Particle Beam Diagnostics

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DESY.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

M T ARD

Introduction to
Particle Beam Diagnostics

Why do we need particle beam diagnostics?

- Control of the Particle Beam
- Characterization of the Particle Beam

Particle Beam Control

- Transport, Tuning, Feedback-systems, machine protection

Charge/Current:
Integrated Current Transformer (ICT), Faraday Cups, etc.

Time of arrival:
Beam arrival time cavities/monitors (BAC/BAM), electro optical sampling (EOS), etc.

Beam losses:
Beam loss monitors

Position (non-destructive):
Beam position monitors (BPMs)

Beam size:
Scintillators and OTR screens

Etc. …

Particle Beam Characterization

- Gain information regarding beam quality and its reproducibility

Charge/Current:
Integrated Current Transformer (ICT), Faraday Cups, etc.

Transverse Phase-Space (Transverse emittance):
quadrupole scan, pepperpot, coherent radiation, etc.

Longitudinal phase-space (Energy, energy-spread, bunch length): RF deflectors, Coherent Radiation, Dipoles, etc.

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Longitudinal phase-space (Energy, energy-spread, bunch length): RF deflectors, Coherent Radiation, Dipoles, etc.

This lecture focuses on those 2 items

Transverse Phase Space Measurements

Correlated transverse momentum spread contribution

$$\epsilon_{n,tr,rms}{}^2 = \langle x^2\rangle\langle p_x{}^2\rangle - \langle xp_x\rangle^2$$

$$\epsilon_{n,tr,rms}{}^2 = \sigma_E{}^2\langle\gamma\rangle^2\langle x'^2\rangle\langle x^2\rangle + \langle\beta\gamma\rangle^2[\langle x'^2\rangle\langle x^2\rangle - \langle xx'\rangle^2]$$

Geometrical emittance term

- The contribution of the transverse momentum spread is important for plasma generated beams.
- The normalized emittance depends on the position of the measurement.

In the following slides we will discuss how to measure the geometrical emittance only

Reference: M- Migliorati et al. , PRSTAB 16 (2013) 011302.

Geometrical RMS Emittance

In the (x, x') plane the geometrical statistical emittance is defined as:

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle (x')^2\rangle - \langle xx'\rangle^2}$$

$$\sigma_x{}^2 = \langle x^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2$$

$$\sigma_{x'}{}^2 = \langle (x')^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2$$

$$\sigma_x\sigma_{x'} = \langle xx'\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle)$$

Therefore the geometrical statistical emittance can be written as the determinant of the matrix:

$$\varepsilon_x = \sqrt{\begin{vmatrix} \sigma_x{}^2 & \sigma_x\sigma_{x'} \\ \sigma_x\sigma_{x'} & \sigma_{x'}{}^2 \end{vmatrix}} = \sqrt{\begin{vmatrix} \sigma_{xx} & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'x'} \end{vmatrix}}$$

The expression on the right-side is just an abbreviation

Coupling of planes in the trace space, 2D-4D-6D emittance

$$\varepsilon^2 = \begin{vmatrix} \sigma_{xx} & \sigma_{xx'} & \sigma_{xy} & \sigma_{xy'} & \sigma_{xz} & \sigma_{xz'} \\ \sigma_{x'x} & \sigma_{x'x'} & \sigma_{x'y} & \sigma_{x'y'} & \sigma_{x'z} & \sigma_{x'z'} \\ \sigma_{yx} & \sigma_{yx'} & \sigma_{yy} & \sigma_{yy'} & \sigma_{yz} & \sigma_{yz'} \\ \sigma_{y'x} & \sigma_{y'x'} & \sigma_{y'y} & \sigma_{y'y'} & \sigma_{y'z} & \sigma_{y'z'} \\ \sigma_{zx} & \sigma_{zx'} & \sigma_{zy} & \sigma_{zy'} & \sigma_{zz} & \sigma_{zz'} \\ \sigma_{z'x} & \sigma_{z'x'} & \sigma_{z'y} & \sigma_{z'y'} & \sigma_{z'z} & \sigma_{z'z'} \end{vmatrix}$$

$$\varepsilon^2 = \begin{vmatrix} \sigma_{xx} & \sigma_{xx'} & 0 & 0 & 0 & 0 \\ \sigma_{x'x} & \sigma_{x'x'} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{yy} & \sigma_{yy'} & 0 & 0 \\ 0 & 0 & \sigma_{y'y} & \sigma_{y'y'} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{zz} & \sigma_{zz'} \\ 0 & 0 & 0 & 0 & \sigma_{z'z} & \sigma_{z'z'} \end{vmatrix}$$

Full expression for the emittance in the 6D trace space: one 6X6 determinant

In case of de-coupling many terms are 0 and we can calculate: three 2X2 determinants, one for each plane

Overview of main techniques for measuring the transverse emittance

- Techniques based on slits/masks:
  - Slit-scan
  - Pepperpot
  - TEM grid

- Techniques based on fit of the beam size for a known lattice:
  - Quadrupole scan
  - Multi-screen method
  - Permanent quadrupoles + energy spectrometer

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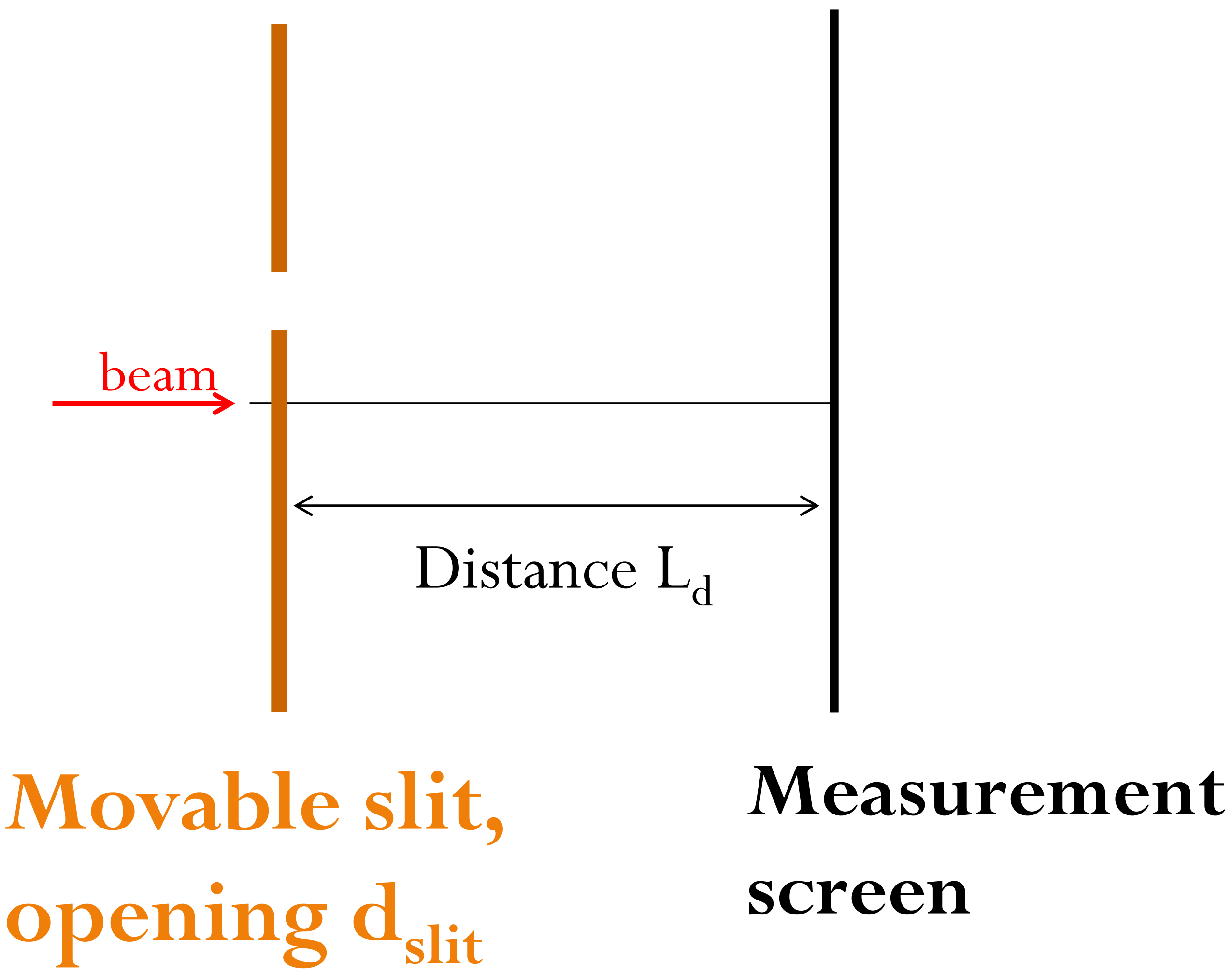
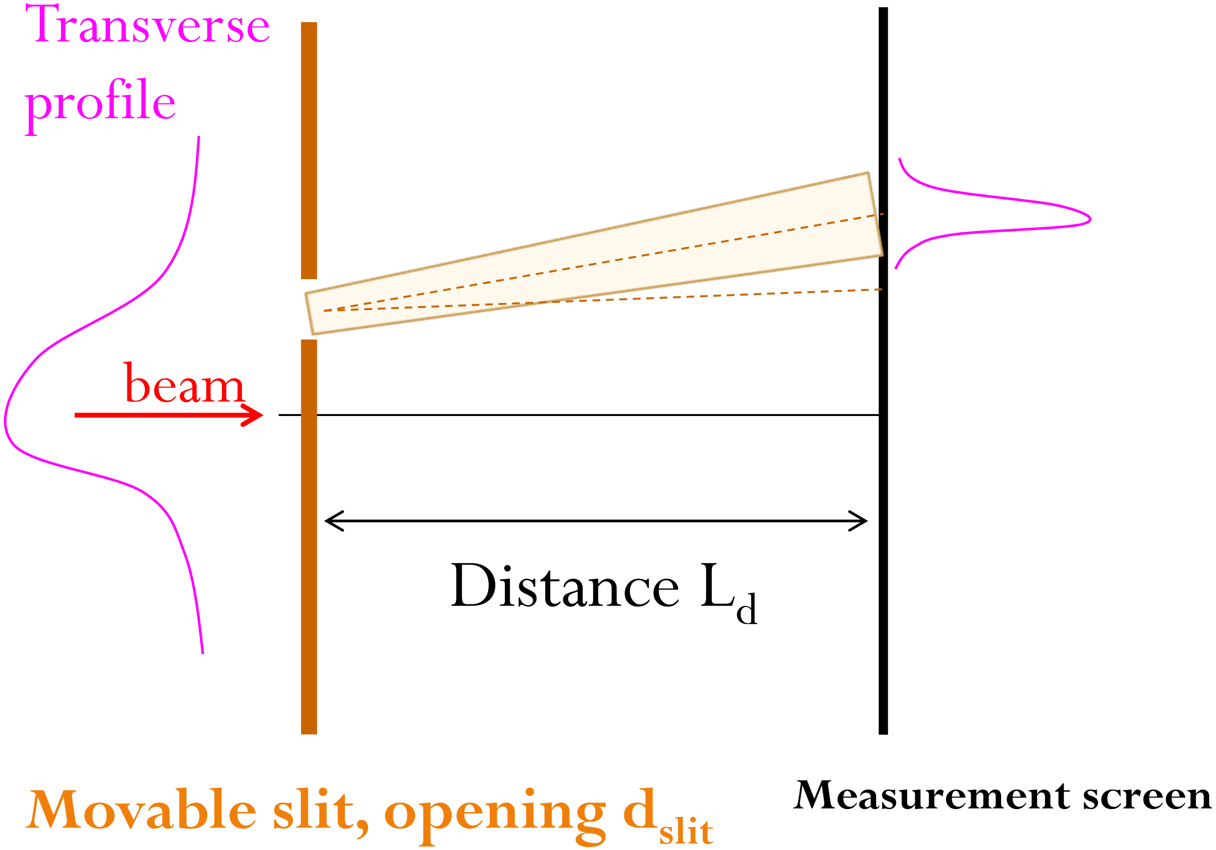
The slit method



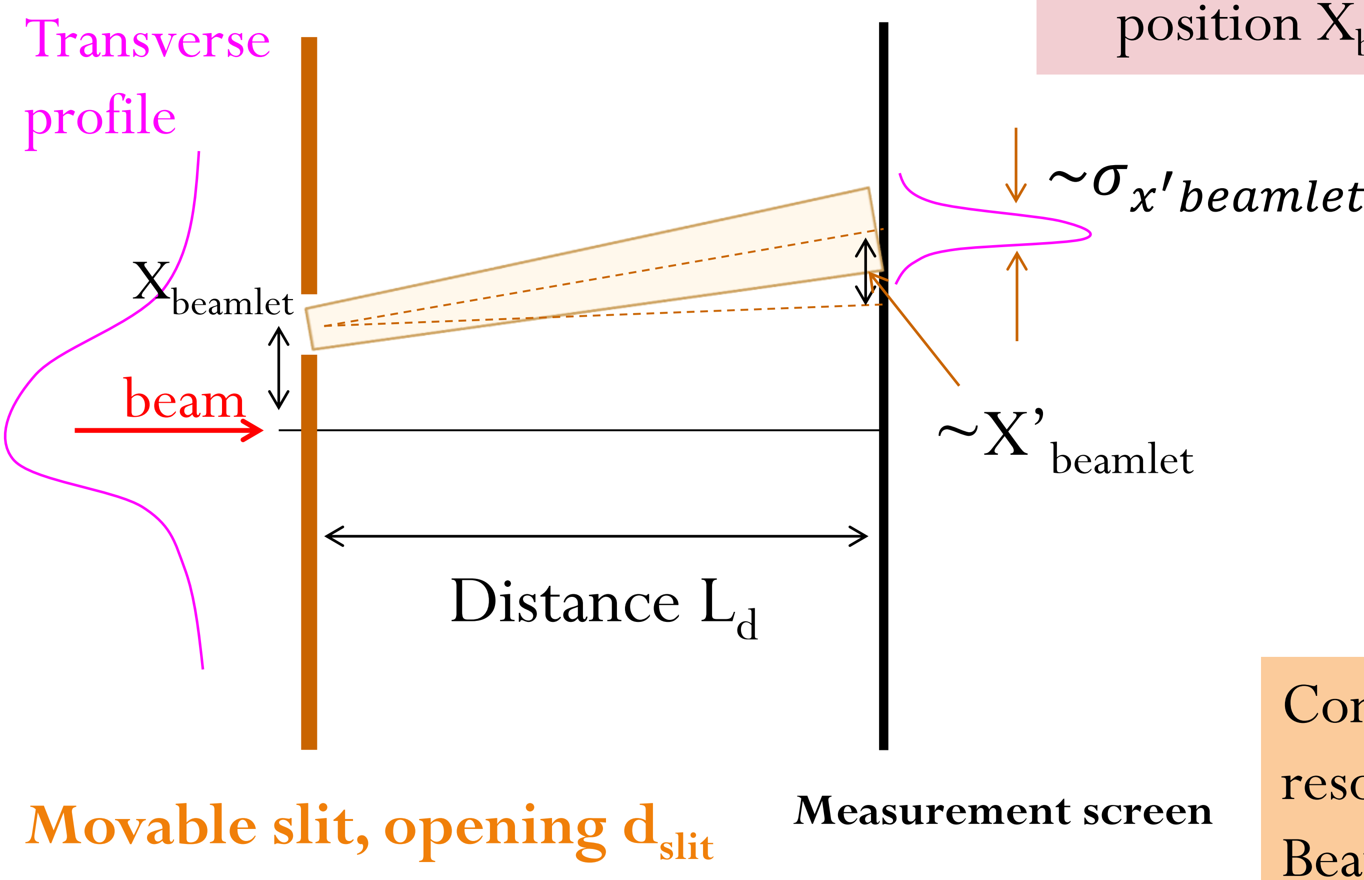
The slit method



The slit mask converts a **space charge dominated** electron beam into an **emittance dominated** beamlet

The slit method

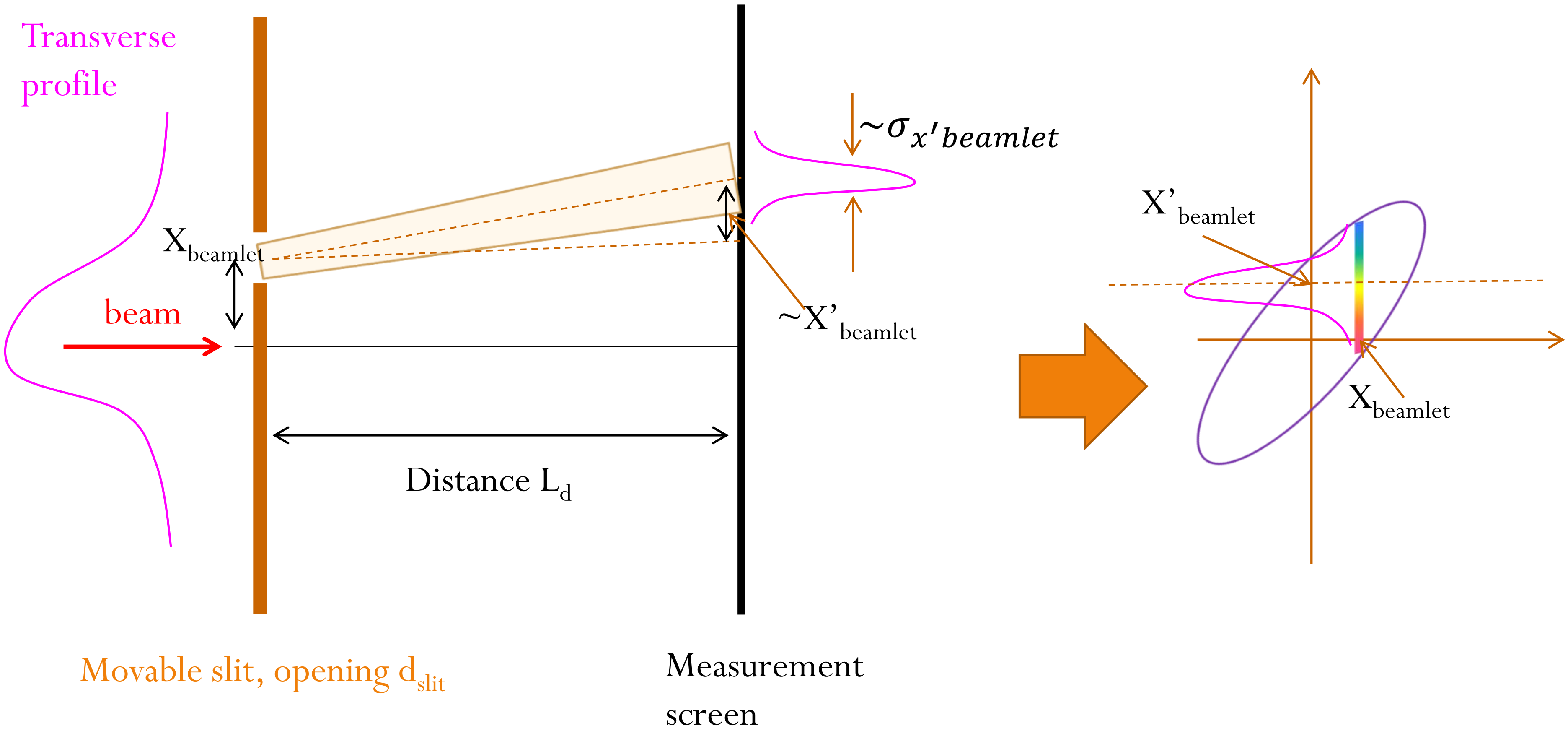
- From width and position of slit image mean beam angle and divergence of beamlet at position $X_{beamlet}$ is computed.



Condition for good resolution:
Beamlet size @ measurement screen >> slit width

The slit method

- By moving slit across the beam complete distribution in x, x' space is reconstructed.



See e.g. S. Rimjaem et al. NIMA 671 (2012) 62-75

Example of measurement

(PITZ, DESY-Zeuthen)

Reference: PRSTAB- 15, 100701 (2012)

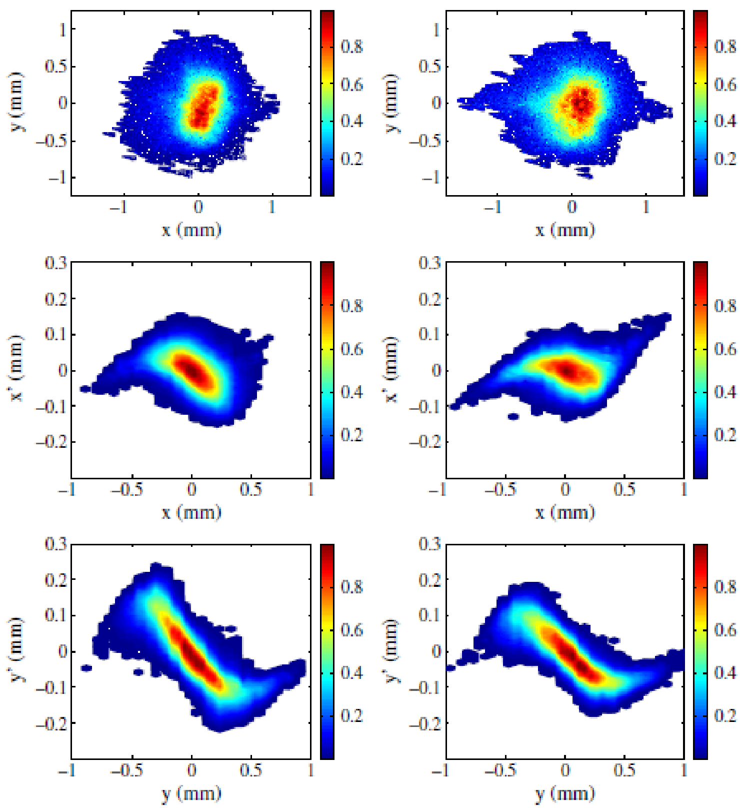


FIG. 22. Measured beam x-y distribution at EMSY1 (upper row), horizontal (middle row), and vertical phase space (bottom row) for a bunch charge of 1 nC. A main solenoid current of 396 A, rf gun phase of +6 deg and laser rms spot size of 0.3 mm were applied. The left column of plots corresponds to the measurements with the cathode #110.2, the right column those with the cathode #11.3 (see Table III).

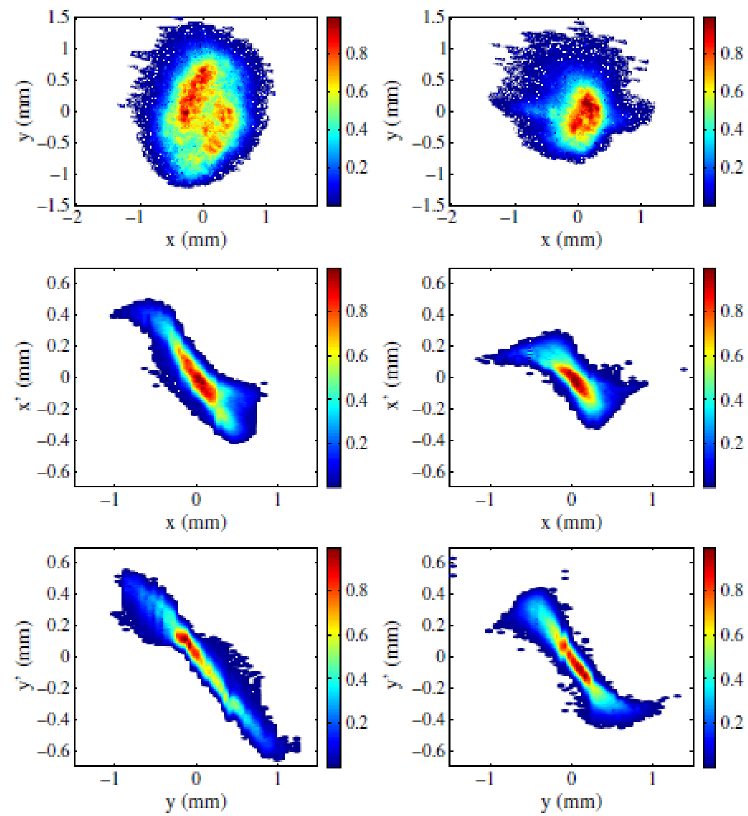
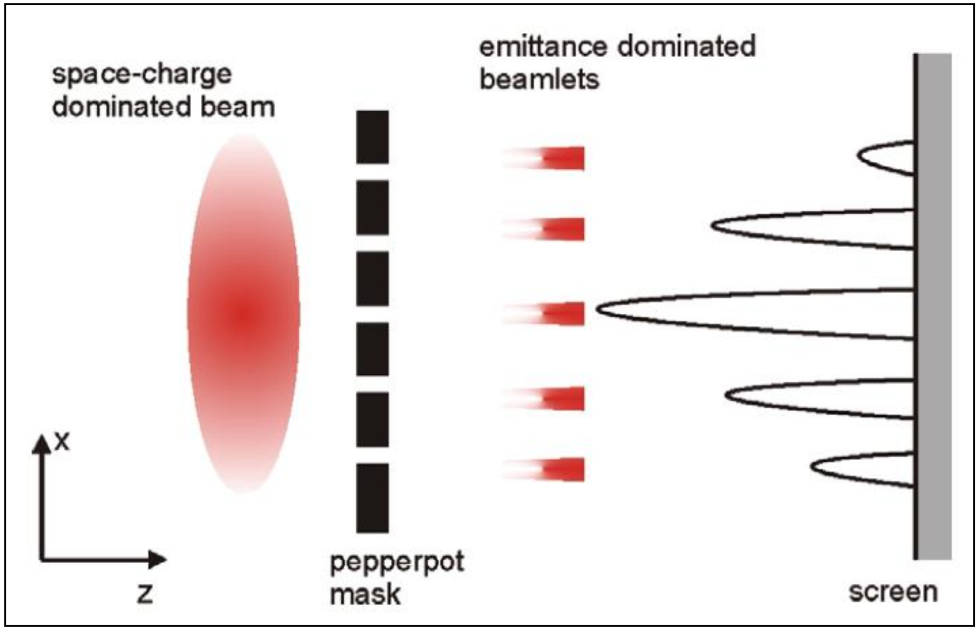


FIG. 23. Measured beam x-y distribution at EMSY1 (upper row), horizontal (middle row), and vertical phase space (bottom row) for a bunch charge of 2 nC. The left column of plots corresponds to the measurements with BSA = 2.0 mm and the main solenoid current of 394 A, the right column of plots is for BSA = 1.5 mm and $I^{*}_{\text{main}} = 395$ A.

Pepperpot



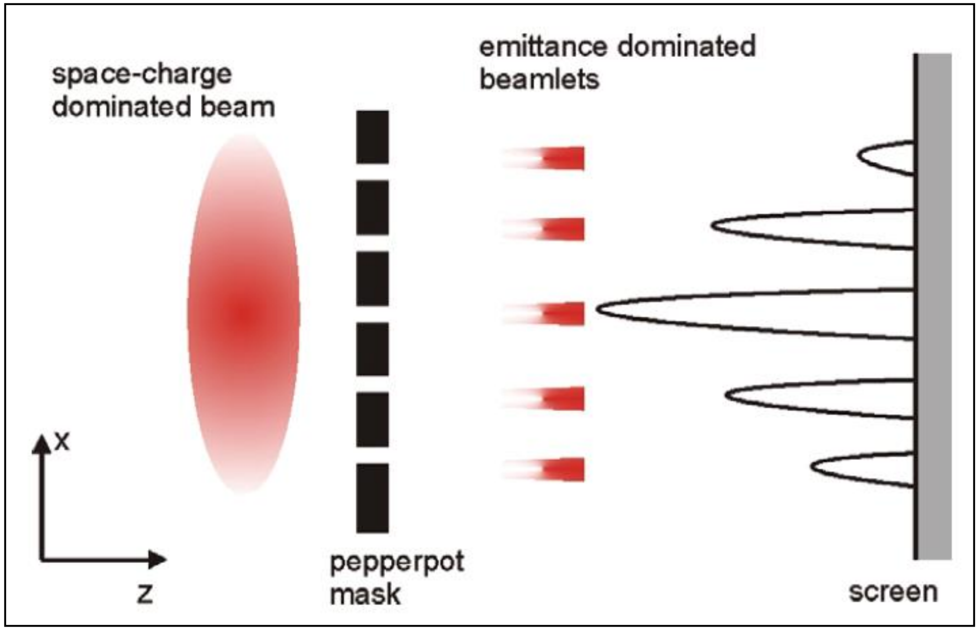
M Hobein *et al* 2011 *Phys. Scr.* **2011** 014062

Similar to the moving slit method, BUT:

- **single shot, allows measurements in both planes simultaneously**

Data analysis procedure:
See e.g. M. Zhang FERMILAB-TM-1988

Pepperpot



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Similar to the moving slit method, BUT:

- **single shot, allows measurements in both planes simultaneously**
- Pepperpot dimensions have to be adapted to particle beam in order to:
  - prevent beamlets overlapping!
  - Guarantee sufficient sampling of the beam

Transmission Electron Microscopy (TEM) grid

- The **shadow of the beam** at the measurement screen is analyzed

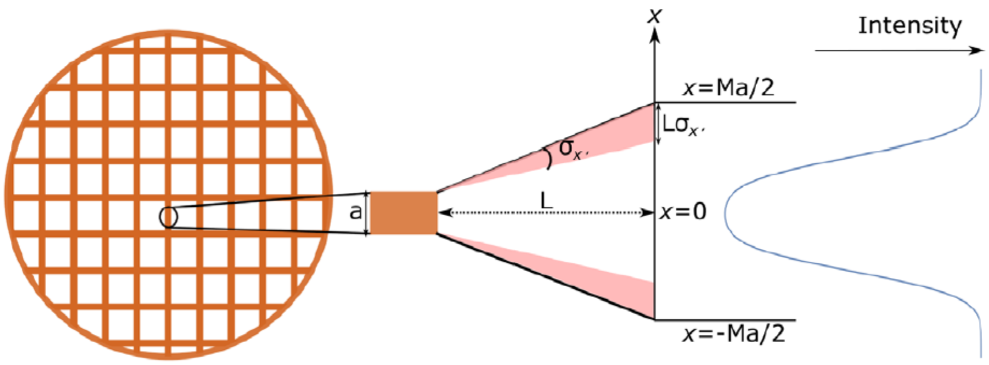

FIG. 2. A schematic of the beam propagating from the TEM grid to the screen, showing how it spreads by $\sigma_{x'}$.

See e.g. R. K. Li et al. PRSAB 15 090702 (2012)

Transmission Electron Microscopy (TEM) grid

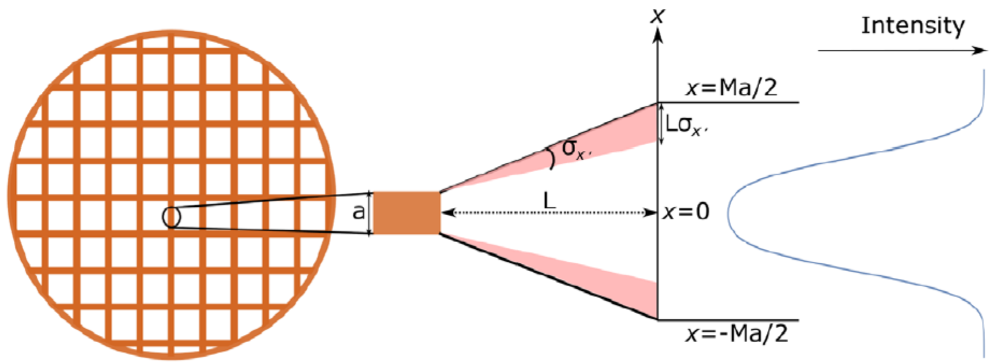

FIG. 2. A schematic of the beam propagating from the TEM grid to the screen, showing how it spreads by $\sigma_{x'}$.

- The **shadow of the beam** at the measurement screen is analyzed
- Very good for **low charge beams** (more charge reaches the screen, reduced noise in the fit of the images)

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Transmission Electron Microscopy (TEM) grid

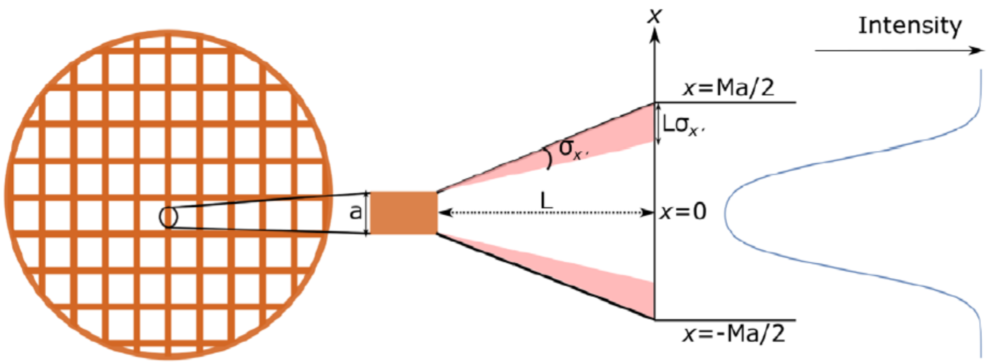

FIG. 2. A schematic of the beam propagating from the TEM grid to the screen, showing how it spreads by $\sigma_{x'}$.

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- The **shadow of the beam** at the measurement screen is analyzed
- Very good for **low charge beams** (more charge reaches the screen, reduced noise in the fit of the images)
- **The method works only for emittance dominated beams!** Since the squares in the grid are bigger (compared to the holes of the pepperpot) beam density must be sufficiently low!

Example of measurement
(Pegasus, UCLA)

Bunch charge 2.3 pC

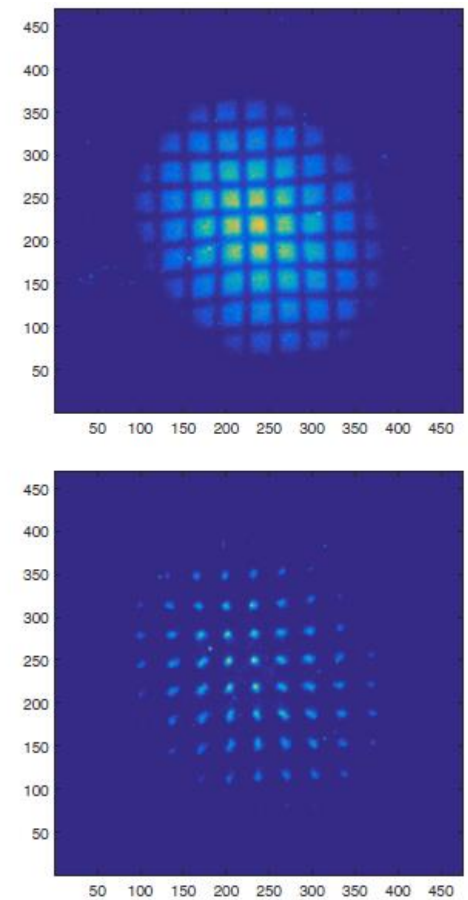

FIG. 10. Sample intensity plot of an image taken in experiments at Pegasus using a TEM grid (top) and a pepper pot (bottom). The images have been cropped to remove the edge of the YAG screen, which was emitting radiation.

Image on the screen using a TEM grid

Image on the screen using a pepperpot

<u>4D phase space can be reconstructed</u> in a single-shot

see

D. Marx et al. PRAB 21, 102802 (2018)

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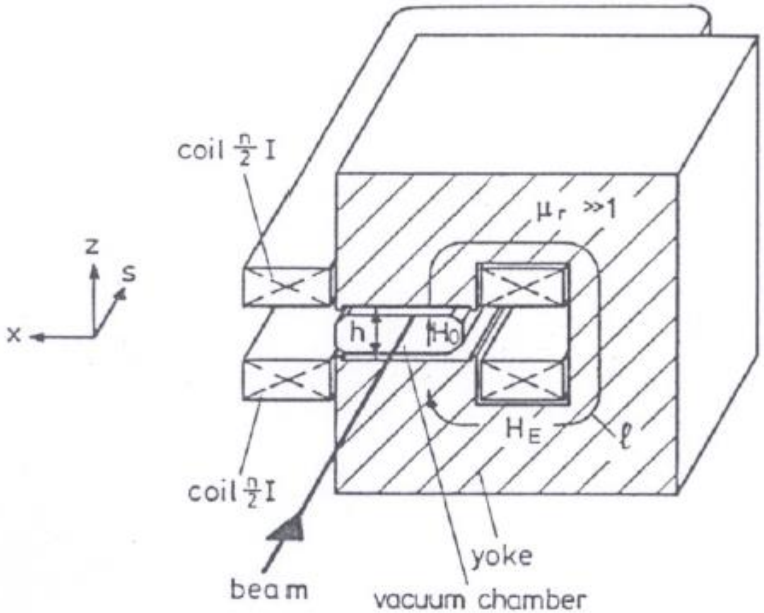
Quick Intro: Dipole Magnet

A magnet with flat pole shoes generates a homogeneous field B_0:

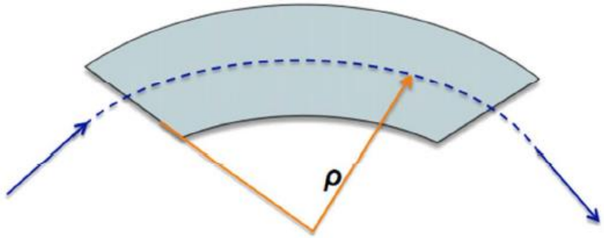
$$B_0 = \frac{\mu_0 n I}{h}$$

With h being the gap size, μ_0 the vacuum permeability.



The **curvature radius** of an electron in the dipole is influenced by **the beam momentum** according to:

$$\frac{1}{\rho}[m^{-1}] = \frac{eB_0}{p} = 0.2998\frac{B_0[T]}{p[GeV/c]}$$



Fugure courtesy: Basic Course on Accelerator Optics, CAS 1992, CERN-1994-001.17

Quick Intro: Quadrupole Magnet

The **gradient** of the quadrupole can be expressed as:

$$g = \frac{2\mu_0 n I}{R^2}$$

Where μ_0 is the vacuum permeability, n is the number of the windings, I is the current, R is the radius of the aperture.

The **strength** of the quadrupole depends on its gradient g and on the beam momentum:

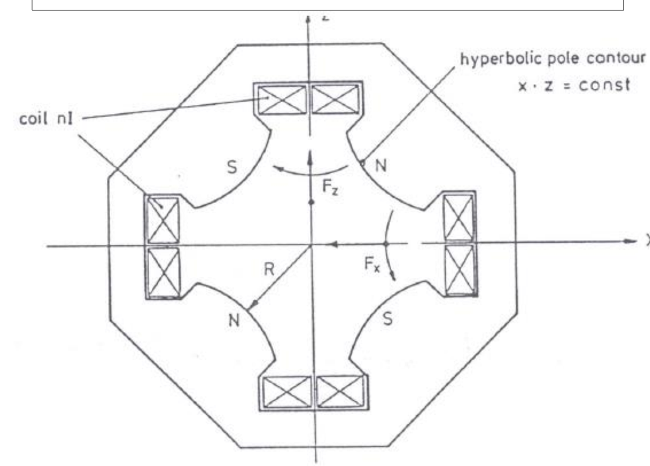
$$k = \frac{eg}{p}$$

A useful formula is: $k[m^{-2}] = 0.2998 \frac{g\,[T/m]}{p[GeV/c]}$

The focal length of the quadrupole can be is given by:

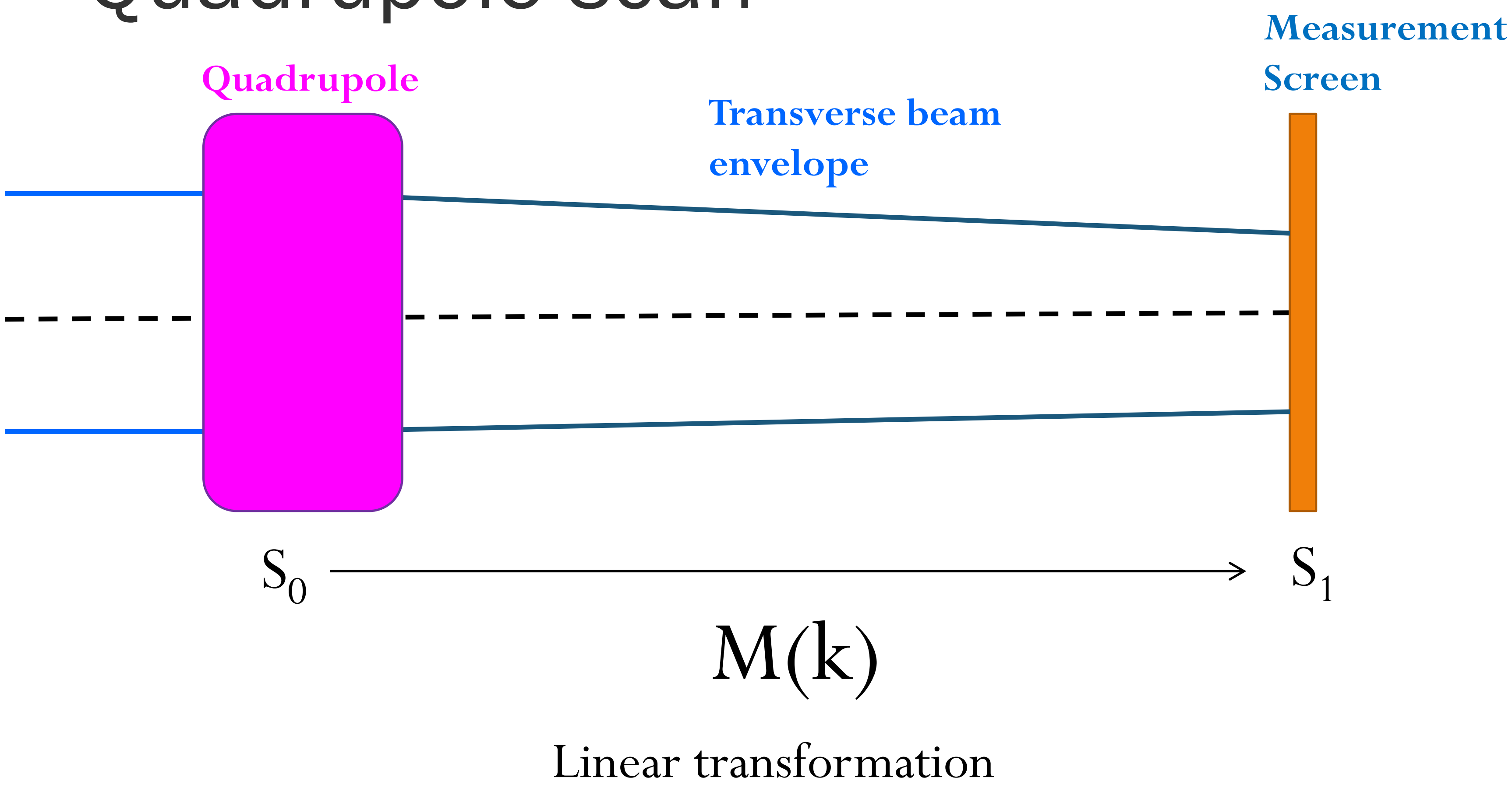
$$\frac{1}{f} = k \cdot l$$

Where l is the length of the quadrupole.

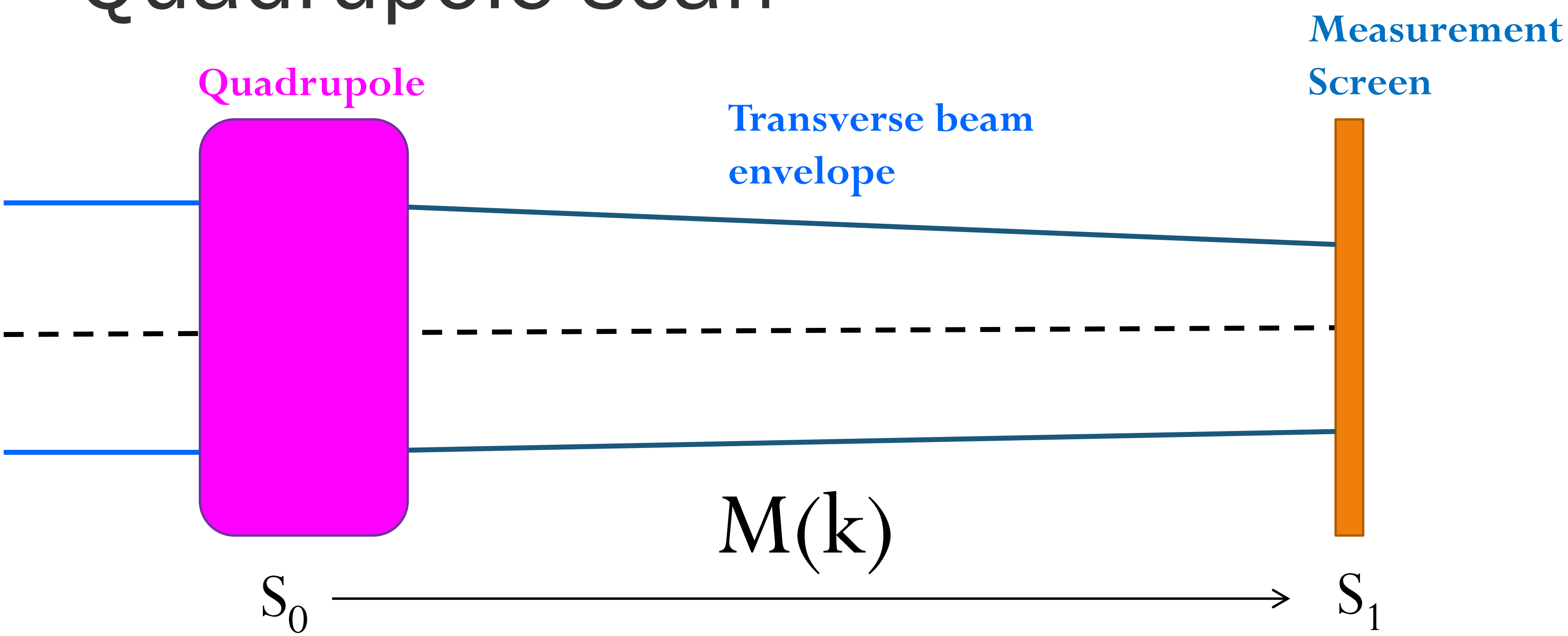


See CERN-optics notes, Rossbach

Quadrupole scan



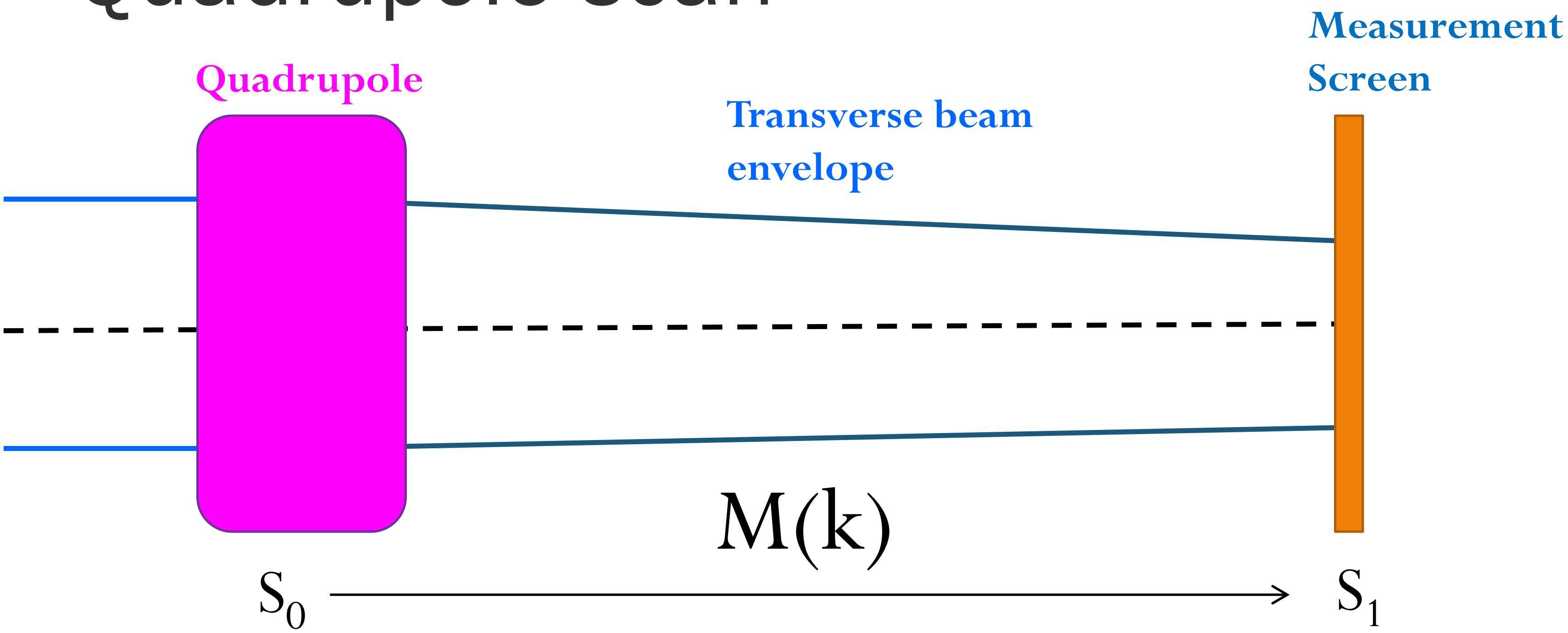
Quadrupole scan



Beam matrix @ s_0 (unknown)

$$\sigma(s_o) = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix}$$

Quadrupole scan



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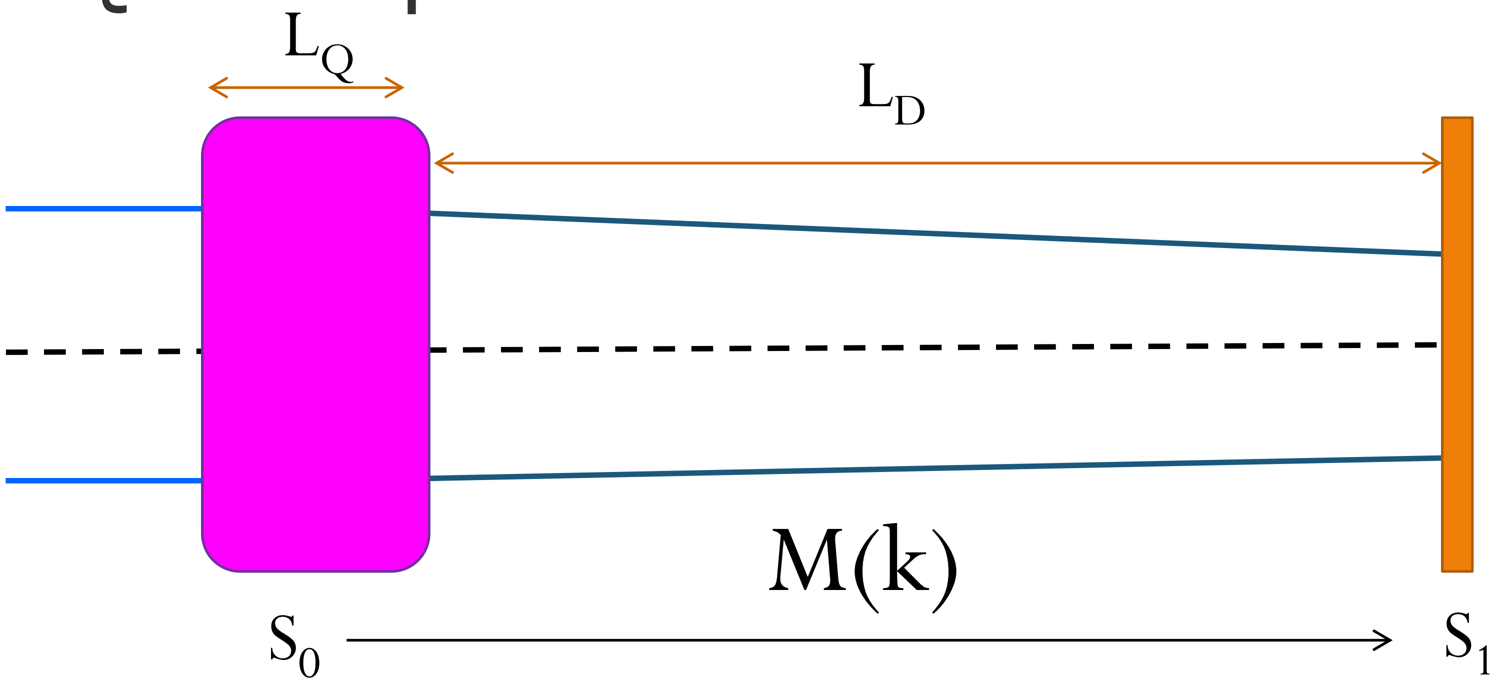
$$\boldsymbol{\sigma}(\boldsymbol{s_o}) = \begin{pmatrix} \langle \boldsymbol{x^2} \rangle & \langle \boldsymbol{xx'} \rangle \\ \langle \boldsymbol{xx'} \rangle & \langle \boldsymbol{x'^2} \rangle \end{pmatrix}$$

Beam matrix @ s_1 (measurement point)

$$\sigma(s_1) = M(k)\sigma(s_0)M^T(k)$$

Quadrupole scan

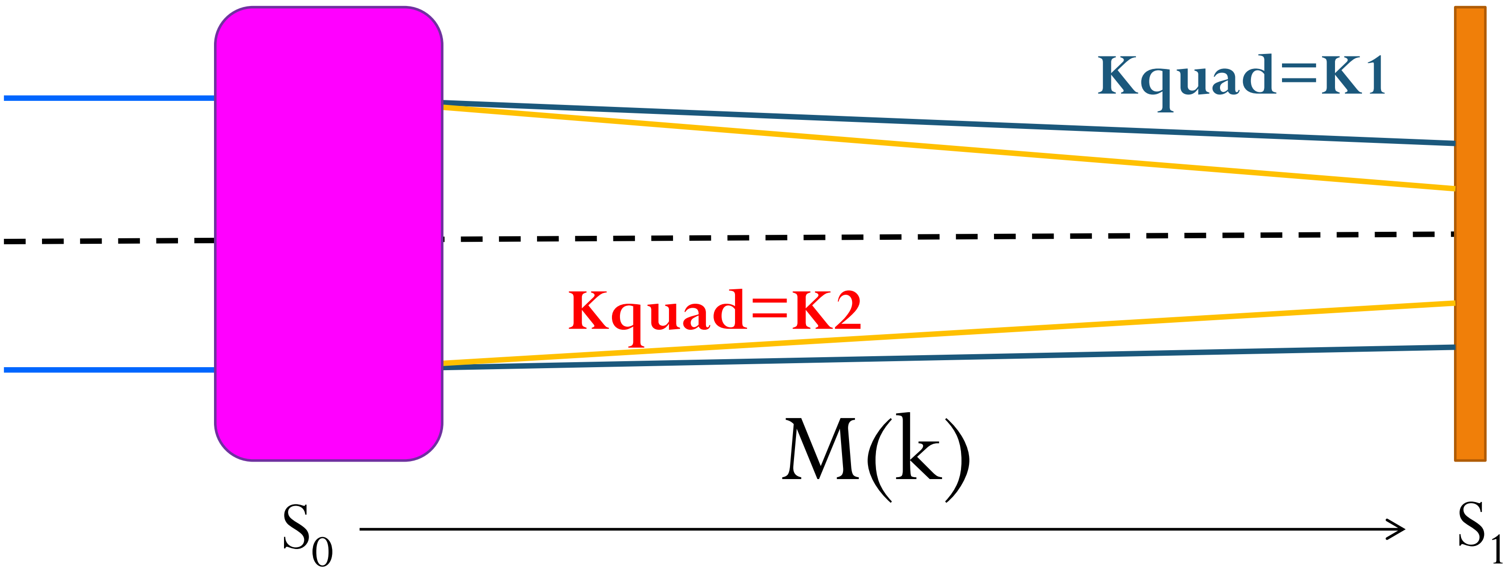


$$M_{quadrupole} = \begin{pmatrix} cos(\sqrt{k}L_Q) & 1/\sqrt{k}sin(\sqrt{k}L_Q) \\ -\sqrt{k}sin(\sqrt{k}L_Q) & cos(\sqrt{k}L_Q) \end{pmatrix}$$

$$M_{drift} = \begin{pmatrix} 1 & L_D \\ 0 & 1 \end{pmatrix}$$

$$M(k) = M_{drift} \cdot M_{quadrupole}(k)$$

Quadrupole scan



$$\sigma_{11}(1,k1) = {M_{11}}^2(k1)\sigma_{11}(0) + 2M_{11}(k1)M_{12}(k1)\sigma_{12}(0) + {M_{12}}^2(k1)\sigma_{22}(0)$$

$$\sigma_{11}(1,k2) = {M_{11}}^2(k2)\sigma_{11}(0) + 2M_{11}(k2)M_{12}(k1)\sigma_{12}(0) + {M_{12}}^2(k2)\sigma_{22}(0)$$

… etc.

Minimum 3 quadrupole strengths are necessary!

Limits of the quadrupole scan

- **Energy spread** produces unwanted emittance dilution due to **chromatic effects** of the quadrupoles (see PRSTAB 15 (2012) 082802)
- Small beamsize in the quadrupole helps damping this error
- For applications to plasma experiments, the quadrupole needs to be placed very close to the plasma chamber (e.g. distance < 50cm)

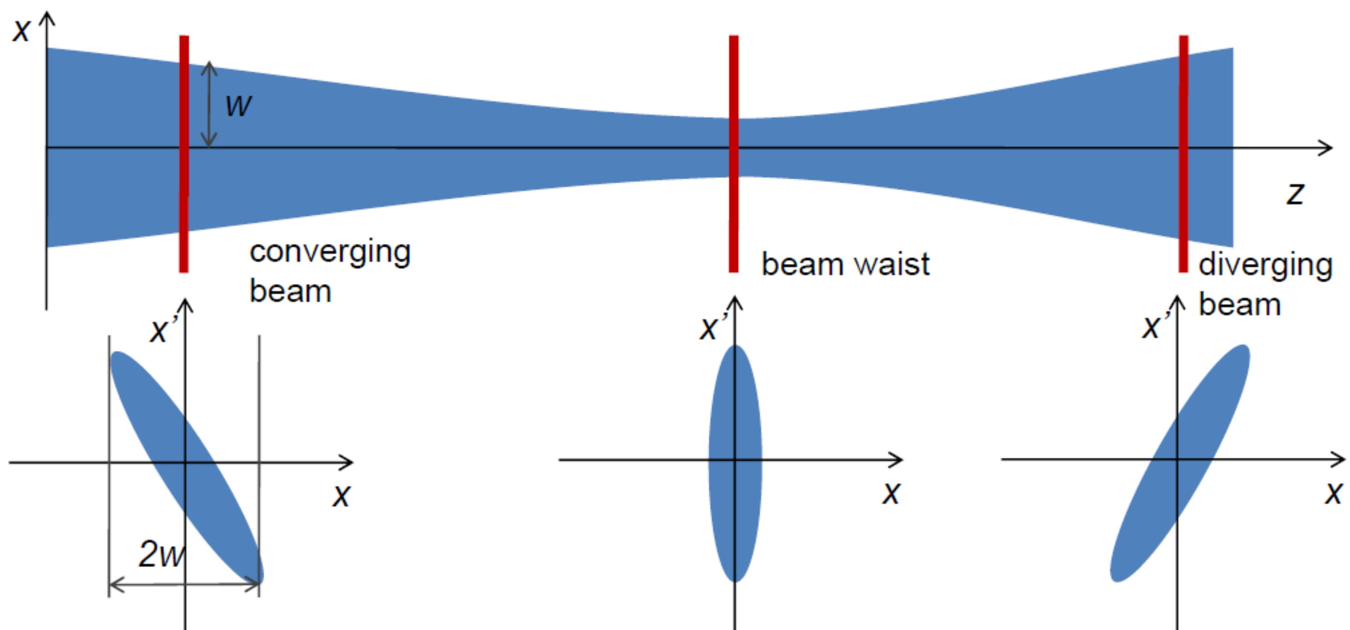
Multi-screen Measurements

Equivalent to the quadrupole scan:

- Instead of varying the current of the quadrupole, we collect images at different screen locations

Multi-screen Measurements

$$S_0 \xrightarrow{M_1} S_1$$



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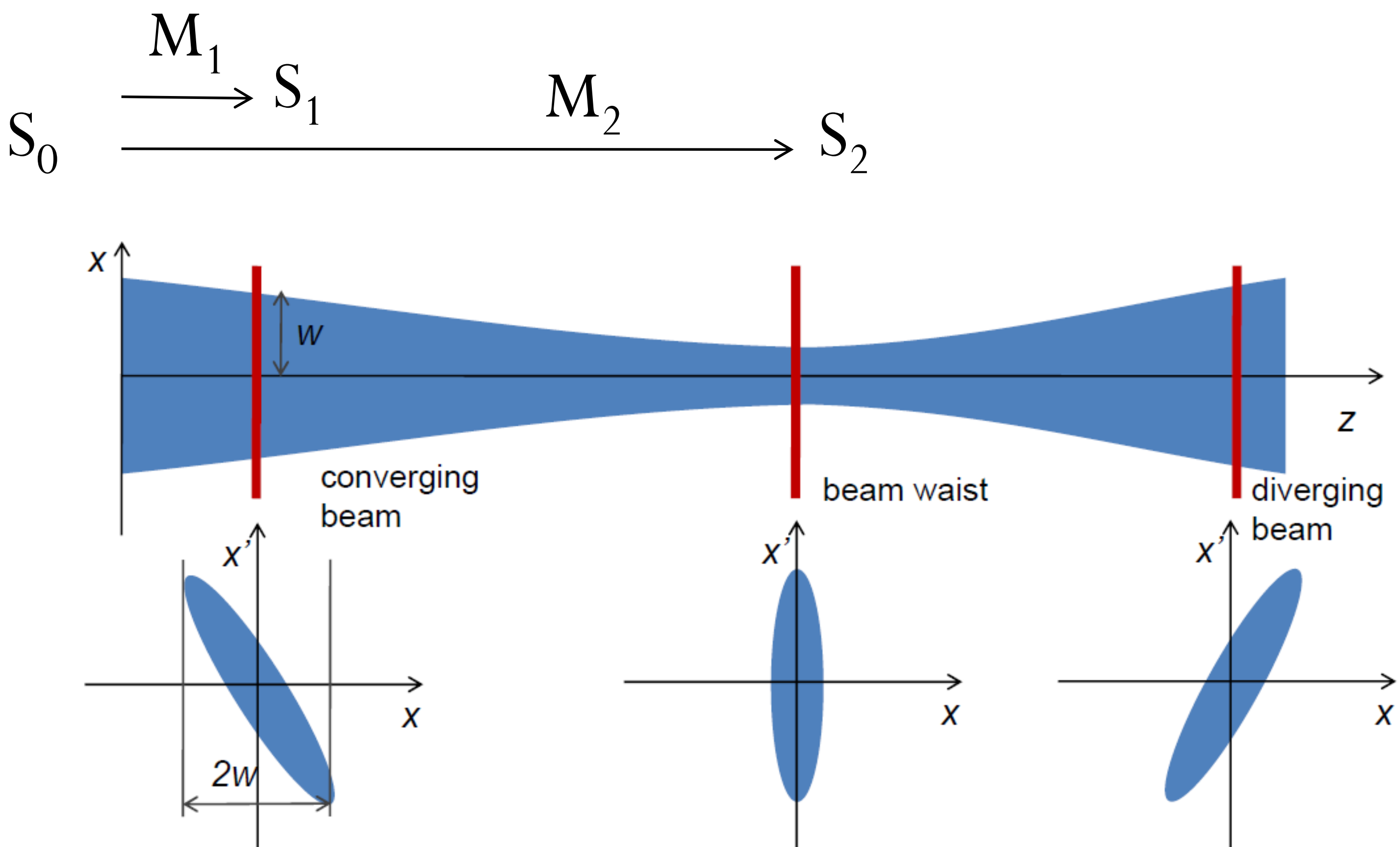

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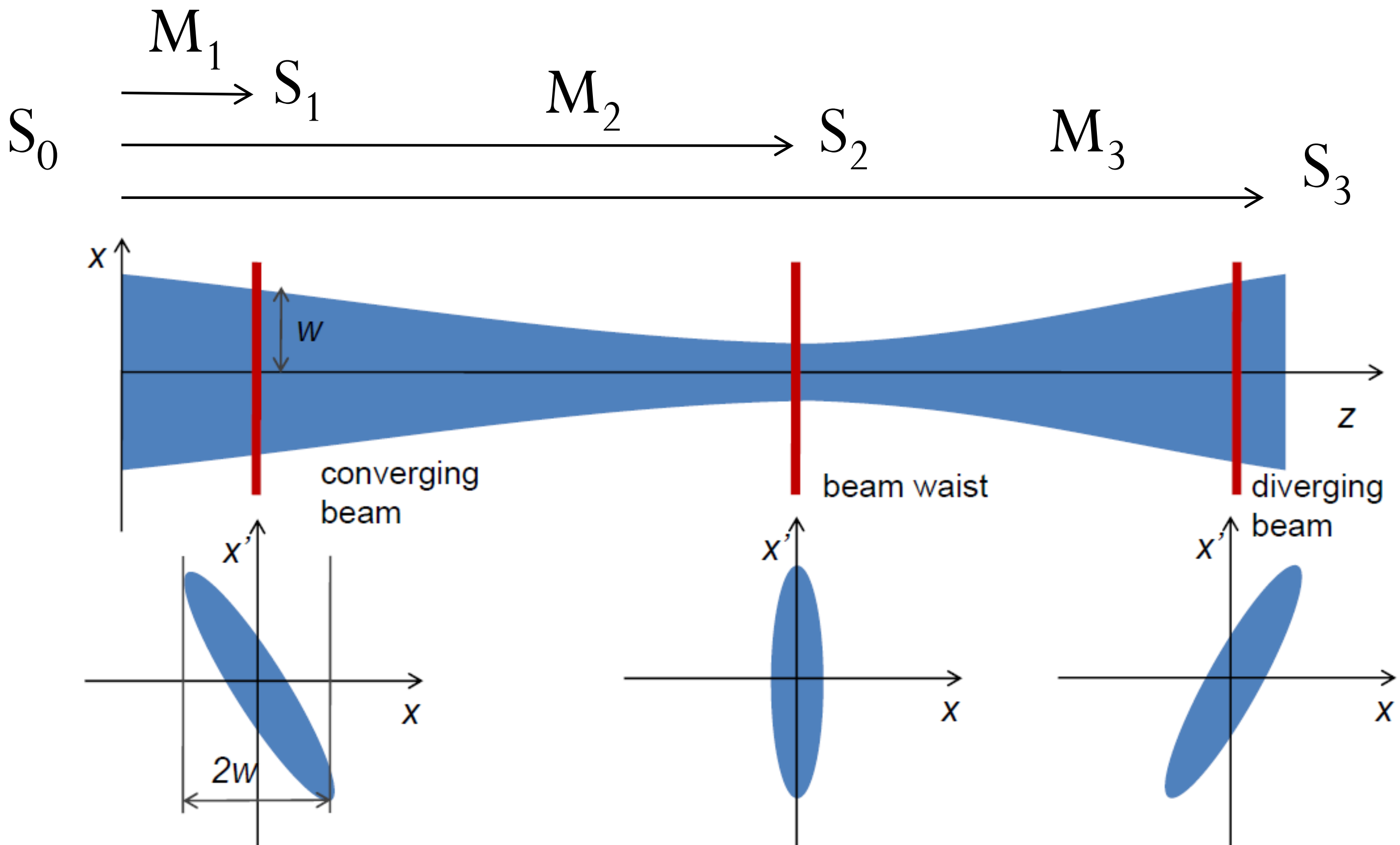

Equivalent to the quadrupole scan:

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Multi-screen Measurements

- Can be done online **using kickers** and selecting 1 bunch of the train

References:
•C. Gerth et al., doi:10.18429/JACoW-IBIC2017-TUPCC03, IBIC2017

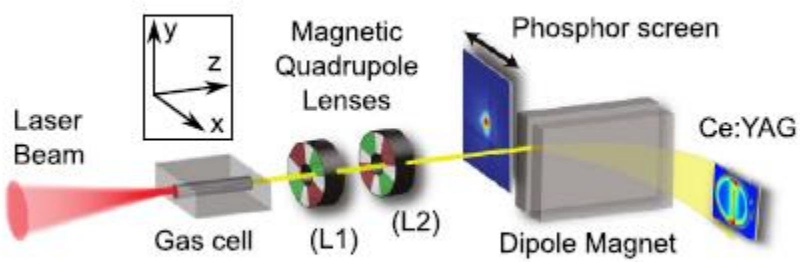
- Research ongoing for **single-shot measurements**:
  - Very interesting for plasma accelerators where **beam fluactuation** is present.
  - Uses thin (2-5 um Mylar) OTR screens.
  - OTR emission needs to be incoherent (long beams). For very short beams the method can be applied in region of the spectrum where the Transition Radiation is not coherent.
  - Scattering at the screen-locations has to be considered **(method usable only for high beam energies)**.

References:
•N. Delerue et al., „Single-shot emittance measurement using Optical Transition Radiation“, arXiv (2010);
•C. Thomas et al. 2011 JINST **6** P07004

Permanent quadrupole scan

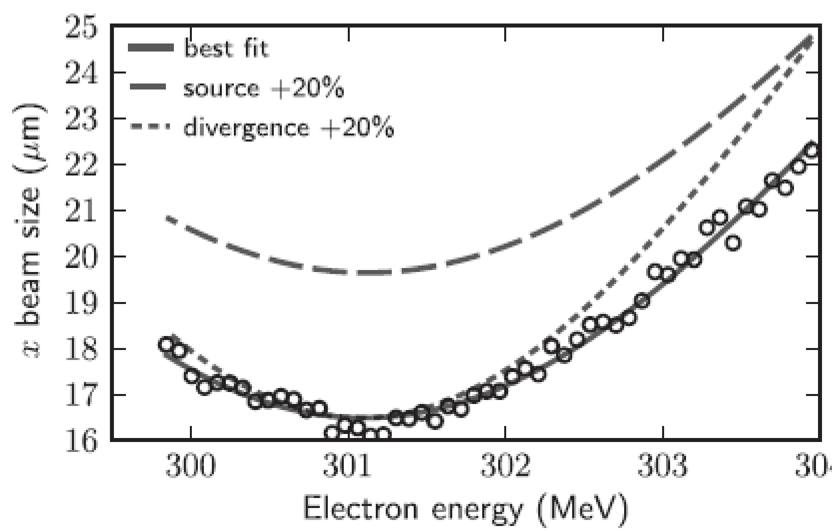
- $\sigma(s_1) = M(k)\sigma(s_0)M^T(k)$
- The quadrupole current is fixed but we vary the energy of the particles

$$k[m^{-2}] = 0.2998\frac{g\,[T/m]}{p[GeV/c]}$$



R. Weingartner et al. 15, 111302 (2012)

$$\sigma(s_1)^2 = M_{11}^2\epsilon\beta(s_0) - 2M_{11}M_{12}\epsilon\alpha(s_0) + M_{12}^2\epsilon\gamma(s_0).$$



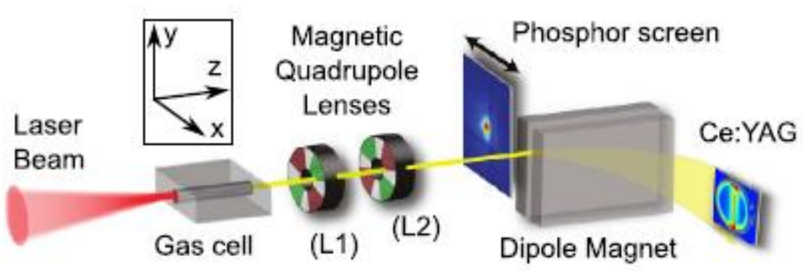
See also:

Barber, S. K., et al., Physical Review Letters 119.10 (2017): 104801.

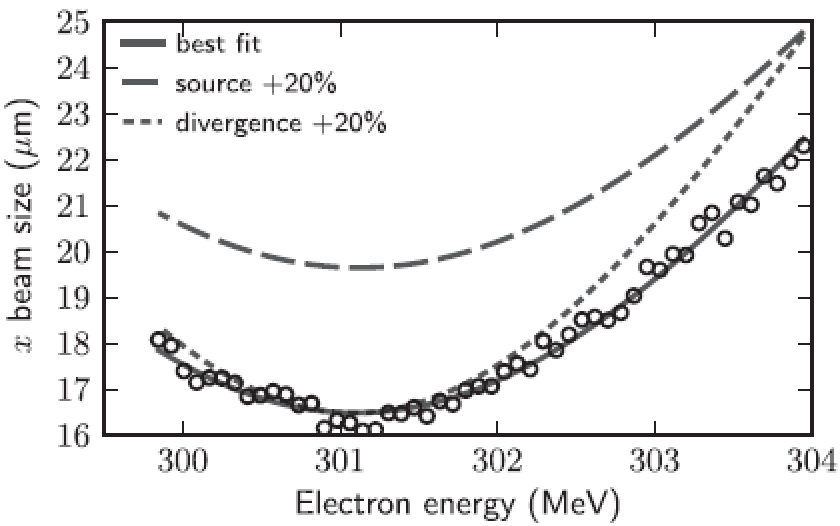
F Li et al 2018 Plasma Phys. Control. Fusion 60 014029

Permanent quadrupole scan

- Assumes that there is **<u>no correlation emittance-energy</u>** within the beam
- Method intrinsically limited to **<u>high-energy spread beams</u>**



R. Weingartner et al. 15, 111302 (2012)



See also:

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Comparison emittance measurement techniques

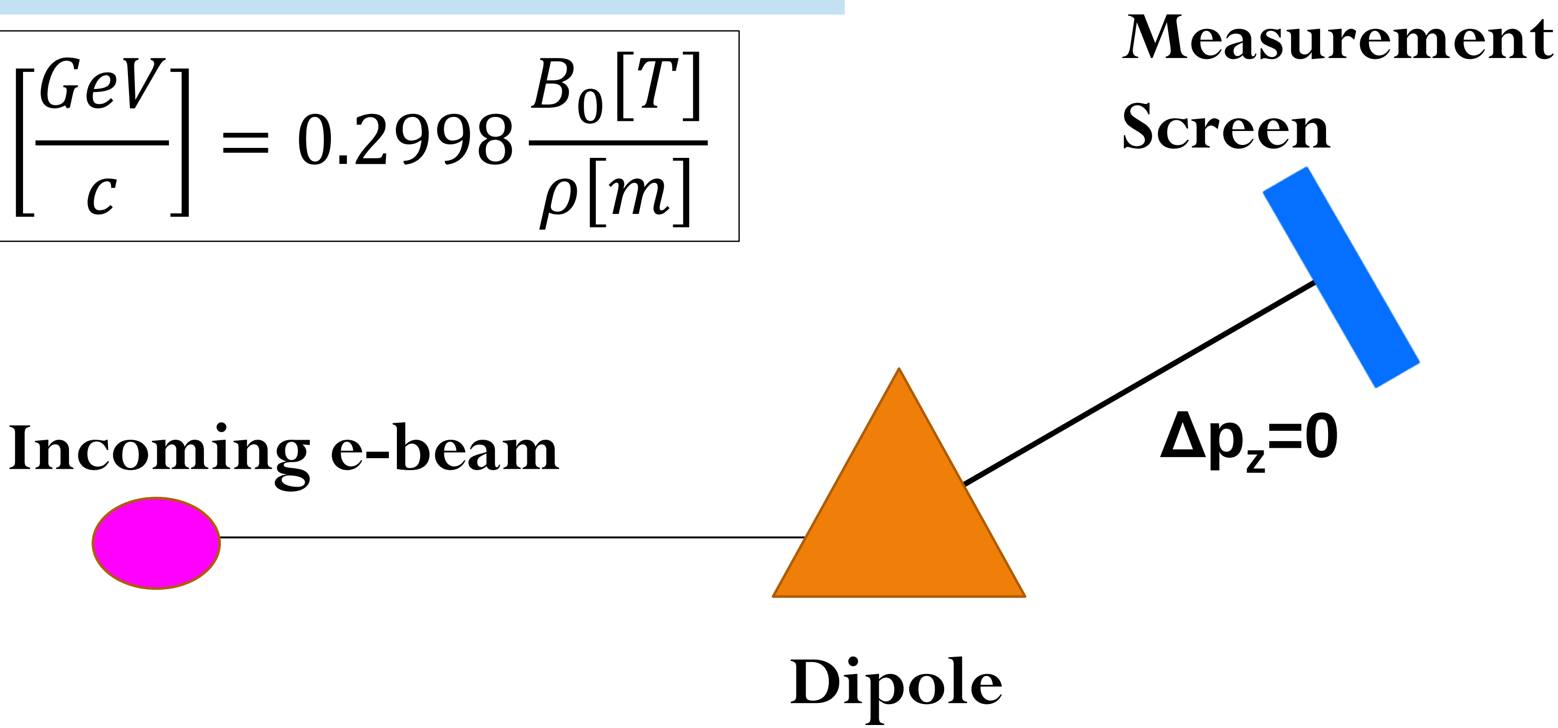
	Destructive?	Single-shot?	Space Charge resistent?	Energy	Large energy spread resistent?	Possible with charge lower than 2pC ?
Slit-scan	Yes	No	Yes	Low	Yes	No
Pepperpot	Yes	Yes	Yes	Low/ High (new dev.)	Yes	No
TEM grid	Yes	Yes	No	Low	Yes	Yes
Quadrupole scan	Yes	No	No	High	No	Yes
Multi-screens Measurement	Yes/No (new dev.)	No/Yes (new dev.)	No	High	No	Yes/No (new dev.)
Permanent quadrupole scan scan + Spectrometer	Yes	Yes	No	High	Yes if uncorrelated with emittance; low E-spread is a problem	Yes

Longitudinal Phase-Space Characterization

Energy and Energy spread measurements

Central momentum of the beam:

$$p_c\left[\frac{GeV}{c}\right] = 0.2998\,\frac{B_0[T]}{\rho[m]}$$



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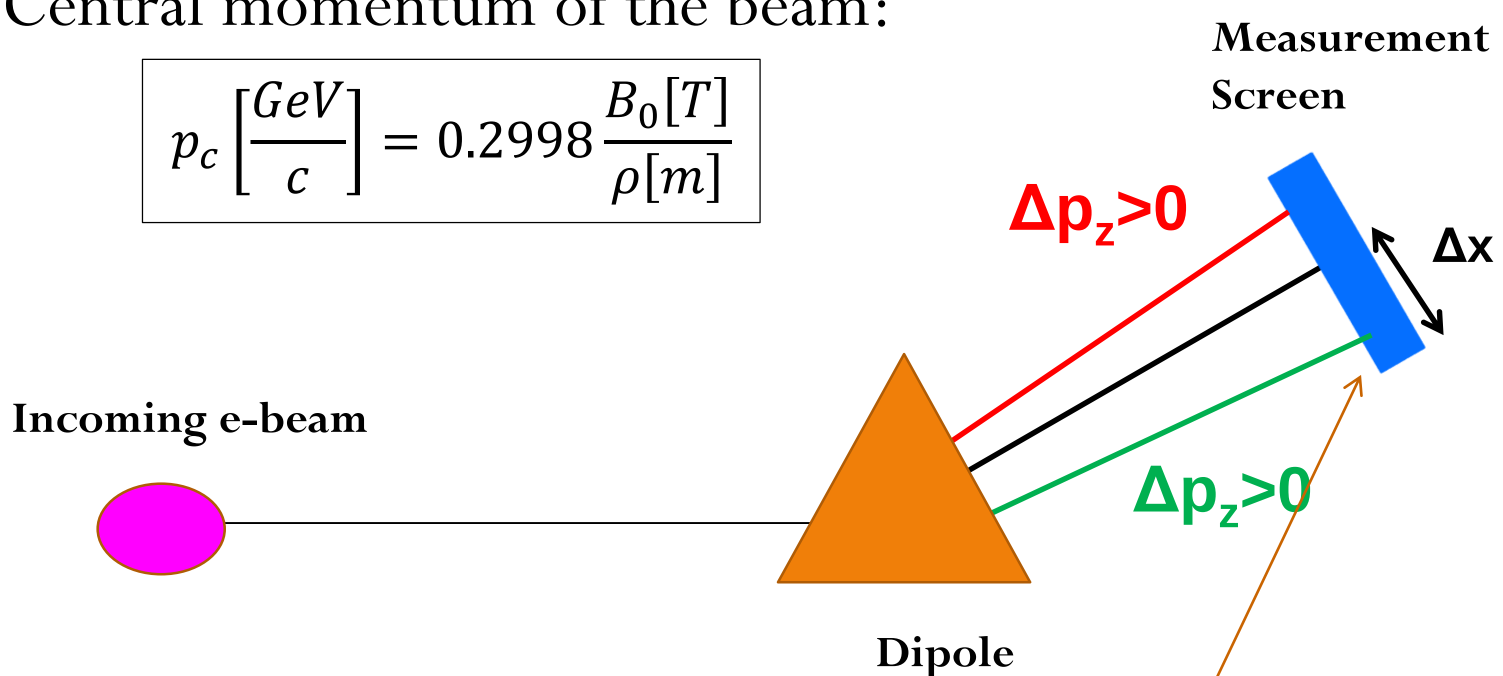

Momentum of the off-energy electrons

$$p_d = p_c\left(1 + \frac{\Delta x}{D_x}\right)$$

Dispersion function

Energy and Energy spread measurements

Beam size @ measurement screen:

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + {D_x}^2 {\sigma_\delta}^2}$$

Betatron oscillations

Dispersive contribution

The **resolution** of the measurement is * :

$$\sigma_{E,res} = 2 \frac{\sqrt{\varepsilon_x \beta_x}}{D_x} \langle E \rangle$$

* See "Particle Accelerator Physics", H. Wiedemann

Bunch length measurements

- Direct particle techniques:
  - RF-Booster + spectrometer
  - RF-Deflectors

- Radiative Techniques
  - CTR, CDR, CSR
  - Undulator radiation
  - Optical Replica
  - Electro-Optical Sampling

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  - RF-Deflectors

- Radiative Techniques
  - CTR, CDR, CSR
  - Undulator radiation
  - Optical Replica
  - Electro-Optical Sampling

Transverse Deflection Structures (or RF-Deflectors)

Working Principle:

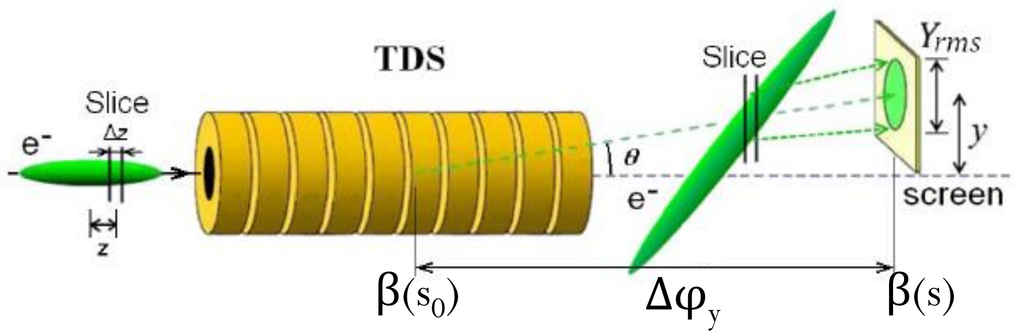


Fig. Credits: D. Malyutin PhD thesis

The longitudinal distribution of the e-bunch is mapped into the transverse one thanks to the time dependent transversely deflecting field

Transverse Deflection Structures (or RF-Deflectors)

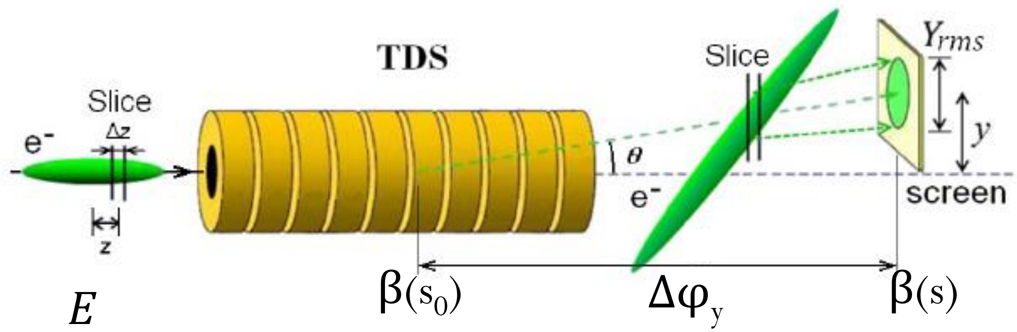


Fig. Credits: D. Malyutin PhD thesis

Resolution:

$$R_t = \frac{\sigma_{y,off}}{S_{y,t}} = \frac{\sqrt{\varepsilon_y \beta_y(s)}}{\sqrt{\beta_y(s)\beta_y(s_0)}sin(\Delta\varphi_y)}\frac{E}{\omega e V_0}$$

e-bunch:

- Kinetic Energy E
- Vertical geometric emittance ε_y

Magnetic Lattice:

- Phase advance in y plane $\Delta\varphi_y$
- Beta function in the TDS $\beta_y(s_0)$

RF cavity:

- Frequency $f = \omega/(2\pi)$
- Peak deflection voltage V_y

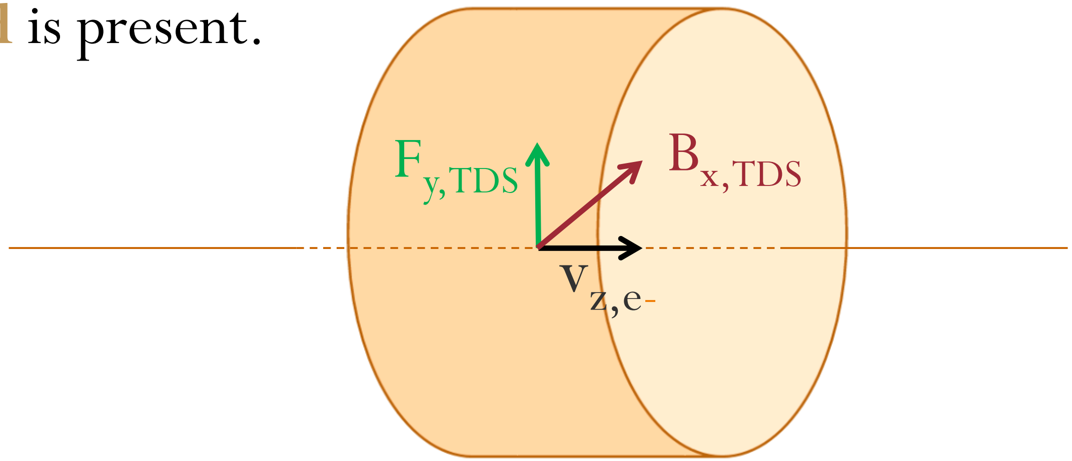
In this example streaking on y plane.

Frequency **~12GHz (X-band)** allows having 4 times higher resolution than **~3GHz (S-band)**

Cfr: P. Emma et al., LCLS-TN-00-12
M. Röhrs et. al., PRSTAB 12 050704 (2009)

Ultimate limitation of time-resolution

- The **Panofsky-Wenzel theorem** states that **transverse deflection** is only **possible** if a **transverse gradient of the longitudinal electric field** is present.



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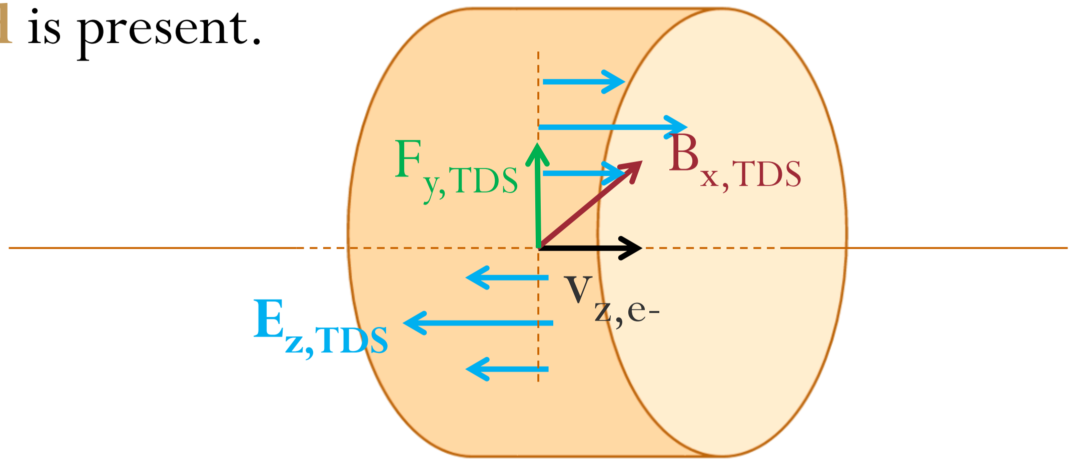

- The particles traveling **off axes** in the cavity are **accelerated** or **decelerated**.
- The TDS induces an increase of the **energy spread** (both uncorrelated and correlated ones).

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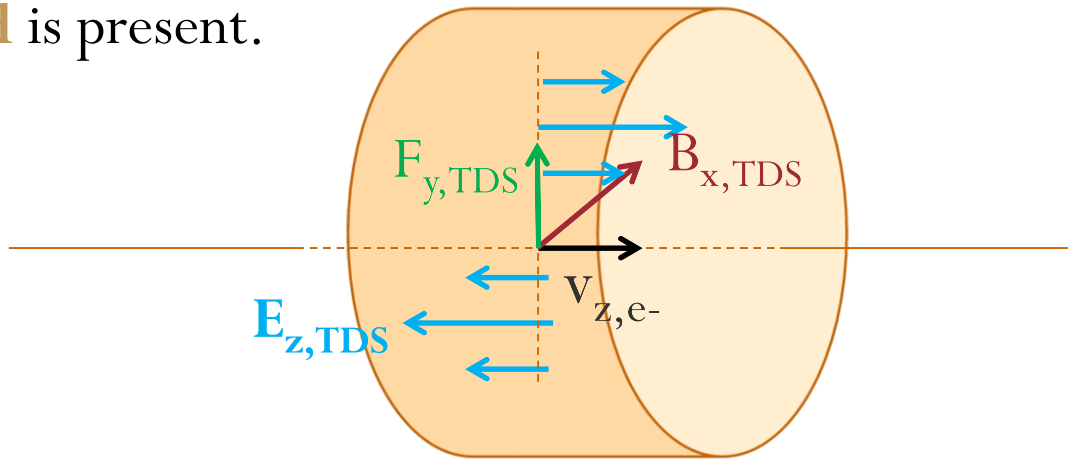


- The particles traveling off axes in the cavity are accelerated or decelerated.
- The TDS induces an increase of the energy spread (both uncorrelated and correlated ones).
  - The **uncorrelated energy spread increase** can be expressed as:

$$\Delta E[keV] = 511 * \frac{\varepsilon_n}{\sin(\Delta\varphi_y) R[m]}$$

→ **It is Resolution dependent!**

TDS Capabilities

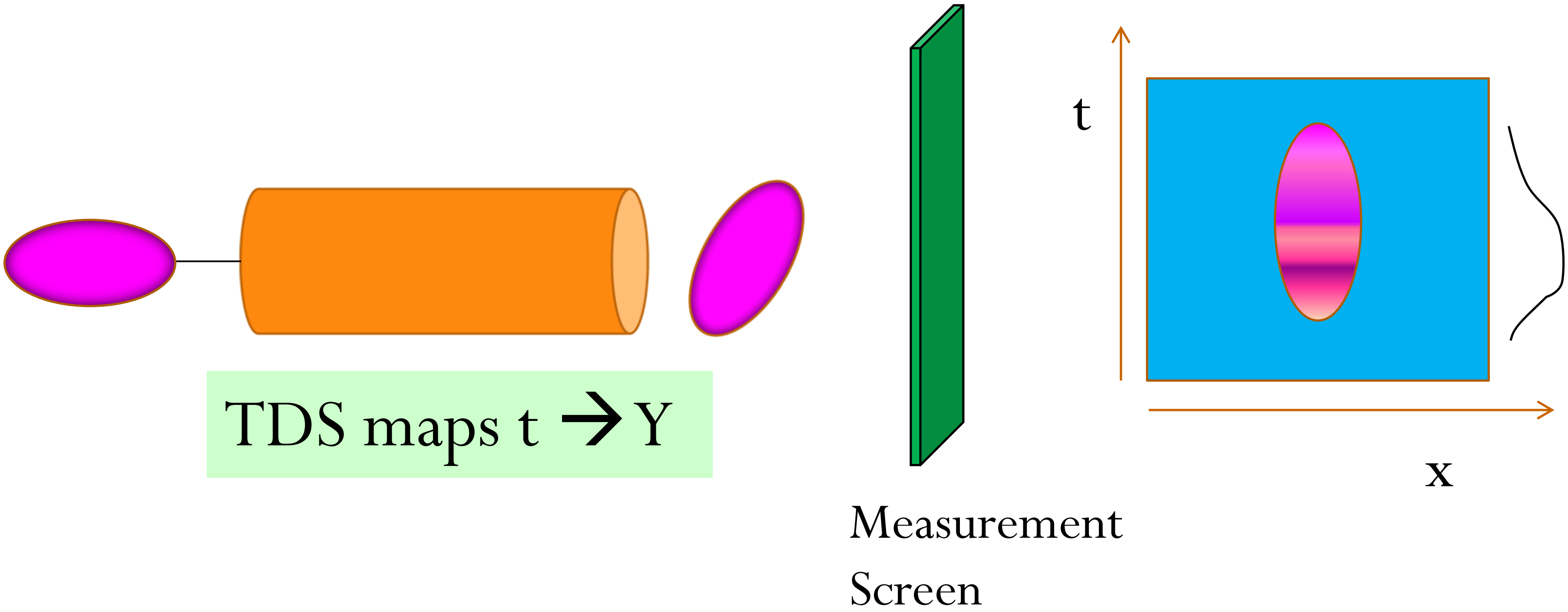
Nevertheless TDSs allow a comprehensive characterization of the e-bunch !

TDS Capabilities

TDSs allow a comprehensive characterization of the e-bunch !

- **Bunch length** measurement
- **Longitudinal charge profile** measurement

Longitudinal current profile Measurement

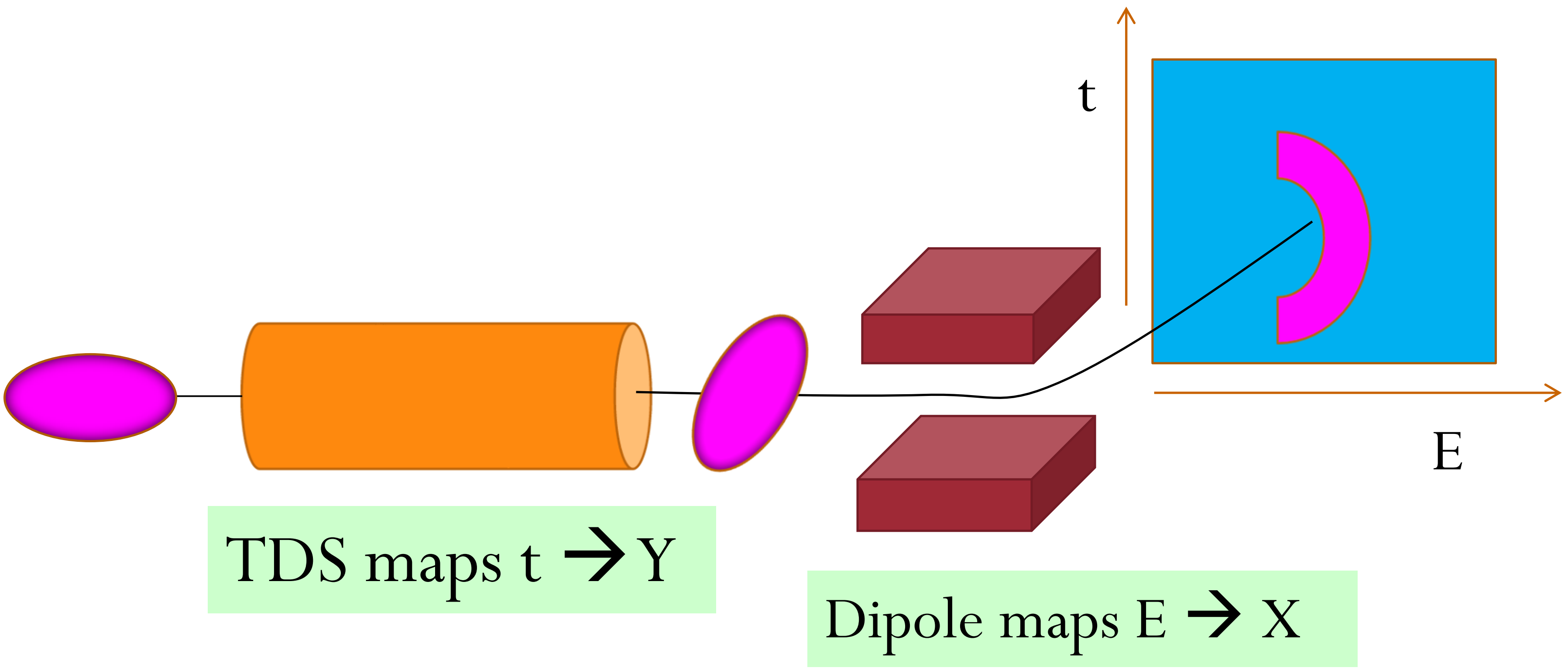


TDS Capabilities

TDSs allow a comprehensive characterization of the e-bunch

- **Bunch length** measurement
- **Longitudinal charge profile** measurement
- Combined with dipole → **longitudinal phase space** measurement

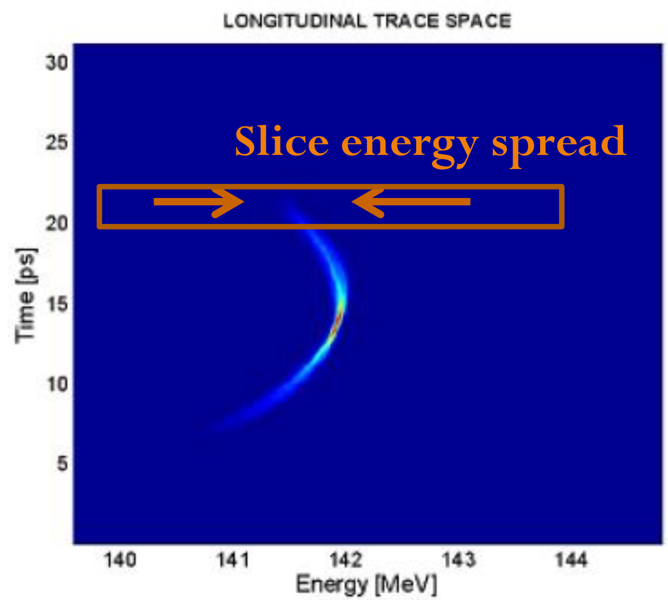
Longitudinal phase space Measurement

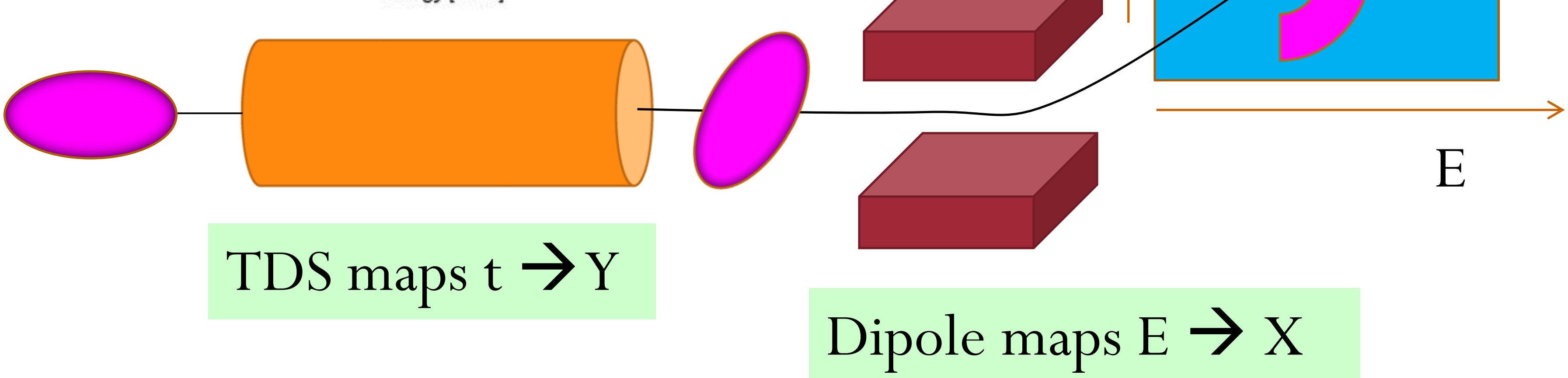


Longitudinal phase space Measurement

Example, measurement at SPARC
See MO6RFP096 PAC2009

→ Energy spread induced by TDS must be subtracted!



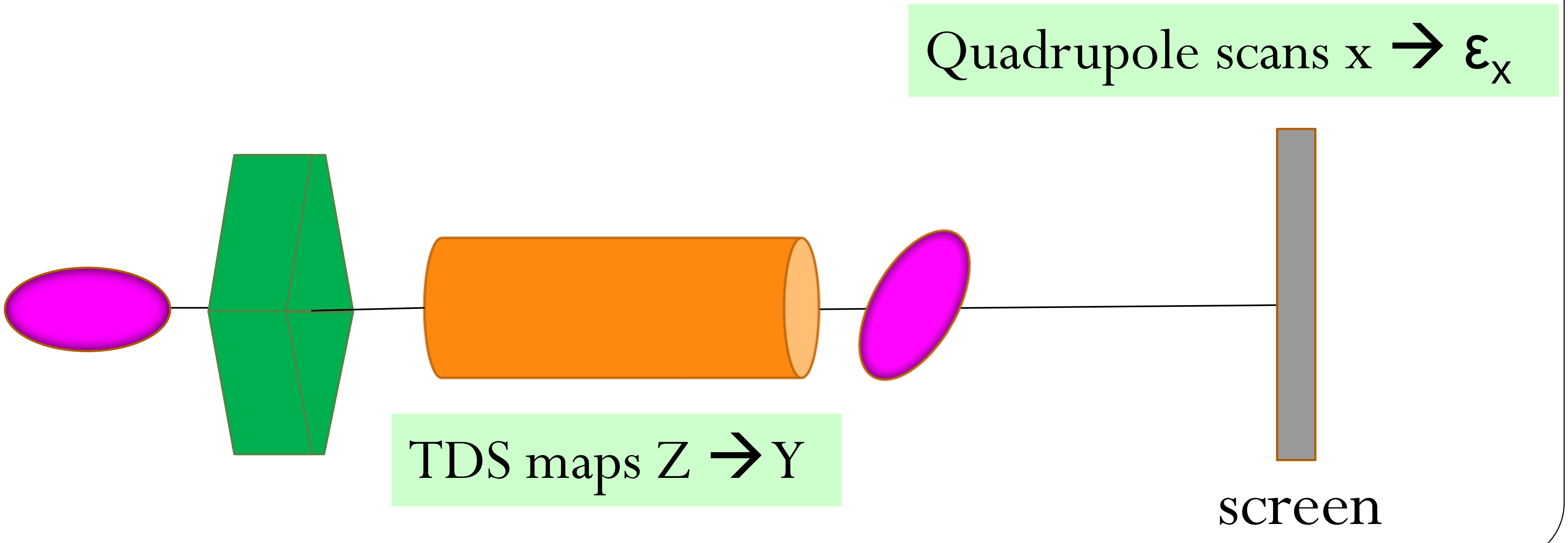


TDS Capabilities

TDSs allow a comprehensive characterization of the e-bunch

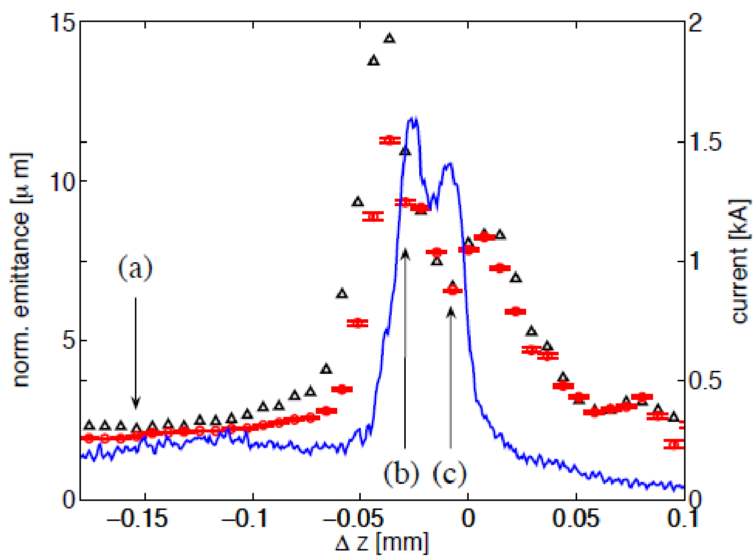
- **Bunch length** measurement
- **Longitudinal charge profile** measurement
- Combined with dipole → **longitudinal phase space** measurement
- Combined with quadrupole scan or multi-screen lattice → **slice emittance** measurement on the plane perpendicular to the streaking direction, **slice transverse phase space** reconstruction

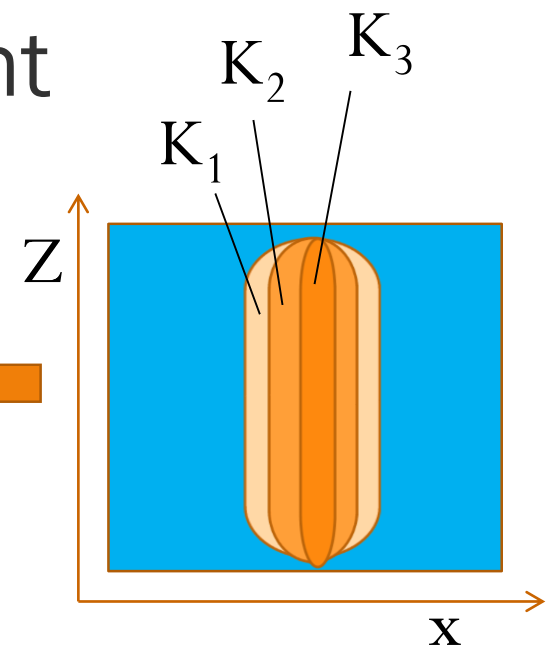
Slice Emittance Measurement



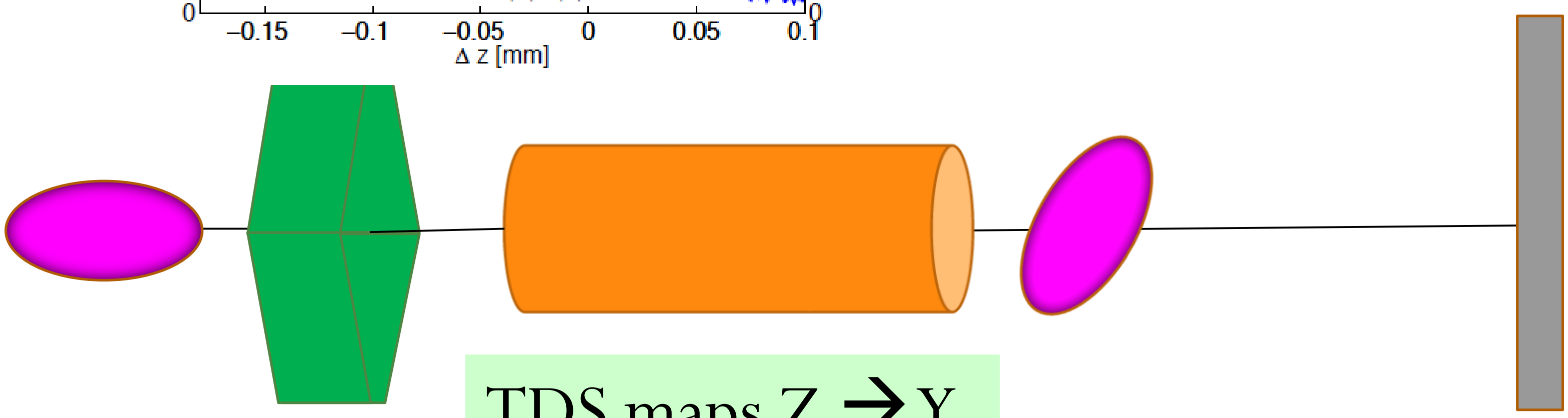
Slice Emittance Measurement

Example, measurement at FLASH
See MOOBAB01 PAC2007





Quadrupole scans x → ε_x



TDS maps Z → Y

screen

TDS Capabilities

TDSs allow a comprehensive characterization of the e-bunch

- **Bunch length** measurement
- **Longitudinal charge profile** measurement
- Combined with dipole → **longitudinal phase space** measurement
- Combined with quadrupole scan or multi-screen lattice → **slice emittance** measurement on the plane perpendicular to the streaking direction, **slice transverse phase space** reconstruction
- **Method capable of fs and sub-fs longitudinal resolution**

Cfr:

- C. Behrens *et al.*, Nat. Commun. **5**, 3762 (2014)
- J. Maxons *et al.*, PRL **118**, 154802 (2017)

Bunch length measurements

- Direct particle techniques:
  - RF-Booster + spectrometer
  - RF-Deflectors

- Radiative Techniques
  - CTR, CDR, CSR
  - Undulator radiation
  - Optical Replica
  - Electro-Optical Sampling

“Recipe” for methods using coherent radiation

- Realize conditions such as the e-bunch emits coherent radiation (see next slides)
- The spectrum of the emitted radiation is measured
  - Correction of the measured spectrum including imperfections of the optical-transport-line (e.g. transmission of vacuum windows, detector response, etc.)
- Retrieve the longitudinal distribution of the beam from the computed radiation spectrum at the source location:
  - Analysis of the Form Factor function (Fourier transformation + phase retrieval)
  - Assumptions concerning the beam distribution need to be made

Many types of radiation can be used:

- **Transition Radiation (TR)** – emitted by a charged particle which crosses the boundary between two media with different refractive index
- **Diffraction Radiation (DR)** – emitted by a charged particle which moves in the vicinity of a conducting screen.
- **Synchrotron Radiation (SR)** – emitted by a charged particle which bends in a magnetic field.
- **Smith-Purcell Radiation** - emitted from the surface of a periodic metallic structure (a grating) when a charged particle beam is travelling past the grating.
- **Undulator radiation** – emitted by a charged particle traveling in an undulator
- **Cherenkov radiation** - emitted by a charged particle which passes through a dielectric medium at a speed greater than the phase velocity of light in that medium.
- …

Why do we need Coherent Radiation Emission?

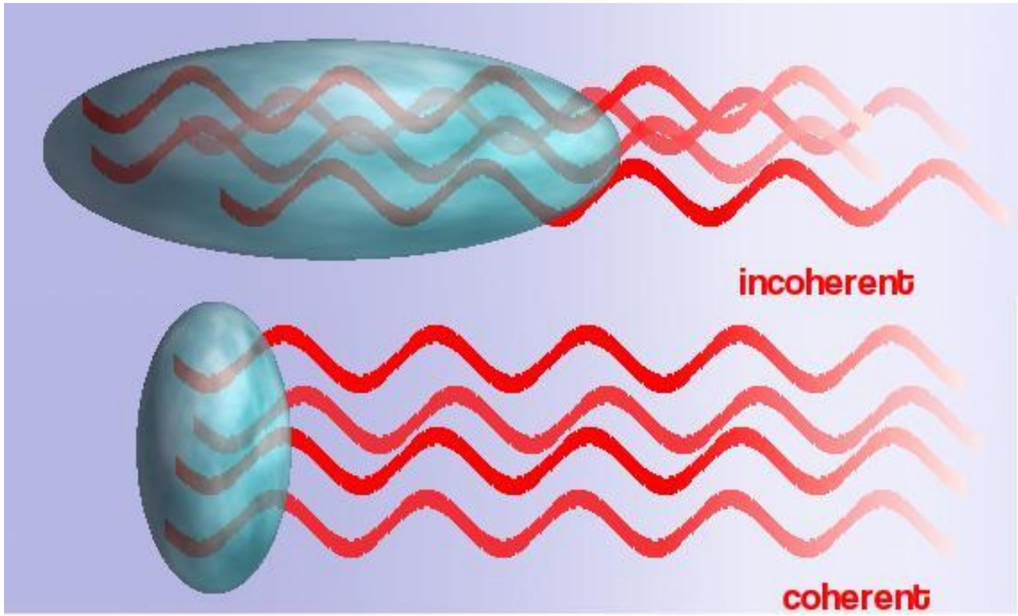
The spectral energy density emitted by a bunch of electrons is given by:

$$\frac{d^2U_b}{d\lambda d\Omega} = \left(\frac{d^2U_{sp}}{d\lambda d\Omega}\right)\left[N + N(N-1)\,|F\,(\lambda,\Omega)|^2\right]$$

Spectrum of the single particle

Incoherent emission

Coherent emission



Particles emit coherent radiation only at wavelengths which are **longer than the bunch dimensions** (longitudinal and transverse)!

Coherent Radiation Emission

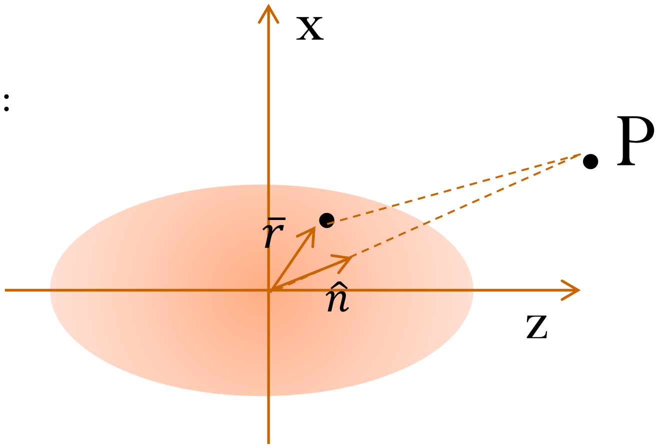
The spectral energy density emitted by a bunch of electrons is given by:

$$\frac{d^2U_b}{d\lambda d\Omega} = \left(\frac{d^2U_{sp}}{d\lambda d\Omega}\right)\left[N + N(N-1)\,|F\,(\lambda,\Omega)|^2\right]$$

- $\frac{d^2U_{sp}}{d\lambda d\Omega}$ is the **spectrum of the single particle** (depends on the source type!)
- N is the number of particles
- $F\,(\lambda,\Omega)$ is the **3D Form Factor of the bunch**, defined as:

$$F(\lambda,\Omega) = \int \boldsymbol{S_{3D}}(\bar{\boldsymbol{r}})e^{-i\overline{k\cdot\bar{r}}}d\bar{r}$$

3D normalized particle density distribution



$$\bar{k} = \frac{2\pi}{\lambda}\bar{n}$$

Reference:E. Hass et al.," Proc. SPIE 8778, Advances in X-ray Free-Electron Lasers II: Instrumentation, 87780M (3 May 2013); doi: 10.1117/12.2021531

Coherent Radiation Emission

- $F\ (\lambda, \Omega)$ is the **3D Form Factor** of the bunch, defined as:

$$F(\lambda, \Omega) = \int S_{3D}(\bar{r}) e^{-i\overline{k \cdot \bar{r}}} d\bar{r}$$

- If longitudinal and transverse charge distributions are uncorrelated :

$$F(\lambda, \Omega) = F_L(\lambda, \Omega) F_T(\lambda, \Omega)$$

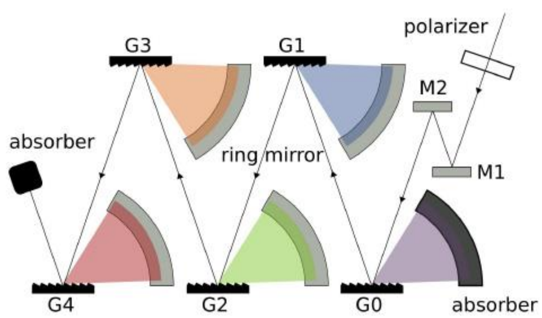
- If:
  - $\gamma \gg 1$, i.e. the radiation is confined in a narrow cone in the forward direction
  - Small observation angle

$$F(\lambda, \Omega) \approx F_L(\lambda, \Omega) = \int_{-\infty}^{+\infty} S(z) e^{-i\frac{2\pi}{\lambda}z}\, dz$$

or $\boldsymbol{F_L(\omega) = \int_{-\infty}^{+\infty} S(t) e^{-i\omega t}\, dt}$ **Longitudinal Form Factor**

Uncertainty in the profile reconstruction

- The **range of the measured spectrum** has to be as large as possible (it has to cover all the main features of the bunch profile)
  - See e.g. TESLA FEL 2006-03
- It is possible to measure directly only the **amplitude of the Form Factor** but its phase remains unknown
- The „**Kramers-Kronig relation***“ retrieves only the „minimum“ phase → the bunch shape with the least complex substructure compatible with the radiation spectrum.



Example of experimental setup for single-shot measurements:

- FLASH CTR spectrometer – see E. Hass et al. Proc. SPIE 8778 May 2013
- Similar concepts applied at HZDR ELBE facility and at SLAC LCLS.

*R. Lai and A. J. Sievers, Nucl. Instruments Methods Phys. Res. Sect. A 397, 221 (1997).

Electro-Optic profile diagnostics

Principle: Convert Coulomb field of the e-bunch into a variation of optical intensity

- The bunch passes close to an electro-optical crystal (ZnTe or GaP)
- Its Coulomb field induces a change in the refractive index of the crystal (Pockels effect)
- The information about the longitudinal profile is encoded in a refractive index change which can be converted into an intensity variation by means of a laser together with polarizers

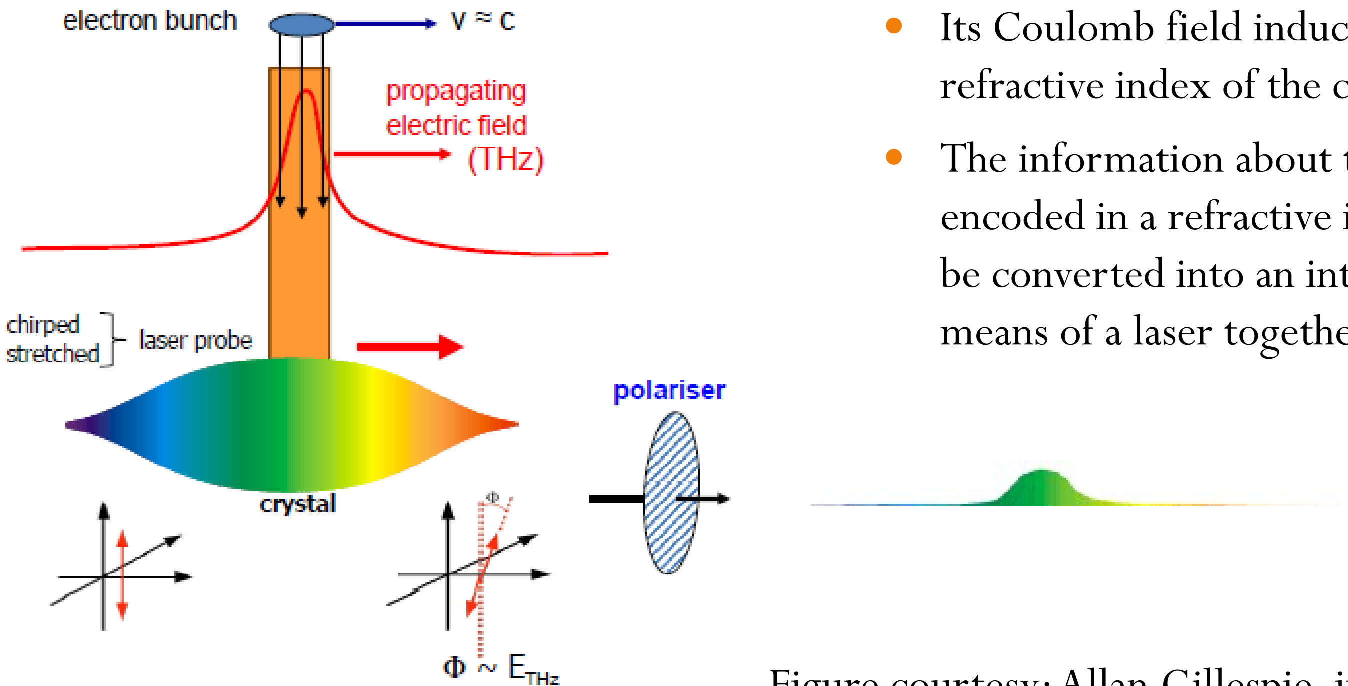
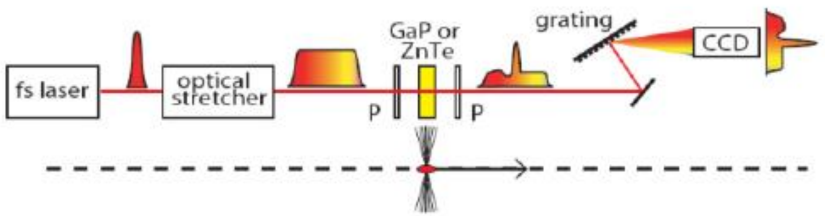


Figure courtesy: Allan Gillespie, invited talk IPAC 2015

Different kinds of encoding

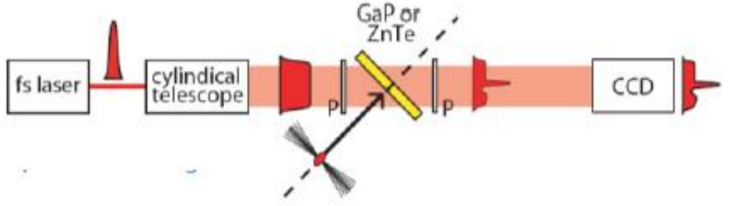
See: Allan Gillespie, invited talk IPAC 2015

Spectral Decoding



See e.g. :
Design of an electro-optic bunch length monitor for the CERN-CTF3 probe beam, R. Pan, et al. Physical Review STAB (2012)

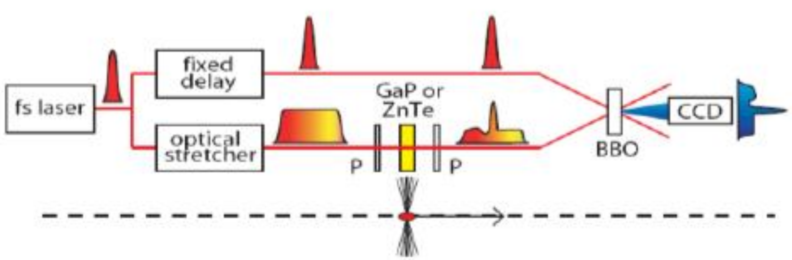
Spatial Encoding



See e.g.:

- A.L.Cavalieri et al, Phys. Rev. Lett. 94, 114801 (2005)
- First single-shot and non-intercepting longitudinal bunch diagnostics for comb-like beam by means of electro-optic sampling. R Pompili, et al , NIM A, 740:216–221, 2014.

Temporal Decoding



See e.g.
Electro-optic time profile monitors for femtosecond electron bunches at the soft x-ray free-electron laser FLASH, B. Steffen et al., Physical Review STAB 12, 032802:1-16 (2009)

Comparison bunch length measurement techniques

	Destructive?	Single-shot?	Ultimate Resolution	Additional Comments
RF-deflector, TDS	Yes	Yes (after calibration)	**Sub-fs** but non-negligible perturbation of energy-spread	• Possible for sub-pC charge • Most expensive • Provides detailed information about the longitudinal charge distribution and slice parameters
Coherent Radiation	Depending on the radiation type used	Only if the measurement of the spectrum of the radiation is single shot	So far **~ 20fs**, not intrinsically limited	• Difficult for low charges • Very good for online tuning of the machine
EOS	No	Yes	So far **~ 40fs**, limited by material of the crystal (limited bandwidth)	• Can be used also as arrival time monitor