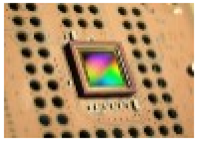
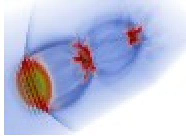
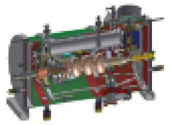




Tutorial: Beam Diagnostics

ARD ST3 Annual Meeting October 2019

GSI Darmstadt, *18th of October 2019*

Peter Forck, GSI

October 18th, 2019

ARD ST3 Annual Meeting

GSI, Darmstadt

Demands on Beam Diagnostics

Standard instrumentation is discussed only!

Some hints to recent developments & comparison electron ↔ proton instrumentation.

Laser wake-field accelerators are not covered.

General usage of beam instrumentation:

- Monitoring of beam parameters for operation, beam alignment & accelerator development
- Instruments for automatic, active beam control e.g. orbit feedback

Non-invasive (= 'non-intercepting' or 'non-destructive') methods are preferred:

- The beam is not influenced ⇒ the **same** beam can be measured at several locations
- The instrument is not destroyed due to high beam power by proton beams

Non-scanning, 'single shot' methods are preferred: Beam fluctuations at LINACs are visible

Observation during entire cycle are preferred: Consistent beam evolution visible at synchr.

General tendencies:

- **Electron accelerator:** High spatial &temporal resolution due to small beams, short pulses
- **Proton & ion accelerator:** Non-invasive methods due to high beam power, radiation hardness
  long pulses $t_{pulse} \gg 1\ \mu s$ (except for laser-wakefield acceleration)
- **Both:** High accuracy required to critical beam setting

Outline of the Tutorial on Beam Diagnostics

Topics of this tutorial:

- **Beam current and bunch charge by transformers**
  1. Broadband, 'fast' current transformer FCT
  2. dc current transformer DCCT e.g. for synchrotron
  3. Integrating current transformer ICT for short pulse at LINAC-FELs
- **Beam center-of-mass by Beam Position Monitors BPM**
- **Transverse profile measurement techniques**
- **Longitudinal profile = bunch shape measurement**

Magnetic field of the beam and the ideal Transformer

➢ Beam current of N_{part} charges with velocity β

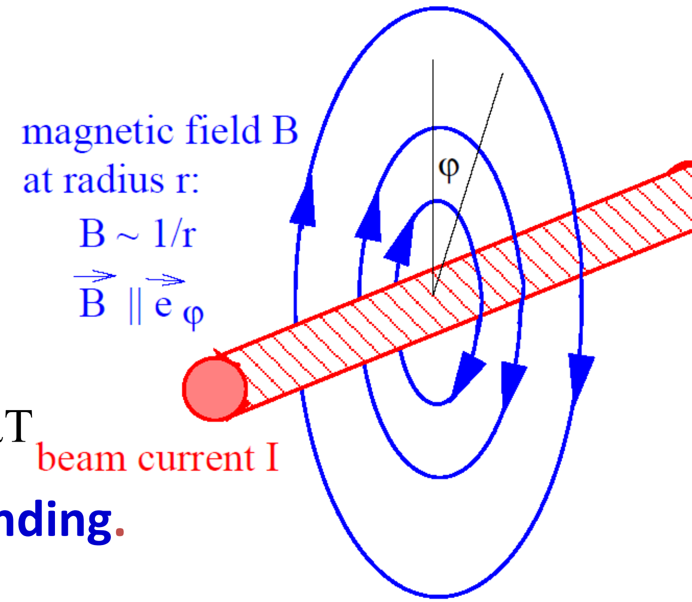
$$I_{beam} = qe \cdot \frac{N_{part}}{t} = qe \cdot \beta c \cdot \frac{N_{part}}{l}$$

➢ cylindrical symmetry

→ only azimuthal component

$$\vec{B} = \mu_0 \frac{I_{beam}}{2\pi r} \cdot \vec{e_\varphi}$$

Example: I =1µA, r =10cm ⇒ B_{beam}= 2pT, earth B_{earth}= 50µT



Idea: Beam as primary winding and sense by sec. winding.

⇒ Loaded current transformer

$$I_1/I_2 = N_2/N_1 \Rightarrow I_{sec} = 1/N \cdot I_{beam}$$

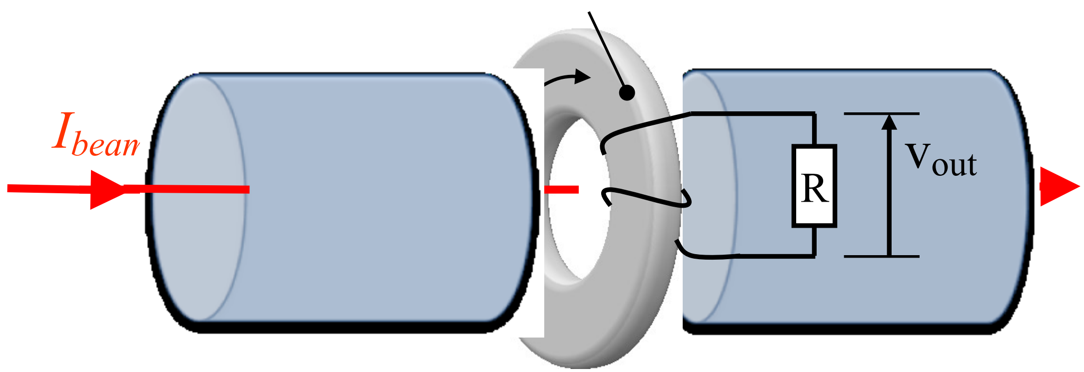
➢ Inductance of a torus of μ_r

$$L = \frac{\mu_0 \mu_r}{2\pi} \cdot l N^2 \cdot \ln \frac{r_{out}}{r_{in}}$$

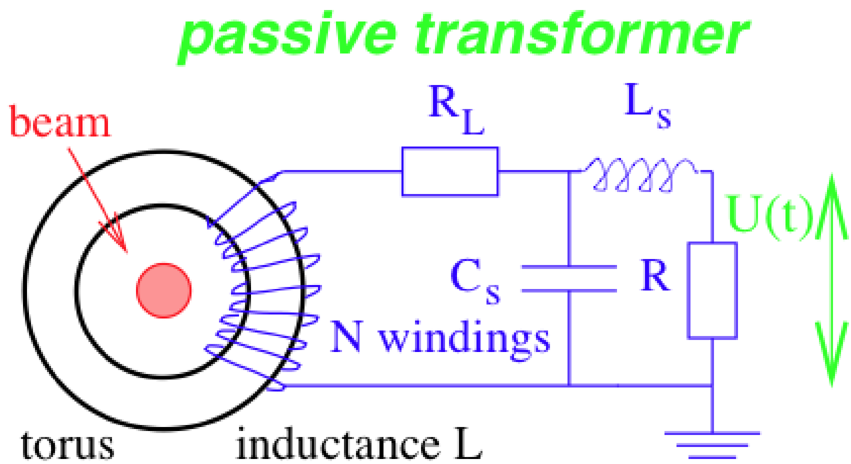
➢ Goal of torus: Large inductance ***L*** ***and*** guiding of field lines.

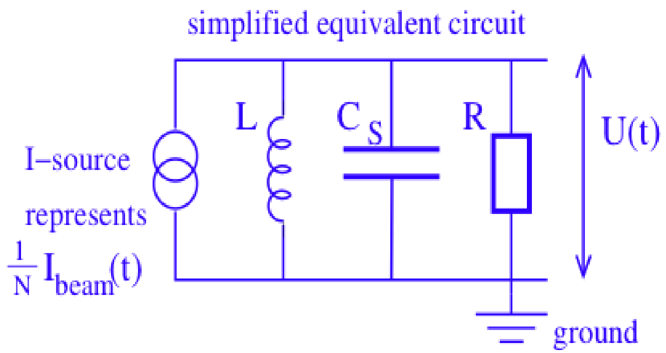
Definition: $U = L \cdot dI/dt$

Torus to guide the magnetic field



Simplified electrical circuit of a passively loaded transfor





Equivalent circuit for analysis of sensitivity and bandwidth (without loss resistivity R_L)

courtesy Company Bergoz

A voltages is measured:

$U = R \cdot I_{sec} = R/N \cdot I_{beam} \equiv S \cdot I_{beam}$ with ***S* sensitivity [V/A],**

equivalent to transfer function or transfer impedance ***Z***

Response of a Transformer: Rise and Droop Time

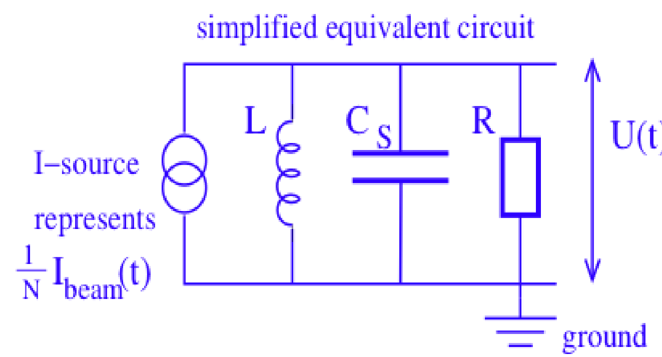
Time domain description:

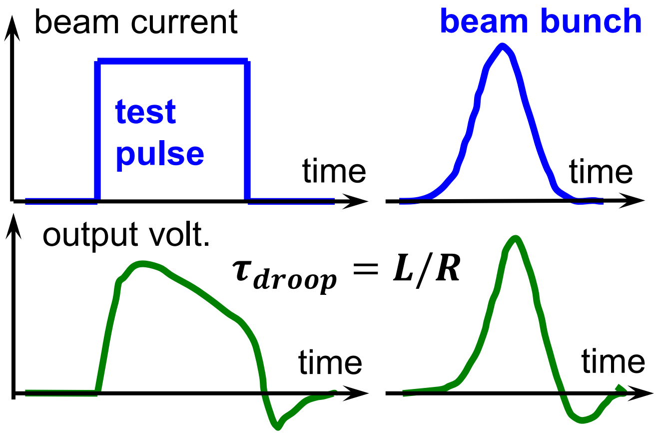
Droop time: $\tau_{droop} = 1/(2\pi f_{low}) = L/R$

Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = 1/RC_S$ (ideal without cable

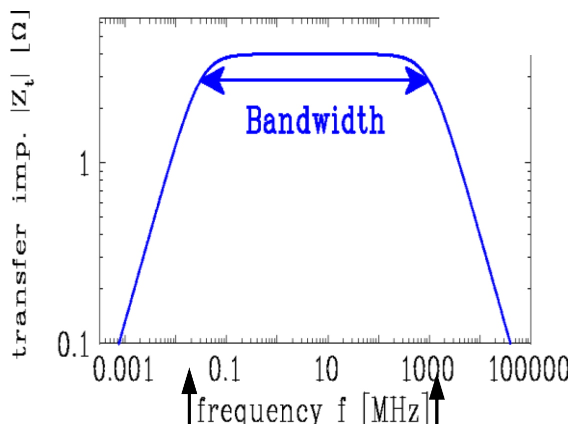
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_s}$ (with cables)

R_L: loss resistivity, R: for measuring.





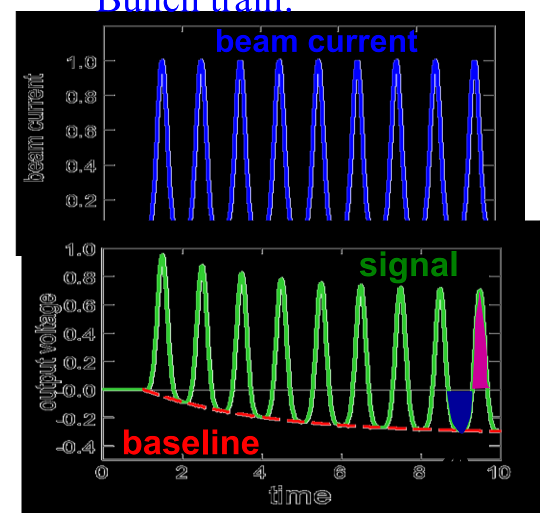
$$\tau_{rise} = \sqrt{L \cdot C_S}$$



$2\pi f_{low}$ $= R/L$

$2\pi f_{high}$ $= 1/RC_S$

Bunch train:



Baseline: $U_{base} \propto 1 - \exp(-t/\tau_{droop})$
positive & **negative** areas are equal

⇒ **No transformation of dc-signals**

Example for Fast Current Transformer

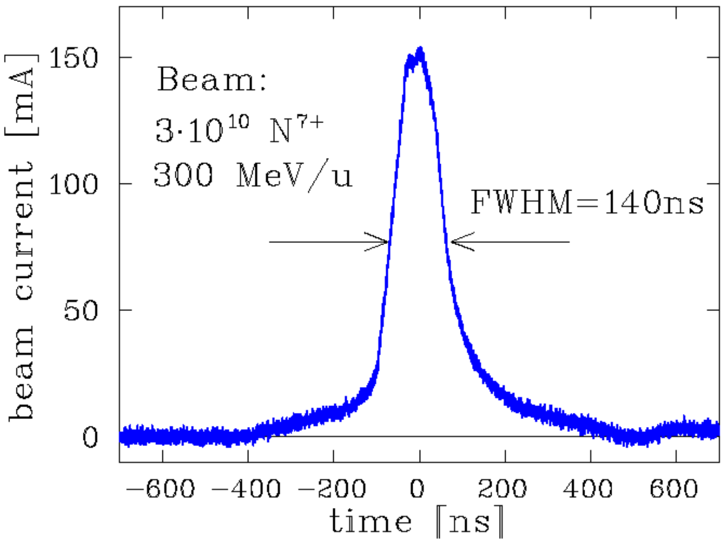
For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < f < 1 GHz

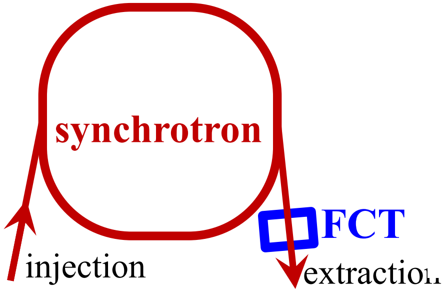
⇔ 10 ns < t_{bunch} < 1 µs is well suited

Example GSI type:

Inner / outer radius	**70 / 90 mm**
Permeability	$\mu_r \approx 10^5$ for f < 100kHz $\mu_r \propto 1/f$ above
Windings	10
Sensitivity	4 V/A for R = 50 Ω
Droop time $\tau_{droop} = L/R$	0.2 ms
Rise time $\tau_{rise} = \sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz ... 500 MHz

Fast extraction from GSI synchrotron:





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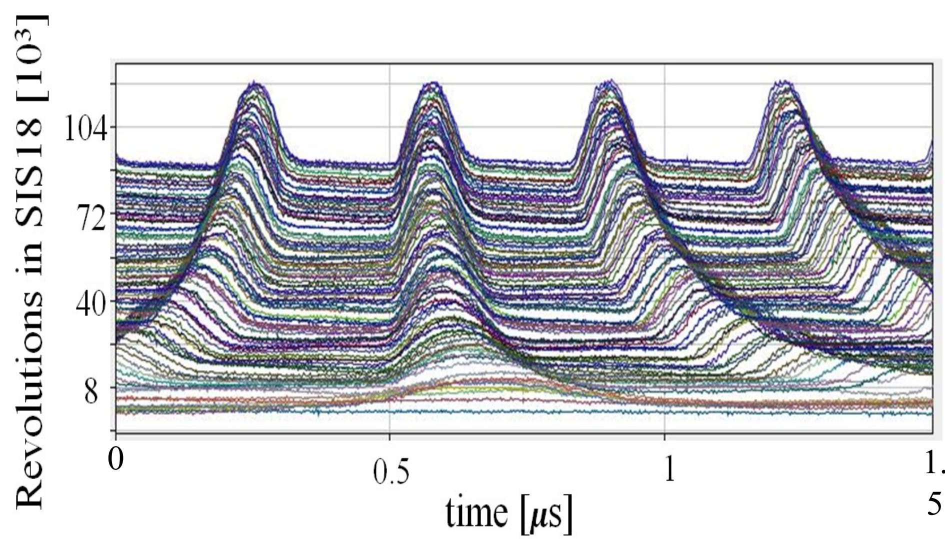
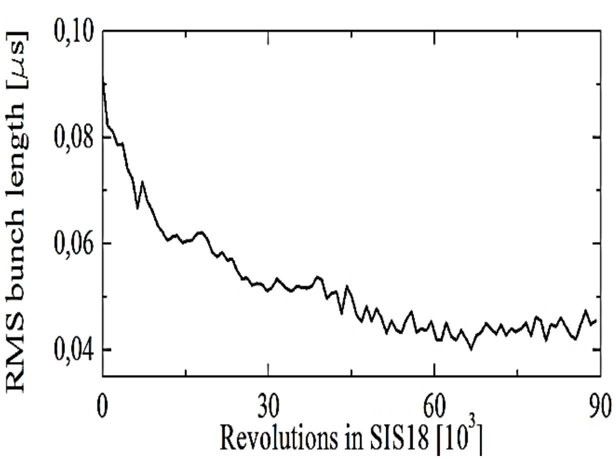
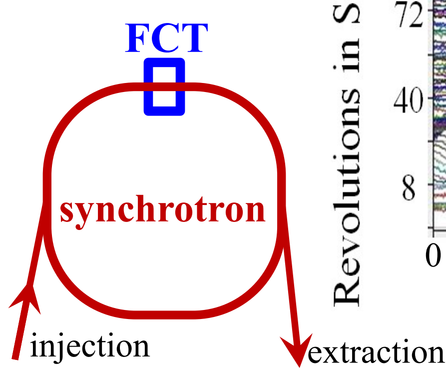
Bandwidth	2 kHz ... 500 MHz

Example: U^{73+} from 11 MeV/u (β = 15 %) to 350 MeV/u

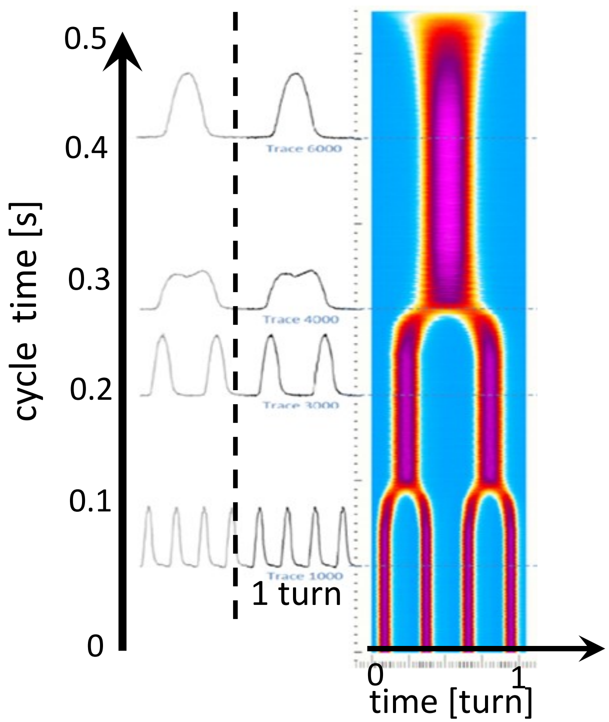






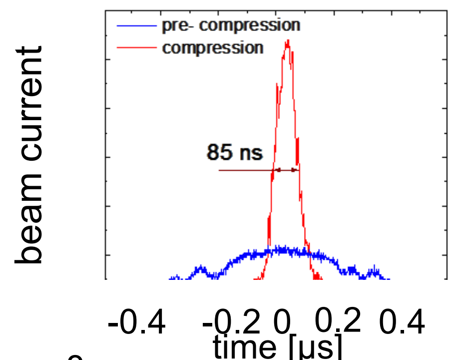
- Acceleration and bunch 'gymnastics' are performed **inside** synchrotrons
- Bunch shaping for fast, single turn extraction

Example: Bunch merging at upper flattop using 2 cavities at GSI synchrotron
Beam: 10^9 U^{73+} at 600 MeV/u, FCT

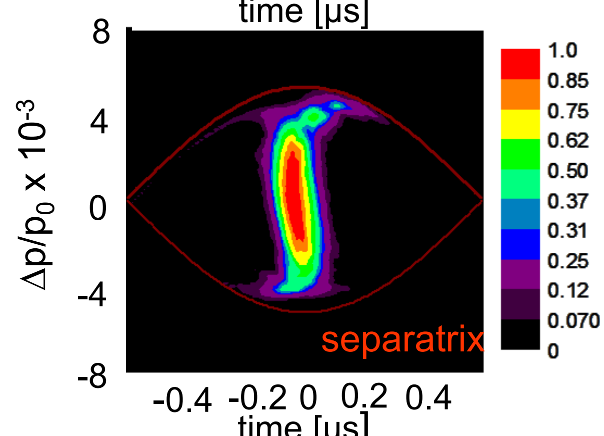


Courtesy H. Klingbeil, U. Hartel, et al. GSI
Further application: Input for cavity regulation loop

Example: 'Bunch compression' prior to extraction
Beam: U^{73+} at 300 MeV/u at GSI synchrotron



After acceleration before & after bunch compression



ıal topic:
ographic
ınstruction of
ıitudinal
ıe space
ıding space charge

ıtesy O. Chroniy, GSI

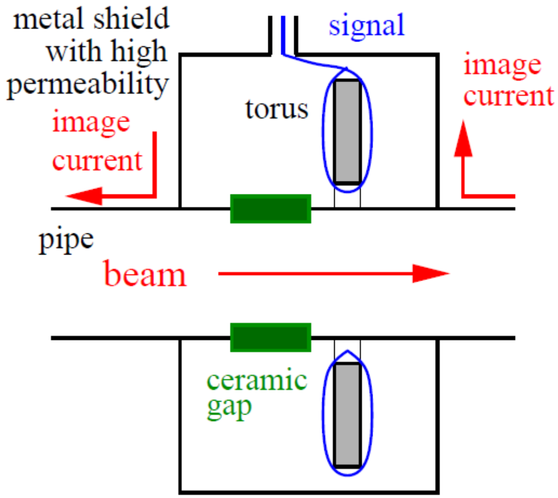
Remark: At synchrotron light sources, bunch shape by streak camera recording synchrotron light.
Example shown in talk by J.G. Hwang for BESSY-VSR

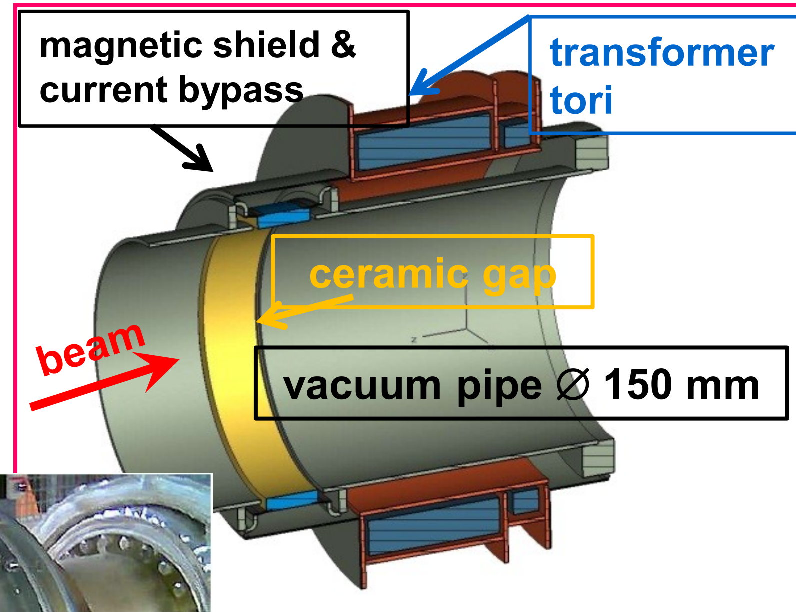
Shielding of a Transformer

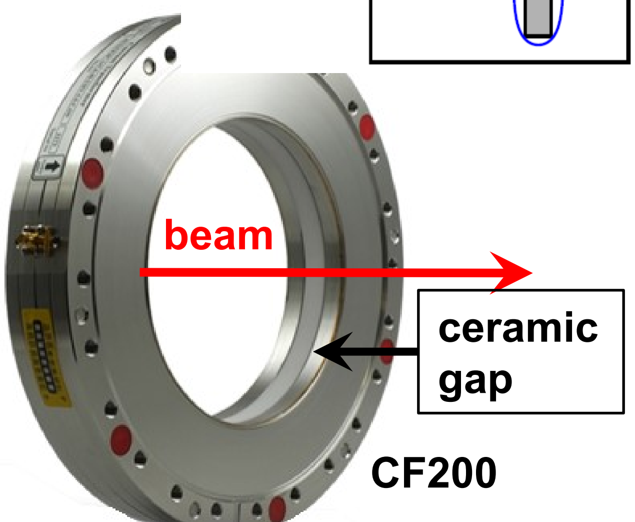
Task of the shield:

- The image current of the walls have to be bypassed by a gap and a metal housing.
- This housing uses μ-metal and acts as a shield of external B-field
  (remember: I_{beam} = 1 μA, r = 10 cm $\Rightarrow$ B_{beam} = 2pT, earth field B_{earth} = 50 μT)

.







courtesy Company Bergoz

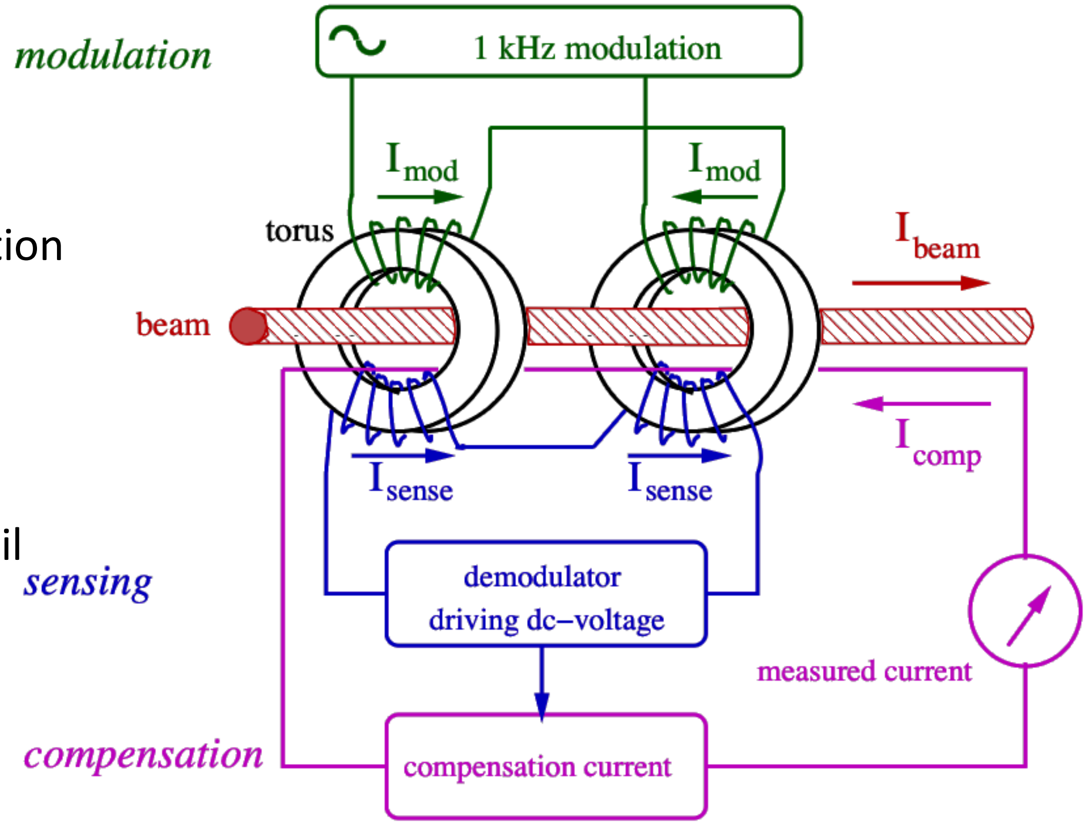
The dc Transformer DCCT

How to measure the DC current? The current transformer discussed sees only B-flux ***changes.***
The DC Current Transformer (DCCT) → look at the magnetic saturation of two tori.

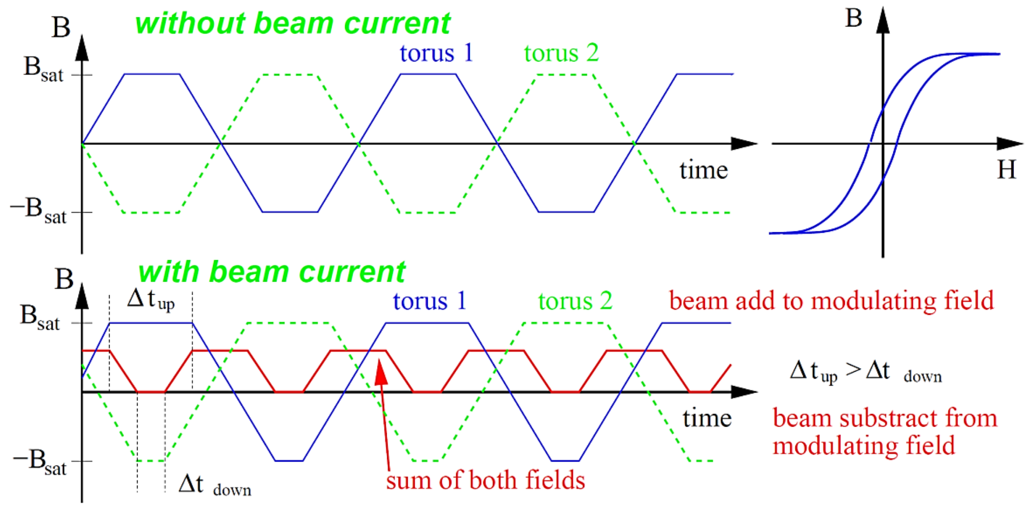
Depictive statement:

A single transformer needs varying beam → DCCT: The trick is to ‘switch two transformers’!

- **Modulation** of the primary windings forces both torii into saturation twice per cycle
- **Sense windings** measure the modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
- **Compensation current** adjustable until I_{sense} is zero once again



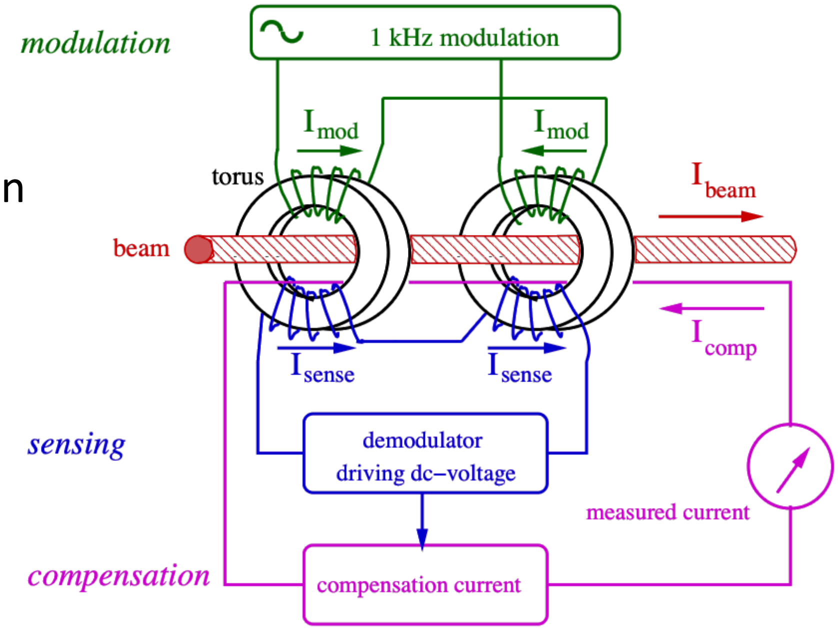
The dc Transformer



Working principle:

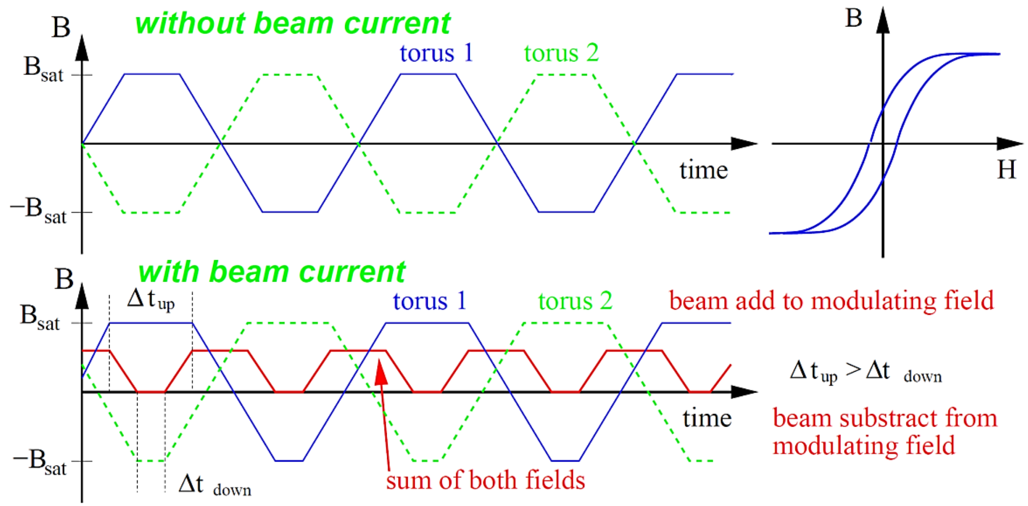
- **Modulation without beam:**
  Typ. 9 kHz modulation to ***B***-saturation
  ⇒ **no** net flux
- **Modulation with beam:**
  Saturation reached at **different times**
  ⇒ net flux
- **Net flux:** Double frequency than modulation
- **Feedback:** Compensating current for large sensitivity
- **Two magnetic cores:** Must be very similar.

Resolution: $I_{min} \approx 1\ \mu A$ at 100 Hz
Reason: Noisy orientation change of magnetic domain called Barkhausen noise



Remark: Same principle used for power suppliers

The dc Transformer



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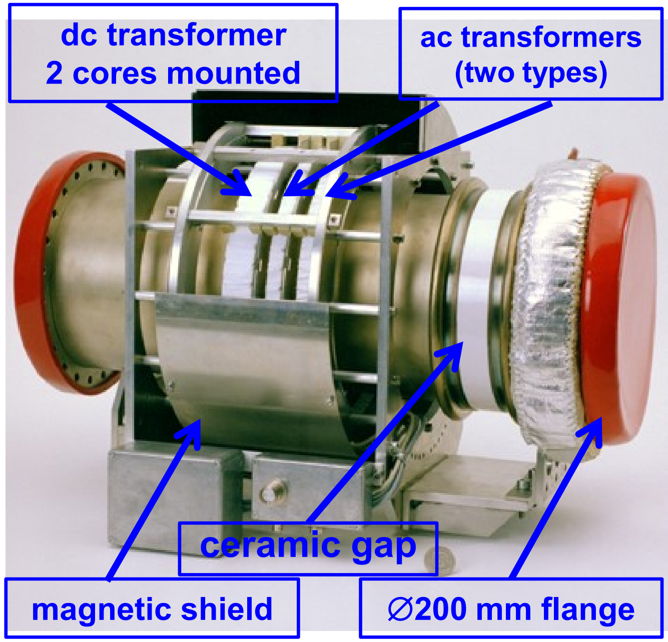
- **Two magnetic cores:** Must be very similar.

Torus radii	r_i = 135 mm r_o=145 mm
Torus thickness	d = 10 mm
Torus permeability	$\mu_r = 10^5$
Saturation inductance	B_{sat} = 0.6 T
Number of windings	16 for mod.& sens. ,12 for feedback
Resolution	I^{min}_{beam} = 2 μA
Bandwidth	Δf = dc .... 20 kHz, τ_{rise} = 10 μs
Temperature drift	1.5 μA/^{o}C

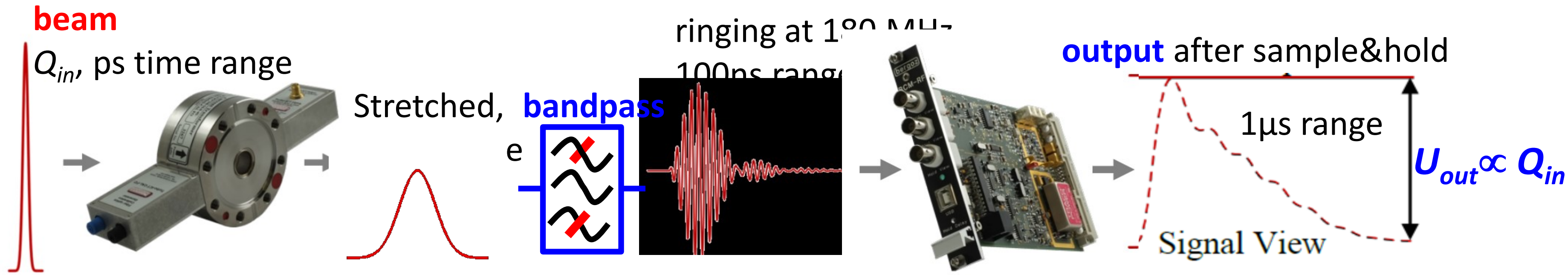
Example: The DCCT at GSI synchrotron



Integrating Current Transformer ICT for short Pulses

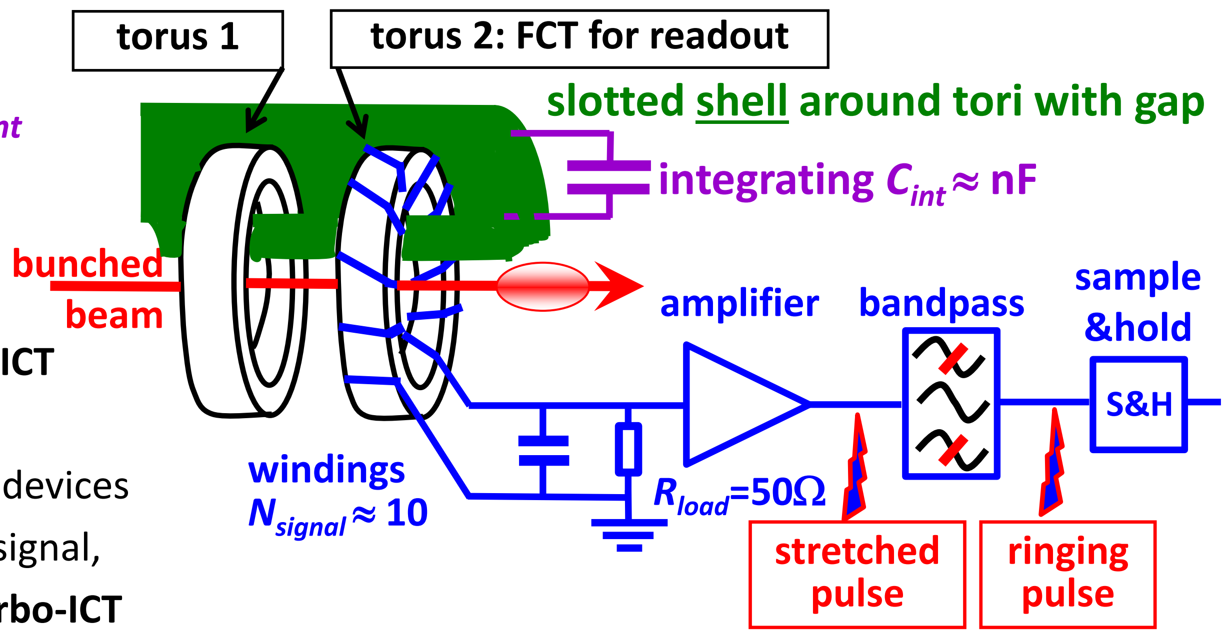
Short, single pulse at FELs: Too short to be recorded by FCT due to rise time $\tau_{pulse} \ll \tau_{rise} \approx 1$ns

$\Rightarrow$ depictive statement: 'analog stretching of signal information' yields charges per bunch



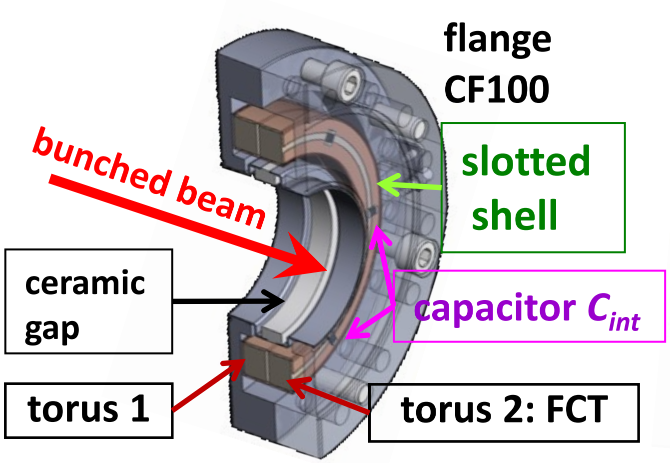
ICT operation principle for ps pulses:

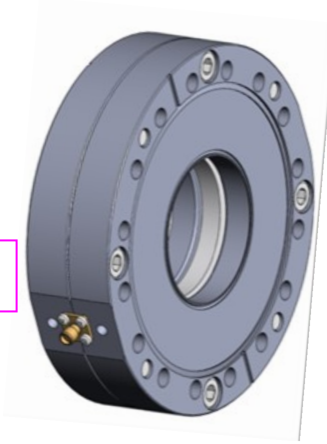
- Image current on **shell with gap**
- Storage of induced charges at C_{int}
- 'Slow' recombination of charges
- Sensing this current with **FCT**
  $\Rightarrow$ **stretched pulse,** length
  independent on input $\rightarrow$ called **ICT**
- Torus1 for correct inductance:
  damped resonant circuit of entire devices
- Broad bandpass filter $\Rightarrow$ ringing signal,
  to enlarge sensitivity $\rightarrow$called **Turbo-ICT**



Typical parameter of a Turbo-ICT as used at FELs and Laser Plasma Accelerators:

Tori thickness	l = 5 mm respectively
Full scale range	500 fC ...1 nC
Resolution	**10 fC_{rms} ⇔ 10^5 e^- / bunch**
Max. pulse repetition	500 ns for single pulses
Dynamic range	80 dB by logarithmic amp.





courtesy Company Bergoz

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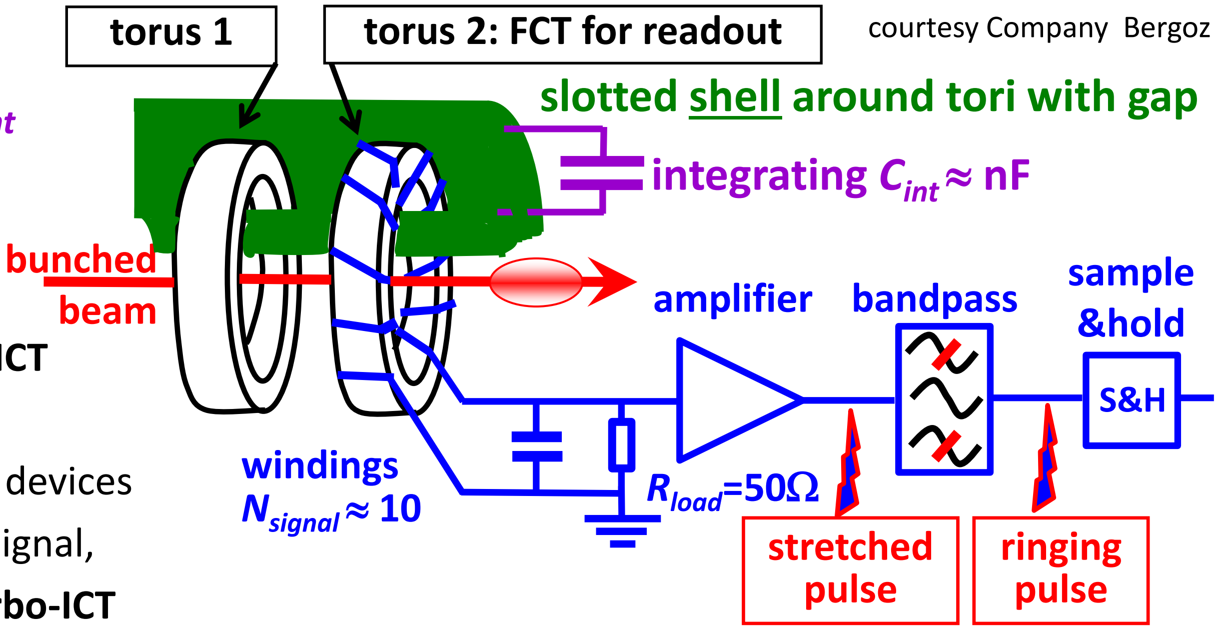


Intermediate Summary for Current Measurement

Transformer: Measurement of the beam's magnetic field

- Magnetic field is guided by a high µ toroid
- **Types of transformers:**

  FCT for bunches: Broadband obseravtion, $\boldsymbol{I}_{min} \approx 30$ µA, BW $\approx$ 10 kHz ... 500 MHz

  DCCT for dc beams: Two toroids + modulation, $\boldsymbol{I}_{min} \approx 1$ µA, BW $\approx$ dc ... 20 kHz

  ICT short pulses: Image charge storage $\rightarrow$ analog pulse stretching, $\boldsymbol{Q}_{min} \approx 10$ fC, no timing
- Non-destructive, used for all beams

Outline:

- Button type for general purpose
- Linear–cut type for proton synchrotrons
- Cavity BPM for short pulses

A Beam Position Monitor is an non-destructive device for bunched beams

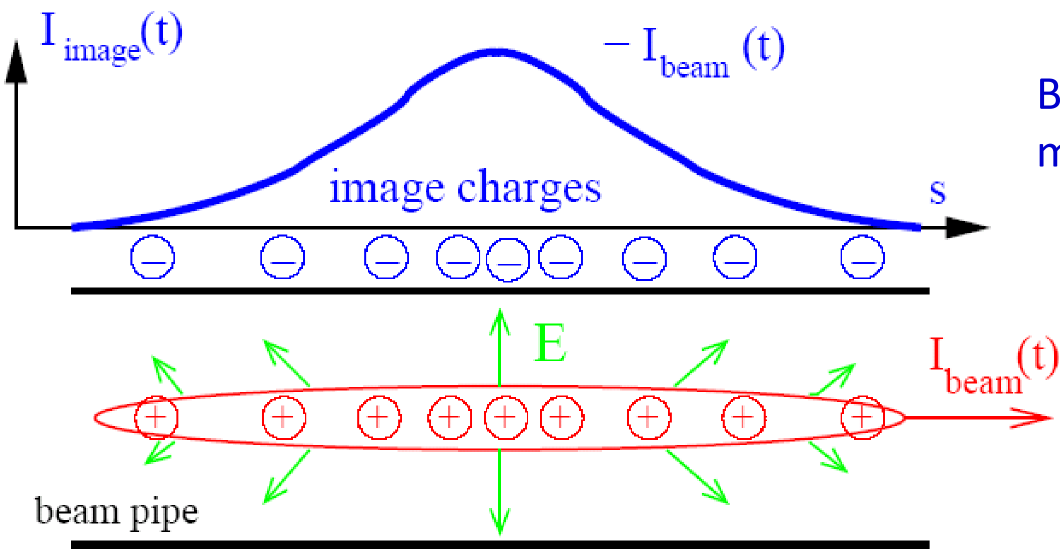
It delivers information about the transverse center of the beam:

- ***Trajectory:*** Position of an individual bunch within a transfer line or synchrotron
- ***Closed orbit***: Central orbit averaged over a period much longer than a betatron oscillation
- ***Single bunch position:*** Determination of parameters like tune, chromaticity, β-function

Remarks: - BPMs have a low cut-off frequency ⇔ dc-beam behavior can't be monitored
- The abbreviation **BPM** and pick-up **PU** are synonyms

Pick-Ups for bunched Beams

The image current at the beam pipe is monitored on a high frequency basis i.e. the ac-part given by the bunched beam.



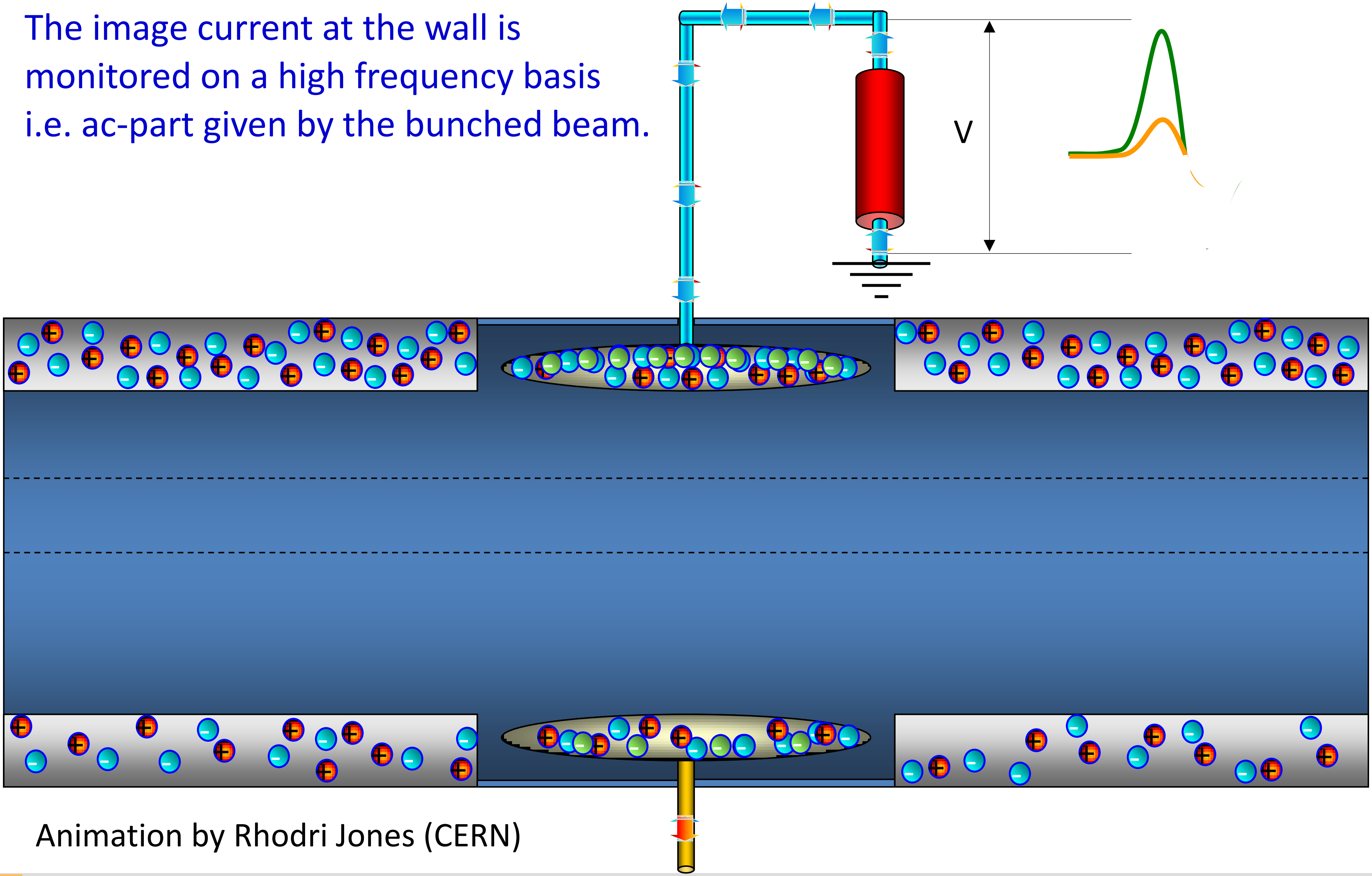
Beam Position Monitor **BPM** is the most frequently used instrument!

For relativistic velocities,
the transversal electric field is:

$$E_{\perp,lab}(t_{lab}) = \gamma\, E_{\perp,rest}(t_{rest})$$

Principle of Signal Generation of a BPMs: off-center Beam

The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.



Animation by Rhodri Jones (CERN)

Principle of Position Determination by a BPM

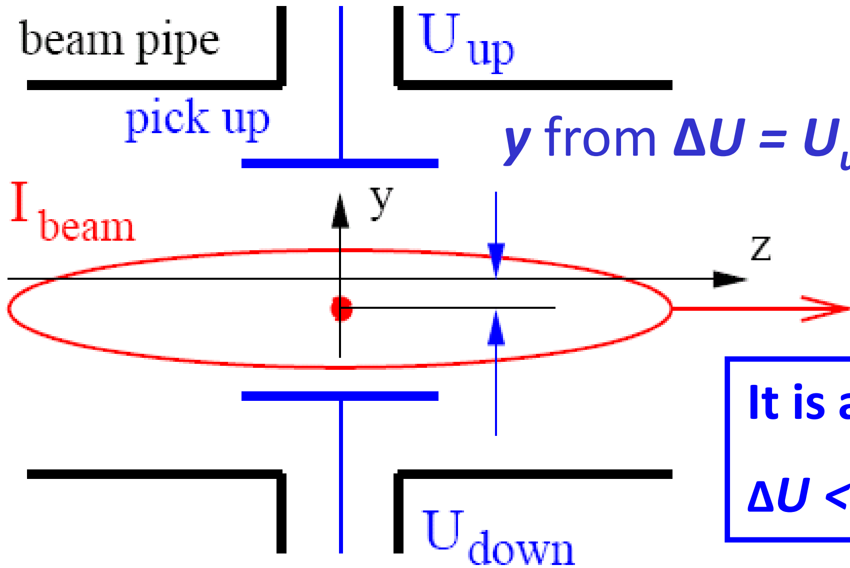
The difference voltage between plates gives the beam's center-of-mass
$\rightarrow$**most frequent application**

'Proximity' effect leads to different voltages at the plates:

$$y = \frac{1}{S_y(\omega)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} + \delta_y(\omega)$$

$$\equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y} + \delta_y$$

$$x = \frac{1}{S_x(\omega)} \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} + \delta_x(\omega)$$



y from **$\Delta U = U_{up} - U_{down}$**

It is at least:

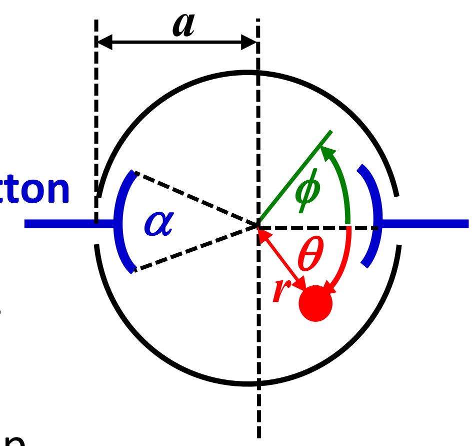
$\Delta U \ll \Sigma U / 10$

S(ω,x) is called **position sensitivity,** sometimes the inverse is used ***k(ω,x)=1/S(ω,x)***
S is a geometry dependent, non-linear function, which have to be optimized
Units: ***S***=[%/mm] and sometimes ***S***=[dB/mm] or ***k***=[mm].

Typical desired position resolution: $\Delta x \approx 0.3 \ldots 0.1 \cdot \sigma_x$ of beam width

2-dim Model for a Button BPM

Ideal 2-dim model: Non-linear behavior and hor-vert coupling:



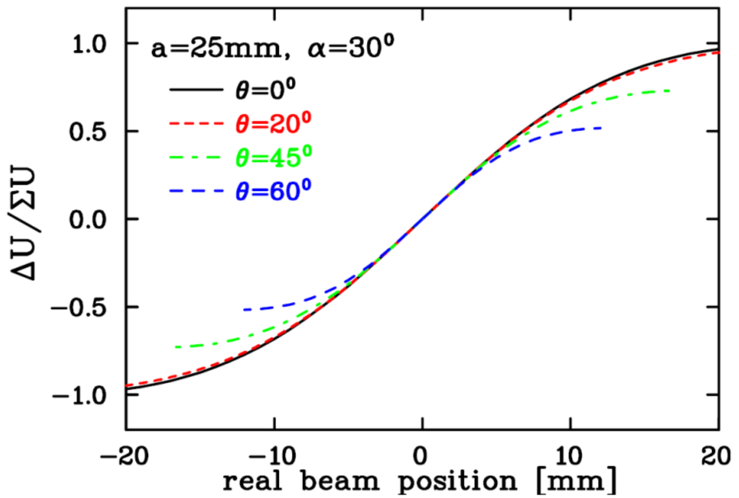
Sensitivity ***S*** is converts signal to position $x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U}$

with S [%/mm] or [dB/mm]

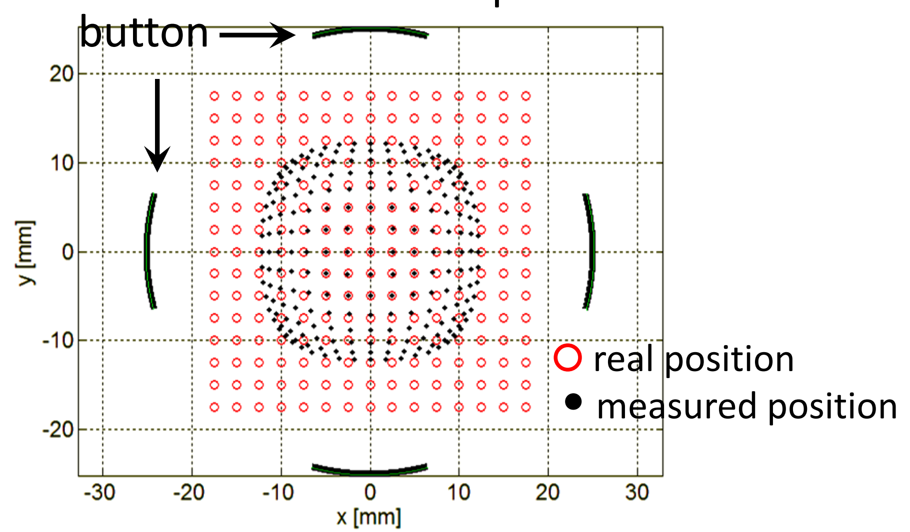
i.e. ***S*** is the derivative of the curve $S_x = \frac{\partial(\frac{\Delta U}{\Sigma U})}{\partial x}$, here $S_x = S_x(x, y)$ i.e. non-linear.

For this example: central part S=7.4%/mm ⇔ $k=1/S$=14mm

Horizontal plane



Position Map



Button BPM Realization

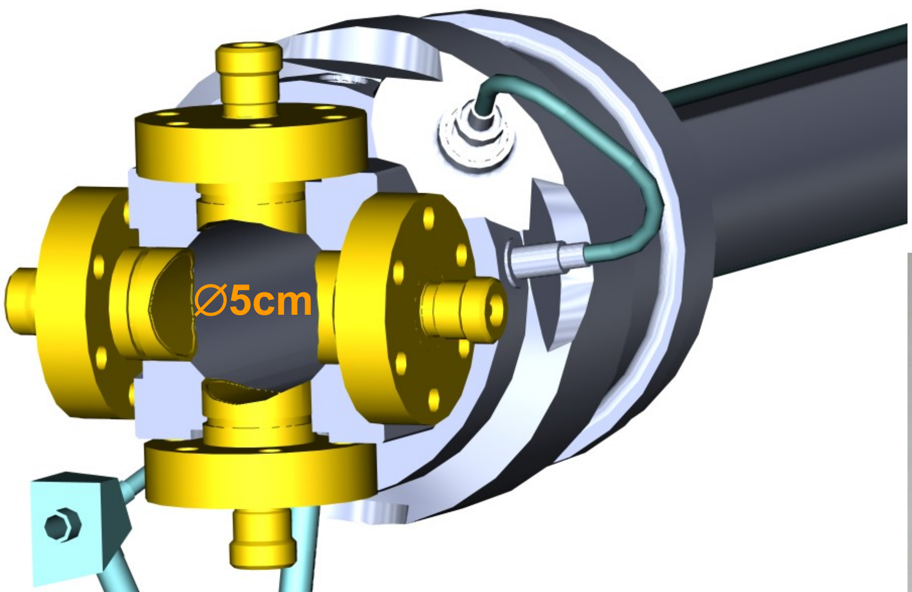
LINACs, e⁻-synchrotrons: 100 MHz < f_{rf} < 3 GHz → bunch length ≈ BPM length

→ 50 Ω signal path to prevent reflections

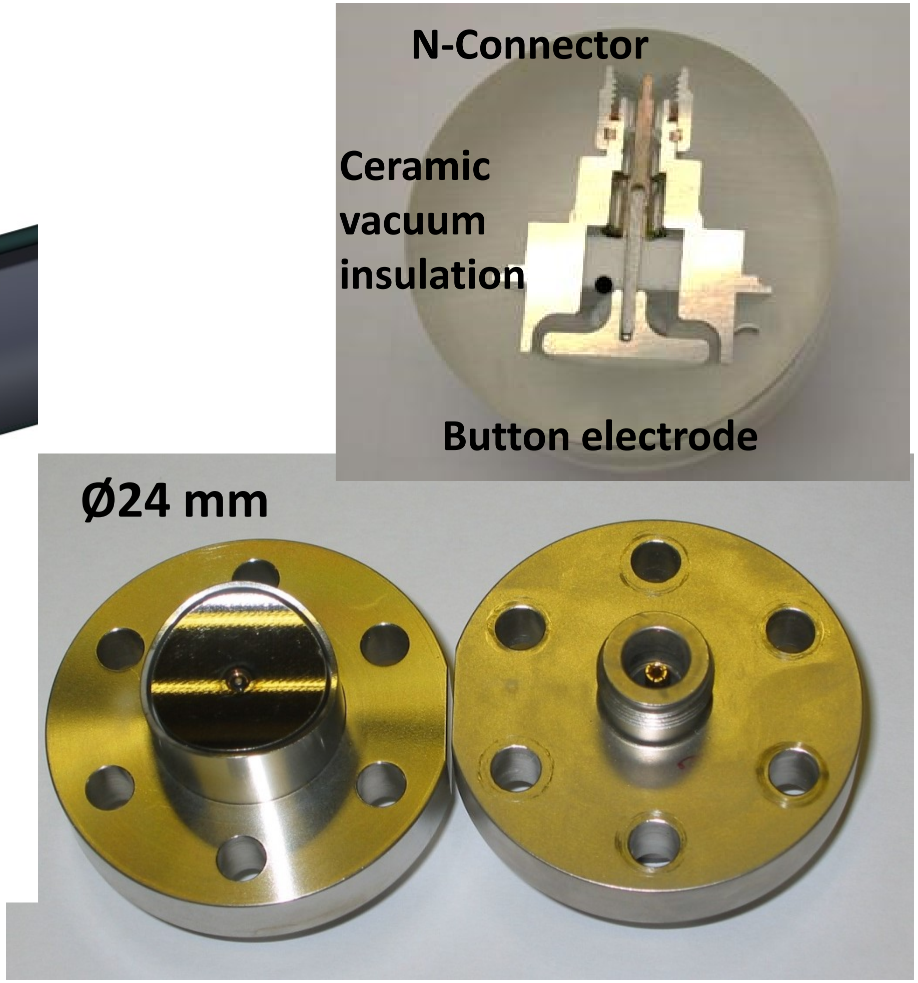
Example: LHC-type inside cryostat:

∅24 mm, half aperture a = 25 mm, C = 8 pF

⇒ f_{cut}= 400 MHz, Z_t = 1.3 Ω above f_{cut}



Courtesy C. Boccard (CERN)

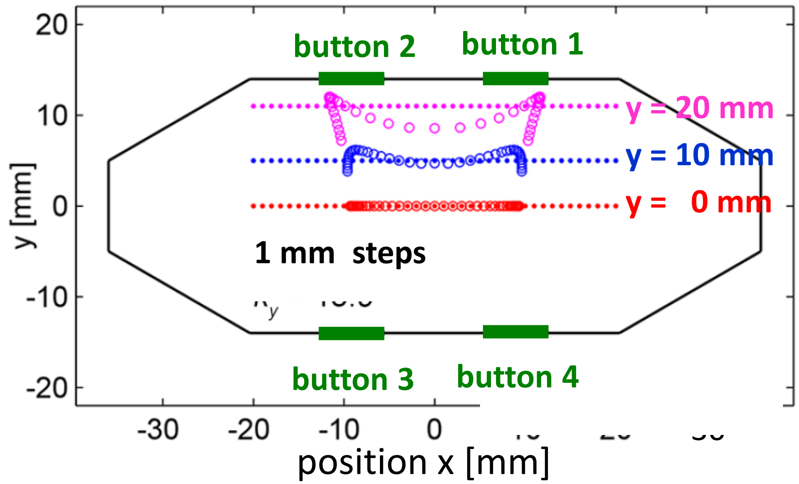


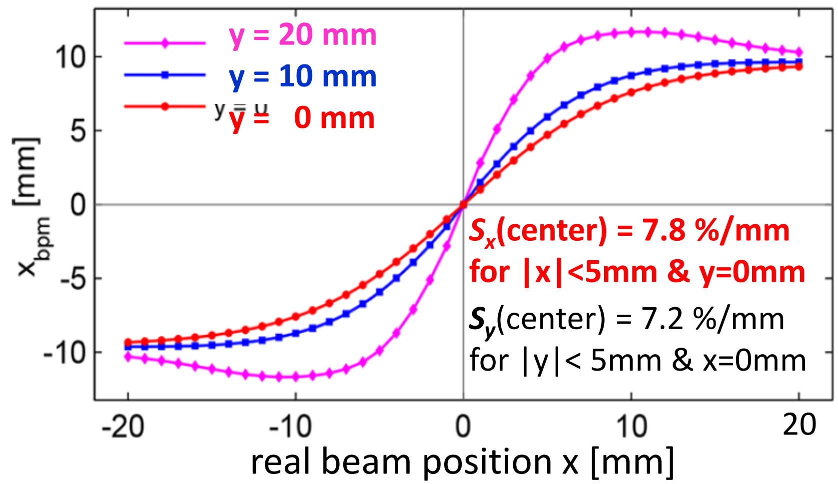
Simulations for Button BPM at Synchrotron Light Sources

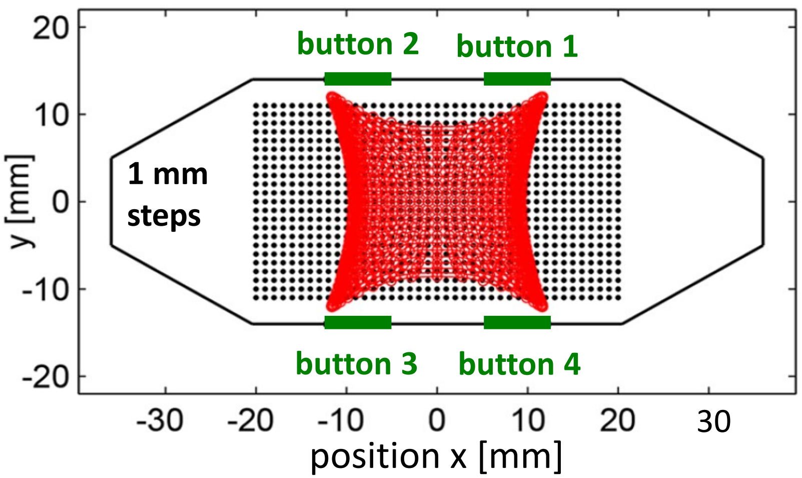
Example: Simulation for ALBA light source for 72 x 28 mm² chamber

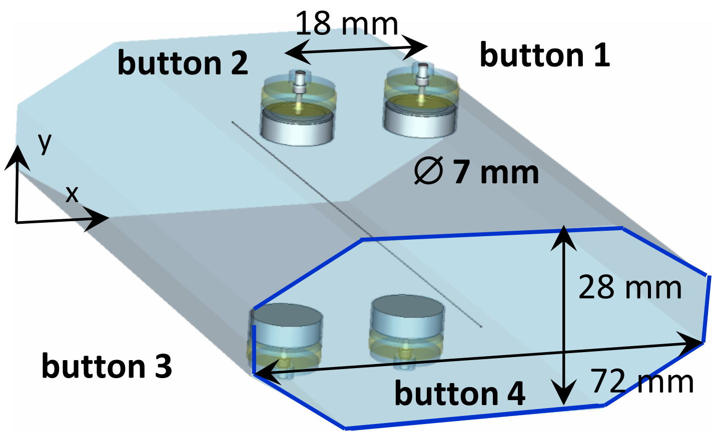
Optimization: horizontal distance and size of buttons

from A.A. Nosych et al., IBIC'14









Result: non-linearity and ***xy***-coupling occur in dependence of button size and position

Linear-cut BPM for Proton Synchrotrons

Frequency range: 1 MHz < f_{rf} < 100 MHz $\Rightarrow$ bunch-length >> BPM length.

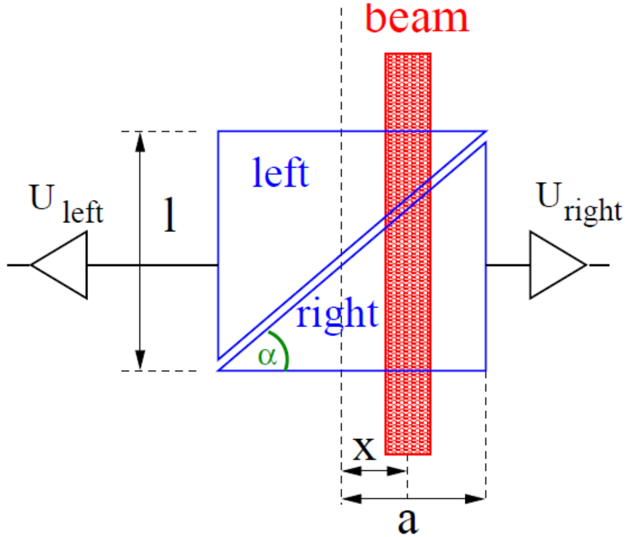
Signal is proportional to actu

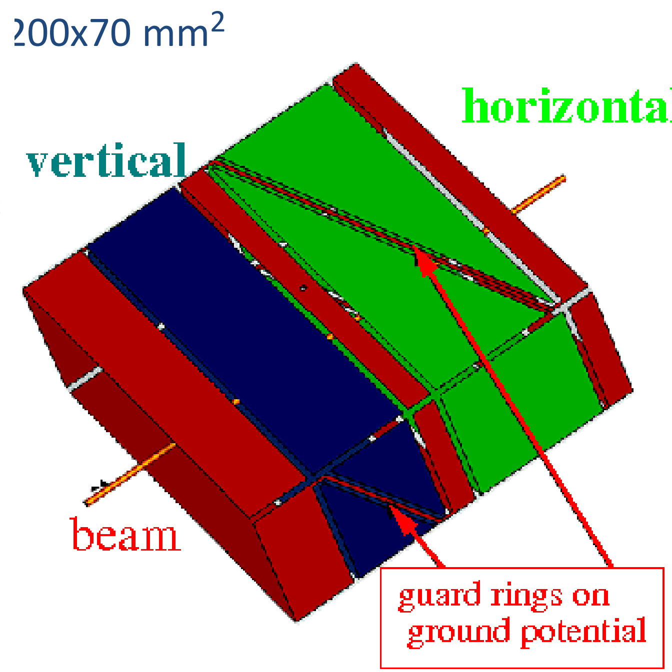
$$l_{right} = (a+x)\cdot\tan\alpha, \quad l_{left} =$$

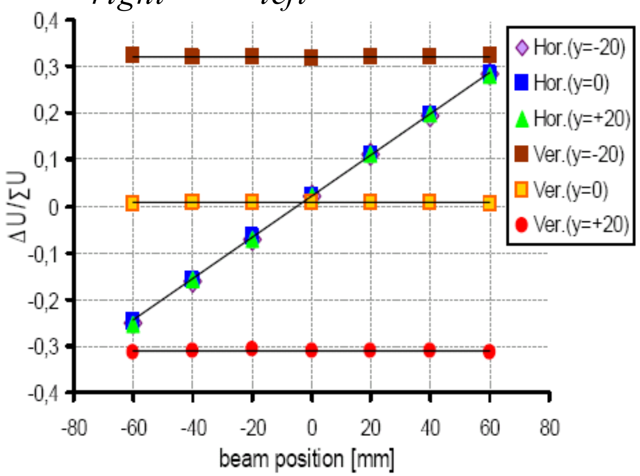
$$\Rightarrow \quad x = a\cdot\frac{l_{right} - l_{left}}{l_{right} + l_{left}}$$

In ideal case: linear readi

$$x = a\cdot\frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a$$







Linear-cut BPM:

Advantage: Linear, i.e. constant position sensitivity ***S***

$\Leftrightarrow$ no beam size dependence

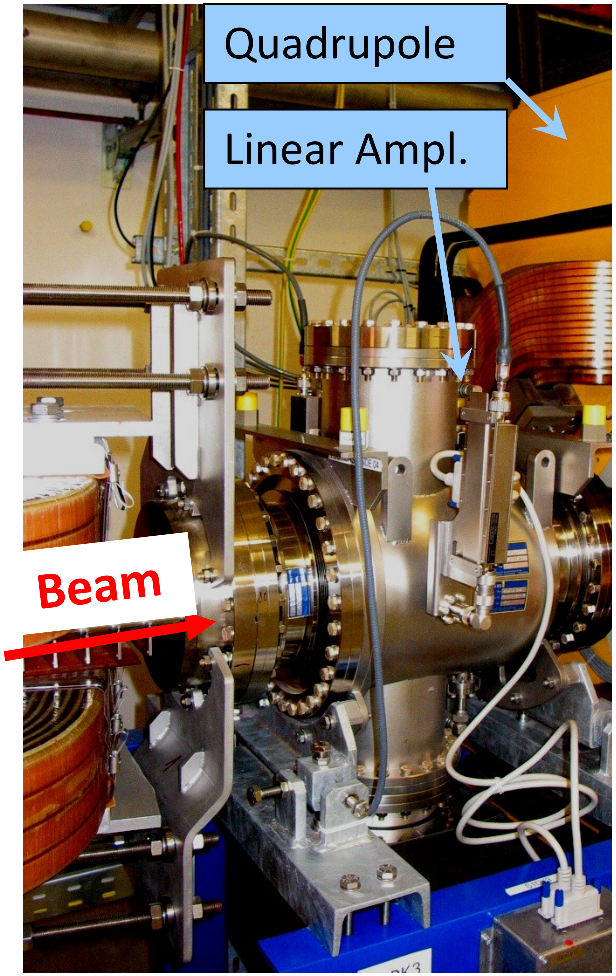
Disadvantage: Large size, complex mechanics

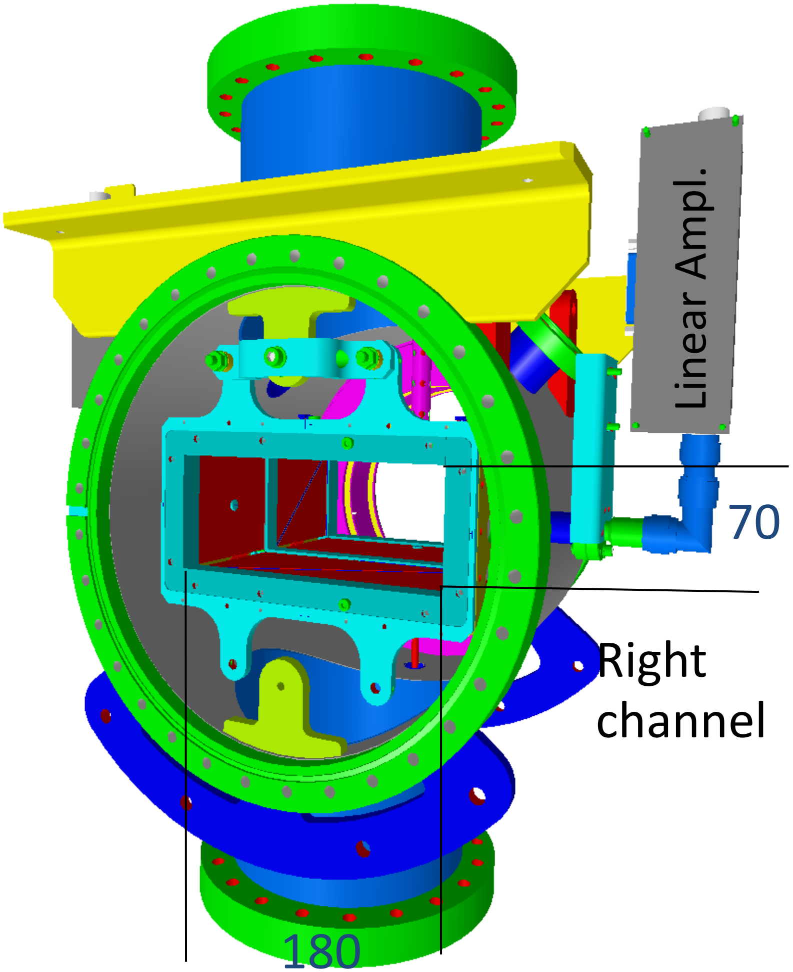
high capacitance

Technical Realization of a linear-cut BPM

Technical realization at HIT synchrotron of 46 m length for 7 MeV/u$\rightarrow$ 440 MeV/u

BPM clearance: 180x70 mm^2, standard beam pipe diameter: 200 mm.





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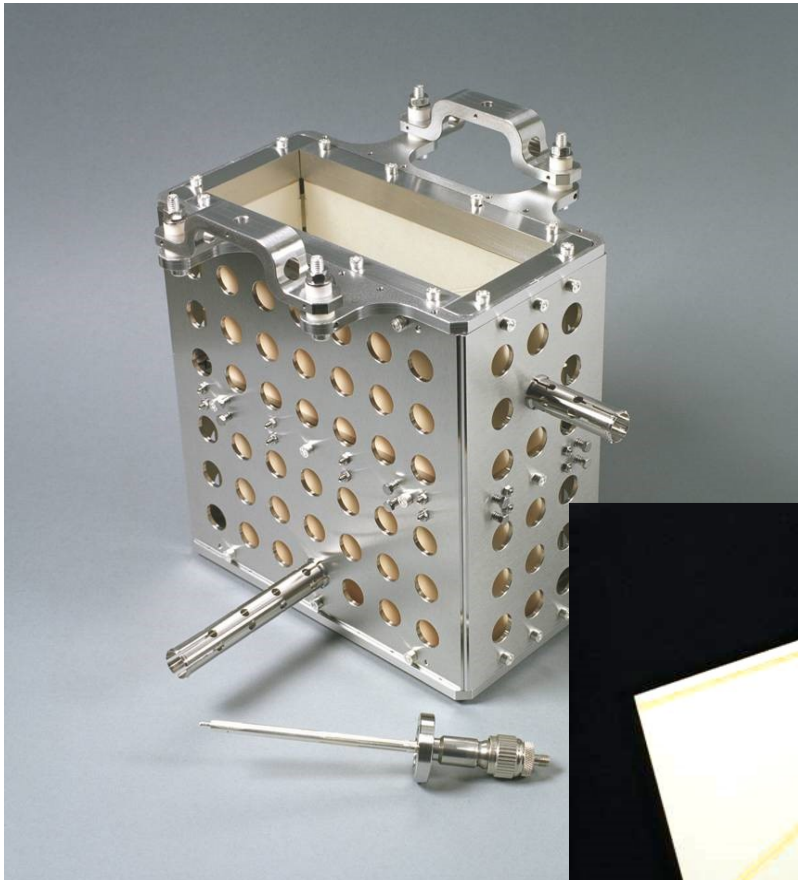
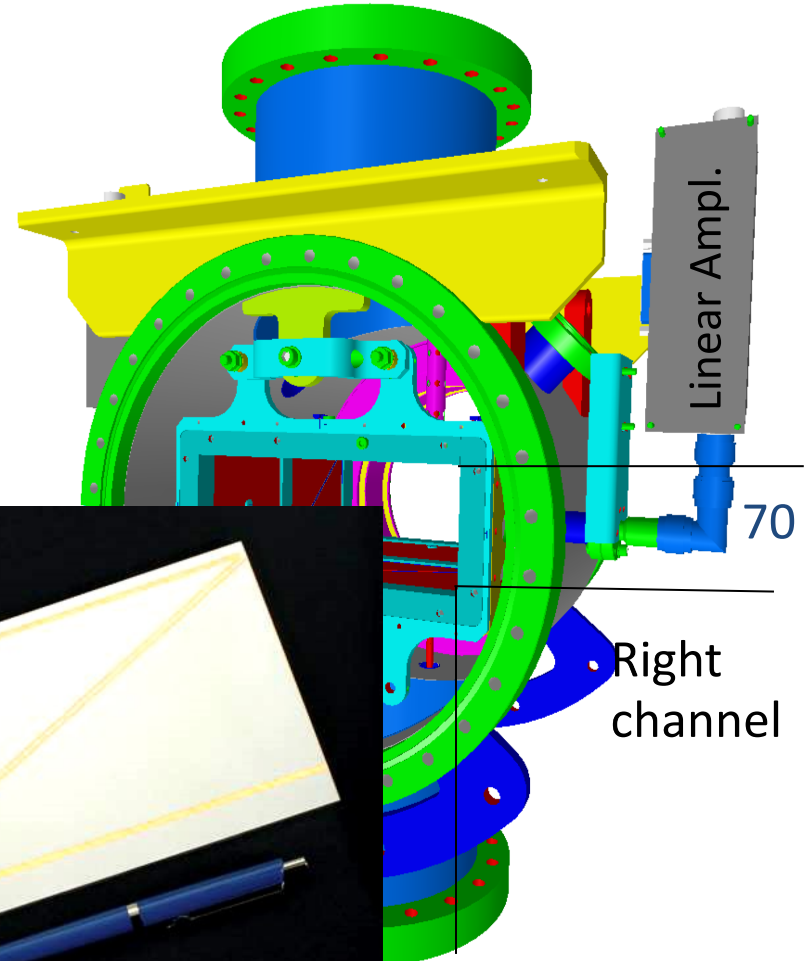


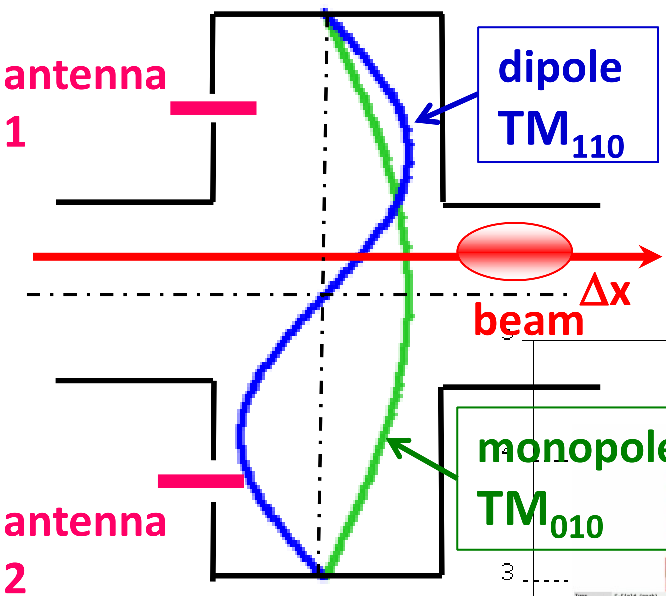


Cavity BPM for FEL-LINACs: Principle

High resolution on ***t* <<** 1 µs time scale can be achieved by excitation of a dipole mode

Depictive statement: ‘The position information is stored due to cavity mode excitation’

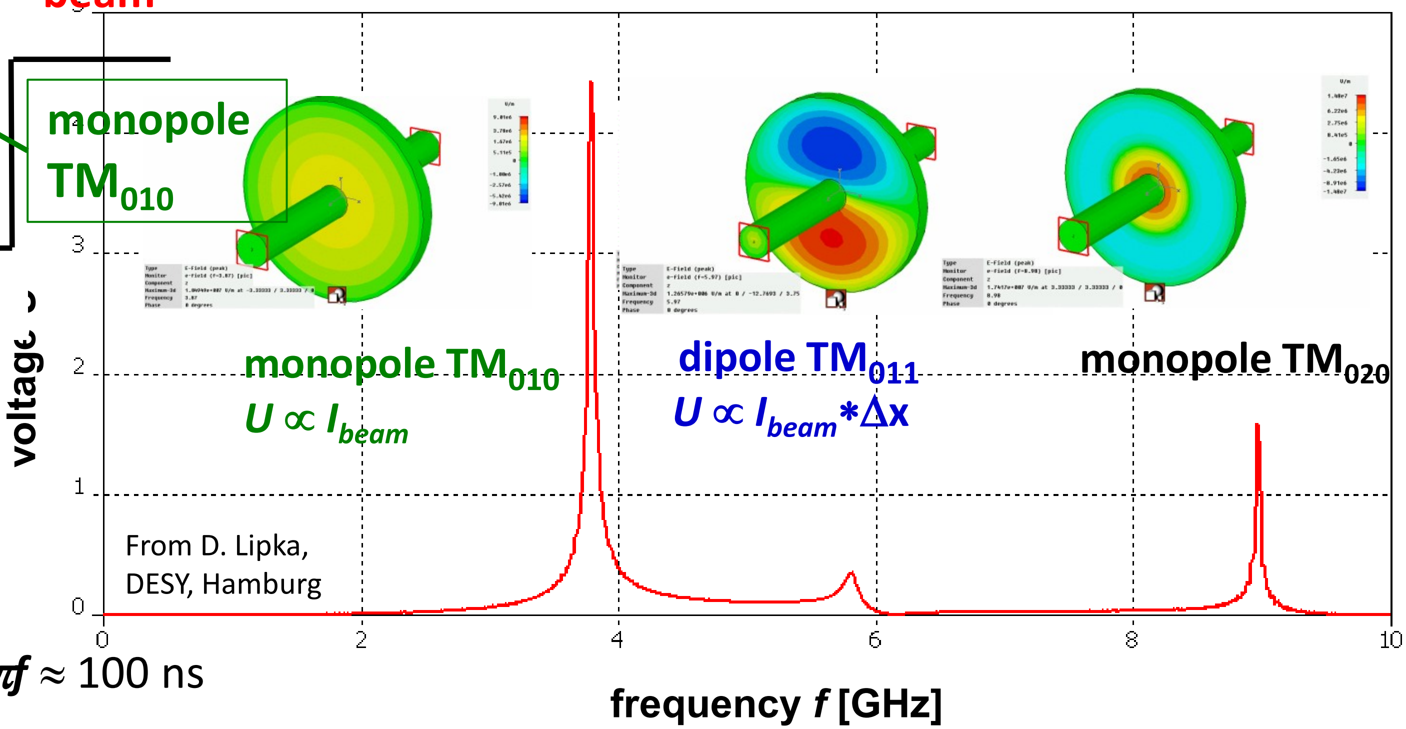
pillbox cavity



For pill box the resonator modes given by geometry:

- **Monopole** mode TM_{010} with $\boldsymbol{f_{010}}$
  $\rightarrow$ maximum at beam center $\Rightarrow$ strong excitation
- **Dipole** mode TM_{011} with $\boldsymbol{f_{011}}$
  $\rightarrow$ minimum at center $\Rightarrow$ excitation by beam offset

$\Rightarrow$ Detection of dipole mode amplitude



Application:
small e⁻ beams
and short pulses < ns

‘δ-excitation’ followed by oscillation with

$\boldsymbol{Q} \approx 1000$ and $\boldsymbol{\tau = 2Q/2\pi f} \approx 100$ ns

Cavity BPM: Example of Realization

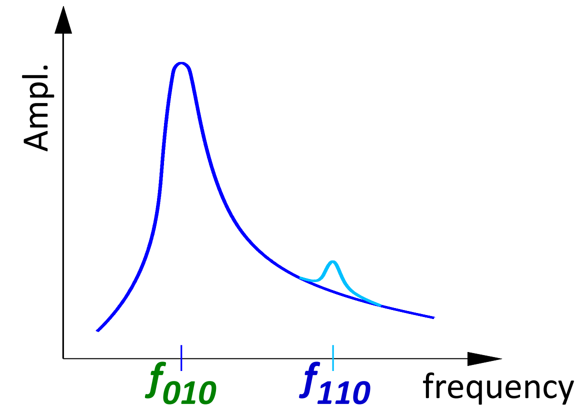
Basic consideration for detection of eigen-frequency amplitudes:

Dipole mode f_{110} separated from monopole mode

due to finite quality factor ***Q*** $\Rightarrow$ ***Δf=f/Q***

- Frequency $f_{110} \approx$1…15 GHz
- Waveguide house the antennas

Task: Suppression of TM_{010} monopole mode



FNAL realization:

Cavity: $\varnothing$ 113 mm

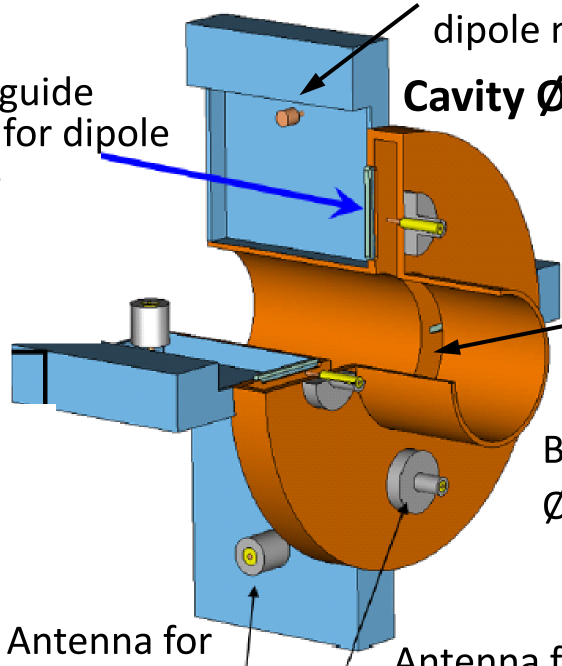
Gap 15 mm

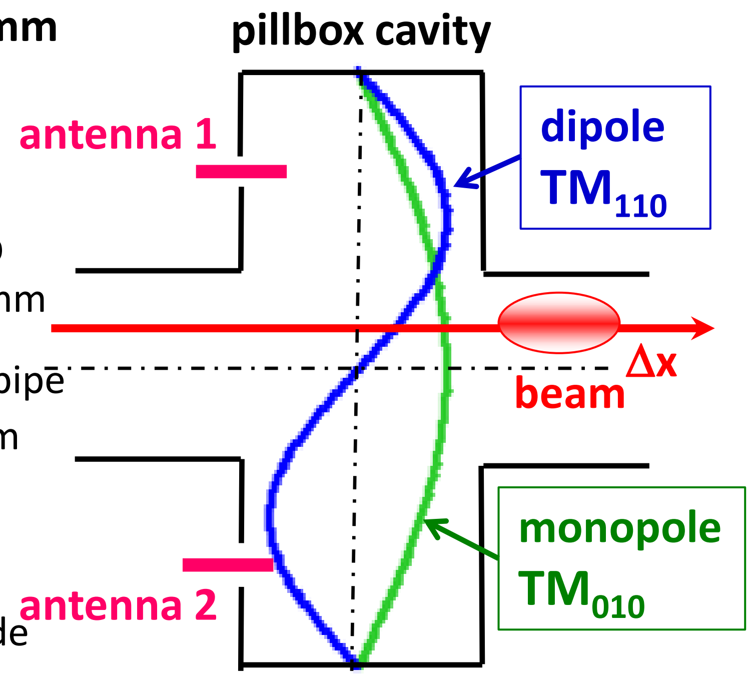
Mono. f_{010}=1.1GHz

Dipole. f_{110}=1.5GHz

$Q_{load} \approx 600$

$\Rightarrow$ **‘0.1 µm resolution within 1 µs‘**



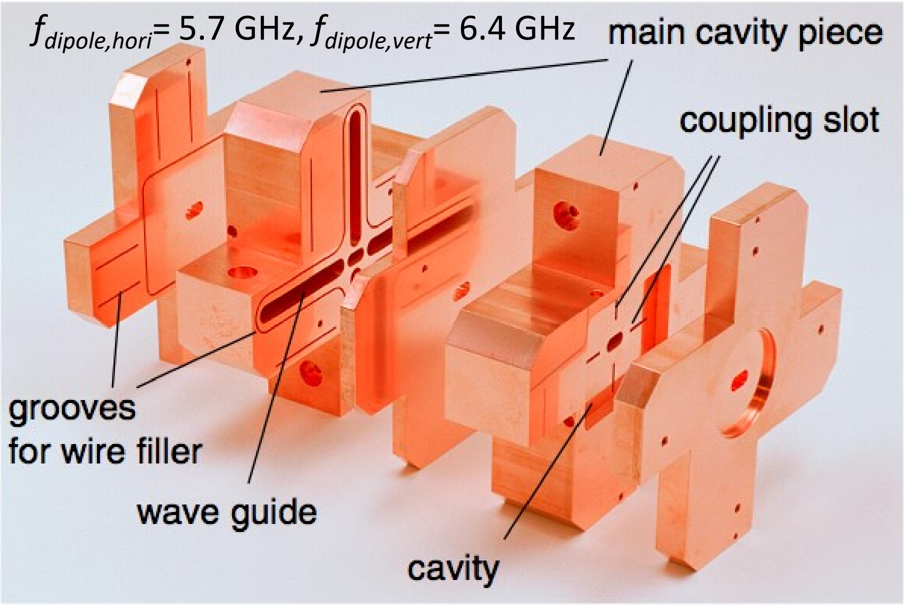


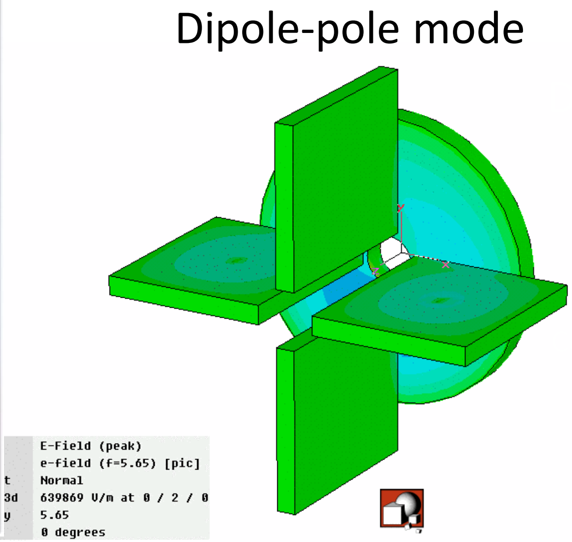
Courtesy M. Wendt (CERN)

Cavity BPM: Suppression of monopole Mode

Suppression of mono-pole mode: waveguide that couple only to dipole-mode

due to $f_{mono} < f_{cut} < f_{dipole}$





Courtesy of D. Lipka, DESY, Hamburg

Prototype BPM for ILC Final Focus:

Achieved **resolution** (i.e. 3 BPM relative) of 8.7 nm in a 6 × 12 mm beam pipe at ATF2 (KEK, Japan)

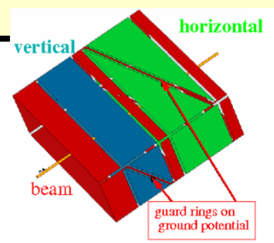
Remark: - Separated, smaller cavity for monopole mode to have **same** frequency for normalization

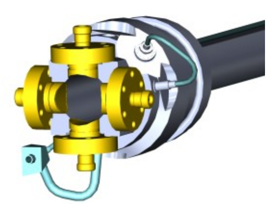
- For typical proton beams **not** required due to long pulses $t_{pulse} \gg 1$ µs

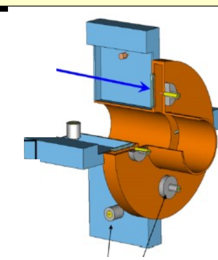
Courtesy of D. Lipka and Y. Honda Phys. Rev. Accel. Beams 11, 062801 (2008)

Intermediate Summary: Comparison of BPM Types (simplified)

Type	Linear-cut	Button	Cavity
Usage	p-synchrotron	p-LINACs, **all** e^- acc.	e^- LINACs (e.g. FEL)
Precaution	Long bunches $f_{rf} < 10$ MHz	Short bunches $f_{rf} > 10$ MHz	Short pulses
Advantage	Large signal Very linear, no ***xy***-coupling For large beams	Simple mechanics Broadband	Very sensitive 'stores' information
Disadvantage	Complex mechanics	Non-linear, ***x-y*** coupling	Very complex, High frequency







Actual challenge for electron & proton accelerators:

- Precise electronics with low drifts to determine position within 10% of beam width
  $\rightarrow$ online calibration required e.g. permanently by 'pilot tone'
- Best performing digital signal processing to achieve highest resolution

Transverse Profile Measurement

Outline:

- Scintillation screens and Optical Transition Radiation OTR screens
- Wire scanner and SEM-Grid
- Non destructive methods

  Proton accelerators: Ionization Profile Monitor, Beam Induced Fluorescence Monitor

  Electron accelerators: Synchrotron Radiation Monitor

Typical beam sizes:

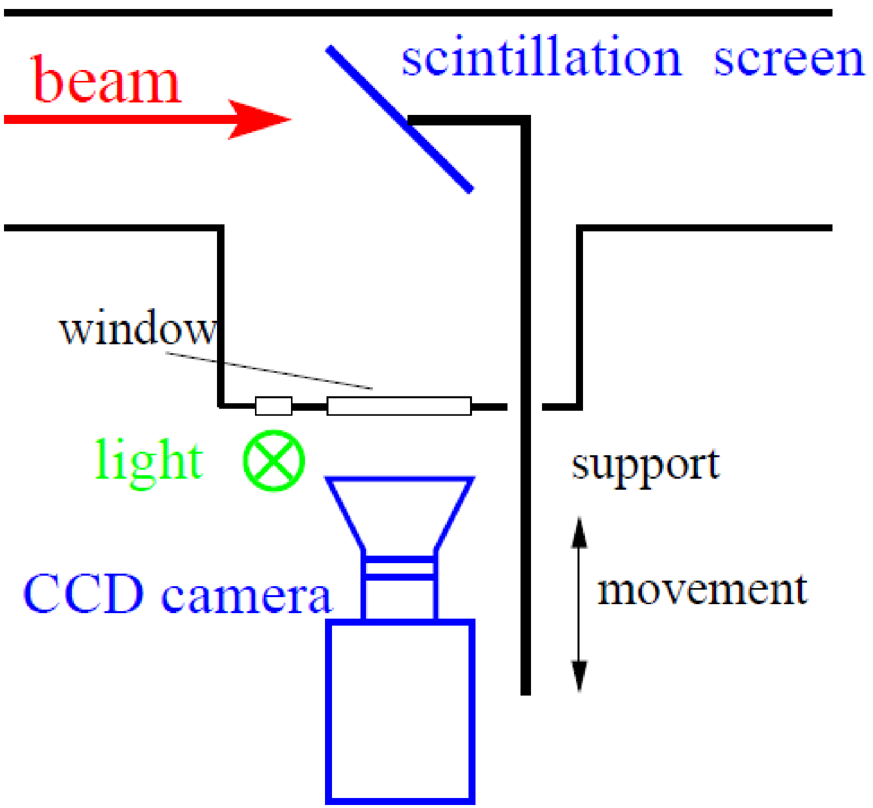
e^--beam: typically Ø 0.01 to 3 mm, **protons:** typically Ø 1 to 30 mm

Scintillation Screen: Principle

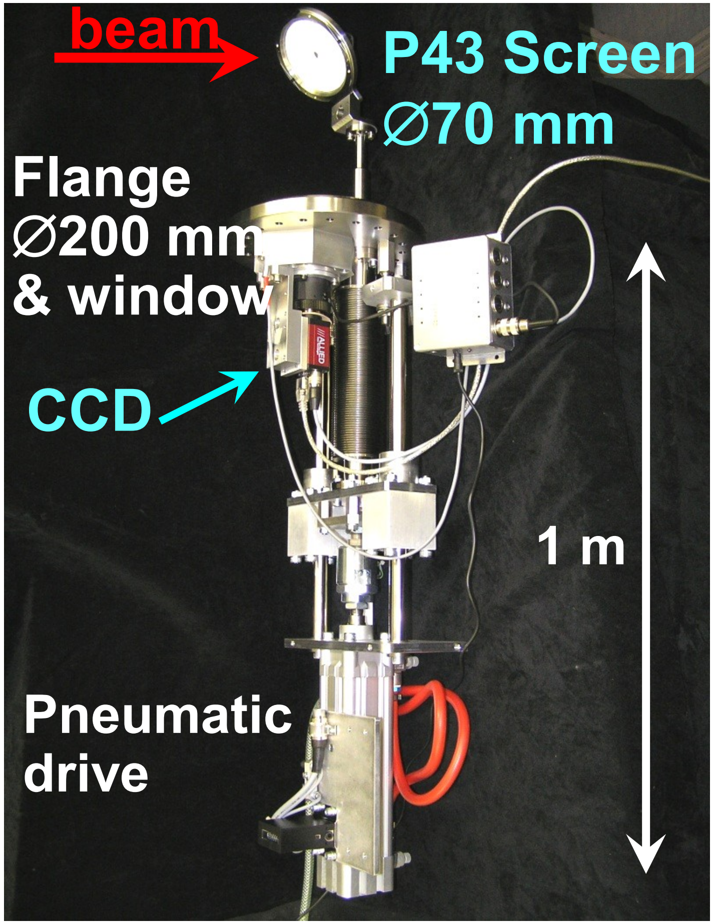
Scintillation: Particle's energy loss in matter causes emission of light

→ the most direct way of profile observation

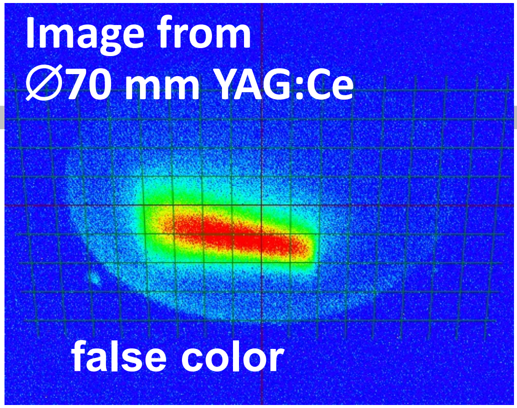
→ used from the early days on & daily operation!



Example: Pneumatic drive with Ø70 mm phosphor screen



Scintillating Screens: Material



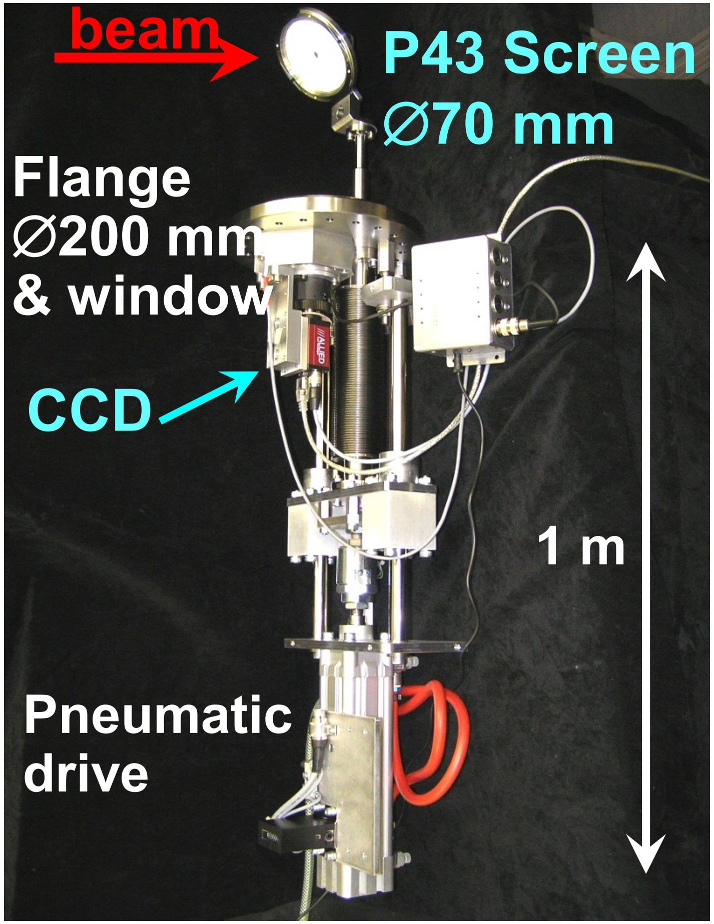
Some materials and their basic properties:

Name	Type	Material	Activ.	Max. λ	Decay
Chromox	Cera-mics	Al_2O_3	Cr	700nm	≈ 10ms
Alumina		Al_2O_3	Non	380nm	≈ 10ns
YAG:Ce	Crystal	$Y_3Al_5O_{12}$	Ce	550nm	200ns
LYSO		$Lu_{1.8}Y_{.2}SiO_5$	Ce	420nm	40ns
P43	Powder of gains Ø≈10µm on glass	Gd_2O_3S	Tb	545nm	1ms
P46		$Y_3Al_5O_{12}$	Ce	530nm	300ns
P47		$Y_3Si_5O_{12}$	Ce&Tb	400nm	100ns

These scintillator have about factor 100 different light yield

Properties of a good scintillator:

- Optical wavelength → standard CCD can be used
- Large dynamic range → usable for different currents
- Short decay time → observation of variations
- Large radiation hardness → long lifetime
- Good mechanical properties → typ. size up to Ø 10 cm



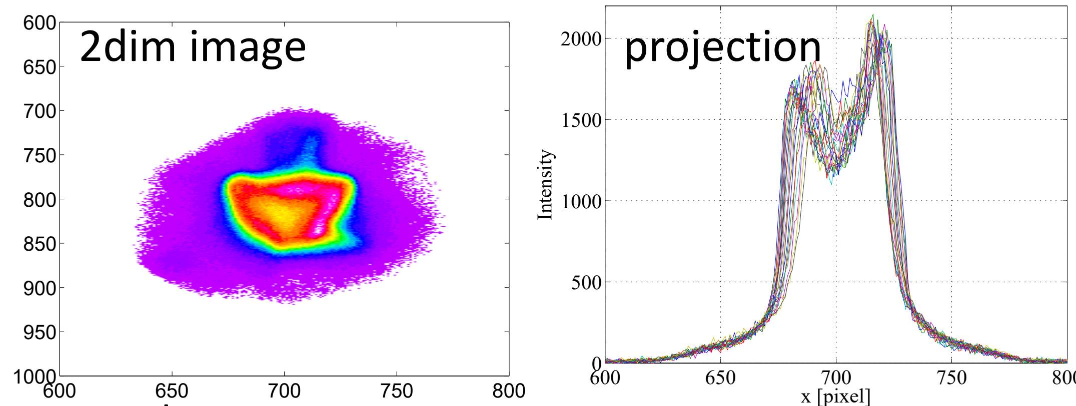
Limitation scintillation Screens: High Ionization Density

Observation:

"Smoke-ring" shaped profiles @ XFEL

for LYSO:Ce scintillator → **wrong measure!**

Example: XFEL, 14 GeV, 1 nC/bunch, σ ≈ 100 μm



G. Kube DESY et al., IBIC 2018

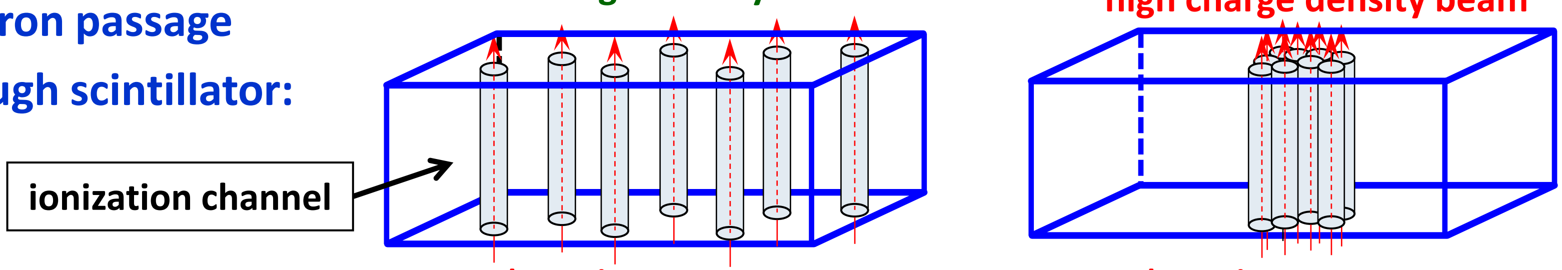
Possible explanation:

- Ionization channel related to secondary electron range
- Quenching of fluorescence close to electron track

⇒ Important for high flux beam (high current, short bunch & transversally focused

- Depends on scintillator material, e.g. YAG:Ce might be better

Electron passage through scintillator:



Proton beam image deformation due to:

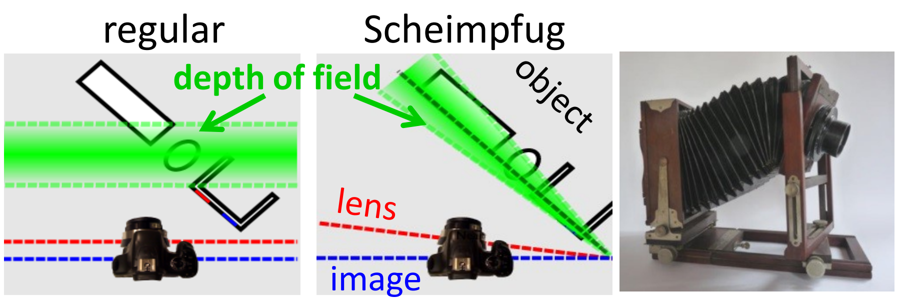
- High ionization density leads to thermal quenching and saturation
- **Radiation damage!**

⇒ Careful choice of scintillation material in dependence of application

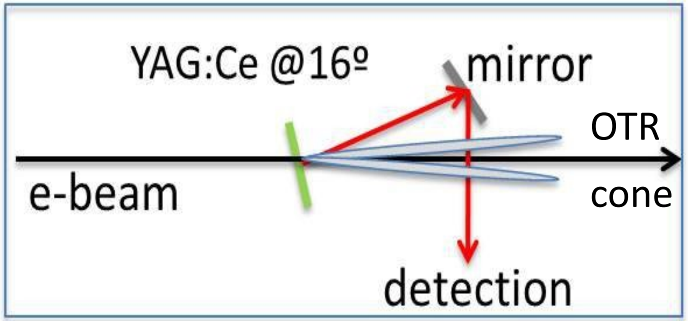
Optical Considerations for small Beam Measurement

Optics: Old principles & recent realization

- Scheimpflug principle:
  object, image & lens plane coincide in one point
  + tele-centric lens
  ⇒ sharp focus & no image deformation



- Screen thickness ≈100 µm > ≈10 µm beam
  (thickness given by free-standing crystal)
  ⇒ optimal angle depends on index of refractivity
  ⇒ condition for angle beam ↔ observation



- FELs: Suppression of coherent OTR (see below)
  ⇒ optimal angle depends beam energy

Remark: Coherent OTR occurs for high intensities if wavelength ≈ bunch size (long.or trans.)

Courtesy S. Gibson RHUL, R. Ischebeck PSI, Phys. Rev. ST Accel. Beams 18, 082802

Optical Considerations for small Beam Measurement

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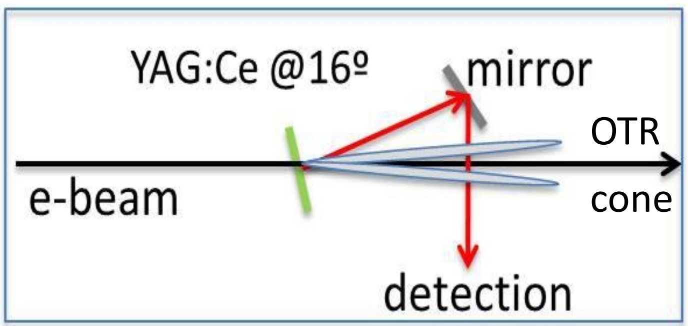
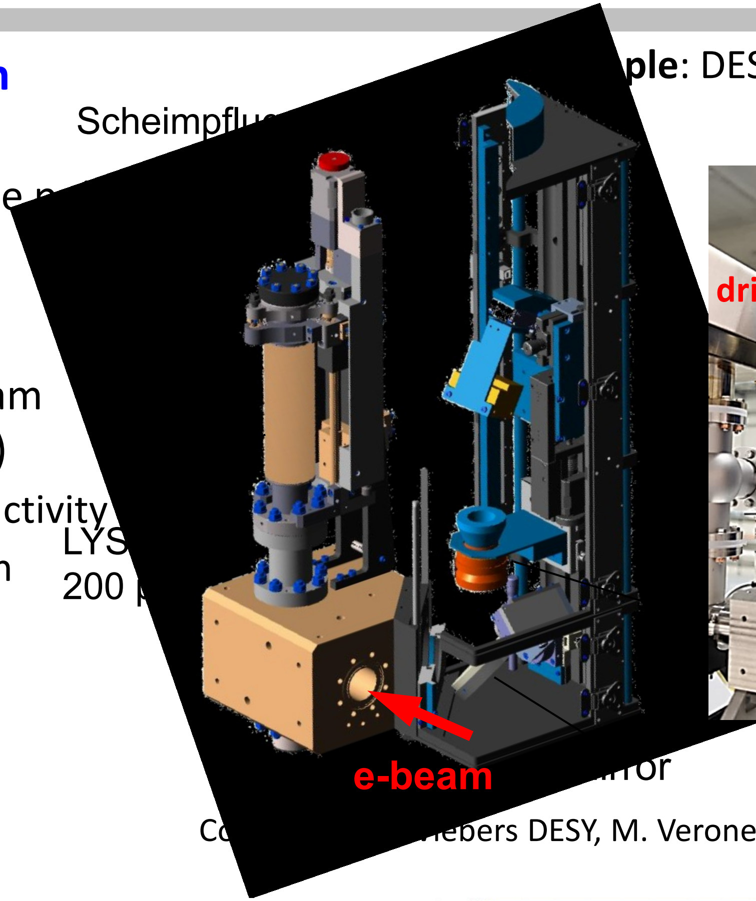


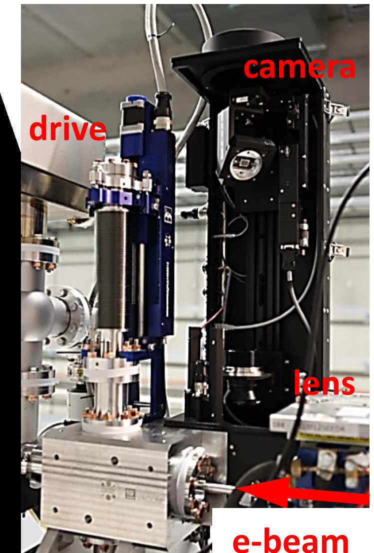
- FELs: Suppression of coherent OTR (see below)
  ⇒ optimal angle depends beam energy

ple: DESY XFEL design

Scheimpflu

LYS
200 µ

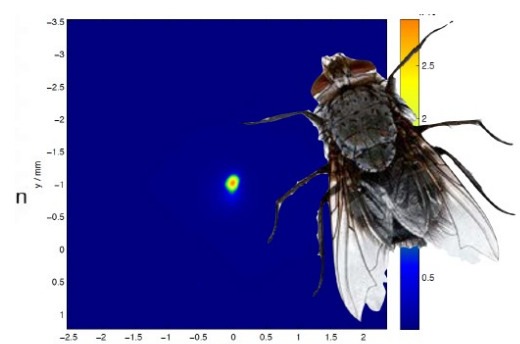




e-beam

rror

Co ebers DESY, M. Verones ELETTRA

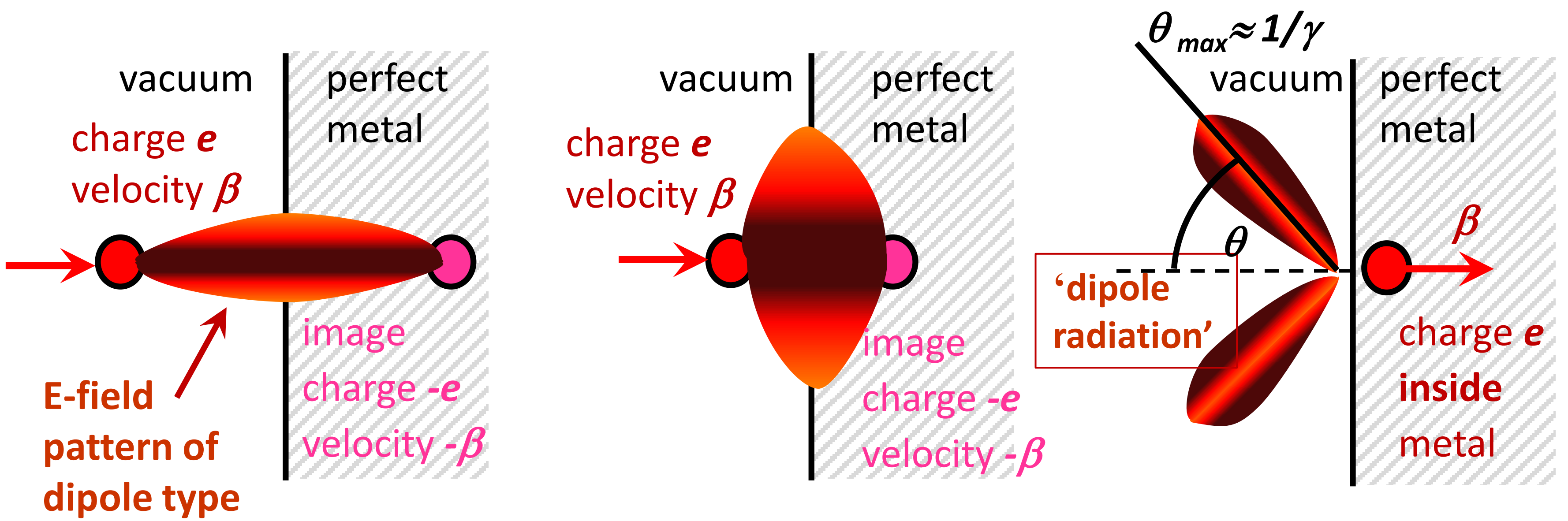


Courtesy S. Gibson RHUL, R. Ischebeck PSI, Phys. Rev. ST Accel. Beams 18, 082802

Optical Transition Radiation OTR for a single charge *e*:

Assuming a charge ***e*** approaches an ideal conducting boundary e.g. metal foil

- Image charge is created by electric field
- Dipole type field pattern
- Field distribution depends on velocity β and Lorentz factor γ due to relativistic trans. field increase
- Penetration of charge through surface within ***t*** < 10 fs: sudden change of source distribution
- Emission of radiation with dipole characteristic



sudden change charge distribution
rearrangement of sources ⇔ radiation

Other physical interpretation: Impedance mismatch at boundary leads to radiation

Optical Transition Radiation: Depictive Description

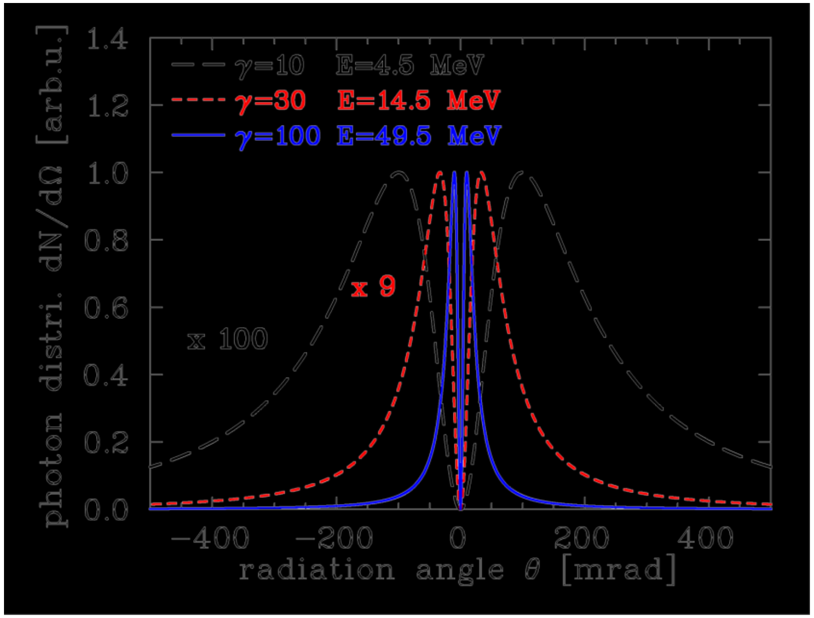
Optical Transition Radiation OTR can be described in classical physics:

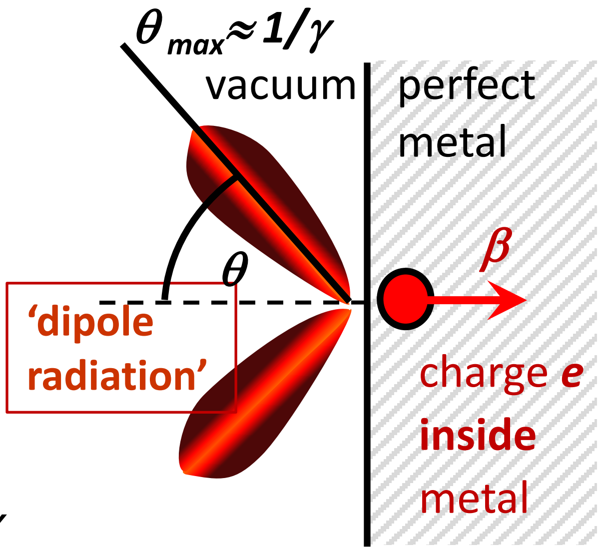
approximated formula
for normal incidence
& in-plane polarization:

$$\frac{d^2W}{d\theta\, d\omega} \approx \frac{2e^2\beta^2}{\pi c} \cdot \frac{\sin^2\theta \cdot \cos^2\theta}{\left(1-\beta^2\cos^2\theta\right)^2}$$

W: radiated energy

ω: frequency of wave





Angular distribution of radiation in optical spectrum:

- Lope emission pattern depends on velocity or Lorentz factor γ
- Emitted energy i.e. amount of photons scales with $W \propto \beta^2$
- Broad wave length spectrum up to plasma frequency

$\Rightarrow$ suited for medium and high energy electrons

sudden change charge distribution
rearrangement of sources $\Leftrightarrow$ radiation

Technical Realization of Optical Transition Radiation OTR

OTR is emitted by charged particle passage through a material boundary.

Photon distribution:
within a solid angle $d\Omega$ and
Wavelength interval λ_{begin} to λ_{end}

$$\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{2e^2\beta^2}{\pi c} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

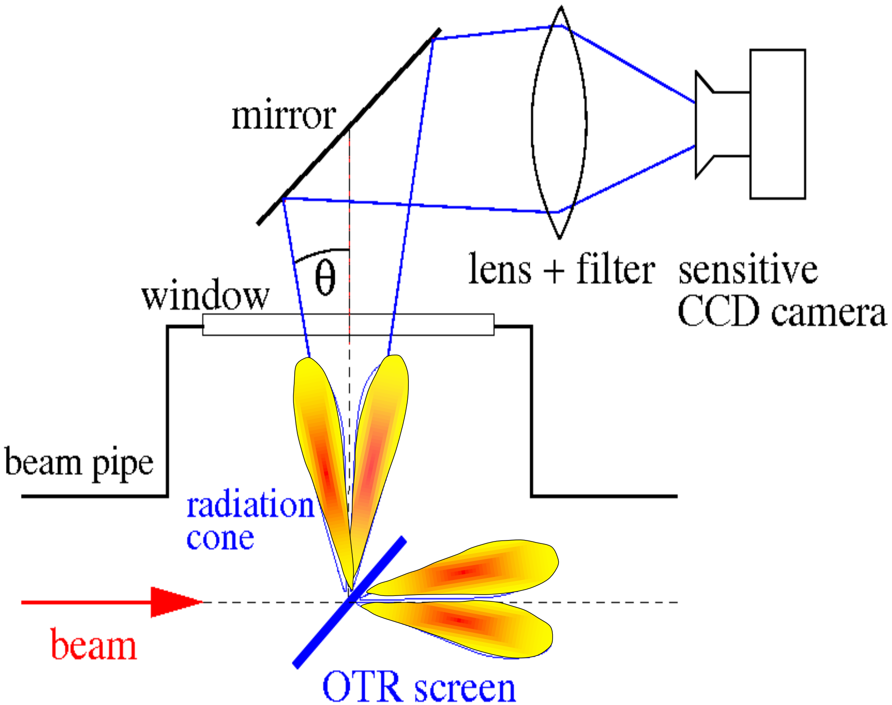
- Detection: Optical 400 nm < λ < 800 nm
  using image (intensified) CCD
- Larger signal for relativistic beam $\gamma >> 1$
- Low divergence for $\gamma >> 1 \Rightarrow$ large signal

$\Rightarrow$ **well suited for e⁻ beams**

$\Rightarrow$ **p-beam only for E_{kin} > 100 GeV $\Leftrightarrow \gamma > 100$**

Advantage:
- Thin foil $\Rightarrow$ low heating & straggling
- 2-dim image visible

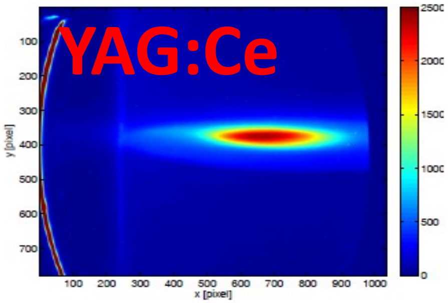
Remark: Comparable processes
- Optical diffraction radiation ODR
- Smith–Purcell radiation from grid-structure

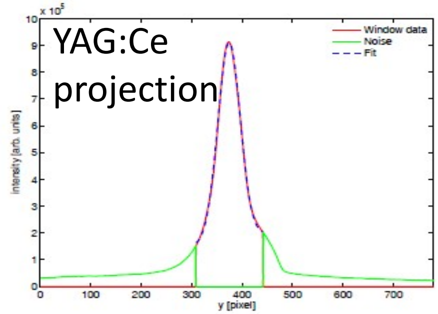


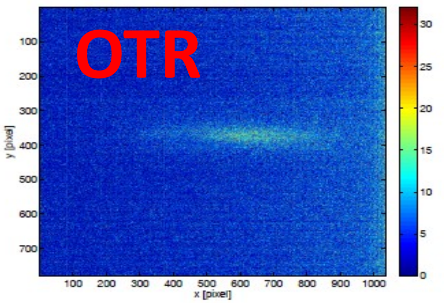
5 μm Kapton or Maylar coated with 0.1μm Al

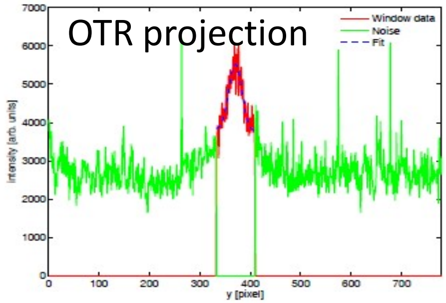
Optical Transition Radiation compared to Scintillation Screen

Installation of OTR and scintillation screens on same drive:





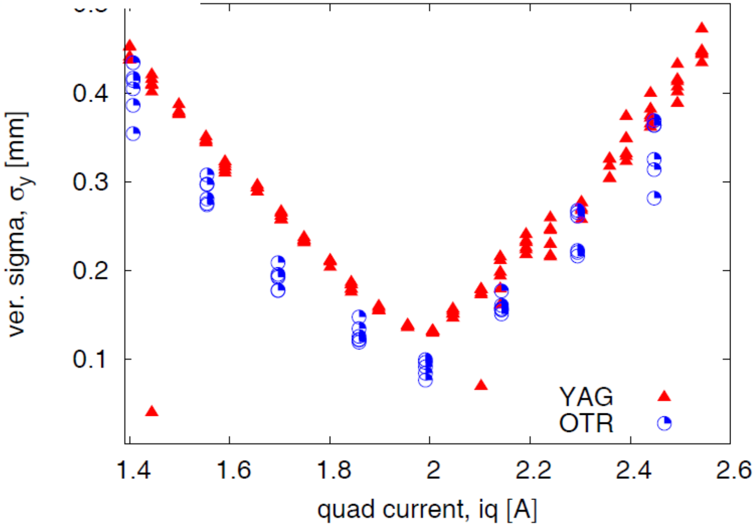




Example: ALBA LINAC 100 MeV

Results:

- Much more light from YAG:Ce for 100 MeV (γ=200) electrons light output $I_{YAG} \approx 10^5 I_{OTR}$ (ratio depends on γ)
- Broader image from YAG:Ce due to finite YAG:Ce thickness



Courtesy of U. Iriso et al., DIPAC'09

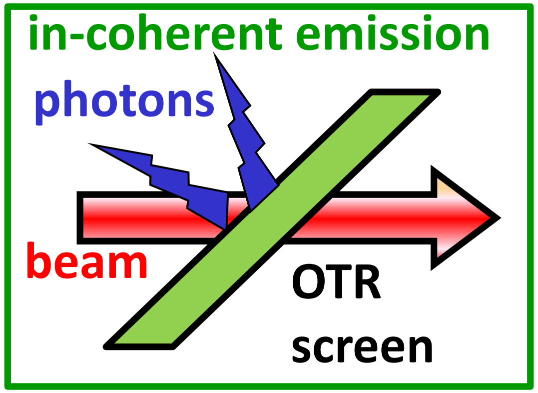
Coherent Optical Transition Radiation

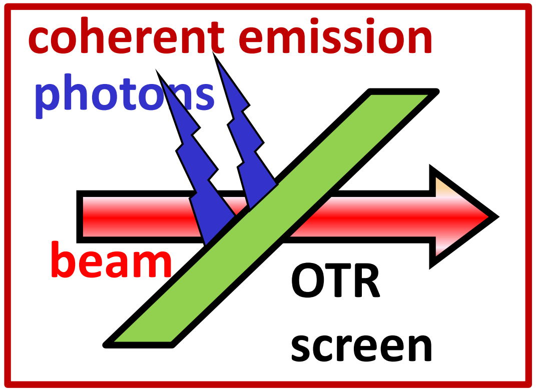
Observation of coherent OTR for **compressed** bunches at LINAC based light sources

Reason: Coherent emission **if** bunch length ≈ wavelength (t_{bunch}=2 fs ⇔ l_{bunch} =600 nm)

or bunch fluctuations ≈ wavelength

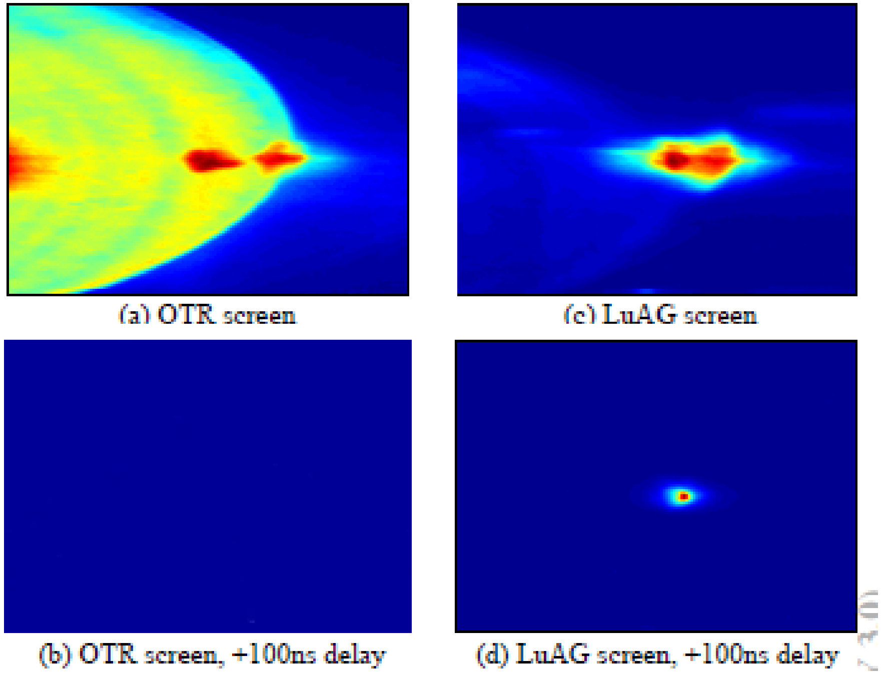
Parameter reach for most LINAC-based FELs!





Beam parameter: FLASH, 700 MeV, 0.5 nC, with bunch compression

OTR screen *scint. screen*



prompt emission for OTR and scint. screen
→ **coherent and in-coherent OTR**

100 ns delayed emission
→ no OTR as expected (classical process)
→ emission by scint. screen due to lifetime
⇔ correct profile image!

Contrary of M. Yan et al., DIPAC'11 & S. Wesch, DIPAC'11

Comparison between Scintillation Screens and OTR

OTR: electrodynamic process $\Rightarrow$ beam intensity linear to # photons, high radiation hardness

Scint. Screen: complex atomic process $\Rightarrow$ saturation possible, for some low radiation hardness

---

OTR: thin foil Al or Al on Mylar, down to 0.25 µm thickness

$\Rightarrow$ minimization of beam scattering (Al is low Z-material e.g. plastics like Mylar)

Scint. Screen: thickness down to 100 µm inorganic, fragile material, not always radiation hard

---

OTR: low number of photons (energy dependent) $\Rightarrow$ expensive image intensified CCD

Scint. Screen: large number of photons $\Rightarrow$ simple CCD sufficient

---

OTR: complex angular photon distribution $\Rightarrow$ resolution limited

Scint. Screen: isotropic photon distribution $\Rightarrow$ simple interpretation

---

OTR: large γ needed $\Rightarrow$ e^--beam with $E_{kin} > 100$ MeV, proton-beam with $E_{kin} > 100$ GeV

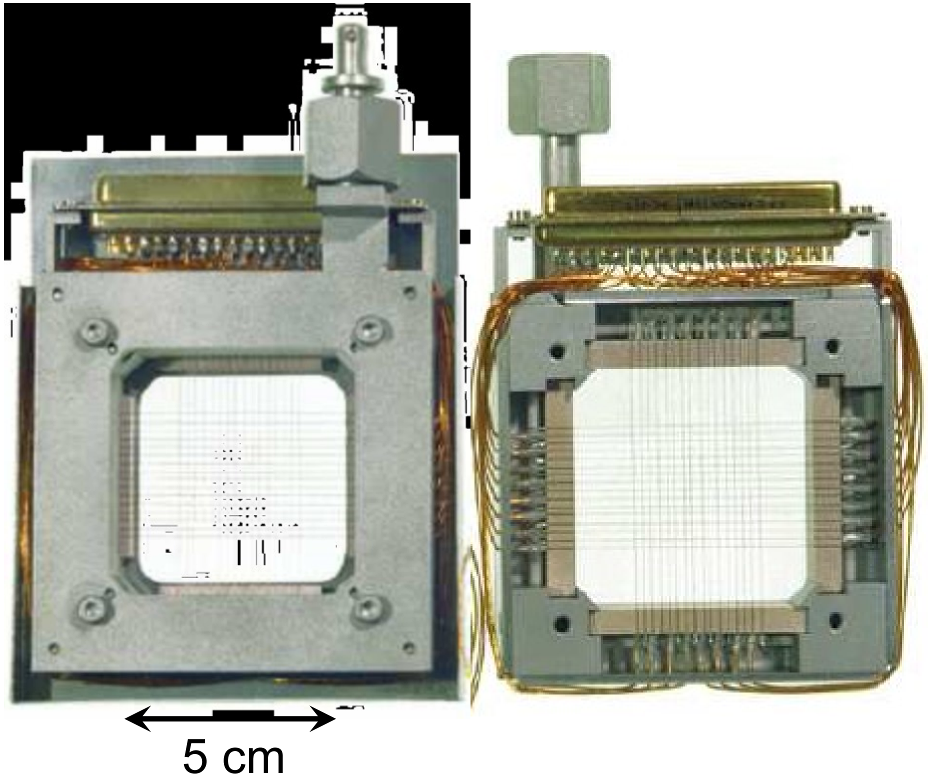
Scint. Screen: for all beams

Remark: OTR questionable for LINAC-FEL due to **coherent** light emission .

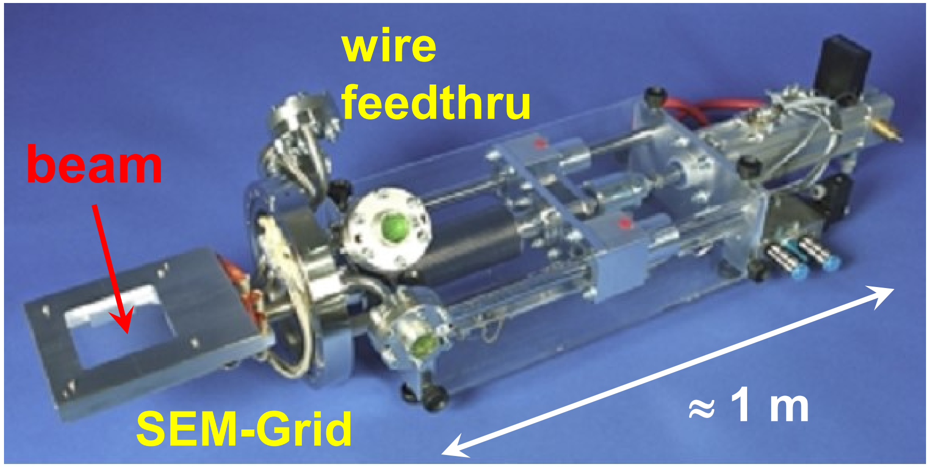
Secondary Electron Emission Grids = SEM-Grid

Beam surface interaction: e⁻ emission proportional to energy loss

Example: 15 wire spaced by 1.5 mm:



SEM-Grid feed-through on CF200:



Parameter	Typ. value
# wires per plane	10 ...100
Active area	(5...20 cm) ^{2}
Wire ∅	25....100 μm
Spacing	0.3...2 mm
Material	e.g. W or Carbon
Max. beam power	1 W/mm

At e⁻ LINACs not used as too large pitch.

Slow, linear Wire Scanner

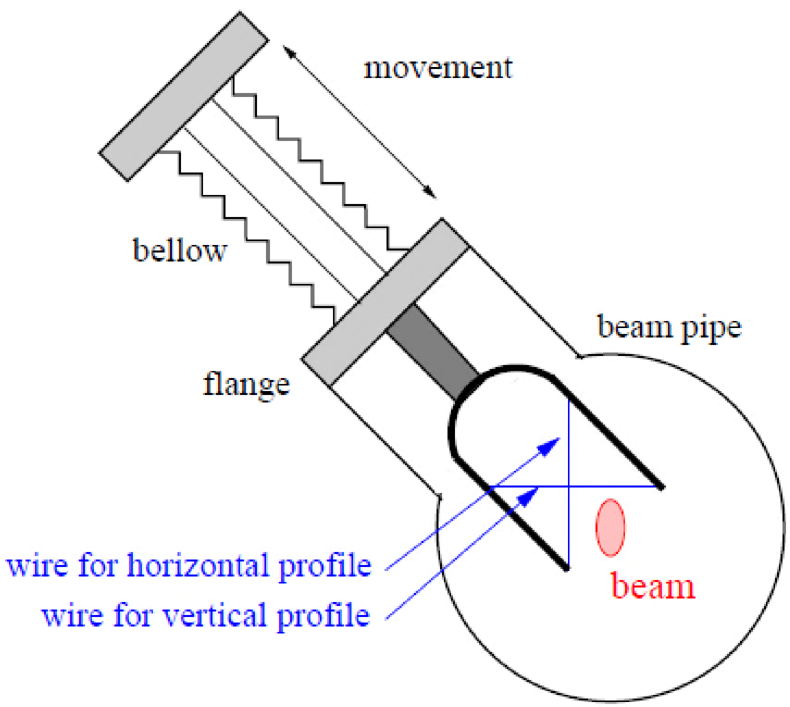
Idea: One wire is scanned through the beam!

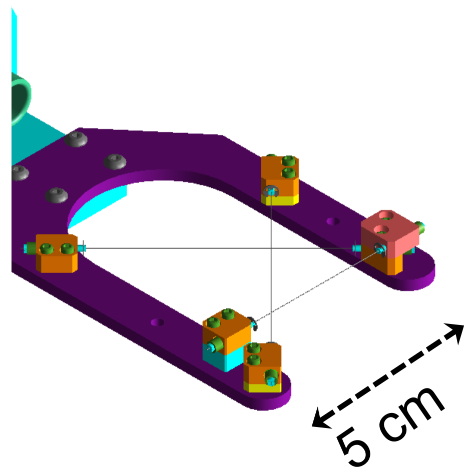
Wire diameter 1 µm < d_{wire} < 100 µm

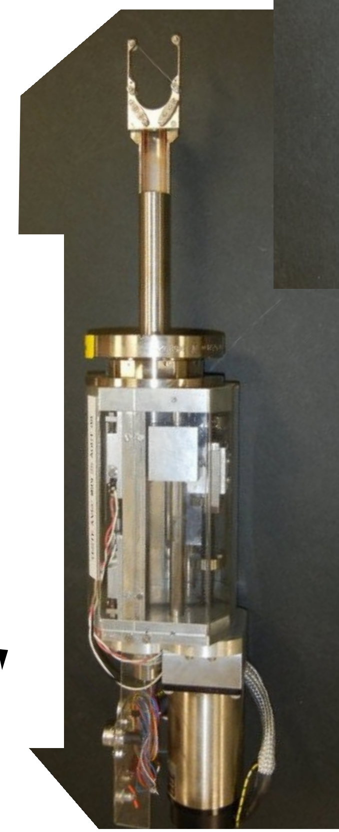
Slow, linear scanner are used for:

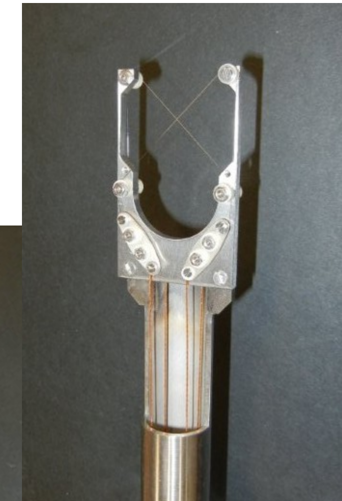
- Low energy proton cw-beam
- High resolution for e⁻ beam as reference method by de-convolution $\sigma^2_{beam}=\sigma^2_{meas}-d^2_{wire}$
  $\Rightarrow$ resolution down to 1 µm range can be reached

Scanners used as reference method!







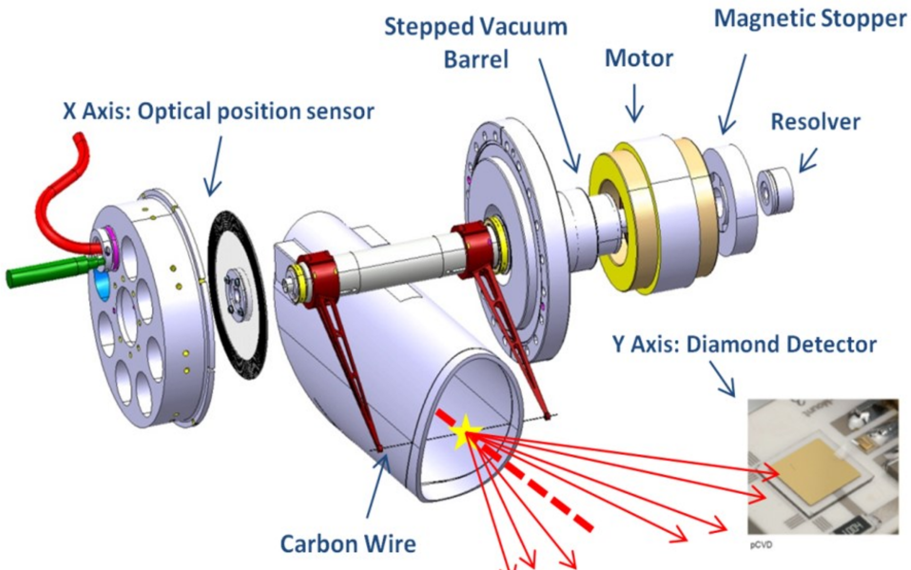


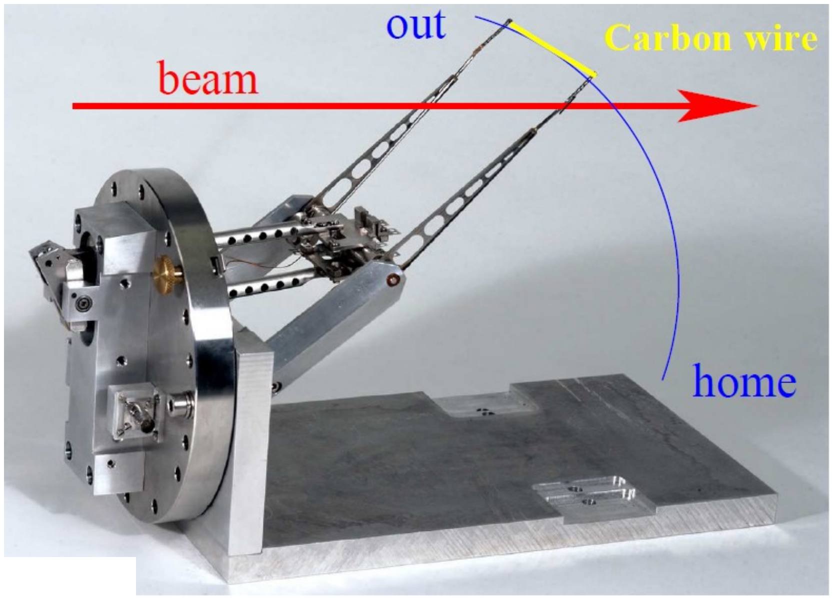
Actual challange for FELs:

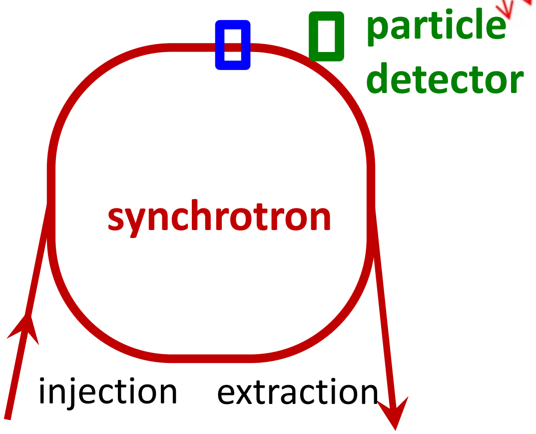
How to produce a thin ≈ 1 µm but stable wire?

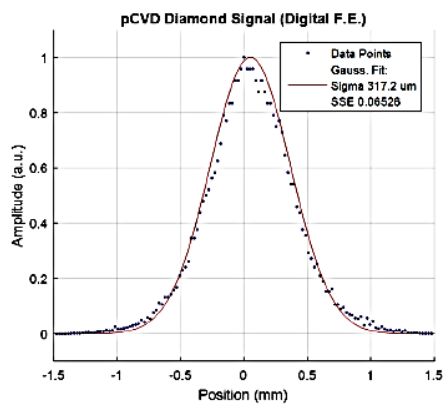
In a synchrotron ***one*** wire is scanned though the beam as fast as possible.

Fast pendulum scanner for synchrotrons; sometimes it is called ***'flying wire'***:









From https://twiki.cern.ch/twiki/bin/viewauth/BWSUpgrade/

Usage of Flying Wire Scanners at Proton Synchrotrons

Material: Carbon or SiC → low Z-material for low energy loss and high temperature.

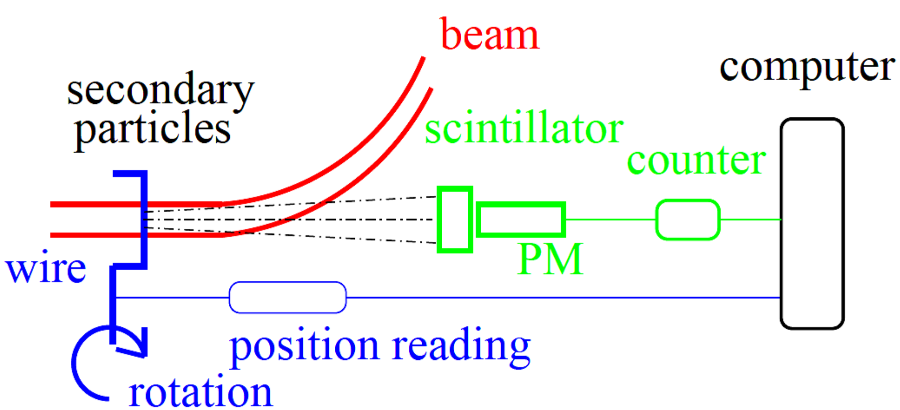
Thickness: Down to 10 μm → high resolution.

Detection: High energy **secondary particles** with a detector like a beam loss monitor

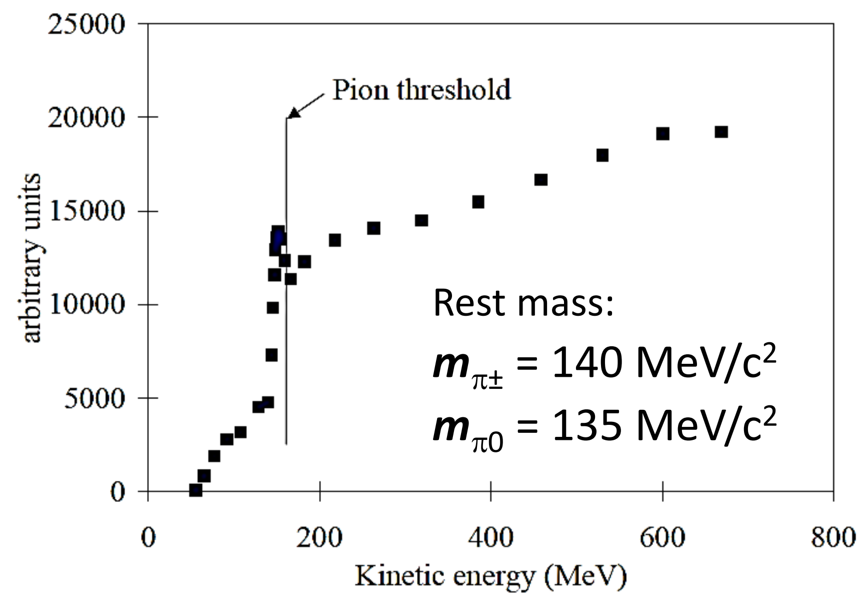
Secondary particles:

Proton beam → hadrons shower (π, n, p...)

Electron beam → Bremsstrahlung photons.



Proton impact on scanner at CERN-PS Booster:



U. Raich et al., DIPAC 2005

Kinematics of flying wire:

Velocity during passage typically 10 m/s = 36 km/h and typical beam size ∅ 10 mm ⇒ time for traversing the beam $t \approx 1$ ms

Actual challenges: Thin wire stability for fast movement with high acceleration, thermal stability due to large beam power

Comparison between SEM-Grid and slow Wire Scanners

Grid: Measurement at a single moment in time

Scanner: Fast variations can not be monitored

$\rightarrow$ for pulsed LINACs precise synchronization is needed

---

Grid: Not adequate at synchrotrons for stored beam parameters

Scanner: At high energy synchrotrons flying wire scanners are nearly non-destructive

---

Grid: Resolution of a grid is fixed by the wire distance (typically 1 mm)

Scanner: For slow scanners the resolution is about the wire thickness (down to 10 μm)

$\rightarrow$ used for e−-beams having small sizes (down to 10 μm)

Grid: Needs one electronics channel per wire

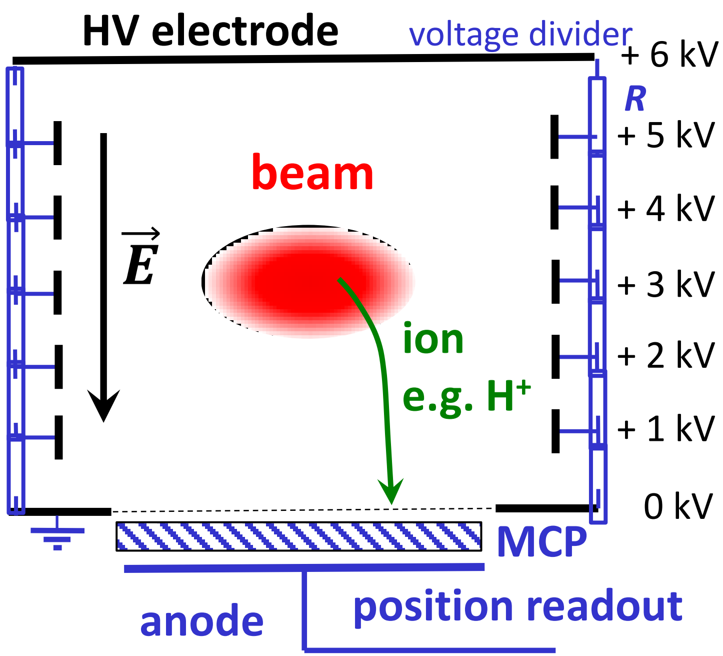
→ expensive electronics and data acquisition

Scanner: Needs a precise movable feed-through → expensive mechanics.

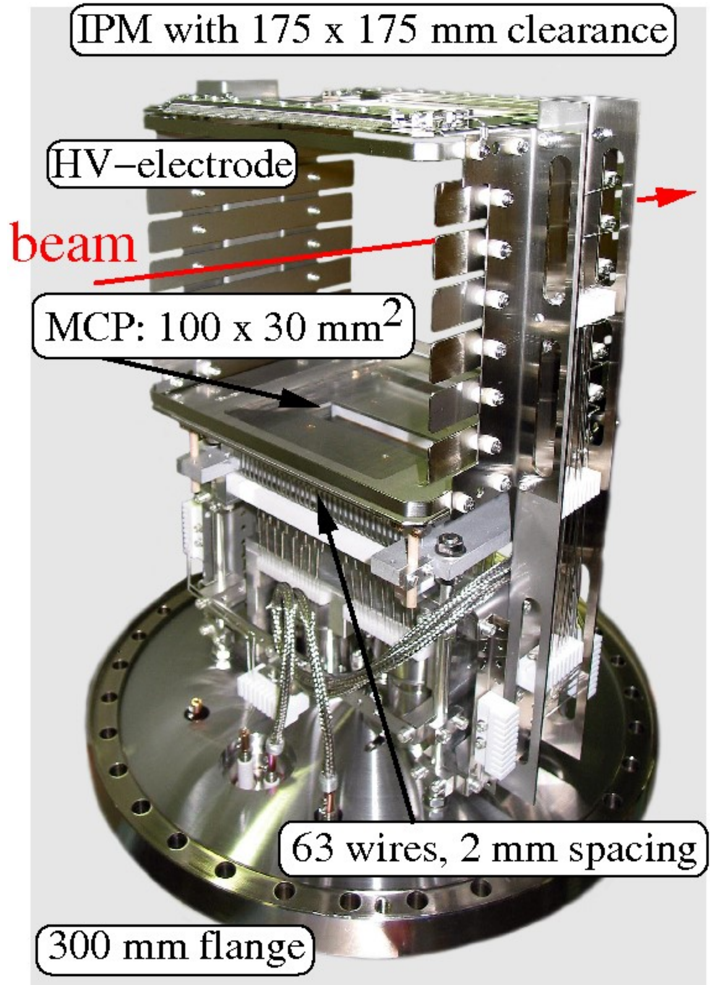
Ionization Profile Monitor at GSI Synchrotron

Non-destructive device for proton synchrotron:

- beam ionizes the residual gas by electronic stopping
- gas ions or e^- accelerated by E -field ≈1 kV/cm
- spatial resolved single particle detection



Realization at GSI synchrotron:
One monitor per plane



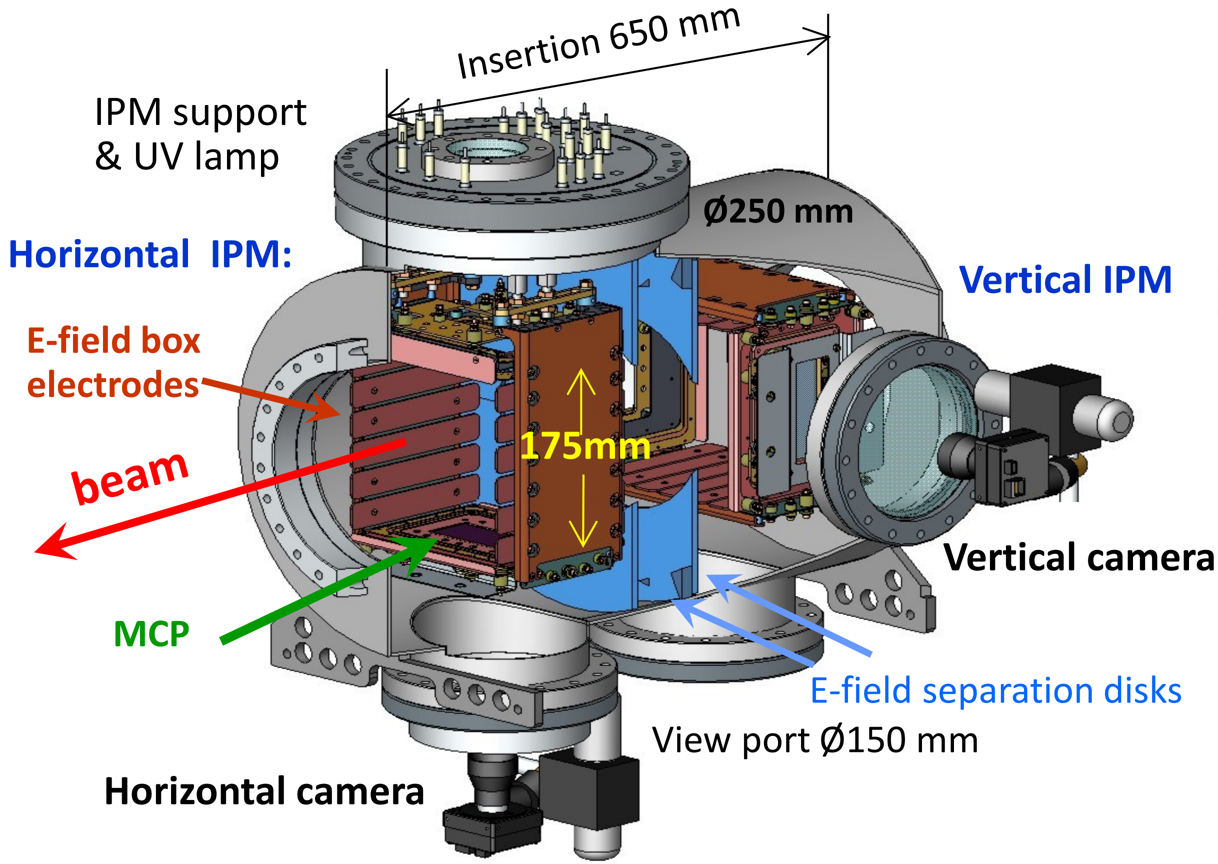
Typical vacuum pressure:

Transfer line: N_2 $10^{-8}...10^{-6}$ mbar $\cong$ $3\cdot10^{8}...3\cdot10^{10}\,\mathrm{cm}^{-3}$

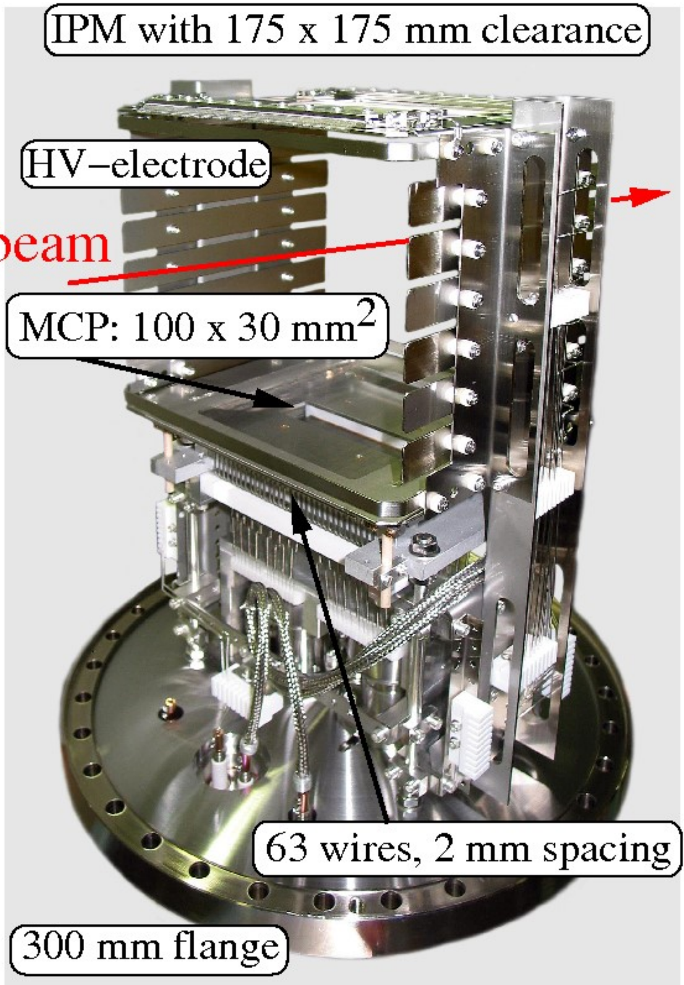
Synchrotron: H_2 $10^{-11}...10^{-9}$ mbar $\cong$ $3\cdot10^{5}...3\cdot10^{7}\,\mathrm{cm}^{-3}$

Ionization Profile Monitor Realization

The realization for the heavy ion storage ring ESR at GSI:



Realization at GSI synchrotron:
One monitor per plane



Ionization Profile Monitor Realization

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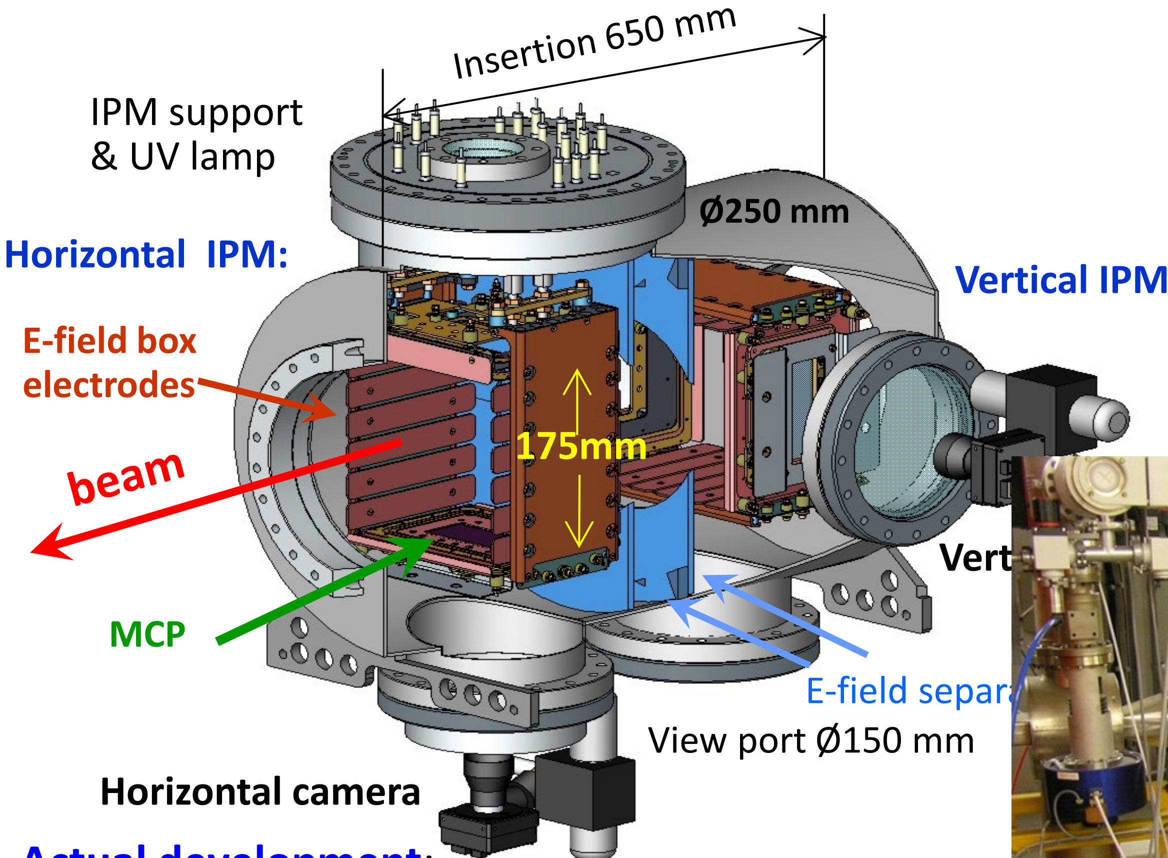
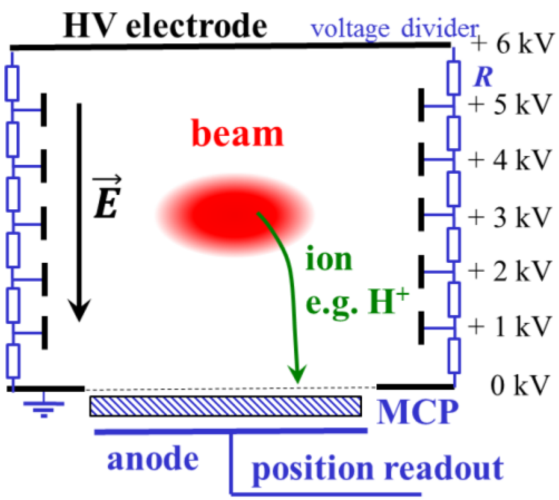


Actual development:
- Usage of pixel detectors
- Correction of space charge influence

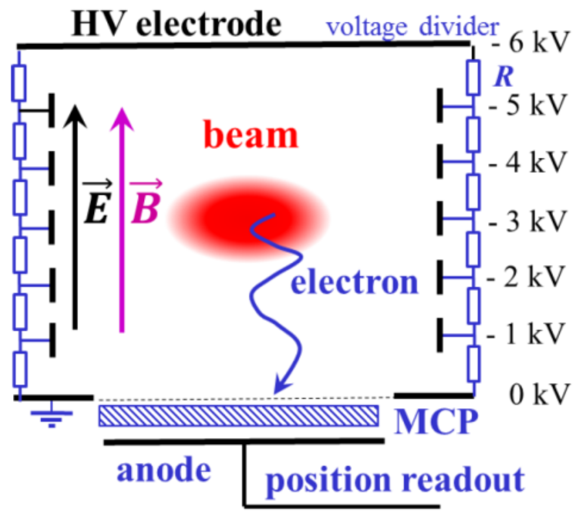
Remark: Not used at e^- –accelerators due to resolution of particle detector ≈ 50 µm.

Electron Detection and Guidance by Magnetic Field

Ion detection mode:

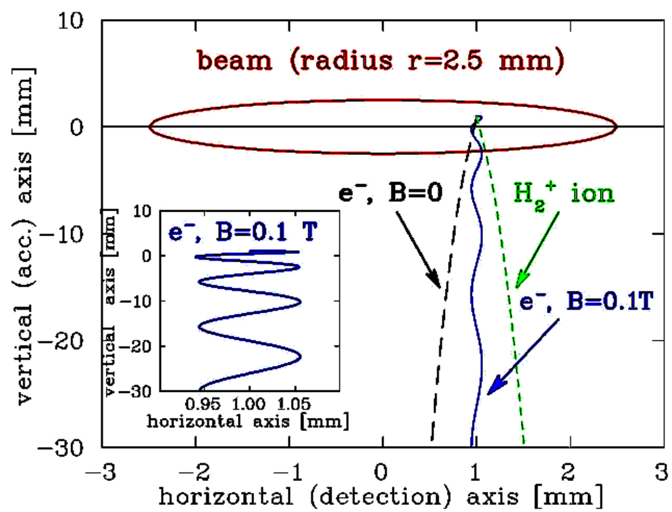


Electron detection mode:



⇒ broadening by beam's electric field

$7 \cdot 10^{10}$ charges per 10 m bunc



e^- detection in an external magnetic field

$\rightarrow$ cyclotron radius $r_C = \frac{mv_\perp}{eB}$

for $E_{kin,\perp} = 10$ eV & $B = 0.1$ T $\Rightarrow r_c \approx 100$ µm

E_{kin} from atomic physics, ≈100 µm resolution of MCP

Time-of-flight: ≈1 - 2 ns ⇒ 2 - 3 cycles.

B-field: Dipole with large aperture

→ IPM is expensive & large device!

Example for Space Charge Broadening at IPMs

Example for SIS18, length $\boldsymbol{C}$ = 216 m: 500 MeV/u with typical SIS18 parameters

H_2^+ detection:

Extr.: σ_{long} = 25 ns

σ_{trans} = 2.3 mm

t_{drift} = 220±15 ns

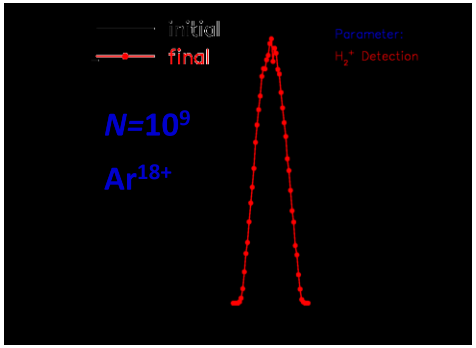
⇒ **broadening for**

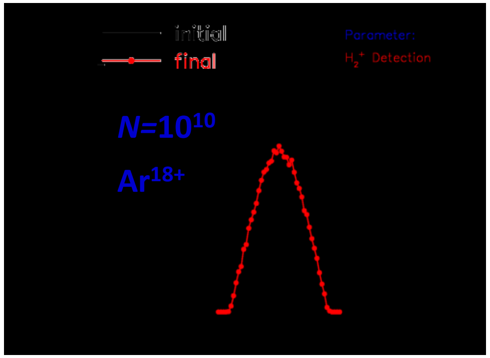
$N > 10^{10}$/bunch

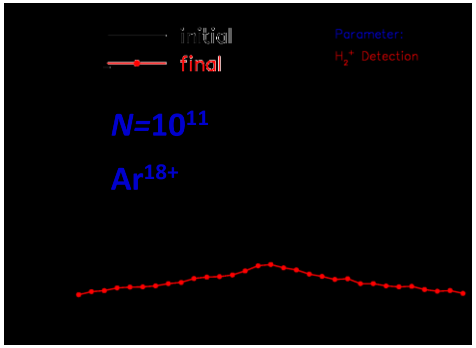
e^- detection:

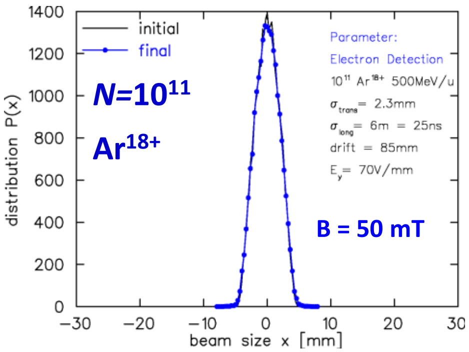
t_{drift}= 4.5±1 ns

⇒ **no broadening**

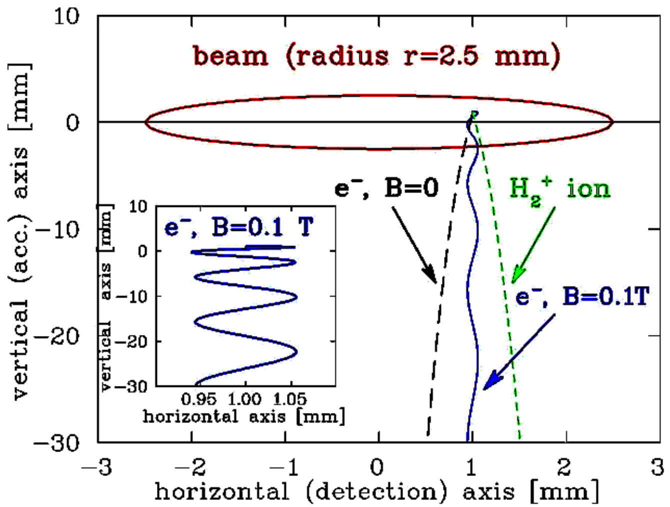








7· 10^{10} charges per 10 m bunch



⇒ **high intensities needs guiding magnetic field of $B \approx 100$ mT**

IPM: Magnet Design

Magnetic field for electron guidance:

Maximum image distortion:

5% of beam width ⇒ $\Delta B/B <$ 1 %

Challenges:

- High ***B***-field homogeneity of 1%
- Clearance up to 50 cm
- Correctors compensating by beam steering
- Insertion length up to 2.5 m incl. correctors

B = 250 mT
Gap 220 mm
Profile 32 strips
2.5 mm width

Actual Challenges for IPM:

- MCP single particle detector lifetime and calibration
  Alternative: Silicon pixel detector
- Turn-by-turn readout due to low signal
  Goal: e.g. control of transverse injection matching
- Correction of space charge broadening e.g. by machine learning for image reconstruction

Electron beams: Resolution of 50 μm is insufficient, but sometimes used for photon beams

Beam Induced Fluorescence BIF Monitor

Detecting ***photons*** from residual gas molecules, e.g. Nitrogen

$N_2 + \text{Ion} \rightarrow (N_2^{+})^* + \text{Ion} \rightarrow N_2^{+} + \gamma + \text{Ion}$

390 nm< λ< 470 nm

emitted into solid angle Ω to camera

single photon detection scheme

Advantage:

- Nearly no installation inside vacuum
- High resolution (here 0.2 mm/pixel) can be matched to application by optics
- Commercial Image Intensifier

Disadvantage:

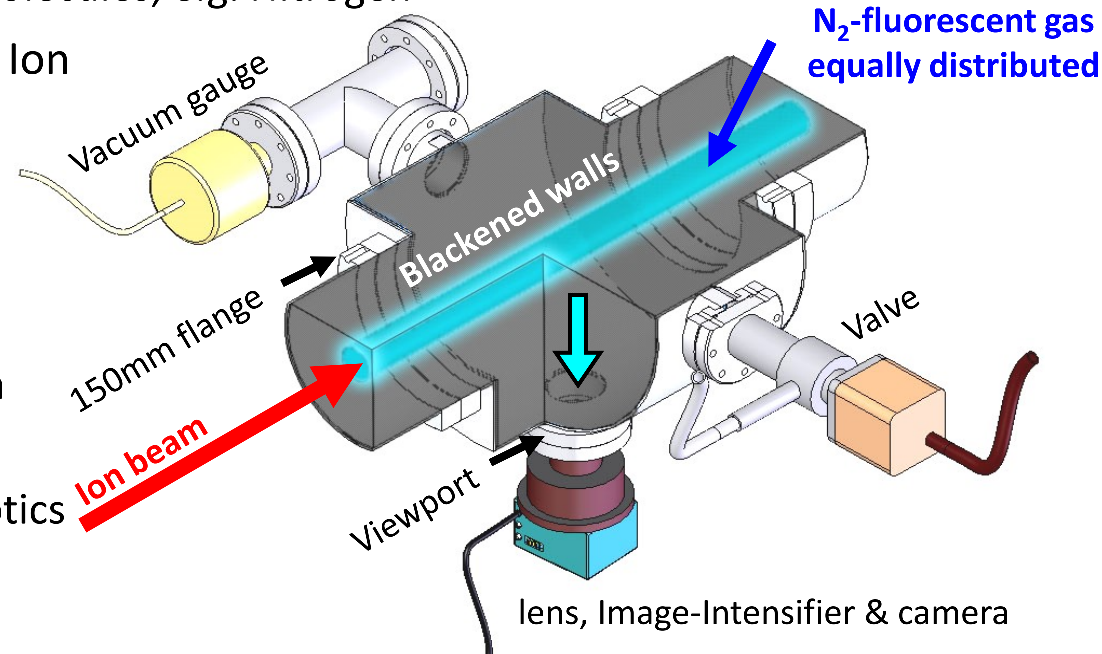
- Low signal strength, $\approx 10^{-4}$ of IPM
- Pressure bump up to 10^{-6} mbar required

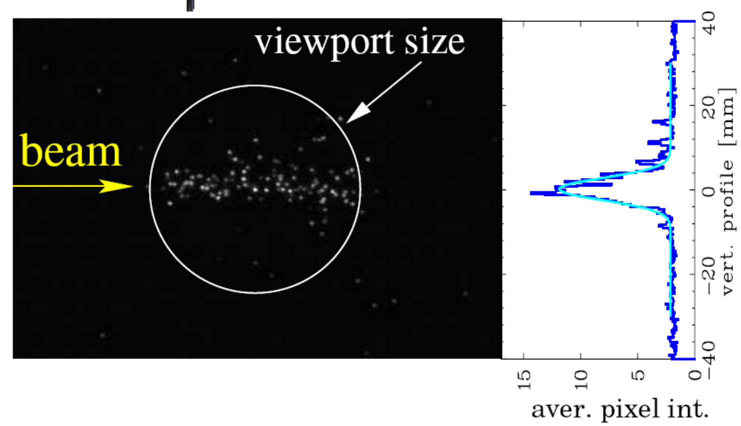
Usage:

At high power proton LINACs,
e.g. GSI-UNILAC, ESS normal conducting $E_{kin} \leq 90$ MeV

Actual challenge:

- Best performing gases, e.g. neutral Ne at 585 nm
- Space charge influence correction





Beam: Ar^{10+} at 4.7 MeV/u, I=2.5 mA, 10^{11} ppp, p=10^{-5} mbar

F. Becker et al., DIPAC'11

Synchrotron Radiation Monitor

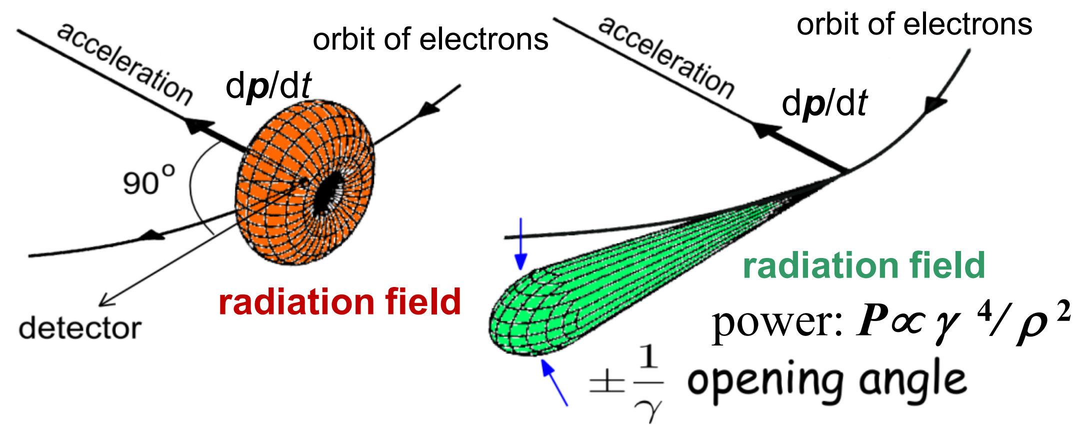
An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light

This light is emitted
into a cone of
opening $2/\gamma$ in lab-frame.
$\Rightarrow$Well suited for rel. e^-

For protons:

Only for energies E_{kin} > 100 GeV
i.e. only at CERN-SPS, BNL-RHIC
(and earlier at Fermilab, DESY)

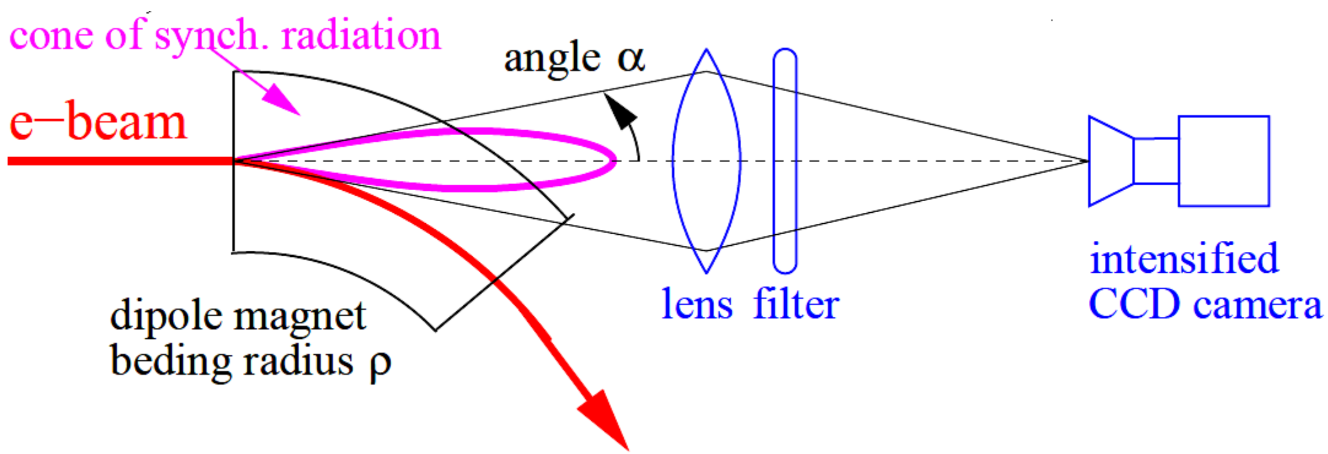
Rest frame of electron: **Laboratory frame:**



The light is focused to a sensitve camera

Advantage:

Signal anyhow available!



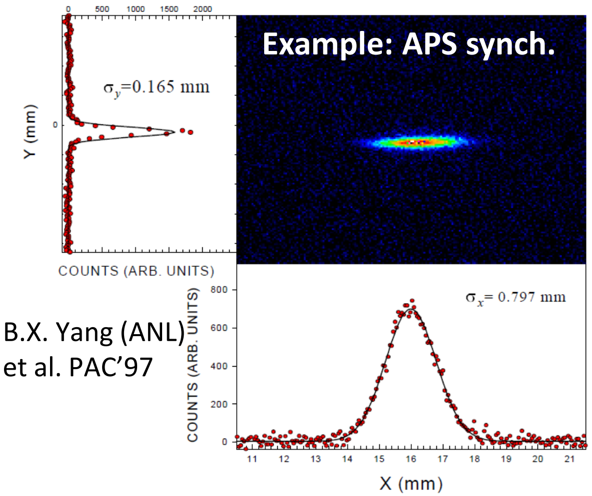
Realization of a Synchrotron Radiation Monitor

Extracting out of the beam's plane by a (cooled) mirror

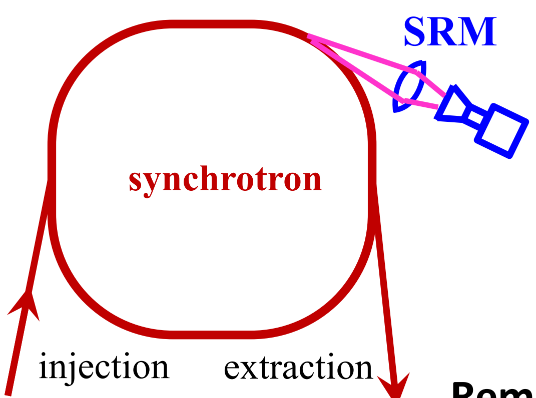
→ Focus to a slit + wavelength filter for optical wavelength

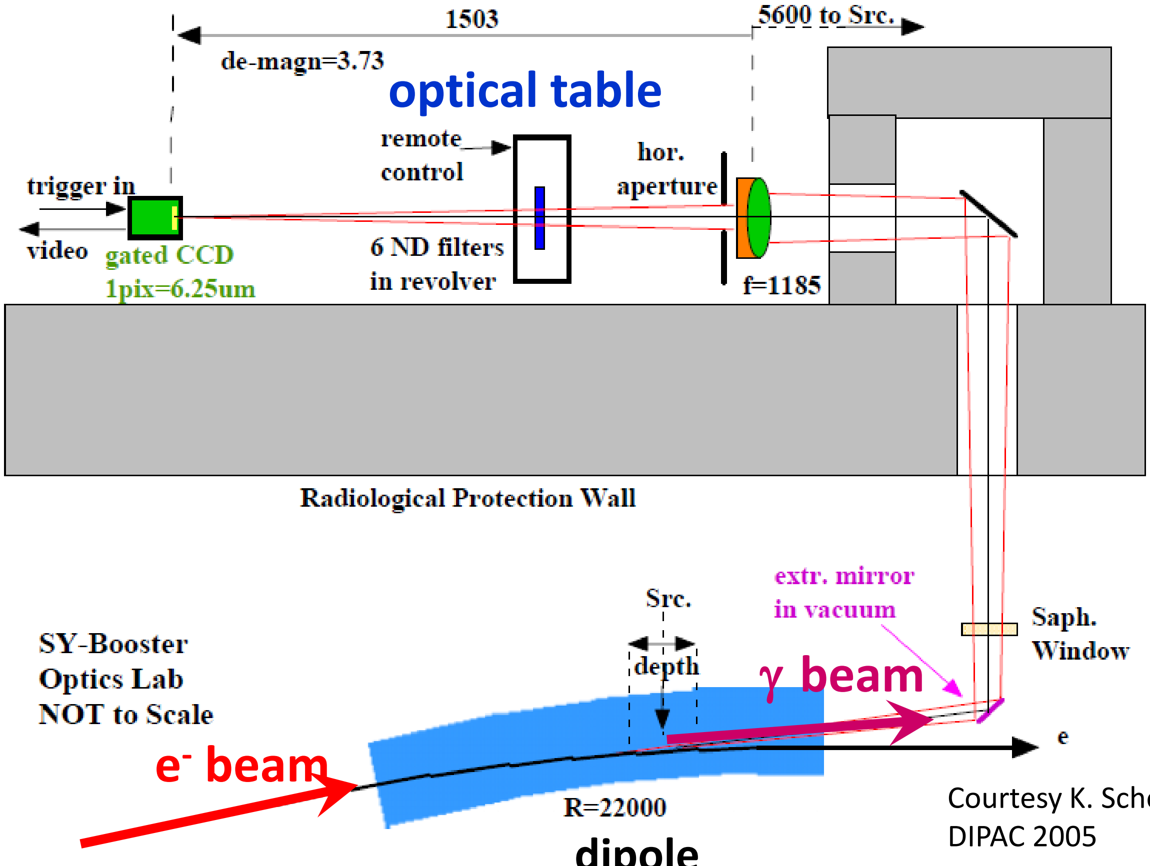
→ Image by sensitive camera

Example: ESRF monitor from dipole with bending radius 22 m (blue or near UV)



B.X. Yang (ANL) et al. PAC'97





Courtesy K. Scheidt et al., DIPAC 2005

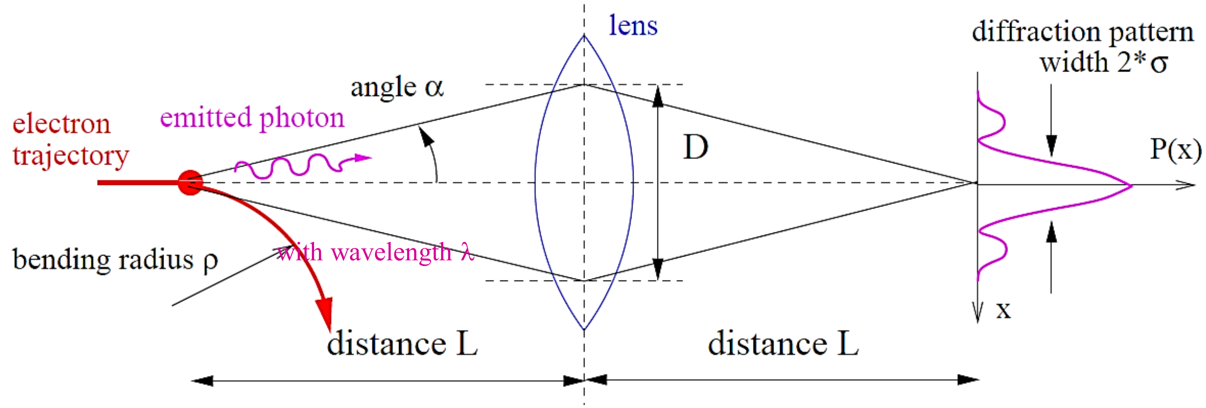
Remark: Time resolved observation with streak camera delivers bunch shape e.g. talk by H.G. Hwang for BESSY-VSR

Diffraction Limit of Synchrotron Light Monitor

Limitations:
Diffraction limits the resolution
due to Fraunhofer diffraction

$$\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$$

$$\approx 100 \ \mu\text{m for typical case}$$



Improvements:

- ***Shorter wavelength:***

  Using X-rays and an aperture of Ø 1m
  → 'X-ray pin hole camera',
  achievable resolution $\sigma \approx 10$ µm

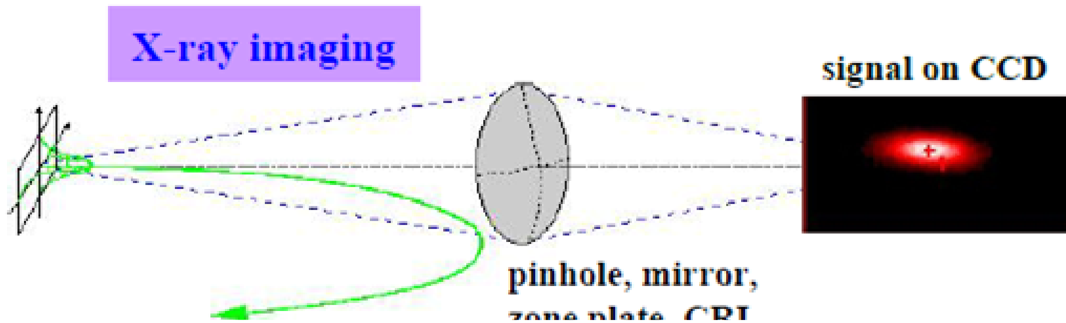
- ***Interference technique:***

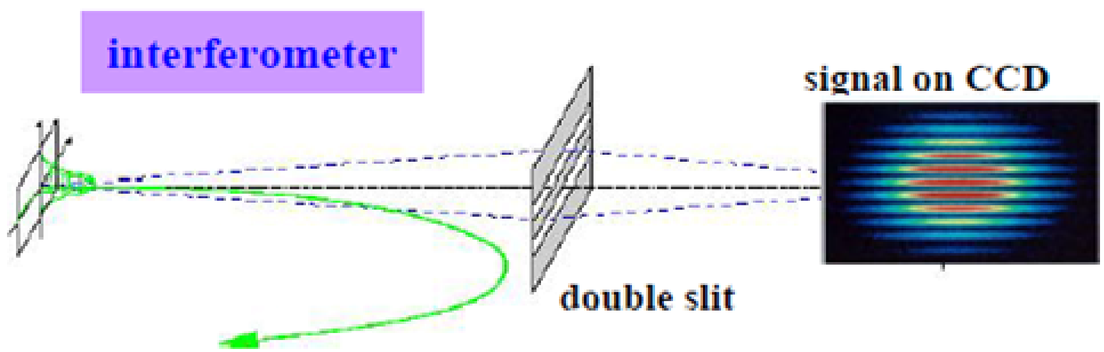
  At optical wavelength

  using a double slit

  → blurring of interference fringes

achievable resolution $\sigma \approx 1$ µm.
Example: Talk by H.G: Hwang for BESSY





Intermediate Summary for Profile Measurement

Different techniques are suited for different beam parameters:

e⁻-beam: typically Ø 0.01 to 3 mm, **protons:** typically Ø 1 to 30 mm

Intercepting ↔ non-intercepting methods (proton beams might have high beam intensity)

Direct observation of electrodynamics processes:

- Synchrotron radiation monitor: non-destructive → e⁻-beams, complex
- OTR screen: nearly non-destructive, large relativistic γ needed → e⁻-beams mainly

Detection of secondary photons, electrons or ions:

- Scintillation screen: destructive, large signal, simple setup → **all** beams
- IPM & BIF: non-destructive, expensive, limited resolution → for high intensity protons

Wire based electronic methods:

- SEM-grid: partly destructive, large signal and dynamic range, limited resolution
- Wire scanner: partly destructive, large signal and dynamics, high resolution, slow scan.

Bunch Length Measurement

Outline:

- Bunch length at non-relativistic proton LINACs
- Bunch length at FEL LINACs
  - electro-optical methods
  - transverse deflecting cavities

Remark: At proton synchrotrons the accelerating frequency is normally $f_{rf} \lesssim 10\text{MHz}$
$\Rightarrow$ bunch shape can be measured by Fast Current Transformer

Bunch Structure at low E_{kin}: Not possible with Pick-Ups

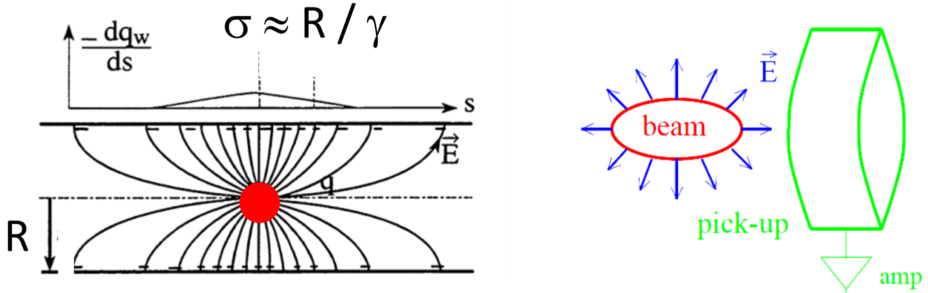
Pick-ups are used for:

- precise for bunch-center relative to rf
- course image of bunch shape

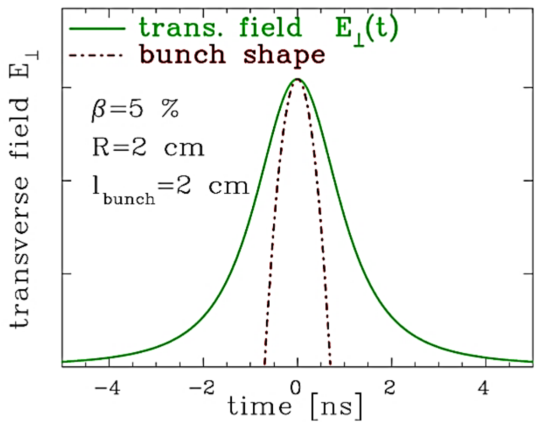
But:

For $\beta << 1 \rightarrow$ long. ***E***-field significantly modified:

$\sigma \approx R / \gamma$

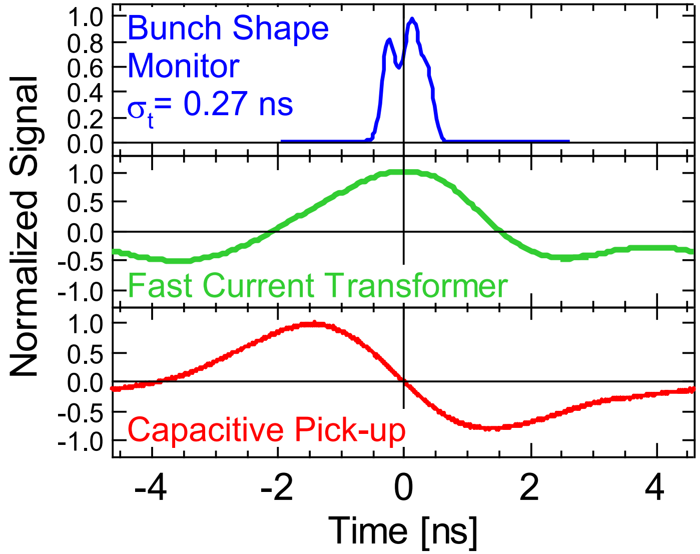


Example: Calculation of transverse eclectic field



Example: Comparison pick-up – particle counter:

Ar beam of 1.4 MeV/u (β = 5.5%) , f_{rf} = 108 MHz



1/ f$_{rf}$ = 9.2 ns

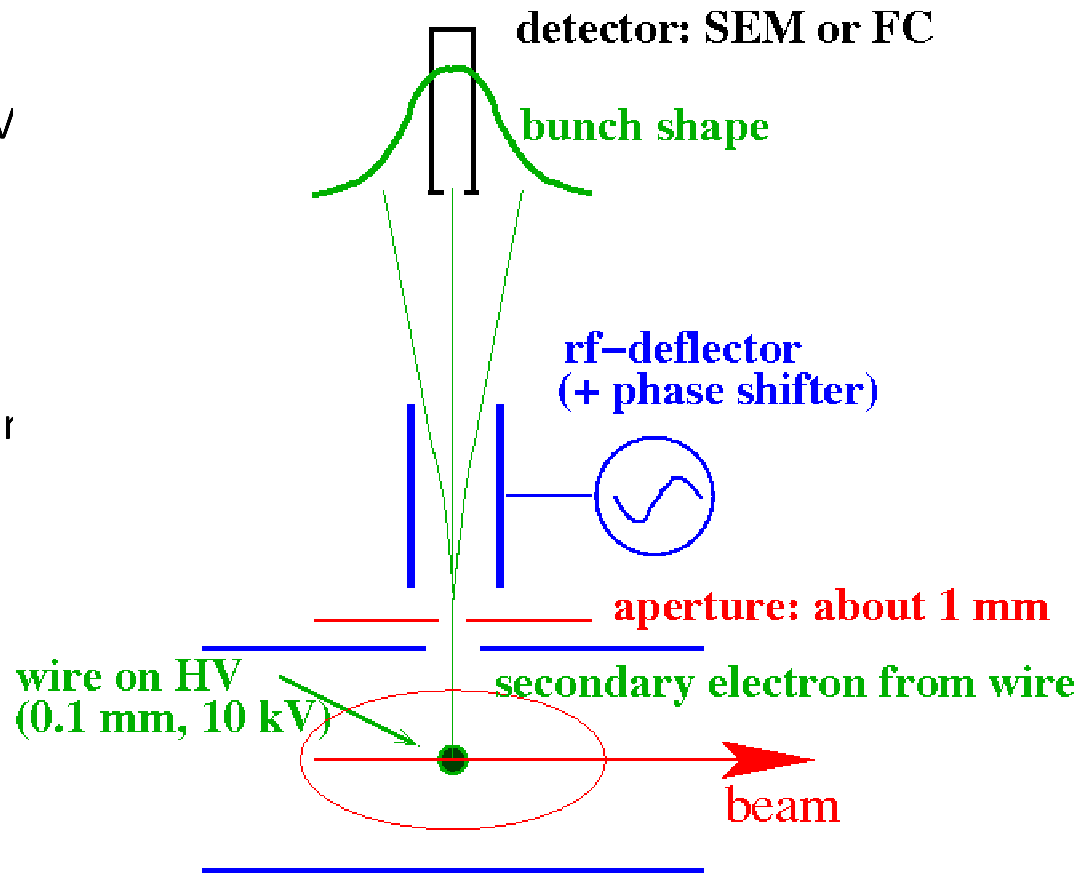
$\Rightarrow$ the pick-up signal is insensitive to bunch 'fine-structure'

Secondary e⁻ liberated from a wire carrying the time information.

→ Bunch Shape Monitor BSM (sometimes called 'Feschenko Monitor')

Working principle:

- insertion of a 0.1 mm wire at ≈ 10 kV
- emission of secondary e⁻ within less
- secondary e⁻ are accelerated
- toward an rf-deflector
- rf-deflector as 'time-to-space' conver
- detector with a thin slit
- slow shift of the phase
- resolution ≈ 1^o of accelerating rf



SEM: secondary electron multiplier

Secondary e⁻ liberated from a wire carrying the time information.

→ Bunch Shape Monitor BSM (sometimes called 'Feschenko Monitor')

Working principle:

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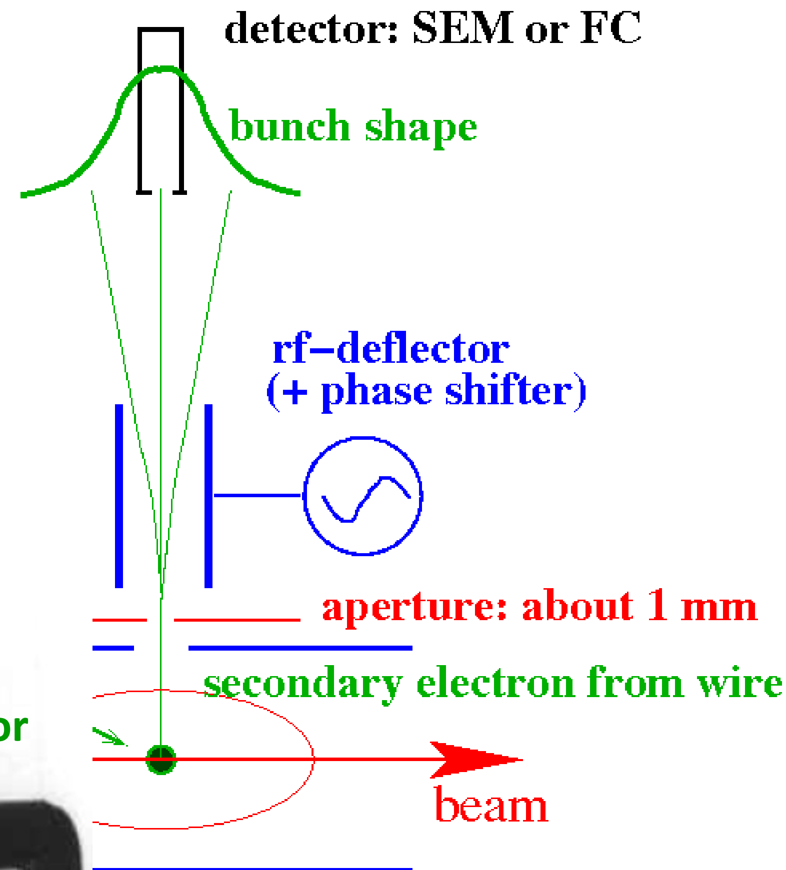
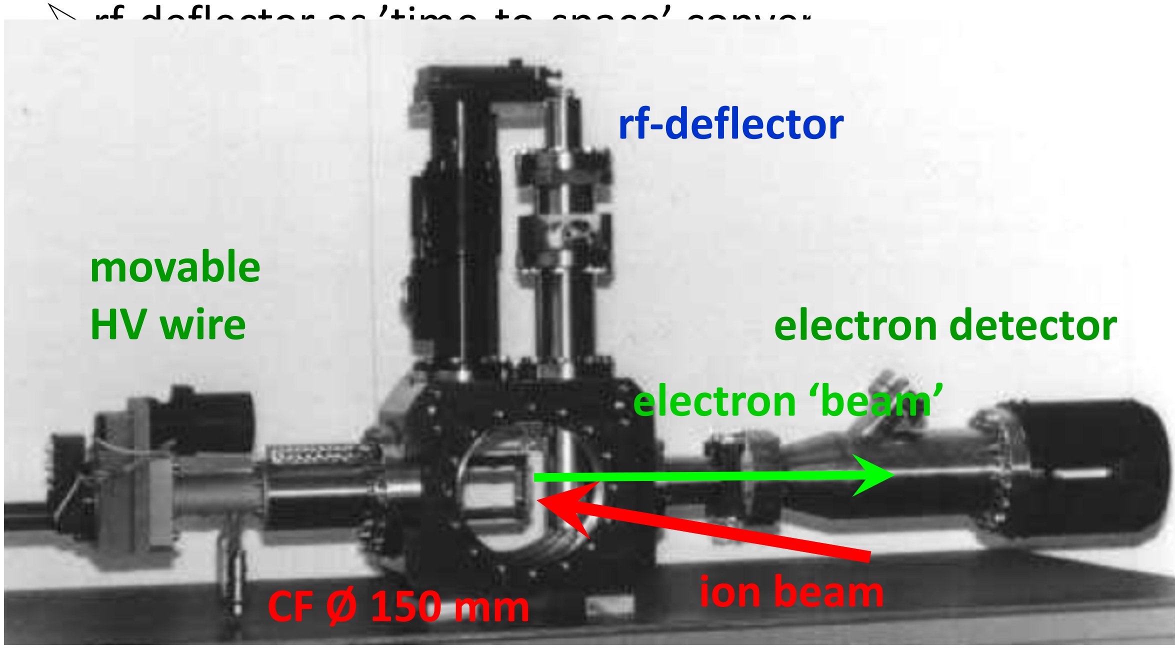




ry electron multiplier

Bunch Length Measurement by electro-optical Method

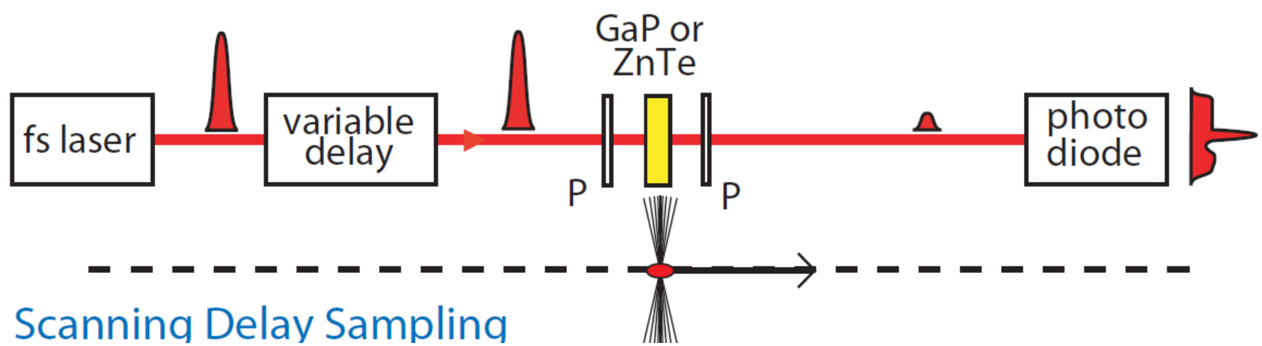
FELs → bunch length below 1 ps is achieved, i.e. below the resolution of streak camera

➢ Short laser pulses with ***t*** **≈ 10 fs** and electro-optical modulator

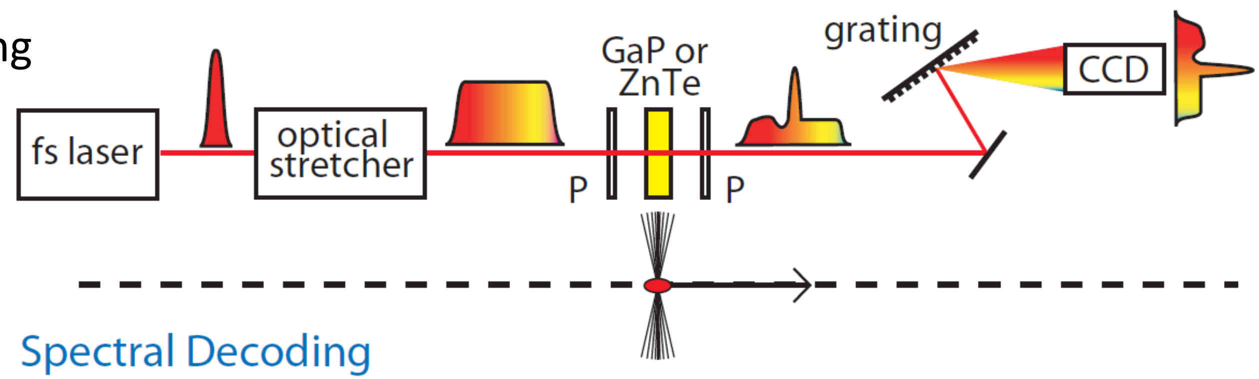
Electro optical modulator: birefringent, rotation angle depends on external electric field

Relativistic electron bunches: transverse field $\boldsymbol{E}_{\perp,lab} = \boldsymbol{\gamma E}_{\perp,rest}$ carries the time information.

Measurement by **scanning**
Short laser pulses ***t*** **< 10 fs**
and delay line
⇒ scanning method

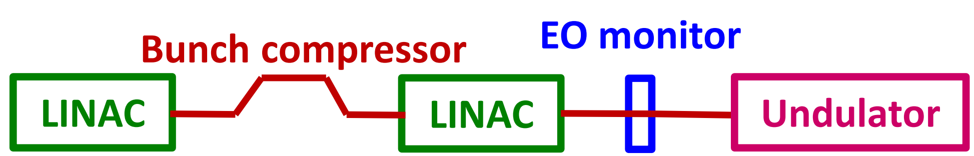


Measurement spectral decoding
Short laser pulses ***t*** **< 10 fs**
has broad frequency spectrum
and delay line
⇒ **single shot** determination

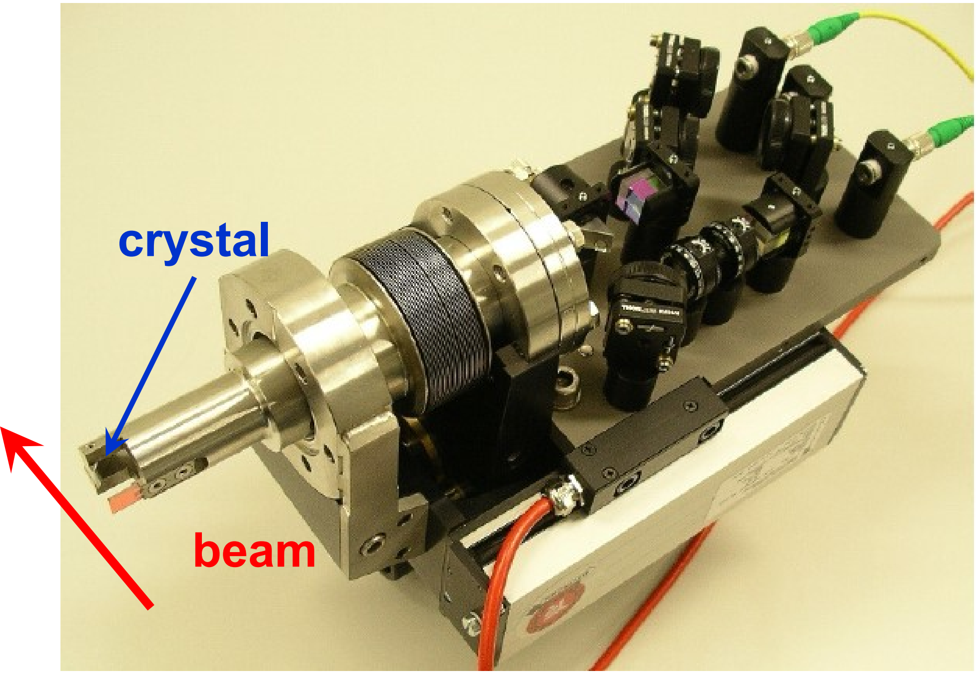


Further methods used!

From S.P.Jamison et al., EPAC 2006

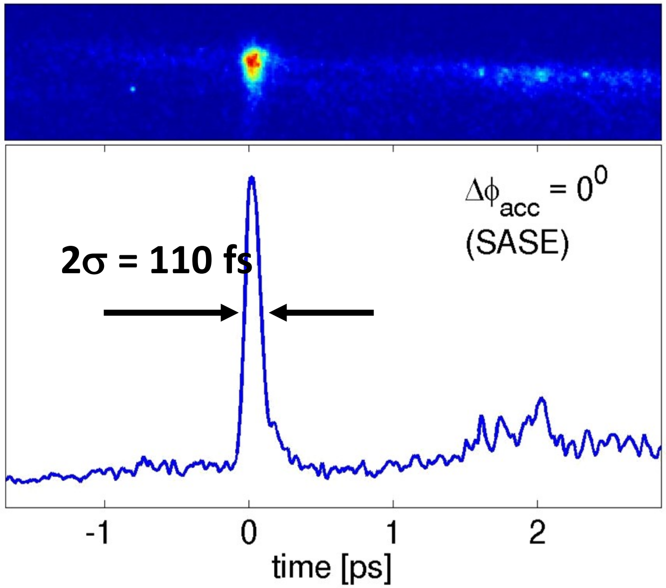


Hardware of a compact EOS Scanning Setup



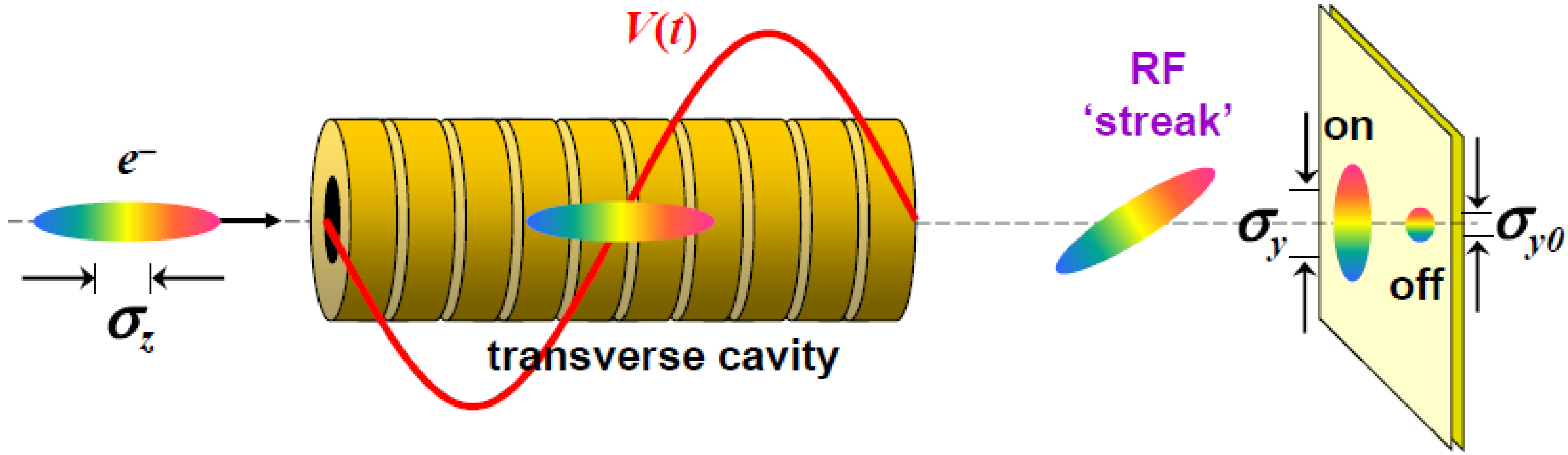
Example: Bunch length at FLASH

100 fs bunch duration = 30 μm length



B. Steffen et al, DIPAC 2009B. Steffen et al., Phys. Rev. AB 12, 032802 (2009)

Transversal deflection of the bunch i.e. time-to-space conversion

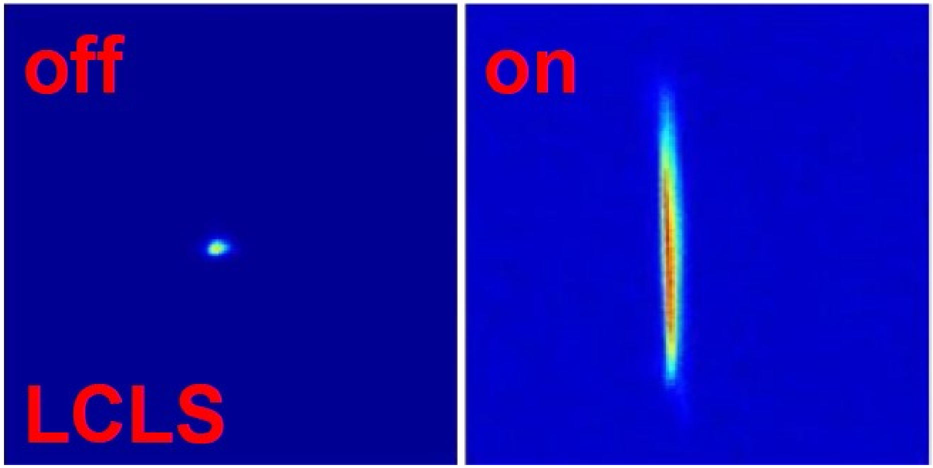


Size of the streak given by

$$\sigma_y = \sqrt{\sigma_{y0}^2 + R_{35} \cdot k \cdot \sigma_z^2}$$

k is determined by the rf-power

$$k = \frac{2\pi e \cdot U_{rf}}{\lambda_{rf} E}$$

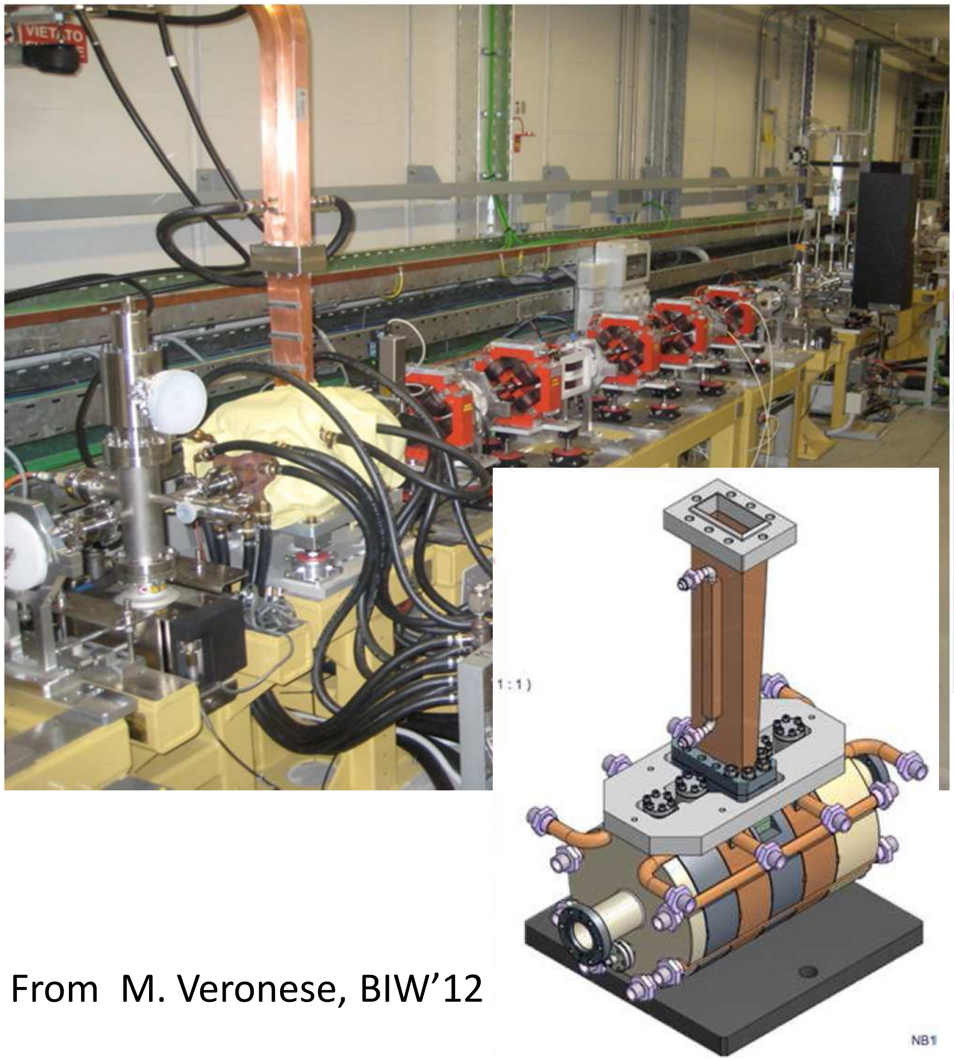


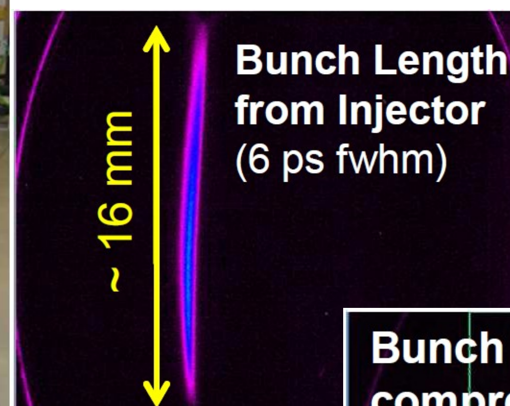
From D. Xiang et al., IPAC'12

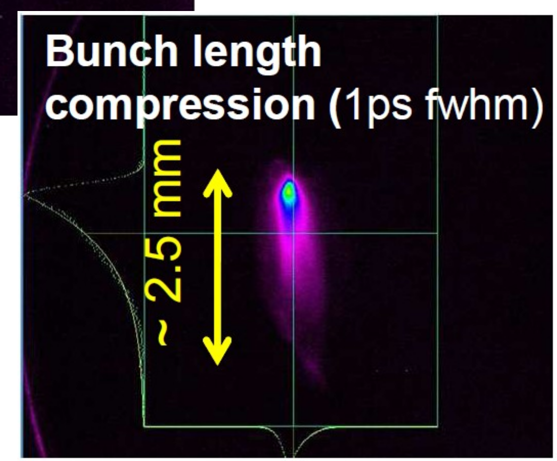
Transversal deflection of the bunch i.e. time-to-space conversion

Example: Cavity at FERMI, Trieste, Italy

Beam energy	320 MeV
Typical beam size	0.2 mm
Length	0.5 m
Frequency	2.998 GHz
Max. rf power	5 MW
Total trans. volt.	4.9 MV
Time resolution	70 fs







From M. Veronese, BIW'12

Conclusion

Diagnostics is required for operation and development of accelerators

Several categories of demands leads to different installations:

- Quick, non-destructive measurements leading to a single number or simple plots
- Complex instrumentation used for hard malfunction and accelerator development
- Automated measurement and control of beam parameters i.e. feedback

The goal and a clear interpretation of the results is a important design criterion.

General comments:

- Quite different technologies are used, based on various physics processes
- Accelerator development goes parallel to diagnostics development

Further instruments and diagnostic methods:

- Beam Loss Monitors, bunch shape monitors, laser-based methods for e^- & H^-, luminosity monitors....
- Diagnostics for closed orbit & lattice parameters, Schottky analysis.....

Thank you for your attention!

Backup slides

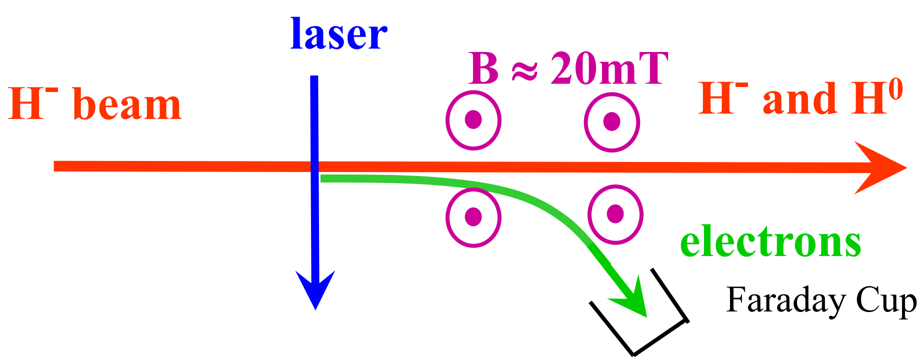
Laser Scanner: Principle for H^- Beams

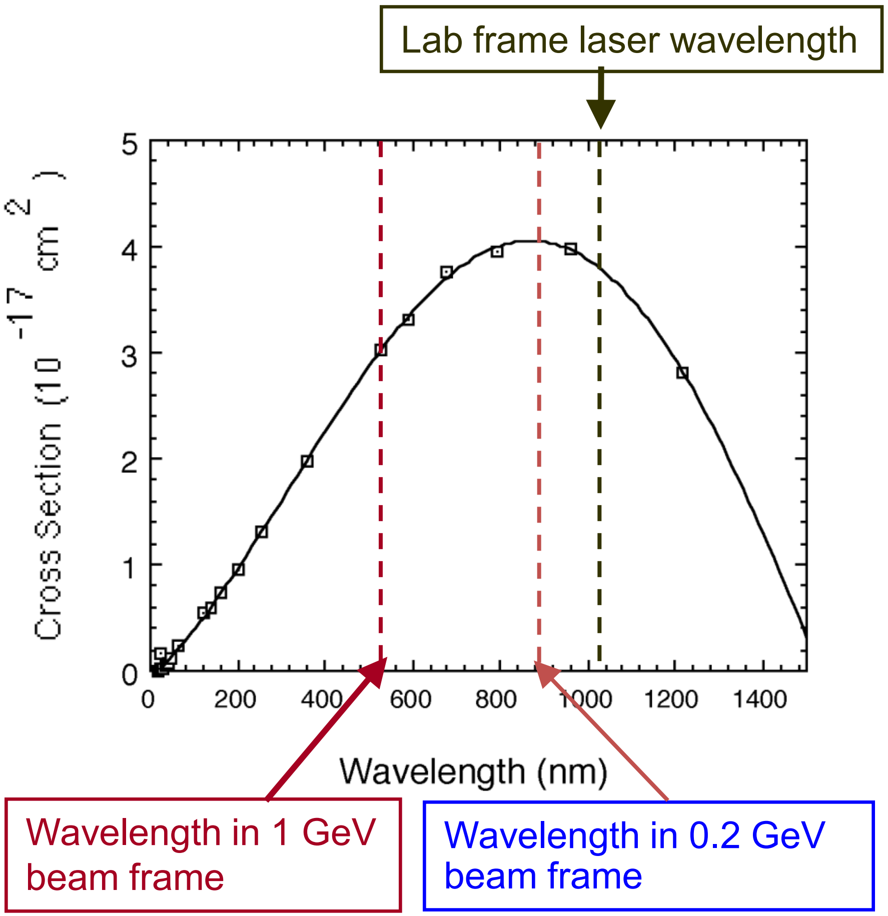
Photo-detachment: **$H^- + \gamma \rightarrow H^0 + e^-$** binding energy E=0.75 eV $\leftrightarrow$ λ=1670 nm

Photo-detachment maximal at λ=830 nm

Doppler shifted photon energy in rest-frame:

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





Example: SNS, CERN LINAC4

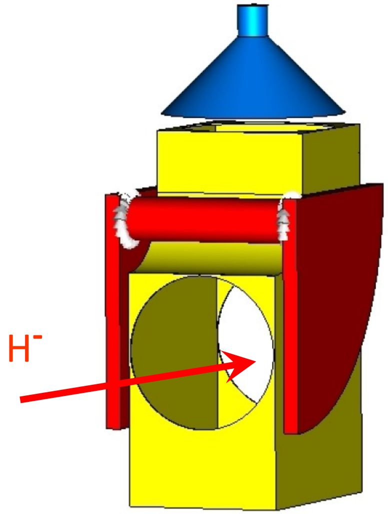
Y. Liu (SNS) et al., NIM **A** 238, 241 (2010) , R.Connolly et al., Proc. LINAC'02

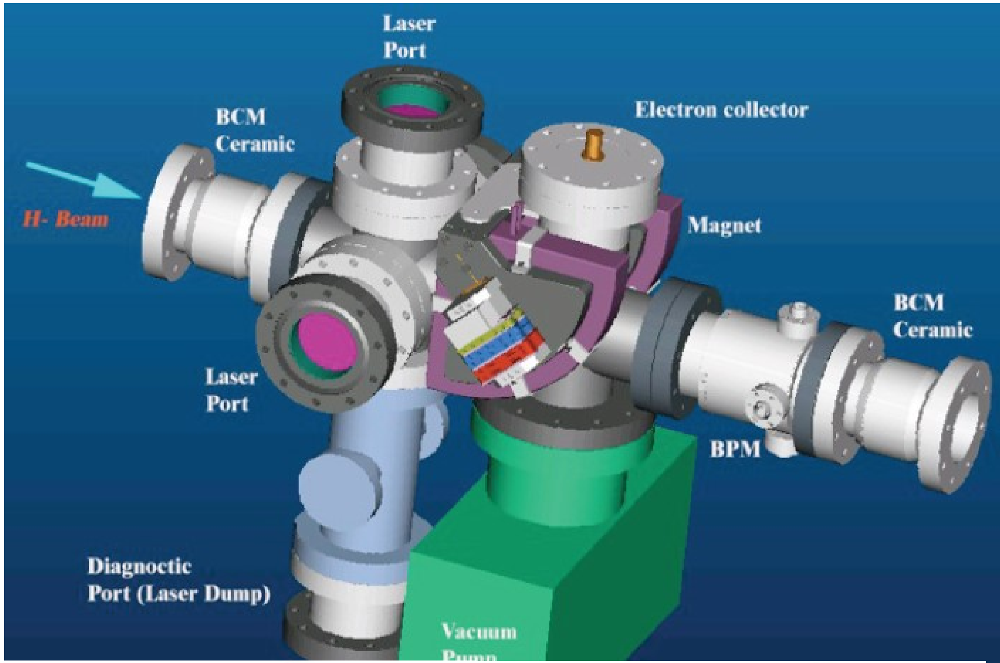
Laser Scanner: Detection Scheme for H$^-$ at SNS-LINAC

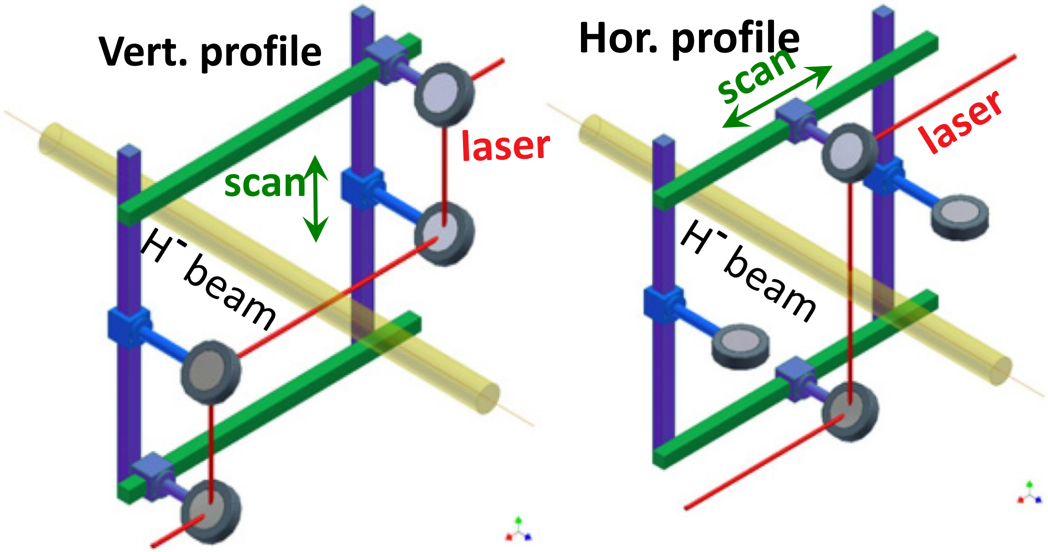
SNS installation:

Nd:YAG (λ_{lab}=1064 nm, 100 mJ, 7ns)

- One of 9 stations is served at a time
- Laser with spot size: 10 to 50 µm
- e$^-$ separation by **B** ≈ 20 mT
- Detection with Faraday Cup







Y. Liu (SNS) et al., NIM **A** 238, 241 (2010),
Y. Liu (SNS) et al., Phys. Rev Accel. Beams 16, 2013)

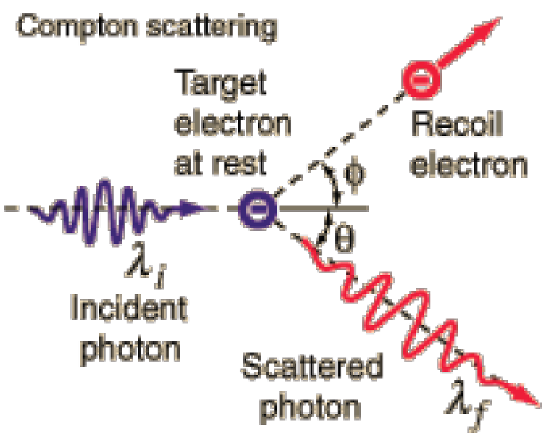
Laser Wire Scanner for Electrons: Principle

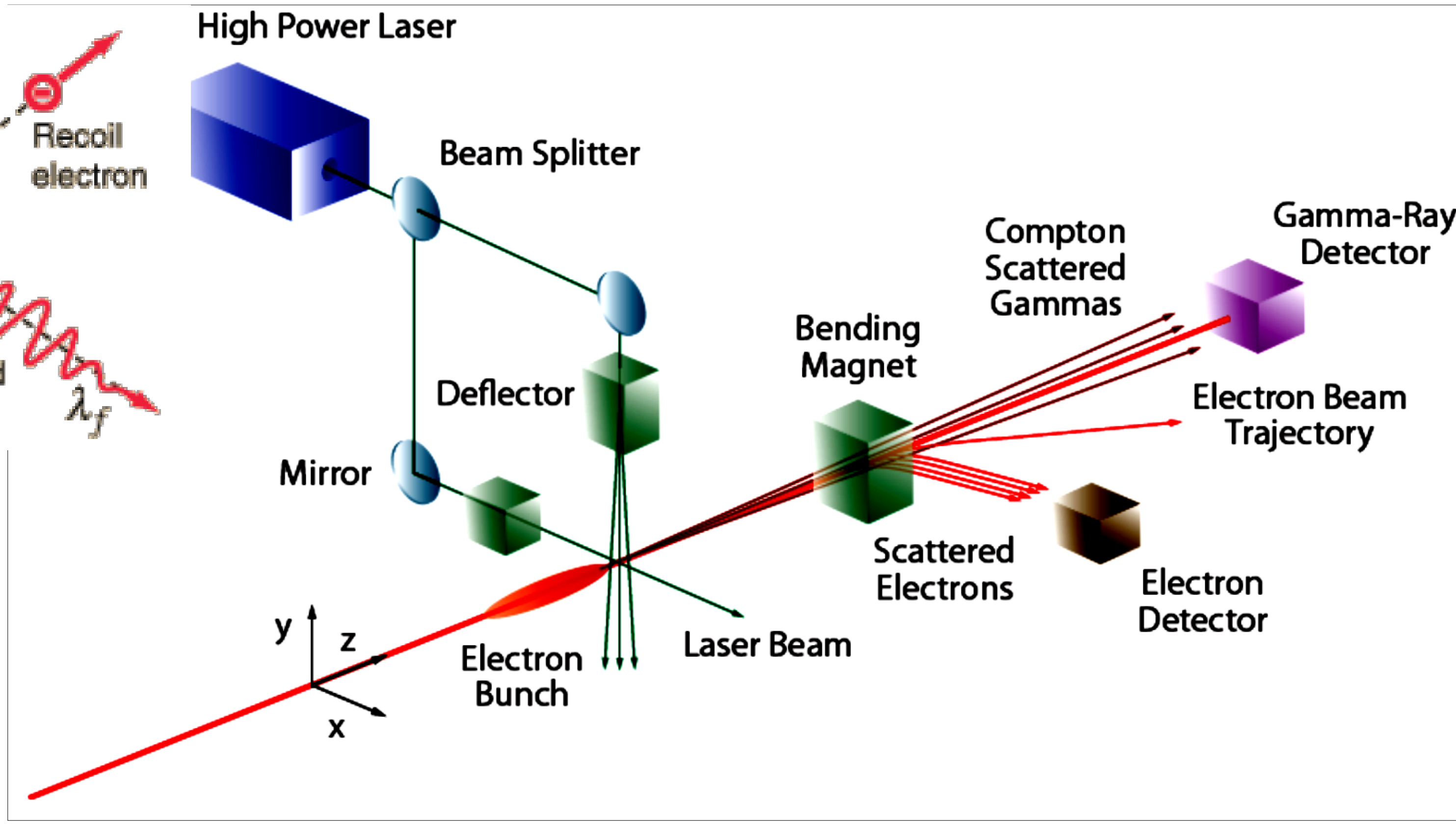
'Inverse' Compton Scattering by photon scattered at high energy electron:

Calculation: Regular Compton scattering in e⁻ rest frame & Lorentz Transformation to lab-frame

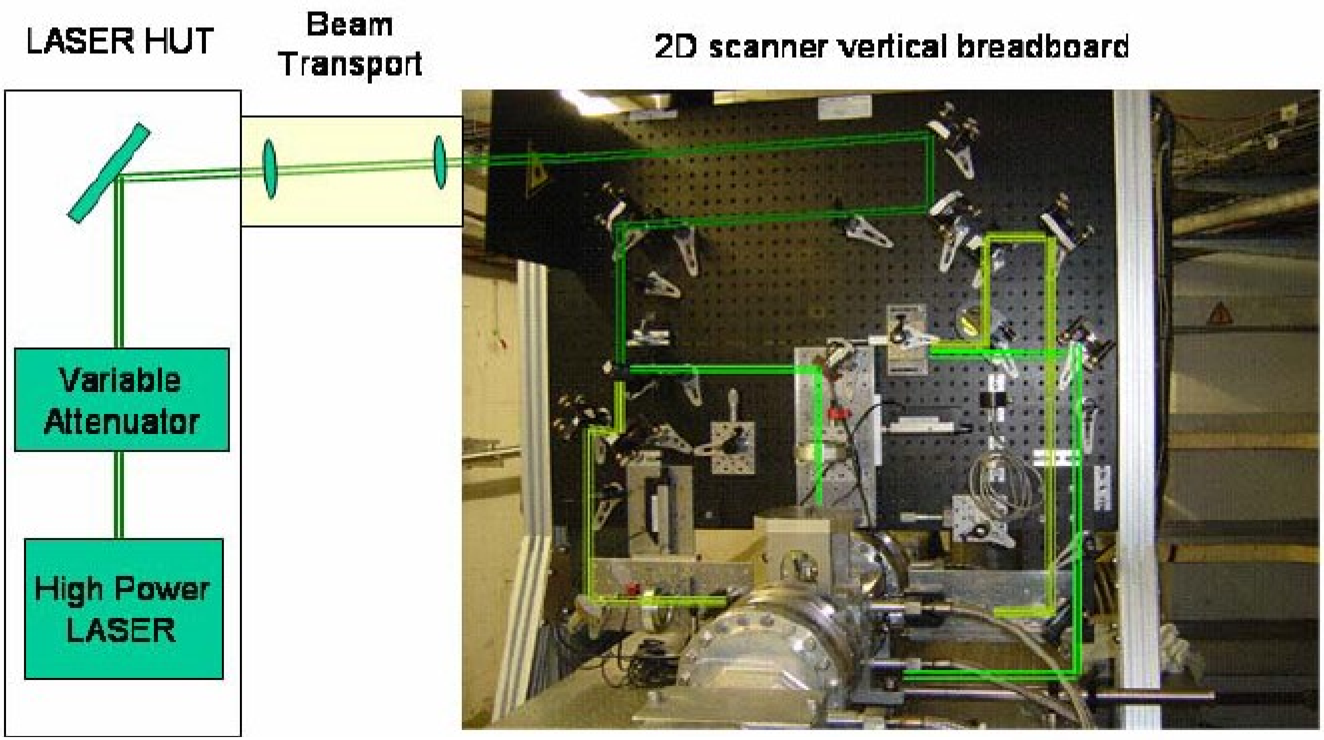
$\Rightarrow$ Increase of photon energy by γ^2 for 90° scattering $h\nu_{sc} = 2\gamma^2 \cdot h\nu_0$ i.e. up to GeV

Detection by γ-ray detector e.g. thick scintillator

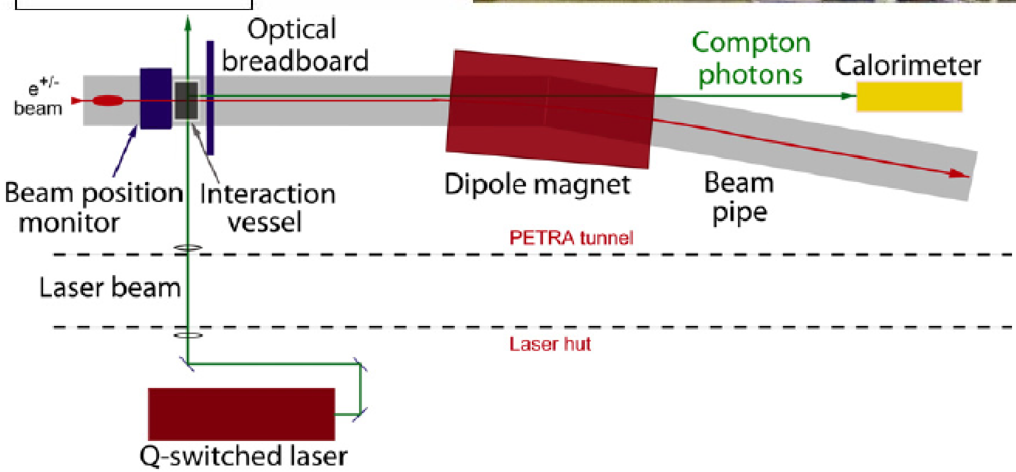




Laser Wire Scanner at PETRA III at DESY: Installation



High power laser, e.g. Nd:YAG laser:
λ = 532 nm, t_{pulse}≈5 ns
W_{pulse} ≈ 60 mJ,
P_{pulse} ≈ 12 MW
scan duration ≈ 100 s

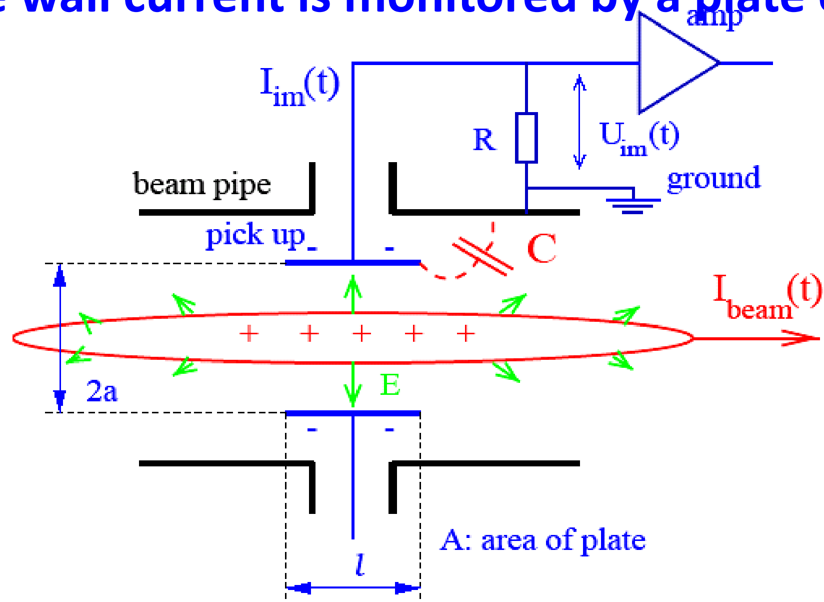


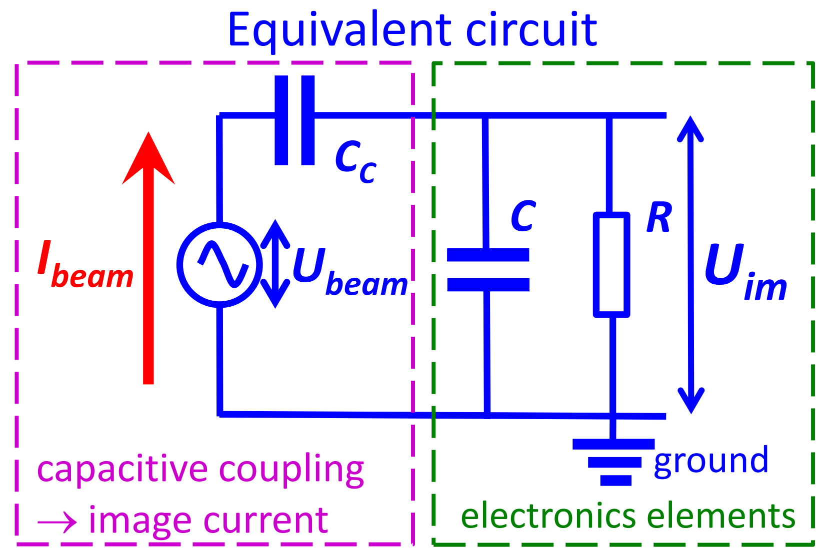
Detector for scattered γ:

- 3x3 $PbWO_4$
- each 18 x 18 x 150 mm^3
- 95 % detection efficiency

T. Aumeyr (Uni. London) et al., PAC 2007, IPAC 2010

The wall current is monitored by a plate or ring inserted in the beam pipe:





At a resistor ***R*** the voltage ***U$_{im}$*** from the image current is measured.

Goal: Connection from beam current to signal strength by transfer impedance $Z_t(\omega)$

in frequency domain: $U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega) \cdot I_{beam}(\omega)$

Result: $$Z_t(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1+i\omega RC} \quad \in \mathbb{C}$$ i.e. complex function

geometry

stray capacitance

frequency response

Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

$$U_{im}(\omega)=Z_t(\omega)\cdot I_{beam}(\omega)$$

$$|Z_t| = \frac{A}{2\pi a}\cdot\frac{1}{\beta c}\cdot\frac{1}{C}\cdot\frac{\omega/\omega_{cut}}{\sqrt{1+\omega^2/\omega^2_{cut}}}$$

$$\varphi = \arctan(\omega_{cut}/\omega)$$

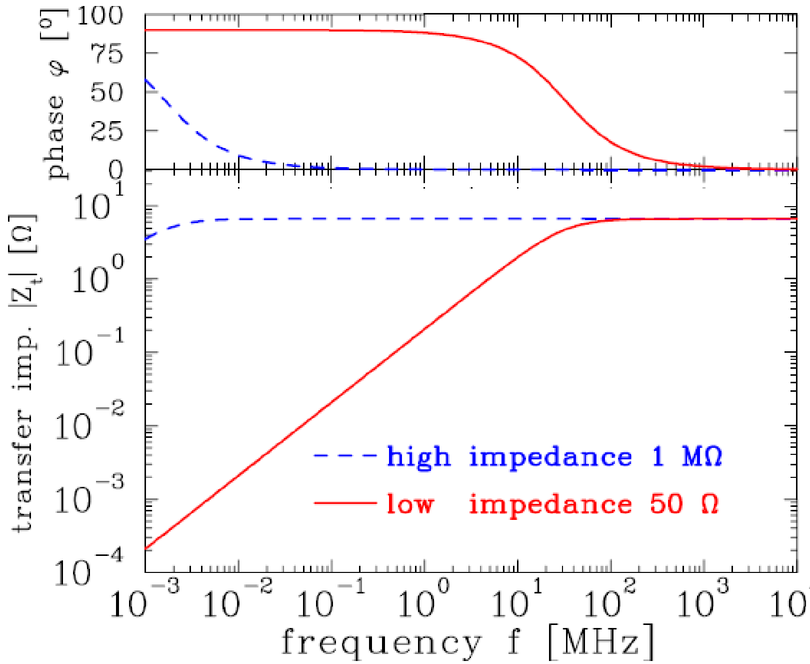
Parameter linear-cut BPM at proton synchr.:

C = 100pF, l = 10cm, β = 50%

$f_{cut} = \omega/2\pi = (2\pi RC)^{-1}$

for $R = 50\ \Omega \Rightarrow f_{cut}$ = 32 MHz

for $R = 1\ M\Omega \Rightarrow f_{cut}$ = 1.6 kHz



Large signal strength for long bunches $\rightarrow$ **high impedance**

Smooth signal transmission important for short bunches $\rightarrow$ **50 Ω**

Remark: For $\omega \rightarrow 0$ it is $Z_t \rightarrow 0$ i.e. **no** signal is transferred from dc-beams e.g.

- de-bunched beam inside a synchrotron
- for slow extraction through a transfer line

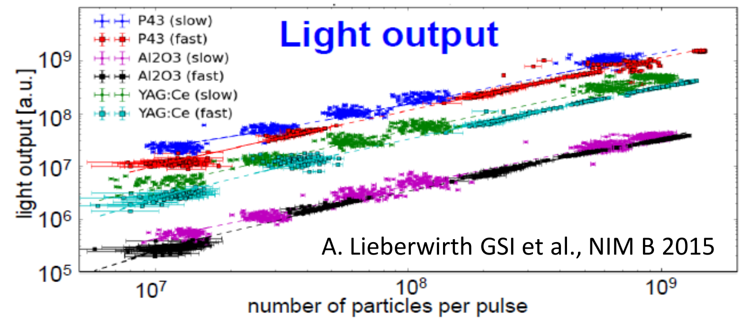
Test of different scintillators

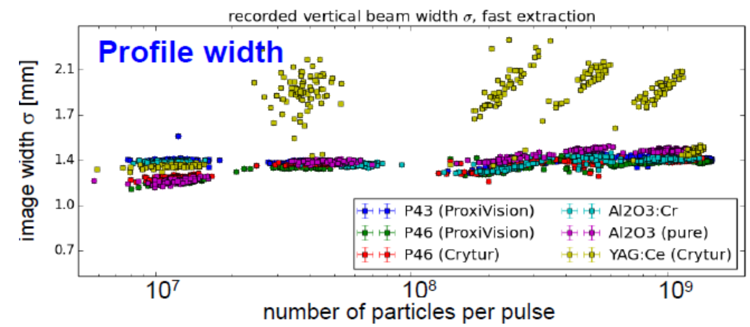
Tpy. scintillators ↔ Phosphor powder ↔ ceramics

Example: Irradiation with ions at GSI

- **Light yield:**
  Very different brightness (here factor 1000)
  Still linear with beam current even for large doses
- **Profile:**
  Most materials show correct results
  Deviation understood and possible cures discussed

Accelerators: ⇒ Material choice matched to beam





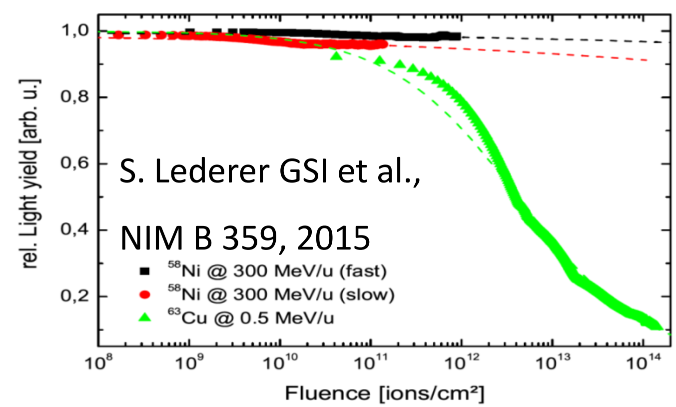
Radiation hardness tests

Example: Irradiation with 0.5 MeV/u and 300 MeV/u

- Damage by irritation depends strongly on
  ion type and energy
- Model calculations discussed with experts

Accelerators:

⇒ Important finding for target diagnostics at SNS or ESS

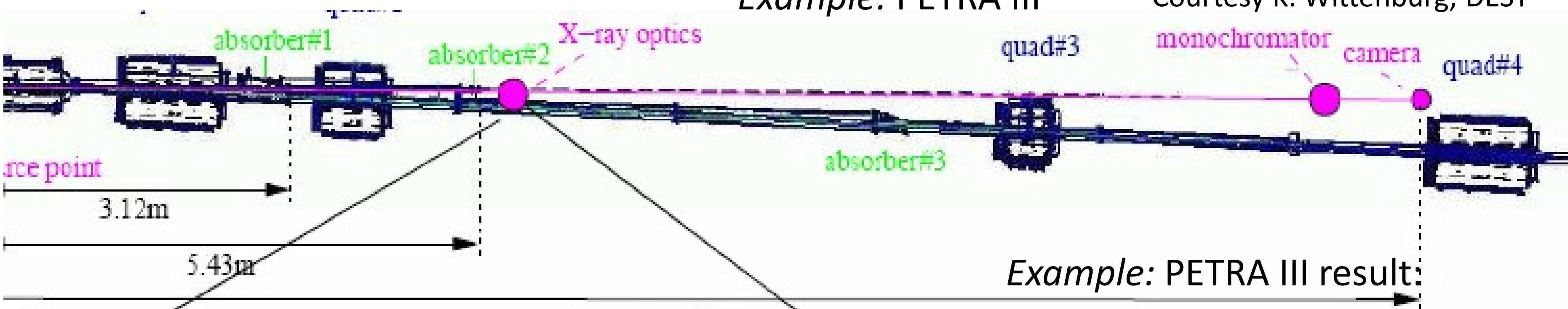


Corutesy B. Walasek-Höhne GSI

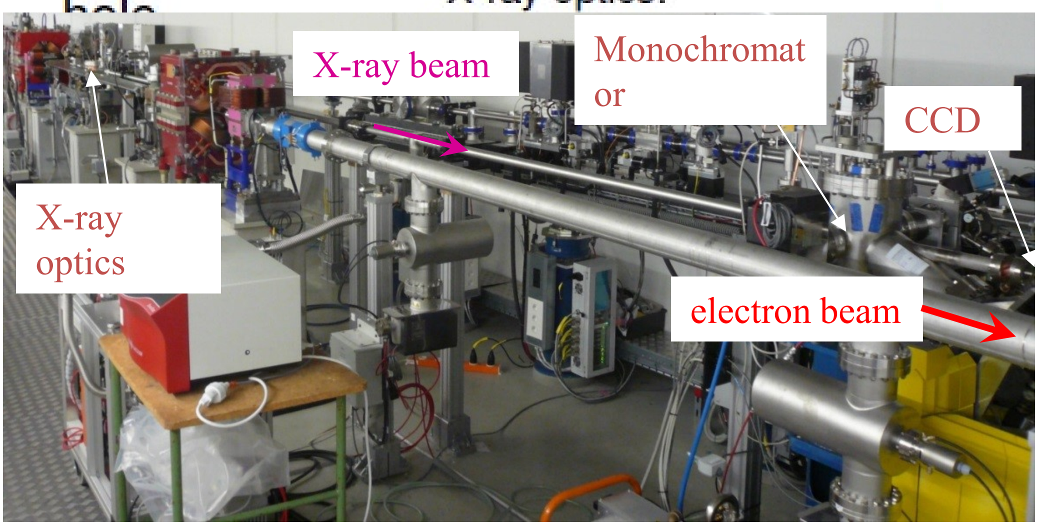
X-ray Pin-Hole Camera

The diffraction limit is $\Rightarrow \sigma \cong 0.6 \cdot \left(\lambda^2 / \rho\right)^{1/3}$ $\Rightarrow$ ***shorter wavelength by X-rays***.

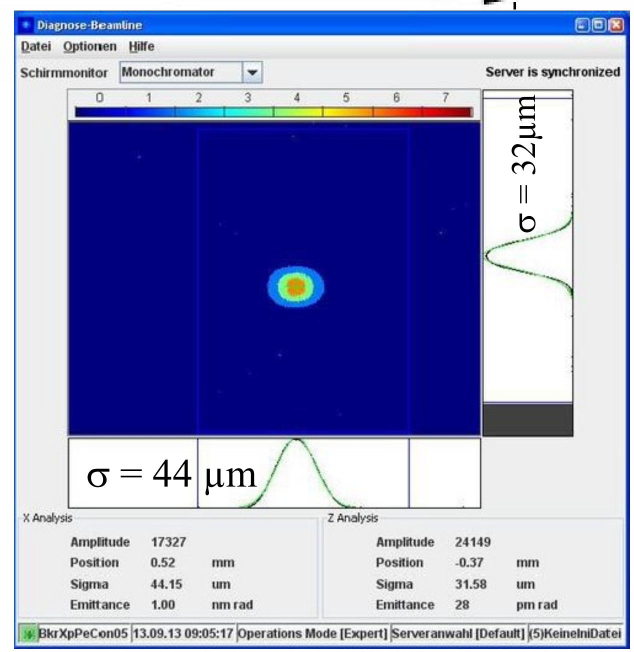
Example: PETRA III Courtesy K. Wittenburg, DESY



Two interchangeable X-ray optics:



Example: PETRA III result:



Energy loss of ions in metals close to a surface:

Closed collision with large energy transfer: $\rightarrow$ fast e^- with E_{kin} >> 100 eV

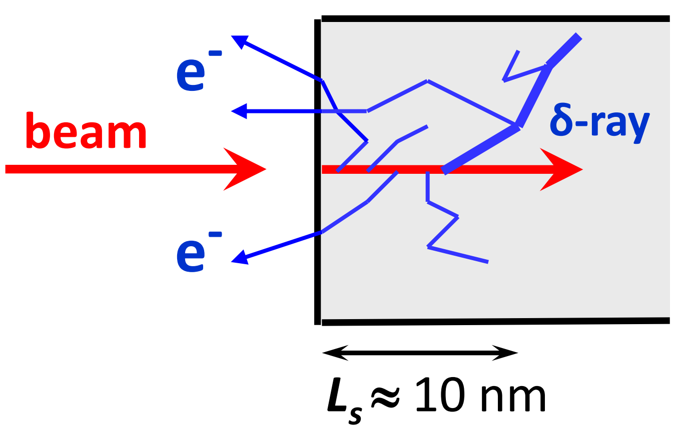
Distant collision with low energy transfer : $\rightarrow$ slow e^- with $E_{kin} \leq$ 10 eV

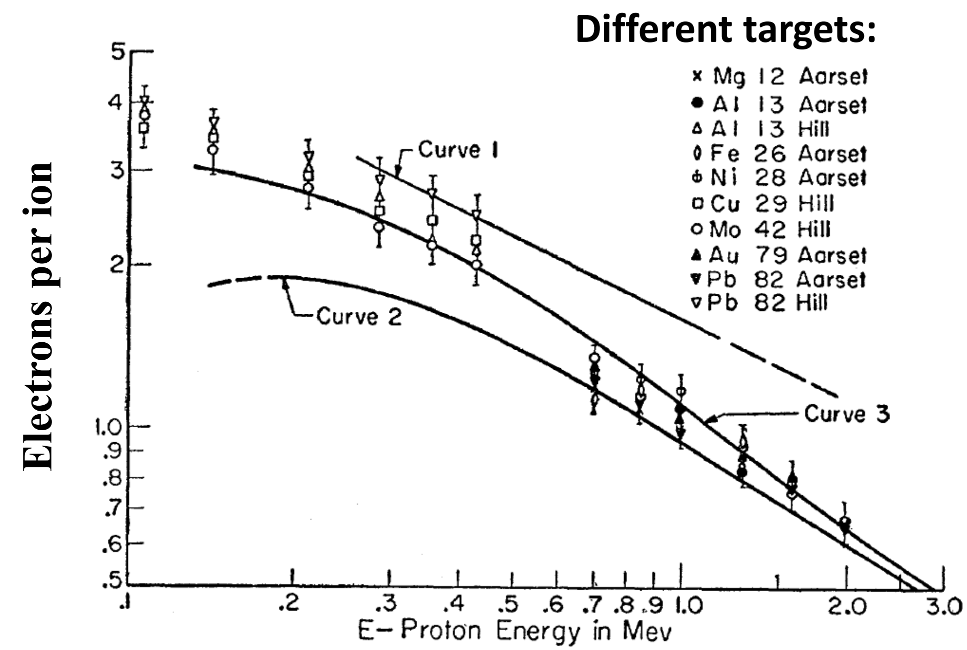
$\rightarrow$ ‘diffusion’ & scattering with other e^-: scattering length $L_s \approx$ 1 - 10 nm

$\rightarrow$ at surface $\approx$ 90 % probability for escape

Secondary **electron yield** and energy distribution comparable for all metals!

$\Rightarrow$ ***Y = const. * dE/dx*** (Sternglass formula)





From E.J. Sternglass, Phys. Rev. 108, 1 (1957)