High Brilliance Beam Diagnostic

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Outline

- Brightness and Brilliance
- Fundamental parameters
- Transverse and longitudinal measurements
- Intercepting and non intercepting diagnostic

Brightness and Brilliance

- Several authors give different definitions
- Brilliance is sometimes used, especially in Europe, instead of brightness
- There is also confusion because the same words apply both to particle beams and photon beams
- The best way is to look to units, which should be unambiguous

Some references

- C. Lejeune and J. Aubert, "Emittance and Brightness, definitions and measurements", Adv. Electron. Electron Phys.,Suppl. A **13**, 159 (1980).
- A. Wu Chao, M. Tigner "Handbook of Accelerator Physics and Engineering" *World Scientific, pag 255*
- C. A. Brau "What Brightness means" in The Physics and Applications of High Brightness Electron Beam", *World Scientific, pag 20*
- *M. Reiser, "Theory and design of charged particle beams", Wiley-VCH, pag 61*
- Shyh-Yuan Lee, "Accelerator Physics", *World Scientific, pag 419*
- J. Clarke "The Science and Technology of Undulators and Wiggles" *Oxford Science Publications, pag 73*

Definitions of Brightness

$$B = \frac{dI}{dS d\Omega}$$

For many practical application it is more meaningful to know the total beam current that can be in a 4 dimensional trace space V_4.

$$\overline{B} = \frac{I}{V_4}$$

For particle distribution whose boundary in 4D trace space is defined by an hyperellipsoid

$$\overline{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$ [A/(m-rad)^2]

$$\overline{B}_n = \frac{2I}{\pi^2 \varepsilon_{nx} \varepsilon_{ny}}$$ Normalized Brightness

But

- Often the factor $2/\pi^2$ is left out in literature
- Often the rms emittance is used in place of effective emittance and so there is another factor to take into the account
- So it is important to agree on the brightness definition, but the difference can be only in numerical factors

Brilliance

$$B = \frac{d^4 N}{dt d\Omega dS d\lambda / \lambda}$$ Photons/ (s mm^2 mrad^2 0.1% of bandwidth)

Wiedeman uses the name of spectral brightness but for photons

Parameters to measure

- High brightness can be achieved with small emittance, high charge or both
- Longitudinal and transverse parameters must be measured
- High charge and small emittance -> high power density beam
- We focus our attention on linac or transfer line where it is possible to use intercepting diagnostic
- For some applications, it is needed to measure also the transverse parameters in different longitudinal positions (correlation)

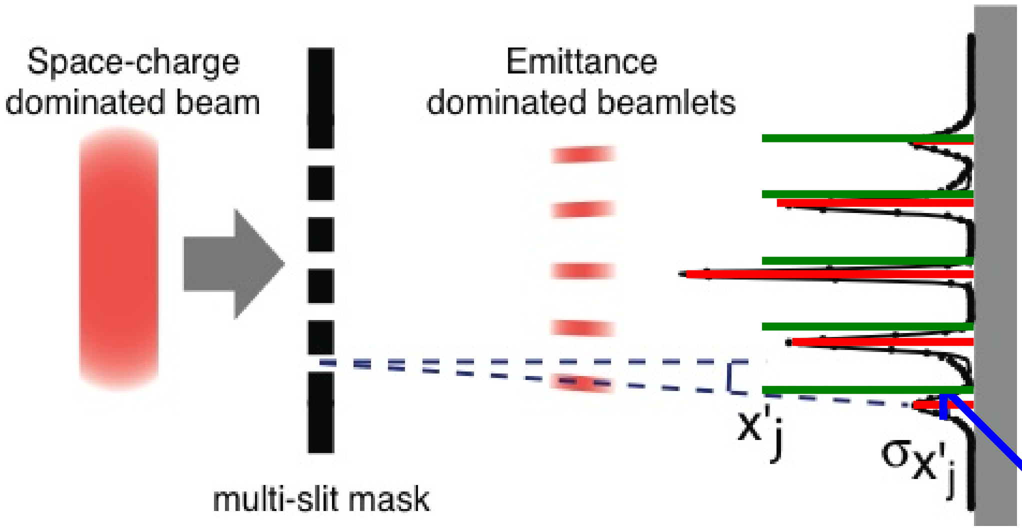
Transverse parameters

- The most important parameter is the transverse emittance
- To obtain high brightness beam it is of paramount importance to keep emittance growth under control
- Different methods apply for beams with or without space charge contribution
- Mainly the space charge is relevant at the exit of the RF GUN (few MeV)

Intercepting devices

- OTR monitors
  - High energy (>tens of MeV)
  - High charge (>hundreds of pC)
  - No saturation
  - Resolution limit closed to optical diffraction limit
  - Surface effect
- Scintillator (like YAG:CE)
  - Large number of photons
  - Resolution limited to grain dimension (down to few microns)
  - Saturation depending of the doping level
  - Bulk effect
  - Thin crystal to prevent blurring effect
- Wire scanner
  - Multiple scattering reduced
  - Higher beam power
  - Multishot measurement
  - 1 D
  - Complex hardware installation

Emittance measurements with space charge



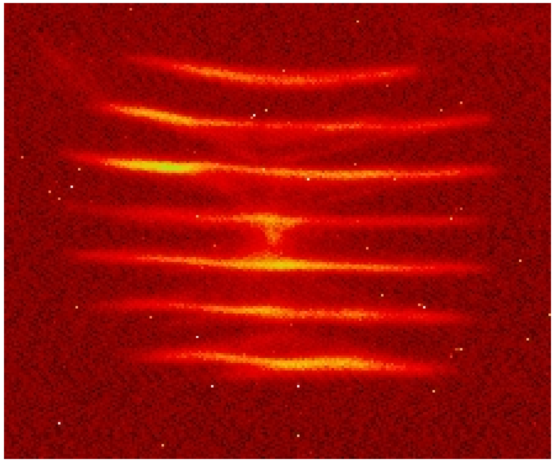
To measure the emittance for a space charge dominated beam the used technique is know 1-D pepper-pot

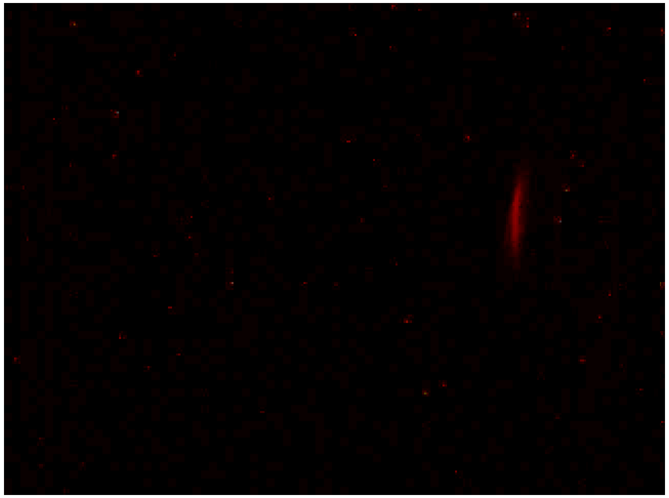
The emittance can be reconstructed from the second momentum of the distribution

$$\varepsilon = \sqrt{\boxed{< x^2 >}\boxed{< x'^2 >} - \boxed{< xx' >}^2}$$

C. Lejeune and J. Aubert, Adv. Electron. Electron Phys. Suppl. A **13**, 159 (1980)

Examples





Design issues

- The beamlets must be emittance dominated

$$\sigma_x'' = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3} + \frac{I}{\gamma^3 I_0 (\sigma_x + \sigma_y)}$$

Martin Reiser, Theory and Design of Charged Particle Beams (Wiley, New York, 1994)

- Assuming a round beam

$$R_0 = \frac{I \sigma_0^2}{2\gamma I_0 \varepsilon_n^2} \qquad \sigma_x = \frac{d}{\sqrt{12}}$$

- *d* must be chosen to obtain R_0<<1, in order to have a beam emittance dominated

Design issues (2)

- The contribution of the slit width to the size of the beamlet profile should be negligible

$$\sigma = \sqrt{L \cdot \sigma' + \left(\frac{d^2}{12}\right)}$$

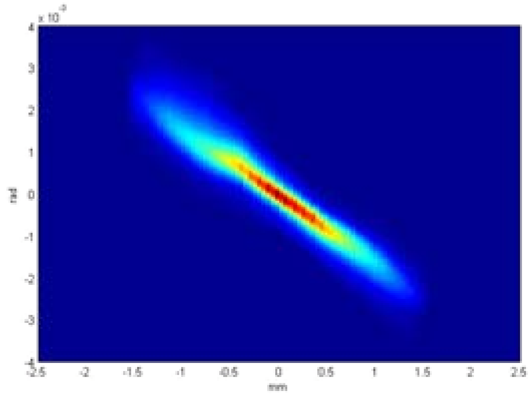
- The material thickness (usually tungsten) must be long enough to stop or heavily scatter beam at large angle

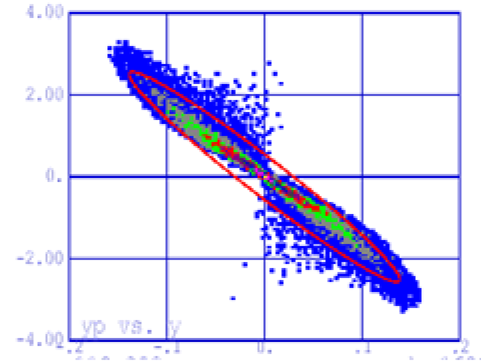
$$L >> \frac{d}{\sigma' \cdot \sqrt{12}}$$

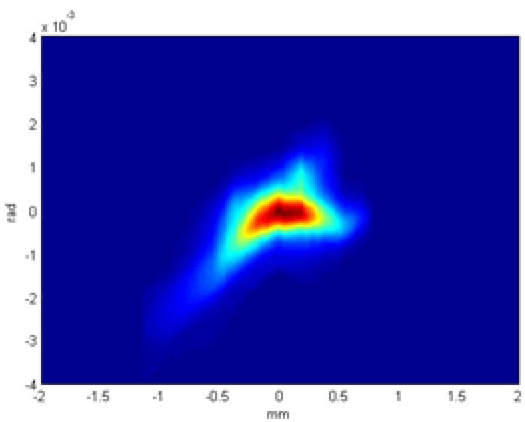
- But the angular acceptance of the slit cannot be smaller of the expected angular divergence of the beam

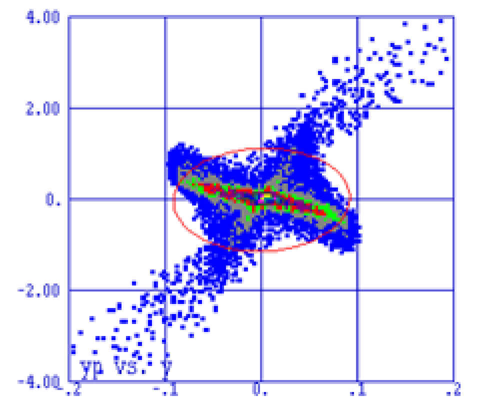
$$l < \frac{d}{2\sigma'}$$

Phase space mapping

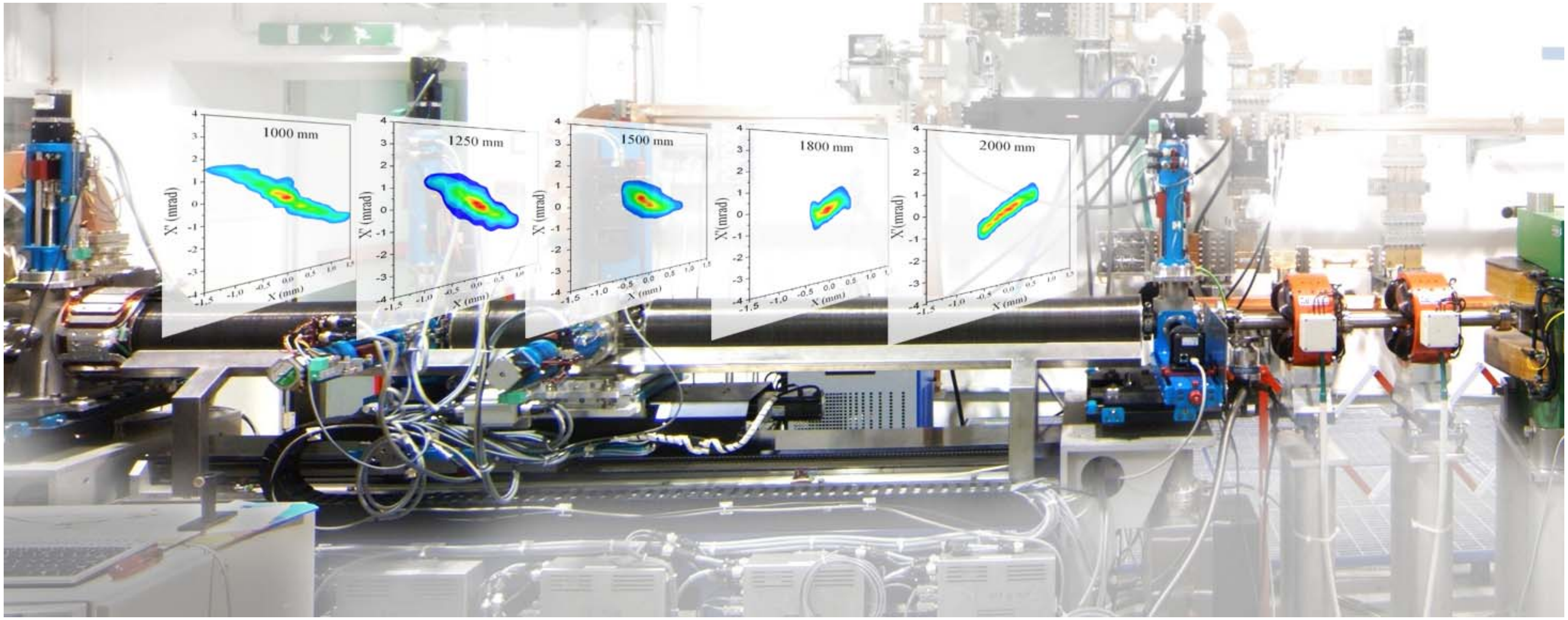








Phase space evolution



A. Cianchi et al., "High brightness electron beam emittance evolution measurements in an rf photoinjector", Physical Review Special Topics Accelerator and Beams 11, 032801,2008

Emittance measurement without space charge

- The most used techniques for emittance measurements are quadrupole scan and multiple monitors

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon = \gamma_0 x_0{}^2 + 2\alpha_0 x_0 x_0' + \beta_0 x_0'^2$$

$$M(s_1 s_2) = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \qquad \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \begin{pmatrix} C^2 & -2SC & S^2 \\ -CC' & S'C + SC' & -SS' \\ C'^2 & -2S'C' & S'^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}$$

Beam Matrix

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

$$\sigma_{11}x^2 + 2\sigma_{12}xx' + \sigma_{22}x'^2 = 1$$

$$\sigma_1 = M\sigma_0 M^T$$

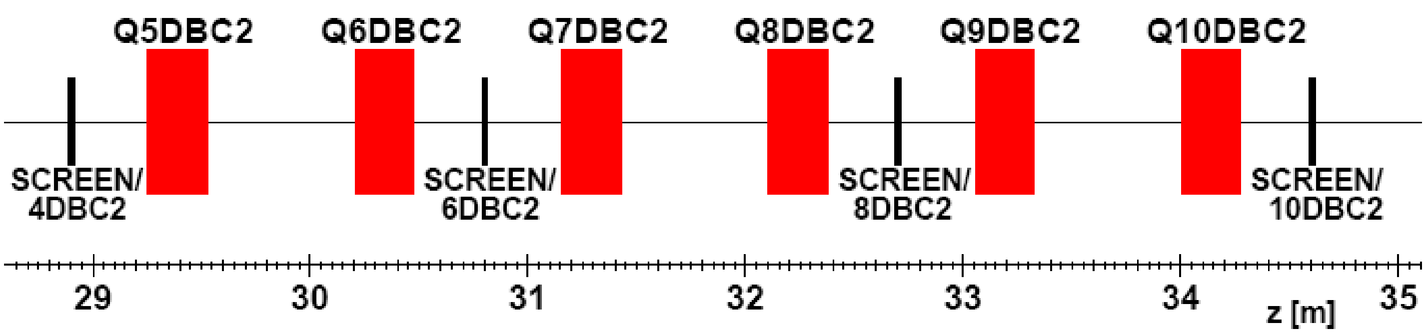
Multiple screens

$$\sigma_{i,11} = C_i^2\sigma_{11} + 2S_iC_i\sigma_{12} + S_i^2\sigma_{22}$$

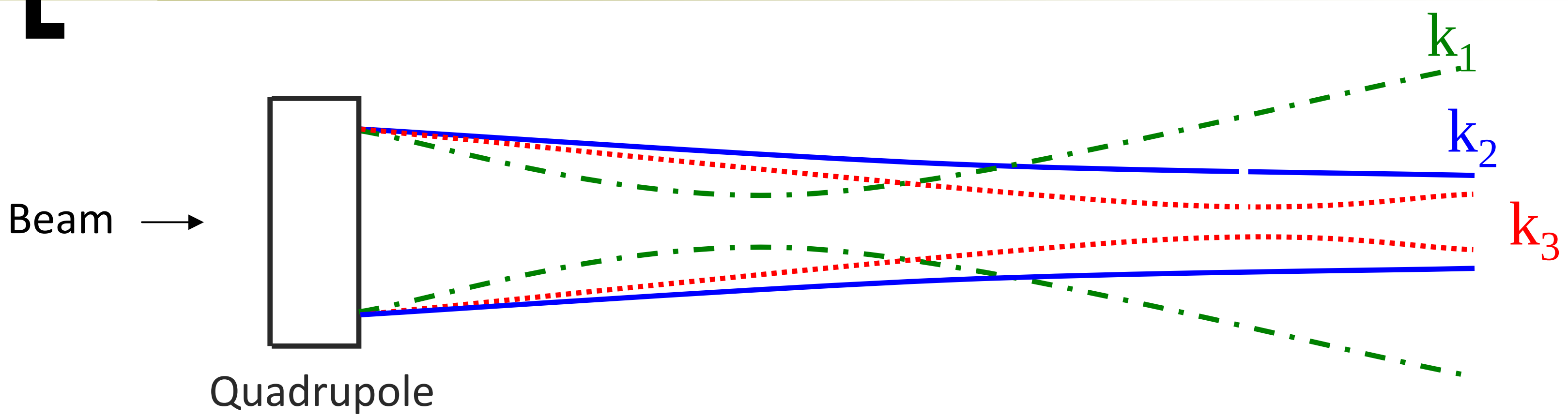
- There are 3 unknown quantities
- $\sigma_{i,11}$ is the rms beam size
- C_i and S_i are the element of the transport matrix
- We need 3 measurements in 3 different positions to evaluate the emittance

Example : FLASH @ DESY

- M. Minty, F. Zimmermann, “Measurement and control of charged particle beams”, Springer (2003)
- DESY-Technical Note 03-03 , 2003 (21 pages) Monte Carlo simulation of emittance measurements at TTF2 P. Castro



Quadrupole scan



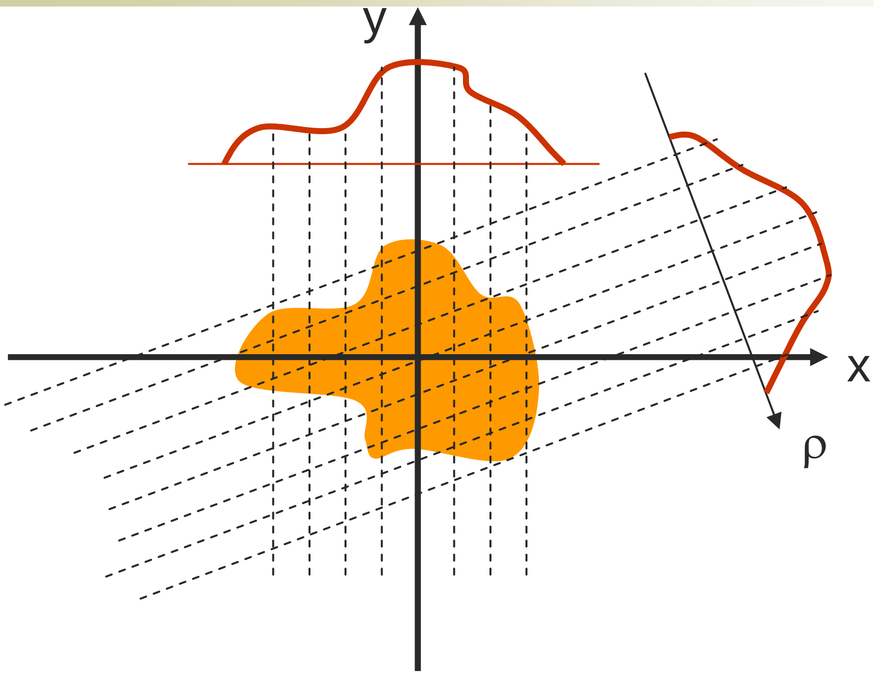
$$\sigma_{11} = C^2(k)\sigma_{11} + 2C(k)S(k)\sigma_{12} + S^2(k)\sigma_{22}$$

- It is possible to measure in the same position changing the optical functions
- The main difference respect to the multi screen measurements is in the beam trajectory control and in the number of measurements

Source of errors

- Usually the largest error is in the determination of the RMS beam size (Mini Workshop on "Characterization of High Brightness Beams“, *Desy Zeuthen 2008*, *https://indico.desy.de/conferenceDisplay.py?confId=806)*
- Systematic error comes from the determination of the quadrupole strength, mainly for hysteresis. So a cycling procedure is required for accurate measurements
- Thin lens model is not adequate
- Energy
- Large energy spread can gives chromatic effect
- Assumption: transverse phase space distribution fills an ellipse

Phase space reconstruction



- Tomography is related to the Radon theorem: a n-dimensional object can be reconstructed from a sufficient number of projection in (n-1) dimensional space

Tomography

$$\hat{f}(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dxdy f(x,y)\delta(\rho - xcos\theta - ysin\theta)$$

Radon Transform

$$f(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(u,v)e^{i2\pi(ux+vy)}dudv. \quad f(x,y) = \int_{0}^{\pi}\int_{-\infty}^{\infty} |w|F(w,\theta)e^{i2\pi w\rho}dwd\theta.$$

$$S(w,\theta) = \int_{-\infty}^{\infty} \hat{f}(\rho,\theta)e^{-i2\pi w\rho}d\theta.$$

Fourier transform of the Radon transform

$$f(x,y) = \int_{0}^{\pi}\int_{-\infty}^{\infty} |w|S(w,\theta)e^{i2\pi w\rho}dwd\theta, \qquad f(x,y) = \int_{0}^{\pi} Q(\rho,\theta)d\theta,$$

- A. C. Kak and Malcolm Slaney, Principles of Computerized Tomographic Imaging, IEEE Press, 1988.
- D. Stratakis et al, “Tomography as a diagnostic tool for phase space mapping of intense particle beam”, *Physical Review Special Topics – Accelerator and Beams 9, 112801 (2006)*

Tomography measurements

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = M_1 \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$s = \sqrt{M_{11}^2 + M_{12}^2},$$ Scaling factor

$$\hat{f}(\rho, \theta) = sC(x, \theta).$$

$$cos(\theta) = \frac{M_{11}}{\sqrt{M_{11}^2 + M_{12}^2}},$$

Rotation angle

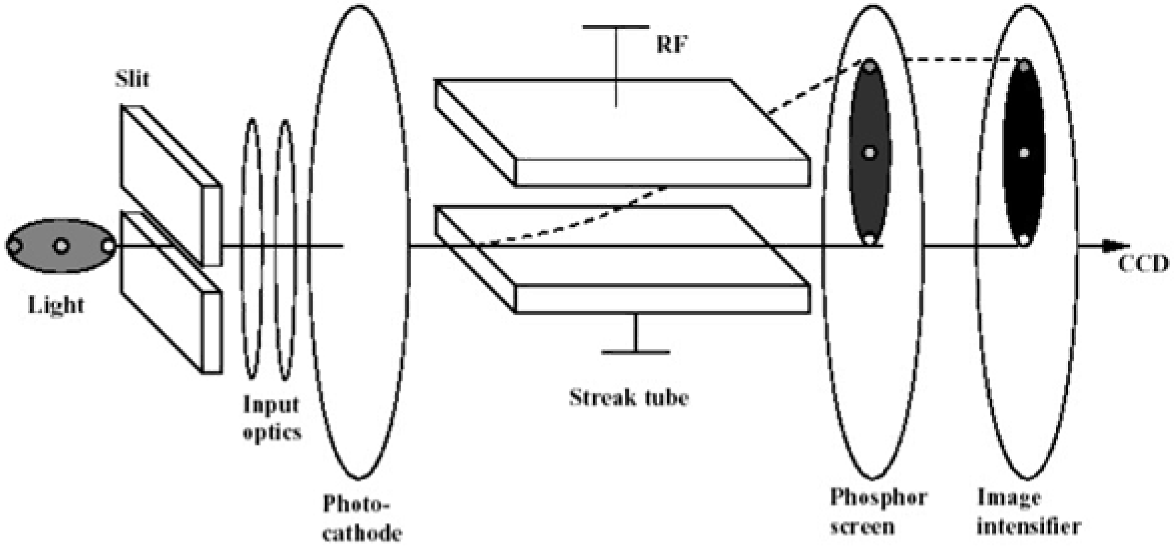
$$sin(\theta) = \frac{M_{12}}{\sqrt{M_{11}^2 + M_{12}^2}}.$$

- C can be easily obtained from beam spatial distribution
- s can be calculated from the beam line optics
- The accuracy of the result depends from the total angle of the rotation and from the number of the projections

Longitudinal parameters

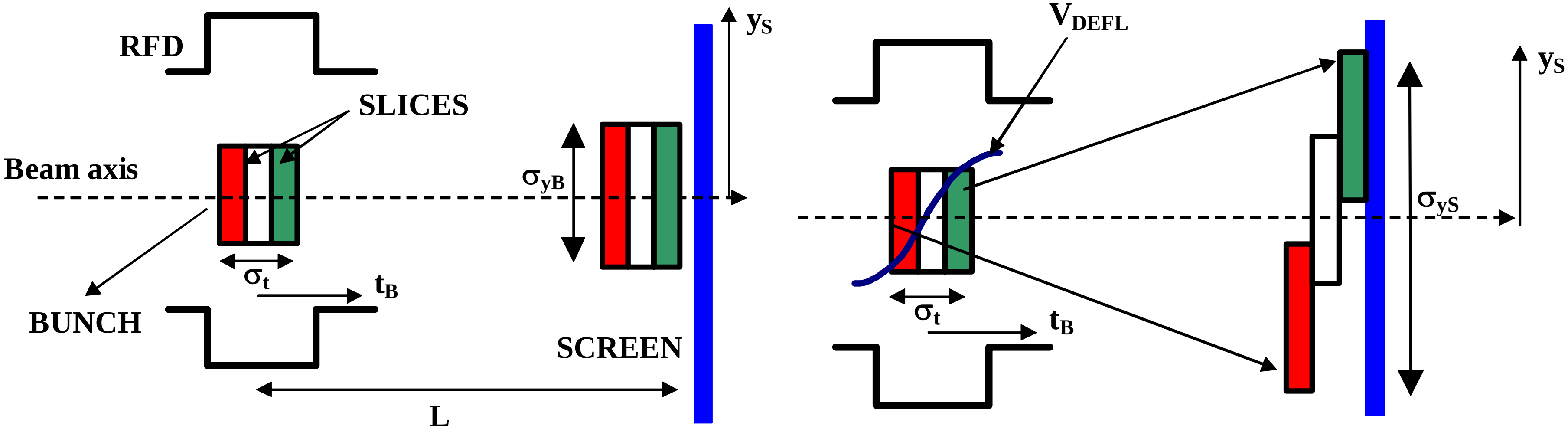
- Fundamental parameter for the brightness
- Bunch lengths are on ps (uncompressed) or sub-ps time scale
- Several methods
  - Streak Camera
  - Coherent radiations
  - RFD
  - EOS
  - Others
- T. Watanabe et al, *"Overall comparison of subpicosecond electron beam diagnostics by the polychromator, the interferometer and the femtosecond streak camera"*, Nuclear Instruments and Methods in Physics Research A 480 (2002) 315–327

Streak camera



- Expensive device
- Resolution limited to 200-300 fs FWHM
- It is better to place the device outside the beam tunnel so a light collection and transport line is needed
- Reflective optics vs lens optics
- Intercepting device

RF deflector



- The transverse voltage introduces a linear correlation between the longitudinal and the transverse coordinates of the bunch

RFD

$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{p_z c}\left[\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right] \qquad |z| << \lambda / 2\pi$$

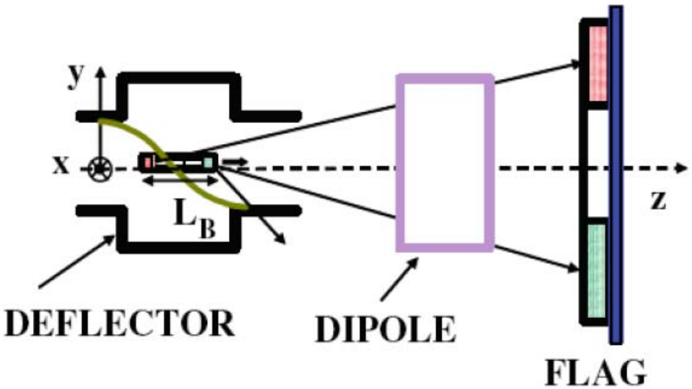
$$\Delta x(z) = \frac{eV_0}{pc}\sqrt{\beta_d \beta_s}\,\sin\Delta\Psi\left[\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right]$$

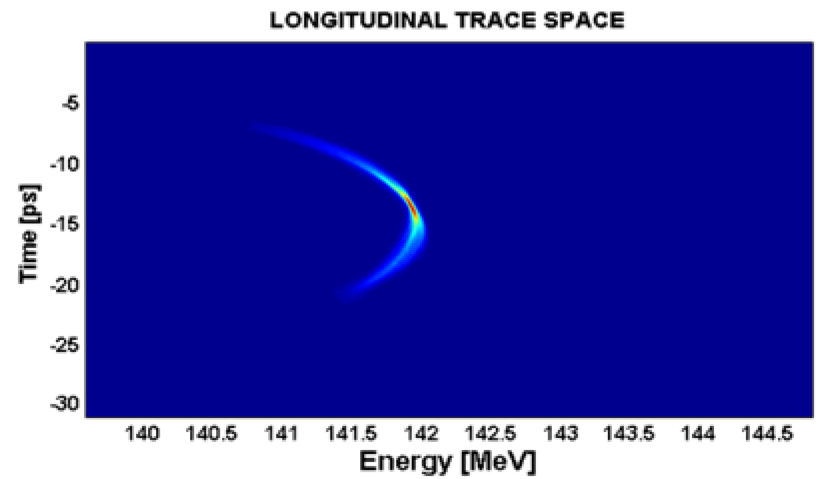
$$\sigma_x = \sqrt{\sigma^2{}_{x0} + \sigma_z^2 \beta_d \beta_s \left(\frac{2\pi eV_0}{\lambda pc}\sin\Delta\Psi\cos\varphi\right)^2} \qquad \sigma^2{}_{x0} = \sqrt{\frac{\beta_s \varepsilon_N}{\gamma}}$$

$$eV_0 >> \frac{\lambda}{2\pi\sigma_z}\frac{1}{|\sin\Delta\Psi\cos\varphi|}\sqrt{\frac{\varepsilon_N pcmc^2}{\beta_d}}$$

- P. Emma, J. Frisch, P. Krejcik ,” *A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics* “ ,LCLS-TN-00-12, 2000
- D. Alesini, “*RF deflector based sub-ps beam diagnostics: application to FEL and Advanced accelerators*”, International Journal of Modern Physics A, 22, 3693 (2007)

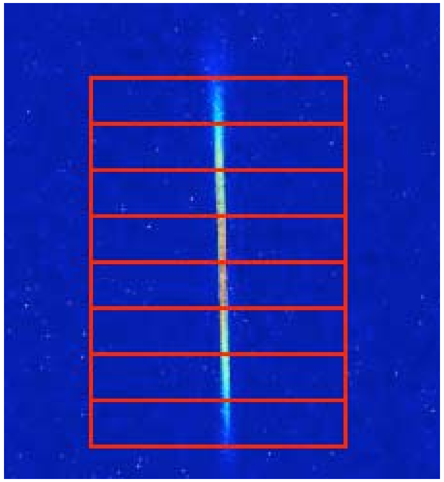
Longitudinal phase space

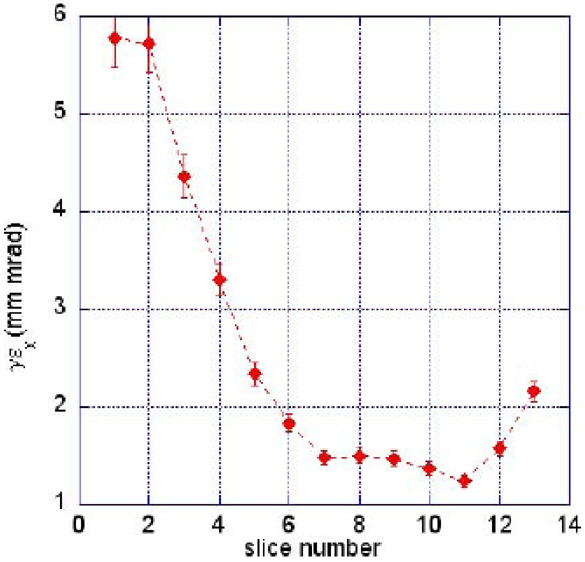




- Using together a RFD with a dispersive element such as a dipole
- Fast single shot measurement

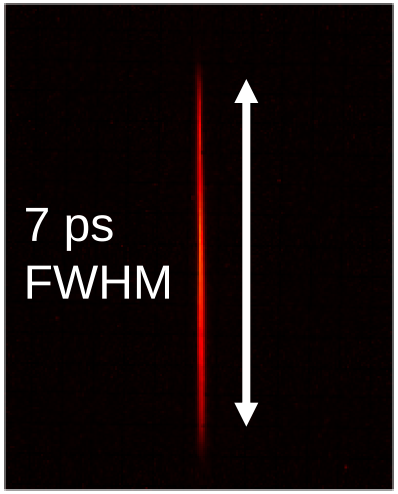
Slice parameters





- Slice parameters are important for linac driving FEL machines
- Emittance can be defined for every slice and measured
- Also the slice energy spread can be measured with a dipole and a RFD

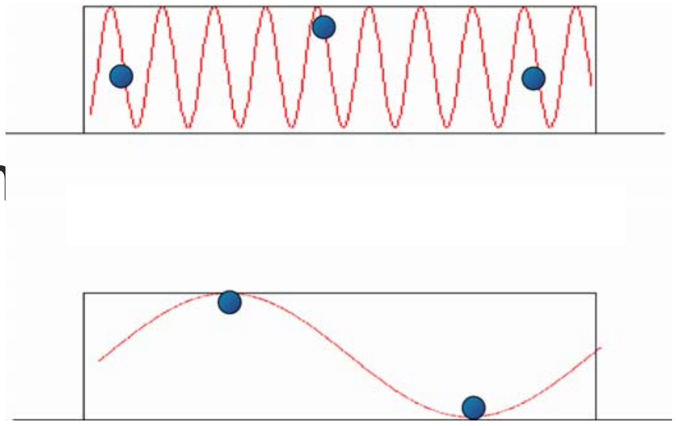
RFD conclusions



- Self calibrating
- Easy to implement
- Single shot
- Resolution down to tens of fs
- Intercepting device
- As energy increases some parameter must be increased:
  - Frequency
  - Voltage or length

Coherent radiation

- Any kind of radiation can be coherent and usable for beam diagnostics
  - Transition radiation
  - Diffraction radiation
  - Synchrotron radiation
  - Undulator radiation
  - Smith-Purcell radiation
  - Cherenkov radiation



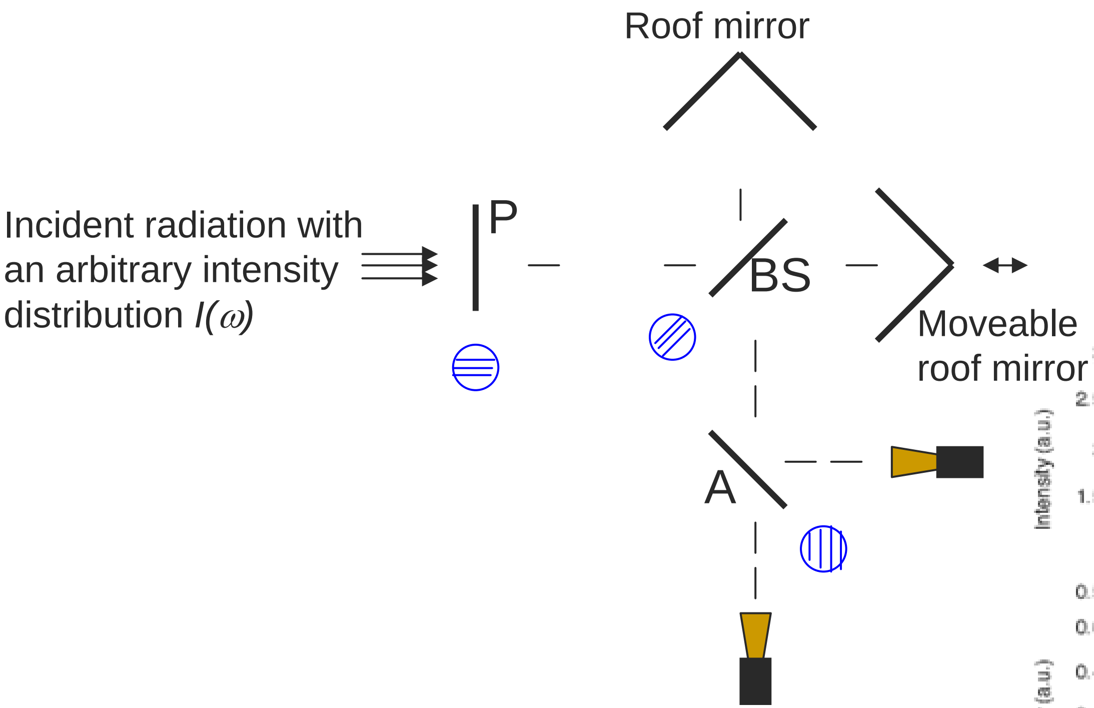
Power Spectrum

$I_{tot}(\omega)=I_{sp}(\omega)[N+N*(N-1)\ F(\omega)]$

$$F(\omega)=\left|\int_{-\infty}^{\infty} dz\,\rho(z)e^{i(\omega/c)z}\right|^2 \qquad \rho(z)=\frac{1}{\pi c}\int_0^{\infty} d\omega\sqrt{F(\omega)}\cos\left(\frac{\omega z}{c}\right)$$

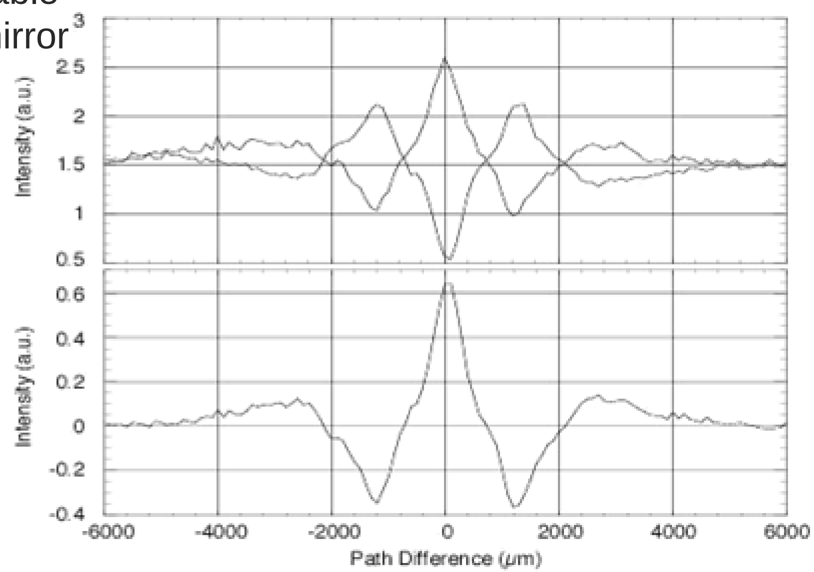
- From the knowledge of the power spectrum is possible to retrieve the form factor
- The charge distribution is obtained from the form factor via Fourier transform
- The phase terms can be reconstructed with Kramers-Kronig analysis (see R. Lai, A.J. Sievers, NIM A **397** (1997) 221-231)

Martin-Puplett Interferometer



$$I(\delta) \propto \int_{-\infty}^{\infty} \left| E(t) + E(t+\delta/c) \right|^2 dt$$

$$I(\omega) \propto \int_{-\infty}^{\infty} I(\delta) \cos\left(\frac{\omega\delta}{c}\right) d\delta$$



- Golay cells or Pyroelectric detector

Experimental considerations

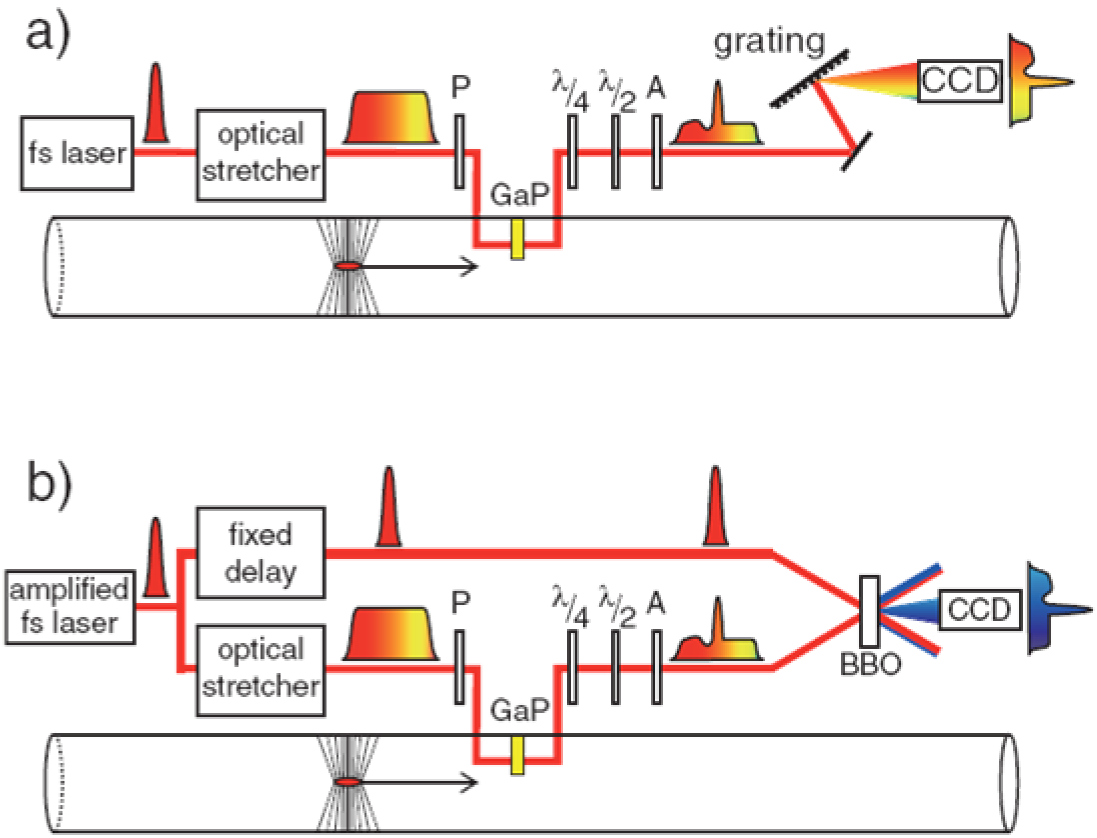
- Spectrum cuts at low and high frequencies can affect the beam reconstruction
  - Detectors
  - Windows
  - Transport line
  - Finite target size
- For this reason usually the approach is to test the power spectrum with the Fourier transform of a guess distribution
- Coherent synchrotron radiation or diffraction radiation can be generated by totally not intercepting devices and so they are eligible for high brightness beams diagnostic

Electro Optical Sample (EOS)

- Totally non intercepting device and not disturbing device
- It is based on the change of the optical properties of a non linear crystal in the interaction with the Coulomb field of the moving charges
- Several schemes has been proposed and tested
- Very promising technique

- I.Wilke et al., “single-Shot electron beam bunch length measurements” PRL, v.88, 12(2002)
- G. Berden et al., “Electo-Optic Technique with improved time resolution for real time, non destructive, single shot measurements of femtosecond electron bunch profiles, PRL v93, 11 (2004)
- B. Steffen, “Electro-optic time profile monitors for femtosecond electron bunches at the soft x-ray free-electron laser FLASH“, Phys. Rev. ST Accel. Beams 12, 032802 (2009)

Spectral vs temporal decoding



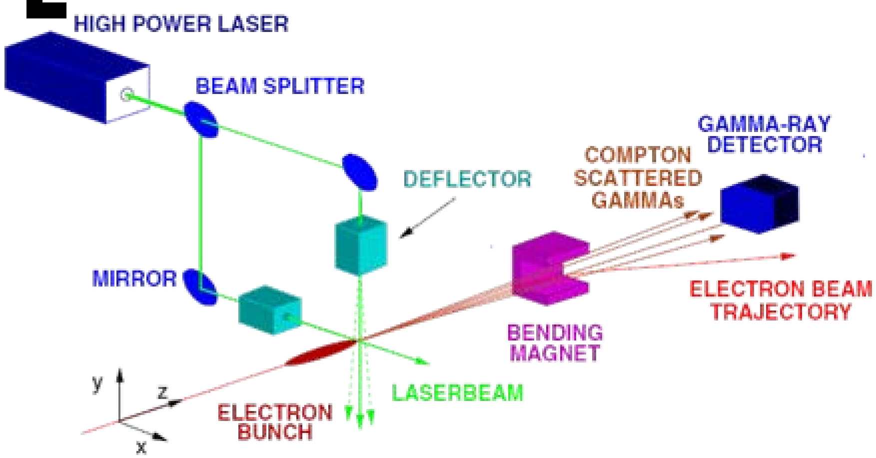
a) Spectral decoding

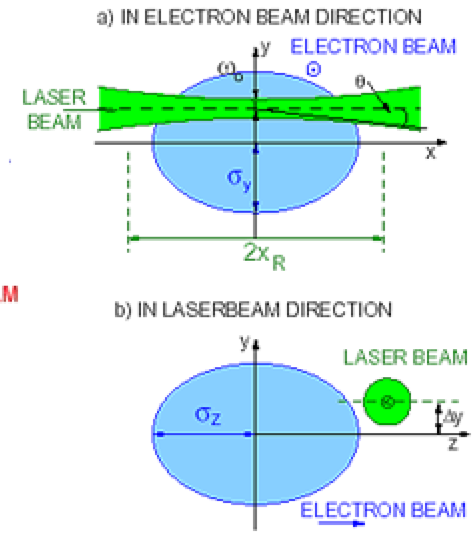
b) Temporal decoding

The problems of intercepting diagnostic

- High charge
- Small beam dimension (between 50 μm down to tens of nm)
- High repetition rate
- All the intercepting devices are damaged or destroyed from these kind of beams
- No wire scanners, no OTR screens, no scintillators
- There are good candidates for longitudinal diagnostic
- It is difficult to replace intercepting devices for transverse dimensions
- There are a lot of ideas in testing

Laser Wire

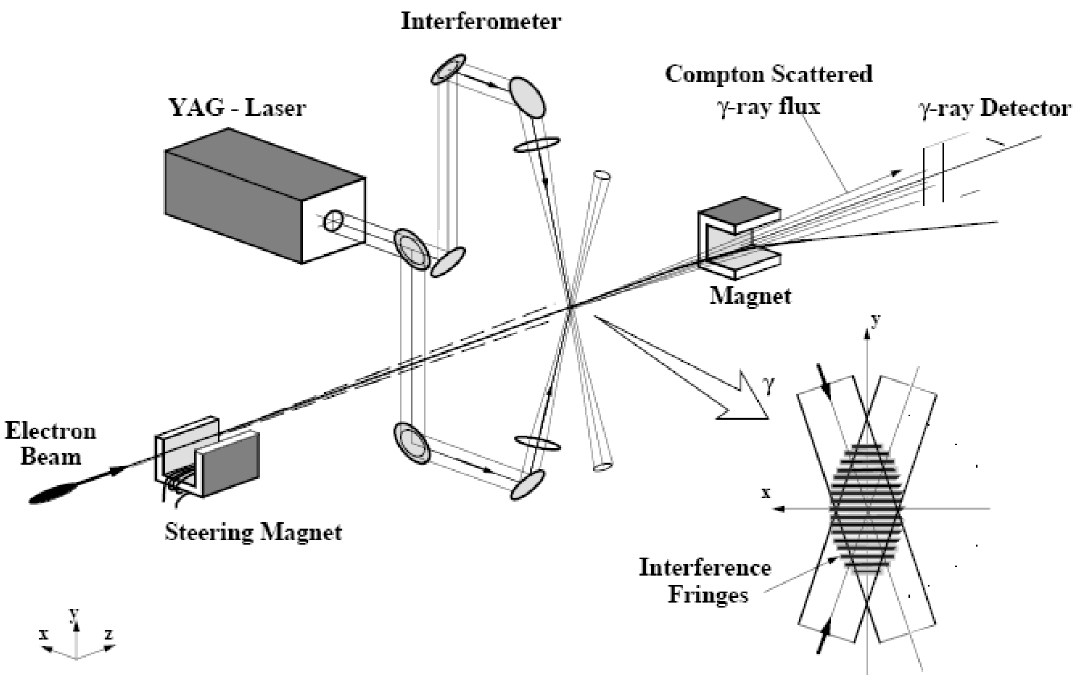


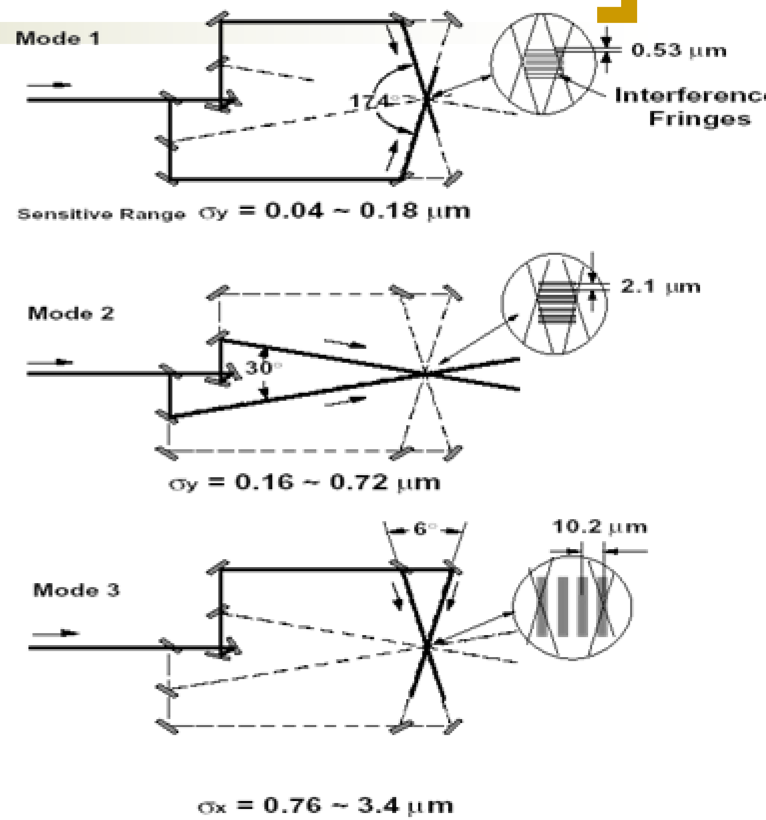


Rayleigh range of the laser beam : distance between the focus and the point where the laser spot-size has diverged to $\sqrt{2}$ of its minimum value

- Not intercepting device
- Multi shot measurement (bunch to bunch position jitter, laser pointing jitter, uncertainty in the laser light distribution at IP)
- Setup non easy
- Resolution limited from the laser wavelength
- Several effects to take into account
- I. Agapov, G. A. Blair, M. Woodley, “Beam emittance measurement with laser wire scanners in the International Linear Collider beam delivery system”, Physical review special topics-accelerators and beams 10, 112801 (2007)

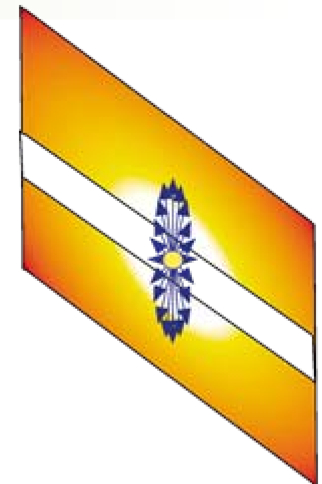
Laser interferometry



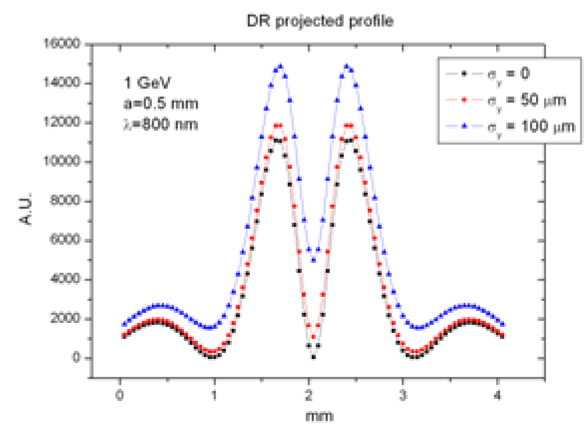


- Tsumoru Shintake, " *Proposal of a nanometer beam size monitor for* e^+e^- *linear collider*", Nuclear Instruments and methods in Physics Research A311 (1992) 453

Diffraction Radiation

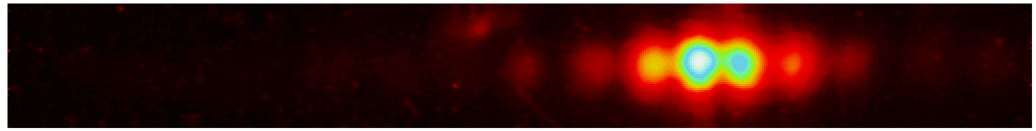


- Similar to transition radiation but without intercepting the target
- Transverse size of the EM field is in the order of $\gamma\lambda/2\pi$
- If the gap is comparable with this value DR is emitted
- Angular distribution of the radiation contains valuable information of the beam size and the beam divergence
- The main limit is the small number of photons

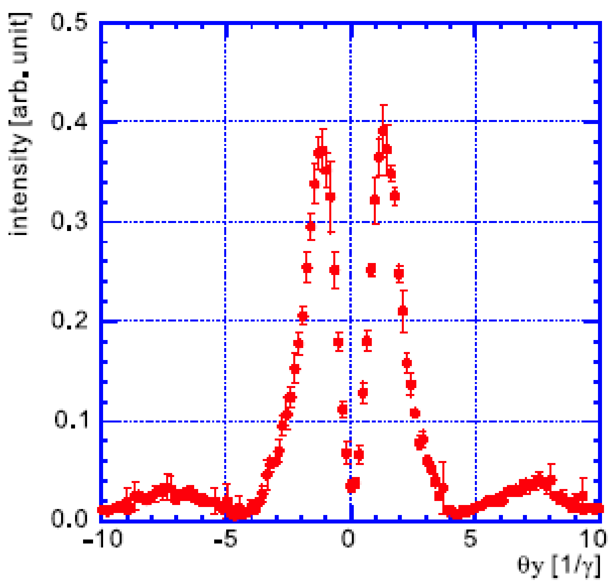


M. Castellano, "*A New Non Intercepting Beam size Diagnostics Using Diffraction Radiation from a Slit*",
Nucl. Instr. And Meth. in Phys. Res. A394, 275, (1997)

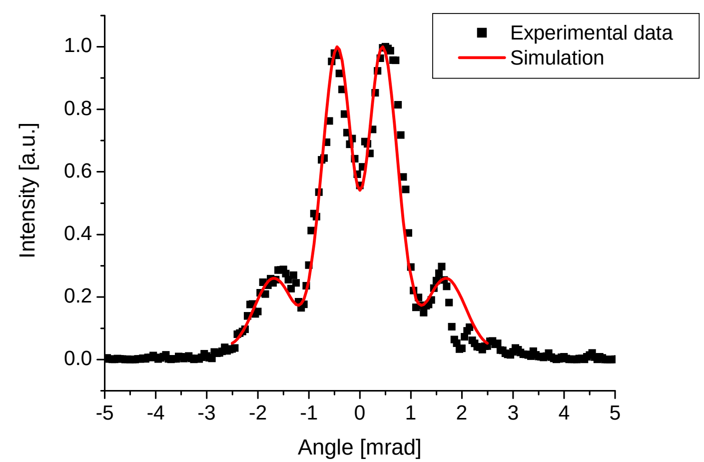
Diffraction



** **P. Karataev et al.**, “*Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility*”,
Phys. Rev. Lett. 93, 244802 (2004)



E. Chiadroni, M. Castellano, A. Cianchi, K. Honkavaara, G. Kube, V. Merlo, F. Stella, *“Non-intercepting electron beam transverse diagnostics with optical diffraction radiation at the DESY FLASH facility”*, NIMB 266 (2008) 3789–3796



Conclusions

- High brightness beam demands particular diagnostic techniques
- Especially non intercepting diagnostics are strongly recommended
- Some of them are already state of the art
- Some others are still developing
- New ideas are daily tested, so if you want your part of glory start to think about today!