Beam Diagnostic Requirements Overview

Gero Kube

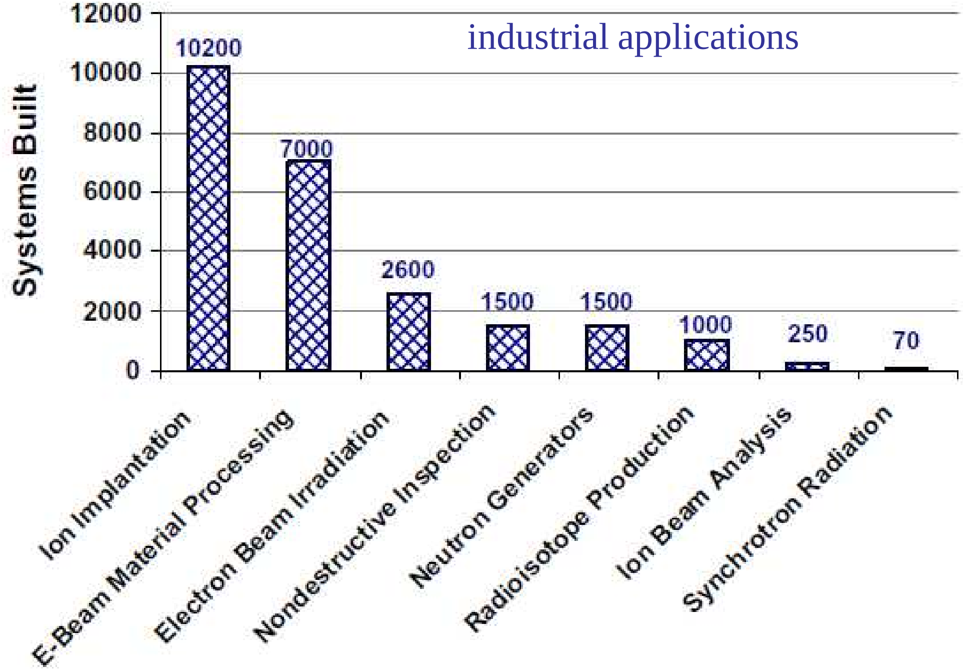
DESY (Hamburg)

- Measurement Principles
- Specific Diagnostics Needs for Hadron Accelerators
- Specific Diagnostics Needs for Electron Accelerators

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Accelerators world wide

- accelerator applications



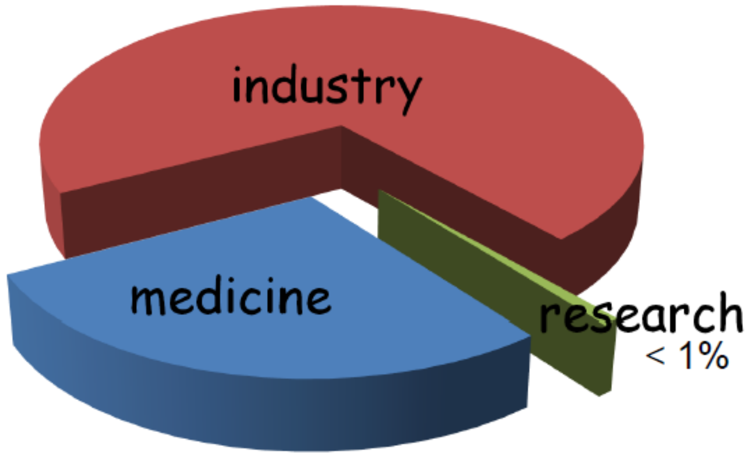
R.W. Hamm, M.E. Hamm, Industrial Accelerators and their Applications, World Scientific (2012)

- industrial applications:

  $\Sigma \approx 24000$

- medical applications:

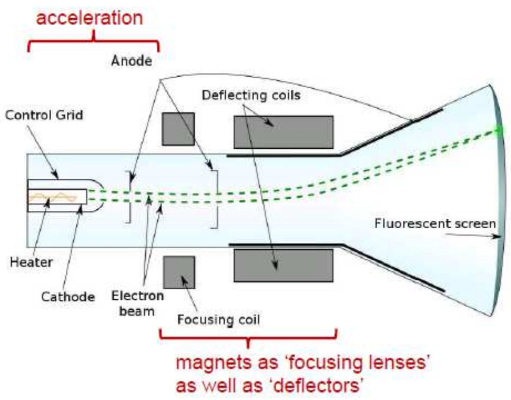
  $\Sigma \approx 11000$



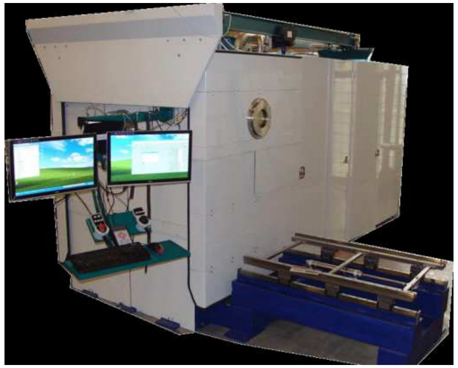
- particle species
  - **lepton beams:** electrons, positrons
  - **hadron beams:** protons, anti-protons, heavy ions

Accelerator Applications

- cathode ray tubes



- electron beam welding

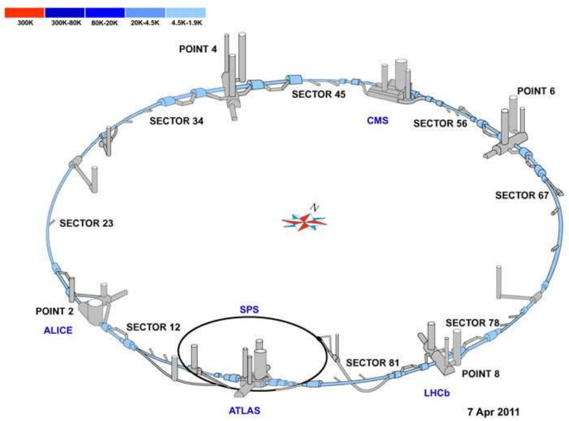


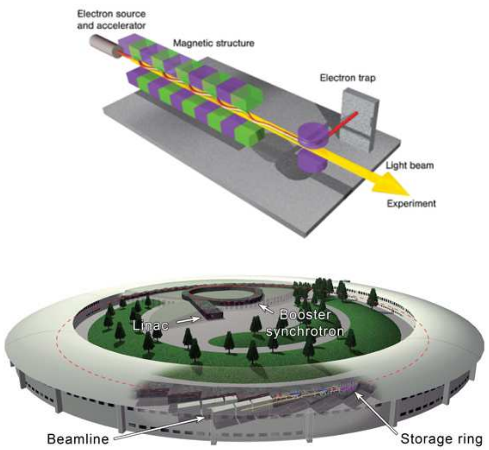
PAVAC Energy Corp., welding and machining

- medical treatment

Siemens Eclipse Cyclotron (11 MeV) marketed for PET isotope production

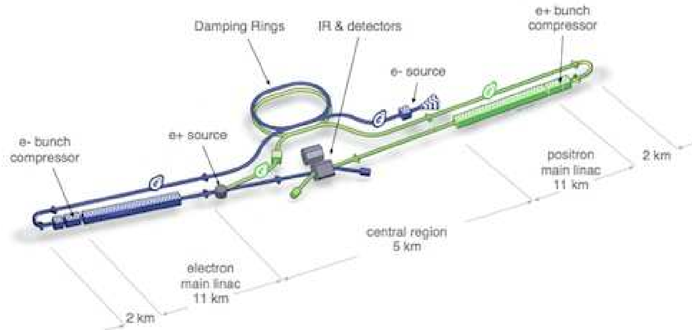
- circular collider





- 3^{rd} / 4^{th} generation light source

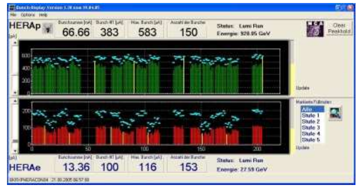
- linear collider



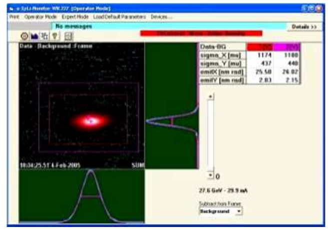
Beam Parameters and Diagnostics

- beam position
  - orbit, lattice parameters, tune, chromaticity, feedback,…

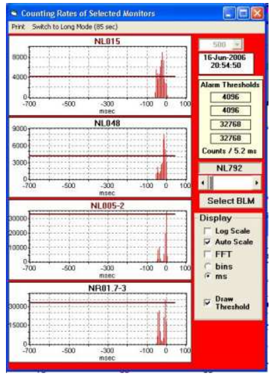
- beam intensity
  - dc & bunch current, coasting beam, lifetime, efficiencies,…



- beam profile
  - longitudinal and transverse distributions, emittances,…



- beam loss
  - identify position of losses, prevent damage of components,…



- beam energy
  - mainly required by users,…

- luminosity (collider)
  - key parameter, collision optimization…

and even more: charge states, mass numbers,…

Reminder: Beam Signal Generation

- hadron / electron machines
  - difference in signal generation and underlying physical principles (→ rest mass)

⇒ **distinguish between hadron / electron beam diagnostics**

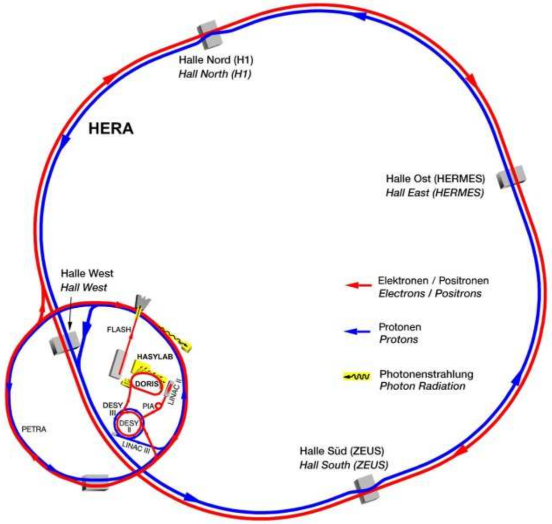
- program for the following lectures
  - **Hadron Accelerators**
    - → Collider, Storage Ring
      incl. Injector Chain (Linac, Injector Synchrotron, Transfer Line)
    - → Spallation Neutron Source
    - → Hadron Therapy Accelerator
  - **Electron Accelerators**
    - → Circular Collider
    - → Synchrotron Light Source (3rd Generation)
    - → Linac based Free Electron Laser
    - → Outlook…

Hadron Collider
(incl. Injector Chain)

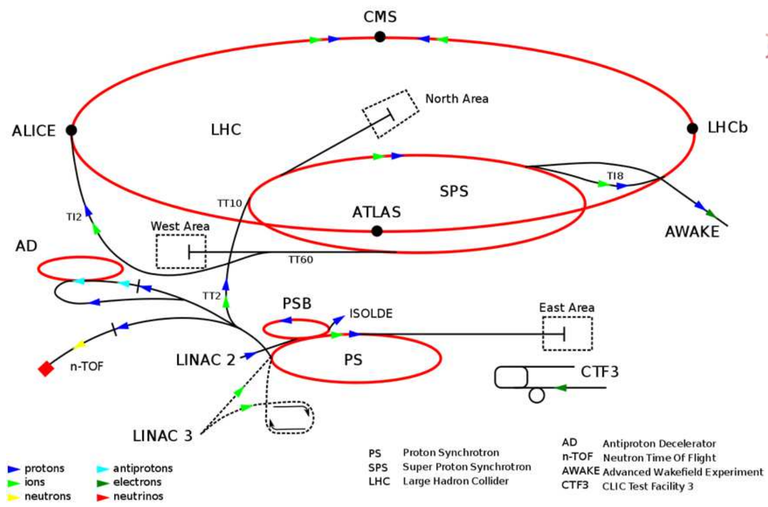
- Linac
- Injector Synchrotrons
- Transfer Line
- Storage Ring

Hadron Collider (Storage Ring)

HERA @ DESY



LHC @ CERN



- collider key parameter
  - luminosity $\mathcal{L}$

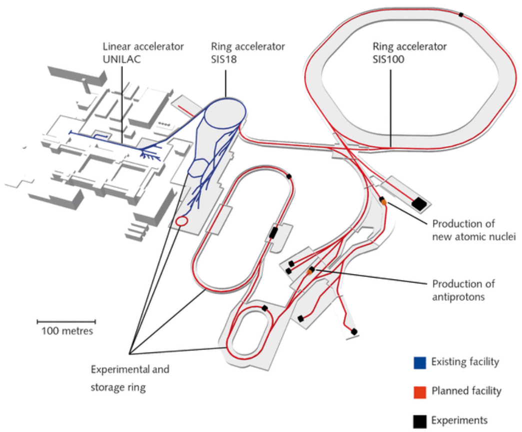
    → collider performance

$$\dot{N} = \mathcal{L} \cdot \sigma$$

σ: cross section

(property of interaction)

FAIR @ GSI



- modern hadron collider (storage ring) with high beam energy
  - **superconducting magnets** to achieve required particle bending

    → parts of diagnostics located in cold vacuum

    → beam-loss monitor system for quench protection required
  - **long injector chain** to reach final energy

    → pre-accelerators / transfer lines with different beam properties

    → different requirements for beam diagnostics

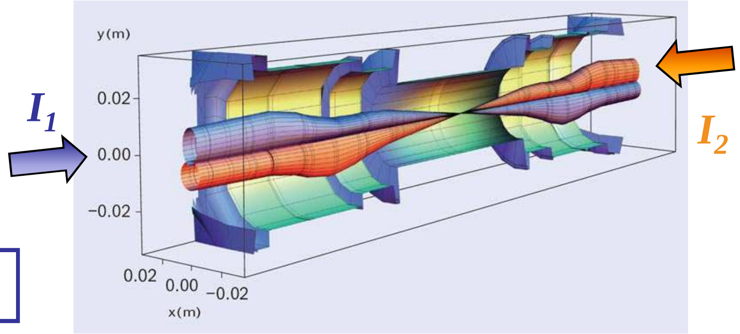
Comments: Injector Chain (1)

- luminosity of collider
  - assumption (for simplicity)

$$\mathcal{L} \propto \frac{I^2}{\varepsilon}$$

→ identical beams: $I_1 = I_2 = I, \quad \varepsilon_x = \varepsilon_y = \varepsilon$

➡ small beam emittances for high luminosity



CERN Courier, August 2013

- beam emittances in circular machines
  - **lepton beams:** formation of ***equilibrium emittances*** because of ***radiation damping*** and ***quantum excitation*** due to synchrotron radiation
  - **hadron beams:** ***synchrotron radiation emission suppressed*** because of large particle masses

➡ emittance essentially determined in injector chain

- consequences for beam diagnostics in injector chain

➡ i) accurate beam characterization already important in low energy machines
ii) minimum disturbing instrumentation in order to avoid emittance blow up

Comments: Injector Chain (2)

- normalized emittance ε_N conserved (Liouville)

absolute emittance: $\varepsilon = \frac{\varepsilon_N}{\beta\gamma}$ with $\beta\gamma = \frac{pc}{m_0 c^2}$ (LHC: ε_N = 3.75 mm mrad)

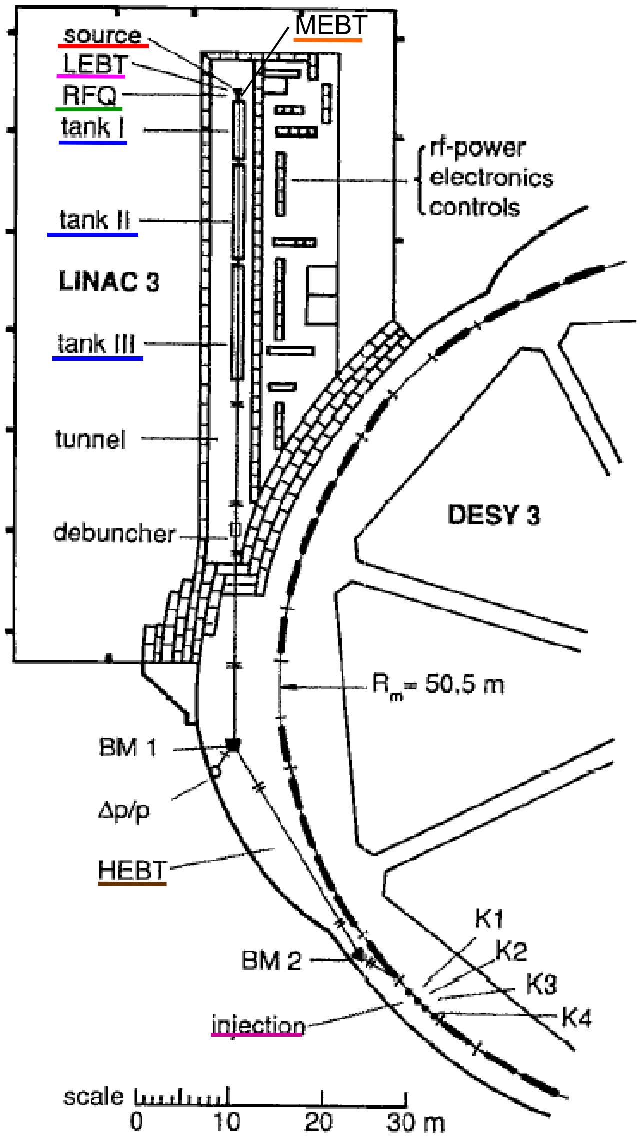
➡ adiabatic shrinking with increasing beam energy

example LHC injector chain

› end of Linac II	**50 MeV**	→	**$\beta\gamma$ = 0.33**	↓ x 1450
› extraction SPS	**450 GeV**	→	**$\beta\gamma$ = 480**	↓ x 15
› maximum energy LHC	**7000 GeV**	→	**$\beta\gamma$ = 7460**	

- consequences for beam diagnostics
  - **large emittances:**
    - i) large beam spots and divergences
    - ii) tight mesh of focusing magnets → little space for instrumentation
  - **low energies:**
    - i) particles have small magnetic rigidity $B\rho$ → easy to bend
    - ii) change of particle speed with acceleration
    - iii) space charge effects (especially heavy ions beams)
    - iv) high energy deposition in matter (Bethe-Bloch)

Source and Injector Linac



- example: H^- Injector Linac @ DESY
  - H^- Sources:

    18 keV magnetron source and rf-driven volume source
  - Low Energy Beam Transport (LEBT)

    beam matching to acceptance of RFQ
  - Radio Frequency Quadrupole (RFQ)

    acceleration from 18 keV up to 750 keV
  - Medium Energy Beam Transport (MEBT)

    beam matching to acceptance of Linac
  - H^- Linac (Tank I – III)

    conventional Alvarez Linac, end energy E_{kin} = 50 MeV
  - High Energy Beam Transport (HEBT)

    measure beam properties for Linac tuning

    match beam to synchrotron acceptance
  - Injection

    H^- multi-turn injection using stripper foil (→ p conversion)

Source and Linac Instrumentation

- key devices for
  - adjusting beam transport through linac sections
  - tuning the RF system (phase, amplitude,…)
  - indicate operating status

    → permanently installed diagnostic beamline behind linac sections

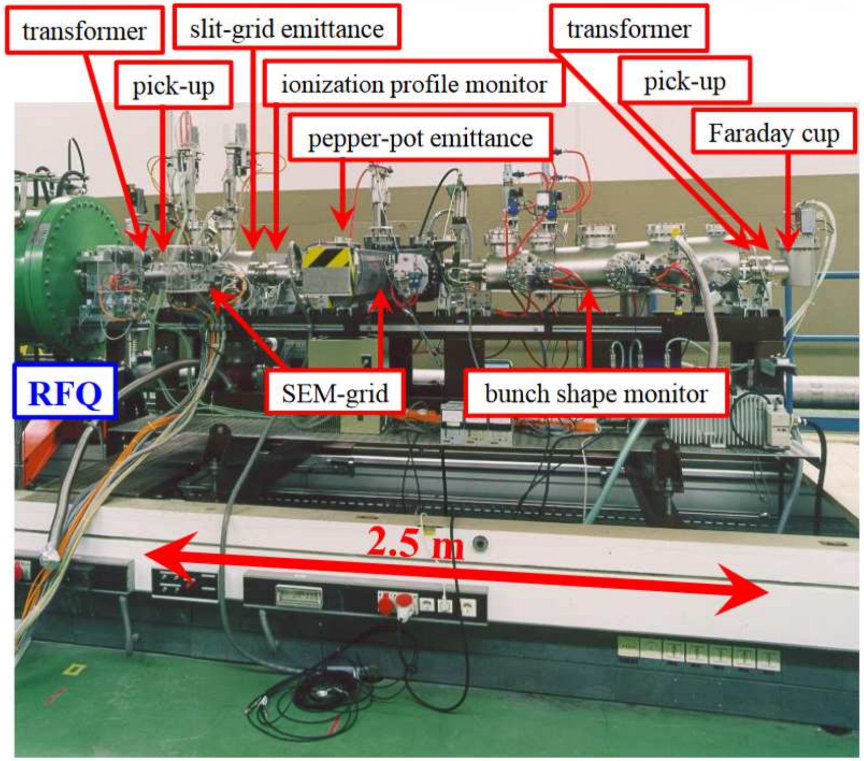
    → moveable diagnostic test bench

    (allows full 6d phase space characterization after each section)

  - example

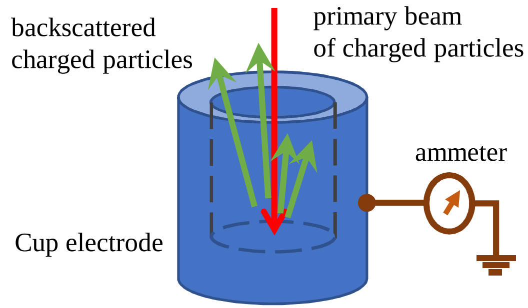
    → diagnostic bench for RFQ commissioning @ GSI

courtesy: P. Forck (GSI)



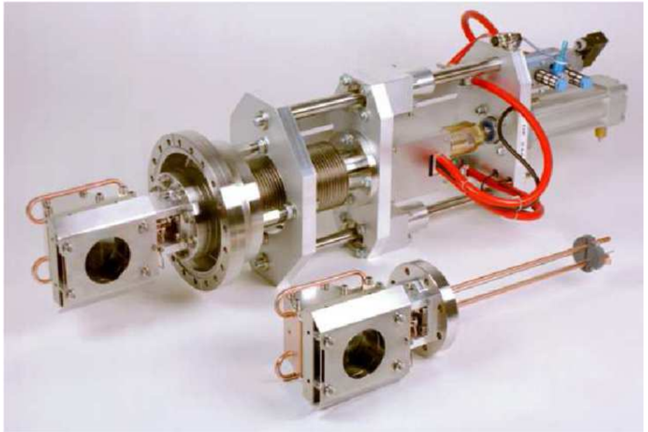
Linac: Current and Transmission

- destructive: Faraday cup



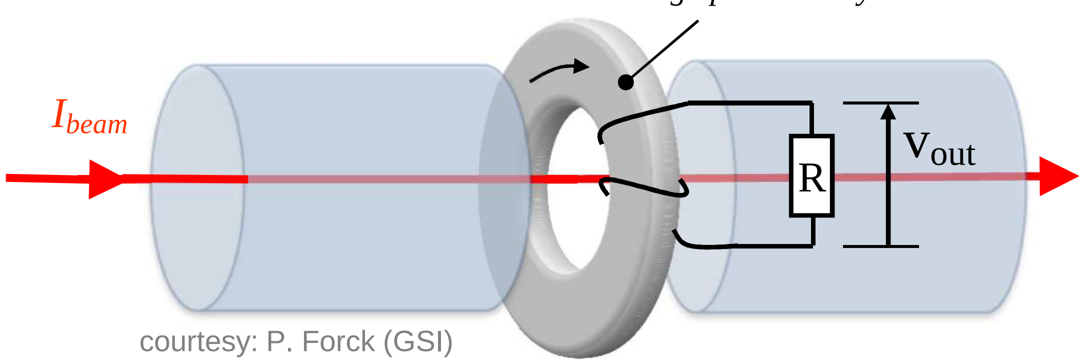
  - low energy particles stopped in material (→ Bethe Bloch)
  - very low intensities (down to 1 pA) can be measured

moveable Faraday cup for GSI linac



courtesy: P. Forck (GSI)

- non destructive: current transformer
  - beam acts as single turn pimary winding of transformer
  - measuring AC component of beam current



courtesy: P. Forck (GSI)

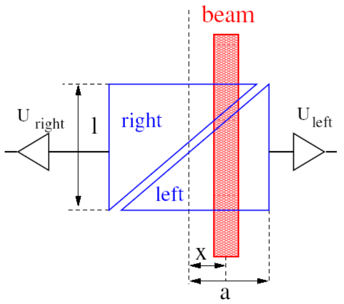
commercially available devices

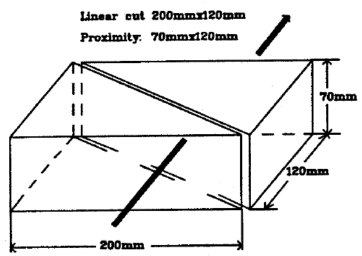
courtesy: J. Bergoz

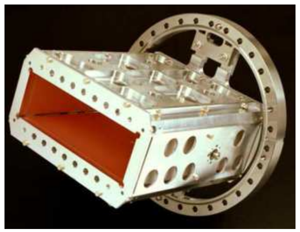
Linac: Beam Position

- position information via electro-magnetic fields possible
- large bunch lengths, low acceleration frequencies
  - beam spectrum contains low frequencies (typically kHz – 100 MHz)
  - requires high sensitivity of pick-up at these frequencies
- small signals (non-propagating field with low γ)
  - capture as much field lines as possible, i.e. large electrodes

capacitive pick-up

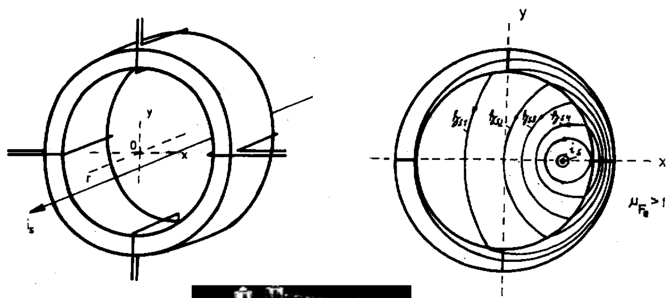


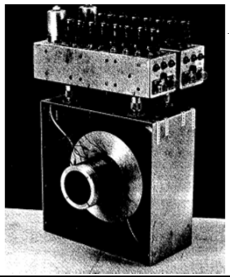




P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

inductive pick-up

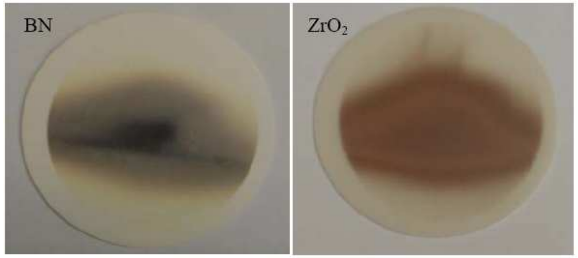




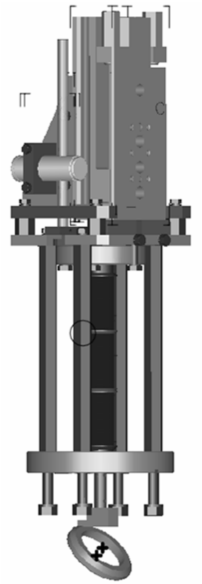
W.Kriens, W.Radloff, DESY-S1-68/1

Linac: Transverse Beam Profile (1)

- luminescent screens
  - destructive method
  - part of deposited energy results in excited electronic states → light emission (CCD)
  - used also for beam position (instead of BPMs)
  - high energy deposition (→ Bethe Bloch)
    especially critical for heavy ion machines
  - degradation of screen material

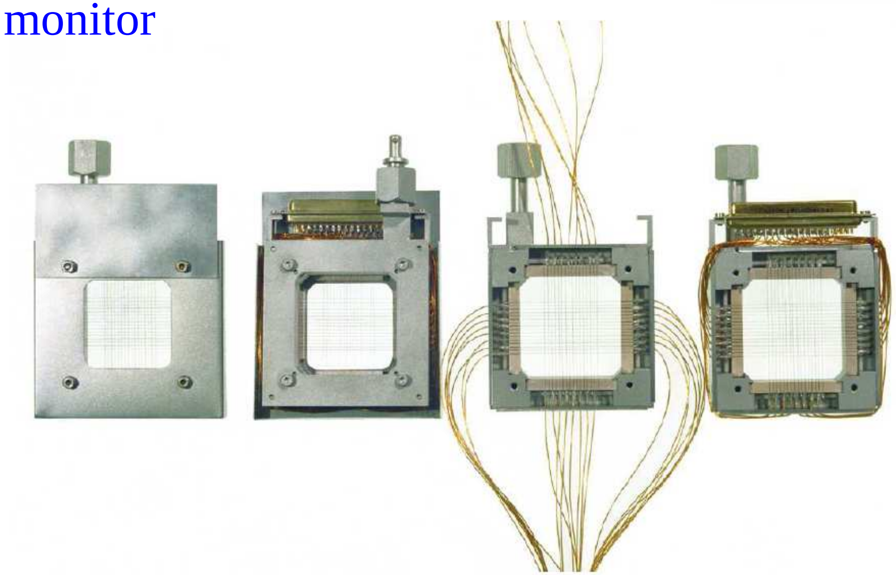


C.Bal et al., Proc. of DIPAC 2005 Lyon, France, 57



courtesy: Ch.Wiebers (DESY)

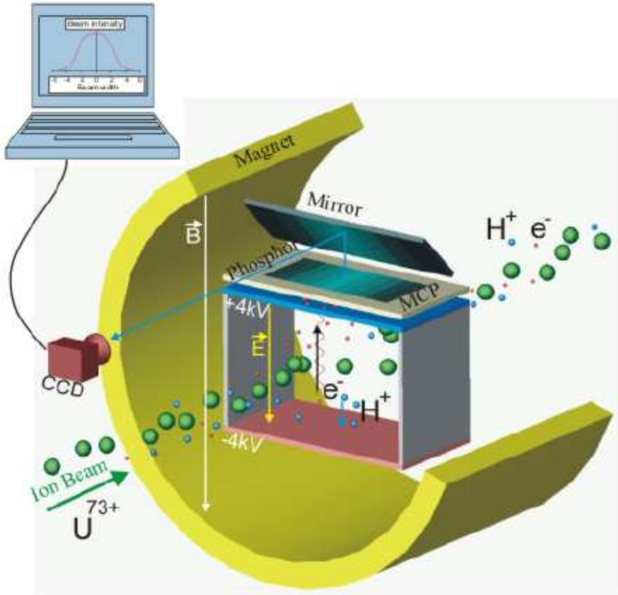
- profile grid, harp, secondary emission monitor
  - less destructive method
  - grid: wires in both transversal planes
    harp: wires in one transversal plane
    SEM: strips, larger surface than wire



P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

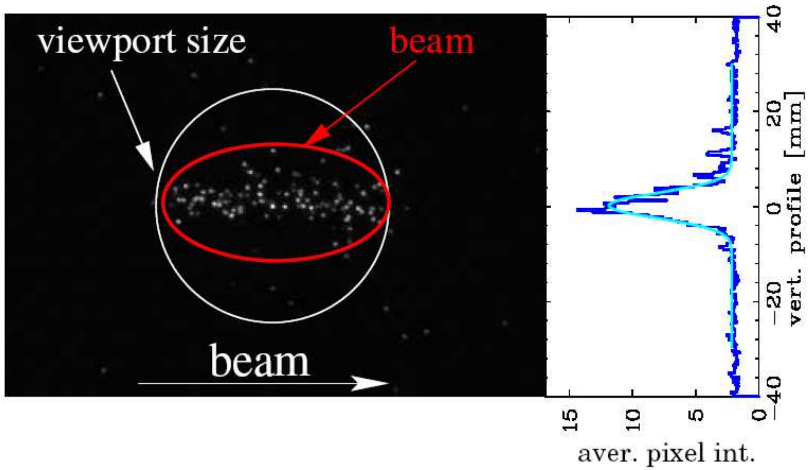
Linac: Transverse Beam Profile (2)

- non-destructive: residual gas monitor
  - beam interaction with residual gas
    → creation of residual gas ions and electrons
  - electrostatic field accelerates ionization products towards Microchannel Plate
    → secondary electron generation (multiplication ~10^6)
  - readout via phosphor screen and CCD (optical) or via wire array and guide field (electrical)



T.Giacomini et al., Proc. BIW 2004, p.286

  - variant: ***residual gas fluorescence monitor***

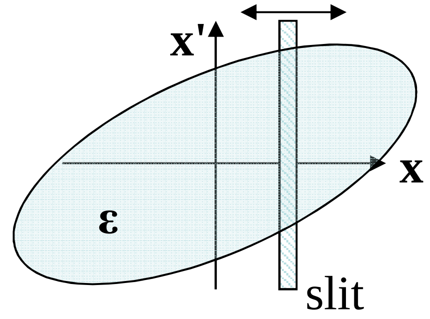


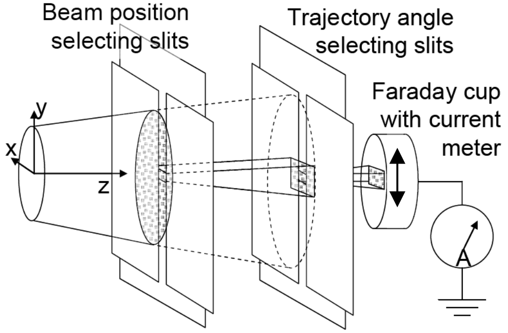
<u>residual gas fluorescence monitor:</u> image of a 2.5 mA Ar^{10+} beam at vacuum pressure of 10^{-5} mbar from GSI LINAC

P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

Linac: Transverse Emittance

- principle of slit-scan method
  - low energy beams often space charge limited → cutting out small beamlet
  - slit produces vertical slice in transverse phase space
  - measure intensity as function of **x'** (→ propagate beamlet along drift space)
  - moving of slit → scan of phase space (**N_x x $N_{x'}$** measurements)





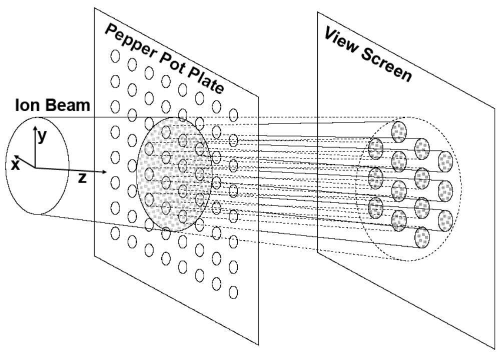
M.P.Stockli, Proc. BIW 2006, p.25

- monitor with **x'** resolution instead of scan:

  SEM, profile grid,…

  → **N_x** measurements

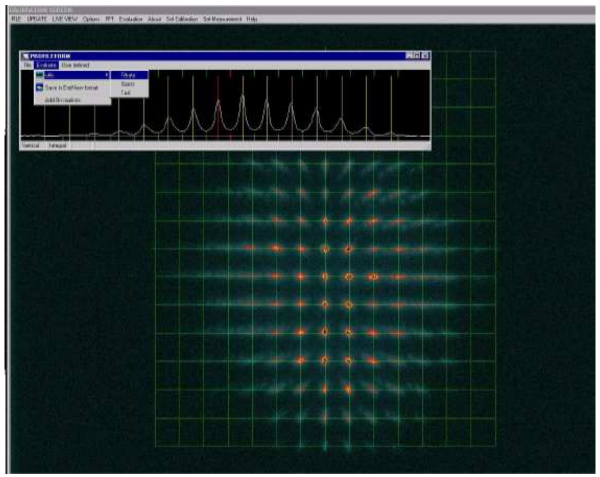
- 2-dimensional extension: Pepper pot



P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

→ **1** measurement

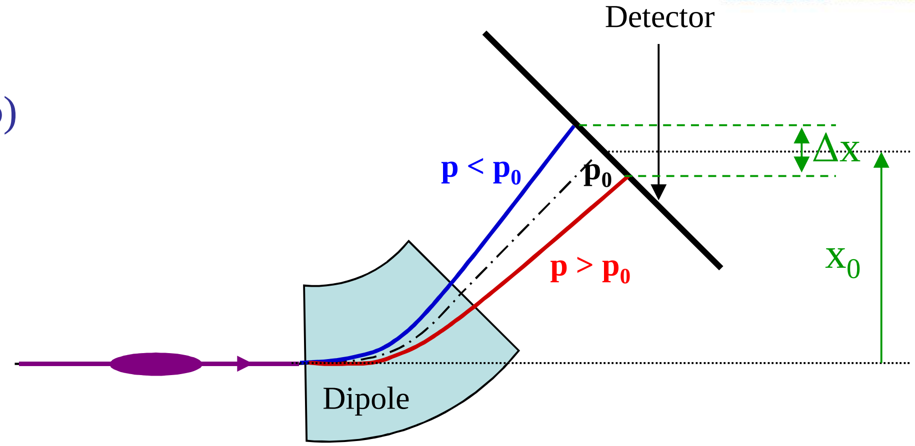
N_x x $N_{x'}$ holes



Linac: Longitudinal Plane

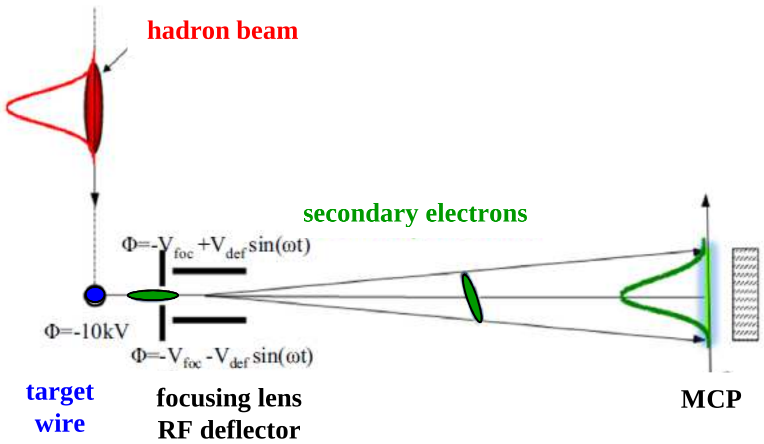
- momentum and momentum spread
  - dipole magnet spectrometer (small rigidity Bρ)
  - transformation of momentum (spread) into position (spread)
  - spatial resolving detector (screen, SEM,…)

$$\frac{\Delta x}{x_0} = \frac{\Delta p}{p_0}$$



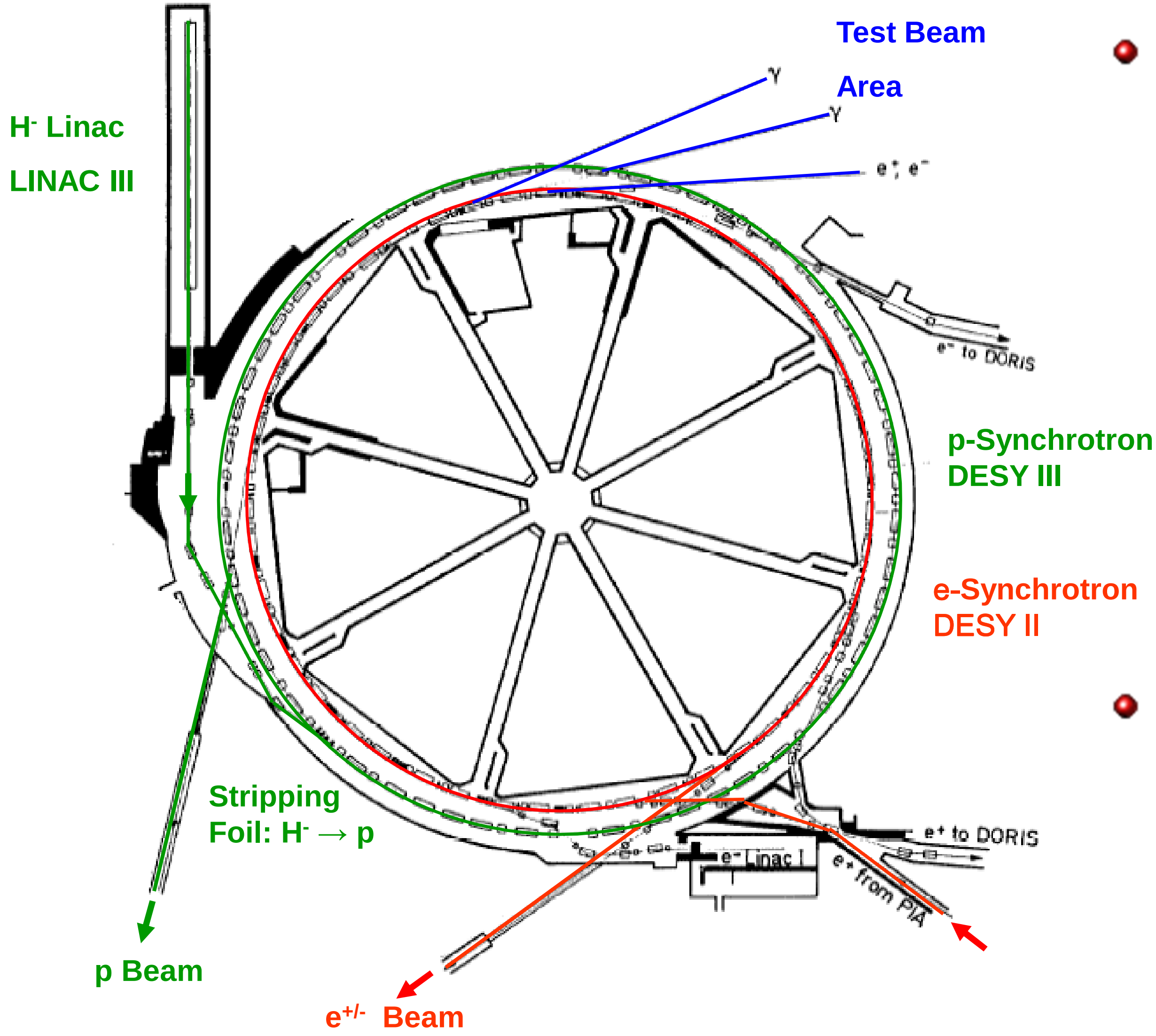
→ alternative method: time of flight (TOF)

- bunch shape and time distribution
  - **Bunch Shape Monitor** (BSM)
  - primary beam hits thin wire → potential -10 keV
  - conversion of primary hadron beam into low energy secondary electrons
  - RF deflector converts time into space coordinates
    → operation close to RF zero-crossing
  - intensity profile → with spatial resolving detector



A. Perry *et al.*, Nucl. Instrum. Meth. **A735** (2014) 163

Injector Synchrotron: DESY III



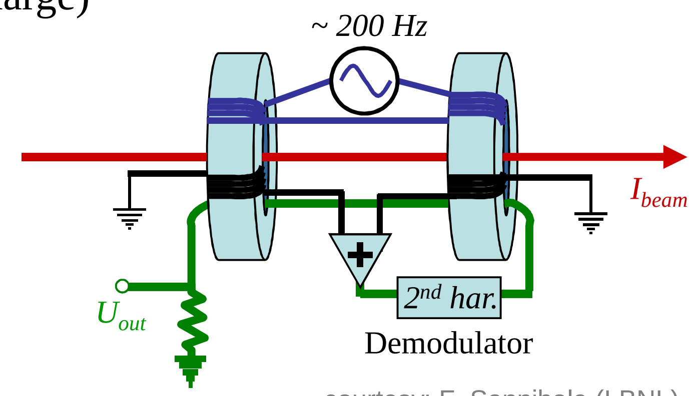
- first synchrotron in injector chain of HERAp
  - mean radius 50.42 m
  - RF frequency 3.27 → 10.33 MHz
  - cycle time 3.6 sec
  - injection *energy* 0.31 GeV/c
  - extraction *energy* 7.5 GeV/c
- diagnostics purposes
  - optimize injection / extraction
  - parameter control during ramp
  - fault finding

G. Hemmie and J.R.Maidment, *Proc. PAC 1987, p. 172*

Injector Synchrotron Diagnostics (1)

- beam current
  - measurement of injection efficiency (→ single bunch charge)
    average current and coasting beam
  - AC current transformer (ACCT)
  - parametric or DC current transformer (DCCT)
  - circular accelerator → one monitor sufficient

DCCT principle



courtesy: F. Sannibale (LBNL)

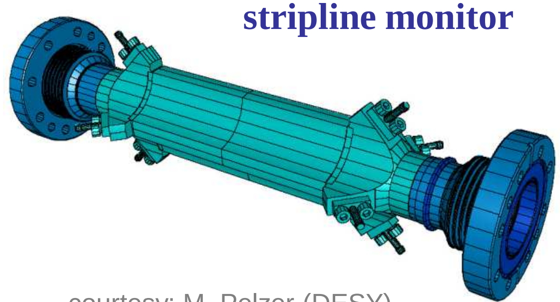
- beam position
  - measurement of beam orbit (oscillation, closed orbit,…)
  - position monitors
    → usually 4 per betatron oscillation (phase shift 90°)
  - large bunch lengths, low acceleration frequencies
    → high pick-up sensitivity @ frequencies of interest

DESY III: inductive pick-ups

other schemes: shoe-box types (capacitive)

higher acceleration frequencies and energies: striplines

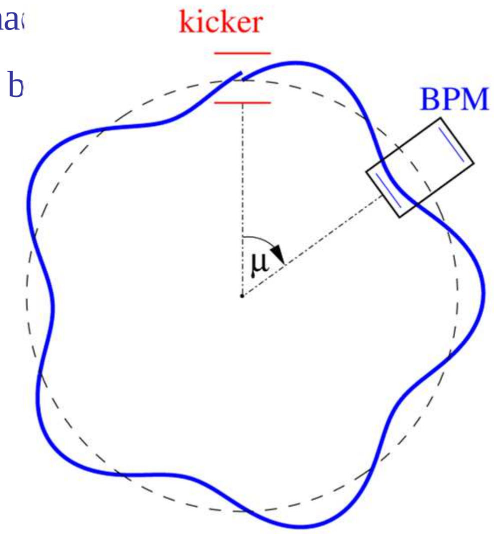
stripline monitor

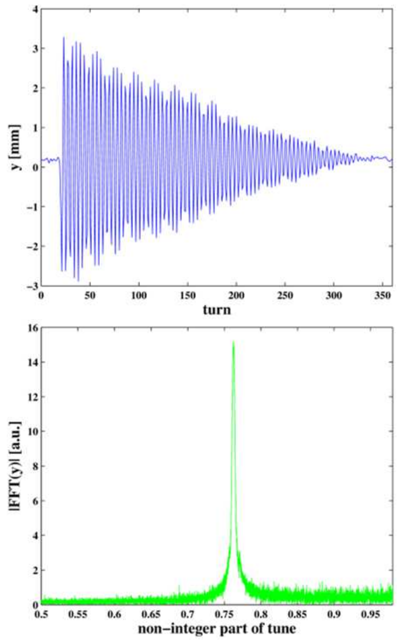


courtesy: M. Pelzer (DESY)

Injector Synchrotron Diagnostics (2)

- tune
  - eigenfrequency of betatron oscillations in circular ma
  - characteristic frequency of magnet lattice, produced b
    strength of quadrupole magnets





- principle of tune measurement
  - excite coherent betatron oscillations (→ kicker)
  - observe dipole moment due to (coherent)
    transverse beam oscillation

    → primary observable: time sequence of turn-by-turn position
  - FFT of response

- comments
  - excitation leads to emittance blow-up

    → small excitation required

    → high pickup sensitivity necessary
  - high space charge at injection (acceptance occupied)

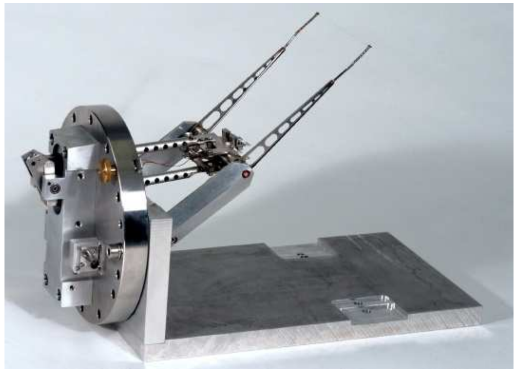
    → excitation can lead immediately to particle losses

- example: DESY III
  - **no** tune measurements in standard operation
  - tune measurements only in dedicated machine studies

    → reproducible set-up of machine

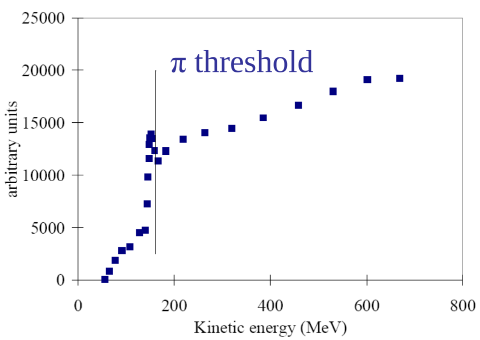
Injector Synchrotron Diagnostics (3)

- transverse profiles / emittances
  - **screens** (destructive)
    → for commissioning, if doubts about signals from other monitor
  - **wire scanners** (less destructive)
    → thin wire quickly moved across the beam (> 1 m/sec)
    → simultaneous detection of secondary particle shower outside vacuum chamber with scintillator/photo-multiplier assembly

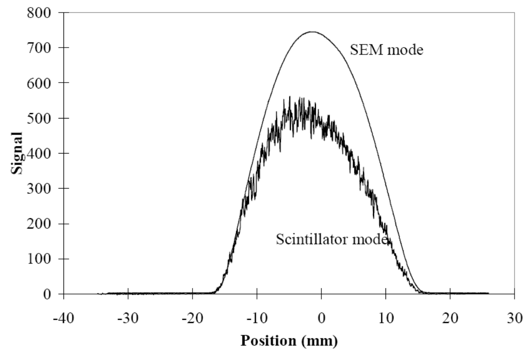


U.Raich, Proc. of DIPAC'05, Lyon (France), 2005, p.1

secondary particle shower intensity in dependence of primary beam energy



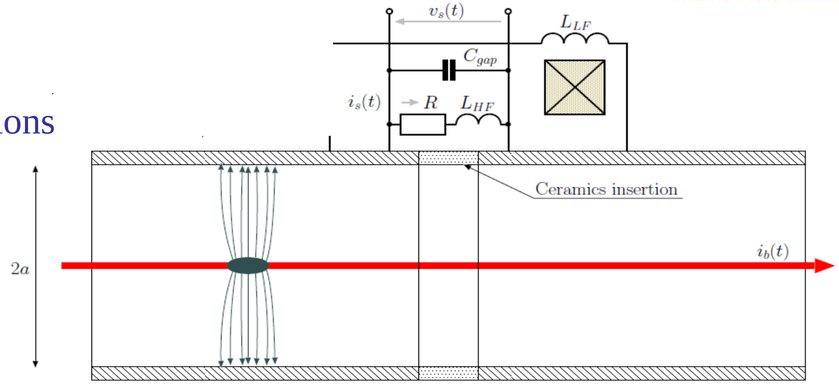
→ for beam energy below 150 MeV use instead secondary emission (SEM) current of isolated mounted wire



  - **residual gas monitor** (non-destructive)
    → vacuum pressure in sycnchrotron much better (10^{-10} mbar) than in linac/transfer line (10^{-6} - 10^{-8} mbar)
    → much lower signal → local pressure bump…

Injector Synchrotron Diagnostics (4)

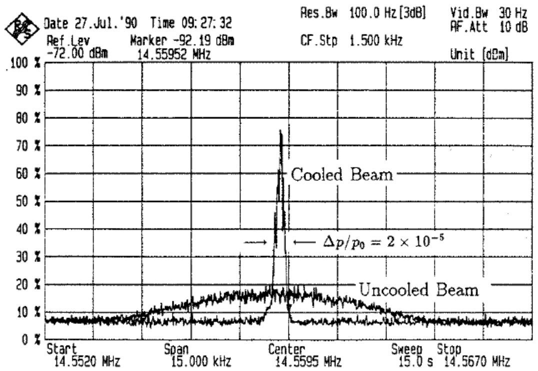
- bunch lengths and time structure
  - measure bunch length (→ nsec) and longitudinal oscillations
  - ***wall current monitor***
    - → offers bandwidth up to a few GHz



D. Belohrad, Proc. DIPAC2011, Hamburg (2011) 564

- losses
  - indication of beam losses in specific critical places
    - → optimization of injection and extraction
  - ***Beam Loss Monitors (BLMs)***

- comment: pbar and heavy ion machines
  - source emittance worse, adiabatic emittance shrinking not sufficient for final beam quality
    - → emittance improvement (for bunched beams) by electron cooling
  - smaller cooling time at smaller beam energy
    - → cooling performed typically in low energy synchrotron
  - ***Schottky diagnostics***
    - → exploit individual particle behavior (Schottky noise) in beam spectrum



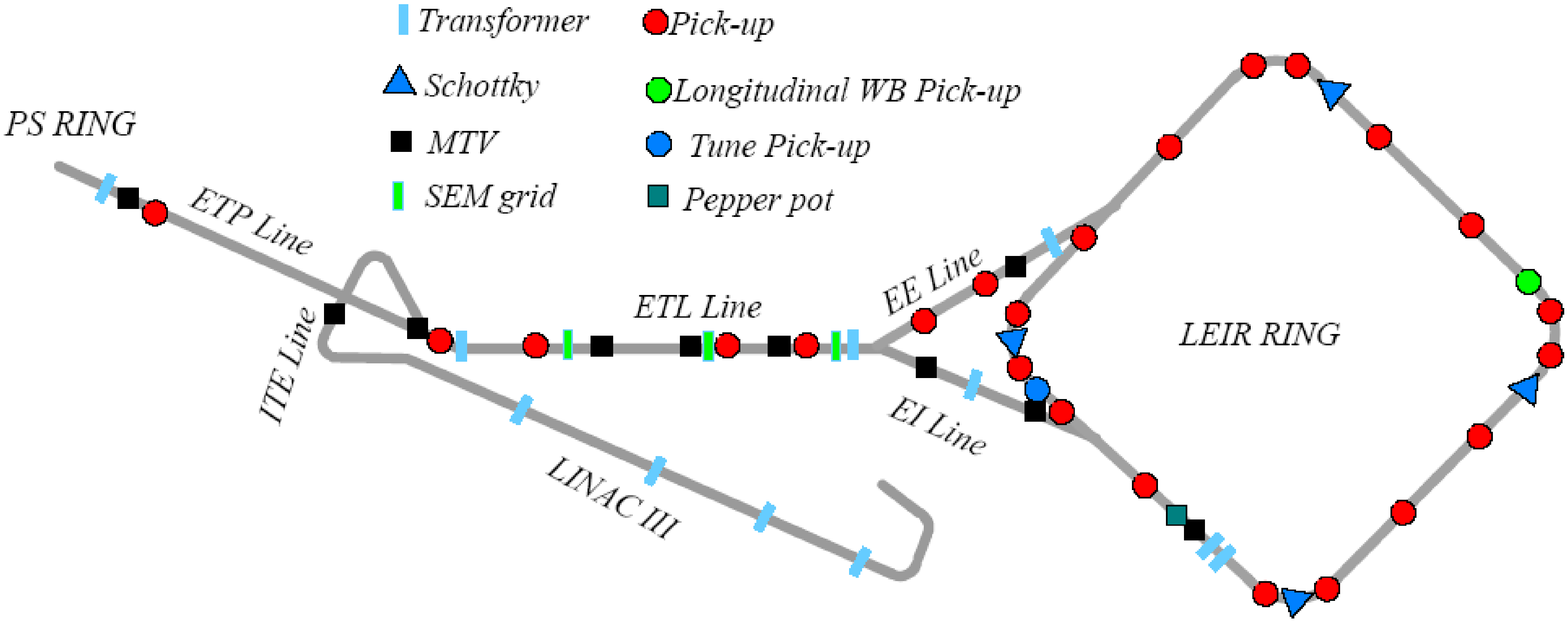
Longitudinal Schottky scan at the 10^{th} harmonic of Ar^{18+} at the GSI storage ring. The broad curve is the frequency spectrum at injection with $\Delta p/p = 1 \cdot 10^{-3}$ and the narrow curve is recorded after electron cooling down to a momentum width of $\Delta p/p = 2 \cdot 10^{-5}$.

P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

Example: LEIR @ CERN

- Low Energy Ion Ring LEIR

M. Chanel, Proc. of EPAC 2002, Paris (France), 2002, p.563



Layout of the LEIR complex and instruments.

C. Bal *et al*., Proc. of DIPAC'05, Lyon (France), 2005, p.258

Transfer Line Diagnostics

- transfer line
  - linking circular machines while matching the optical beam parameters
  - adjust beam transport
    - → control transfer efficiency:

      AC current transformers
    - → control beam position (steering)

      BPMs and/or screens
  - determine beam quality
    - → transverse emittance via beam profiles

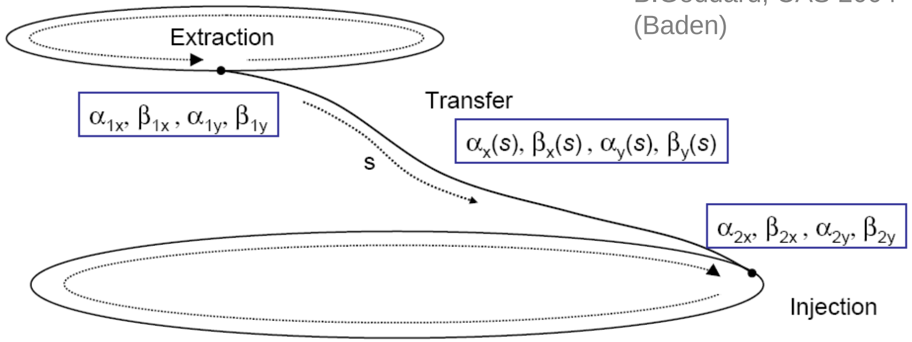
      i) measure beam size versus quadrupole field strength using one device

      ii) measure beam size using multiple measurement devices for fixed optics

      screens, residual gas monitors,…
  - protect machine
    - → control of beam losses, machine interlock

      BLMs

B.Goddard, CAS 2004 (Baden)



The Twiss parameters can be propagated when the transfer matrix **M** is known

$$\begin{bmatrix} x_2 \\ x'_2 \end{bmatrix} = M_{1\to 2} \cdot \begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} C & S \\ C' & S' \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}$$

$$\begin{bmatrix} \beta_2 \\ \alpha_2 \\ \gamma_2 \end{bmatrix} = \begin{bmatrix} C^2 & -2CS & S^2 \\ -CC' & CS'+SC' & -SS' \\ C'^2 & -2C'S' & S'^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{bmatrix}$$

Transfer Line Diagnostics (2)

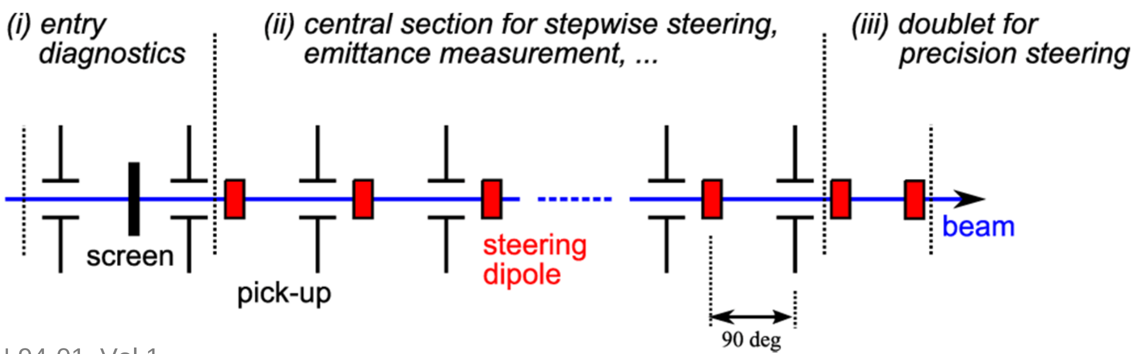
- beam steering philosophy
  - entry of transfer line: ***extracted beam information***
    - → position/angle: ***pair of pick-ups***
    - → qualitative shape: ***screen***
  - central section: ***stepwise steering & beam quality***
    - → each steering magnet paired with ***pick-up*** (phase advance ~90°)
    - → emittance measurement: ***screen(s)*** in dispersion-free section
  - exit of transfer line: ***precision steering***
    - → two steerer magnets used as doublet
    - → adjust angle/position at septum to match condition for closed orbit of next accelerator section

best sensitivity

→ for measurement / control

→ ***maximum of β-function***

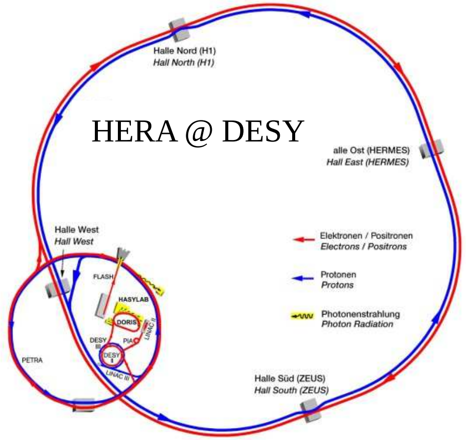
(i.e. close to quads)



P.J. Bryant, Proc. CERN Accelerator School, CERN 94-01, Vol.1

Storage Ring (Collider) Diagnostics

- intensity
  - bunch charge, stored dc current: lifetime, coasting beam
- orbit
  - lattice parameters (co): comparison between design and real machine
  - injection: elimination of mismatches (oscillations)
- tune, chromaticity, coupling
  - working point: avoid instabilities and losses
- beam distribution, emittance
  - beam profile: control of beam quality for luminosity
  - injection mismatch: optimization of injection
  - instabilities: observation of shape oscillations
- luminosity
  - count rate in experiments: tuning of collision at IP
- energy
  - cms energy for particle production



required B field → **superconducting magnets**

- quench protection
  - loss monitors: prevent damage of magnets

Storage Ring Diagnostics: Remarks

- superconducting magnets and consequences
  - cold environment because of liquid He

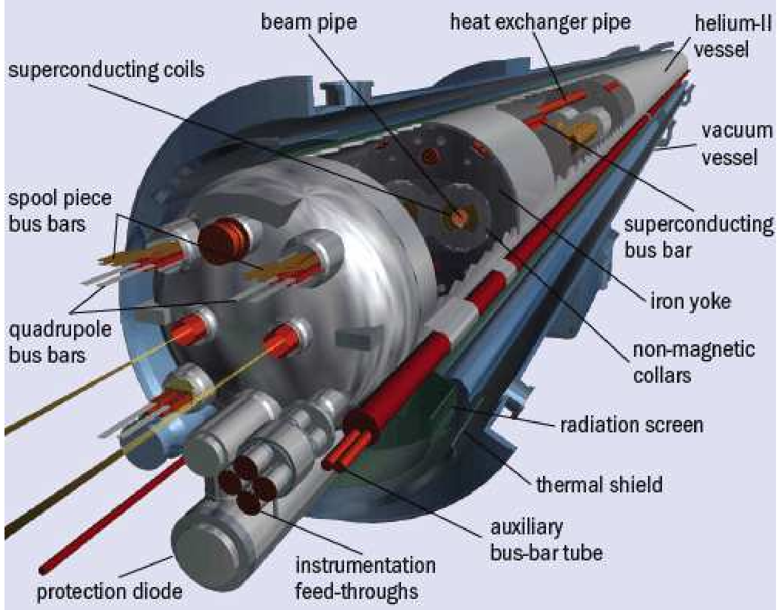
    HERA @ 4.4 K, LHC @ 1.8 K
  - consequence for beam diagnostics

    → beam instruments in cold environment

    → careful instrument design: minimum heat transfer from beam instruments to the environment (e.g. by HOM heating)

    → no intercepting diagnostics in (close to) cold sections because particle shower may lead to magnet quenches

    → protect beam intercepting monitors against possible misuse, i.e. ***interlock system***



CERN Courier, October 2006

- common strategy
  - concentration of beam instrumentation in straight sections (***insertions***) without need for particle bending

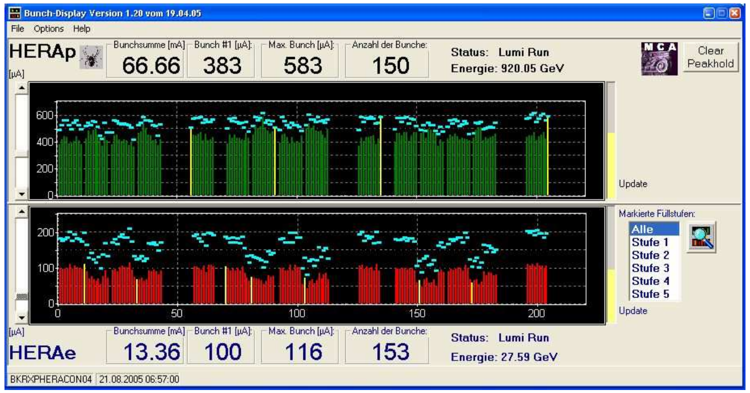
    → most instruments can be placed in warm environment
  - BPMs (which has to be placed all around the ring for closed orbit) partly in cold environment

    → BLMs (not in vacuum) installed all around the ring

Storage Ring Diagnostics (1)

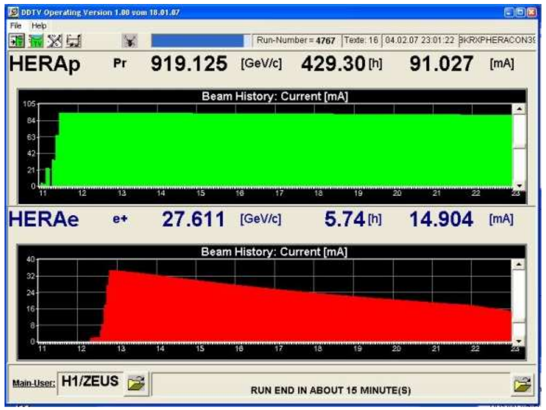
- intensity
  - bunch charge, filling pattern: AC current transformer (ACCT)
  - mean current: DC or parametric current transformer (DCCT)
  - examples: from HERA p diagnostics

ACCT



DCCT

- intensity related parameters
  - coasting (unbunched) beam: $$I_{CB} = I_{DC} - \sum_{i=1}^{N_{bunch}} I_{AC(i)}$$
  - life time: $$\frac{1}{\tau(t)} = -\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}t}$$



Storage Ring Diagnostics (2)

- orbit, trajectory, oscillations
  - BPMs: for ***cold*** and ***warm*** environment
  - choice of type depends on:

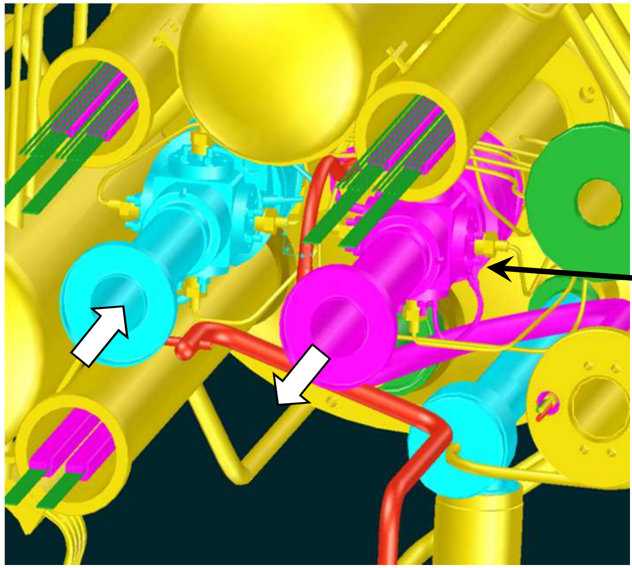
    linearity, dynamic range, resolution

    → stripline monitor, button electrode pick-up

    LHC resolution achieved:

    < 150 μm (single bunch & single turn), < 10 μm (avg. orbit of all bunches)

LHC orbit during commissioning



LHC cold button pick-up

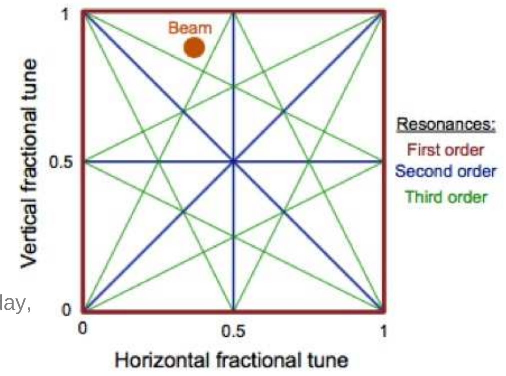
courtesy: Ch. Boccard (CERN)

HERA p cold stripline

courtesy: S.Vilcins (DESY)

Storage Ring Diagnostics (3)

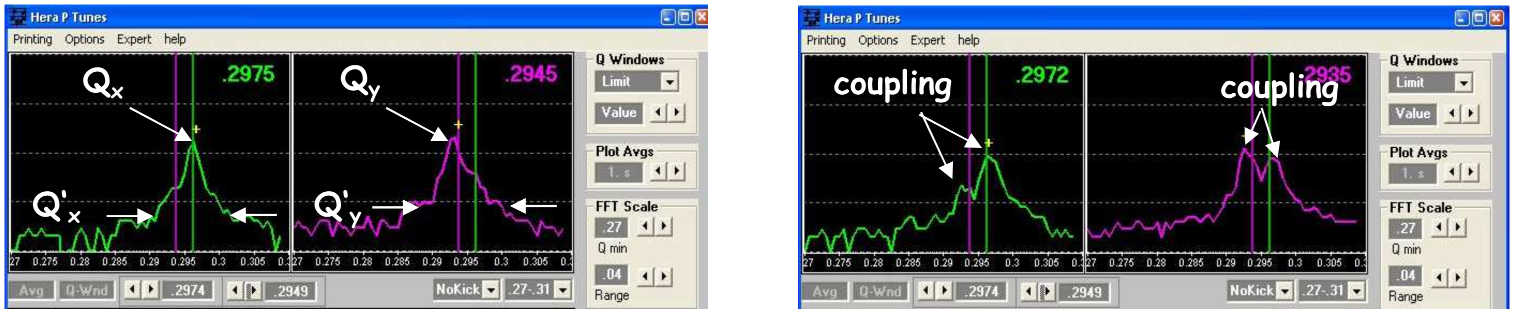
- tune (chromaticity, coupling) → defines working point of accelerator
  - principle: transverse beam excitation → excite coherent transv. oscillations
    → FFT mode / Swept Frequency mode / PLL mode
  - constraint: minimize ***emittance blow*** up due to excitation
    → high sensitivity pick-up detector
    → minimum disturbing excitation scheme



Fermilab Today, July 2015

  - excitations: i) ***tune kicker:*** white noise kick, simple and robust (typically for commissioning)
    ii) ***tune shaker:*** swept frequency (sine wave)

HERA p tune spectrum *(repetitive chirp excitation & resonant „Schottky type“ pick-up)*



- comments
  - chromaticity: via head-tail phase shift — D. Cocq, O.R. Jones, H. Schmickler, AIP Conf. Proc. **451** (1998) 281
  - passive (without external excitation): Schottky spectrum contains informations about tune, chromaticity,…

Storage Ring Diagnostics (4)

- tune, chromaticity: dynamic effects in superconducting storage rings
  - s.c. eddy currents / persistent currents: strong influence on storage ring performance at ***injection energy***

    → affect ***multipole components*** of s.c. dipole magnet (***HERA:*** most important sextupole component)

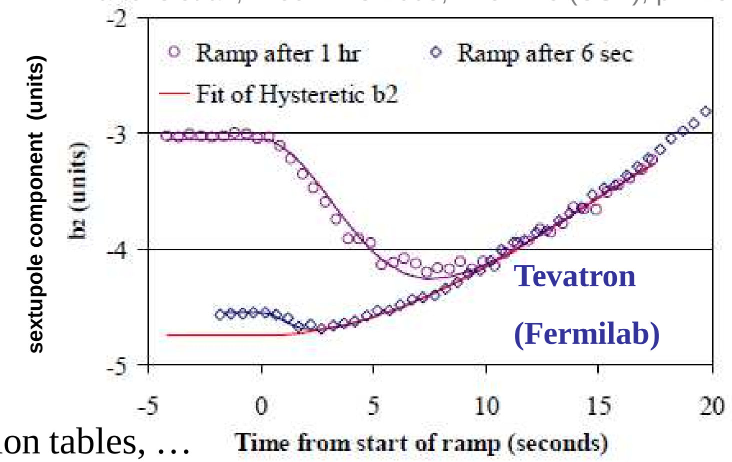
    → are ***not really persistent*** (decay with time)

    → need correction

  - persistent currents are ***reinduced to their full strength*** on first steps of the ramp, approaching original hysteresis curve

    ➡ ***"Snap Back":*** requires reliable control during ramp

M.A. Martens *et al.*, Proc. PAC 2005, Knoxville (USA), p. 725



  - online measurements (magnetic multipole components), correction tables, …

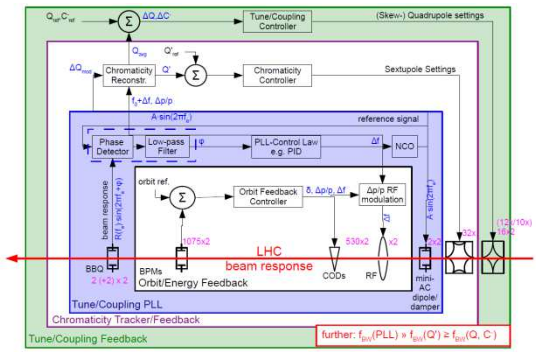
- beam ramping up
  - **tune and chromaticity feedback**

    → HERA @ DESY: **"Brain Locked Loop" (BLL)**

    6 knobs (2 x tune, 2 x chromaticity, 2 x coupling)

    experienced shift crew (at least two people)

    → LHC @ CERN: **Phase Locked Loop (PLL)**

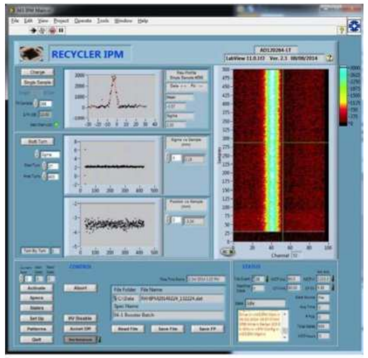


R. Steinhagen, Proc. CAS 2008, CERN-2009-005

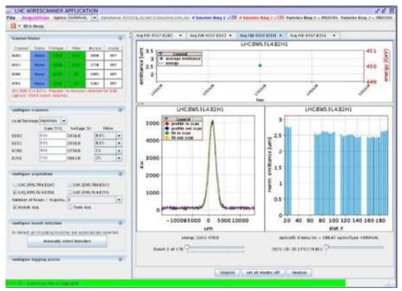
Storage Ring Diagnostics (5)

- transverse beam profile and emittance
  - single pass diagnostics
    - → simple and robust, high sensitivity (single or few bunches only), modest demand on accuracy
    - → ***luminescent screens***
  - profile diagnostics for few turns
    - → study of injection mismatch (betatron, dispersion matching on first turns observing shape oscillations)
      turn by turn acquisition (10-20 turns), modest demand on accuracy
      only moderate beam blow up allowed, energy deposition in screen is critical
    - → ***Optical Transition Radiation (OTR)*** using thin foils
  - diagnostics for the circulating beam
    - → evolution of the rms beam size, emittance measurements, tilt due to coupling
      minimum beam blow-up (→ non-intercepting measurements), high accuracy
    - → ***residual gas (luminescence) monitors***
    - → ***fast wire scanners*** (flying wires, > 1 m/sec)
    - → ***synchrotron radiation monitor***
      (fringe field, short magnet, undulator)

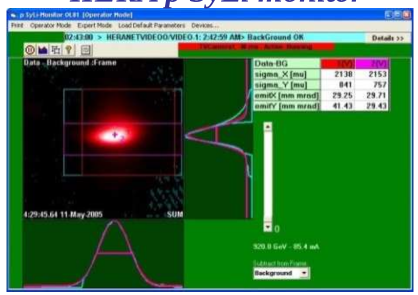
Fermilab IPM



LHC wire scanner



HERA p SyLi monitor

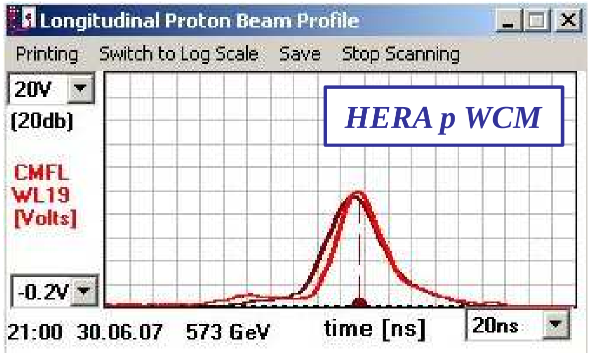


Storage Ring Diagnostics (6)

- longitudinal beam distribution and time structure
  - longitudinal profile
    - → classical longitudinal bunch parameters:

      bunch center of gravity, rms bunch length, core distribution
  - examples (1σ values)
    - → ***HERA p*** @ 920 GeV: $\sigma_t = 1.6$ nsec
    - → ***LHC*** @ 450 GeV: $\sigma_t \sim 0.425$ nsec

      @ 7 TeV: $\sigma_t \sim 0.250$ nsec



LHC WCM: T. Bohl and J.F.Malo, CERN-BE-2009-06

➡ **wideband Wall Current Monitor**

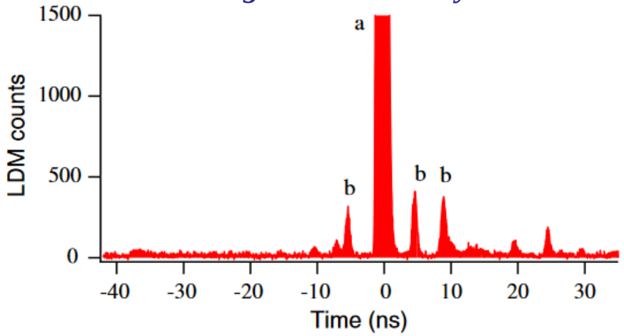
  - abort gap monitoring
    - → continuous monitoring that rise time gap of dump extraction kicker is free of particles

      if particles in gap would not receive proper kick when dump system is fired:

      damage of machine components
  - detection of ghost bunches
    - → may disturb BPM system read-out or physics data taking

➡ **synchrotron radiation based diagnostics**

LHC Longitudinal Density Monitor



A. Jeff *et al*., Proc. PRST-AB **15** (2012) 032803

Storage Ring Diagnostics (7)

- luminosity
  - need: determines accelerator performance

    parameter for optimization of beam collisions at IP
  - principle: choose reaction channel with known cross section σ_{rc}

    count rate measurement for events N_{rc} of this channel

    → ***luminosity:*** $\mathcal{L} = \dot{N}_{rc}/\sigma_{rc}$
  - problem: ***hadronic*** cross sections are ***not precisely calculable*** because of constituent particle nature

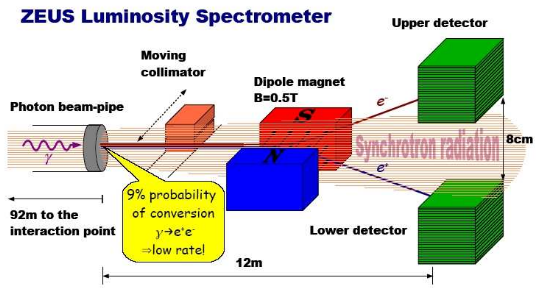
    → reaction rates do not serve as absolute luminosity monitors, i.e. only for optimization

    → absolute luminosity determination complicated task, often duty of experiments
  - example: ep collider ***HERA***, absolute luminosity determination via

    Bremsstrahlung (Bethe-Heitler): $e\,p = \gamma\,e'\,p'$

    → cross section well known

HERA luminosity at H1



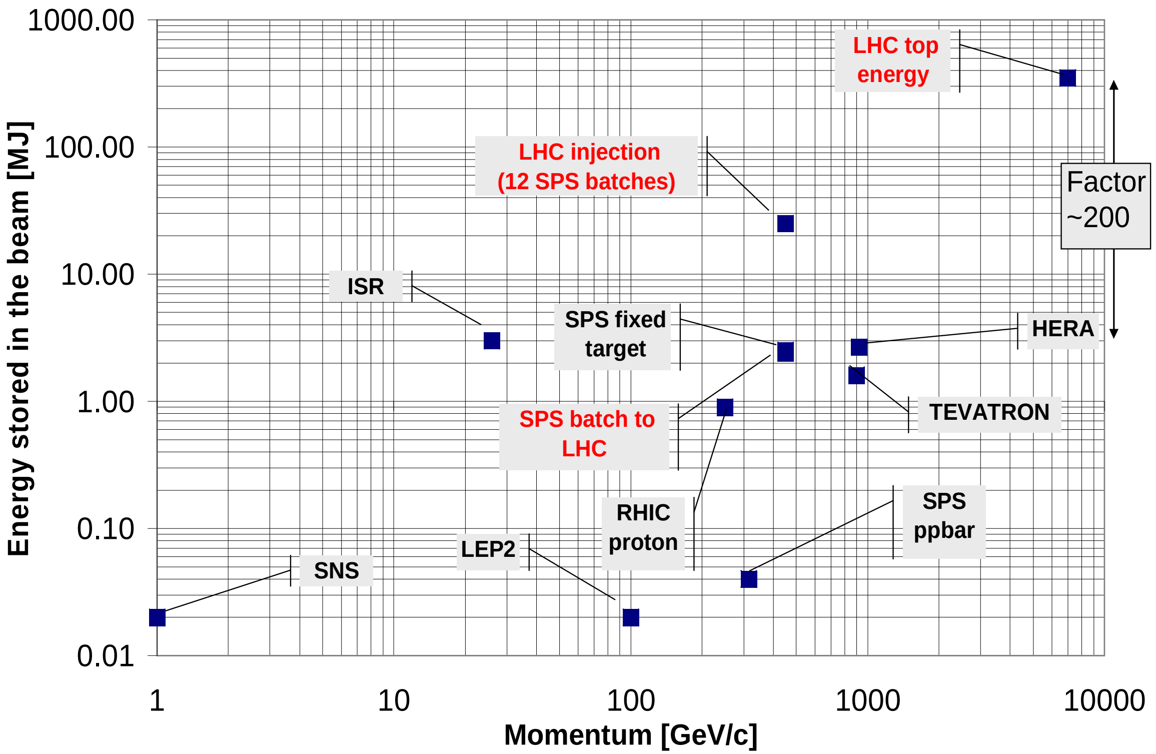
- energy
  - importance: hadron-hadron collider absolute energy determination relatively unimportant

    → constituent nature of hadrons (quarks and gluons) which share beam momentum

    → total energy in reaction only loosely related to beam energies
  - measurement: beam momentum via dipole current is sufficient

Storage Ring Diagnostics (8)

- quench protection / loss monitors
  - stored beam energy:



courtesy: R.Jones (CERN)

  - quench level of a cable: HERA @ 820 GeV

    $\Delta T_c = 0.8$ K between He bath temperature T_b = 4.4 K and quench temperature T_{cs} = 5.2 K !

  - beam loss monitors

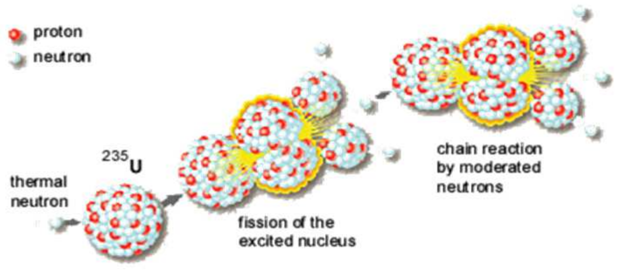
    → gas ionization chambers, PIN diodes, photomultipliers & scintillators, SE multiplier tubes…

Examples for Hadron Accelerator Diagnostics

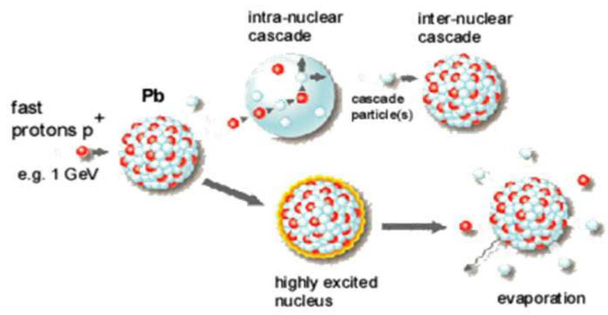
- Spallation Neutron Source
- Hadron Therapy Accelerator

Spallation Neutron Source

- motivation: n production mechanisms
  - fission (reactor)
    - → chain reaction
    - → continuous flow
    - → 1 neutron / fission



  - spallation (accelerator driven)
    - → no chain reaction
    - → of interest: short pulse operation allows time resolved experiments
    - → 20 ~ 30 neutrons / proton

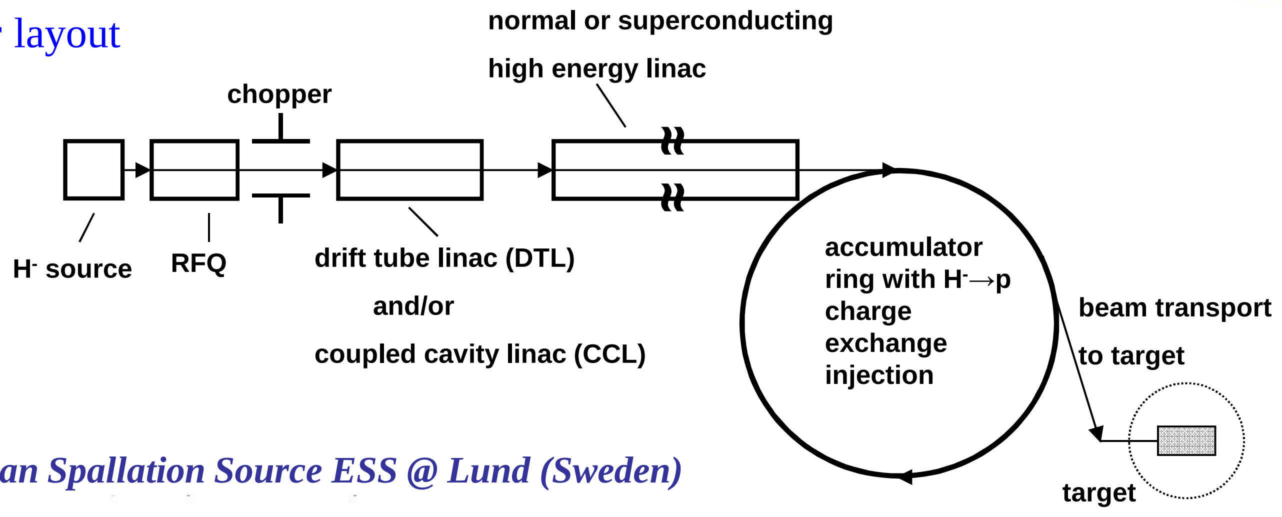


- beam characteristics
  - proton beam energy
    - → number of neutrons proportional to E in range of 0.2 … 10 GeV ⇒ **E = 1 … 3 GeV**
  - average beam power: $\bar{P}_{beam}[\text{MeV}] = \text{E}[\text{GeV}] \cdot I_{pulse}[\text{mA}] \cdot \Delta t_{pulse}[\text{sec}] \cdot f_{rep}[\text{Hz}]$

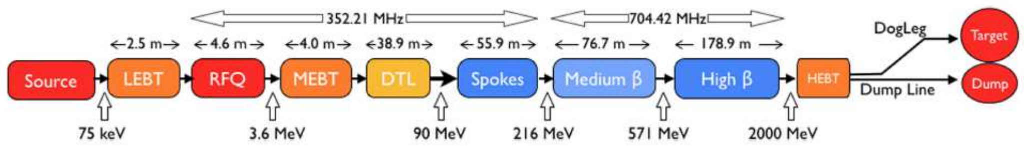
⇒ **P_{beam} = 1 … 5 MW**

Spallation Neutron Source

- general accelerator layout



- example: ***European Spallation Source ESS @ Lund (Sweden)***



R. Garoby *et al.*, Phys. Scr. **93** (2018) 014001

Parameter	Units	Value
Average beam power	MW	5
Proton kinetic energy	GeV	2.0
Pulse repetition rate	Hz	14
Energy per pulse	kJ	357
Average pulse current	mA	62.5
Macro-pulse length	ms	2.86

→ ***Spallation Neutron Source SNS @ Oak Ridge (USA)***

→ ***Japan Spallation Neutron Source JSNS of J-PARK, Tokai (Japan)***

standard hadron linac & injector synchrotron

→ ***Swiss Spallation Neutron Source SINQ @ PSI (Switzerland):*** (continuous beam from cyclotron)

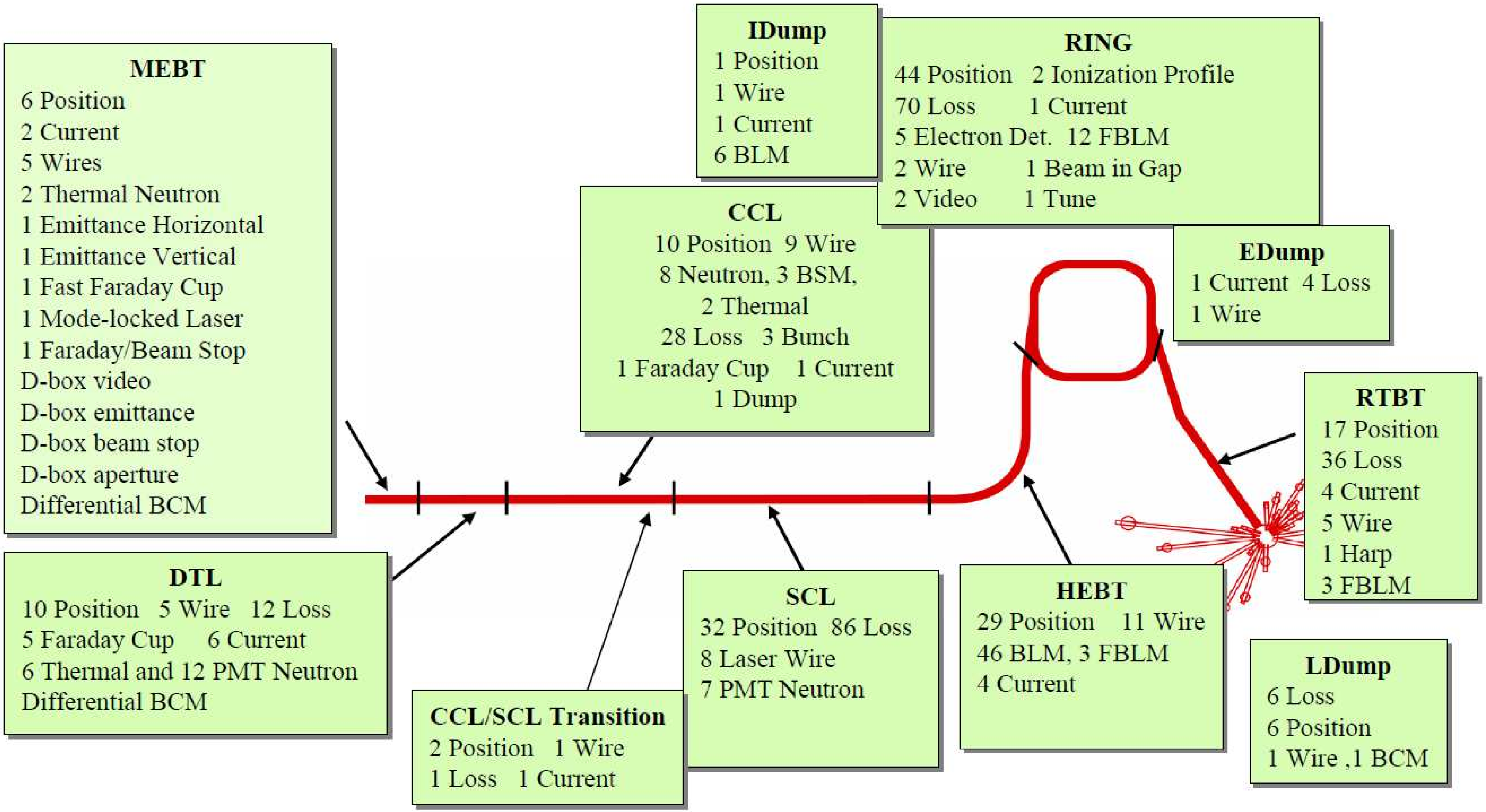
- implications on beam diagnostics → handling of high beam power

High Power Diagnostics

- achieving high beam power
  - systems to help understanding dynamics of intense beams
    → **beam halo measurements, …**
- measuring high power beams
  - diagnostic systems that can measure fundamental beam parameters during full power operation
  - challenging: transverse beam profiles
    → **laser systems for H^- beams, ionization profile monitors for p beams, …**
- protecting the diagnostics
  - protect diagnostic systems that cannot survive high power beams
    → **machine protection interfaces for intercepting devices, …**
- protecting the facility
  - diagnostics that protect the facility from beam-induced damage or activation
    → **loss monitors, beam-on-target diagnostics, …**

T.Shea (SNS/ESS), talk held at EPAC04

Diagnostics for SNS @ ORNL

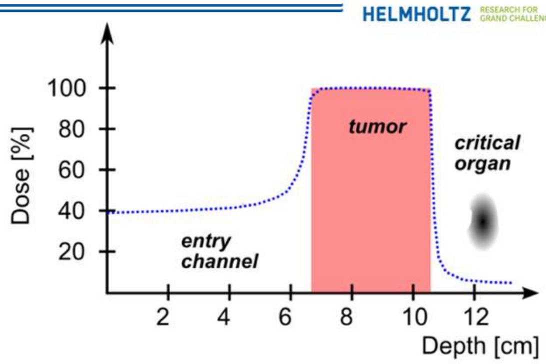


courtesy: T.Shea (ESS/SNS)

Hadron Therapy Accelerator

- hadron therapy
  - damage DNA of tumor cells with high-energetic ion beams
  - **requirement:** constant and high dose profile at tumor

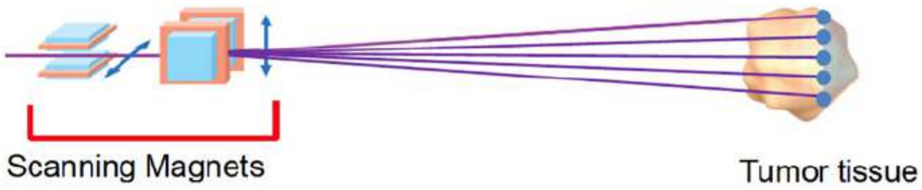
    low dose at critical organs



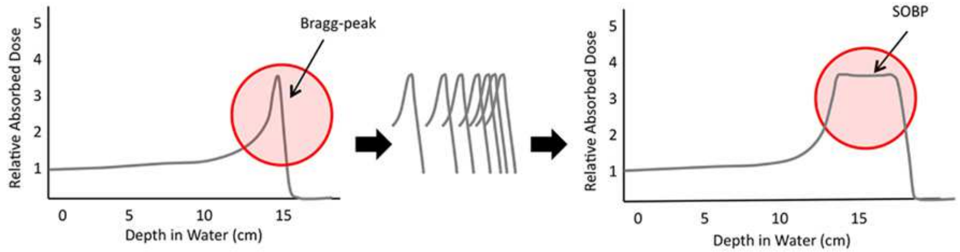
- 3D beam scanning over tumor region
  - transverse directions

    → pencil beam scanning
  - longitudinal direction

    → energy/intensity alignment of many Bragg-peaks allow creation of Spread-Out Bragg Peak (SOBP)



M. Durante and H. Paganetti, Rep. Prog. Phys. **79** (2016) 096702

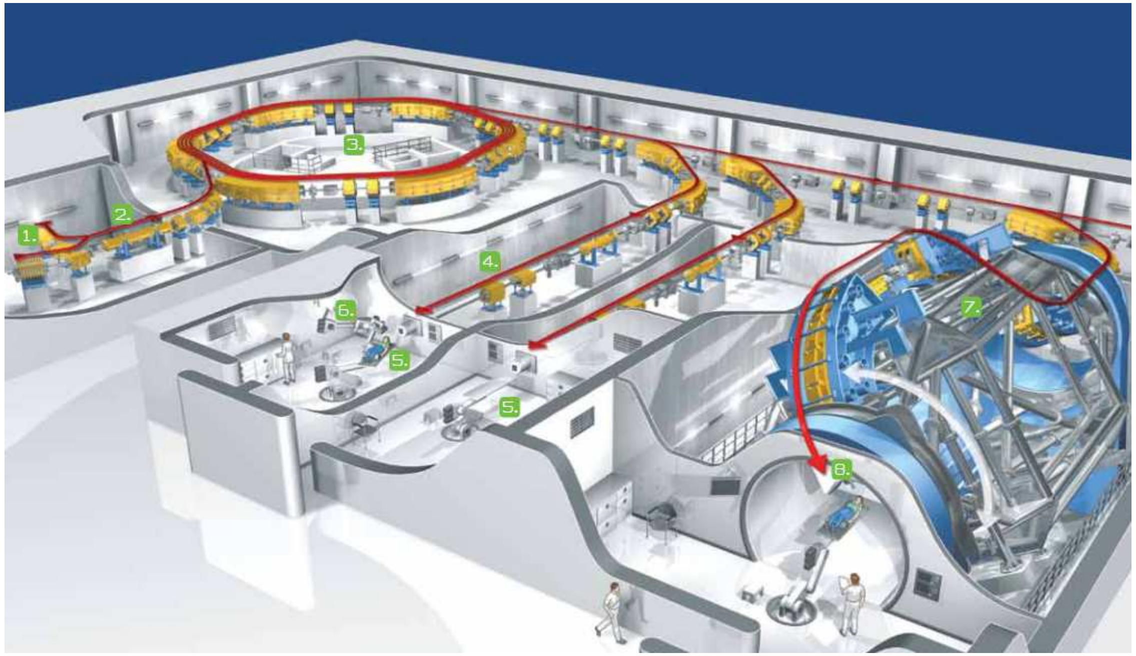


Ch. E. Hill-Kayer et al., Front. Oncol., 06 Sept. 2011

- implications on beam diagnostics
  - non destuctive diagnostics during patient treatment
  - precise determination of **position & size** **energy & intensity**

Facility Layout

- example: Heidelberger Ionenstrahl-Therapiezentrum (HIT), Germany



(1) ion sources

- 2 ion sources (p, H_2, C^{4+} , O^{6+})
- typical 130 μA C^{4+} DC-beam

(2) 2-stage linac

- four-rod RFQ-structure (400 keV/u)
- IH-DTL (7 MeV/u)
- 30μs-Macropulse: 50 μA C^{6+}

(3) synchrotron

- 64 m circumference
- magnetic rigidity: 6.6 Tm
- E= 48 - 220 MeV/u (proton)
- E= 88 - 430 MeV/u (carbon)
- 6×10^8 Carbon

(4) heading towards treatment room

(5) treatment room

(6) position control

(7) gantry

(8) treatment room in gantry

https://www.klinikum.uni-heidelberg.de/fileadmin/hit/dokumente/121019KV_SS_HITImage_engl_web_ID17763.pdf

Beam Diagnostics for Medical Accelerators

- OMA: Optimization of Medical Accelerators
  - EU project
    → https://www.liverpool.ac.uk/oma-project/
  - organization
    → University of Liverpool

- Workshop about Beam Diagnostics: