High brightness beam science

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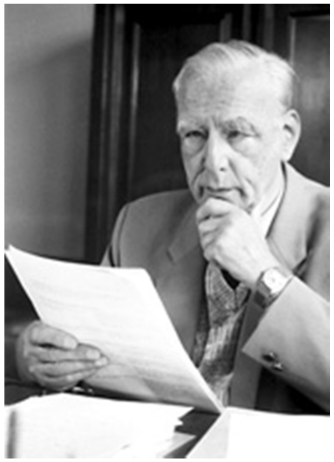
Outline

- Beam brightness.
  - Useful figure of merit to compare different sources
  - Bridge between different electron beam user communities
- A high brightness beam source: the RF photoinjector
  - “Pancake” and “Cigar” operation regimes
- MeV UED
  - Towards 30 fs temporal resolution using relativistic electrons
  - Liquid cell diffraction
- MeV UEM
  - New RF photoinjector design based on cigar beam dynamics
  - Conical illumination scheme

Beam brightness: early history

Intuitively the most important beam parameters are its peak current or charge per pulse and its ability to be transversely focused or collimated.



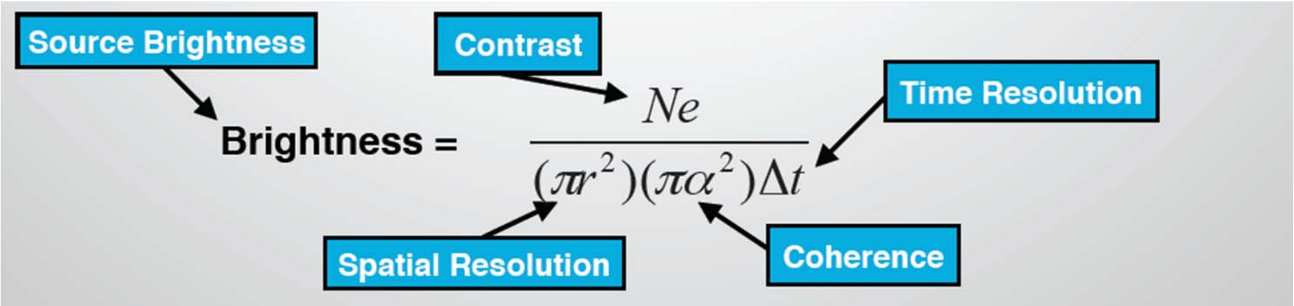
E. Ruska
1986 Nobel prize

In the `30s von Borries and Ruska (Nobel prize in Physics for the invention of the Electron Microscope) introduced the so-called beam brightness ("Richstrahlwert") defined as:

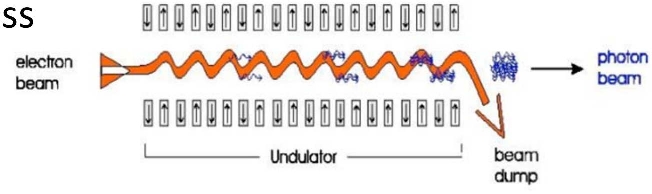
$$B_{micr} = \frac{I}{A\Omega}$$

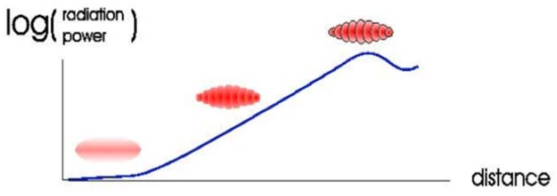
Empirically constant along the microscope column.
The smaller the spot --- the larger the divergence.

This definition still holds today in the field of electron microscopy with peak numbers of B_{micr} up to 10^{13} Amps/m^2/sr



Common brightness definitions in accelerator and beam physics





The 5D brightness is the relativistic analog of the microscope brightness

$$B_{5D} = \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}} \sim \frac{2I}{(\beta\gamma)^2\varepsilon_x\varepsilon_y}$$

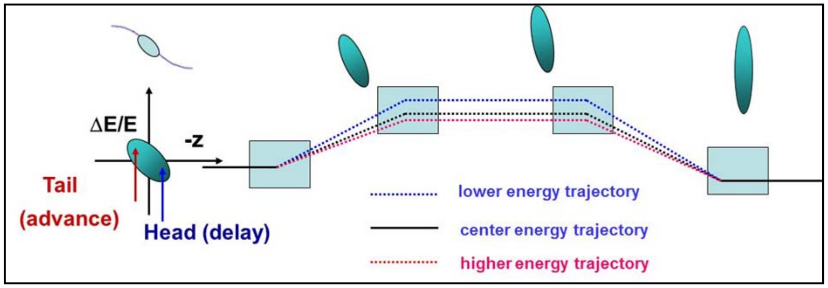
- ✓ For example it enters directly in FEL ρ determining gain and efficiency.
- ✓ The main difference with electron microscopy brightness is the use of normalized emittances to take into account relativistic effects.

4D transverse brightness is used in high average power applications

$$B_{4D} = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}}$$

where the longitudinal beam properties are not considered. The average 5D brightness is then $B_{4D}\,f$ where f is the repetition rate of the source.

Another reason to introduce the 4D brightness is due to the development of bunch compressors to increase the final current.



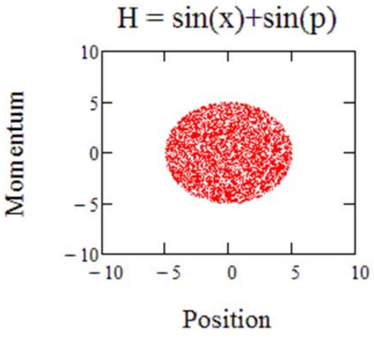
Liouville's theorem

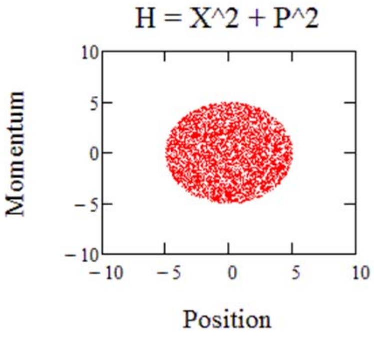
- Liouville theorem states that for Hamiltonian systems the phase space density stays constant.
- As long as the particle dynamics in the beamline elements (transport optics, accelerating sections) can be described by Hamiltonian functions (no binary collisions, stochastic processes, etc.), the 6D phase space density will stay constant throughout the accelerator.
- The meaningful quantity to describe electron sources should then be the 6D beam brightness defined as

$$B_{6D} = \frac{Ne}{V_{6D}} = \left(\frac{m_0 c}{\pi}\right)^3 F \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

Note that :

- 6D brightness is the true figure of merit, but in practice it is hard to measure experimentally !
- RMS brightness is only conserved when forces are linear !





Brightness quantum limit

Pauli exclusion principle prevents electrons from being in the same quantum state.

Since the elementary quantum of phase space area is set by *Heisenberg uncertainty principle*, we find a quantum limit for the maximum beam brightness

$$B_{quantum} = \frac{2e}{h^3}(m_0 c)^3 = \frac{2e}{(\lambda_c)^3}$$

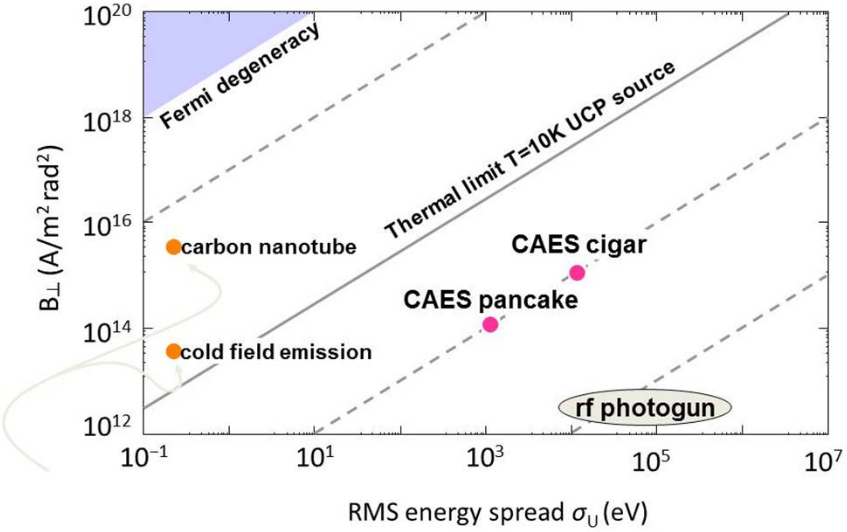
M. B. Callaham, IEEE J. quantum electronics, 24:1958, 1988

$$B_{quantum} \sim 10^{25}\ A/m^2$$

No beam can ever beat this limit. In practice state-of-the-art electron sources, as we will see, do not even come close and have $B_{6D} \sim 10^{-4} B_{quantum}$ or worse.

We can introduce the Degeneracy Factor representing the number of particles per elementary volume of phase space $\delta = B/B_{quantum}$

W. Pauli
Nobel prize 1945



W. Heisenberg
Nobel prize 1932

Microscope brightness for conventional electron sources

- Thermionic (Langmuir 1937)

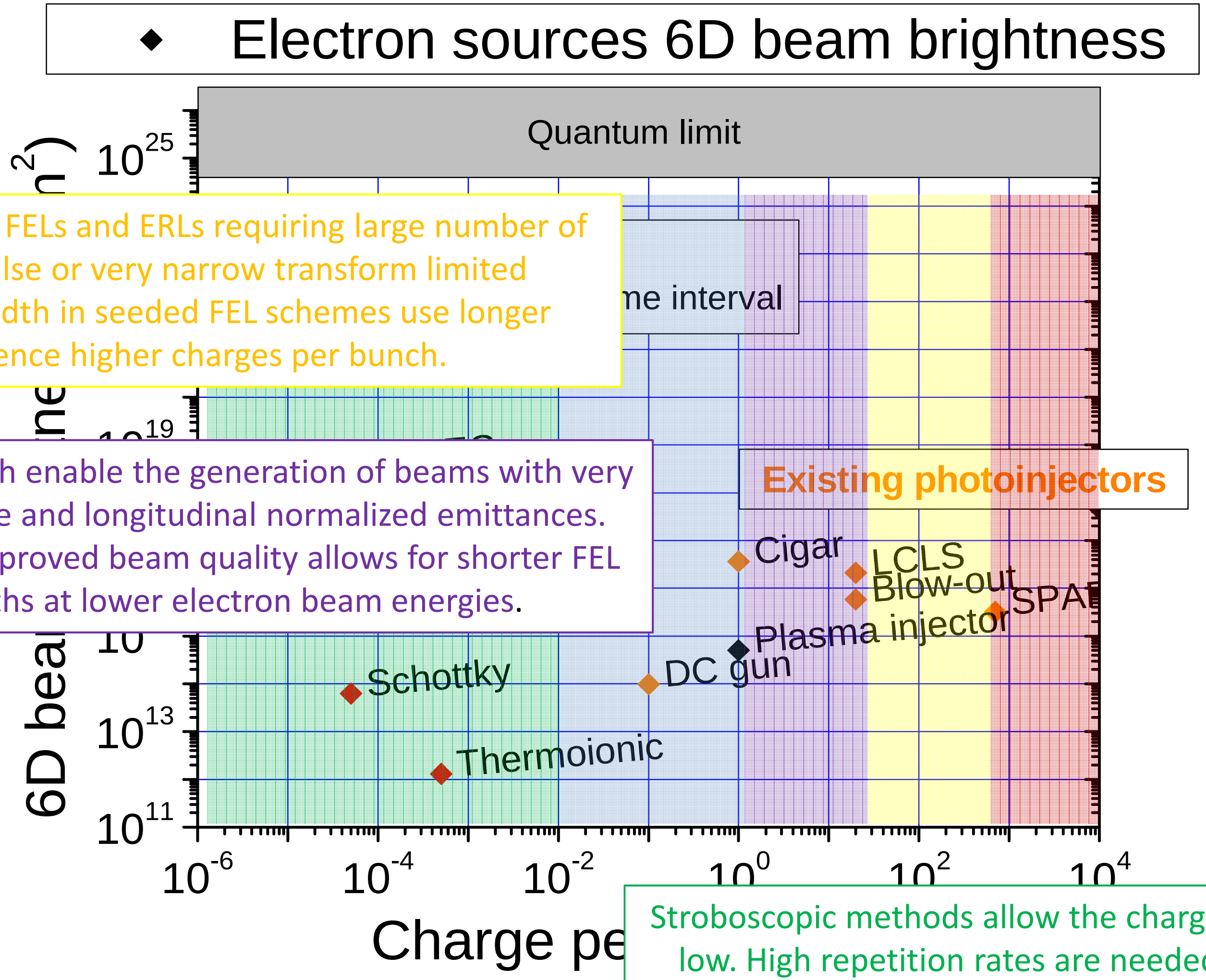
$$J_c = A_c T^2 \exp(-E_w / kT) \qquad \beta_{\max} = \frac{J_c e V_o}{\pi k T}$$

- Field emission (Crewe et al, 1971)

$$J = aE^2 \exp[-B\Phi^{\frac{3}{2}}/E], \qquad \beta_{\max} = \frac{J_c e V_0}{\pi \Delta E}$$

- Photoemission

$$J_n = \alpha_n A \left(\frac{e}{h\nu}\right)^n (1-R)^n I^n T_e^2 F\left(\frac{nh\nu - e\Phi_0}{kT_e}\right) \qquad \beta_{max} = \frac{J_{ph} e V_0}{\pi\ (h\nu - e\Phi)}$$



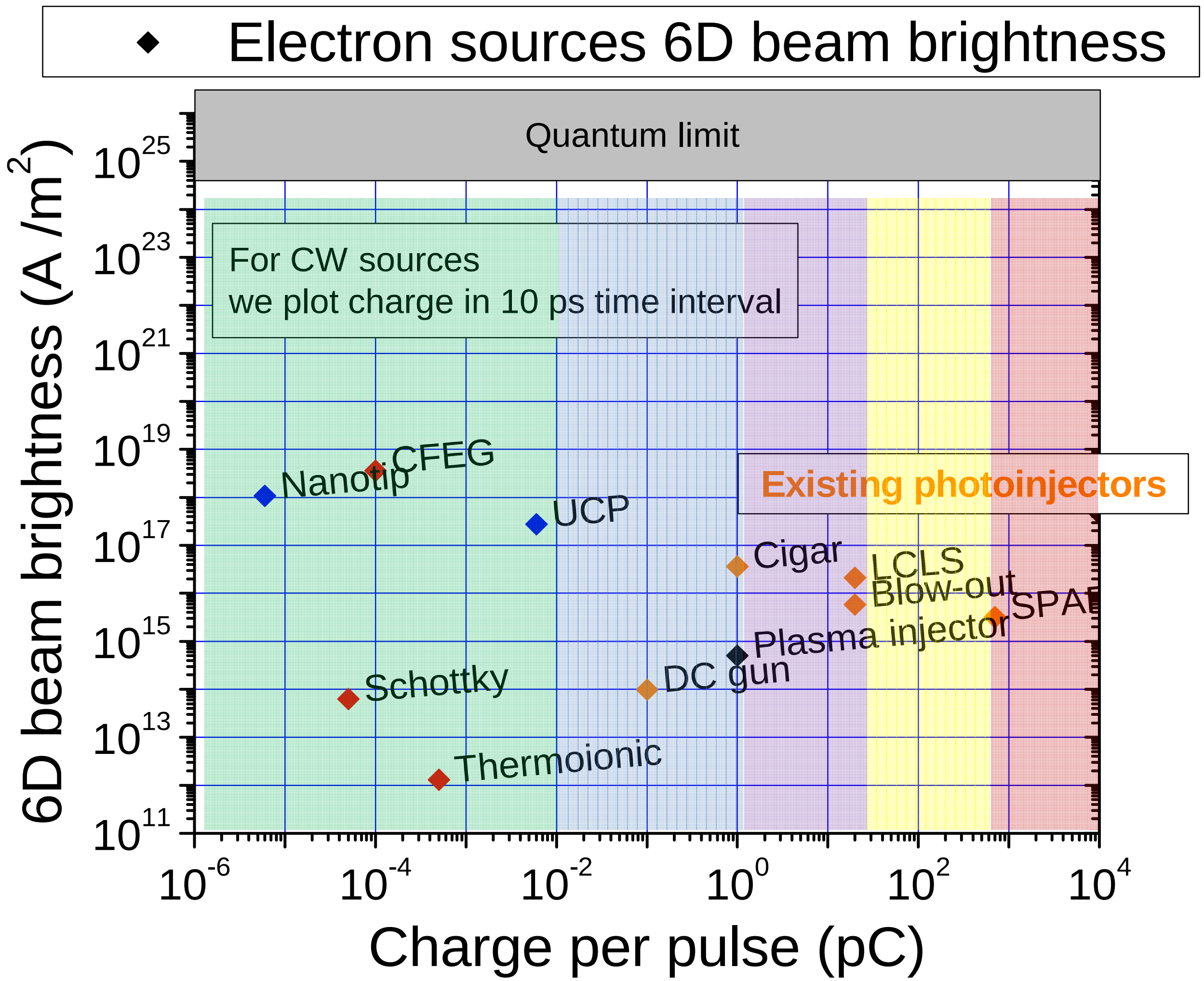
Experiments in FELs and ERLs requiring large number of photons per pulse or very narrow transform limited photon bandwidth in seeded FEL schemes use longer bunches and hence higher charges per bunch.

1-10 pC per bunch enable the generation of beams with very small transverse and longitudinal normalized emittances. The resulting improved beam quality allows for shorter FEL gain lengths at lower electron beam energies.

Stroboscopic methods allow the charge per pulse to be very low. High repetition rates are needed to acquire enough signal-to-noise ratio.

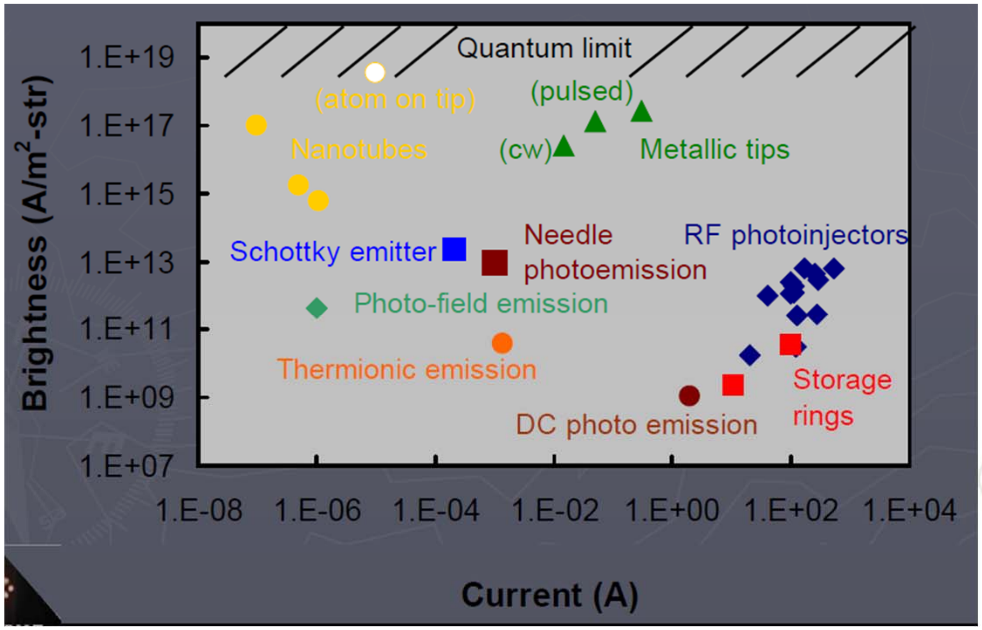
For single shot electron diffraction and microscopy the number of particles per bunch should be enough to allow sufficient contrast in the diffraction pattern/image. For a diffraction pattern of a single crystal, we only need 10^5 particles. At least 10^8 particles are required to form an image.

Beams for HEP and plasma wakefield drivers require very large charges, over 1 nC

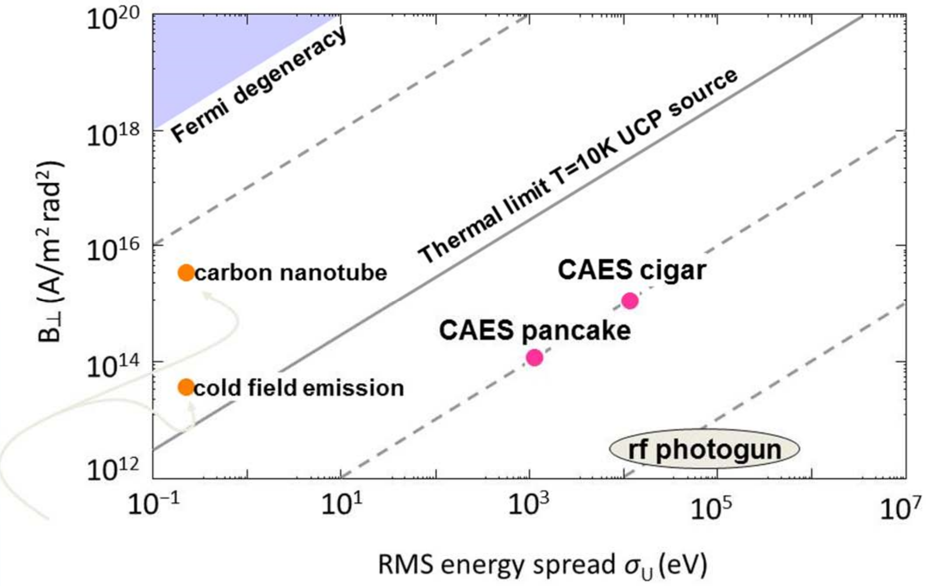


For CW sources
we plot charge in 10 ps time interval

Other beam brightness plots



From C. Brau

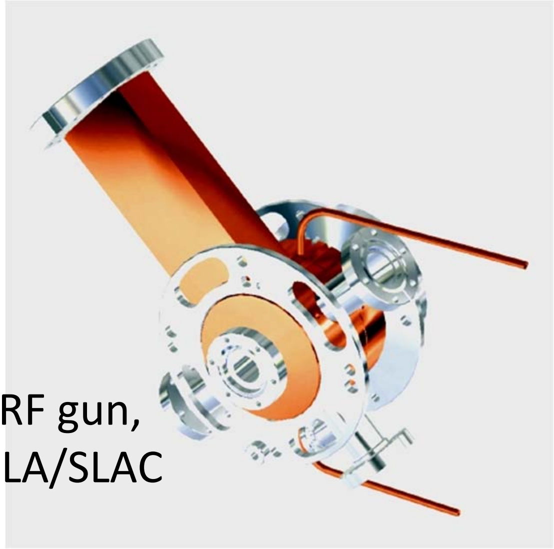


From J. Luiten

The RF photoinjector

- *State-of-the-art high brightness electron beam source*
  - Developed for advanced accelerators & FELs
  - Applications to UED (X. J. Wang, 1996, PRE 54 R3121)
- Photo-emission inside ultrahigh field RF cavity
  - Peak field $E_0 > 100$ MV/m
  - 3-5 MeV output energy

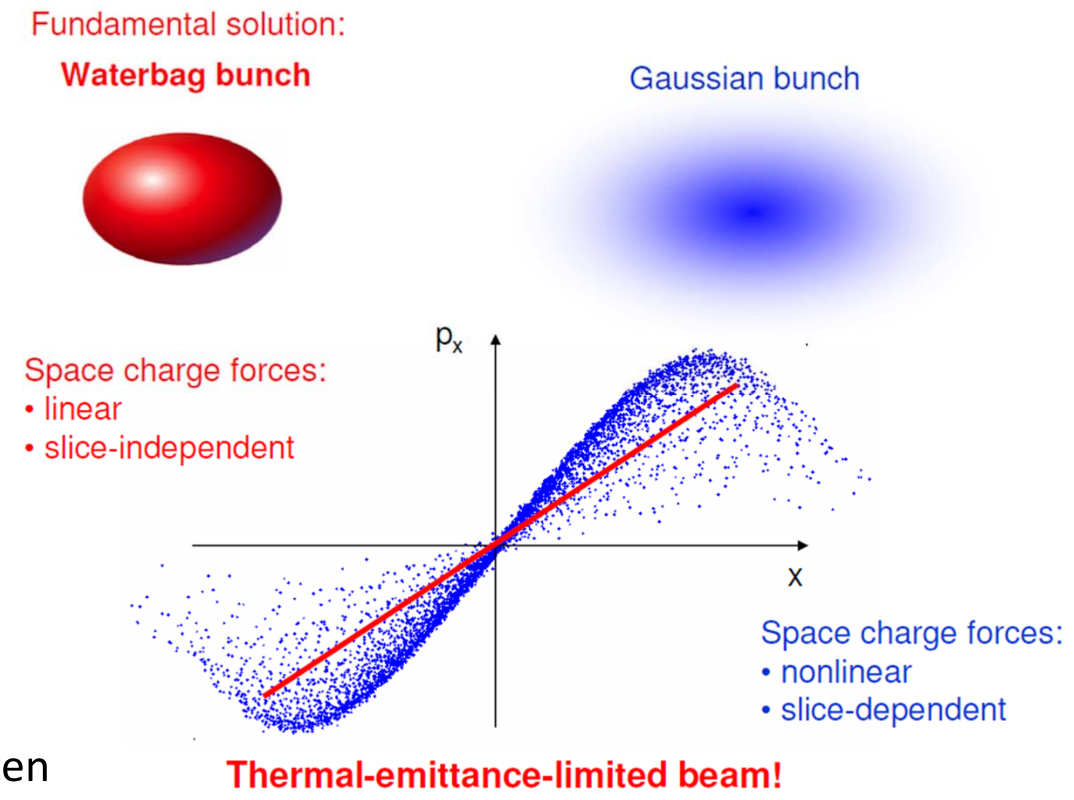
- Well characterized – Mature technology
  - Sub-ps beams possible (response time from metal cathodes is <50 fsec)
  - Flexible charge (few fC – few nC)
  - Very low emittance
- Space charge effects suppression
  - High field at the cathode
  - High final energy.
  - Beam distribution shaping.



1.6 cell RF gun,
BNL/UCLA/SLAC
design

Preserve brightness during transport

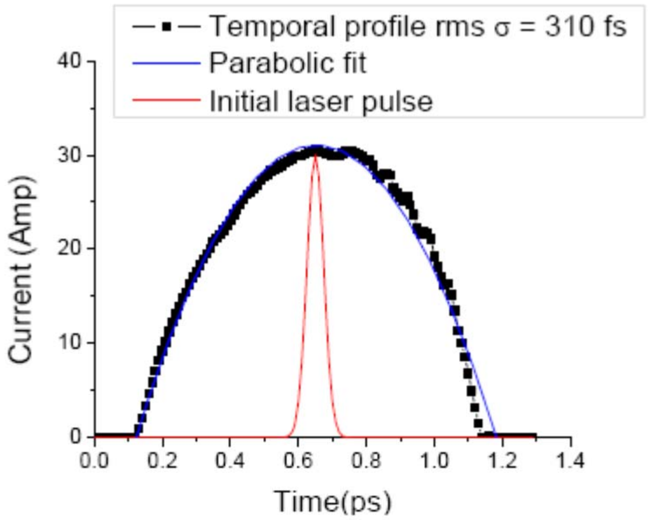
- Uniformly filled ellipsoidal distribution is the ideal case.
- How to create these distributions:
  - Illuminate cathode with short pulse and use longitudinal space-charge expansion (PANCAKE)
  - Illuminate cathode with long and skinny pulse and use transverse space-charge expansion (CIGAR)
  - Direct ellipsoidal laser pulse shaping (not yet demonstrated)



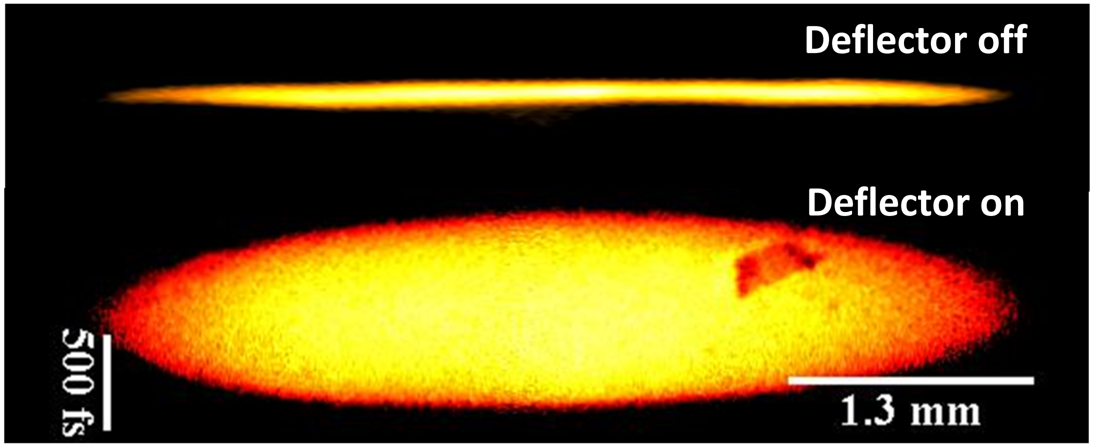
Courtesy of J. Luiten

Ellipsoidal beam experimental demonstration At Pegasus

- Charge 20 pC. Laser spot size 400 μm rms (limited by asymmetry due to image charge)
- rms length ~300 fs
- Very sharp ellipsoidal beam boundary due to the ultrashort beam on the cathode.
- When charge exceeds 10% strong asymmetry develops.

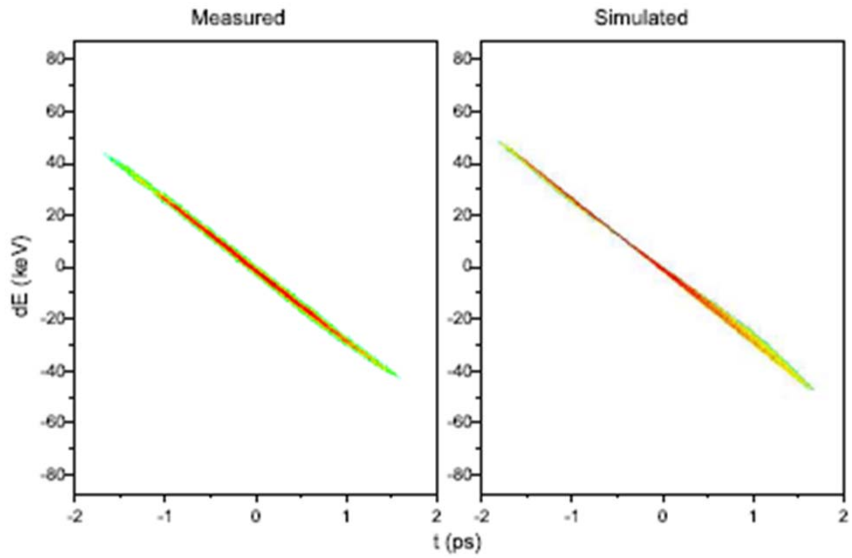


P. Musumeci, J. T. Moody, R. J. England, J. B. Rosenzweig, and T. Tran, *Phys. Rev. Lett.* **100**, 244801 (2008)



Longitudinal phase space

- Use vertically deflecting cavity in conjunction with horizontally dispersing dipole
- Record resolution in time (50 fs) and energy (1 keV).
    - Advantages of measurement on low energy beams.
- Can compress !



Very linear phase space

High 6D beam brightness

Ultralow longitudinal emittance (<0.5 um)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 070704 (2009)

Longitudinal phase space characterization of the blow-out regime of rf photoinjector operation

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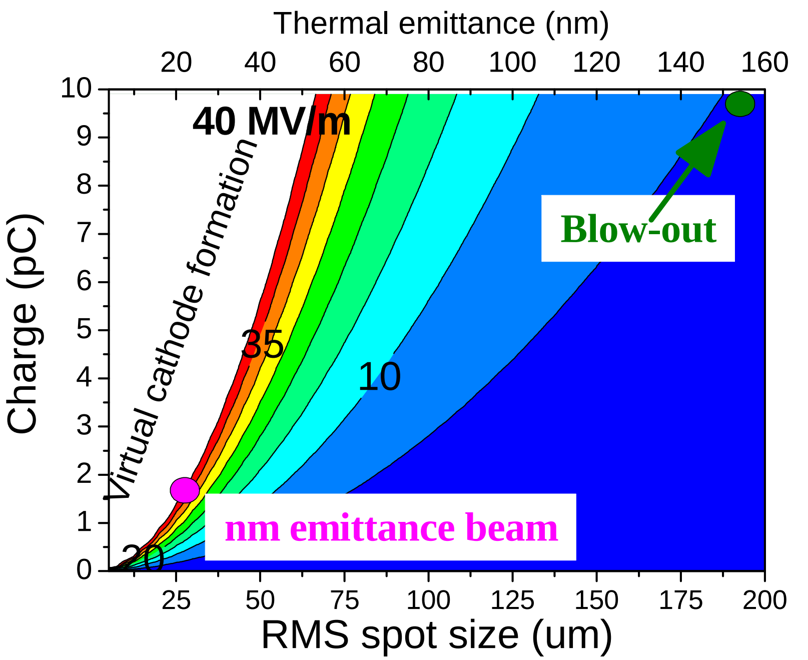
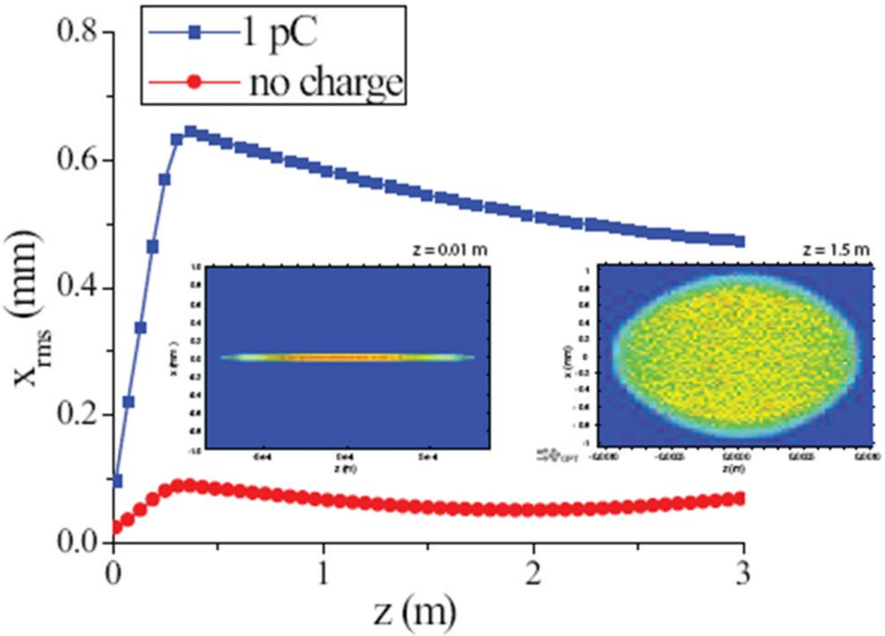
(Received 27 April 2009; published 29 July 2009)

Cigar beams

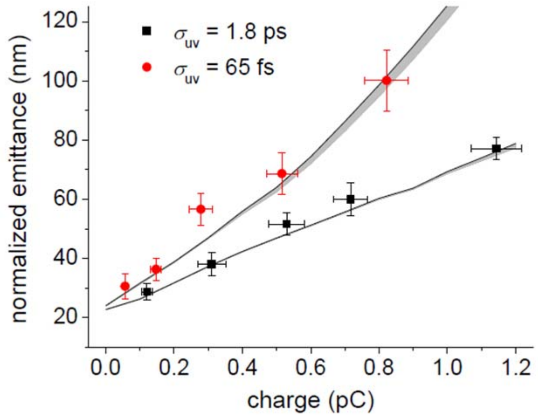
- “Blow-out” or “pancake” regime requires large initial laser spot by definition.
- Large cathode (thermal) emittance contribution
- Alternative :
  - Focus laser to tight transverse spot on cathode.
  - Stretch laser pulse and use long parabolic temporal profile.
  - Transverse space charge expansion creates ellipsoidal beam (again!) preserving emittance (transverse counterpart of blow-out).



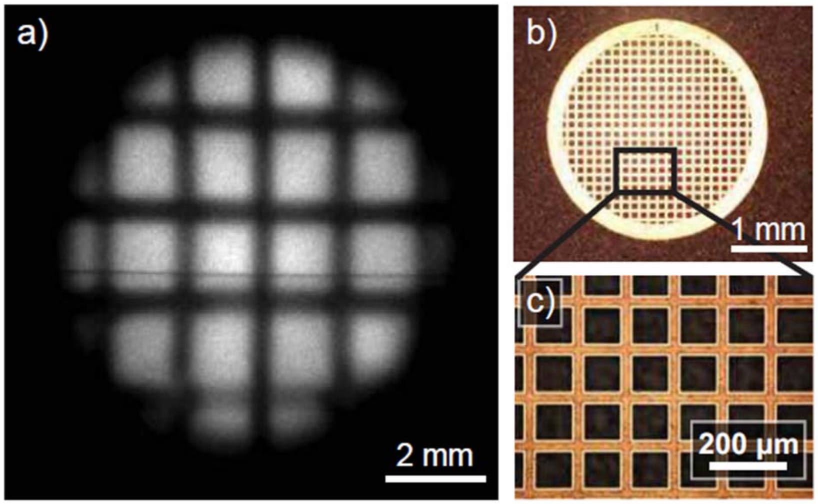


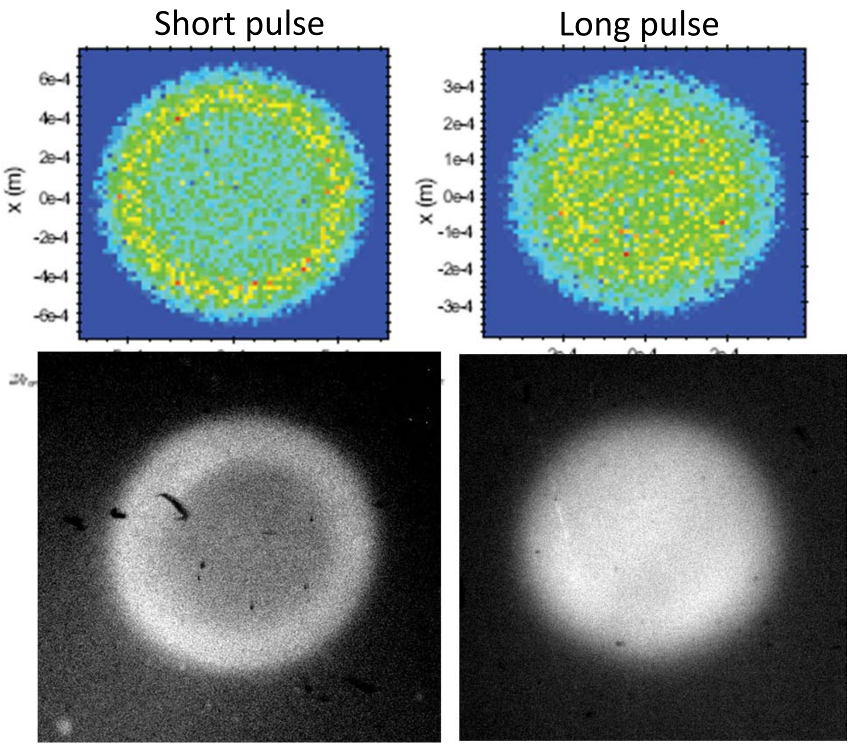
Ultralow charge nm-emittance beams.

- Electron sources in low charge regime. 0.1 pC – 1 pC.
  - ✓ UED
  - ✓ FELs
  - ✓ laser-based Advanced Accelerators
- Normalized transverse emittance below 20 nm (comparable with TEMs)



TEM grid-based emittance measurement





Space charge limits in the emission

2 cases:

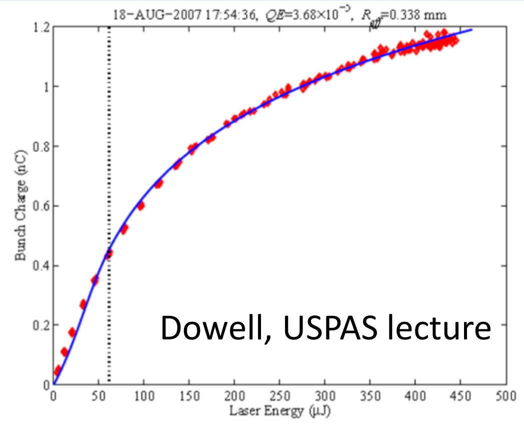
$R > \Delta z_e$ *pancake aspect ratio*

$R < \Delta z_e$ *cigar aspect ratio*

- Pancake

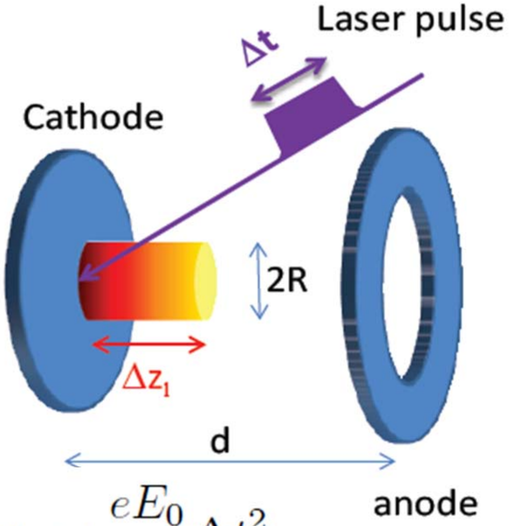
Maximum surface charge density set by the cathode extraction field.

$$\frac{Q}{\pi R^2} < \epsilon_0 E_0$$

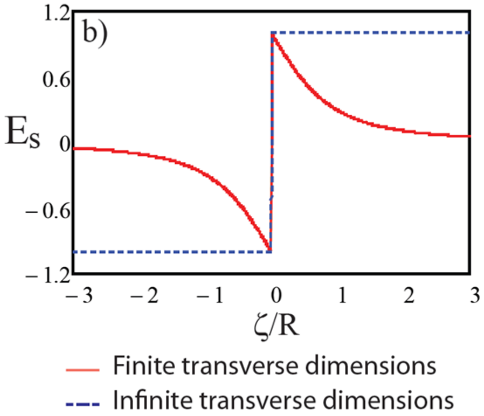


Dowell, USPAS lecture

D. Filippetto, P. Musumeci, M. Zolotorev, G. Stupakov, to appear in PRSTAB



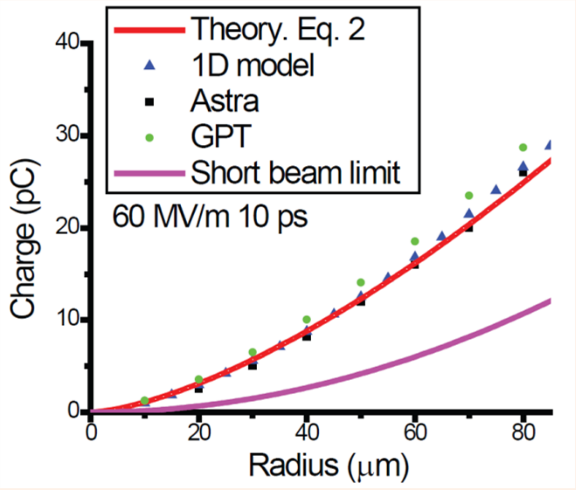
$$\Delta z_e = \frac{eE_0}{2m}\Delta t_l^2$$



- Cigar

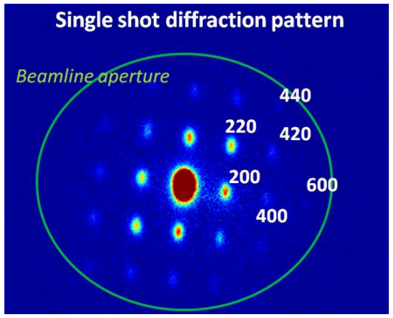
Only charge within a radius distance from the cathode contributes to space charge field

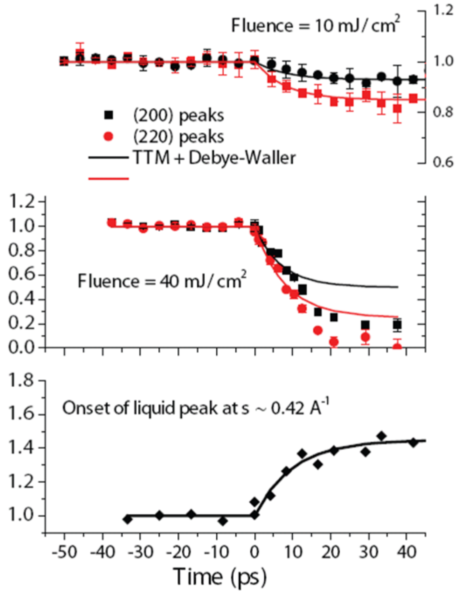
$$Q = J_{CL}\pi R^2 \propto \frac{V^{\frac{3}{2}}}{d^2}R^2 \propto (E_0 R)^{\frac{3}{2}}$$



MeV UED science

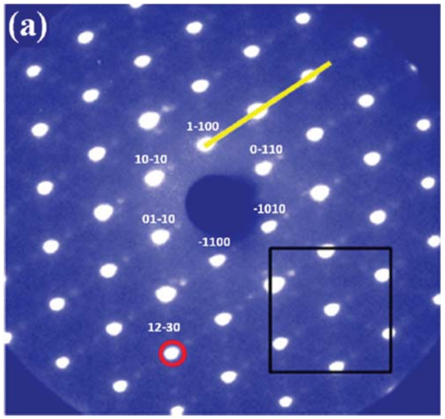
- Few published studies with time-resolved data
- Each one points to a specific MeV advantage
  - ❖ Single shot
  - ❖ Thickness of sample
  - ❖ < 100 fs temporal resolution

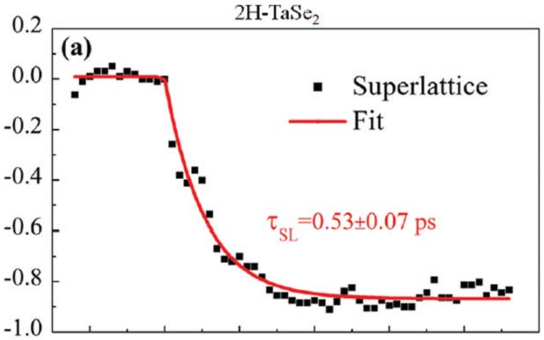


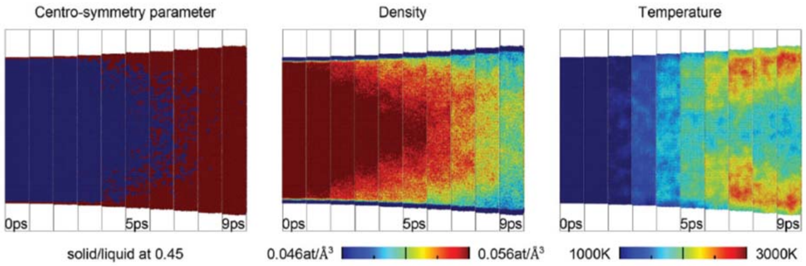


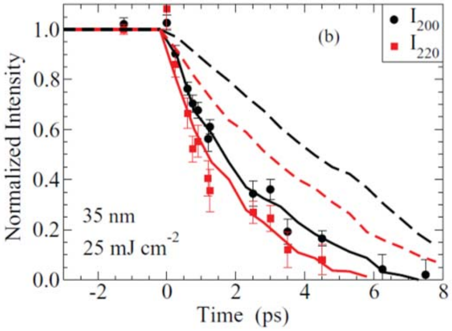
P. Musumeci et al. Applied Physics Letters, 063502 (2010)

P. Zhu et al. Appl. Phys. Lett. 103, 071914 (2013)





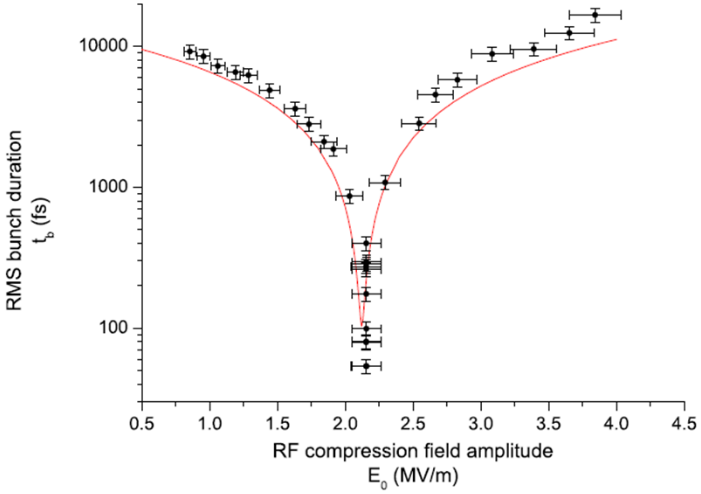




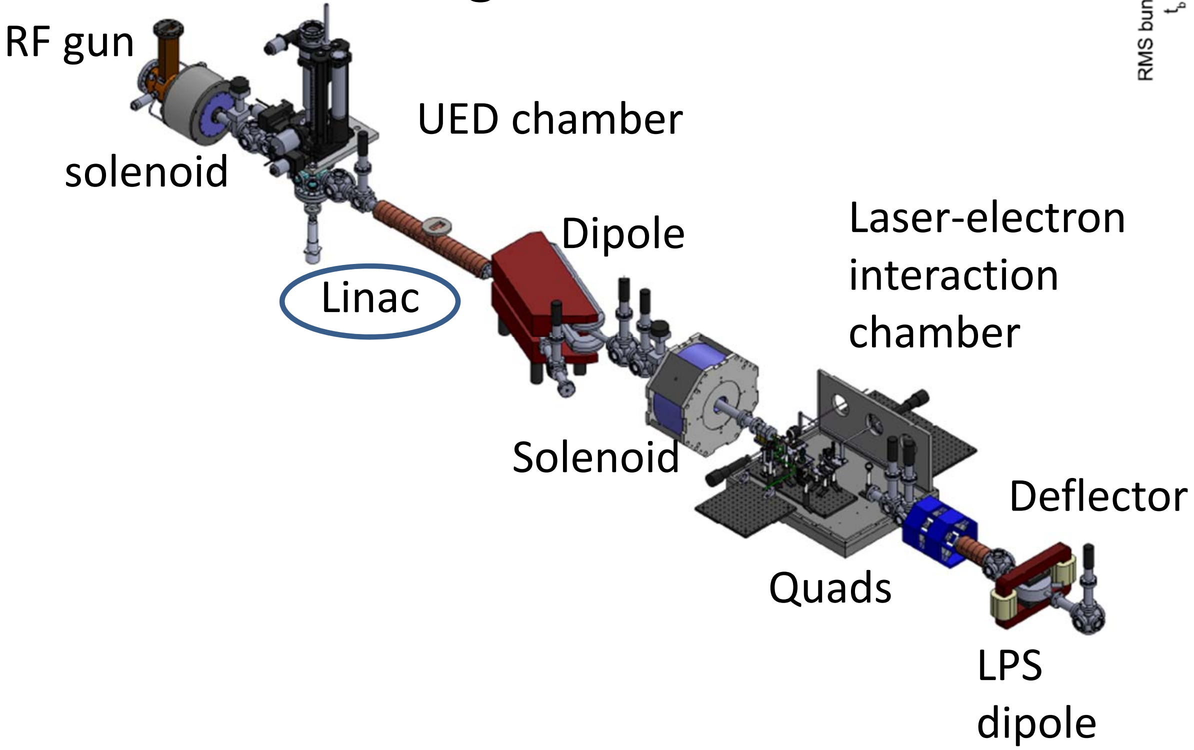
S. Daraszewicz et al.
Phys Rev B 184101 (2013)

Beam compression

- Phase space manipulation to increase 5D brightness.
  - Pay a price in correlated energy spread
  - Hard to apply to microscopy
- Suggested first and demonstrated for DC gun. Van Oudheusden *Phys. Rev. Lett*. 105, 264801 (2010)
- Workhorse for many RF compressed DC gun setups
- Concept can be applied to MeV beam as well

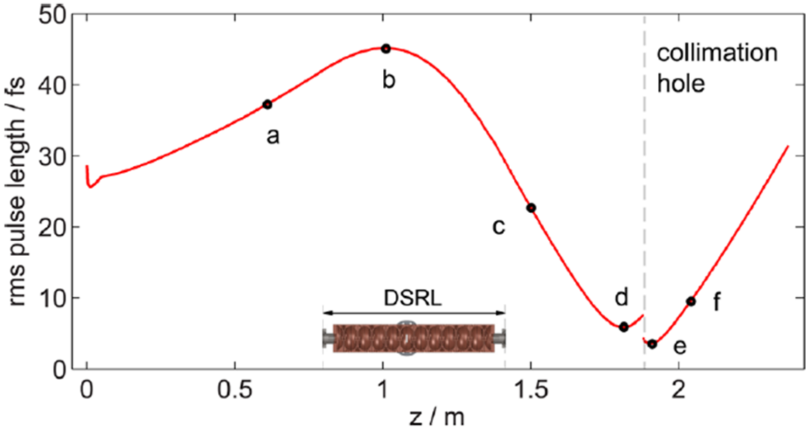


Pegasus beamline

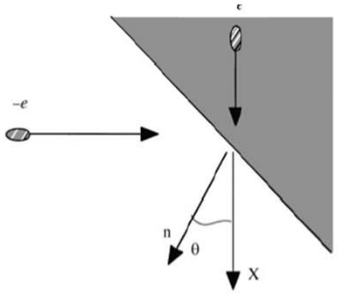


RF linac compression

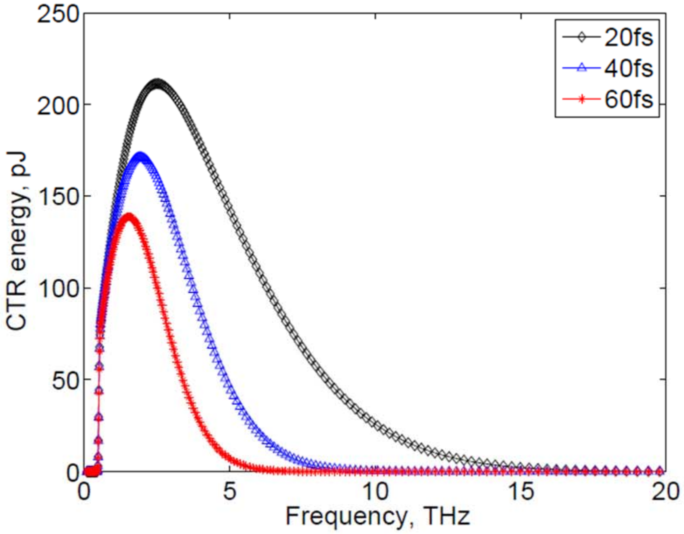
- High shunt impedance linac
- *Independent RF feed*
  - Adjust phase and amplitude
- Beam too short for RF deflection resolution (?)
- CTR diagnostics (Xianhai Lu visiting student from Tsinghua University)



$$
\begin{aligned}
E_T(\omega) &= |f(\omega)|^2 E_{e-} \\
&= N^2 \exp(-\sigma_t^2 \omega^2) E_e
\end{aligned}
$$

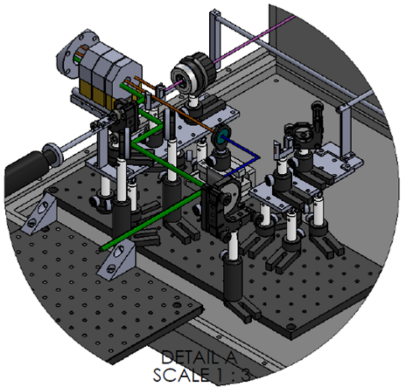


A. Murokh et al./Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 452—460

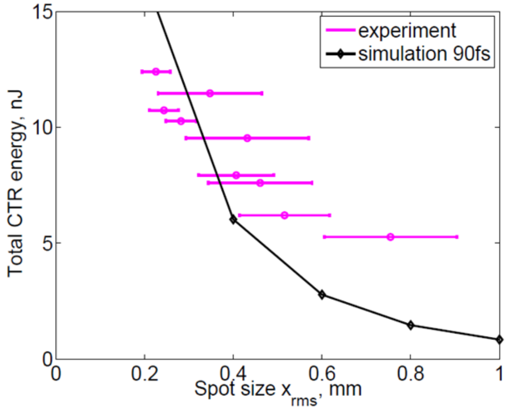


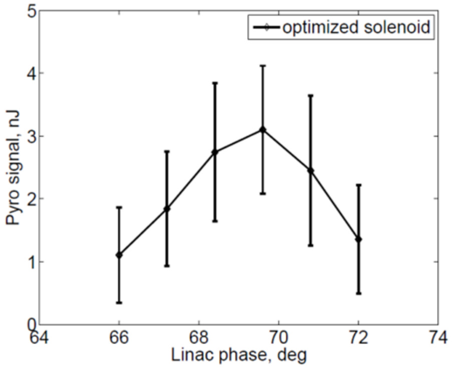
RF compression results

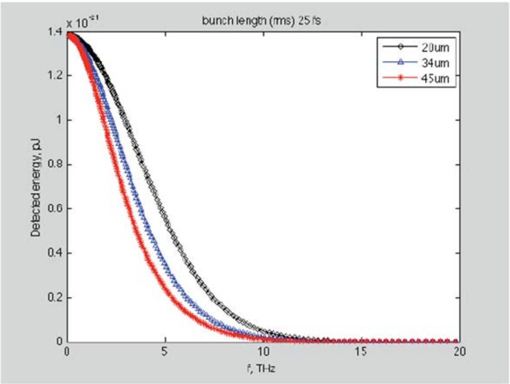
- Maximize CTR signal with linac phase
- Strong dependence on transverse spot size
- Use filters at 1 THz and 5 THz to reconstruct spectral content
- Huge fluctuations due to RF – laser jitter !



Data analysis in progress

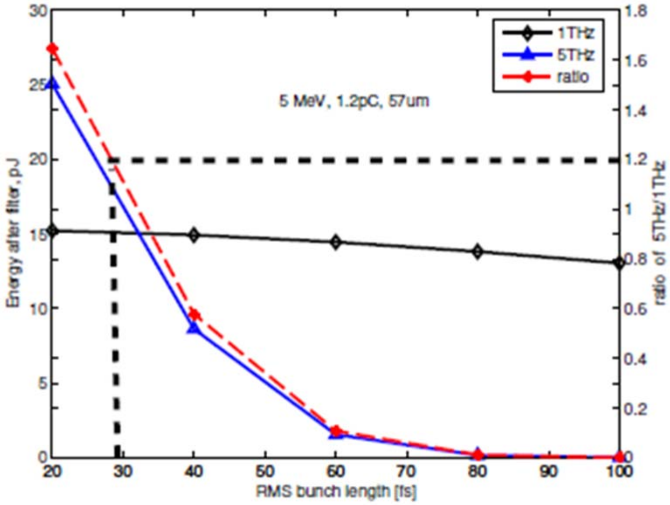






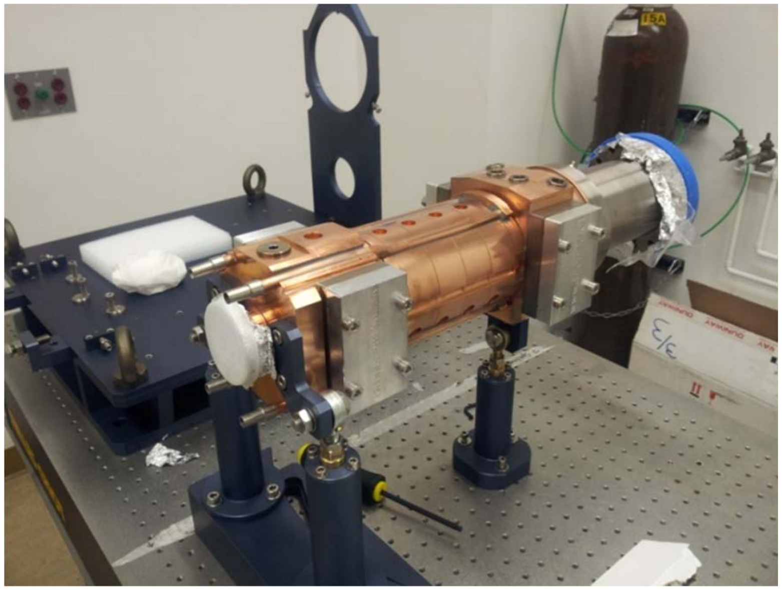
Due to fluctuations it is expected that the 1 THz detector should see near constant energy. 5 THz detector more sensitive.

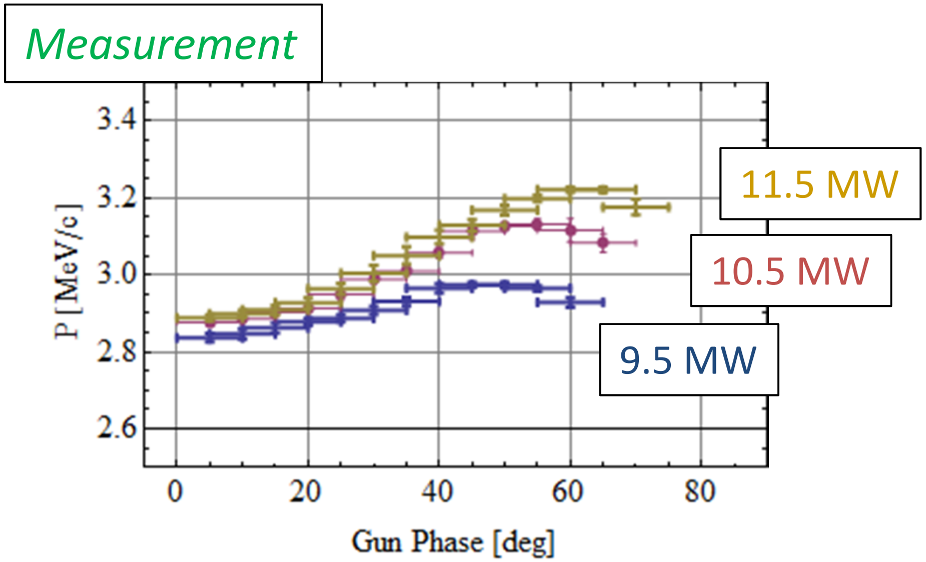
Take peak ratio of the two detectors and extract bunch length ~ 30 fs !

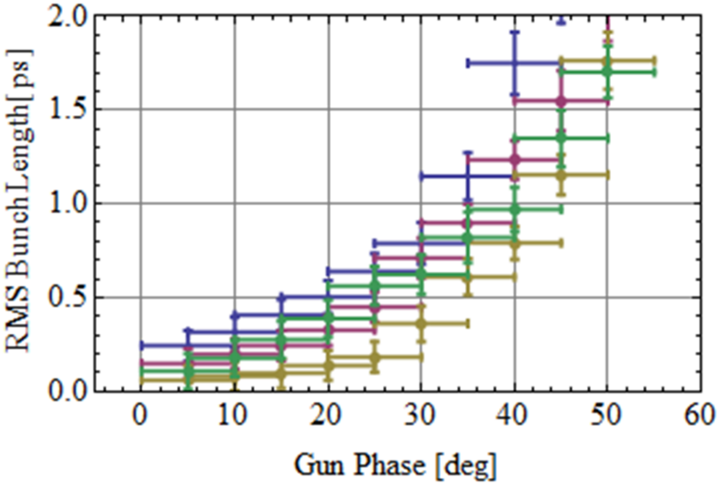


New hybrid gun compression

- The idea: combine in a single structure beam generation and beam compression.
- Traveling wave section acts as a buncher
- Beam tests at UCLA Pegasus Laboratory (A.Fukasawa)
- Bunch length measurements with 9.6 GHz deflecting cavity
- Obtained 1 pC - 100 fs resolution limited
- Scaling to X-band gun (UCLA/SLAC/INFN collaboration) yields sub-10 fs beams in simulations.



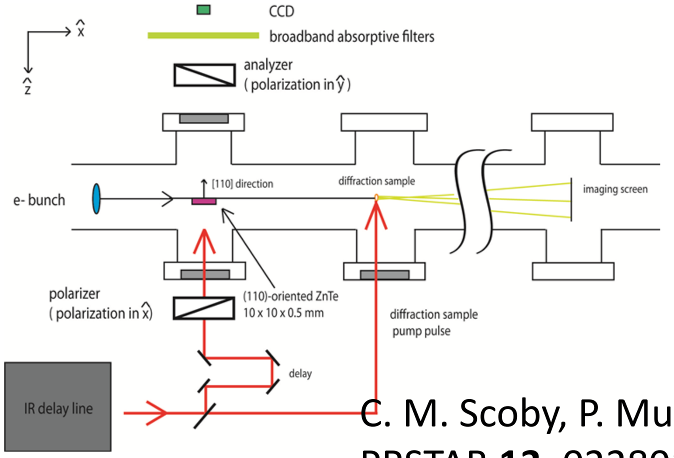




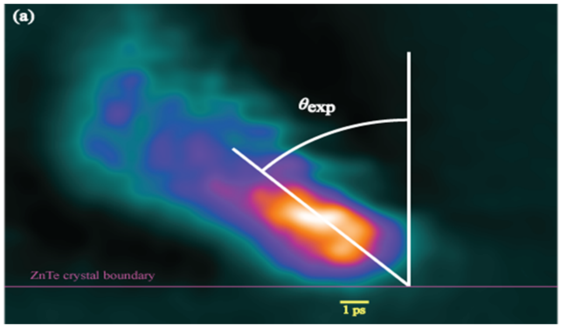
Beyond time jitter-limited resolution

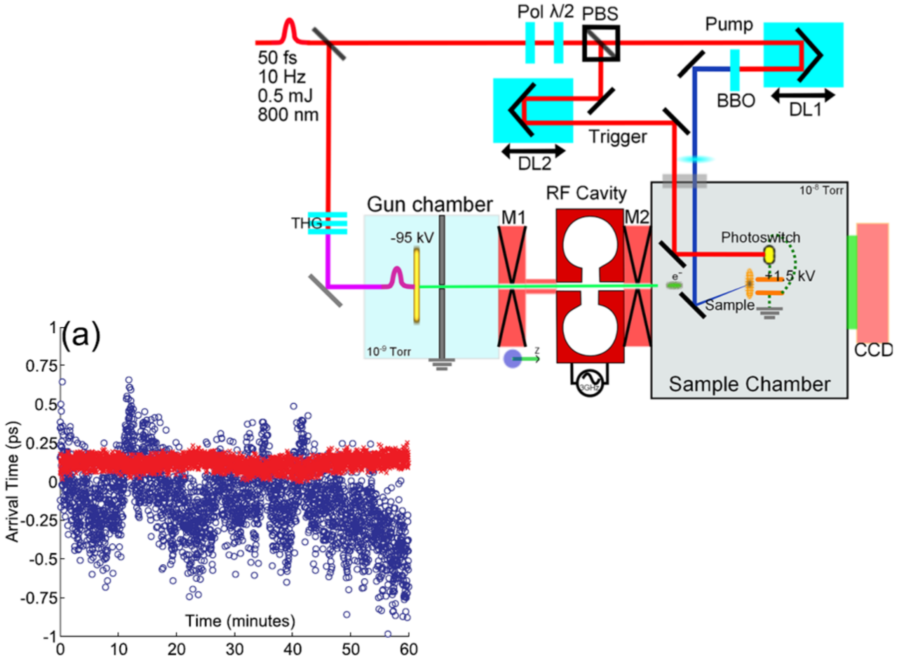
Timing jitter is at this point the main limitation in temporal resolution of electron scattering instruments.

- Electro-Optic Sampling based time stamping before sample
  - Down to 1 pC
  - MeV beams
- Time stamp using laser triggered streak camera kick on the main beam after diffraction
  - Low charge
  - < 50 fs resolution (high voltage photoswitch stability)



C. M. Scoby, P. Musumeci et al., PRSTAB **13**, 022801 (2010)





APPLIED PHYSICS LETTERS **103**, 033503 (2013)

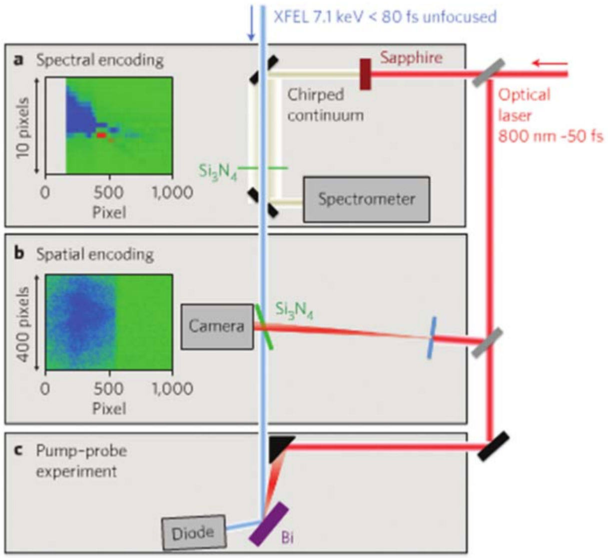
Single shot time stamping of ultrabright radio frequency compressed electron pulses

M. Gao,[1,2] Y. Jiang,[2] G. H. Kassier,[2] and R. J. Dwayne Miller[1,2,a)]

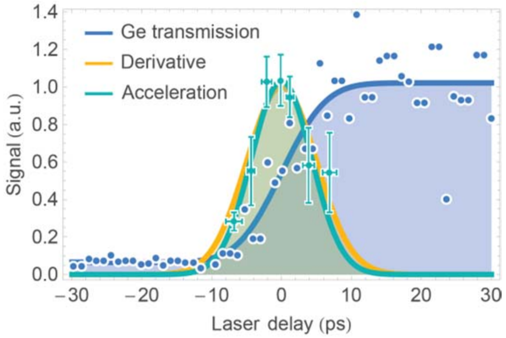
New concepts for time stamping

- Electron beam controlled transmission through semiconductor membrane
  - Done with X-ray demonstrated < 5 fs accuracy
  - Routinely used in laser accelerators (Ge and Co2)
  - Challenge to create enough electron-hole pairs

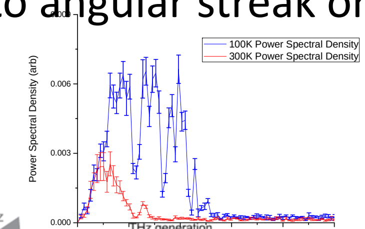
M. Harmand, Nature Photonics, 2013

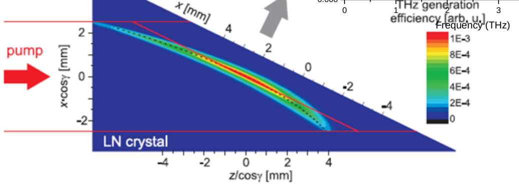


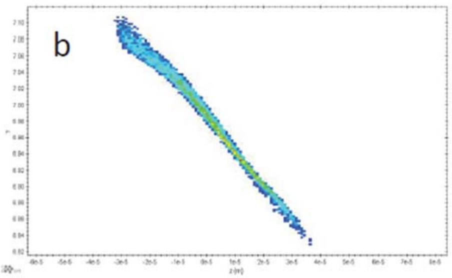
From UCLA BNL IFEL experiment



- THz streaking
  - Also used at LCLS
  - THz with laser (optical rectification). Generates MV/m THz field.
  - Use IFEL interaction with TEM01 mode to angular streak or with TEM00 mode to energy streak
  - 10 fs resolution
  - Can use THz to compress too….

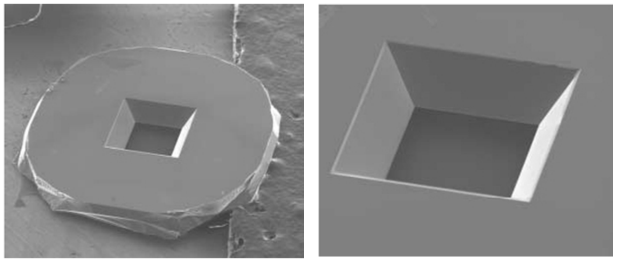




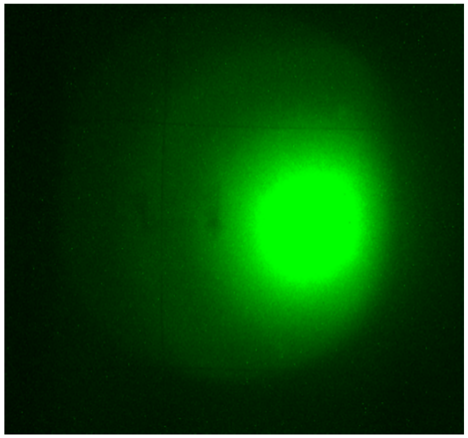


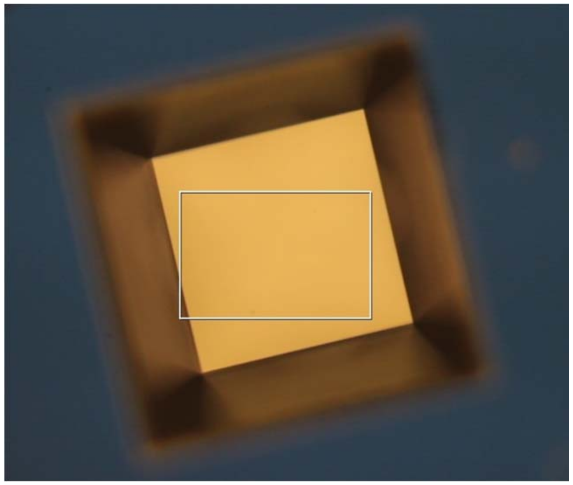
Liquid cells

- Take advantage of larger penetration of MeV beams
- Collaboration with UCLA C. Regan's group
- Assembled from Si3N4 75 nm thick windows
- Cell thickness set using 4.5 um polystyrene beads as spacers (EMFP@ 3 MeV 1.5 um)
- Illuminated with beam. Imaging and diffraction pattern (ring from Si3N4)
- Open the door to time-resolved liquid phase experiments !
- Post mortem after 4 hrs (10^{11} e^{-} total dose) shows gas bubbles: pulsed radiolysis?

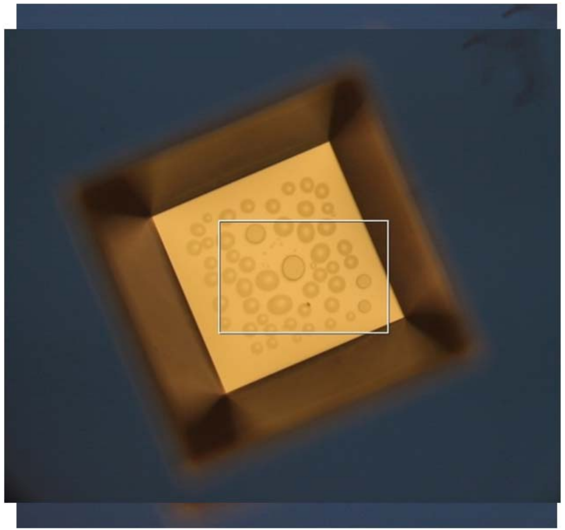


Single shot Diffraction pattern



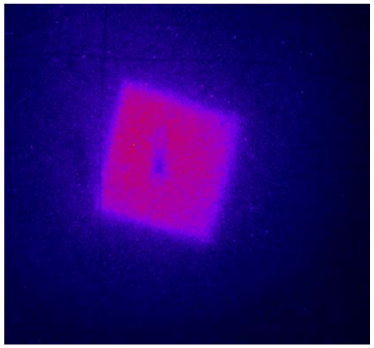


Not irradiated



After e-beam

Optical microscope

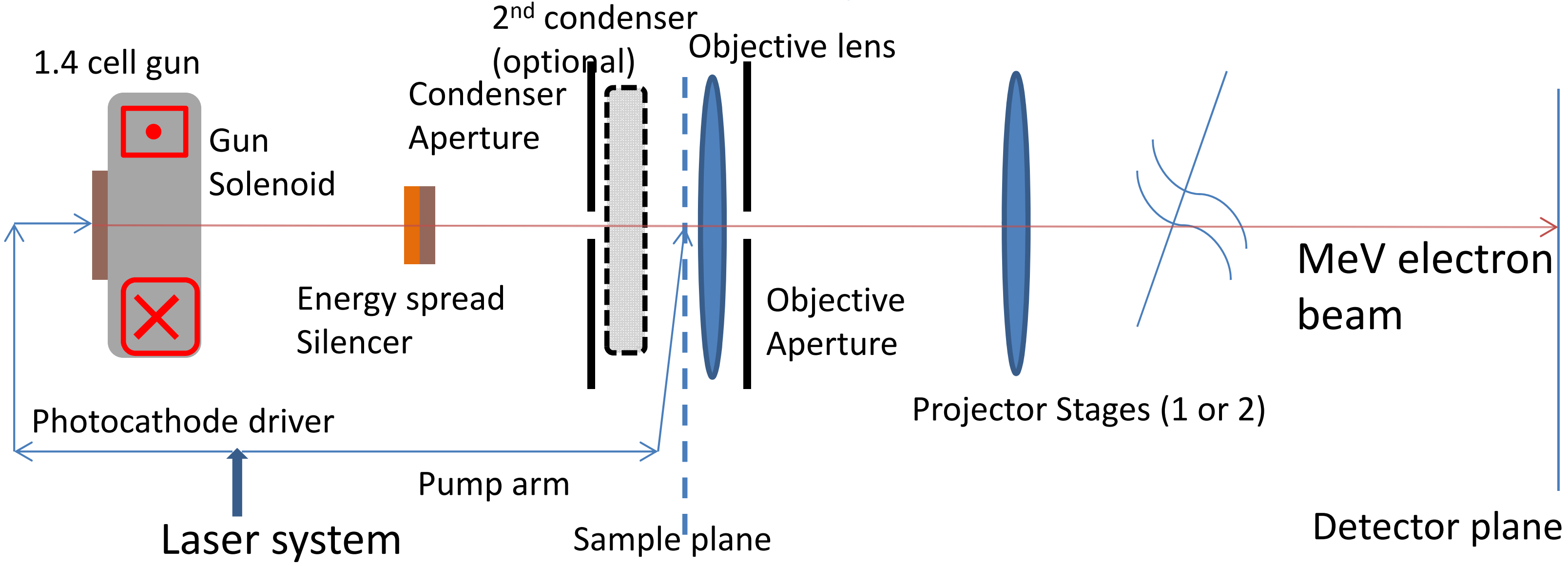


Electron image

UCLA concept for MeV-ps microscopy

- Limit to incoherent imaging, 10 ps temporal resolution and 10 nm spatial resolution.
  - Dislocation and shock dynamics studies
- A simple path would be to modify an existing MeV microscope….
- Based on cigar aspect ratio regime
- Condenser stage: energy spread silencing
- Objective lenses: permanent magnet quadrupoles

Parameters	Values
Gun gradient	120 MV/m
Initial beam charge	1 pC
Laser spot-size	40 um rms
Laser pulse length	10 ps
Normalized emittance	**10 nm**
Kinetic beam energy	5.00 MeV
Relative energy spread	**5e-6 rms**

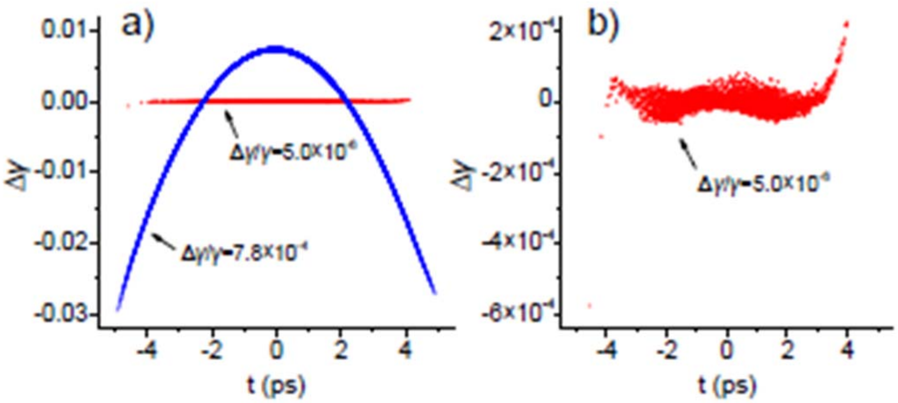


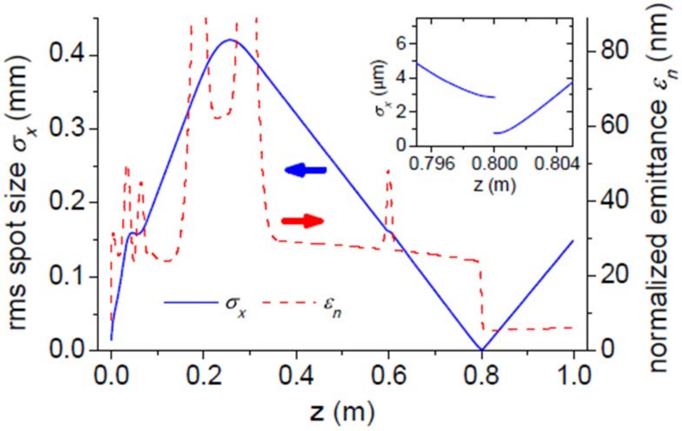
Energy spread silencing

- Radiofrequency accelerating field not constant in time
- 10 ps (10 deg @S-band) long pulse shows large curvature in longitudinal phase space and large energy spread $p_g = p_0 \cos(\varphi)$
- Use 3rd harmonic cavity to compensate and cancel 2nd order curvature

$$p_c = p_0 \cos(\varphi) - p_3 \cos(3\varphi) \qquad \text{with} \qquad p_3 = p_0/9$$

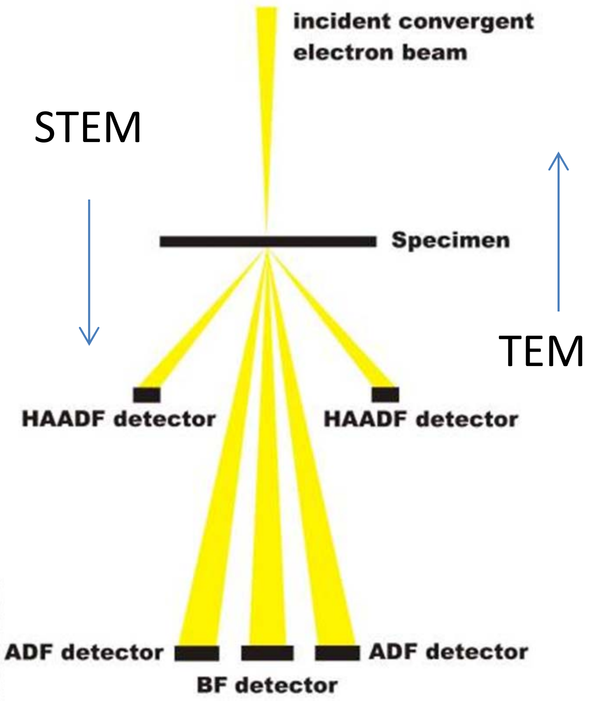
- Partial compensation of slice energy spread too…
- Final rms energy spread < 10^{-5} or in absolute terms < 20 eV !

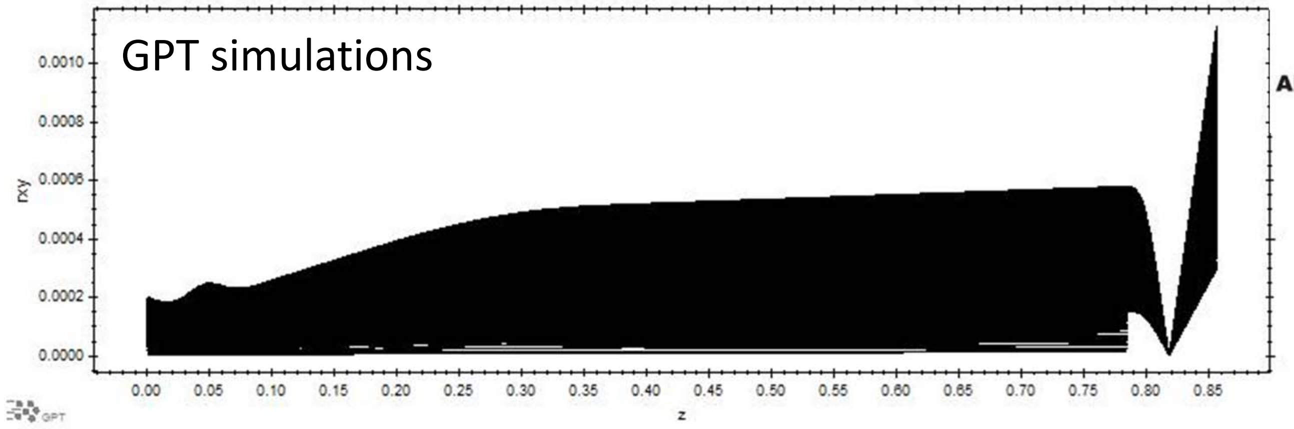




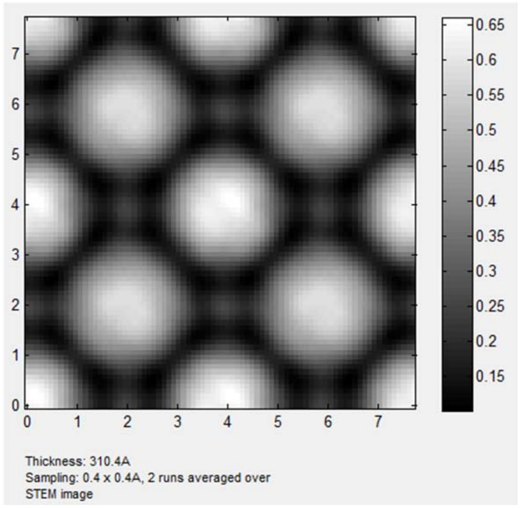
Conical illumination MeV TEM

- Collaboration with J. Spence & C. Koch
- Reciprocity theorem
- Equivalent to HAADF-STEM
- Could obtain atomic resolution with large angle illumination (incoherent illumination)
- BUT need extremely large flux (2 orders of magnitude larger than current state-of-the-art)




GPT simulations

STEM Image simulation: 30 nm thick SrTiO3
Detector collects scattering angles from 10 .. 60 mrad
Probe convergence semi-angle: 4.3 mrad



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- External collaborators: L. Faillace, S. Boucher, F. Carbone, J. Luiten, X. J. Wang, D. Xiang, D. Filippetto, W. Wan, B. Reed

Conclusions

- Better beam brightness key to all electron scattering research
- Phase space shaping might help specific applications (UED, UEM). Pancake, Cigar and Beam Compression.
- Relativistic electrons from RF photoinjectors competitive with other approaches. Lots of room for improvements
  - Lower thermal emittance cathode research
  - High field RF cavity design
- MeV UED taking advantage of its unique characteristics.
  - Liquid phases
  - sub-50 fs time-resolution.
- Future goal within reach: MeV UEM with 10 nm-10 ps resolution