Overview on advanced diagnostics for High Brightness Beams

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Outline

- Brightness
- Emittance
- Incoming and outcoming beam measurements
- State of the art
- Conclusion

Definitions of Brightness

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

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

From diagnostics point of view what does it mean high brightness?

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

Parameters to measure

- Charge
- Energy
- Energy spread
- Transverse and longitudinal profile
- Emittance
- 6D

Geometrical vs Normalized

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

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

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

M. Migliorati et al, Physical Review Special Topics,Accelerators and Beams 16, 011302 (2013)

K. Floettmann, PRSTAB,6, 034202 (2003)

Fundamental issue

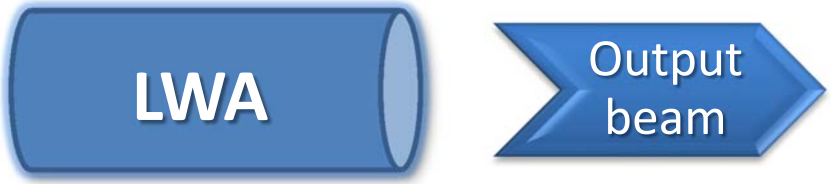
$$\varepsilon_n^2 = <\gamma>^2 \left(\sigma_\varepsilon^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2\right)$$

$$\sigma_x(s) \approx \sigma_{x'} s$$

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

- **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**

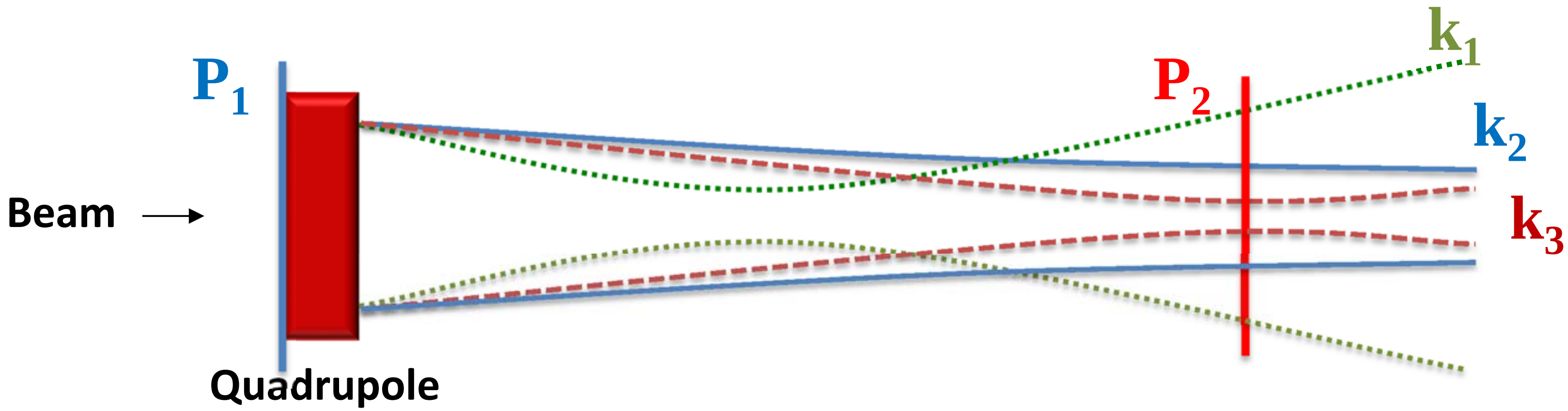
Two main scenarios



- LWA: Diagnostics of the output beam

- PWFA: Diagnostics of both input (hopefully not intercepting) and output beam

Quad scan



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

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

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

We need at least 3 measurements in 3 different positions to evaluate the emittance

Main limitations

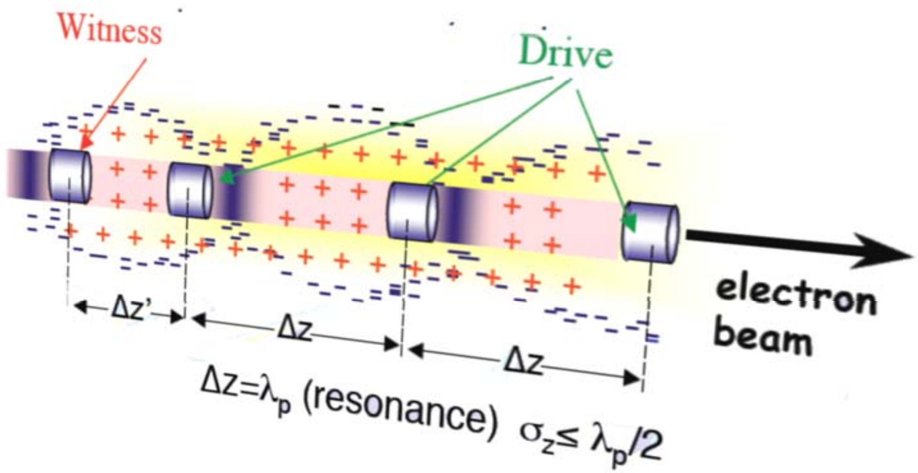
- Multi shots

- Intercepting

- Chromaticity

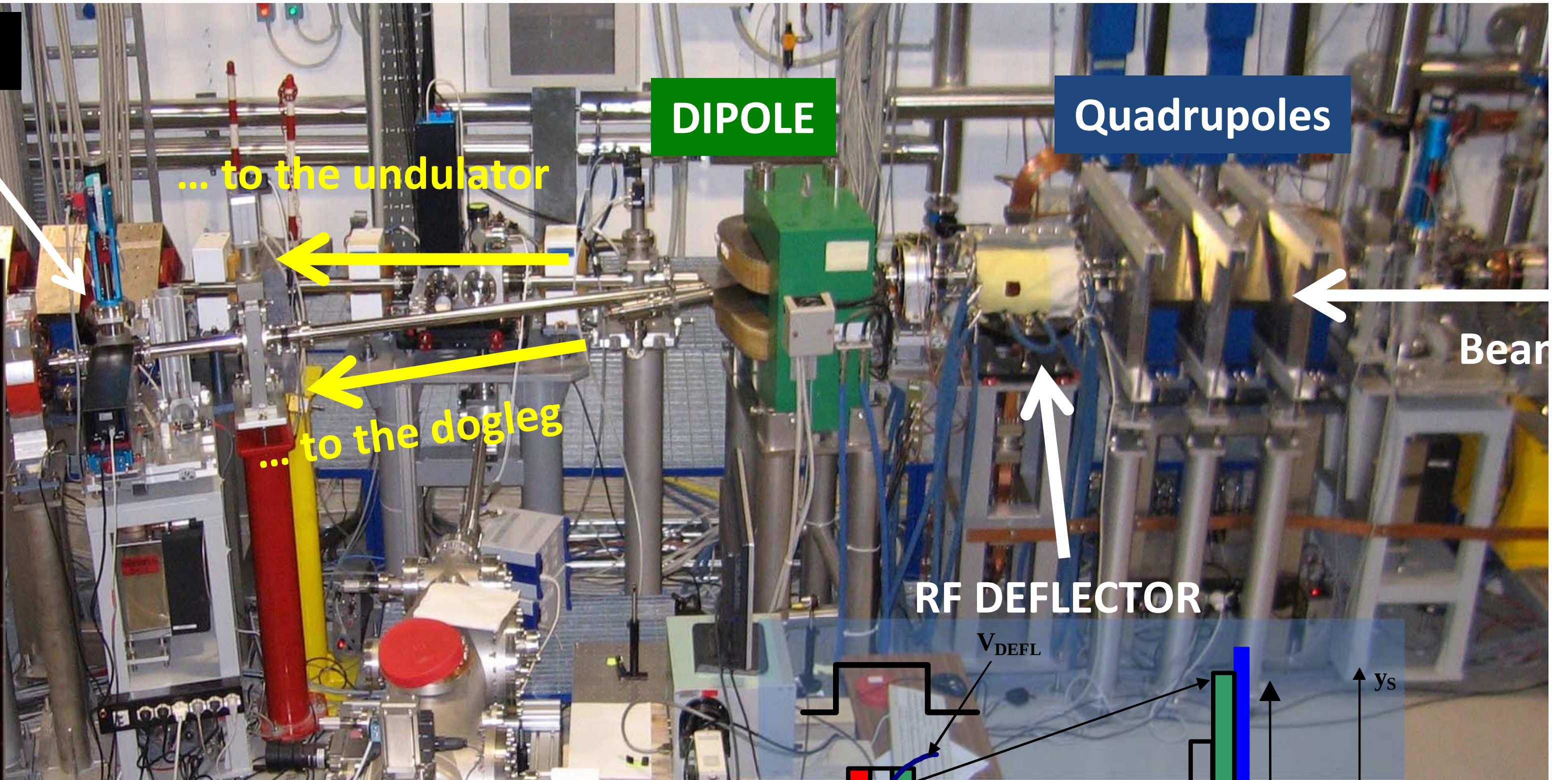
$$\varepsilon_1^2 = \langle x_1^2 \rangle \langle x_1'^2 \rangle - \langle x_1 x_1' \rangle^2 = \varepsilon_0^2 + \underbrace{(kl)^2 \sigma_x^4 \sigma_\gamma^2}_{\varepsilon_{chr}^2} = f(\varepsilon_0, \sigma_\gamma, \sigma_x)$$

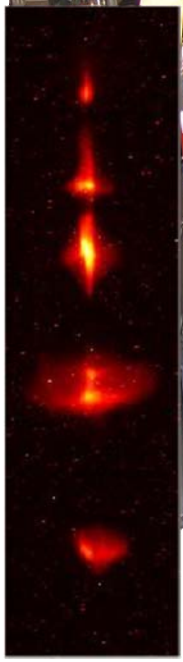
Train of bunches

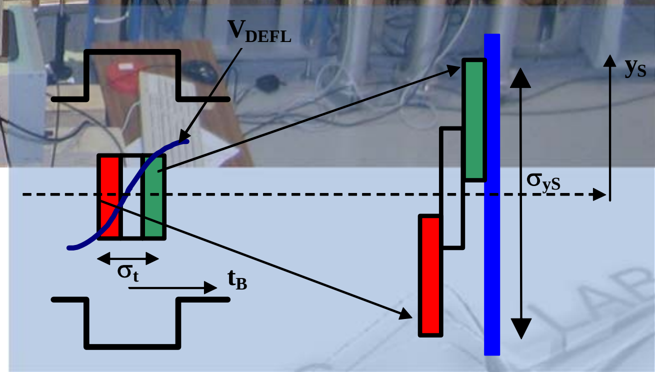


- **COMB-like electron bunches are injected inside the preformed plasma. The first bunches create the wakefield, which is then seen from the last bunch (witness) which will be then accelerated**
- **Challenge: creation and manipulation of driver bunches and matching all the bunches with the plasma**
- **In order to fulfil this requirement a diagnostic of the single bunch is needed**

Time separation



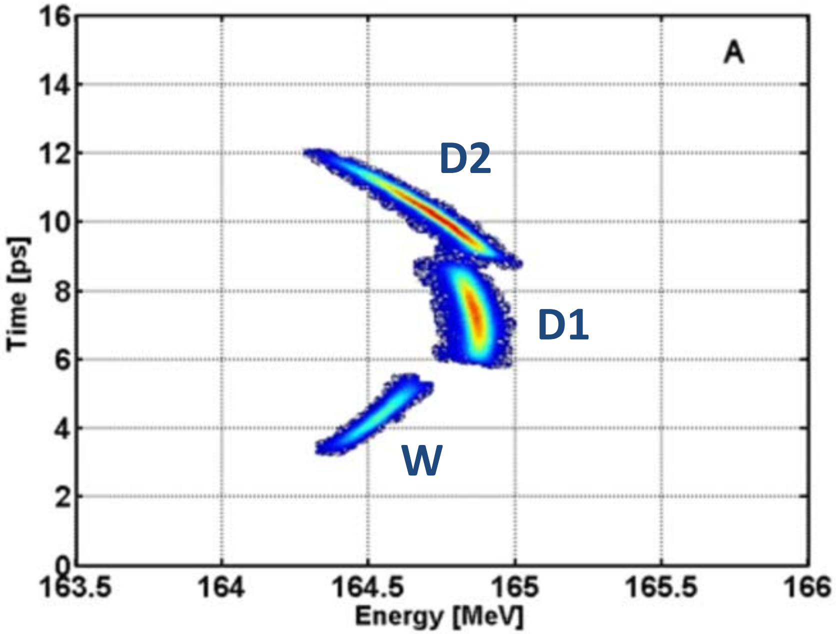


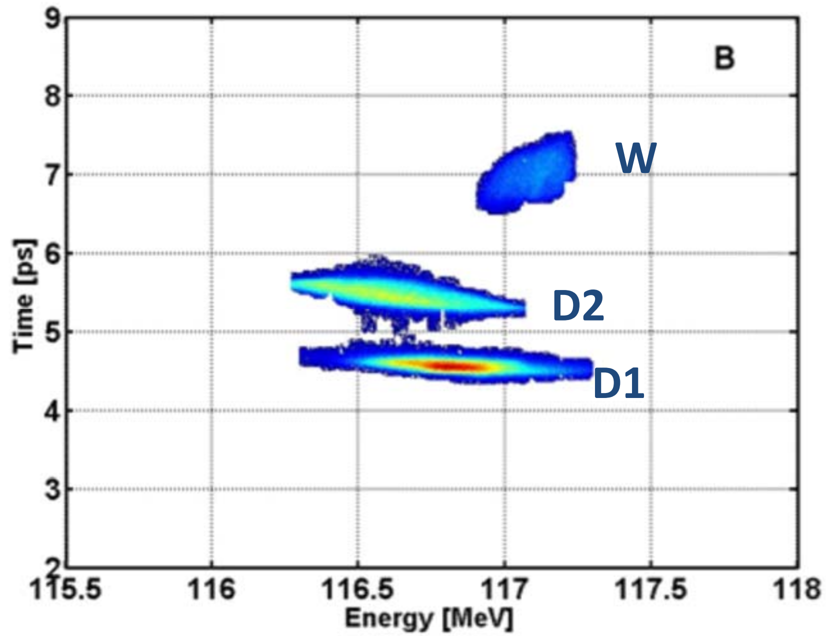


$$\sigma_y = \sqrt{\sigma^2_{y\_RFD} + \sigma^2_{y\_beam}}$$

Paul Emma, Josef Frisch, Patrick Krejcik, A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics, LCLS-TN-00-12
Christopher Behrens, Measurement and Control of the Longitudinal Phase Space at High-Gain Free-Electron Lasers , FEL 2011, Shanghai

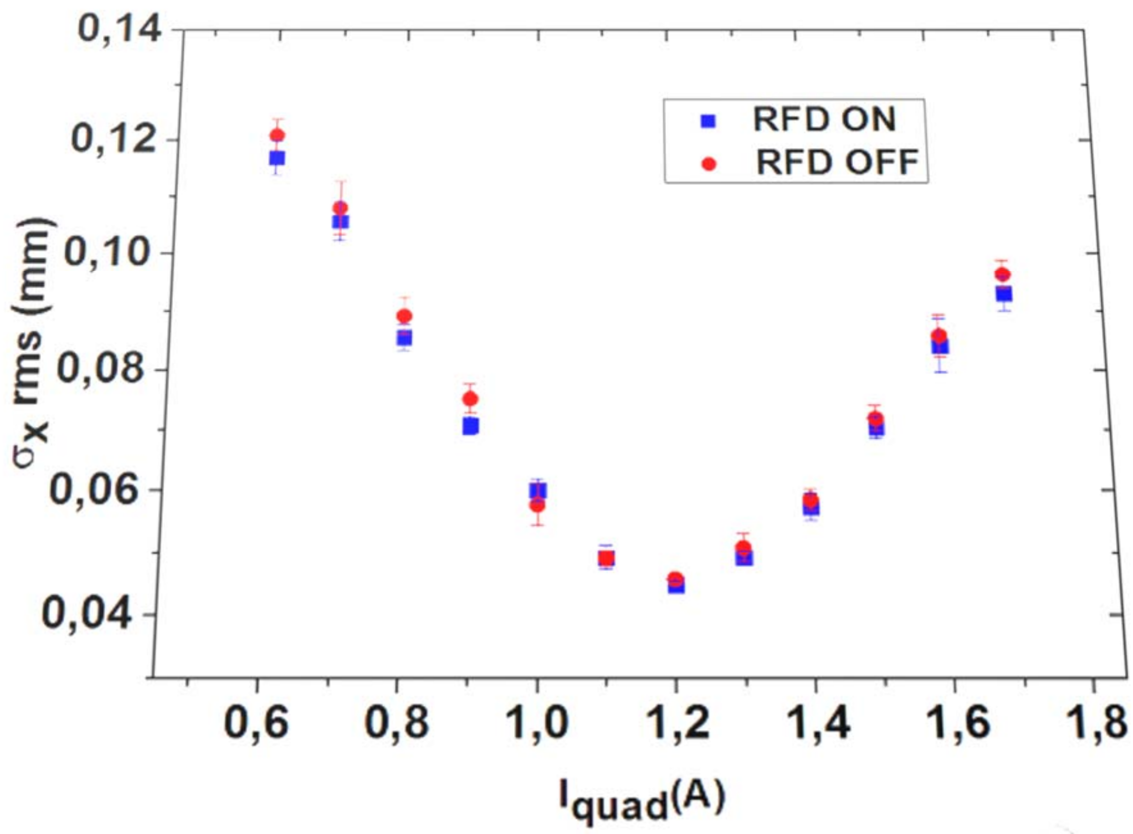
Longitudinal phase space





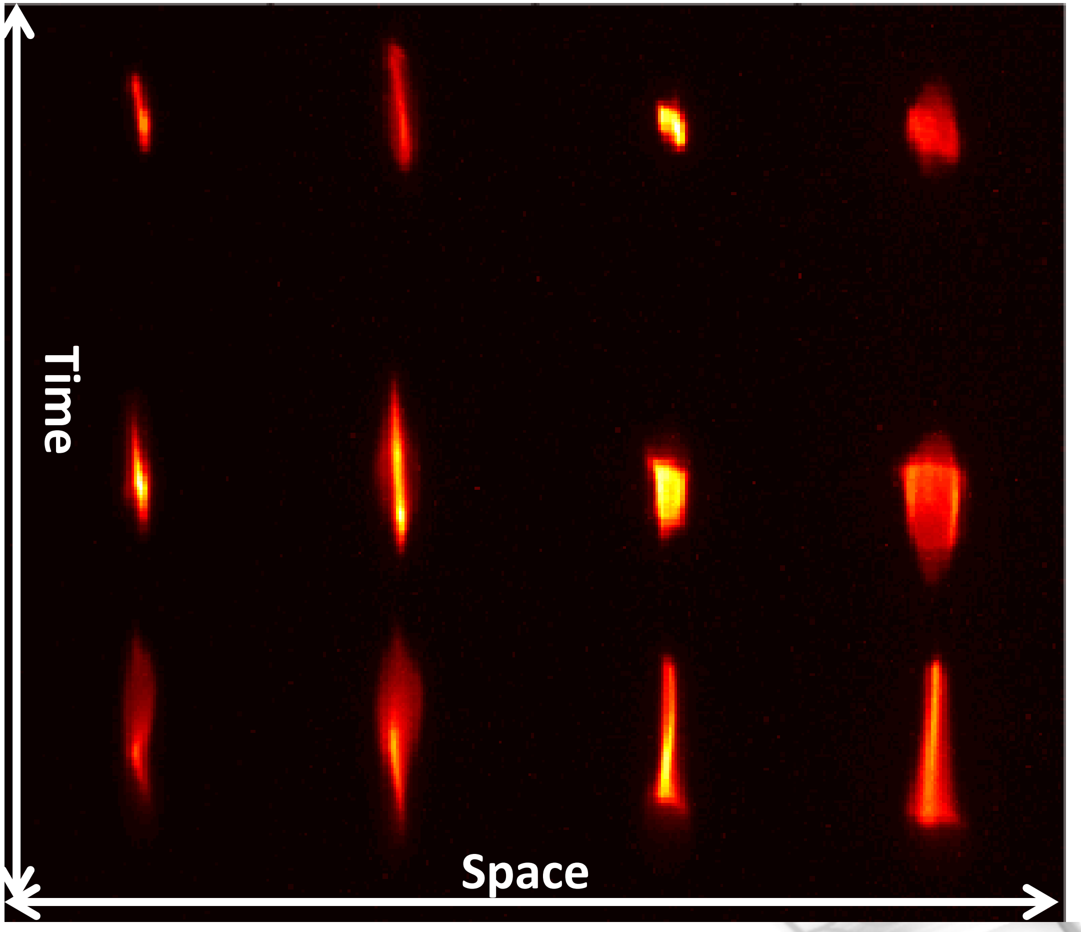
Bunch	Beam Energy(MeV)	Energy Spread(%)	Position (ps)	Bunch Length (ps)	Long. Emit(keV mm)
W	117.12 (0.02)	0.067 (0.002)	6.39 (0.02)	0.19 (0.03)	4.0 (0.2)
D1	116.65 (0.02)	0.158 (0.005)	5.02(0.02)	0.12 (0.02)	5.6 (0.2)
D2	116.82 (0.02)	0.175 (0.009)	4.19 (0.02)	0.08 (0.02)	4.6 (0.4)
Whole	116.80 (0.02)	0.210 (0.005)	4.92 (0.02)	7.67 (0.02)	53.4 (1.2)

Single bunch test

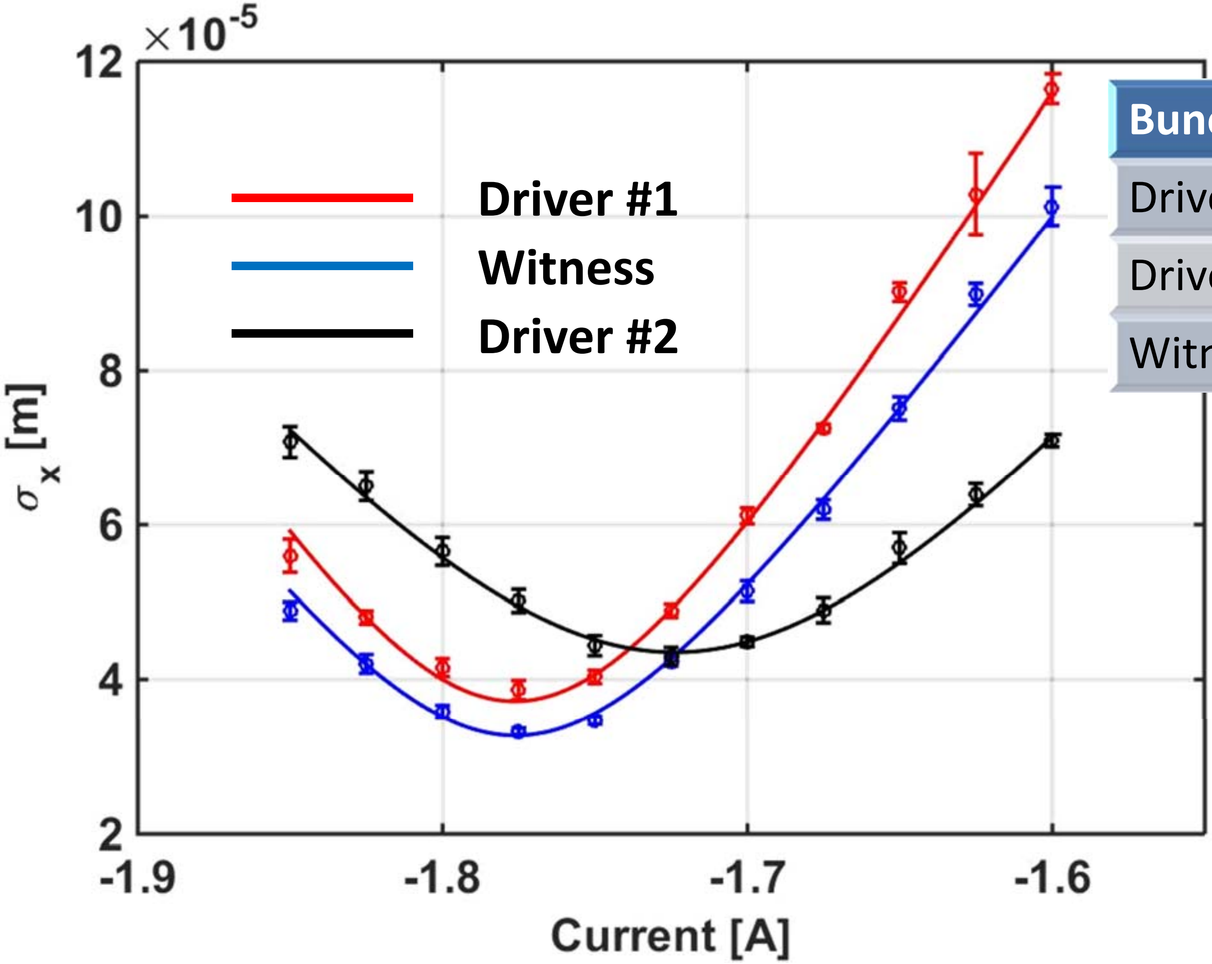


- Transverse size with RFD on/off

Quad scan comb beam



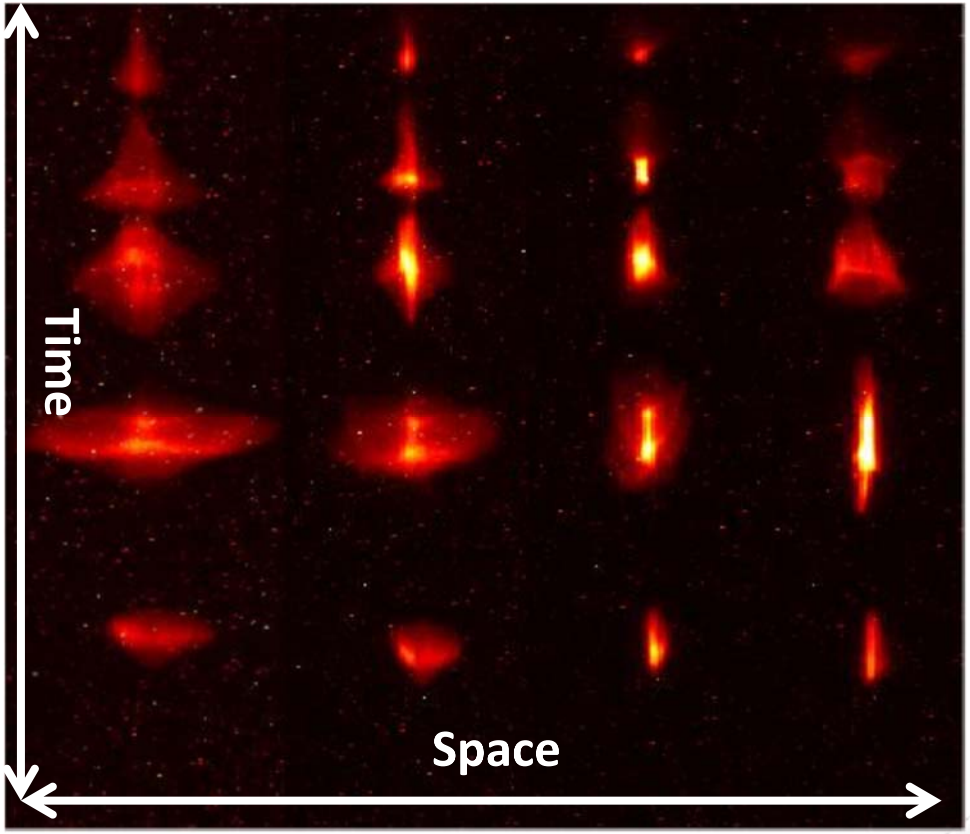
Results



Bunch	Emittance (mm-mrad)
Driver #1	1.38 (0.04)
Driver #2	1.61 (0.07)
Witness	1.22 (0.06)

A. Cianchi et al. "Six-dimensional measurements of trains of high brightness electron bunches", Physical Review Special Topics Accelerators and Beams 18, 082804 (2015)

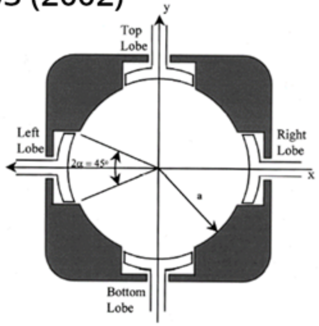
5 bunches

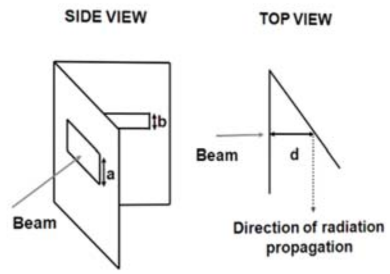


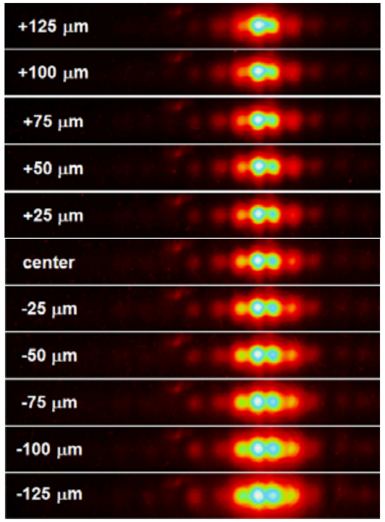
Not intercepting but multi shot

Steven J. Russell, Emittance measurements of the Sub-Picosecond Accelerator electron beam using beam position monitors, Review of Scientific Instruments 70, 2, February 1999

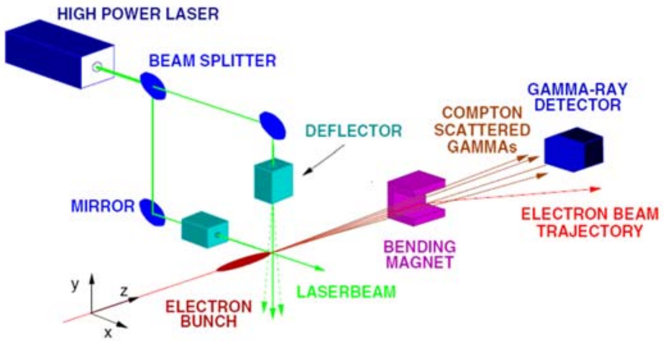
A. Jansson, "Noninvasive single-bunch matching and emittance monitor", PRSTA-AB 5, 072803 (2002)







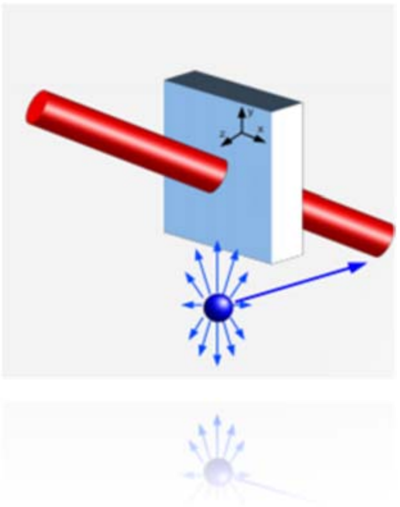
Cianchi, A., et al. "First non-intercepting emittance measurement by means of optical diffraction radiation interference." *New Journal of Physics* 16.11 (2014): 113029.



I. Agapov, G. A. Blair, M. Woodley, Physical Review Special Topics Accelerators And Bemas10, 112801 (2007)
L. J. Nevay et al, Laserwire at the Accelerator Test Facility 2 with submicrometer resolution, Physical Review Special Topics Accelerators and Beams 17, 072802 (2014)

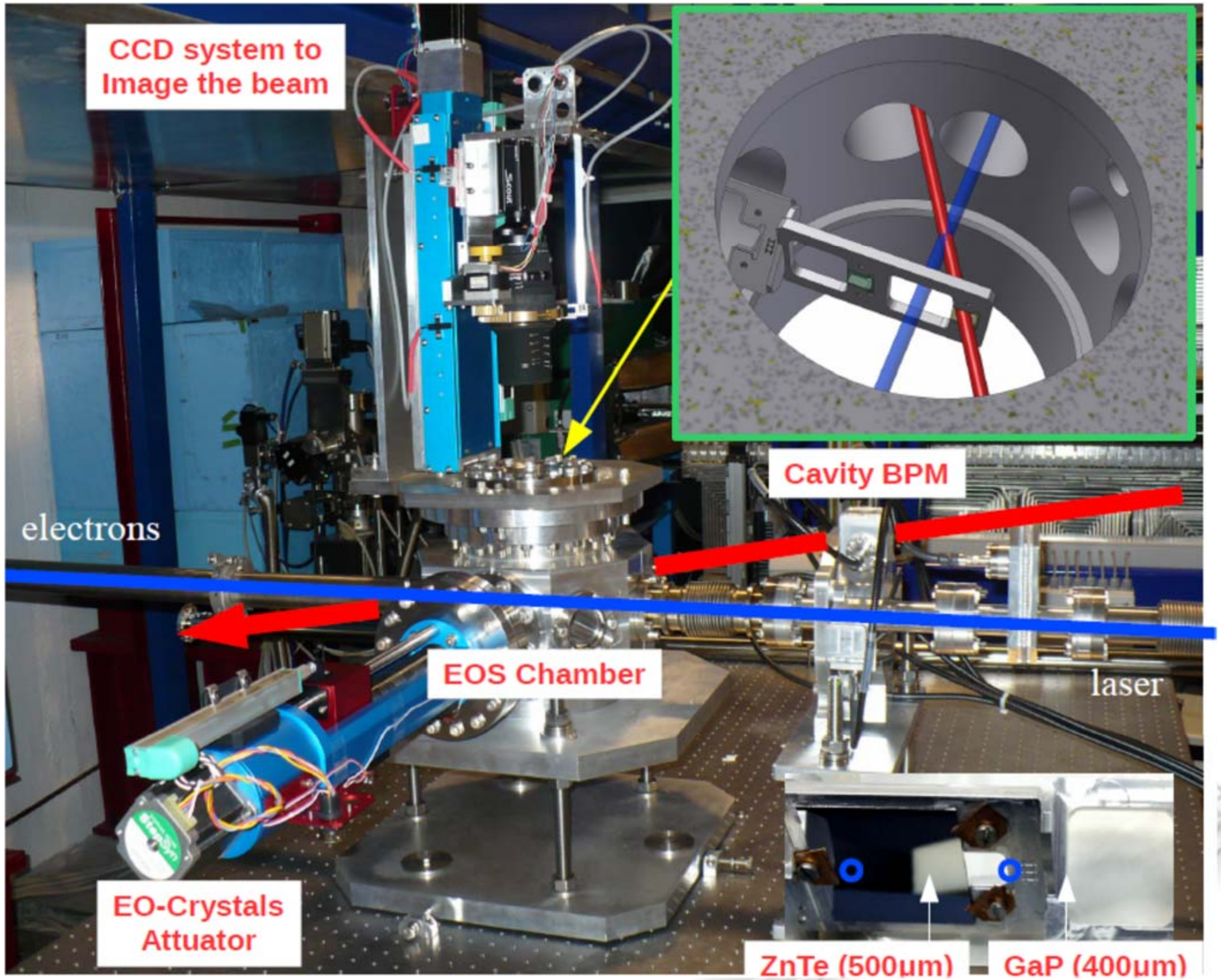
EOS enconding

- I.Wilke et al., PRL, v.88, 12(2002)
- G. Berden et al, PRL v93, 11 (2004)
- A. L. Cavalieri et al., PhysRevLett.94.114801(2005
- B. Steffen, Phys. Rev. ST Accel. Beams 12, 032802 (2009)



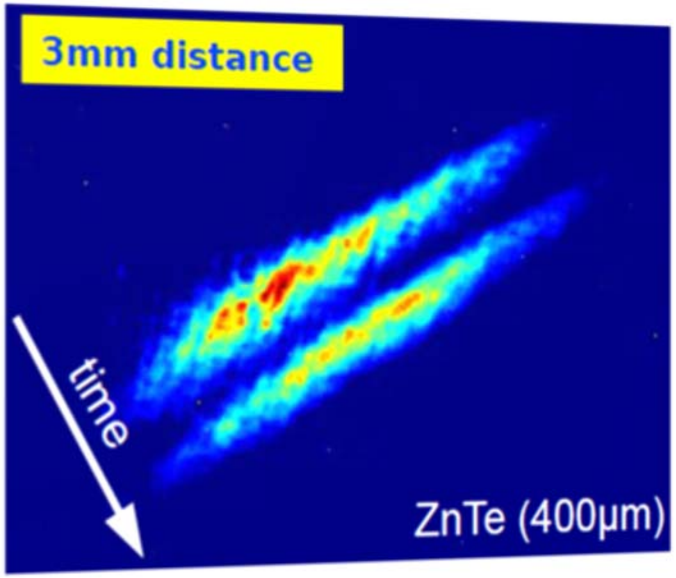
- Laser crosses the crystal with an incident angle
- One side of the laser pulse arrives earlier on EO crystal with respect the other by a time difference Δt
- Columb field inducing birefringence is encoded in the spatial profile of laser pulse

EOS setup



CCD system to Image the beam
Cavity BPM
electrons
EOS Chamber
laser
EO-Crystals Attuator
ZnTe (500μm)
GaP (400μm)

A comblike beam

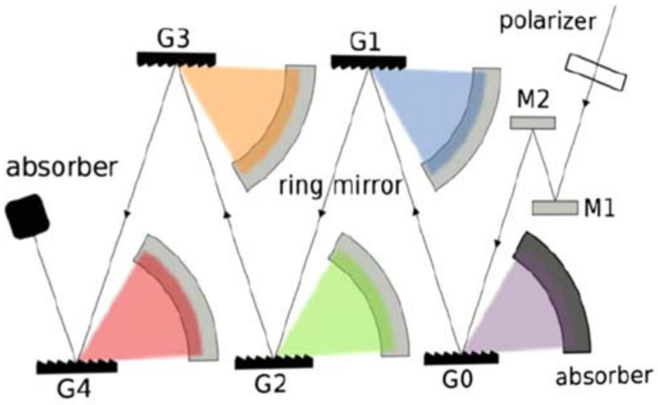


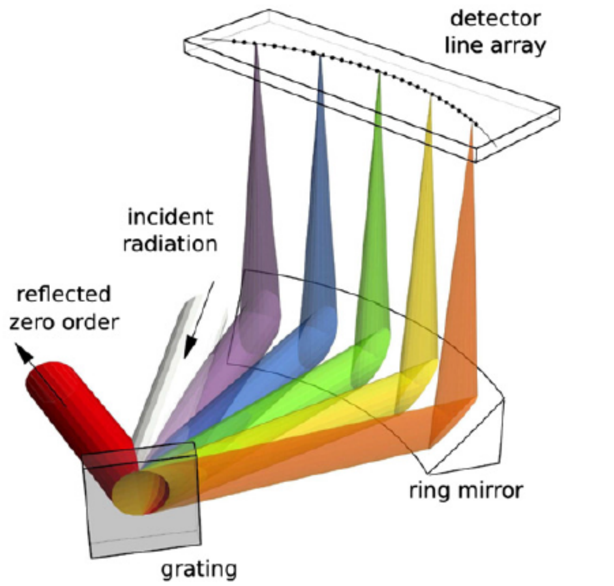
- σ_1=(375±10) fs
- σ_2=(344±10) fs
- dist=(879±9) fs

- R. Pompili et al. "First single-shot and non-intercepting longitudinal bunch diagnostics for comb-like beam by means of Electro-Optic Sampling", Nuclear Instruments and Methods in Physics Research A740 (2014) 216–221

Single shot CTR measurements I

- S. Wesch, B. Schmidt, C. Behrens, H. Delsim-Hashemi, P. Schmuser, A multi-channel THz and infrared spectrometer for femtosecond electron bunch diagnostics by single-shot spectroscopy of coherent radiation Nuclear Instruments and Methods in Physics Research A 665 (2011) 40–47

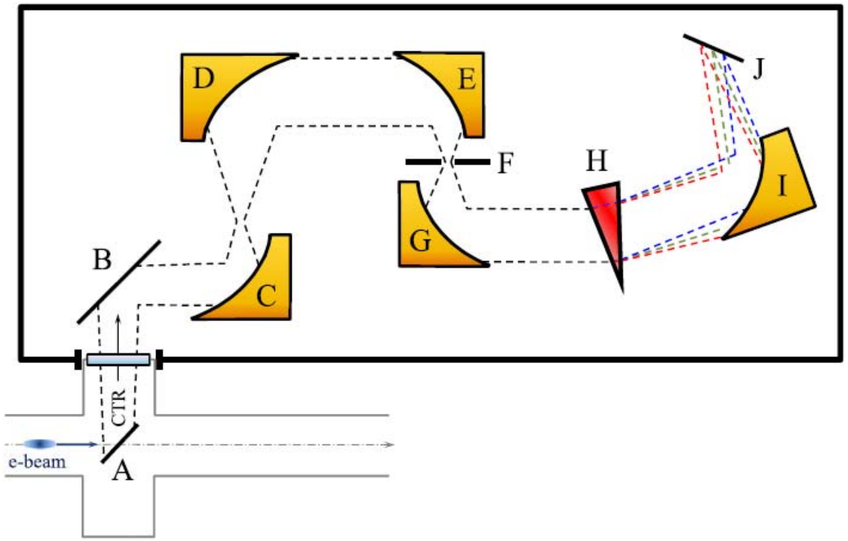




Pyro-electric line detector 30 channels @ room temperature no window, works in vacuum fast read out sensitivity

Single shot CTR measurements II

- T. J. Maxwell et al. "Coherent-radiation spectroscopy of few-femtosecond electron bunches using a middle-infrared prism spectrometer." *Physical review letters* 111.18 (2013)



KRS-5 (thallium bromoiodide) prism based spectrometer developed

Images OTR from foil onto 128 lead zirconate titanate pyroelectric elements with 100 μm spacing line array

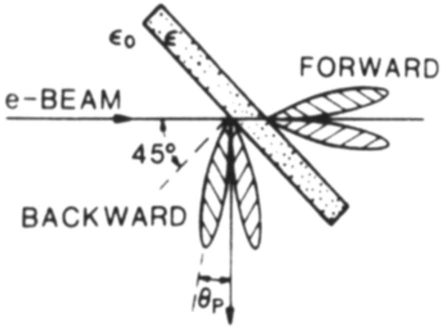
Also double prism (ZnSe), S. Wunderlich et al., Proceedings of IBIC2014

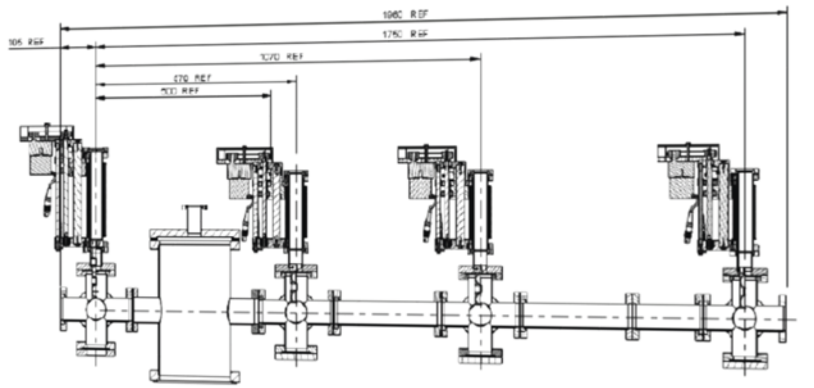
Summary input beam

- There are well established solution for
  - Emittance measurement
    - Quad scan
  - Longitudinal phase space
    - Eos, dipole, RFD, CTR etc
- Not all of them are single shot or not intercepting

Multiple OTR monitors

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





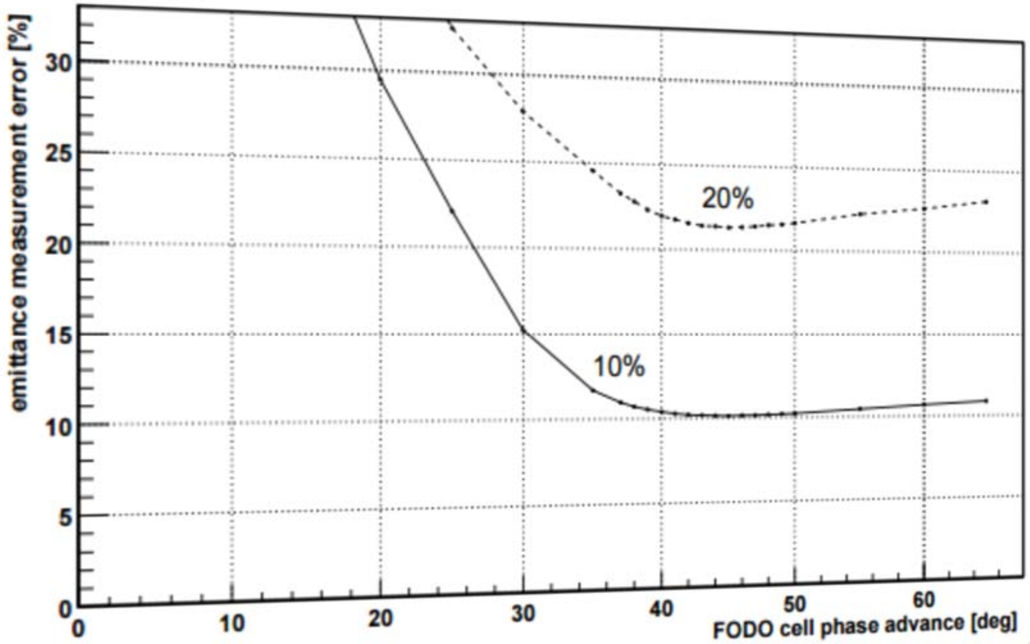
$$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left(1+0.038 ln\frac{x}{X_0}\right)$$

- ✓ 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
- ✓ This system seems not feasible for beams with energy in the range of hundreds of MeV
- ✓ A waist is a must

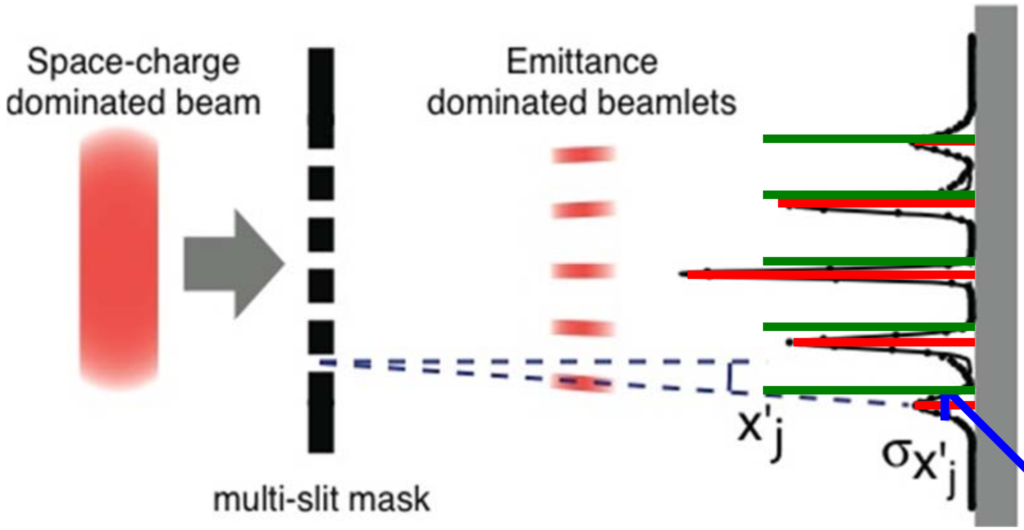
LWA application: Krůs, M., et al. *SPIE Optics+ Optoelectronics*. International Society for Optics and Photonics, 2015.

Best phase advance

P. Castro, “Monte Carlo simulations of emittance measurements at TTF2”, Desy Technical-Note-03-03



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

$$\varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

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

Design issues

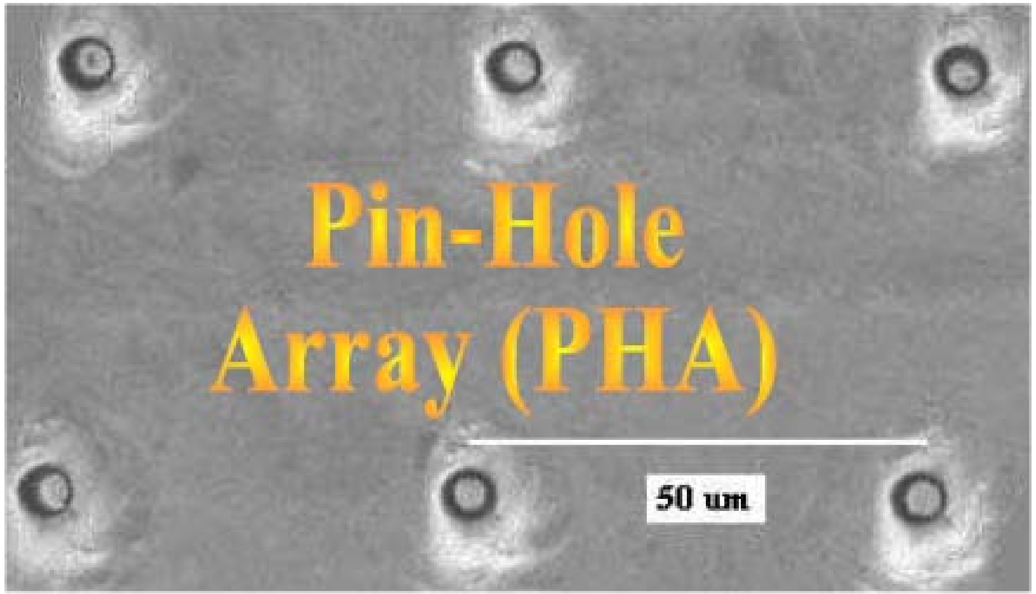
- The contribution of the slit width to the size of the beamlet profile should be negligible
- The material thickness (usually tungsten) must be long enough to stop or heavily scatter beam at large angle (critical issue at high energy)
- The angular acceptance of the slit cannot be smaller of the expected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

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

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

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

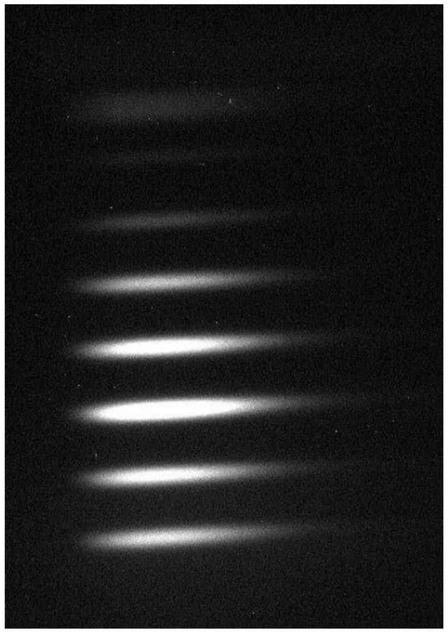
Holes machining

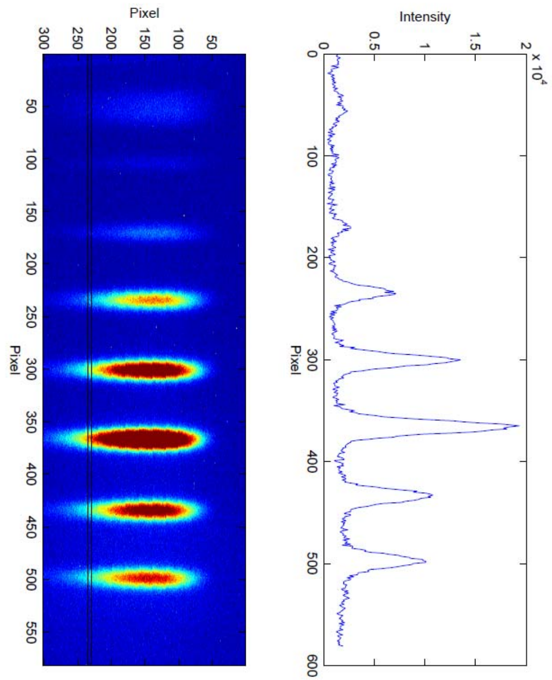


- **Holes array have been successfully produced.**
- **The thickness of the material can be as large as 100 times the hole diameter**

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)

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 Nuclear Instruments and Methods in Physics Research A 644 (2011) 1–10
C. Thomas, N. Delerue, R. Bartolini, Nuclear Instruments and Methods in Physics Research A 729 (2013) 554–556

Pepper pot fans

VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

Emittance Measurements of a Laser-Wakefield-Accelerated Electron Beam

S. Fritzler,[1] E. Lefebvre,[2] V. Malka,[1] F. Burgy,[1] A. E. Dangor,[3] K. Krushelnick,[3] S. P. D. Mangles,[3] Z. Najmudin,[3] J.-P. Rousseau,[1] and B. Walton[3]

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 092803 (2010)

Emittance and divergence of laser wakefield accelerated electrons

Christopher M. S. Sears,[1,*] Alexander Buck,[1,2] Karl Schmid,[1] Julia Mikhailova,[1] Ferenc Krausz,[1,2] and Laszlo Veisz[1,†]
[1]*Max-Planck-Institüt für Quantenoptik, 85748 Garching, Germany*
[2]*Fakultät für Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany*
(Received 31 May 2010; published 22 September 2010)

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

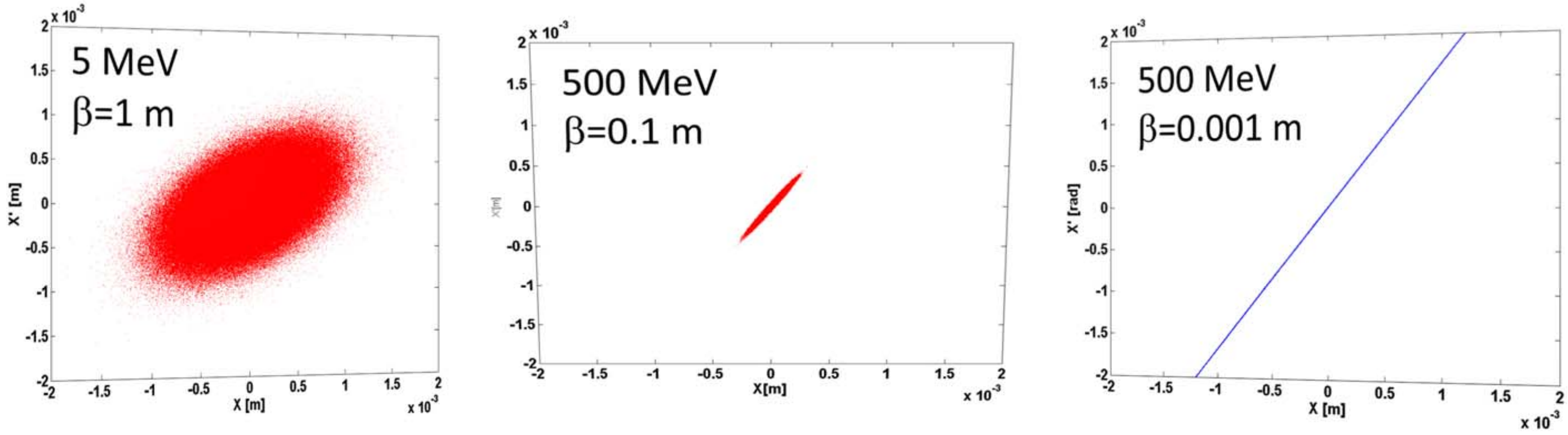
Low Emittance, High Brilliance Relativistic Electron Beams from a Laser-Plasma Accelerator

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*
Physics Department, University of Strathclyde, Glasgow G4 0NG, United Kingdom
(Received 31 August 2010; published 19 November 2010)

Intrinsic limit for LWFA beams

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

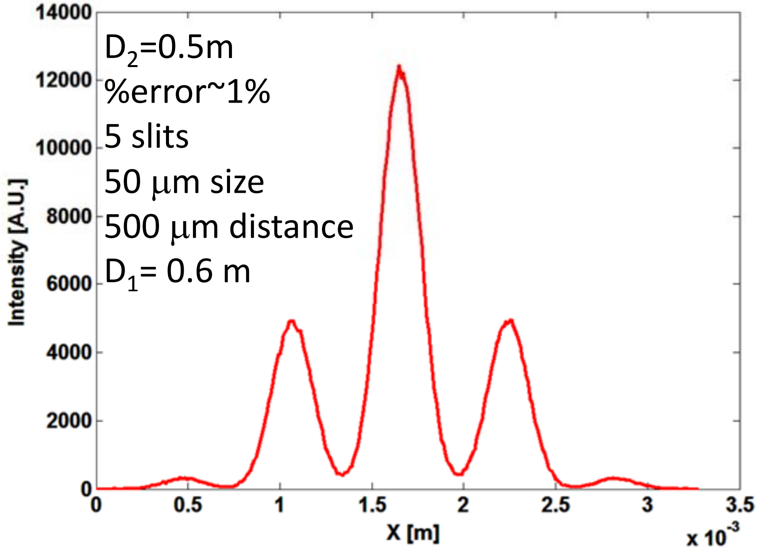
Trace spaces



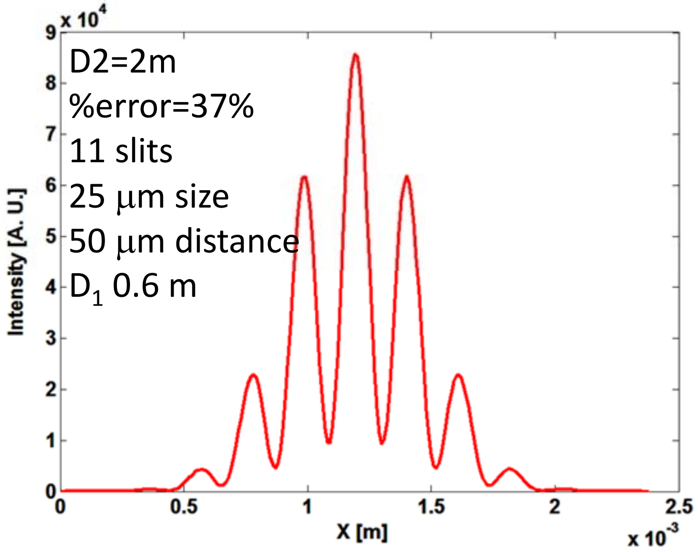
- All beams have ε_n=1 mm-mrad
- z=0.6 m
- β=0.1 m means 10 μm on the source
- β=0.001 m means 1 μm on the source

No problems

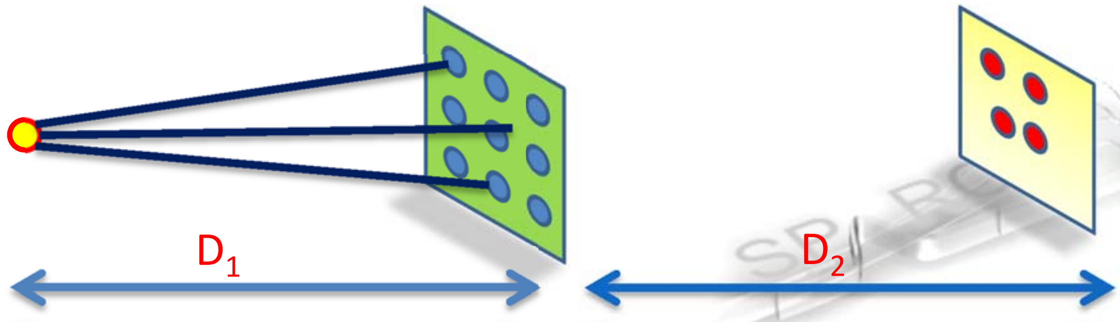
- Everything roughly optimized in to minimize the error and to use all the particles



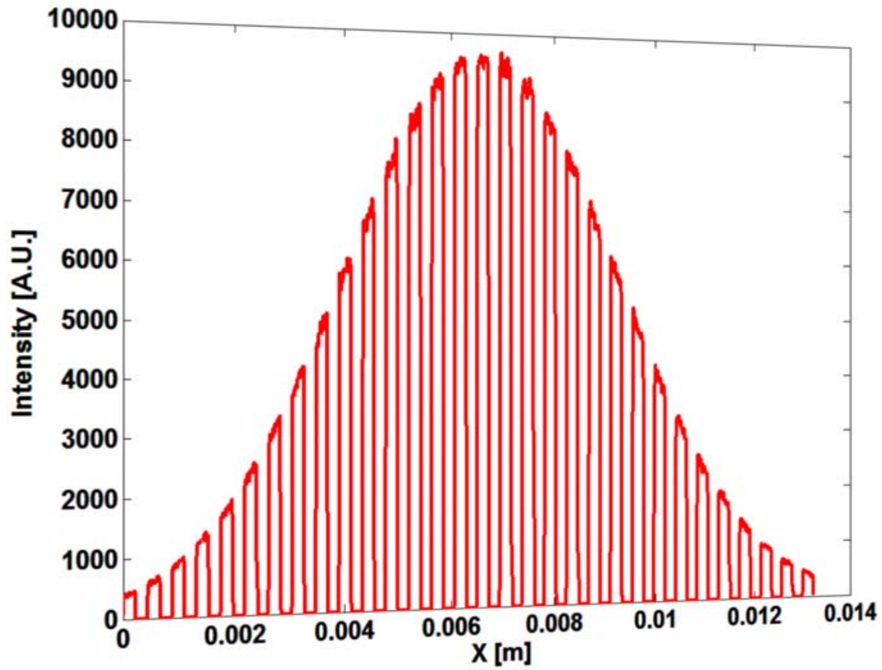
5 MeV β=1 m



500 MeV β=.1 m



No chances for β=0.001 m



D_2=2m
%error>1000%
31 slits
50 μm size
100 μm distance
D_1 0.6 m

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

Cianchi, A., et al. "Challenges in plasma and laser wakefield accelerated beams diagnostic." *NIM A* 720 (2013): 153-156.

Quantization error

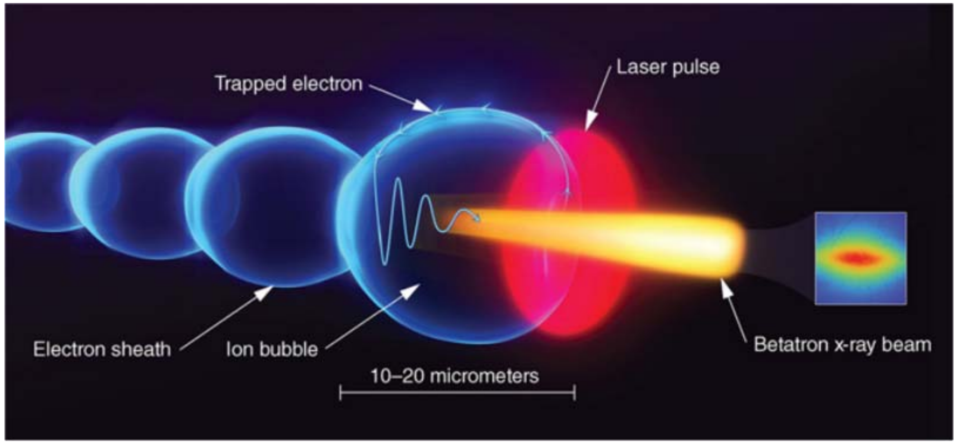
- T. Ludwig, K. Volk, W. Barth, and H. Klein, "Quantization error of slit-grid emittance measurement devices", Review of Scientific Instruments 65, 1462 (1994)

$$\varepsilon_{err} = \frac{2}{\pi}\left(x_{\max}\Delta x' + x'_{\max}\Delta x\right)$$

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)

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

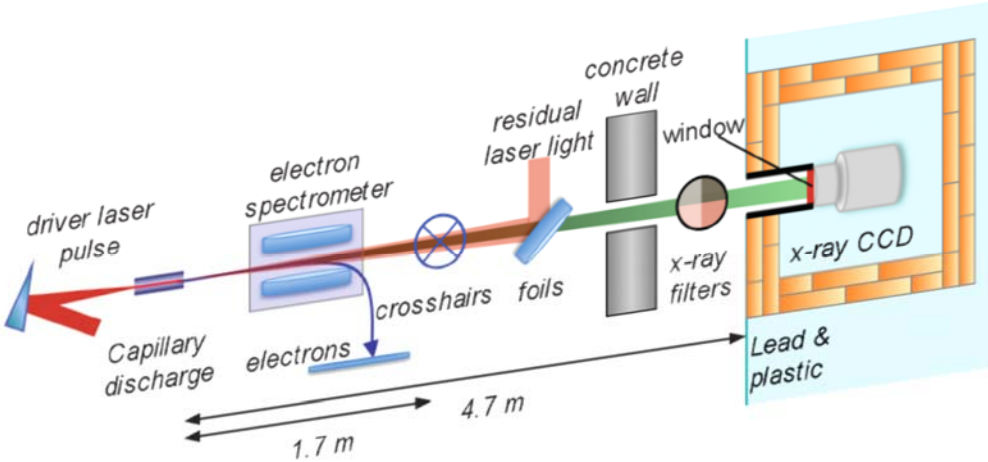


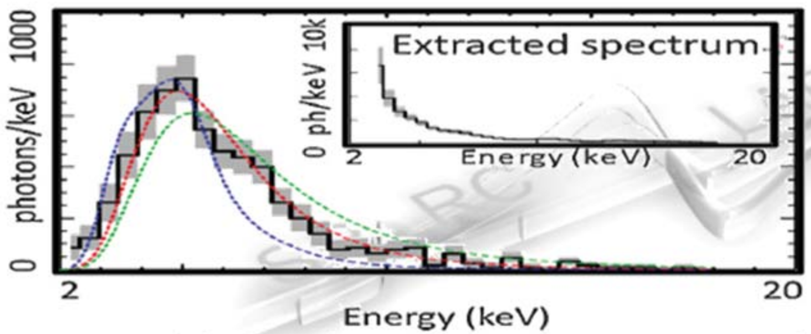
Picture from F Albert et al Plasma Phys. Control. Fusion 56 (2014) 084015

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)

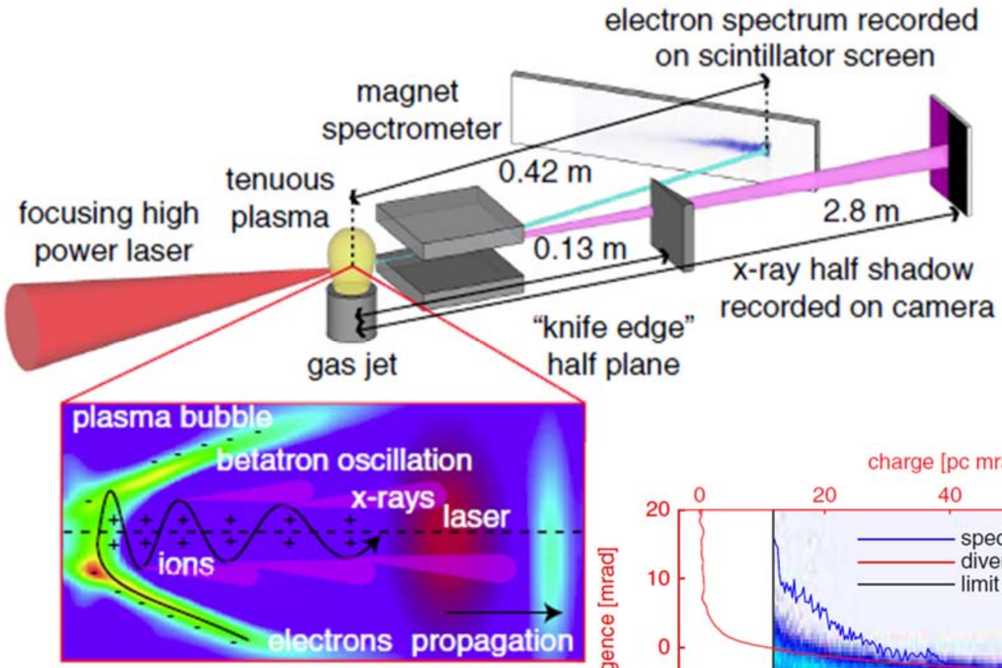
- **400 MeV energy with a rms energy spread of less than 5% and 1 mrad divergence from a plasma density of 5 10^{18}cm^{3}**

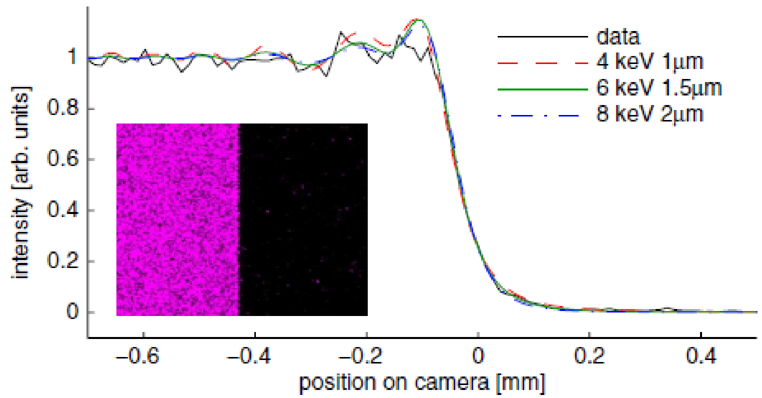




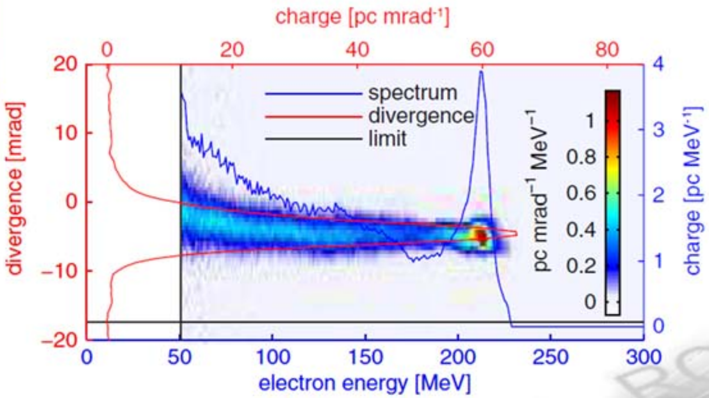
σ σ' γ Δγ at the same time

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



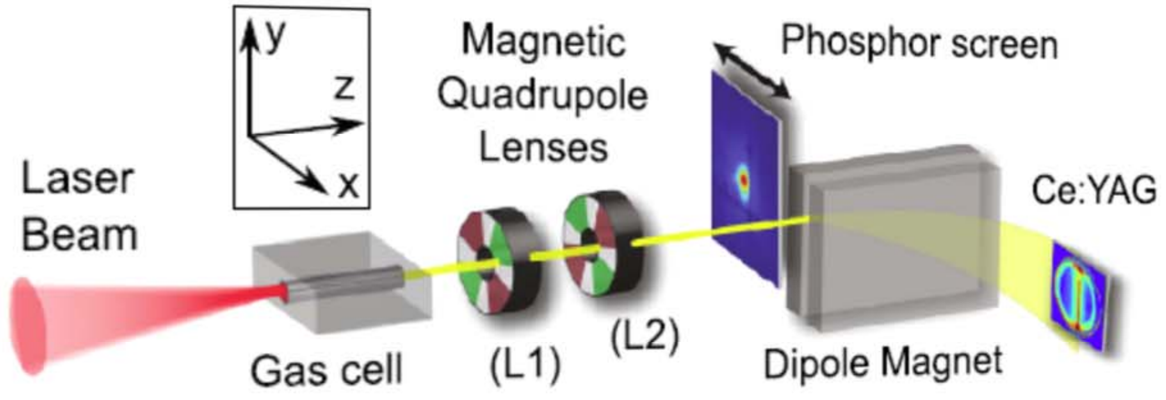


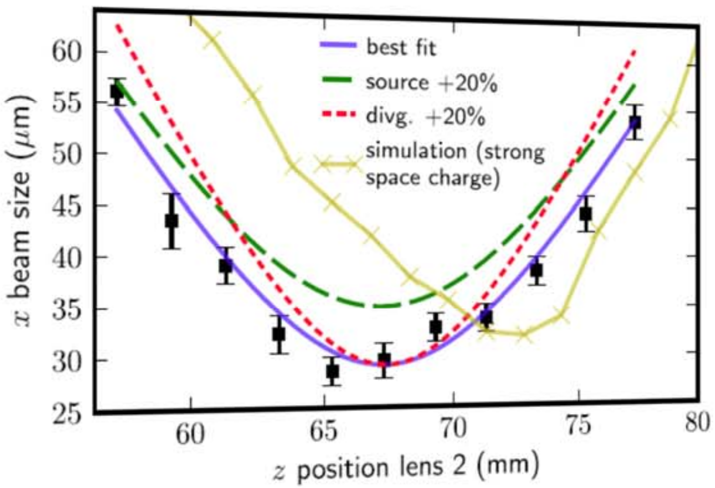
Source size by Fresnel diffraction

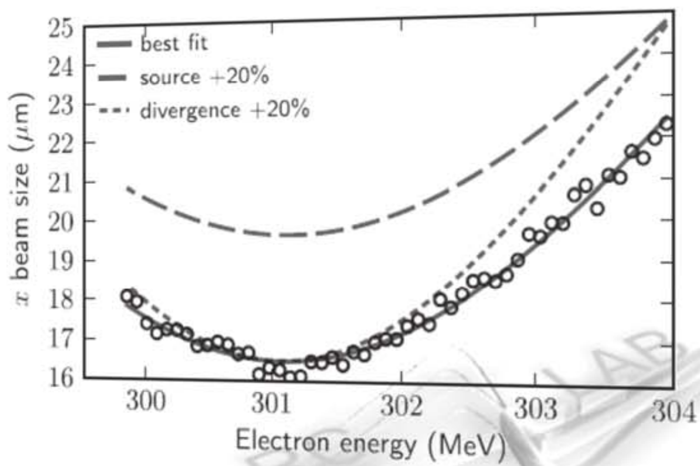


Energy, energy spread and divergence behind the dipole

A new kind of Quadscan

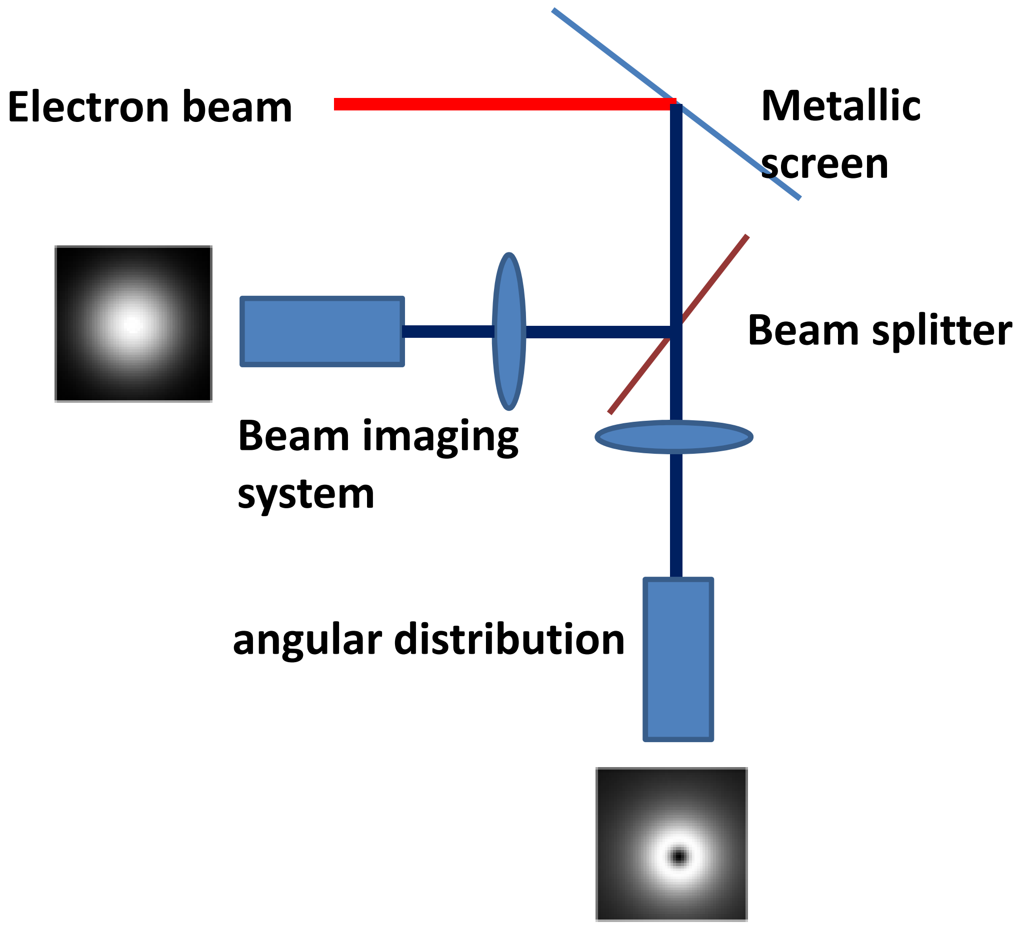


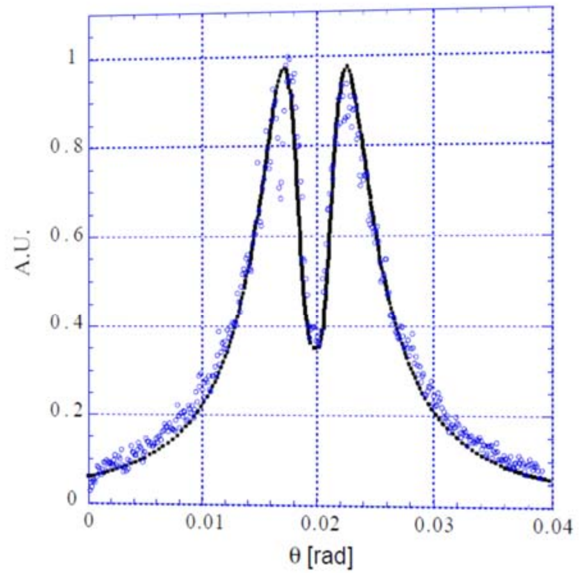




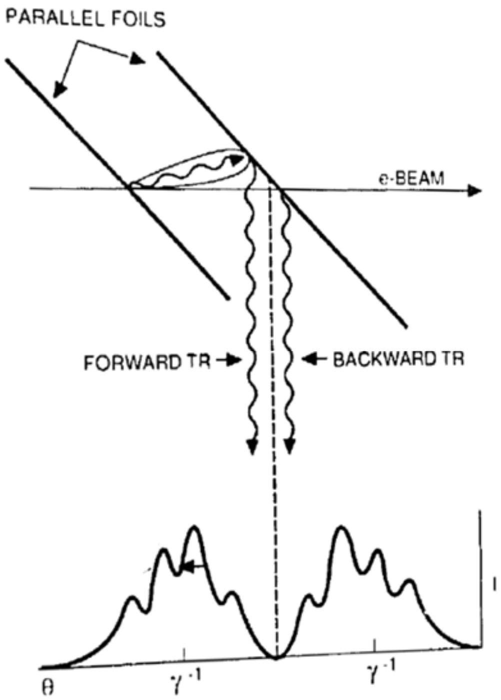
- R. Weingartner and al., PRST-AB 15, 111302 (2012),

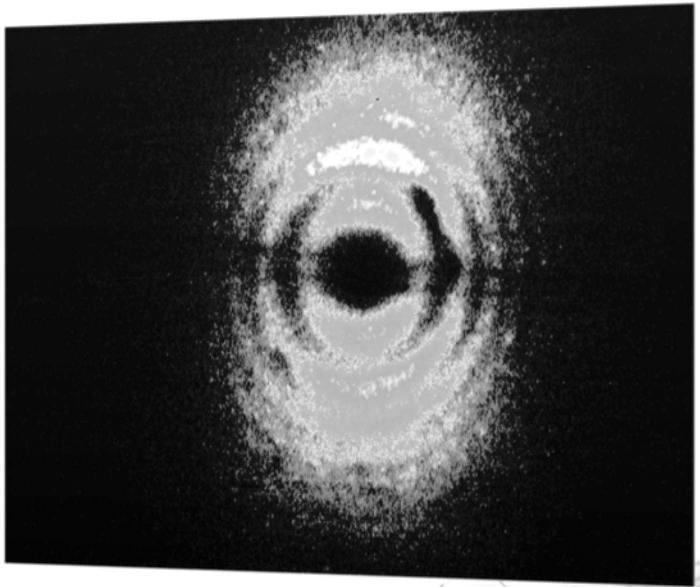
Transition radiation



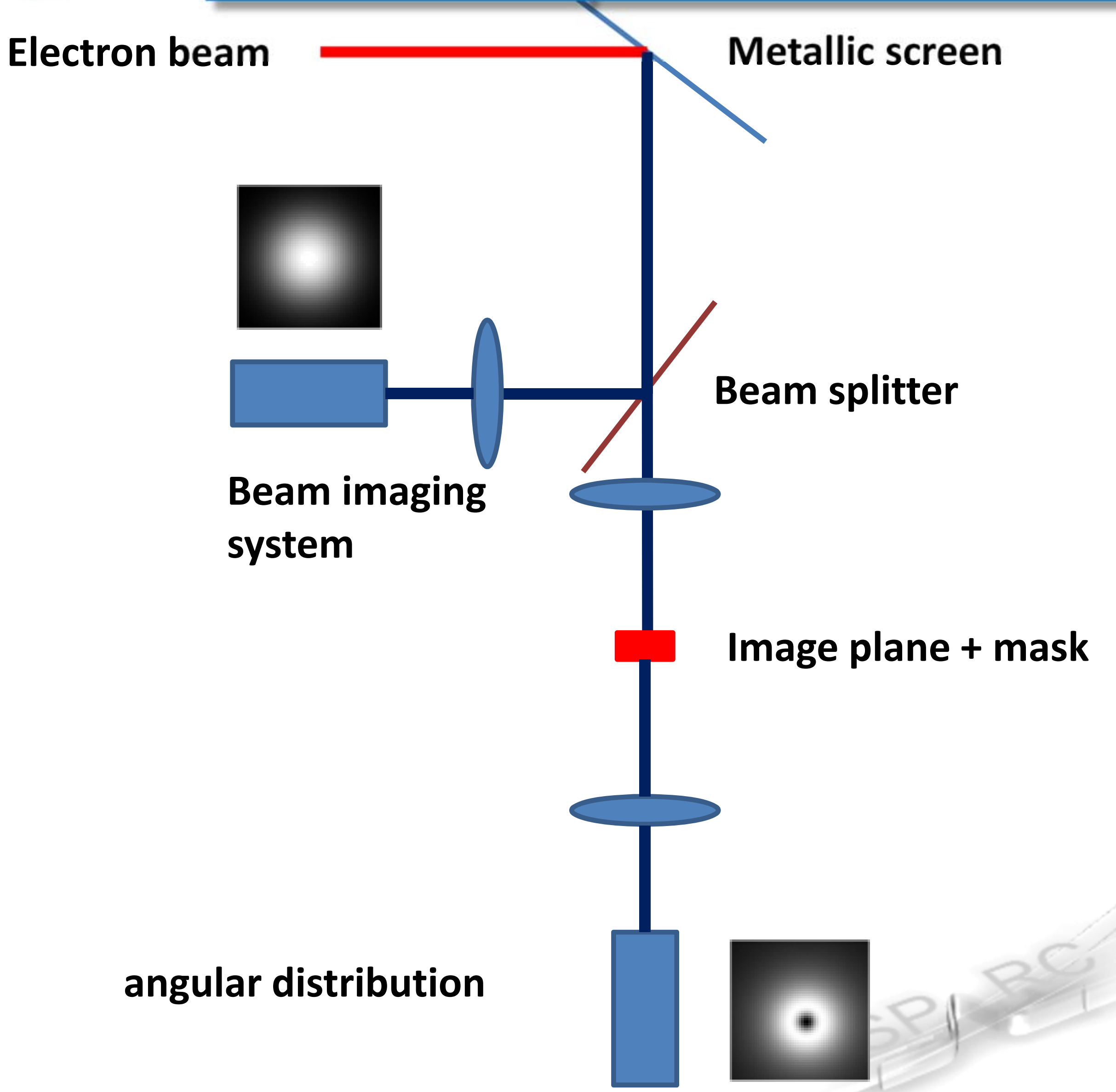


- C. Couillaud, A. Loulergue, G. Haouat, "ELECTRON BEAM TRANSVERSE EMITTANCE MEASUREMENT USING OPTICAL TRANSITION RADIATION INTERFEROMETRY", Proceedings of Epac96, Spain
- Feldman, R. B., et al. "Developments in on-line, electron-beam emittance measurements using optical-transition radiation techniques." NIMA: 296.1 (1990): 193-198

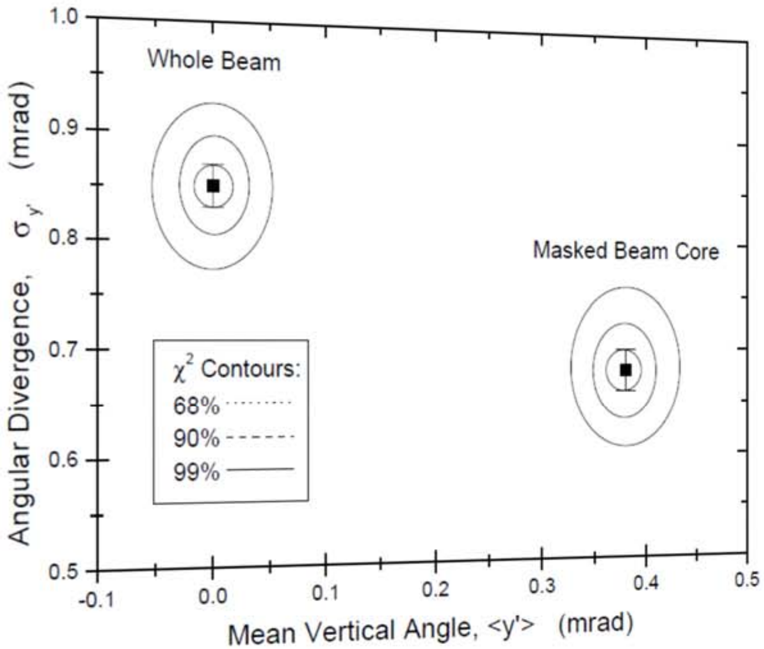




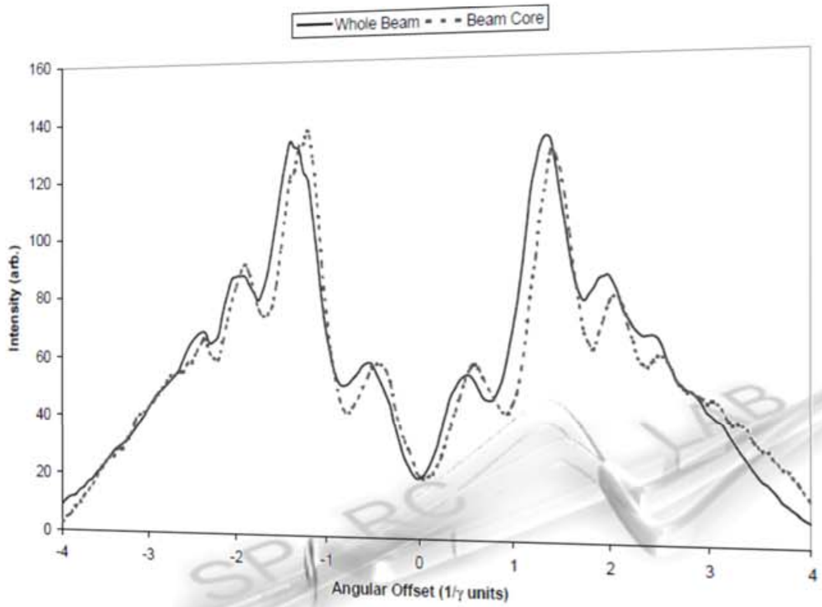
Further improvement



With a mask



G. P. Le Sage, T. E. Cowan, R. B. Fiorito, and D. W. Rule, "Transverse phase space mapping of relativistic electron beams using optical transition radiation" , PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 2, 122802 (1999)



Conclusions

- High brightness beam diagnostics is very challenging especially for emittance measurements
- Well established methods are available for input beams even in case of comb like structure
- A lot of work must be dedicated for output beams
- It is not ancillary part because as the saying goes: «an accelerator is just as good as its diagnostics».

It is over, finally!!

Thank you for your attention