Diagnostic Needs for Wakefield Accelerator Experiments

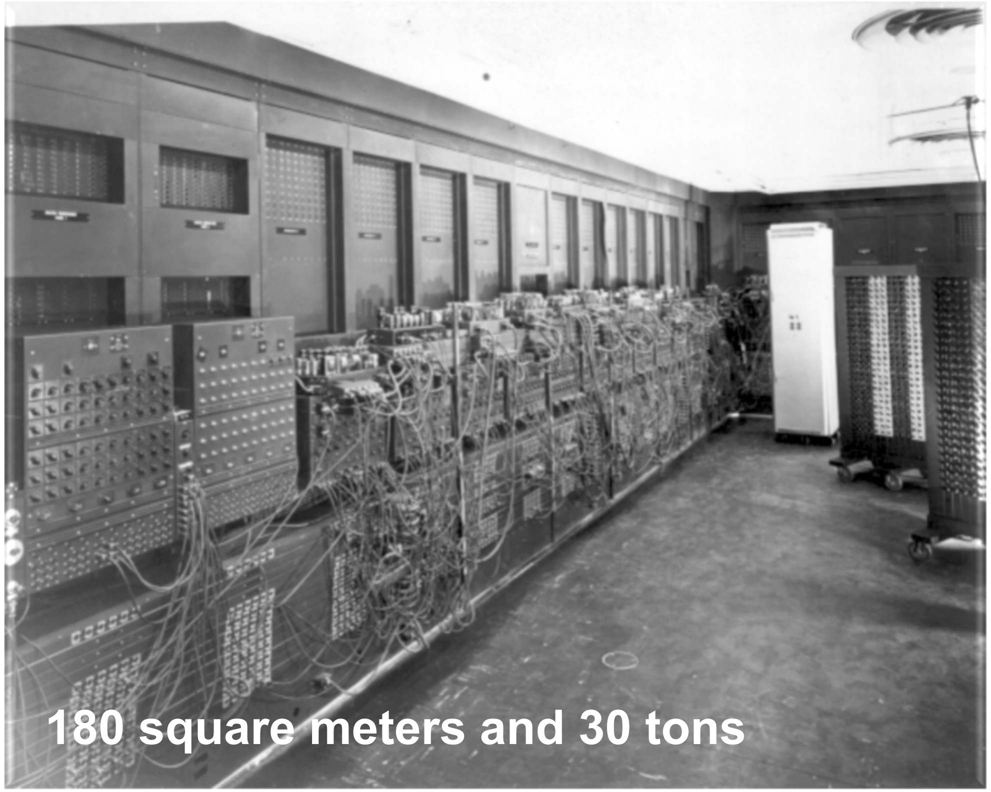
A. Cianchi
University of Rome "Tor Vergata"
and INFN

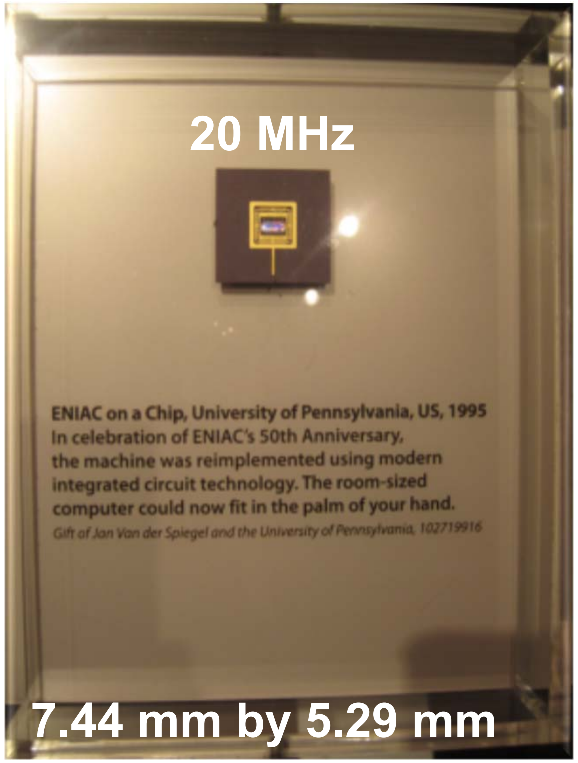
The CERN Accelerator School

Outline

- Wakefield accelerators and acceleration methods
- Diagnostics challenges
- Ongoing solutions
- Conclusions? No it's just the beginning

ENIAC Then and now…





1946

1995

SLAC Now and Tomorrow

2018 **20??**

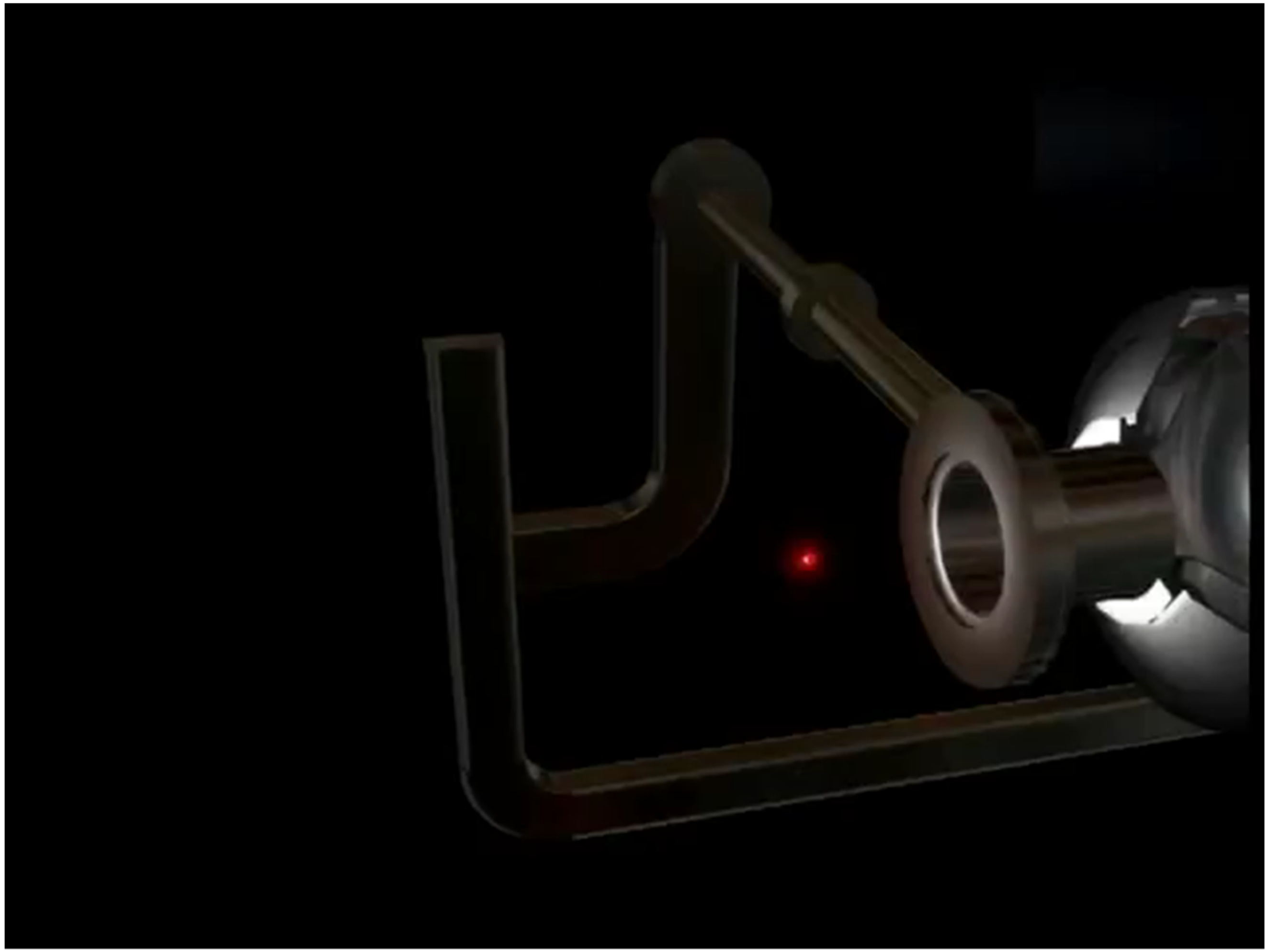
The CERN Accelerator School

Accelerating gradient

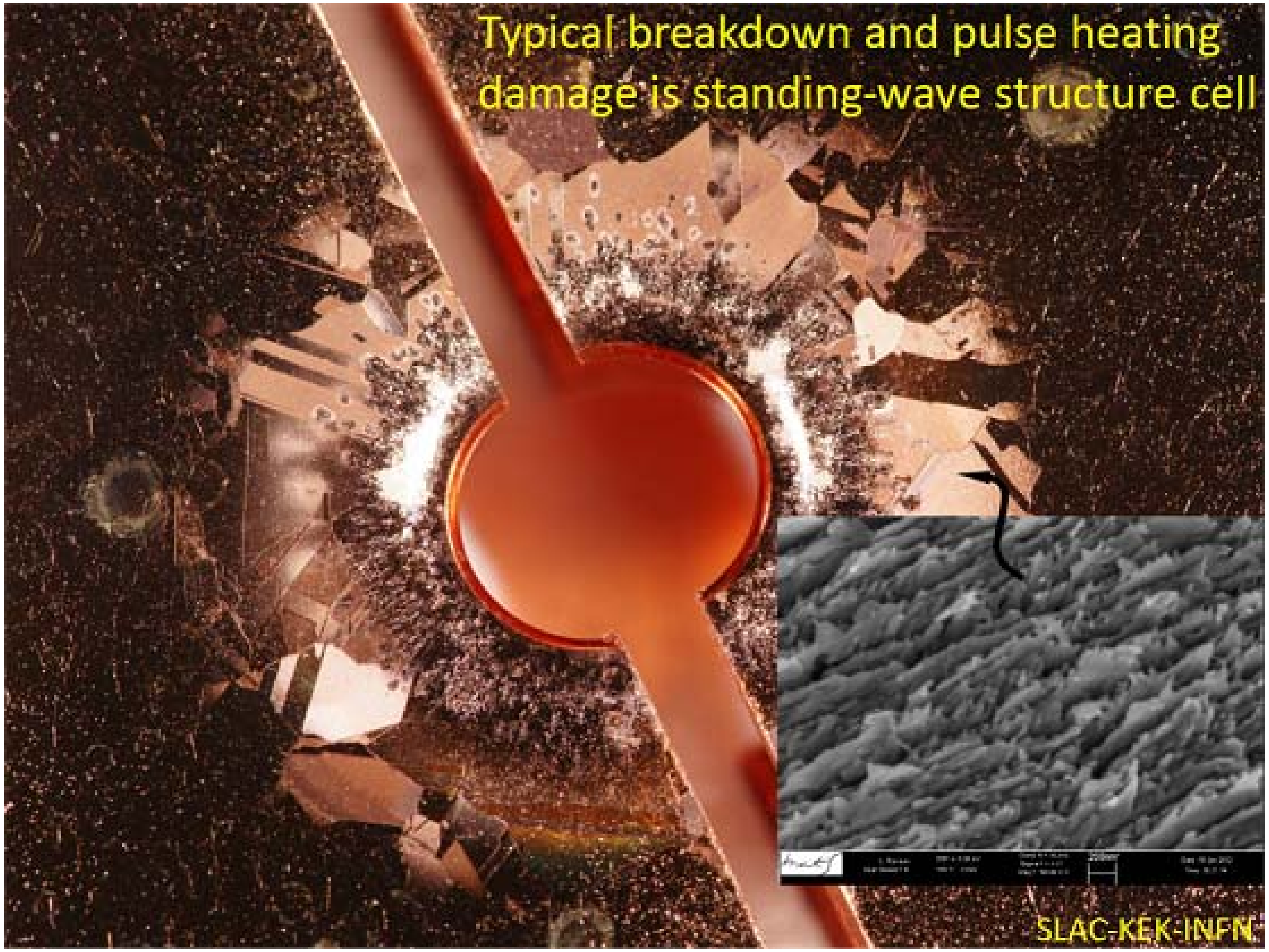
- The reason why the cost has been scaling with the collider energy is that the accelerating gradients (i.e., the energy gained per unit length) have more or less remained constant over the **past few decades**.
- Therefore, the only way to scale into higher energies is to simply make the accelerating portion longer, thus increasing the construction and maintenance costs at the same time

The CERN Accelerator School

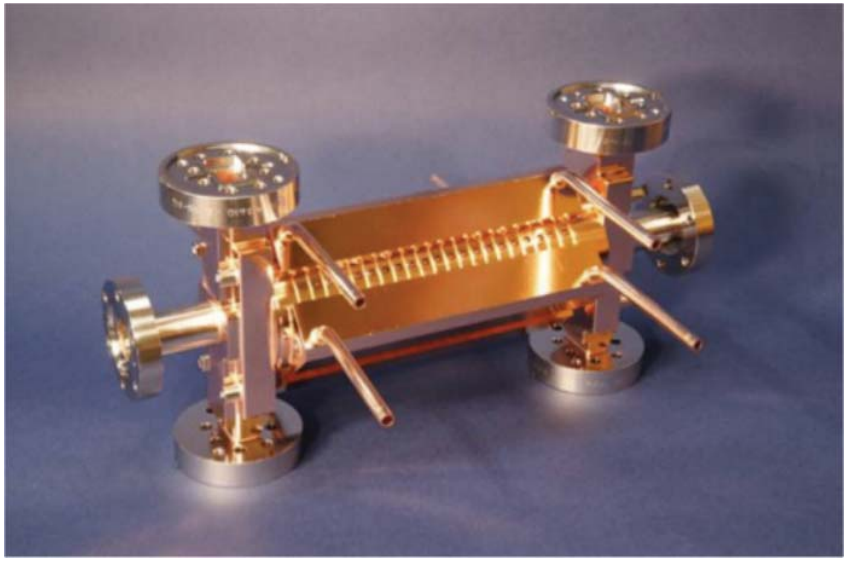
Acceleration

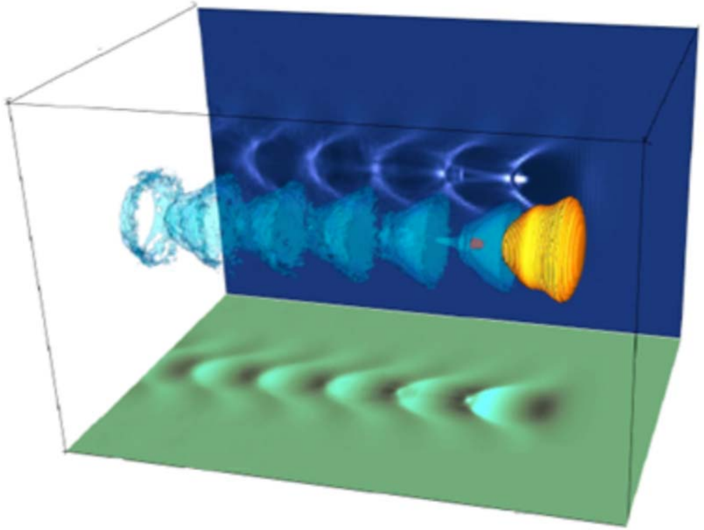


Breakdown


Typical breakdown and pulse heating damage is standing-wave structure cell
SLAC-KEK-INFN

Scaling factor



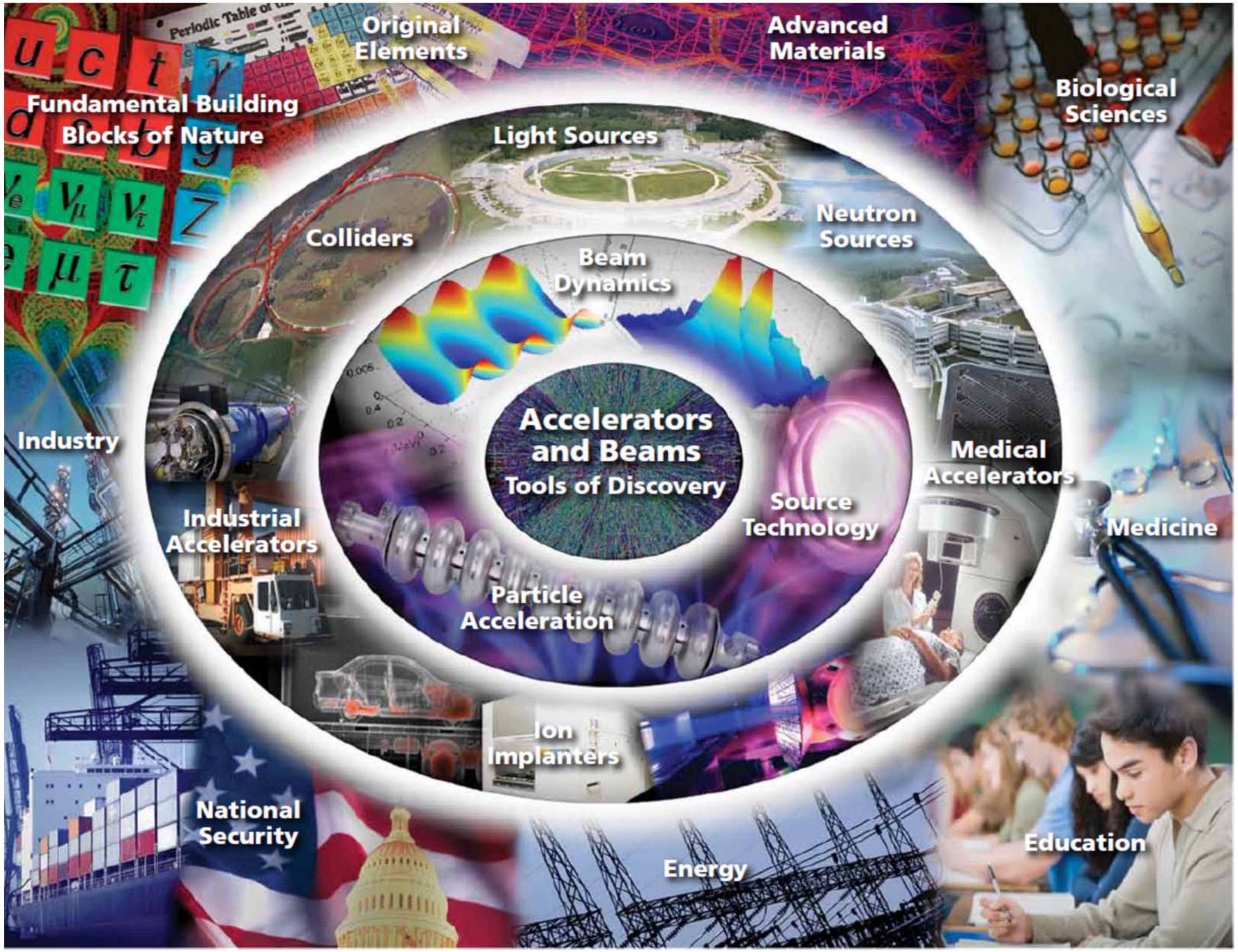


4‡þ #~ 100 MeV

4‡þ p #~ 100 MeV

Importance of accelerators

Courtesy Oak Ridge National Laboratory



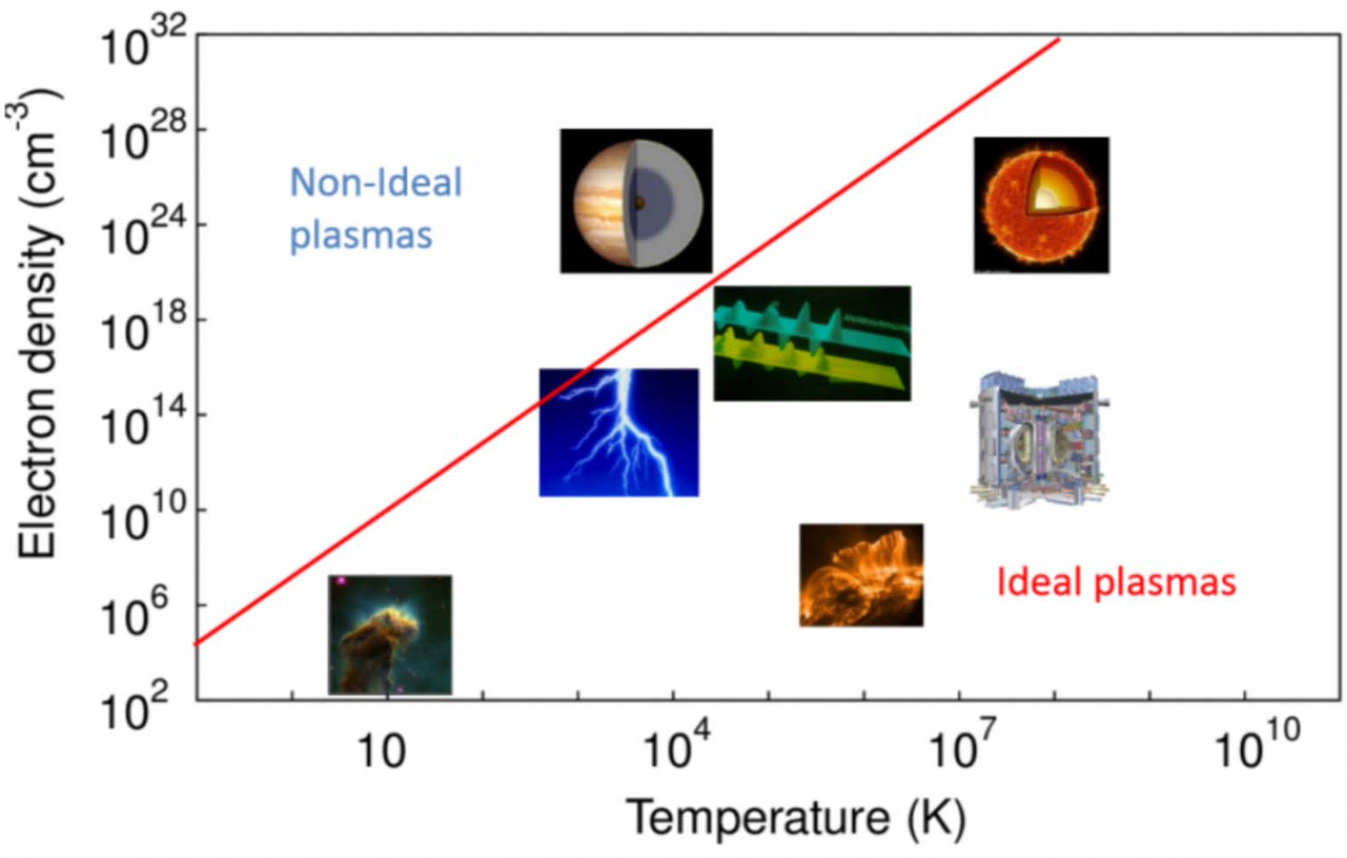
Three main categories

- LWFA (Laser Plasma Acceleration)
  - Based on the use of high power laser (>10^{18} W/cm^2)
- PWFA (Plasma Wakefield Acceleration)
  - Based on a train of high brightness bunches
- DWFA (Dielectric Wakefield Acceleration)
  - Can use both laser and beam without the plasma

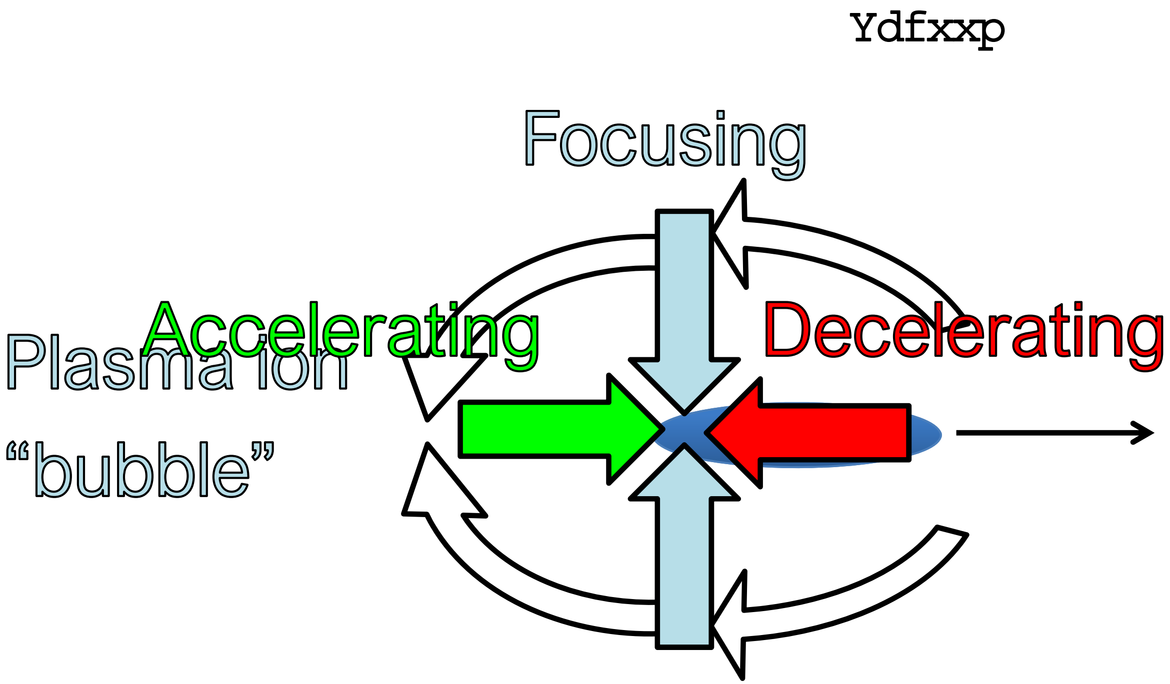
What is plasma?

- Simple definition: a quasi-neutral gas of charged particles showing collective behavior
- Quasi-neutrality: number densities of electrons, n_e, and ions, n_i , with charge state Z are locally balanced
- Collective behavior: long range of Coulomb potential usually dominate over microscopic fluctuations

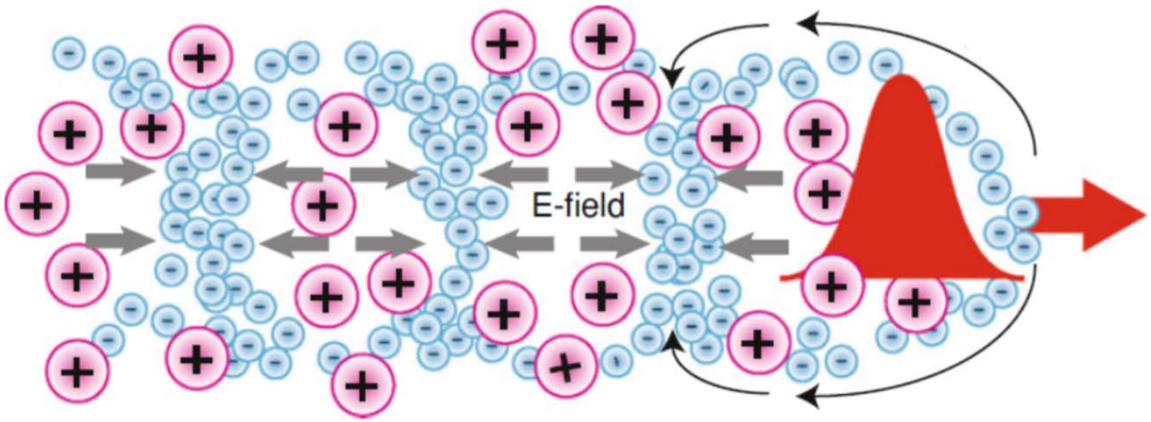
Plasma categories



What is a Plasma Wakefield Accelerator?

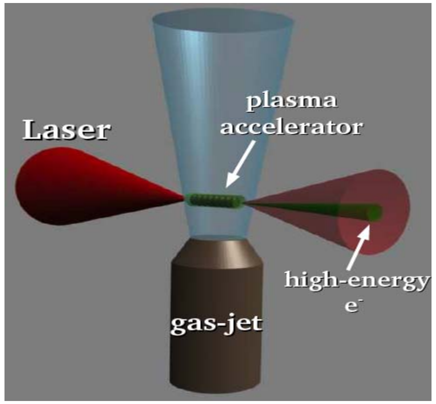


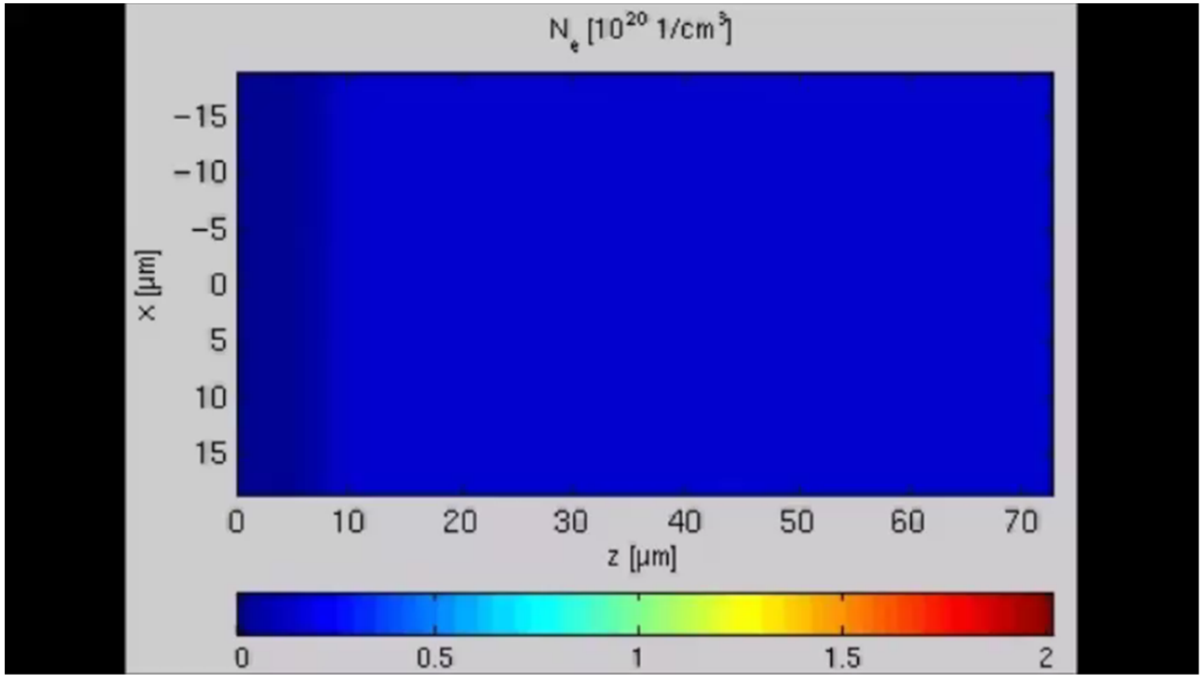
Plasma wake by Laser



LWFA
Laser
Plasma
Acceleration

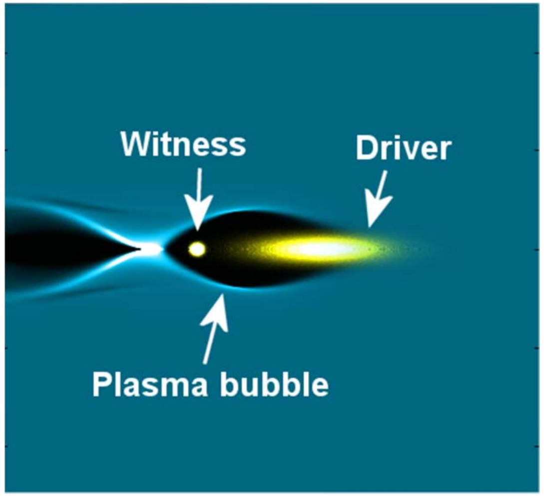
LWFA





- Billions of free electrons inside the plasma can be manipulated together and forced to act coherently.
- Plasma acts as an energy transformer. It does not provide energy; it only transfer the energy of an existing beam to a trailing beam.

PWFA



- PWFA not limited by diffraction or by dephasing
- Particle bunches have long Rayleigh length (up to m)

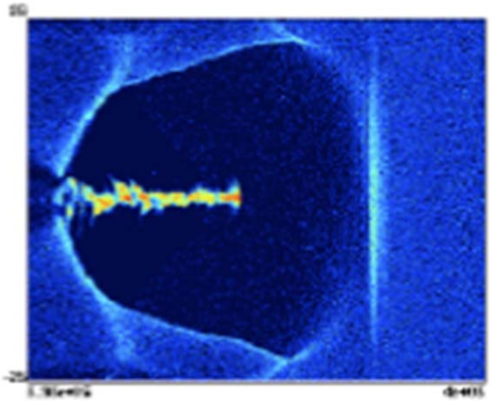
$$N_2 \Delta E_2 \leq N_1 \Delta E_1$$

- N_1 particles in the drivers, N_2 particles in the witness
- ΔH_4 energy loss in the drivers,
- ΔH_5 energy gain in the witness

Different schemes

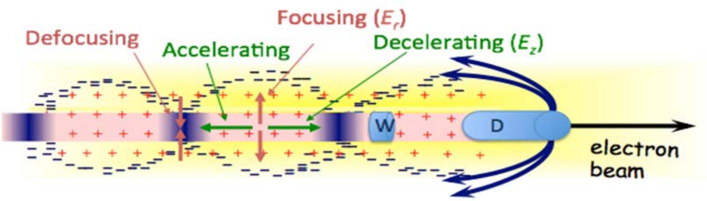
Laser only

- The "easiest" to implement (requires "only" to tune the laser and the target)
- Difficult control over the whole process



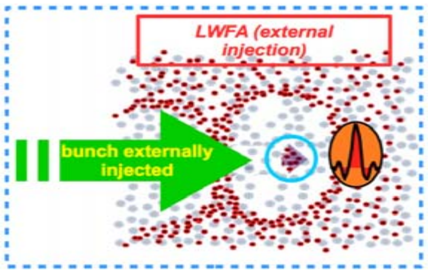
Electrons only

- Easier implementation than laser+electrons (no need for independent synchronization system and driver guiding)
- It depends heavily on the ability to properly tailor the driver(s) and witness phase spaces

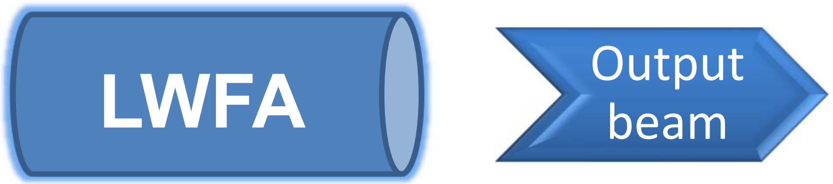


Laser and electrons

- In principle has the best potentialities in term of e-beam brightness and energy
- The hardest to implement (laser guiding, synchronization issues, …)



Two main scenarios



- LWFA: Diagnostics of the output beam

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

The CERN Accelerator School

Place the diagnostics

- The first problem is to put the diagnostics
  - In the LWFA there is the laser that must be removed before to put everything
  - In the PWFA there is the driver beam that must be eliminated

Resolution is not the only constrain

- Resolution for emittance must better than 1mm-mrad
- Time resolution must be in the fs scale
- The device must work even with shot by shot pointing, energy, time jitter instabilities
- Compactness is a fundamental requirement
- Maybe we have to change our perspective and accept quite large error bars
- The diagnostics is not the experiment for which we built the machine!

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

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

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

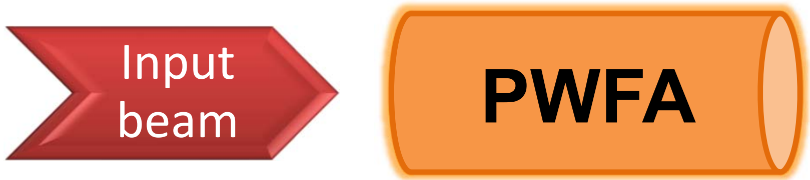
$$\varepsilon_n^2 = <\gamma>^2 \left(s^2 \sigma_\varepsilon^2 \sigma_{x'}^4 + \varepsilon^2\right)$$

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

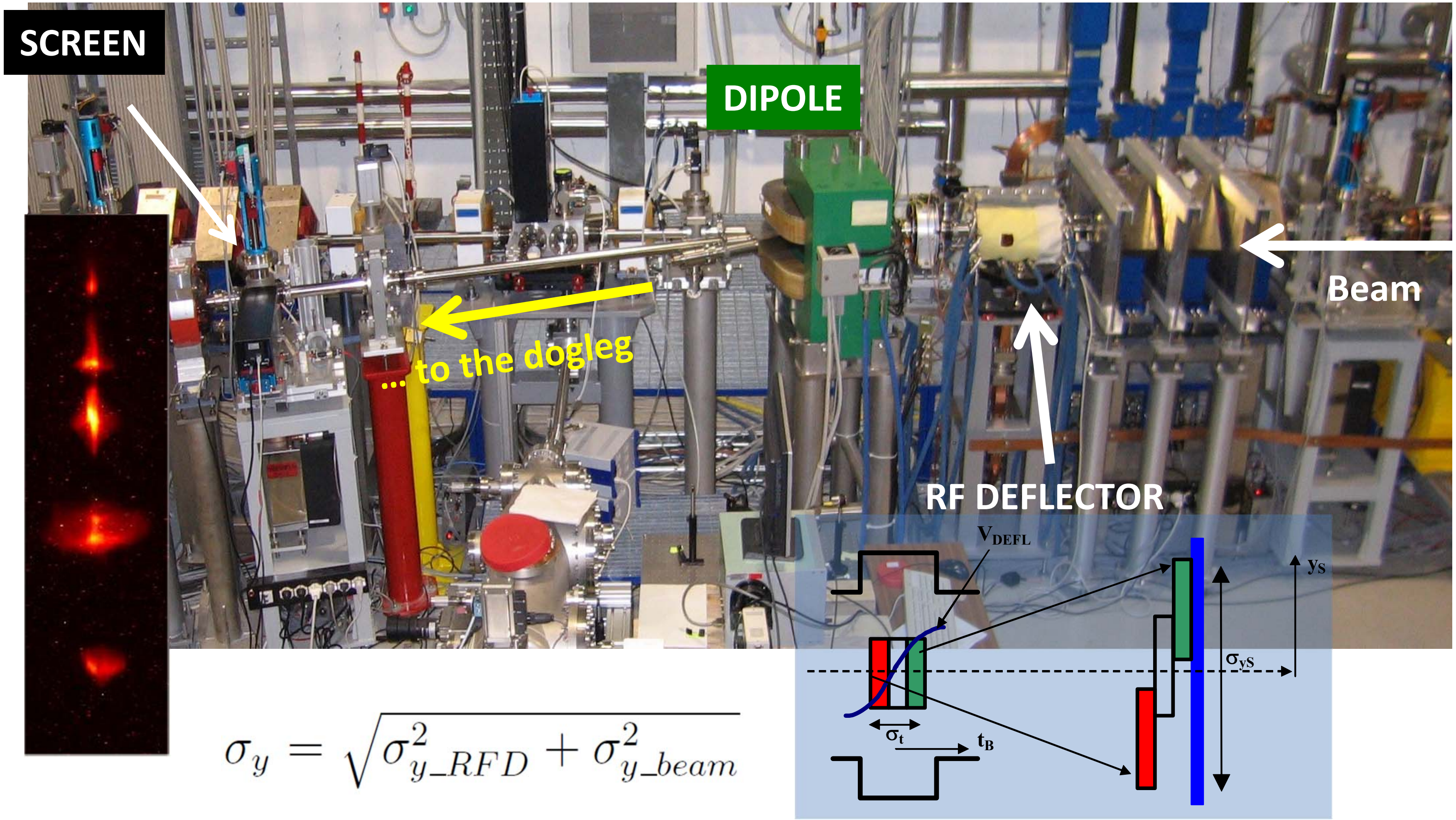
$$L_C = \frac{\gamma \sigma_x^2}{\varepsilon_n \, \delta\gamma / \gamma}$$

PWFA

Input beams



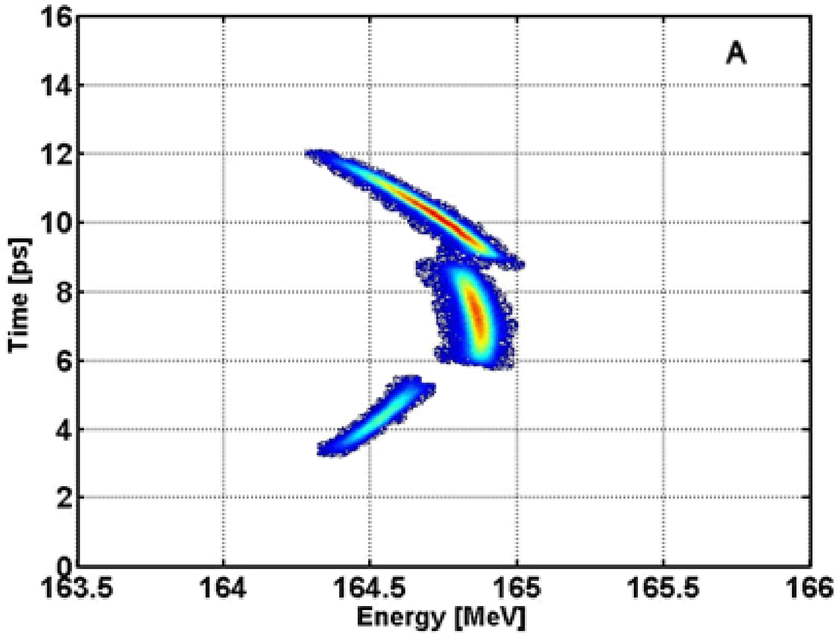
Time separation

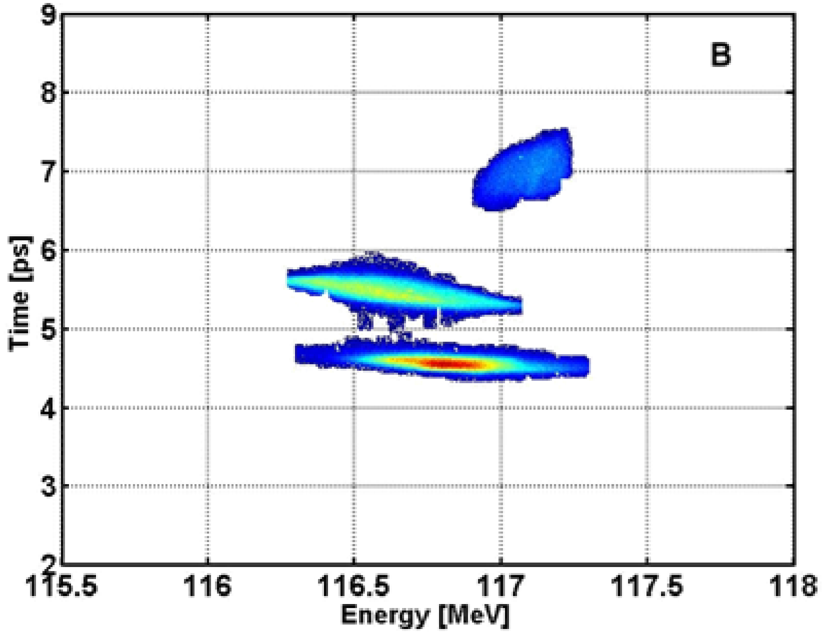


$$\sigma_y = \sqrt{\sigma^2_{y\_RFD} + \sigma^2_{y\_beam}}$$

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

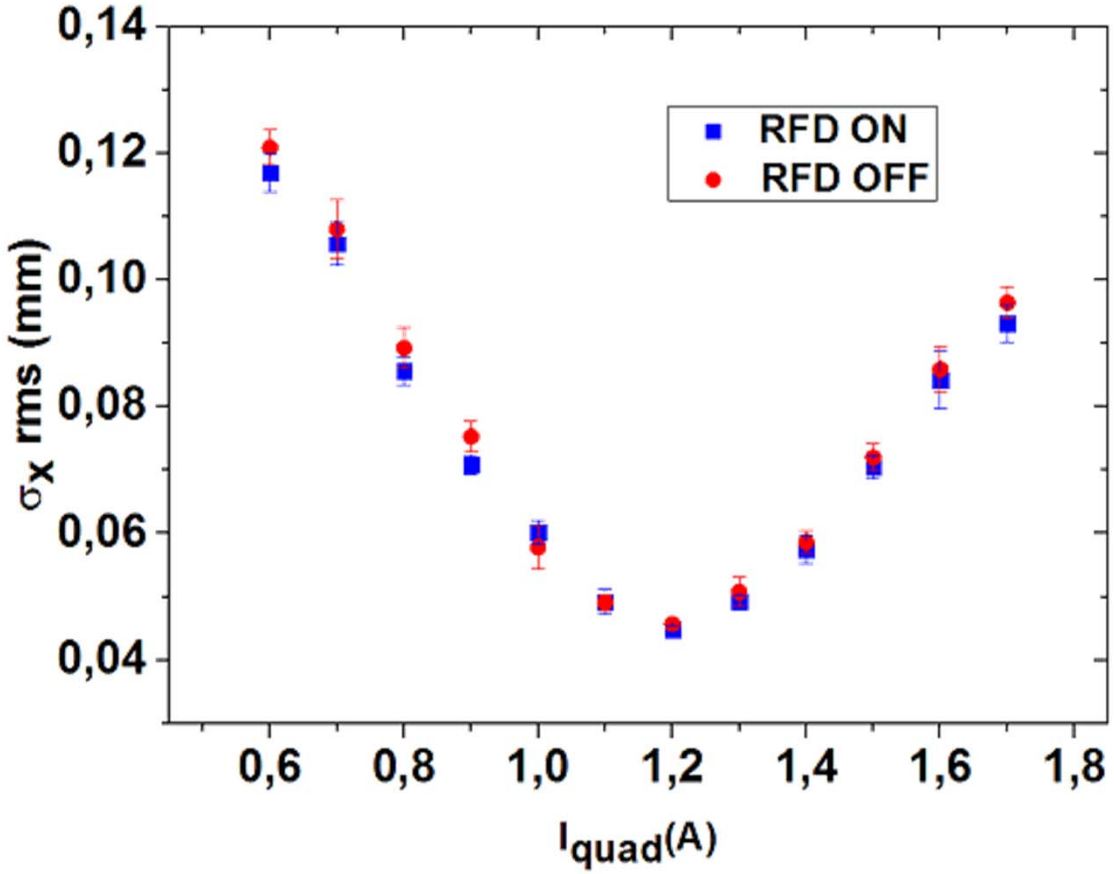
Longitudinal phase space





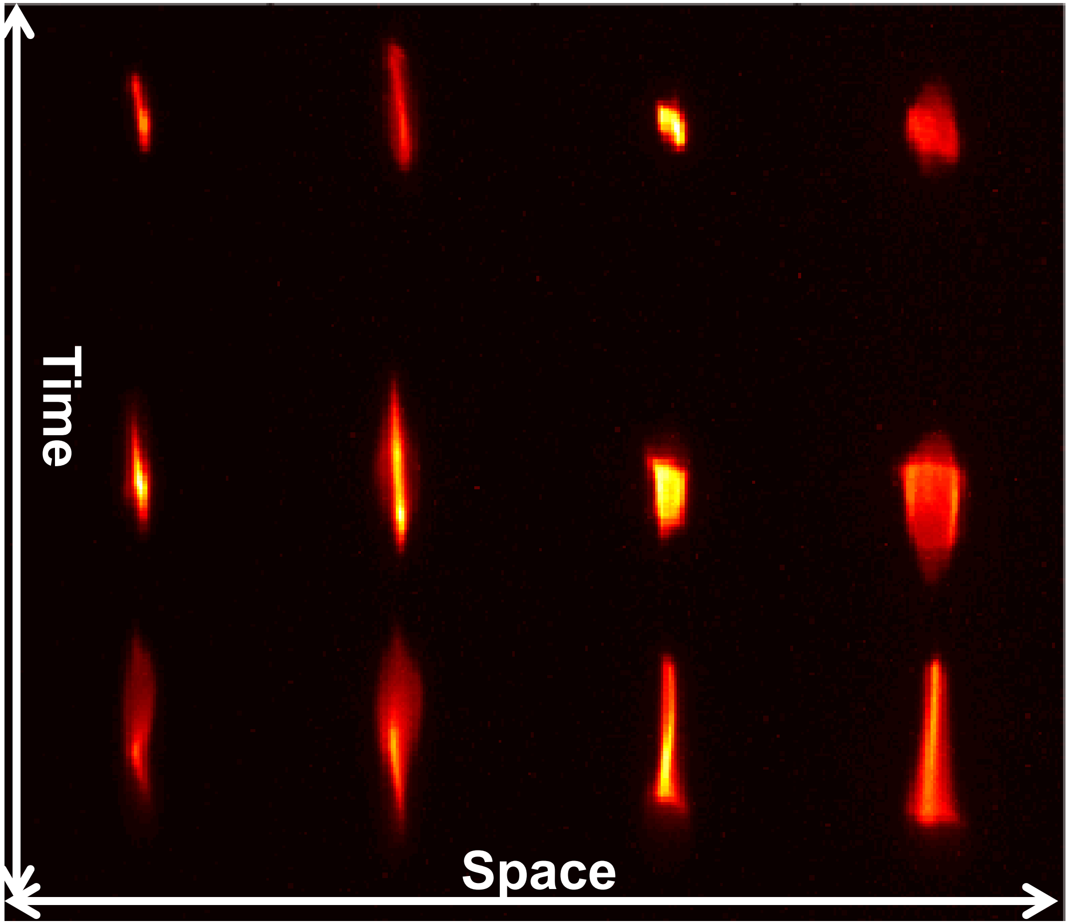
Bunch	Beam Energy(MeV)	Energy Spread(%)	Position (ps)	Bunch Length (ps)	Long. Emit(keV mm)
W	164.50 (0.02)	0.051 (0.005)	4.28 (0.02)	0.54 (0.02)	5.3 (0.2)
D1	164.82 (0.02)	0.030 (0.005)	7.12 (0.02)	0.73 (0.02)	9.8 (0.3)
D2	164.66 (0.02)	0.086 (0.005)	10.01 (0.02)	0.74 (0.02)	9.6 (0.5)
Whole	164.71 (0.02)	0.092 (0.005)	7.91 (0.02)	2.13 (0.02)	96.5 (1.4)

Single bunch test

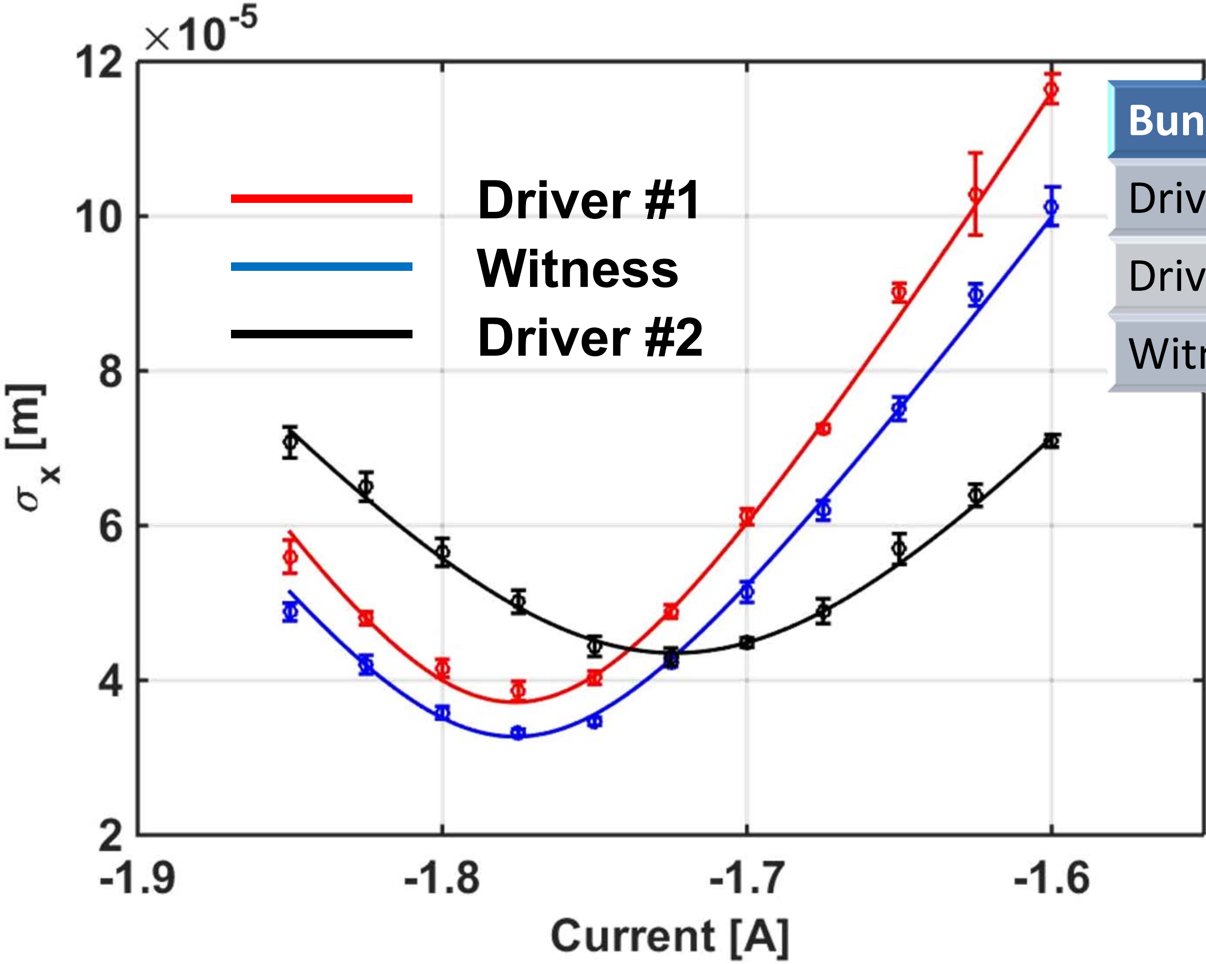


- Transverse size with RFD on/off

Quad scan comb beam



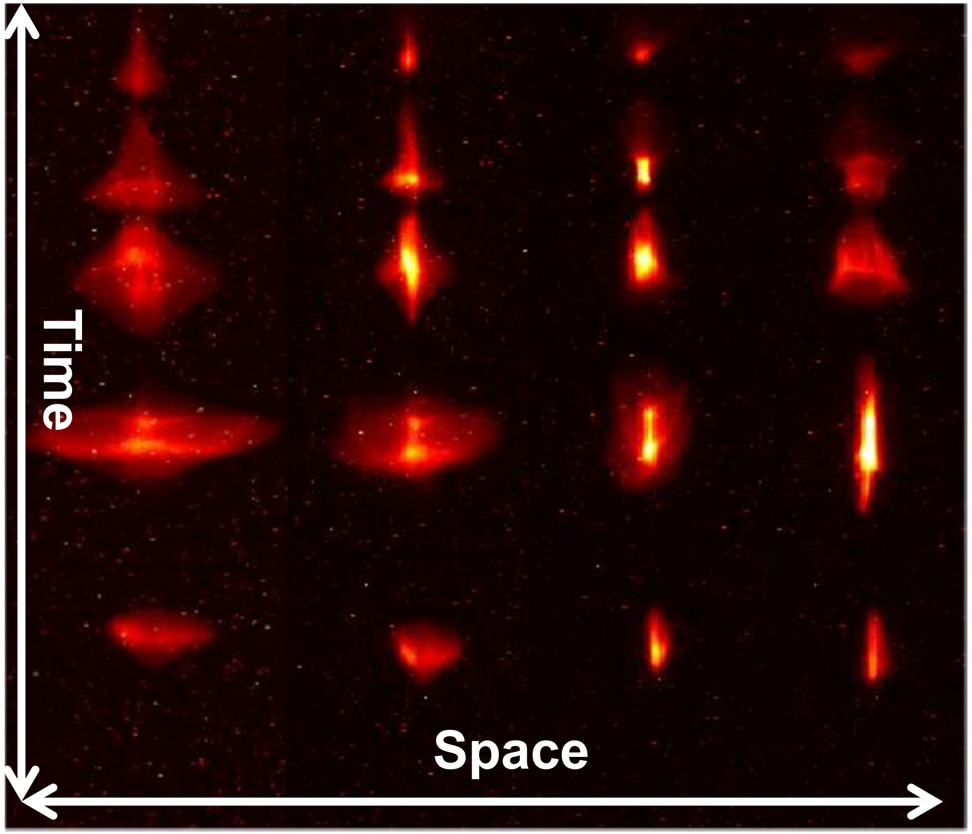
Results



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

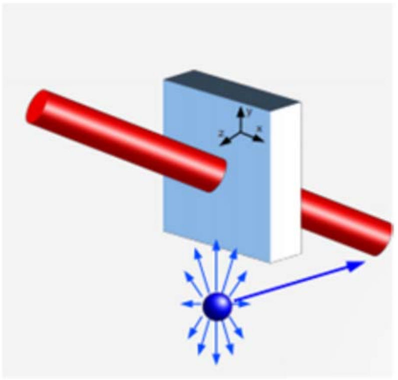
A. Cianchi et al. "Six-dimensional measurements of trains of high brightness electron bunches", Physical Review Special Topics Accelerators and Beams 18, 082804 (2015)

5 bunches



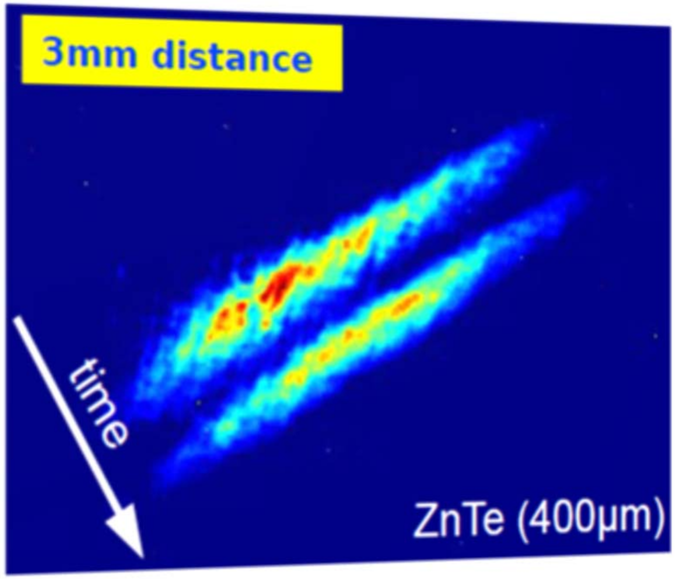
EOS systems

- 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

A comblike beam



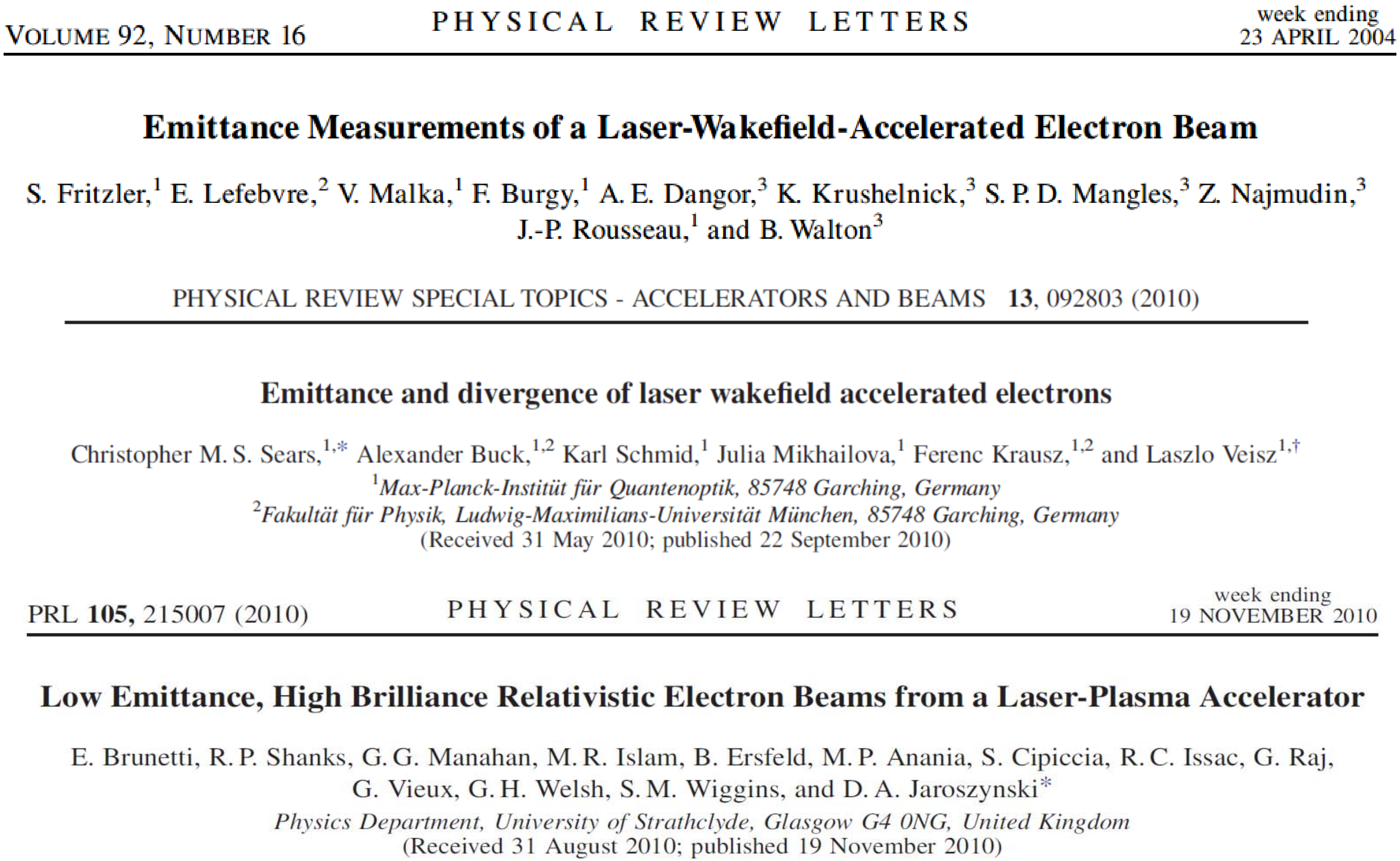
- σ_1=(375±10) fs
- σ_2=(344±10) fs
- dist=(879±9) fs

- 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

LWFA & PWFA

Output beams

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

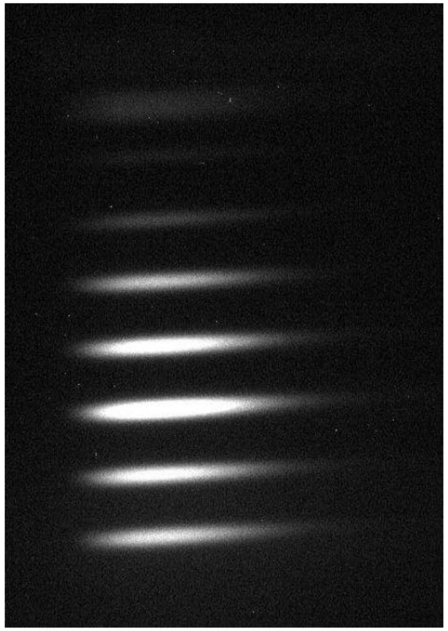
Christopher M. S. Sears,[1,*] Alexander Buck,[1,2] Karl Schmid,[1] Julia Mikhailova,[1] Ferenc Krausz,[1,2] and Laszlo Veisz[1,†]
[1]*Max-Planck-Institüt für Quantenoptik, 85748 Garching, Germany*
[2]*Fakultät für Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany*
(Received 31 May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

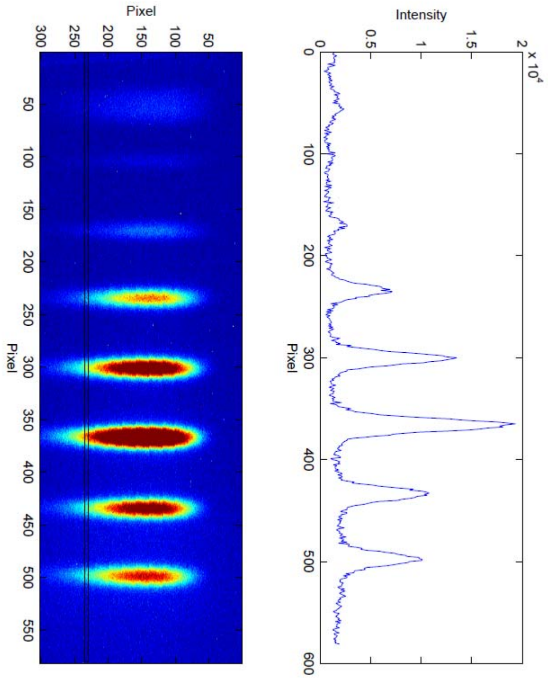
PRL **105,** 215007 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

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)

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

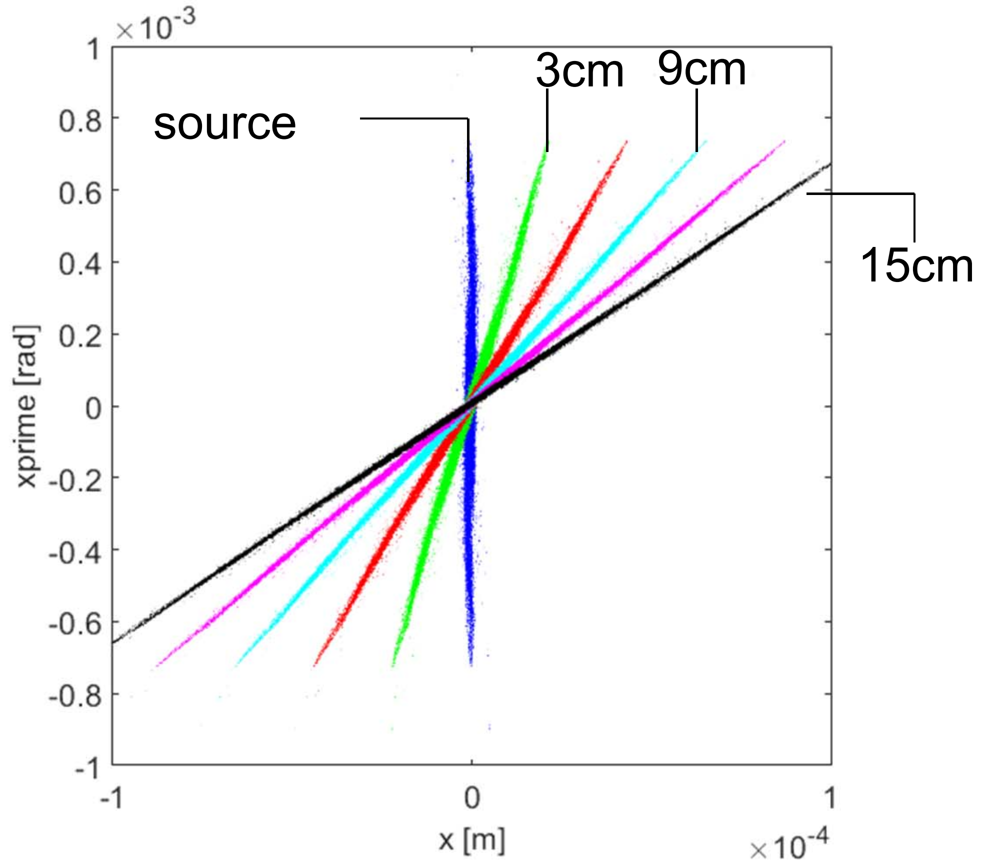
N. Delerue Nuclear Instruments and Methods in Physics Research A 644 (2011) 1–10

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

Intrinsic limit for LWFA beams

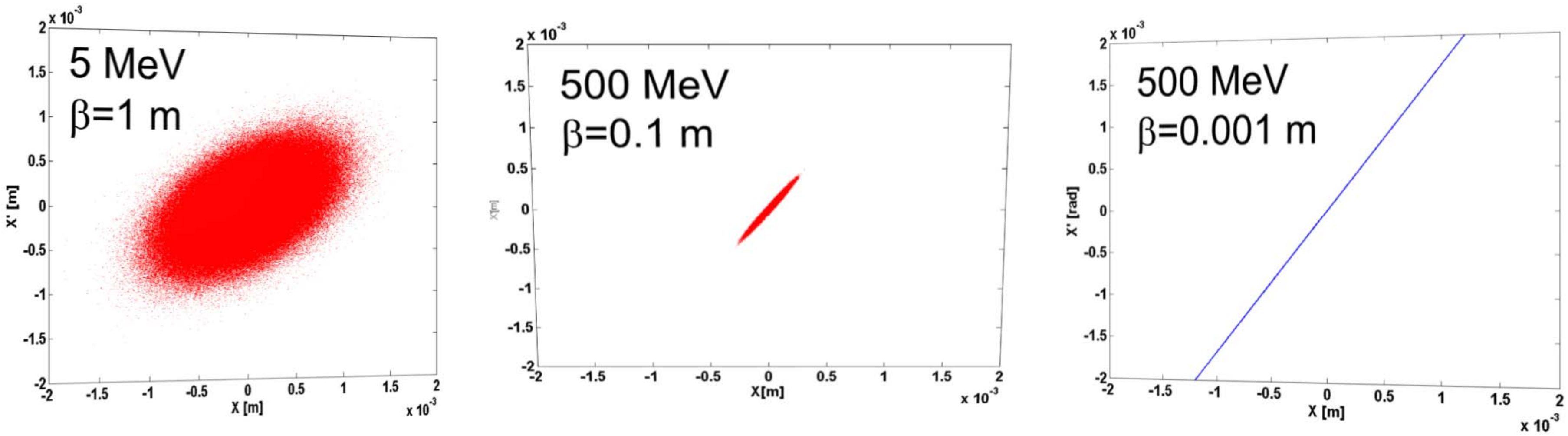
- No considerations about
  - S/N ratio
  - Detector
  - Multiple scattering
  - Background
- Mask thickness neglected

Strongly correlated beam



The CERN Accelerator School

Trace spaces

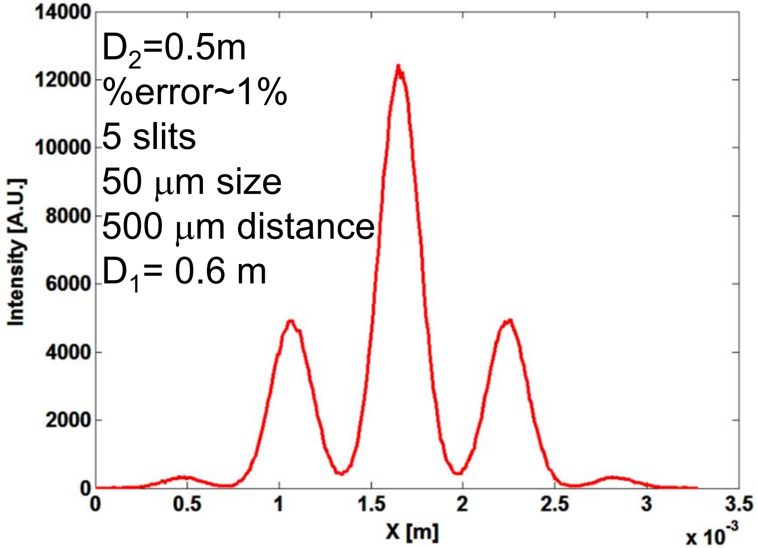


- All beams have ε_n=1 mm-mrad
- z=0.6 m
- β=0.1 m means 10 μm on the source
- β=0.001 m means 1 μm on the source

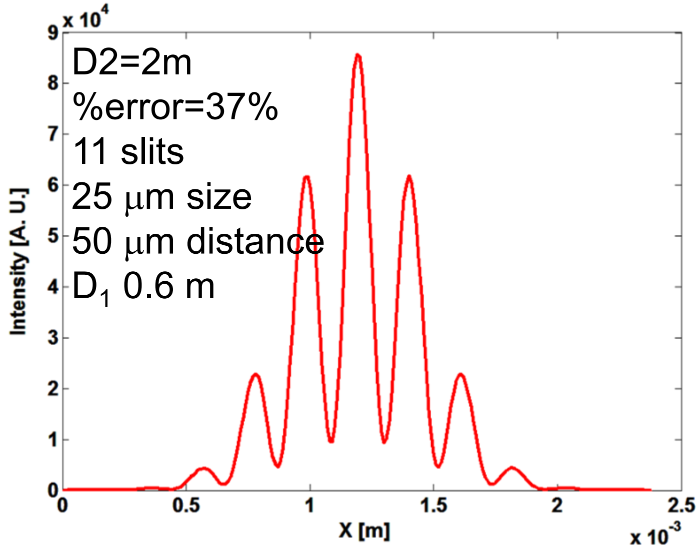
The CERN Accelerator School

No problems

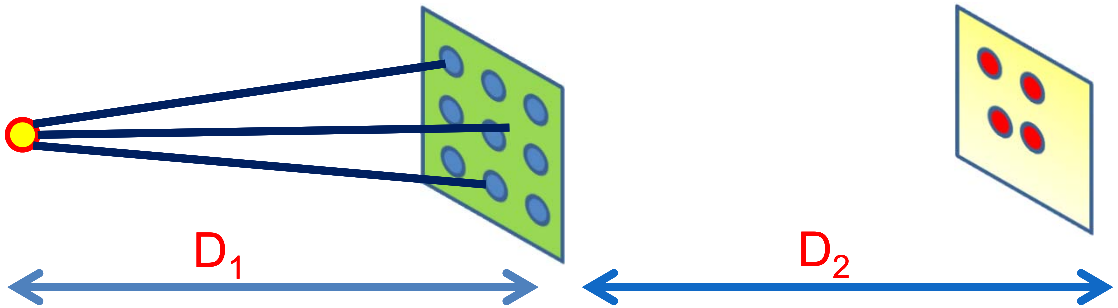
- Everything roughly optimized in to minimize the error and to use all the particles



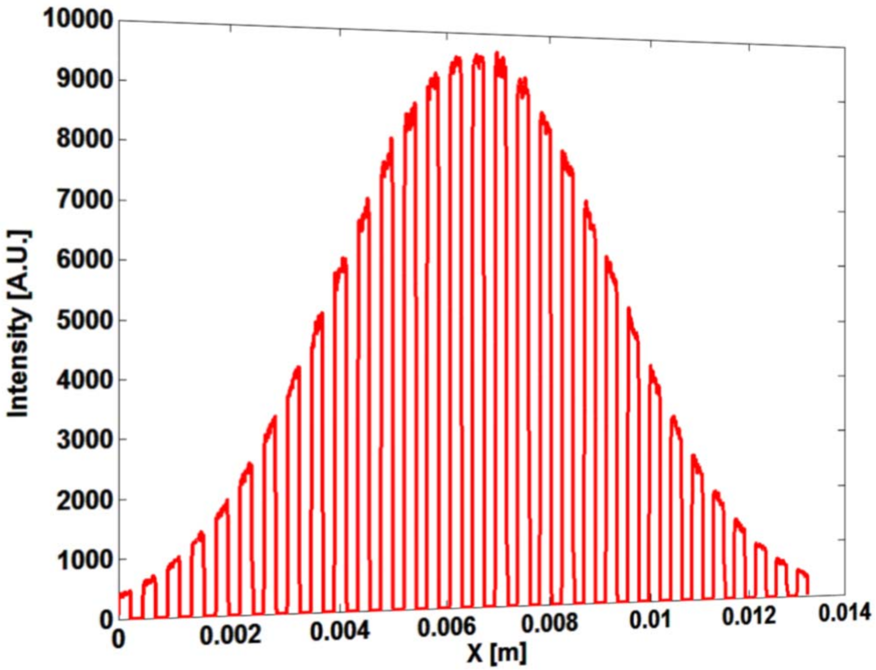
5 MeV β=1 m



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

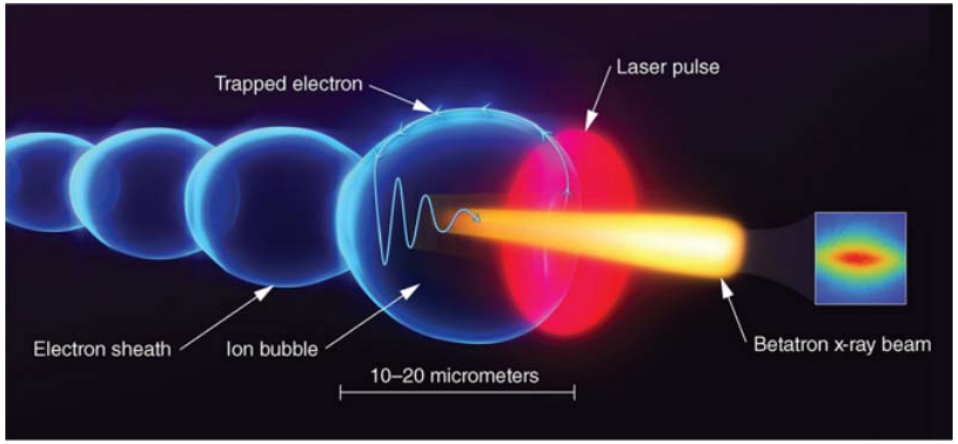
- T. Ludwig, K. Volk, W. Barth, and H. Klein, "**Quantization error of slit-grid emittance measurement devices",** Review of Scientific Instruments **65**, 1462 (1994)

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

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)

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

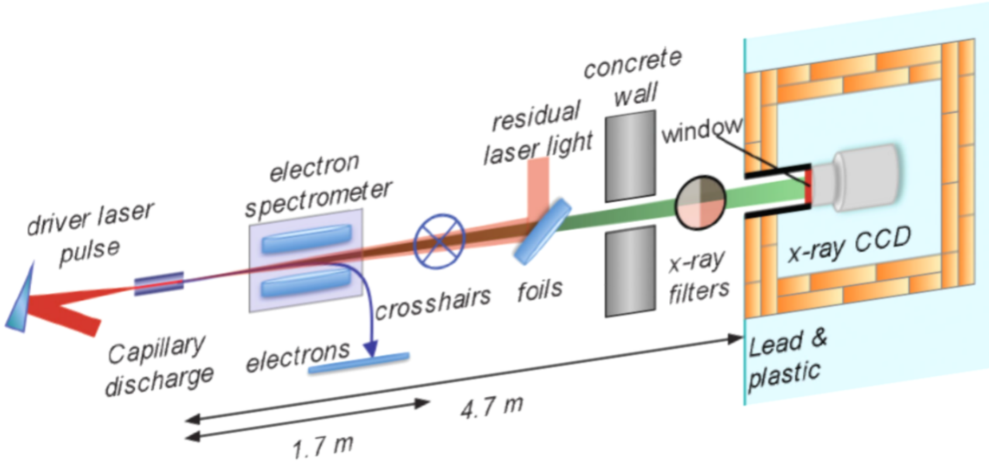


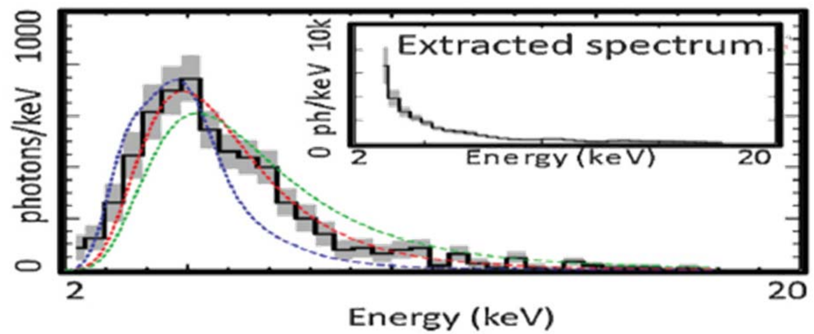
Picture from F Albert et al Plasma Phys. Control. Fusion 56 (2014) 084015

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)

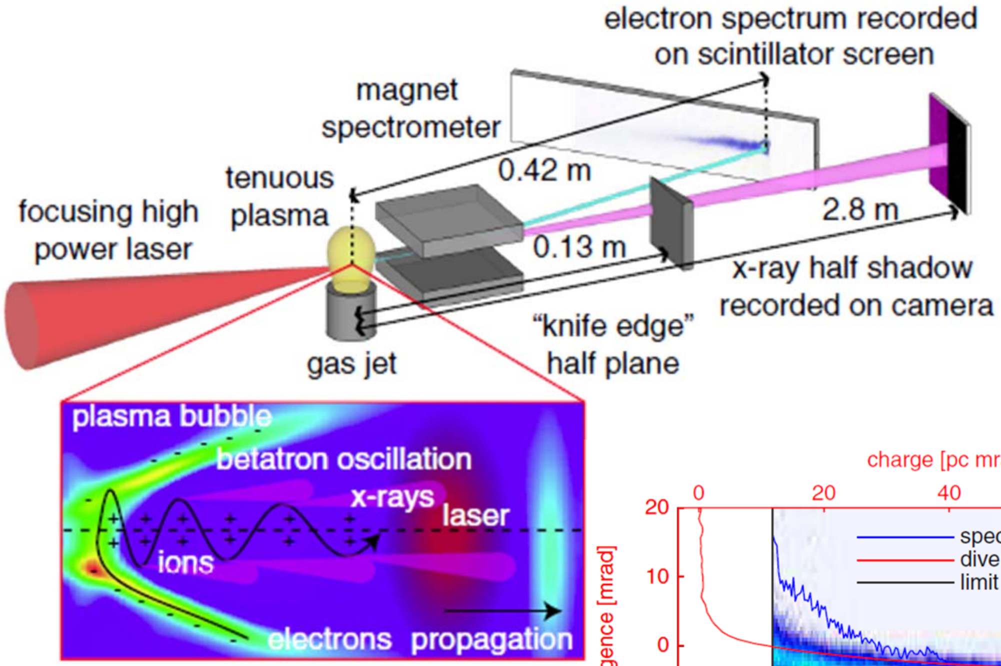
- 400 MeV energy with a rms energy spread of less than 5% and 1 mrad divergence from a plasma density of 5 10^{18}cm^3

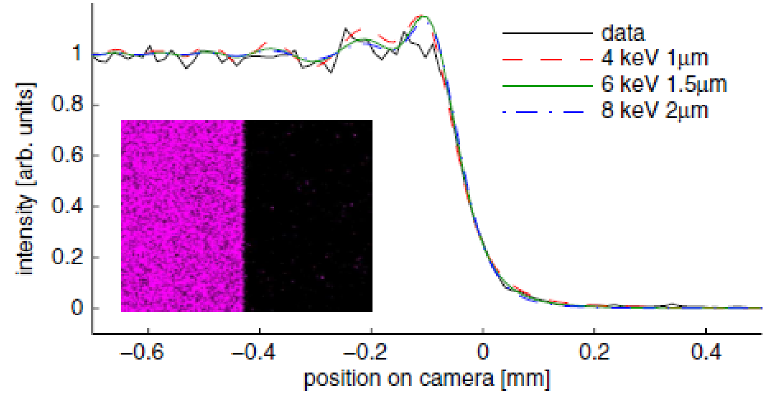




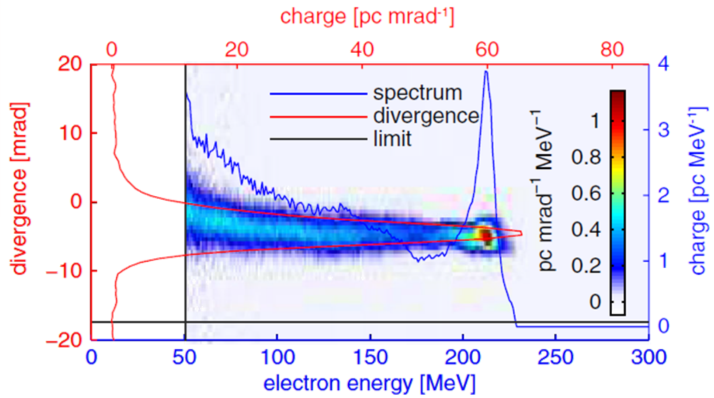
σ σ' γ $\Delta\gamma$ at the same time

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





Source size by Fresnel diffraction

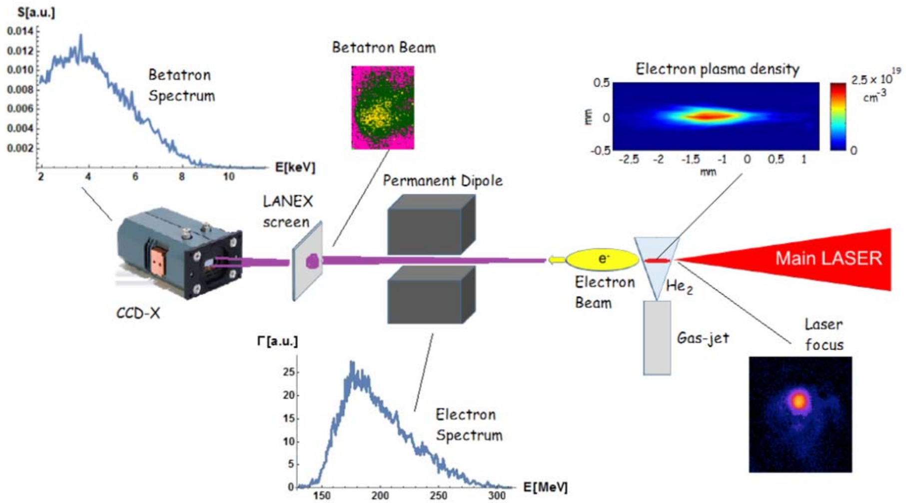


Energy, energy spread and divergence behind the dipole

Emittance with the correlation term

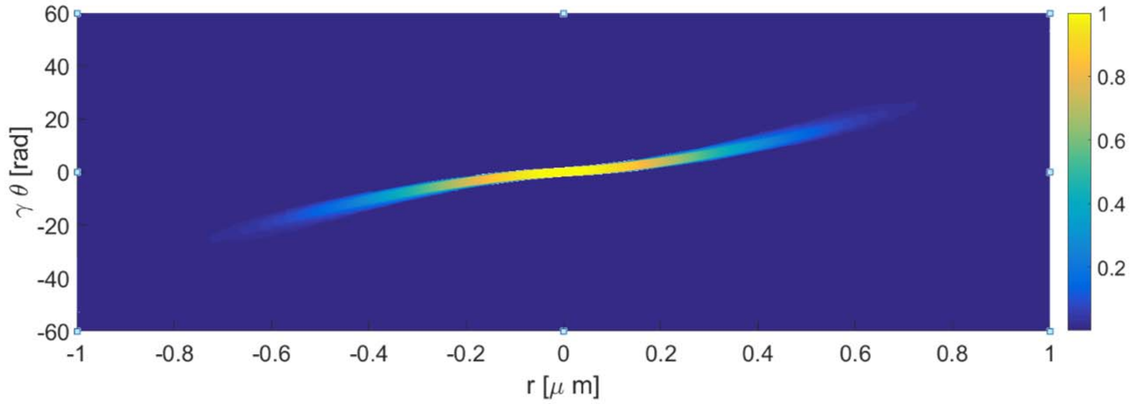
- First measurement of the emittance including the correlation term
- The beam profile is retrieved not simply the average dimensions
- An expression is given for the correlation function between the betatron oscillation amplitude and the divergence of the single accelerated electrons, i.e. the angle with respect the acceleration axis, in order to obtain the distribution of the electron divergences.

4#M
63#v#+IZ KP ,#
43#up #gldp hwhu#rfxv,
d3#~ 717
q_h@+;±4,43^4; fp^06



Fxufl r/#D1/#hw#do1#Wudfh0vsdfh#uhfrqvwuxfwlrq#ri#orz 0hp lwwdqfh#hohfwurq#ehdp v#wkurxjk#ehwdwurq udgldwlrq#lq#odvhu0sodvp d#
dffhohudwruv1%Sk|vlfdo#Uhylhz #Dffhohudwruv#dqg#Ehdp v 5314#534:,=#345;341

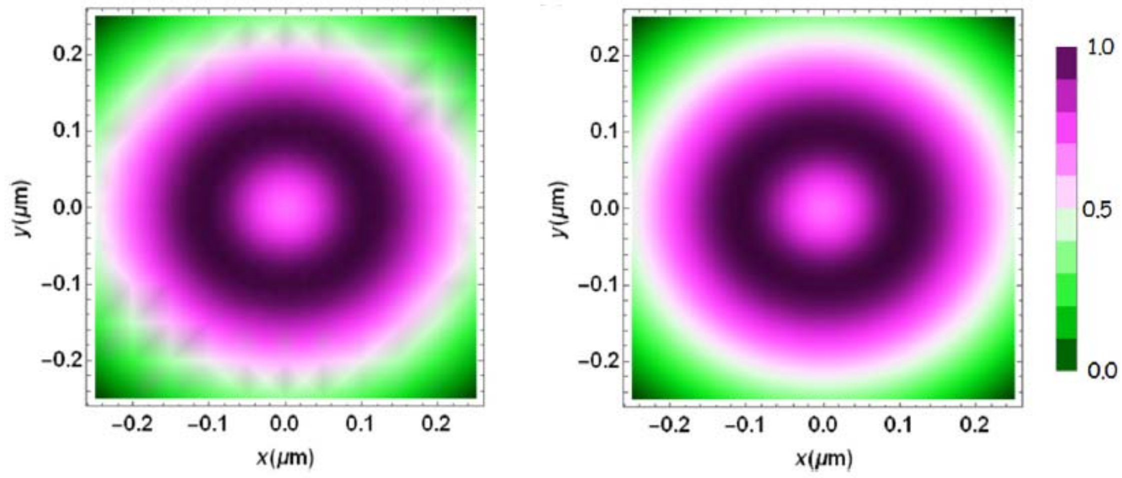
Phase space recontruction



- Normalized rms emittance (correlated): 0.6 mm mrad
- Normalized rms emittance (non correlated, upper limit): 1.6 mm mrad

From 1D to 2D

2D beam profile monitor could be therefore possible only when the correlated angular-spectral distribution of the betatron radiation is detected
Great monitor for nm beam size

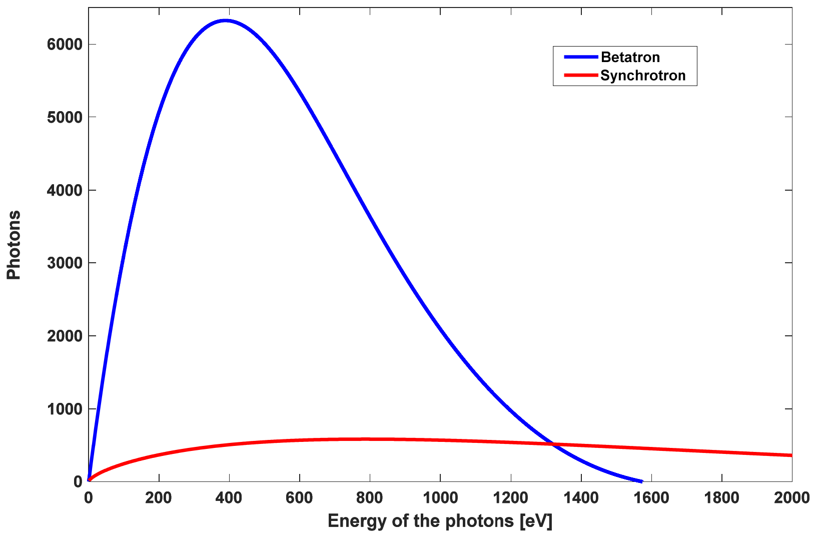


Retrieved　　Simulation

- Curcio, A., et al. "Single-shot non-intercepting profile monitor of plasma-accelerated electron beams with nanometric resolution." *Applied Physics Letters* 111.13 (2017): 133105.

Open problems

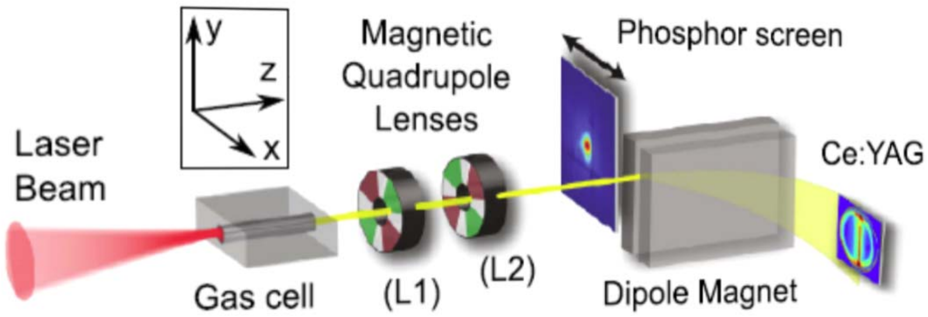
- Separation of Betatron radiation from Synchrotron radiation coming from a bending magnet: not big deal

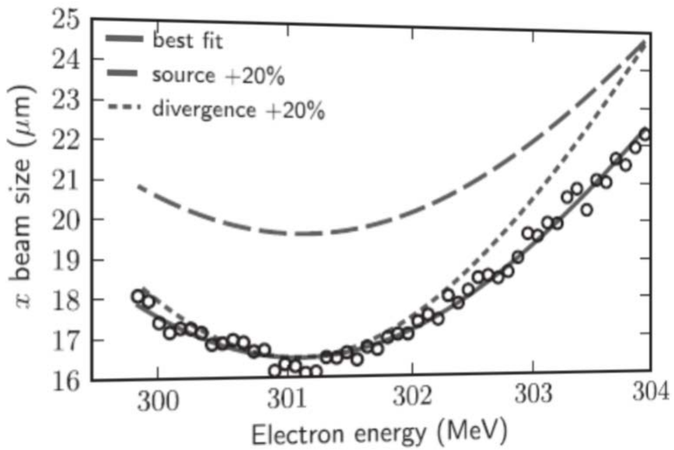


Beam charge 30 pC
Energy 1 GeV
plasma density 2 10^{16}cm^{-3}
magnet filed 1.5 T
radius of curvature 2.2 m

- Separation of witness and driver radiation in case of beam driven: it is a problem!

A new kind of Quadscan



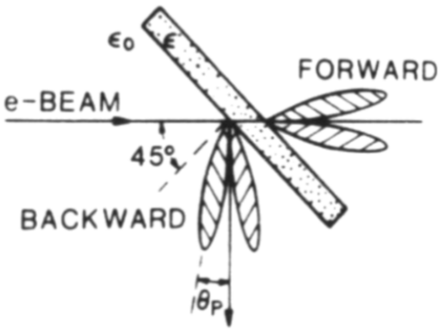


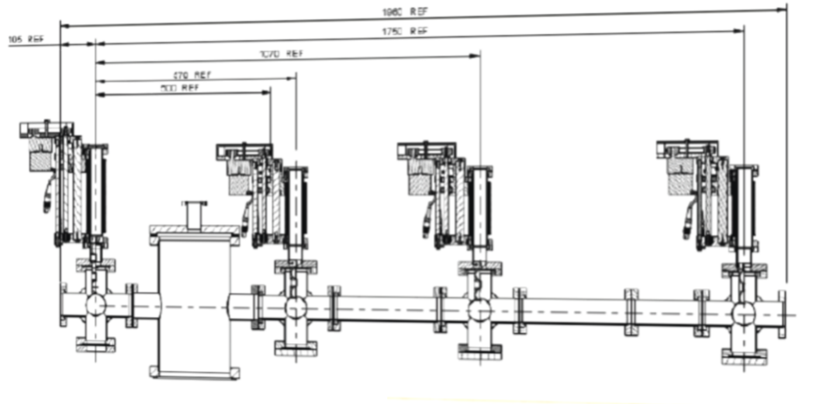
- Reduction of energy spread (highly desirable) will dramatically reduce the resolution of this measurement

- R. Weingartner and al., PRST-AB 15, 111302 (2012),
- Barber, S. K., et al., Physical Review Letters 119.10 (2017): 104801.
- F Li et al 2018 Plasma Phys. Control. Fusion 60 014029

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



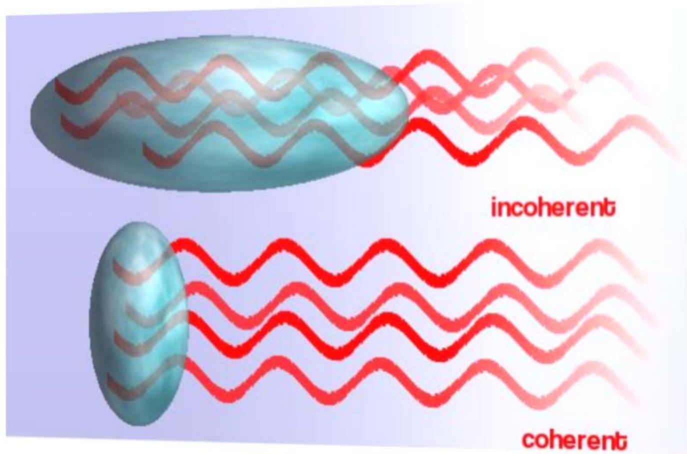


$$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left(1+0.038 ln\frac{x}{X_0}\right)$$

- ✓ 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

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



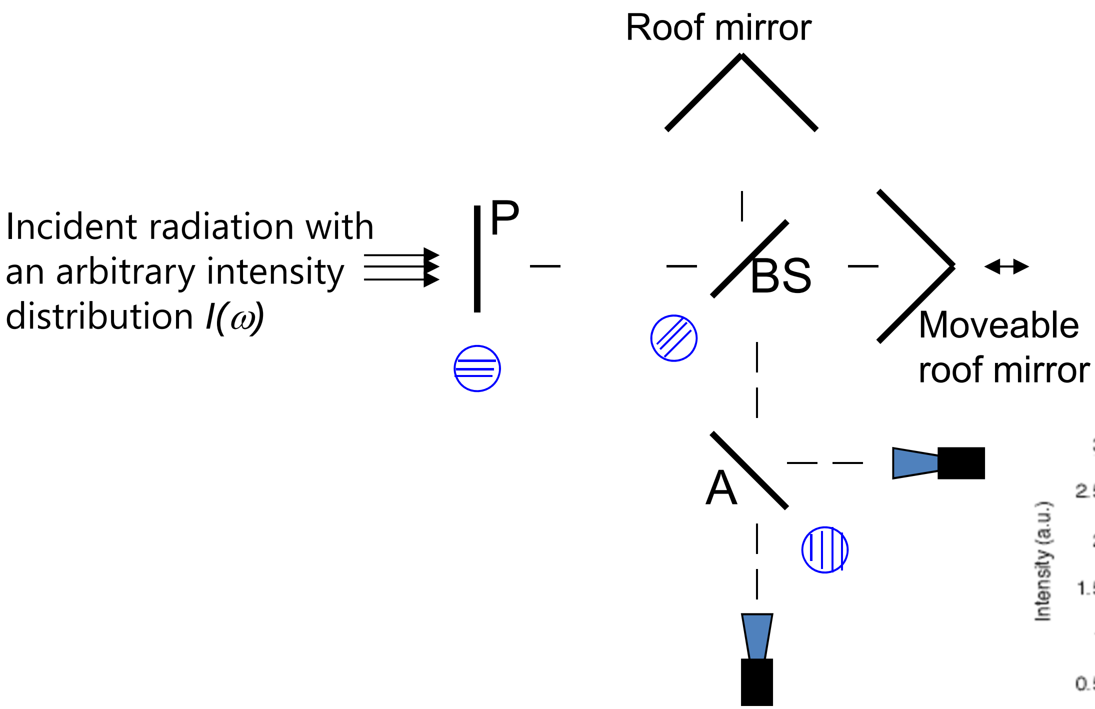
Power Spectrum

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

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

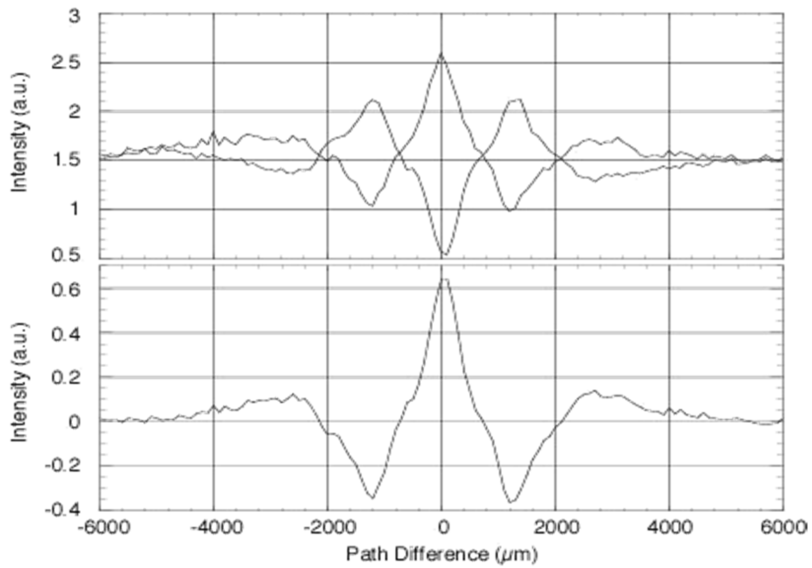
- From the knowledge of the power spectrum is possible to retrieve the form factor
- The charge distribution is obtained from the form factor via Fourier transform
- The phase terms can be reconstructed with Kramers-Kronig analysis (see R. Lai, A.J. Sievers, NIM A **397** (1997) 221-231)

Martin-Puplett Interferometer



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

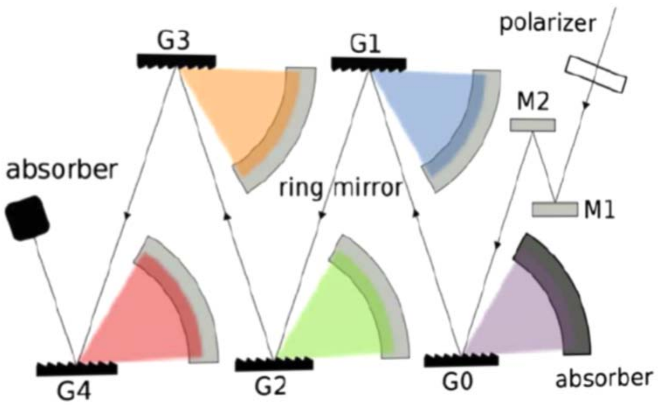
$$I(\omega) \propto \int_{-\infty}^{\infty} I(\delta) \cos\left(\frac{\omega \delta}{c} \right) d\delta$$

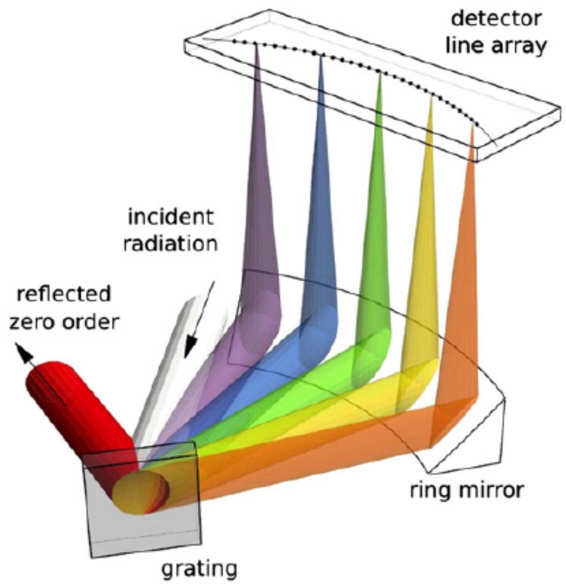


- Golay cells or Pyroelectric detector

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

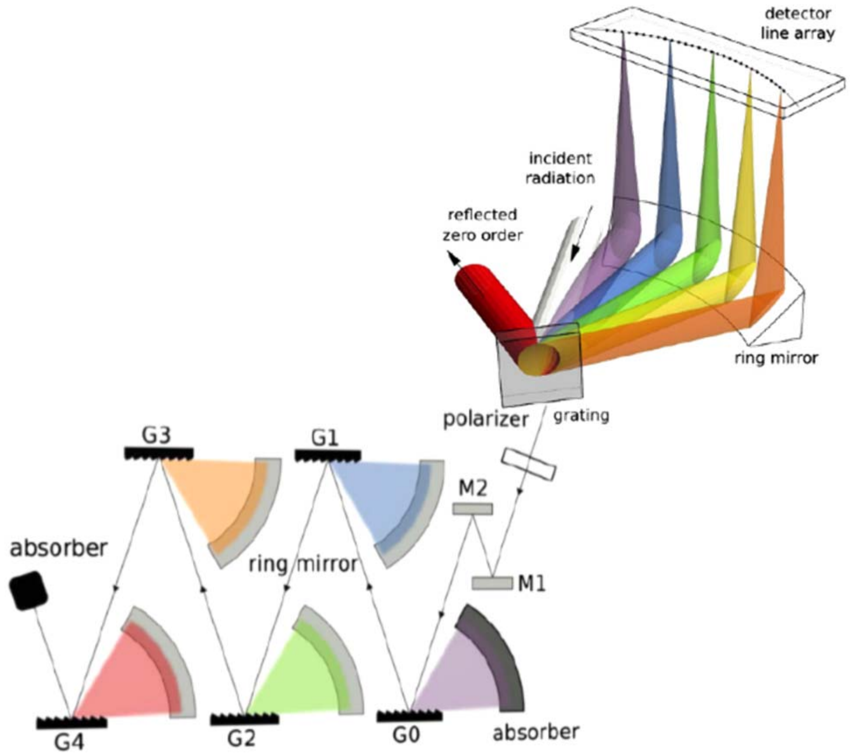


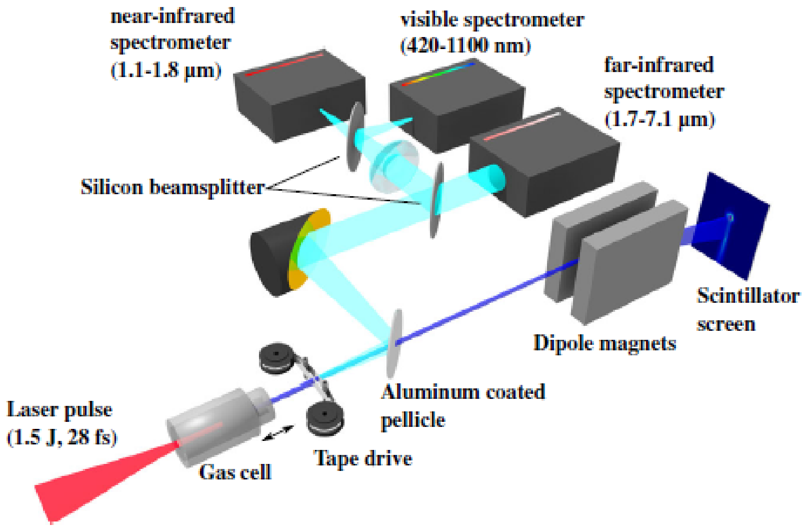


Pyro-electric line detector 30 channels @ room temperature no window, works in vacuum fast read out sensitivity

Single shot CTR measurements

Heigoldt, Matthias, et al. "Temporal evolution of longitudinal bunch profile in a laser wakefield accelerator." *Physical Review Special Topics-Accelerators and Beams* 18.12 (2015): 121302.

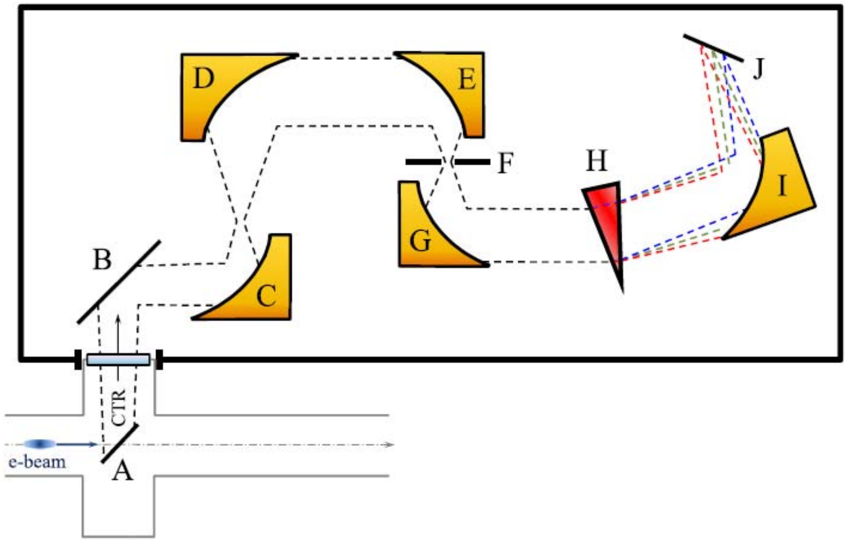




- S. Wesch, B. Schmidt, C. Behrens, H. Delsim-Hashemi, P. Schmuser, Nuclear Instruments and Methods in Physics Research A 665 (2011) 40–47

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

Conclusions

- There a lot of other techniques that are under investigations
- We are developing:
  - Plasma accelerator structures
  - Plasma lenses
  - Plasma dipoles
  - Plasma deflectors
  - Plasma dumps
- We need to develop also solutions for the diagnostics of plasma accelerated beams

Finally it's over

- Thank you for your attention, if you are still alive…