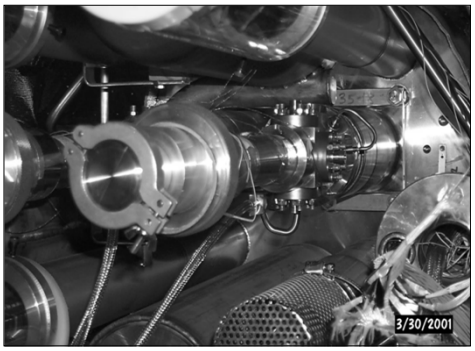
$$U_{im}(t) = \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{A}{2\pi d} \cdot I_{beam}(t)$$

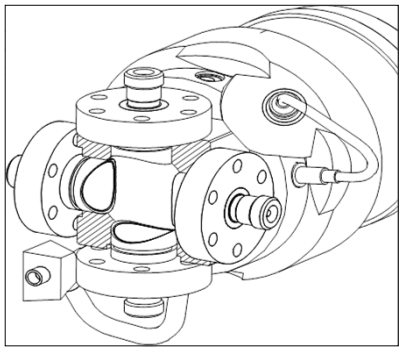


Beam Position Monitor (BPM) –buttons-

In practice that means, that button type pick-ups with about 100 mm² < A < 500 mm² are used only in high energy hadron accelerators, since their coupling to the beam is strong due to the short bunch length.

LHC pick-ups: Each electrode has a capacitance of 7.6 pF, giving a transfer impedance of 1.4 Ω

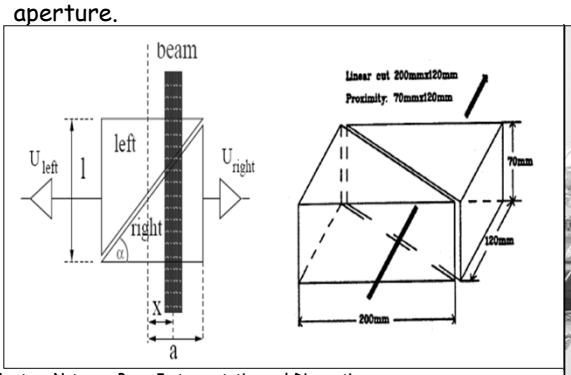




H. Schmickler, Talk on Intermediate CAS 2009

Beam Position Monitor (BPM) –Shoebox-

For low energy accelerators with large bunch length and sometimes large apertures d, the common way for a sufficient signal is to increase the size A of the pick-up and to use high impedance amplifiers in the readout. An example is a shoe-box type of BPM. It has a large aperture but also large size electrodes which are separated diagonal in respect to the beam. Therefore the induced voltage on both plates is proportional to the length of the beam projection on the electrodes. These types of BPMs are very linear over nearly their whole aperture.

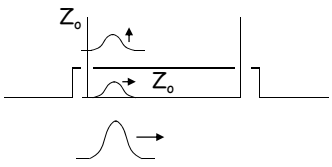


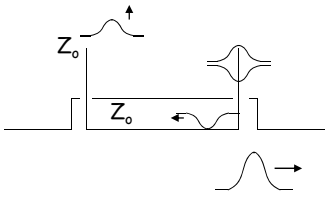
Lecture Notes on Beam Instrumentation and Diagnostics
Peter Forck (GSI) , Joint University Accelerator School January – March 2009

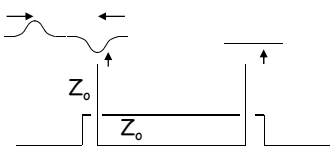
The BPM Measurement System in HIRFL-CSR, DIPAC2009

Beam Position Monitor (BPM) –Stripline-

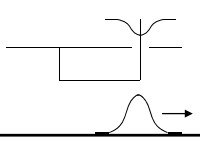
Stripline types of pick-ups are used in the case where the bunch length is shorter or about the length of the electrode. A signal is created by the beam on each end of the line which depends on the characteristic impedance Z_{strip} of the electrode, often $Z_{strip}=50\Omega$. Depending on the termination R of the downstream port the signal there is canceled ($R=Z_{strip}$) or appears partially ($R \neq Z_{strip}$). A complete cancellation at the downstream port happens only if the speed of the beam is equal to the speed of the signal in the transmission line which is almost true for $\beta\approx1$. In this case a stripline is known as "directional coupler" since the signal on one port depends on the beam direction. The upstream port always includes the induced signal and the reflected inverted signal separated in time by $\Delta t=2l/c$ (for $\beta=1$).







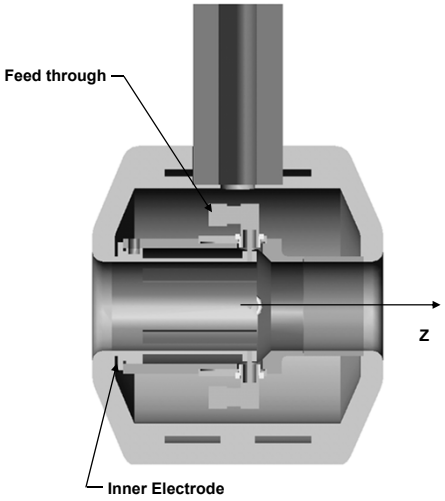
Upstream port signal also zero in steady state case if electrode electrical length is ½ bunch spacing!



When the upstream end is shorted and the downstream end is terminated with $R = Z_{strip}$ then there is an inverted signal observed at the downstream end.

Beam Position Monitor (BPM) –Stripline-

Stipline in SNS LINAC



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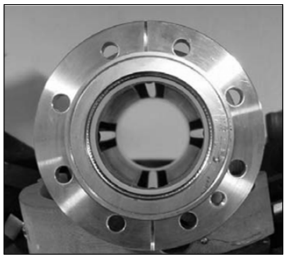
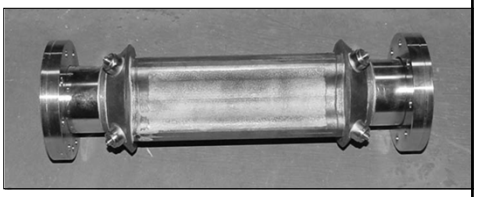




SNS LINAC Beam Position Monitor Pickups Final Design Review, March 12, 2002, Jim O'Hara - LANL

Beam Position Monitor (BPM) –Stripline-

The characteristic frequency of a stripline-signal is defined by Δt and is $\omega_{strip} = 2\pi \cdot 2 \cdot c/2l$. Assuming a short bunch, the Fourier transformation of the response is the transfer impedance $Z_t(\omega)$

$$Z_t(\omega) = Z_{Strip} \cdot \frac{\alpha}{2\pi} \cdot \sin(\omega l / c) \cdot e^{i(\pi/2 - \omega l/c)}$$

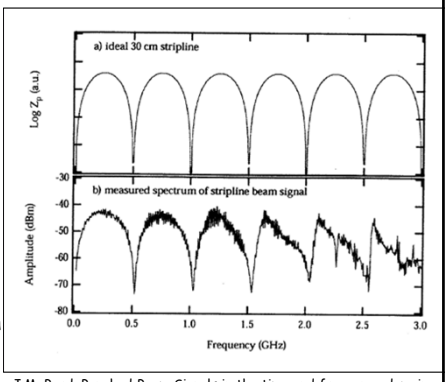
with α = azimuthal coverage angle (width of the electrode).

$Z_t(\omega)$ shows a maximum response at a bunch repetition frequency of $\omega = \omega_{RF} = n \cdot \omega_{strip}/4$ and zero response at $\omega = \omega_{RF} = n \cdot \omega_{strip}/2$; n=1, 2, 3, …

Therefore the optimum length of the stripline electrode is $l = l_{RF}/4$.

If on the other hand the bunch length exceeds the length of the electrode, partially cancellation occurs at the upstream port which reduces the signal.

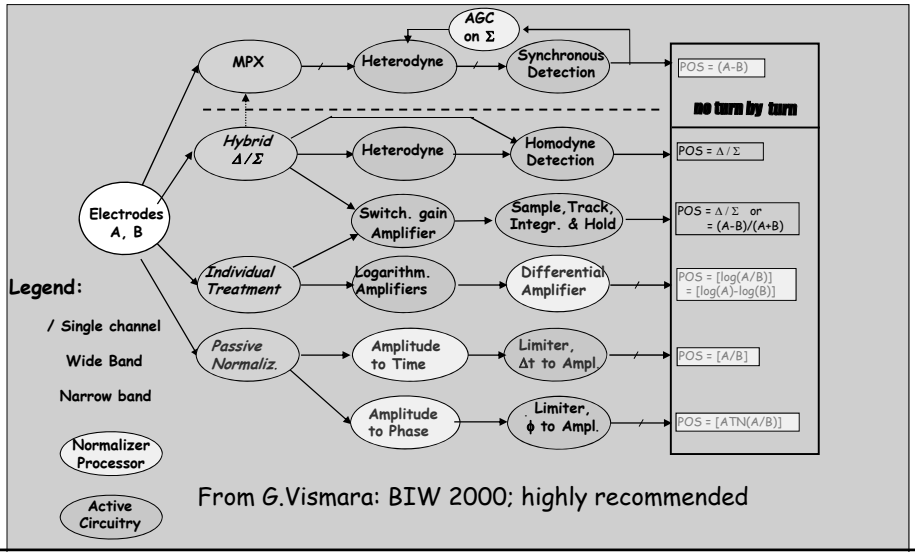
This is also valid for $\beta << 1$, since the field of the bunch is not a pure TEM wave any more. Note that therefore also the coupling to the 4 pick-up electrodes became strongly non-linear with the beam position .



J.M. Byrd, Bunched Beam Signals in the time and frequency domain, in Proceeding of the School on Beam measurement, Montreux, p. 233 World Scientific Singapore (1999).

Beam Position Monitor (BPM) –readout-

There are various electronic concepts in use which are discussed in detail in



From G.Vismara: BIW 2000; highly recommended

Beam Position Monitor (BPM) –readout-

- The beam position of one plane is derived from the difference of the signal of the two opposite electrodes and after applying corrections to the non-linear position response of the BPM.
- The signals are also intensity dependent; therefore normalization to the intensity is always necessary. Position = Δ/Σ
- Their sensitivity has to be as low as the minimum expected bunch charge has to produce position readings with the required accuracy and resolution.
- Their dynamic rage is defined by the various intensity conditions, e.g. acceleration of proton and ion beams. A dynamic range of several decades might be necessary in such a case. (+ position variations)
- A bunch-by-bunch measurement of the beam position requires a broadband signal processing. In this case the dynamic range is defined by the variation in bunch charge only (+ position and β variations).
- An orbit measurement requires a narrowband signal processing with a maximum update rate of the revolution frequency. In this case the required dynamic range is defined by the stored or accelerated current which might include in addition a variable number of bunches. But due to the lower speed of the signal processing there are electronic components (e.g. ADCs) available which have a very high dynamic range.

Beam Position Monitor (BPM) –readout-

- A high bandwidth offers some advantages, e.g. a measurement of the individual bunch current by summing up all four signals from the electrodes (to be position independent). Especially during commissioning of an accelerator this feature becomes important to detect places of beam losses.
- The BPMs are best located at local maxima of the β-function (close to focusing quadrupoles in both planes) to get maximum sensitivity. This already implies two beam position measurements per betatron wavelength with a four electrode BPM. This is typically sufficient for a useful orbit distortion measurement.
- Often some BPMs are added at critical regions like high dispersion, injection, extraction or collimation + sensitive tune monitor (circ. accel.).
- In high intense beams the beam position excursions have to be carefully monitored and controlled. Too high excursions should cause an alarm signal to the machine protection system to avoid damage of components due to a mis-steered high intense beam.

Measurement of beam emittance

It is very important to understand and control transverse (and longitudinal) beam transport an emittance at the beginning of an accelerator chain since any kind of **mismatch may result in emittance growth and halo formation**.
And, in contrast to electron circular machines, the normalized emittance cannot shrink. Therefore the luminosity is defined by the whole beam transport. **Measurements of the emittance** at the beginning and at every stage are most helpful **to understand problems in the accelerator chain**.

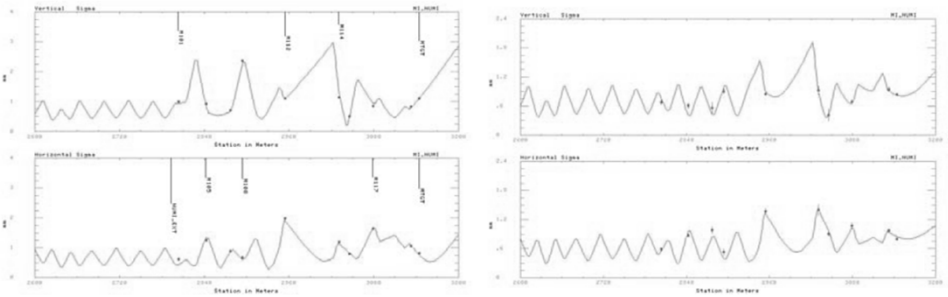


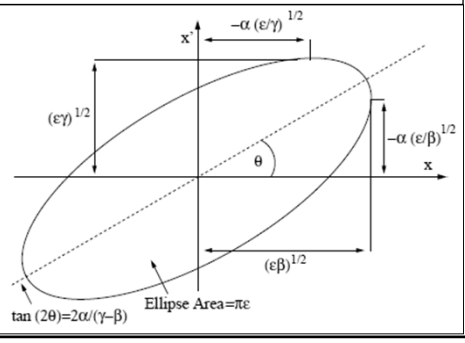
Figure 18. MuMI beam-line: Beam sigma with Q101 error (left), and after error correction (right).

Beam Emittance Measurements at Fermilab Manfred Wendt; FERMILAB-CONF-08-665-AD

Measurement of beam emittance

$$\varepsilon_{rms}(x,x') = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

In linear machines and transport lines the optic parameters depend on the incoming beam and the emittance has to be determined by measuring ⟨x⟩ and ⟨x'⟩. Methods and instruments for this purpose are discussed now.



$$\varepsilon_x = \frac{1}{\beta_x(s)}\left[\sigma_x^2(s) - \left(D_x(s)\frac{\Delta p}{p}\right)^2\right]$$

In circular accelerators a measurement of the beam profile width σ is often sufficient to determine the beam emittance since Δp/p = momentum spread, β(s), D(s) and Δp/p can be determined sufficiently precise by common diagnostic methods. Minimum invasive instruments are needed not to destroy the circulating beam. These instruments are discussed in "Profile Monitors".

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \varepsilon \cdot \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \quad with \quad \varepsilon = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

Federico Roncarolo :
Accuracy of the transverse emittance measurements of the CERN large hadron collider. Thèse EPFL, no 3402 (2005).

Measurement of beam emittance

Due to their nature of measuring the angular and spatial beam distributions at the same time these type of instruments are fully destructive to the beam. They cannot be used in full power high intense beams. However, they are installed in nearly all machines to enable a measurement of the optic parameters at low current to tune the machine and to prove its health.

Most typical devices for emittance measurement use fluorescent screens or Secondary Emission- (SEM-) Harps as detectors, therefore a brief introduction is given first.

Many useful information at:

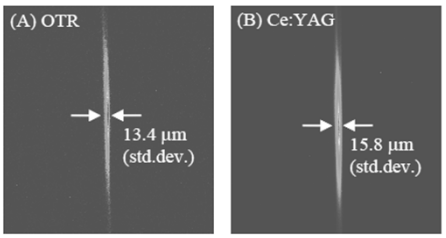
Proceedings of the 6th CARE-HHH-ABI workshop on **"Transverse and Longitudinal Emittance Measurement in Hadron-(Pre-)Accelerators"**. Date: December 10th to 12th , 2008, Castle Kauzenburg in Bad Kreuznach.
CARE-Conf-08-033-HHH,
http://adweb.desy.de/mdi/CARE/Bad_Kreuznach/Reports/ABI-Workshop_Proceedings_all.pdf

Measurement with –Screens-

The observation of beam **profiles on fluorescent or scintillation screens** is one of the oldest and most common diagnostic techniques. Together with modern TV cameras and imaging processing this technique offers simplicity, reliability and high resolution.

Resolution issues:
- grain size and CCD pixels
- optical effects
- radiation damage (screen and camera)
- non-linear response of the screen
- saturation of the light yield inside the material at high beam intensities

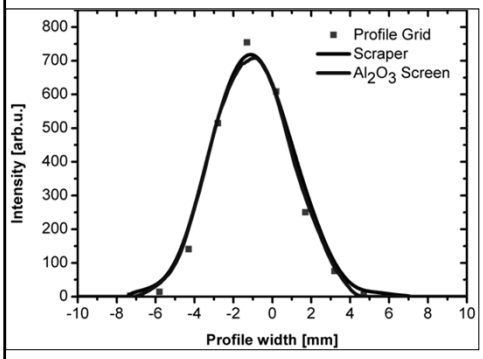
H. Maesaka et al.,DIPAC09

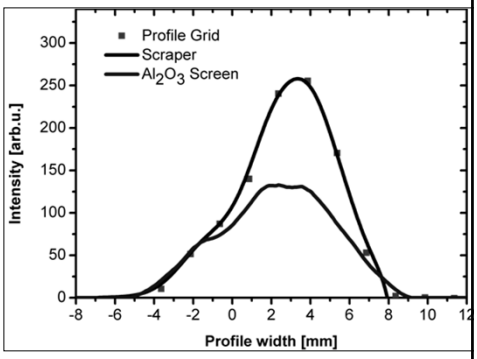


Unfortunately for the moment there is no clear recommendation for "the best" material for the use in high current applications and further studies are still needed and ongoing. Lot of details at: **http://www-bd.gsi.de/ssabd/**

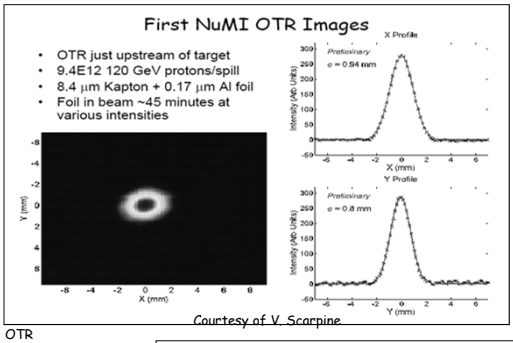
Measurement with –Screens-

4.8 MeV/u	← Same pulse energy →	11.4 MeV/u
$4.3*10^{10}$ ppp	(~similar flux [ions/(cm² s)])	$1.8*10^{10}$ ppp
5ms	Ion beam: Ca^{10+},	1,2 ms





Measurement with –OTR Screens-

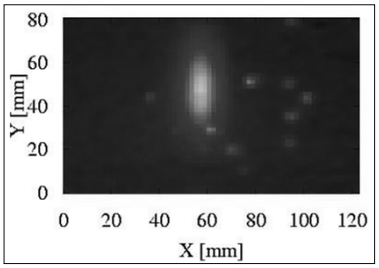


Courtesy of V. Scarpine

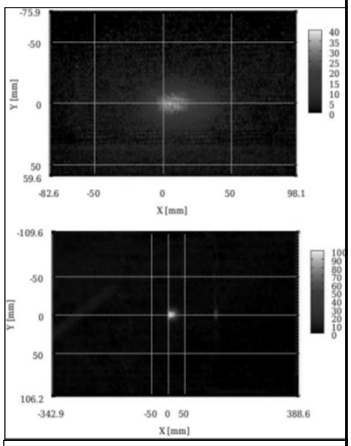
INITIAL OTR MEASUREMENTS OF 150 GEV PROTONS IN THE TEVATRON AT FNAL. V.E. Scarpine BIW06

KEK 12-GeV PS (γ = 12.8), 2 x 10^{12} protons per pulse.

A. Toyoda et al., "Optical transition radiation monitor for high intensity proton beam at the JPARC", DIPAC2007,



J-Parc: 50 GeV p; 1.5 x 10^{11} p/spill



A typical OTR image (top) and a Luminescence screen image (bottom)

First Light for Optical Transition Radiation Monitor at the J-PARC; A. Toyoda, et al, DIPAC2009

OTR Cases Show Potential for Ions

Fermilab

- **Table I. Comparison of various particle beam cases and estimated OTR photons generated for ions (Preliminary).**

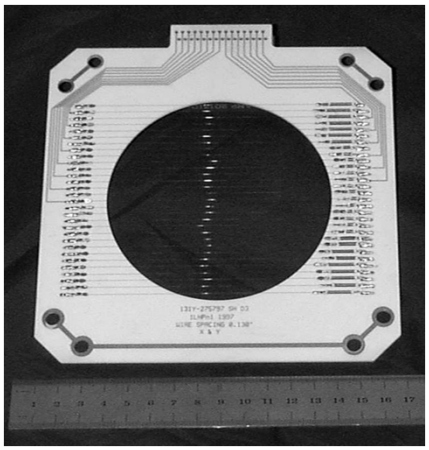
Part.	E(MeV)	Q	β	γ	Y(ph/e)	N	Mult.	Photon #	CCD
e^-	.080	1	0.63	1.15	$2x10^{-6}$	$4x10^{11}$	1	$7x10^5$	*Int.
e^-	150	1	0.99	300	$2x10^{-3}$	$6x10^9$	-	$1x10^7$	yes
p^+	$120x10^3$	1	0.99	129	10^{-3}	10^{11}	-	10^8	CID
	MeV/u								
Ar^+	11.4	10	0.15	1.01	10^{-6}	10^{10}	5.3	$5x10^4$	*Int.
U^+	11.4	28	0.15	1.01	10^{-6}	10^{11}	42	$4x10^6$	*Int.
U^+	300	73	0.65	1.21	10^{-6}	10^9	5329	$5x10^6$	*Int.

Calculated from measurements above:

*Use intensifier for gain and the gating feature. More discussions later today. Also the ion intensity increases projected for FAIR look even better for photon numbers. The Multiplier (Mult.) column is the estimated scaling with $Q^2\beta^2$.

Measurement with –Harps-

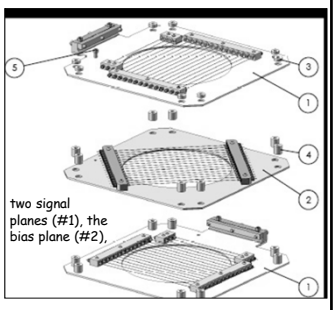
- Each individual wire is connected to an electrical vacuum feedthough and an amplifier.
- Beam particles hitting a wire create secondary electrons of 20 – 100 eV from its surface.
- The secondary electron yield Y varies between about 300% for low energy ions (e.g. 40 keV) to about 2% for minimum ionizing particles for most common metals.
- The SEM current is linear over many orders of magnitude.
- The spacing and the diameter of the wire defines the resolution of the instrument. Typical values of both are between 20 μm to about 2 mm.
- Materials are tungsten and titanium due to their good mechanical and thermal properties but also carbon and aluminum.
- Low-Z materials have the advantage of lower beam losses



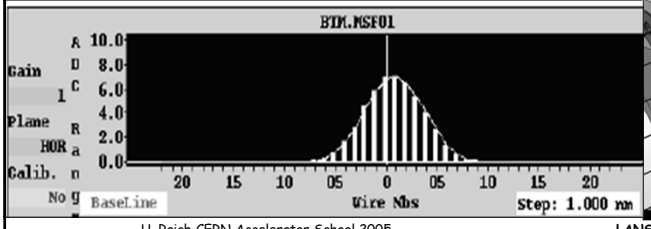
Harps in high radiation environments
11th ICFA International Mini-Workshop on Diagnostics for High-Intensity Hadron Machines, 2002, by Mike Plum

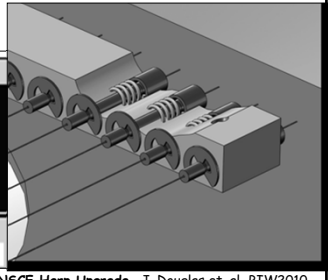
Measurement with –Harps-

- A negative bias voltage on the wires or positive collection electrodes avoids recollection of the secondary electrons by the same or another wire.
  => Avoid signal coupling (also electrical).
- The dynamic range of a SEM harp is limited the electronic noise on the low beam current end and by thermal electron emission due to heating of the wire at the high beam current end.
- Beside thermal electron emission the wire itself or its support (e.g. soldering) may melt and the elongation of the wires changes with heat.
- A SEM Harp (or a thin screen) is quite transparent for not too low energetic beams and successive harps are possible.



two signal planes (#1), the bias plane (#2),





U. Raich CERN Accelerator School 2005

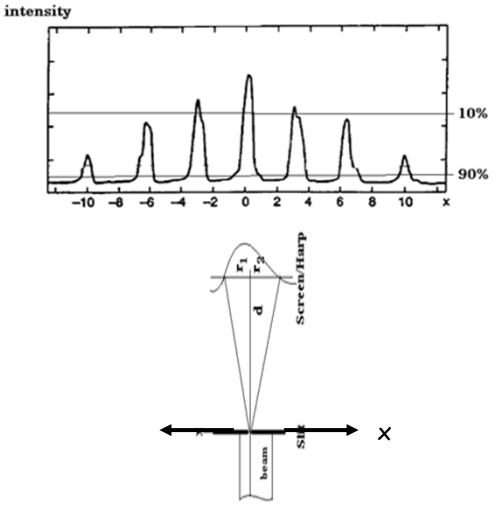
LANSCE Harp Upgrade, J. Douglas et. al, BIW2010

Emittance measurement by Slit + screen/harp

Low energy hadron particles which have a **penetration depth of a cm or less** can be stopped by a simple metallic plate. A small transversal slit of height h_{slit} selects a beamlet which shines on a screen or harp monitor in a drift distance d.
The width of the measured beamlet is defined by

- the **divergence of the beam x'** at the slit position x_n, on the distance d and
- on the **resolution of the system defined by the h_{slit}** and
- the **resolution of the screen/harp device**.

The height of the signal depends on the bunch current I_0 and on the current distribution in the bunch (the beam profile). The slit is scanned across the beam profile and for each position x_n a beamlet distribution $I(x_n, x')$ is collected.



Emittance measurement by Slit + screen/harp

The radii $r_{1,2}/d = x_{1,2}'$ give the angular spread of the beam at the position x_n at **a defined amount of current** included in the emittance ellipse.
The emittance is:

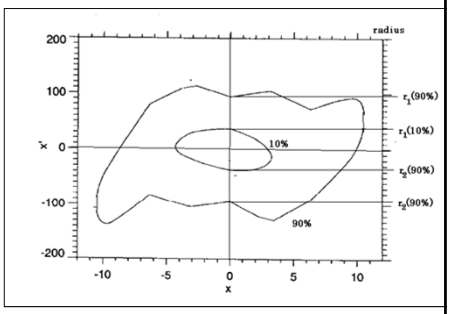
$$\varepsilon_x(x,x') = 1/\pi \int dx\, dx' = 1/\pi \cdot A_x$$

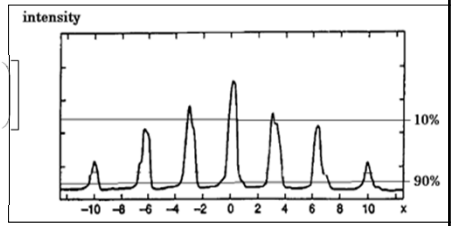
The rms emittance of the incident beam is:

$$\varepsilon_{rms}(x,x') = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

$$\varepsilon_{rms}^2 \approx \frac{1}{N^2} \cdot \left[\sum_{j=1}^{p} n_j \left(x_{nj} - \bar{x} \right)^2 \right] \cdot \left[\sum_{j=1}^{p} \left(n_j \cdot \left(\frac{\sigma_j}{d} \right)^2 + n_j (\bar{x'}_j - \bar{x'})^2 \right) \right] - \frac{1}{N^2} \left[\sum_{j=1}^{p} n_j x_{nj} \bar{x'}_j - N \bar{x} \bar{x'} \right]^2$$

Calc. details see: M. Zhang, Emittance Formula for Slits and Pepper-pot Measurement, TM-1988, Fermilab, 1996.





Emittance measurement by Slit + screen/harp

The procedures descript above neglect the finite **resolution** of the device.
- A **small h_{slit} and small step sizes** of the slit positioning improve the resolution.
- When using a grid as detector its resolution can be improved by **scanning the grid** as well.
- A **position of the device in a region with high x'** is most helpful for a good resolution.
- In high density beams care has to be taken that **space charge in a beamlet** might extend the angular spread of its on the way to the detector.

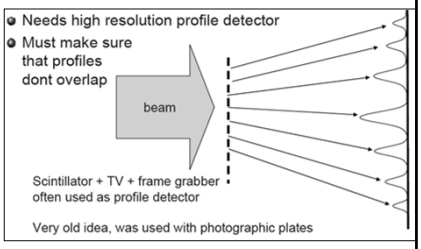
Comparisons (simulations 3 MeV protons) of different geometries (stainless steel) show that
- geometry (d) gives results similar to geometry (a),
- geometry (b) gives the best (smallest) results and
- geometry (c) gives the worse results, with about 30% of the particles that reach the SEM-grid being scattered.

But at (b) the aperture of the slit is smaller than its thickness => the measured phase-space distribution is flowed by an **angular cut** and the emittance is **underestimated**.

From: Design of a New Emittance Meter for LINAC4; B. Cheymol, et al. ; DIPAC2009

Emittance measurement by Pepperpot

The scanning of the whole beam size in both planes needs quite a lot of time with very stable beam conditions. To overcome the scanning procedure a plate with thin holes in defined distances (pepperpot) produces a lot of beamlets in the x, y plane. Therefore the whole phase space can be measured with one single shot onto the pepperpot mask. This will reduce the heat load of the plate drastically in respect to slowly scanning slits.



U. Raich CERN Accelerator School 2005

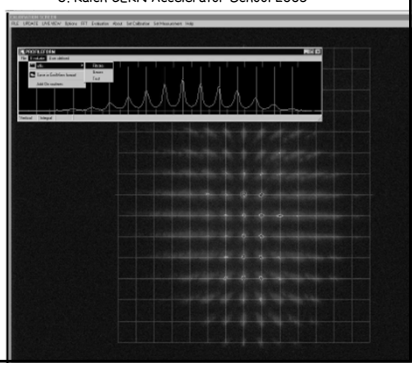
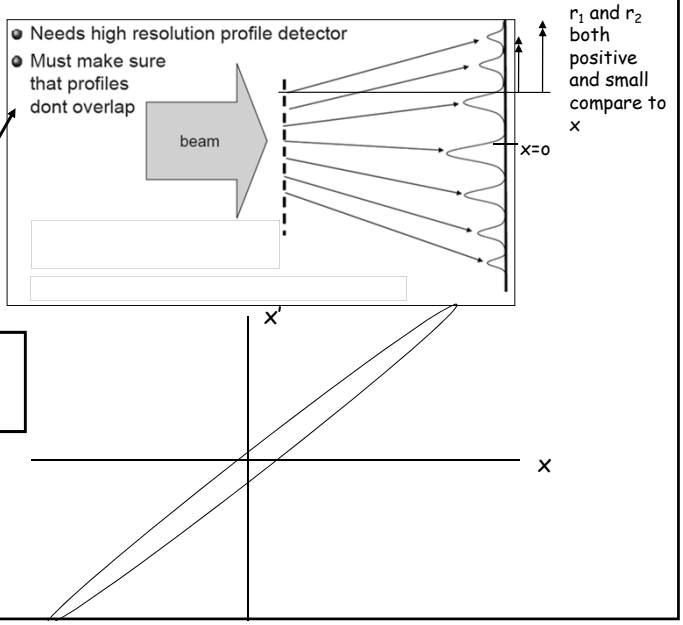


Photo P. Forck

Emittance measurement by Pepperpot

What kind of emittance-picture do you expect from this picture at ≈ 95%?

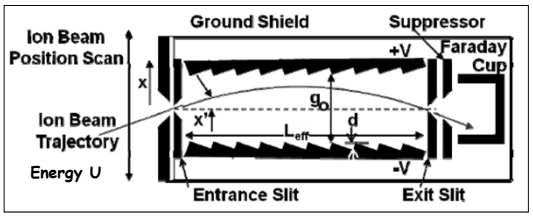


r_1 and r_2 both positive and small compare to x

=> very good resolution is required !

Emittance measurement by Allison Scanner

Measures the trajectory angle distribution x' with an electric sweep while a mechanical scan probes the particle position distribution x.



Issues:

- The entrance angle-to-voltage conversion is $x' = V \cdot L_{eff}/(2 \cdot g \cdot U)$ where g is gap between the plates and L_{eff} the effective length of the deflection field.
- The deflector plates are stair-cased to prevent impacting particles from being scattered into the exit slit.
- Space charge effect can yield error up to few dozens %.
- Resolution comparable with pepperpot.
- Only for low energy beams (<100 KeV).

Low-Energy Emittance Studies with the New SNS Allison Emittance Scanner
M.P. Stockli, et al, Proceedings of PAC09, Vancouver, BC, Canada

Emittance measurements by quadrupole variation or 3 screens/harps methods

For higher beam energies

In a beam transport system the sigma matrix σ is transformed from one point s_0 to another s_1 by

$$\sigma(s_1) = M\sigma(s_0)M^T$$

where M and M^T are the transport Matrix between the two points and its transposed, respectively. In a dispersion free beam transport all are 2x2 Matrices and the measured width $\sigma_{measured}$ at (s1) is then:

$$\sigma^2_{measured}(s_1) = \sigma_{11}(s_1) = M^2_{11}\sigma_{11}(s_0) + 2 \cdot M_{11}M_{22}\sigma_{12}(s_0) + M^2_{12}\sigma_{22}(s_0)$$

The matrix elements M_{ij} are known by the elements of the transport system between the two points. The three unknown elements of the $\sigma_{ij}(s_0)$ matrix can now be resolved by at least three different measurements, either by three profiles at three different locations in the transport system or by three different transport optic settings e.g. by variation of the focusing strength of a quadrupole.
The matrix elements M_{ij} of different measurements have to differ significantly to solve the linear system, therefore the different locations have to have enough phase advance or the focal strength of the quadrupole have to be varied large enough.

Introduction of σ-Matrix

(see for example: K. Wille; Physik der Teilchenbeschleuniger, Teubner)

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{yy'} & \sigma_{y'}^2 \end{pmatrix} = \varepsilon_{rms} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} = \sigma\, matrix$$

$$\varepsilon_{rms} = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

$(\beta\gamma - \alpha^2 = 1)$

Beam width$_{rms}$ of measured profile = $\sigma_y = \sqrt{\beta(s) \cdot \varepsilon}$

Transformation of σ-Matrix through the elements of an accelerator:

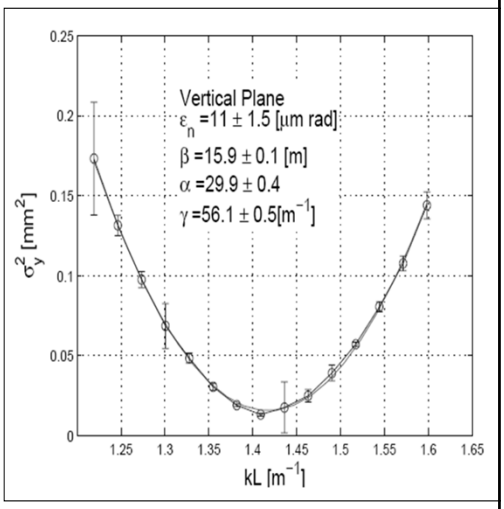
$$\sigma_s = M \cdot \sigma_0 \cdot M^t$$

$$M = \begin{pmatrix} M_{11} M_{12} \\ M_{21} M_{22} \end{pmatrix}; M^t = \begin{pmatrix} M_{11} M_{21} \\ M_{12} M_{22} \end{pmatrix}$$

Emittance measurements by quadrupole variation or 3 screens/harps methods

Profiles are measured by thin screens or harps.
=> small and almost negligible beam blowup due to the measurement itself so that the beam can transverse a few screens.
=> "one shot" measurement
=> scanning methods need a stable beam over the scanning time.

Three measurements give a unique solution but no error estimation.
=> more stations or by more quadrupole settings are recommended.
=> variation of the quadrupole settings allows a quadratic fit of the square of the measured beam size versus the quadrupole gradient together with an estimate of the errors in the measurement.



Beam Emittance Measurement for the New Full Energy Injector at ELETTRA; Giuseppe Penco et al, EPAC'08,

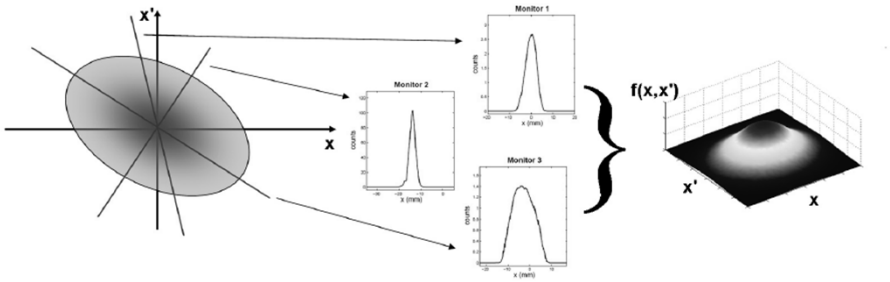
Emittance measurements by quadrupole variation or 3 screens/harps methods

The standard methods descript above are valid under the assumption that:
- the dispersion along the section is zero,
- the transfer matrices are known,
- no coupling between the two planes is present and
- no space charge or other non-linear forces are present.

With dispersion the particle trajectory vector then includes the momentum spread = (x,x',Dp/p) and the σ-matrix and the transport matrix M become 3x3 matrices. In this case at least six measurements are necessary to determine all σ-matrix elements to resolve the emittance.

The influence of space charge in high intense beams can be measured by observing the emittance evaluation in dependence of the intensity. As discussed before, care has to be taken not to saturate or even destroy the monitor with the beam.

Emittance measurement by Tomography



The plot on the left side represents the unknown beam transverse phase-space distribution at the reference position $z = z_0$. Beam profile monitors acquire projections of the phase-space onto the x coordinate (= profiles) at different locations with a certain phase advance (middle plots). These projections are related to the beam distribution at $z = z_0$ through linear transport matrices accounting for drift space and/or quadrupole magnets. In beam tomography the profile data are employed by a mathematical algorithm in order to reconstruct the two-dimensional beam density distribution (right plot).

MENT code at PSI: Beam Tomography for non-destructive Projected Emittance Measurements: http://aea.web.psi.ch/Urs_Rohrer/MyWeb/ment.htm

Transverse Phase-Space Beam Tomography at PSI and SNS Proton Accelerators D. Reggiani, et al., HB2010,

Emittance measurement by Tomography

Reconstruction algorithm used:

- convolution and back projection methods (FBP)
- maximum entropy (MENT) algorithm
- maximum likelihood - expectation maximization (MLEM)

The "filtered back projection" or "convolution" reconstruction process is widely used because the mathematics is simple and easily programmable. However, for a small number of projections, streaking artifacts dominate the reconstructed image. Choosing the optimum algorithm to use is largely dependent on the problem being solved. Some algorithms are better at reconstructing Gaussian distributions, whilst others are suited to detailed distributions.

Some questions arise regarding the limitations of tomography technique for space charge dominated beams. The use of linear space charge forces led to inconsistent results.

Phase Space Tomography Using the Cornell ERL DC Gun
F. E. Hannon etal, EPAC'08

Instruments for beam profile measurements

The meaning of transversal beam profile measurement is to determine the transverse shape of the beam down to about 3 - 4 σ. (beyond=halo). Therefore a dynamic range of 10^3 to 10^4 is sufficient. Typical beam dimensions of hadron beams are in the mm range so that a resolution of 100 μm is often sufficient.

In contrast to the destructive emittance measurement the profile measurement needs to be minimal invasive for two reasons:
1. not to influence the beam and
2. not to destroy the monitor.

Emittance ε

$$\varepsilon_x = \frac{1}{\beta_x(s)}\left[\sigma_x^2(s) - \left(D_x(s)\frac{\Delta p}{p}\right)^2\right]$$

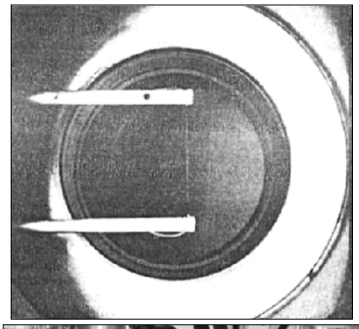
In rings β(s), Δp/p, D(s) is known by other diagnostic methods

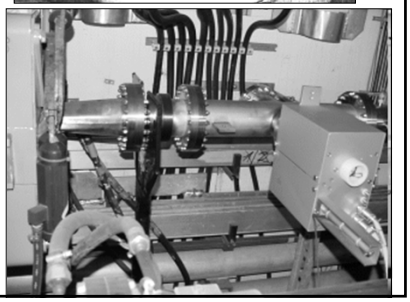
Instruments for beam profile measurements -Wire Scanner-

Conventional wire scanners with thin solid wires are widely used for beam size measurements in particle accelerators.

Their advantages:
- Resolution of down to 1 μm
- Trusty, reliable
- Direct

Their known limitations are:
- The smallest measurable beam size is limited by the finite wire diameter of a few microns
- High beam intensities combined with small beam sizes will destroy the wire due to the high heat load.
- Emittance blow up





Instruments for beam profile measurements -Wire Scanner-

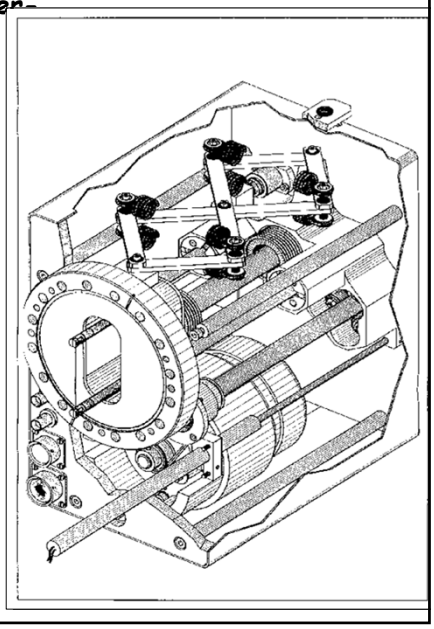
High speed (e.g. 5m/s at Tevatron and up to 20m/s CERN, KEK) is required for intense and high brilliant beams in circular machines for two main reasons:

1) to reduce the heat-load of the wire; the heat load is inverse proportional to the speed.

2) to reduce the emittance blow-up; the emittance blow up is also inverse proportional to the speed of the wire.

=> High speed is realized by circular movement of the wire which reduces the position resolution and therefore the profile resolution to 10-100 μm.

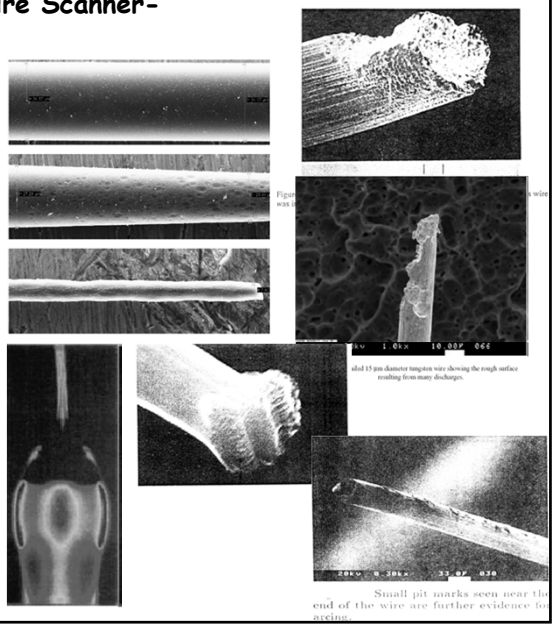
=> The speed of a linear wire scanner is mainly limited by the vacuum bellow stress property which limits the acceleration of the mechanical feedthrough to a few g



Fast and High Accuracy Wire Scanner
M. Koujili, et al, DIPAC2009

Instruments for beam profile measurements -Wire Scanner-

- Light materials with long radiation length are preferred to reduce the emittance blow-up and to minimize the energy deposition in the wire.
- A high melting point is preferred to extend the lifetime of the wire. For that reason a thin (7-20 μm) Carbon wire is often a good choice due to its high melting temperature of about 3500 ^{0}C and its excellent mechanical stability.
- Sublimation of the wire material takes place even before the melting temperature is reached and reduces the material at each scan.
- The heating of the wire limits the use of wire scanners in high intense and high brilliant beams often to low currents only.

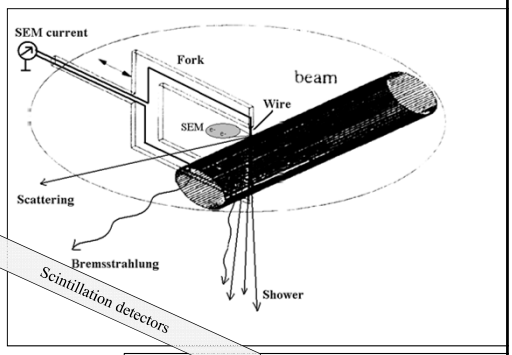


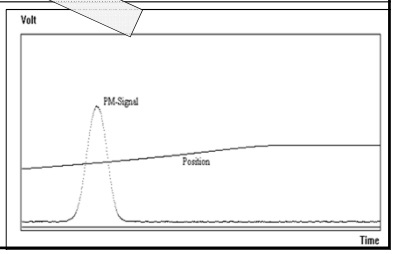
Instruments for beam profile measurements -Wire Scanner-

The signal from the beam-wire interaction can be detected with two different methods:

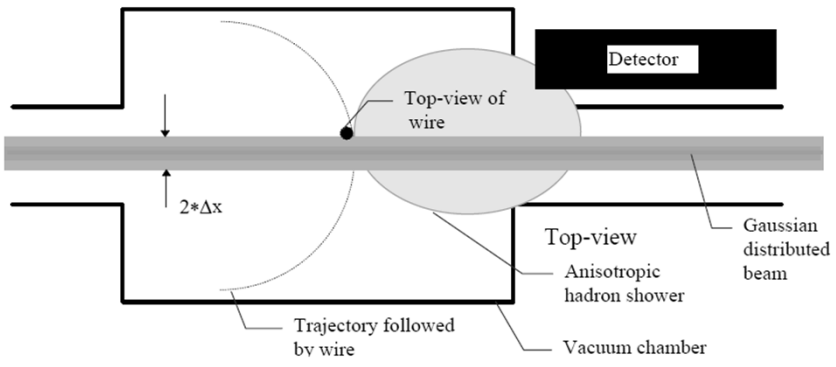
1) Detection of scattered beam particles outside the vacuum chamber by fast scintillation counters.

- Monte Carlo studies are most helpful to find an efficient position for the detector somewhere downstream of the scanner.
- Note that the signal can depend on the wire position, especially when using asymmetric detector positions at large beam sizes.
- A fast scintillation counter is able to resolve single bunches





Instruments for beam profile measurements -Wire Scanner-



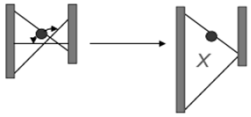
Wire scanners in low energy accelerators
P. Elmfos ar. Al.; NIM A 396

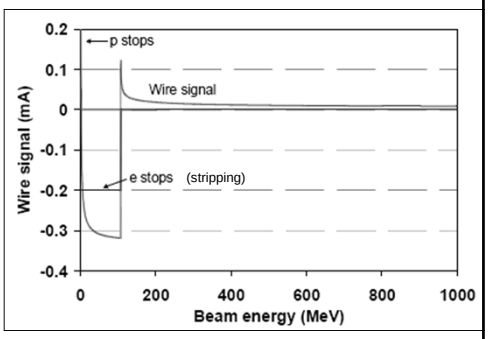
Instruments for beam profile measurements -Wire Scanner-

2) Secondary electron emission (SEM) .

- This method is often used at low energy beams where the scattered particles cannot penetrate the vacuum pipe wall (below pion threshold).
- Avoid cross talk of wires
- In this low energy regime the hadron beam particles stop in the wire, so that the signal is a composition of the stopped charge (in case of H-: proton and electrons) and the secondary emission coefficient. Therefore the polarity of the signal may change, depending on the beam energy and particle type (true also for grids!).
- If the temperature of the wire exceeds the themionic threshold the emission of thermal electrons starts to superimpose the SEM signal. => Profile useless!

Cross-talk between wires is the main dynamic range limiting factor for 3-wires scanner





M. A. Plum, et al, SNS LINAC WIRE SCANNER SYSTEM, Signal Levels and Accuracy; LINAC2002

Instruments for beam profile measurements -Laser Wire Scanner- (LINAC only)

Photo-detachment: $H^- + \gamma \rightarrow H^0 + e^-$ binding energy E=0.75 eV ↔ λ=1670 nm

(the second electron (=13.6 eV) will not be stripped)

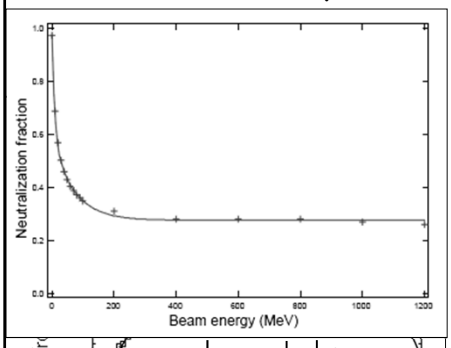
Threshold at λ=1670 nm (IR) ↔ E=0.75 eV

Maximum at λ=930 nm (near IR) ↔ E=1.3 eV

Doppler shifted photon energy in rest-frame:

$$E_{cm}=\gamma(1-\beta\cdot\cos\theta)\cdot E_{lab}$$

Frequently used Nd:YAG laser with λ_{lab}=1064 nm

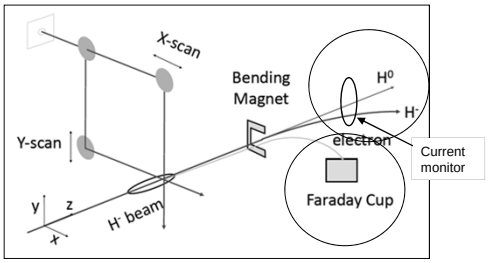


The relativistic increase in photon flux compensates Doppler shift

Photo-detachment cross section is flat 0.4– 1 GeV

Wavelength in 1 GeV beam frame	Wavelength in 0.2 GeV beam frame

Laser Beam-Profile Monitor Development at BNL for SNS [R. Connolly , LINAC02

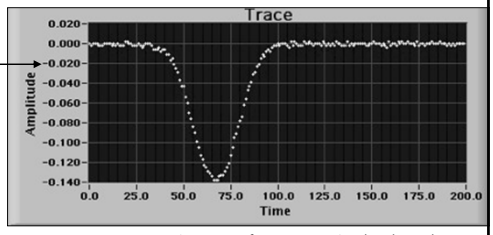


From S. Assadi, W.Blokland, R.Connolly, Y.Liu, T.Shea

Detection of:

1. Reduction the bunch current.
2. Liberated electrons
3. Remaining H^0
4. Bunch length by short pulse laser

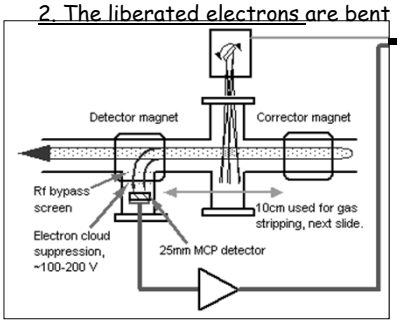
Plotted versus the laser beam position.

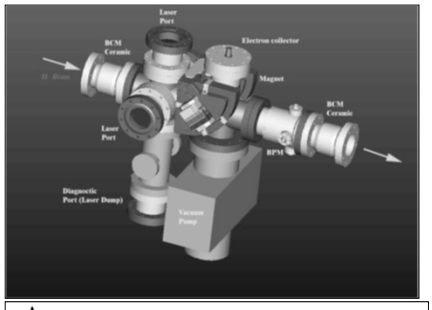


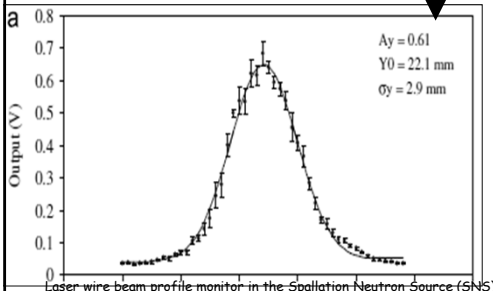
Laser Diagnostic for H- Beams; T. Shea (ORNL), 2009

Instruments for beam profile measurements
-Laser Wire Scanner-

2. The liberated electrons are bent by a small dipole field into a Faraday cup.







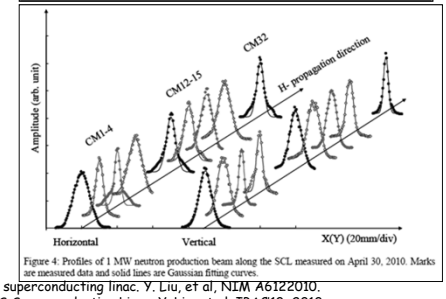


Figure 4: Profiles of 1 MW neutron production beam along the SCL measured on April 30, 2010. Marks are measured data and solid lines are Gaussian fitting curves.

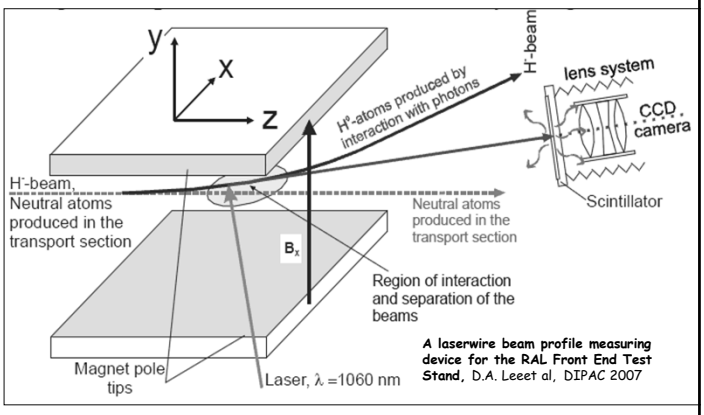
Laser wire beam profile monitor in the Spallation Neutron Source (SNS) superconducting linac. Y. Liu, et al, NIM A6122010.
Parasitic Profile Measurement of 1 MW Neutron Production Beam at SNS Superconducting Linac. Y. Liu, et al. IPAC'10, 2010.

Instruments for beam profile measurements
-Laser Wire Scanner-

3. The direct use of H^0: Direct emittance measurement using the laser as a "slit". After bending the H- beam the neutral H0 remain on a straight line where a screen or grid measures their distribution. The laser "slit" has the advantage of no thermal problems which exists in conventional slit-grid monitors.

Interaction with the laser in the middle of a dipole reduces the background of H0 produced in front of the laser

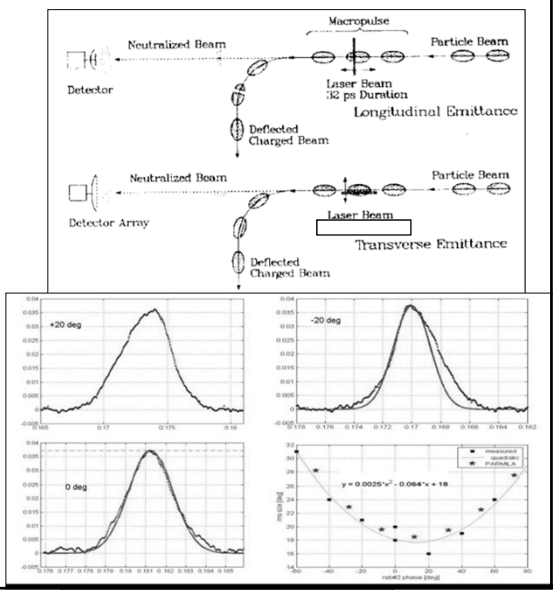
The laser neutralisation takes place after a small bend and only those H^0 are collected on the target.



A laserwire beam profile measuring device for the RAL Front End Test Stand, D.A. Leeet al, DIPAC 2007

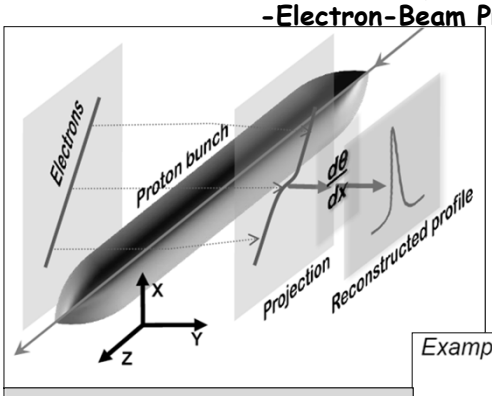
Instruments for beam profile measurements
-Laser Wire Scanner-

4) Bunch length by short pulse laser
A laser pulse much shorter than the temporal current distribution of the bunch enables also a bunch length measurement. A mode locked Ti_Sapphire laser reaches a wavelength of 950 nm and pulse lengths from ps down to tens of fs. For the typical some ns long H- bunches the timing requirements are somewhat relaxed. The transversal size of the laser spot and of the beam should be roughly the same and stable in their positions. The laser pulse is locked to the RF frequency and its phase is scanned across the bunch length



SNS Transverse and Longitudinal Laser Profile Monitors Design, Implementation and Results, EPAC2006

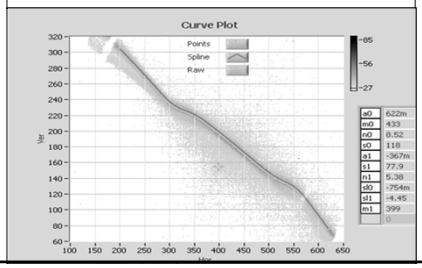
Instruments for beam profile measurements -Electron-Beam Probe-



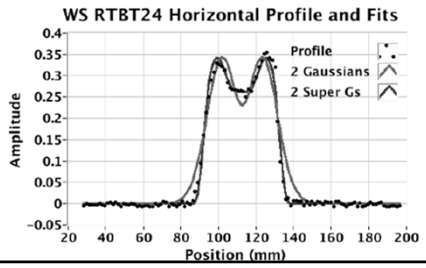
Old idea:
P. Gross, et al, ; **An electron beam probe for ion beam diagnosis**; EPAC 1990

Shown results in SNS ring:
W. Blokland, **Non-invasive Beam Profile Measurements using an Electron-Beam Scanner**, HB2010

Scan duration = 20 ns!



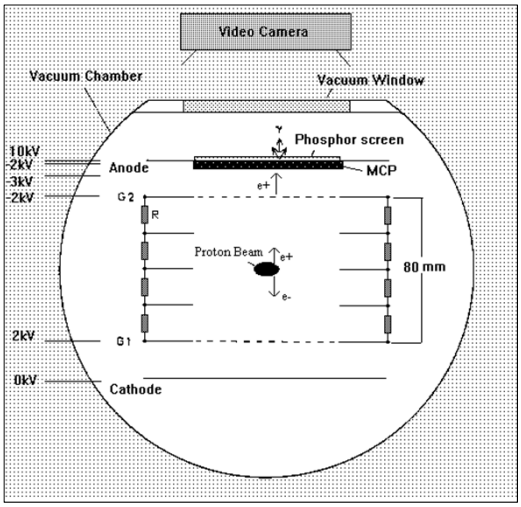
Example of profile due to injection painting only



Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

Residual gas atoms or molecules are always present in the vacuum system of every accelerator. The simple model of Beth-Bloch Formula results in N ≈ 40 ion-electron-pairs per cm at a H_2 pressure of 10^{-9} mbar at 10^{13} minimum ionizing particles.

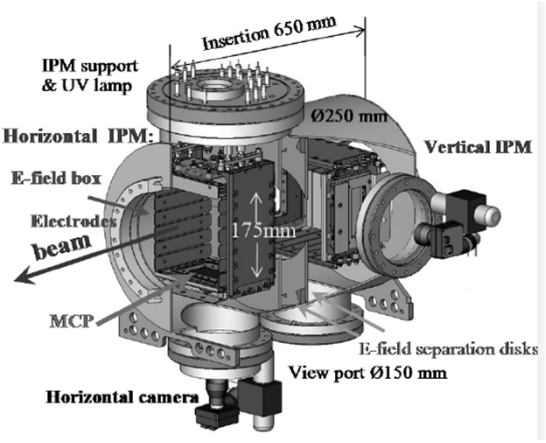
- Electron ion pairs are separated by the use of an extraction field E_{ext} perpendicular to the beam axis.
- Field forming electrodes guarantee a highly parallel field so that the electrons or ions are projected onto the readout plane.
- One or two Micro-Channel-Plates (MCP) inside the beam vacuum to amplify the resulting current.
- Just after the MCP the amplified current is collected by a phosphor screen or multi-anode strips.
- The phosphor screen is viewed by a standard CCD video camera



- Extend electrodes (cleaning) (HERA)
- Coated wall to suppress second. Electrons (SNS)

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

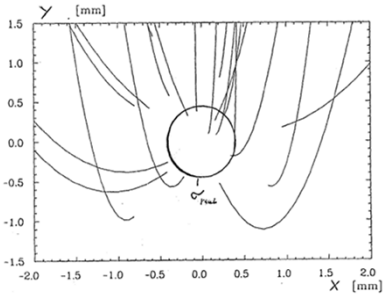
- The video frame rate limits the bandwidth of this readout to 50 (60) Hz which is sufficient for storage rings, but not for cycling synchrotrons or LINACs. A fast readout can be achieved by position sensitive (Silicon-) photomultipliers or photodiode arrays.
- A very fast readout can be achieved by anode strips as a collector of the MCP-electrons.
- The use of resistive plate or wedge-and-stripe anodes can reduce the number of channels and vacuum feedthroughts, but readout is slow.
- Resolution with CCD ≈ 50 µm, with strips ≈ 250 µm.
- Strips are sensitive to RF coupling to beam (increase noise)



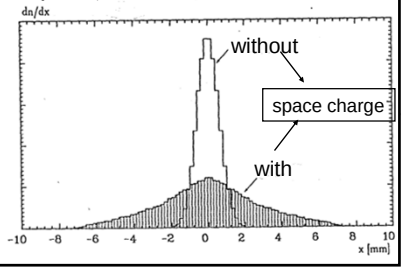
MINIMAL INVASIVE BEAM PROFILE MONITORS FOR HIGH INTENSE HADRON BEAMS, Peter Forck, IPAC'10

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

- IPMs at high intense accelerators suffer from the high space charge of the (bunched) beam, exceeding the extraction field E_{ext}. The space charge disturbs the exact projection of the beam profile by bending the trajectories of the ions and electrons.
- Applying a magnetic field parallel to the extraction field forces the electrons to spiral around the magnetic lines with the cyclotron radius $r_c = m_e v_\perp / eB$.

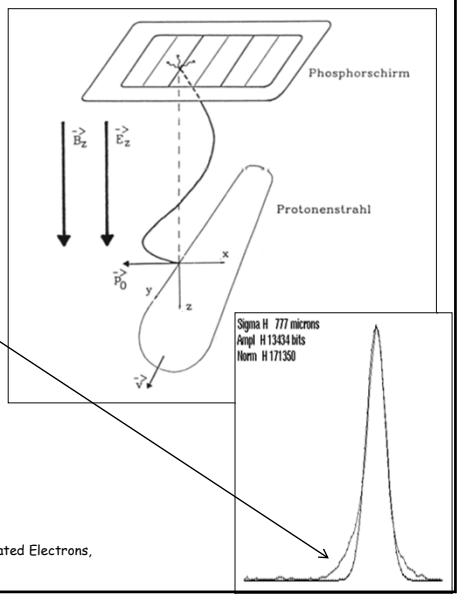


Trajectory Simulations



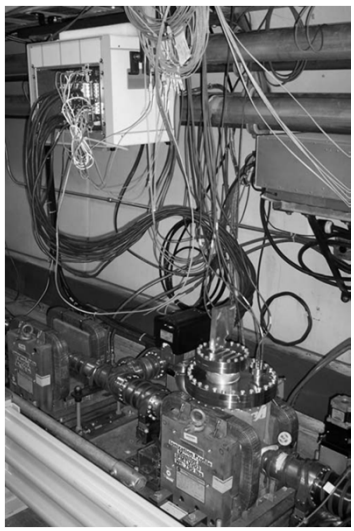
Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

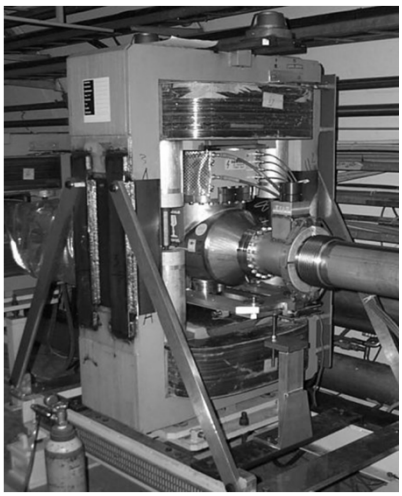
- The radius depends only from the initial transverse kinetic energy defined by the kinematics of the ionization process and is for 90% of the electrons below 50 eV.
- A magnetic field of about 0.1 T is then sufficient to keep the radius (and therefore the monitor resolution) below about 0.1 mm [ion13].
- But note that some electrons may reach much higher kinetic energies which lead to tails of the distribution produced by intrinsic effects and not by beam halo.
- -> Dynamic range limited to $<10^3$?
- The extraction field E_{ext} and the magnetic field B have to be compensated by opposite fields close to the monitor to minimize any influence on the beam.



Results with the SPS Rest Gas Profile Monitor by Collecting the Liberated Electrons, **LHC Emittance Workshop, 2000, C. Fischer, J. Koopman**

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-





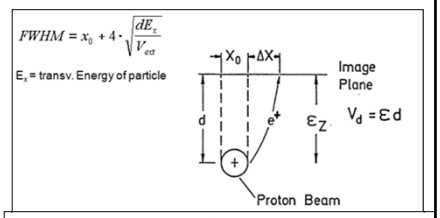
THE TEVATRON IONIZATION PROFILE MONITORS. By A. Jansen, BIW06

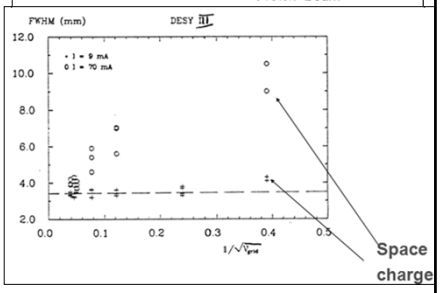
Results with the SPS Rest Gas Profile Monitor by Collecting the Liberated Electrons, **LHC Emittance Workshop 2000, C. Fischer, J. Koopman**

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

Ion collection:

- By changing the polarity of the extraction field E_{ext}, it is also possible to collect the ions on the MCP. The heavy ions are not so strong affected by the space charge and the distortion can be analyzed and subtracted. A precise correction includes also terms from the collision impact and from the thermal movement of the residual gas molecules.
- The collision impact on the ions is quite small but the thermal velocity spread contributes already with a profile broadening of ≈200-300 μm, depending on E_{ext} and on the monitor geometry.
- The broadening of the measured profile due to space charge is reasonable at lower bunch densities but can exceed by far the real beam width at high bunch density. Under those conditions a correction might become useless.



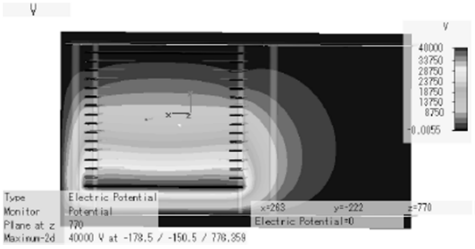


K. Wittenburg ; **Experience with the Residual Gas Ionization Beam Profile Monitors at the DESY Proton Accelerators,** EPAC92

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

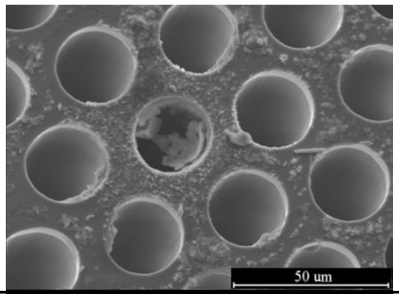
Issues:

- Good design of field forming electrodes



IPM systems for J-PARC RCS and MR: HB2010, 2010, K. Satou

- A well known problem of MCPs, phosphor screens and anodes is their aging with the amplified charge.
- A continuous monitoring of the gain distribution is required.

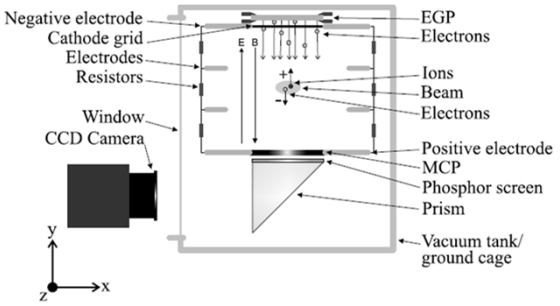


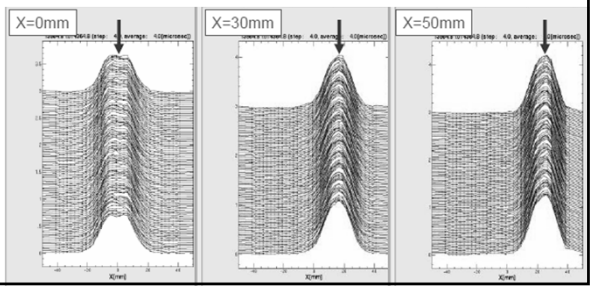
IONISATION BEAM PROFILE MONITOR AT THE COOLER SYNCHROTRON COSY-JÜLICH, V. Kamerdzhiev, J. Dietrich, DIPAC 2003

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

Various calibration methods are in use or discussed:

- α-source,
- Electron Generator Plate,
- tungsten filament emitter,
- UV-lamp
- Motorized 90^0 flip of the MCP,
- A simple way to proof the aging is to steer the beam to an unused part of the sensitive area = beam based calibration.





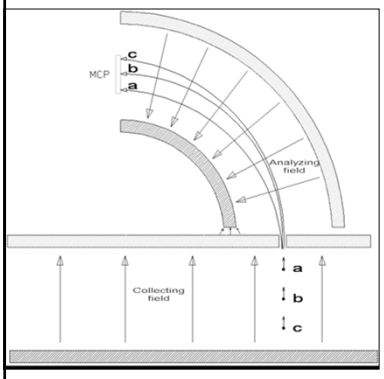
Simulation of an electron source based calibrating system for an ionisation profile monitor. B. Dehning, Lyon 2005/06/06

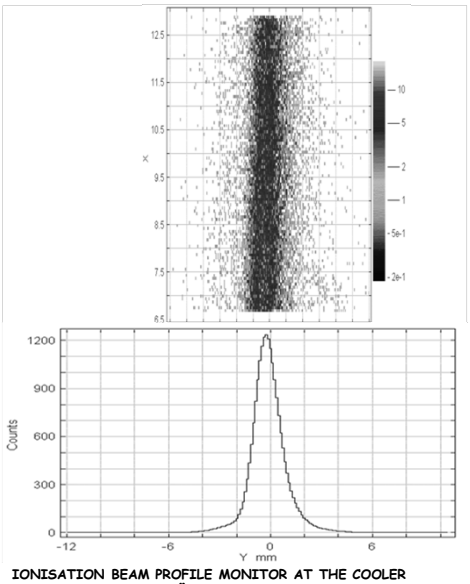
IPM systems for J-PARC RCS and MR; HB2010, 2010, K. Satou

Instruments for beam profile measurements -Ionization Profile Monitor, IPM-

Image of the beam on the phosphor screen (upper part) and its projection on the y-plane of the beam (lower part)

=> Two devices for x and y





TWO-DIMENSIONAL IONIZATION BEAM PROFILE MEASUREMENT, M. Poggi,et al, DIPAC09

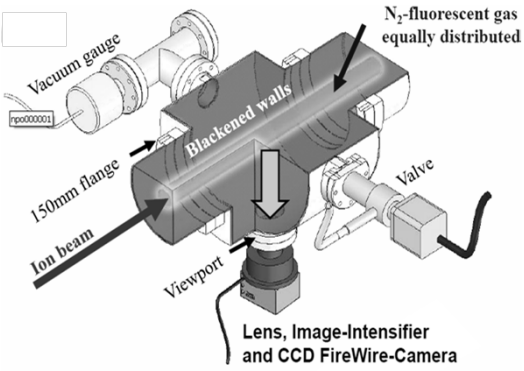
IONISATION BEAM PROFILE MONITOR AT THE COOLER SYNCHROTRON COSY-JÜLICH, V. Kamerdzhiev, J. Dietrich, DIPAC 2003

Instruments for beam profile measurements -Beam Induced Gas Fluorescence, BIF-

The molecules of the residual gas are not only be ionized but also be excited by the beam particles. During their de-excitation they emit light in the visible range (depending on the gas type).

- The cross section for gas scintillation is much smaller than for gas ionization; only a few percent of the ionization loss is converted into detectable visible light.
- The light is emitted into the full solid angle while the detector only covers a fraction of it.
- The finite sensitivity of the photocathode of a position sensitive detector.

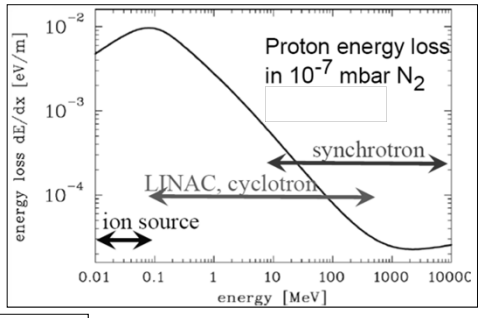
Because of this small efficiency typically a pressure bump is needed to increase the signal to a sufficient level. Nitrogen (N_2) is often used for local gas bumps since the vacuum system can efficiently pump this gas.

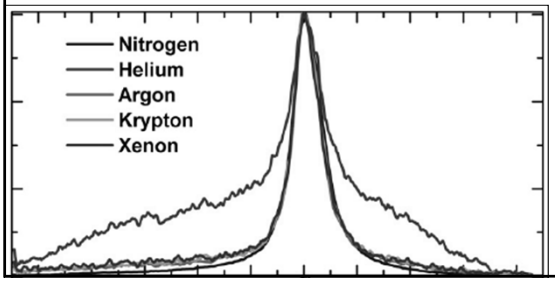


But note that a partially stripped ion beam cannot stand significant added gas pressure.

Instruments for beam profile measurements -Beam Induced Gas Fluorescence, BIF-

The dependence of the cross section on the ionization loss (Bethe-Bloch formula) has been proven over a wide energy range with proton and ion beams, as well as its linear dependence on the N_2 gas pressure .



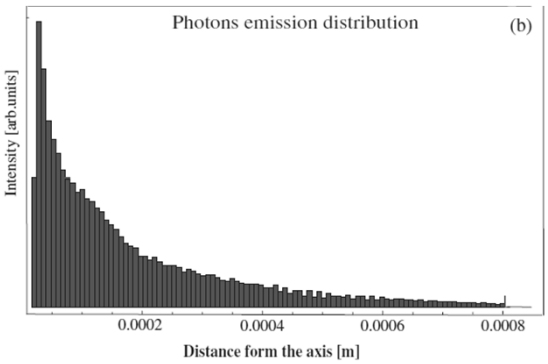


He seems not suitable

Instruments for beam profile measurements -Beam Induced Gas Fluorescence, BIF-

If the excited residual gas atoms are still neutral atoms, they not affected by the space charge.
But the excitation cross section is highest for the ionized state N_2^+ with a half lifetime of the de-excitation of about 60 ns.

- The movement of the excited ions during this time depends mainly on the space charge of the bunch. Simulations for LHC have shown drifts of some hundred μm, creating long tails in the measured beam profile.
- Using Xe as a working gas with a lifetime of 6 ns (Xe^+) can improve the situation but a much lower cross section has to take into account.



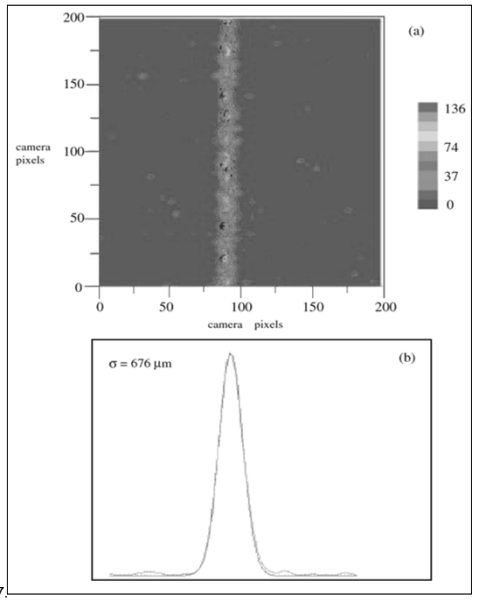
Characterization of a nondestructive beam profile monitor using luminescent emission. A. Variola, Phys.Rev.ST Accel.Beams 10:122801,2007.

Instruments for beam profile measurements -Beam Induced Gas Fluorescence, BIF-

Other contributions which further broaden the measured profile in the order of some ten μm:

- Thermal movement of the ions
- Momentum exchange during ionization
- Finite impact parameter
- Secondary electrons create additional excitations far away from the beam
- Optics

Due to low light generation a sensitive camera (position sensitive PMT) is required. Devices are sensitive to radiation and background due to beam losses.



The measurement conditions were σ=676 μm, beam current 140 mA, $2x10^{13}$ protons, beam energy 450 GeV, and nitrogen pressure $5x10^{-7}$ Torr

Characterization of a nondestructive beam profile monitor using luminescent emission. A. Variola, Phys.Rev.ST Accel.Beams 10:122801,2007.

Instruments for beam profile measurements

Not mentioned:

Gas jets: for low beam intensities
Synchrotron light: For very high energy proton beams -> see long. Halo
Schottky monitors: betatron tune, chromaticity and particle momentum spread

see Proceedings of the 5th CARE-HHH-ABI workshop on
"Schottky, Tune and Chromaticity Diagnostic (with real time feedback)".
2007,Chamonix. CARE-Conf-08-003-HHH
http://adweb.desy.de/mdi/CARE/Chamonix/Care-Proceedings-Chamonix.pdf

Energy measurement Injection mismatch

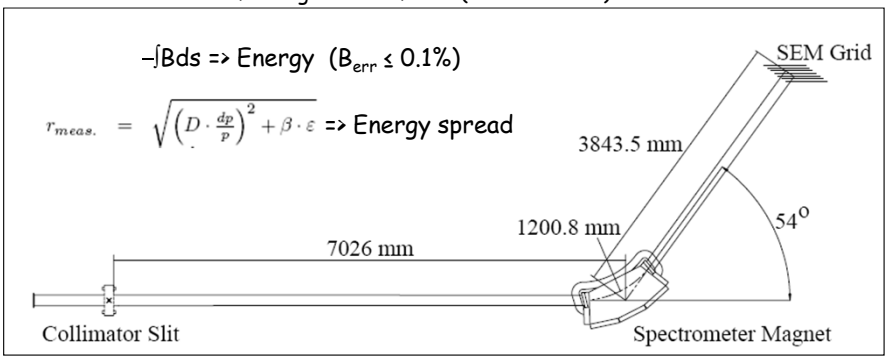
Energy Measurement
1) Spectrometer
2) Time of Flight (Phase)
3) Some others

Energy measurement

1) Spectrometer => beam momentum p and momentum spread Δp
Requirements
1. A large dispersion, i.e. using a strong spectrometer magnet with a significant bending
2. Reducing the beam size, i.e. absorbing particles by means of a slit
3. Installing the detector in a beam waist, i.e. the minimum of the beta-function.
4. A position sensitive detector enables the measurement of energy spread and energy distribution.
5. Exactly known magnetic field and length (precise spectrometer magnet) and beam optics.
6. Also determination of charge state of ions (discrete lines).

$-\int B ds$ => Energy ($B_{err} \leq 0.1\%$)

$r_{meas.} = \sqrt{\left(D \cdot \frac{dp}{p}\right)^2 + \beta \cdot \varepsilon}$ => Energy spread



CERN-sLHC-PROJECTReport-0033, K. Hanke, T. Hermanns,
"Measurement of the Energy Distribution of the CERN Linac4 160 MeV H- Beam Close to the PS Booster Injection"

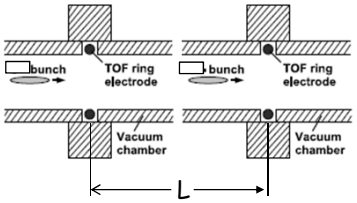
Energy measurement

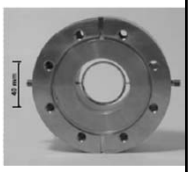
2) TOF (Phase) => beam velocity β => non-relativistic particles only!

- Two fast pickups (BPMs, Wall current monitor, FCT, special design, Scintillators) in exactly known distance L.
- Their well-known signal properties will define the start and end of the measured time t, e.g. maximum or half height of a unipolar signal, zero-crossing of a bipolar signal (more precise).
- When picking-up the same bunch its velocity β is simply given by $t=L/\beta c$.
- Value has to be corrected for signal propagation delays along the cables.

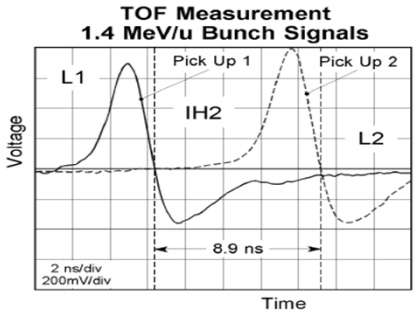
$$t_j = \frac{l_{cab,j}}{v_{cab}} + \frac{L_j}{\beta \cdot c}; \quad E = m_0 c^2 \cdot \left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

with v_{cab} = cable phase velocity, $l_{cab,j}$ length of the cable of each station j; $L_1 = 0$.





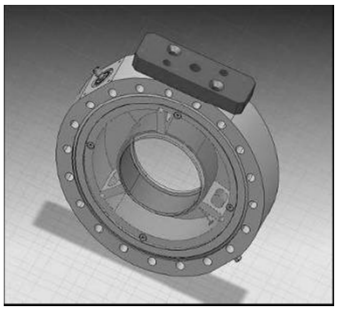
M. Kollewe et al,; Linac06



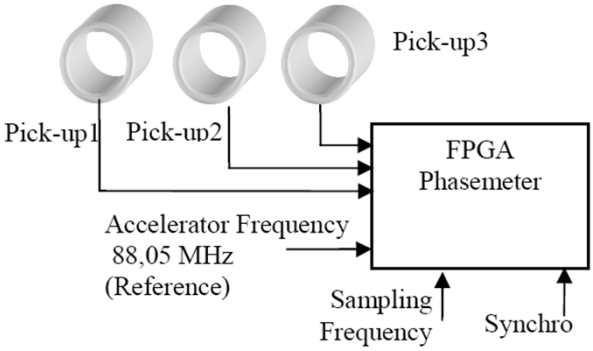
COMMISSIONING OF THE 1.4 MeV/u HIGH CURRENT HEAVY ION LINAC AT GSI; W. Barth, LINAC10

Energy measurement

Modern digital processing allows an I/Q method in a FPGA which results in better precision of the TOF measurement as well as a possible comparison of the bunch with the cavity phase.



Capacitive probe; Diameter: 80 mm, Length: 30 mm.



FPGA phasemeter is able to measure sinusoidal signal phase precisely (+/-0.1°) which corresponds to < 10^{-4} accuracy in Energy at tens of MeV and few m of distance.

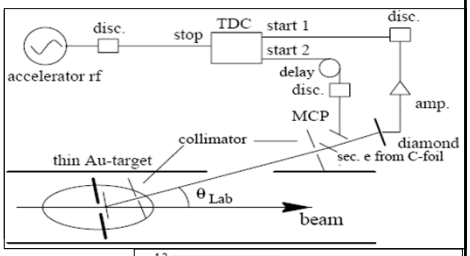
Phase and Amplitude Measurements for the SPIRAL2 Accelerator; C. Jamet etal, DIPAC 2009

Energy measurement

Feschenko Monitor:

When moving the detector one can observe a relative displacement of the bunch shape functions being measured along a phase axis. Measuring $\Delta\varphi$ and d one can find the beam velocity β.

Bunch Length and Velocity Detector and its Application in the CERN Heavy Ion Linac; Yu.V.Bylinsky, EPAC94



Scattering:

Low energy: Rutherford scattering on foil

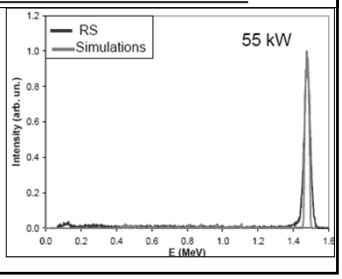
First Experience at SARAF with Proton Beams using the Rutherford Scattering Monitor; L. Weissman, DIPAC09

Use of fast detectors for bunch length meas.

Aspects of Bunch Shape Measurements for Slow, Intense Ion Beams, P Forck, DIPAC09

Laser wire scanner:

Beam electrons have the same velocity as the beam and so have an energy of 1/1836 of the beam protons. A 200MeV H- beam yields 109keV electrons. Energy measurements can be made with either laser-stripped or gas-stripped electrons. The beam energy spectrum is determined by measuring the electron charge vs. repelled voltage on a FC.



BEAM-ENERGY AND LASER BEAM-PROFILE MONITOR AT THE BNL LINAC; R. Connolly, BIW2010

Injection mismatch (transversal)

HHH accelerators need their full aperture at injection.

Avoiding mismatch allows a beam of larger normalized emittance ε and containing more protons.

Any type of injection mismatch will lead to an emittance blow-up. Off axis injection can be detected easily by turn-by-turn BPMs in the ring (before Landau damping occurs) but also by turn-by-turn profile monitors.

The orbit mismatch can be corrected by a proper setup of the steering magnets, kickers and septas.

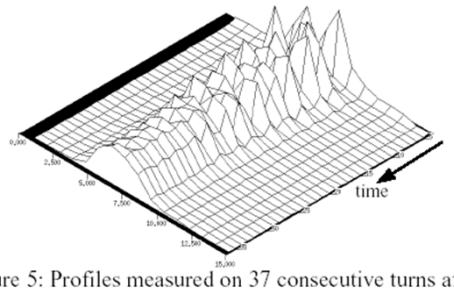


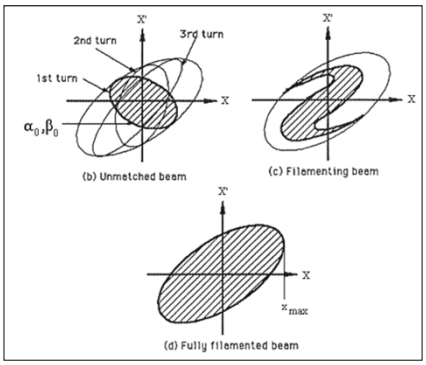
Figure 5: Profiles measured on 37 consecutive turns after injection of a beam of 1.5×10^{12} protons (40 bunches).

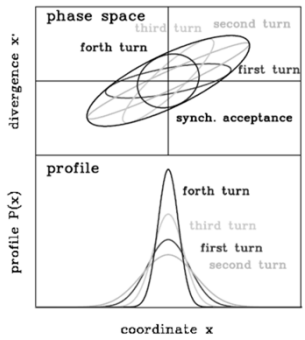
A Photo Multiplier Tube (PMT) with 16 anode strips and high speed acquisition electronics were associated to the IPM. The phosphor used was of the P46 type, claimed to have a decay time of 0.3 μs down to 10% and 90 μs down to 1%.

SENSITIVITY STUDIES WITH THE SPS REST GAS PROFILE MONITOR G. Ferioli, et al, DIPAC2001,

Injection mismatch (transversal)

- Any mismatch of the optical parameters α, β (and therefore γ) will lead to an emittance blow-up (and beam losses) and is <u>not detectable</u> by BPMs but by profile monitors.
- A mismatch of the phase space will result in t<u>ransverse shape oscillations</u>, at least for some ten turns, before the filamentation of the beam. =>
- Observation of the width-oscillation at one location.
- Frequency is twice the betatron frequency (tune).

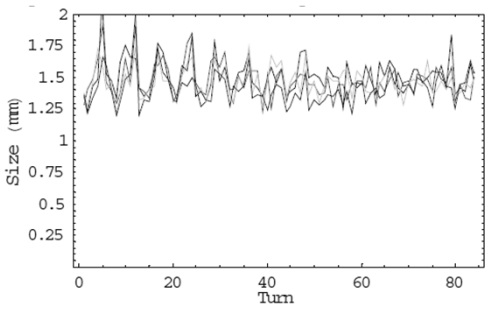




Injection mismatch (transversal)

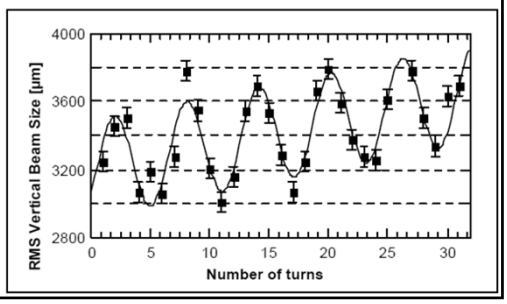
Measured with a turn-by-turn IPM in Tevatron

IPM Measurements in the Tevatron A. Jansson, et al, PAC 07,



Vertical beam size modulation measured over 32 turns in the SPS for a mismatched beam by OTR screen. Note the blowup due to scattering on screen.

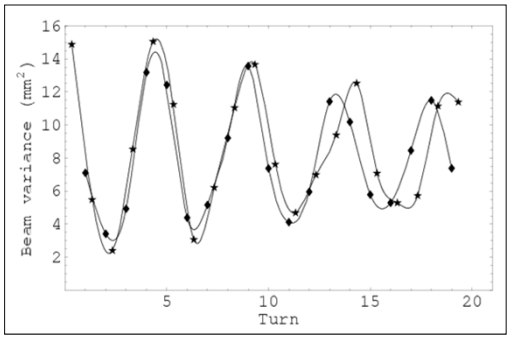
THE OTR SCREEN BETATRON MATCHING MONITOR OF THE CERN SPS.C. Bovet, et al, DIPAC '99



Injection mismatch (transversal)

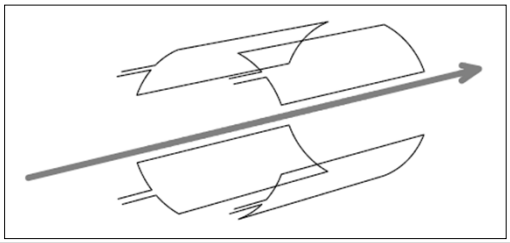
Horizontal beam width oscillations measured with the quadrupole pick-up (stars) and a SEMgrid (diamonds). The lines are spline interpolations.

The contribution of the beam width due to scattering on the SEM-Grid wires is barely visible.



Sketch of a Quadrupolar pick-up. The dipole oscillation response is heavily suppressed.

It is (completely) non-invasive.



Measurements with the Magnetic Quadrupole Pick-up in the CERN PS, A. Jansson, EPAC2000

End of first part

Needs for High Power Machine Diagnostic:

- What is the goal of the instrumentation and diagnostic

Instruments:	Diagnostic methods:	
➢ Beam Current/Shape ➢ Beam Position ➢ Beam Profile	➢ Emittance ➢ Energy ➢ Mismatch	Today
➢ Beam Loss	➢ Machine Protection Systems ➢ Transversal Halo ➢ Longitudinal Halo ➢ E-cloud diagnostic ➢ Target/Dump Instrumentation	Monday