Lecture 22
Beam Instrumentation & Diagnostics

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Introduction

- Beam circulating inside closed vacuum chamber is not visible from outside.

- Access close to accelerator prohibited during operation.

- Equip accelerator with wide range of measuring instruments - monitors

  - Establish whether there is beam in machine.
  - Measure physical parameters of machine.

An accelerator is only as good

as its diagnostic equipment.

What are Beam Diagnostics?

- Diagnostics are the 'eyes and ears' of accelerator:
  - Measure **physical properties** of the beam, like charge, position, transverse and temporal profile.
  - Consist of devices to **sense** these properties (pick-ups) and associated **processing** electronics and **software** (amplifiers, filters, converters, calculations).
  - Essential in the **commissioning** phase to establish operating conditions and tune parameters for optimum performance (beam optics, timing, accelerating field amplitudes and phases).
  - Essential in the **operation** to ensure stable conditions (stable orbit, tune, timing). Thus, diagnostics are required to be reliable and stable in their own right.

OBSERVATION OF BEAM & MEASUREMENT OF BEAM CURRENT

Screens (Phosphor or Scintillator)

- Full 2D transverse profile in one shot.

- Generally destructive to the beam (energy absorbed, scattering of particles as they pass through screen).

- Actuator required to remove screen from beam path.

- Camera shutter should be synchronised to beam arrival for best results.

Actuator

Screen

Vacuum Window

Lens

CCD camera
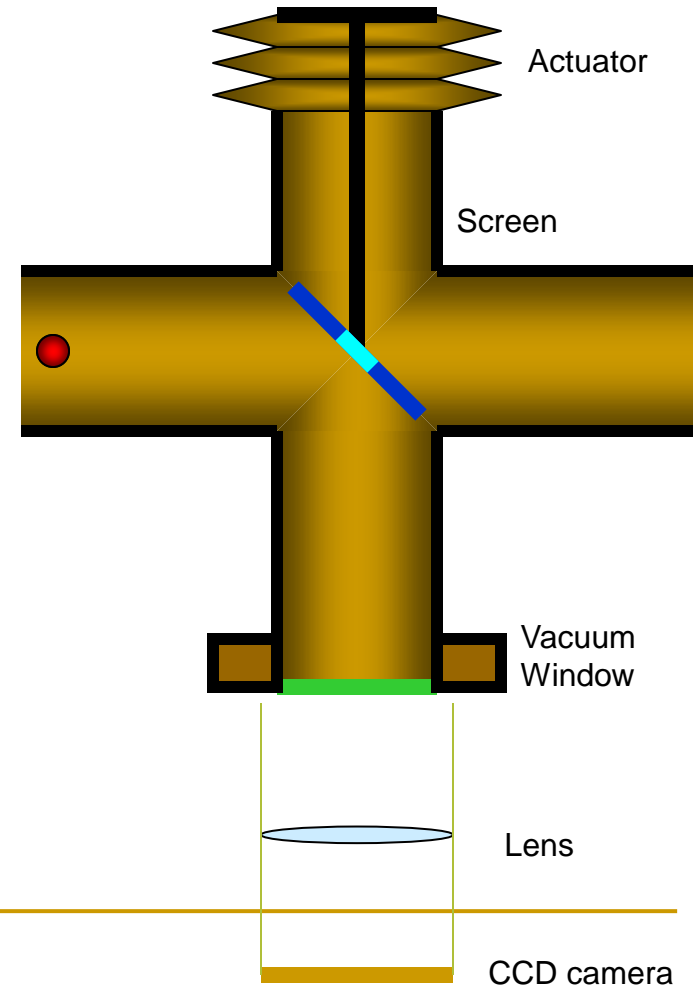
Fluorescent Screen

- **Applications**
  - Measurement of beam position
  - Beam profile
  - Beam intensity

- ZnS is effective fluorescent material
  - Mixed with sodium silicate, it is applied in thin layers onto glass, ceramic or metal.
  - Screens emit green light with high light yield.
  - Disadvantages
    - Limited use in high-vacuum environments.
    - Limited lifetime & burn out at beam spot after extended exposure.

Fluorescent Screen

- Thicker screens made of Al_2O_3 doped with chrome.
  - Predominantly red light.
  - High tolerance to beam exposure.
  - Low degassing rate and may be used in UHV.
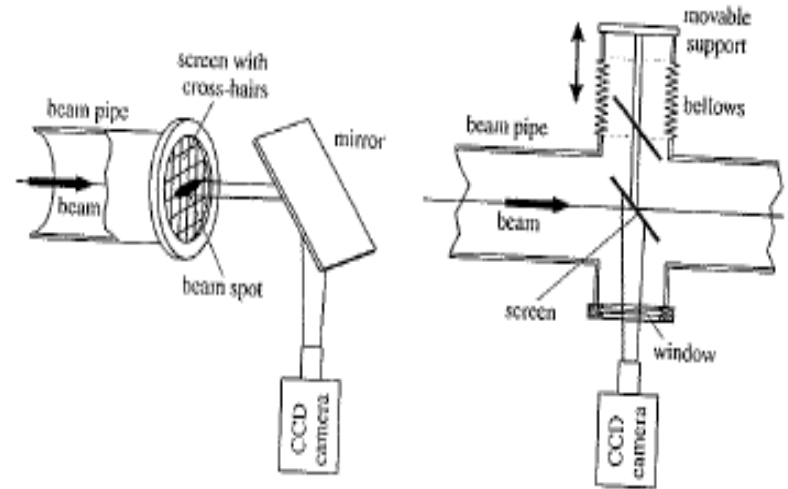
Left – fixed version at the end of linac.

Right – movable screen which may be moved in/out of beam line.

Fluorescent Screen

- **Read-out**
  - Emitted light viewed using television (CCD) camera in control room.
  - CCDs are susceptible to radiation damage.
    - Protect by lead shielding and install at low radiation level locations.

- **Limitations**
  - Non-linear relationship between light yield and beam intensity
  - Long afterglow
    - Several ms to seconds
      - Not possible to resolve time structure of beam (ns. range).

Optical Transition Radiation (OTR)

- Transition Radiation is created when relativistic charged particles cross a dielectric boundary.

- Typically, metal targets are used, as metals have large negative dielectric constant at optical frequencies.

- A part of the emitted photons (OTR) is in the visible spectrum and can be used to image the particle distribution.

- Forward OTR is emitted in a cone around the particle trajectory.

- Backward OTR is emitted in a cone around the 'reflected' particle trajectory.

Forward OTR

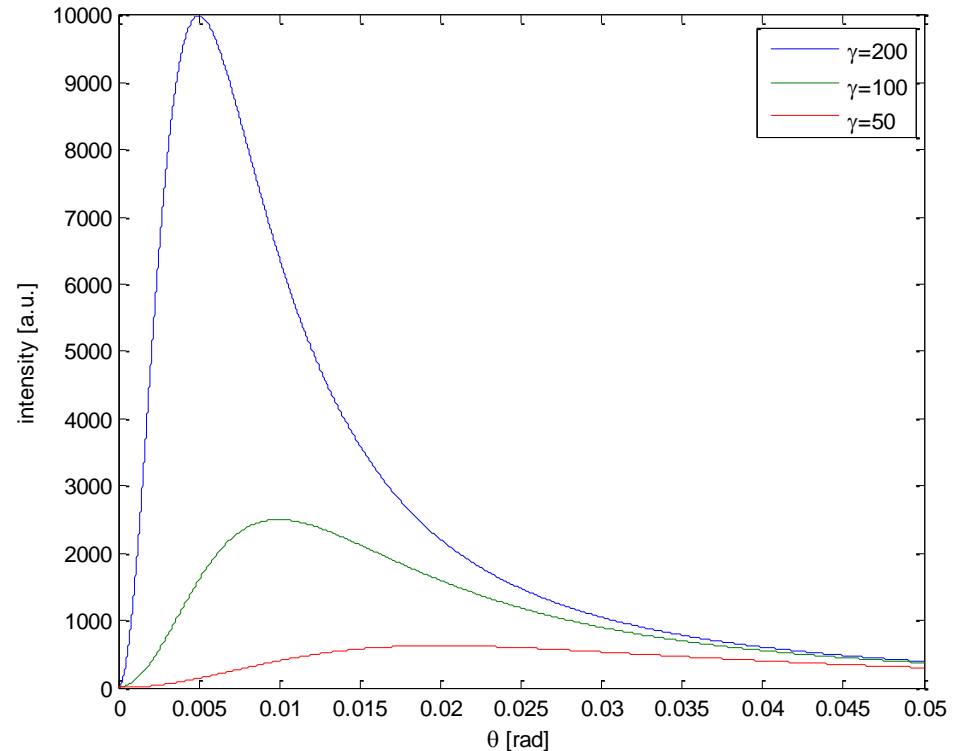Backward OTR
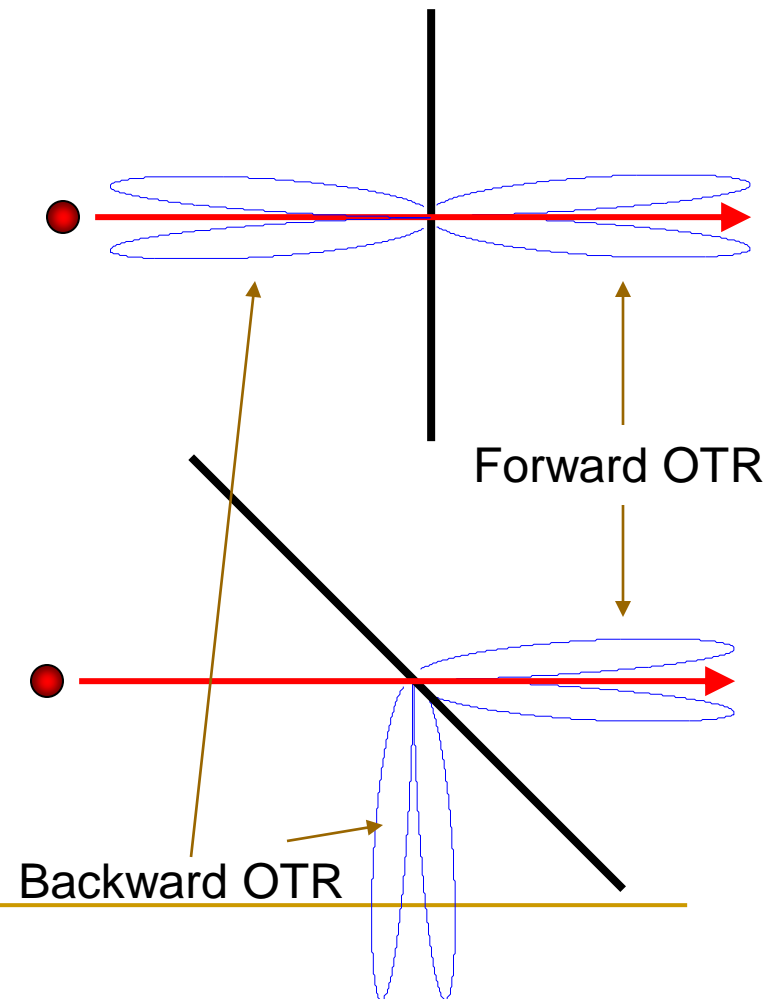
Properties of OTR

- Intensity scales with:

$$I \propto \frac{\theta^2}{(\theta^2 + \gamma^{-2})^2}$$

- Maximum at $1/\gamma$
- Number of (visible) photons per electron:

$$N = \frac{1}{137\pi}(2\ln\gamma - 1) \cdot \ln\left(\frac{\lambda_{red}}{\lambda_{blue}}\right)$$

- Practically: 1-3%

OTR Advantages/Disadvantages

- **Advantages**
  - Like a phosphor screen, but without resolution limits (resolution possible down to optical wavelength).
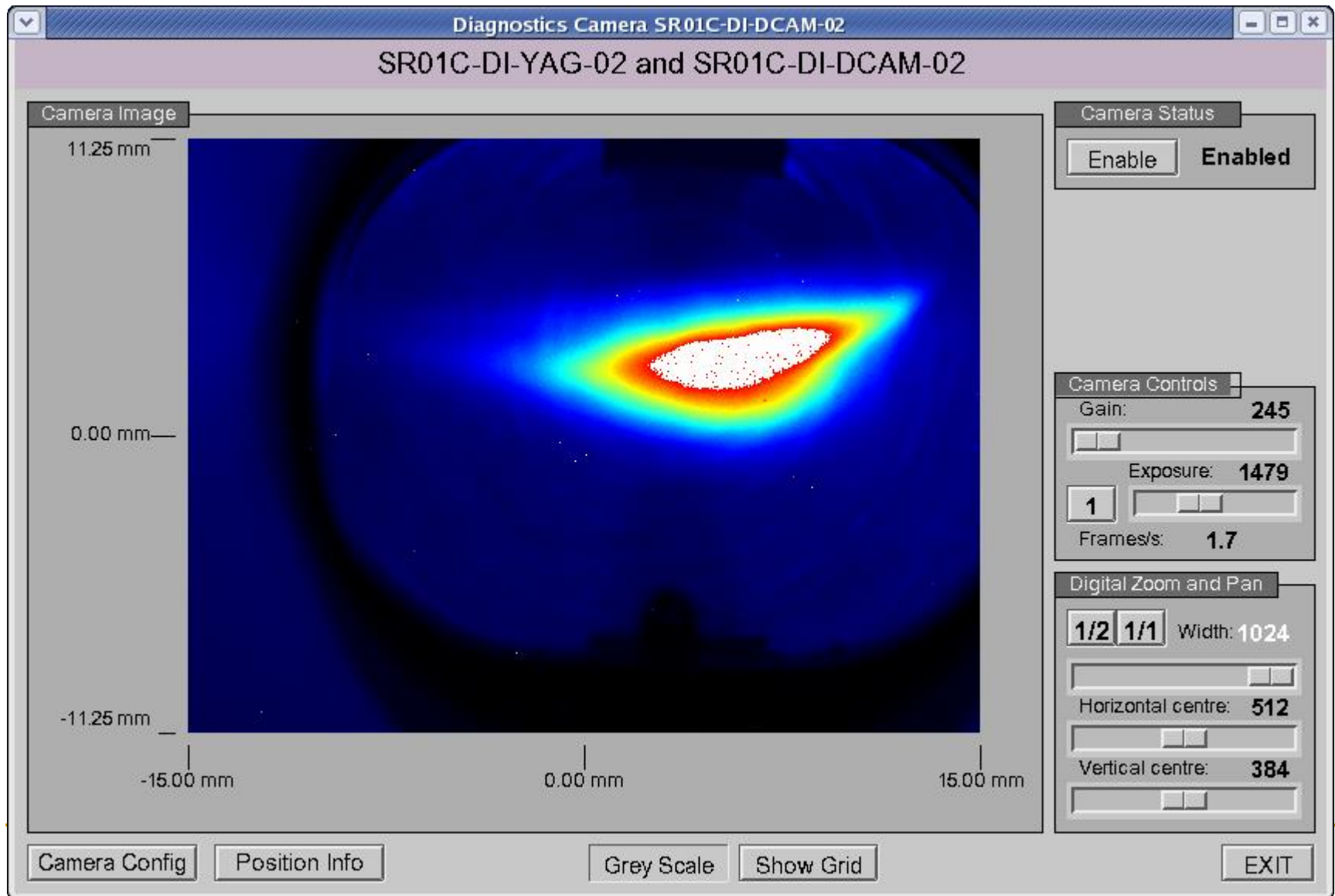 - No saturation, linear intensity to destruction threshold ($>10^{12}e^-/mm^2$).

- **Disadvantages**
  - Few photons per electron, which are emitted in a large angle at low particle energies.
  - Practically only feasible for strongly relativistic particles ($\gamma>100$).
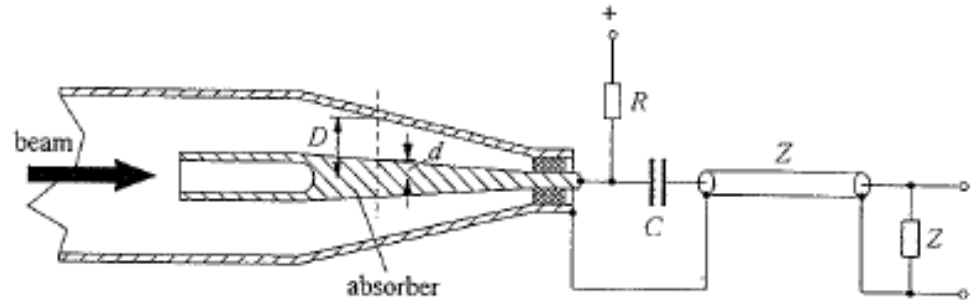
Screens and Optics

Pneumatic Actuator

e⁻ beam

Mirror

CCD-Camera

OTR

YAG:Ce
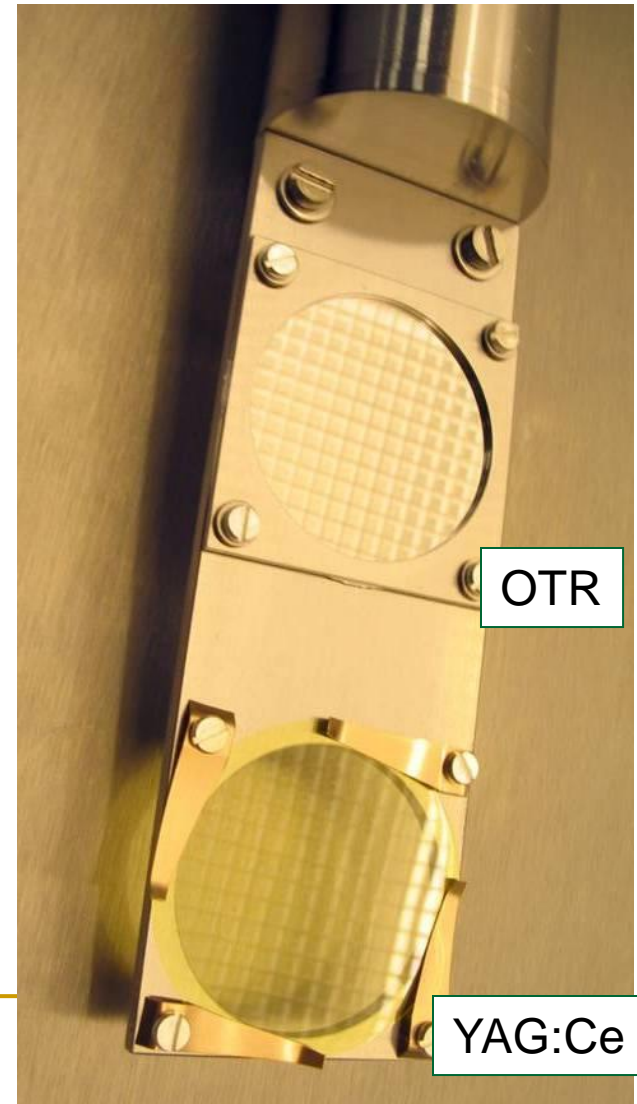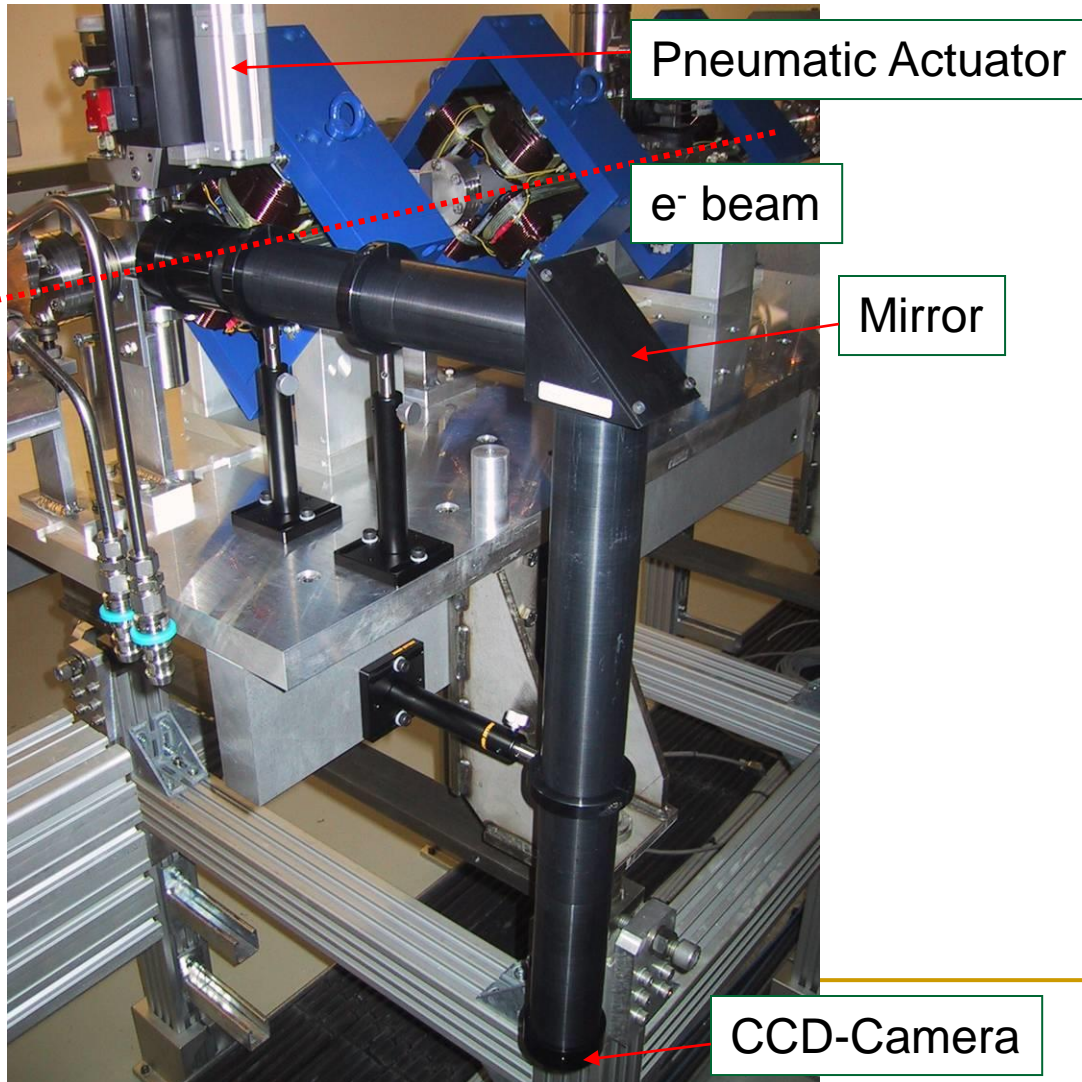
Beam Profiles in the Diamond Injector

Faraday Cup

Faraday cup with coaxial structure

- **Applications**
  - ☐ Simplest method to measure beam current/intensity is to completely absorb beam in block of conducting material.
   - Measure captured charge by measuring resulting current.

• At high energies, penetration depth is large – material block must be very thick.

• Large energy transfer to absorber – strong heating.

• Multiple scattering – transverse broadening of beam -> particle losses

• Secondary particle production by pair production.

• Therefore, Faraday cup restricted to low-energy beam applications.

Faraday Cup Principle
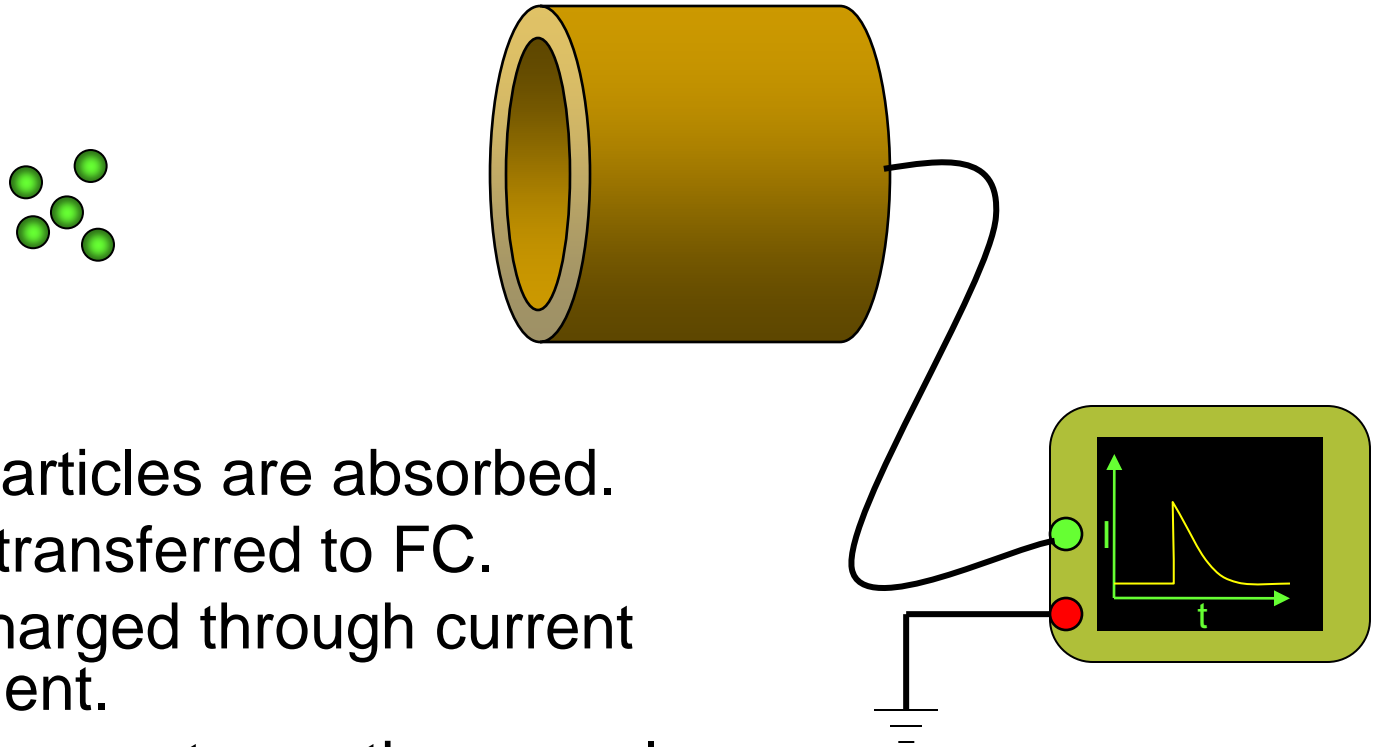
- Charged particles are absorbed.
- Charge is transferred to FC.
- FC is discharged through current measurement.
- Integral of current over time equals charge.

Interaction of Particles with Matter
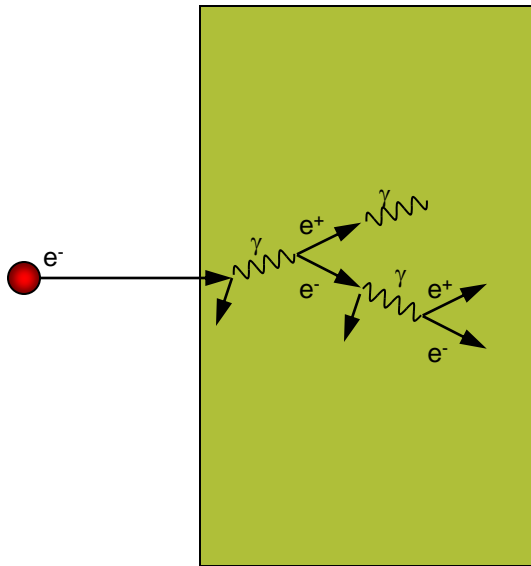
- Need to consider ionisation losses (dominant up to a few MeV), bremsstrahlung and e^+e^- pair production.
- Higher energy particles will need more length or higher density material to be stopped.
- At lower energies (up to a few 10MeV) calculations of absorption length and Moliere radius etc. using empirical formulae will be sufficient.
- At higher energies, simulation of scattering, pair-production and energy deposition is required (e.g. Electron Gamma Shower)
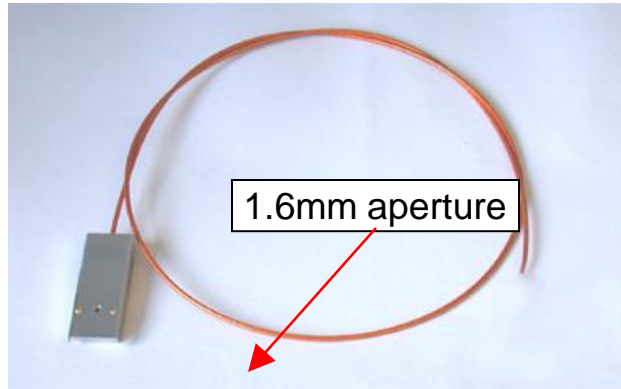
Backscatter
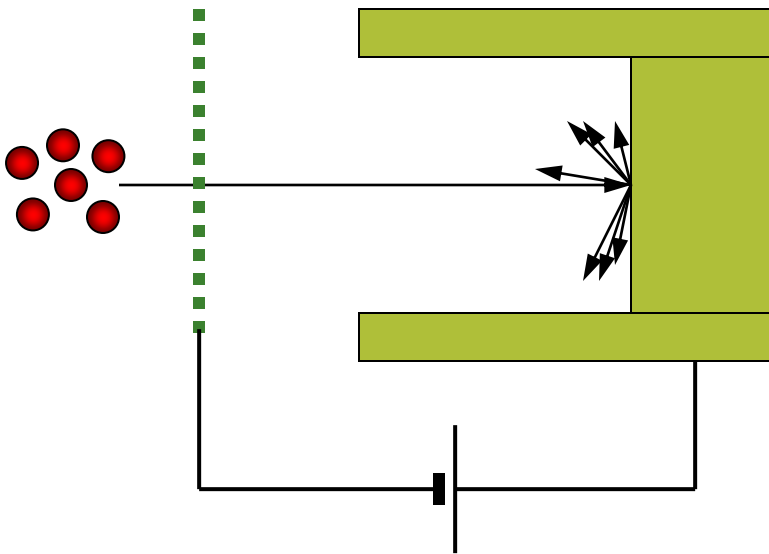
- Angular distribution depends on energy of particles and on density of material.

- Generally least in direct reverse direction.

- Backscattered (or secondary) particles have less energy.

- Low Z material, side walls or biased grid to reduce.
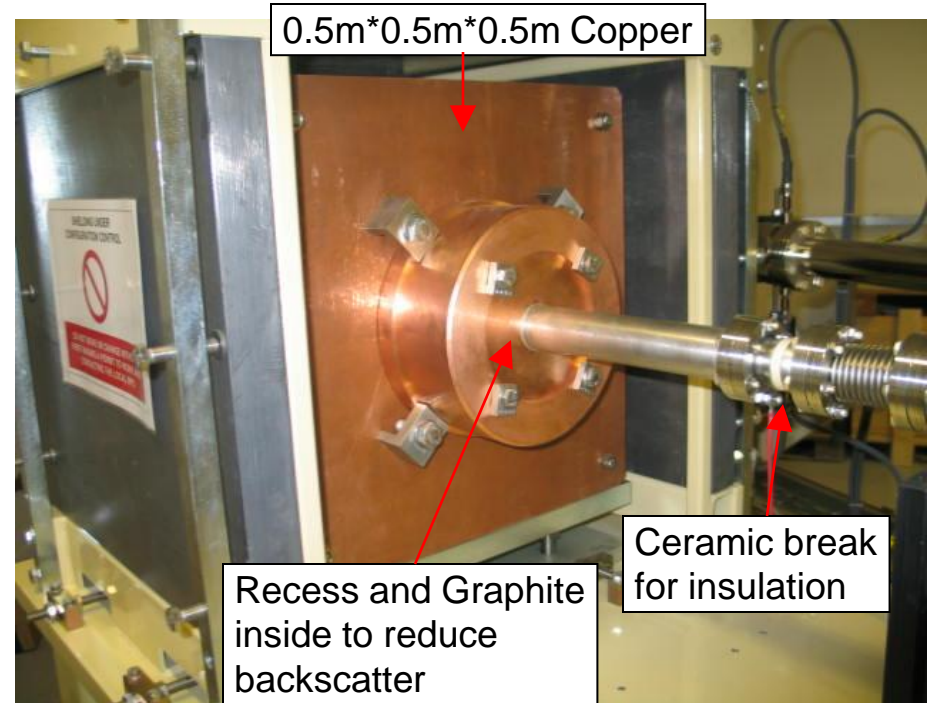
Some Faraday Cups

1.6mm aperture

Kimball Physics

Flange mounted, 4W beam power

Graphite insert

Actuator mounted coaxial FC
Diamond LINAC @ 90 keV and 4 MeV

0.5m*0.5m*0.5m Copper

Ceramic break
for insulation

Recess and Graphite
inside to reduce
backscatter

3 GeV FC at the exit
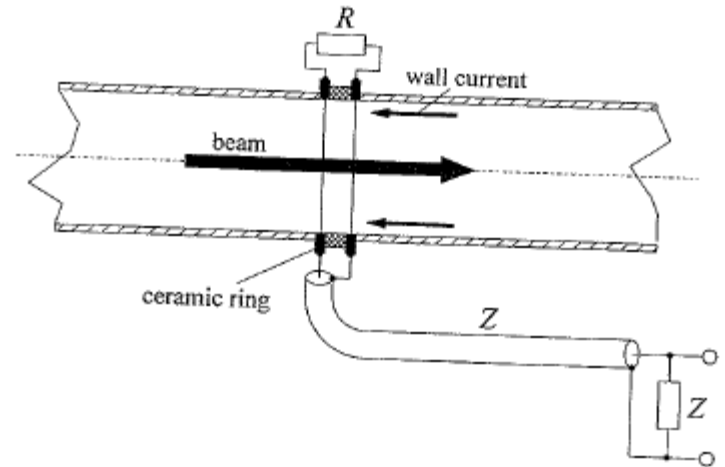of the Diamond Booster

Wall Current Monitor (WCM)

- **Cyclic Accelerator**
  - Need to measure the current without disturbing the beam.
- **Current**
  - Outside vacuum tube

    $$\oint B_{external} \cdot dr = 0.$$

  - Within vacuum tube

    $$\frac{1}{\mu_0} \oint B_{beam} \cdot dr = I_{beam},$$

  - There is a wall current I_{wall} flowing in vacuum chamber

Lay-out of wall current monitor
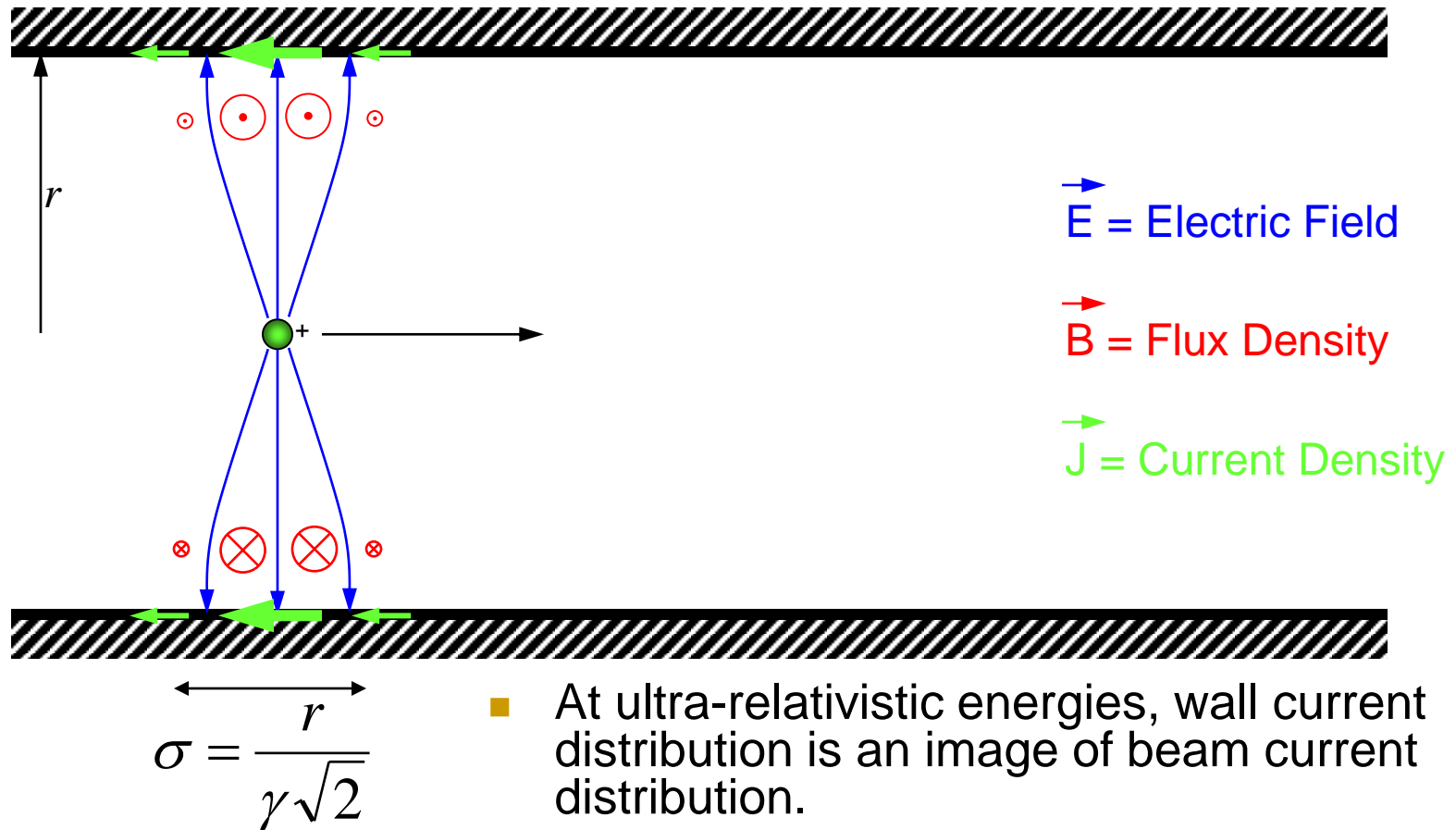
$$I_{beam} = -I_{wall}$$

Wall Current Monitor (WCM)

- Beam current determined by measuring current in vacuum chamber wall.

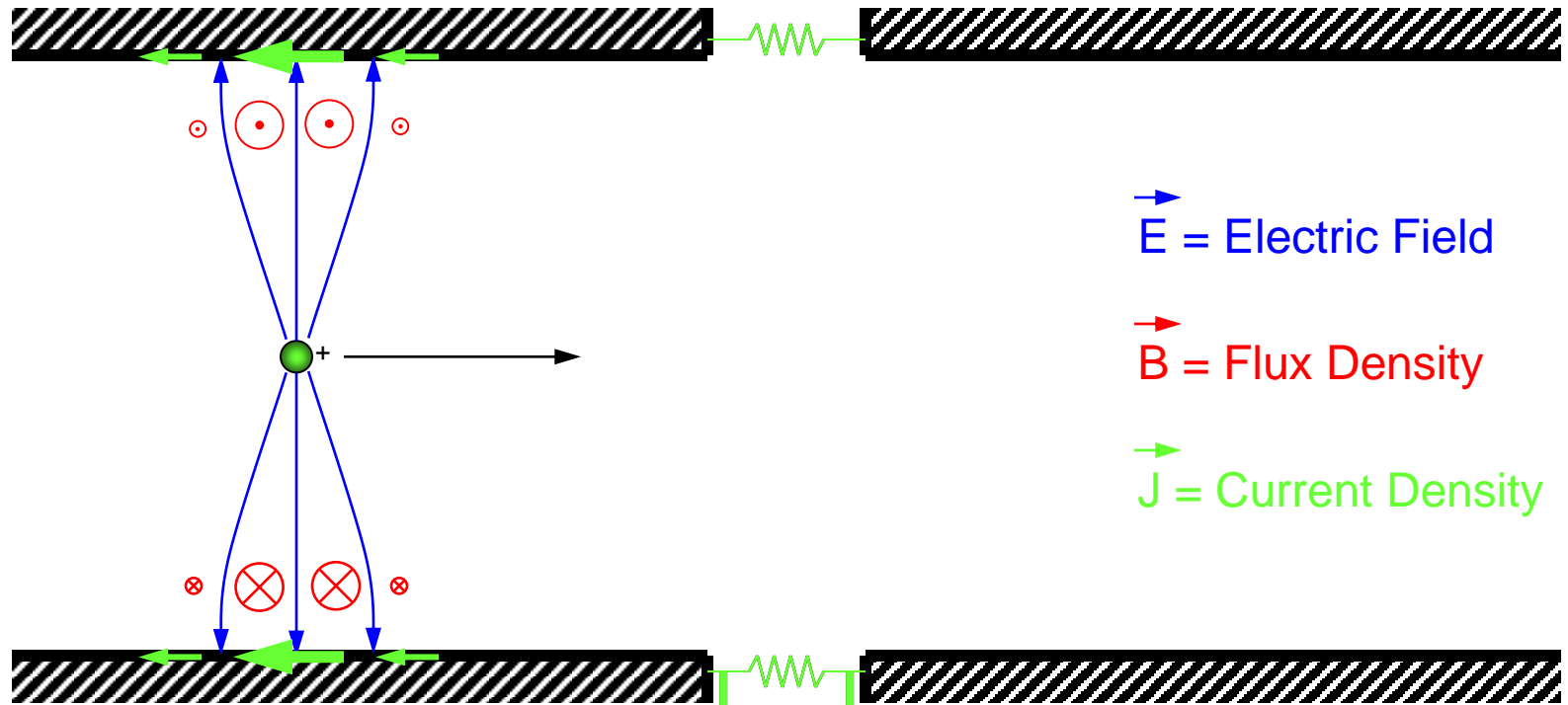- Measure voltage *V* developed over ohmic resistance *R* (~ 1 Ω) across a ceramic gap.

$$U_R = R\, I_{beam} \;=\; -R\, I_{wall}.$$

- Large number of resistors are used, connected in parallel around the vacuum chamber

  - Wall current monitor can achieve very high bandwidths (several GHz).

Fields and Currents of a Charged Particle at Relativistic Speed

$\vec{E}$ = Electric Field

$\vec{B}$ = Flux Density

$\vec{J}$ = Current Density

$$\sigma = \frac{r}{\gamma\sqrt{2}}$$

- At ultra-relativistic energies, wall current distribution is an image of beam current distribution.

- No field outside tube (only DC magnetic field)

Wall Current Monitor (WCM)

$\vec{E}$ = Electric Field

$\vec{B}$ = Flux Density

$\vec{J}$ = Current Density

Typical resolution 100ps RMS
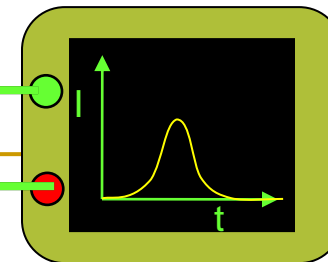
WCM Example Measurements

Mechanical Assembly

Bunch train from LINAC

Individual bunches in train
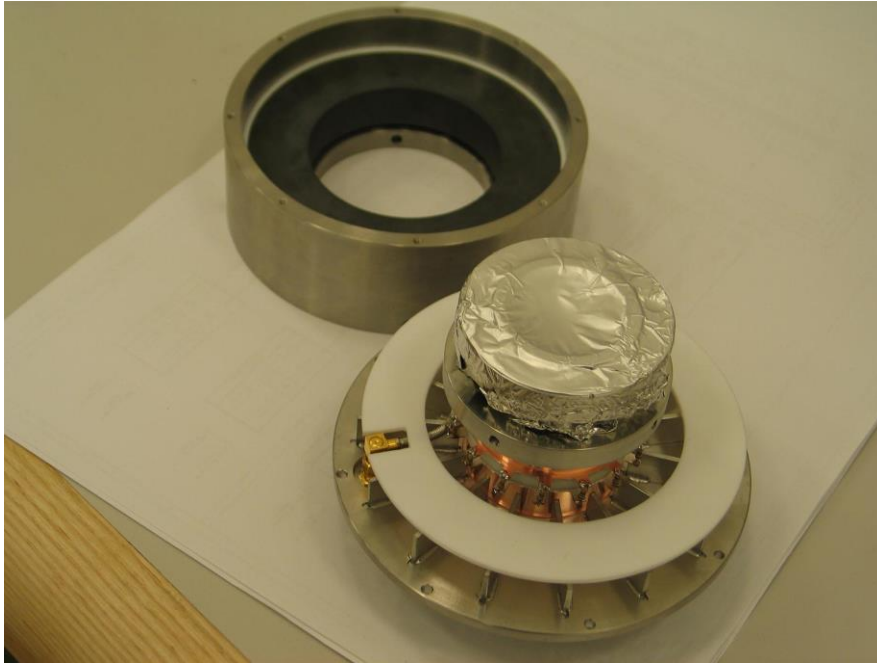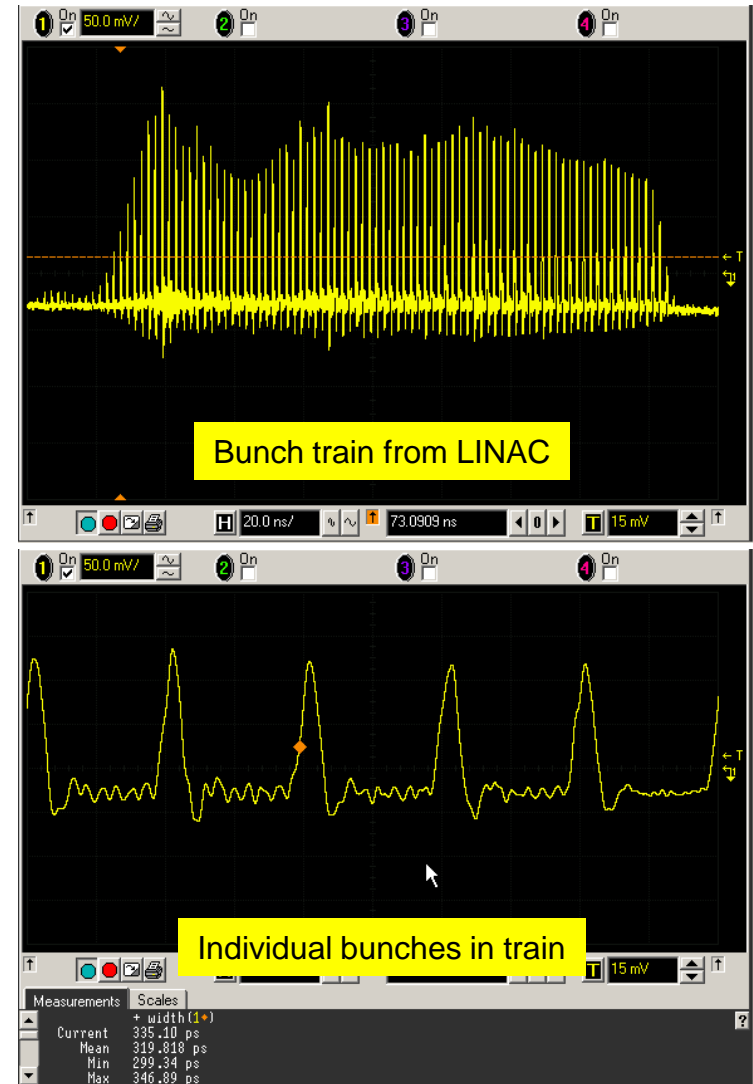
Beam Current Transformer

$$I_{\text{beam}}(t) = \frac{Ne}{\sqrt{2\pi}\,\tau} \exp\left(-\frac{(t-t_0)^2}{2\tau^2}\right) \qquad \text{with} \qquad \tau = \frac{\sigma_s}{c}$$

$$B(t) = \frac{\mu_0\mu_r}{2\pi\,R_{\text{core}}}\,I_{\text{beam}}(t)$$

$$U_{\text{ind}}(t) = n\,A\,\dot{B}(t) = \frac{\mu_0\mu_r\,n\,A}{2\pi\,R_{\text{core}}}\,\dot{I}_{\text{beam}}(t)$$

Ideal iron core around particle beam

This arrangement acts like a transformer:
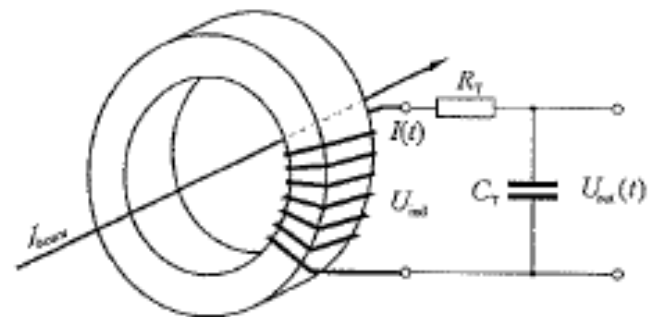
Primary winding – particle beam

Secondary winding – inductive coil

→ *Beam Transformer*

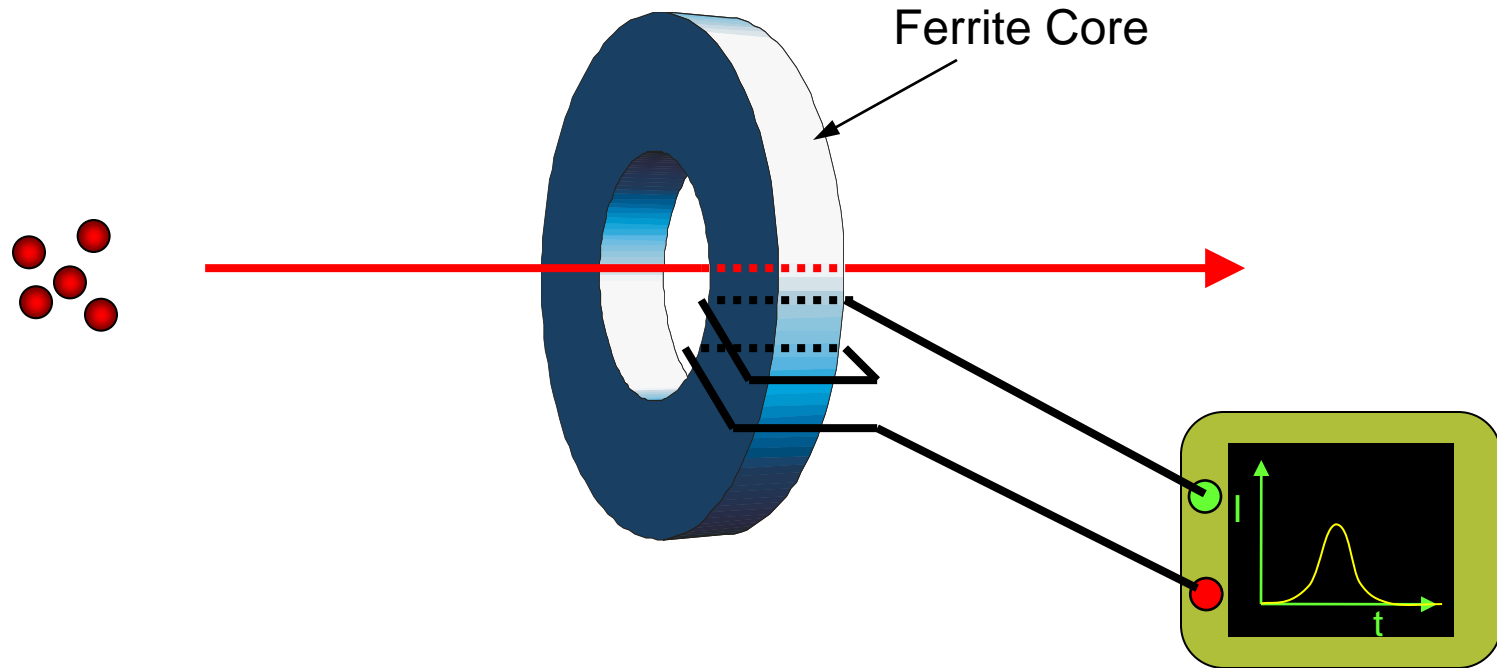Equivalent circuit of beam transformer

Beam Current Transformer Principle

Ferrite Core

- Charged particles act as 'single turn' in a transformer.
- Proportional current is induced into windings.
- Integral of current over time equals charge.

Beam Current Transformer

- Beam transformer output (secondary) voltage U_{out}

$$U_{out}(t) = \frac{1}{C_T} \int I(t)\, dt.$$

$$\dot{I}(t) + \frac{1}{C_T R_T} I(t) = \frac{\dot{U}_{ind}}{R_T}.$$

- $C_T R_T$ long compared to duration of bunch pulses →

$$\dot{I}(t) \approx \frac{\dot{U}_{ind}}{R_T} \implies I(t) \approx \frac{U_{ind}}{R_T} + C_1.$$

- Secondary voltage becomes:

$$U_{out}(t) = \frac{1}{C_T} \int I(t)\, dt \approx \frac{1}{C_T R_T} \int U_{ind}\, dt.$$

$$U_{out}(t) = \frac{1}{C_T R_T} \frac{\mu_0 \mu_r\, n\, A}{2\pi\, R_{core}} I_{beam}(t).$$

- Time dependence of output voltage U_{out} is only roughly proportional to beam current $I_{beam}(t)$.
- True for relatively long bunches with limited frequency components
  - For short bunches U_{out} is considerably longer than the current pulse.
  - Area under voltage pulse can be used as good approximation of number of particles.
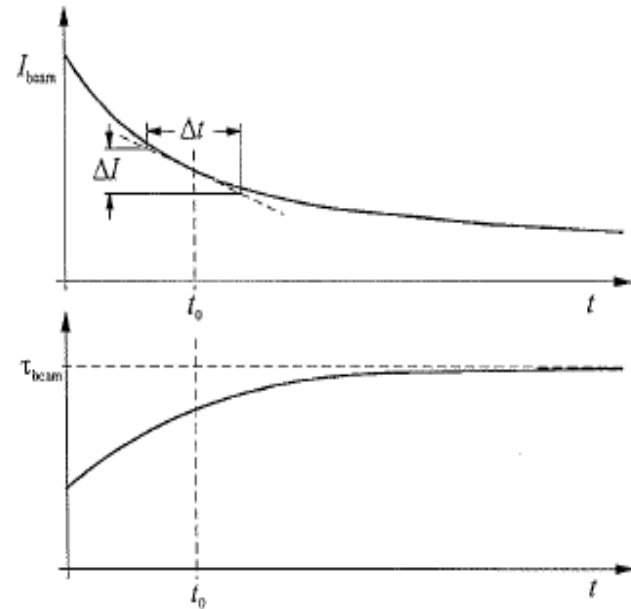
BEAM LIFETIME IN STORAGE RING

Beam Lifetime in Storage Ring

- **Beam circulating in storage ring decays in intensity due to:**
  - Collisions with residual gas molecules.
  - Occasional large energy losses through synchrotron radiation (for electrons).
  - Non-linear resonances

Time dependence of beam current and lifetime

Beam Lifetime in Storage Ring

- Decline in intensity has exponential form with τ_{beam} being the beam lifetime:

$$I(t) = I_0 \exp\left(-\frac{t}{\tau_{beam}}\right).$$

$$dI(t)/dt = -I_0/\tau_{beam}\ exp(-t/\tau_{beam}) = I(t)/\tau_{beam}$$

$$\tau_{beam} = \frac{I(t)}{dI/dt}.$$

- Lifetime is not constant during machine operation.
  - Lifetime relatively short at beginning (when intensity is high) because intense synchrotron radiation (for electron beams) causes high level of gas desorption on vacuum chamber surface increasing vacuum pressure.
  - As beam current decreases, vacuum improves and lifetime increases.

Beam Lifetime in Storage Ring

- Using a beam current monitor, the current is continuously monitored, with measurements repeated at frequent intervals.

- Since beam lifetime can vary from few seconds to many hours (depending on operating conditions), it is useful to vary the time interval between measurements.

  - Short lifetimes – beam current varies rapidly & only few measurements required for reliable lifetime measurement → short time interval.

  - Long lifetimes – individual current measurements must last sufficiently long for statistical fluctuations not to cause large errors in lifetime measurement.

MEASUREMENT OF MOMENTUM & ENERGY OF PARTICLE BEAM

Measurement of Momentum & Energy

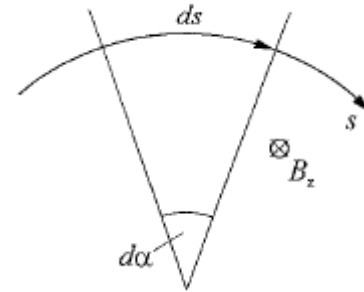- Measure angle of deflection in known B-field.

$$d\alpha(r) = \frac{e}{p} B_z(r)\, ds,$$
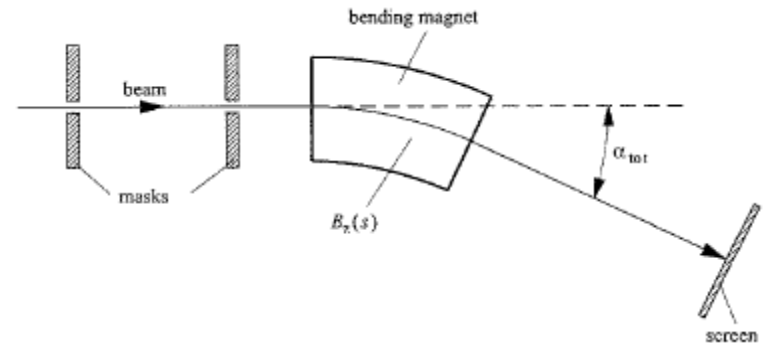
$$p = \frac{e}{\alpha_{tot}} \int_{path} B_z\, ds.$$

$$E = \sqrt{p^2 c^2 + (m_0 c^2)^2},$$

$$E = p\, c = \frac{e\, c}{\alpha_{tot}} \int_{path} B_z\, ds.$$

Deflection of a charged particle in a magnetic field.

Magnetic spectrometer to measure particle momentum & energy

Measurement of Momentum & Energy

- **Measurement Parameters**
  - Incoming beam angle must be precisely defined.
    - Fix beam position using precisely aligned screens.
    - Measure bending angle after deflection using fluorescent screen.
  - $\int B_z$ required, which is obtained by measurement of the B-field as a function of coil current.
    - Watch out for hysteresis of iron magnets!

- **Cyclic Accelerators**
  - Total bending angle of all dipole magnets must be 2π.

$$E = \frac{e\,c}{2\pi} \oint_{dipole} B_z\,ds.$$

  - Connect additional dipole in series with accelerator dipoles and install precise field gauge within it – e.g. NMR probe.
   - Field and energy continuously monitored.
    - $\Delta E/E \sim 2\ 10^{-4}$.
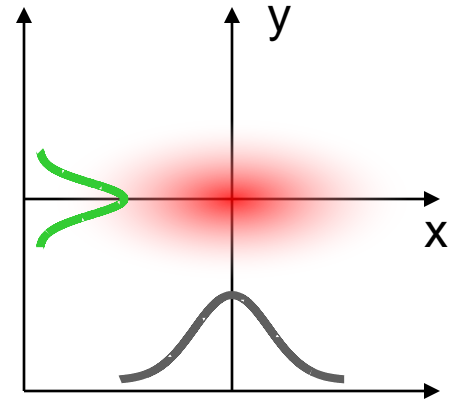
MEASUREMENT OF TRANSVERSE BEAM POSITION

Transverse Space v Phase Space

- Transverse profile is distribution of particle positions in the x/y plane at a fixed s location.

- Transverse phase space are the distributions of particle positions and directions at a fixed s location.

- Transverse emittances equal 'areas' of phase space distributions.

Horizontal Profile

Vertical Profile
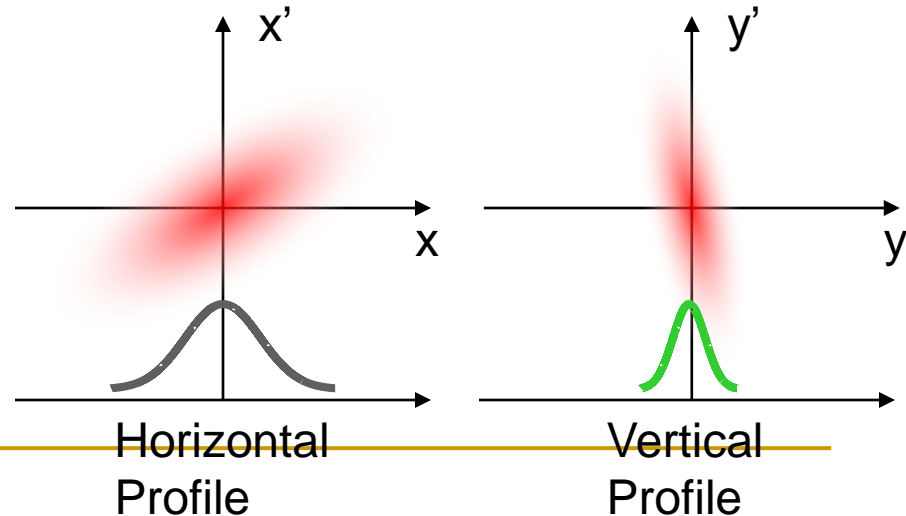
Transverse Beam Position

- Require centre of beam to always lie as close as possible to ideal orbit.
  - Defined by quadrupole axes.
  - Transverse deviation of circulating beam from orbit must be less than 100-150 μm.
- Measure transverse position of beam at as many points around the accelerator and implement corrective measures.
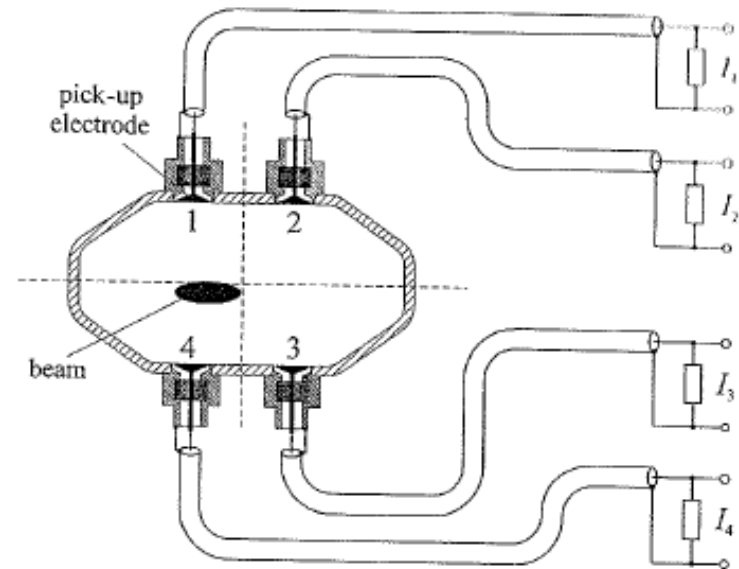
Magnetic Beam Position Monitor

- Measure induced B-field due to beam.
- The difference in signals from the two opposite coils within each pair provides measure of beam position in that plane.
- In order to measure position in both planes simultaneously, install 4 coils arranged at 90° intervals around transformer coil.
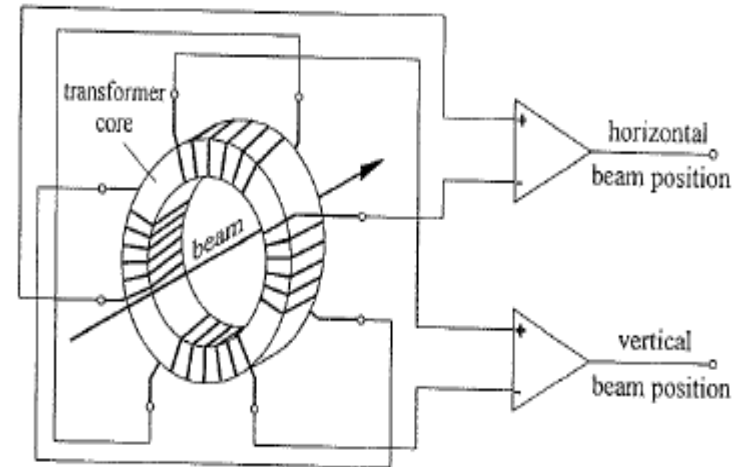
Magnetic beam position monitor

Electrode Beam Position Monitor

- Consists of 4 electrodes (electrical pick-ups) arranged symmetrically around beam axis coupling to E-field.

- Electrodes tilted away from beam axis by 45º in order to reduce amount of synchrotron radiation hitting them directly.

Beam position monitor with four electrodes

$$\Delta x = a \frac{(I_2 + I_3) - (I_1 + I_4)}{\sum\limits_{j=1}^{4} I_j}$$

$$\Delta z = a \frac{(I_1 + I_2) - (I_3 + I_4)}{\sum\limits_{j=1}^{4} I_j},$$

Monitor with Four Electrodes

- If beam lies exactly in middle of monitors, ideally all signals will have same intensity.
- But there are variations in signal sizes –
  - Electrode tolerance
  - Vacuum chamber geometry
  - Cables and electronics which follow for read-out
- If signal has intensity $I_o + \Delta I$, will then have position error of

$$\Delta x_{error} = a \frac{\Delta I}{4\, I_0}.$$

- For $a = 35$ mm and want $\Delta x_{error} < 0.1$ mm then the relative error in an electrode signal may not be larger than

$$\frac{\Delta I}{I_0} = \frac{4\, \Delta x_{error}}{a} < 1.2\%.$$

Monitor with Four Electrodes

- Fundamentally, it is not possible to define with arbitrary precision the point relative to which the beam position is being measured.
  - Monitor connected to vacuum chamber, which is generally fixed to magnets.
    - Magnets positioned with tolerance of ± 0.2 mm.
    - Alignment errors of quadrupoles also create orbit distortions.
- Even if beam position adjusted so that it has no offset in any of the monitors, this will not necessarily correspond to real ideal orbit.

Principle of Wire Scanner

Radiation detector

Intensity
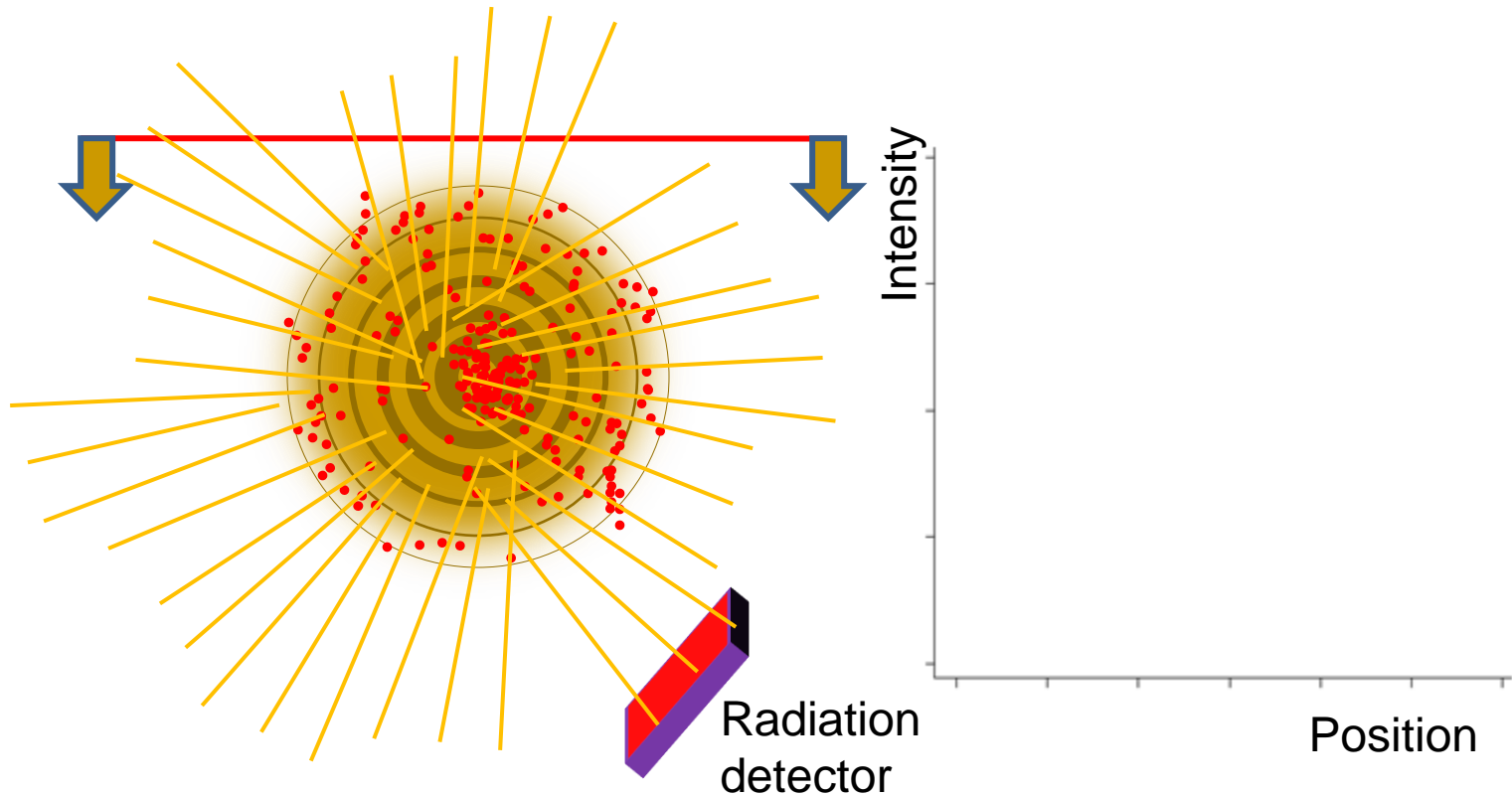
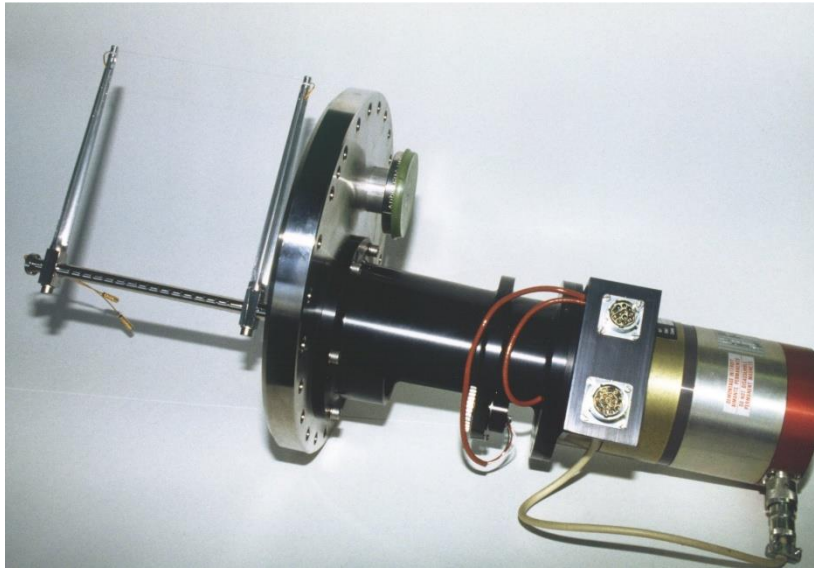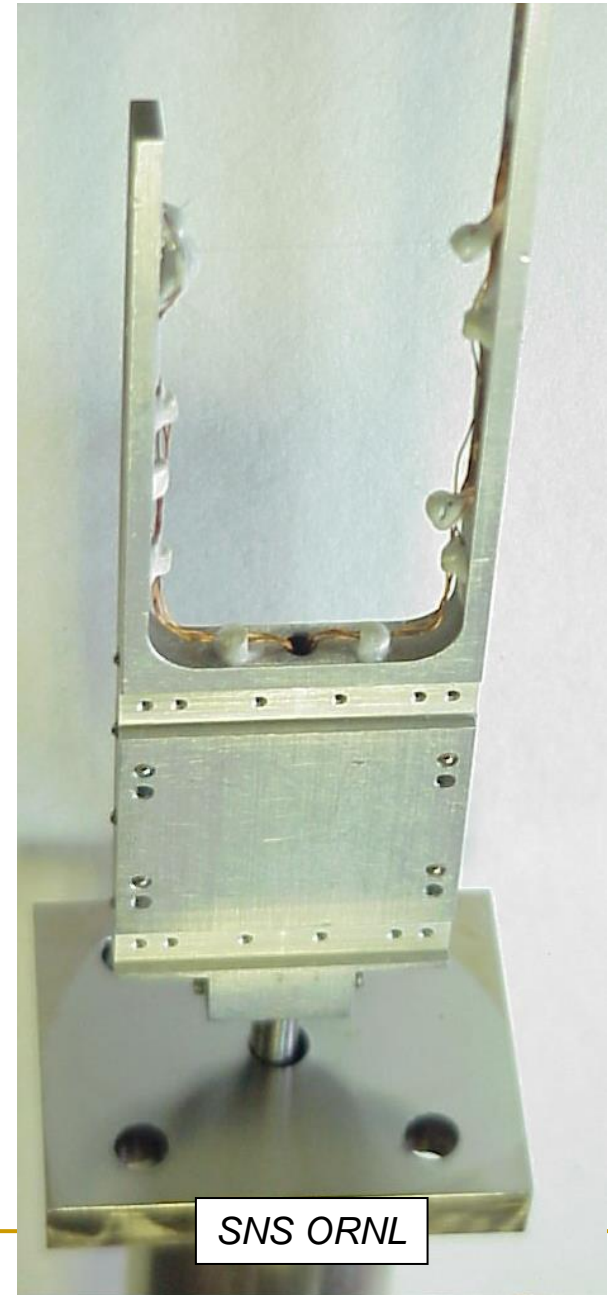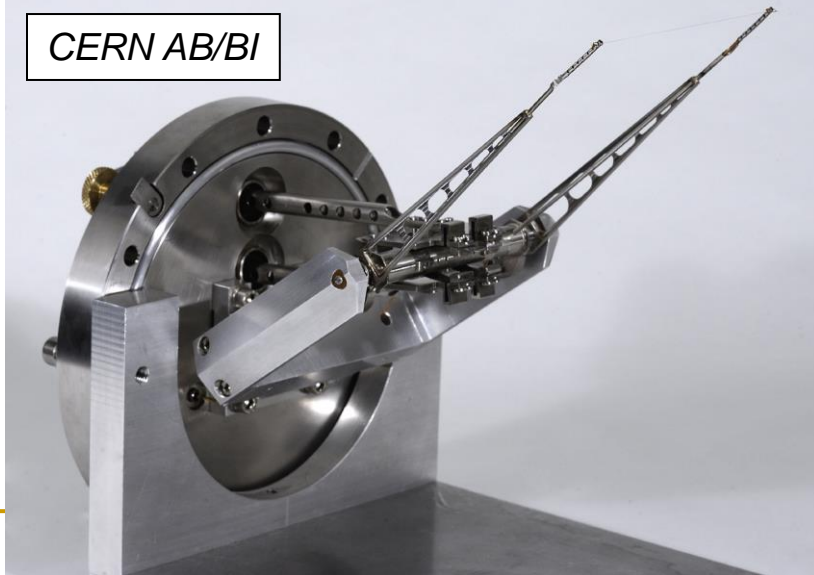Position

- 1D-Profile is measured either as intensity of radiation (Bremsstrahlung) or as secondary emitted electron current over position of wire.
- Resolution down to wire diameter (5-6 µm).
- Instead of movement, many wires can be used in a 'harp'.

Wire Scanner Designs

CERN AB/BI

SNS ORNL

Limitations of Wire Scanners

- The smallest measurable beam size is limited by the finite wire diameter of a few microns.

- Higher Order Modes may couple to conductive wires and can destroy them.

- High beam intensities combined with small beam sizes will destroy the wire due to the high heat load, thus scan as fast as possible.
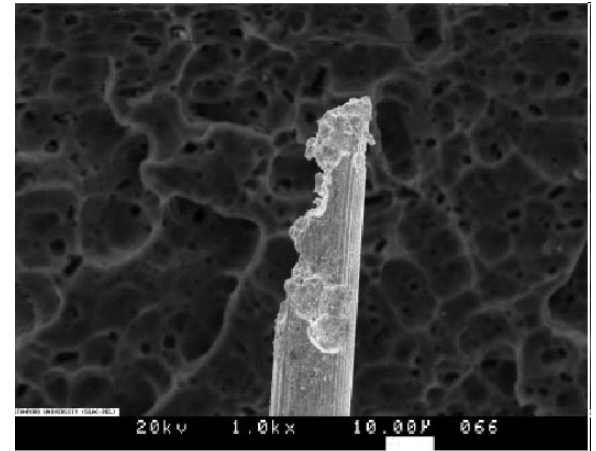
- Emittance blow up.

20kv   1.0kx   10.00μ   066

FIGURE 3. Failed 15 μm diameter tungsten wire showing the rough surface resulting from many discharges.
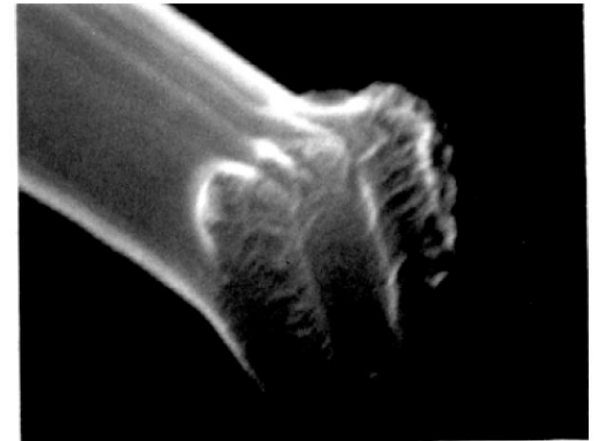
Figure 2: Broken 4μm carbon wire at SLC. It is possible to observe how successive pulses have eroded the wire.

MEASUREMENT OF BETATRON FREQUENCY & TUNE

Betatron Frequency & Tune

- Once set of beam optics has been installed, the working point – tune Q – must be measured to check that it lies far enough away from strong optical resonances.
  - Tune Q = q + a
    - q = integer
    - $0 \leq a \leq 1$
- Measuring tune also allows detection of changes in focusing.
  - B-field imperfection
  - Space charge effect

- Use the tune to monitor stability of the beam focusing during machine operation.
- Amounts to measuring frequency of transverse beam oscillations.

Betatron Frequency and Tune

- **The solution of the oscillation equation**

$$\bar{x}(t) + \frac{2}{\tau}\dot{x}(t) + \Omega^2 x(t) = 0$$

$$\Omega = \frac{2\pi}{T_u}\, a = \omega_u\, a \qquad 0 \le a \le 0.5.$$

(assuming very weak damping from synchrotron radiation)

$$x(t) = \exp\left(-\frac{t}{\tau}\right)\left\{ x_0 \cos\left(2\pi a \frac{t}{T_u}\right) + \left[\frac{\beta_0\, \dot{x}_0}{c} + a_0\, x_0\right] \sin\left(2\pi a \frac{t}{T_u}\right)\right\}$$

- **Measurement**
  - **Fractional tune *a***
    - If beam undergoes betatron oscillations, measure Ω with fast position monitor since revolution frequency is fixed.
  - **Integer tune *q***
    - Difference between reference orbit and standing betatron oscillation about reference orbit caused by altering steering coil strength.
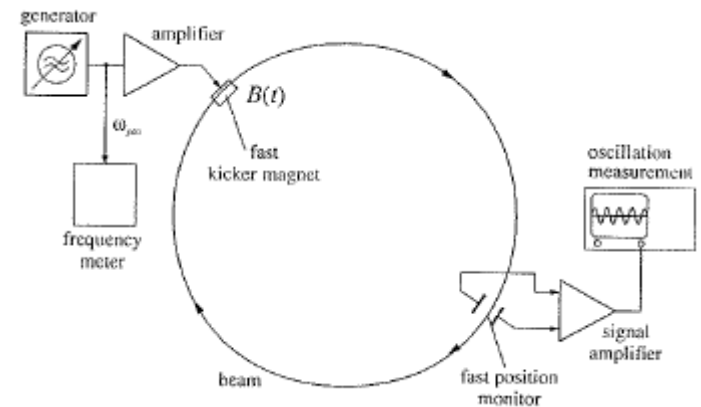
Betatron Frequency & Tune

- Excite beam into coherent transverse oscillations.
  - Fast bending magnet (10^{-4} Tm) which produces periodic field

$$B(t) = B_0 \sin \omega_{gen} t$$

- Equation of forced motion

$$\ddot{x}(t) + \frac{2}{\tau}\dot{x}(t) + \Omega^2 x(t) = \kappa_{\text{eff}} \sin \omega_{\text{gen}} t.$$

- As damping is very weak, resonance occurs if $\omega_{gen} = \Omega$

A fast kicker magnet stimulates beam at frequency ω_{gen}, which is varied until resonance is found.

Amplitude of induced betatron oscillation measured using fast position monitor

MEASUREMENT OF BEAM OPTICAL PARAMETERS

Beam Optical Parameters - Dispersion

- Determined from position measurements at several points around the orbit.

- Vary momentum *p* of particles by *Δp* while keeping magnet strengths constant.

- Beam position shifts distance

  Δx(s) = D(s) Δp/p

  onto dispersive trajectory.

- Dispersion is

$$D(s_i) = \frac{\Delta x(s_i)}{\Delta p/p} \qquad \text{with} \qquad \Delta x(s_i) = u(s_i) - u^0(s_i).$$

Beam Optical Parameters - Dispersion

- Change frequency ν_{RF} of accelerating voltage by $\Delta\nu$.

- Since phase focusing means the harmonic number remains constant, circumference of particle trajectory changes and hence no longer matches orbit.

- Stable particle path shifts onto dispersive trajectory → corresponding change of momentum Δp

$$\frac{\Delta p}{p} = -\frac{1}{\alpha}\frac{\Delta \nu_{RF}}{\nu_{RF}}.$$

Beam Optical Parameters – β Function

- If strength of quadrupole changes by amount *Δk*, tune of cyclic machine shifts by

$$\Delta Q = \frac{1}{4\pi} \int_{s_0}^{s_0+l} \Delta k \; \beta(s) \; ds.$$

  - The size of shift is proportional to value of β function in quadrupole.

- Assuming *k* is constant along quadrupole axis and variation of β function is small in quadrupole

$$\Delta Q = \frac{\Delta k}{4\pi} \int_{s_0}^{s_0+l} \beta(s) \; ds \approx \frac{\Delta k}{4\pi} \langle \beta \rangle \, l.$$

- Start from particular set-up of beam optics and impose well-defined change in quadrupole strength *Δk.*

- By measuring tune *Q* before & after change the average β function in quadrupole is

$$\langle \beta \rangle = \frac{4\pi}{l} \frac{\Delta Q}{\Delta k}.$$

Beam Optical Parameters - Chromaticity

- Chromaticity measurement essential for correct tuning of sextupoles.

- Vary the momentum of circulating particles and measure tune *Q* before and after change.

- Momentum varied by changing RF frequency.

- Relationship between change in momentum and tune is far from linear.

  - Measure function *ΔQ(Δp/p)* whose value in the region around nominal value yields chromaticity.

Acknowledgements and References

- Guenther Rehm, *Diagnostics*, Cockcroft Institute Academic Training Programme 2008-2009

- Klaus Wille, *The Physics of Particle Accelerators*, Oxford University Press, 2005

- Edmund Wilson, *An Introduction to Particle Accelerators*, Oxford University Press, 2006

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