Uniformly filled ellipsoidal beam distributions at the UCLA Pegasus Laboratory

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Frontiers in FEL Physics and Related Topics
Elba Island-La Biodola

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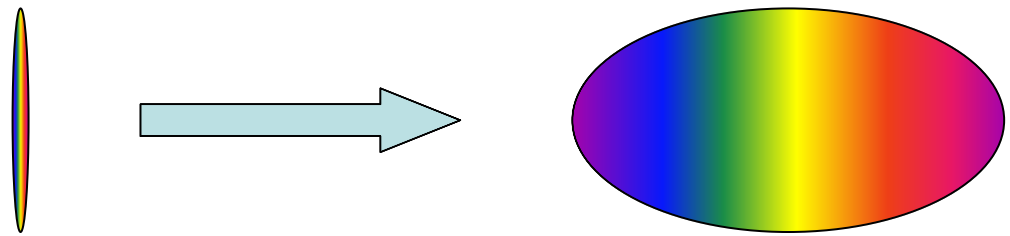
Outline

- Ellipsoidal beam distributions
- Pegasus photoinjector
- Ultrashort photocathode driver laser pulses
- Longitudinal diagnostics: RF deflecting cavity
- Beam measurements
- Beam brightness
- Conclusions

A little bit of history

- Ideal beam distributions.
  - Kapchinksy-Vladimirsky, uniformly filled ellipsoids, waterbags, pancakes and cigars have always helped theorists in accelerator beam physics.
  - The problem is how to generate such beams in real systems

- Serafini, *AIP Conf. Proc.*, **413**, 321, (1997)
  - Blow-out regime of photoinjectors.



- Luiten et al. *Phys. Rev. Lett.* **93**, 094802 (2004)
  - No particular longitudinal shape needed
- Rosenzweig et al., *Nucl. Instr. Meth.*, **57**, 87, (2006)
  - Existing hardware compatibility

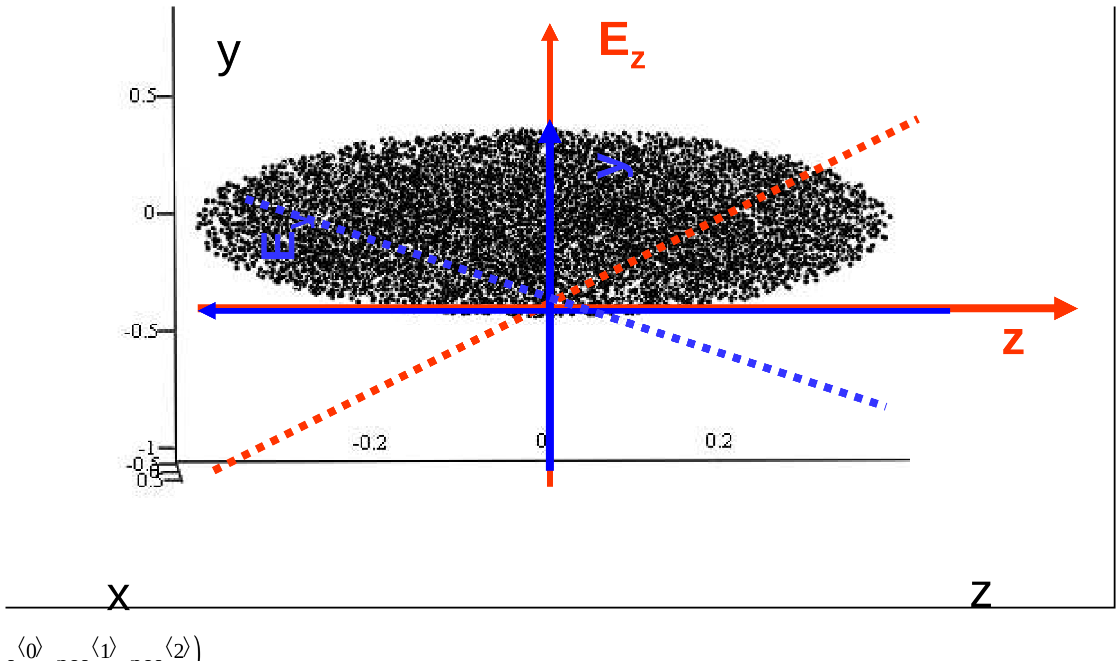
What's so special about ellipses?

- Analytical field expressions
- Linear space charge fields in each direction [Kellogg, Foundation of potential theory, 1929].

$$\vec{\mathbf{E}} = (E_x, E_y, E_z) = \frac{\rho_0}{\varepsilon_0}(M_x x, M_y y, M_z z)$$

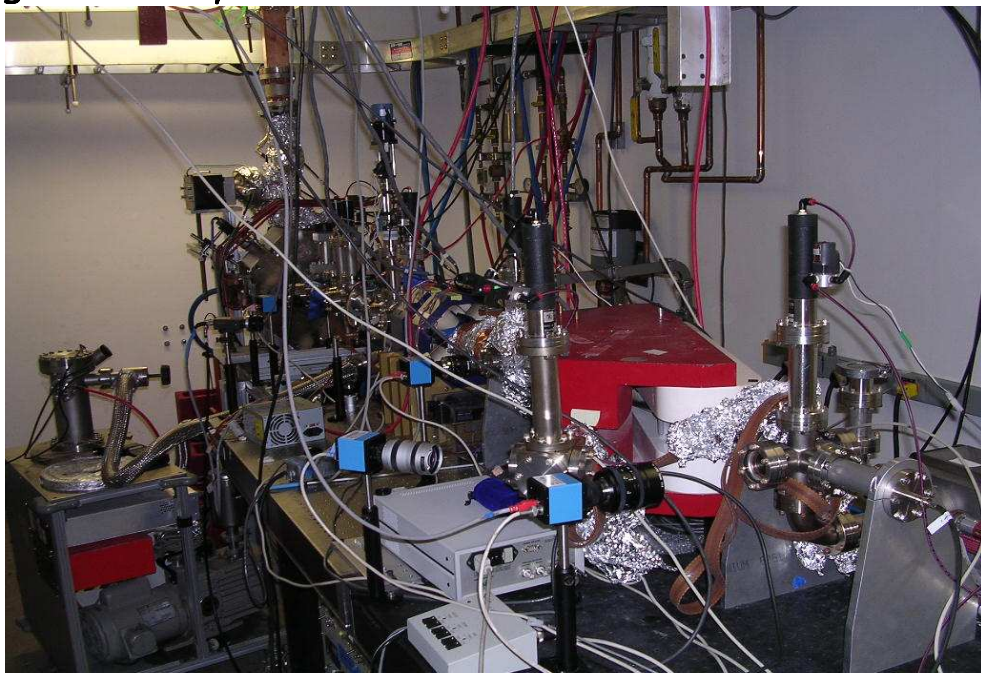
- For a spheroid

$$M_z = \frac{1+\Gamma}{\Gamma^3}(\Gamma - \arctan(\Gamma)), \qquad M_x = M_y = \tfrac{1}{2}(1 - M_z) \qquad \Gamma = \sqrt{A^2/C^2 - 1}$$



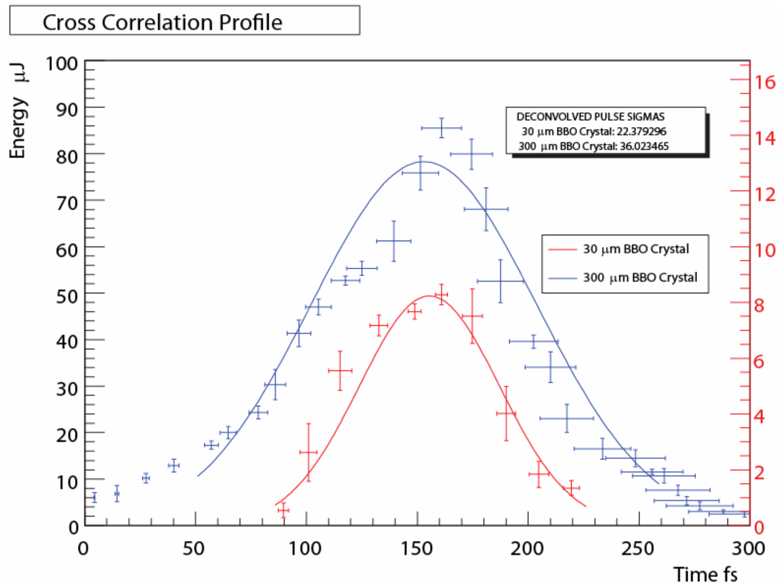
Pegasus laboratory

- Small accelerator laboratory in the sub-basement of the physics department (joint program with Rosenzweig, Pellegrini)
- Laser room, control room, radiation shielded bunker
- Home of the first UCLA SASE FEL experiments
- Now advanced photoinjector laboratory just recently commissioned
  - New state-of-the-art ultrafast drive laser Ti:Sa
  - Currently 2 grad, 2 undergraduate students
- Initial laboratory mission:
  - Study photoinjector extreme longitudinal dynamics.
  - Tests of blow-out regime.
  - Develop advanced longitudinal diagnostics.
  - Applications of ultrafast beams. (electron diffraction, FELs)

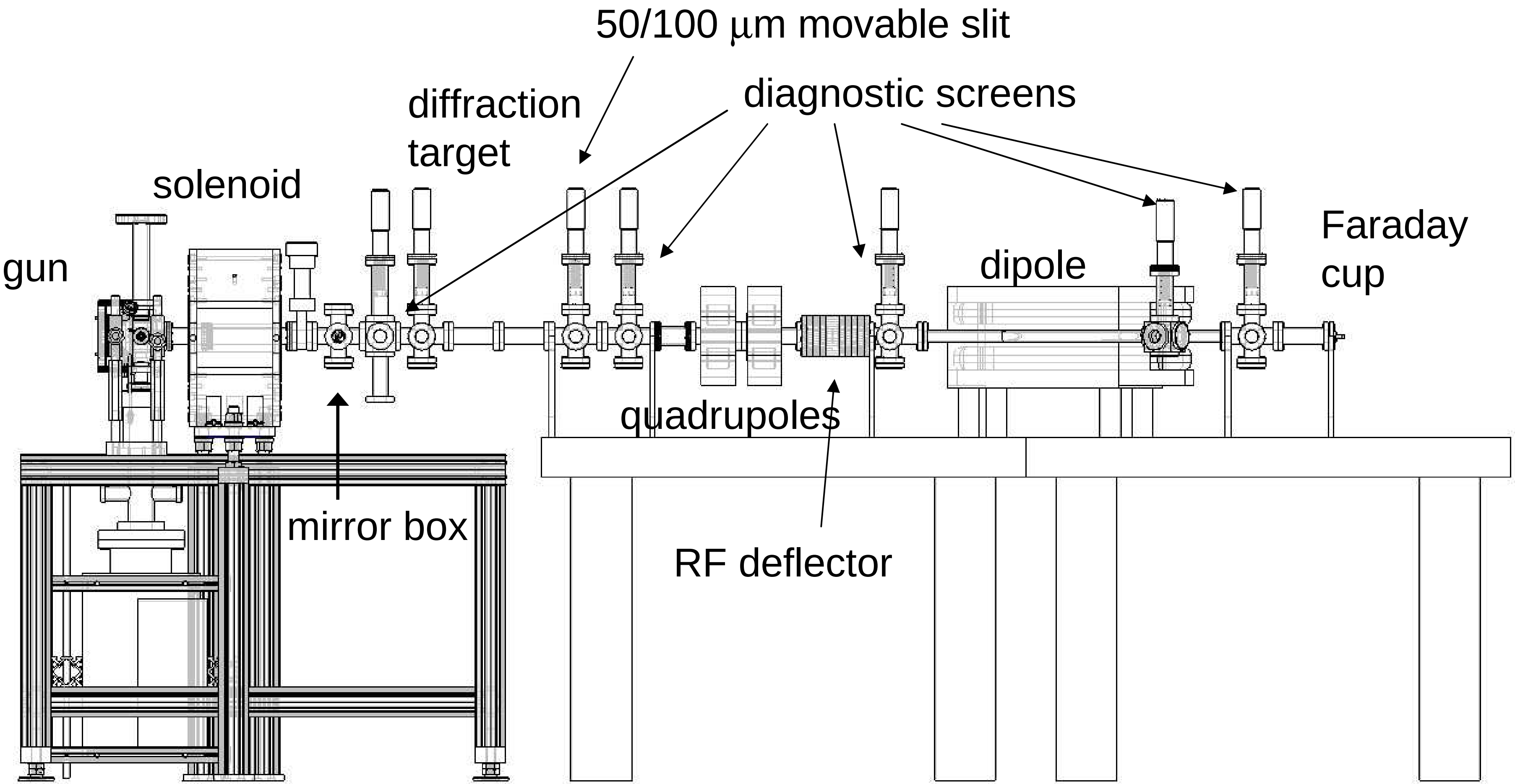


Ultrashort laser pulses

- New state-of-the-art Ti:Sa laser system.
  - Micra.
    - Feedback on Verdi pump alignment
    - 100 nm bandwidth (adjustable)
    - Integrated pump
  - Legend-Elite
    - Integrated Evolution 30
    - 1 KHz rep rate
    - 3.3 mJ after compression
    - 35 fs FWHM
- Ultrashort laser pulses cathode illumination
  - Control dispersion in transport
  - Thin non linear crystals
- Iris imaged onto cathode.
  - Dynamics dominated by surface charge density on the cathode.

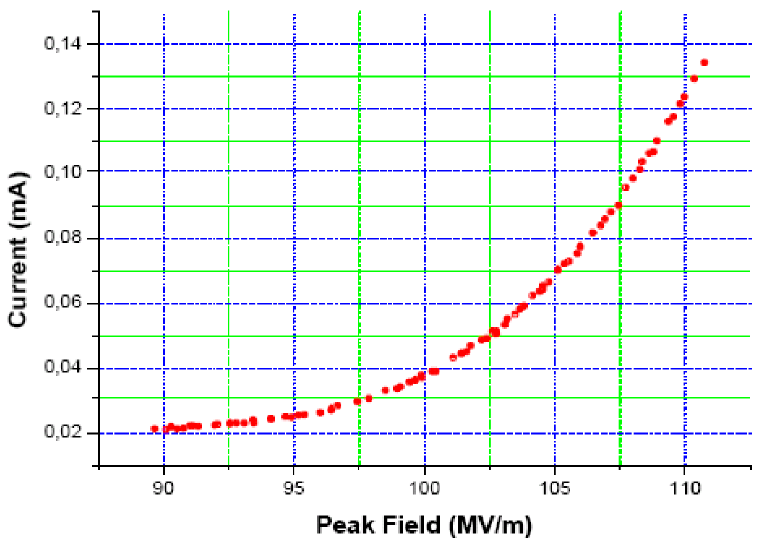


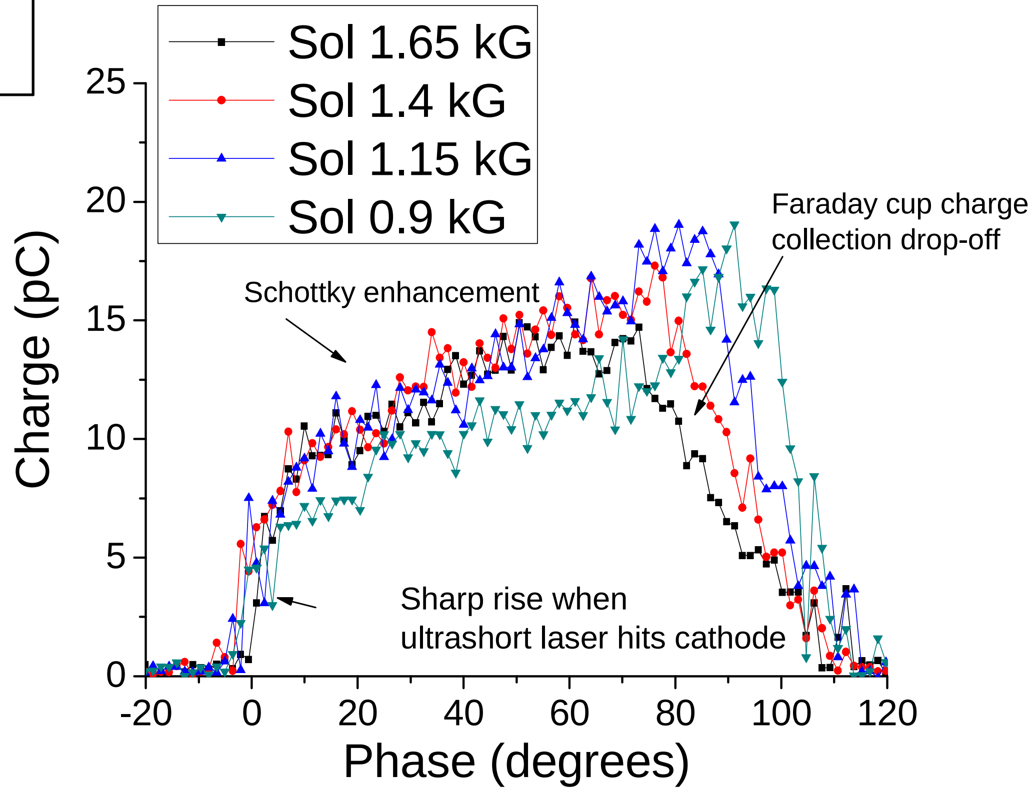
Pegasus beamline



Photoinjector commissioning. Spring 07

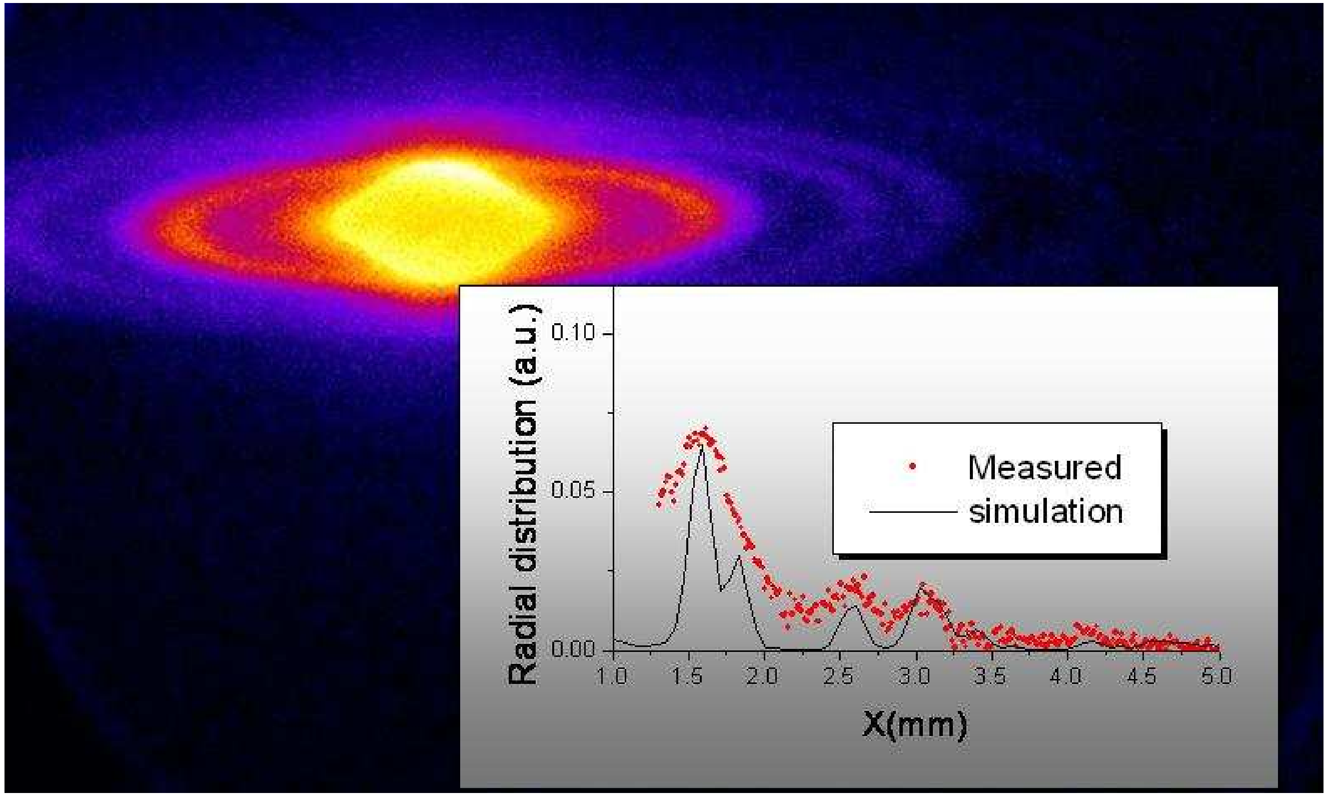
Laser pulse length	30 fs (rms)
Laser energy	0.5 - 300 μJ
Laser spot size	0.1 – 1 mm
E-beam energy	3-5 MeV
E- beam charge	1 – 300 pC





Pegasus relativistic electron diffraction

- Diffraction pattern using 10^8 electrons with an electron beam 5 times shorter than current state-of-the-art.
- Not the subject of this talk (but ellipses even here….)



RF deflector

Courtesy of J. England

- X–band cavity (9.6 GHz)
- Originally designed for a 12-15 MeV beam. (up 500 kV deflecting voltage)
- Plug-n-play (portable rf source).
- Very good temporal resolution (< 50 fs) for the 4-5 MeV Pegasus beam even on the closest beamline screen.
- Two independent calibration methods
  - Measure power in cavity
  - Measure centroid position vs. phase

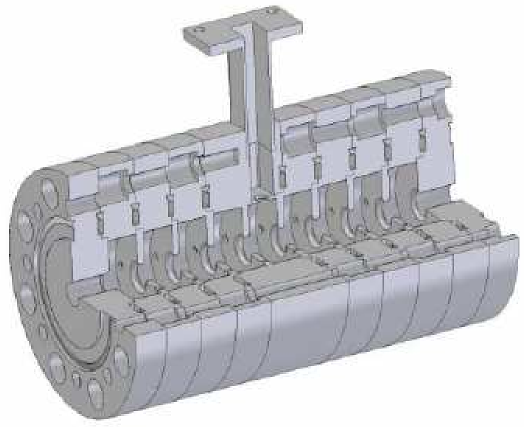
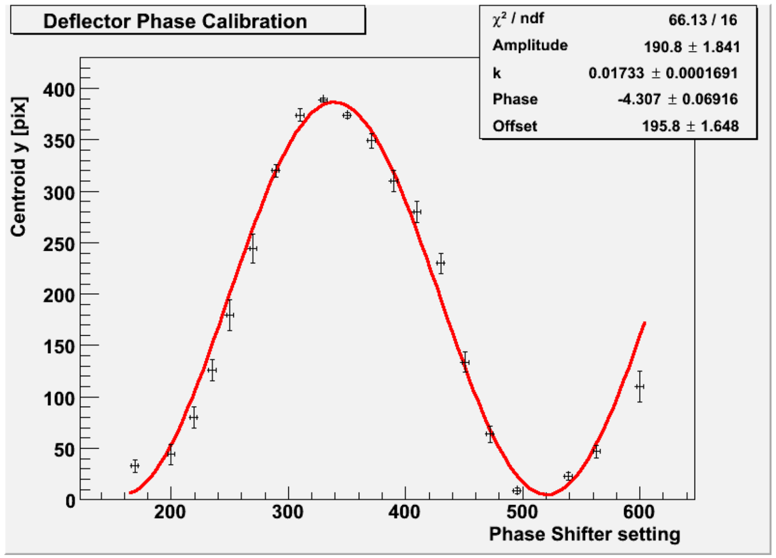


Figure 3: Cutaway drawing of the assembled 9-cell cavity design.

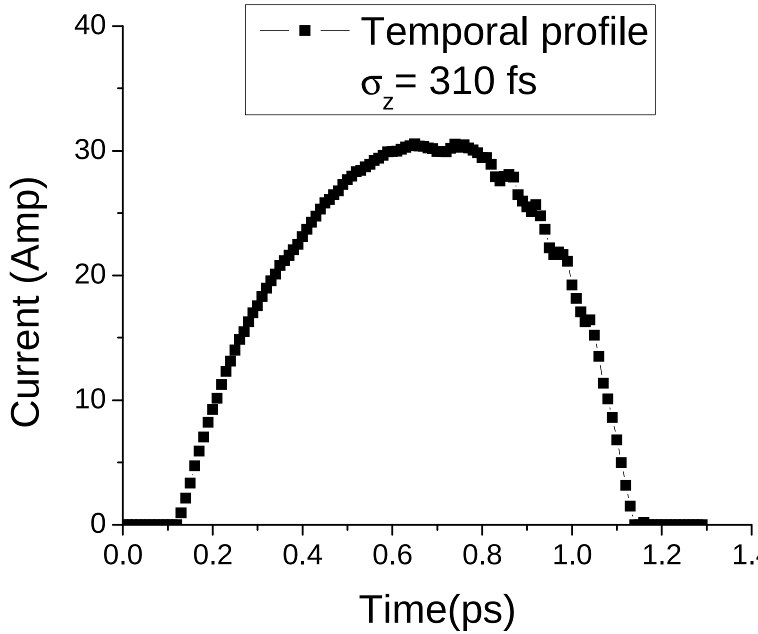


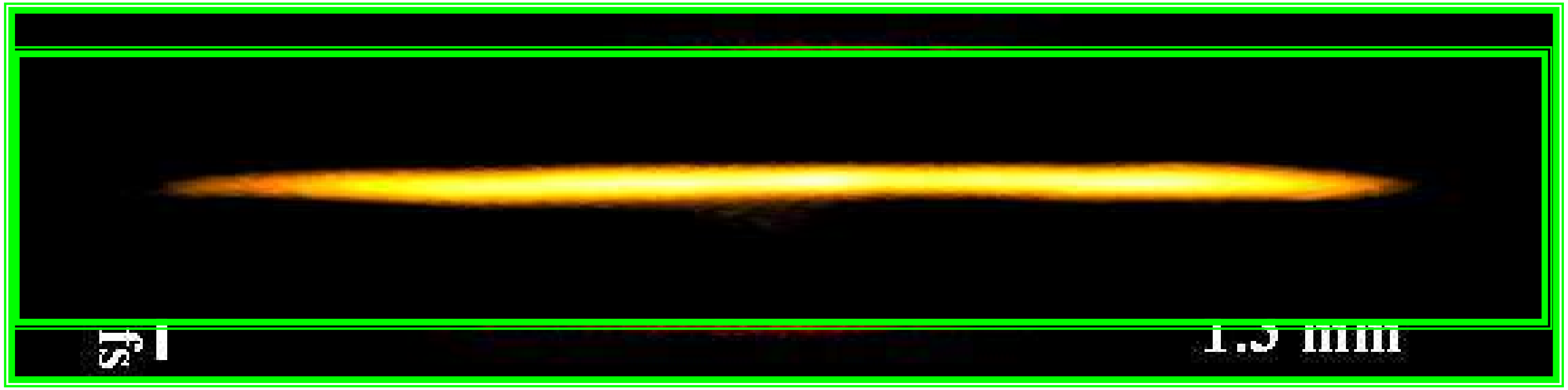
- Fundamental diagnostics in low-energy beam line. (allow to see *inside* the beam…)

Ellipsoidal beam I: projected ellipse

Using the quadrupole to focus vertically the beam to an horizontal line

- Charge 17 pC
- rms length ~300 fs
- Very sharp ellipsoidal beam boundary due to the ultrashort beam on the cathode



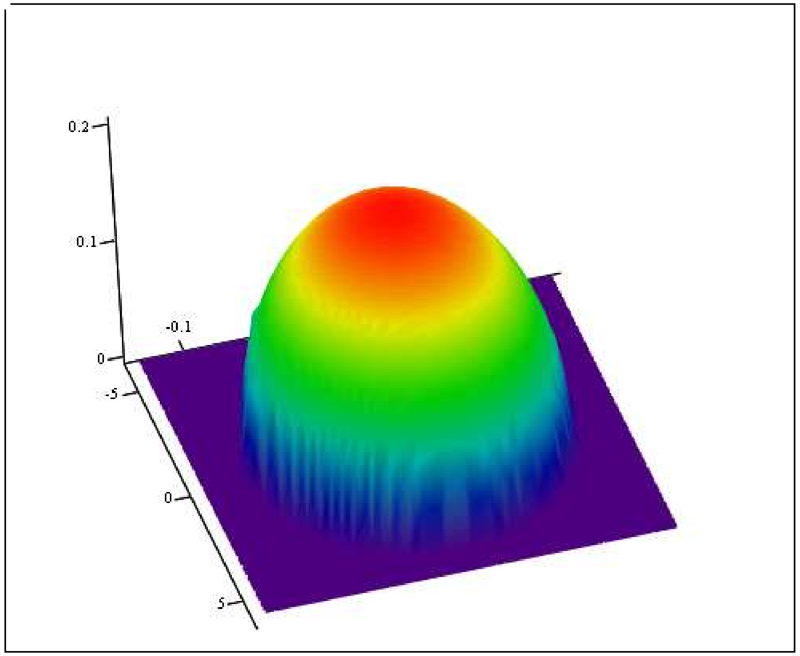


Ellipsoidal beam I: projected ellipse (cont)

Using the quadrupole to focus the beam on the screen, we effectively obtain a two dimensional projection of the uniformly charged ellipsoidal distribution

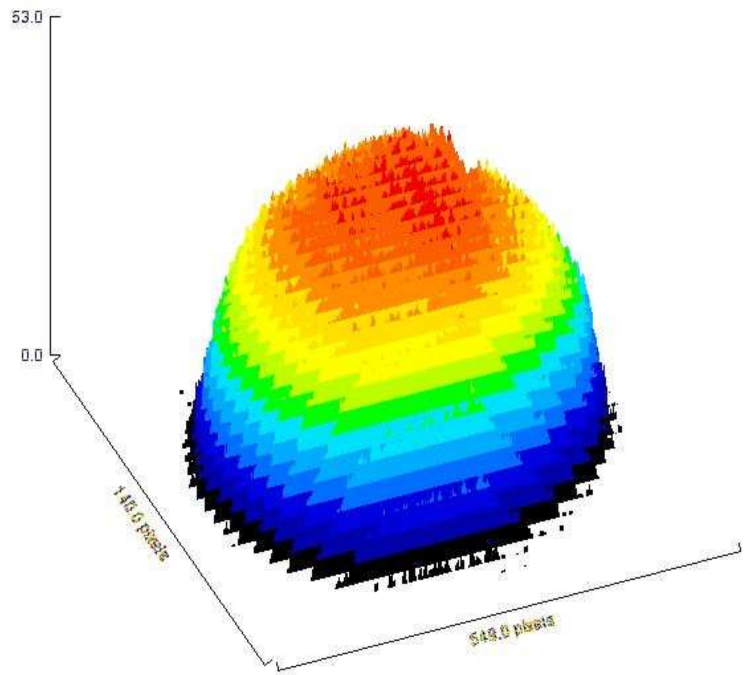
$$\rho(x,y,z) := \begin{cases} 1 & \text{if } \sqrt{\dfrac{x^2}{a^2}+\dfrac{y^2}{b^2}+\dfrac{z^2}{c^2}} < 1 \\ 0 & \text{otherwise} \end{cases} \qquad \rho_{proj}(x,z) := \int_{-\infty}^{\infty} \rho(x,y,z)\,dy$$

Simulated uniformly charged ellipsoid



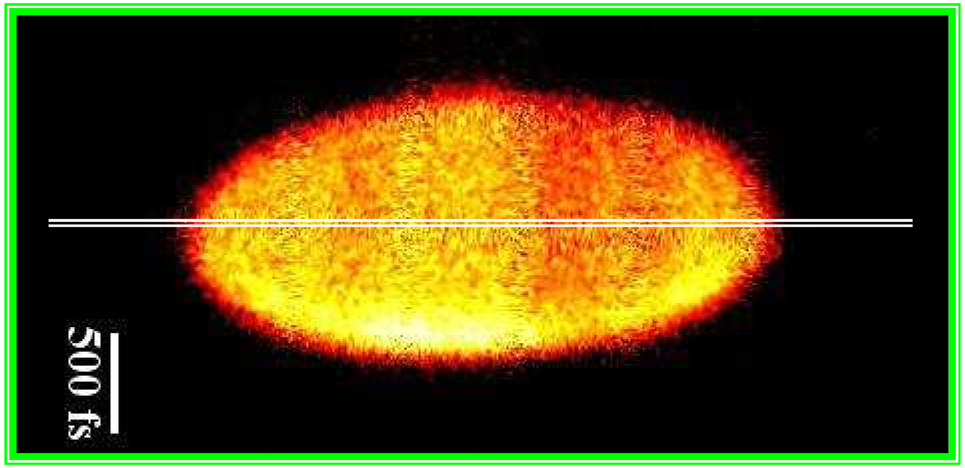
ρp

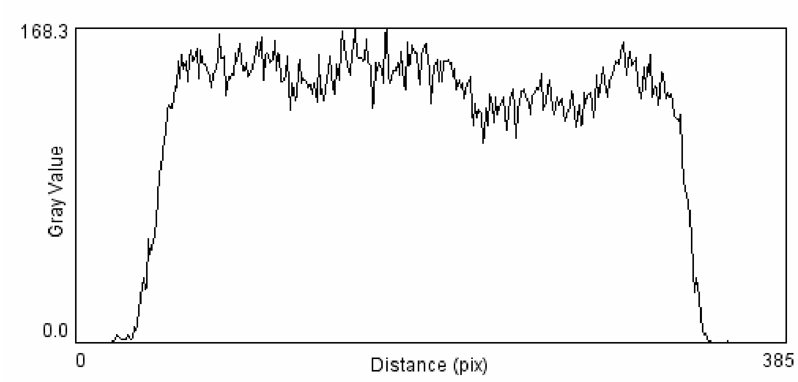
Experimental streak



Ellipsoidal beam II: sliced ellipse

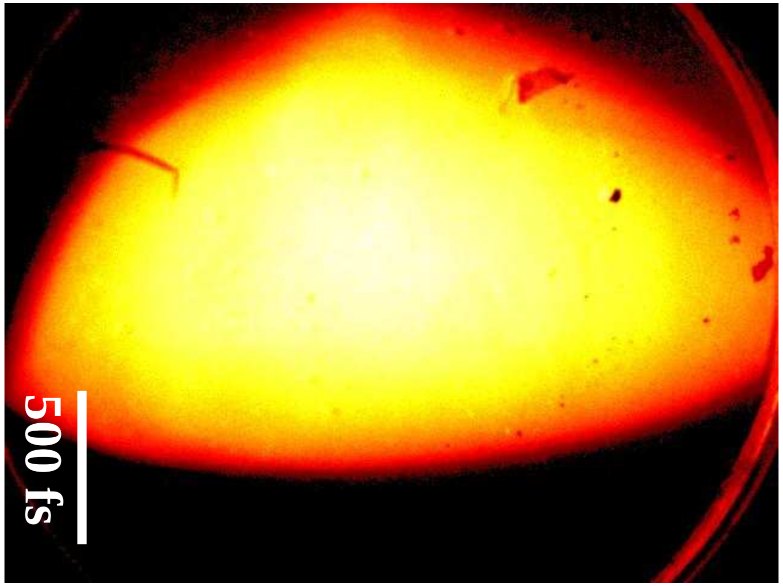
Using the slit aperture to select an horizontal slice of the beam distribution

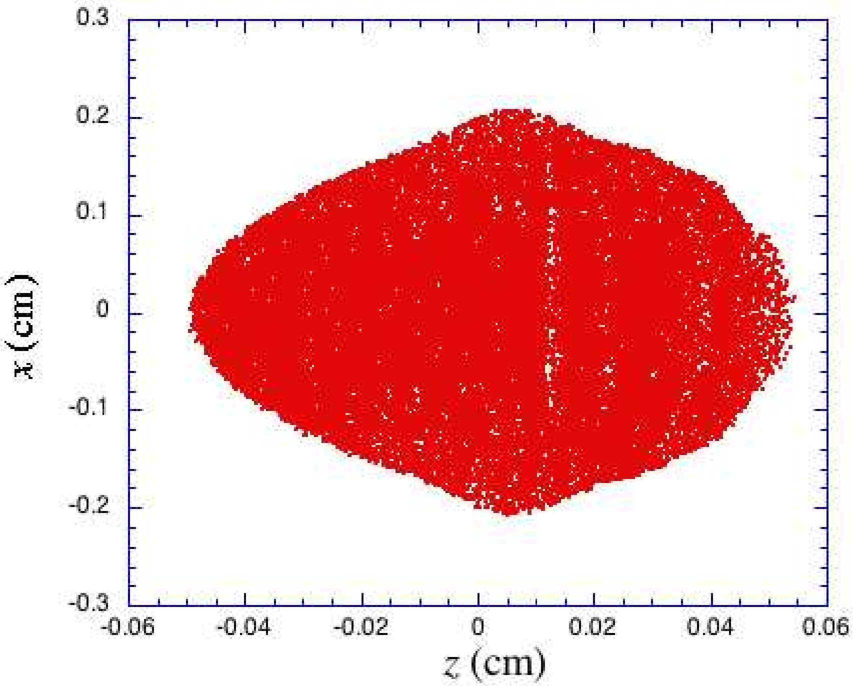




Asymmetry in ellipsoidal boundary

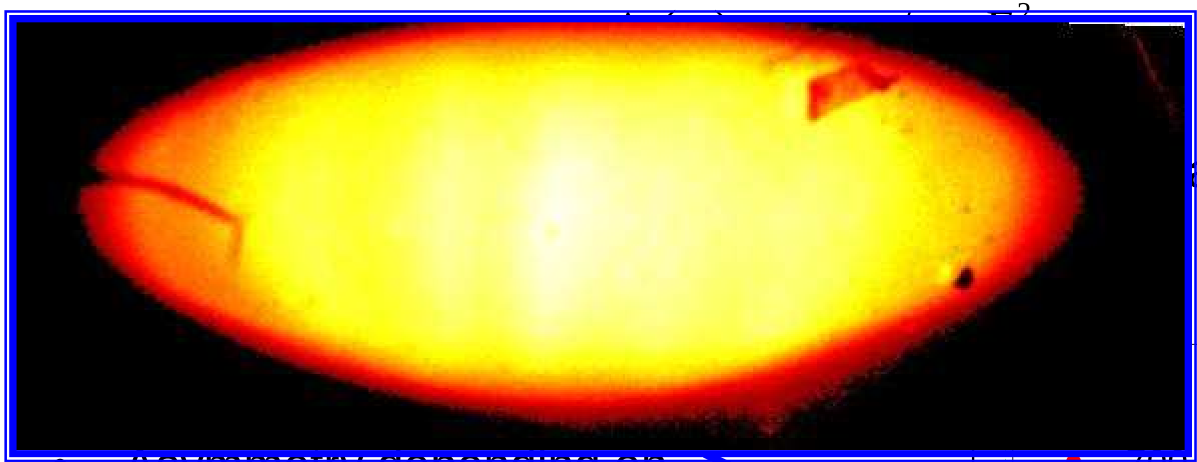
- Increasing the charge we observe the development of an asymmetry in the ellipse boundary.
- Reversing the deflecting voltage by going 180 degrees off in phase, we obtain the same picture upside down.
- Simulations predict this effect, which is mainly due to the image charge at the cathode that pulls on the beam tail.





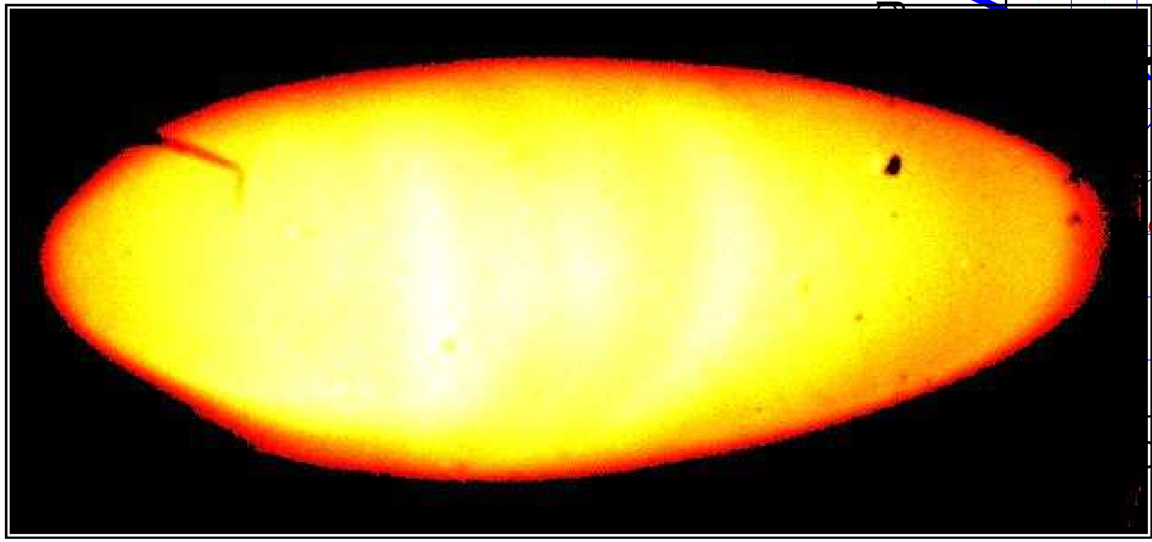
Bunch length vs. Q

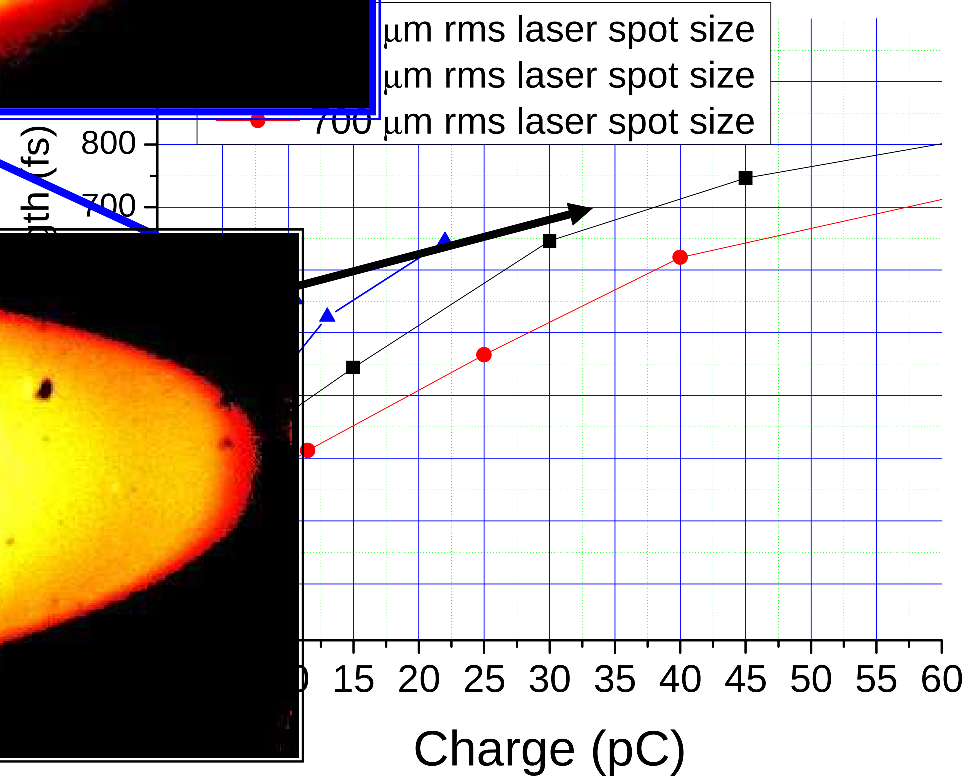
- Luiten's paper gives a simple formula for asymptotic bunch length:



atio in its own rest

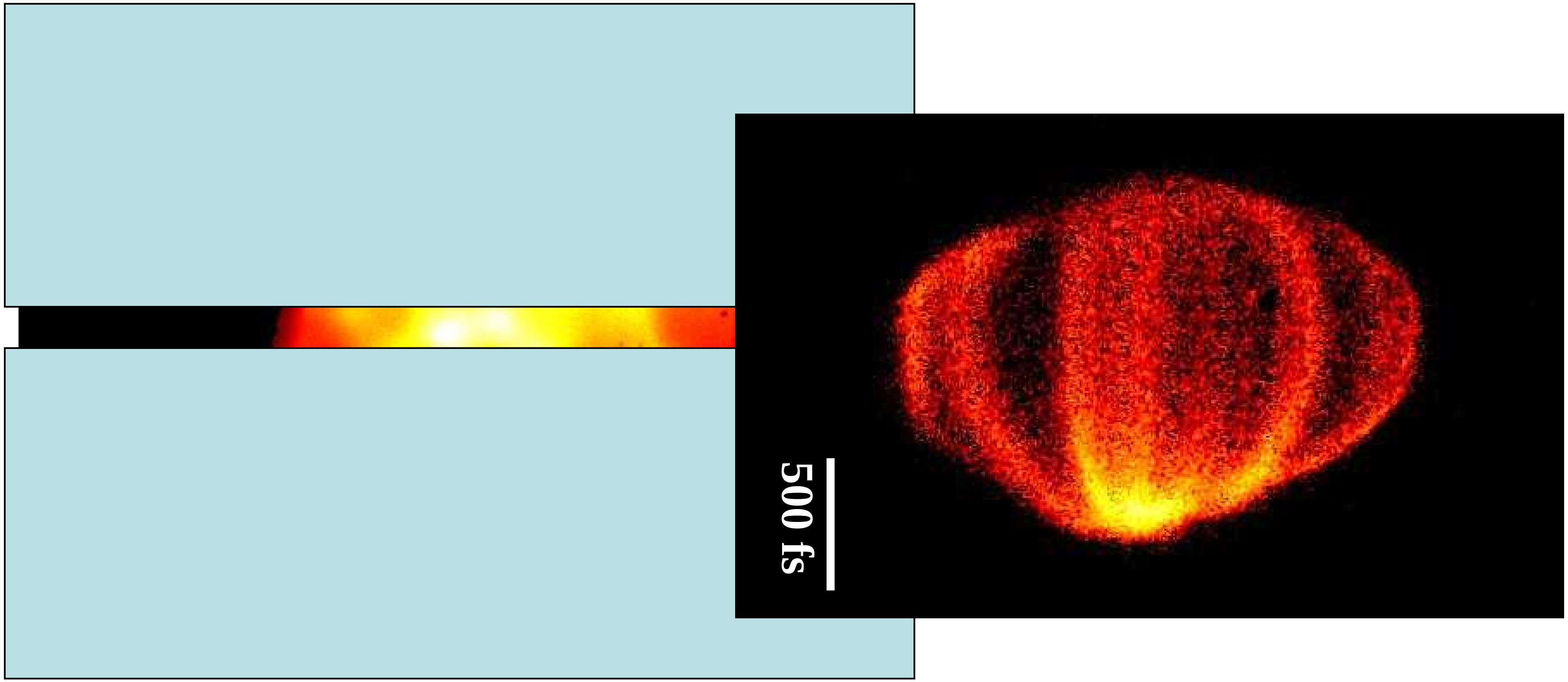
- Asymmetry depending on surface charge density.





Wonders of a deflecting cavity

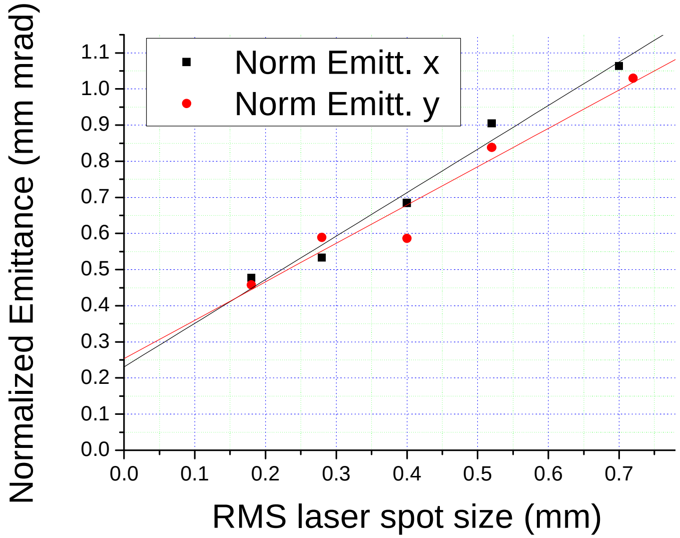
- Inhomogeneous emission from cathode

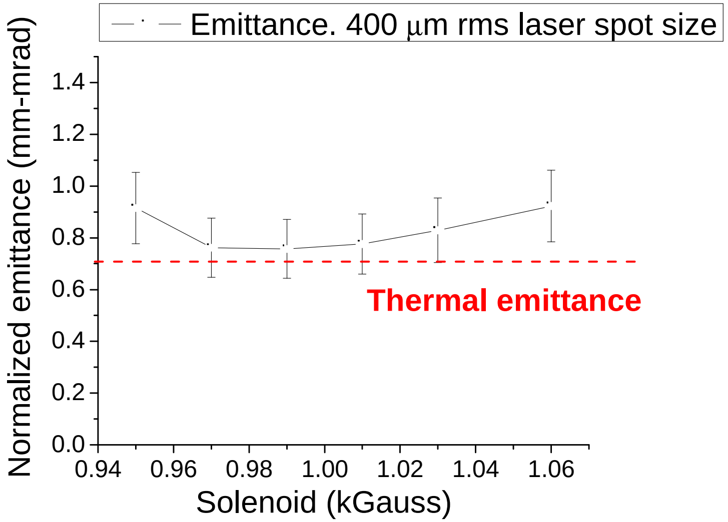


Transverse emittance

- Transverse beam quality (measured with pepper-pot technique allowing phase space reconstruction) is at the thermal emittance level.

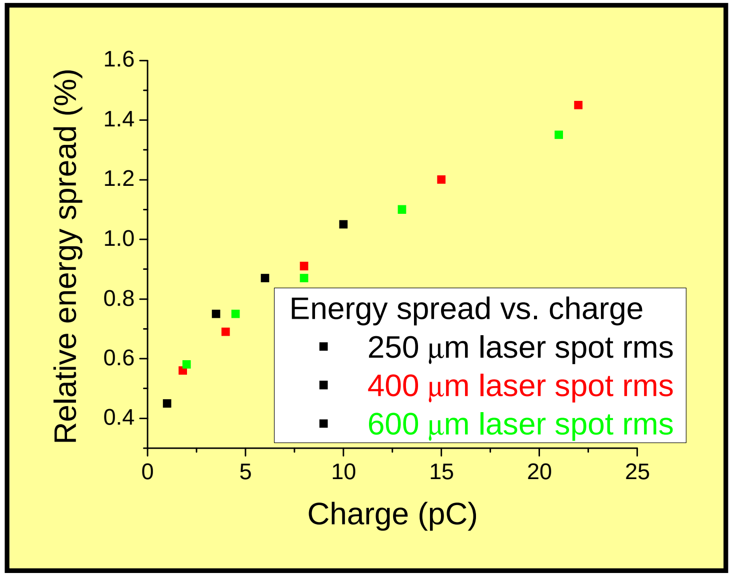
- …which unfortunately is quite high (Mg cathode + surface roughness). Measured with solenoid scan.

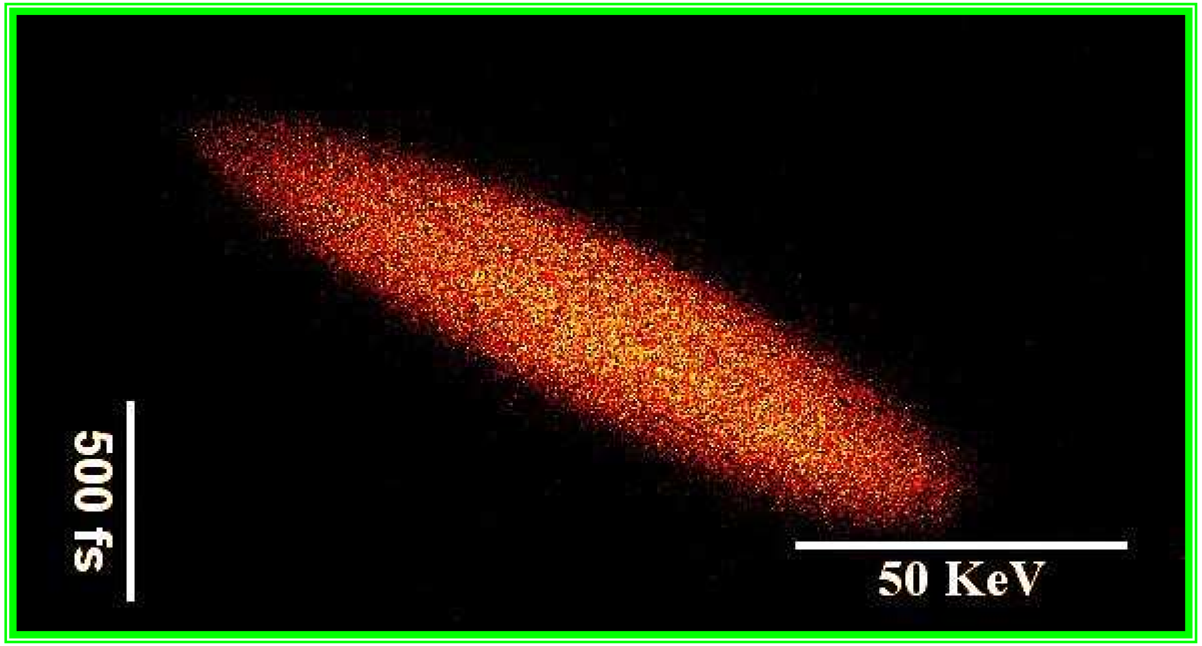




Longitudinal phase space

- Diagnostic screen around the bend.
  - Dispersion. Horizontal axis is energy.
  - Turn deflector on. Vertical axis is time.
- Need to decrease betatron beam size at the diagnostics screen.
- Design shorter dipole to allow quadrupole lenses closer to detection screen. (in progress)
- Aim to resolve <20 KeV uncorrelated energy spread (experiment in the next six months).



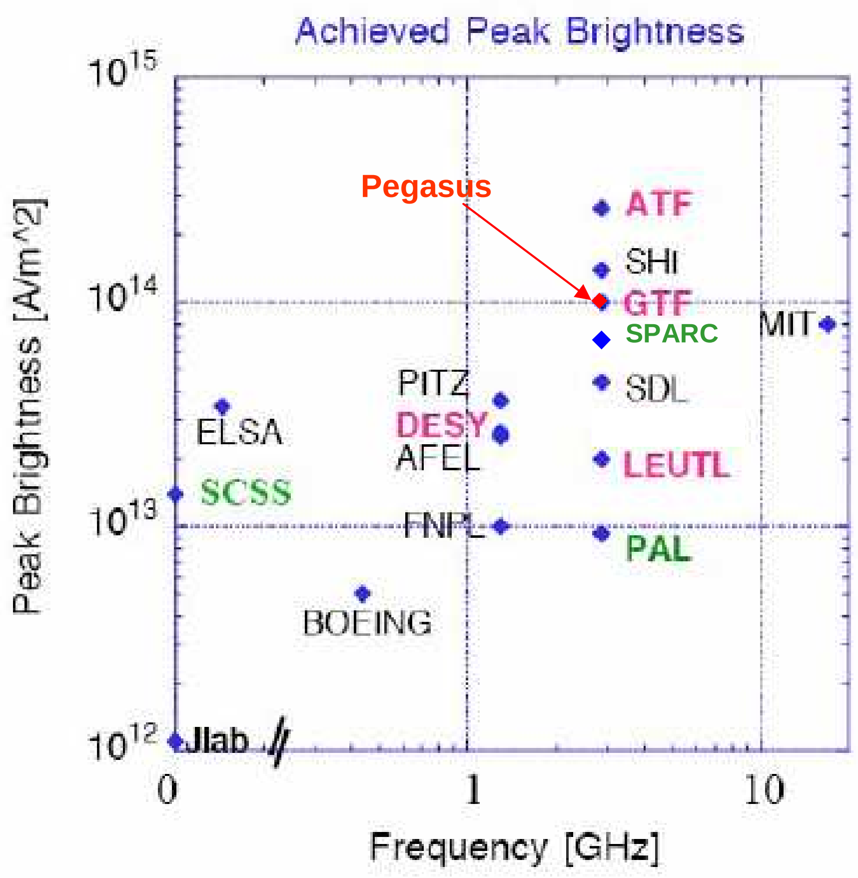


Peak brightness

- Peak brightness at low energy is very high, but not much different than other optimized designs (working point of current state-of-the-art injectors).

- 18 pC, 300 fs rms,
  0.7 mm-mrad. ~1•10^{14} A/m^2

- What is really new here is:
  - ✓ Shorter beams.
  - ✓ More linear phase spaces (transverse and longitudinal).
  - ✓ Control beam tails.
  - ✓ Ease requirements on laser system.



Conclusions

- First direct observation of uniformly filled ellipsoidal beam distribution
- Dynamic regime. Need to take into account beam evolution. (need particle tracking simulations)
- Simple configuration of photoinjector yielding relatively good results.
- Clear path for improving brightness at Pegasus (higher field on cathode, better thermal emittance).
- Low charge, ultrashort beams are the future of photoinjectors (ultrafast beam sourcing).

Acknowledgements.

J. Moody, R. J. Englang, T. Tan.

Aspect ratio

- Analytical field expressions
- Linear space charge fields in each direction [Kellogg, Foundation of potential theory, 1929].

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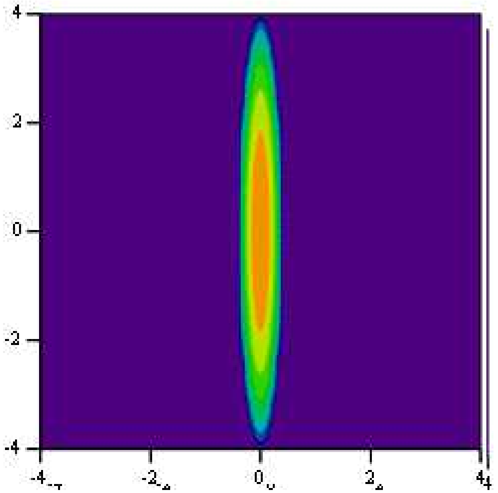
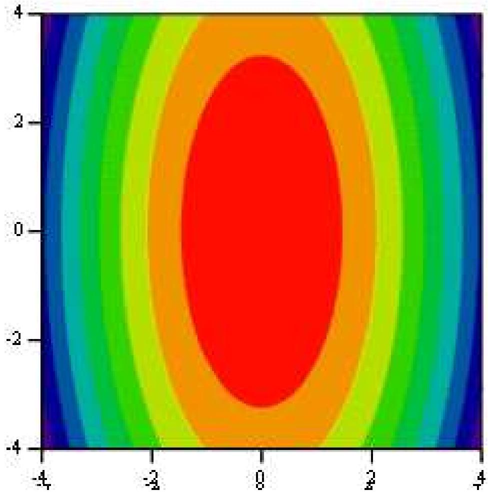
- For a spheroid

$$M_z = \frac{1+\Gamma}{\Gamma^3}(\Gamma - \arctan(\Gamma)), \qquad M_x = M_y = \tfrac{1}{2}(1 - M_z) \qquad \Gamma = \sqrt{A^2 / C^2 - 1}$$

Charge density



Scalar potential



Electric field