

Beam Emittance and Beam Profile Monitors


Transport lines and Linacs



Phosphor Screens
SEM Grids/Harps
OTR
Wire scanners (Linacs)


Emittance of single shots

Hadron accelerators

Wire scanners 
Residual Gas Ionization (IPM)
Residual Gas Scintillation
Synchrotron light (Edge effect, wigglers)
Scrapers/current (destructive)

Emittance preservation

Electron accelerators

Synchrotron light 
Wire Scanners
Scrapers/current (destructive)
Laser Wire Scanner

Aspect ratio/coupling

Idea of this course: Beam Profile monitors use quite a lot of different physical effects to measure the beam size. Many effects on the beam and on the monitor have to be studied before a decision for a type of monitor can be made. In this session we will

- 1) discuss emittance measurements and we will make
- 2) some detailed examinations of at least two monitor types to demonstrate the wide range of physics of the profile instruments.

Synchrotron Light Profile Monitor



- Introduction
- Resolution limits
- Small Emittance Measurements
- (Proton Synchrotron Radiation Diagnostics)

Synchrotron light profile monitor

In electron accelerators the effect of synchrotron radiation (SR) can be used for beam size measurements. In this course we will **focus on profile determination**, but SR can also be used for bunch length measurements with e.g. streak cameras with a resolution of < 1 ps. From classical electrodynamics the radiated power is given for a momentum change dp/dt and a particle with mass m_0 and charge e :

$$P_{SR} = \frac{e^2 c}{6\pi\epsilon_0(m_0 c^2)} \left[\frac{dp}{dt} \right]^2$$

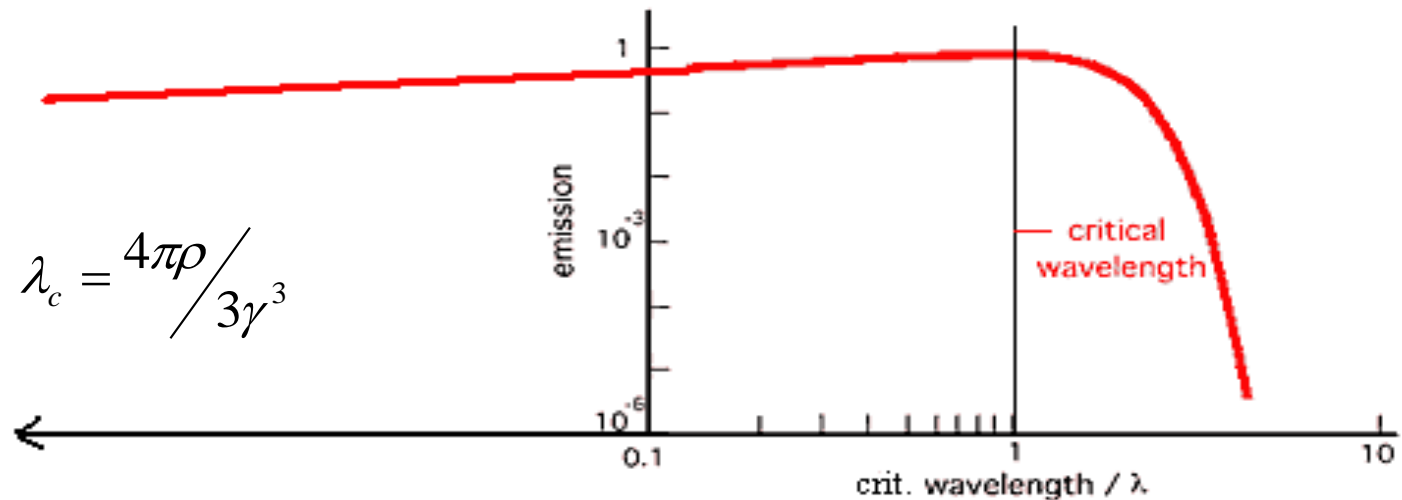
For linear accelerators $dp/dt = dW/dx$. For typical values of $dW/dx = 10 - 20$ MeV/m the **SR is negligible**. In bending magnets an **acceleration perpendicular to the velocity** exists mainly in the dipole magnets (field B) with a bending radius $\rho = \beta\gamma m_0 c / (eB)$. The **total power** of N circulating particles with $\gamma = E/m_0 c^2$ is than

$$P_{tot} = \frac{e^2 c \gamma^4}{6\pi\epsilon_0 \rho^2} N$$

This expression is also valid for a ring having all magnets of the same strength and field-free sections in between.

The critical wavelength λ_c divides the Spectrum of SR in two parts of equal power:

$$\lambda_c = \frac{4\pi\rho}{3\gamma^3}$$



Opening angle Ψ of SR (1/2 of cone!) for $\lambda \gg \lambda_c$ (!!!):
with

$$\Psi = \frac{1}{\gamma} \left(\frac{\lambda}{\lambda_c} \right)^{1/3} = \left(\frac{3\lambda}{4\pi\rho} \right)^{1/3}$$

$$\gamma = E/m_0c^2 = E [\text{MeV}]/0.511$$

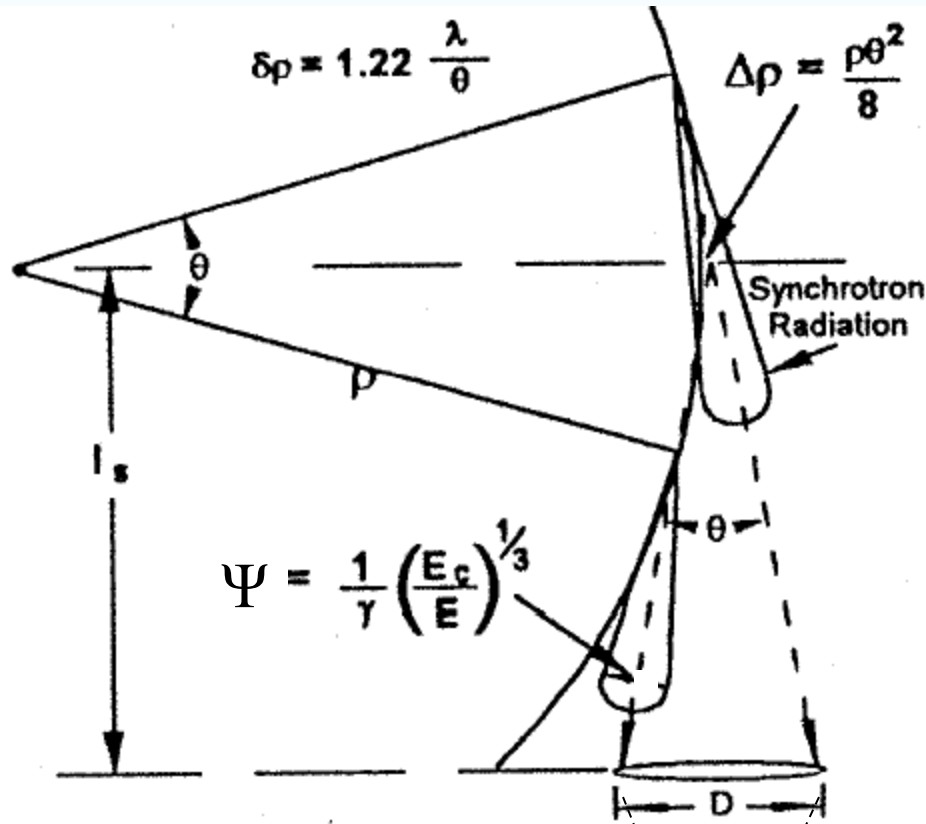
$$\gamma = 23483 \text{ at } 12 \text{ GeV and}$$

$$\gamma = 52838 \text{ at } 27 \text{ GeV}$$

Path length s :

$$s = \rho\theta$$

ρ = Bending radius of Dipole

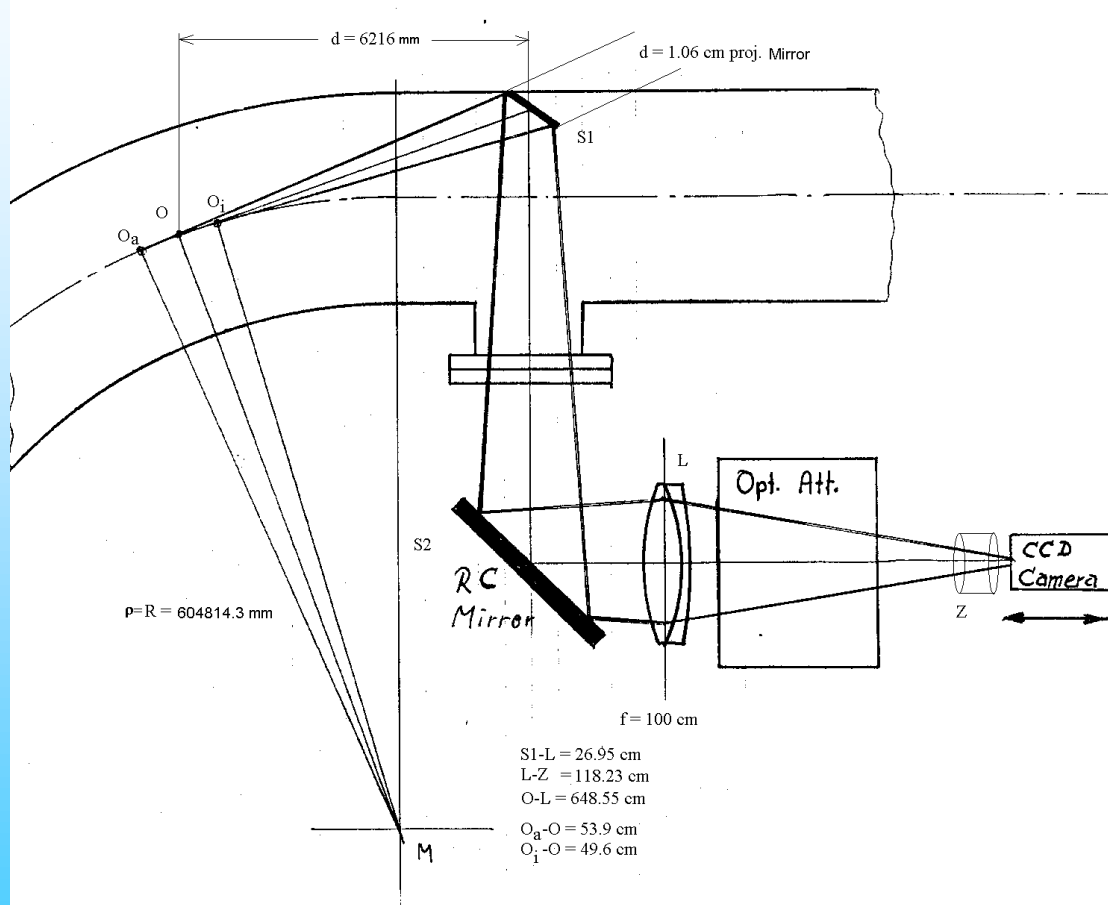


J. Flanagan (IPAC2011)

$$\sigma_{\psi} = \begin{cases} 1.07[3\lambda/(4\pi\rho)]^{1/3} & ; \lambda \gg \lambda_c \\ 0.64/\gamma & ; \lambda \approx \lambda_c \\ 0.58[3\lambda\gamma/(4\pi\rho)]^{1/2} & ; \lambda \ll \lambda_c \end{cases}$$

Example HERAe (46 mA circulating electrons at 27 GeV)

Synchrotron radiation profile monitor in HERAe



$$R = \rho = 604814.3 \text{ mm}$$

$$G = O-L = 6485.5 \text{ mm}$$

$$B = L-Z = 1182.3 \text{ mm}$$

$$O-S1 = 6216 \text{ mm}$$

$$L = O_a-O_i = 1035 \text{ mm}$$

$$\text{opening angle (horizontal): } \tan \theta/2 = d/2/6216 \Rightarrow \theta/2 = \arctan d/2/6216 = 0.85 \text{ mrad}$$

$$\text{opening angle (vertical):}$$

$$\Psi(\lambda) = 1/\gamma (\lambda/\lambda_c)^{1/3}$$

$$\lambda_c = \frac{4\pi\rho}{3\gamma^3} = 0.017 \text{ nm} \ll \lambda \approx 500 \text{ nm}$$

Exercise SR1 : Which problems with the setup can be expected?:

Heating of mirror:

⇒ total emitted Power per electron:

$$P = \frac{e^2 c \gamma^4}{6 \pi \epsilon_0 \rho^2}$$

total Power of 46 mA circulating electrons at 27 GeV (Number of electrons $N_e = 6 \cdot 10^{12}$)

$$P_{\text{tot}} = 6 \cdot 10^6 \text{ W}$$

The mirror will get $P_{\text{tot}} * \Theta / (2 \pi) = 1600 \text{ W}$ (Integral over all wavelength!!!)

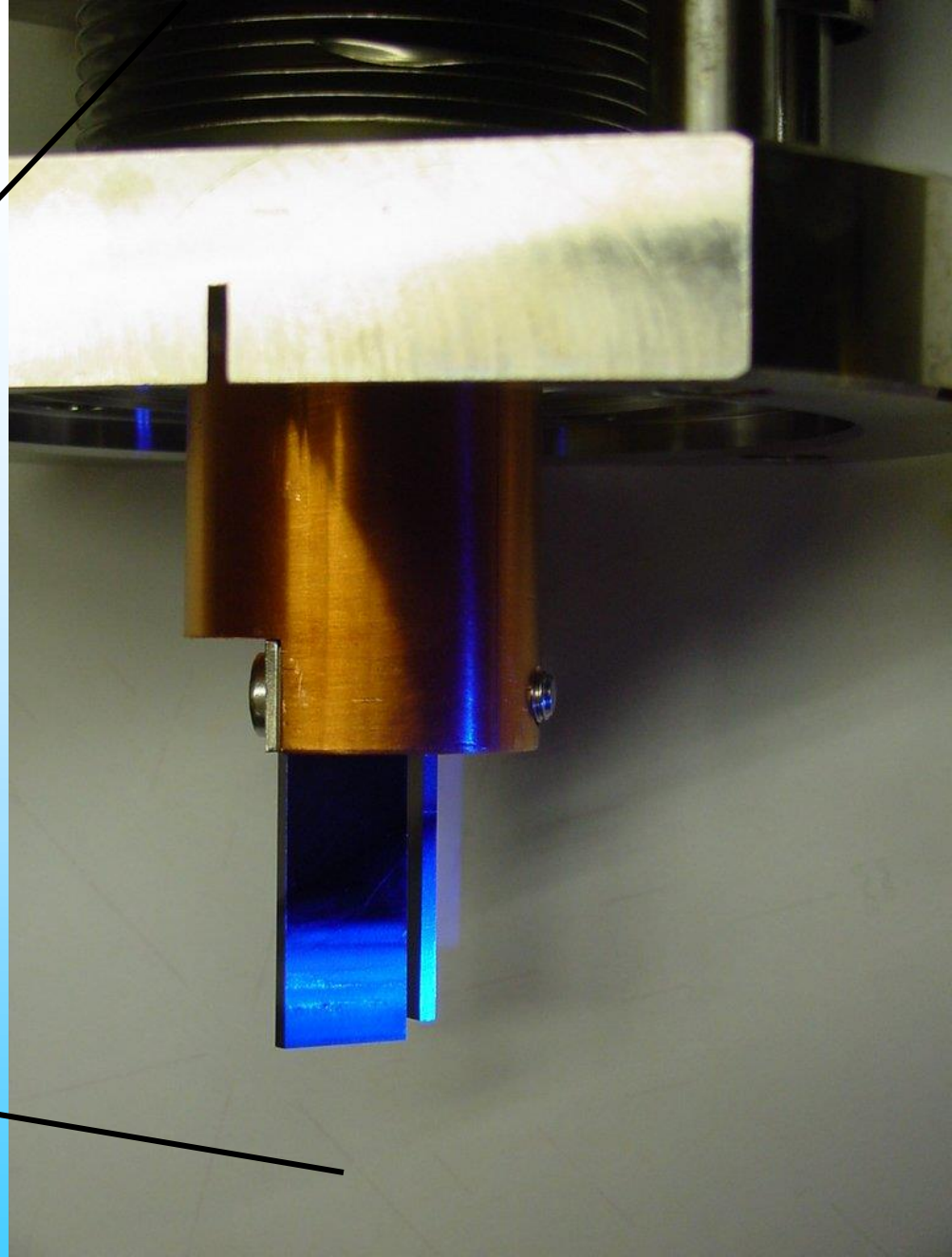
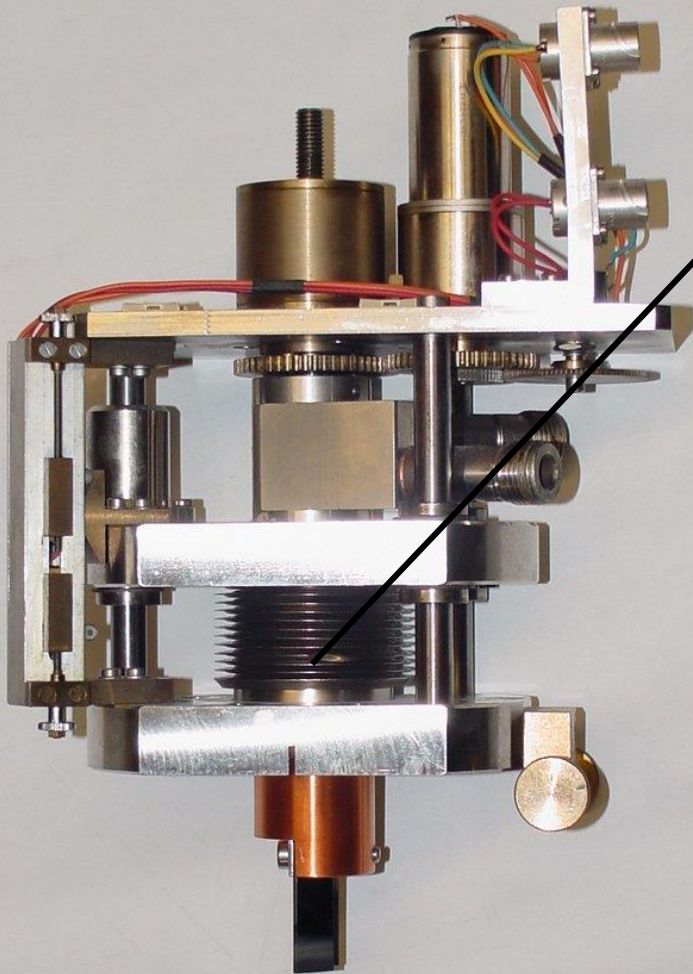
Solutions?

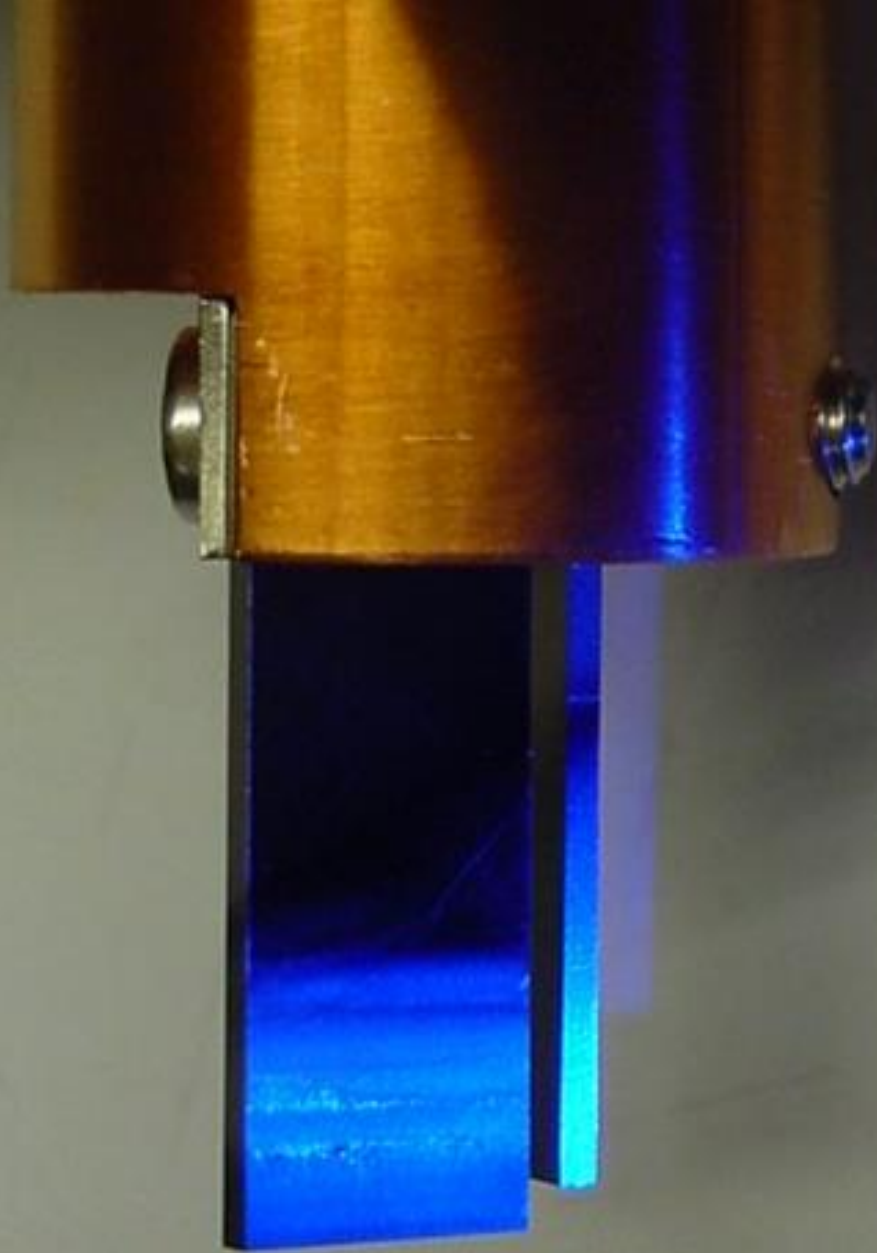
⇒ mirror is moveable, mirror has to be cooled

Material with low Z is nearly not visible for short wavelength ⇒ Beryllium

Still 100 W on mirror in HERAe

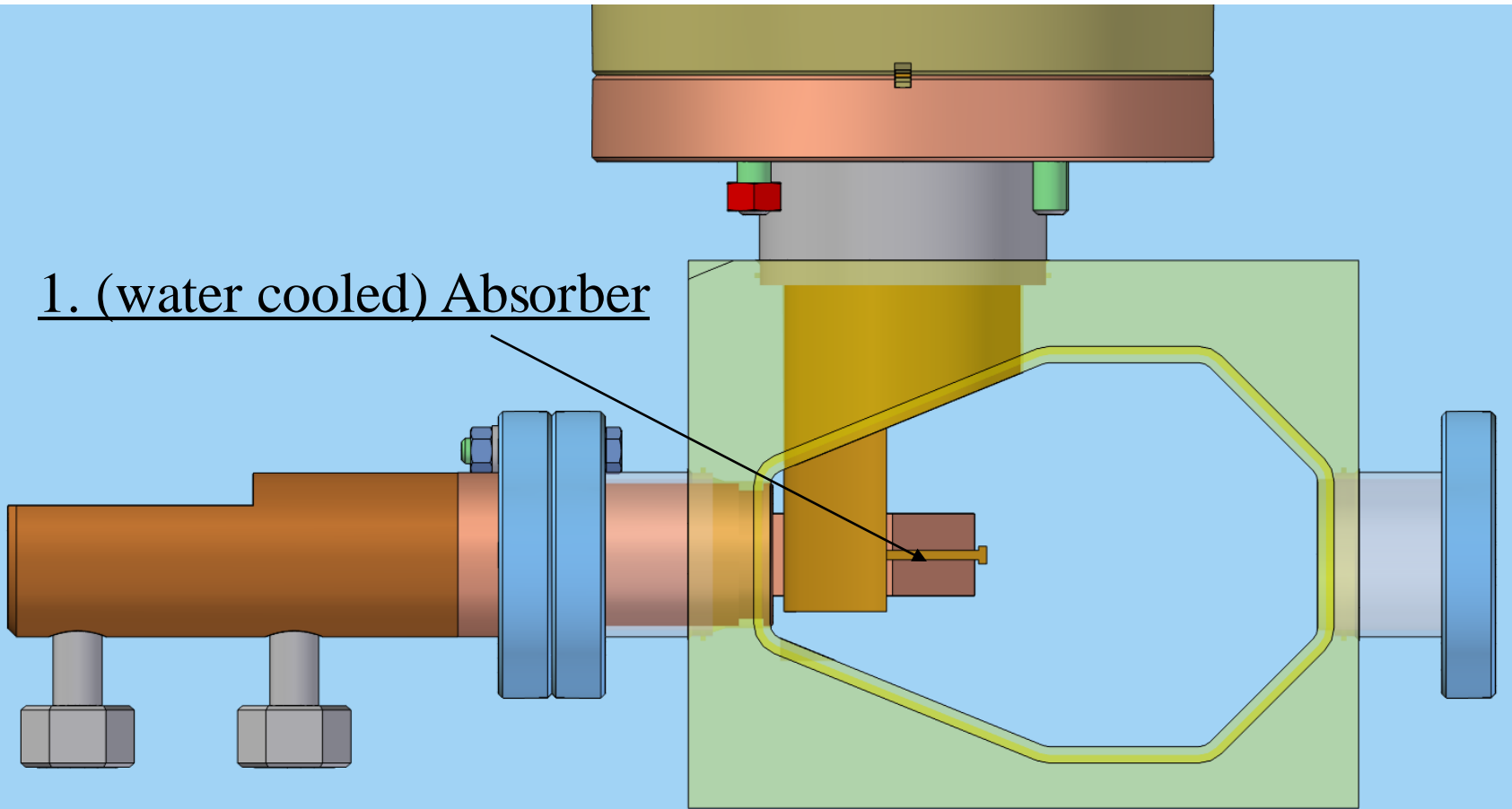
not sufficient to prevent image distortion



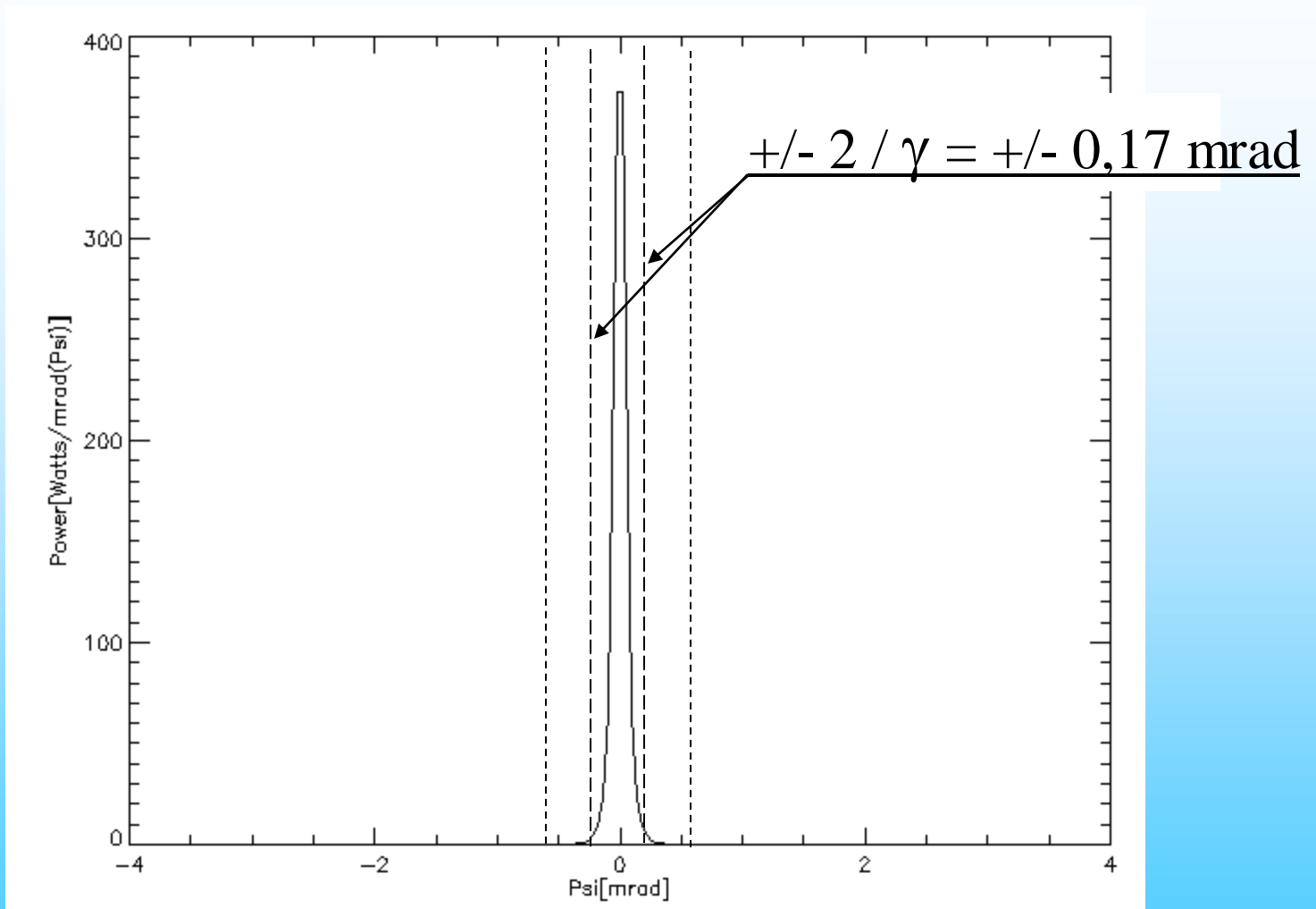


Proposals to solve the problem?

1. (water cooled) Absorber

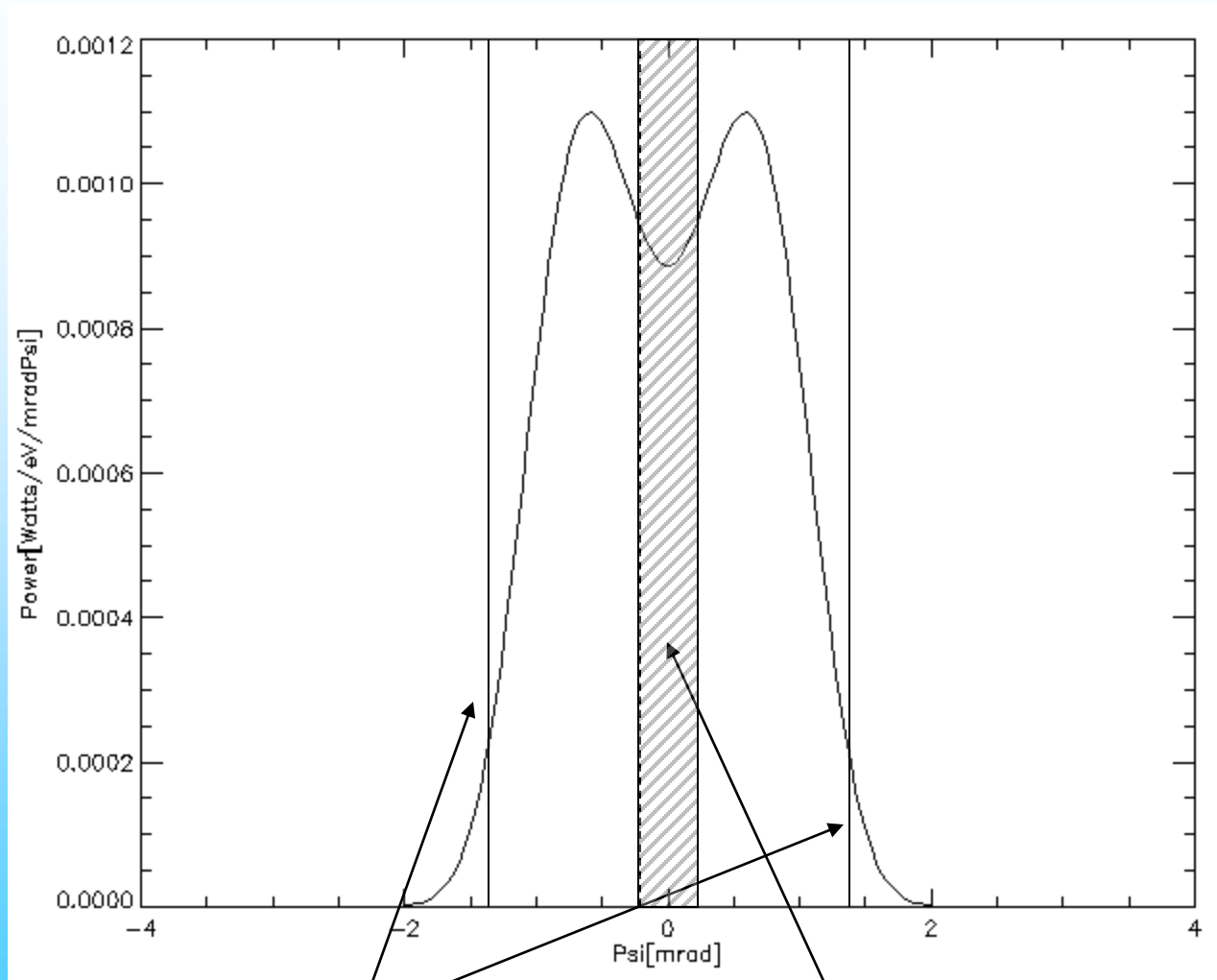


2. Do not move the whole mirror into the beam, stop before center



„Total“ power within $\pm 0,6 \text{ mrad}$

Visible part



Mirror size

Fade out $\pm 2/\gamma$ by
Absorber

Exercise SR2: What limits the spatial resolution?

Diffraction, depth of field, arc, camera

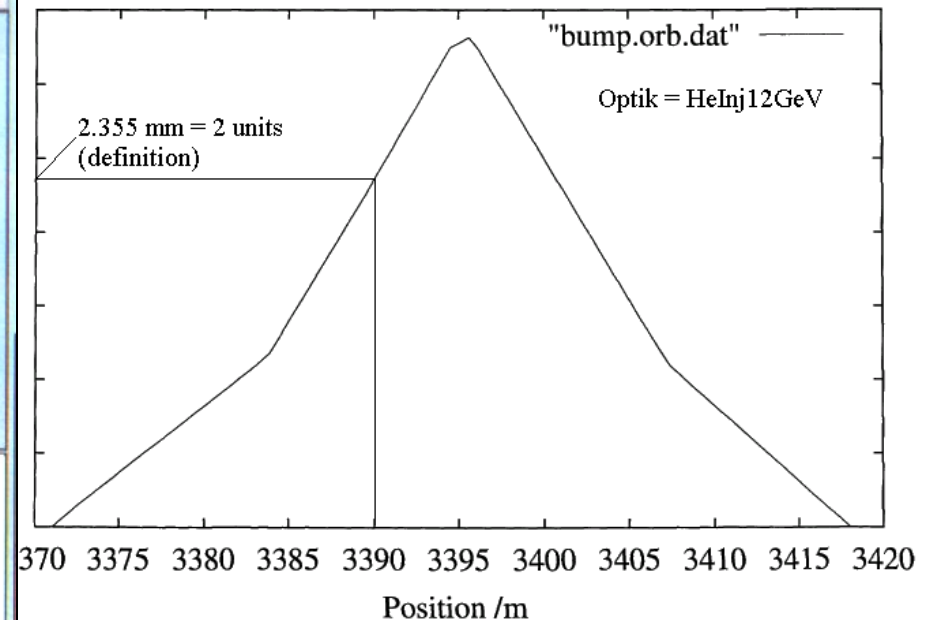
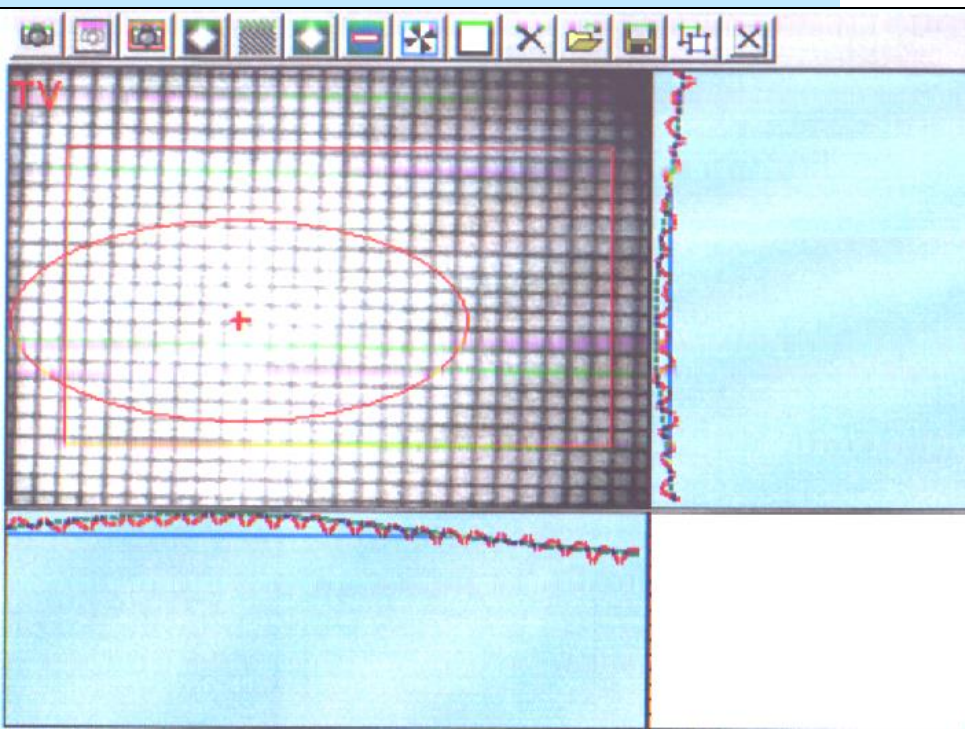
=> physical

Alignment, lenses, mirrors, vibrations

=> technical

How to calibrate the optics?

Grid (yardstick) at point of emission, orbit bumps, ...



Diffraction:

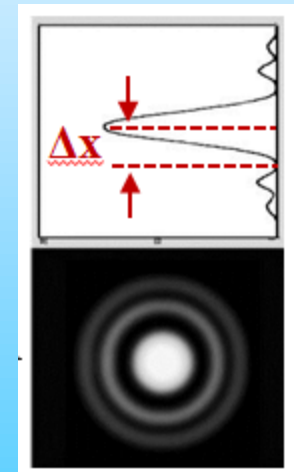
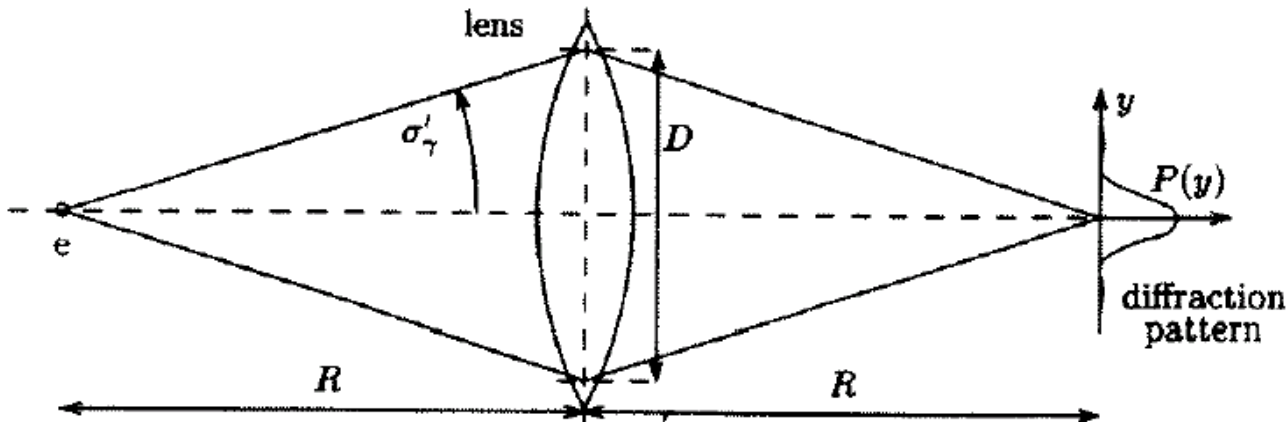
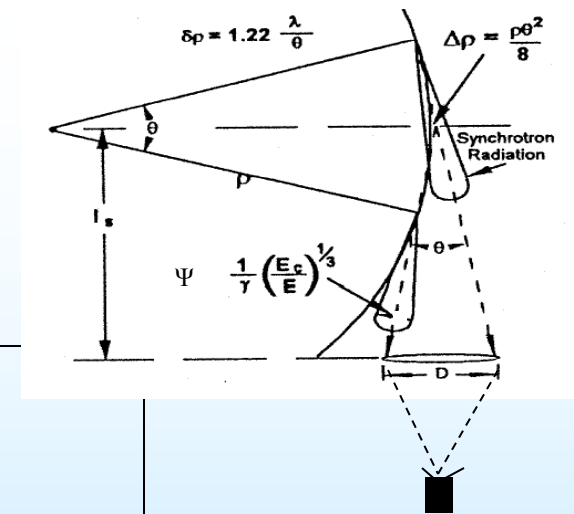
EQ 1:

Diffraction limit (for Object):

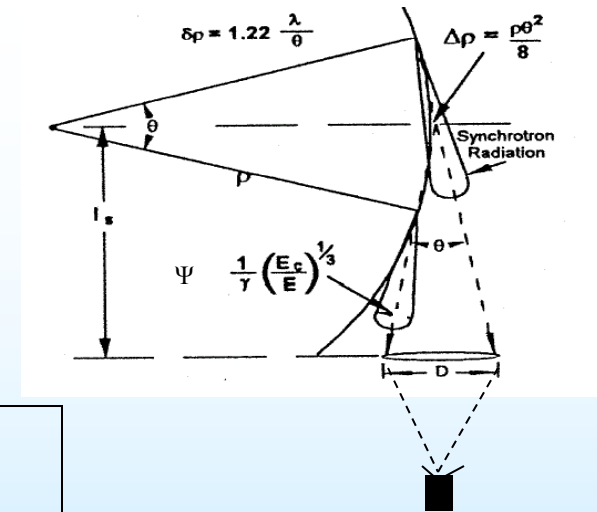
For normal slit:

$\sigma_{\text{Diff}} = 0.47 * \lambda / \theta / 2$ (horizontal, mirror defines opening angle θ)

$\sigma_{\text{Diff}} \approx 0.47 * \lambda / \Psi$ (vertikal)



Depth of field:



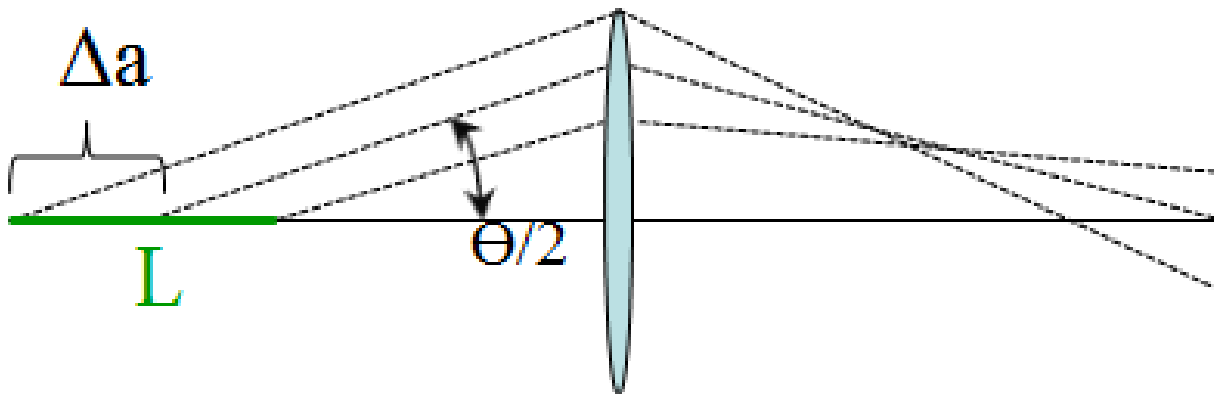
EQ 2:

depth of field:

Vertical: $\Delta_{\text{depth}} \approx L/2 * \Psi = \sigma_{\text{depth}}$

Horizontal: $\Delta_{\text{depth}} \approx L/2 * \theta/2 = \sigma_{\text{depth}}$ (mirror defines opening angle θ)

$L \approx \rho \tan \theta$ or $2\rho (\theta/2 + \Psi)$



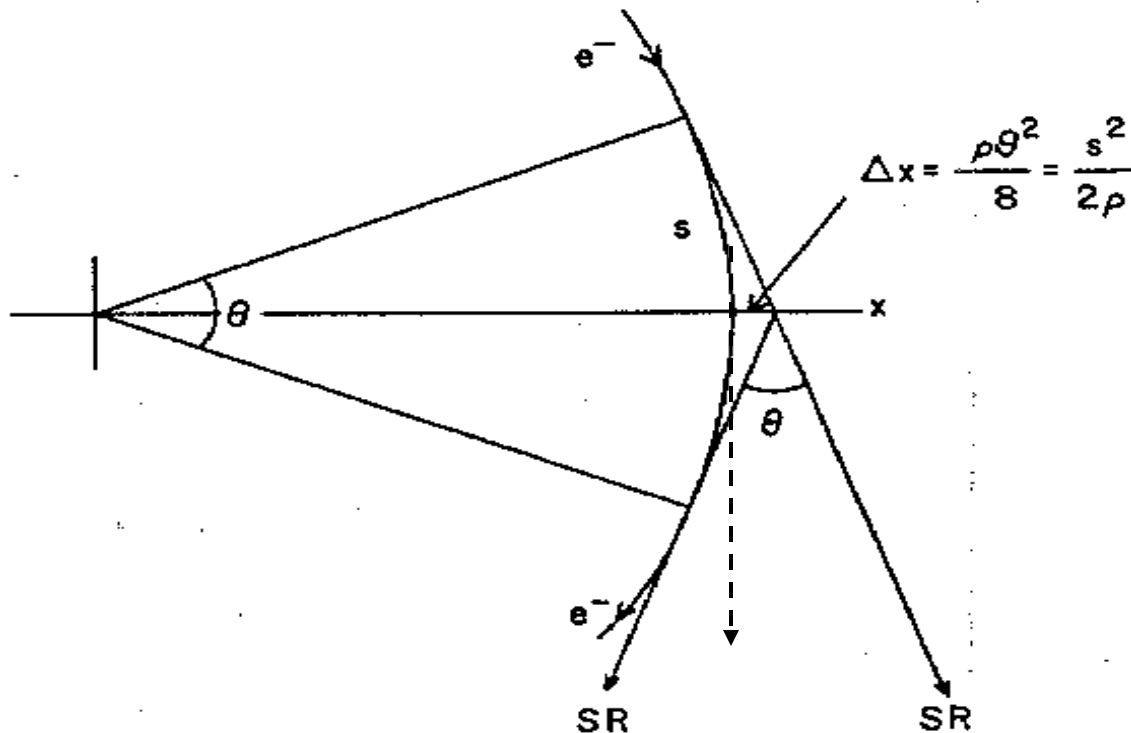
Arc:

EQ 3:

Arc (horizontal):

Observation of the beam in the horizontal plane is complicated by the fact that the light is emitted by all points along the arc. The horizontal width of the apparent source is related to the observation angle as:

$$\Delta x_{\text{arc}} = \rho \theta^2 / 8 = \sigma_{\text{arc}} \text{ (mirror defines opening angle } \theta \text{)}$$



Camera (finite pixel size)

EQ 4:

Camera:

image gain = $G/B = 5.485$

typical resolution of camera CCD chip: $\sigma_{\text{chip}} = 6.7 \mu\text{m}$

$\sigma_{\text{camera}} = \sigma_{\text{chip}} * G/B = 37 \mu\text{m}$

Resolution:

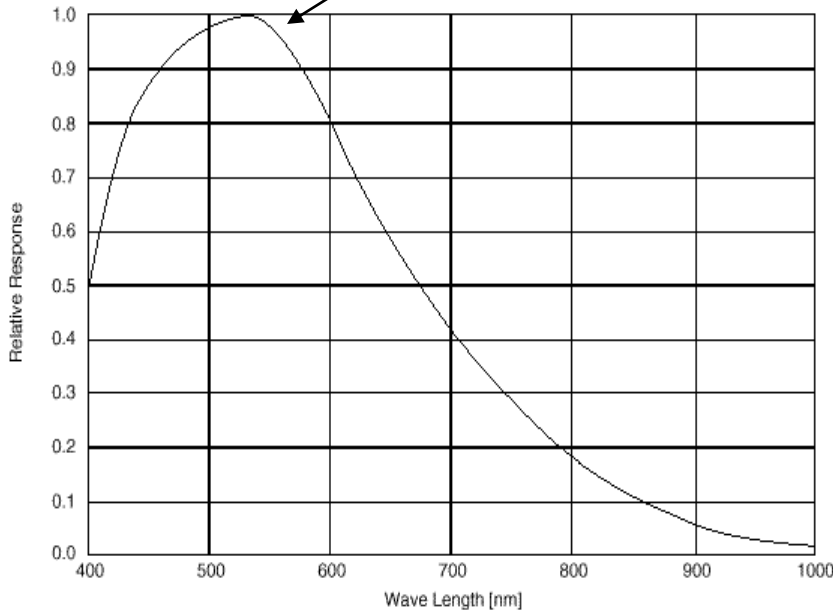
λ not monochromatic !

$\sigma_{\text{Diff}} =$	$0.47 * \lambda/\theta$ (horizontal)	$=$ <u>??? Depends on wavelength</u>
$\sigma_{\text{Diff}} =$	$0.47 * \lambda/\Psi$ (vertikal)	$=$ <u>??? Depends on wavelength</u>
$\sigma_{\text{depth}} =$	$L/2 * \theta/2$	$=$ <u>440 μm</u>
$\sigma_{\text{arc}} =$	$\rho \theta^2/8$	$=$ <u>219 μm (horizontal)</u>
$\sigma_{\text{camera}} =$	$\sigma_{\text{chip}} * G/B$	$=$ <u>37 μm</u>

typical spectral sensitivities from CCD Sensors:

SONY

Spectral Sensitivity Characteristics
(Includes lens characteristics, excludes light source characteristics)



Assume: $\lambda = 550 \text{ nm};$
 $(\gamma = E/m_0c^2)$
 $\gamma_{12} = 2.35 * 10^4 \text{ (E = 12 GeV)}$
 $\gamma_{35} = 6.85 * 10^4 \text{ (E = 35 GeV)}$
 $\lambda_{c,12} = (4\pi\rho)/(3\gamma^3) = 0.195 \text{ nm at 12 GeV}$
 $\lambda_{c,35} = (4\pi\rho)/(3\gamma^3) = 0.008 \text{ nm at 35 GeV}$

opening angle (horizontal): $\tan\theta/2 = d/2/6216 \Rightarrow$
 $\theta/2 = \text{arc tan } d/2/6216 = \underline{0.85 \text{ mrad}}$

opening angle (vertikal):
 $\Psi(\lambda) = 1/\gamma (\lambda/\lambda_c)^{1/3} = [(3\lambda)/(4\pi\rho)]^{1/3} = 0.6 \text{ mrad}$

(mirror has to be larger than spot size on mirror)
 \Rightarrow

σ_{diff} (horizontal)	$= 0.47 * \lambda/\theta/2$	$= \underline{304 \mu\text{m}}$
σ_{diff} (vertical)	$= 0.47 * \lambda/\Psi$	$= \underline{431 \mu\text{m}}$
σ_{depth}	$= L/2 * \theta/2$	$= \underline{440 \mu\text{m}}$
σ_{arc} (horizontal)	$= \rho \theta^2/8$	$= \underline{219 \mu\text{m}}$
σ_{camera}	$= \sigma_{\text{chip}} * G/B$	$= \underline{37 \mu\text{m}}$

$$\sigma_{\text{cor}} = (\sigma_{\text{diff}}^2 + \sigma_{\text{depth}}^2 + \sigma_{\text{arc}}^2 + \sigma_{\text{camera}}^2)^{1/2}$$

$$\sigma_{\text{cor}} = (\sigma_{\text{diff}}^2 + \sigma_{\text{depth}}^2 + \sigma_{\text{camera}}^2)^{1/2}$$

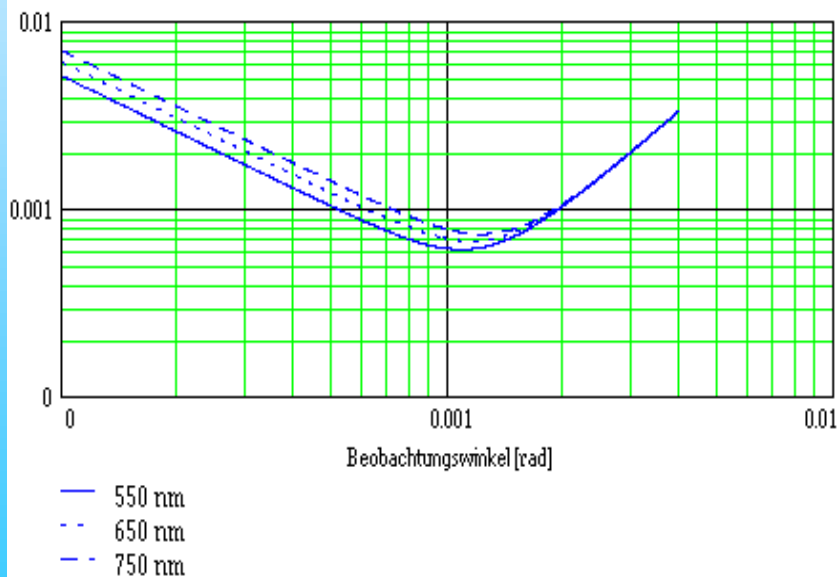
= 579 μm ; (horizontal)

= 617 μm ; (vertical)

Horizontal:

$$\sigma_{\text{cor}} = [(\rho \theta^2/8)^2 + (L/2 * \theta/2)^2 + (0.47 * \lambda/\theta/2)^2]^{1/2}$$

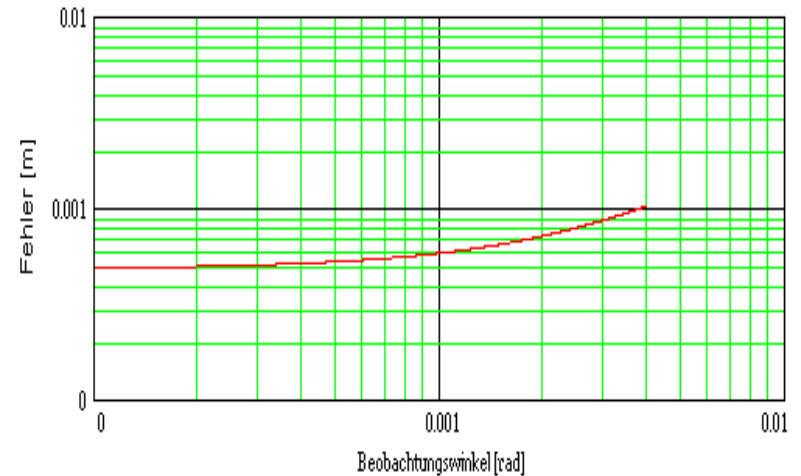
with $L \approx \rho \tan \theta \approx \rho \theta$



Vertical:

$$\sigma_{\text{cor}} = [(L/2 * \Psi)^2 + (0.47 * \lambda/\Psi)^2]^{1/2} \quad \text{with}$$

$$L \approx \rho \tan \theta \approx \rho \theta$$



We measured sometimes a negative emittance??? (Not the whole truth so far)

1) Diffraction:

a) Ψ_{exact} is larger than the Gauss approximation (e.g. $0.79 \rightarrow 1.08$ mrad at Tristan)

b) For a gaussian beam the diffraction width is $\sigma_{\text{diff}} \approx 1/\pi * \lambda/\Psi$

(Ref: **ON OPTICAL RESOLUTION OF BEAM SIZE MEASUREMENTS BY MEANS OF SYNCHROTRON RADIATION**. By A. Ogata (KEK, Tsukuba). 1991. Published in Nucl.Instrum.Meth.A301:596-598,1991)

$\Rightarrow \sigma_{\text{diff}} \approx 1/\pi * \lambda/\Psi_{\text{exact}} = \underline{218 \mu\text{m}}$ ($\Psi_{\text{exact}} = 0.8$ mrad, $\lambda = 550$ nm) vertical

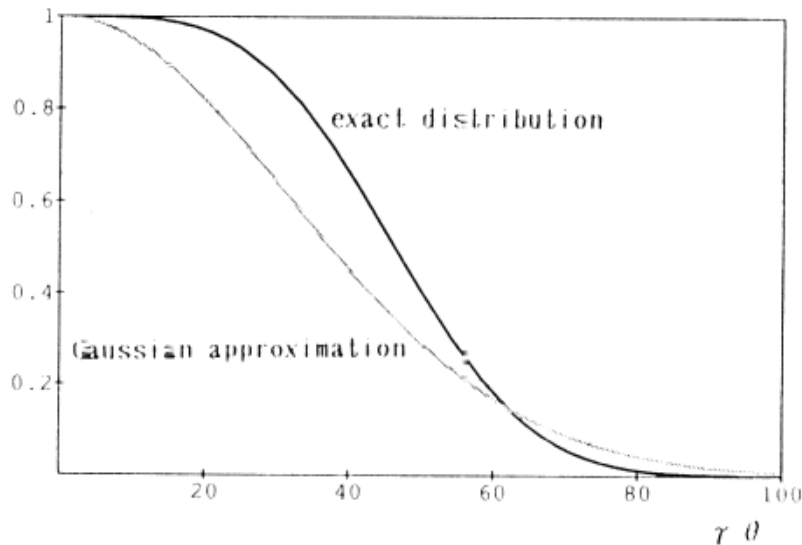
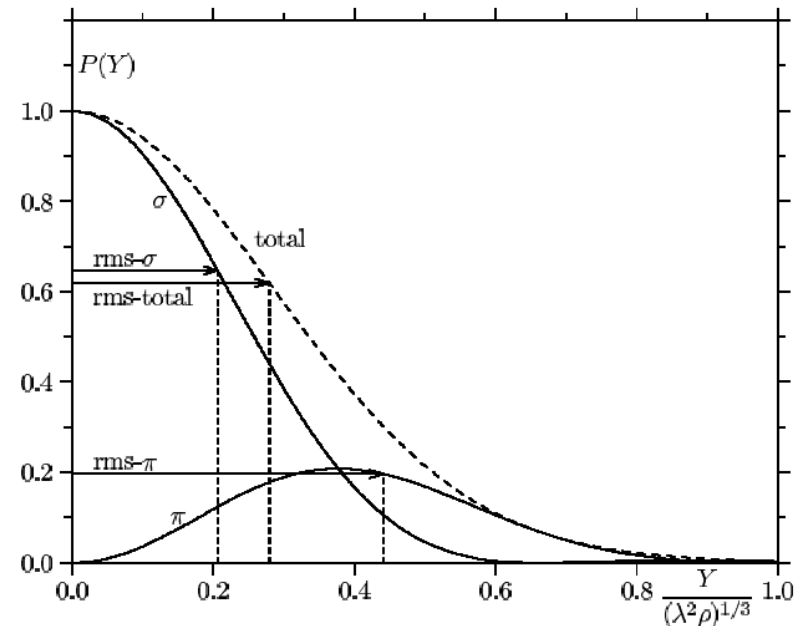


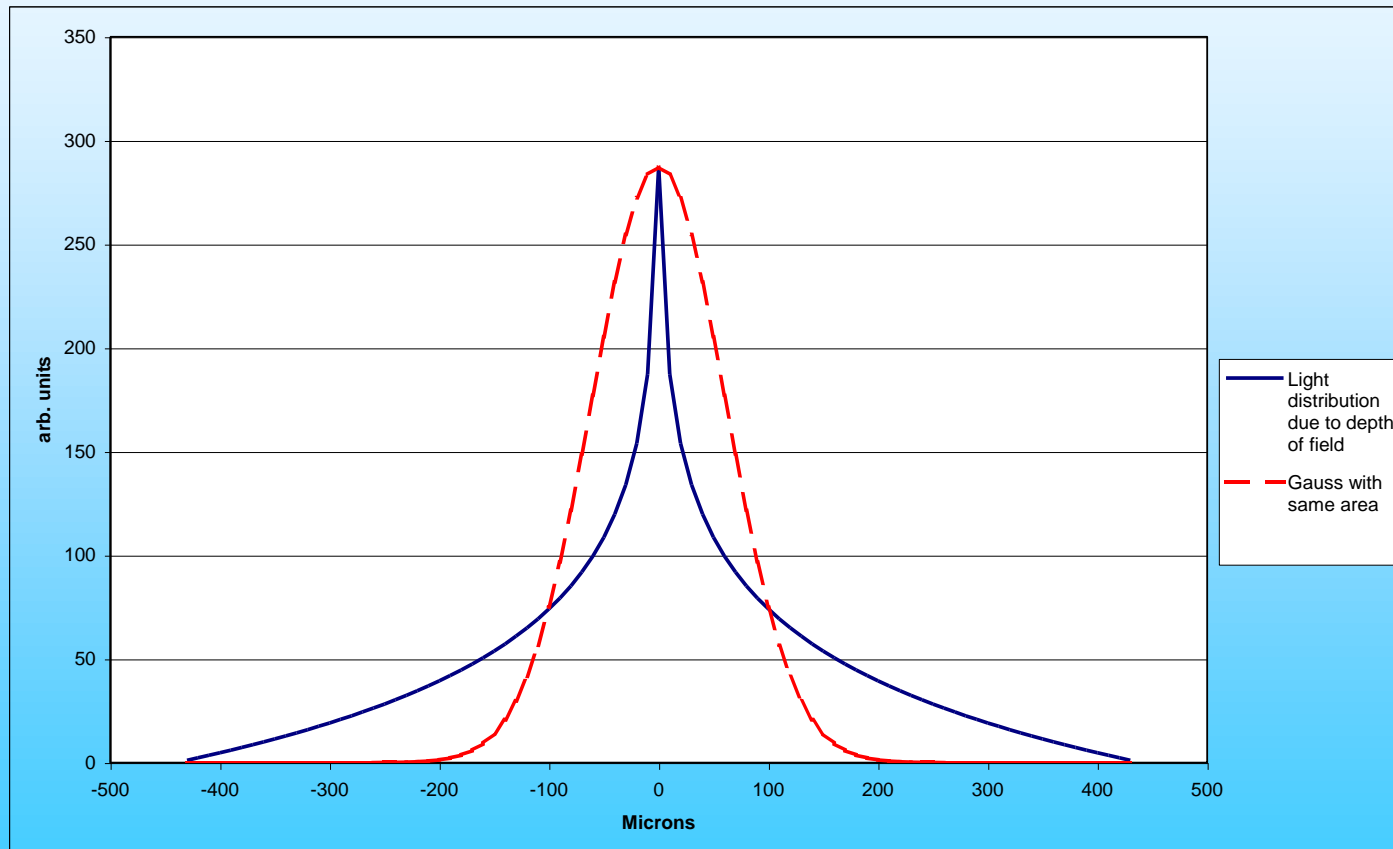
Fig. 1 Angular distribution of the 500 nm component of the synchrotron radiation from the TRISTAN MR bending magnet (246 m bending radius) operated at 30 GeV, and its Gaussian approximation.



8: Fraunhofer diffraction for synchrotron radiation from long magnets

2) Depth of field:

The formula $R_{\text{depth}} = L/2 * \theta/2$ describes the radius of the distribution due to the depth of field effect. It is not gaussian and has long tails. The resolution of an image is probably much better than the formula above. A gaussian approximation with the same integral is shown in the figure below resulting in a width of $\sigma_{\text{depth}} = 61 \mu\text{m}$.



$$\begin{aligned}\sigma_{\text{diff}} &= 0.47 * \lambda / \theta / 2 \\ \sigma_{\text{diff}} &= 1 / \pi * \lambda / \Psi \\ \sigma_{\text{depth}} &= L / 2 * \theta / 2 \\ \sigma_{\text{arc}} &= \rho \theta^2 / 8 \\ \sigma_{\text{camera}} &= \sigma_{\text{chip}} * G / B\end{aligned}$$

$$\begin{aligned}&= \underline{304 \mu\text{m}} \text{ (horizontal)} \\ &= \underline{218 \mu\text{m}} \text{ (vertical)} \\ &= \underline{61 \mu\text{m}} \\ &= \underline{219 \mu\text{m}} \text{ (horizontal)} \\ &= \underline{37 \mu\text{m}}\end{aligned}$$

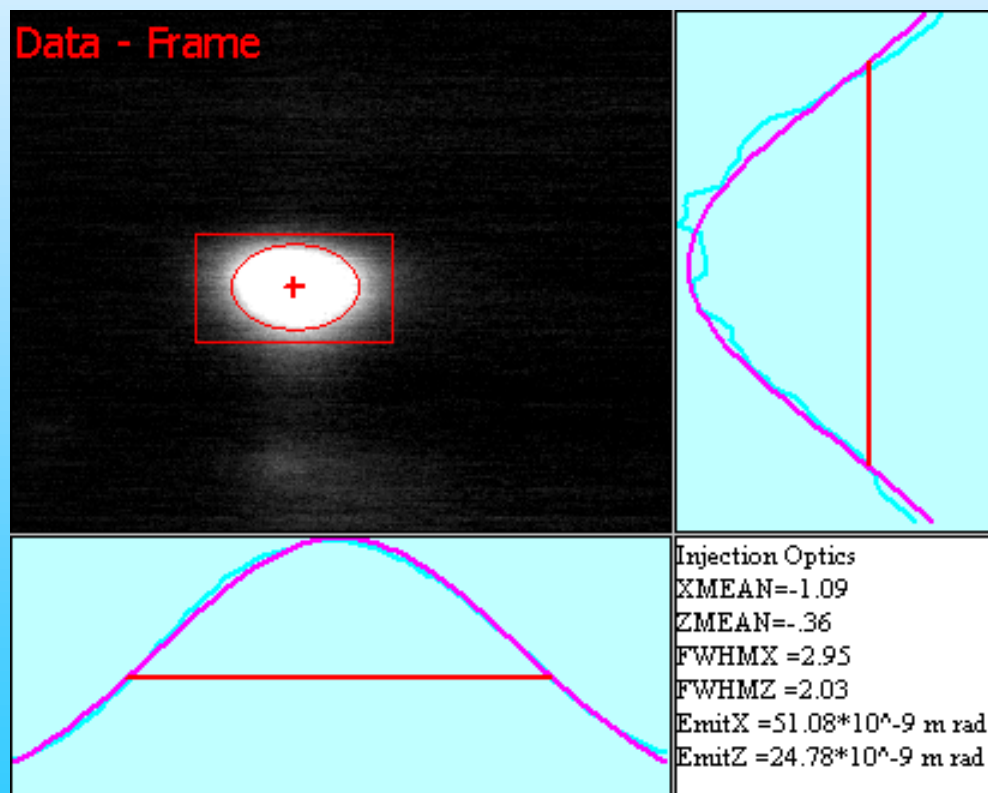
before:
(431 μm)
(440 μm)

$$\begin{aligned}\sigma_{\text{cor}} &= (\sigma_{\text{diff}}^2 + \sigma_{\text{depth}}^2 + \sigma_{\text{arc}}^2 + \sigma_{\text{camera}}^2)^{1/2} \\ \sigma_{\text{cor}} &= (\sigma_{\text{diff}}^2 + \sigma_{\text{depth}}^2 + \sigma_{\text{camera}}^2)^{1/2}\end{aligned}$$

$$\begin{aligned}&= \underline{381 \mu\text{m}} ; \text{ (horizontal)} \\ &= \underline{229 \mu\text{m}} ; \text{ (vertical)}\end{aligned}$$

(579 μm)
(617 μm)

$$\text{Beam width } \sigma_{\text{beam}} = (\sigma_{\text{fit_measured}}^2 - \sigma_{\text{cor}}^2)^{1/2}$$



$$\sigma_{\text{vert}} = 860 \mu\text{m}$$

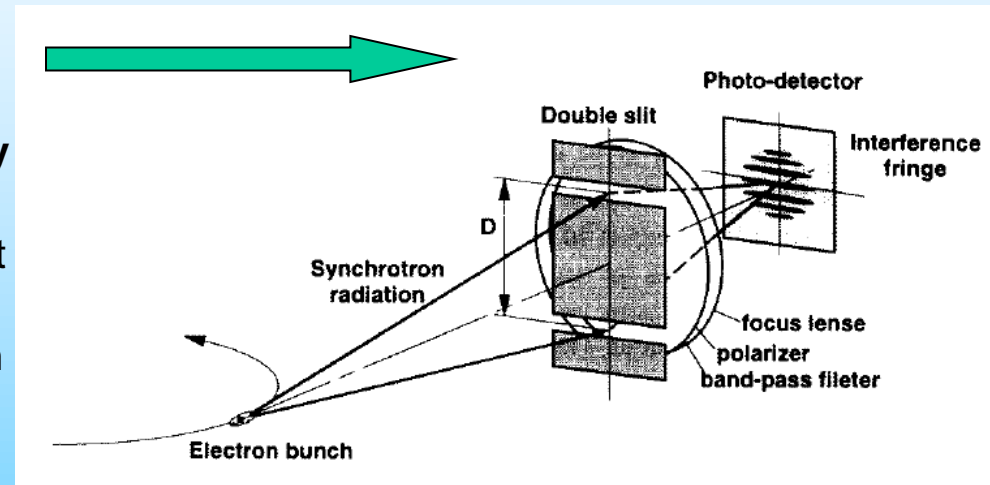
Exercise SR3: Discuss possible improvements of an SR-monitor:

- Monochromator at shorter wavelength (x-rays, need special optic) →
- Use optimum readout angle
- Polarization - filter
- Use x-ray ($\lambda < 0.1$ nm)

More:

Interferometer

The principle of measurement of the profile of an object by means of **spatial coherency** was first proposed by H. Fizeau and is now known as the Van Cittert-Zernike theorem. It is well known that A.A. Michelson measured the angular dimension (extent) of a star with this method.



Referenzen

SPATIAL COHERENCY OF THE SYNCHROTRON RADIATION AT THE VISIBLE LIGHT REGION AND ITS APPLICATION FOR THE ELECTRON BEAM PROFILE MEASUREMENT.

By T. Mitsuhashi (KEK, Tsukuba). KEK-PREPRINT-97-56, May 1997. 4pp. Talk given at 17th IEEE Particle Accelerator Conference (PAC 97): Accelerator Science, Technology and Applications, Vancouver, Canada, 12-16 May 1997.

Intensity Interferometer and its application to Beam Diagnostics, Elfim Gluskin, ANL, publ. PAC 1991 San Francisco

MEASUREMENT OF SMALL TRANSVERSE BEAM SIZE USING INTERFEROMETRY

T. Mitsuhashi

High Energy Accelerator Research Organisation, Oho, Tsukuba, Ibaraki, 305-0801 Japan

DIPAC 2001 Proceedings - ESRF, Grenoble

X-ray Pinhole Camera

• „camera obscura“

description of phenomenon already by Aristoteles (384-322 b.C.) in „Problemata“

• most common emittance monitor

simple setup

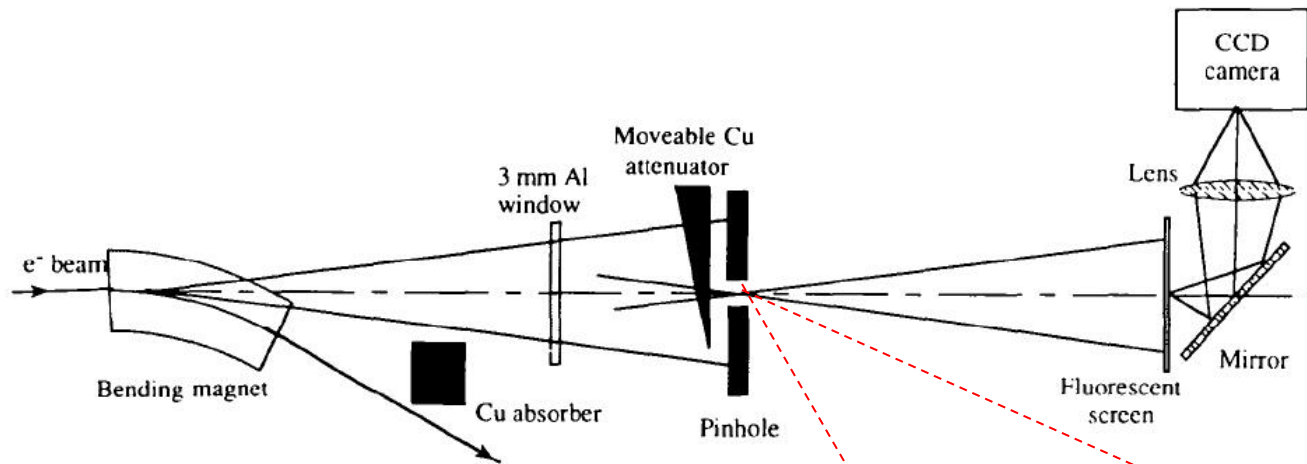


limited resolution

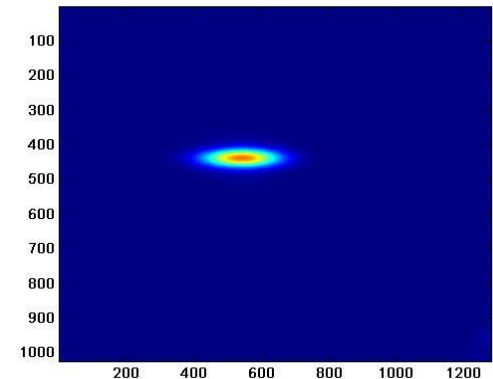
$$\sigma_{res} \geq 10 \mu m$$

example: ESRF

P.Elleaume, C.Fortgang, C.Penel and E.Tarazona, J.Synchrotron Rad. 2 (1995) , 209



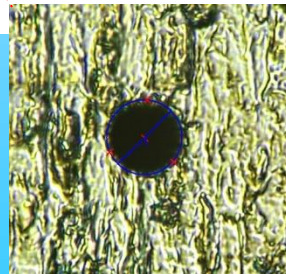
ID-25 X-ray
pinhole camera:



courtesy of K.Scheidt, ESRF

PETRA III pinhole camera:

Ø 18 µm hole in 500 µm thick W plate



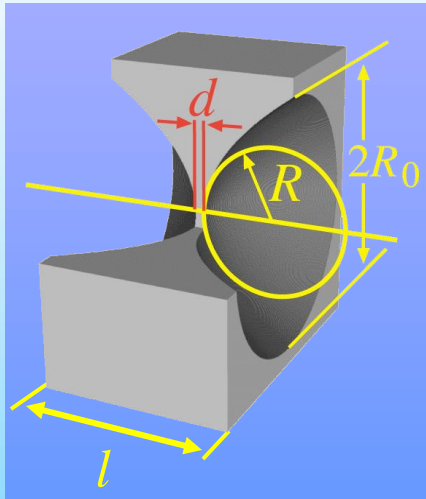
Compound Refractive Lens

lens-maker formula: $1/f = 2(n-1)/R$

X-ray refraction index: $n = 1 - \delta + i\beta$, $\delta \approx 10^{-6}$

➤ concave lens shape

➤ strong surface bending R



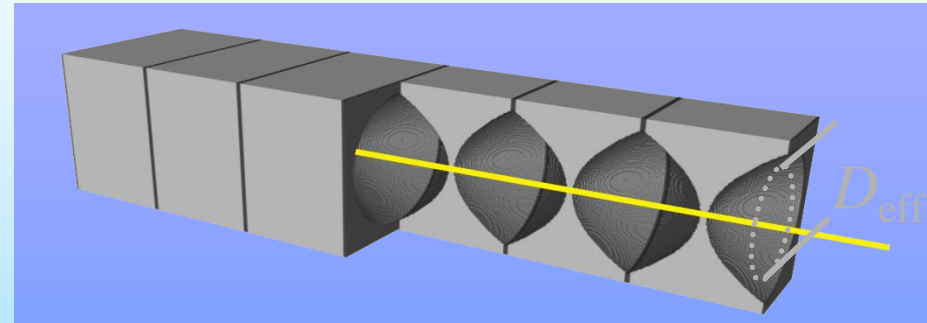
➤ small Z (Be, Al, ...)

➤ small d

$$f = \frac{R}{2\delta N}$$



many lenses ($N=10\dots300$)



PETRA III @ 20 keV:

- $R = 200 \mu\text{m}$, $R_0 = 500 \mu\text{m}$, $d = 10 \mu\text{m}$, $l = 1\text{mm}$
- $N = 31$
- material: beryllium

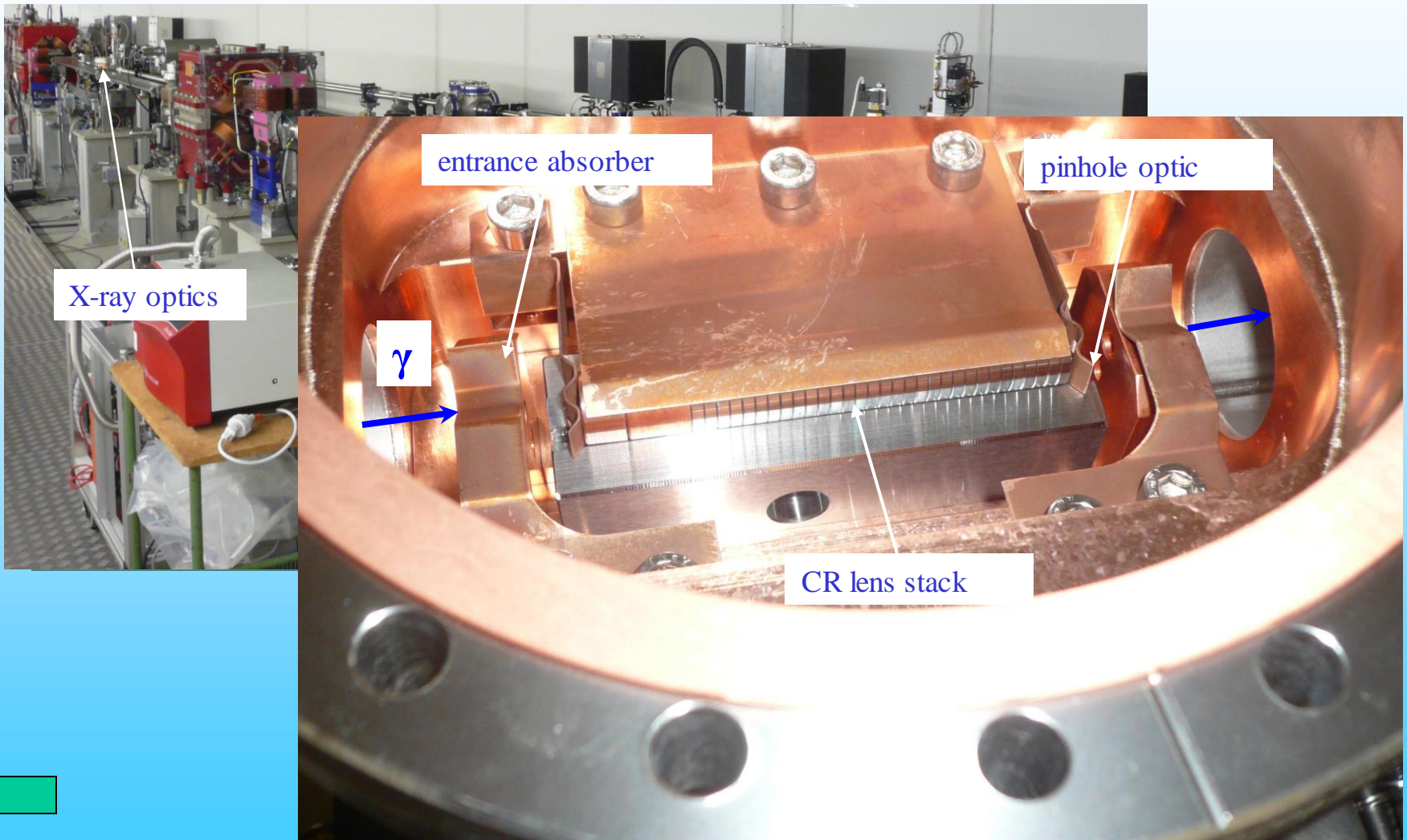
$$f = 3.8\text{m}$$

$$\sigma_{\text{res}} \approx 0.6 \mu\text{m}$$



CRL Monitor @ PETRA III (DESY)

● PETRA III diagnostics beamline



2.) interferometric approach

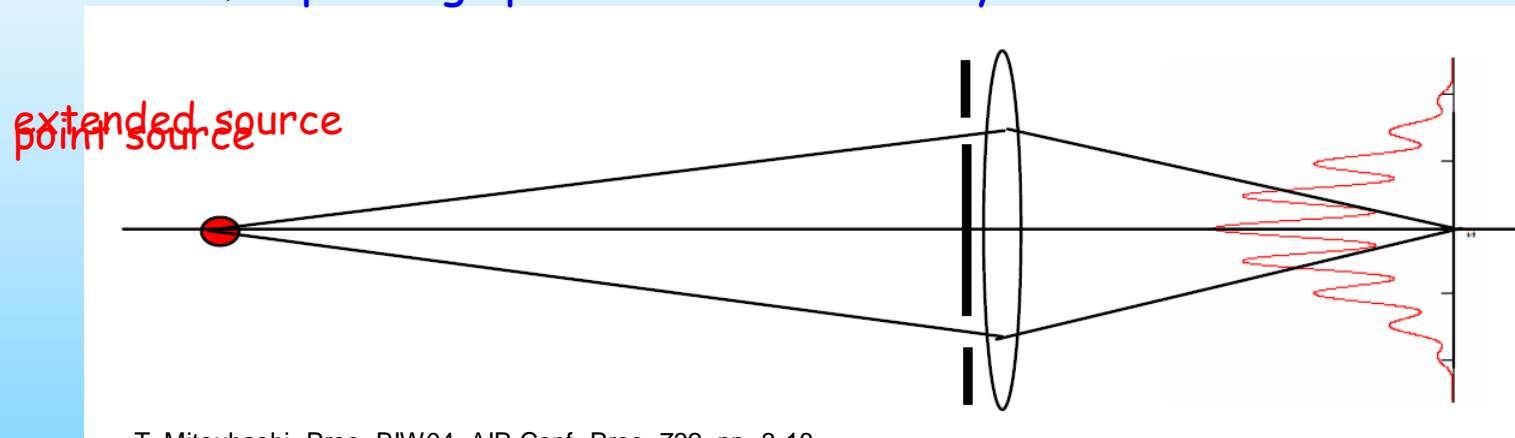
T. Mitsuhashi, Proc. Joint US-CERN-Japan-Russia School of Particle Accelerators, Montreux, 11-20 May 1998 (World Scientific), pp. 399-427.

⇒ probing spatial coherence of synchrotron radiation

visibility:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$V \leq 1$$



T. Mitsuhashi, Proc. BIW04, AIP Conf. Proc. 732, pp. 3-18

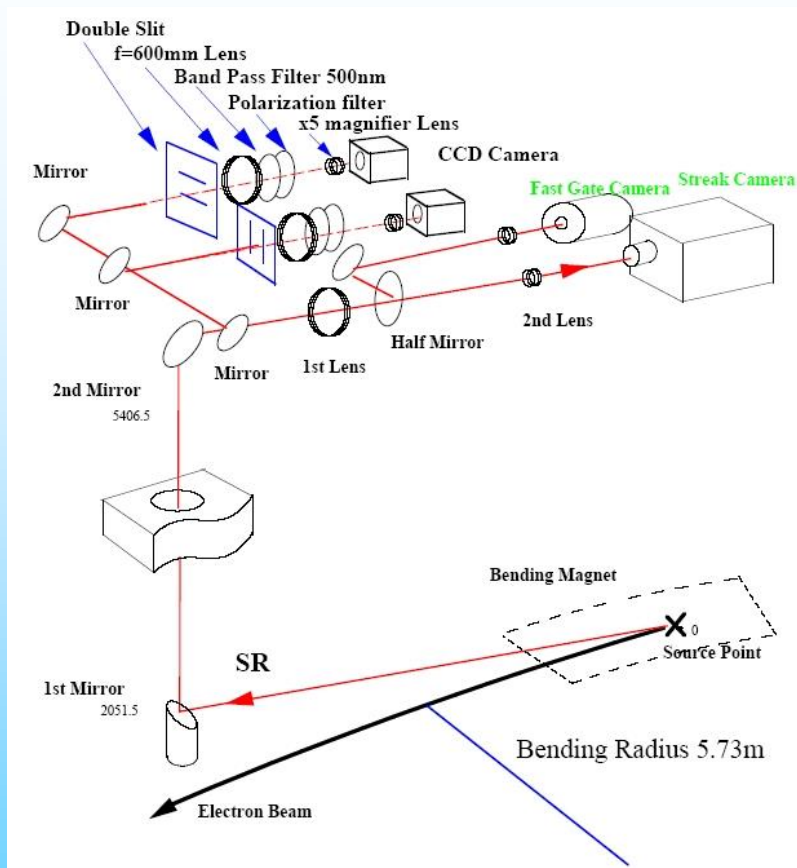
► resolution limit: uncertainty principle

$$\Delta n \cdot \Delta \Phi \approx 1$$

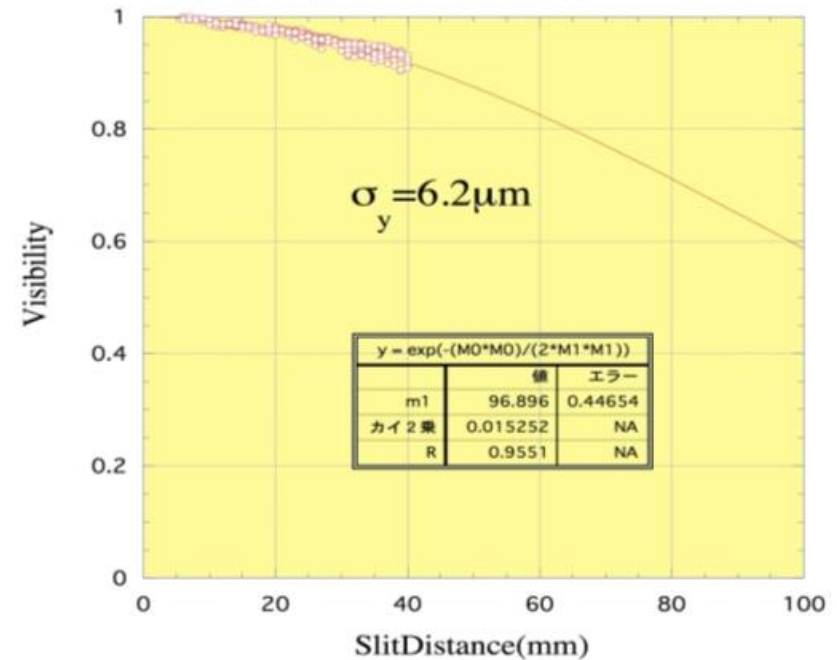
Δn : photon number

$\Delta \Phi$: photon phase

Interference: ATF (KEK)



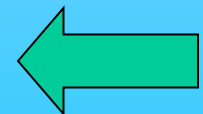
ATF-Damping Ring Vertical Beam Size Measurement



H.Hanyo et al., Proc. of PAC99 (1999), 2143

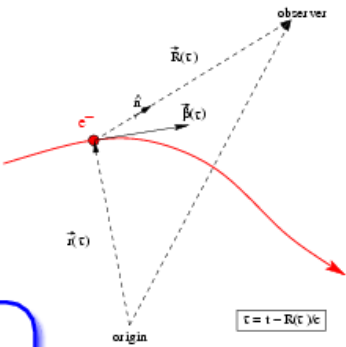
courtesy of T.Mitsuhashi, KEK

- smallest result: 4.7 μm with 400nm @ ATF, KEK
accuracy $\sim 1 \mu\text{m}$



Back to an imaging SR-Monitor: Still not the whole truth:

(Diffraction Limited) Resolution



Liénard –Wiechert potentials:

$$\varphi(t) = \left[\frac{-e}{R(1-\hat{n}\cdot\vec{\beta})} \right]_{ret}, \quad \vec{A}(t) = \left[\frac{-e\vec{\beta}}{R(1-\hat{n}\cdot\vec{\beta})} \right]_{ret}$$

Liénard –Wiechert fields:

$$\vec{E}(t) = -e \left(\frac{(1-\beta^2)(\hat{n}-\vec{\beta})}{R^2(1-\hat{n}\cdot\vec{\beta})^3} + \frac{\hat{n} \times [(\hat{n}-\vec{\beta}) \times \dot{\vec{\beta}}]}{cR(1-\hat{n}\cdot\vec{\beta})^3} \right)_{ret}$$

$$\vec{H}(t) = \hat{n} \times \vec{E}(t)$$

Fourier transform:

$$\vec{E}_\omega \approx -\frac{i\omega e}{cR} \int [\hat{n} \times [\hat{n} \times \vec{\beta}]] e^{i\omega(\tau+R(\tau)/c)} d\tau$$

point charge on circular orbit
 ↪ analytical far field expressions for E_σ, E_π

Fourier transform:

$$\varphi_\omega = -e \int \frac{1}{R(\tau)} e^{i\omega(\tau+R(\tau)/c)} d\tau$$

$$\vec{A}_\omega = -e \int \frac{\vec{\beta}(\tau)}{R(\tau)} e^{i\omega(\tau+R(\tau)/c)} d\tau$$

Electric field:

$$\vec{E}_\omega = -\frac{i\omega e}{c} \int \left[\frac{\vec{\beta}-\hat{n}}{R(\tau)} - \frac{ic}{\omega} \frac{\hat{n}}{R^2(\tau)} \right] e^{i\omega(\tau+R(\tau)/c)} d\tau$$

numerical near field calculation depending on field geometry
 ↪ free codes available (SRW, SPECTRA, . . .)

propagation in frame of scalar diffraction theory

$$\vec{E}_{\omega \perp, 2} = -i \frac{\omega}{2\pi c} \int \int_\Sigma \frac{\vec{E}_{\omega \perp, 1}}{\rho} \exp[i\omega/c \rho] d\Sigma$$

Classical way:
approximation

spectral flux density

$$\frac{d^2 N_\omega}{dA d\omega/\omega} = \frac{\alpha c^2}{4\pi^2 e^2} |\vec{E}_{\omega \perp, 2}|^2$$

Numerical way
 Includes real electron path,
 depth of field and diffraction

Point spread Function

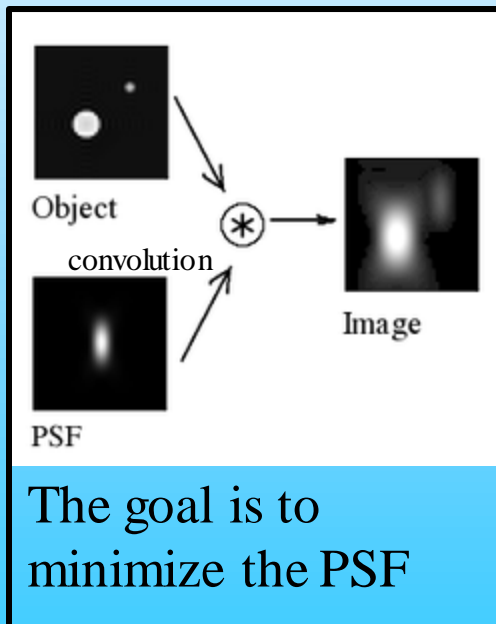
● Fraunhofer diffraction pattern for spherical wave
 ↪ depth of field, orbit curvature: additional contributions

● accounts for the fact that SR is not actually a spherical wave
 ↪ depth of field and orbit curvature included

Point Spread Function

The **point spread function (PSF)** describes the response of an imaging system to a **point source or point object!!!** A more general term for the PSF is a system's impulse response, the PSF being the impulse response of a *focused* optical system. In functional terms it is the spatial domain version of the transfer function of the imaging system. It is a useful concept in many imaging. The degree of spreading (blurring) of the point object is a measure for the quality of an imaging system. In non-coherent imaging systems such as telescopes or optical microscopes, the image formation process is linear in power and described by linear system theory. This means that when two objects A and B are imaged simultaneously, the result is equal to the sum of the independently imaged objects. In other words: the imaging of A is unaffected by the imaging of B and *vice versa*, owing to the non-interacting property of photons. The image of a complex object can then be seen as a convolution of the true object and the PSF. However, when the detected light is coherent, image formation is linear in the complex field. Recording the intensity image then can lead to cancellations or other non-linear effects.

from Wikipedia



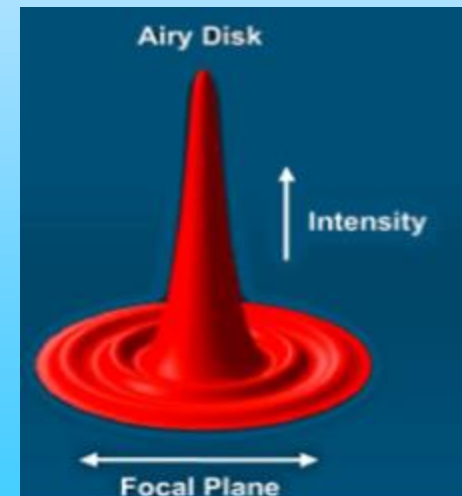
Because convolution in the spatial domain is equal to multiplication in the frequency domain, convolutions are more easily manipulated by taking their Fourier transform (F).

$$F\{i(x,y,z,t)\} = F\{o(x,y,z,t)\} \times F\{psf(x,y,z,t)\}$$

The frequency domain is characterized by the modulation transfer function MTF or by the optical transfer function OTF with $MTF = |OTF|$. The MTF is the Fourier transform of the PSF and describes how spatial frequency is affected by blurring.

Theoretically, it should be possible to reverse the convolution of object and PSF by taking the inverse of the Fourier transformed functions. However, deconvolution increases noise, which exists at all frequencies in the image. Many deconvolution algorithms (filters) exist: Richardson-Lucy, van Cittert, Wiener, Blind,

Done in astronomy, starting for beam diagnostics



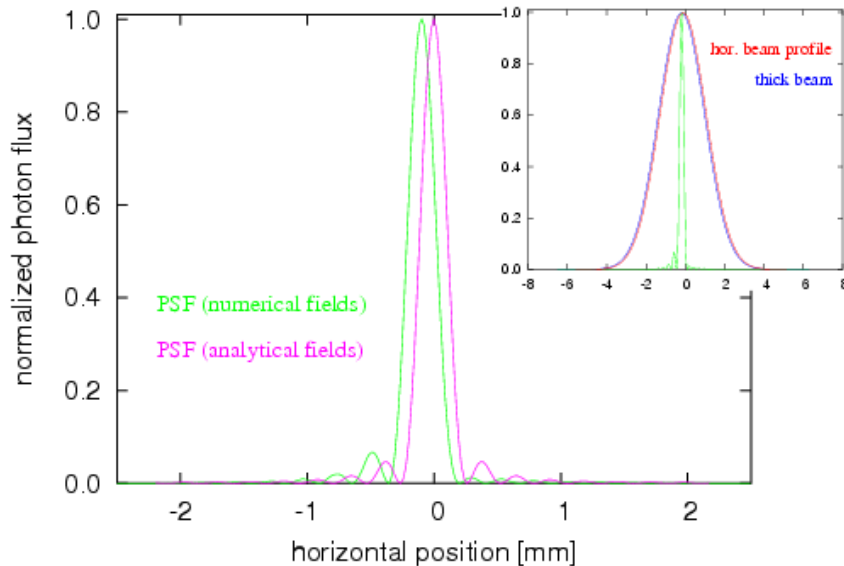
Resolution Broadening Effects for the HERAe Emittance Monitor

determination:

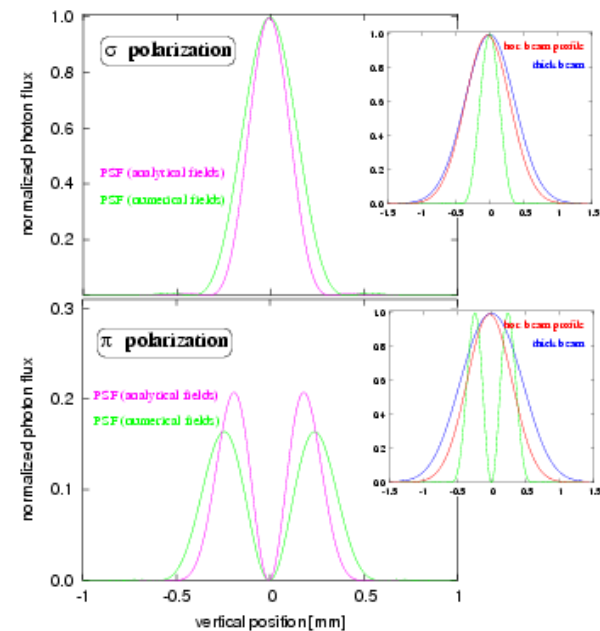
- calculation of spatial SR intensity distribution including beam emittance
- quadratical subtraction of beam size

For ∞ mirror size

horizontal profile



vertical profile



New

broadening contribution:

$$\sigma_{res} = 203 \mu\text{m}$$

numerical

● broadening contribution:

$$\sigma_{res} = 138 \mu\text{m}$$

So far

$$\sigma_{diff fract} = 188 \mu\text{m}$$

$$\sigma_{dof+curv} = 275 \mu\text{m}$$

\hookrightarrow

$$\sigma_{res} = 333 \mu\text{m}$$

analytical

$$\bullet \sigma_{diff fract} = 106 \mu\text{m}$$

$$\sigma_{dof} = 134 \mu\text{m}$$

\hookrightarrow

$$\sigma_{res} = 171 \mu\text{m}$$

$$579 \rightarrow 381 \rightarrow 333 \rightarrow 203 \mu\text{m}$$

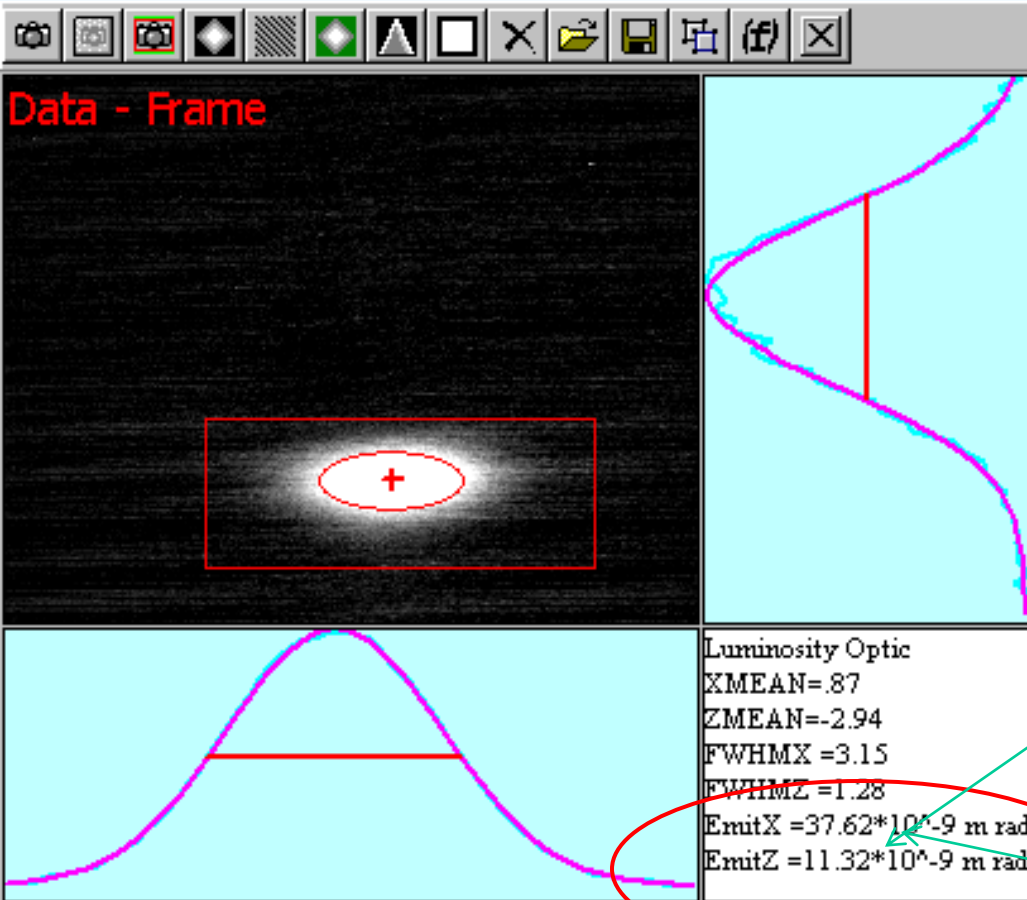
$$617 \rightarrow 229 \rightarrow 171 \rightarrow 138 \mu\text{m}$$

- G. Kube, R. Fischer, K. Wittenburg, in *Proceedings of BIW2004, AIP Conf. Proc.* **732** (2004), p.350–357

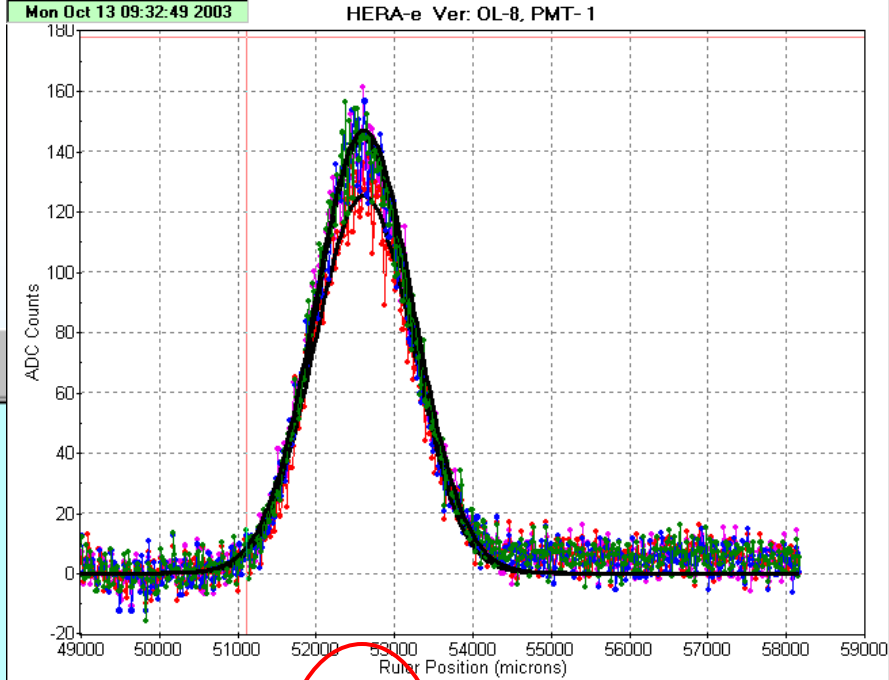
- G. Kube, R. Fischer, Ch. Wiebers, K. Wittenburg, in *Proceedings of DIPAC2005*

Comparison

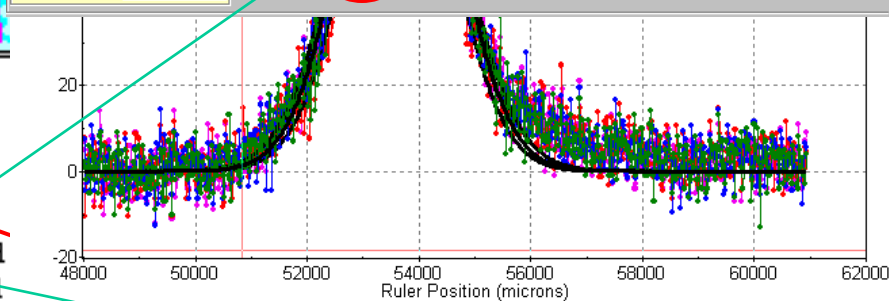
SR-monitor vs Wire scanner



$$\sigma_v = 542 \mu\text{m}$$



	ϵ (nm.mrad)	σ (mm)	Mean	Offset	Ampl
<input checked="" type="checkbox"/> B6	10.65	0.617	52.601	0.000	145.374
<input checked="" type="checkbox"/> B7	11.01	0.628	52.607	0.000	125.148
<input checked="" type="checkbox"/> B8	9.96	0.597	52.597	0.000	144.053
<input checked="" type="checkbox"/> B9	11.07	0.629	52.612	0.000	146.765
<input type="checkbox"/> B10					



	ϵ (nm.mrad)	σ (mm)	Mean	Offset	Ampl
<input checked="" type="checkbox"/> B6	37.18	0.963	53.616	0.000	101.469
<input checked="" type="checkbox"/> B7	34.25	0.924	53.648	0.000	87.769
<input checked="" type="checkbox"/> B8	41.71	1.020	53.646	0.000	97.571
<input checked="" type="checkbox"/> B9	35.90	0.946	53.649	0.000	103.283
<input type="checkbox"/> B10					

End of Synchrotron Radiation Monitor



Vertical Resolution for Off-Axis Observation at HERAe

motivation:

- high heat load of extraction mirror
- opening angle Ψ_c for optical SR larger than for X-rays \rightarrow x-ray miss the mirror

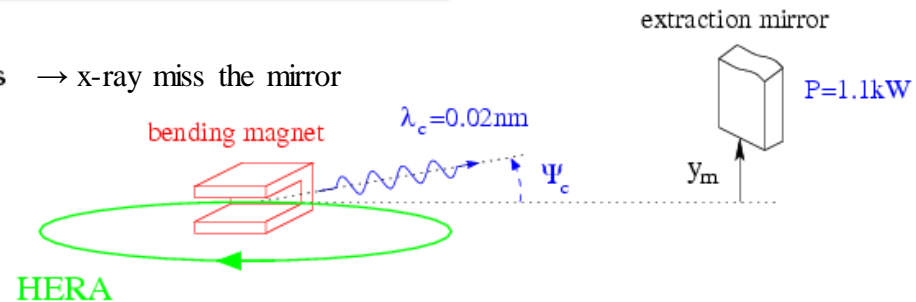
solution:

- observation in off-axis geometry ($y_m \geq 0$)

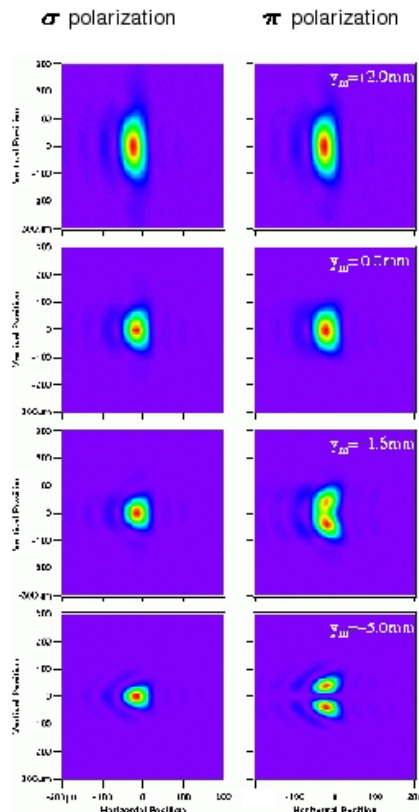
consequence:

- modification of lower bound in Kirchhoff integral (SR propagation through optical system)

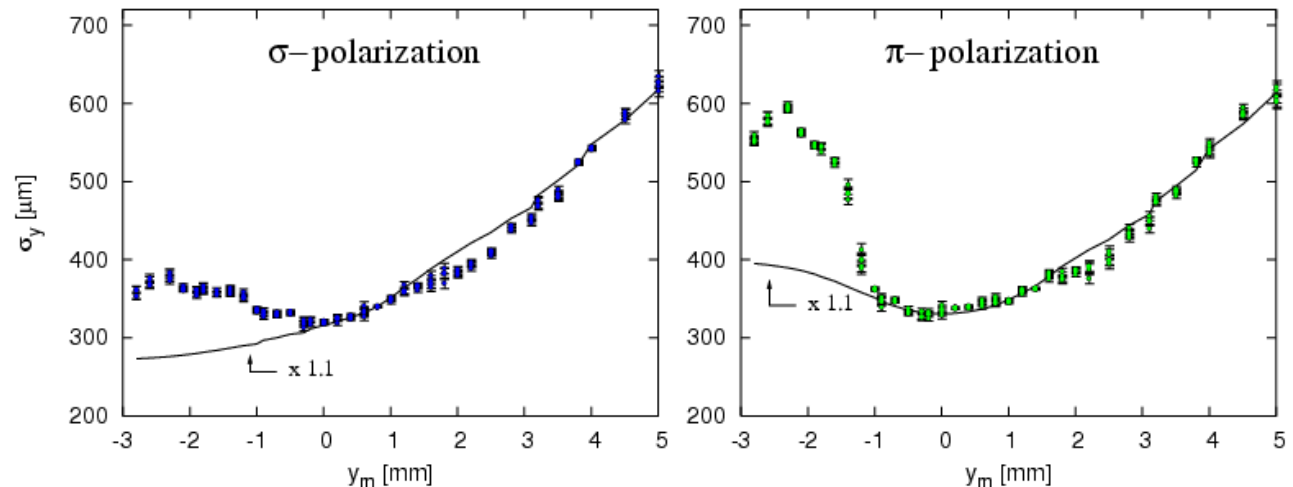
\rightarrow additional resolution broadening



point spread function:

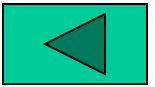


comparison:



G. Kube, R. Fischer, K. Wittenburg, in *Proceedings of BIW2004*, AIP Conf. Proc. **732** (2004), p.350–357

G. Kube, R. Fischer, Ch. Wiebers, K. Wittenburg, in *Proceedings of DIPAC2 005* (in press)

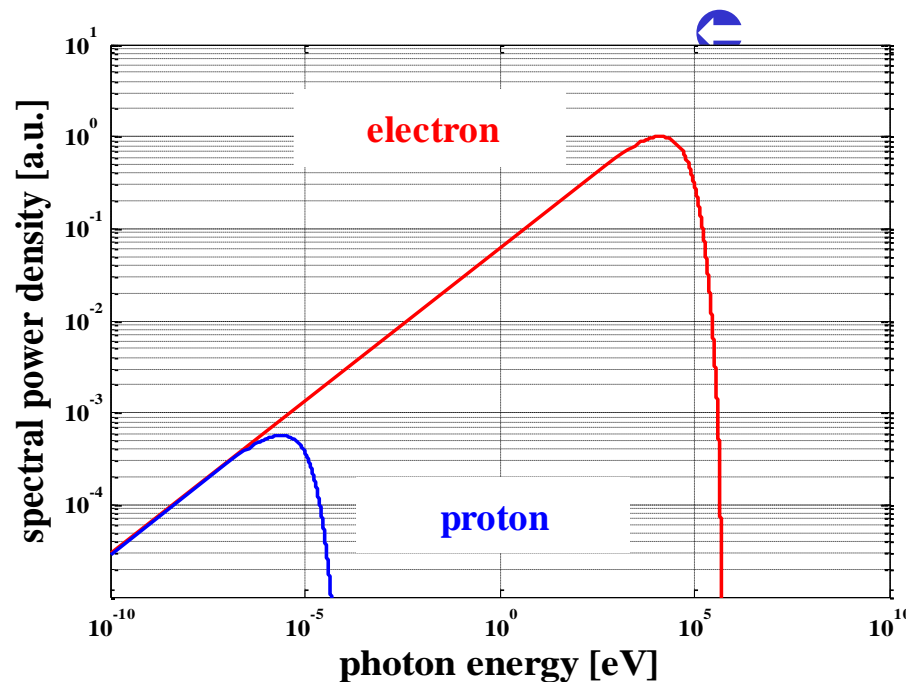


- spectrum characterized by λ_c :
- large p mass \implies small $\gamma = E/m_p c^2$

$$\lambda_c = \frac{4\pi}{3} \frac{\rho}{\gamma^3}$$

γ : Lorentz factor

ρ : bending radius



$$E_{\text{kin}} = 20 \text{ GeV}$$

$$\rho = 370 \text{ m}$$

HERA-p: $E = 40 \dots 920 \text{ GeV}$ $\lambda_c = 55 \text{ mm} \dots 4.5 \text{ } \mu\text{m}$

\implies large diffraction broadening, expensive optical elements, ...

“Frequency Boost” of Synchrotron Radiation

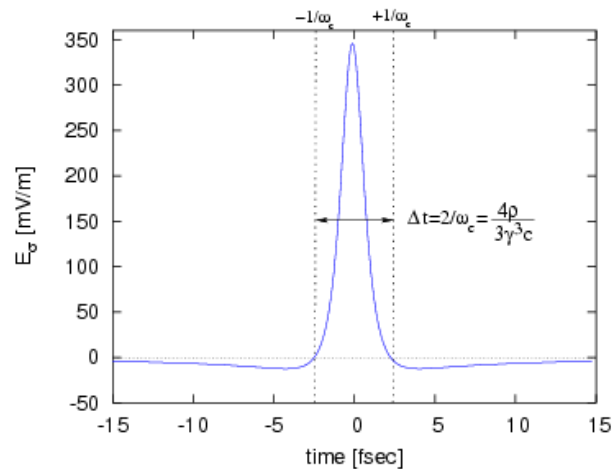
task: production of sufficient synchrotron radiation intensity at high frequencies $\omega \gg \omega_c$

\hookrightarrow intensity: $\frac{d^2 W}{d\Omega \frac{d\omega}{\omega}} \propto |\vec{E}_\omega|^2$ with $\vec{E}_\omega = \frac{1}{\sqrt{2}\pi} \int_{-\infty}^{+\infty} dt \vec{E}(t) e^{i\omega t}$

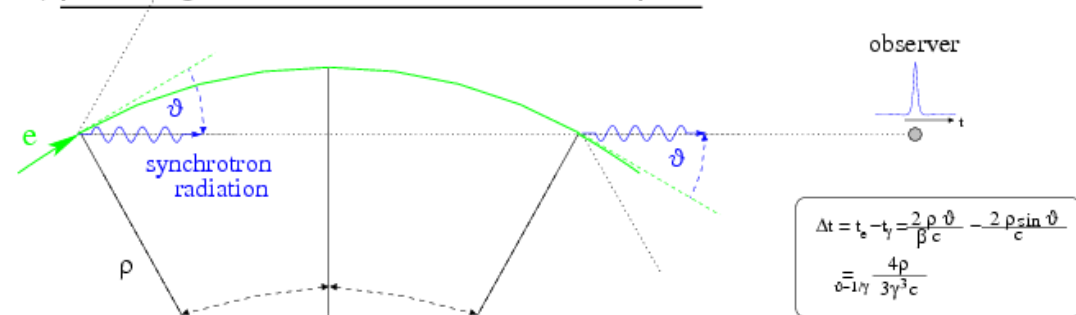
intuitive approach: synchrotron radiation in time domain

1.) field shape for on-axis observation

(i.e. $E_\pi = 0$)

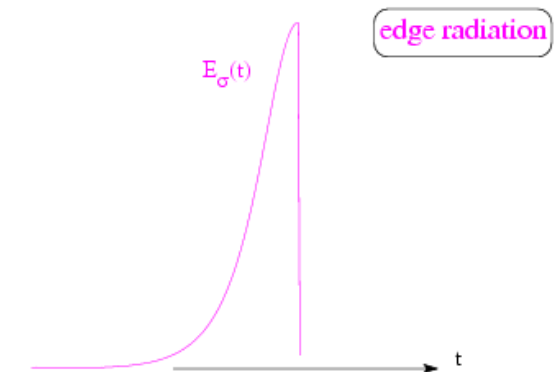
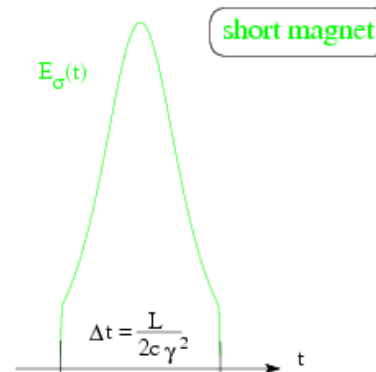


2.) pulse length estimation at fixed observation point



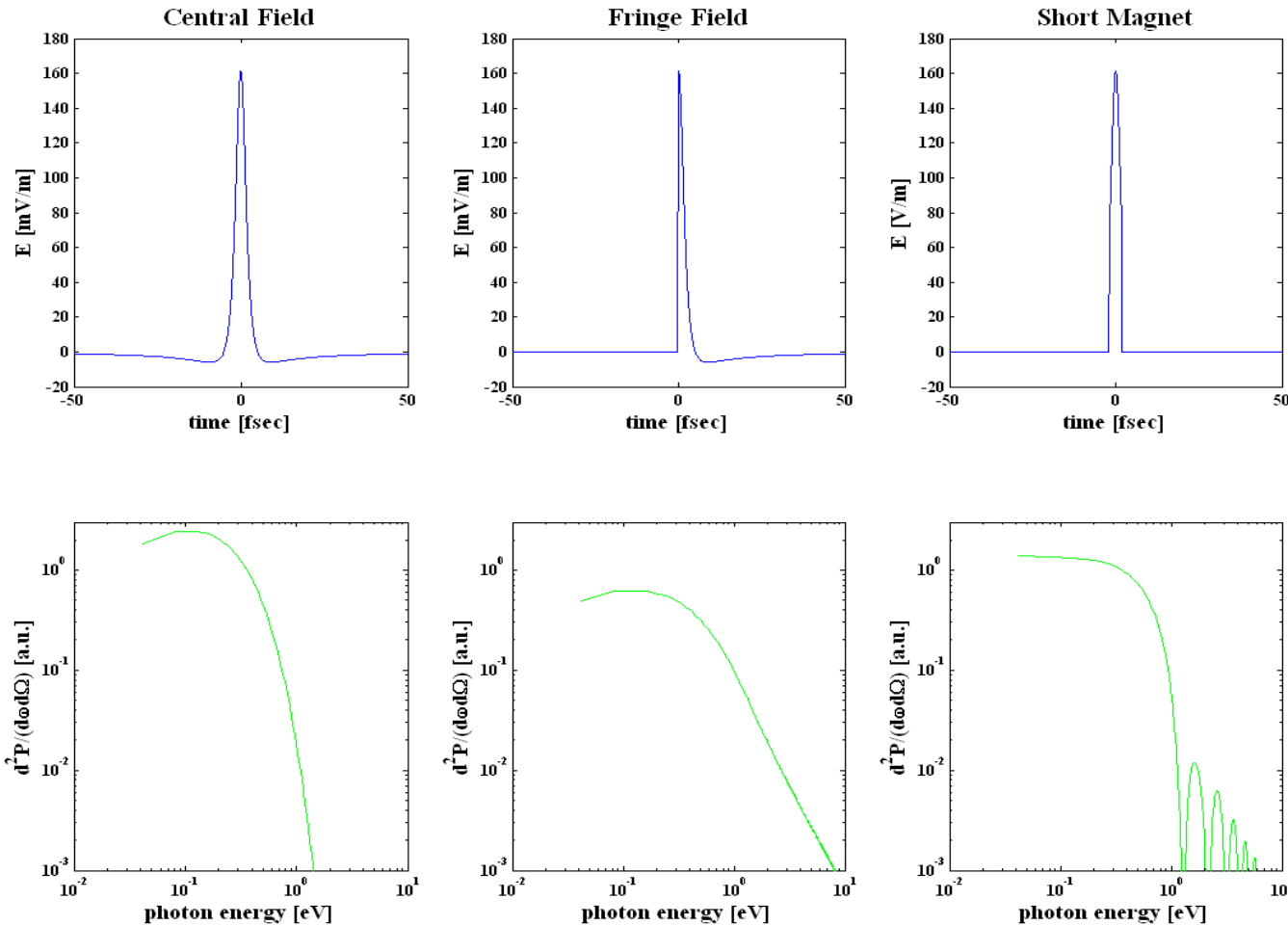
consequence:

Observation time interval defines spectrum (ω_c)



Generation of Frequency Boost

sharp cut-off of wavetrain in time domain



$$\frac{d^2N}{d\Omega d\omega/\omega} \propto |\vec{E}_\omega|^2$$

with

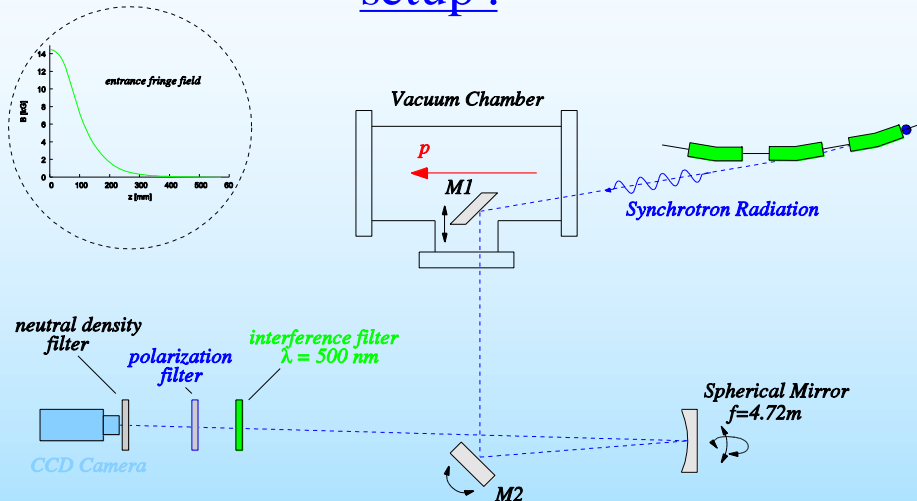
$$\vec{E}_\omega = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dt \vec{E}(t) e^{i\omega t}$$

← still requires high beam energies (CERN, Tevatron, HERA)

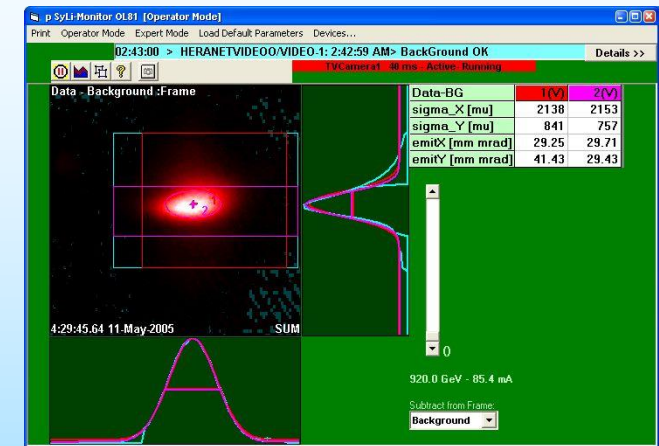
p SyLi Monitor @ HERA (DESY)

fringe field of vertical deflecting dipole

setup :



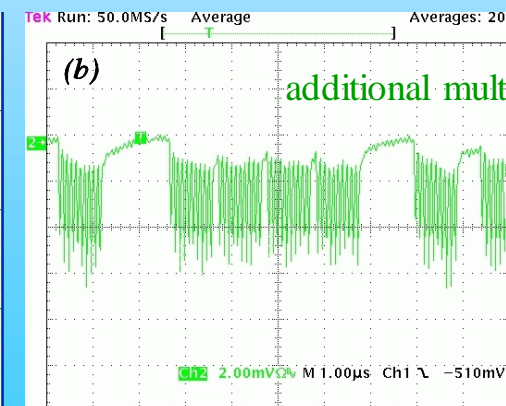
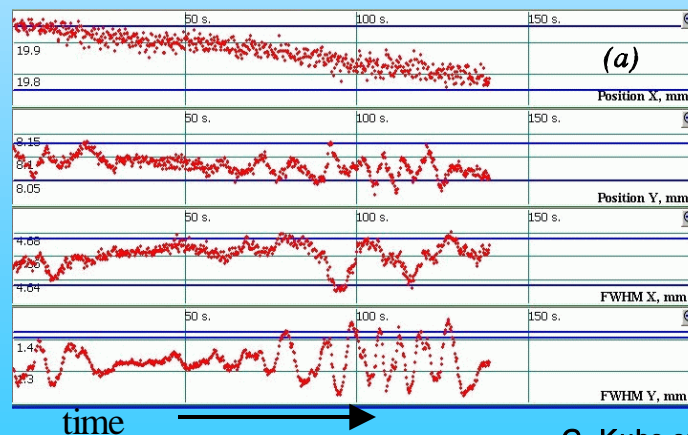
screen shot :



visible light spot for E > 600 GeV

dynamics study:

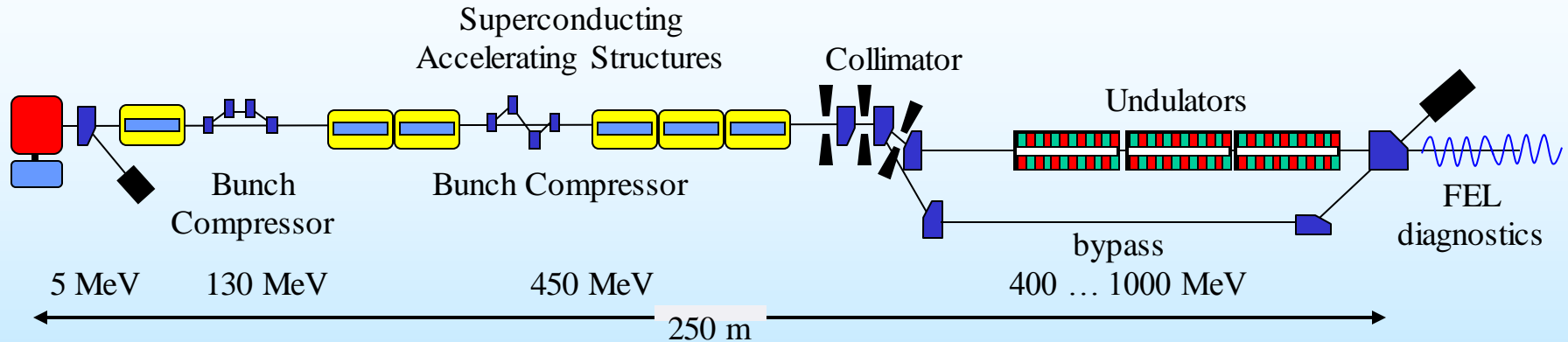
moving collimators
towards the beam



G. Kube et al., Proc. of BIW06 (2006), Batavia, Illinois, p.374

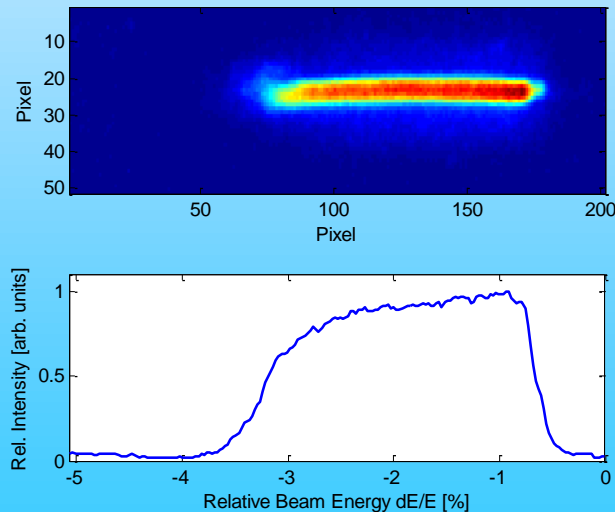
Energy Monitor @ FLASH (DESY)

SR based profile diagnostics in bunch compressor

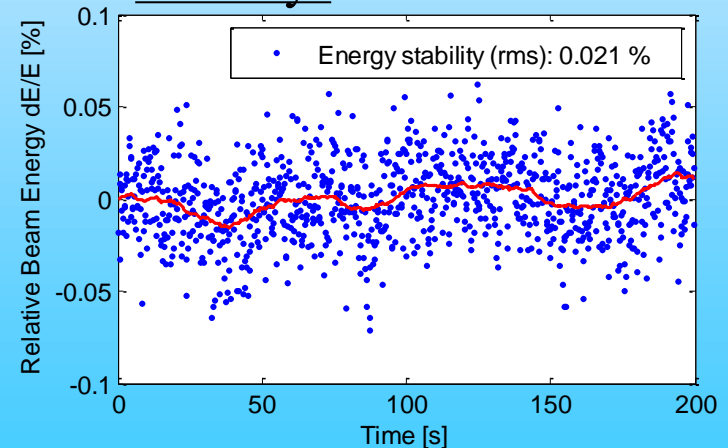


dispersive section \Rightarrow information about energy distribution (and more...)

single
bunch



stability:



Ch. Gerth, Proc. of DIPAC07 (2007), Venice, p.150

End of Synchrotron Light session

Video



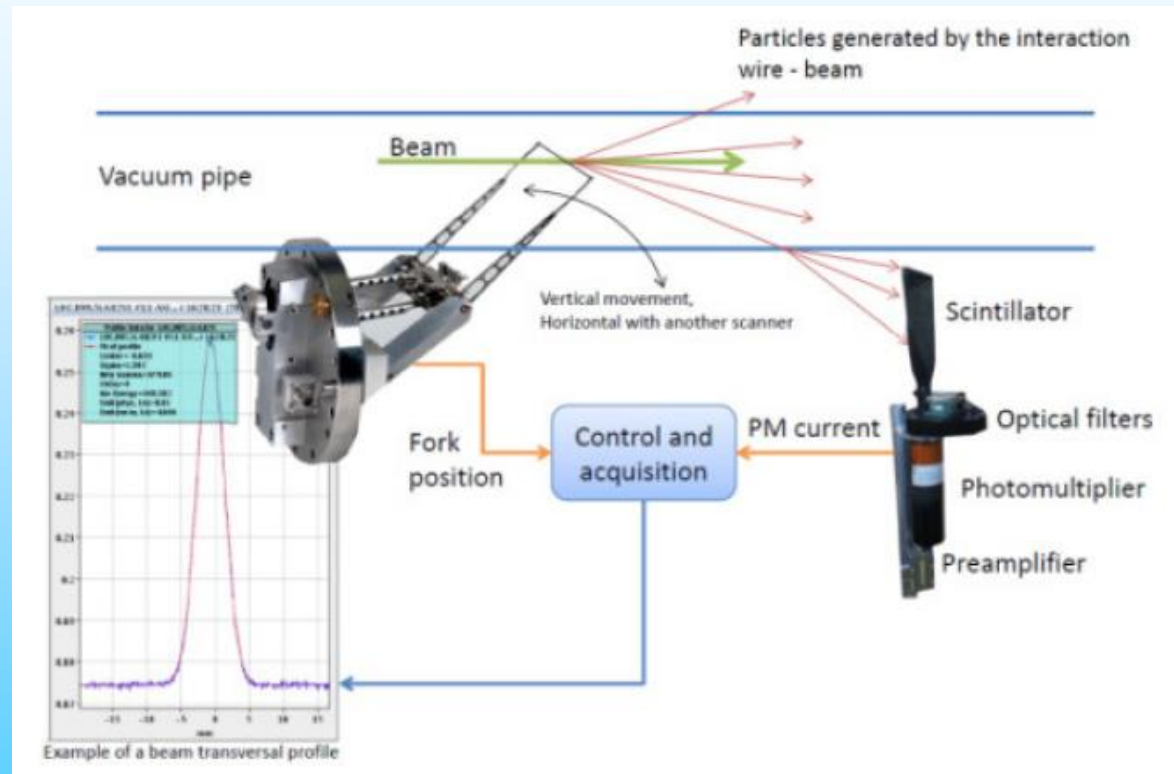
Wire Scanners

Introduction

Conventional wire scanners with thin solid wires (conventional compared with new techniques using, for example, Lasers) are widely used for beam size measurements in particle accelerators.

Their advantages:

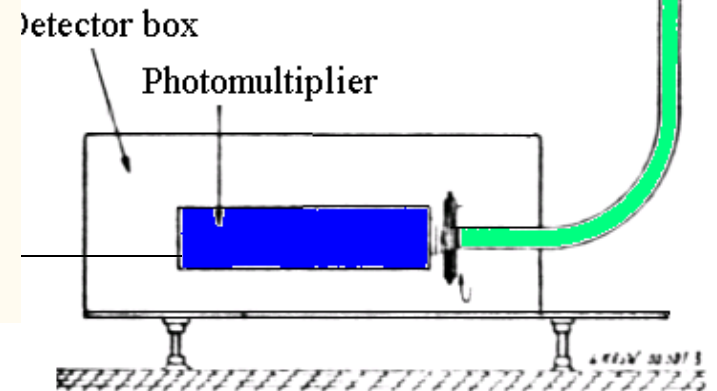
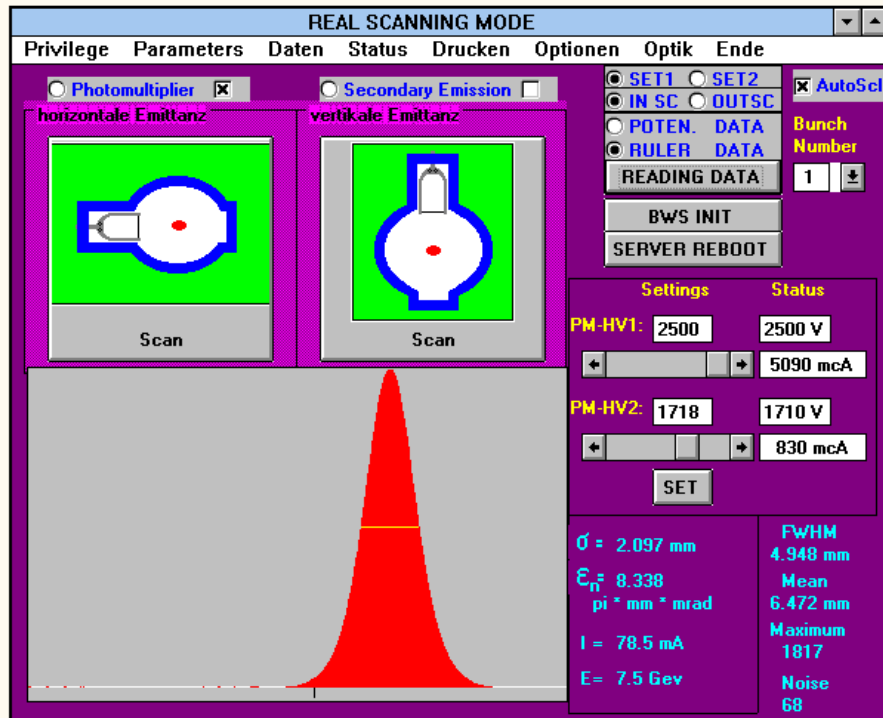
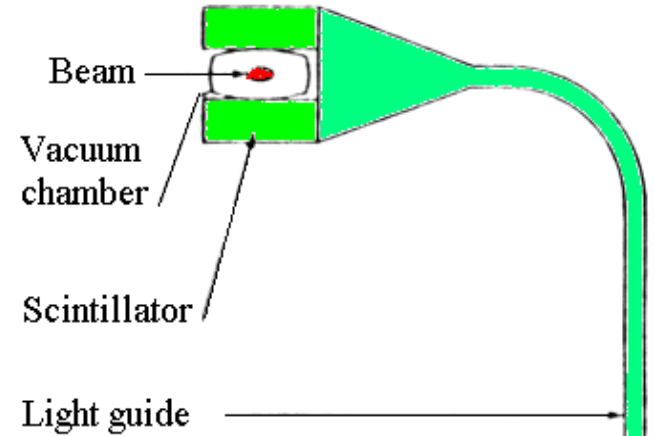
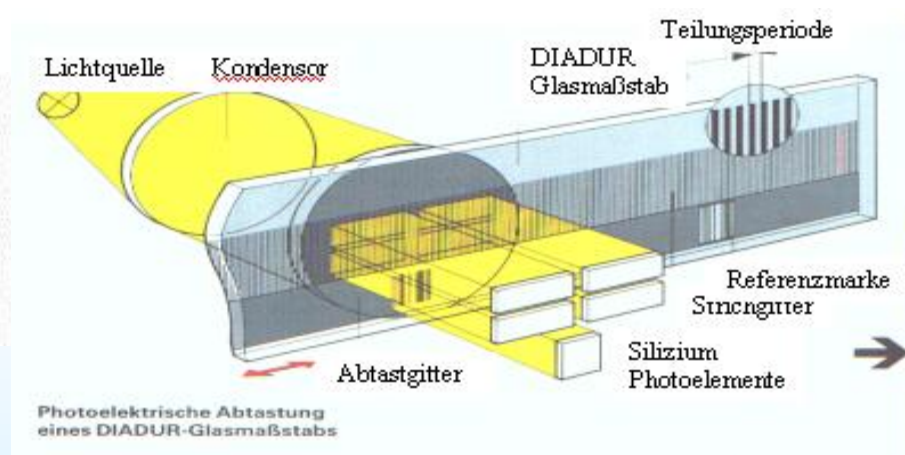
- 1) Resolution of down to $1\ \mu\text{m}$
- 2) Trusty, reliable
- 3) Direct

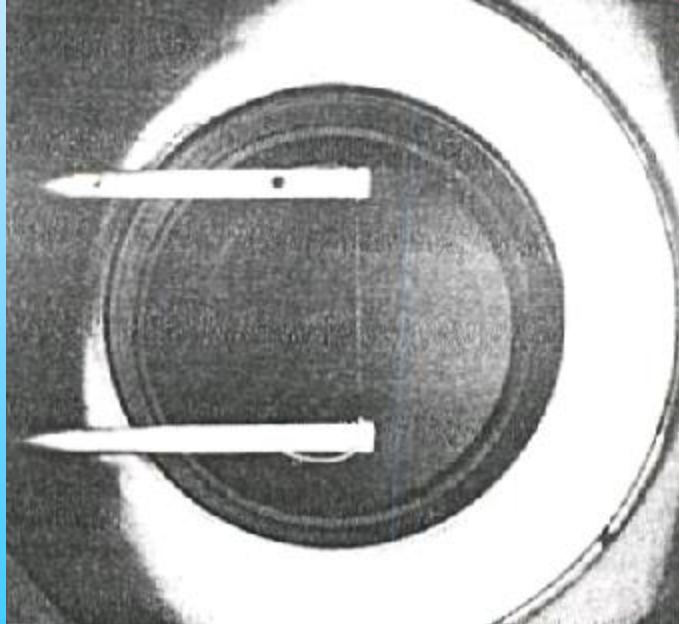
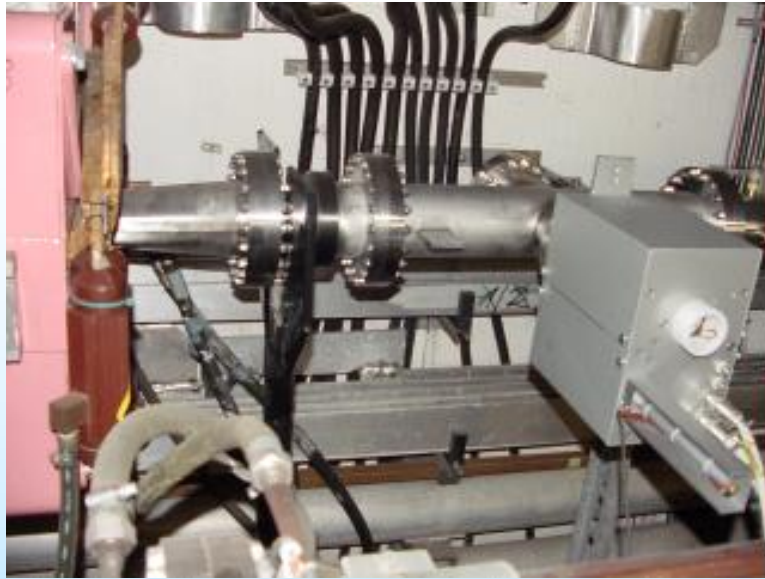


CERN-SPS Wire Scanner Impedance and Wire Heating Studies

E.Piselli, et al. IBIC 2014, Monterey, California, USA September 14-18, 2014.

0.1 micron position resolution is possible





CERN/DESY 1990-2007 FLASH: 2002 - now

Speed: 0 - 1 m/s

Scanning area: approx. 10 cm

Wire material: Carbon/Quartz

Wire diameter: 7 microns

50 μ m at Flash

Signal: shower

1 micron resolution

Where one should locate the Scintillator?

Projected angular distribution could be approximated by Gaussian with a width given by

$$\Theta_{mean} = \frac{0.014 \text{ GeV}}{pc} \cdot \sqrt{\frac{d'}{L_{rad}}} \cdot \left(1 + 1/9 \cdot \log_{10} \frac{d'}{L_{rad}} \right)$$

$d' = 1.5 \times 10^{-3} \text{ cm}$ - the thickness of the target, $X_0 = 12.3 \text{ cm}$ - quartz-wire radiation length,
 $x/X_0 = 1.22 \times 10^{-4}$

It is corresponding to:

$$\Theta_{mean} \approx 3.0 \times 10^{-6} \text{ rad}$$

for electron momentum of $30 \text{ GeV}/c$.

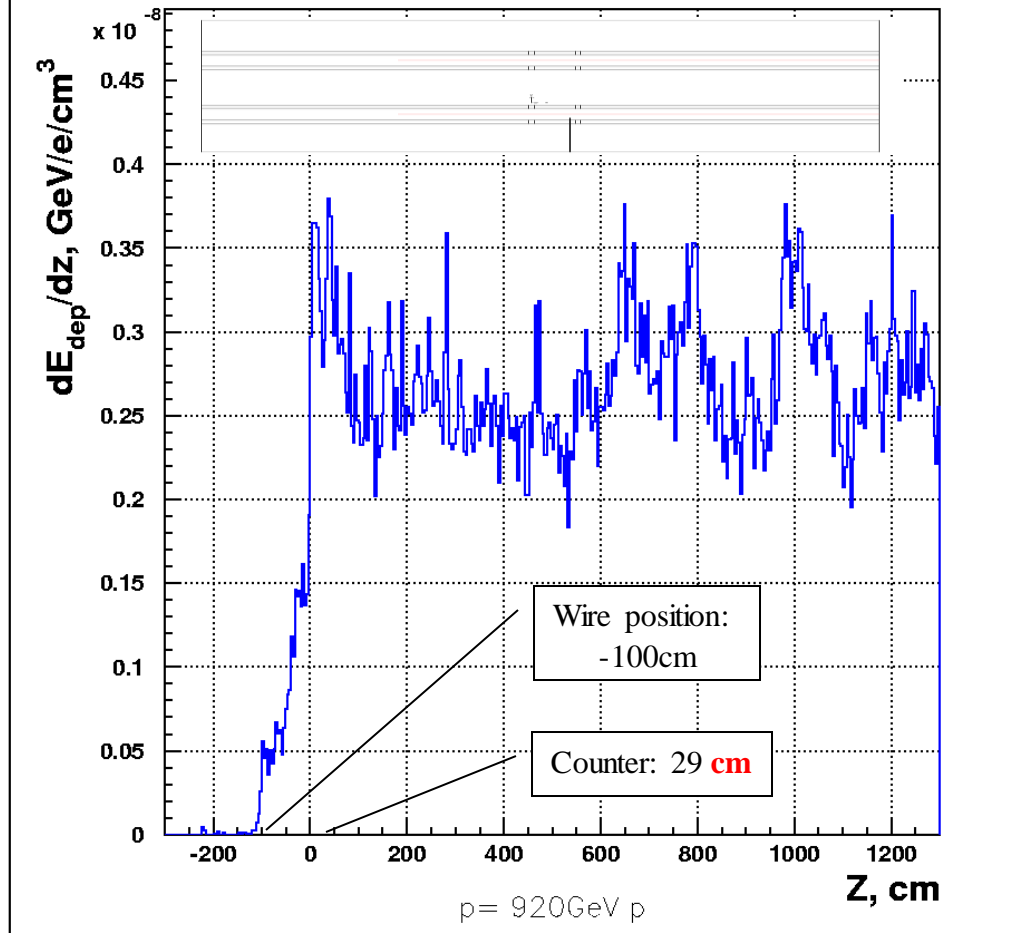
Scattered particles will arrive vacuum chamber of radius $R = 2 \text{ cm}$ at:

$$z \approx \frac{R}{\Theta_{mean} \sqrt{2}} \approx 4.9 \text{ km!!!!}$$

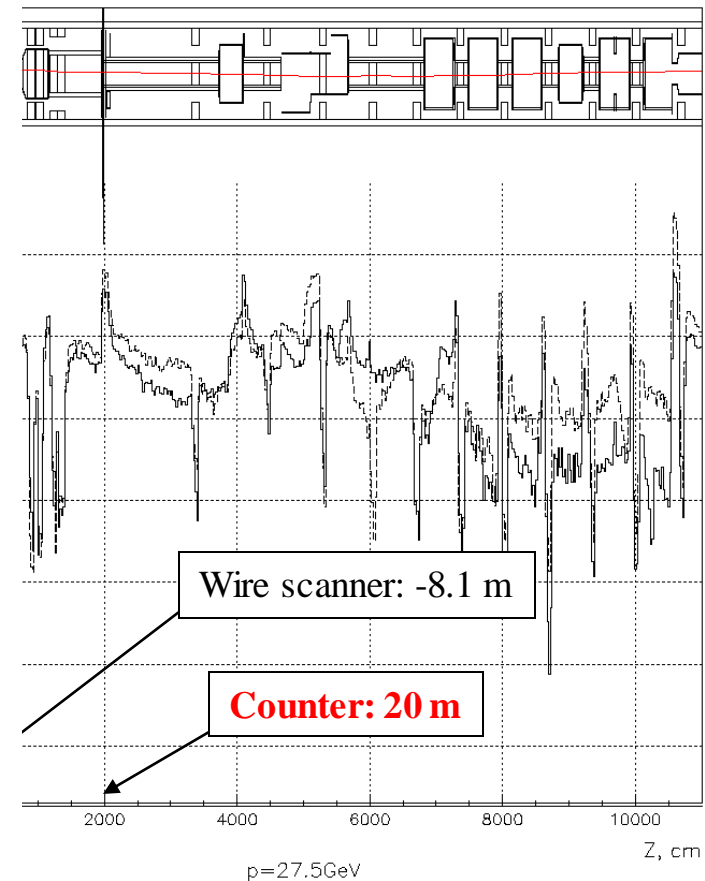
What to do?

Monte Carlo simulations for finding best location of scintillators

Protons at 920 GeV/c

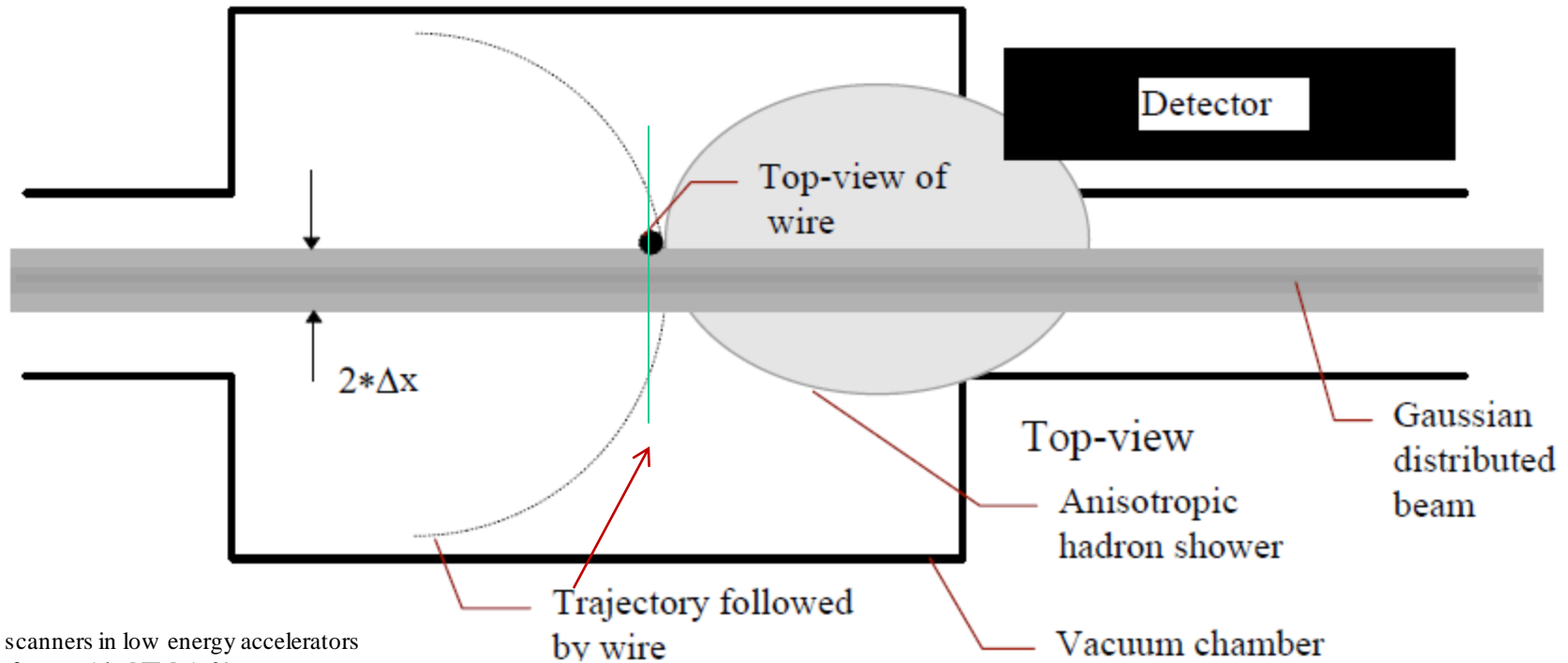


Electrons at 30 GeV/c



Simulation includes all magnetic fields
as well as all elastic and inelastic scattering cross sections

Wire Scanner at low energies



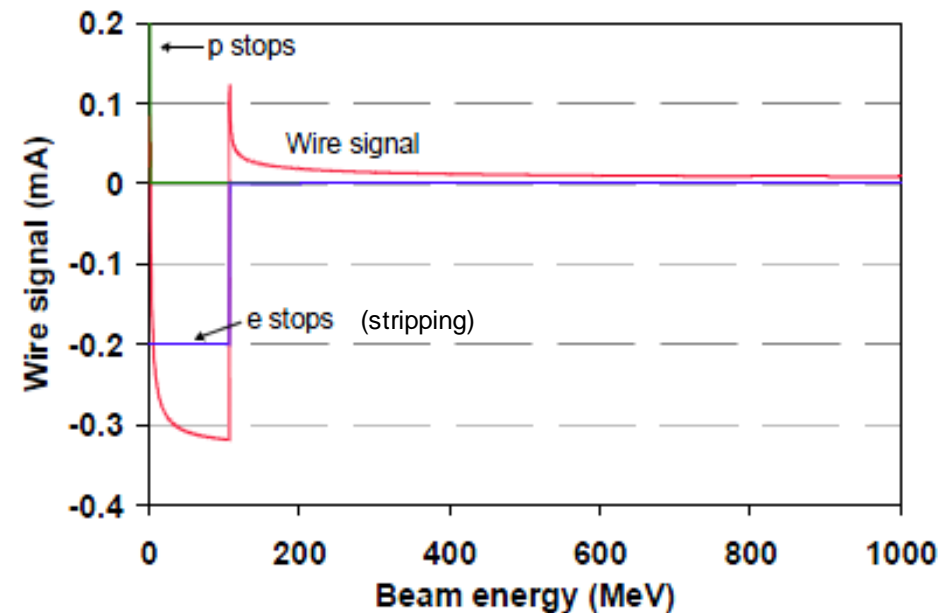
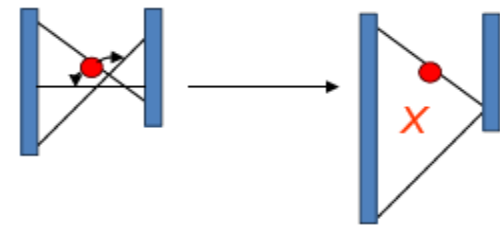
Wire scanners in low energy accelerators
P. Elmfos ar. Al.; NIM A 396

Wire Scanner at low energies

2) Secondary electron emission (SEM) .

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

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



Wire scanner's limitations are?

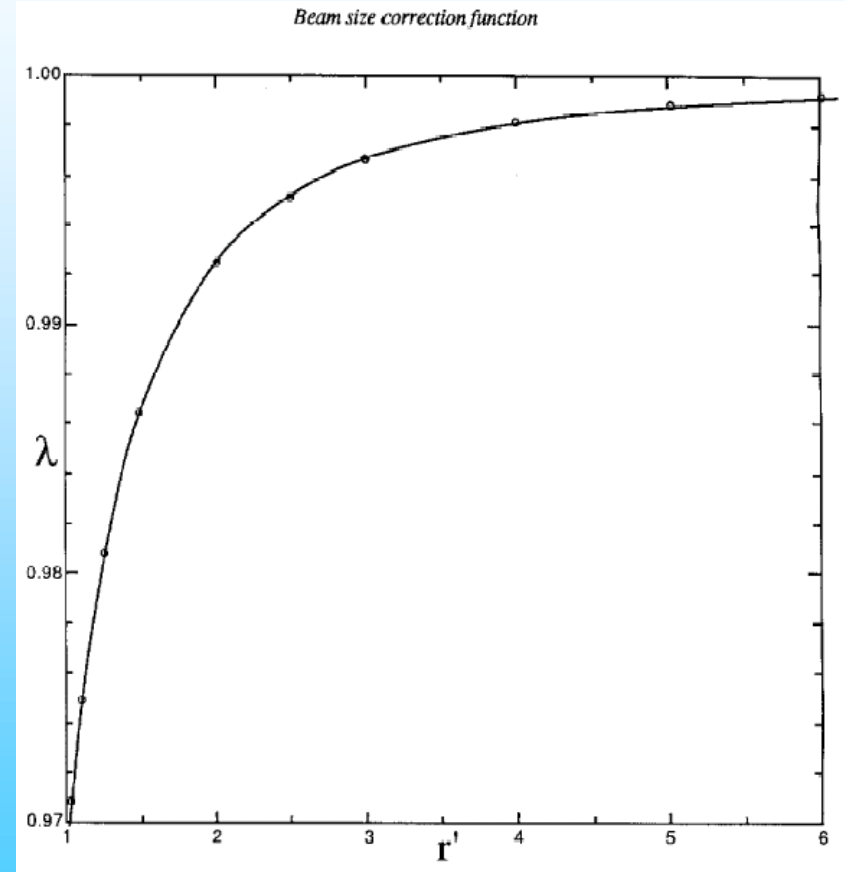
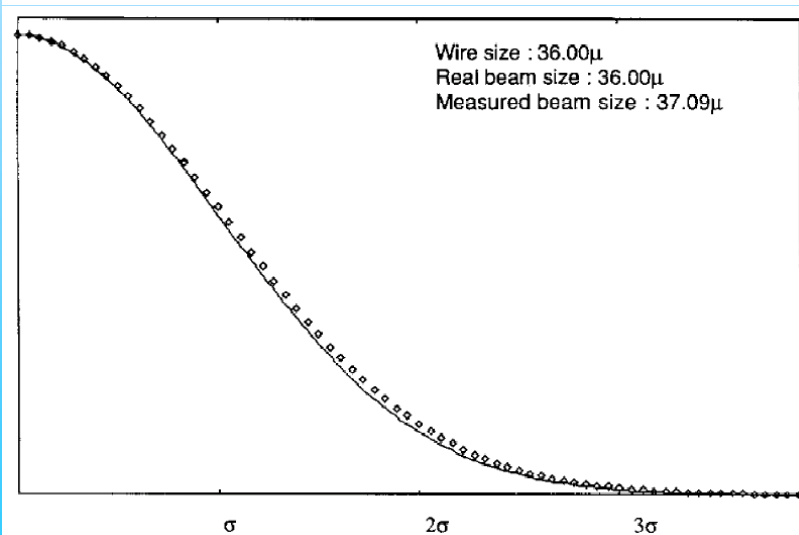
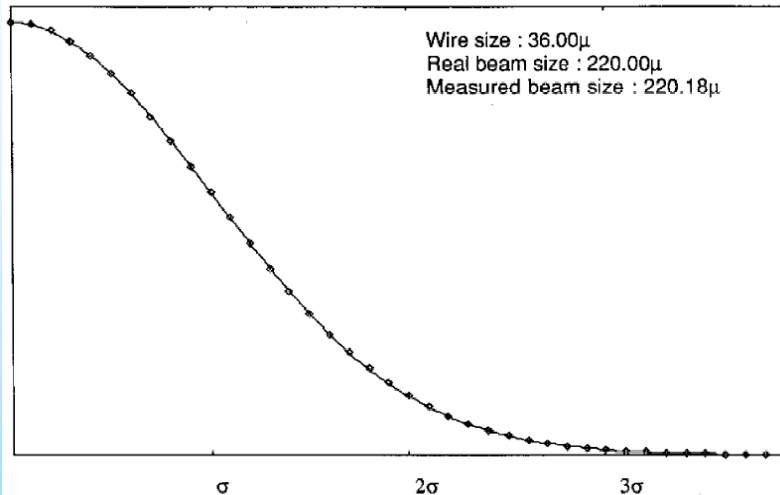
1. The smallest measurable beam size is limited by the finite wire diameter of a few microns,
2. Higher Order Modes may couple to conductive wires and can destroy them,
3. High beam intensities combined with small beam sizes will destroy the wire due to the high heat load.
4. Emittance blow up

Limitations:

1. Wire size

The smallest achievable wires have a diameter of about 5-6 μm .

An example of the error in the beam width determination is shown for a 36 μm wire.



Influence of the wire diameter on the measured beam width.

(All figures from: Q. King; **Analysis of the Influence of Fibre Diameter on WireScanner Beam Profile Measurements**, SPS-ABM-TM/Note/8802 (1988))

Limitations:

2. Higher Order modes

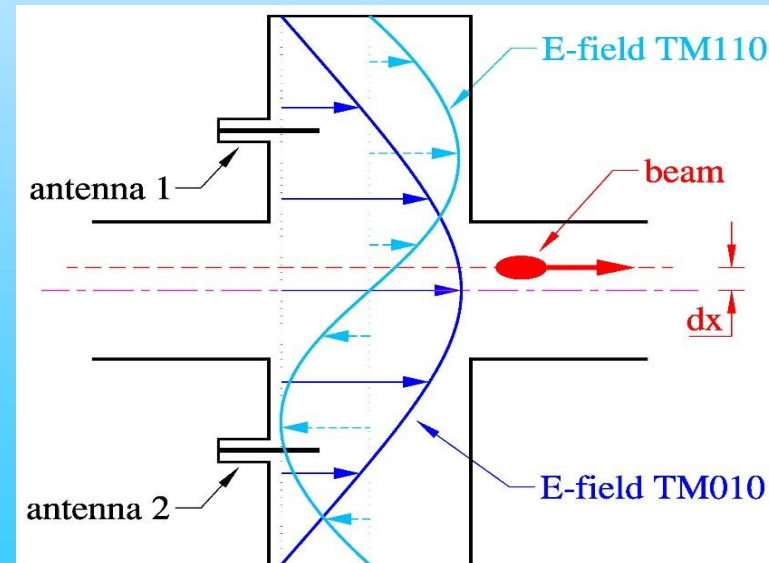
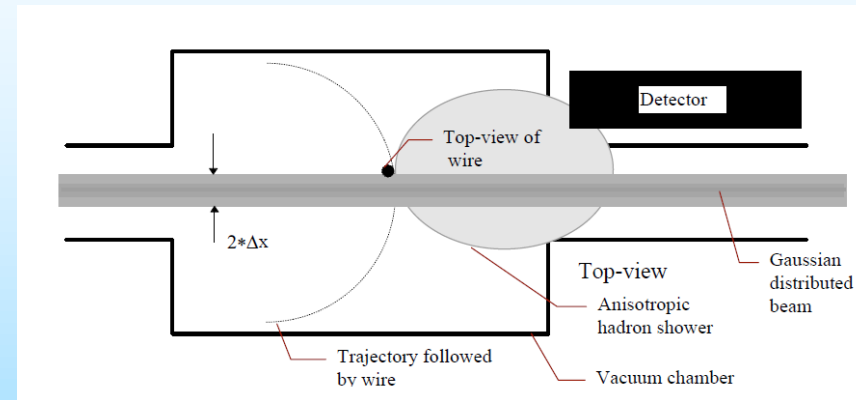
An early observation (1972 DORIS) with wire scanners in electron accelerators was, that the wire was always broken, even without moving the scanner into the beam. An explanation was that Higher Order Modes (HOM) were coupled into the cavity of the vacuum chamber extension housing the wire scanner fork. The wire absorbs part of the RF which led to strong RF heating.

Exercise WIRE1:

1) Discuss methods of proving this assumption.

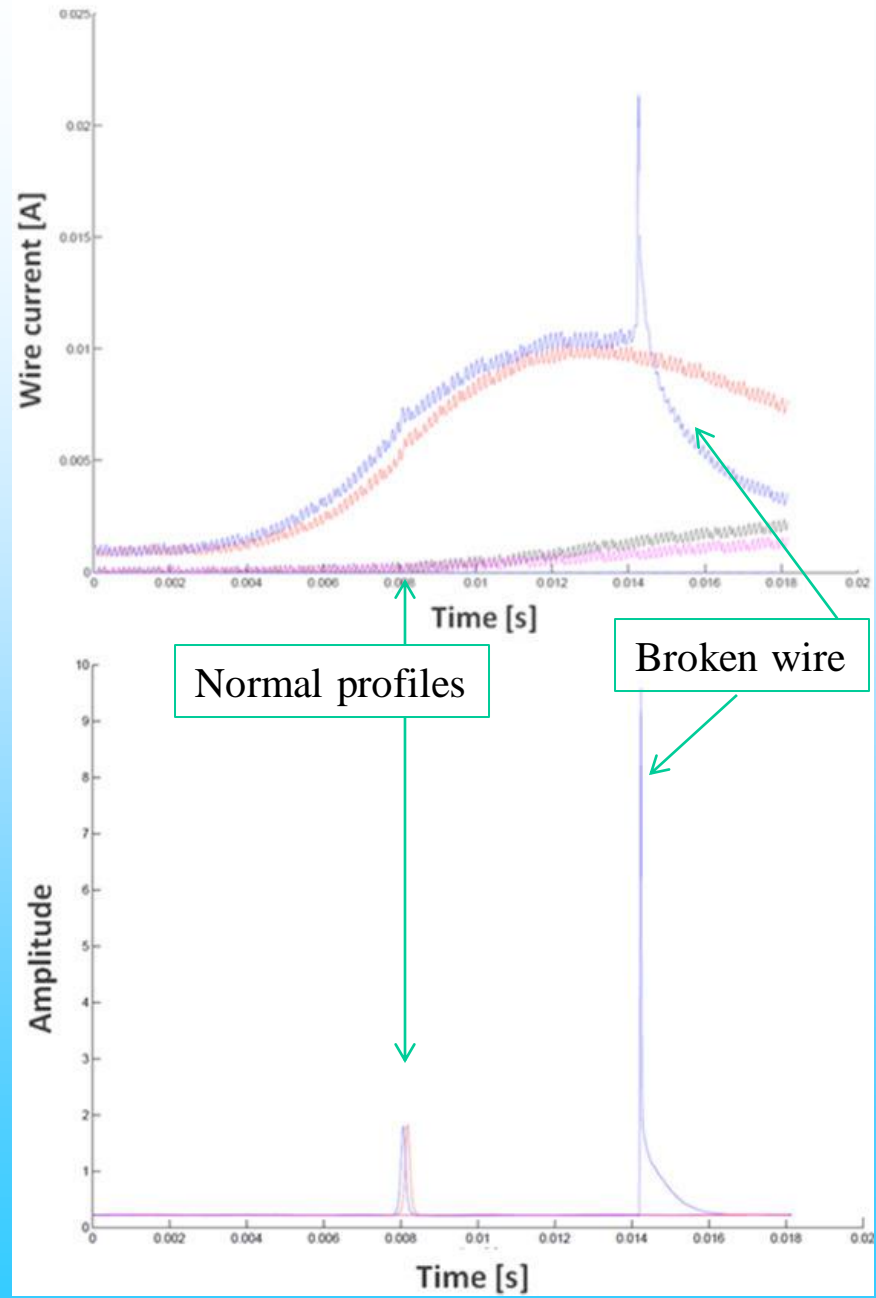
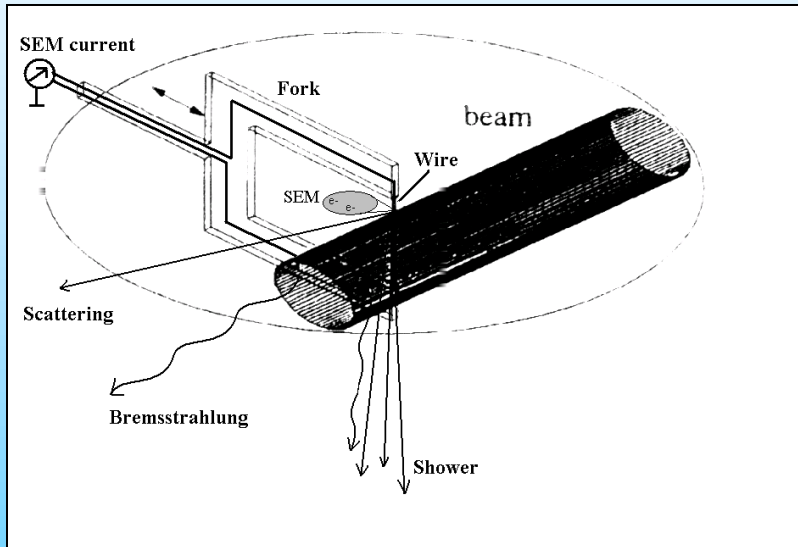
Methods:

1. Measurement of thermo-ionic emission
2. Measurement of wire resistivity
3. Optical observation of glowing wire
4. Measurement of RF coupling in Laboratory with spectrum analyzer

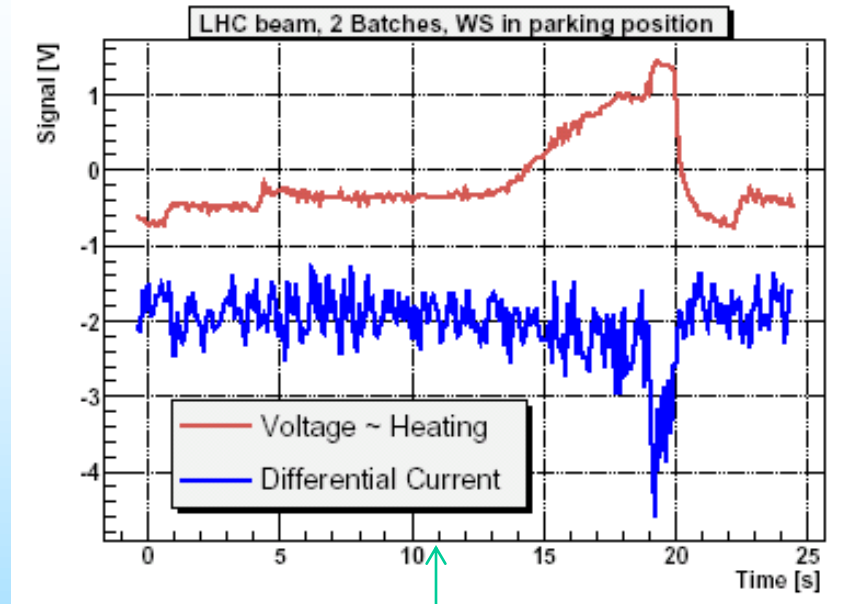


1a. Measurement of thermo-ionic emission, during scan

CERN SPS 2012



1b. Measurement of thermo-ionic emission, no scan



Wire heating due to the LHC beam injection in the SPS (No scan, wire in parking position).
The beam energy ramp/bunch length decreasing begin $t=11$ s.

A constant current was supplied to the wire and the voltage drop across it was fed to a digital scope together with the difference between the input and output currents. The differential current ($I_{\text{out}} - I_{\text{in}}$) grow up is due to the wire heating and consequent emission of electrons for thermionic effect. Fig. WIRE5 shows such voltage and differential current evolutions during the SPS cycle with LHC type beam. No scans were performed along this cycle. It is thus evident that the wire heating does not depend on the direct wire-beam interaction only.

(From CAVITY MODE RELATED WIRE BREAKING OF THE SPS WIRE SCANNERS AND LOSS MEASUREMENTS OF WIRE MATERIALS
F. Caspers, B. Dehning, E.Jensen, J. Koopman, J.F. Malo, CERN, Geneva, Switzerland
F. Roncarolo, CERN/University of Lausanne, Switzerland; DIPAC03)

2. Measurement of wire resistivity

The wire resistivity will change depending on the temperature of the wire, even without scanning.

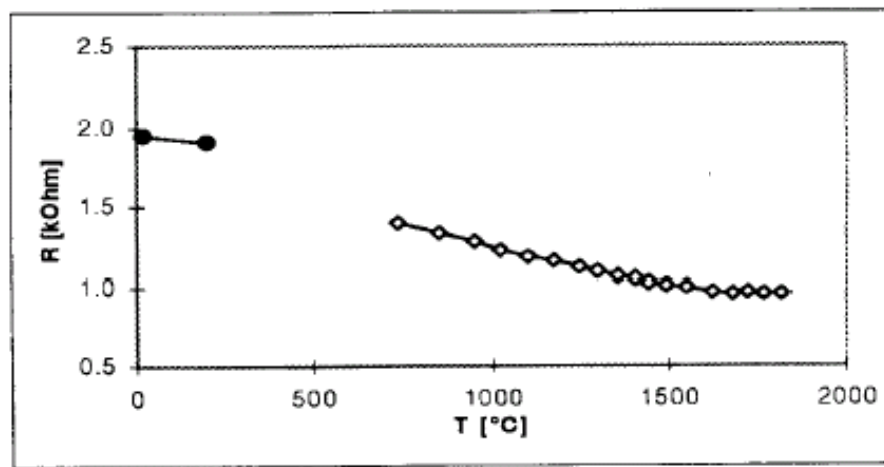
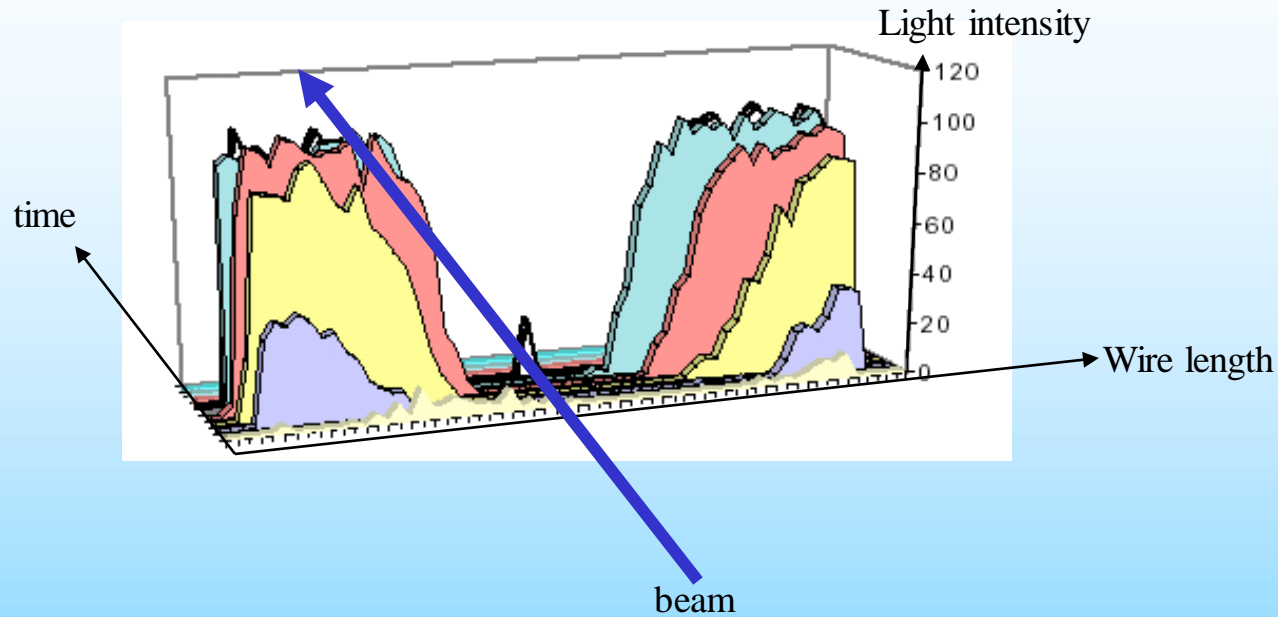


Fig 4: Measured wire resistance variations with temperature.

Here: 8 μm Carbon wire

(from OBSERVATION OF THERMAL EFFECTS ON THE LEP WIRE SCANNERS. By J. Camas, C. Fischer, J.J. Gras, R. Jung, J. Koopman (CERN). CERN-SL-95-20-BI, May 1995. 4pp. Presented at the 16th Particle Accelerator Conference - PAC 95, Dallas, TX, USA, 1 - 5 May 1995. Published in IEEE PAC 1995:2649-2651)

3. Optical observation of glowing wire

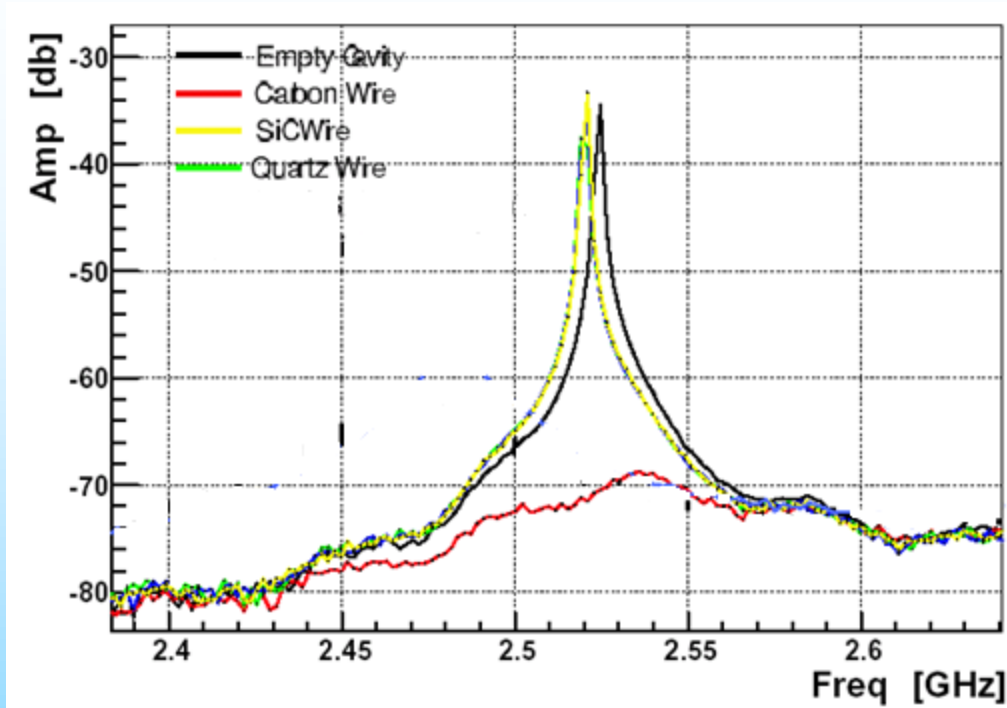


Digitized video recording of an 8 μm carbon wire scanning a 0.8 mA beam. The wire is parallel to the horizontal axis, and the light intensity is plotted along the vertical axis (arbitrary units). Successive profiles are separated by 20 ms. The central spot corresponds to the passage of the wire through the beam. Thus, RF heating led to (huge) thermal glowing before the beam interacts with the wire.

(from: QUARTZ WIRES VERSUS CARBON FIBERS FOR IMPROVED BEAM HANDLING CAPACITY OF THE LEP WIRE SCANNERS.

By C. Fischer, R. Jung, J. Koopman (CERN). CERN-SL-96-09-BI, May 1996. 8pp. Talk given at 7th Beam Instrumentation Workshop (BIW 96), Argonne, IL, 6-9 May 1996.

4. Measurement of RF coupling with spectrum analyzer

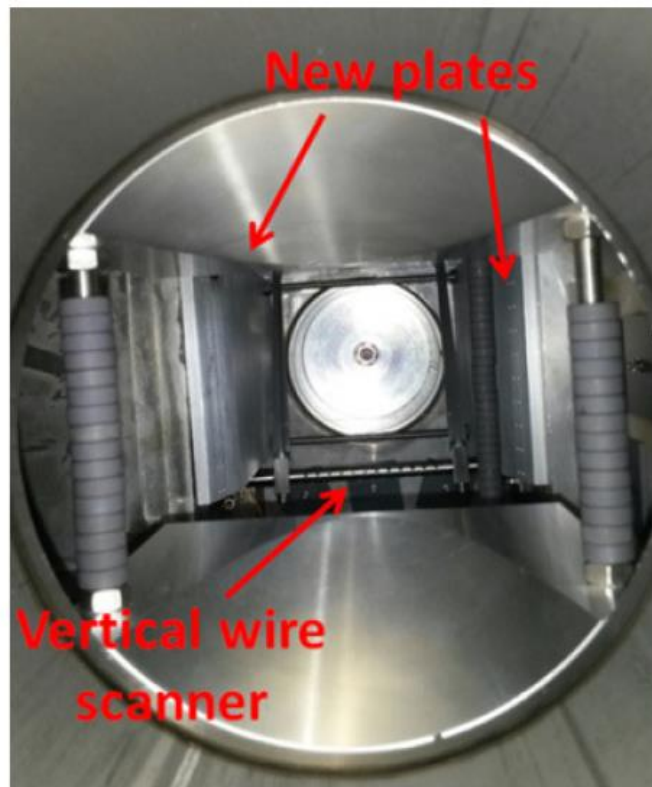


Resonance cavity signal in presence of Carbon (3.6 m), Silicon Carbide and Quartz wires

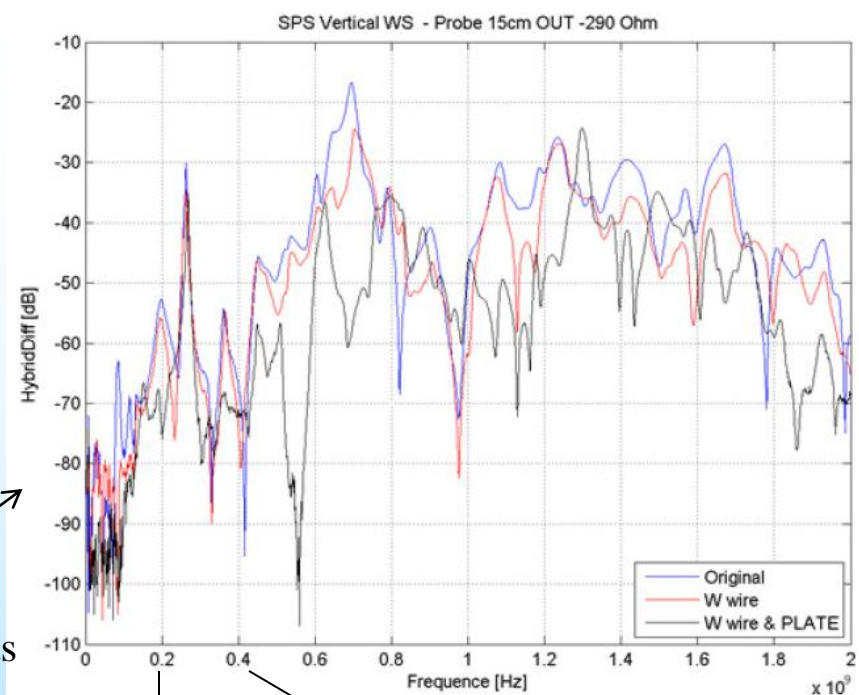
The plot qualitatively proves the RF power absorption for Carbon. The absorbed energy of Silicon Carbide and Quartz. Absorbed energy is mainly converted into heat.

What are solutions for the problems 1-4?

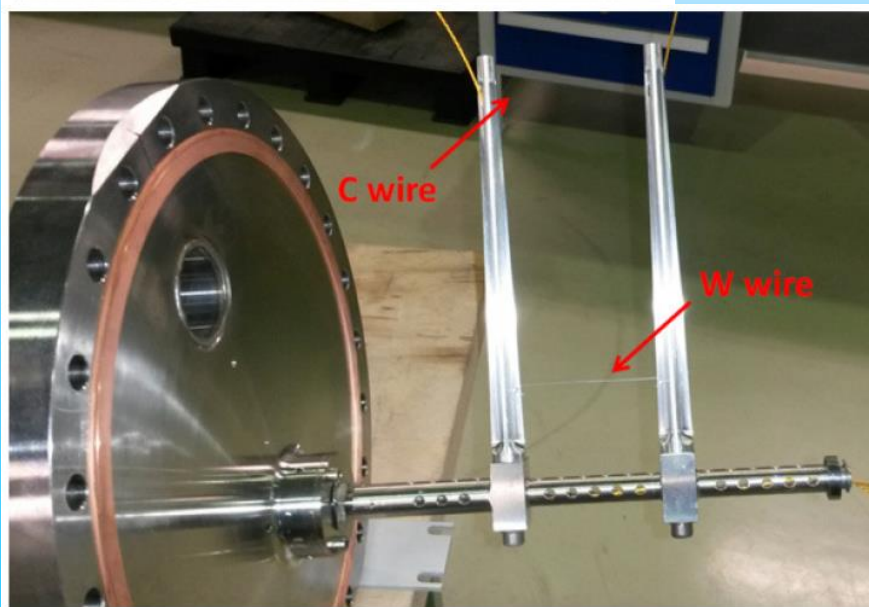
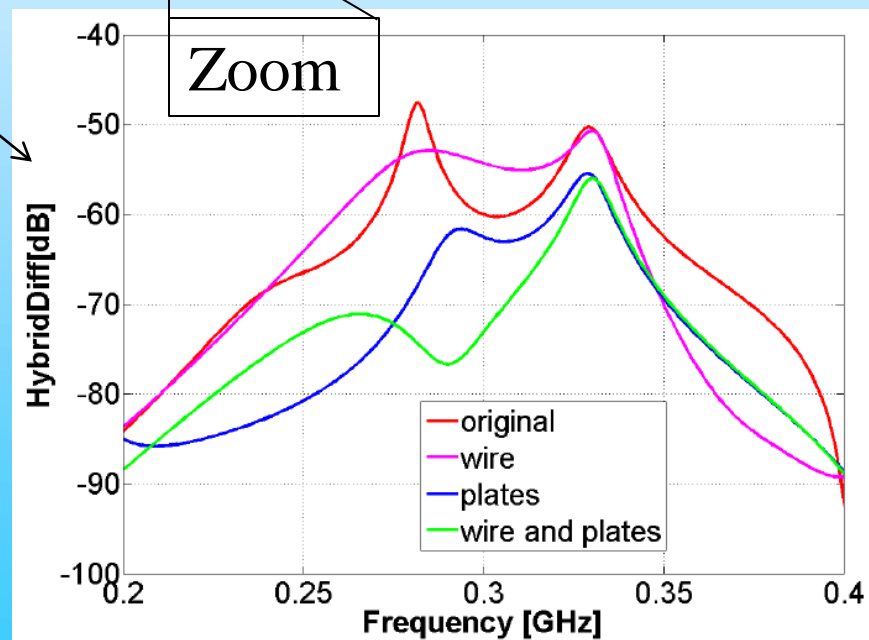
- Damping of Higher Order Modes with Ferrites etc.
- Non conducting wires



Lab. Measurements



CST Simulations



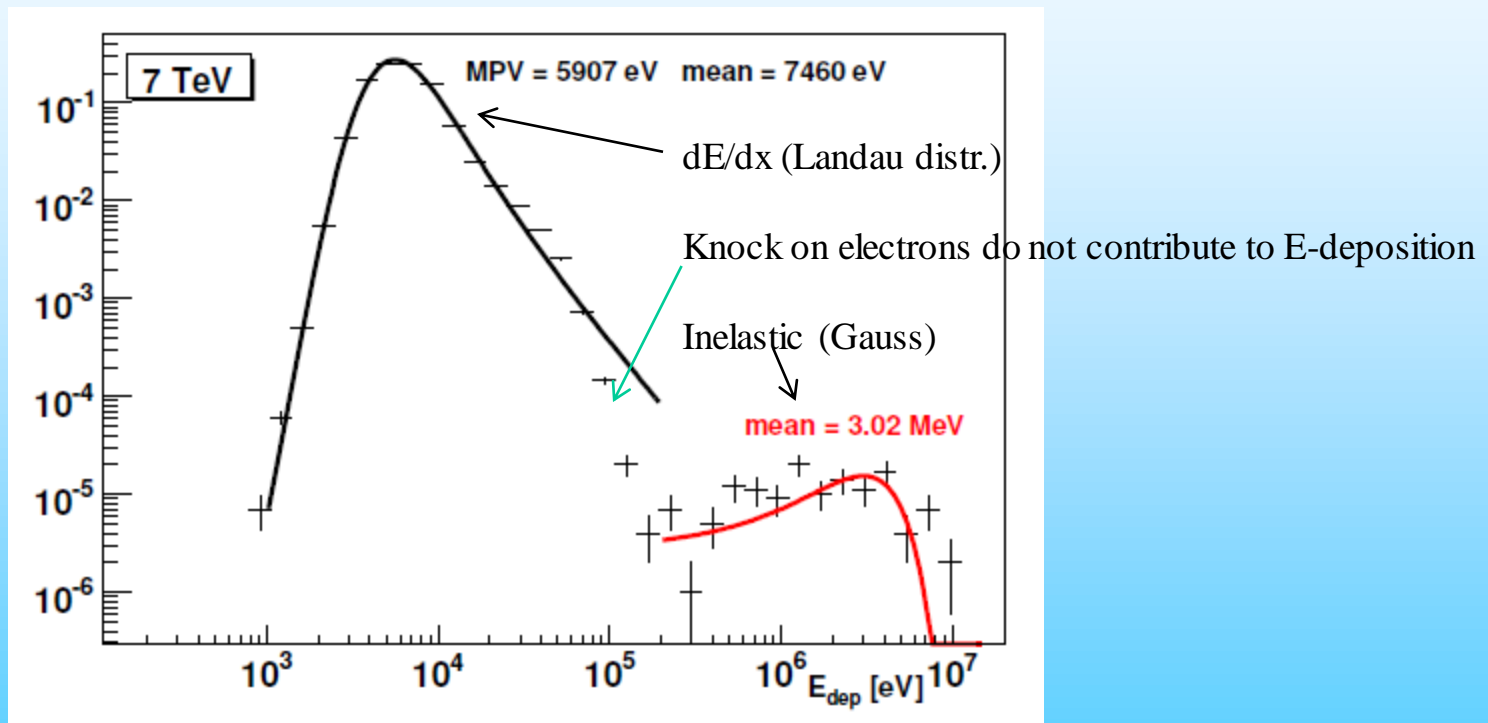
CERN-SPS Wire Scanner Impedance and Wire Heating Studies

E.Piselli, et al. IBIC 2014, Monterey, California, USA September 14-18, 2014.

Limitations:

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle.



Geant Simulation: Distribution of 7 TeV proton energy deposit in 33 micron carbon fiber.

Limitations:

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$T = C \cdot dE / dx_m \cdot d' \cdot \frac{N}{c_p \cdot G} [^{\circ}C]$$

unknown

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction):

Estimation of the wire temperature after one scan with speed v (assume no cooling mechanisms):

Solving G : G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction) and by the wire diameter d' :

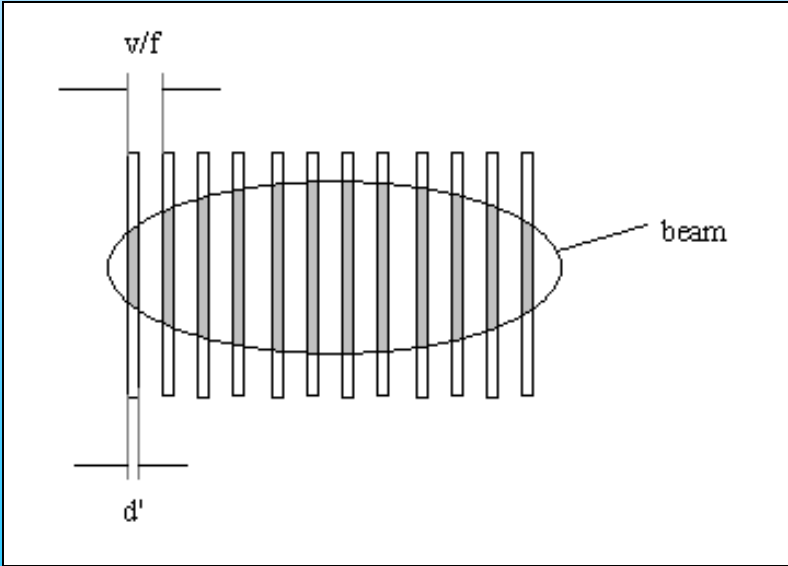
$$G = \text{wire volume} \cdot \rho = 2 \cdot \sigma_v \cdot d'^2 \cdot \rho \quad [g]$$

Solving N :

The number of particles N hitting the wire during one scan depends on the speed of the scan ($\sim 1/v$), the revolution frequency ($\sim f_{rev}$), the wire diameter ($\sim d'$) and the beam current ($\sim NB \cdot n_{bunch}$):

$$N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})$$

The figure shows the a graphical representation of the parameters. The quotient $d \cdot f/v$ is the ratio of the scanned beam area or, in other words, like a grid seen by one bunch, assuming that all bunches are equal. However, the ratio can exceed the value 1 (a foil) if the scanning distance between two bunches is smaller than the wire diameter. Note that N does not depend on the beam widths σ .



Geometrical meaning of the parameters v/f and d'

Therefore, the temperature increase of the wire after one scan becomes:

$$T = C \cdot dE / dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^{\circ}C]$$

In MeV/cm

$$Mass G = \text{wire volume} \cdot \rho = 2 \cdot \sigma_v \cdot d'^2 \cdot \rho \quad [g]$$

$$N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})$$

$$T_h = C \cdot dE / dx_m \cdot \cancel{d'} \cdot \frac{\cancel{d'} \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch}) \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v \cdot \cancel{d'}^2 \cdot \rho} \cdot \alpha \quad [^{\circ}C]$$

$$\text{with } \frac{dE / dx_m}{\rho} = dE / dx \left[\frac{MeV \cdot cm^2}{g} \right] \quad \text{and} \quad f_{rev} \cdot NB = f_{bunch}$$



$$T_h = C \cdot dE / dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^{\circ}C]$$

Where h, denotes the horizontal (h) scanning direction. The cooling factor ' α ' is described in the next section. **Note that the temperature does not depend on the wire diameter and that it depends on the beam dimension perpendicular to the measuring direction. The temperature increase is inverse proportional to the scanning speed, therefore a faster scanner has a correspondingly smaller temperature increase.**

Exercise WIRE2: Which kind of wire Material you will prefer for a wire scanner in this accelerator?

Parameter table

The beam parameters used in this exercise are shown in the following table:

Parameter	Symbol	Unit	Value
circumference of accel.	circ.	m	300
particle		Proton	
Beam particle momentum	p	GeV/c	0.3-7
Beta function	$\beta_h=\beta_v$	m	11.8
Emittance	$\varepsilon_h=\varepsilon_v$	π mm mrad	15
revolution Frequency	f_{rev}	MHz	0.93
Bunch spacing	t_{bunch}	ns	98
	f_{bunch}	MHz	10.2
Number of bunches in accel.	NB		11
Bunch charge	n_{bunch}	1/e	$1.1 \cdot 10^{11}$
Beam width measurement ¹	σ_h	mm	1.5
Beam width perpendicular to meas. ¹	σ_v	mm	1

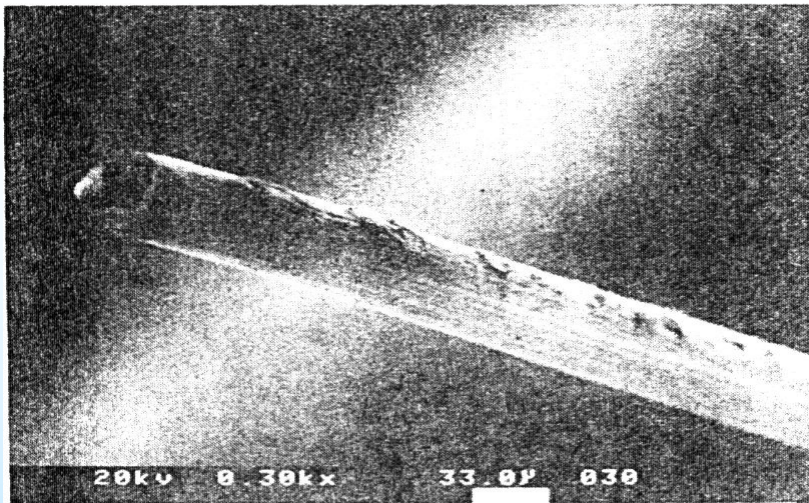
Table WIRE2: Parameters of Beam

The wire
choice of

minimal for a

TableWire3: calculated Temperatures

From Table WIRE3 follows, that even the best material (Carbon) will be a Factor 2.2 above its melting temperature.



Small pit marks seen near the end of the wire are further evidence for arcing.

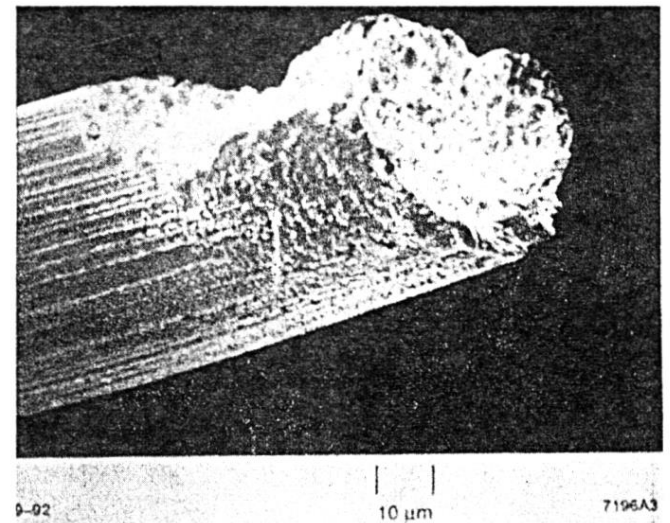
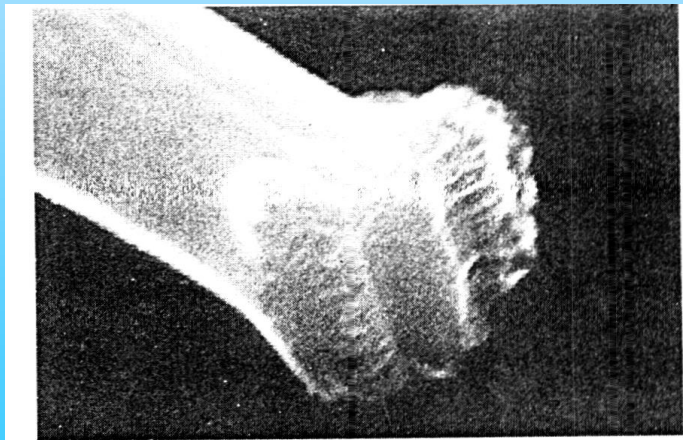


Figure 3. Electron microscope picture of a 40 μm tungsten wire break. This wire was installed in an SLC linac wire scanner.

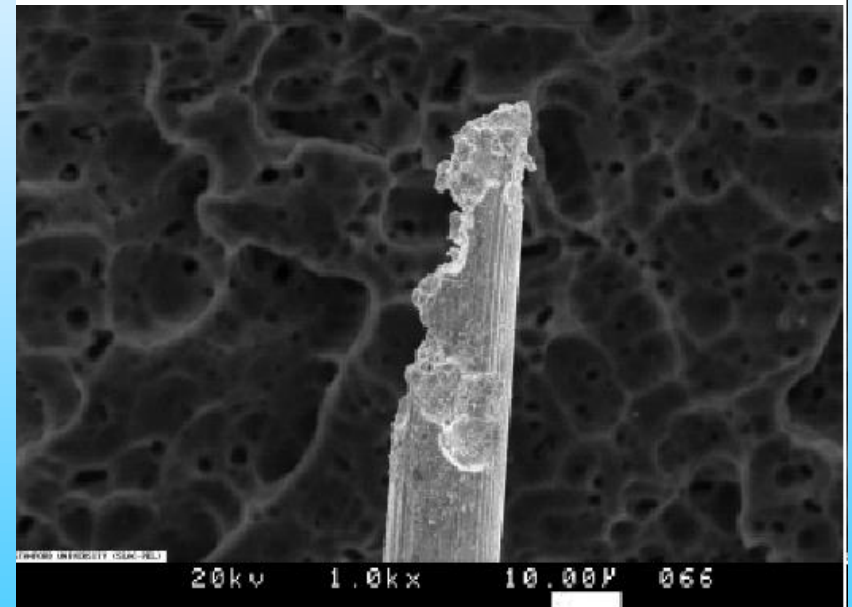


FIGURE 3. Failed 15 μm diameter tungsten wire showing the rough surface resulting from many discharges.

Burned by the e-beam at SLC

Exercise WIRE2a: Discuss cooling mechanisms which will cool the wire.

- 1) Secondaries emitted from the wire
- 2) Heat transport along the wire
- 3) Black body radiation
- 4) Change of c_p with temperature
- 5) Thermionic emission
- 6) Sublimation

Wire type	Approximation Q (μ J)	Monte Carlo Q (μ J)
10 μ m graphite	0.140	0.169 ± 0.002
10 μ m tungsten	1.01	2.19 ± 0.04
15 μ m tungsten	2.27	4.90 ± 0.05
50 μ m tungsten	25.3	32.0 ± 0.1

Heat deposited in various wire types by a passing bunch of 1 nC. The approximated value follows (1), the “Monte Carlo” result is obtained by the simulation of an electromagnetic shower with Fluka.

1) Secondaries:

Some energy is lost from the wire by secondary particles. In the work in (J. Bosser et al.; The micron wire scanner at the SPS, CERN SPS/86-26 (MS) (1986)) **about 70% is assumed**. In DESY III (example above) no carbon wire was broken during more than 10 years of operation. At HERA, the theoretical temperature of the carbon wire (without secondaries) exceeds the melting temperature after a scan by far ($T = 12800^\circ\text{C}$). Considering the loss by secondaries of 70%, the temperature reaches nearly the melting point. In practice, the wire breaks about once in 2 months. The observation is that the wire becomes thinner at the beam center. This may indicate, that during a scan some material of the wire is emitted because of nuclear interactions or is vaporized because it is very close to the melting temperature. This supports the estimate of the 70% loss and one has to multiply the factor $\alpha = 0.3$ in the equation above

Thermal Load on Wire scanners

Lars Fröhlich

37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources; May 15-19, 2006 in Hamburg, Germany

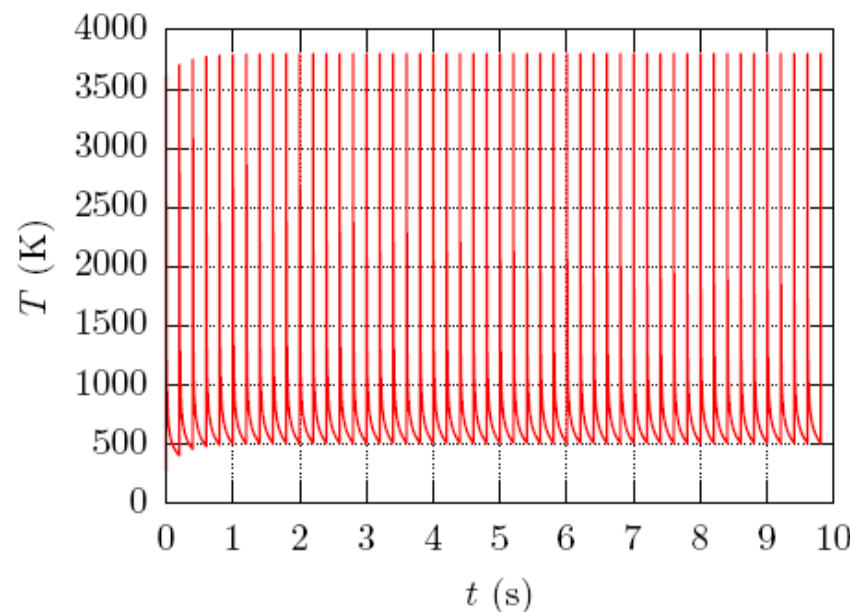
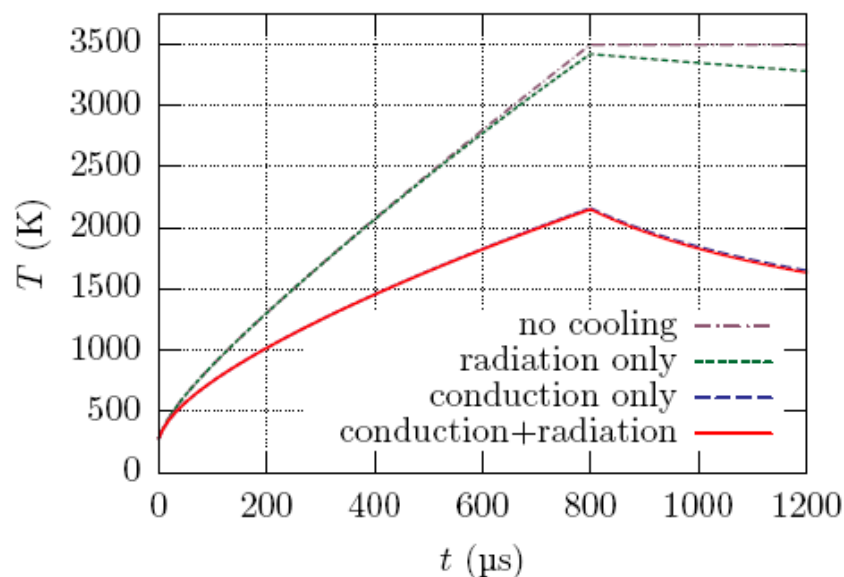
2) Heat transport:

The transport of heat along the wire does not contribute to short time cooling of the wire (P. Lefevre; CERN PS/DL/Note 78-8). However, frequent use of the scanner heats up also the ends of the wire and its connection to the wire holders (fork).

For small temperatures (low repetition rates (LINACs)) this is the major cooling mechanism.

$$P_{cool}^{cond} = -\lambda(T)A_d \frac{dT}{dx}$$

with λ = thermal cond. , A = Surface



10 μm graphite wire bombarded with 800 bunches at 1 MHz; simulated with various combinations of cooling mechanisms, 5 Hz rep. rate.

3) Black body radiation: The temperature T_{bb} at which the radiated power is equal to the deposited power in the wire during one scan P_{dep} [MeV/s] can be calculated from the Stefan-Boltzmann-law:

$$T_{bb} = \sqrt{\sqrt{\frac{P_{dep}}{s \cdot A}}}$$

where $s = 35.4 \text{ MeV} / (\text{s}^1 \text{ cm}^2 \text{ } ^\circ\text{K}^4)$ is the Stefan-Boltzmann-constant and A is the area of radiating surface. The surface of the heated wire portion A is $2 \cdot \sigma_v \cdot d \cdot \pi [\text{cm}^2]$. The power can be calculated by:

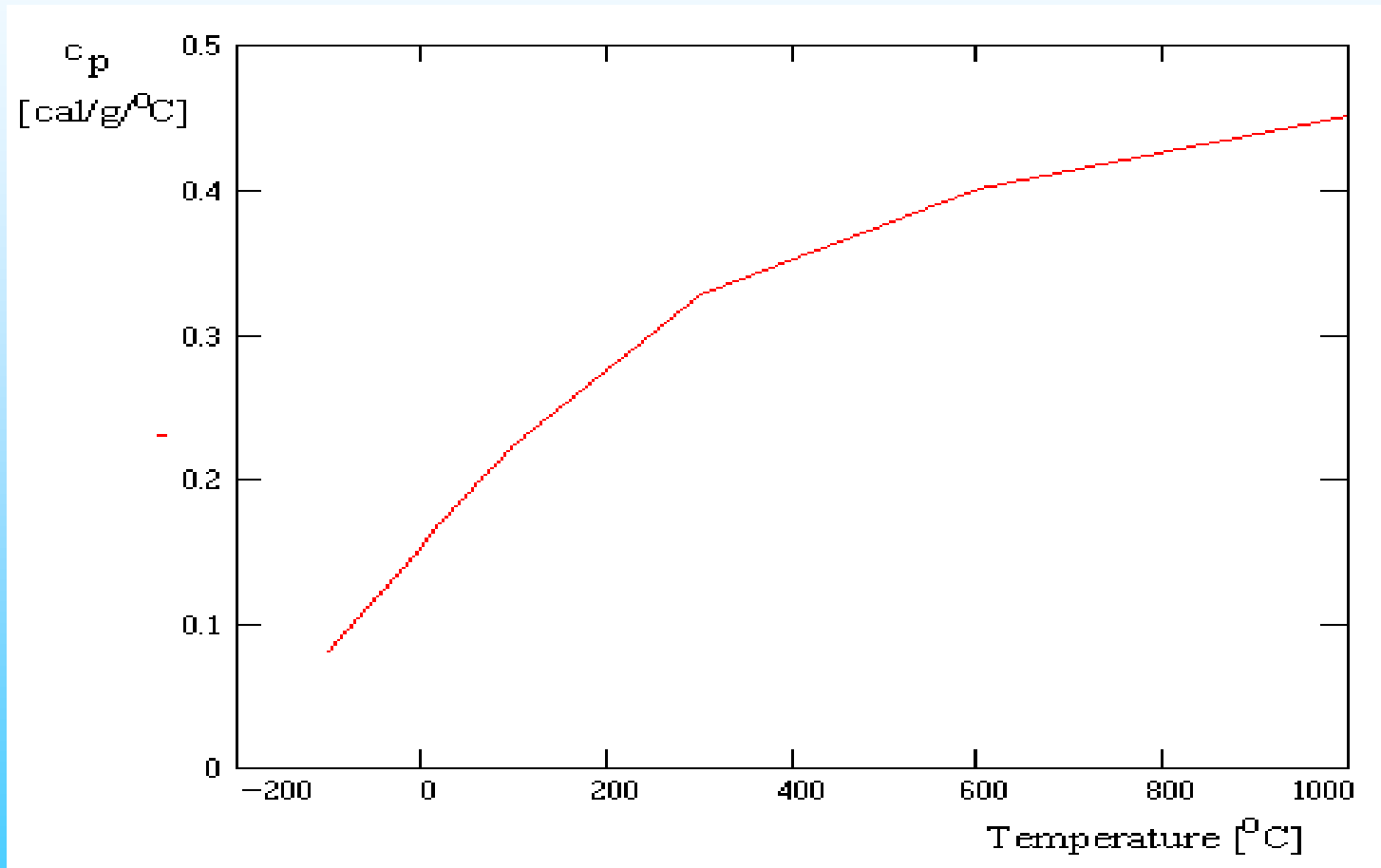
$$P_{dep\ h,v} = \alpha \cdot dE / dx \cdot d' \cdot n_{bunch} \cdot \frac{f_{bunch} \cdot d'}{v} \cdot \frac{1}{t_{scan}} \quad [MeV / s]$$

where $t_{scan} = 2 \cdot \sigma_{h,v} / v$ is the time for a scan (in the assumption of 2σ it is neglected that only about 70% of the power is concentrated within 2σ). α is the expected loss from secondaries.

For the example above: $T_{bb} = 3900 \text{ } ^\circ\text{C}$.

$$P_{cool}^{rad} = A \cdot s (T^4 - T_{env}^4)$$

4) $c_p(T)$: The heat capacitance is a function of the temperature. The figure shows the increase of c_p for Carbon with T . The expected temperature after a scan is inversely proportional to c_p . **Therefore one can expect a slightly smaller resulting temperature because of this dependence.**

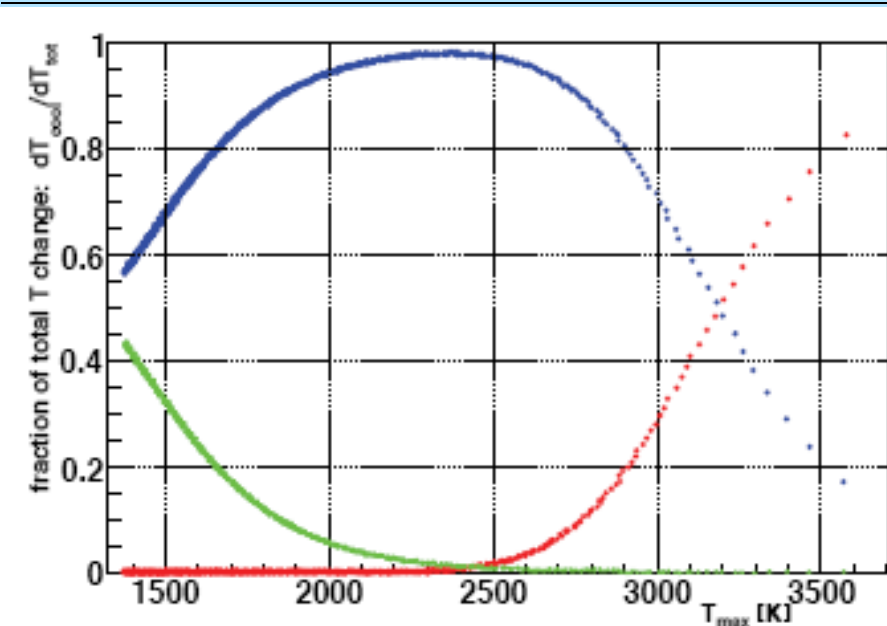


5) Thermionic emission

The thermionic emission is a dominant cooling process for temperatures above 3200 K. It determines the wire temperature for scans of the high intensity beams. The electric current emitted by the hot body is described by Richardson-Dushman Equation:

$$J_{th} = A_R \cdot T^2 \cdot e^{-\frac{\Phi}{k_B T}} \quad \text{or} \quad P_{cool}^{th} = A_R \left(\Phi + \frac{2k_b T}{q} \right) J_{th}$$

where A_R is Richardson constant and Φ is the material work function. The power dissipated by the thermionic current is proportional to the surface of the wire and depends exponentially on the temperature. The thermionic emission removes electrons which are replaced by a current flowing from the fork supporting the wire. This current has a negligible contribution as an additional source of heating.



Relative contribution of cooling processes to the total temperature change as a function of temperature. Blue points are for radiative cooling, red for thermionic emission and green are for the heat transfer.

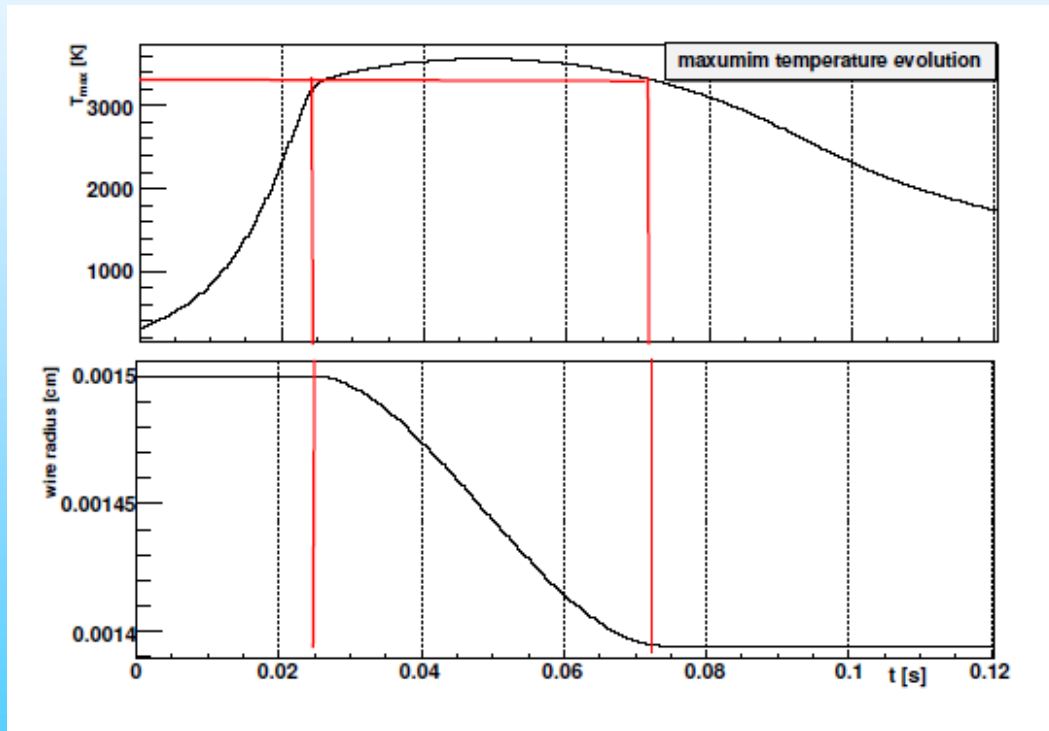
Operational Limits of Wire Scanners on LHC Beam

Mariusz Sapinski, Tom Kroyer (CERN, Geneva)

2008 Beam Instrumentation Workshop (BIW08) held on May 4-8, 2008 at the Granlibakken Conference Center and Lodge in Tahoe City, CA, USA, pp.383-388

5) Sublimation Cooling

The material behavior in high temperatures and in a vacuum can be read from a phase diagram. Materials which sublime under these conditions have an advantage because the sublimation temperature and sublimation heat are higher than melting temperature and heat. Sublimation removes the hottest fraction of the material from the surface, what is equivalent to a cooling, which is weak in comparison to other cooling processes.



$$P_{cool}^{sub} = H_{sub} \frac{\Delta n}{\Delta t}$$

With:

H_{sub} = Entalpie of Sublimation,

Δn = amount of material sublimated

$$P_{total} = P_{dep} - \sum P_{cool}$$

Evolution of the wire temperature during a scan of the beam is shown together with decrease of the wire diameter due to sublimation.

Temperature of the wire (v=1m/s)

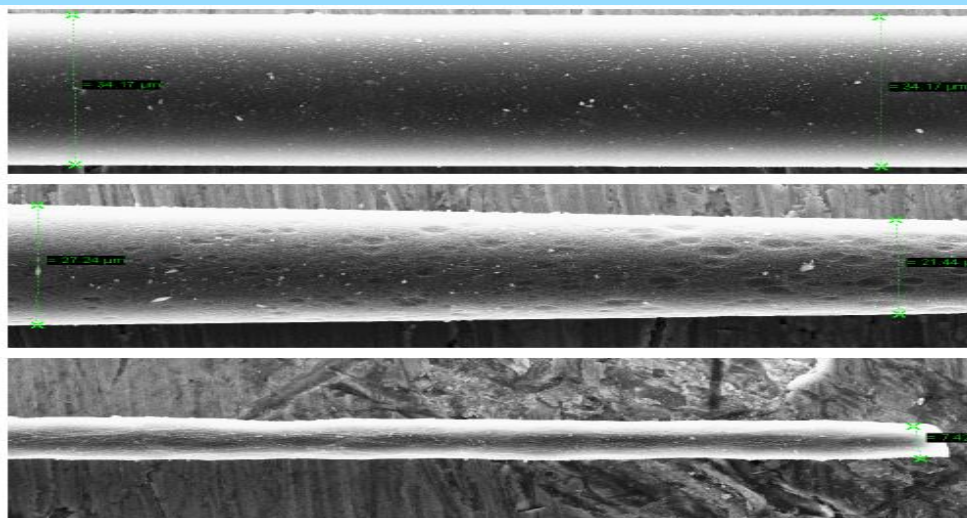
	Num. of part.	Typ. Beam diam.	Temp. after scan [C]	Eqi. - Temp [Celsius]
HERAp	$1 \cdot 10^{13}$	0.7 mm	3900	5100
HERAe	$6.5 \cdot 10^{12}$	0.2 mm	4800	4500
PETRAp	$4.8 \cdot 10^{12}$	2 mm	980	3500
PETRAe	$1.5 \cdot 10^{12}$	0.1 mm	4700	6800
DESYIII	$1.2 \cdot 10^{12}$	1 mm	3400	5300
TTF fast	$2.8 \cdot 10^{13}$	0.05 mm	4000	7400
TTF slow	$2.8 \cdot 10^{13}$	0.05 mm	286 000	2900

Melting temperature = 3500 °C for Carbon
= 1700 °C for Quartz

The wire in DESY III existed with 200 mA = $1.25 \cdot 10^{12}$ p for all times.

In HERAp we exchanged the wires every 2 month after "normal" use. Unusual frequent use destroyed the wires much earlier.

Reason: Sublimation of material:



Fiber fracture at three distances from the beam impact location: 1 mm (upper plot), 0.5 mm (middle plot) and at beam center location (bottom plot).

CERN-BE-2009-028

Carbon Fiber Damage in Accelerator Beam

Sapinski, M ; Dehning, B ; Guerrero, A ; Koopman, J ;
Métral, E ; DIPAC09, Basel

New concept to reach $v=20$ m/s and a resolution of 5 microns

$$T_h = C \cdot dE / dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^{\circ}C]$$

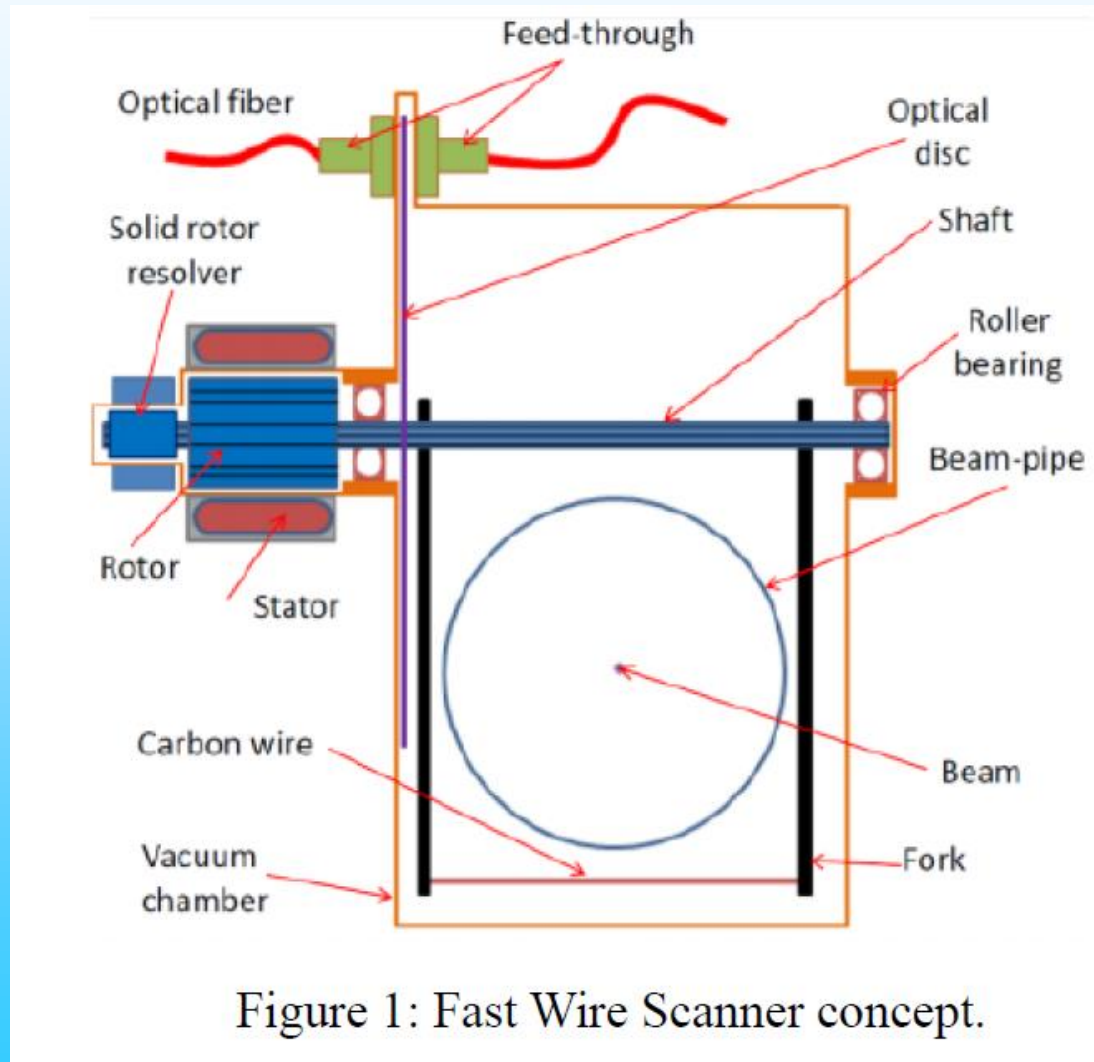


Figure 1: Fast Wire Scanner concept.

Design of a High-precision Fast Wire Scanner for the SPS at CERN

R. Veness, N. Chritin, B. Dehning, J. Emery, J.F. Herranz Alvarez, M. Koujili, S. Samuelsson, J.L. Sirvent Blasco; CERN, Geneva, Switzerland
IBIC2012, Tsukuba, Japan, Oct 1-4, 2012,

Limitations

4: Emittance blow up

Exercise WIRE3: Calculate the emittance blowup of the proton beam after one scan at a position with $\beta = 11.8$ m for $p = 0.3$ and 7 GeV/c (Carbon wire):

Assume a measurement position close to a Quadrupole ($\alpha=0$)

For small deflection angles a good approximation for average root mean square scattering angle is given by:

$$\delta \Theta = \frac{0.014 \text{ GeV}}{pc} \cdot \sqrt{\frac{d'}{L_{rad}}} \cdot \left(1 + 1/9 \cdot \log_{10} \frac{d'}{L_{rad}} \right)$$

Remember:

$$\gamma(s)y^2 + 2\alpha(s)yy' + \beta(s)y'^2 = \varepsilon$$

A fraction Ψ of the circulating beam particles will hit the wire:

$$\Psi = \frac{d' \cdot f_{rev}}{v}$$

$$\Rightarrow \Theta = \Psi \cdot \delta \Theta \approx y'$$

(see exercise WIRE2) | mean deflection angle

The resulting emittance blowup is than (7 GeV/c):

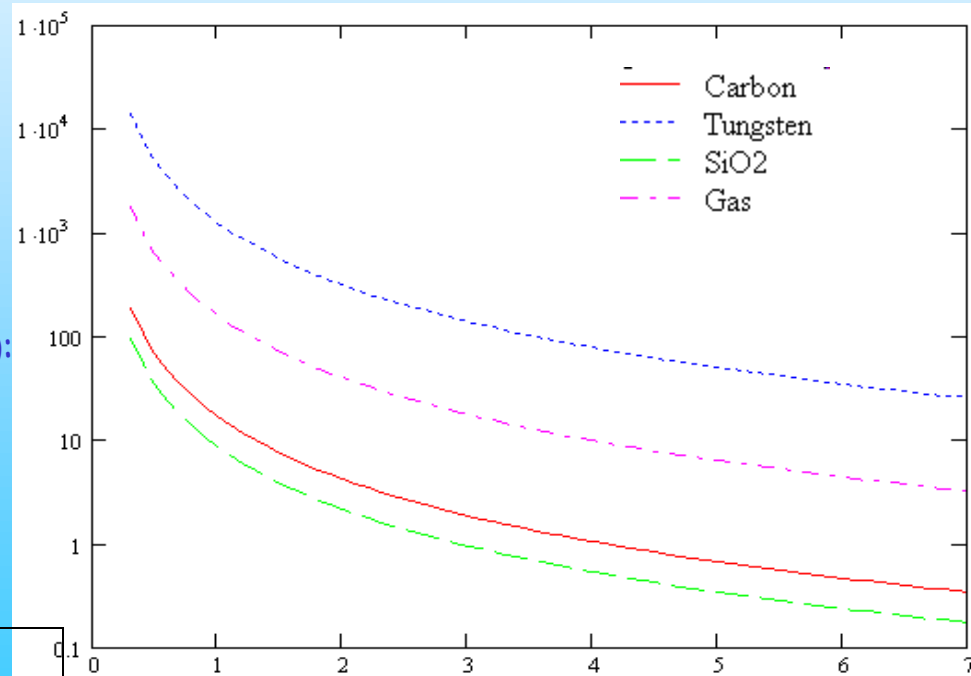
$$\delta \varepsilon_{rms} = \sqrt{2\pi} \cdot \delta \Theta^2 \cdot \Psi^2 \cdot \beta(s)$$

$$= 5.1 \cdot 10^{-2} \pi \text{ mm mrad}$$

$\sqrt{2\pi}$ from Literature

Gas: emittance growth due to residual gas per hour ($P=10^{-9}$ mbar)

$\delta \varepsilon / \varepsilon$ [%/scan]



Momentum [GeV/c]

D. Möhl, Sources of emittance growth (also P. Bryant;
CAS, Beam transfer lines):

$$\delta \varepsilon = \pi \frac{1}{2} \cdot \Theta_{rms}^2 \cdot \beta$$

Averaging over all Betatron-phases

Unit of phase space emittance

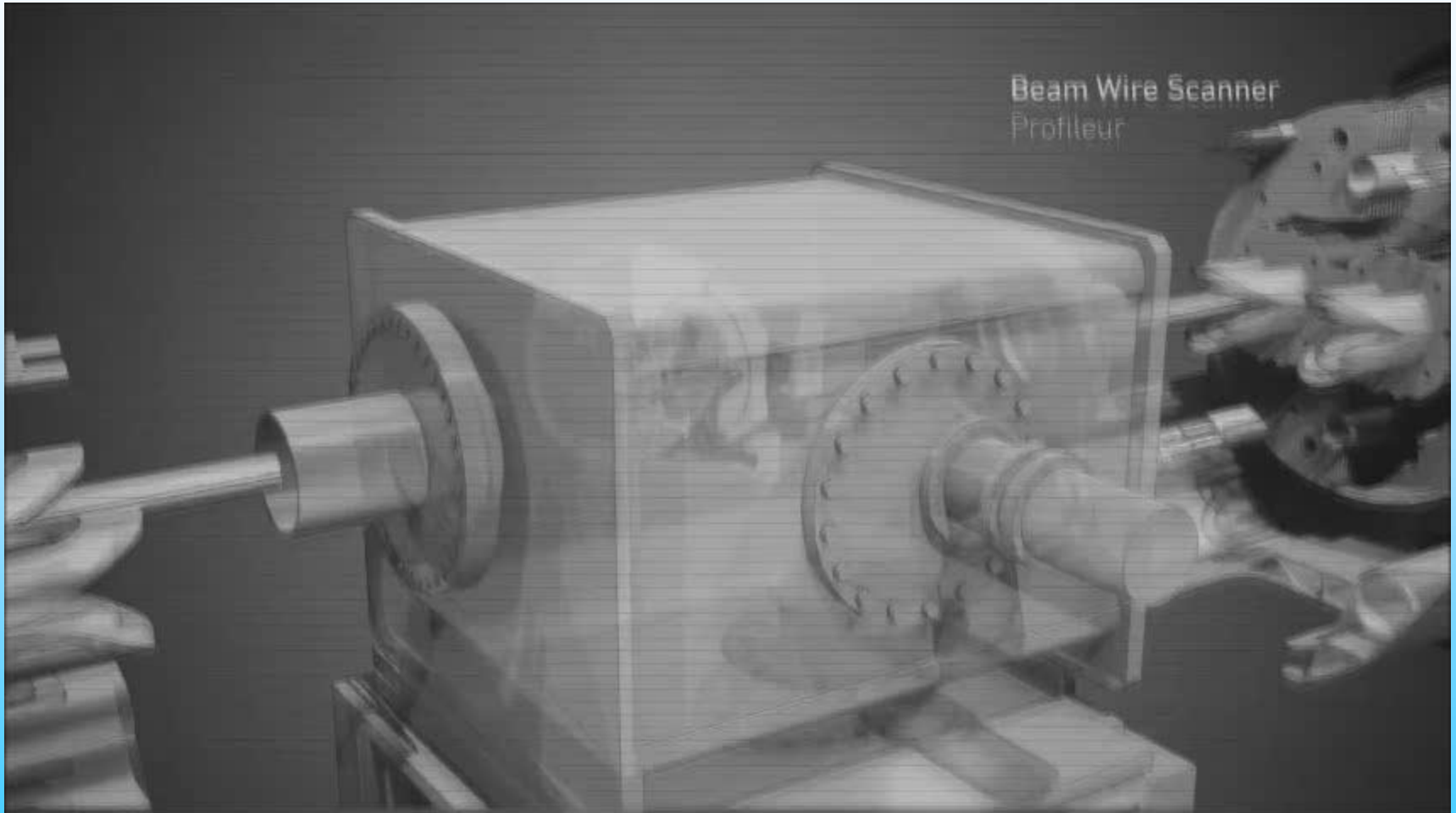
M. Giovannozzi (CAS 2005)

$$\delta \varepsilon = \pi \frac{1}{4} \cdot \Theta_{rms}^2 \cdot \beta$$

D. Möhl, Sources of emittance
growth, 2007:

$$\delta \varepsilon_{\sigma} = \frac{1}{2} \cdot \Theta_{rms}^2 \cdot \beta$$

The End of Wire Scanner Session



Wire Parameters

Parameter	Symbol	Unit	wire material				
			AL	W	Carbon	Beryllium	Quartz (SiO ₂)
wire diameter	d $= 7 \cdot 10^{-4}$	cm					
mean wire diameter	$d' = d/2 \cdot \sqrt{\pi}$ $= 5.5 \cdot 10^{-4}$	cm					
Conversion	0.239	cal/Joule					
Conversion factor	$C = 3.8 \cdot 10^{-14}$	MeV / cal					
Speed of wire	$v = 100$	cm/s					
specific heat capacity*	c_p	cal / g / °C	0.21	0.036	0.42 (>400°C) 0.17 (< 400°C)	0.43	0.18
Energy loss of min. ion. part. (MIPs)	dE/dx	MeV cm ² / g	1.62	1.82	2.3	1.78	2.33
	dE/dx_m	MeV/cm	4.37	35.13	5.3	3.3	5.3
density	ρ	g/cm ³	2.7	19.3	2.3	1.85	2.29
melting temp.	T_m	°C	650	3400	ca 3500	1200	1700
Heat conductivity	λ	W/(m K)	230	100-160	30-3000	200	1.2-1.4
Radiation length	l_{rad}	cm	8.9	0.35	18.8	34.7	12.3
Nuclear coll length	l_{nuc}	cm	26	9.6	34	30	25.4

Table WIRE1: Parameters of wire materials. * > 500 °C

The beam parameters used in this exercise are shown in the following table:

Parameter	Symbol	Unit	Value
circumference of accel.	circ.	m	300
particle		Proton	
Beam particle momentum	p	GeV/c	0.3-7
Beta function	$\beta_h = \beta_v$	m	11.8
Emittance	$\varepsilon_h = \varepsilon_v$	π mm mrad	15
revolution Frequency	f_{rev}	MHz	0.93
Bunch spacing	t_{bunch}	ns	98
	f_{bunch}	MHz	10.2
Number of bunches in accel.	NB		11
Bunch charge	n_{bunch}	1/e	$1.1 \cdot 10^{11}$
Beam width measurement ¹	σ_h	mm	1.5
Beam width perpendicular to meas. ¹	σ_v	mm	1

Table WIRE2: Parameters of Beam

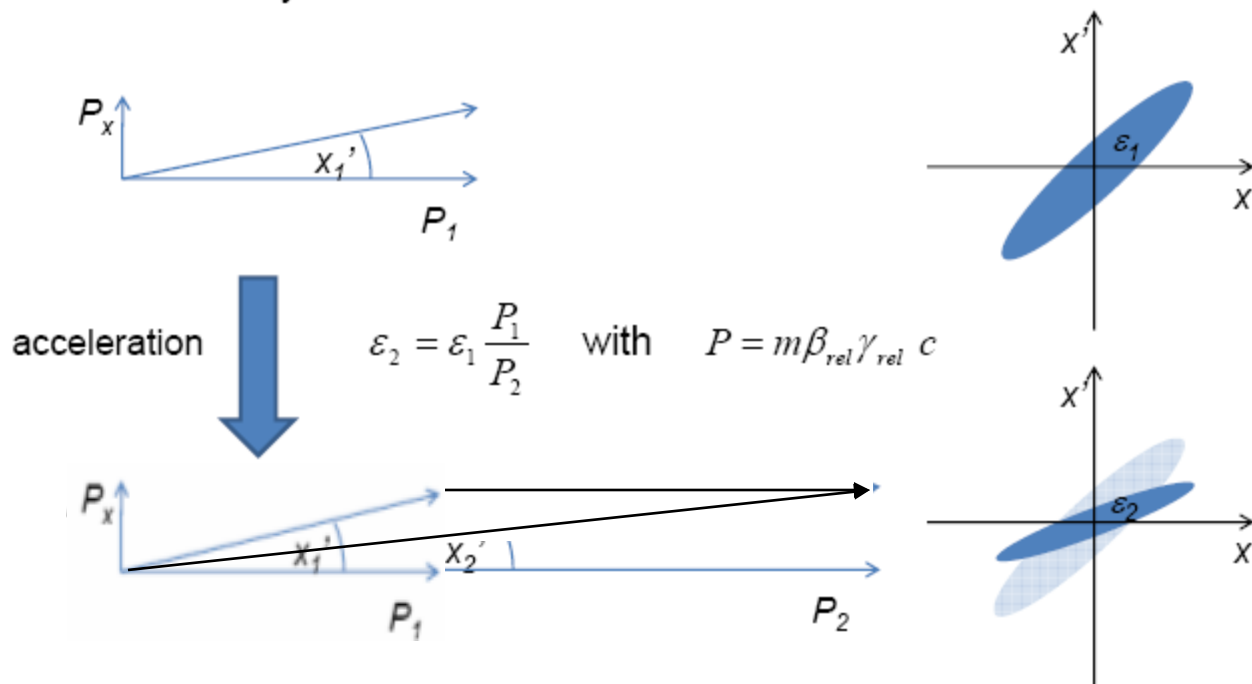
LINACS/Transport Lines Emittance Measurement

In a transfer line, the beam passes once and the shape of the ellipse at the entry to the line determines its shape at the exit. Thus α and β , γ depend on the input beam and their propagation depends on the structure. Any change in the structure will only change the α and β , γ values downstream of that point. ... The input ellipse must be chosen by the designer and should describe the configuration of all the particles in the beam.

In the following let's assume a transport line or the part of the Linac where no acceleration takes place. What about the emittance?

If no energy is transferred to the beam (Hamiltonian systems), the emittance is conserved.

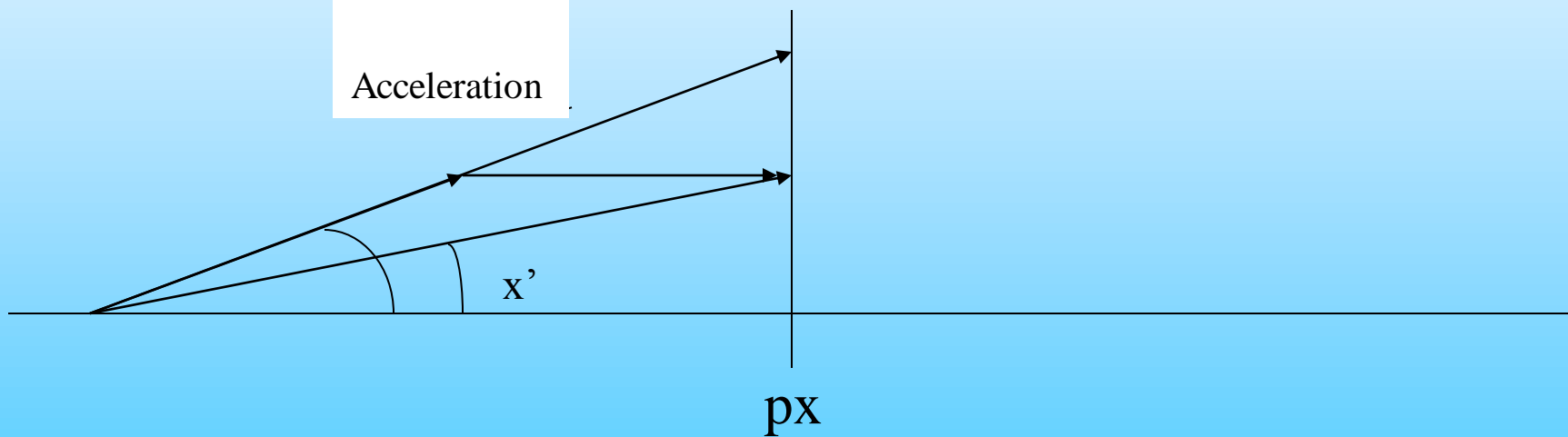
Emittance is only constant in beamlines without acceleration

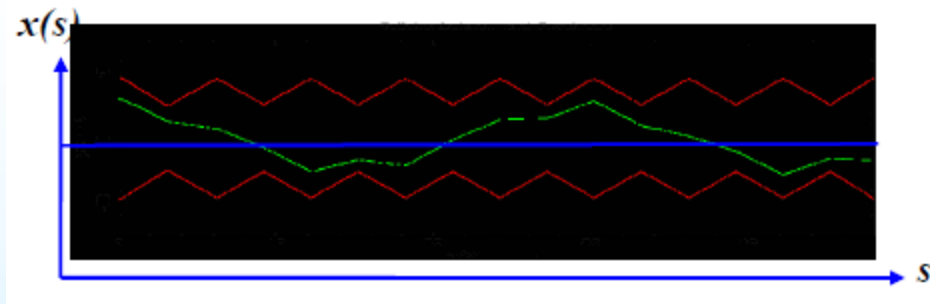


normalised emittance $\varepsilon_N = \beta_{rel}\gamma_{rel} \varepsilon$ preserved with acceleration !

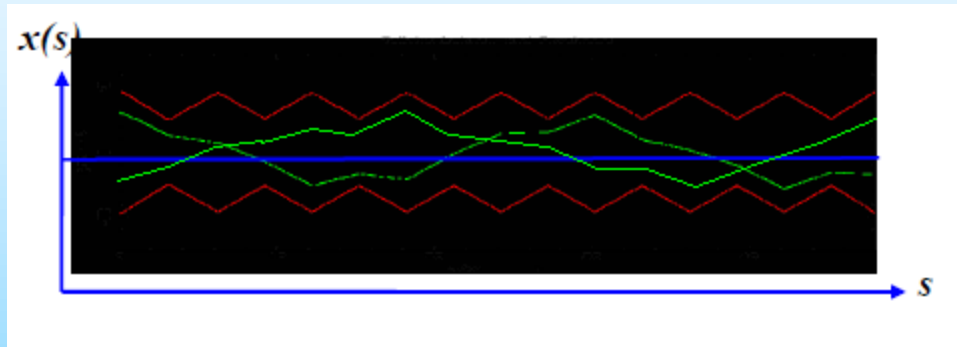
To distinguish from normalised emittance ε_N , ε is quoted as “geometric emittance” !

Exercise: Draw radiation damping by Synchrotron Radiation

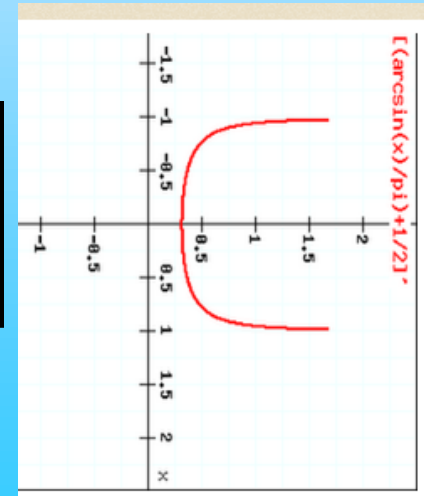
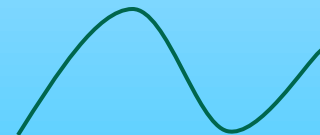
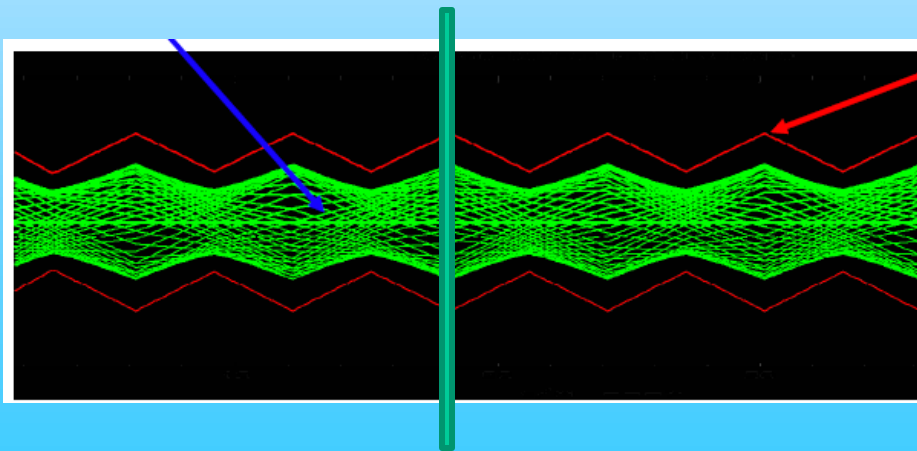




$Q = \text{irrational}$



$$x(s) = \sqrt{\varepsilon} * \sqrt{\beta(s)} * \cos(\psi(s) + \phi)$$



The Ellipse and the Twiss parameter:

diverging beam: $\alpha < 0$

waist or lens: $\alpha = 0$

converging beam $\alpha > 0$

$\beta > 0$ by definition [mm/mrad]

$0 < \varepsilon = \text{constant}$ [mm·mrad]

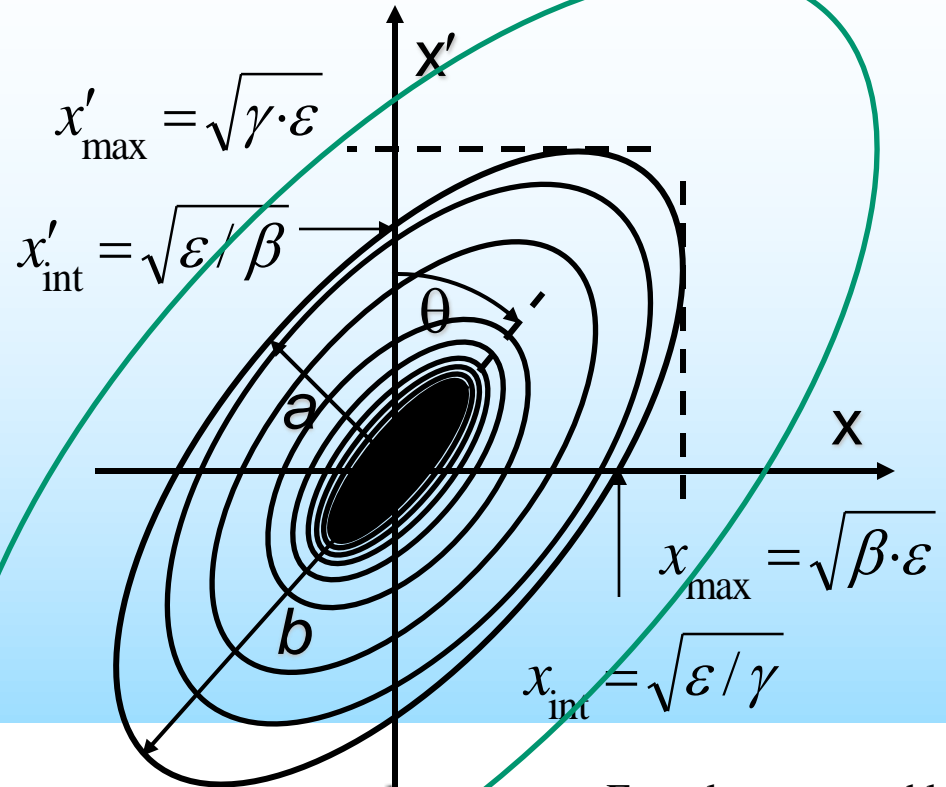
$$0 < \gamma = (1 + \alpha^2) / \beta \quad [\text{mrad/mm}]$$

2) Divergence:

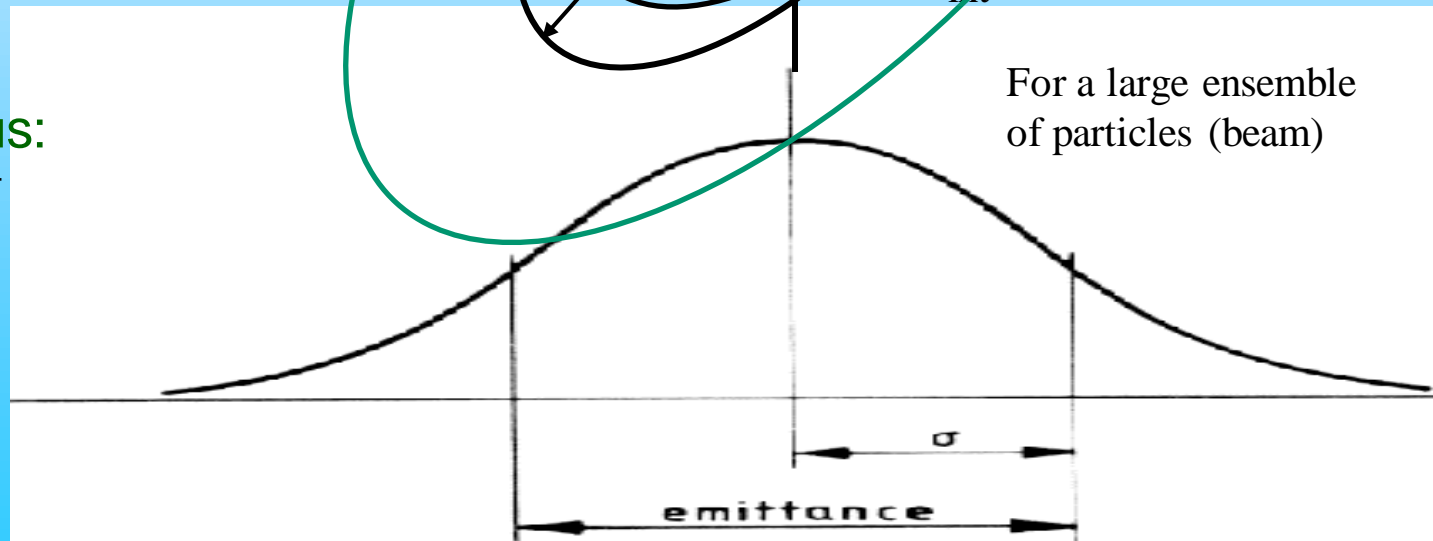
$$x'_{\text{max}} = \sqrt{\gamma \cdot \varepsilon} = \sqrt{(1 + \alpha^2) \cdot \varepsilon / \beta}$$

1) Beam radius:

$$x_{\text{max}} = \sqrt{\beta \cdot \varepsilon}$$



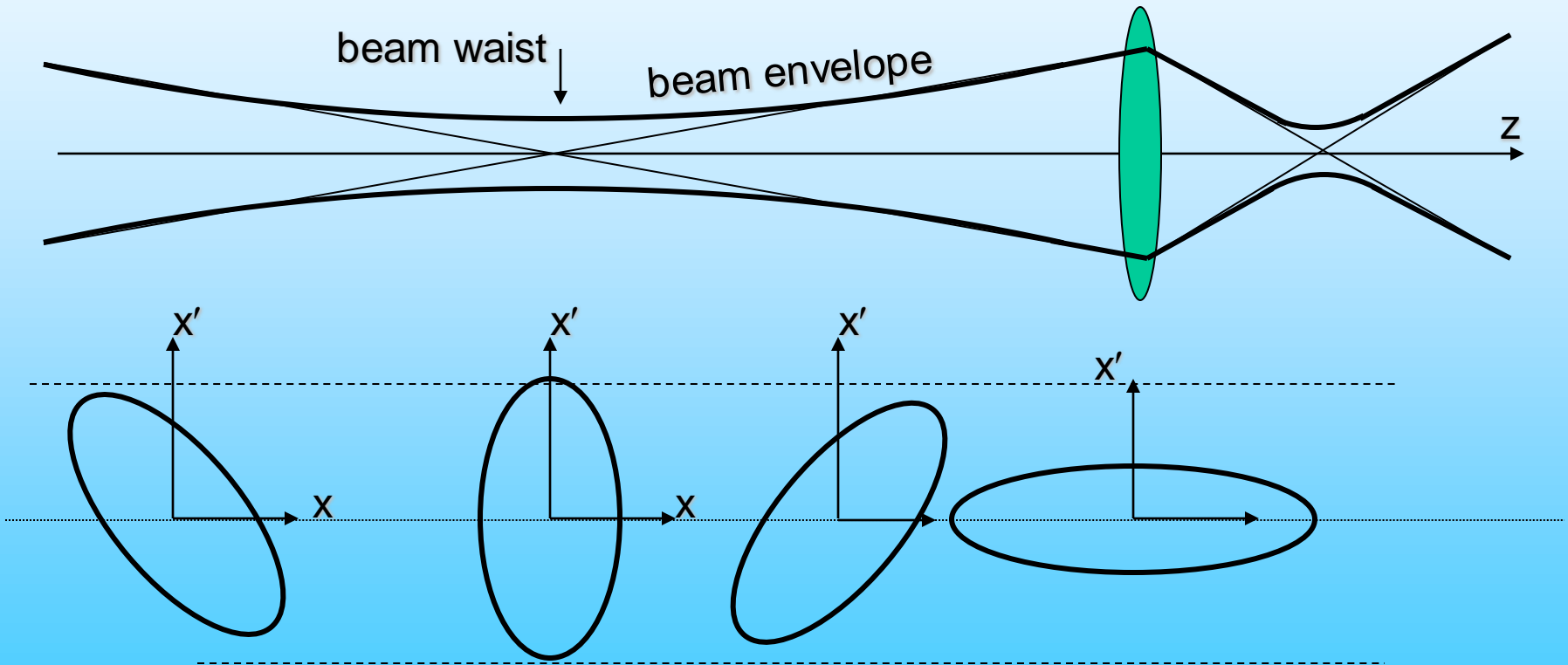
For a large ensemble of particles (beam)



The Emittance ellipse

While the area is constant, the emittance ellipse shape and orientation changes. It is described by:

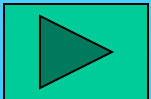
$$\gamma \cdot x^2 + 2 \cdot \alpha \cdot x \cdot x' + \beta \cdot x'^2 = A / \pi = \varepsilon$$

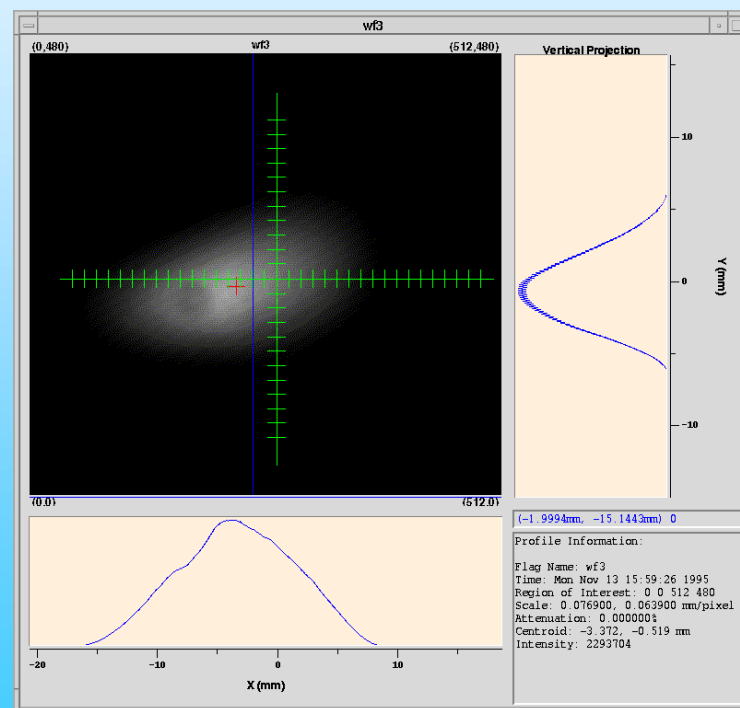
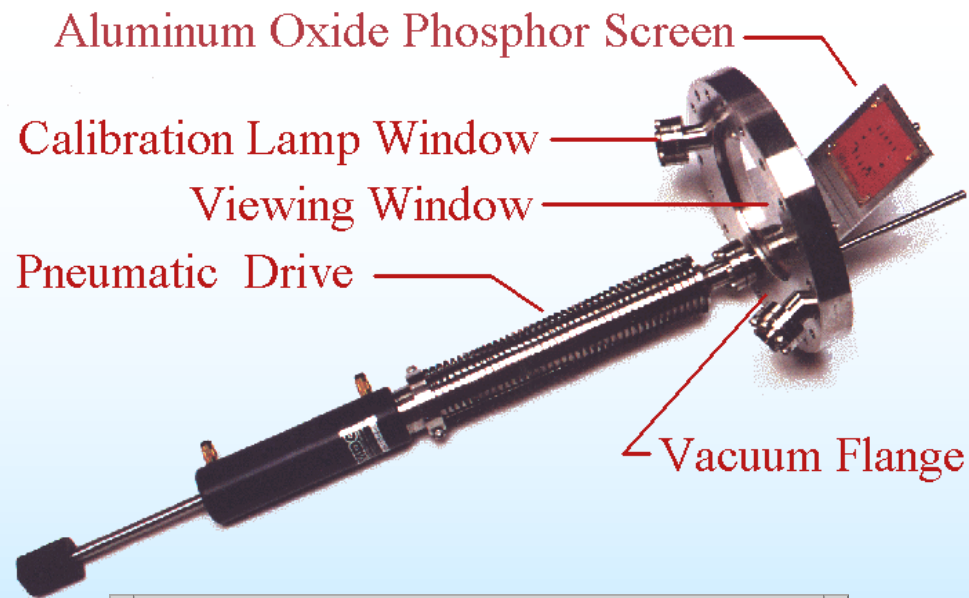
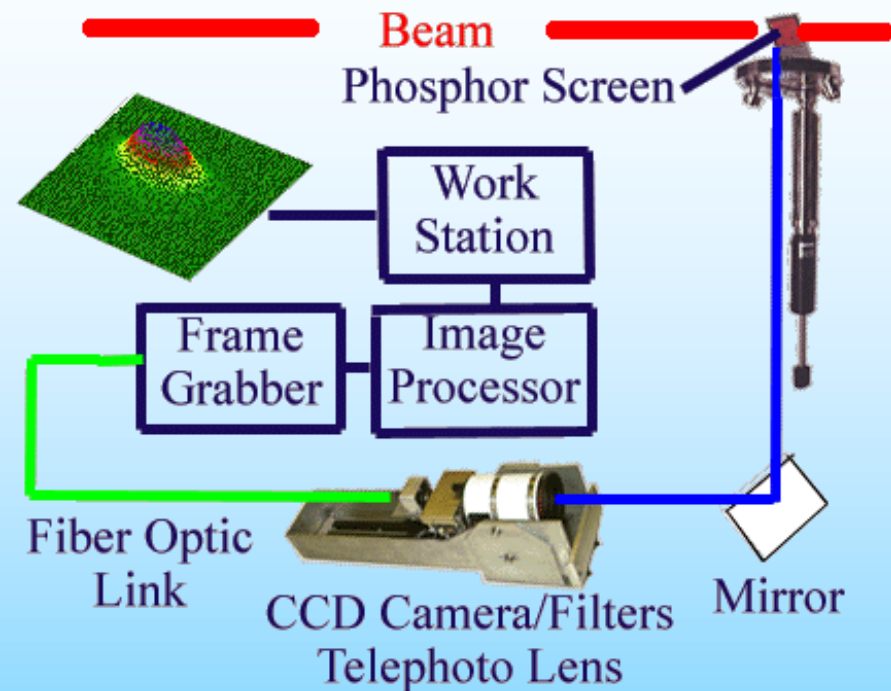


Explain ways of measuring the emittance of a charged particle beam in a Linear Accelerator or a transport line without knowing the beam optic parameters α , β , γ .

Exercise L1: Which is (are) the preferable method(s) for a high energy proton transport line ($p > 5 \text{ GeV}$)?

Solution: 3 (thin) screens or SEM grids or varying quadrupole which measure the different beam widths σ . For pepper pot or slits one needs a full absorbing aperture.



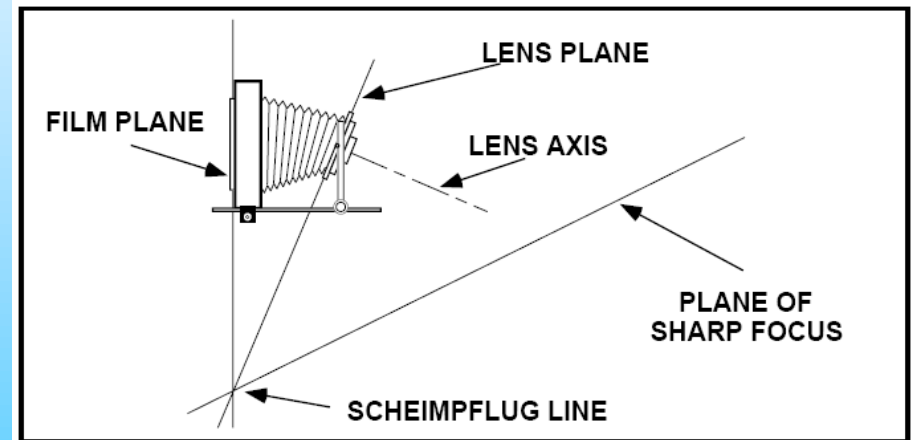
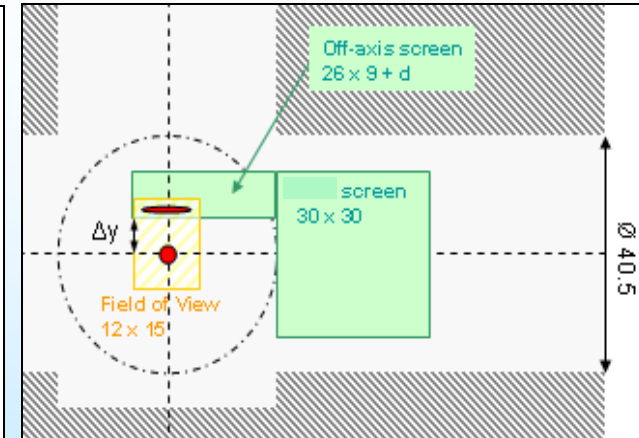
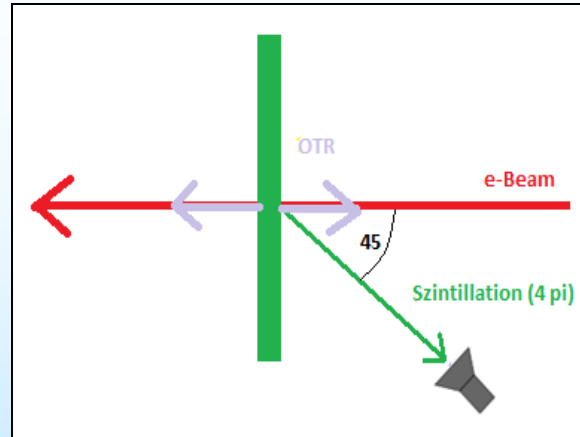


Substrate: Aluminum Foil, 0.001" thick

XFEL-Screens (ca. 50 Stations)

Idea 1: $90^\circ / 45^\circ$ Geometrie for removing (C)OTR

Idea 2: “Scheimpflug”
Prinziple from Large-Picture-Photography to remove depth-of-field



“Get a sharp image of an entire plane, if focus, image, and object plane cut in a single line.”

Scintillating Screen Applications in Beam Diagnostics

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

4.8 MeV/u

← Same pulse energy →

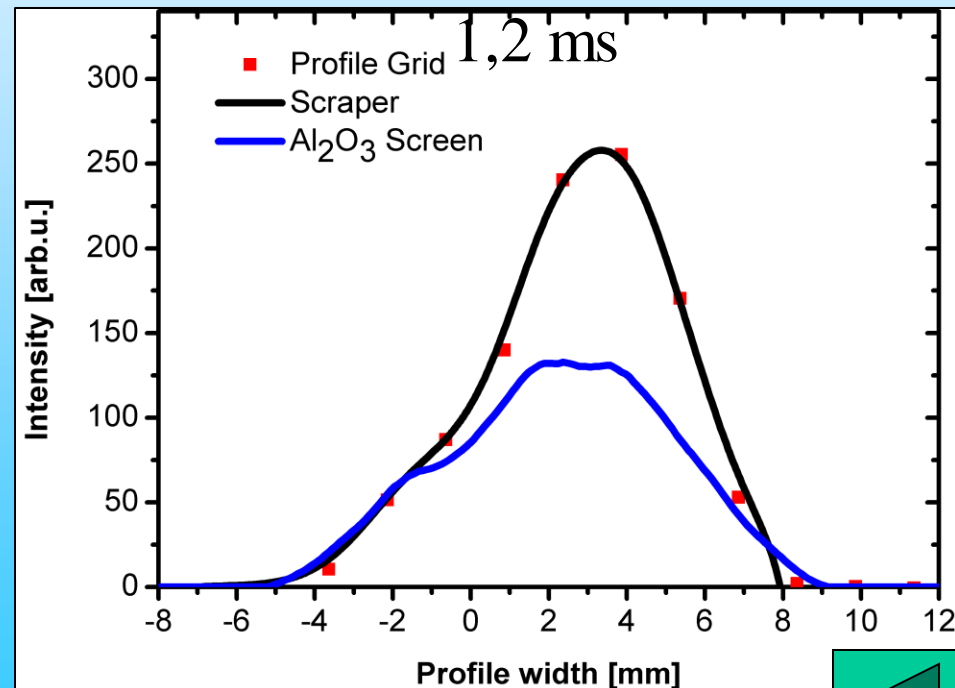
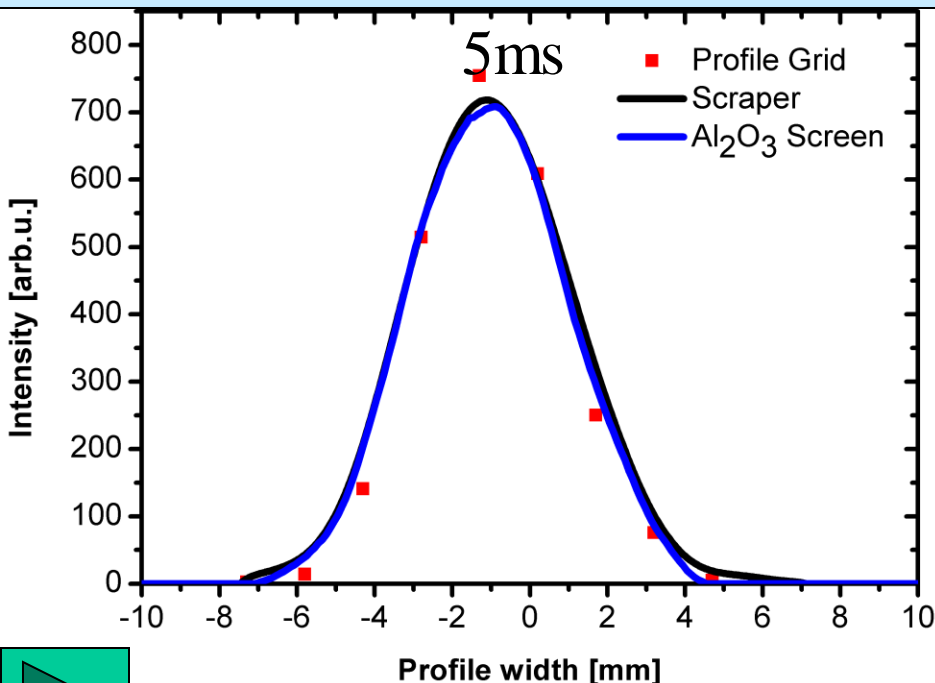
11.4 MeV/u

$4.3 \cdot 10^{10}$ ppp

(~similar flux [ions/(cm² s)])

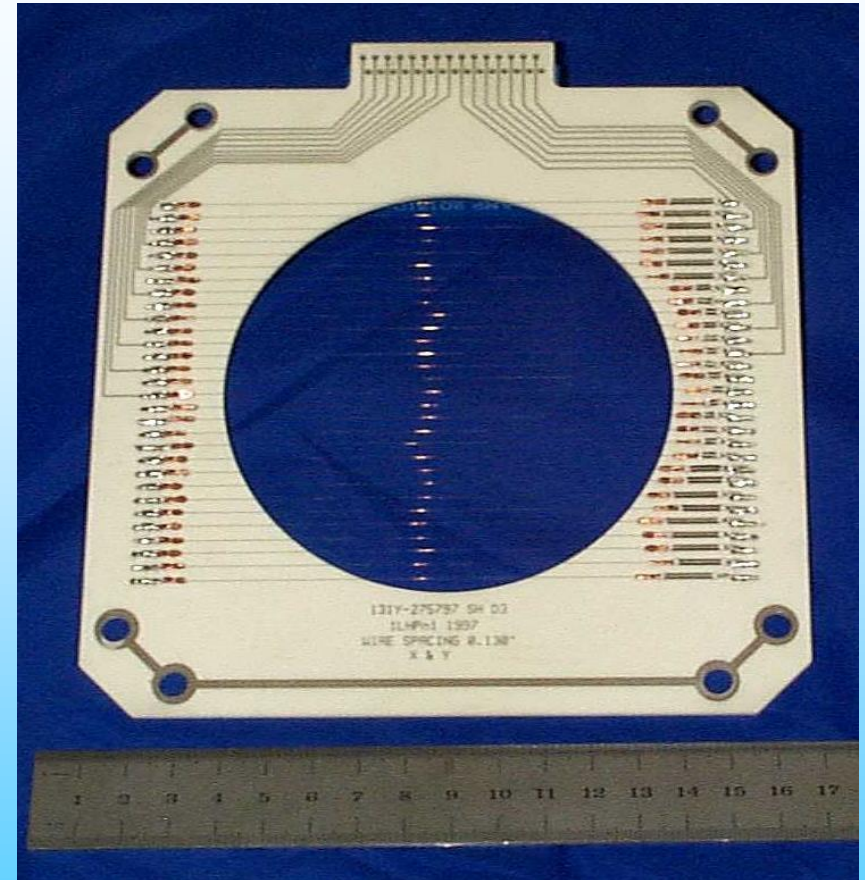
$1.8 \cdot 10^{10}$ ppp

Ion beam: Ca¹⁰⁺,



Measurement with –Harps–

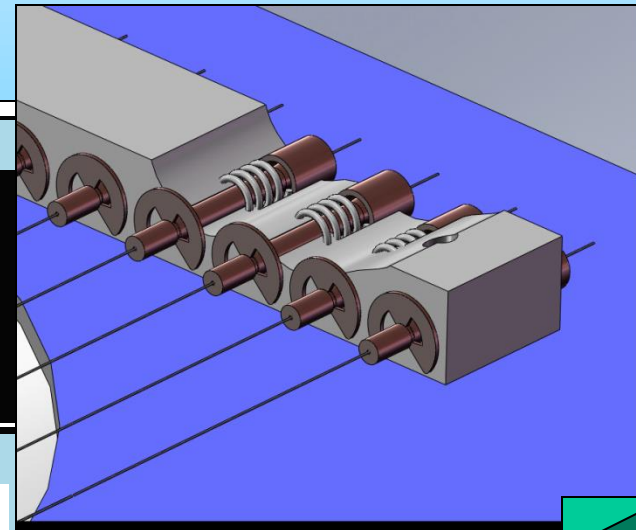
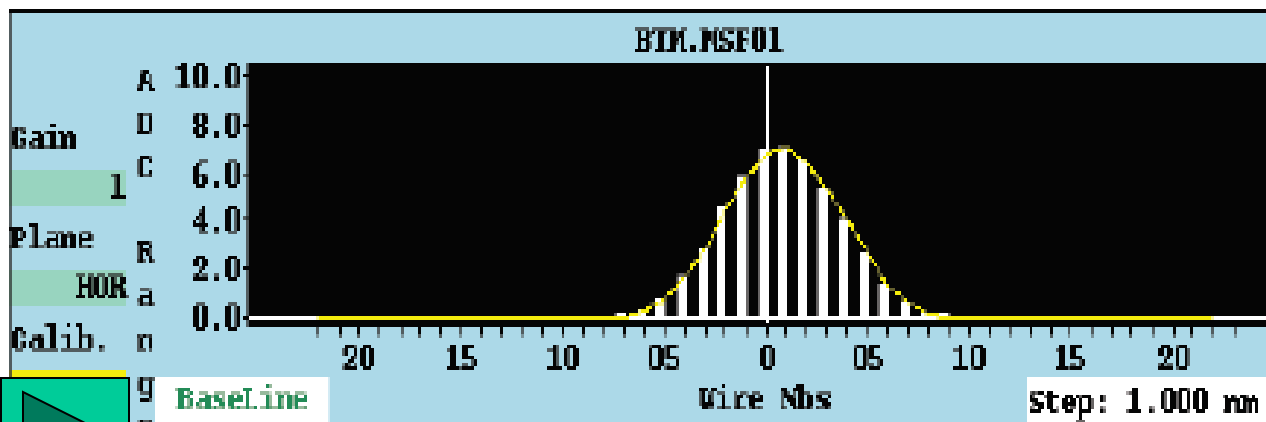
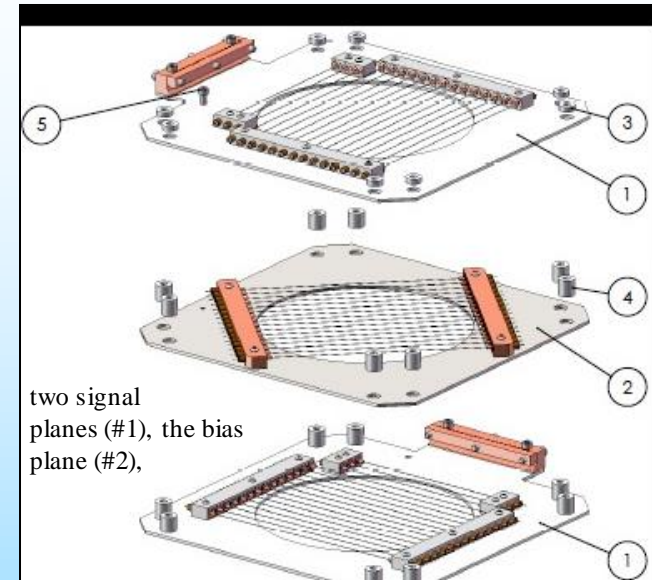
- Each individual wire is connected to an electrical vacuum feedthrough and an amplifier.
- Beam particles hitting a wire create secondary electrons of 20 - 100 eV from its surface.
- The secondary electron yield γ varies between about 300% for low energy ions (e.g. 40 keV) to about 2% for minimum ionizing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

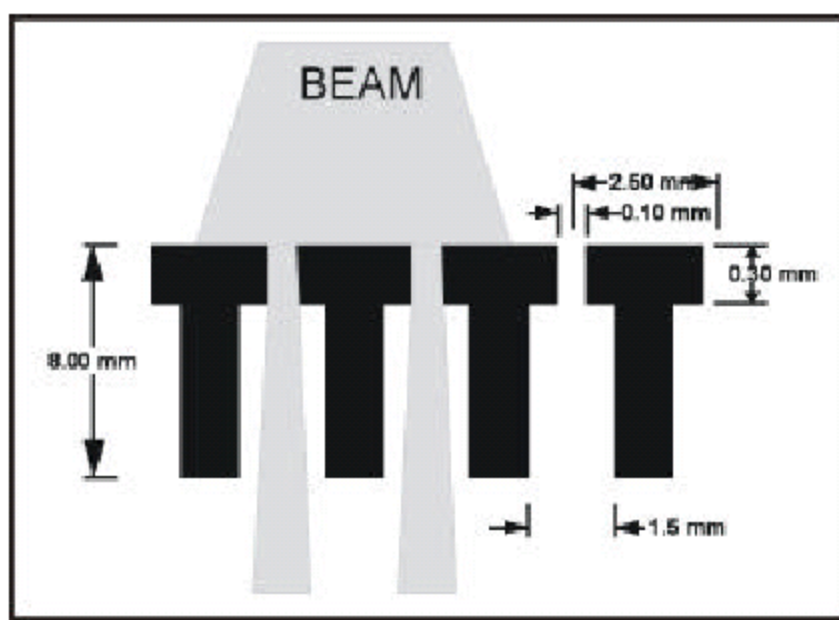


Harps in high radiation environments
11th ICFA International Mini-Workshop on Diagnostics for High-Intensity Hadron Machines, 2002, by Mike Plum

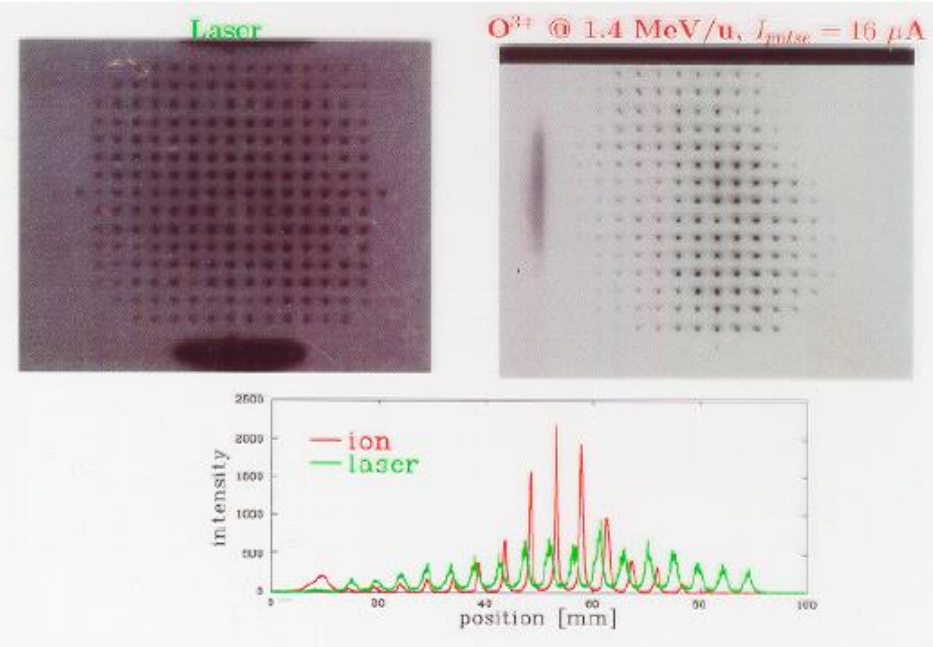
Measurement with –Harps–

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

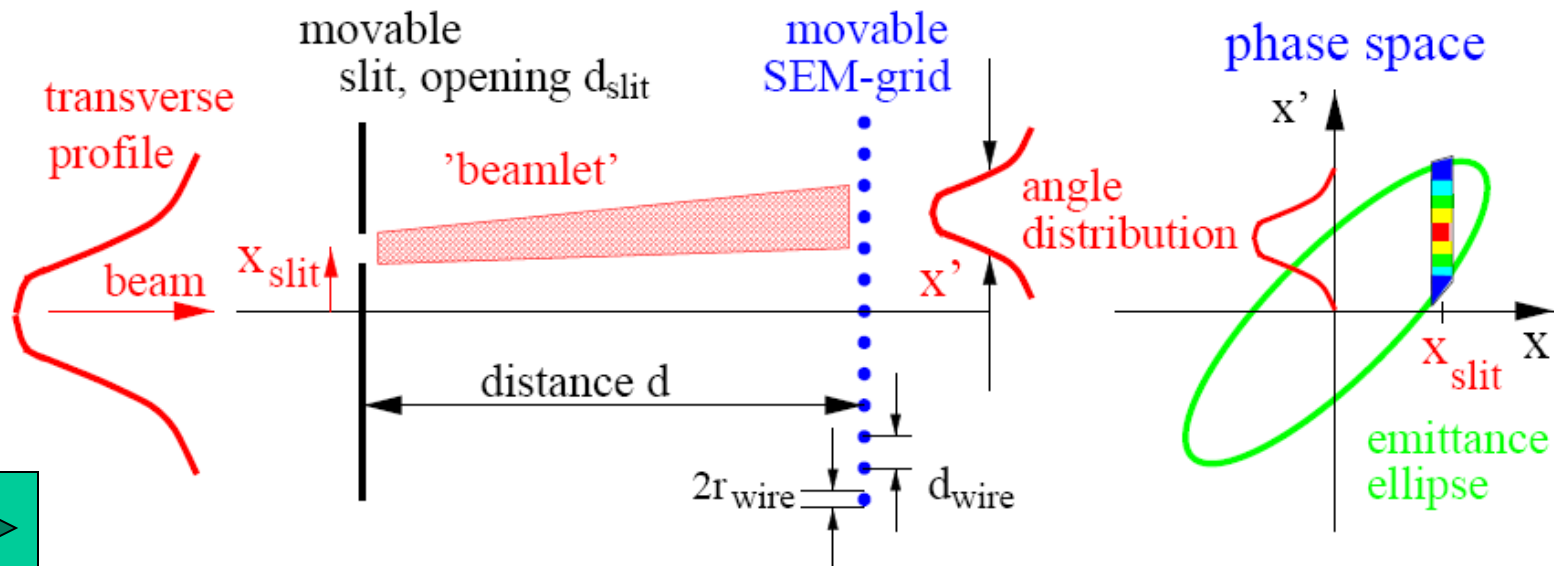




Scheme of the pepperpot plate in a cross sectional view and relevant dimensions



Light spots observed on the viewing screen of a Pepperpot device. Top left: Spots generated for calibration using a laser beam. Top right: Spots from an oxygen beam. Bottom: Intensity distribution along one line.



By P. Forck
Juas 2009

If β is known unambiguously as in a circular machine, then a single profile measurement determines ε by

$$\sigma_y^2 = \varepsilon \beta_y.$$

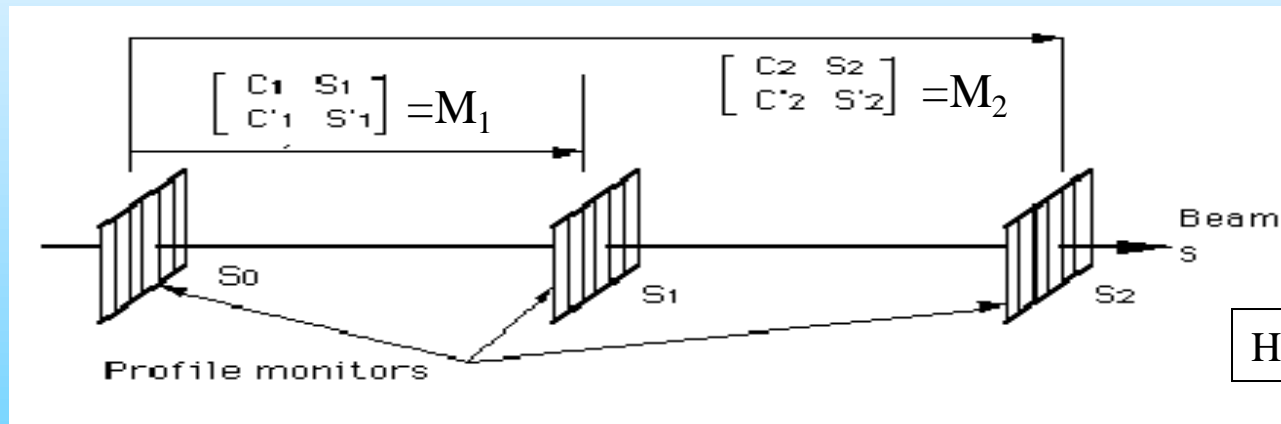
But it is not easy to be sure in a transfer line which β to use, or rather, whether the beam that has been measured is matched to the β -values used for the line. This problem can be resolved by using ...

Three screen method:

If β is known unambiguously as in a circular machine, then a single profile measurement determines ε by

$$\sigma_y^2 = \varepsilon \beta_y.$$

But it is not easy to be sure in a transfer line which β to use, or rather, whether the beam that has been measured is matched to the β -values used for the line. This problem can be resolved by using **three monitors (see Fig. 1)**, i.e. the **three width measurement determines the three unknown α , β and ε of the incoming beam.**



Exercise L2: Assuming that the geometry between the measurement stations and the transport matrices $M_{1,2}$ of the transport line are well defined (including magnetic elements), describe a way to get the emittance using the 3 screens and the σ -matrix.

Write down the equation how the beam width σ is transferred from s_0 to the next screen s_1 .

Introduction of σ -Matrix (see for example: K. Wille; Physik der Teilchenbeschleuniger, Teubner)

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

$$\boxed{\varepsilon_{rms} = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}} \quad (\beta\gamma - \alpha^2 = 1)$$

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

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

$$\boxed{\sigma_{s1} = M \cdot \sigma_{s0} \cdot M^t} \quad M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}; M^t = \begin{pmatrix} M_{11} & M_{21} \\ M_{12} & M_{22} \end{pmatrix}$$

L_1, L_2 = distances between screens or from Quadrupole to screen and Quadrupole field strength are given, therefore the transport matrix M is known.

Applying the transport matrix gives (now time for exercise):

Exercise L2: Assuming that the geometry between the measurement stations and the transport matrices $M_{1,2}$ of the transport line are well defined (including magnetic elements), describe a way to get the emittance using the 3 screens and the σ -matrix.

Write down the equation how the beam width σ is transferred from s_0 to the next screen s_1 .

$$\sigma_{s_1} = M \cdot \sigma_{s_0} \cdot M^t$$

$$= \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix}_{s_0} \cdot \begin{pmatrix} M_{11} & M_{21} \\ M_{12} & M_{22} \end{pmatrix} = \sigma^{measured} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{y'y} & \sigma_{y'}^2 \end{pmatrix}_{s_1}^{measured} = \varepsilon_{rms} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

Exercise L2: Assuming that the geometry between the measurement stations and the transport matrices $M_{1,2}$ of the transport line are well defined (including magnetic elements), describe a way to get the emittance using the 3 screens and the σ -matrix.

Write down the equation how the beam width σ is transferred from s_0 to the next screen s_1 .

Exercise L3: In a transport line for $p = 7.5 \text{ GeV}/c$ protons are two measurement stations. The first is located exactly in the waist of the beam and shows a beam width of $\sigma_y = 3 \text{ mm}$, the second at a distance of $s = 10 \text{ m}$ shows a width of $\sigma_y = 9 \text{ mm}$. Assuming no optical elements in this part, calculate the emittance and the normalized emittance of the beam.

No optical elements $\Rightarrow M =$

Waist $\Rightarrow \alpha =$

Width at $s = 0 \Rightarrow \sigma_{11} =$

Momentum $p =$

Exercise L3: In a transport line for $p = 7.5 \text{ GeV}/c$ protons are two measurement stations. The first is located exactly in the waist of the beam and shows a beam width of $\sigma_y = 3 \text{ mm}$, the second at a distance of $s = 10 \text{ m}$ shows a width of $\sigma_y = 9 \text{ mm}$. Assuming no optical elements in this part, calculate the emittance and the normalized emittance of the beam.

No optical elements $\Rightarrow M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}$ (3)

Waist $\Rightarrow \alpha = \sigma_{12} = \sigma_{21} = 0 \quad \left(= -\frac{1}{2} \cdot \frac{d\beta}{ds} \right) \quad (\varepsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2} = \sqrt{\sigma_{11}\sigma_{22}})$ (4)

Measured width at $s = 0 \Rightarrow \sigma_{11} = (3 \text{ mm})^2 = \sigma_y^2(0)$ (5)

Momentum $p = 7.5 \text{ GeV}/c \Rightarrow \text{relativistic } \gamma\beta \approx 7.5$

Calculate σ_{22} with width measured at $s = 10 \text{ m}$ and with (1 and $\alpha=0$) \Rightarrow

$(9 \text{ mm})^2 = \sigma_y^2(10) = M_{11}^2 \sigma_{11} + M_{12}^2 \sigma_{22} = \sigma_{11} + s^2 \sigma_{22} \quad (\sigma_{11} \text{ and } \sigma_{22} \text{ at } s=0)$ (6)

with (5) $\Rightarrow \sigma_{22} = \frac{\sigma_y^2(10) - \sigma_y^2(0)}{s^2}$ (7)

With (4) and (7) \Rightarrow

$$\varepsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22}} = \sqrt{\sigma_y^2(0) \cdot \frac{\sigma_y^2(10) - \sigma_y^2(0)}{s^2}} = \frac{\sigma_y(0)}{s} \sqrt{\sigma_y^2(10) - \sigma_y^2(0)}$$

$\varepsilon_{rms} = \underline{2.5 \cdot 10^{-6} \pi \text{ m rad}}$ or $\varepsilon^{\text{normalized}} = \varepsilon_{rms} \gamma \beta = 19 \cdot 10^{-6} \pi \text{ m rad} = \underline{19 \pi \text{ mm mrad}}$

$$\varepsilon_{\text{rms}} = \underline{2.5 \cdot 10^{-6} \pi \text{ m rad}} \quad \text{or}$$

$$\varepsilon_{\text{normalized}} = \varepsilon_{\text{rms}} \gamma \beta = 19 \cdot 10^{-6} \pi \text{ m rad} = \underline{19 \pi \text{ mm mrad}}$$

Additional exercise: Calculate $\beta(s=0$ and $s=10\text{m}$)

$$\text{Beam width } \sigma_{\text{rms}} = \sqrt{\beta(s) \cdot \varepsilon}$$

$$\text{At } s=10 \text{ m: } \sigma^2 = \beta \varepsilon \Rightarrow \beta = 32.4 \text{ m}$$

$$\text{At } s=0 \text{ m: } \beta = 3.6 \text{ m}$$

Still more:

What is the influence on the emittance ε assuming at $s = 10\text{m}$, this β , a dispersion of $D = 1 \text{ m}$ and a momentum spread of $\Delta p/p = 10^{-3}$?

$$\varepsilon = \frac{\sigma^2 - \left(D \cdot \frac{\Delta p}{p} \right)^2}{\beta} = \frac{81 \cdot 10^{-6} - 1 \cdot 10^{-6}}{32.4} = 2.469 \pi \text{ mm mrad}$$

$\Delta p/p$ is 1 σ for the particle ensemble!

or $\approx 1\%$ which is less than the typical accuracy of a profile measurement

Emittance measurements by quadrupole variation or 3 screens/harps methods

Profiles are measured by thin screens or harps.

=> small and almost negligible beam blowup due to the measurement itself so that the beam can transverse a few screens.

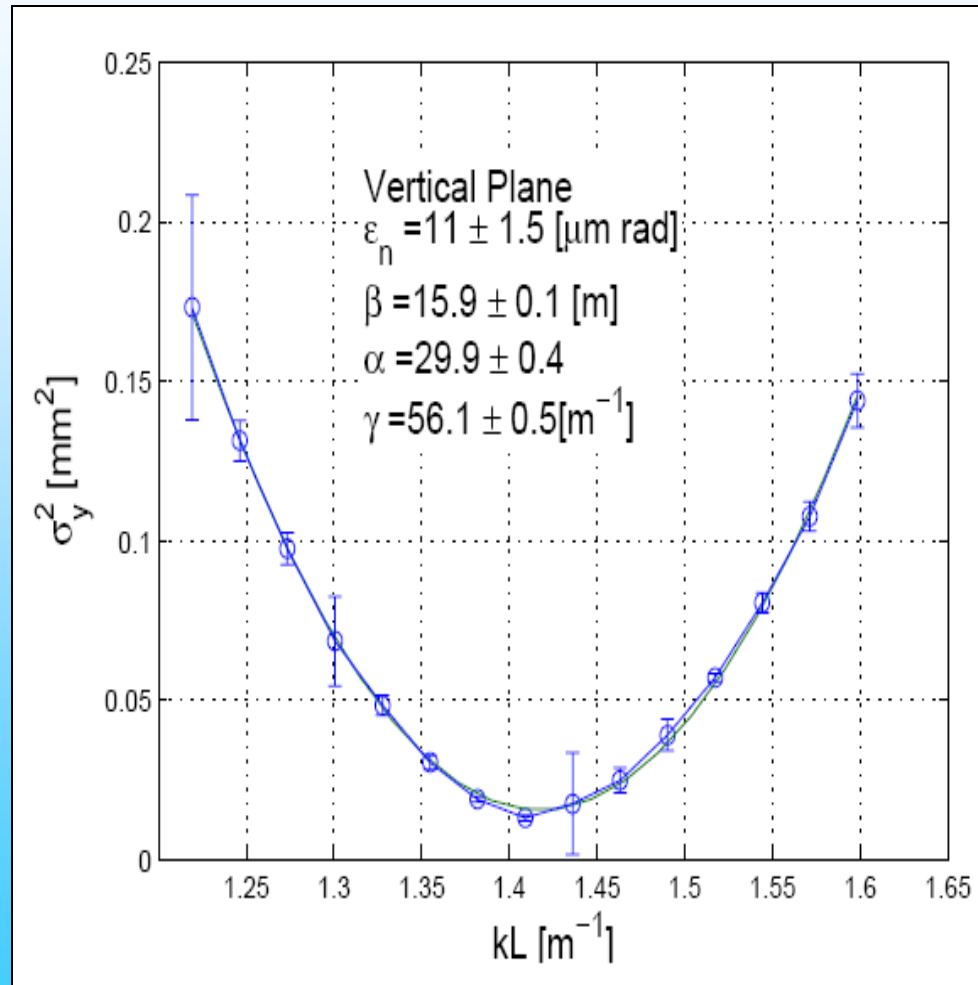
=> "one shot" measurement

=> scanning methods need a stable beam over the scanning time.

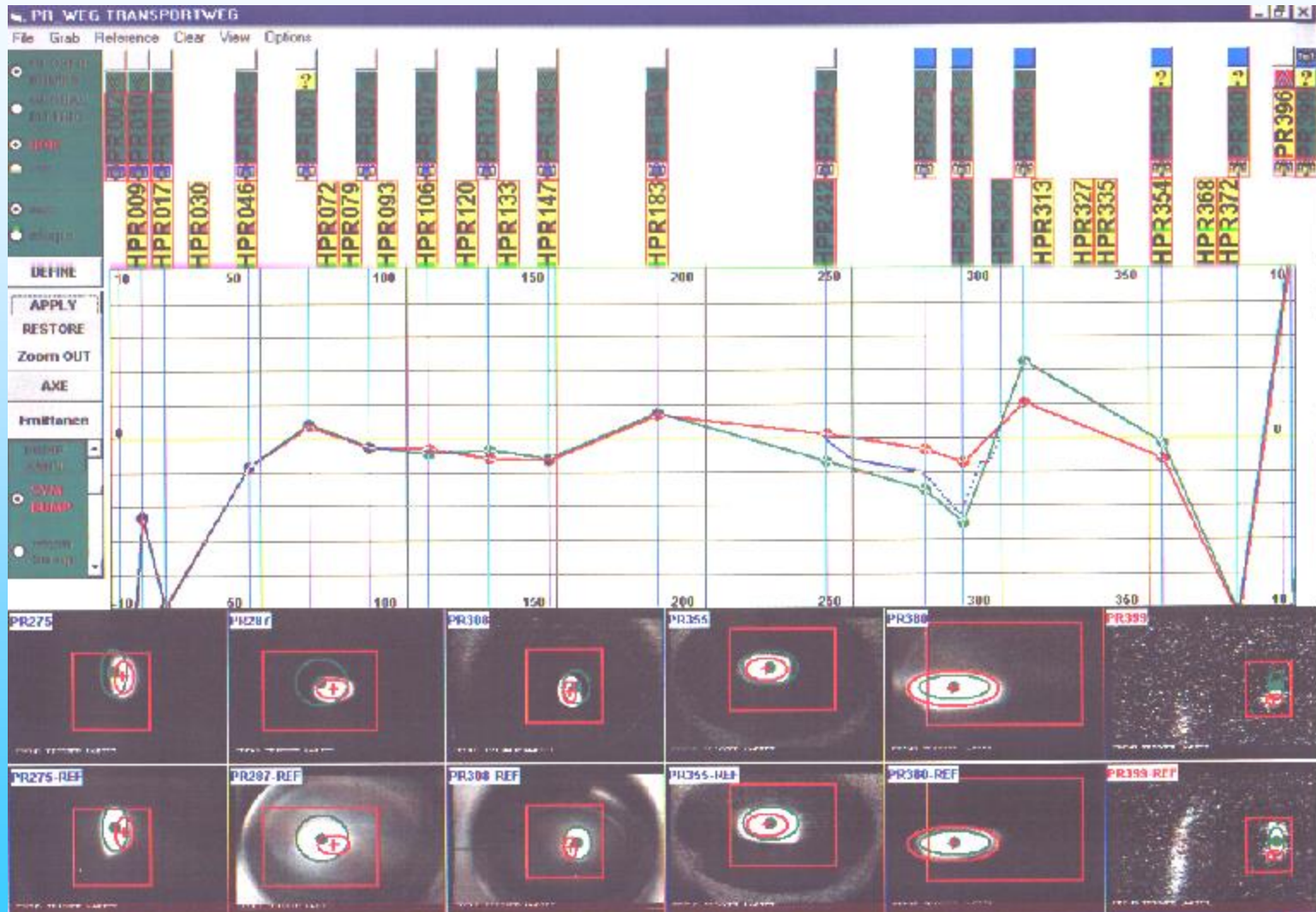
Three measurements give a unique solution but no error estimation.

=> more stations or by more quadrupole settings are recommended.

=> variation of the quadrupole settings allows a quadratic fit of the square of the measured beam size versus the quadrupole gradient together with an estimate of the errors in the measurement.



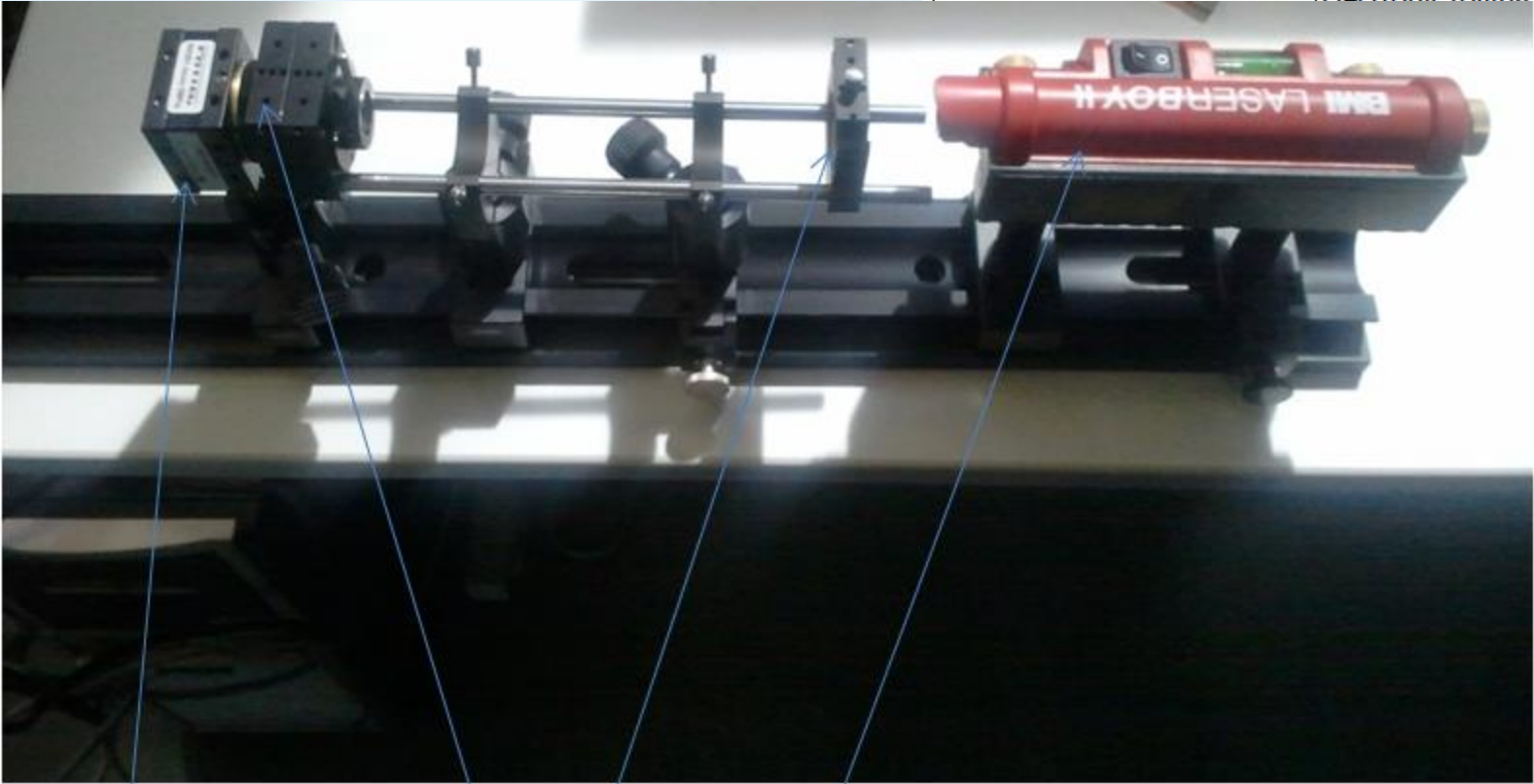
Screens will show often this kind of beam profiles, sometime not really Gaussian. Let's make an emittance measurement on a real beam with real pictures:



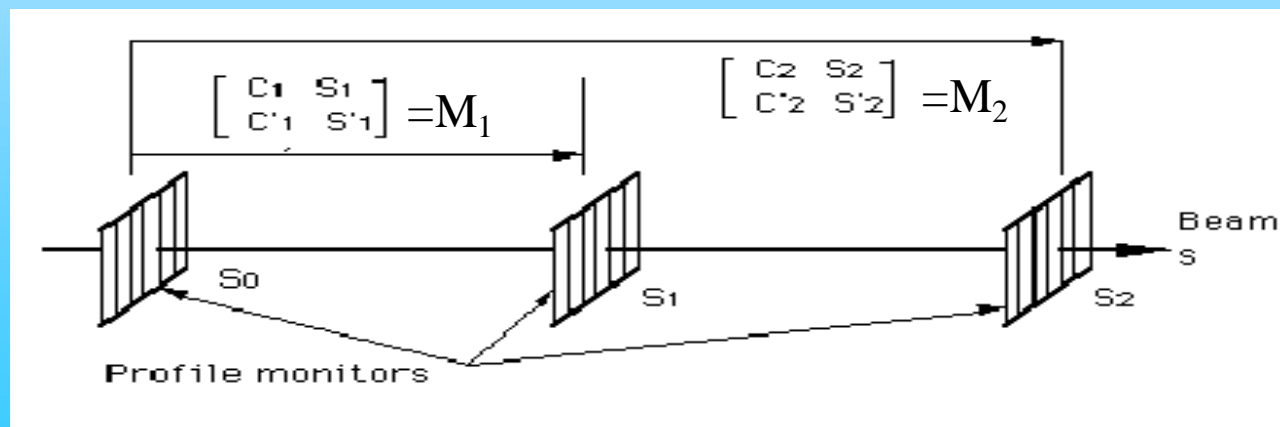
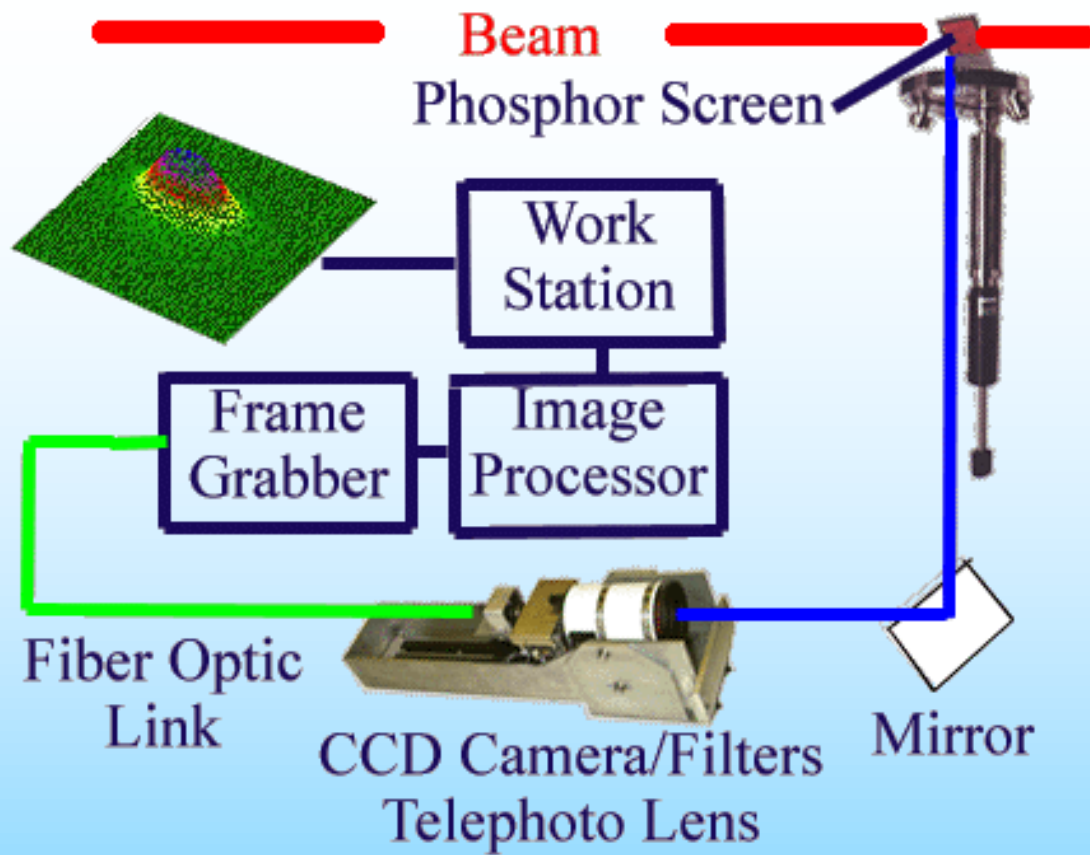
Camera Sensor

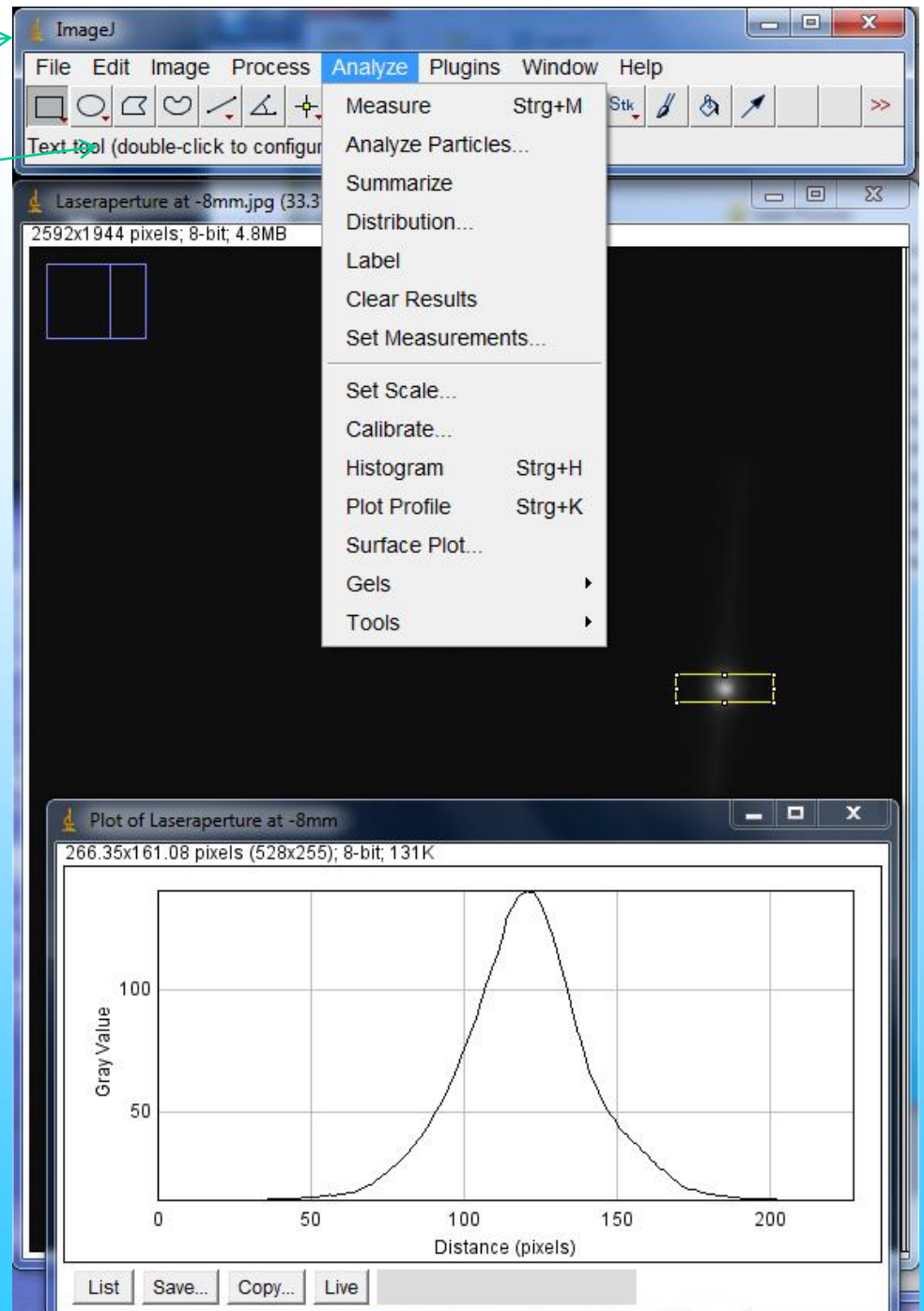
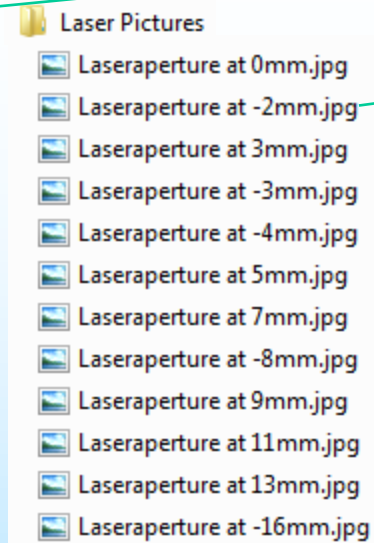
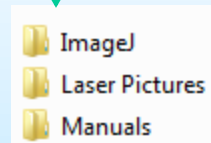
$$\varepsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22}} = \frac{\sigma_y(0)}{s} \sqrt{\sigma_y^2(s) - \sigma_y^2(0)}$$

Parameter	Value
Optical format	1/2.5-inch (4:3)
Active imager size	5.70mm(H) x 4.28mm(V) 7.13mm diagonal
Active pixels	2592H x 1944V
Pixel size	2.2 x 2.2µm
Color filter array	RGB Bayer pattern
Shutter type	Global reset release (GRR), Snapshot only
	Electronic rolling shutter (ERS)
	(2.8V I/O)
	(1.8V I/O)
	o 14 fps
	o 53 fps
	m)
	inal)
	inal)
	all resolution



High resolution USB Camera, Filter, moveable Lens, Laser





Waist at $s = 0$ mm

$$\sigma = \text{FWHM}/2.35$$

Pixel size = $2.2 \mu\text{m}$

$$\varepsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22}} = \frac{\sigma_y(0)}{s} \sqrt{\sigma_y^2(s) - \sigma_y^2(0)}$$

Results of Laser Emittance

s [mm]	left[pixels]	right[pixels]	FWHM [pixel]	sigma [m]	emittance
--------	--------------	---------------	--------------	-----------	-----------

-16
-8
-4
-3
-2
0
3
5
7
9
11
13

From pictures

From Solutions: LINACS/Transport Lines
Emittance Measurement

$$\varepsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22}} = \sqrt{\sigma_y^2(0) \cdot \frac{\sigma_y^2(s) - \sigma_y^2(0)}{s^2}} = \frac{\sigma_y(0)}{s} \sqrt{\sigma_y^2(s) - \sigma_y^2(0)}$$

at s=0mm: FWHM = 32 pixels

pixel = 2.20E-06 m

1 mm = 1.00E-03 m

From picture at s=0

From camera manual, pixel size

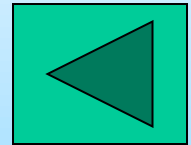
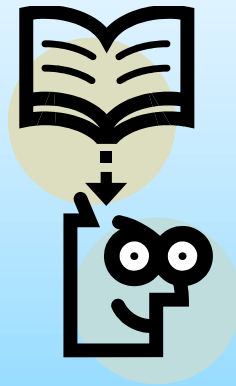
Emittance measurements by quadrupole variation or 3 screens/harps methods

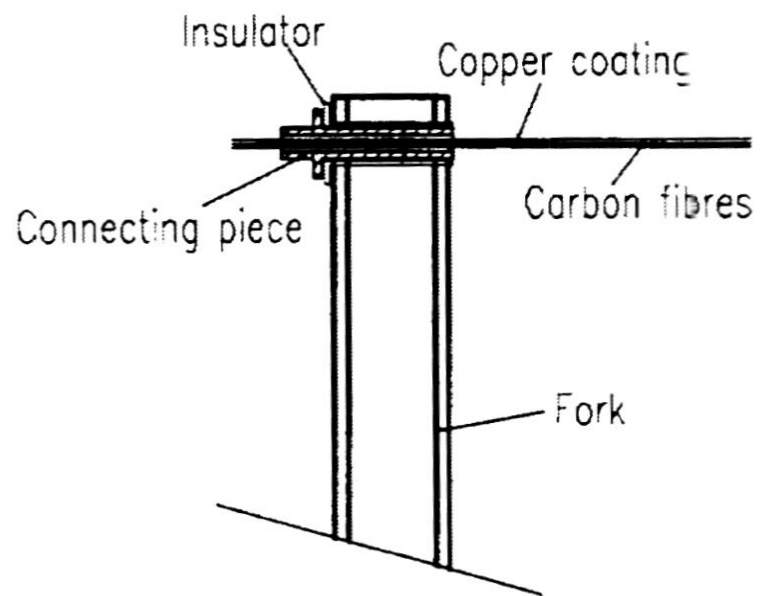
The standard methods described above are valid under the assumption that:

- the dispersion along the section is zero,
- the transfer matrices are known,
- no coupling between the two planes is present and
- no space charge or other non-linear forces are present.

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

End of emittance calculations, let's go to some instruments





Discussing Wire Scanner heat load:

$$T_h = C \cdot dE / dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^{\circ}C]$$

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$T = C \cdot dE / dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^{\circ}C]$$

unknown

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction):

Therefore, the temperature increase of the wire after one scan becomes:

$$T = C \cdot dE / dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^{\circ}C]$$

In MeV/cm

$$MassG = wire\ volume \cdot \rho = 2 \cdot \sigma_v \cdot d'^2 \cdot \rho \quad [g]$$

$$N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})$$

$$T_h = C \cdot dE / dx_m \cdot \cancel{d'} \cdot \frac{\cancel{d'} \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch}) \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v \cdot \cancel{d'^2} \cdot \rho} \cdot \alpha \quad [^{\circ}C]$$

$$with \quad \frac{dE / dx_m}{\rho} = dE / dx \left[\frac{MeV \cdot cm^2}{g} \right] \quad and \quad f_{rev} \cdot NB = f_{bunch}$$



$$T_h = C \cdot dE / dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^{\circ}C]$$

Parameter table

Where h, denotes the horizontal (h) scanning direction. The cooling factor 'α' is described in the next section. **Note that the temperature does not depend on the wire diameter and that it depends on the beam dimension perpendicular to the measuring direction. The temperature increase is inverse proportional to the scanning speed, therefore a faster scanner has a correspondingly smaller temperature increase.**

Emittance growth due to
a wire scan:

$$\delta \varepsilon_{rms} = \sqrt{2\pi} \cdot \delta \Theta^2 \cdot \Psi^2 \cdot \beta$$

$$= 5.1 \cdot 10^{-2} \pi \text{ mm mrad}$$

$\sqrt{2\pi}$ from Literature

D. Möhl, Sources of emittance growth (also P. Bryant;
CAS, Beam transfer lines):

$$\delta \varepsilon = \pi \frac{1}{2} \cdot \Theta_{rms}^2 \cdot \beta$$

Averaging over all Betatron-phases

Unit of phase space emittance

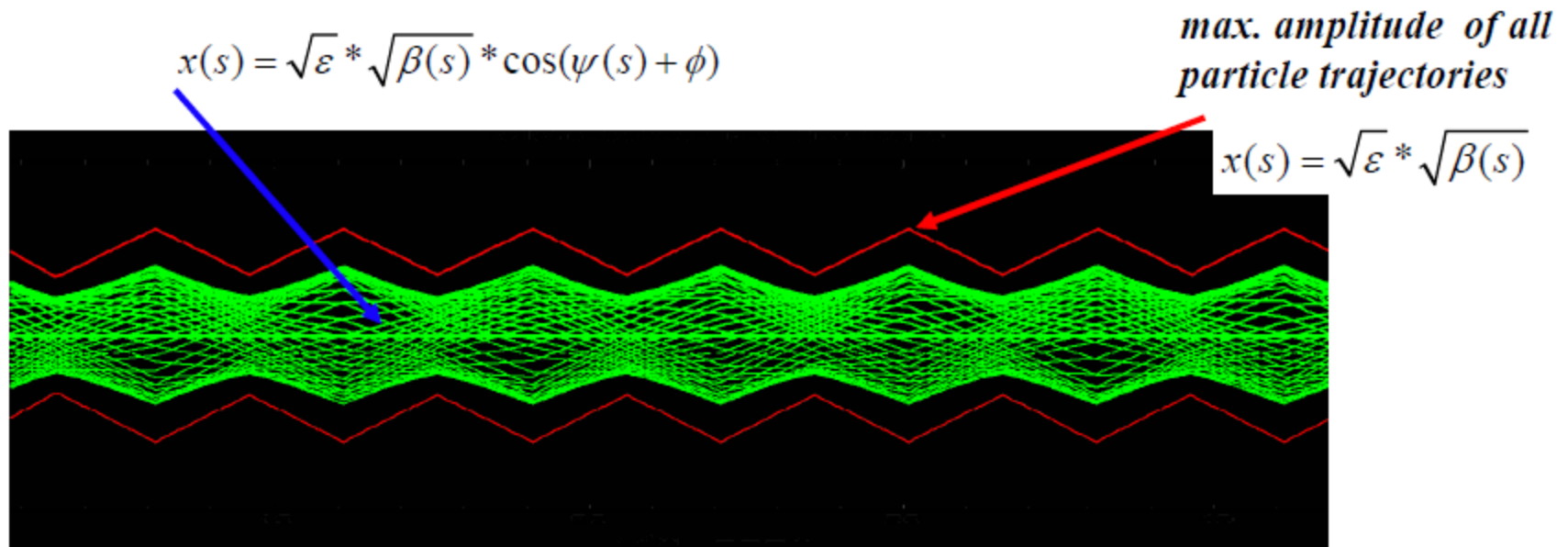
M. Giovannozzi (CAS 2005)

$$\delta \varepsilon = \pi \frac{1}{4} \cdot \Theta_{rms}^2 \cdot \beta$$

D. Möhl, Sources of emittance
growth, 2007:

$$\delta \varepsilon_{\sigma} = \frac{1}{2} \cdot \Theta_{rms}^2 \cdot \beta_x$$

Ensemble of many (...all) possible particle trajectories



Beam Dimension:

determined by two parameters

$$\sigma = \sqrt{\varepsilon * \beta}$$

*Example: transverse beam profile
measured using a wirecam*

vertical:

$$\sigma_{\text{fit}} = 24.376 \cdot \mu\text{m}$$

HERA beam size

