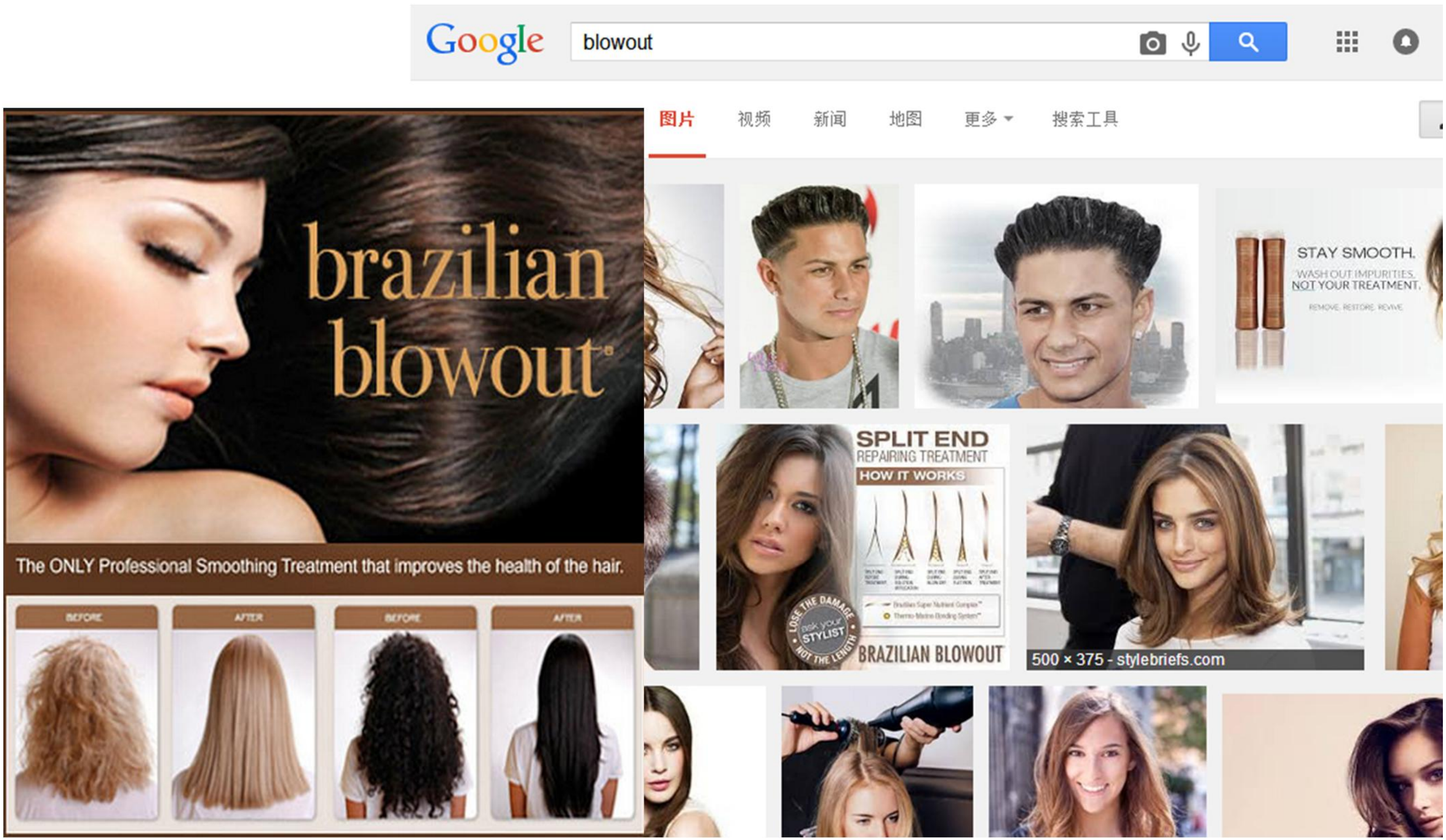
Blowout regime for generation of ellipsoidal beam

C. Emma, J. Franssen, X. Nie, M. Weikum

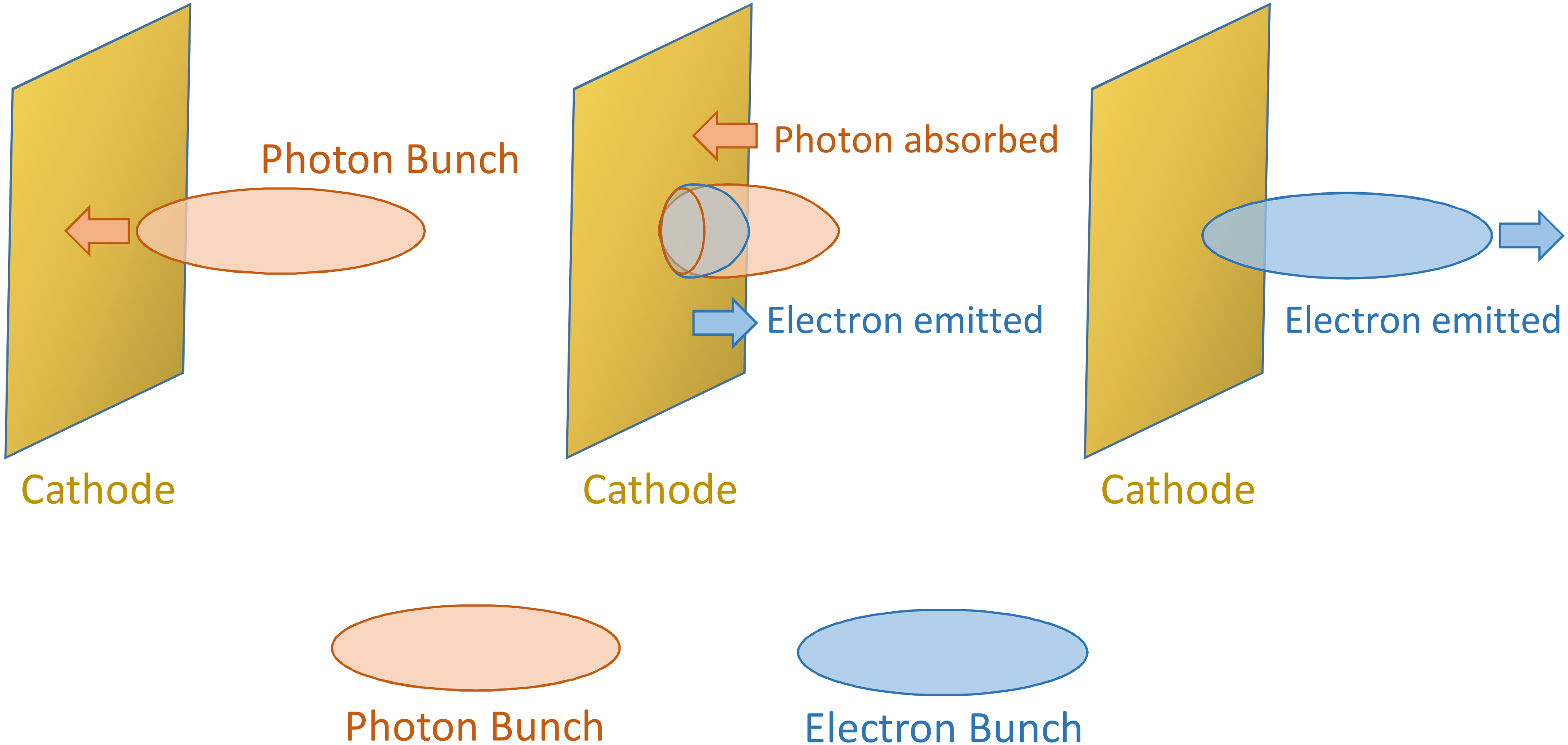
August 6th 2015

SLAC Summer School on Electron and Photon Beams

What is the Blowout Regime????



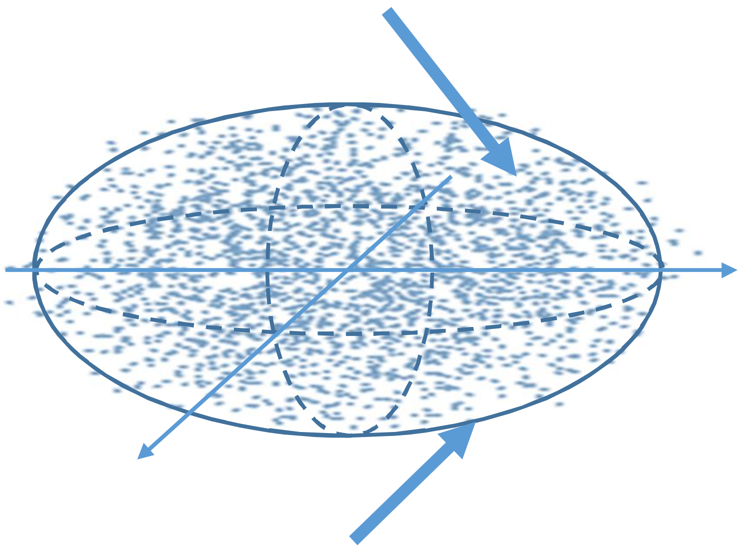
Basic Physics Image



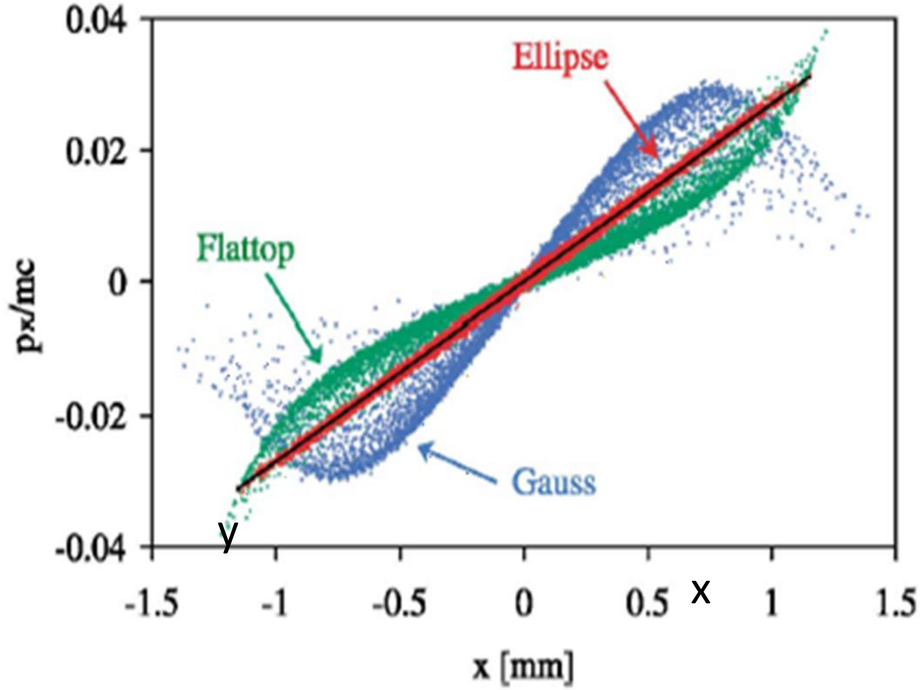
Same transverse and longitudinal distribution

What we want: Ideal Ellipsoidal Electron Bunch

Inside: Uniform distribution



Boundary: Sharp edge



- O.J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004)

Why the uniformly filled ellipsoid?

Self-electric fields in the beam are our enemy!

$$E_z(\tilde{z}, r=0) = \frac{\tilde{\rho}}{2\varepsilon_0}\left[\sqrt{R^2 + (\tilde{L}-\tilde{z})^2} - \sqrt{R^2 + \tilde{z}^2} + \left(2\tilde{z} - \tilde{L}\right)\right]$$

Uniformly filled Cylinder:
Beer Can Beam

Suffers from:
Edge erosion
Nonlinear fields at edges
Severe practical difficulties with laser

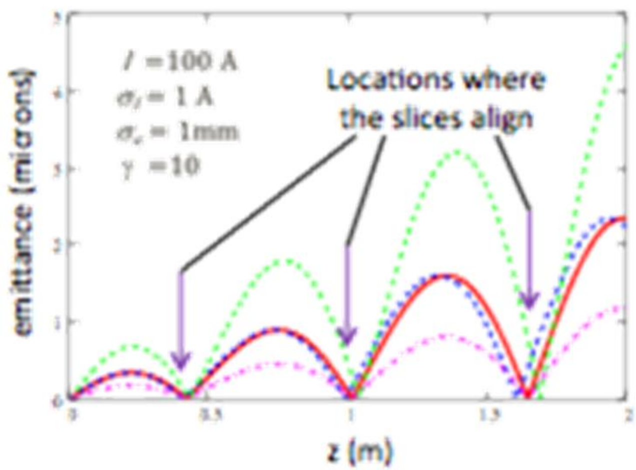
Self-electric fields in the beam can be our friends!

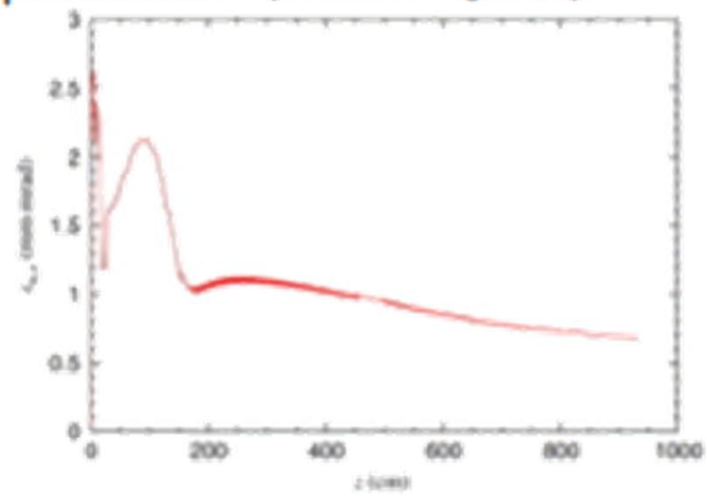
Uniformly Filled Ellipsoid:
Waterbag Beam

Suffers from…nothing! Linear emittance growth can always be corrected

Advantages !

- Linear phase space distribution → ideal for compression
- Compatible with emittance compensation [Rosenzweig2006]



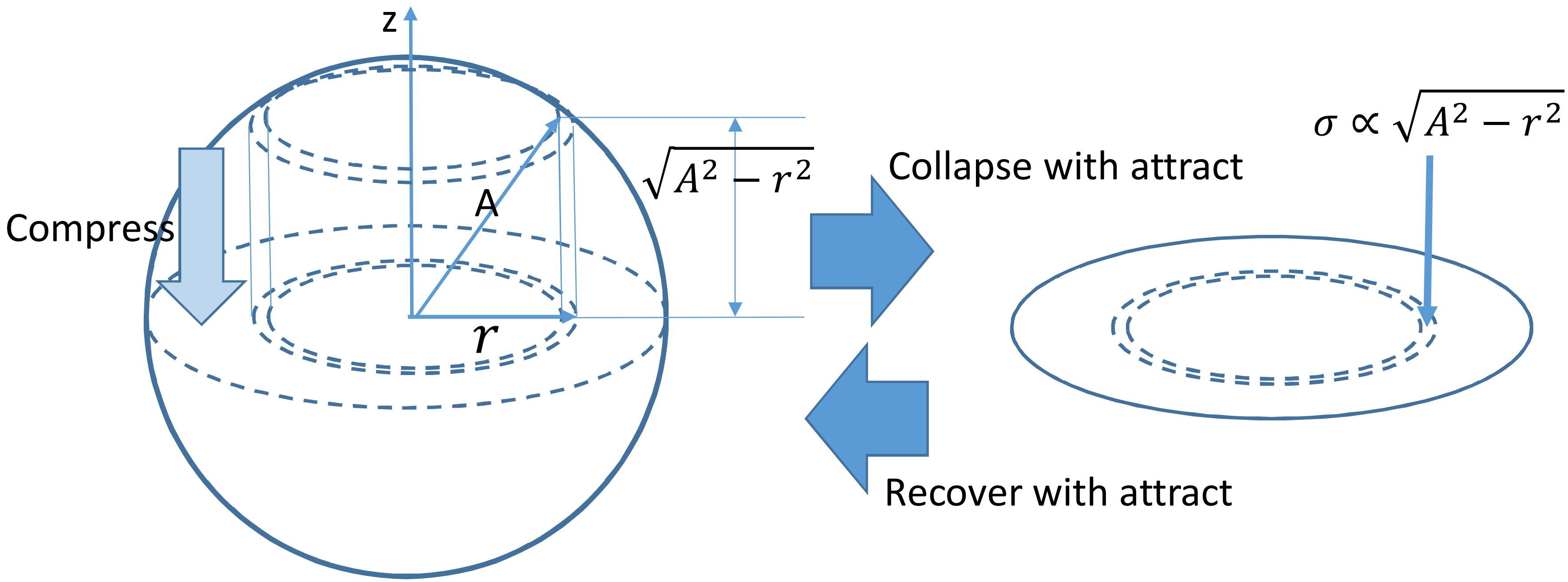


- Initial longitudinal electron density profile is irrelevant, if bunch duration is short


Blowout

Blowout: Similar to a Collapsed Star

A typical uniform 3D ellipsoidal model: Star



The cylinder is compressed into a ring, with area dencity$\sigma \propto \sqrt{A^2 - r^2}$

$$\rho(r, z) = \sigma_0 \sqrt{1 - \left(\frac{r}{A}\right)^2}\, \delta(z)$$

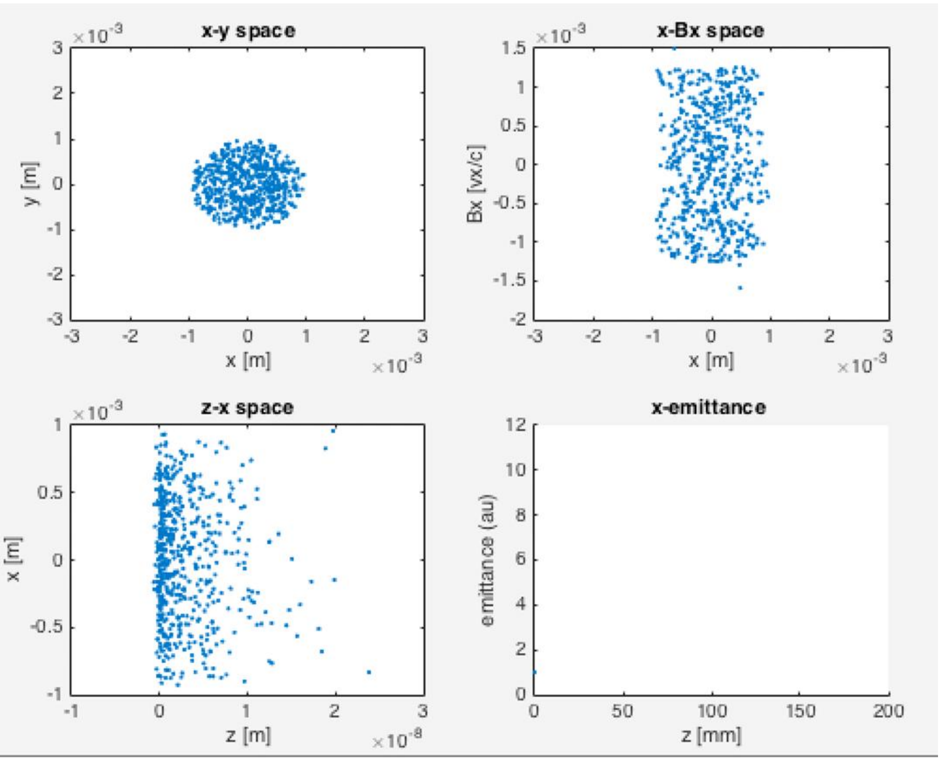
O.J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004)

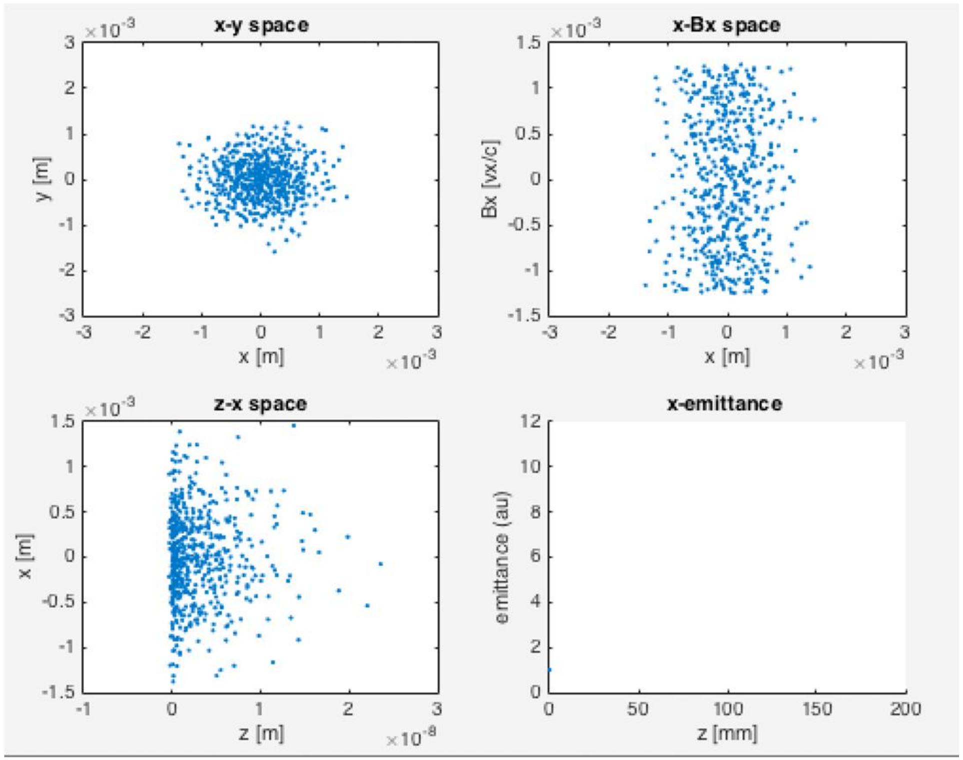
Basic Mechanism->simulations

Input radial electron distribution

Uniform ellipsoid

Gaussian





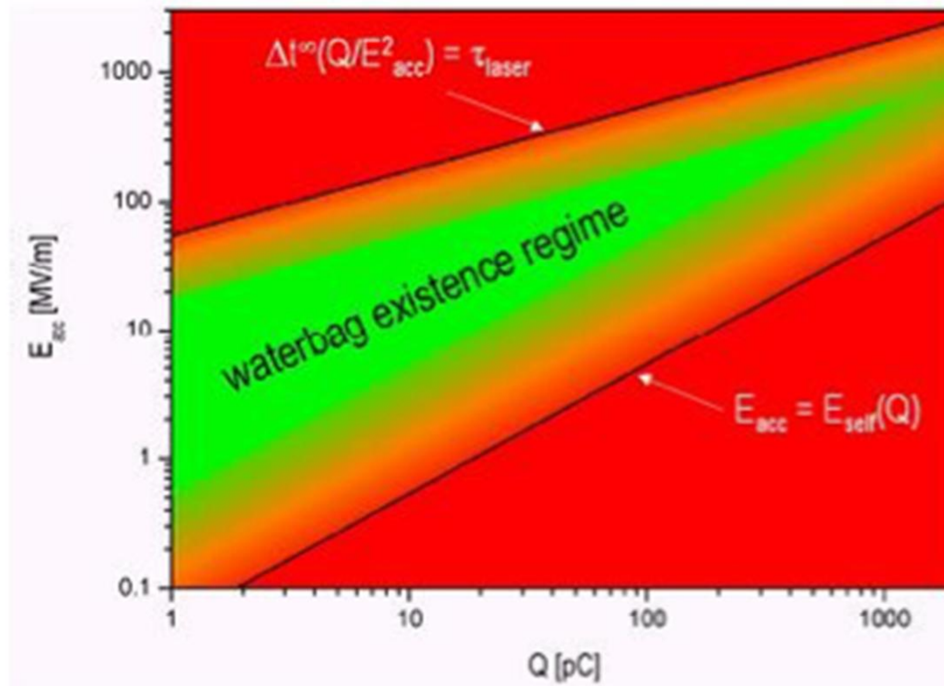
IT WORKS…at least on a computer!!

Real Experimental Results

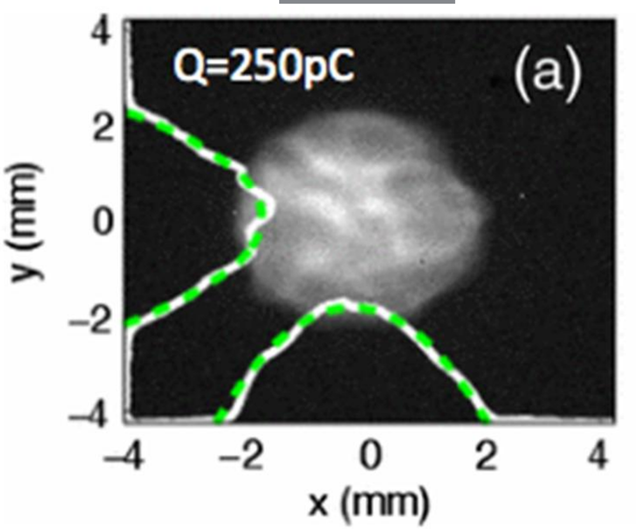
Reality check:

- What laser pulse length is small enough?
- When can we ignore image charge space charge fields?

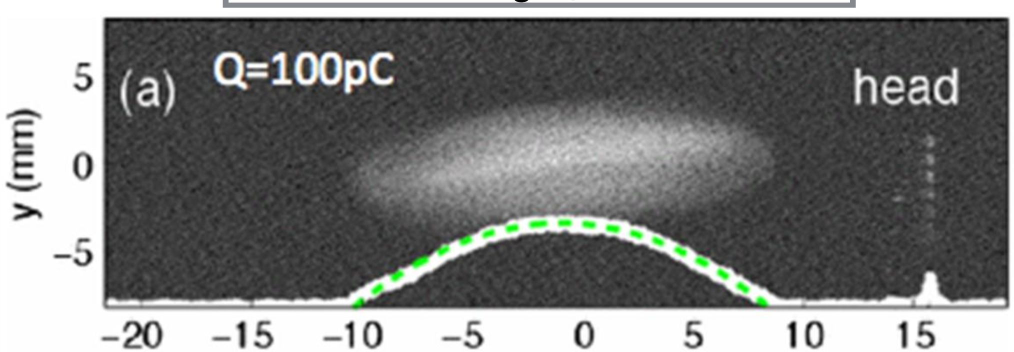
$$\frac{eE_{acc}c\tau_l}{mc^2} \ll \frac{\sigma_0}{\varepsilon_0 E_{acc}} \ll 1$$



YAG screen

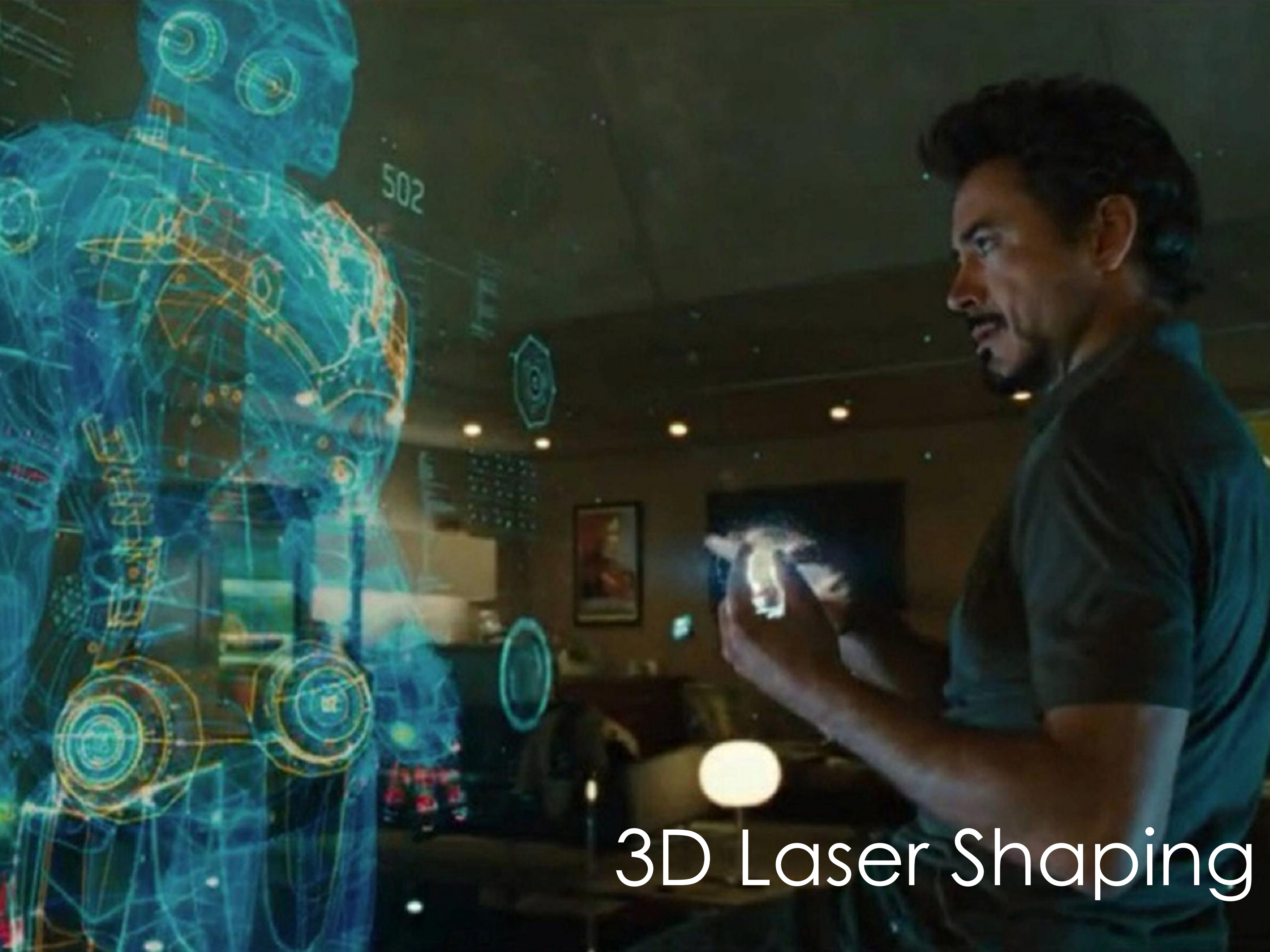


Streak Camera Image @ end of beamline



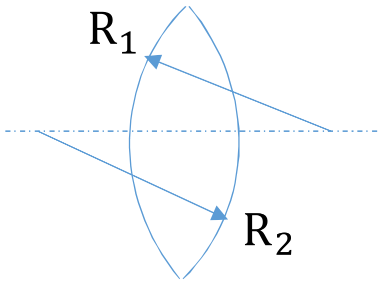
TIME in mm

IT WORKS…even in reality!!



3D Laser Shaping

3D Laser Shaping



Focus length of a lense:

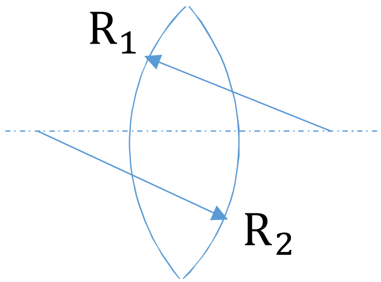
$$\frac{1}{f(\omega)} = (n(\omega) - 1)(\frac{1}{R_1} - \frac{1}{R_2})$$

Change in ω → Change in f → Change in bunch size w

$$\delta f = -\frac{f_0}{n_0 - 1}\frac{dn}{d\omega}\,\delta\omega \qquad w \approx w_0\left[1 + \left(\frac{\delta f}{z_R}\right)^2\right]^{1/2}.$$

- Y. Li and J. Lewellen, Phys. Rev. Lett. 100, 074801 (2008)

3D Laser Shaping



Focus length of a lense:

$$\frac{1}{f(\omega)} = (n(\omega) - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Change in ω → Change in f → Change in bunch size w

What we need:

$$\delta\omega(t) = \Delta\omega_{max}\left[1 - \left(\frac{t}{T}\right)^2\right]^{\frac{1}{2}}$$

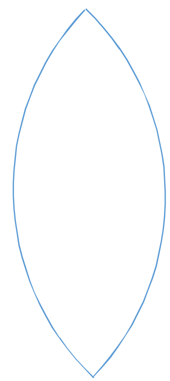
What we want:

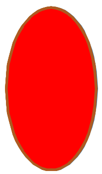
$$w(t) = w_{max}\left[1 - \left(\frac{t}{T}\right)^2\right]^{\frac{1}{2}}$$

- Y. Li and J. Lewellen, Phys. Rev. Lett. 100, 074801 (2008)

What's going on

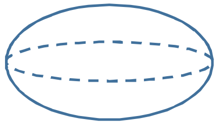
Lens





Modification of ω
Depends on time

Modification of w
Depends on time



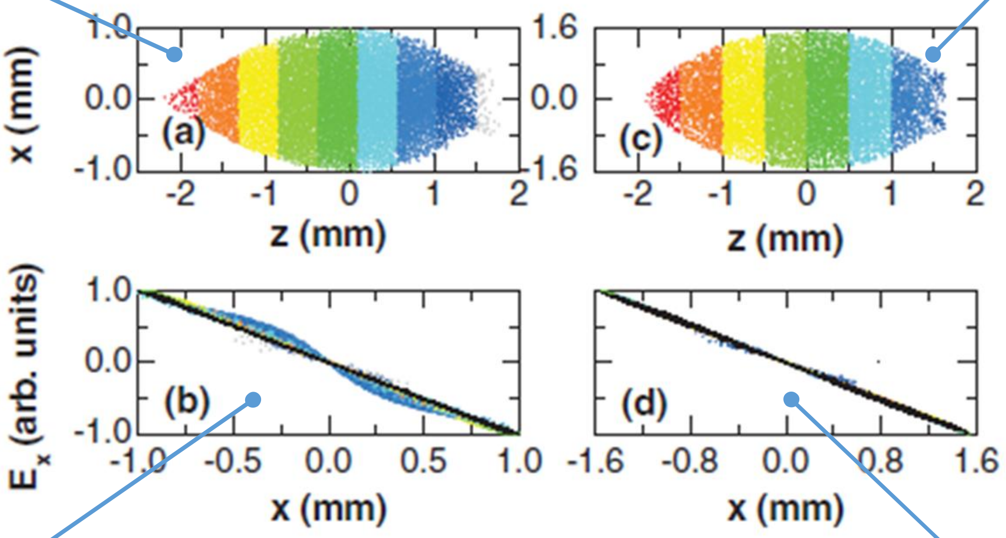
Modification of Electron beam size
Depends on z

Simulation Results

SLAC

Initial Distribution

Distribution after 80 ps



Initial Phase space

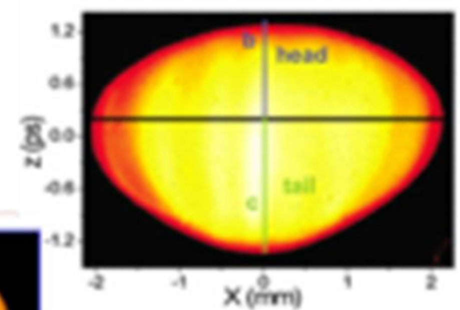
Phase space after 80 ps

Y. Li and J. Lewellen, Phys. Rev. Lett. 100, 074801 (2008)

…& limitations

- Large transverse laser spot size required to limit surface charge density:

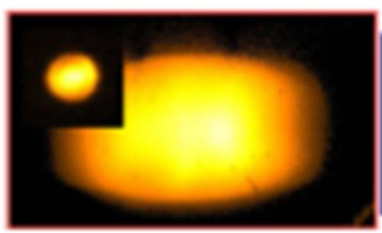
→ Increase in thermal transverse norm. emittance with respect to other beam shapes (Luiten regime)



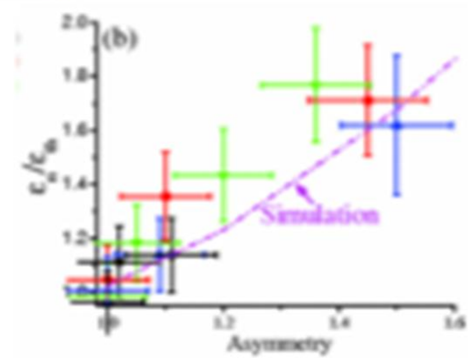
- Distortions from the ideal ellipsoid due to:

❖ group velocity delay and diffraction effects (laser shaping)

❖ Radial laser profile



❖ Space charge field of the image charge at the cathode → asymmetry at the bunch tail



Need to limit the space charge field to less than 10% of the accelerating field to avoid beam degradation

Conclusions

I. The uniformly filled ellipsoid is awesome…at least in theory.

II. Analytical calculations have been verified by both simulation and experiment with good agreement

III. Limitations of the scheme are:

    I. Challenging experimental realization particularly in the laser pulse

    II. Only valid for laser pulses very short compared to the radial size of the beam

IV. Ideal for applications in future FEL facilities or any high brightness electron beam sources

References

- O.J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004)
- P. Musumeci et al., Phys. Rev. Lett. 100, 244801 (2008)
- B. O'Shea et al., Phys. Rev. ST Accel. Beams 14, 012801 (2011)
- P. Piot et al., Phys. Rev. ST Accel. Beams 16, 010102 (2013)
- Y. Li and J. Lewellen, Phys. Rev. Lett. 100, 074801 (2008)

Thanks for a great week!