Diagnostics for Charged Particle Beams II.

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Diagnostic Parameters of Interest

(Grouped by similarity of technique)

- size (x, y)   how big is it?   does it have a halo?
- position (x, y) (offset)   where is it? how stable is its position?

- divergence (x', y')   is it expanding, by how much?
- trajectory angle: is it on course in the accelerator, device?
- emittance (e_x, e_y)   how compact is its phase space?

- energy: what its average and what spread does it have?

- bunch length: how long is it?
- bunch distribution: what's its shape?

Types of Measurements

rms (transverse ensemble scale)

local (within the beam profile) → mapping

time integrated (over some time scale)

time resolved (within a time slice of some duration)

evolution (as a function of distance of travel in the beam line)

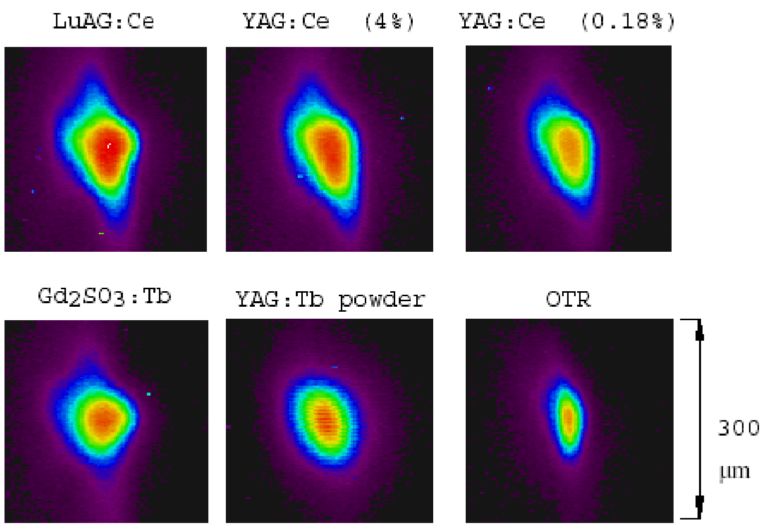
6-dimensional Phase Space

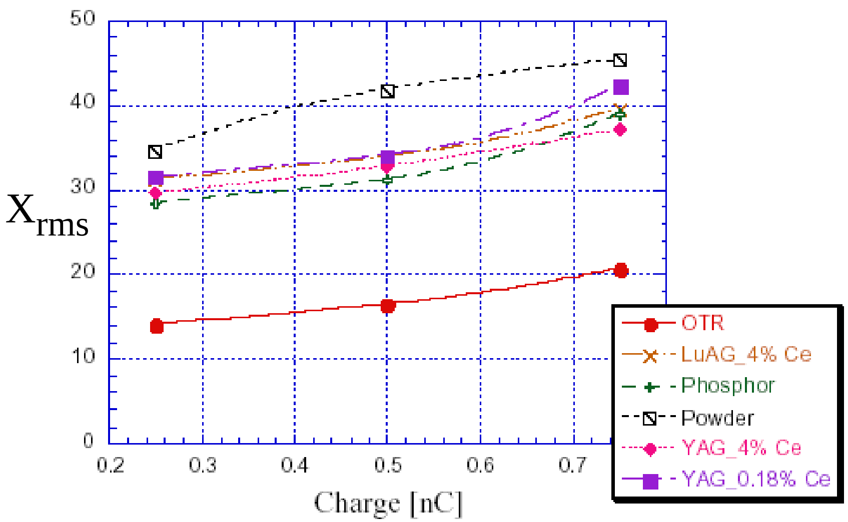
- Transverse phase space:
  - x,x’ (x-position, angle in horizontal plane)
  - y,y’ (y-positon, angle in vertical plane)
- Longitudinal phase space
  - E, Φ (Energy and phase or time of arrival)

Transverse Phase Space Diagnostics

Transverse Profile Diagnostics

Imaging Screens:



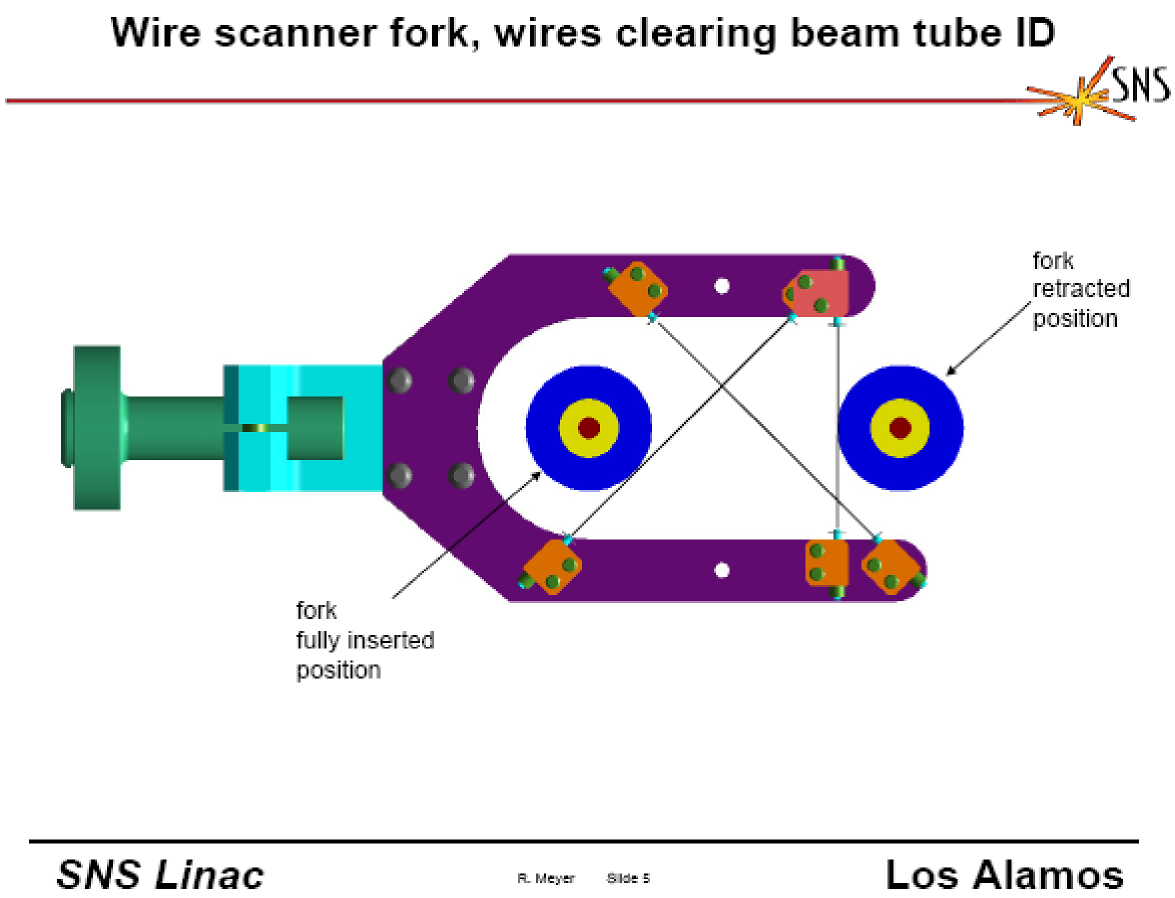


Hi spatial resolution: Beam images taken with six different diagnostic screens under the stable experimental conditions (Q ~ 500 pC) at the ATF/BNL 40 MeV linac.

Linearity : Electron beam horizontal spot size as a function of charge, measured with scintillating diagnostics and OTR (sub micron resolution independent of energy).

Time response :
OTR (sub fs)
YAG (10's of ns)
Phospors (µsec-msec)

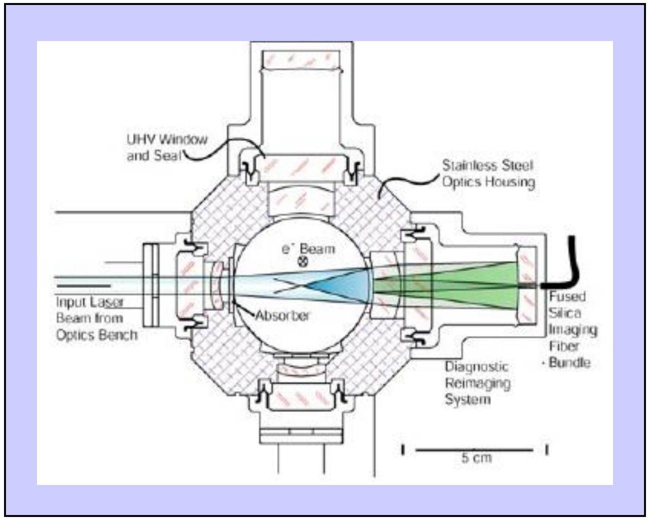
Wire Scanner: Beam Profile Diagnostics

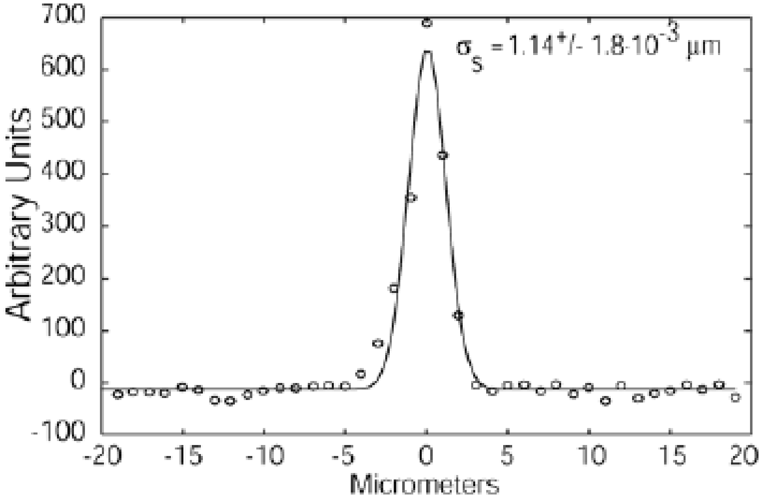


Idea:

Use light, SEM, x-rays, etc. signal as a function of wire position to profile the beam.
Resolution: depends on wire size and signal, but 10's microns possible.
Limitation: beam jitter, vibrations, wire survival

Laser "Wire" Beam Profile Monitors





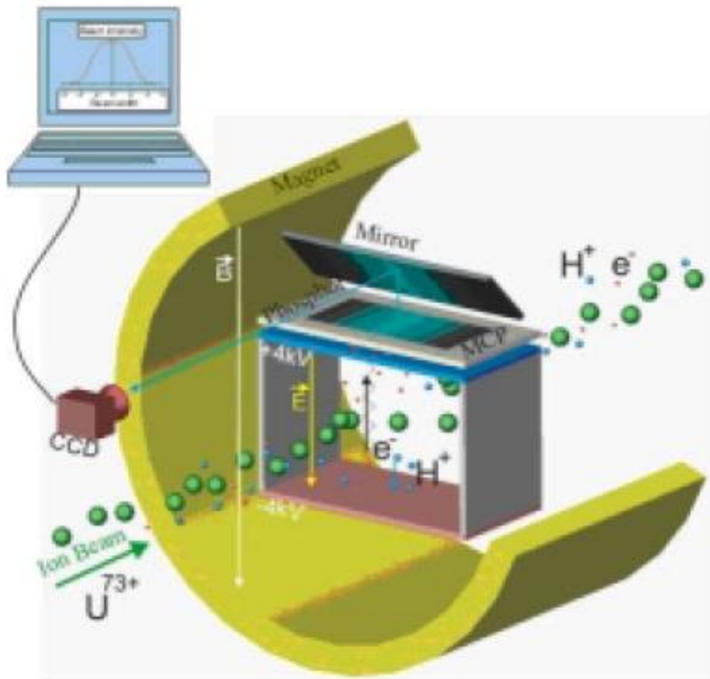
Uses Compton upscattering of laser photons from x-rays to γ rays which are detected as function of laser position

Submicron resolution possible

Residual Gas Profile Monitors

Use visible light or ions from excitation of gas atoms by charged particles

Heavy Ion residual
Gas ionization
profile monitor
at GSI Darmstadt



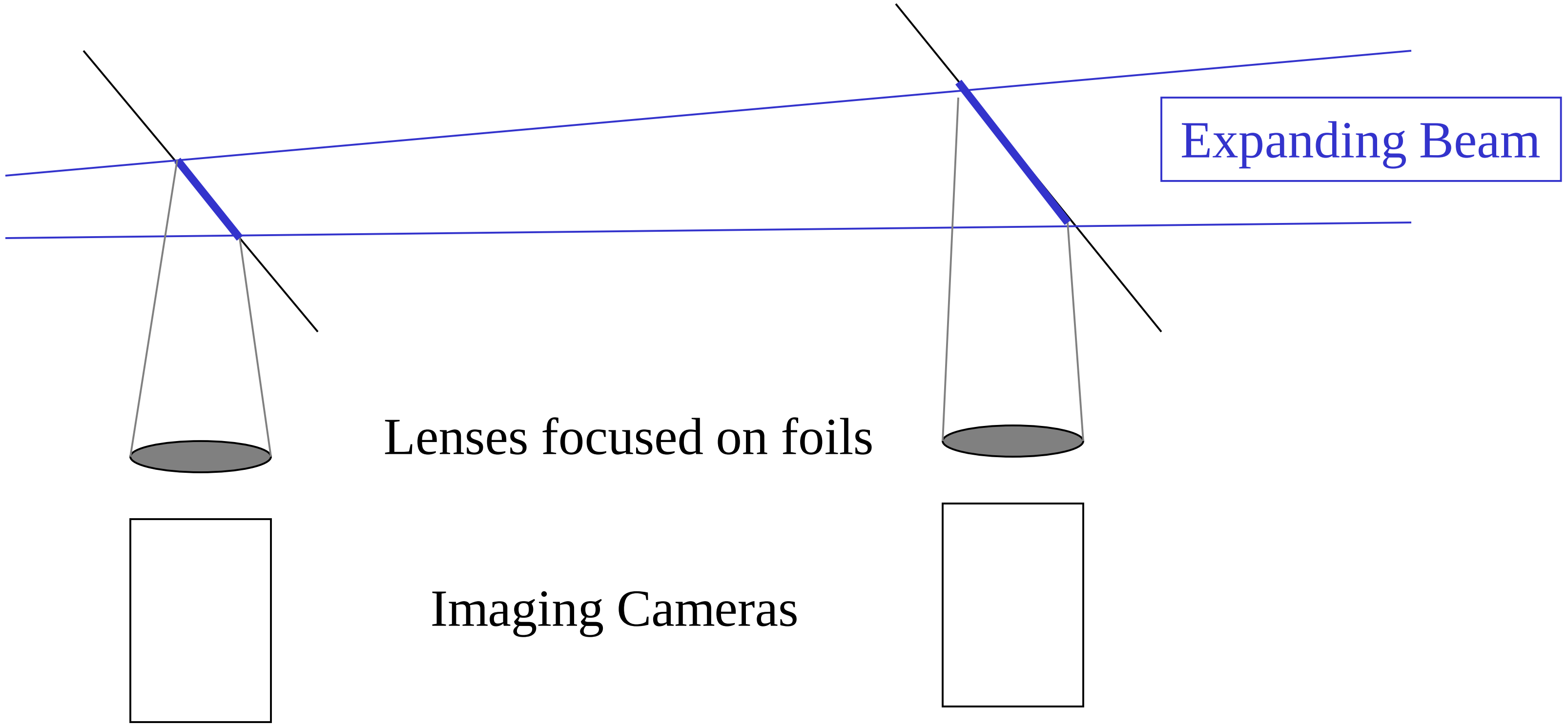
Operation:

1- An electrostatic field **E** accelerates the ionization products (ions or electrons) towards a Micro Channel Plate producing secondary electrons which are multiplied by a factor of about 100.

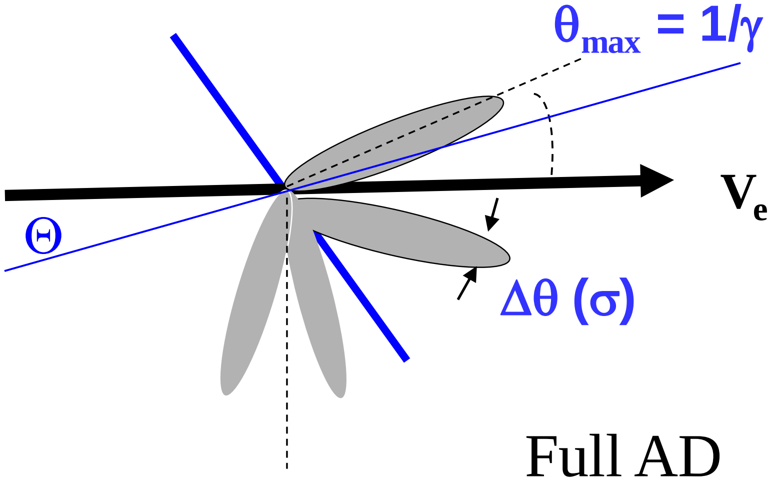
2- Output electrons from MCP with energies of several keV hit a phosphor screen producing light spots which can be observed by a CCD camera, photo-diodes or other light detectors.

Beam Divergence Diagnostics

1) RMS Beam Divergence easurement using two imaging creens (e. .g. OTR or phosphor) in a force free (drift) region



2) OTR (far field) Angular Distribution: Measures Beam Trajectory Angle and RMS divergence from a single foil



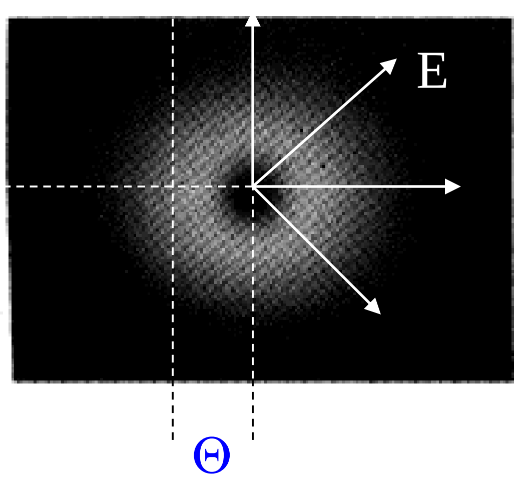
$$\frac{d^2 I^{(S)}}{d\omega d\Omega} = \frac{e^2}{c\pi^2} \frac{\theta^2}{(\gamma^{-2} + \theta^2)^2},$$

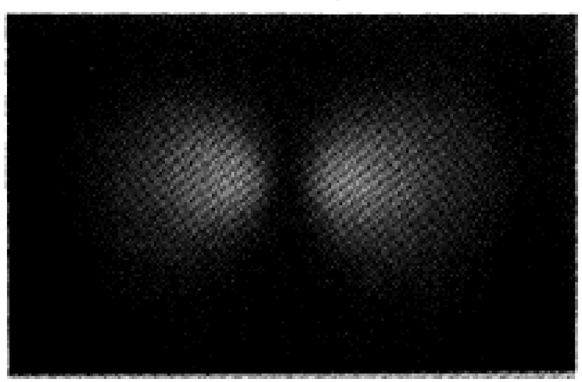
$$\theta \;\square\; \gamma^{-1} \;\square\; 1$$

Full AD

Horizontally Polarized AD

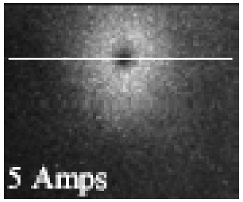
Radially Polarized AD Pattern Centered on Direction of $\mathbf{V_e}$

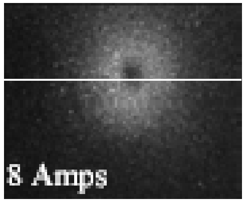


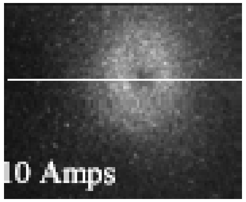


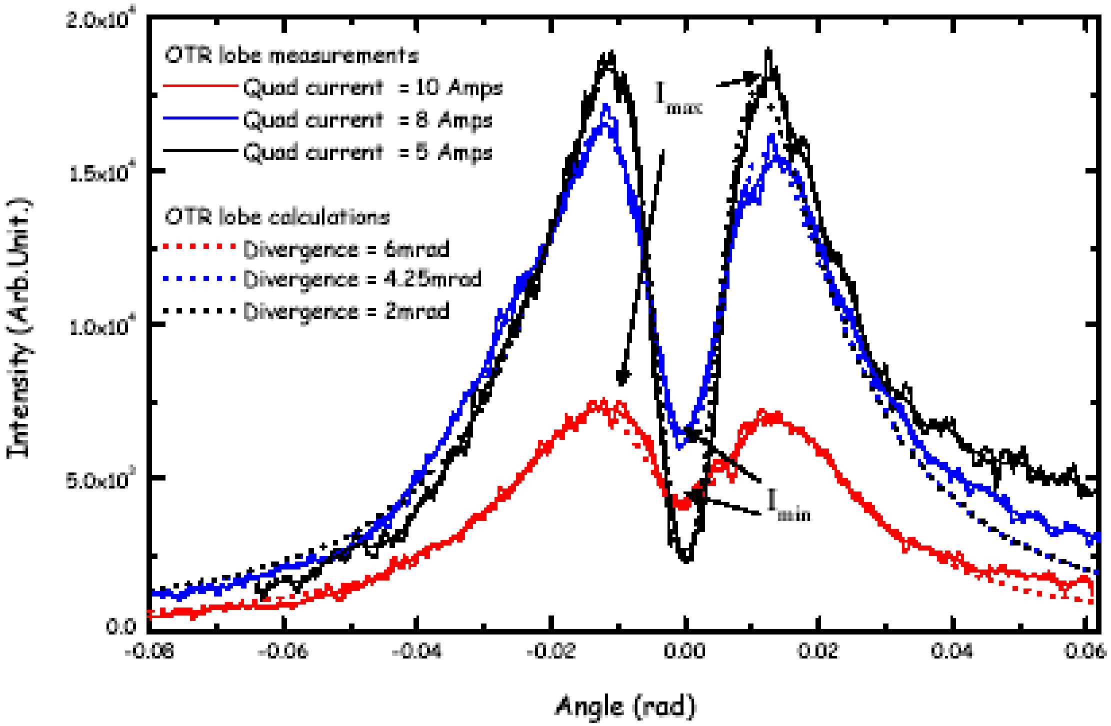
Effect of Beam Divergence on OTR Angular Distribution

(48 MeV CLIC2 Test Facility Beam)

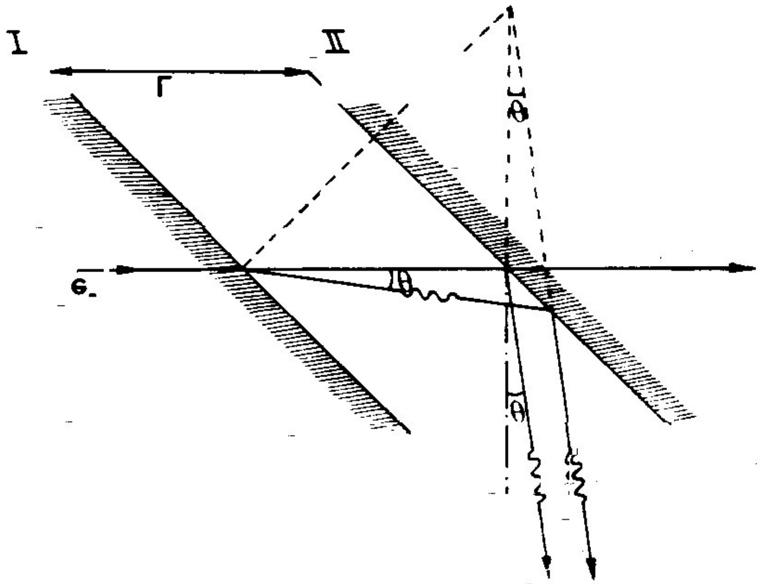




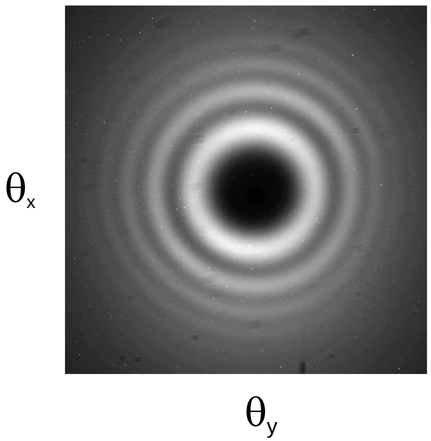




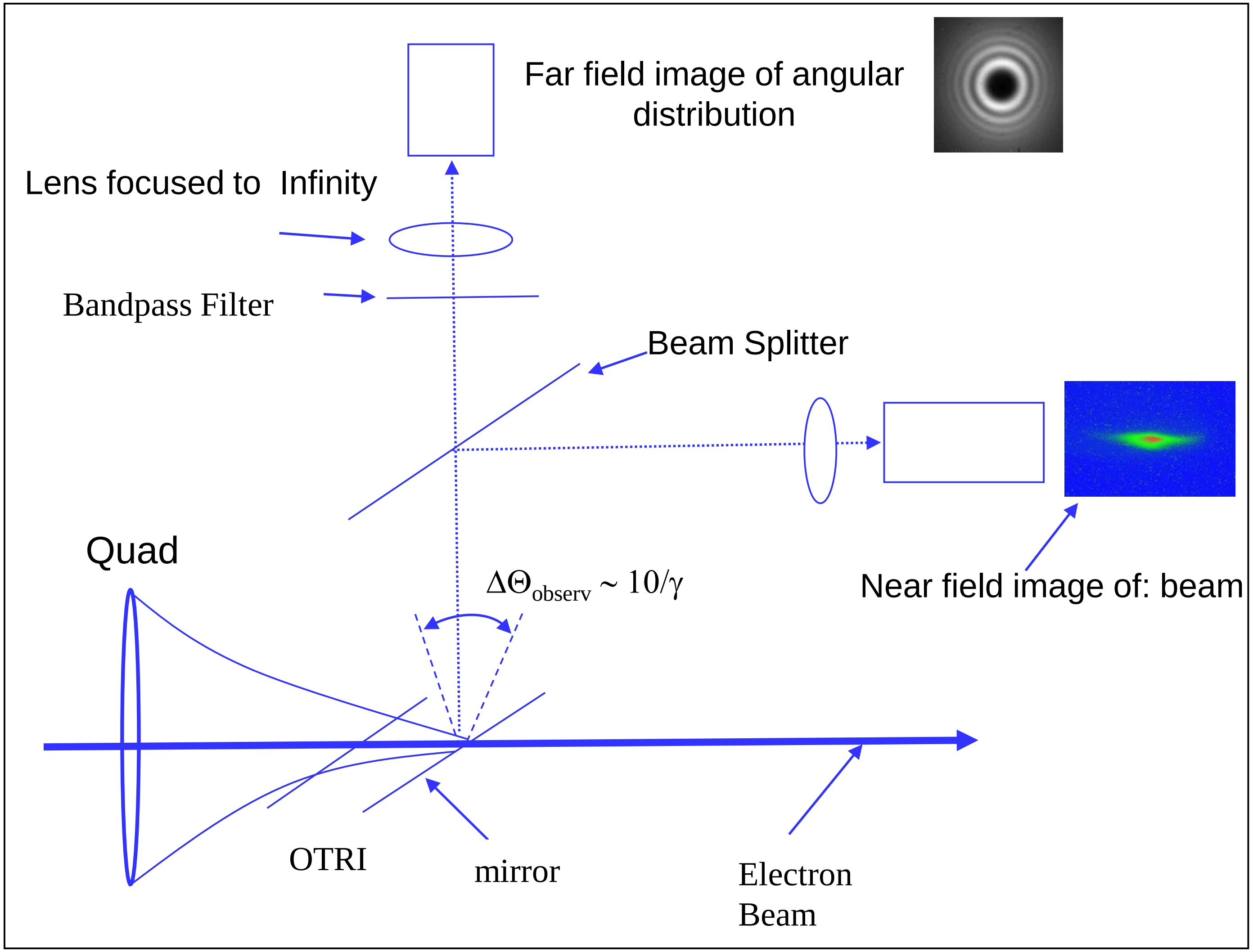
OTR Interferometer (2 parallel foils) provides greater sensitivity to beam divergence and can also be used to measure E and ΔE/E



- Center of pattern measures trajectory angle of particle
- Visibility of OTRI measures beam divergence *(and/or ΔE/E)*
- Radial Polarization of OTRI can be used to *separately* measure x' and y'
- *Fringe position measures beam energy (E)*

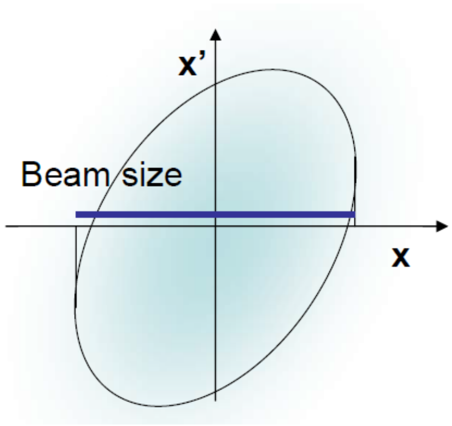


Simultaneous RMS beam size and divergence measurements with OTR



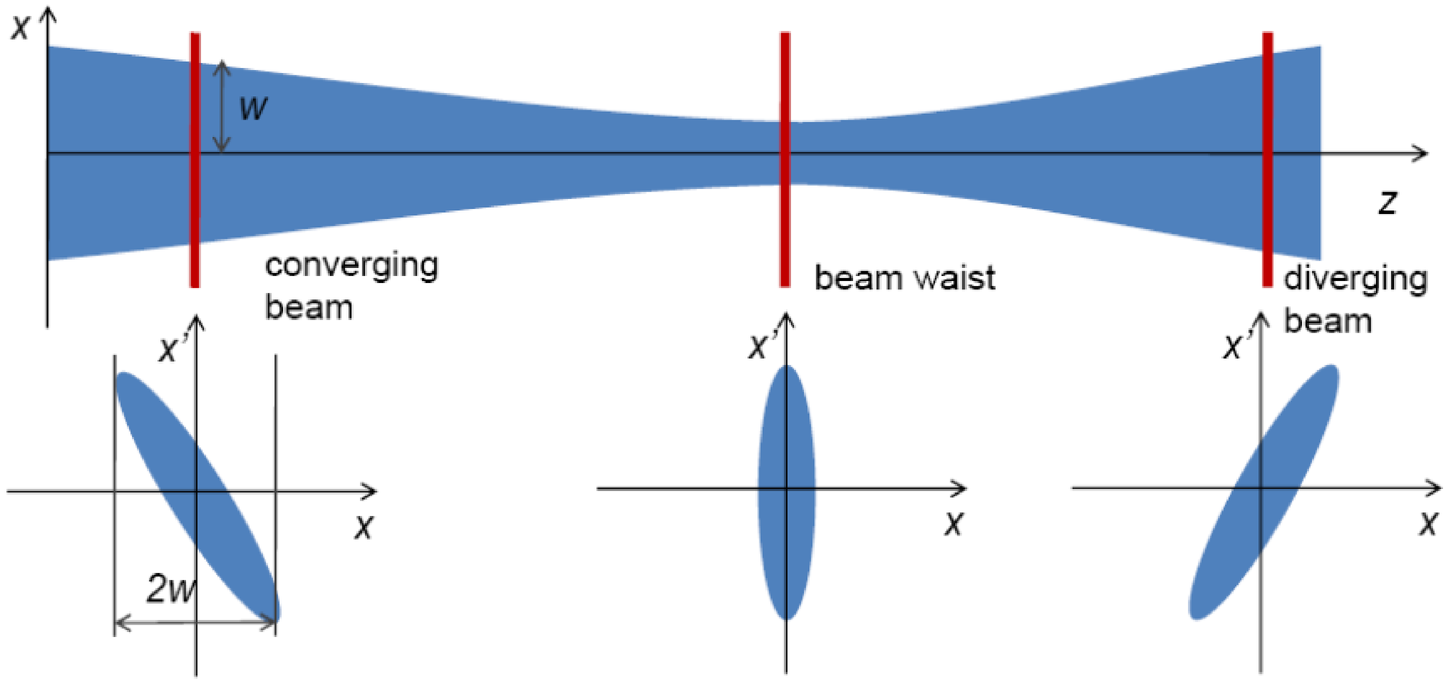
Transverse Emittance

- If for each beam particle we plot its position and its transverse angle we get a particle distribution who's boundary is an usually ellipse.
- The projection onto the x axis is the beam size



- **The emittance is defined as the Area of this ellipse in x,x' or y,y' trace space which is a subset of the beam's 4D transverse phase space**
- Emittance can be defined in terms of the geometric properties of the ellipse
- Tilt angle of ellipse related to the correlation between x and x' , i.e. <xx'>

Variation of the ellipse along the transport line



Along a beamline the orientation and aspect ratio of beam ellipse in x, x' plane varies, but area $\pi\varepsilon$ remains constant

Emittance Measurement Techniques

1. Quad Scan method (limited to low charge/current)

2. Pepperpot Technique

3. Phase Space Tomography

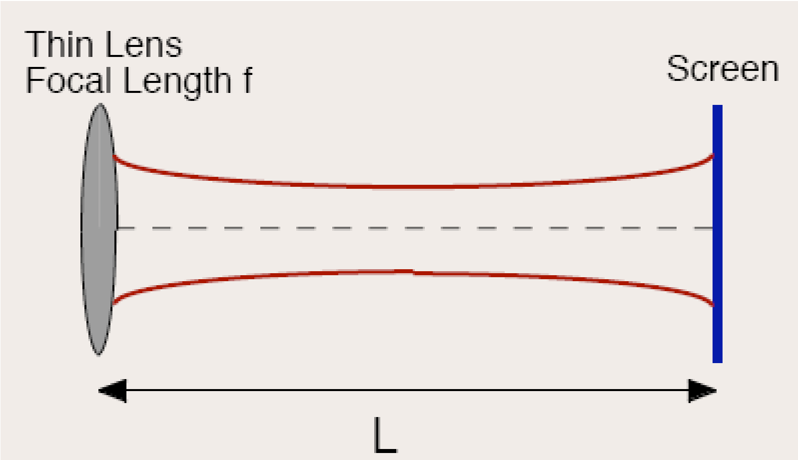
I. Quadrupole Scan Measurements

Neglecting space charge we can write an equation for σ^2 based on the Twiss parameters of the beam.

$$\sigma^2 = \varepsilon[\beta_1 - 2\alpha_1 L + L^2\gamma_1] - \frac{\varepsilon}{f}[2L\beta_1 - 2L^2\alpha_1] + \frac{\varepsilon}{f^2}[L^2\beta_1]$$

The procedure then, is to measure σ^2 *(the mean square beam size)* versus the focal length of the lens and fit the resulting curve to calculate the emittance.

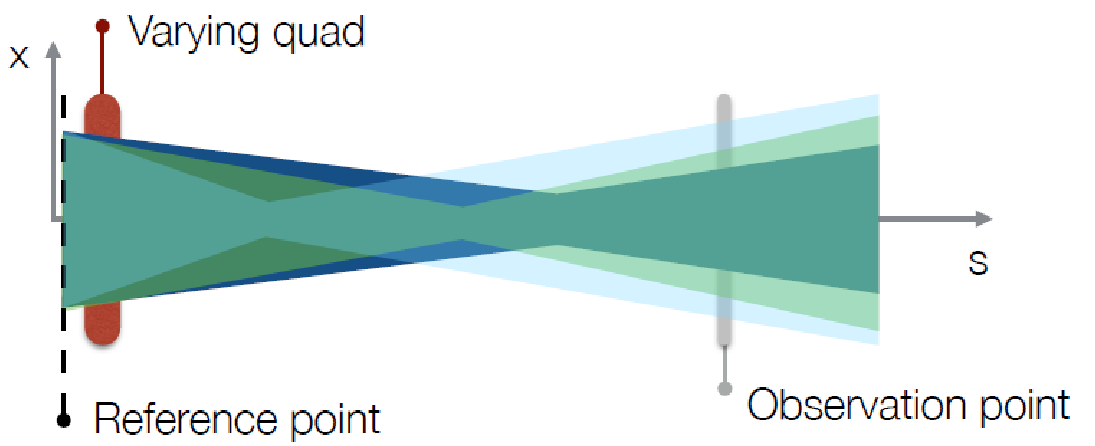
- Thick lens treatment often necessary in compact beamlines.



Problems:

- Resolution of screen,
- Time for scan (stability)
- Difficulty in fitting minimum
- Space charge effects

Present plan for rms emittance diagnostic for ~15-20 MeV e-beam: Quad Scan-Courant Snyder Fit



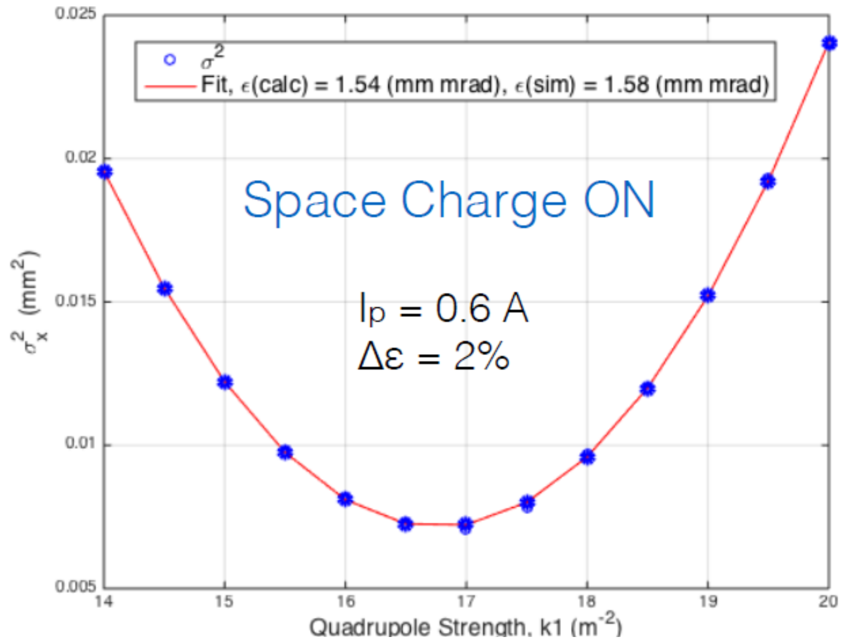
$$\sigma_{k,11} = \underbrace{(l^2 l_q^2 \sigma_{11})}_{A} k^2 + \underbrace{(2 l l_q \sigma_{11} + 2 l^2 l_q \sigma_{12})}_{B} k + \underbrace{(\sigma_{11} + 2 l \sigma_{12} + l^2 \sigma_{22})}_{C}$$

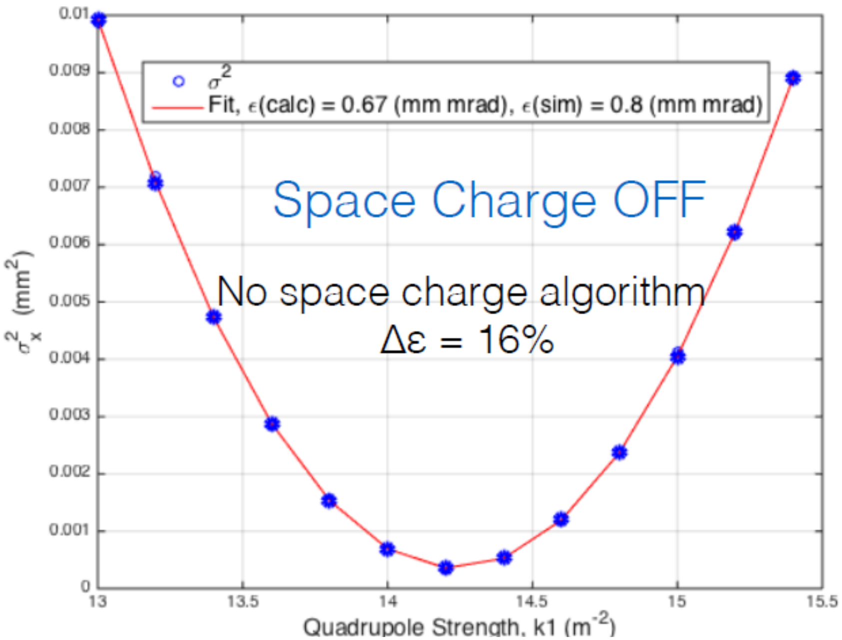
- Fit the square of the beam size to a second degree polynomial curve and get the parameters A, B and C.

$$\epsilon^2 = \sigma_{22}\sigma_{11} - \sigma_{12}^2$$

- Calculate σ_{11}, σ_{12}, and σ_{22} by using the fit parameters and calculate the emittance.
- Very sensitive to where we fit, work in the vicinity of the beam waist.

PARMELA RESULTS Q =0.2nC
Post Booster

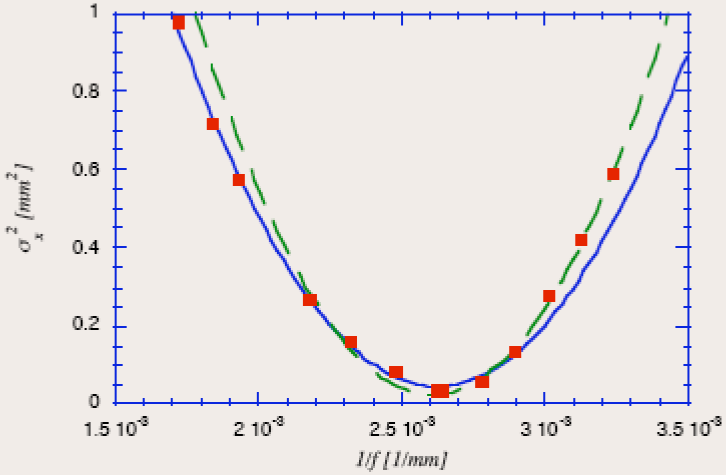


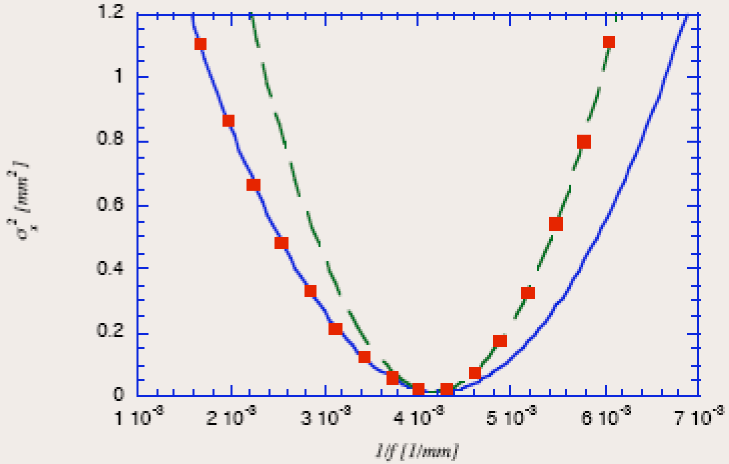


Limitations

- Very sensitive to beam size near the minimum and therefore resolution of the imaging system - problem if beam sizes are very small (<0.2mm)
- Fails to give good fit in presence of high charge high current beams.

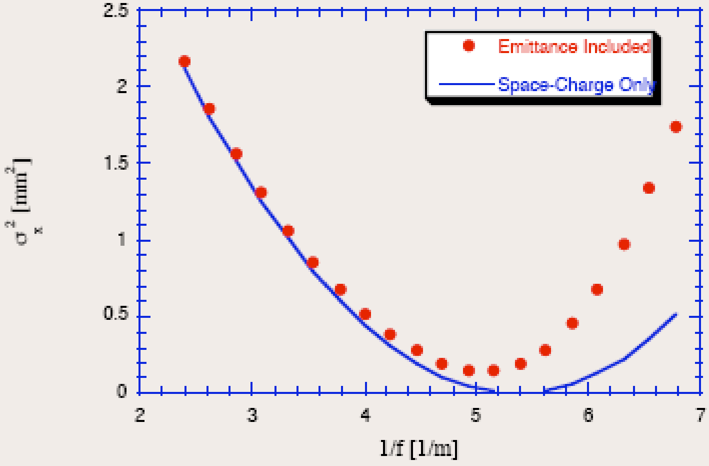
Interplay of Space-charge and Emittance: Simulation





Fitting on either side of minimum gives different result

- Data and simulation both show asymmetry about minimum spot size.
- Asymmetry is due to differential *emittance* forces. If waist is emittance dominated, then envelope looks very different before and after waist.
- Asymmetry makes fitting to a parabola problematic.



Define: geometric rms emittance

$$\tilde{\varepsilon}_x = \left(< x^2 >< x'^2 > - < xx' >^2 \right)^{1/2}$$

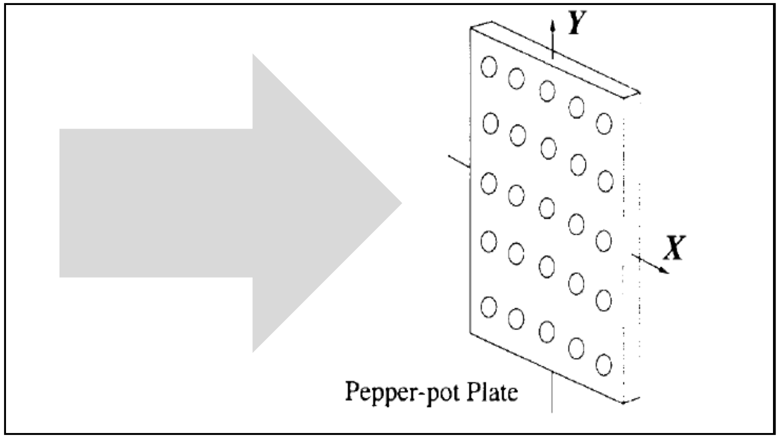
Under the conditions of zero acceleration and linear forces rms emittance is conserved.

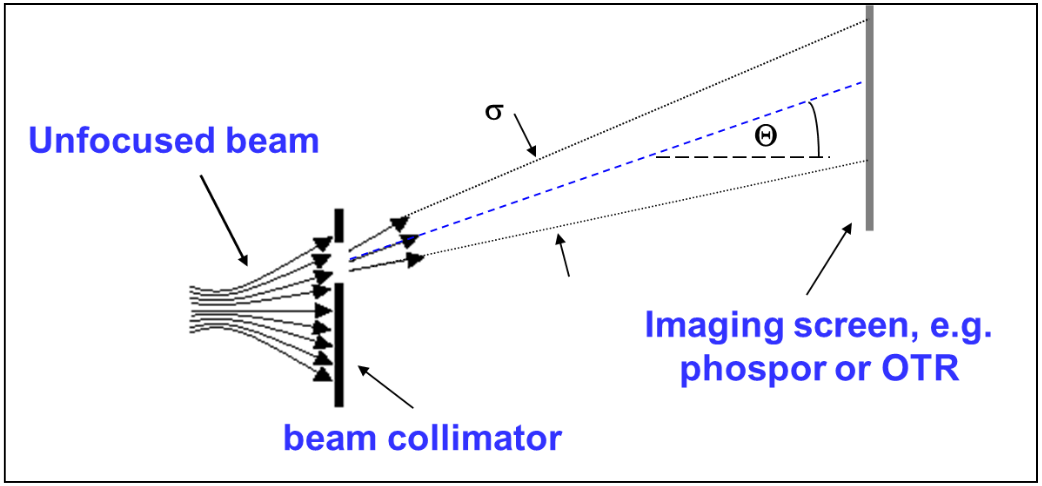
Define normalized, rms emittance

$$\tilde{\varepsilon}_{x,n} = \beta\gamma\tilde{\varepsilon}_x$$

Under the conditions of linear forces *normalized* rms emittance is conserved. even if the beam is accelerated.

2. Transverse Phase Space (x,x',y,y') mapping and rms emittance measurements





RMS beam size, divergence and cross correlation <xx'> can be all be calculated from the local values of x_i , x'_i measured at each pinhole position (i) in the pepperpot array

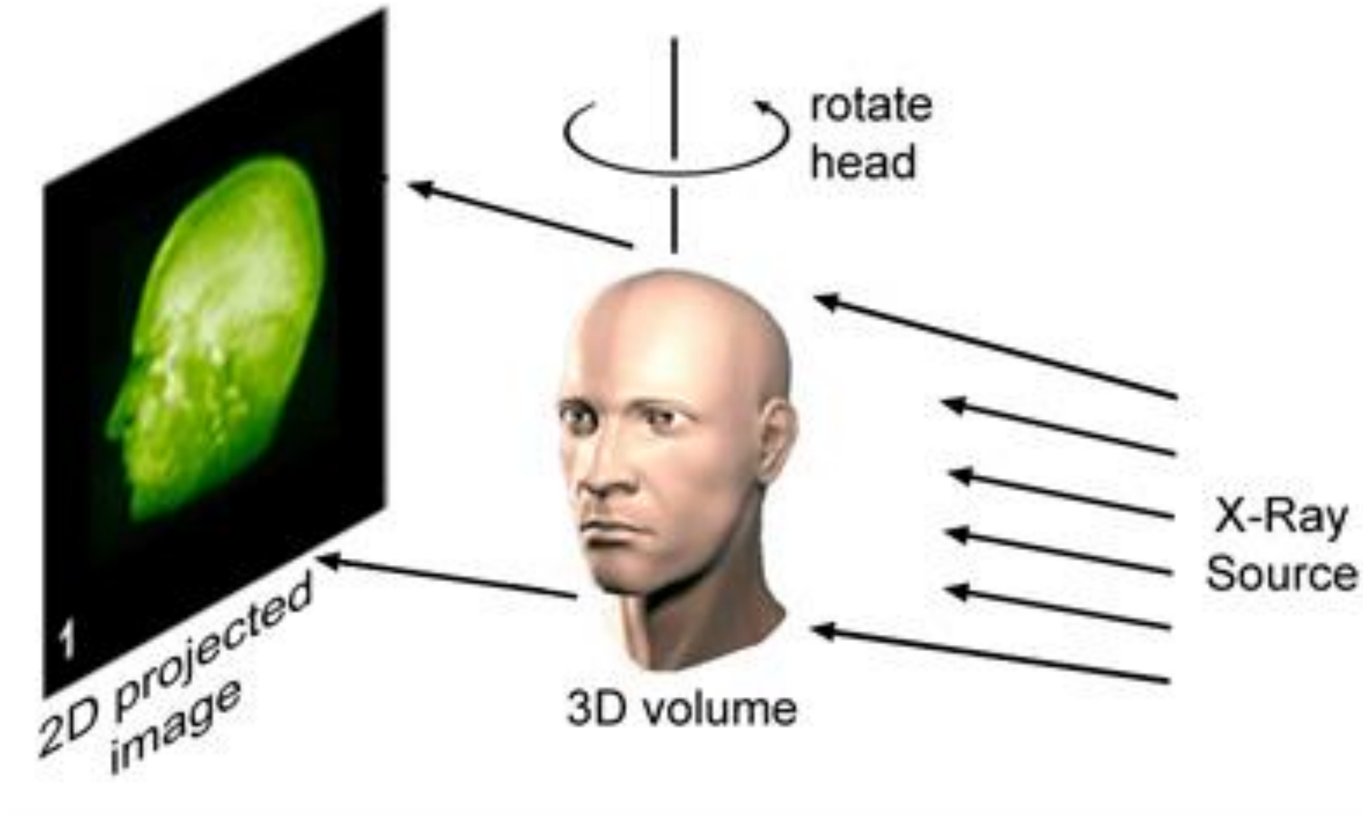
$$< x^2 > \equiv \frac{1}{M}\sum_{i=1}^{M}(x_i - \bar{x})^2, \quad \bar{x} \equiv \frac{1}{M}\sum_{i=1}^{M} x_i, \quad < xx' > \equiv \frac{1}{M}\sum_{i=1}^{M}(x_i - \bar{x})(x'_i - \bar{x}')$$

Thus the rms geometric emittance can be determined:

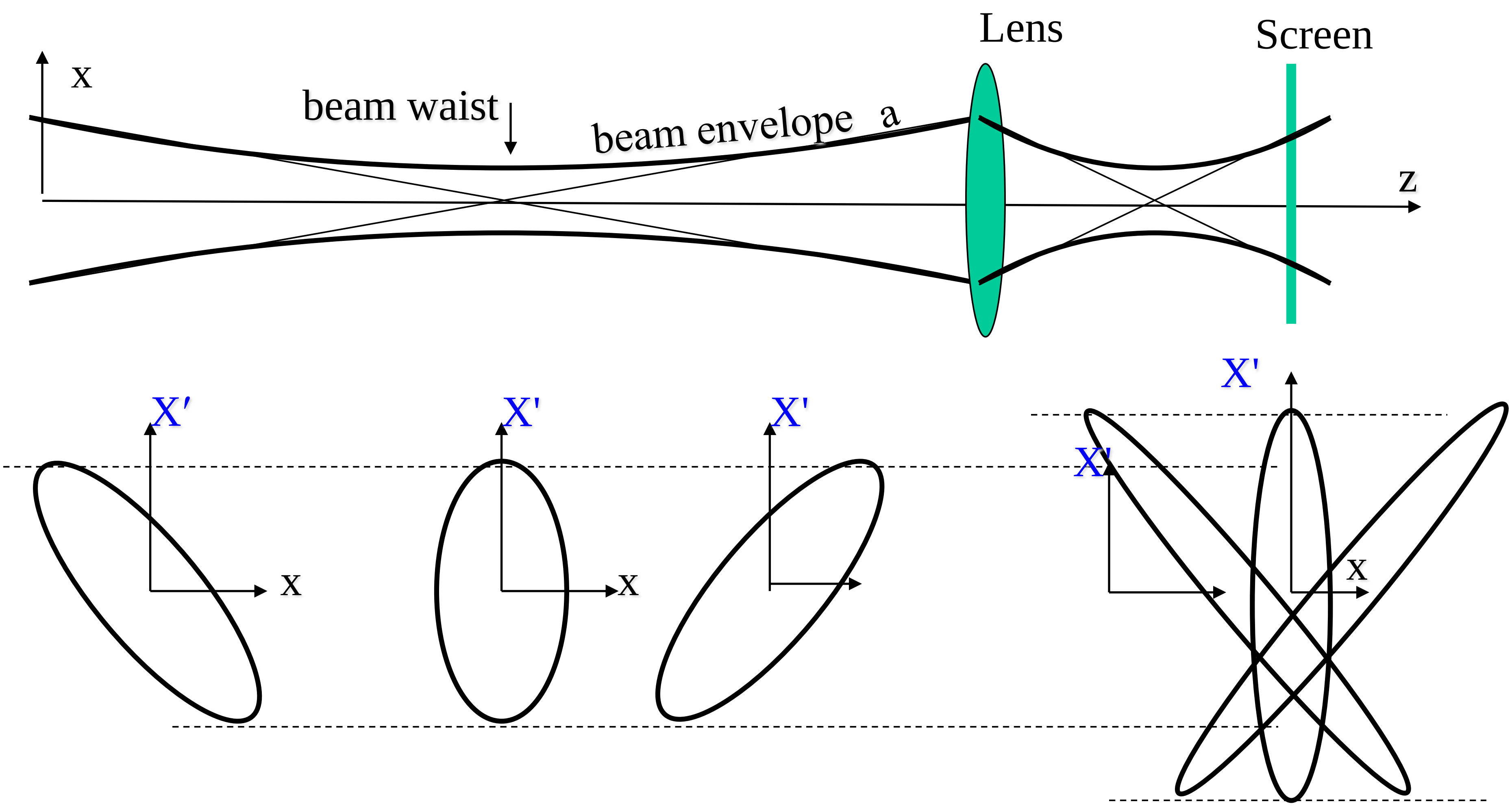
$$\tilde{\varepsilon}_x = \left(< x^2 >< x'^2 > - < xx' >^2\right)^{1/2}$$

3. Phase Space Tomography

Tomographic Principle: An object in n-dimensional space can be recovered from a sufficient number of projections onto (n-1)-dimensional space



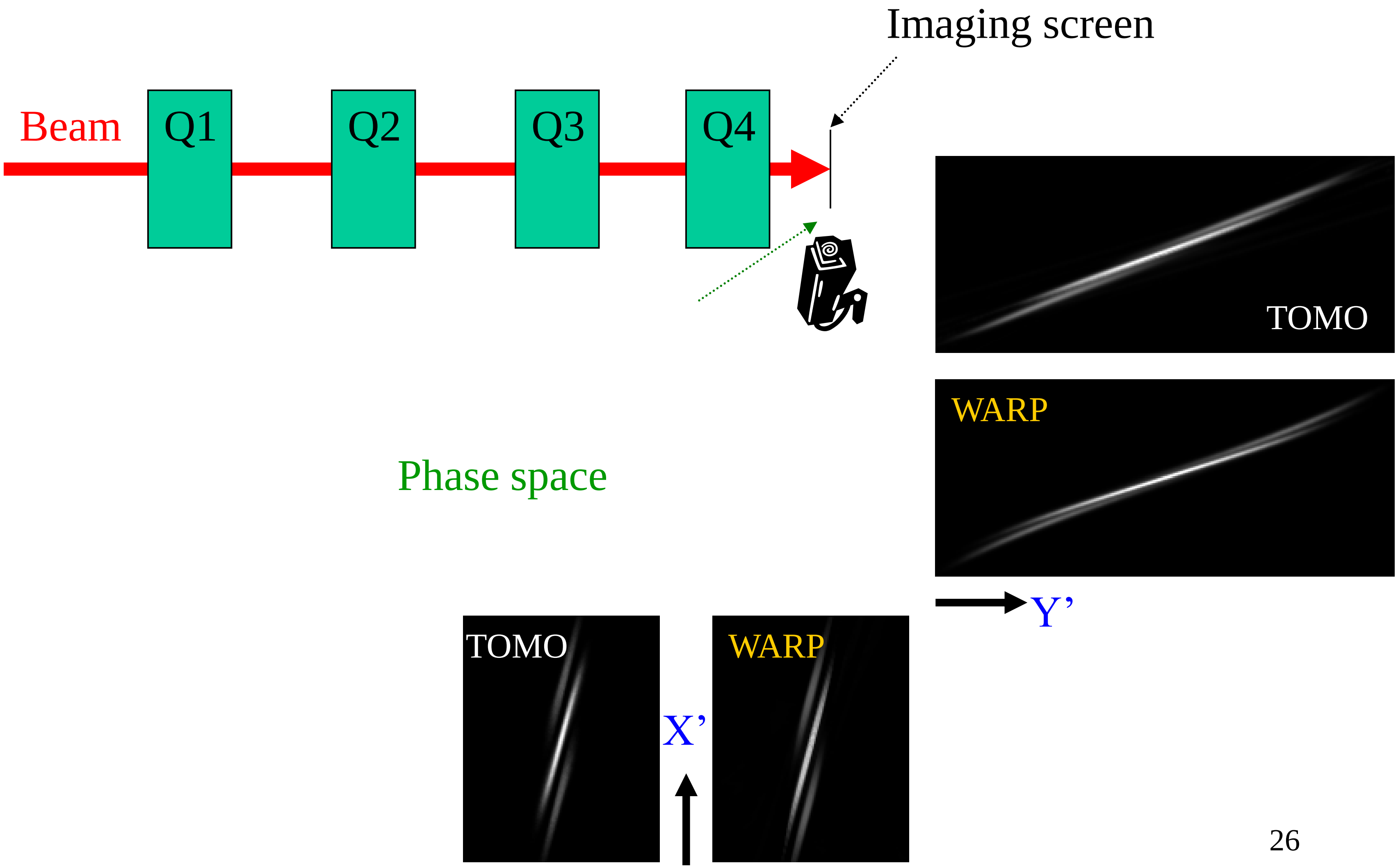
Phase-Space Tomography



- By varying focus (1/f) of magnetic lens (quadrupole) we rotate emittance ellipse in phase space and observe the effect at imaging screen ; rms beam size measured at Screen for each (1/f) is **a projection of the ellipse along x**;
- Reconstruction algorithm produces the phase (trace) space distribution P(x,x’).

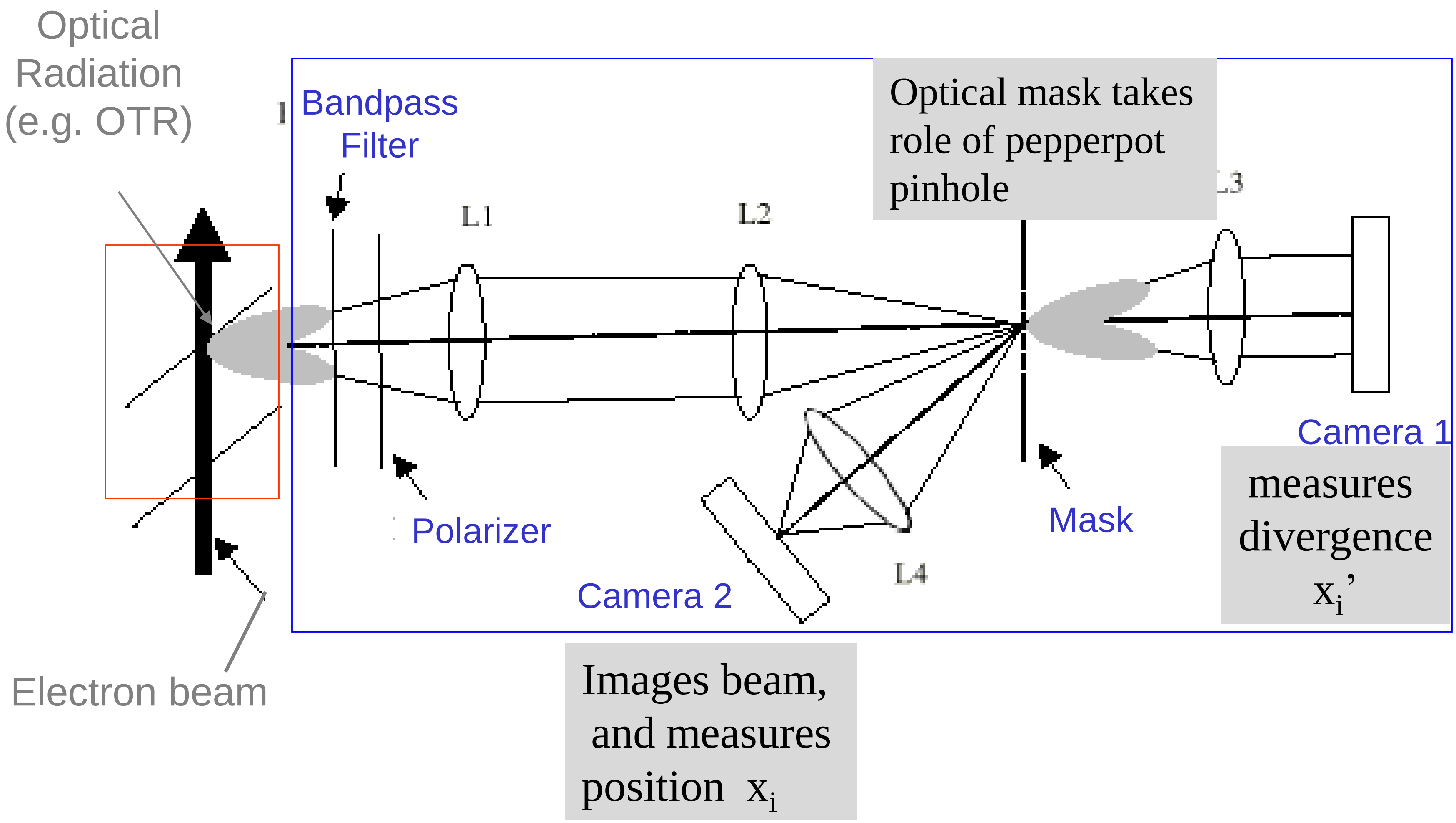
Tomography Simulation/ Validation

$$\chi = 0.72$$

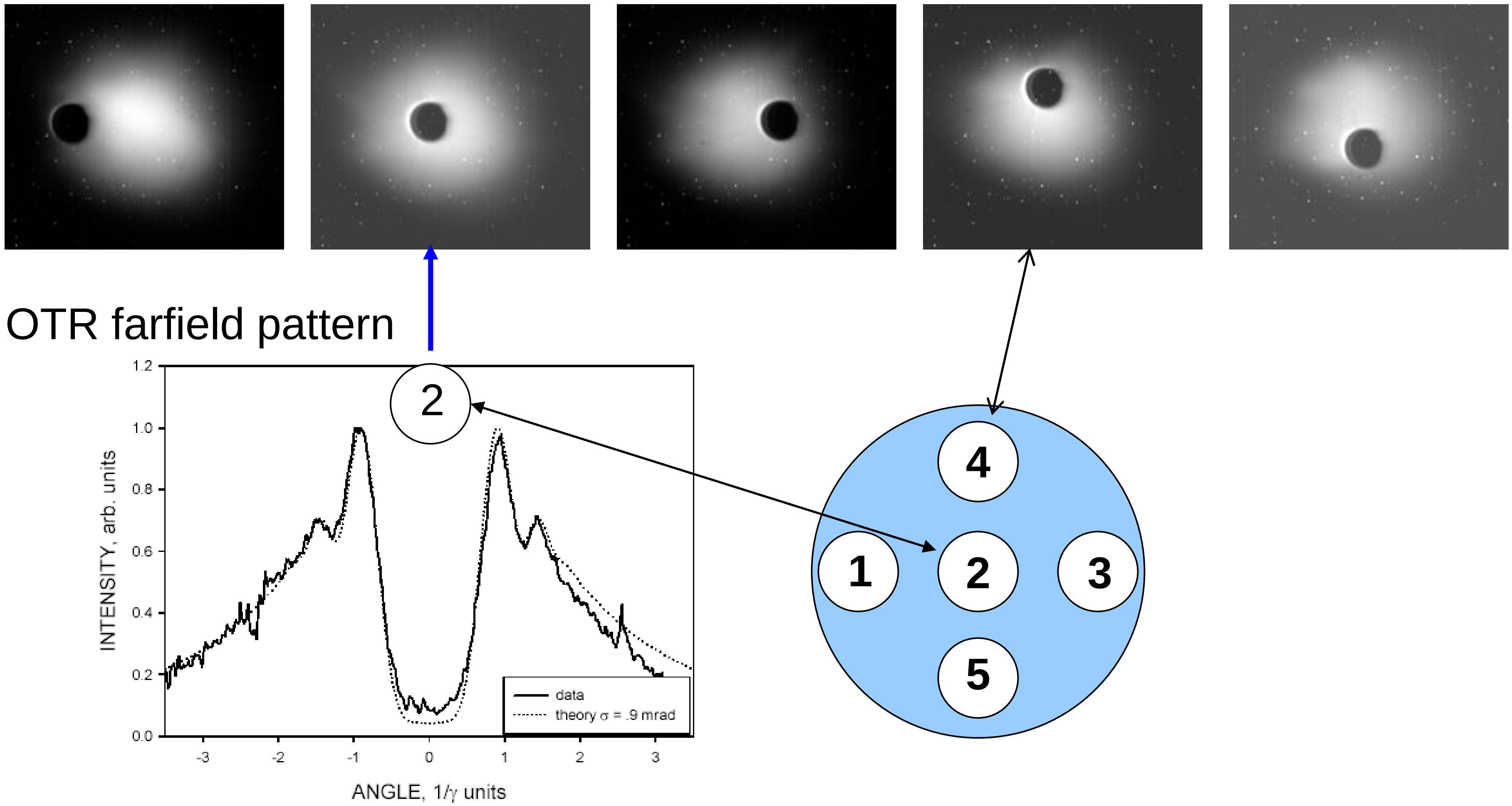


Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

Optical Phase Space Mapping (no beam collimator)

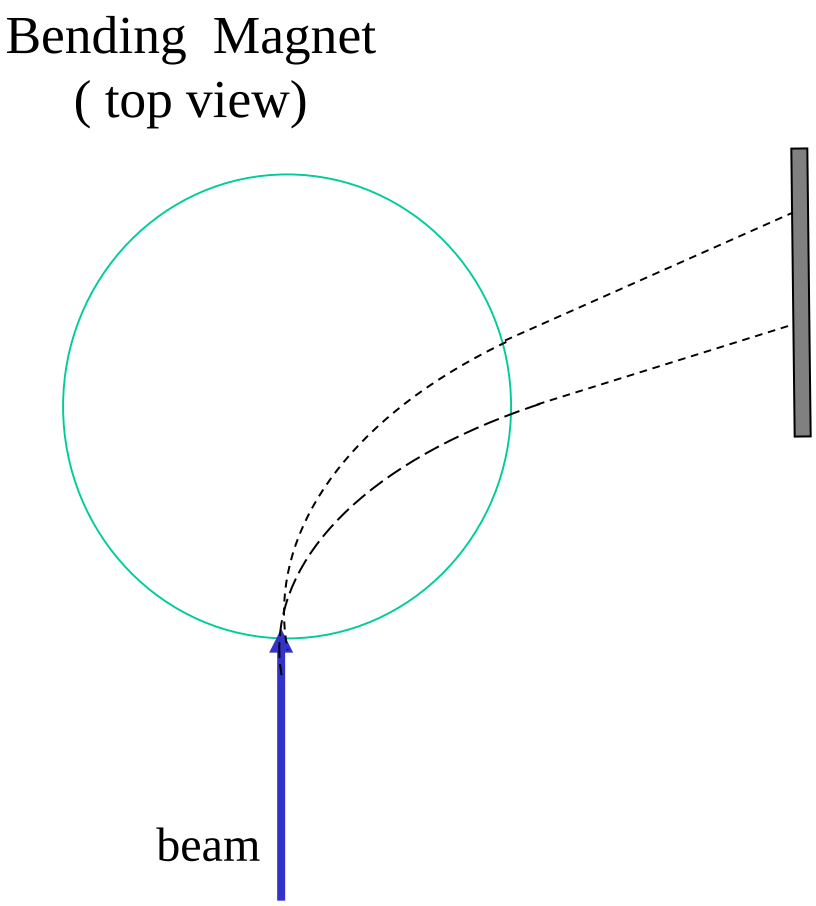


Local OTR divergence measurements using a scanning pinhole mask



Longitudinal Phase Space: Energy, arrival time of beam particles

Standard Energy and Energy Spread Diagnostic: High resolution Magnetic Spectrometer



Energy dispersion converted to position on imaging screen

Advantage:

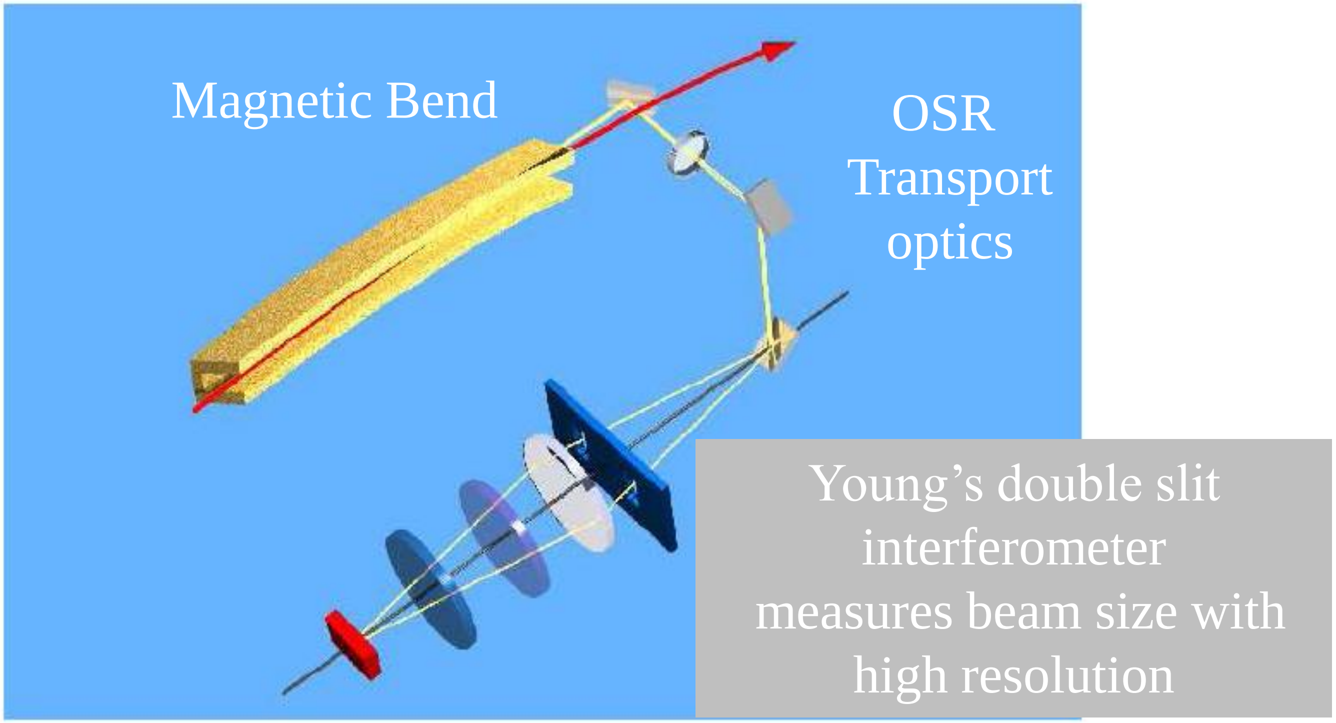
- can use any imaging method: phospor, OTR, OSR, etc.

Problems:

- usually large, bulky costly
- fixed position in beam line
- **resolution** usually limited by optics used to image beam,

(also beam energy and strength of the magnetic field)

Energy spread measurement using optical radiation and a double slit interferometer to measure beam size in a magnetic bend



In dispersive (magnetic) region, beam size is directly related to energy spread

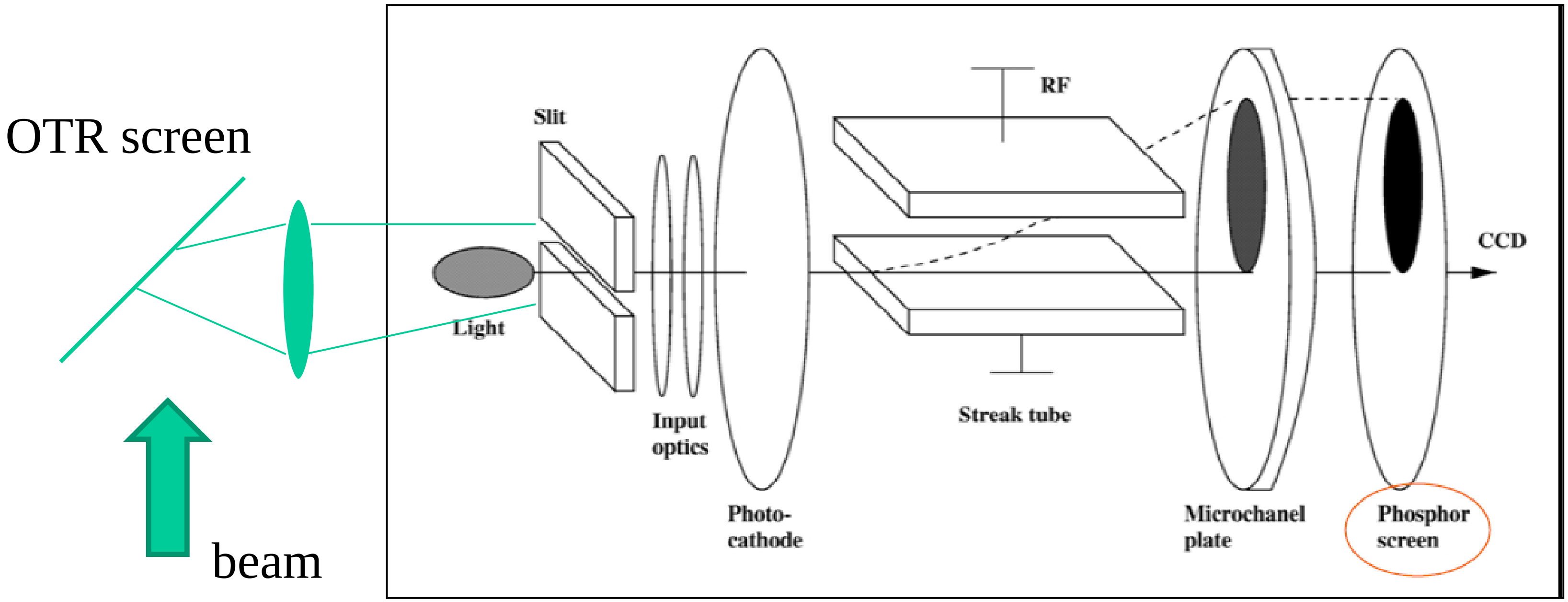
$$\sigma_E / E = \sigma_{beam} / R$$

e.g. $\sigma_E / E \sim 3 \times 10^{-5}$

when $\sigma_{beam} \sim 80$ microns, $R = 4$ m

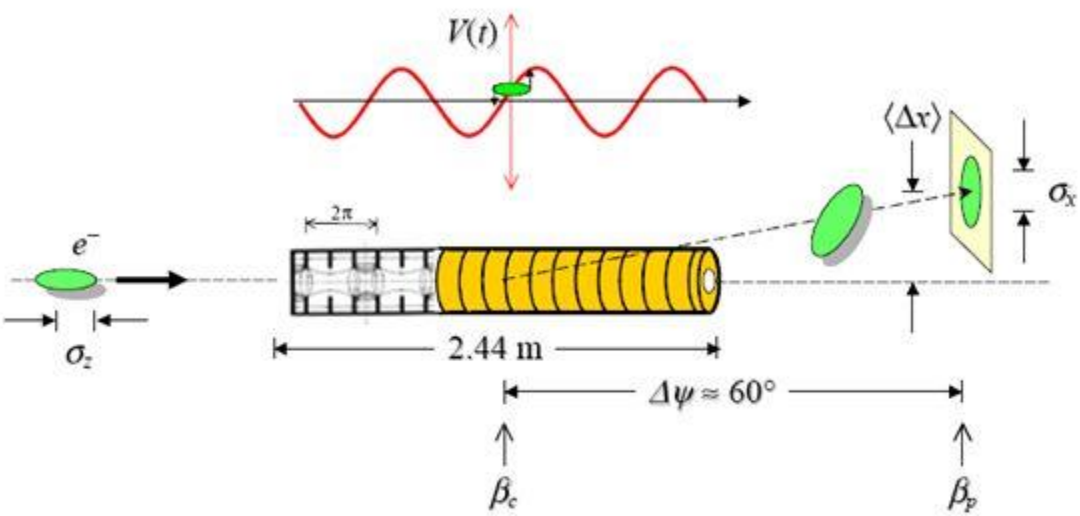
Longitudinal Bunch Distribution Diagnostics

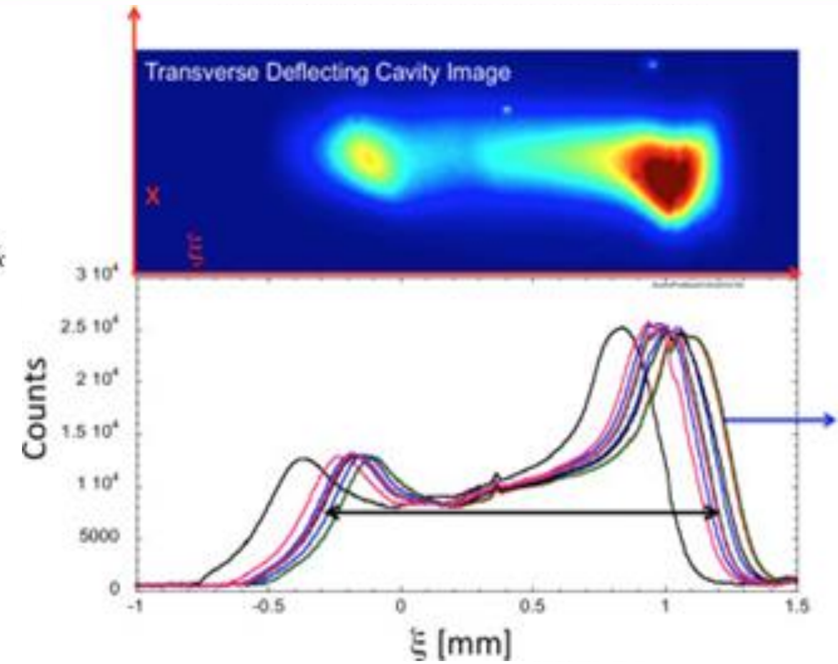
1. Fast optical emission from beam: OTR, OSR, etc. + Streak Camera



Resolution:
Spatial (depends on slit size 2- 20 microns
Temporal (200fs (best); 2ps (typical)

Bunch Length Measurement Using a RF Deflector





Principal of operation of the TM11 transverse deflecting RF cavity to crab the electron beam and measure its bunch length on a profile monitor.

Bunch Distribution (density) as a function of arrival time (ξ).

Temporal resolution: ~10's fs

SLAC-PUB-9241 by R. Akre, L. Bentson, P. Emma, P. Krejcik

Effect of Young's Double Slit Interference Visibility on Beam Size