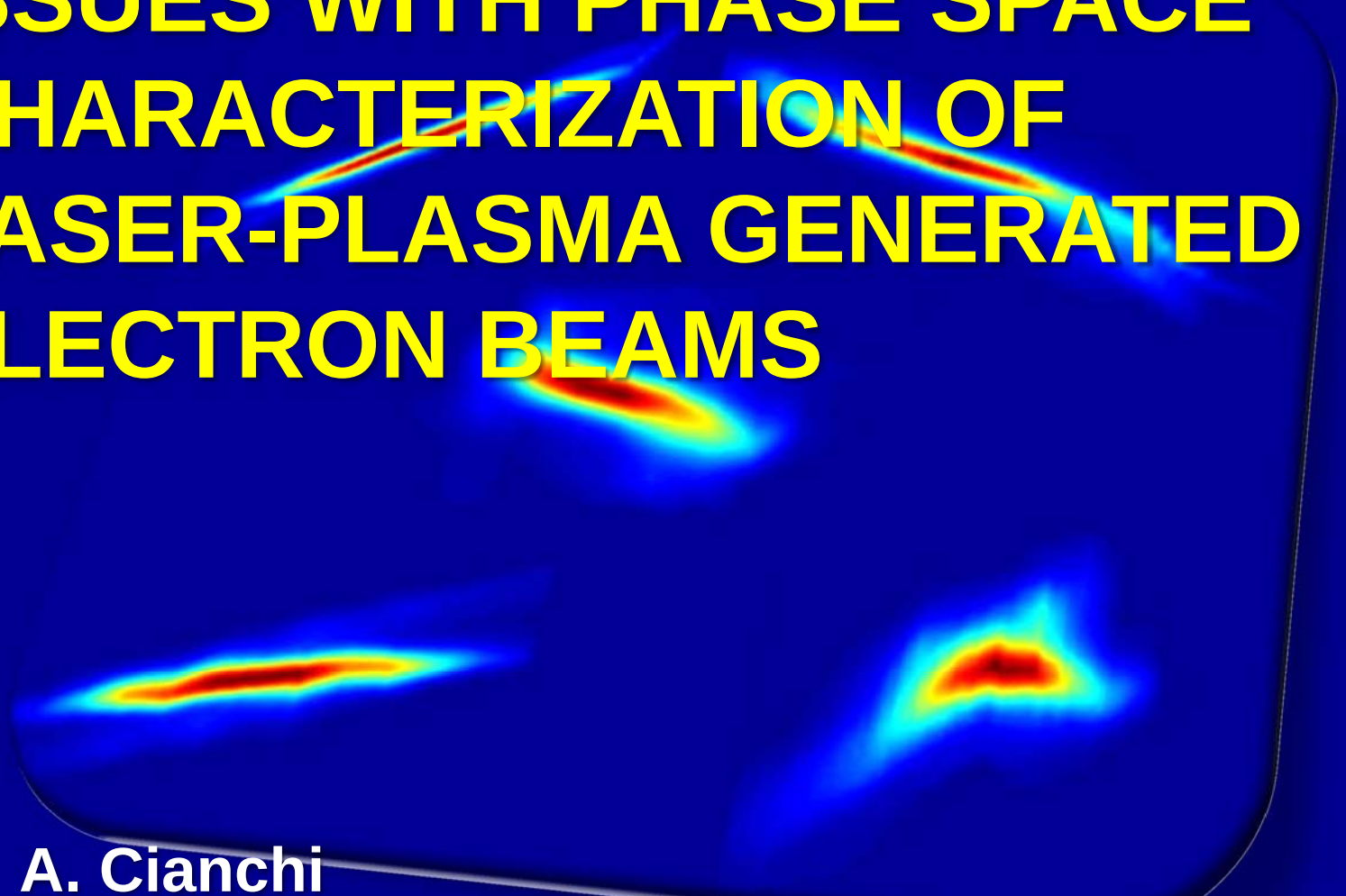
ISSUES WITH PHASE SPACE CHARACTERIZATION OF LASER-PLASMA GENERATED ELECTRON BEAMS



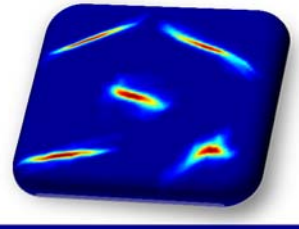
A. Cianchi

University of Rome “Tor Vergata & INFN

EAAC2013

1st European Advanced Accelerator Concepts Workshop

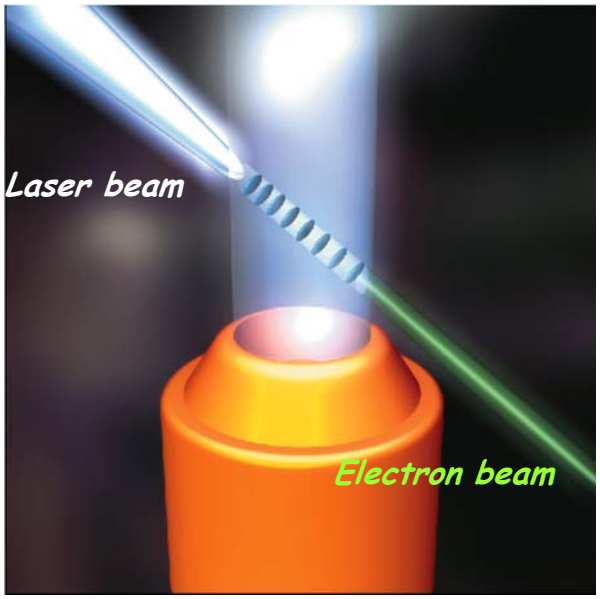
Diagnostics



- Point of view: electron beam diagnostics.
- We are looking not for a proof of principle experiment but for standard diagnostics:
  - Simple effect
  - Reliable and hopefully easy to implement

- Old sentence: an accelerator is just as good as its diagnostics

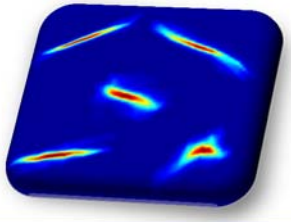
Plasma acceleration

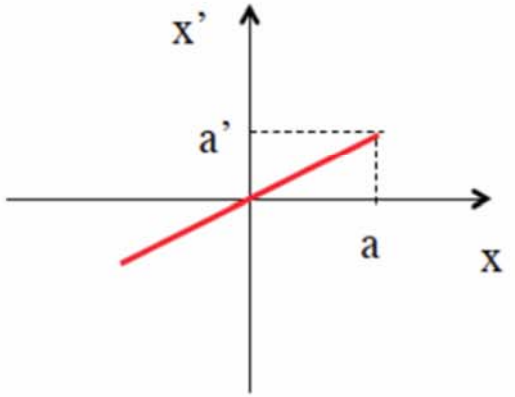


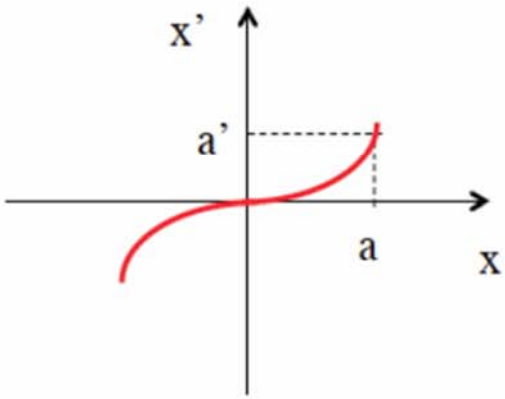
- We'll talk mainly about LWFA because there is much more work already done
- Some concepts we can extend also to PWFA

- The main problems in using conventional diagnostics
  - Energy spread
  - Angular spread

Importance of RMS emittance







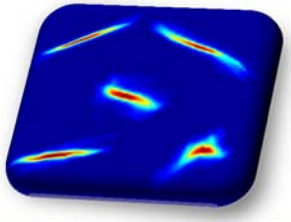
$$x' = Cx^n$$

$$\varepsilon_{rms}^2 = C\sqrt{\langle x^2 \rangle \langle x^{2n} \rangle - \langle x^{n+1} \rangle^2}$$

$$\begin{cases} n = 1 \Rightarrow \varepsilon_{rms} = 0 \\ n > 1 \Rightarrow \varepsilon_{rms} \neq 0 \end{cases}$$

Even when the phase-space area is zero, if the distribution lies on a curved line its rms emittance is not zero.
RMS emittance is not an invariant for Hamiltonian with non linear terms.

Geometrical vs Normalized



$$\varepsilon_n^2 = \left\langle x^2 \right\rangle \left\langle \beta^2 \gamma^2 x'^2 \right\rangle - \left\langle x \beta \gamma x' \right\rangle$$

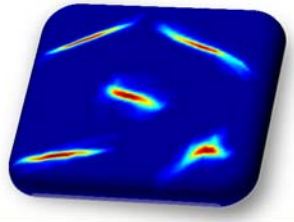
$$\sigma_E^2 = \frac{\left\langle \beta^2 \gamma^2 \right\rangle - \left\langle \beta \gamma \right\rangle^2}{\left\langle \gamma \right\rangle^2}$$

$$\varepsilon_n^2 = \left\langle \gamma \right\rangle^2 \sigma_\varepsilon^2 \left\langle x^2 \right\rangle \left\langle x'^2 \right\rangle +$$

$$+ \left\langle \beta \gamma \right\rangle^2 \left(\left\langle x^2 \right\rangle \left\langle x'^2 \right\rangle - \left\langle x x' \right\rangle^2 \right)$$

P. Antici, et al., Journal of Applied Physics 112, 044902 (2012)

Fundamental issue



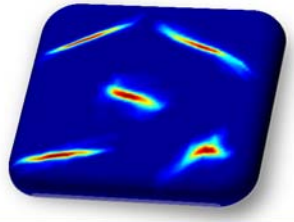
$$\varepsilon_n^2 = < \gamma >^2 \left(\sigma_\varepsilon^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2 \right) \qquad \sigma_x(s) \approx \sigma_{x'} s$$

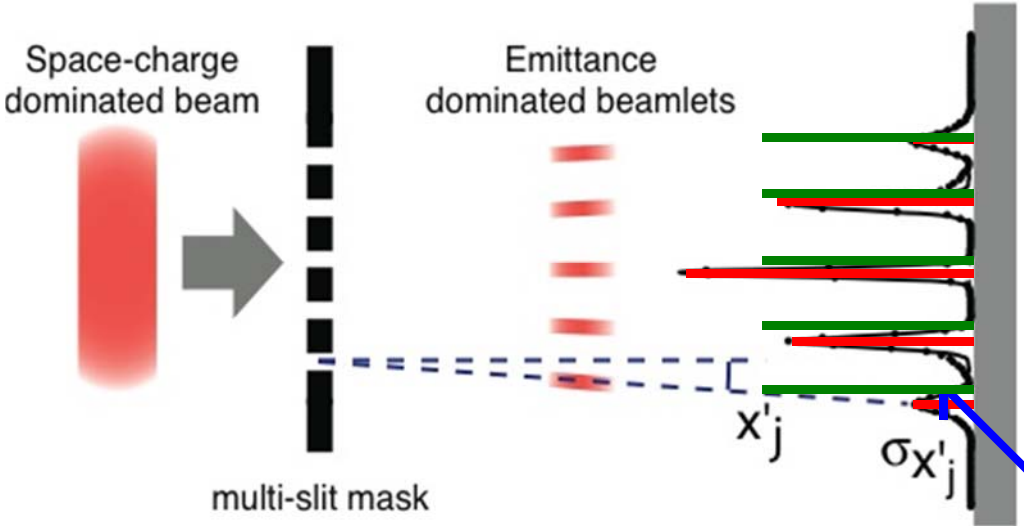
$$\varepsilon_n^2 = < \gamma >^2 \left(s^2 \sigma_\varepsilon^2 \sigma_{x'}^4 + \varepsilon^2 \right)$$

- For the accelerator community the normalized emittance is one of the main parameter because is constant
- For such a beam, due to the large energy spread and huge angular divergence, it is not true anymore

P. Antici, et al., Journal of Applied Physics 112, 044902 (2012)

RMS Emittance measurements with pepper-pot like structures





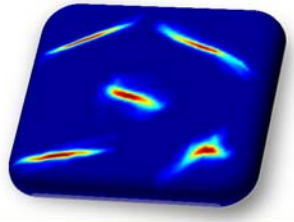
To measure the emittance for a space charge dominated beam the used technique is the well known 1-D pepper-pot

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

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

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

Design issues



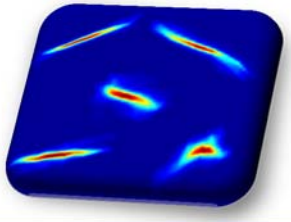
- The contribution of the slit width to the size of the beamlet profile should be negligible
- The material thickness (usually tungsten) must be long enough to stop or heavily scatter beam at large angle (critical issue at high energy)
- The angular acceptance of the slit cannot be smaller of the expected angular divergence of the beam

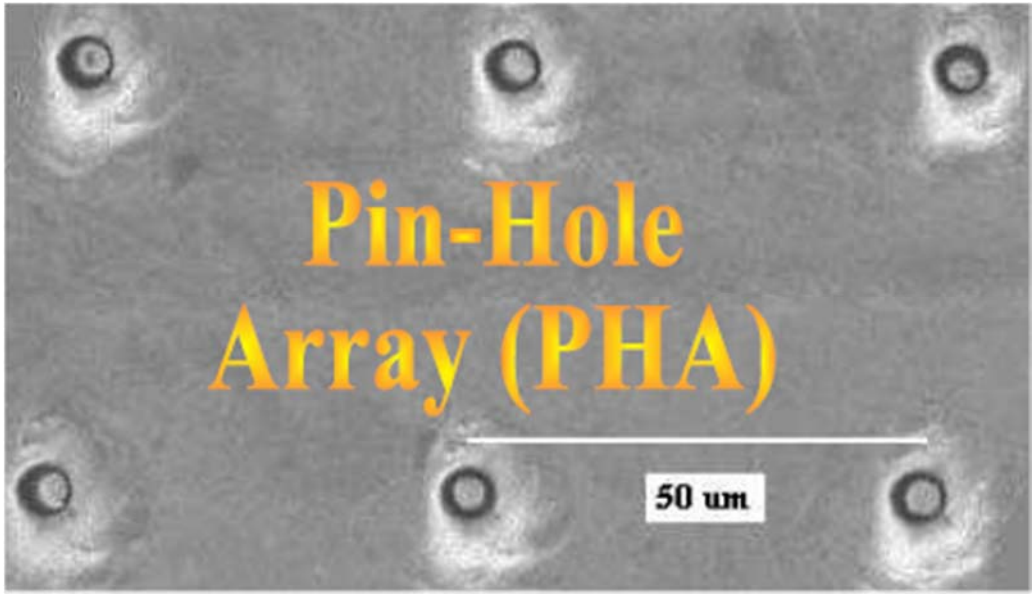
$$\sigma = \sqrt{(L \cdot \sigma')^2 + \left(\frac{d^2}{12}\right)}$$

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

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

Holes machining

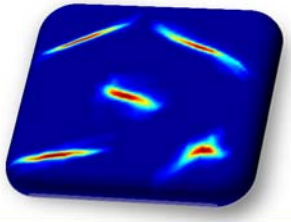


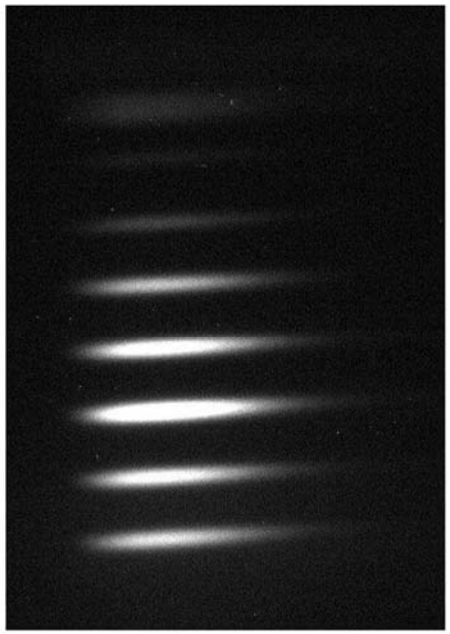


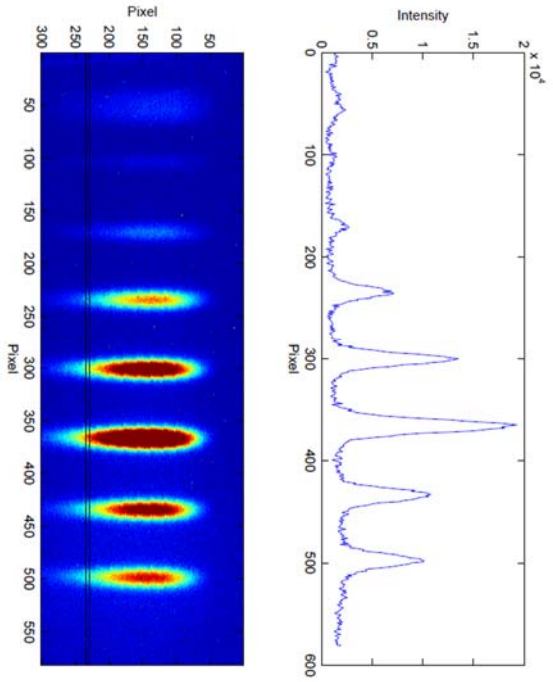
T. Levato and al. "*Fabrication of 3 μm diameter pin hole array (PHA) on thick W substrates*", AIP Conf. Proc. Vol 1209, pp 59-62 (2010)

- Holes array have been successfully produced.
- The thickness of the material can be as large as 100 times the hole diameter

High energy pepper pot



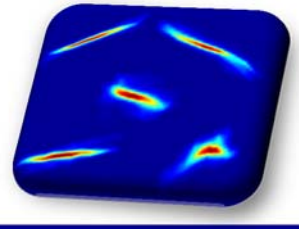




- In principle can operate also at moderate to high energy (500 MeV- 1 Gev)
- Length 50 mm, slit 500 μm, spaced 2 mm

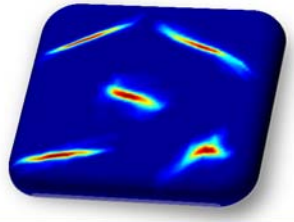
N. Delerue and al. "TRANSVERSE EMITTANCE MEASUREMENT AT HIGH ENERGY USING LONG PEPPER-POT", Proceedings of IPAC'10, Kyoto, Japan MOPE078

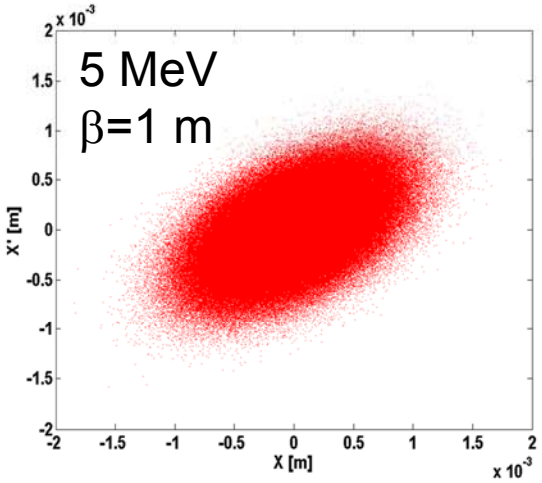
Looking for intrinsic limit of this technique for LWFA beams

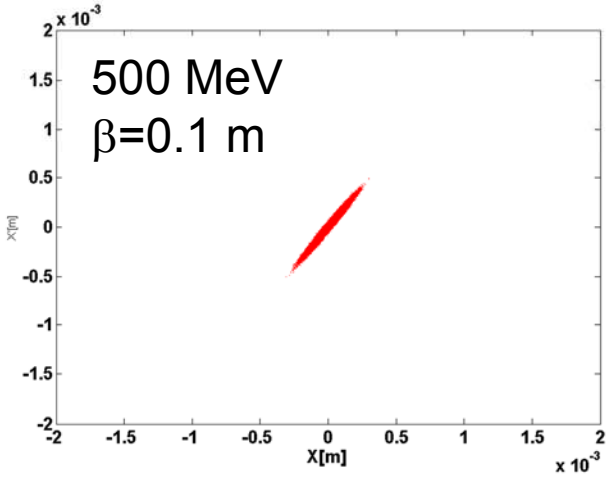


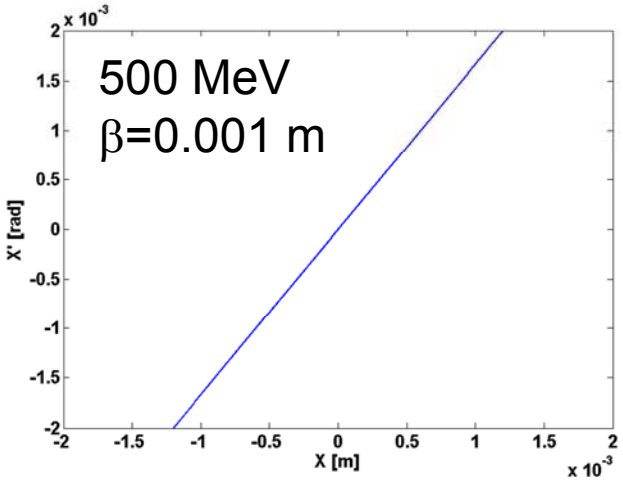
- No considerations about
  - S/N ratio
  - Detector
  - Multiple scattering
  - Background
- Mask thickness neglected

Trace spaces



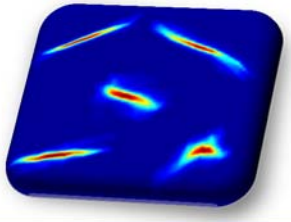


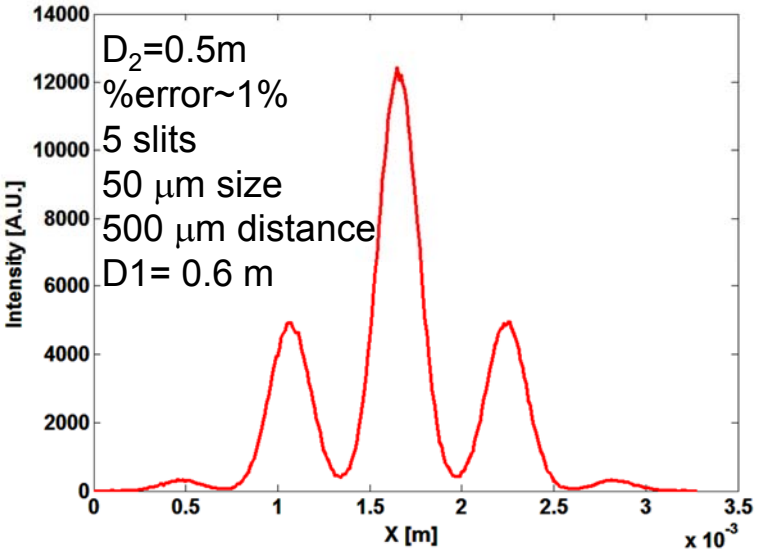




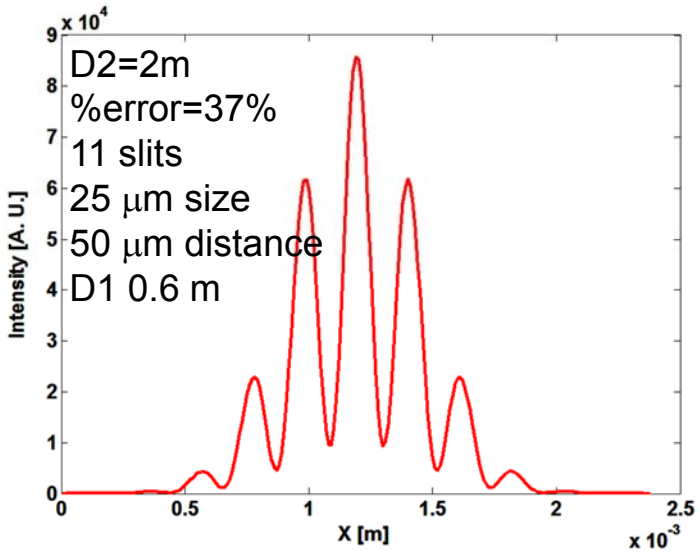
- All beams have ε_n=1 mm-mrad
- z=0.6 m
- β=0.1 m means 10 μm on the source
- β=0.001 m means 1 μm on the source

No problems

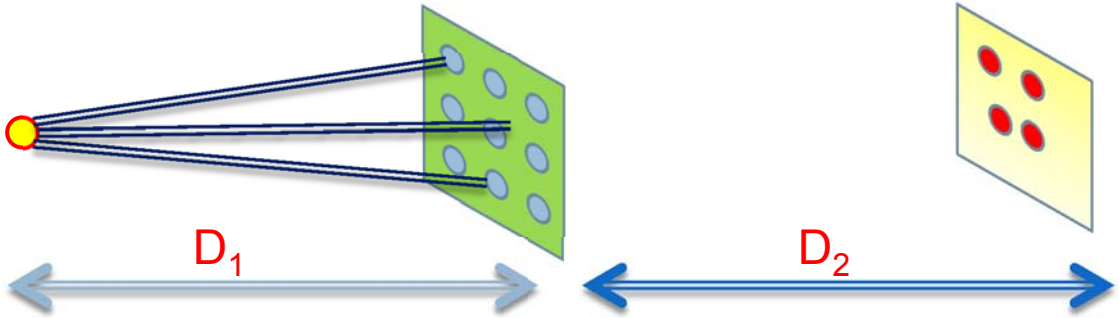




5 MeV β=1 m

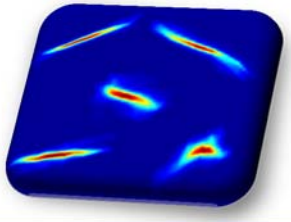


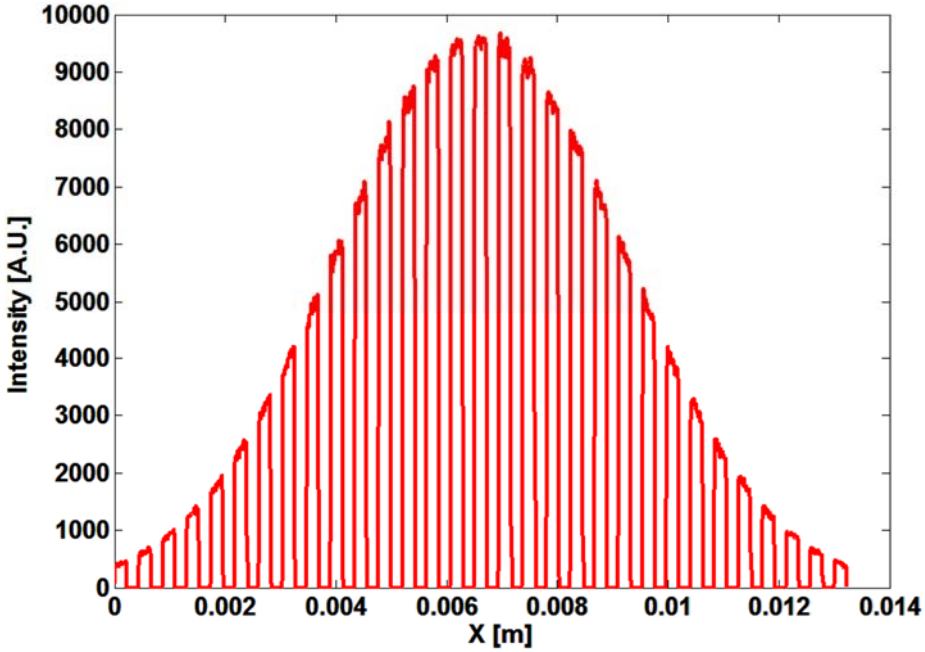
500 MeV β=.1 m



- Everything roughly optimized in to minimize the error and to use all the particles

No chances for β=0.001 m

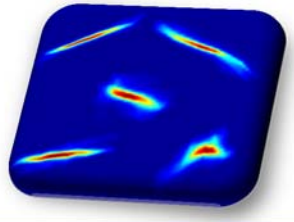




D2=2m
%error>1000%
31 slits
50 μm size
100 μm distance
D1 0.6 m

- The phase space is so thin that the sampling is very inefficient especially in angle

Bibliography



PRL 105, 215007 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

Low Emittance, High Brilliance Relativistic Electron Beams from a Laser-Plasma Accelerator

E. Brunetti, R. P. Shanks, G. G. Manahan, M. R. Islam, B. Ersfeld, M. P. Anania, S. Cipiccia, R. C. Issac, G. Raj, G. Vieux, G. H. Welsh, S. M. Wiggins, and D. A. Jaroszynski*

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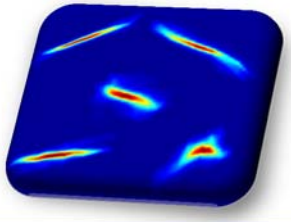
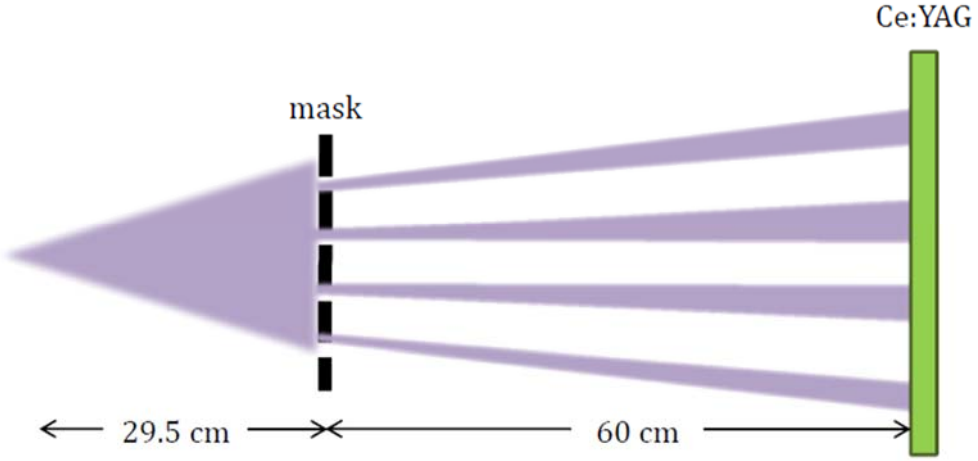
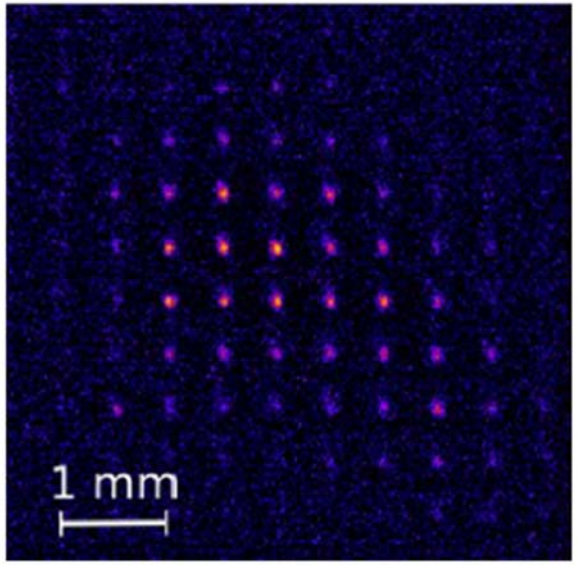
(Received 31 August 2010; published 19 November 2010)

- Very good paper, well documented, a lot of details, except for the definition of the normalized emittance.
- Energy 125 MeV, energy spread 1%
- 125 μm mask thick
- Charge in the order of few pC
- Normalized emittance in the order of mm-mrad

Experimental setup

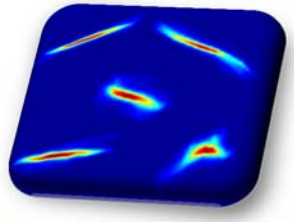






- 25 μm diameter
- 150 μm spaced
- Assuming β=0.025 and neglecting any other source of noise the error coming from undersampling is about 47% in my calculation
- Just increasing the drift up to 2 meter would reduce it to 27%

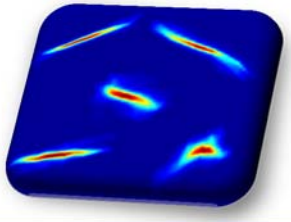
Multiple screens



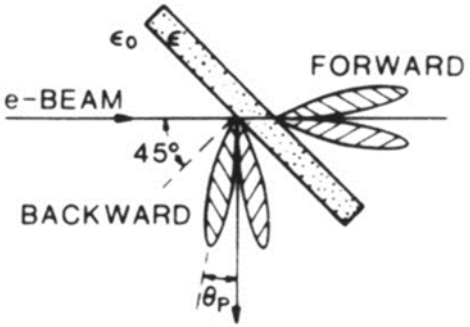
$$\sigma_{i,11} = C_i^2 \sigma_{11} + 2 S_i C_i \sigma_{12} + S_i^2 \sigma_{22}$$

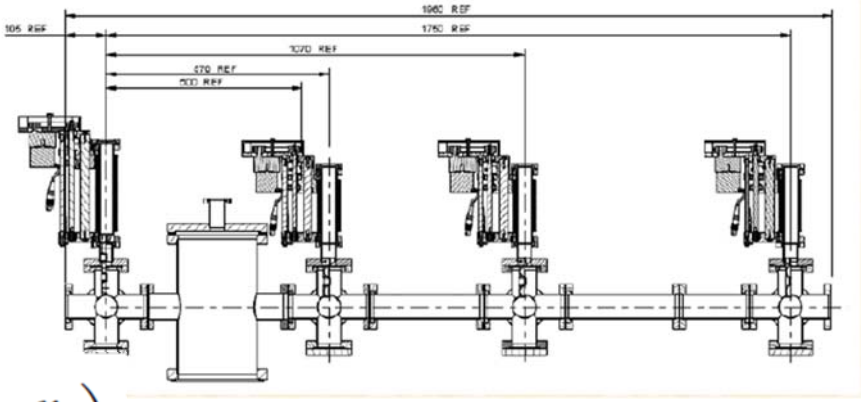
- There are 3 unknown quantities
- $\sigma_{i,11}$ is the rms beam size squared
- C_i and S_i are the element of the transport matrix
- We need 3 measurements in 3 different positions to evaluate the emittance

Multiple OTR monitor?



- C. Thomas, N. Delerue and R. Bartolini “Single shot transverse emittance measurement from
- OTR screens in a drift transport section”, 2011 JINST 6 P07004

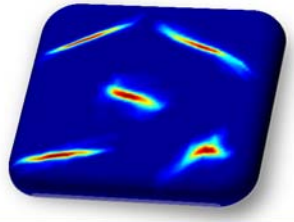




$$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left(1+0.038ln\frac{x}{X_0}\right)$$

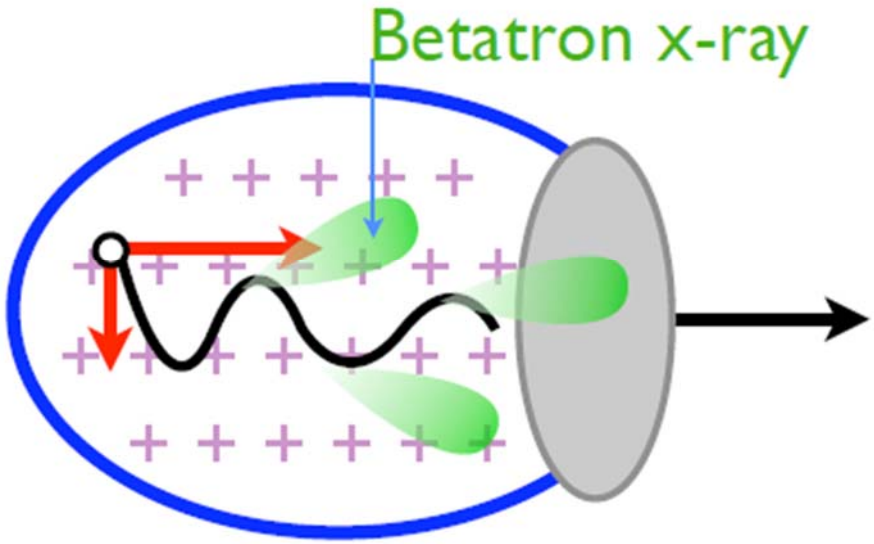
- ✓ In their case (3GeV) the multiple scattering is not a factor for thin (5 μm) screens
- ✓ It is possible to produce even 1 μm aluminum screen
- ✓ A waist in the drift region is a must!
- ✓ This system seems not feasible for beams with energy in the range of hundreds of MeV

Betatron radiation

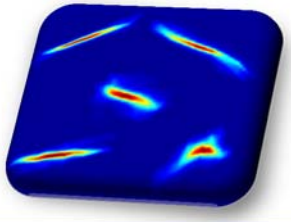


A.Rousse et al. “Production of a keV X-Ray Beam from Synchrotron Radiation in Relativistic Laser-Plasma Interaction”, PRL 93, 13, 135005 (2004)

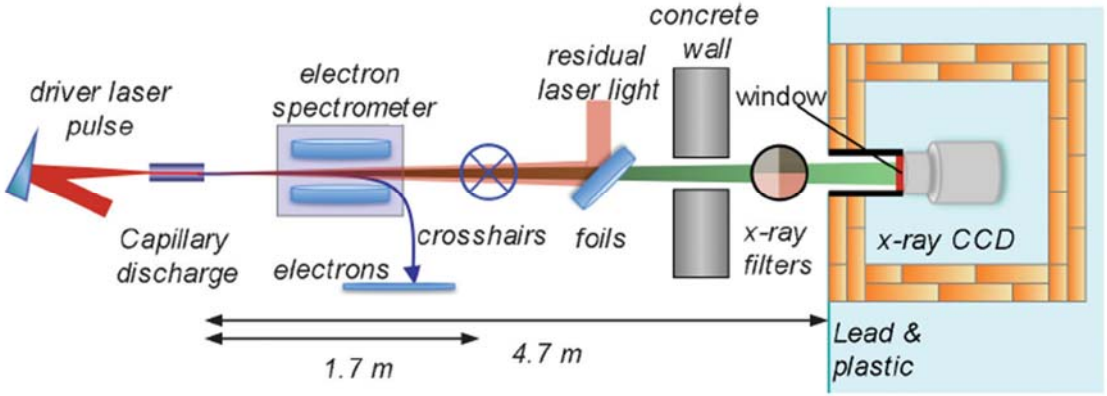
$$\lambda_b = \lambda_p \sqrt{2\gamma} \propto \sqrt{1/n_e}$$

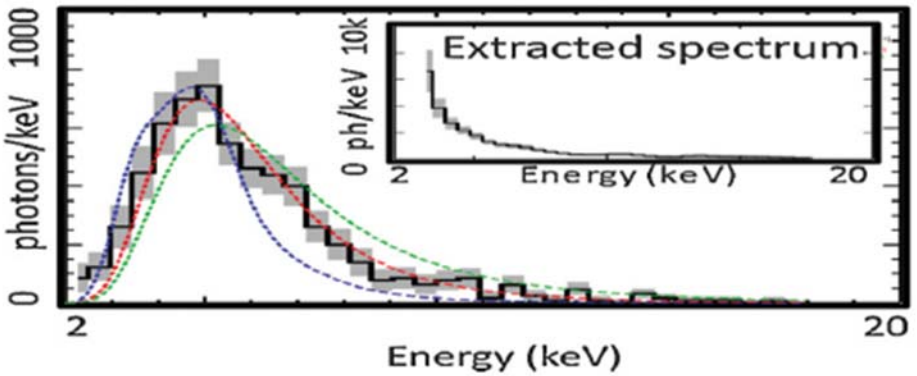


Betatron spectroscopy



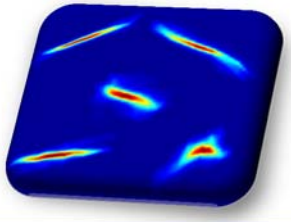
G. R. Plateau and al., Low-Emittance Electron Bunches from a Laser-Plasma Accelerator Measured using Single-Shot X-Ray Spectroscopy, PRL 109, 064802 (2012)



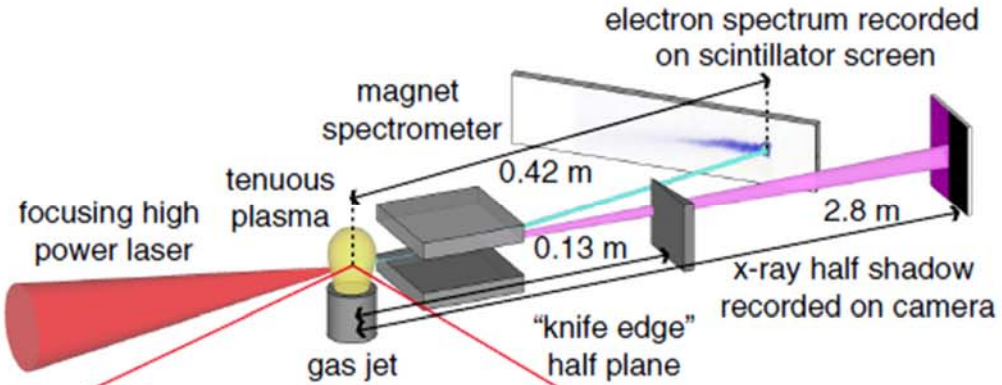


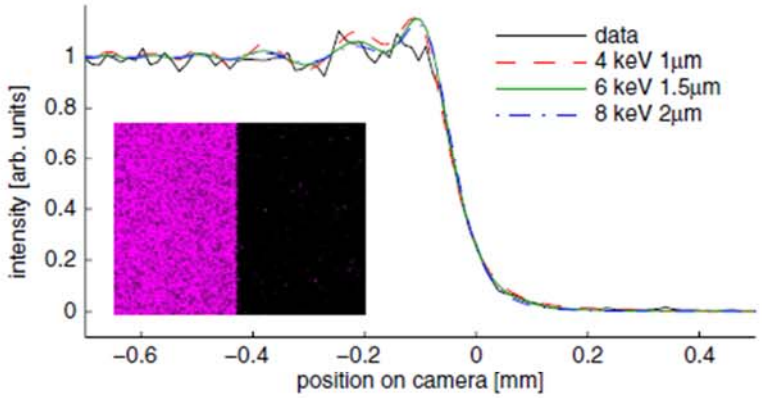
- 400 MeV energy with a rms energy spread of less than 5% and 1 mrad divergence from a plasma density of 5 $10^{18}cm^3$

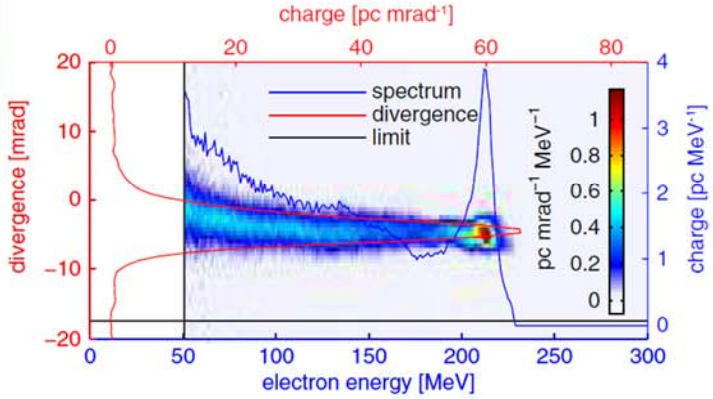
$\sigma\ \sigma'\ \gamma\ \Delta\gamma$ at the same time



- S. Kneip and al., PRST-AB 15, 021302 (2012)



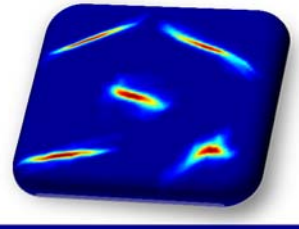




Source size by
Fresnel diffraction

Energy, energy spread and divergence
behind the dipole

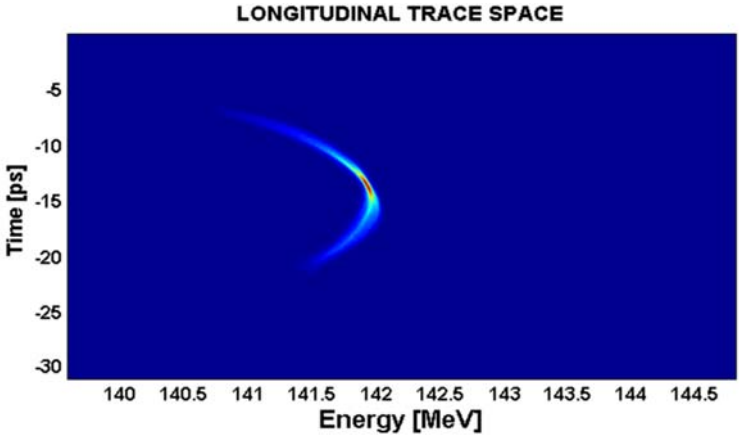
Deflecting cavity



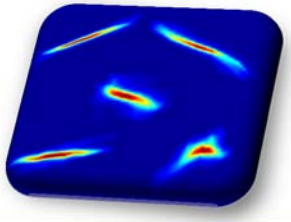
$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{p_z c}\left[\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right]$$

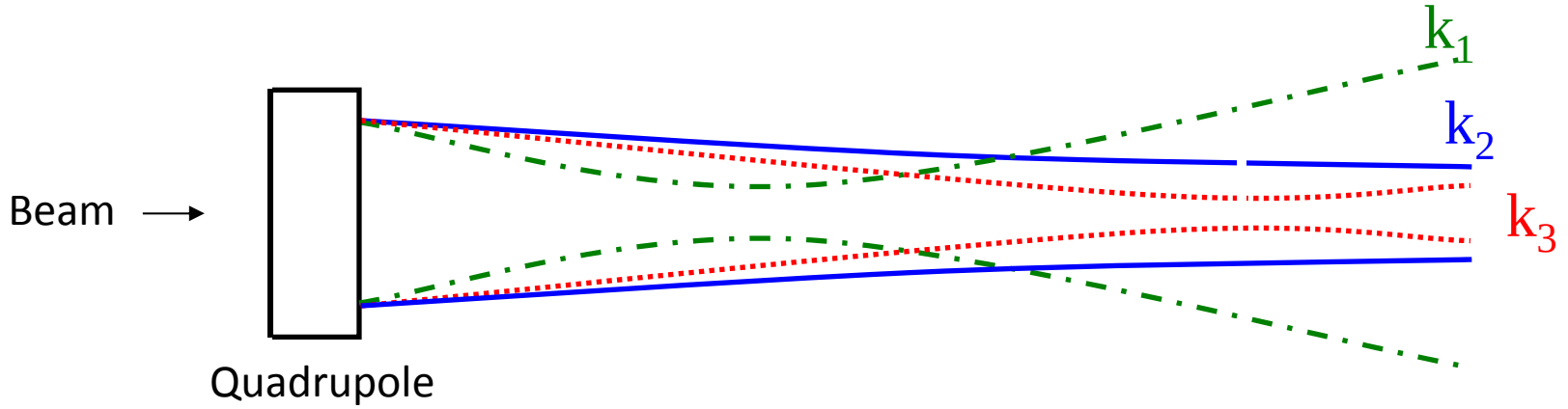
$$\Delta x'_{RFD} >> \Delta x'_{beam}$$

- In a S band deflector with V_0= 2 MV and bunch length ~ 100 fs $\Delta x'$~37 urad
- C-band can have V_0=10MV with shorter wavelength resulting in $\Delta x'$ 370 urad!
- The RFD can be used with a quadrupole to focus at least in the vertical plane -> limit to the energy spread.



Quadrupole scan

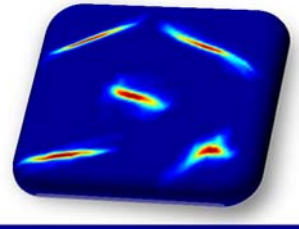




$$\sigma_{11} = C^2(k)\sigma_{11} + 2C(k)S(k)\sigma_{12} + S^2(k)\sigma_{22}$$

- Changing the strength of a magnetic lens is possible to measure the beam size
- With a least 3 different measurements is possible to retrieve the elements of the sigma matrix that are related with the emittance
- Multi shot measurement

Chromatic effects



Assuming the particle energy uncorrelated from its transverse position/divergence

$$\varepsilon_1^2 = \left\langle x_1^2 \right\rangle \left\langle x_1'^2 \right\rangle - \left\langle x_1 x_1' \right\rangle^2 = \varepsilon_0^2 + \underbrace{(kl)^2 \sigma_x^4 \sigma_\gamma^2}_{\varepsilon_{chr}^2} = f(\varepsilon_0, \sigma_\gamma, \sigma_x)$$

CASE 1: Moderate spot size ≈ 0.3 mm

	REF	Simulated
ε_{nx} (mm-mrad)	1.375	1.372
ε_{ny} (mm-mrad)	1.413	1.419

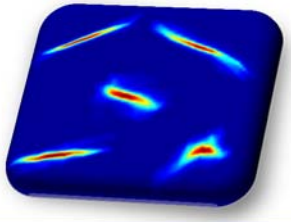
CASE 2: Large spot size ≈ 1.7 mm

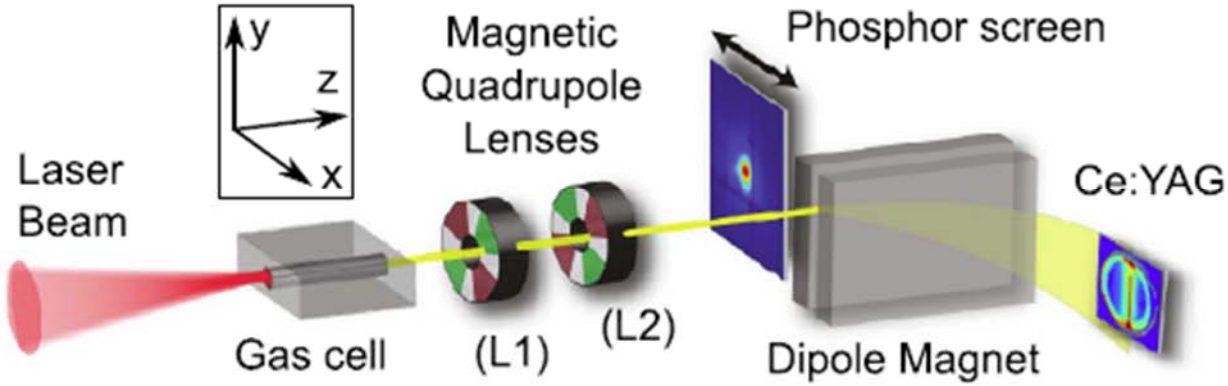
	REF	Simulated
ε_{nx} (mm-mrad)	3.07	4.32
ε_{ny} (mm-mrad)	3.02	4.38

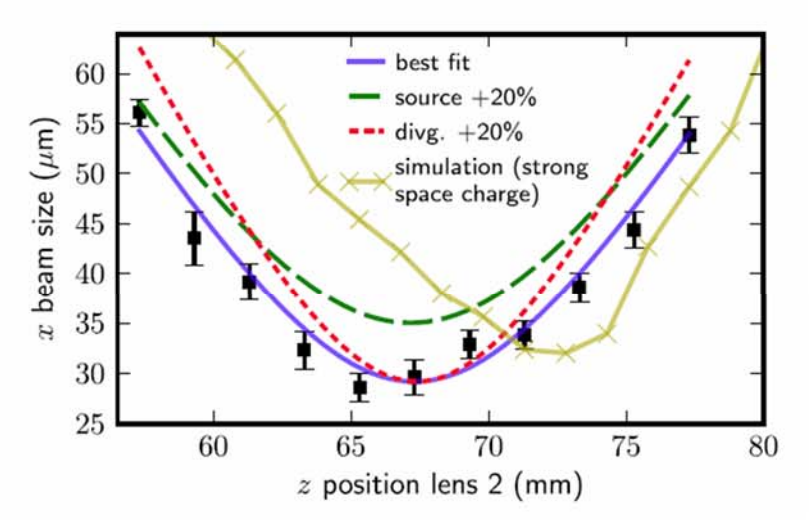
From the experience at SPARC, we learnt that a 1.7 mm spot size at the quadrupole, with 1% energy spread, produces an error of 50% on the emittance.

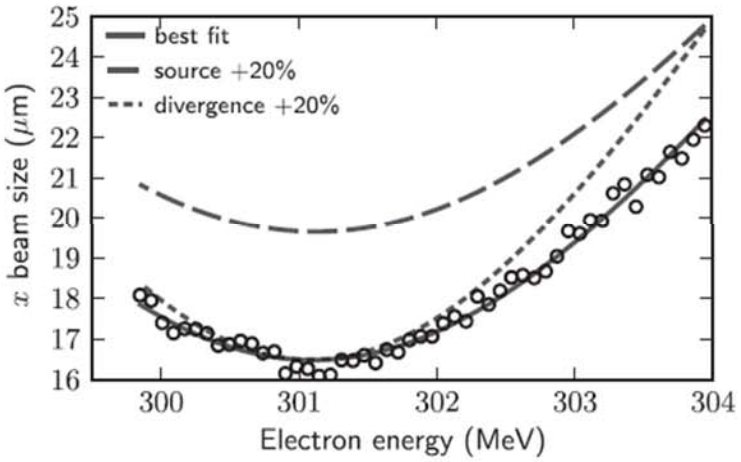
A. Mostacci, M. Bellaveglia, E. Chiadroni, A. Cianchi, M. Ferrario, D. Filippetto, G. Gatti, and C. Ronsivalle
Chromatic effects in quadrupole scan emittance measurements PRST-AB 15, 082802 (2012)

A new kind of Quadscan



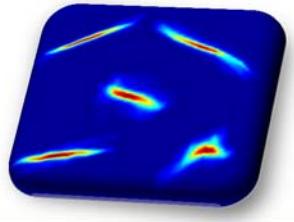






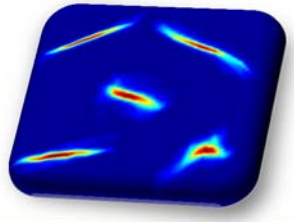
- R. Weingartner and al., PRST-AB 15, 111302 (2012),

Conclusions?



- Conventional diagnostic are sometimes not adequate, mainly due to the energy spread and the large angular divergence.
- The same meaning of normalized emittance must be revised.
- Pepper pot is not adequate for strongly correlated beams.
- Interesting techniques has been tested to measure the transverse and the longitudinal properties but there are still some concerns about emittance.
- Is the large energy spread (>few%) an ‘hic sunt leones’ for reliable emittance beam measurements?

Many thanks to…



- D. Alesini, M. P. Anania, M. Castellano, E. Chiadroni, S. Cipiccia, D. Di Giovenale, M. Ferrario, P. Musumeci, G.Penco, R. Pompili, A. R. Rossi, L. Serafini, C. Vaccarezza, F. Villa and maybe somebody else that I forgot!