Specific Diagnostics Needs for Different Machines

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- Introduction
- Diagnostics for Hadron Accelerators
- Diagnostics for Electron Accelerators

Accelerator Applications

Category	Number
Ion implanters and surface modifications	7000
Accelerators in industry	1500
Accelerators in non-nuclear research	1000
Radiotherapy	5000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

$\Sigma = 15000$

World wide inventory of accelerators.
U.Amaldi, Proceedings of EPAC 00, Vienna, Austria, 2000, p. 3

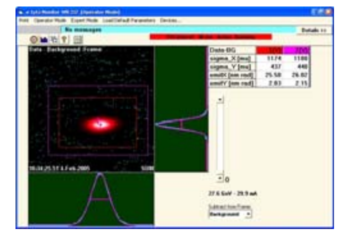
Beam Parameters and Diagnostics

DESY
HELMHOLTZ GEMEINSCHAFT

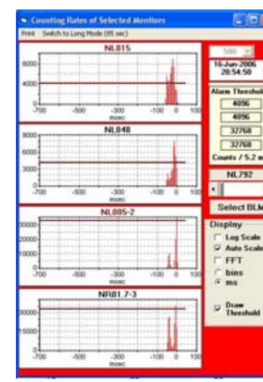
- **beam position**
  - orbit, lattice parameters, tune, chromaticity, feedback,…

- **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,…

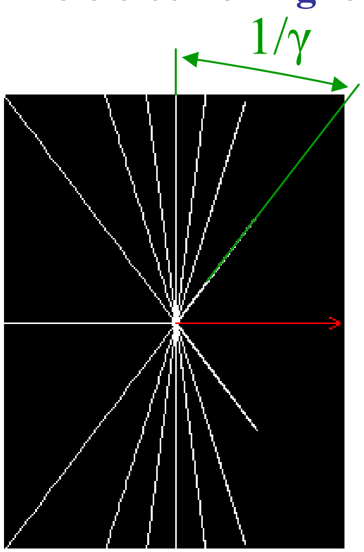
Beam Monitors: Physical Processes

- influence of particle electromagnetic field
  - non-propagating fields, i.e. electro-magnetic influence of moving charge on environment

    → beam transformers, pick-ups, …
  - propagating fields, i.e. emission of photons

    → synchrotron radiation monitors, (OTR), …

particle electromagnetic field



electric field lines in LAB frame

relativistic contracion characterized by Lorentz factor

$$\gamma = E / m_0 c^2$$

E : total energy

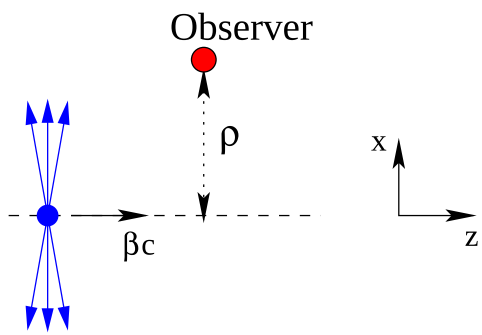
$m_0 c^2$: rest mass energy

proton: $m_p c^2 = 938.272$ MeV

electron: $m_e c^2 = 0.511$ MeV

Beam Monitors: Physical Processes

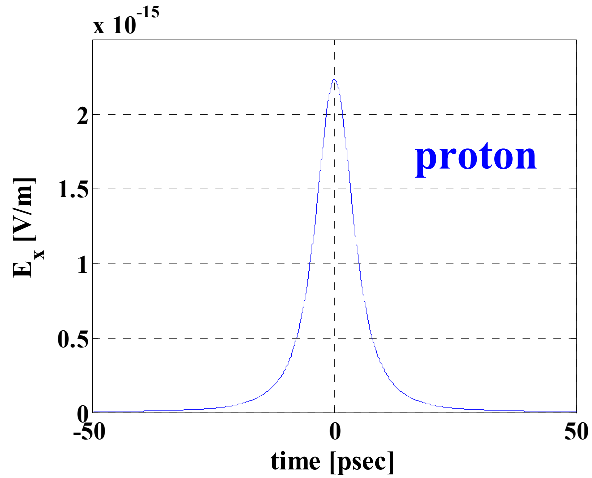
- non-propagating field

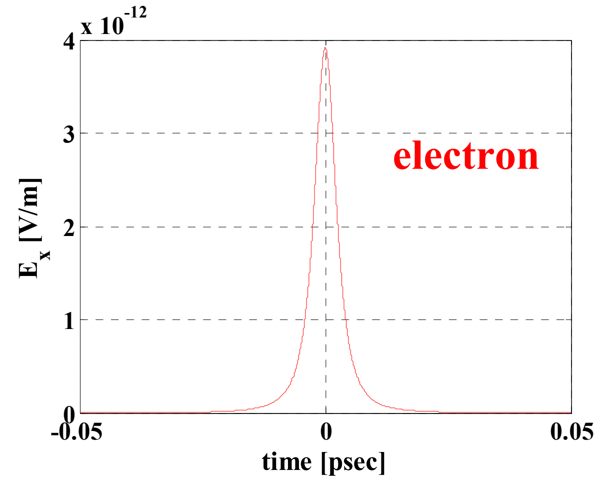


$E_{kin} = 20$ GeV

$\rho = 40$ mm

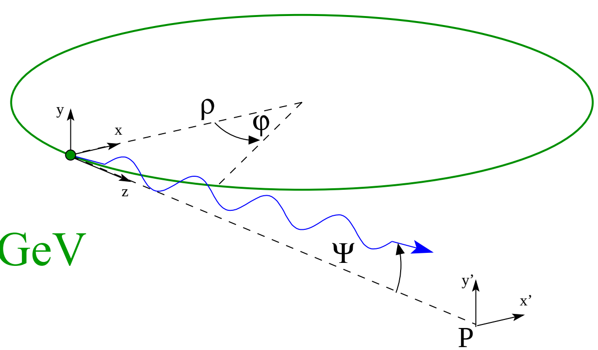
transverse electrical field components





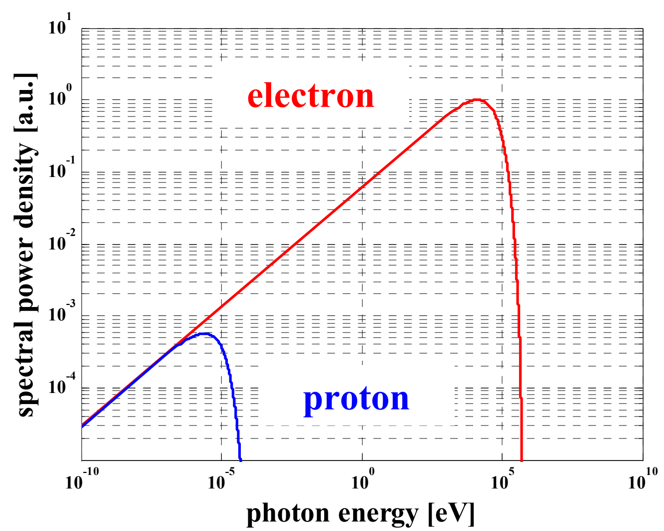
- propagating field

(synchrotron radiation)



$E_{kin} = 20$ GeV

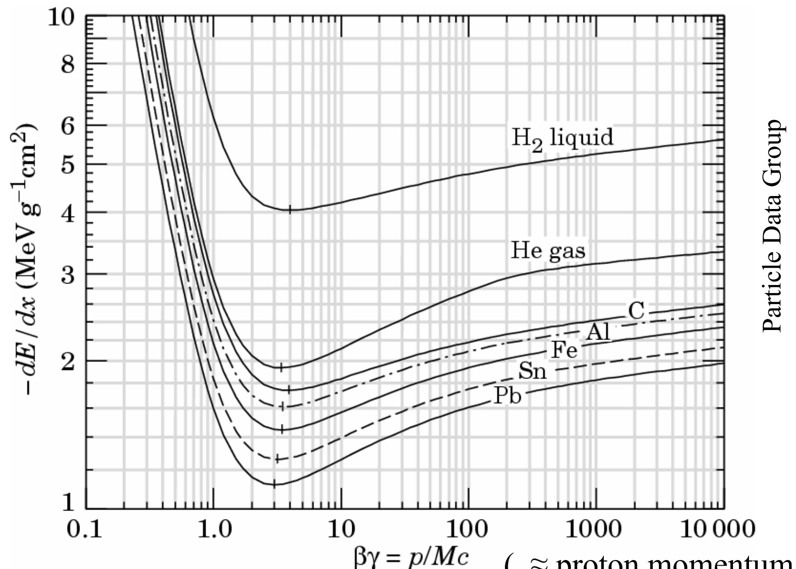
$\rho = 370$ m



Beam Monitors: Physical Processes

- Coulomb interaction of charged particle penetrating matter

→ viewing screens, residual gas monitors, …

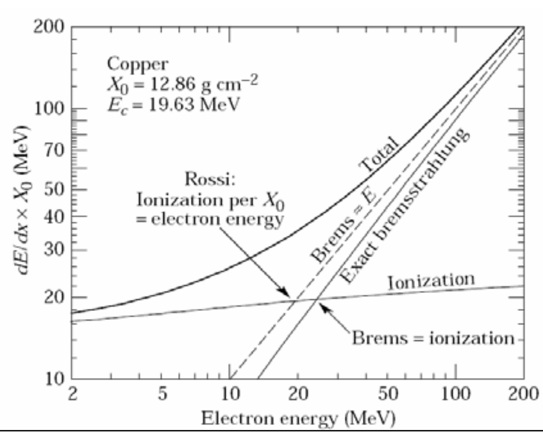


(≈ proton momentum [GeV/c])

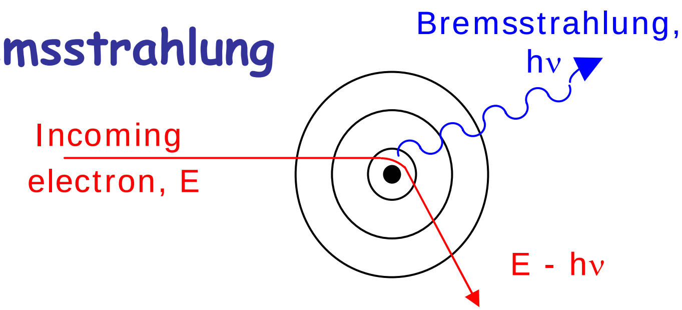
$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z_T}{A_T} \rho \frac{Z_p^2}{\beta^2}[\ln \frac{2m_e c^2 \gamma^2 \beta^2}{I} - \beta^2]$$

Bethe Bloch Equation („low-energy approximation“)

- **constants:**
  - N_A: Avogadro number
  - m_e, r_e: electron rest mass, classical electron radius
  - c: speed of light
- **target material properties:**
  - ρ: material density
  - A_T, Z_T: atomic mass, nuclear charge
  - I : mean excitation energy
- **particle properties:**
  - Z_p: charge
  - β: velocity, with $\gamma^2 = \frac{1}{1-\beta^2}$



- **Electrons : Bremsstrahlung**



Beam Monitors: Physical Processes

- nuclear or elementary particle physics interactions

  → beam loss monitors, luminosity monitors…

electrons

- simple (point) objects
- interaction cross sections into final states can be calculated precisely

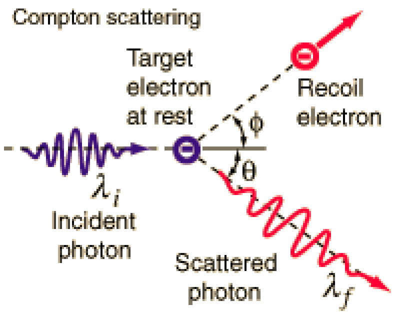
hadrons

- constituent nature (collection of quarks and gluons)
- interaction cross sections not precisely calculable

- interaction of particles with photon beams

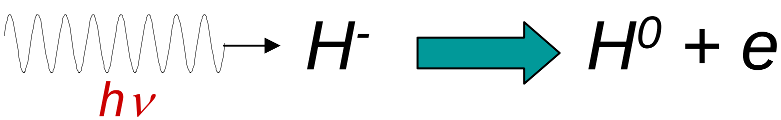
  → laser wire scanners, Compton polarimeters, …

electrons: Compton scattering



$$\frac{d\sigma}{d\Omega} \propto \left(\frac{e^2}{m_0 c^2}\right)^2$$

hadrons: laser photo neutralization (H^- beam)



applied for high power H^- beam profile diagnostics

Conclusion

- hadron / electron machines

  ⇒ difference in signal generation and underlying physical principles

  - distinguish between hadron / electron beam diagnostics

- program

  - **Hadron Accelerators**

    → Collider, Storage Ring

    incl. Injector Chain (Linac, Injector Synchrotron, Transfer Line)

    → Spallation Neutron Source

    → Hadron Therapy Accelerator

  - **Electron Accelerators**

    → Circular Collider

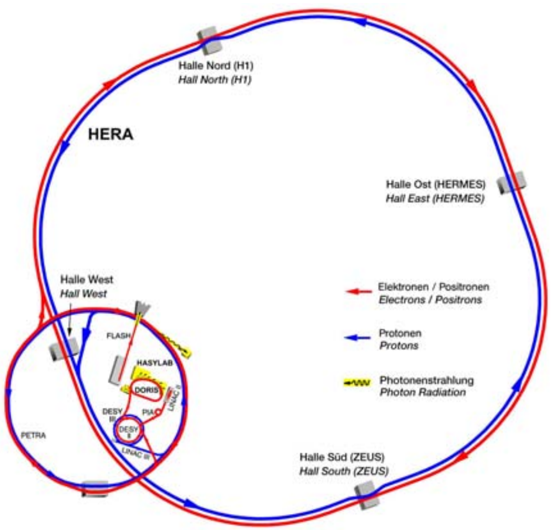
    → Synchrotron Light Source (3rd Generation)

    → Linac based Free Electron Laser

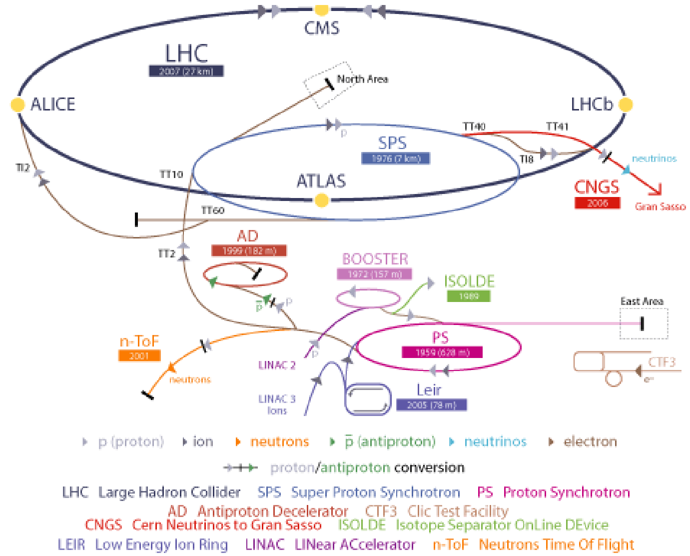
    → Outlook…

Hadron Collider (Storage Ring)

HERA @ DESY



LHC @ CERN



collider key parameter:

→ **luminosity $\mathcal{L}$**

(collider performance)

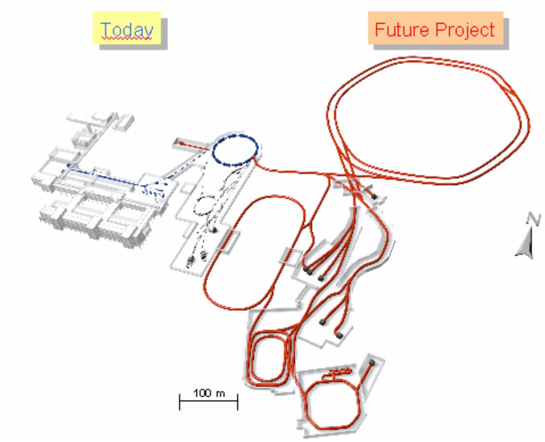
$$\dot{N} = \mathcal{L} \cdot \sigma$$

σ: cross section

(property of interaction)

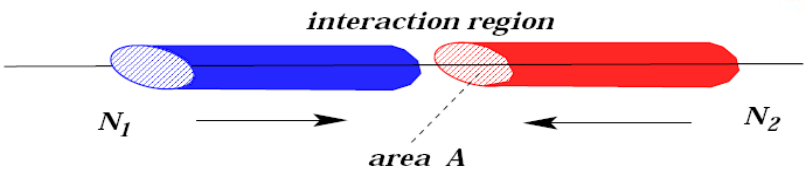
- modern hadron collider (storage ring) with high beam energy
  - **superconducting magnets** to achieve required particle bending
    - → parts of diagnostics located in cold vacuum
    - → beam-loss monitor system for quench protection required
  - **long injector chain** to reach final energy
    - → pre-accelerators / transfer lines with different beam properties
    - → different requirements for beam diagnostics

FAIR @ GSI



Comments: Injector Chain (1)

- luminosity of collider



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

for two identical beams, currents $I_1 = I_2 = I$ and emittances $\varepsilon_x = \varepsilon_y = \varepsilon$

$\Rightarrow$ small beam emittances preferable

- 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 very much suppressed*** because of large particle masses

$\Rightarrow$ **emittances essentially determined in the injector chain**

- consequences for beam diagnostics in injector chain

$\Rightarrow$
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)

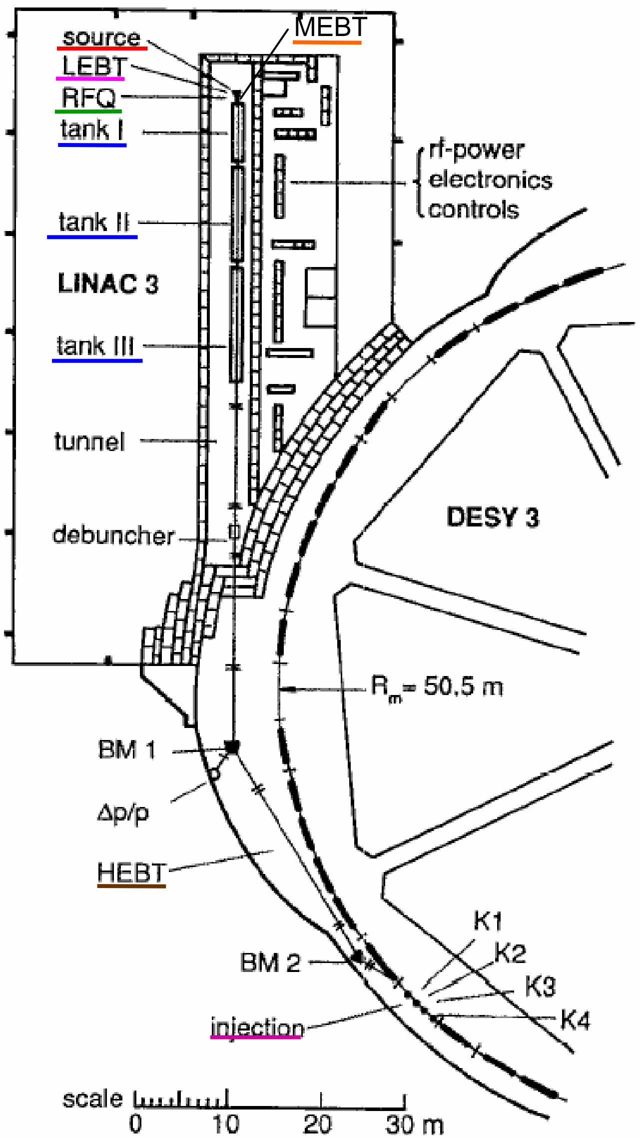
⇒ adiabatic shrinking with increasing beam energy

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)
    meaure 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 diagnostics beamline behind linac sections

→ moveable diagnostics test bench

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

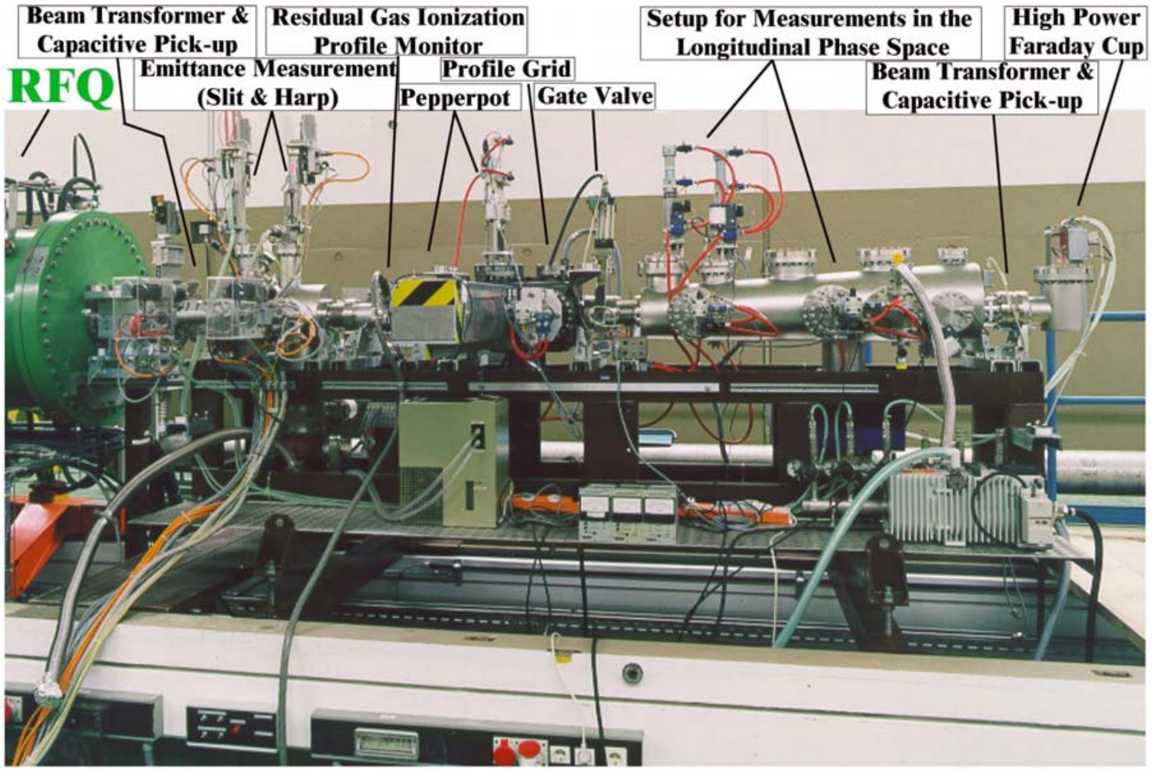
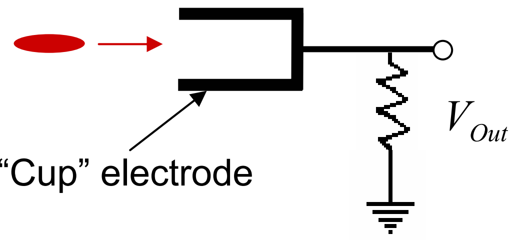


Photo GSI Darmstadt

Linac: Current and Transmission

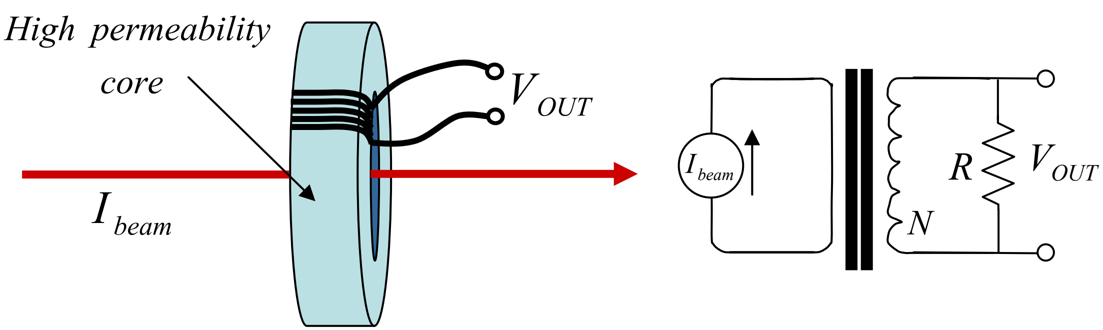
- destructive: Faraday cup



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

J.Rodriguez et al., Proc. of EPAC 2004 Lucerne, Switzerland, 2798

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

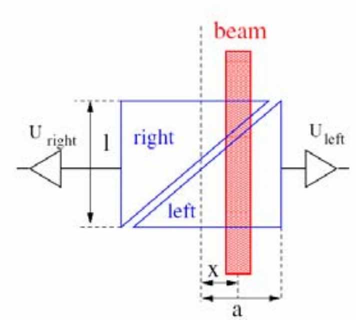


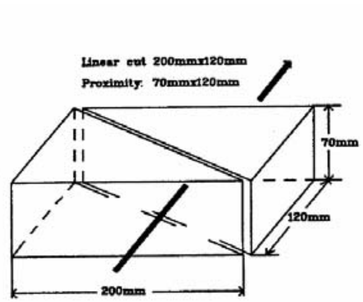
courtesy: F. Sannibale (LBNL)

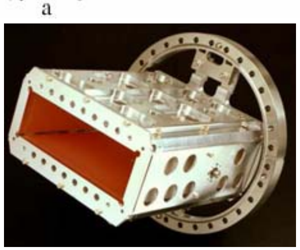
Linac: Beam Position

- position information via electric, magnetic, or electromagnetic field
- 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

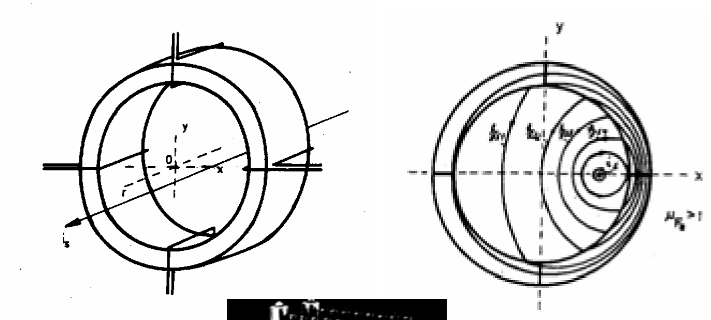


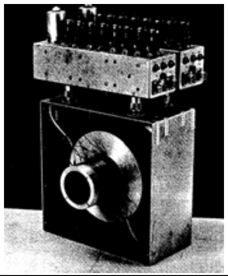




P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

inductive pick-up





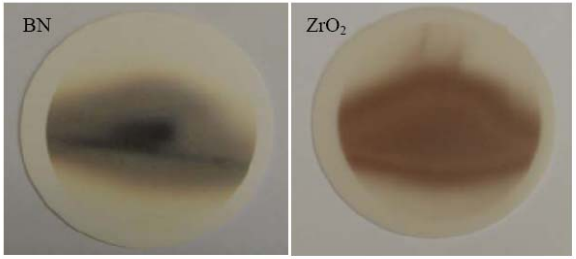
W.Kriens, W.Radloff, DESY-S1-68/1

Linac: Transverse Beam Profile (1)

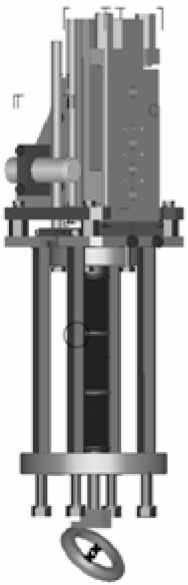
luminescent screens

- 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



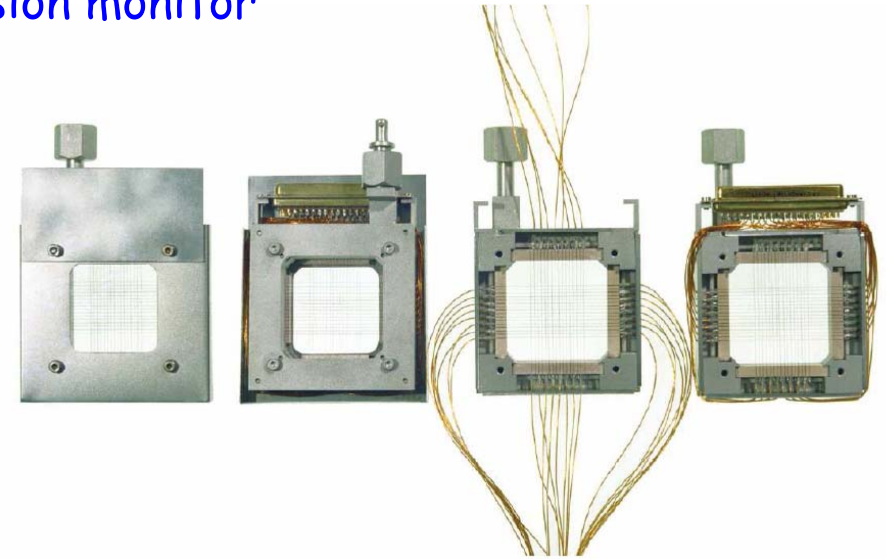
courtesy: Ch.Wiebers (DESY)

profile grid, harp, secondary emission monitor

- less destructive method
- grid: wires in both transversal planes

  harp: wires in one transversal plane

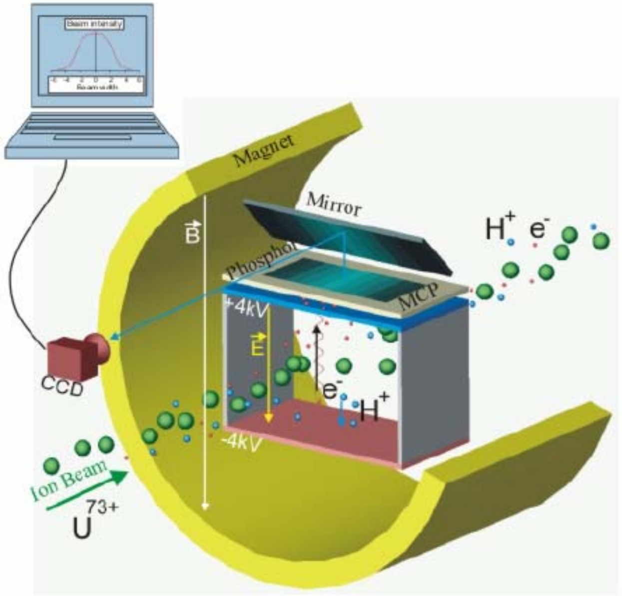
  SEM: strips, larger surface than wire



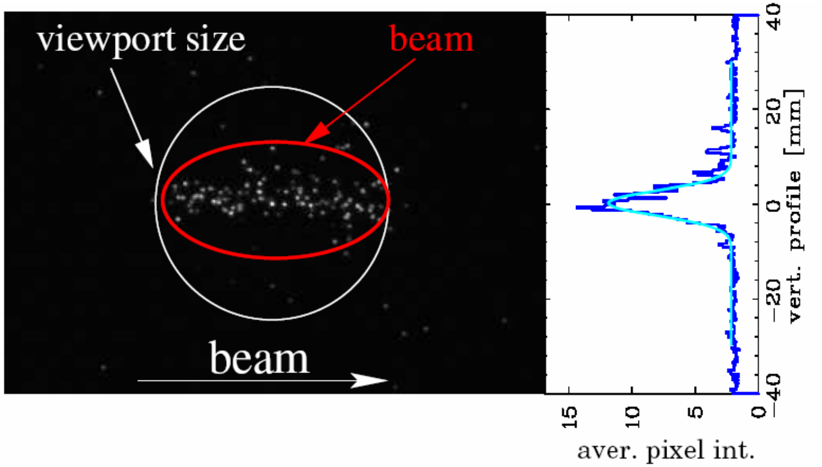
P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

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)
  - variant: residual gas fluorescence monitor



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

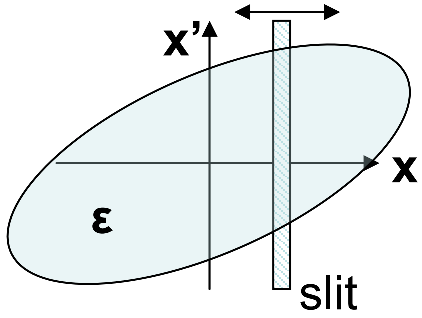


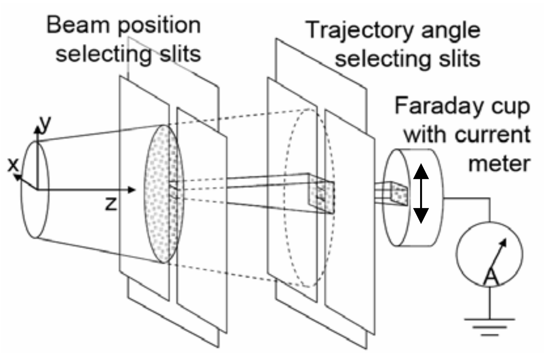
residual gas fluorescence monitor: image of a 2.5 mA Ar^{10+} beam at vacuum pressure of 10^{-5} mbar from GSI LINAC

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

Linac: Transverse Emittance

- principle
  - slit produces vertical slice in transverse phase space
  - measure intensity as function of **x'**
  - moving of slit → scan of phase space (N_x x $N_{x'}$ measurements)





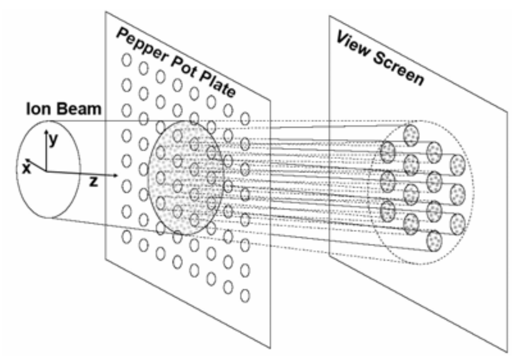
M.P.Stockli, Proc. BIW 2006, p.25

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

  SEM, profile grid,…

  → N_x measurements

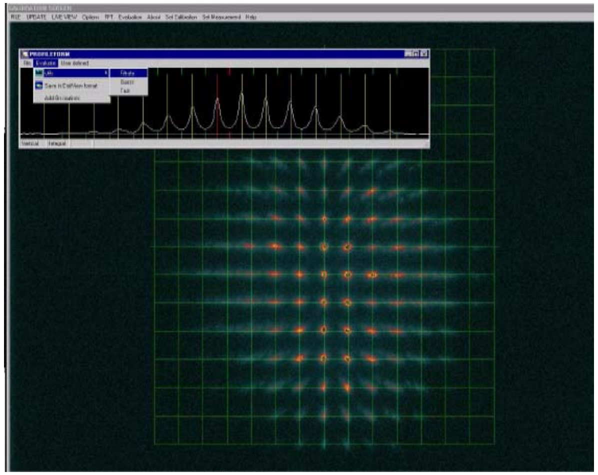
- 2-dimensional extension: Pepper pot



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

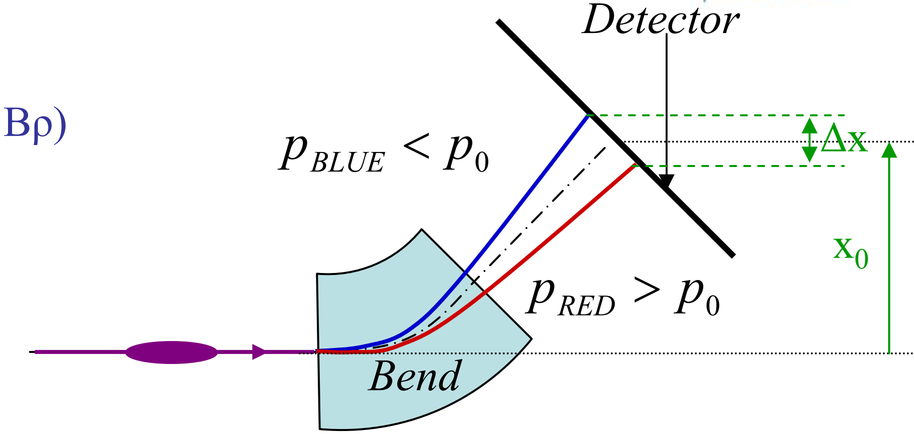
→ 1 measurement

N_x x $N_{x'}$ holes



Linac: Longitudinal Plane

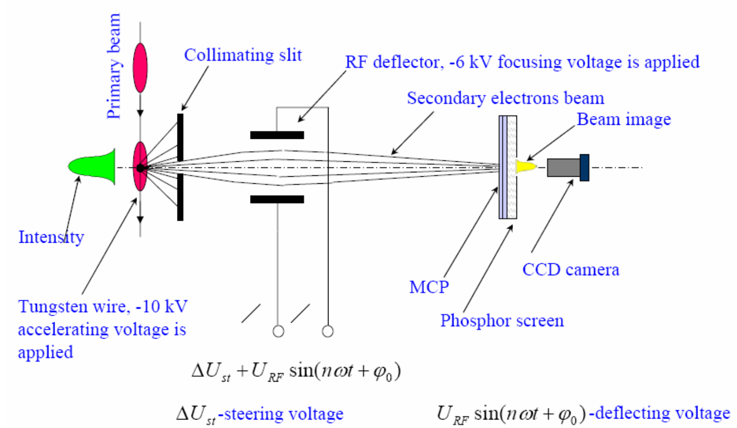
- momentum and momentum spread
  - dipole magnet spectrometer (small rigidity Bρ)
  - transformation of momentum (spread) into position (spread)
  - spatial resolving detector (screen, SEM,…)



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

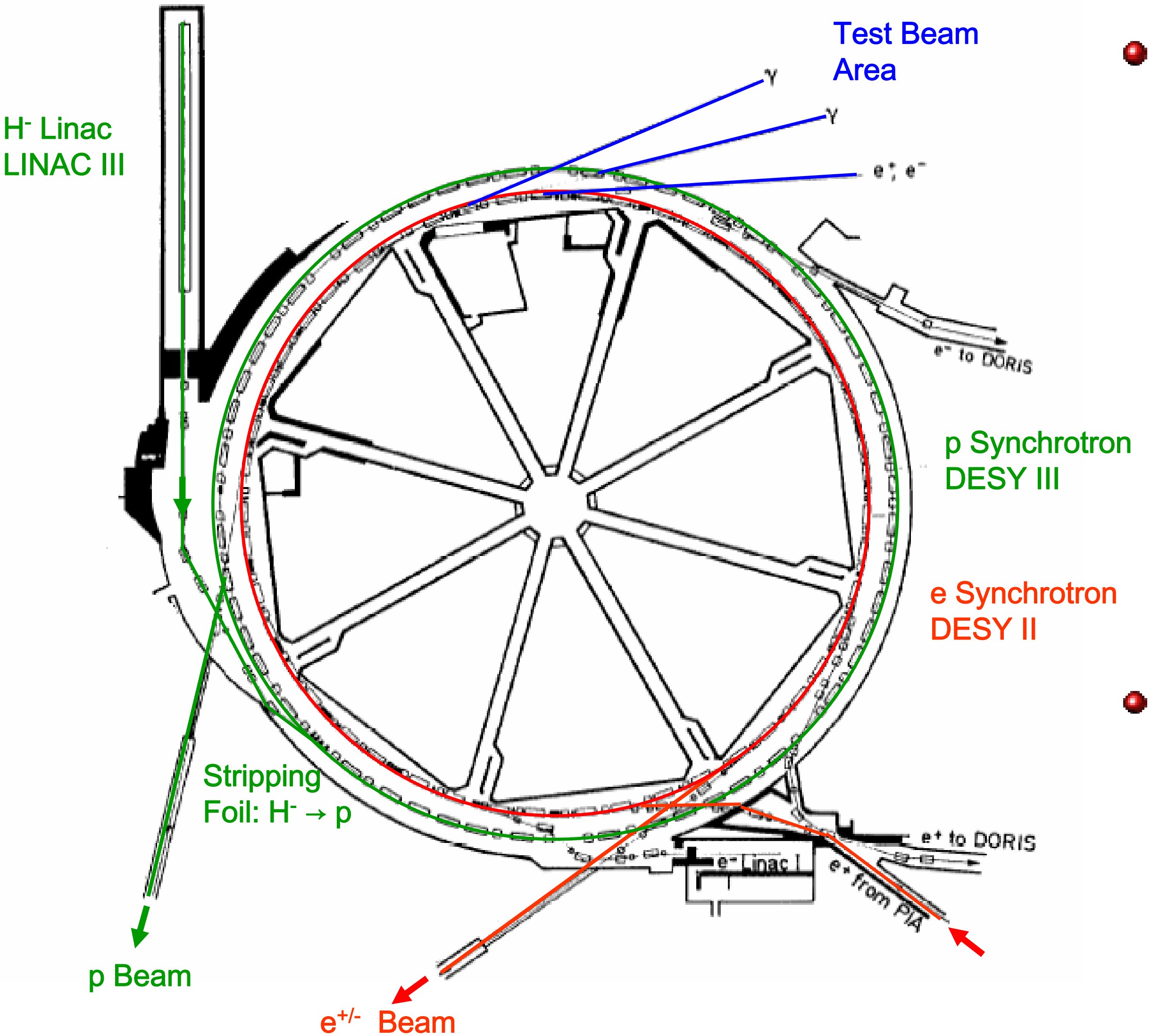
→ alternative method: time of flight (TOF)

- 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 spatial resolving detector



R.Pardo, *RIA Diagnostics Development at Argonne*

Injector Synchrotron: DESY III



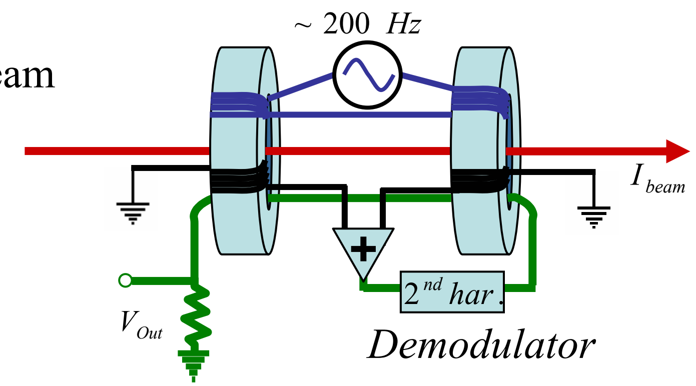
G. Hemmie and J.R.Maidment,
Proc. PAC 1987, p. 172

- 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

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)

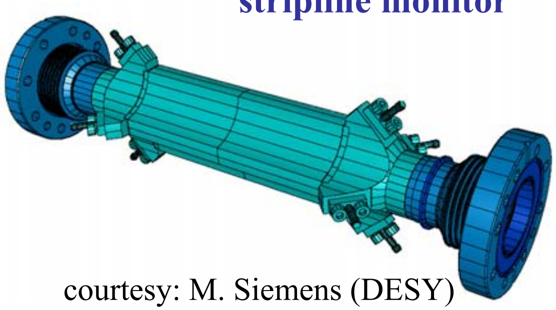
- beam position
  - measurement of beam orbit (oscillation, closed orbit,…)
  - position monitors
    → usually 4 per betatron oscillation (phase shift 90°)
  - large bunch lengths, low acceleration frequencies
    → high sensitivity pick-up at these frequencies

DESY III: inductive pick-ups

other schemes: shoe-box types (capacitive)

higher acceleration frequencies and energies: striplines

stripline monitor



courtesy: M. Siemens (DESY)

Injector Synchrotron Diagnostics (2)

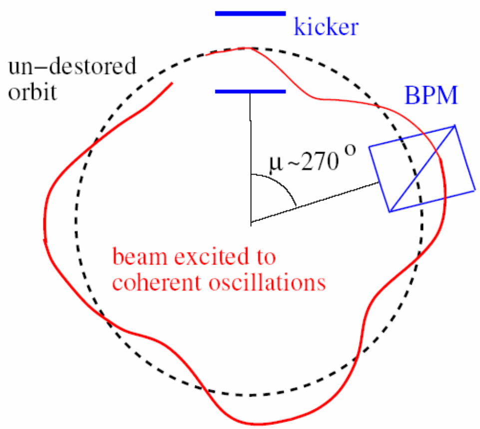
- **tune**

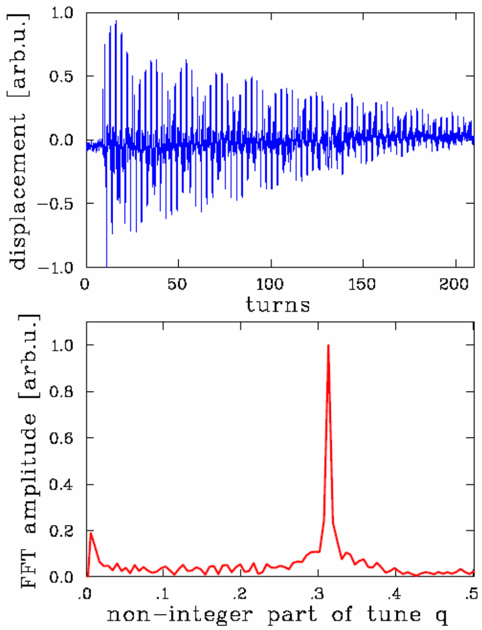
P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

- eigenfrequency of betatron oscillations in circular machine
- characteristic frequency of magnet lattice, produced by strength of quadrupole magnets

principle

- excitation of coherent betatron oscillations (kicker)
- observation of dipole moment due to (coherent) transverse beam oscillation (primary observable: time sequence of turn-by-turn beam position)
- FFT of response





comments

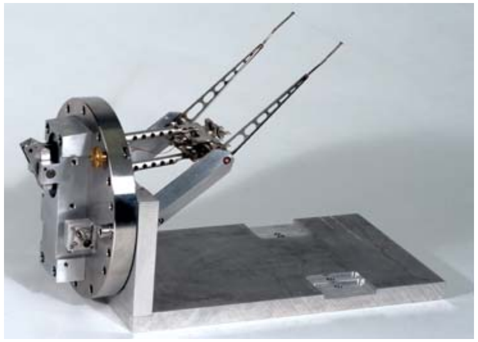
- excitation leads to emittance blow-up
  - → small excitation required
  - → high pickup sensitivity necessary
- high space charge at injection (acceptance occupied)
  - → excitation can lead immediately to particle losses

example: DESY III

- **no** tune measurements in standard operation
- tune measurements only in dedicated machine studies
  - → reproducible set-up of machine

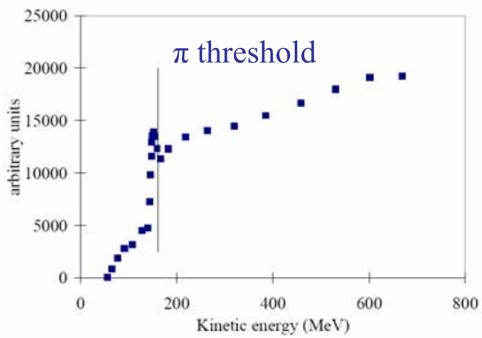
Injector Synchrotron Diagnostics (3)

- 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

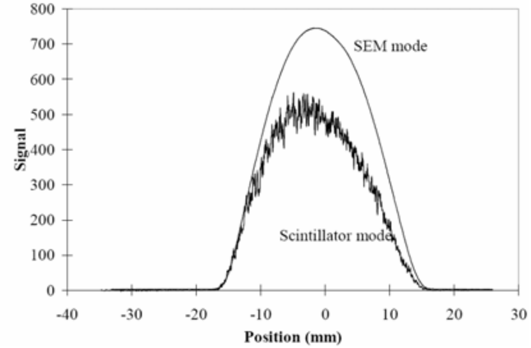


U.Raich, Proc. of DIPAC 2005 Lyon, France, 1

secondary particle shower intensity in dependence of primary beam energy



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

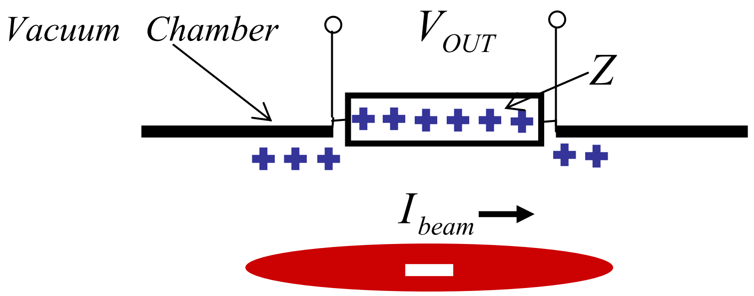


  - **residual gas monitor** (non-destructive)
    → vacuum pressure in sycnchrotron much better (10^{-10}mbar) than in linac/transfer line (10^{-6} - 10^{-8} mbar)

Injector Synchrotron Diagnostics (4)

- bunch lengths and time structure
  - measure bunch length and longitudinal oscillations
  - **wall current monitor**

    → offers bandwidth up to a few GHz



courtesy: F. Sannibale (LBNL)

- losses
  - indication of beam loss in specific critical places

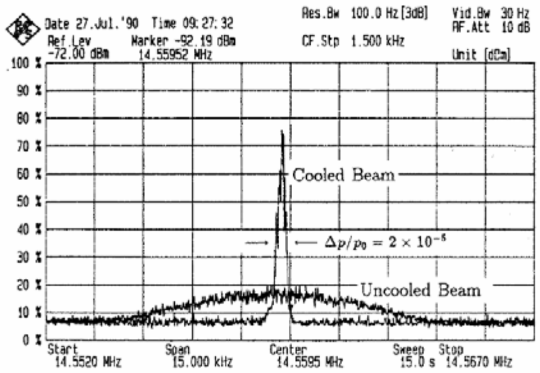
    → optimization of injection and extraction
  - **beam loss monitors**

- 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

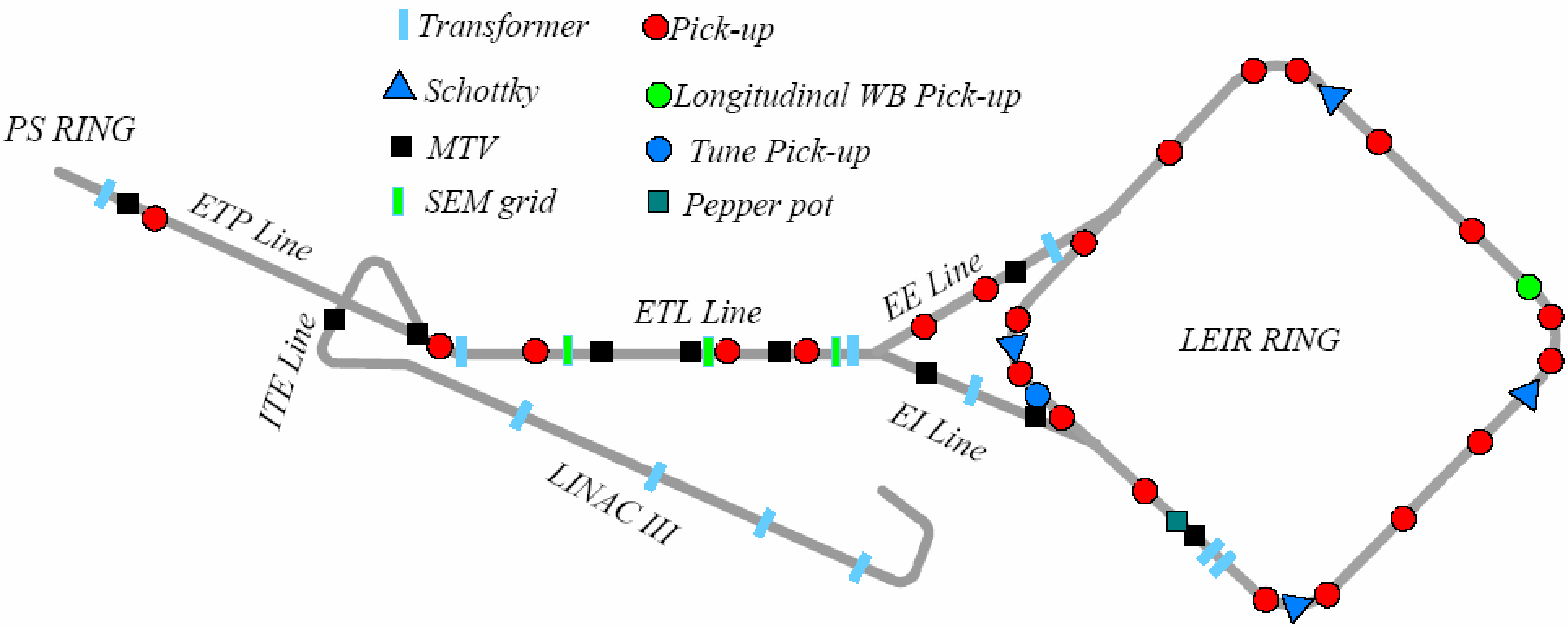


Longitudinal Schottky scan at the 10^{th} harmonic of Ar^{18+} at the GSI storage ring. The broad curve is the frequency spectrum at injection with $\Delta p/p = 1 \cdot 10^{-3}$ and the narrow curve is recorded after electron cooling down to a momentum width of $\Delta p/p = 2 \cdot 10^{-5}$.

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

Example: LEIR @ CERN

(Low Energy Ion Ring)



Layout of the LEIR complex and instruments.

C.Bal et al., Proc. of DIPAC 2005 Lyon, France, 258

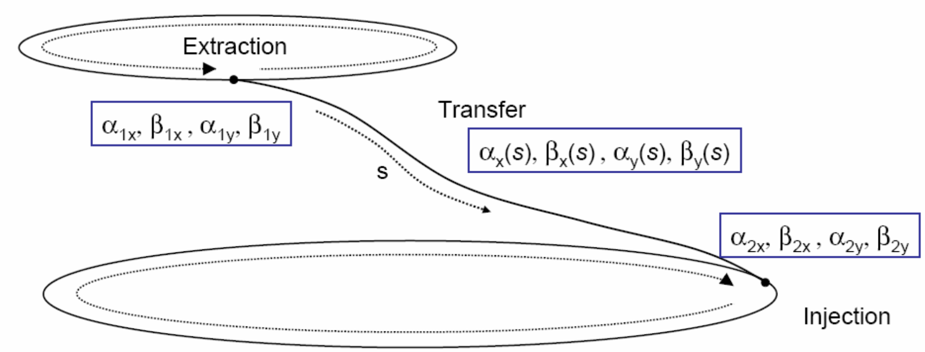
Transfer Line Diagnostics

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 (distance ~ 90° phase advance)



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

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

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

B.Goddard, CAS 2004 (Baden)

determine beam quality

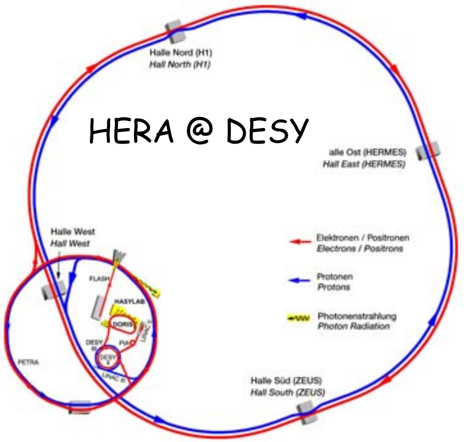
- transverse emittance via beam profiles
  - ➢ measure beam size versus quadrupole field strength using one device
  - ➢ measure beam size using multiple measurement devices for fixed optics
  - → screens, residual gas monitors,…

protect machine

- control of beam losses, machine interlock → beam loss monitors

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



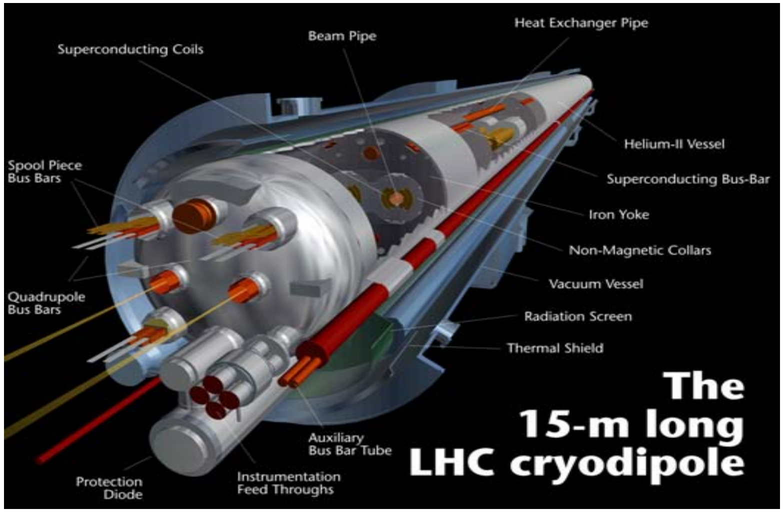
required B field ⇒ superconducting magnets

- **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 keeping in mind 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**

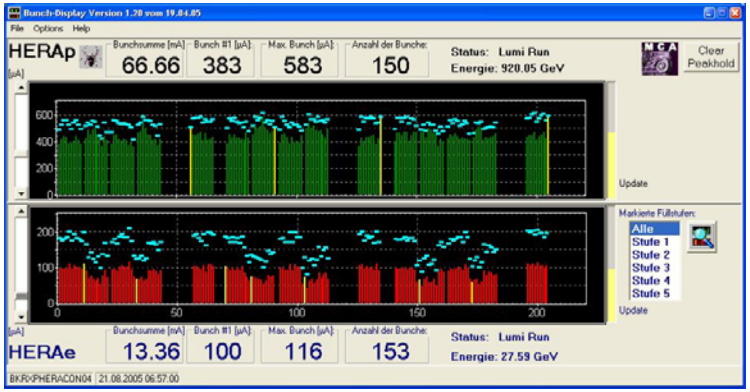


- **common strategy**
  - concentration of beam instrumentation in straight sections (***insertions***) without need for particle bending
    - → most instruments can be placed in warm environment
  - only BPMs (which has to be placed around the ring for closed orbit) partly in cold environment

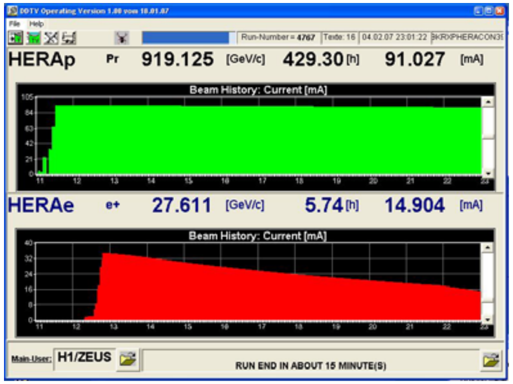
Storage Ring Diagnostics (1)

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

ACCT



DCCT



related parameters

- coasting (unbunched) beam: $I_{cb} = I_{DC} - \sum_{i}^{bunches} I_{AC,i}$
- life time: $\frac{1}{\tau(t)} = -\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}t}$

Storage Ring Diagnostics (2)

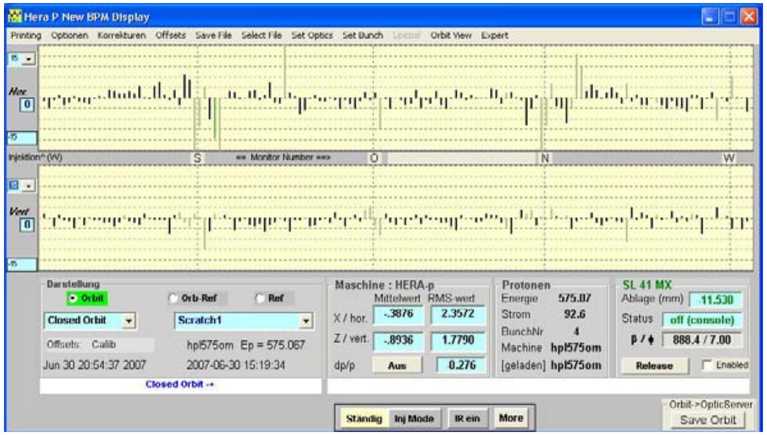
- orbit, trajectory, oscillations
  - BPMs: for cold and warm environment
  - choice of type depends on:

    linearity, dynamic range, resolution

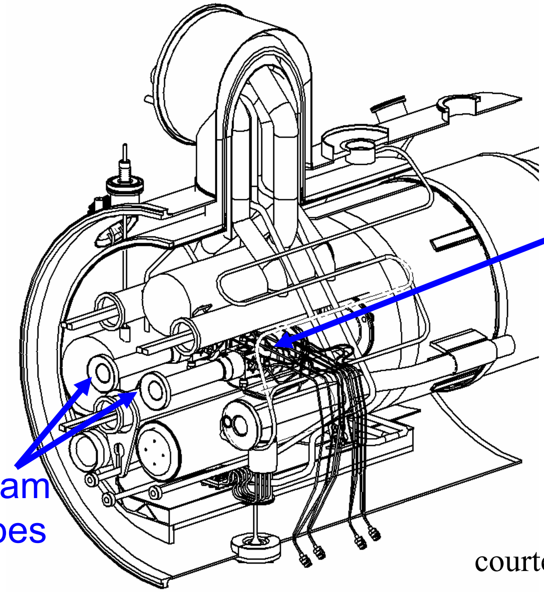
    → stripline monitor, button electrode pick-up

    LHC resolution requirement (full beam intensity):

    50 μm rms (trajectory), 5 μm rms (orbit)



HERA p orbit display



LHC cold button pick-up

courtesy: R.Jones (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

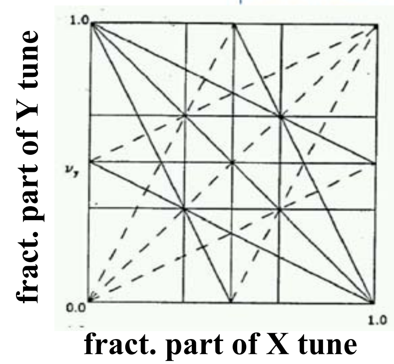
    → measure turn-by-turn beam position → FFT

  - **constraint:** minimize emittance blow up due to excitation

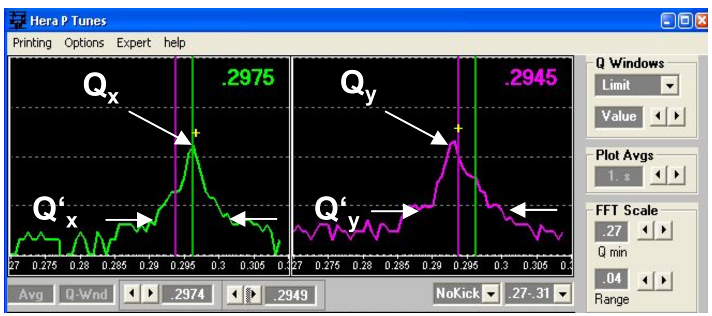
    → high sensitivity of pick-up detector & minimum disturbing excitation scheme

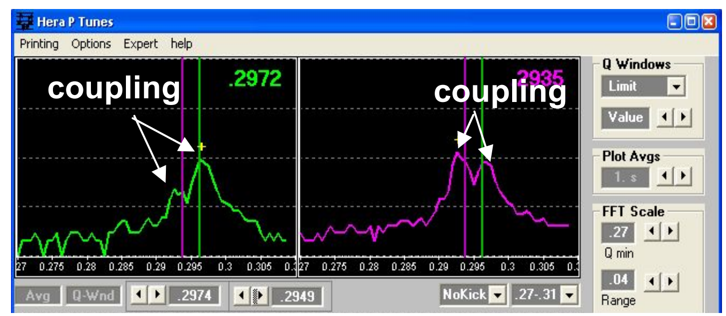
  - **excitations:** i) tune kicker: kick method, simple and robust (typically for commissioning)

    ii) tune shaker: continuous excitation → monitoring and feedback loop



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





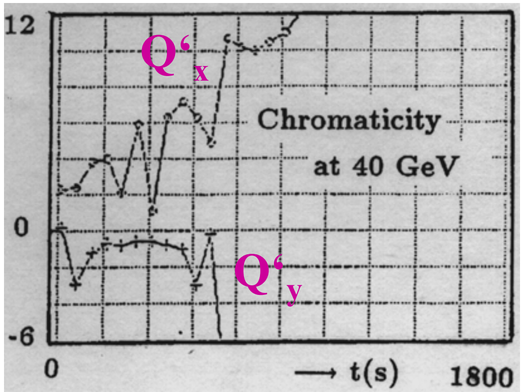
- comment: passive methods (without external excitation)

  - **Schottky diagnostics**: Schottky spectrum contains informations about (incoherent) tune, chromaticity,…

Storage Ring Diagnostics (4)

- tune, chromaticity: dynamic effects in superconducting storage rings
  - **s.c. eddy currents / persistent currents** have strong influence on performance of storage ring at injection energy
    - → affect ***multipole components*** of s.c. dipole magnets
      - (HERA: most important sextupole component b_3)
    - → are ***not really persistent*** (decay with time)
    - → ***need correction***
  - persistent currents are ***reinduced to their full strength*** on the first steps of the ramp, approaching the original hysteresis curve
    - → ***„Snap Back“***

HERA p beam at injection energy



courtesy: B.Holzer (DESY)

⇒ **reliable control during ramp**

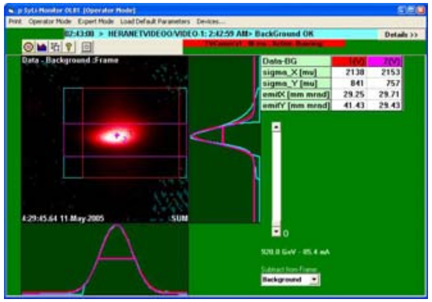
…besides online measurements of multipole components, correction tables, …

- feedbacks on tune and chromaticity
  - **Phase Locked Loop (PLL):** solution forseen for LHC
  - **„Brain Locked Loop“ (BLL):** realized at HERA
    - → 6 knobs (2 x tune, 2 x chromaticity, 2 x coupling)
    - → experienced shift crew (at least two people)

even best BLL fails sometimes…

Storage Ring Diagnostics (5)

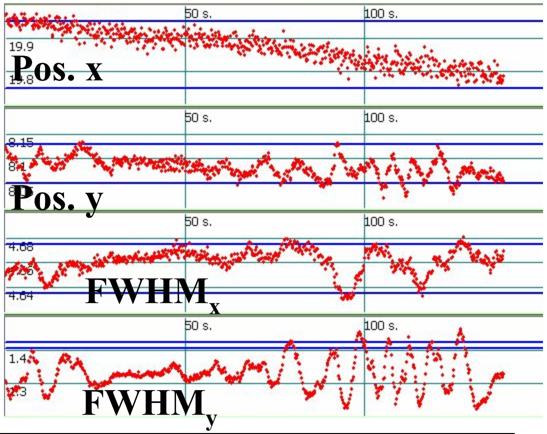
- transverse beam distribution, emittance
  - **single pass:** simple and robust, high sensitivity (single or few bunches only), modest demand on accuracy
    → **luminescent screens**
  - **few pass:** study of injection mismatch (betatron, dispersion matching on first turns observing shape oscillations)
    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
  - **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**
    → **flying wires** (1 m/sec, typically for calibration)
    → **synchrotron radiation monitor**
    (from fringe field or undulator)



HERA p SyLi monitor: screenshot

HERA p SyLi monitor: moving p collimators

time/sec →



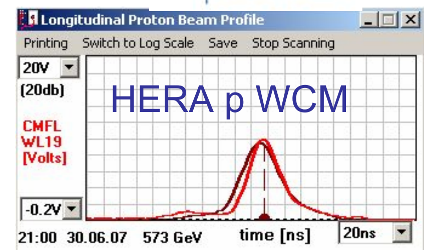
Storage Ring Diagnostics (6)

- longitudinal beam distribution, time structure
  - **longitudinal profile:** determination of classical longitudinal bunch parameters

    → bunch center of gravity, rms bunch length, core distribution

    <u>examples:</u> HERA p @ 920 GeV, σ = 1.6 nsec → **wall current monitor**

    LHC @ 7 TeV, σ = 0.28 … 0.62 nsec → **synchrotron light monitor**



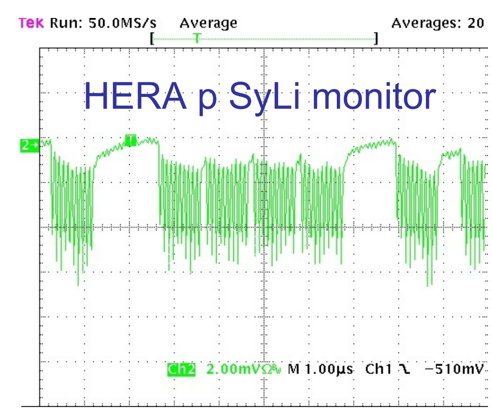
  - **abort gap monitoring:** continuous monitoring that rise time gap of dump extraction kicker is free of particles; particles in gap would not receive proper kick when dump system is fired → damage of machine components

    → **synchrotron light monitor**

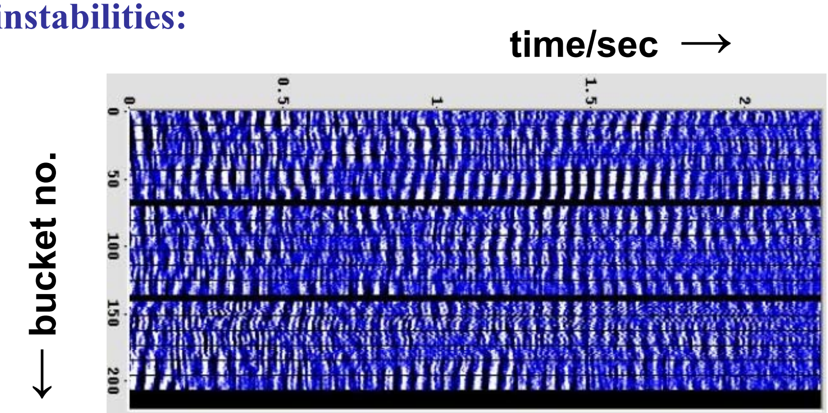
  - **detection of ghost bunches:**

    may disturb BPM system read-out or physics data taking

    → **synchrotron light monitor**



  - **observation of instabilities:**



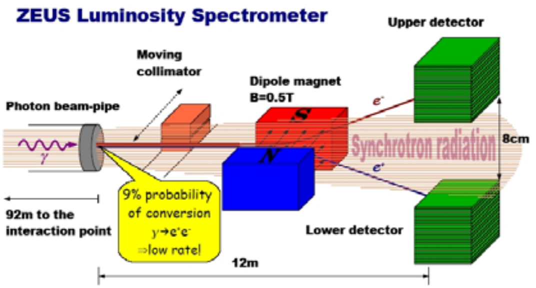
HERA p: long. multibunch instability

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:** $\mathcal{L} = \dot{N}_{rc} / \sigma_{rc}$

HERA luminosity at H1

  - **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 → γ e‘ p‘
    → cross section well known

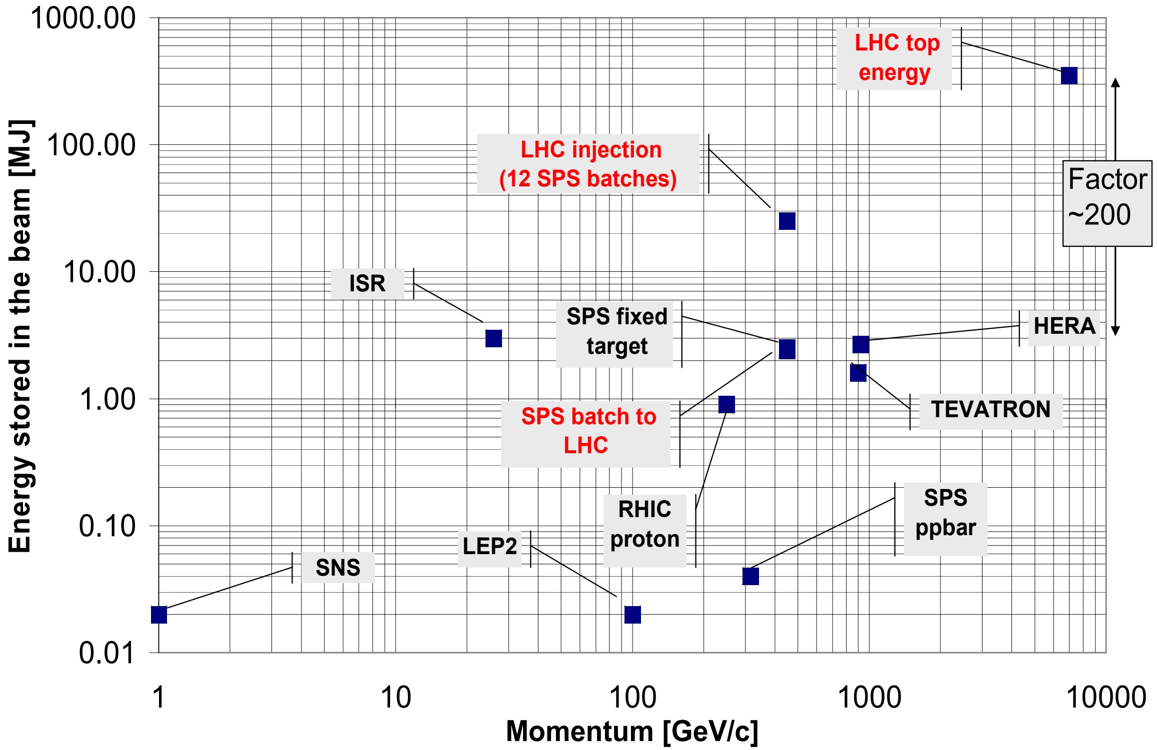


- **energy**
  - **importance:** hadron-hadron collider absolute energy determination relatively unimportant
    → constituent nature of hadrons (quarks and gluons) which share beam momentum
    → total energy in reaction only loosely related to beam energies
  - **measurement:** beam momentum via dipole 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**

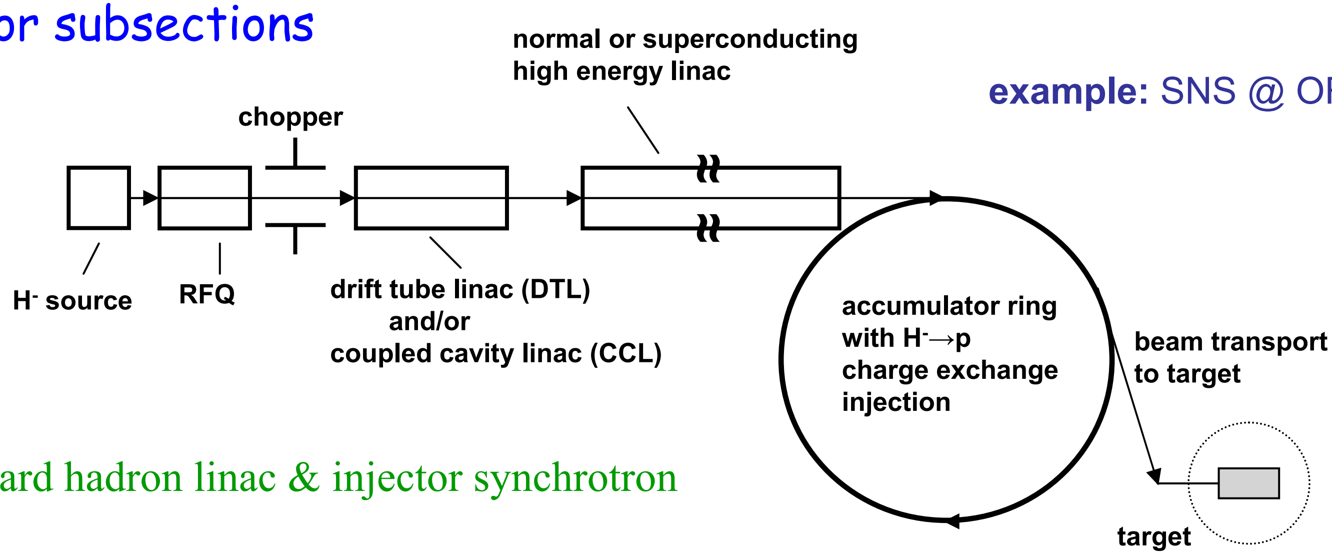
    → gas ionization chambers, PIN diodes, photomultipliers & scintillators, SE multiplier tubes…

Spallation Neutron Source

- general features
  - proton accelerator, production of ~30 neutrons/proton at about 1 GeV beam energy
  - pulsed operation allows time resolved experiments
  - high beam power in the order of 1 ... 2 MW

- accelerator subsections

example: SNS @ ORNL (USA)



⇒ standard hadron linac & injector synchrotron

- implications on beam diagnostics
  - **handling of high beam power**

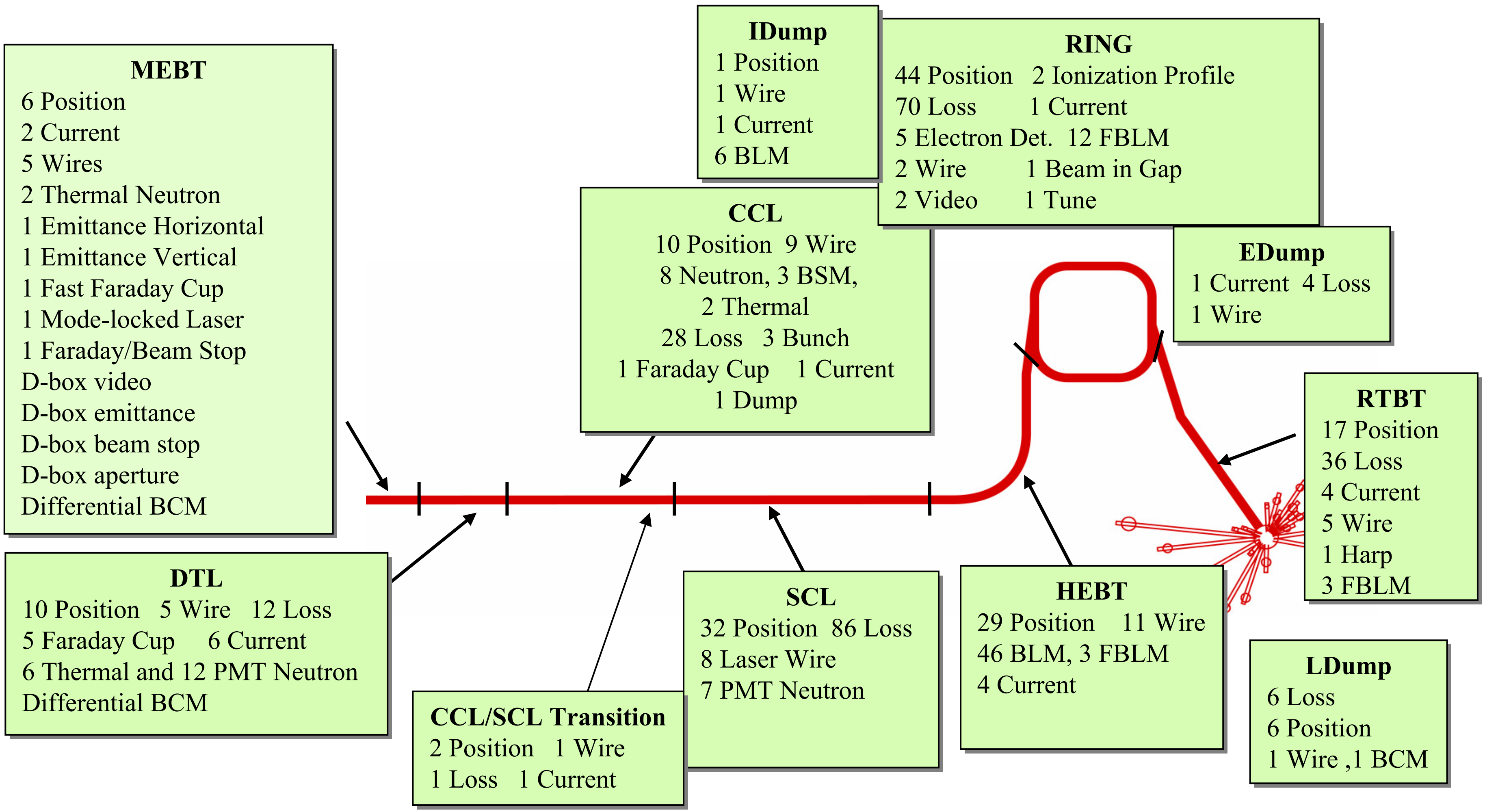
High Power Diagnostics

- achieving high beam power
  - systems to help understanding dynamics of intense beams
    - → **beam halo measurements, …**
- measuring high power beams
  - diagnostic systems that can measure the 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), talk held at EPAC04

SNS Diagnostics



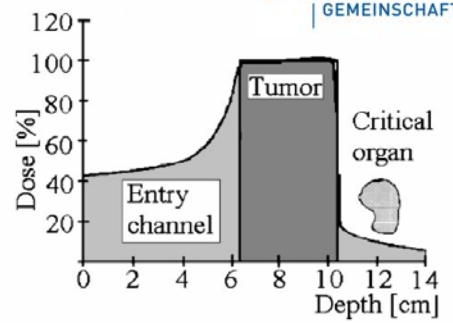
courtesy: T.Shea (SNS)

Hadron Therapy Accelerator

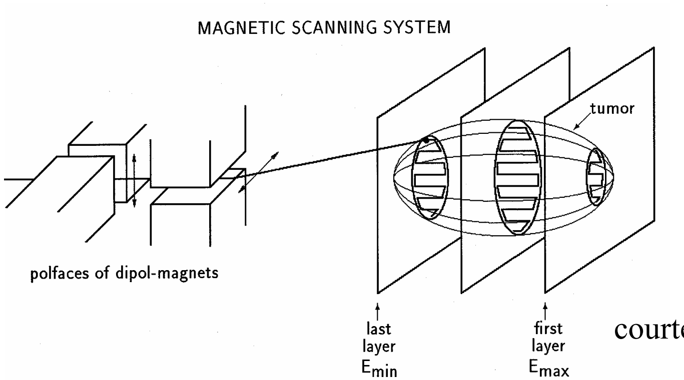
hadron therapy

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

  low dose at critical organs
- 3d scanning of beam over tumor region



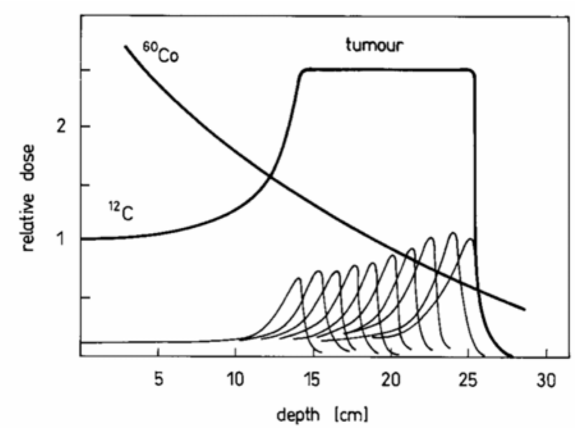
P.Bryant, Rev. Sci. Instr. 73 (2002) 688



courtesy: A.Peters (Hit GmbH),

M.Schwickert (GSI)

2d excitation of scanner magnets: varying beam position



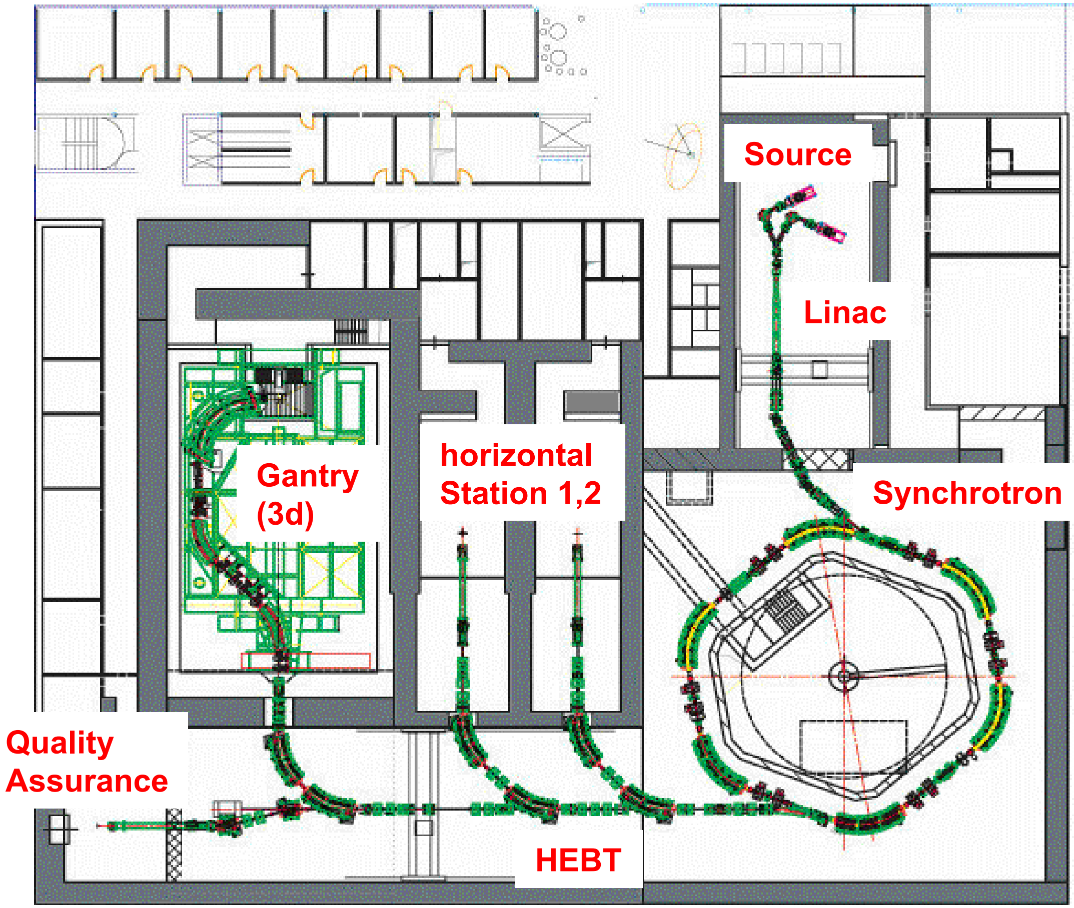
control of penetration depth (location of Bragg peak) via energy, adjusting beam intensity

implications on beam diagnostics

- non destuctive diagnostics during patient treatment
- precise determination of **position, size** **energy, intensity**

Accelerator Layout

- example: Heidelberger Ionenstrahl-Therapiezentrum (HIT)



courtesy: A.Peters (Hit GmbH), M.Schwickert (GSI)

Ion Source

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

Linac

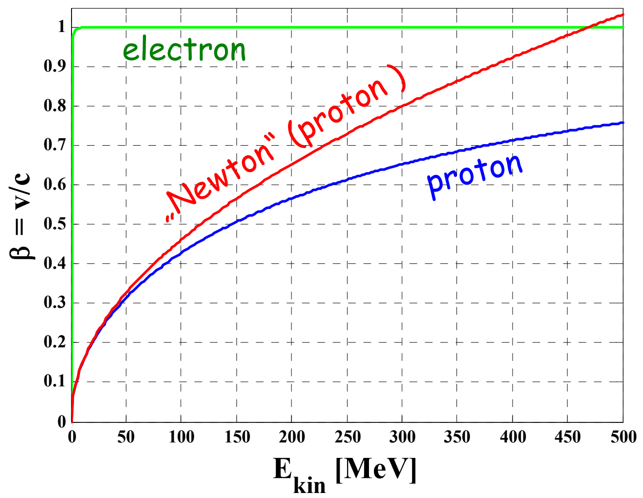
- Four-rod RFQ-structure (400 keV/u)
- IH-DTL (7 MeV/u)
- 30μs-Macropulse: 50 μA C^{6+}

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

Reminder: Lepton Properties

- properties of electrons/positrons
  - simple point objects
  - small rest mass $m_e c^2 = 0.511\ \text{MeV}$



- consequences
  - particles are already relativistic at a few MeV
    - ➢ typically at first accelerating section
  - particle produce strong electromagnetic field

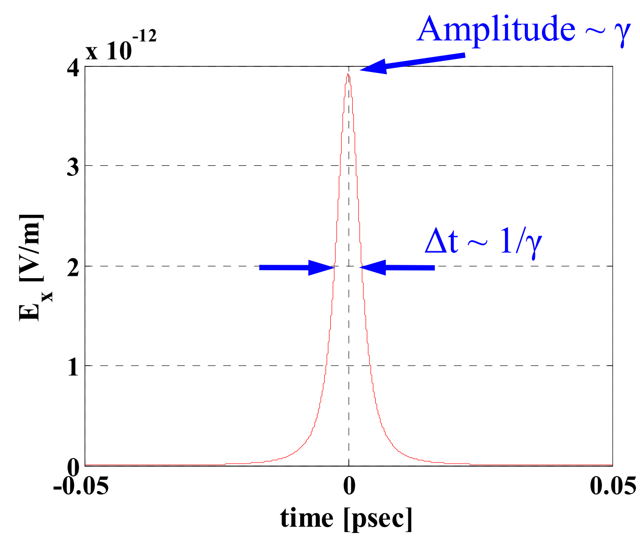
scale factor: $\gamma = E / m_e c^2$

- ➢ **long range of transverse non-propagating fields**
- ➢ **emission of synchrotron radiation (bend motion)**

$\Rightarrow$ influence on particle dynamics

impact on beam diagnostics

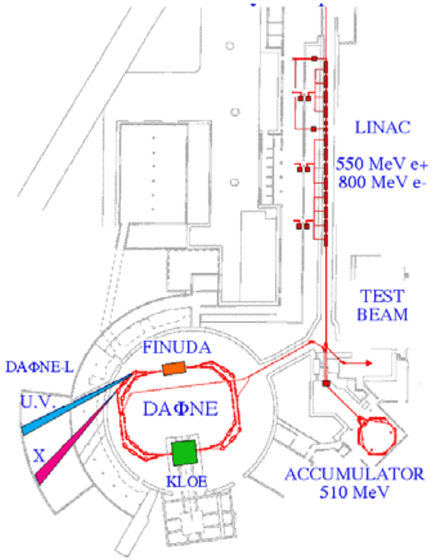
…discussion in context with different accelerator types



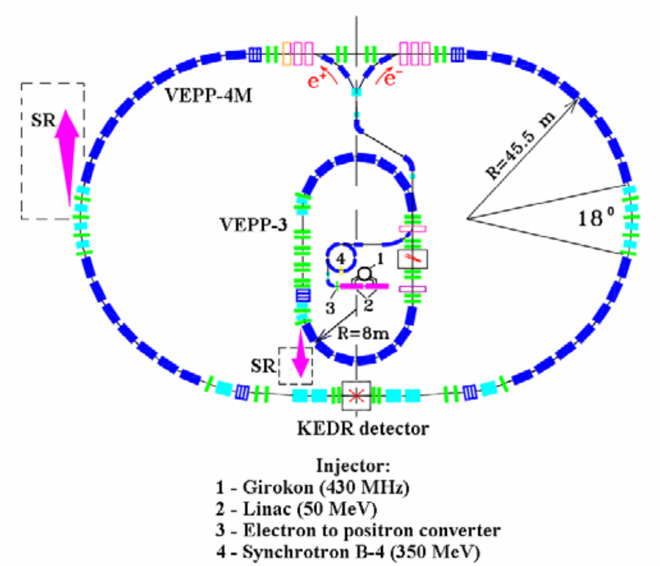
non-propagating transverse el. field

Lepton Collider (Storage Ring)

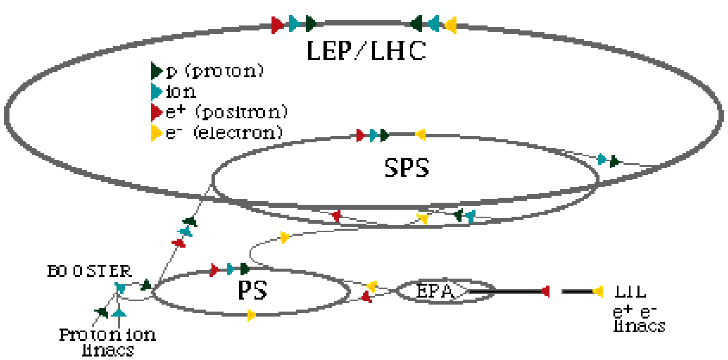
DAΦNE @ INFN (Frascati)
0.7 GeV e^+/e^-



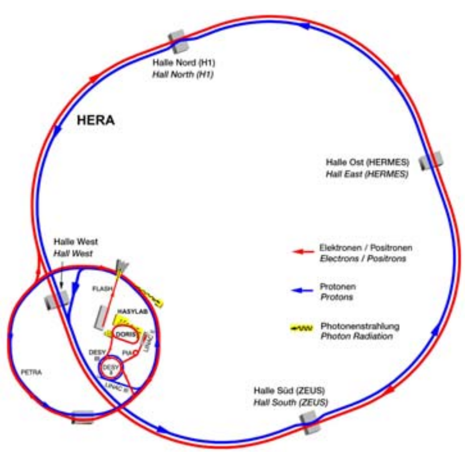
VEPP-4M @ Budker (Novosibirsk)
6 GeV e^+/e^-



LEP @ CERN
100 GeV e^+/e^-



HERA @ DESY
27.5 GeV $e^+(e^-)$ / 920 GeV p



- general comments on lepton colliders (storage rings)
  - standard, normal conducting dipole magnets
    → sufficient to achieve final energies
  - long injector chain with different beam properties
    → relaxed requirements, particle dynamics with radiation

SR Emission in circular Accelerators

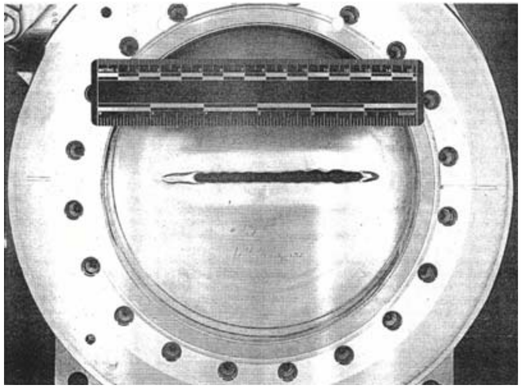
- emitted power

$$P_\gamma[\mathrm{MW}] = 8.85 \cdot 10^{-2} \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{m}]} I[\mathrm{A}]$$

HERA e (I=50 mA, E=27.5 GeV, ρ=550 m): $P_\gamma = 4.6$ MW

protect accelerator components from direct SR illumination !

power is real!



L.Rivkin (PSI), CAS 2004

Damaged front end gate valve. Incident power about 1 kW for time estimated to 2-10 min.

- energy loss per turn

$$\Delta E[\mathrm{keV}] = 88.5 \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{m}]}$$

HERA e @ 27.5 GeV: $\Delta E = 92$ MeV

- average radiated power restored by RF

cavity provides voltage to accelerate particles back to nominal energy

⇒ requires typically a large number of cavities

HERA e: 98 cavities, grouped in 8 sections; 8 transmitter stations, each with 1.4 MW nominal power, fed by 2 Klystrons.

Consequences of SR Emission

- large number of cavities
  - cavity represents **high impedance** → excitation of (multibunch) **instabilities**

    ⇒ need for feedback systems
- high SR power
  - heat load critical ⇒ protection of machine and instrumentation, necessity of cooling
- high total cavity voltage V_r for loss compensation & lifetime
  - **rms bunch length**

$$\sigma_t = \frac{\alpha_c - 1/\gamma^2}{2\pi f_s}\sigma_\delta \propto 1/\sqrt{V_r}$$

(above transition energy)

⇒ smaller bunch lengths, i.e. beam spectrum with higher frequencies

- beam emittance
  - formation of **equilibrium emittances in all 3 planes** because of **radiation damping** and **quantum fluctuations** (random excitation of oscillations) due to synchrotron radiation ⇒ ***emittance determined by storage ring itself***

⇒ emittance blow-up not critical, relaxed requirements for injector chain

e^-/e^+ Injector Complex @ DESY

- **Thermionic Gun**

  150 keV, 3 µsec long pulses @ 50 Hz

- **Chopper and Collimator**

  shortening of long gun pulses (60/20 nsec for e+/e-)

- **Prebuncher**

  single cell cavity, matching to linac RF

- **Linac Sections**

  3 GHz (S-band) travelling wave structure, f_{rep} = 50 Hz

- **Converter for e^+ Production**

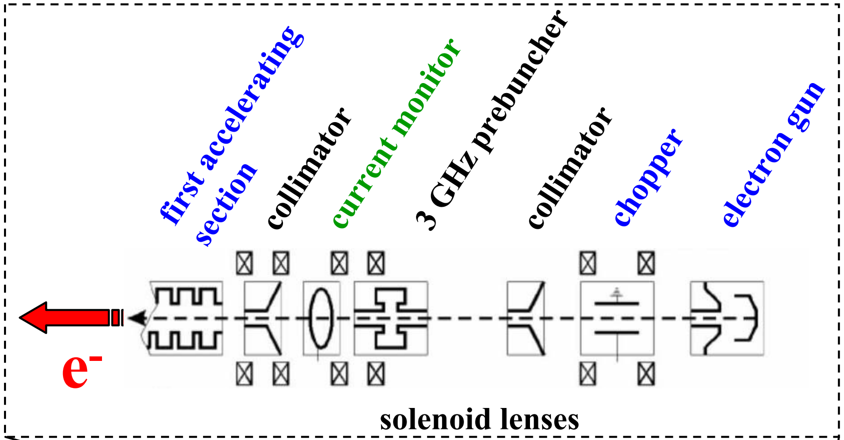
  7 mm (2 rad. length) thick W target in 1.8 T solenoid field

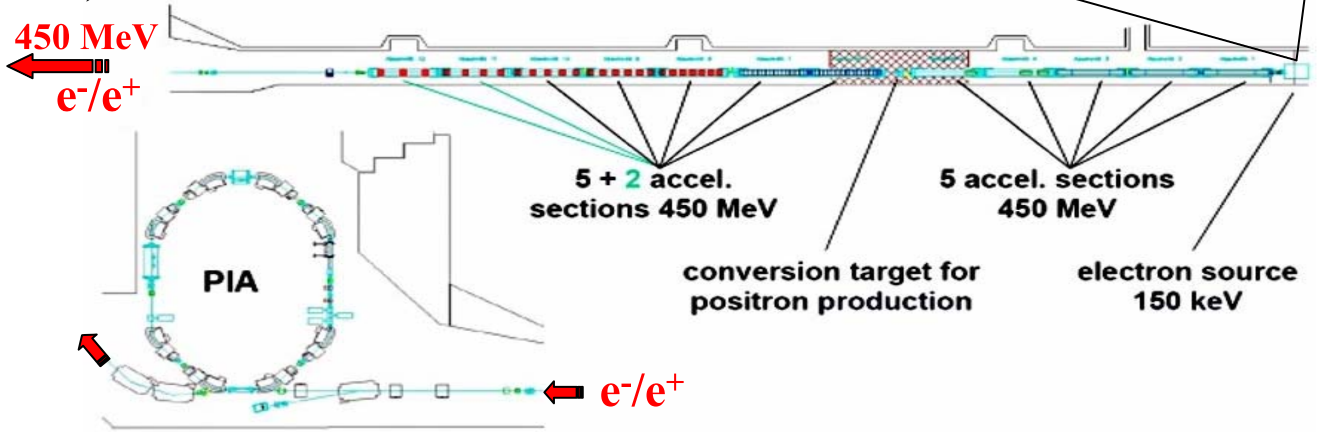
- **Positron Intensity Accumulator (PIA)**

  re-formation of time structure for synchrotrons (→ 500 MHz)

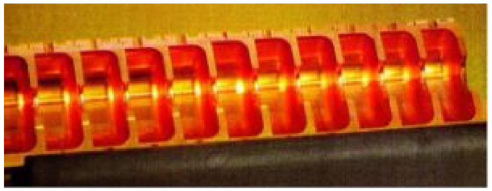
  two RF systems (10.4 MHz and 125 MHz)

Linac Front-End





3 GHz Linac Section



Injector Complex Instrumentation

- key devices for
  - adjusting beam transport through injector sections
  - tuning the RF system
  - indicating operating status
- overview: standard instrumentation and their tasks

in principle same than for hadron machines

transfer efficiency

→ current transformers

beam position for beam steering

→ screens (low energy deposition)

→ BPMs (sensitivity for long linac bunch trains)

beam profiles for beam optics matching

→ fluorescent/OTR screens (in straight section)

→ synchrotron light (accumulator ring)

transverse emittance

→ multi-screen or k-modulation of quads (in straight section)

→ synchrotron light (accumulator ring)

longitudinal plane

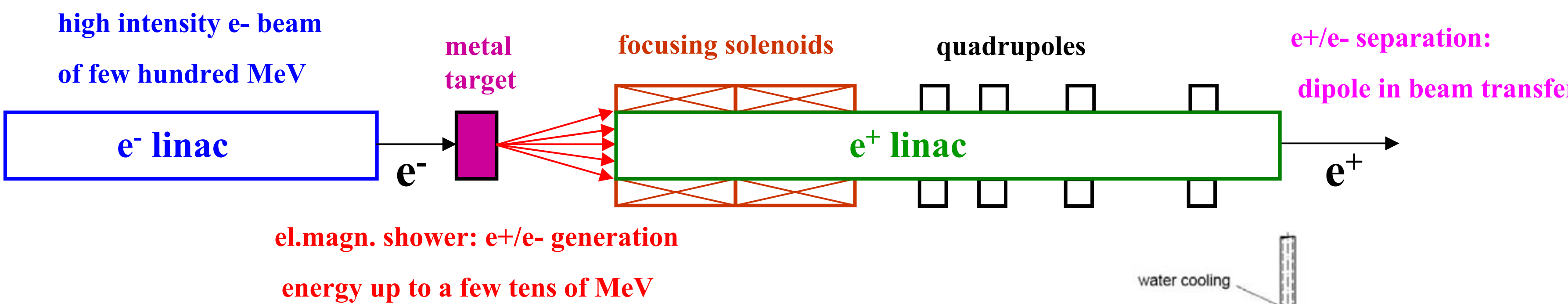
→ magnet spectrometer for energy (-spread) (diagnostics beamline)

→ time structure via RF deflector, wall current monitor, coh. radiation diagnostics

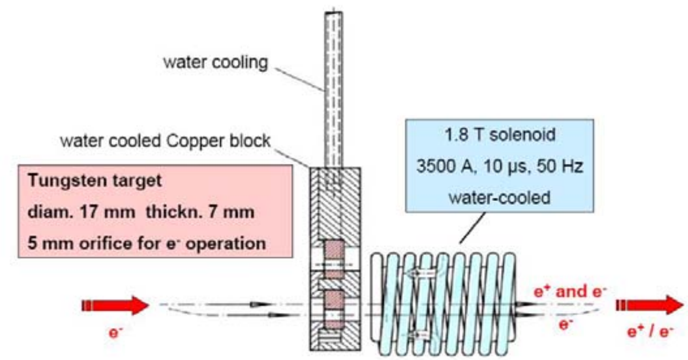
Comment: e^+ Production

- principle of positron production

K.Hübner, Hyperfine Interactions 44 (1988) 167

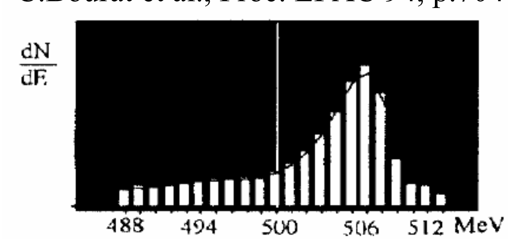


- **conversion target in harming radiation environment**
  - → only radiation resistive diagnostics close to target
- **high e^+ yield: focus at converter**
  - → profile measurement close to target desirable
  - → secondary emission monitors (no screens because of degradation)
- **matching the energy acceptance (ΔE/E) of accumulator ring**
  - → i) spread from conversion process, ii) microbunch length
  - → precise measurements of energy spread and bunch length



conversion target @ DESY Linac II

C.Bourat et al., Proc. EPAC 94, p.704



Storage Ring Diagnostics: Remarks

- walk along injector chain to storage ring / collider
  - no fundamental difference in requirements compared to hadron machines
  - no fundamental difference in instrumentation between e-linac and storage ring

    → **direct descripton of needs for storage ring diagnostics**

- diagnostics system of storage ring / collider
  - current monitors (AC and DC) → bunch charge, stored dc current
  - BPMs → orbit
  - tune measurement → working point
  - feedback system → stabilization
  - synchrotron light diagnostics → beam profile, emittance
  - energy measurement → cms energy for particle production
  - luminosity monitors → collider key parameter, optimization

    simple point objects, i.e. absolute luminosity
  - beam loss monitors → control losses, optimization

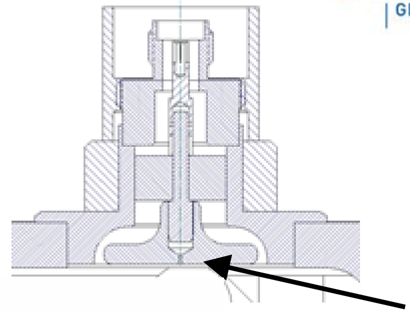
    not only protection, also for machine physics
  - machine protection system → temperature control,…

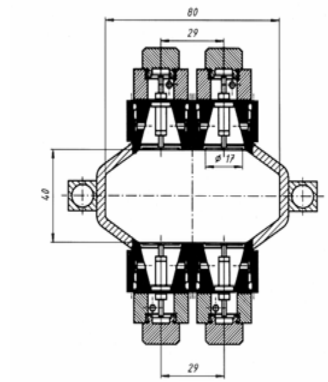
    protection of sensitive components (heat load)

Storage Ring Diagnostics (1)

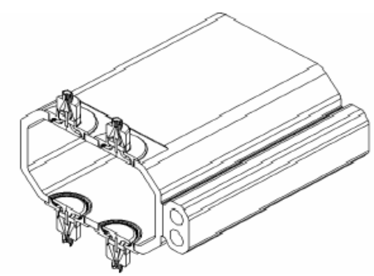
- **beam position monitors (BPMs)**
  - short electron bunches $\mathcal{O}$(10 - 100 psec)
    - → use of **button pickups**
  - synchrotron radiation emission
    - → pickups mounted **out of orbit plane**
  - vacuum chamber profile not rotational-symmetric
    - → **horizontal emittance » vertical emittance**
      (SR emission in horizontal plane)
    - → **injection oscillations due to off-axis injection**
      (allows intensity accumulation)

⇒ correction of non-linearities in beam position

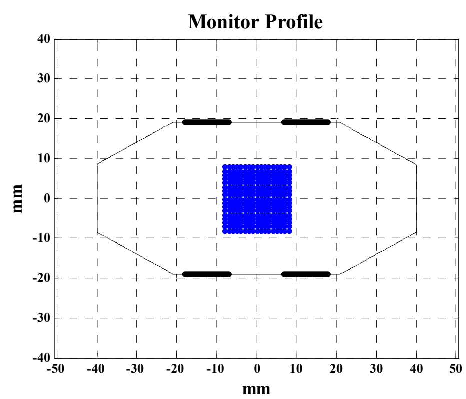


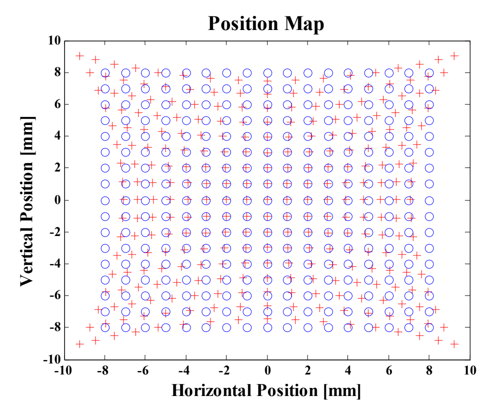


HERA e



PEP II



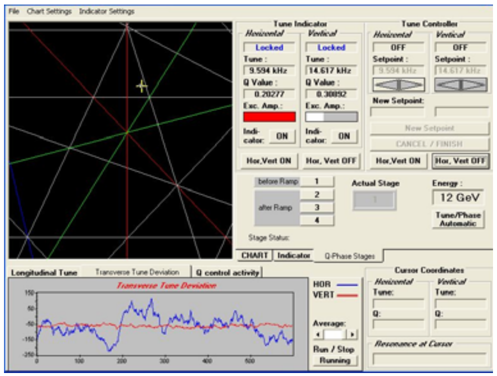


Storage Ring Diagnostics (2)

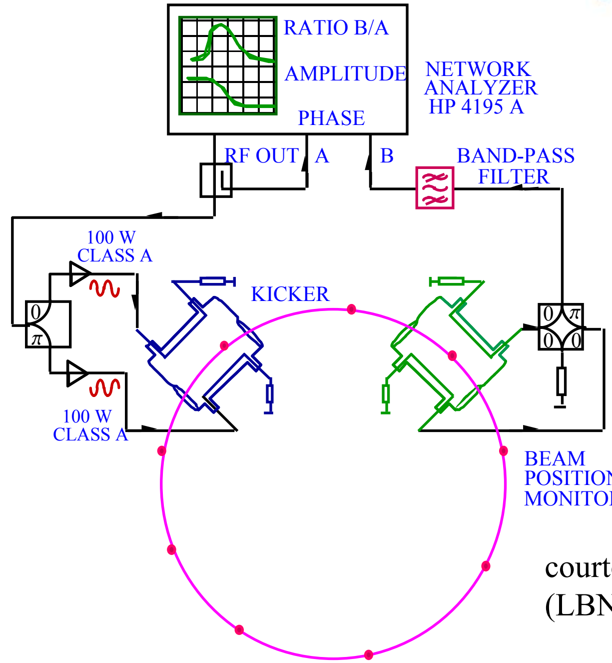
tune

- radiation damping due to SR emission

  → **permanent excitation, online tune control**



HERA e tune controller



courtesy: F.Sannibale (LBNL)

feedback

- **long-range electromagnetic fields** and **short bunch lengths** (→ broad beam spectrum)

  → fields act back on beam itself

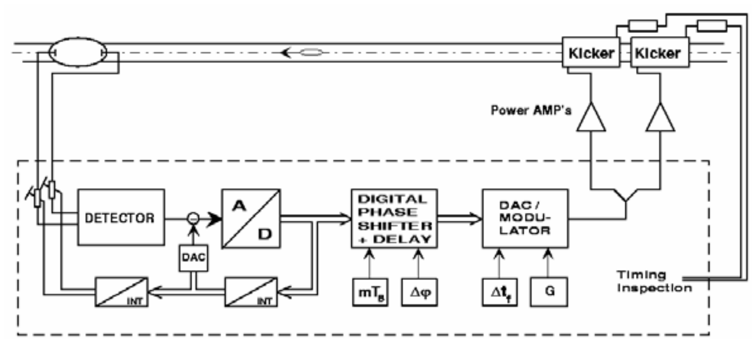
  → excitation of **coupled bunch instability**

- **feedback system** for **damping** instability:

  i) detection system to measure beam oscillations

  ii) signal processing unit to derive correction signal

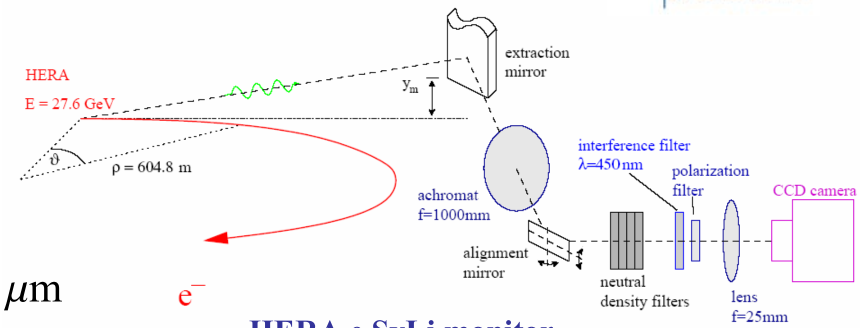
  iii) broad band amplifier and beam deflector to act on beam



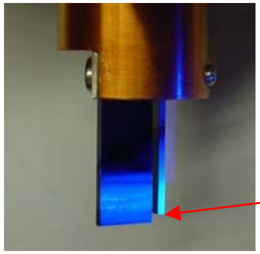
HERA e transverse feedback

Storage Ring Diagnostics (3)

- transverse profile / emittance
  - **imaging** with **synchrotron radiation (SR)**
    - → non-destructive profile diagnostics
  - HERA e beam size: $\sigma_{hor} = 1200\ \mu m$, $\sigma_{vert} = 250\ \mu m$
    - → resolution with **optical SR** sufficient
  - problem: **heat load** on **extraction mirror** (X-ray part of SR)
    - → material with low absorption coefficient (Be)
    - → cooling of extraction mirror
    - → **not sufficient to prevent image distortion…**
  - solutions:



HERA e SyLi monitor

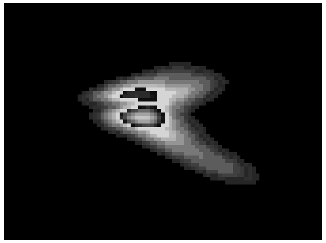


T_{max} = 1200°C

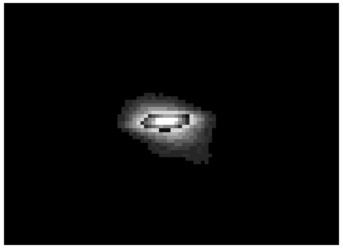
HERA e: observation out of orbit plane

Photon Factory, LEP: adaptive optics

uncorrected

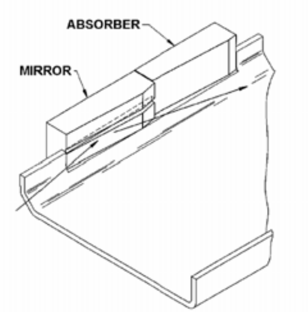


corrected



courtesy: T.Mitsuhashi (KEK)

PEP II: slotted mirror



A.S.Fisher et al., Proc. EPAC 1996 , TUP098L

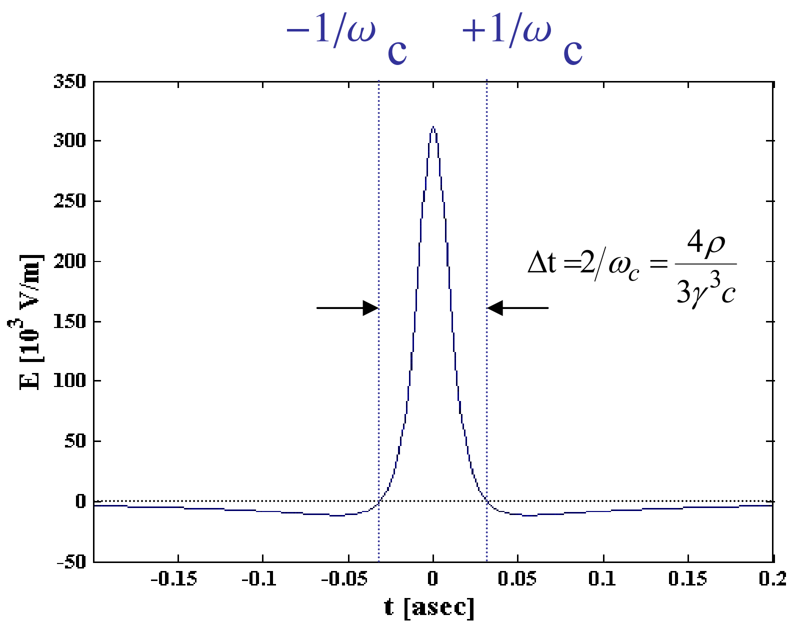
Storage Ring Diagnostics (4)

- longitudinal profile
  - **SR single particle time structure**

    → calculation for 6 GeV electron,

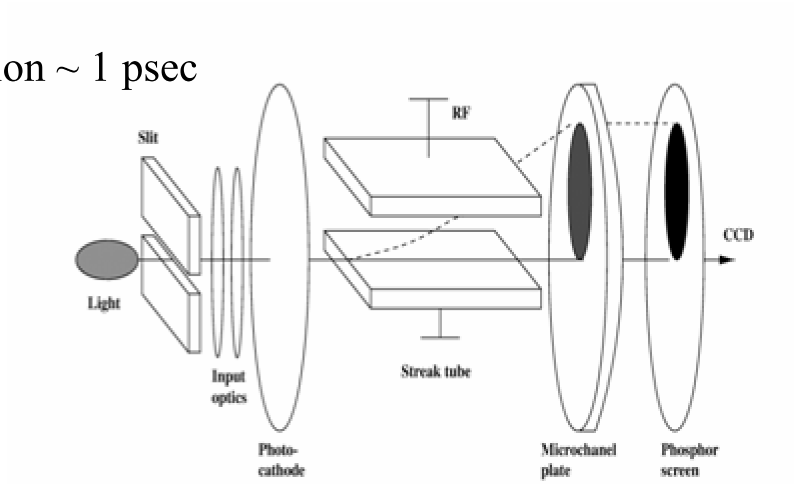
    electric field vector in orbit plane

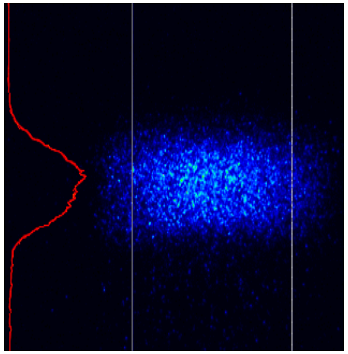
    ⇒ time structure of SR suitable to resolve longitudinal profiles $\mathcal{O}$(10-100 psec)



  - **streak camera**

    → time resolution ~ 1 psec

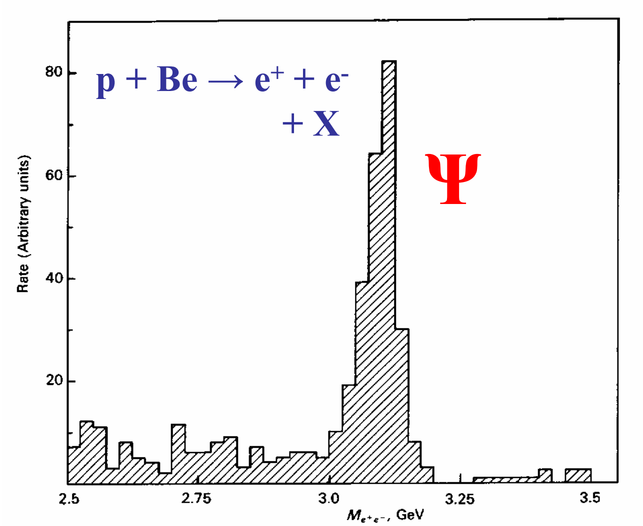




courtesy: D.Lipka (DESY)

Storage Ring Diagnostics (5)

- **beam energy:** e^+/e^- are point objects, i.e. reaction energy directly related to beam energy

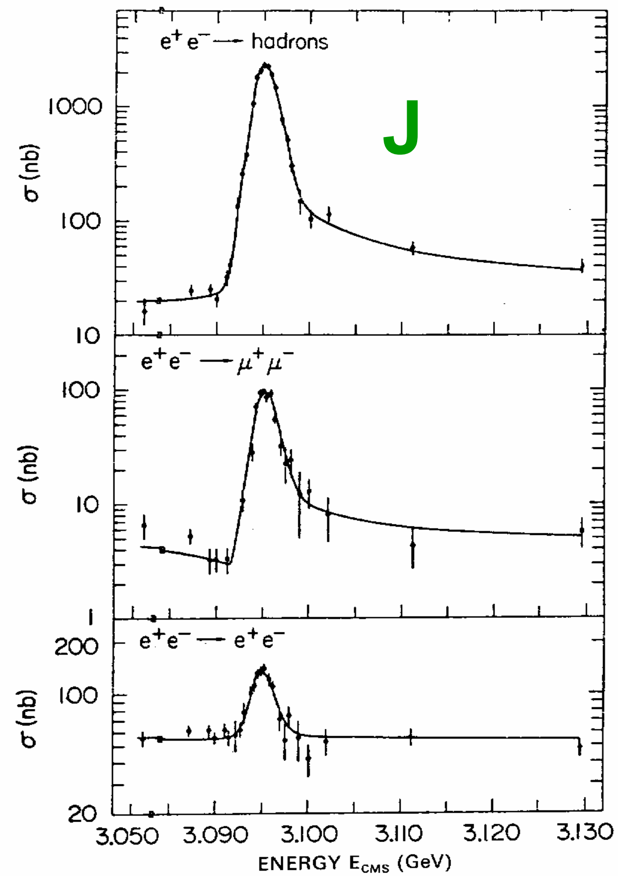


J.J.Aubert et al., Phys. Rev. Lett. 33 (1974) 1404

fixed target

AGS (BNL)

e^+/e^- collider SPEAR (SLAC)



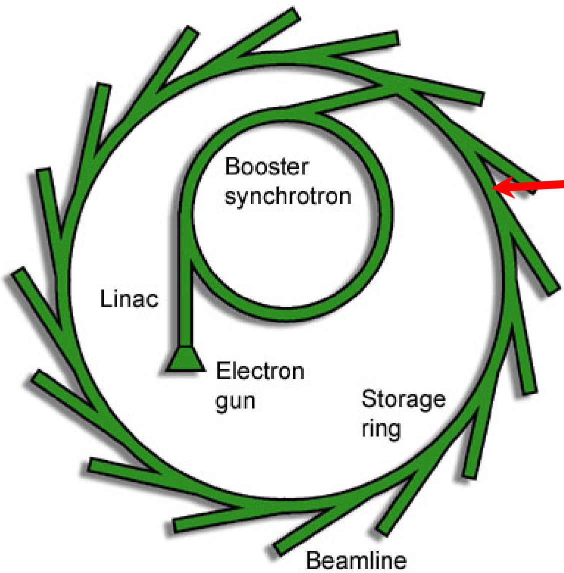
J.-E.Augustin et al., Phys. Rev. Lett. 33 (1974) 1406

- Nobel Prize  (1976)
  - discovery of **J/Ψ** for Samuel Ting & Burt Richter

- *measurement techniques*
  - determination via dipole current not sufficient
  - schemes: **resonant depolarization** or **Compton backscattering**

Storage Ring based Light Sources

- storage ring based 3rd generation light source

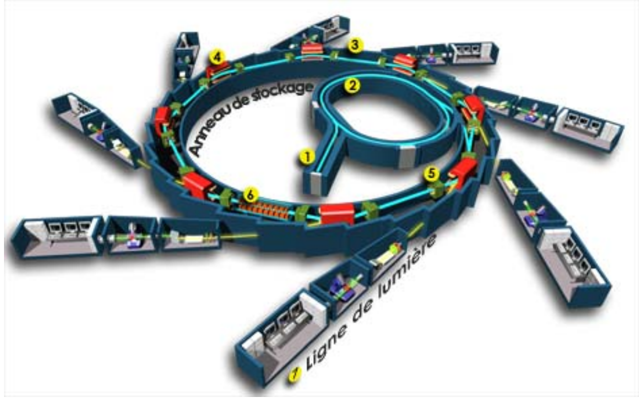


undulator: radiation source

(PETRA III prototype undulator)

SOLEIL

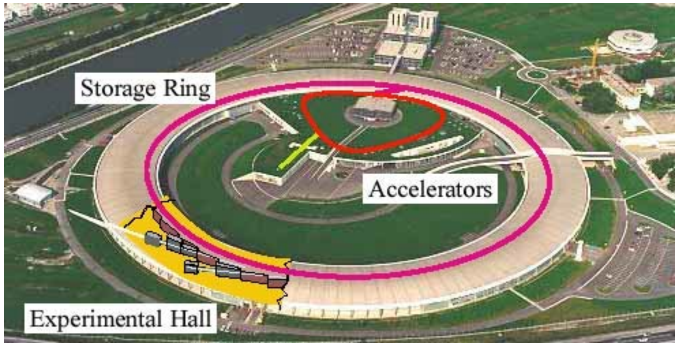
2.75 GeV / C = 354 m



http://www.diamond.ac.uk/AboutDiamond/Diamondstep-by-step/default.htm

ESRF

6 GeV / C = 844 m



- storage ring: energy 1 – 8 GeV, circumfence O(100 - 2000 m)
  - → insertion devices integrated part of storage ring (straight sections)
  - → user experiments at end of beamlines (~50-100m away from source)
- short injector chain
  - → standard instrumentation

Light Sources: Remarks

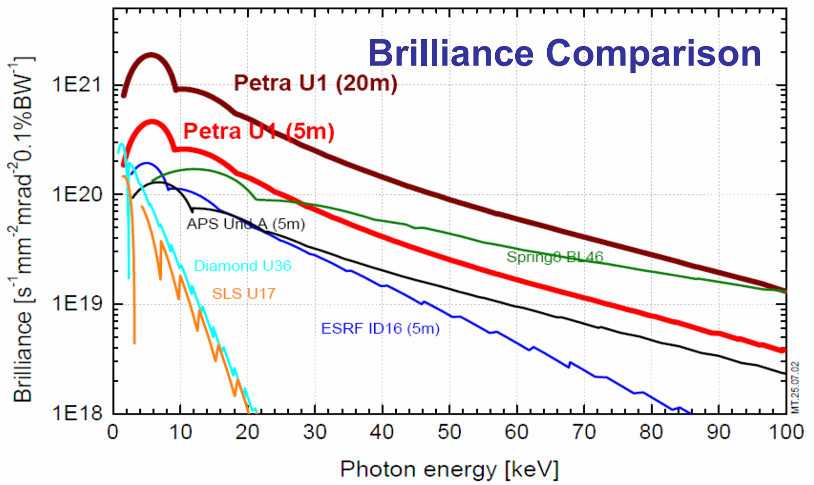
- key parameter: spectral brilliance

  - measure for phase space density of photon flux

$$B = \frac{\text{Number of photons}}{[\text{sec}][\text{mm}^2][\text{mrad}^2][0.1\%\ \text{bandwidth}]}$$

  - user requirement: high brightness

    → lot of monochromatic photons on sample



  - connection to machine parameters

$$B \propto \frac{N_\gamma}{\sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \propto \frac{I_{\text{beam}}}{\varepsilon_x \varepsilon_y}$$

  - requirements for storage ring and diagnostics

i) high beam current

- achieve high currents
- cope with high heat load (stability)

ii) small beam emittance

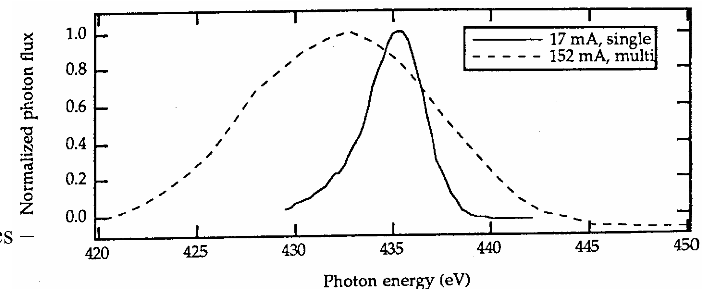
- achieve small emittance (task of lattice designer)
- measure small emittance
- preserve emittance (stability)

⇒ stability is critical issue

Light Sources: Stability

- energy stability, suppression of energy widening effects
  - cause: **(long.) multibunch instabilities**
  - shift of radiation harmonics from undulator
    → intensity fluctuation, line broadening
  - multibunch feedback systems

undulator radiation (3rd harmonic) @ ALS

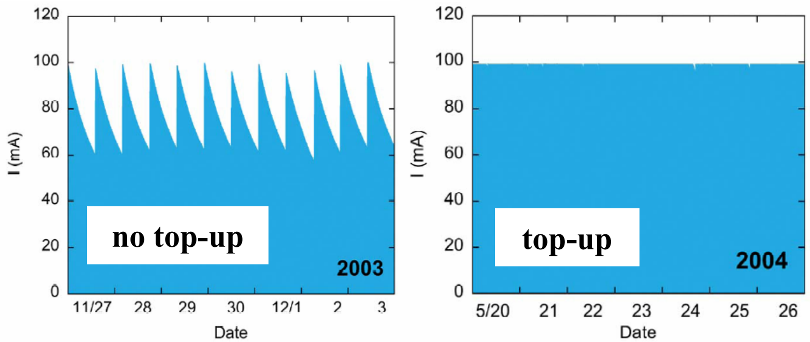


Synchrotron Radiation Sources – A Primer, ed. H.Winick

- intensity stability
  - change in background conditions and thermal load on beamline and machine components
    → position stability!
  - transv. multibunch instabilities → multibunch feedback
  - operation in top-up mode
    → loss compensation by refill small amount of charges in short time intervals

  vast dynamic range for instruments, starting from injector chain

Example: stored current (1 week) @ Spring8



H.Tanaka et al., J. Synchrotron Rad. 13 (2006) 378

- position stability
  - intensity fluctuations, emittance dilution → reduction of brilliance
  - orbit feedback systems including high resolution e BPMs and photon BPMs in beamlines

Light Sources: BPMs

- high resolution e BPM
  - typical stability tolerance: **20% emittance growth** $\frac{\Delta\varepsilon}{\varepsilon} = 2\frac{\Delta\sigma}{\sigma}$ → **10% of the (1σ) beam size**

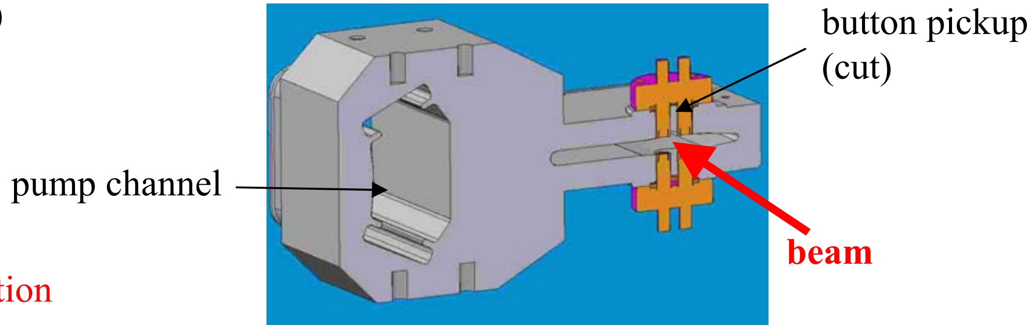
    example: position stability for PETRA III close to insertion devices (ID) $\Delta\sigma_{hor} = 2\ \mu m$, $\Delta\sigma_{vert} = 0.3\ \mu m$

BPM between canted IDs (PETRA III @ DESY)

- asymmetric chamber profile

  height: 7 mm, width: 83.5 mm

  → avoid heat load (SR fan)
- correction of strong non-linearities in beam position



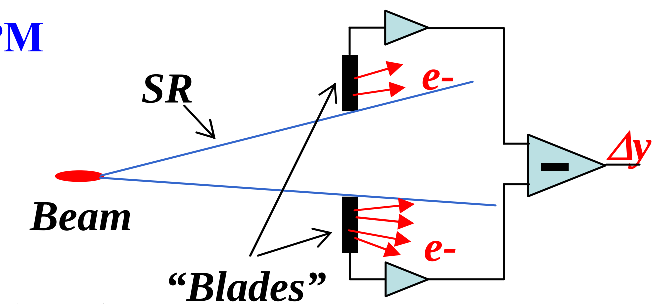
courtesy: A.Brenger (DESY)

- photon BPM
  - location in user beamlines: two monitors (per plane) → correction of position and angle

„blade“ type BPM

sensitive for tails

of distribution



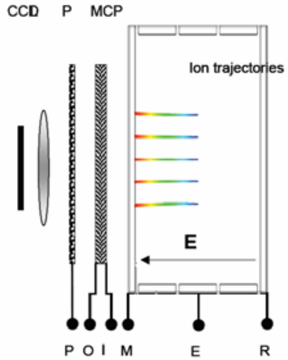
courtesy: F.Sannibale (LBNL)

residual gas XBPM

sensitive also for

distribution core

courtesy: P.Ilinski (DESY)

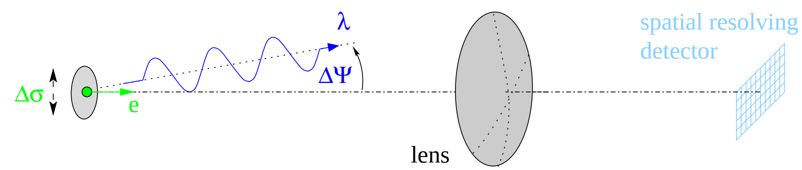


Light Sources: Emittance Diagnostics

- **emittance** typical value $\epsilon_x = 1\ \pi$ **nm rad and 1% emittance coupling**
  - principle: synchrotron radiation based diagnostics
  - example: $\sigma_{hor} = 40\ \mu m$, $\sigma_{vert} = 20\ \mu m$ (PETRA III @ DESY)

SR based imaging: resolution limit (uncertainty principle)

$$\Delta\sigma \approx \frac{\lambda}{2\,\Delta\Psi}$$

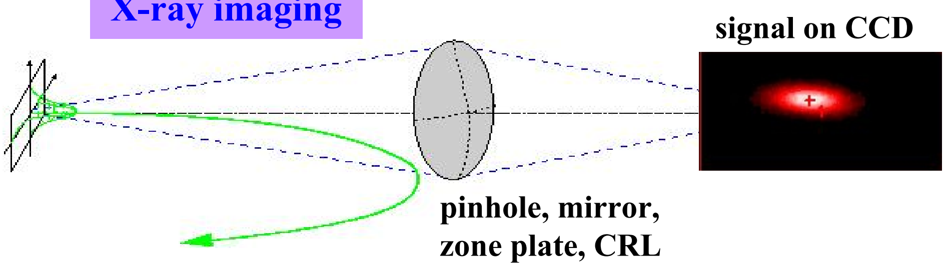


optical imaging: $\lambda = 500$ nm and $\Delta\Psi \approx 1.7\ \mu rad$ $\Rightarrow$ $\Delta\sigma_{vert} = 150\ \mu m$

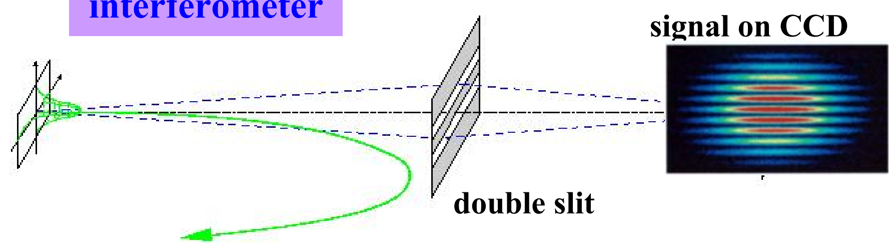
$\Rightarrow$ **resolution fully limited by uncertainty principle**

- widely used schemes for emittance diagnostics

X-ray imaging



interferometer



$\Rightarrow$ dedicated diagnostics beamline

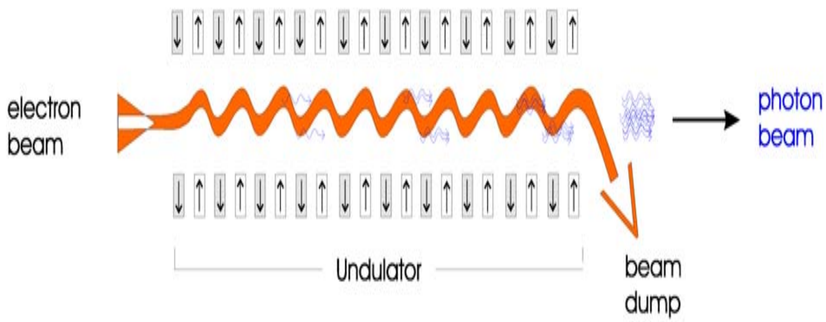
$\Rightarrow$ scanning device, 1 interferometer/plane

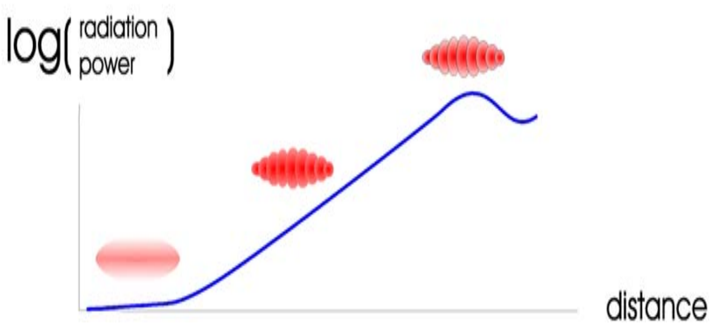
Free Electron Lasers (FELs)

- linac (single pass) based 4th generation light sources

Linac based Self Amplification of Spontaneous Emission (SASE) FELs

(→ no matter for diagnostics which FEL type)





Electron bunch modulated with its own synchrotron radiation field

- micro-bunching
- more and more electrons radiate in phase until saturation is reached

- SASE FEL projects
  - FLASH (6 – 30 nm)
  - European X-FEL (0.1 – 6 nm)
  - SPARC (500 nm)
  - LCLS (~ 0.15 nm)
  - SCSS (~ 3.6 nm)….

- beam energy defines photon wavelength λ_r

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

λ_u : undulator period

K : undulator parameter (measure for field)

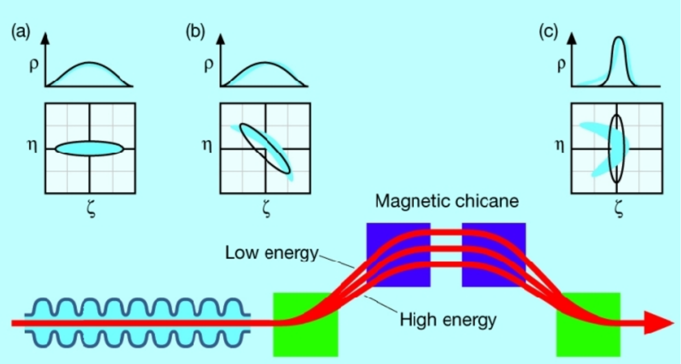
FELs: Requirements (1)

- high current density
  - sufficient energy transfer from electron beam to radiation field
  - natural scale: number of electrons per wavelength

$$N_{e,\lambda} = \frac{I\lambda}{ec}$$

$$N_{e,\lambda} = 1 \quad \Rightarrow \quad I = \begin{cases} 0.5\ \mu\text{A} & (\lambda = 100\ \mu\text{m}) \\ 0.5\ \text{A} & (\lambda = 0.1\,\text{nm}) \end{cases}$$

$\Rightarrow$ requires additional bunch compression in order to increase current density



$\Rightarrow$ extremely small bunch lengths $\mathcal{O}(< 100$ fsec$)$

- good electron beam quality
  - energy spread

$$\frac{\sigma_e}{E} \approx 10^{-4}$$

  - transverse emittance

$$\varepsilon \le \frac{\lambda}{4\pi}, \qquad \varepsilon = \varepsilon_n / \beta\gamma$$

($\rightarrow$ high energy helps)

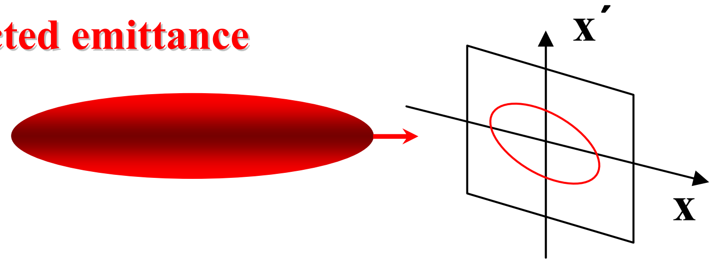
for resonant energy exchange and good overlap with radiation field

$\Rightarrow$ high demands on 6-dimensional phase space

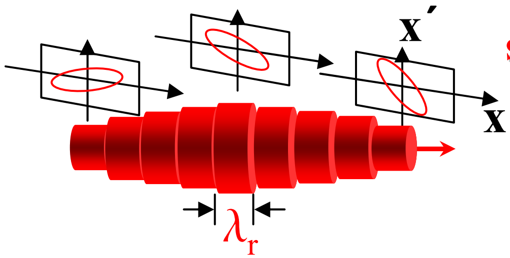
FELs: Requirements (2)

- comment: transverse emittance
  - electrons slip back in phase with respect to photons by λ_r each undulator period
  - FEL integrates over slippage length → **slice emittance** of importance

projected emittance

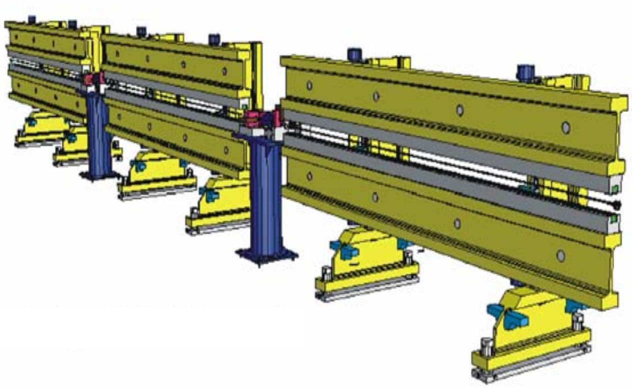


slice emittance



- stability
  - energy stability → wavelength stability $$\frac{\Delta\lambda}{\lambda} = -2\frac{\Delta E}{E}$$ and arrival time stability → for experiments
  - position stability
    → overlap between beam and radiation in undulators

example: XFEL @ DESY



- length of undulator section: 100-150 m
- BPM position resolution:

  1 µm (single bunch), **100 nm** (average over bunch train)

  → requires cavity BPMs

FELs: Comments

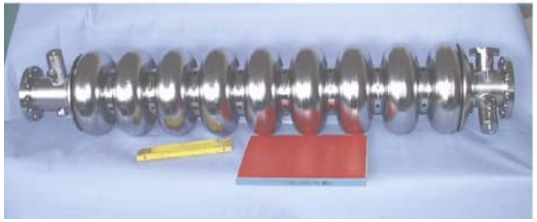
- linac-based FEL
  - no radiation damping → beam quality determined already from the gun

    ⇒ careful diagnostics and control of beam parameters

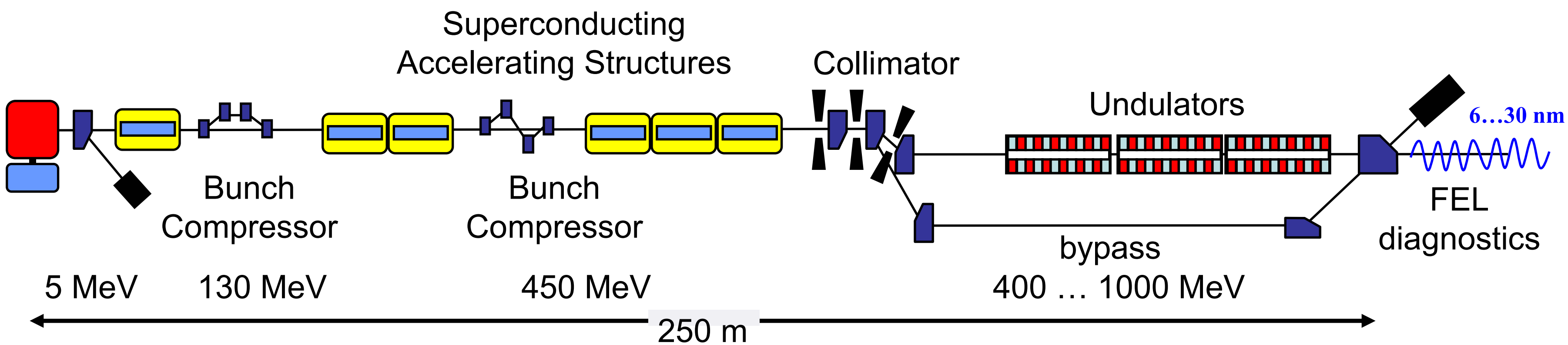
    SASE FEL is not forgiving – instead of reduced brightness, power nearly switches **OFF**

- accelerating structures
  - part of SASE FELs (will) use superconducting rf cavities

    ⇒ part of diagnostics (BPMs) in cold vacuum
    particle-free environment


9 cell, 1.3 GHz Nb TESLA cavity

- SASE FEL: FLASH @ DESY



FEL Diagnostics: Overview

- standard electron beam diagnostics to operate the linac

  instrumentation to measure

  - electron beam orbit
  - bunch charge
  - beam size
  - beam phase
  - energy and energy spread

  fast protection system to shut-off the beam in case of high losses

  - prevent damage on undulator (demagnetization) and vacuum system (leakage)

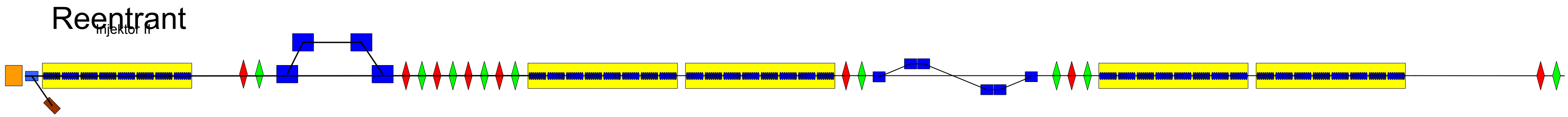
- diagnostics needed to control and optimize the FEL

  - **beam size / transverse emittance**
    → OTR/wire-scanner stations, resolution < 10 μm
  - **bunch length / longitudinal profile** ⇦
    → bunch length < 100 fsec, reconstruction of bunch shape
  - **slice emittance** ⇦
  - **bunch compression** → online signal for optimization of SASE process ⇦

- diagnostics needed for user experiments

  - characterization of radiation pulse (energy, spectral distribution)
  - synchronisation (required for time-resolved experiments → pump-probe)

FEL Diagnostics @ FLASH



GUN:
2 BPM
1 Toroid
3 Screens
3 F-Cups
4 Loss

BC2:
9 BPMs
2 Toroids
6 Screens
4 Wirescanners
2 Phase
1 Resistive
FIR Diagnostics
6 Loss

2 Cavity BPM

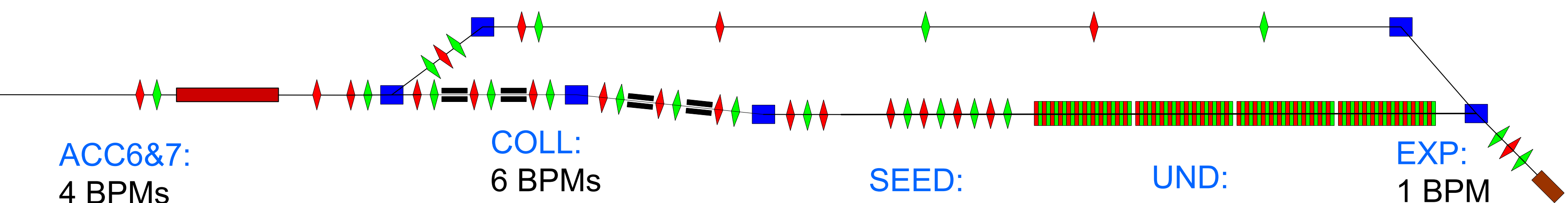
BYP:
7 BPMs
1 Toroid
4 Screens
1 Wirescanner
10 Loss

BC3:
6 BPMs
2 Toroids
4 Screens
1 Wirescanner
1 Phase
1 Resistive
FIR Diagnostics
6 Loss

2 Cavity BPM

&

FEL BL:
Intensity
Spektrum
Position



ACC6&7:
4 BPMs
LOLA
EOS
3 Loss

COLL:
6 BPMs
2 Toroids
1 Phase
1 Resistive
3 Screens
2 Wirescanner
9 Loss

SEED:
4 BPMs
4 Screens
4 Wirescanners
FIR Diagnostics
1 TEO
Optical Replica

UND:
13 BPMs
7 Wirescanners
22 Loss

EXP:
1 BPM
1 Toroid
1 Screen

DUMP:
2 BPM
1 Toroid
1 Screen
4 Loss

courtesy: D. Nölle (DESY)

FEL Diagnostics: Bunch Length/Profile

- coherent radiation diagnostics
  - **principle:** bunch length/shape dependent emission spectrum of coherent radiation

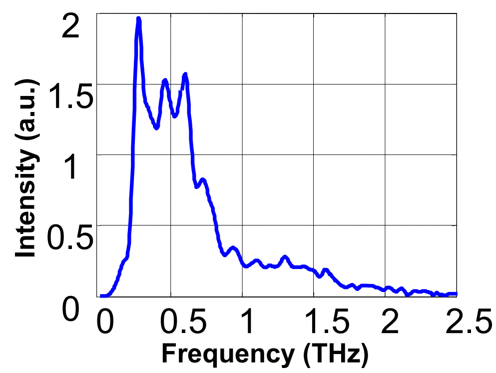
single particle spectrum — bunch form factor

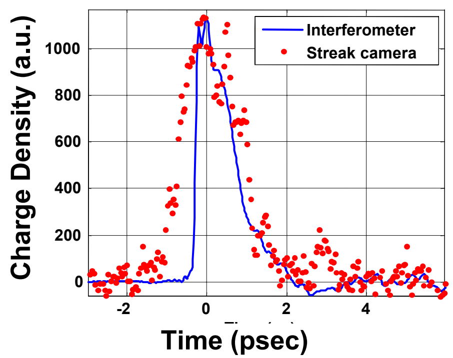
$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_1 \left(N + N(N-1)\left|F(\lambda)\right|^2\right) \quad \text{with} \quad F(\lambda) = \int \mathrm{d}z\, S(z)\, e^{i\frac{2\pi z}{\lambda}}$$

no. of particles per bunch — bunch profile

  - spectral decomposition and Fourier transform: → **bunch length and shape**

source: synchrotron radiation, transition radiation, diffraction radiation, Smith-Purcell radiation,…

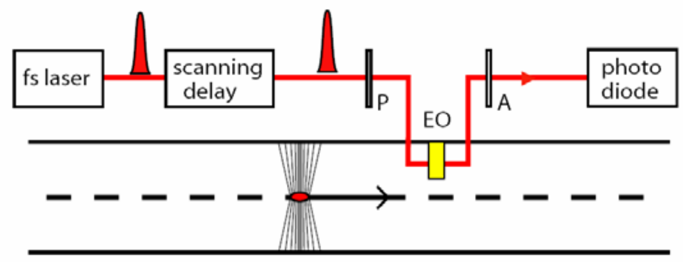




courtesy: O.Grimm (DESY)

- electro optical sampling (EOS)
  - **principle:** Coulomb field induces refractive index change in EO crystal (Pockels effect)
    → effective polarization rotation proportional to Coulomb field
  - Coulomb field converted in opt. intensity variation
    → **laser + polarizer (P) + analyzer (A)**

example: EOS using variable delay (simple scheme)
more sophisticated: temporal, spectral, spatial encoding



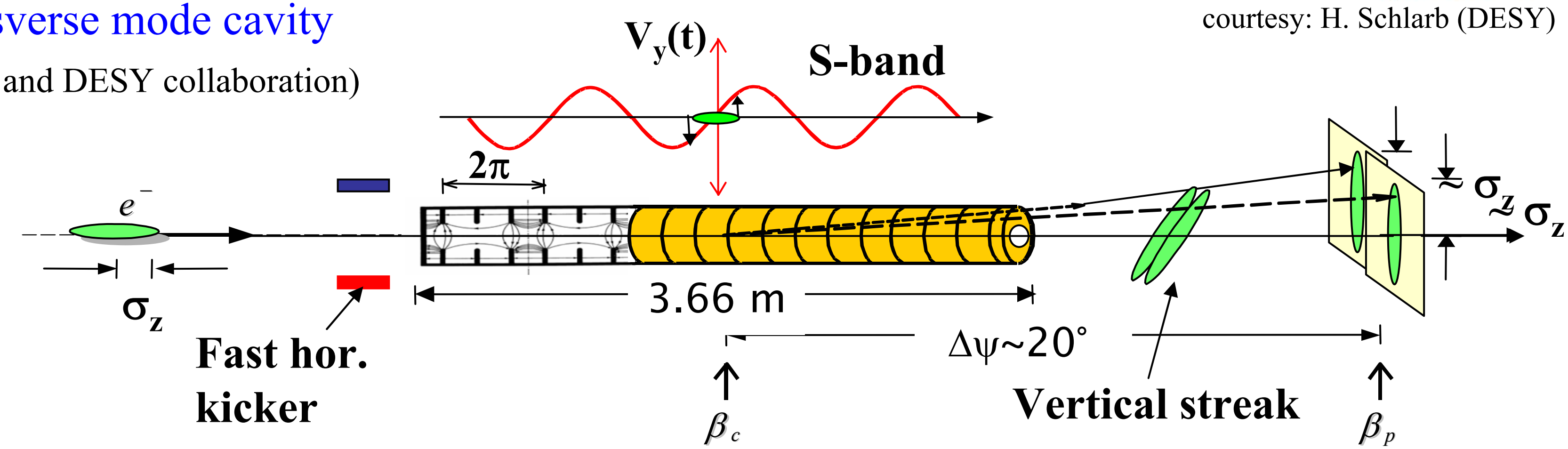
courtesy: B. Steffen (DESY)

FEL Diagnostics: Slice Emittance

- transverse mode cavity

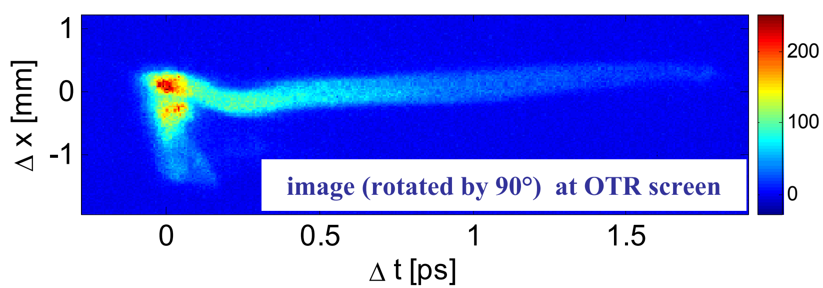
(SLAC and DESY collaboration)

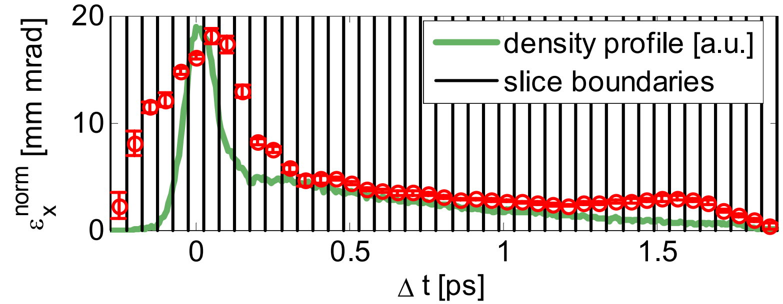
courtesy: H. Schlarb (DESY)



- 'Intra Beam Streak Camera':
  → vertical deflecting RF structure
  (2.856 GHz) operated at zero crossing
- 'parasitical' measurement using
  hor. kicker and off-axis OTR screen
- vertical size of beam at imaging screen
  ⇒ bunch length
- horizontal size at imaging screen
  ⇒ access to slice emittances

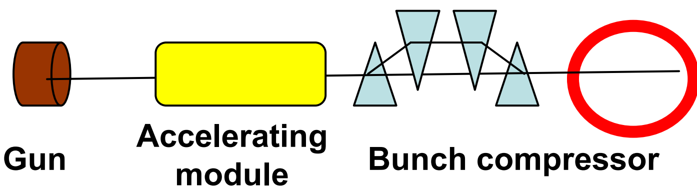
FLASH: slice emittance under SASE conditions @ 13.7 nm

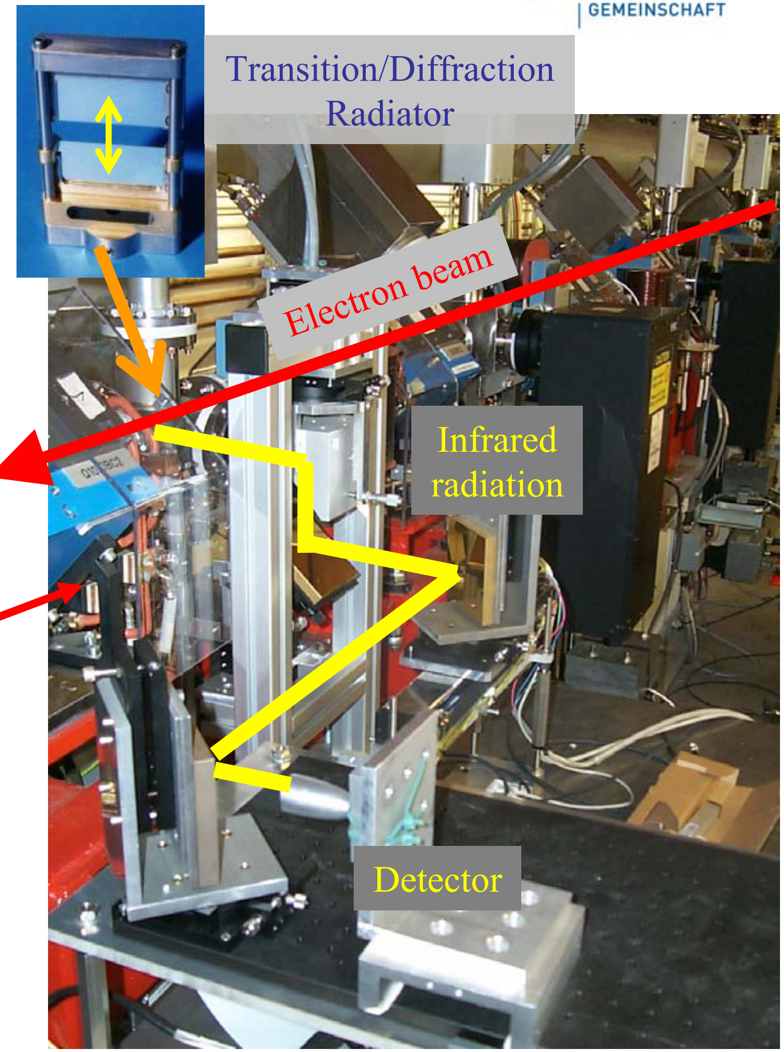


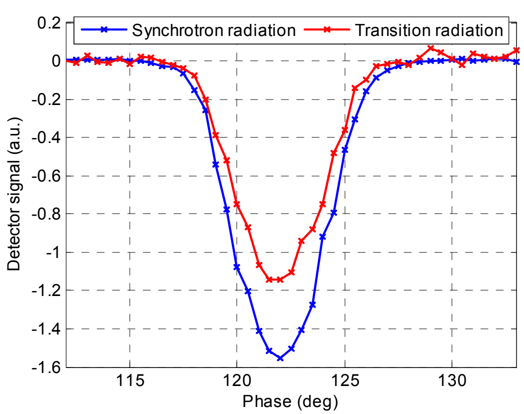


FEL Diagnostics: Bunch Compression

- bunch compression monitor
  - for optimization of compression:
    → sufficient to see trends in bunch lengths
  - principle: increase of FIR radiation intensity for smaller beam sizes due to extension of coherence
  - observation of FIR radiation intensity behind bunch compressor







example:
phase/compression scan at FLASH (DESY)

courtesy: O.Grimm (DESY)

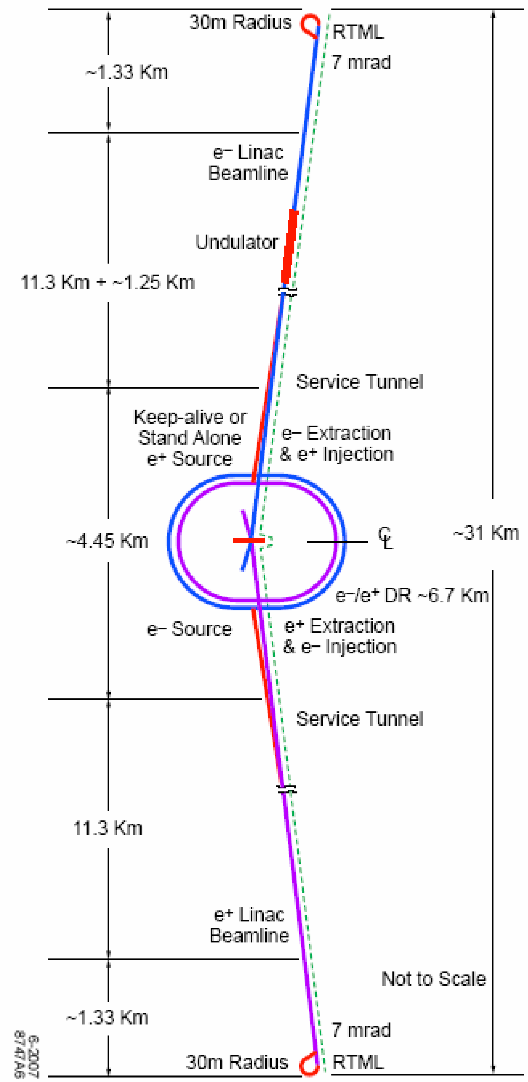
Outlook

- putting it all together…
  - injector linac, including e^+ production
  - storage ring with opportunity of radiation damping
  - superconducting linac with stringent requirements for
    6-dimensional phase space

…and build a linear collider:

international linear collider ilc

- 2 x 11 km long superconducting linacs, operating at 31.5 MV/m
  → e^-/e^+ collisions at center-of-mass energies of 500 GeV
- circular damping rings for e^- and e^+, incl. sc. damping wigglers
  → energy at damping rings: 5 GeV
- undulator-based e^+ source
- single interaction point (IP), crossing angle 14 mrad



ILC Reference Design Report (2007)

International Linear Collider

- key parameters (nominal values)

train repetition rate / Hz	**5**
bunches per train	**2625**
bunch spacing / nsec	**369.2**
train length / µsec	**~ 970**
particles per bunch / x 10^{10}	**2**
normalized emittance at IP $\gamma\varepsilon_{x,y}$ / mm mrad	**10 / 0.04**
r.m.s. beam size at IP $\sigma_{x,y}$ / nm	**639 / 5.7**
r.m.s. bunch length σ_z / µm	**300**
power per beam at IP / MW	**10.5**
Luminosity $\mathcal{L}$ 10^{34} / cm^2 / sec	**2**

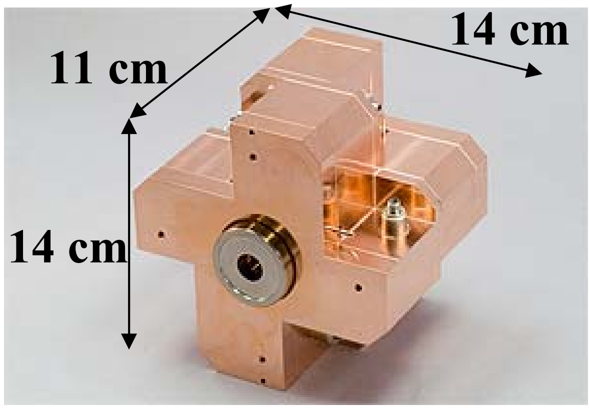
ILC Reference Design Report (2007)

challenges:

- beam position
  - → measurement
  - → stability
- beam size
  - → measurement
  - → non-invasive

ILC: Diagnostics

- beam position measurements with sub-µm resolution
  - Cavity BPMs for higher resolution applications
  - location in cold and warm sections
  - variety of R&D activities for ILC BPMs at different laboratories
  - single bunch position resolution of ~20 nm achieved at ATF (KEK)



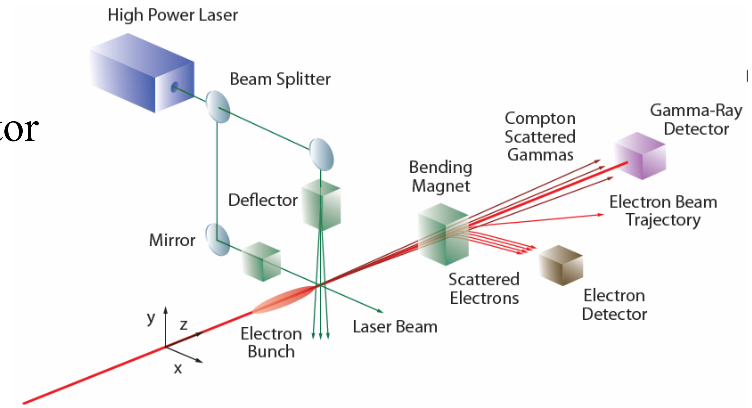
courtesy: T.Nakamura (Tokio University)

high resolution cavity BPM for ILC final focusing system

- non-invasive beam profile monitors
  - laser wire scanner
    - scanning a finely focussed laser beam across bunches
    - measure Compton scattered photons in downstream detector
    - photon rate as function of relative laser beam position

      → beam profile
  - optical diffraction radiation (ODR)
    - diffraction of particle Coulomb field at a slit

principle of laser wire scanner



ILC Reference Design Report (2007)

ILC: Diagnostics

INSTRUMENT requirements (e.g. resolution)	AREA					
	e^- source	e^+ source	DR	RTML	ML	BDS
Button/stripline BPM resolution (μm)	69 10-30	400 10-30	2 × 747 <0.5			120 <100
C-Band Cavity BPM (warm) resolution (μm)		109 <0.1-0.5		2 × 649 <0.1-0.5		262 <0.1-0.5
S-Band Cavity BPM (warm) resolution (μm)						14 < 0.1-0.5
L-Band Cavity BPM (warm) resolution (μm)				2 × 27 <1-5		42 <1-5
L-Band Cavity BPM (cold) resolution (μm)				2 × 28 ~0.5-2	2 × 280 ~0.5-2	
Laser-wire IP resolution (μm)	8 <0.5-5	20 <0.5-5	2 × 1 <0.5-5	2 × 12 <0.5-5	2 × 3 <0.5-5	8 <0.5-5
Wirescanner	12	8				
Optical Monitors	6	17	2 × 2	2 × 8		11
DMC resolution $\Delta E \sim 0.1\%$ / $s_z \sim 100\ \mu$m	3	4		2 × 2		2 (cold)
Beam Current Monitors	7	11	2 × 1	2 × 2	2 × 3	10
Beam Phase Monitor	4	2		2 × 3		2
BLM (PMT/IC)	60/2	400/20	2 × 40/4	2 × 75/2	2 × 325/10	100/10
Feedback System	5	10	2 × 2	2 × 1	2 × 10	12

ILC Reference Design Report (2007)