Ultra-low Charge, Ultra-high Brightness Frontiers of Photoinjectors: Challenges and Perspectives

Renkai Li

37th FEL Conference (FEL 2015)
August 25, 2015 - Daejeon, Korea

Outline

- Pursuing better beams - FEL, UED/UEM
- Generation of higher brightness
- Characterizing these extreme beams
- Better machines and new science
- Summary and outlook

Pushing Science frontiers with electron beams

SLAC

Linac Coherent Light Source

1.7 km

3 m

TEAM: Transmission Electron Aberration-corrected Microscope

Pushing Science frontiers with electron beams

Linac **C**oherent **L**ight **S**ource

1.7 km

TEAM: **T**ransmission **E**lectron **A**berration-corrected **M**icroscope

3 m

Enabled by EXTREME, but very different electron beams

Pushing Science frontiers with electron beams

SLAC

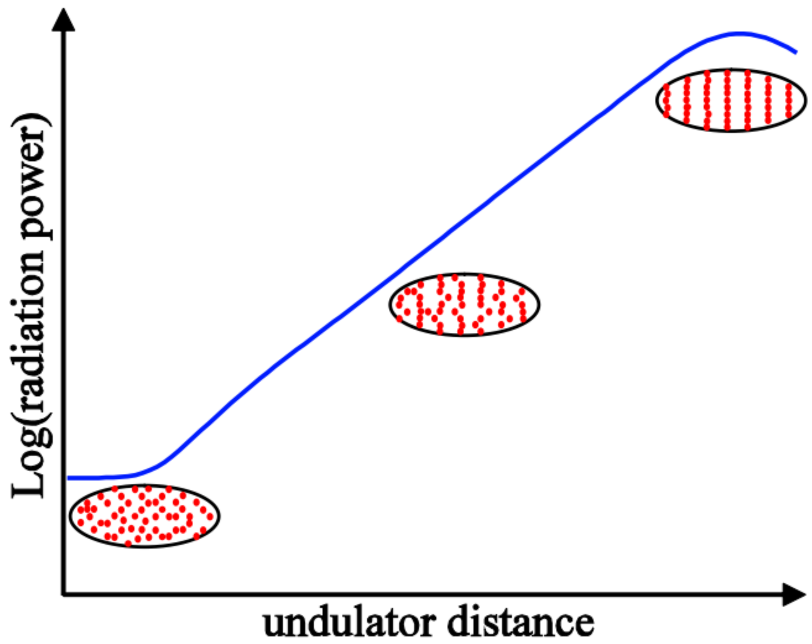
Linac Coherent Light Source		TEAM: Transmission Electron Aberration-corrected Microscope
e-beams for XFEL		**e-beams for TEM/STEM**
> ~10 GeV beam energy		< ~300 keV beam energy
$\Delta E/E \sim 1\times10^{-4}$		$\Delta E/E < 1\times10^{-6}$
10^{8}-10^{9} *e-* per pulse		10^{6}-10^{9} *e-* per image
kA beam current		pA beam current
extremely short – 10 fs		extremely narrow – 50 pm
flat photocathode		tip field-emission source
control the collective effects		optics, with aberration correction

1.7 km

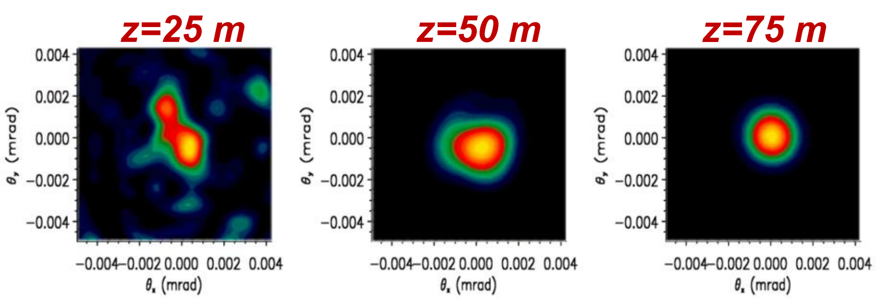
3 m

FEL requirement on e-beams

SASE FEL: *high gain & trans. coherence*



LCLS transverse profile at



1D gain length $L_G^{1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$

Saturation power $P_{\mathrm{sat}} \approx \rho P_{\mathrm{e}}$

Pierce parameter $\rho = \left[\frac{1}{16}\frac{I_e}{I_A}\frac{K_0^2[\mathrm{JJ}]^2}{\gamma_0^3\sigma_x^2 k_u^2}\right]^{1/3}$

Geometric emittance $\frac{\epsilon_n}{\gamma_0} \leqslant \frac{\lambda}{4\pi}$

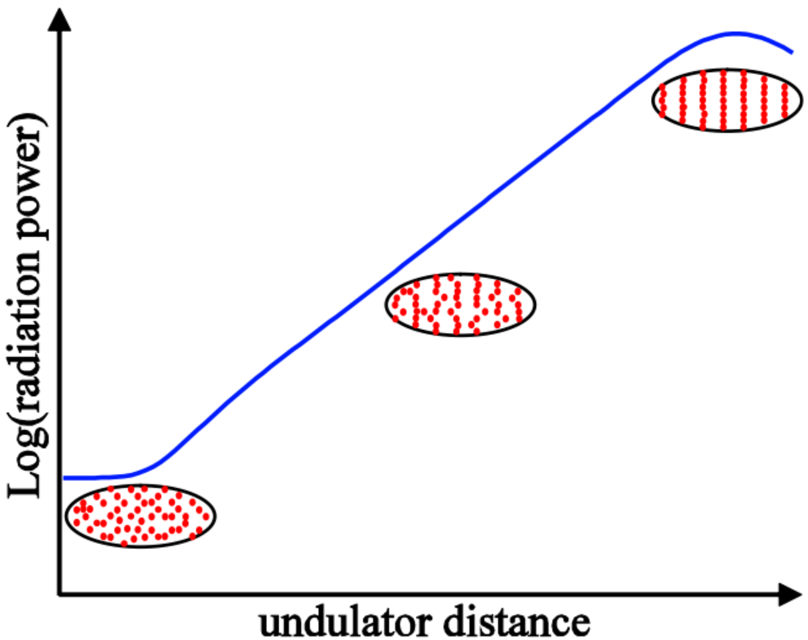
energy spread $\sigma_\eta \ll \rho$

*Z. Huang and K.-J. Kim, PRSTAB **10**, 034801 (2007)*

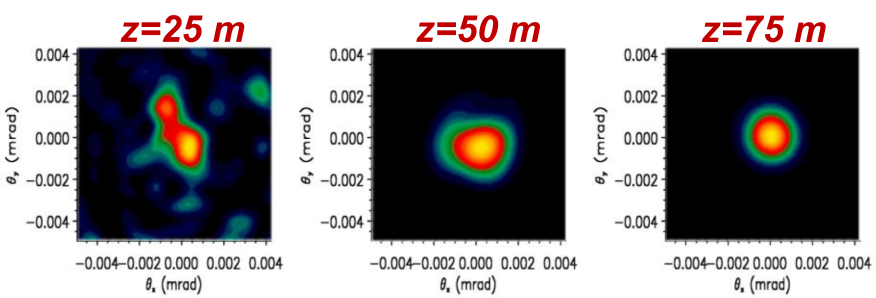
FEL requirement on e-beams

SLAC

SASE FEL: *high gain & trans. coherence*



LCLS transverse profile at



Z. Huang and K.-J. Kim, PRSTAB ***10****, 034801 (2007)*

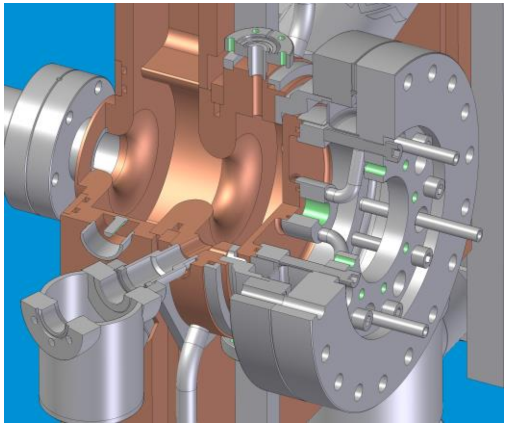
1D gain length $L_G^{1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$

Saturation power $P_{\mathrm{sat}} \approx \rho P_{\mathrm{e}}$

Pierce parameter $\rho = \left[\frac{1}{16}\frac{I_e}{I_A}\frac{K_0^2[\mathrm{JJ}]^2}{\gamma_0^3\sigma_x^2k_u^2}\right]^{1/3}$

Geometric emittance $\frac{\epsilon_n}{\gamma_0} \leqslant \frac{\lambda}{4\pi}$

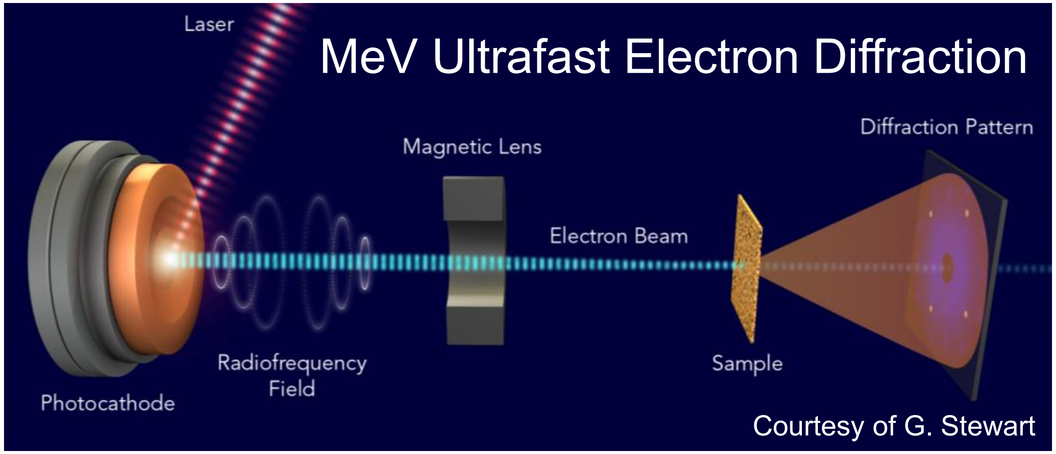
energy spread $\sigma_\eta \ll \rho$



Photoinjectors deliver required e-beams for FEL

Cut-away view of the LCLS gun. Courtesy of E. Jongewaard

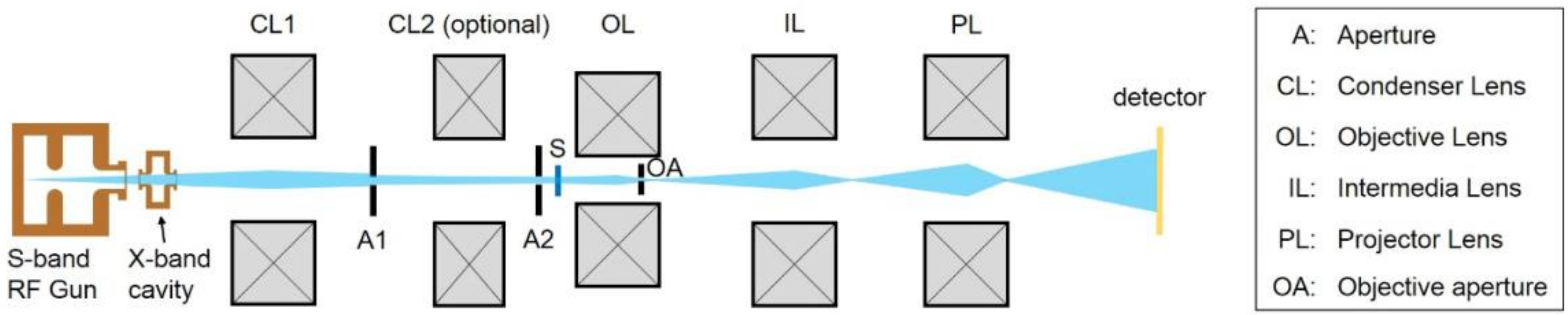
RF photoinjector-based MeV UED and UEM



- ultralow charge (< ~1 pC)
- ultralow emittance (< ~10 nm)
- directly serve ultrafast science
- R&D at SLAC, UCLA, Tsinghua, Osaka, BNL, DESY, LBL, Shanghai Jiaotong, SFTC, KAERI

X. J. Wang et al., PAC'03, p. 420. *P. Musumeci and R. K. Li, in ICFA Newsletter No. 59 (2013)*

MeV Ultrafast Electron Microscope

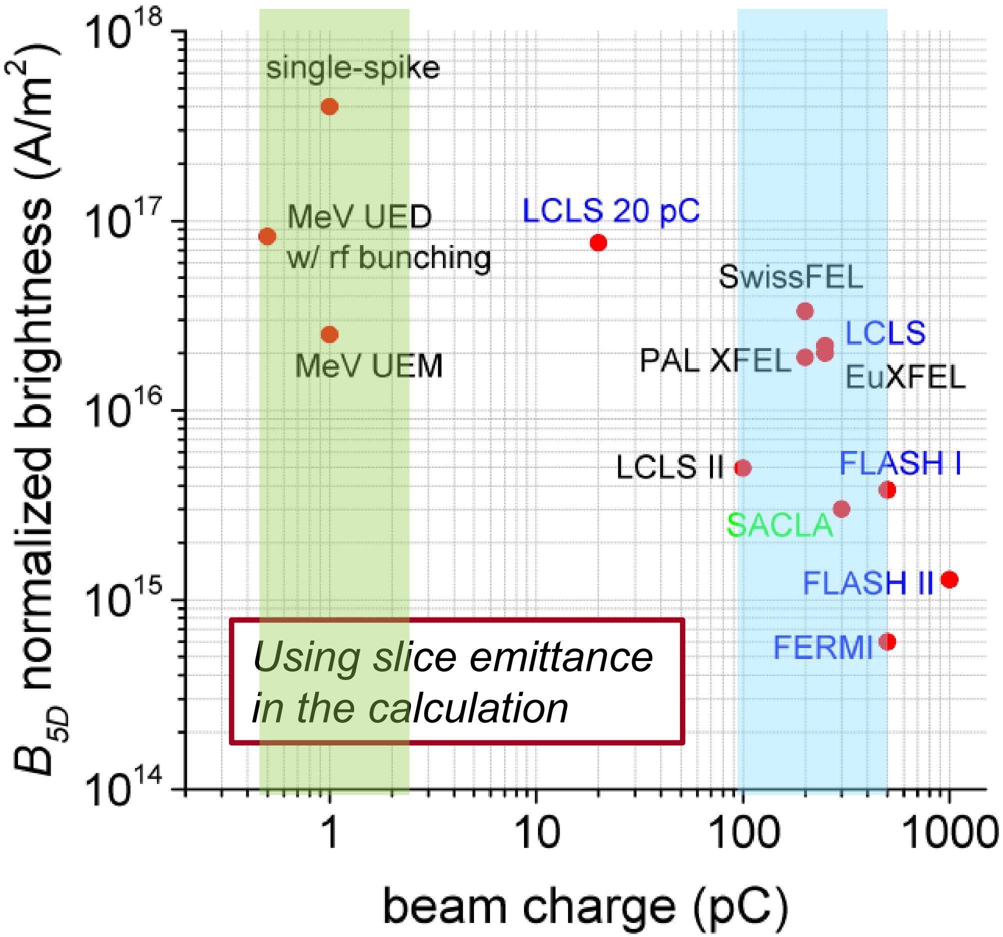


Beam brightness from photoinjectors

- 5-D normalized beam brightness

$$B_{5\mathrm{D}} = \frac{I}{\epsilon_{n,x}\epsilon_{n,y}}$$

- Most XFELs driven by photoinjectors
- Photoinjectors deliver excellent transverse emittance, as well as longitudinal emittance
- Most facilities operate at 0.1 – 0.5 nC
- Higher $B_{5\mathrm{D}}$ at lower charge, but beam diagnosis becomes more challenging
- Many new techniques for low charge (<1 pC) developed for UED and UEM



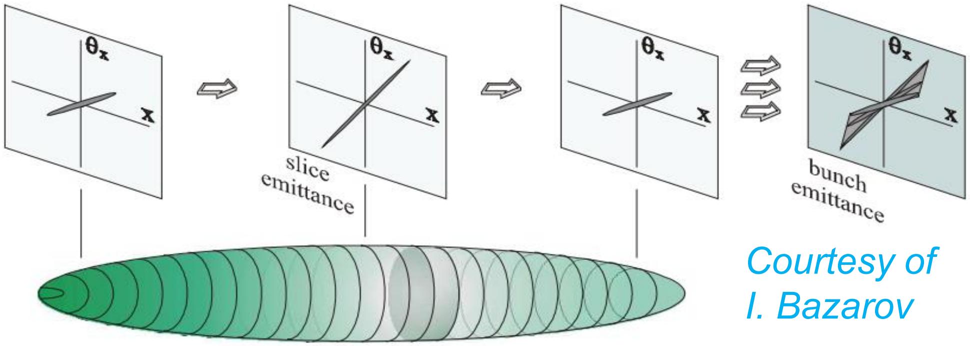
S. Di Mitri and M. Cornacchia, Phys. Rep. 539, 1 (2014).

emittance of low charge electron beams

- Project and slice emittance
- $\epsilon_{\mathrm{rf}}, \epsilon_{\mathrm{optics}}, \epsilon_{\mathrm{sc}}, \epsilon_{\mathrm{intri}}, \cdots$

B. E. Carlsten, NIMA 285, 313 (1989)

Serafini & Rosenzweig, PRE 55, 7565 (1997)



Courtesy of I. Bazarov

- ϵ_{rf}, mainly projected emittance, is much reduced for smaller beam dimensions

$$\epsilon_{\mathrm{rf}} = \frac{eE_0}{2\sqrt{2}mc^2}\sigma_x^2\sigma_\phi^2, \quad \langle\phi\rangle = 90^\circ$$

K.-J. Kim, NIMA 275, 201 (1989)

- $\epsilon_{\mathrm{optics}}$ - chromatic and spherical aberrations
  - Chromatic: different $x - x'$ slope for different slice energy
  - Spherical: nonlinearity in slice $x - x'$ distribution – might be corrected

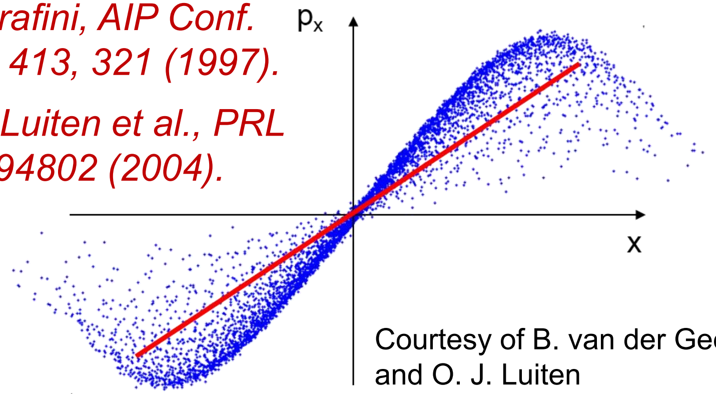
An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

Beam shaping – low charge but still high charge density

- Uniformly filled ellipsoidal is ideal – linear SC forces and phase-space

L. Serafini, AIP Conf. Proc. 413, 321 (1997).

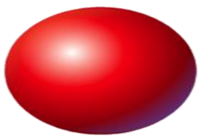
O. J. Luiten et al., PRL 93, 094802 (2004).



Courtesy of B. van der Geer and O. J. Luiten

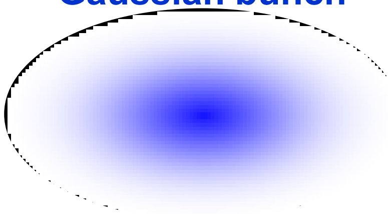
Thermal-emittance-limited beam!

Uniformly filled ellipsoidal bunch



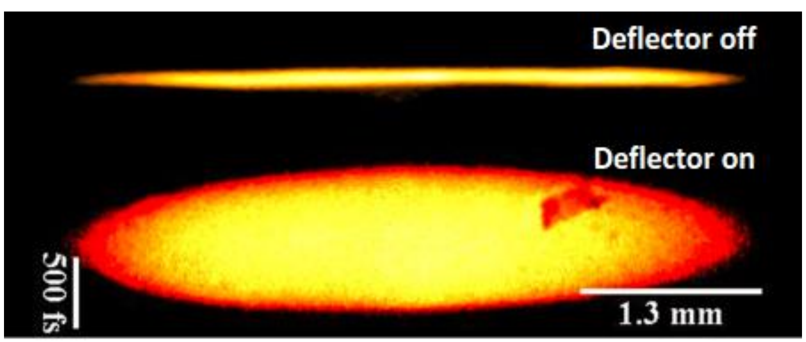
Space charge forces:
- Linear
- Slice-independent

Gaussian bunch



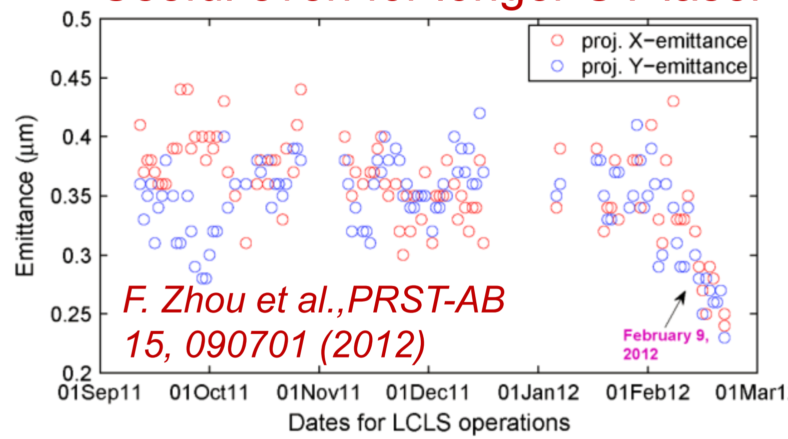
Space charge forces:
- Non-linear
- Slice-dependent

- Practical and robust in experiment – *transverse shaping of ultrashort laser*



P. Musumeci et al., PRL 100, 244801 (2008)

Useful even for longer UV laser

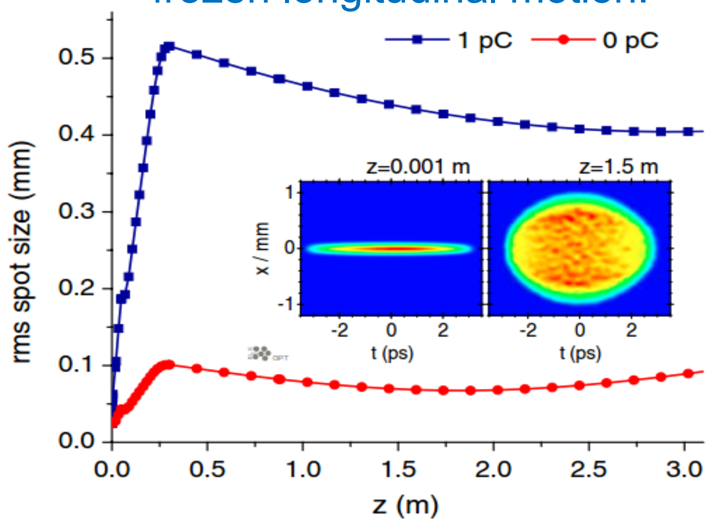


F. Zhou et al., PRST-AB 15, 090701 (2012)

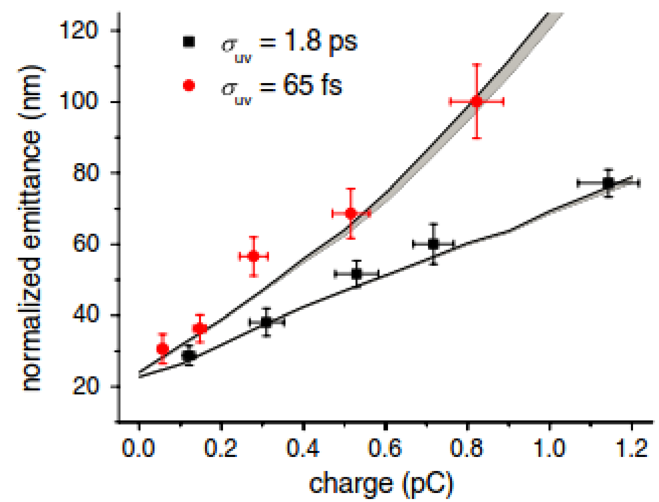
Cigar-shape beams

- Pancake regime: relatively large initial spot size and intrinsic emittance
- Cigar regime – an alternative way to generate 3D ellipsoid beam
  - Tiny laser spot (10s of um) on the cathode, hence very low $\epsilon_{\mathrm{intri}}$
  - Long (several ps), parabolic laser temporal profile
  - Transverse SC expansion creates ellipsoidal beam, again

Transverse SC expansion, & frozen longitudinal motion.



Ideal regime for ultralow charge, nm-emittance beams!



R. K. Li et al., PRST-AB 15, 090702 (2012)

Space charge limit in emission

SLAC

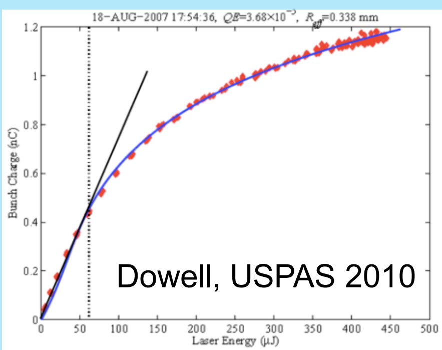
$R > \Delta z_e$ pancake regime

$R < \Delta z_e$ cigar regime

- pancake

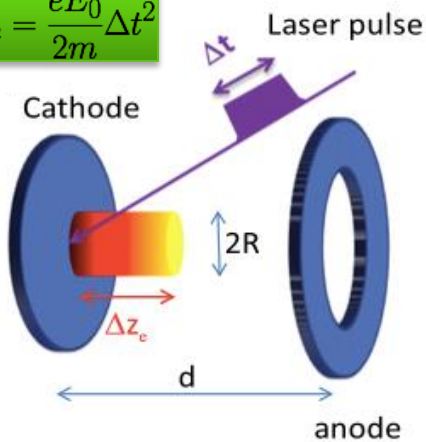
Maximum surface charge density set by the extraction field

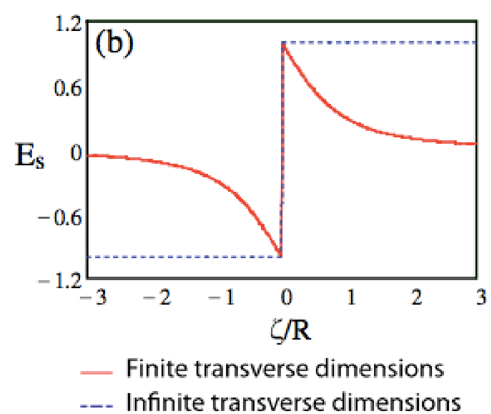
$$\frac{Q}{\pi R^2} < \epsilon_0 E_0$$



Courtesy of P. Musumeci

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

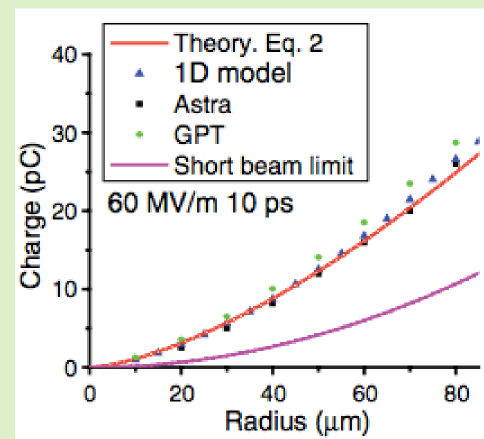




- cigar

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

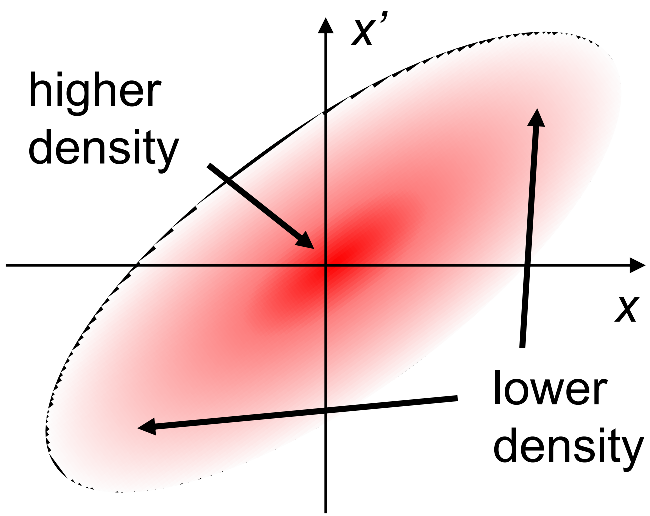
$$Q = J_{CL}\pi R^2 \propto \frac{V^{\frac{3}{2}}}{d^2}R^2 \propto (E_0 R)^{\frac{3}{2}}$$



D. Filippetto et al., PRST-AB 17, 024201 (2014)

Collimation can improve the brightness

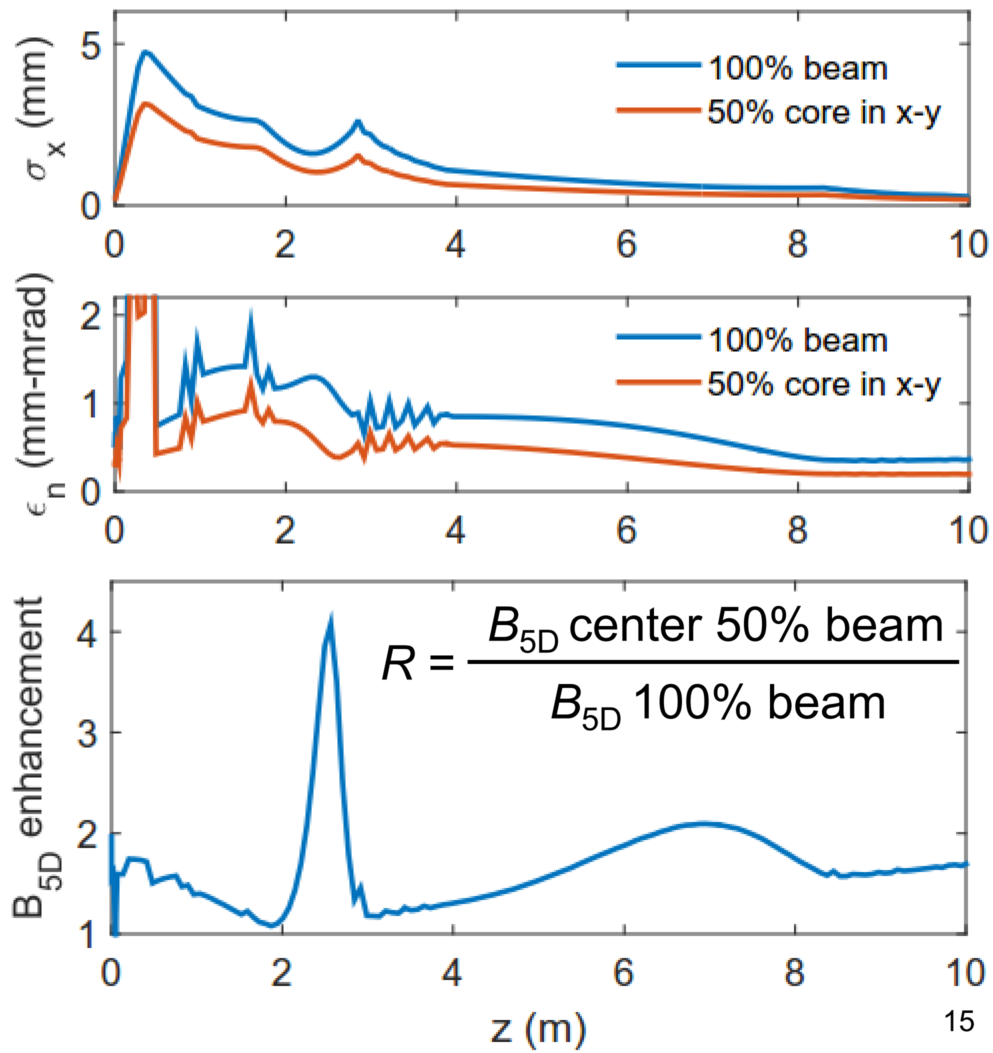
- Part of the beam (always) has higher phase-space density



- outside electrons help maintain the high density in the core

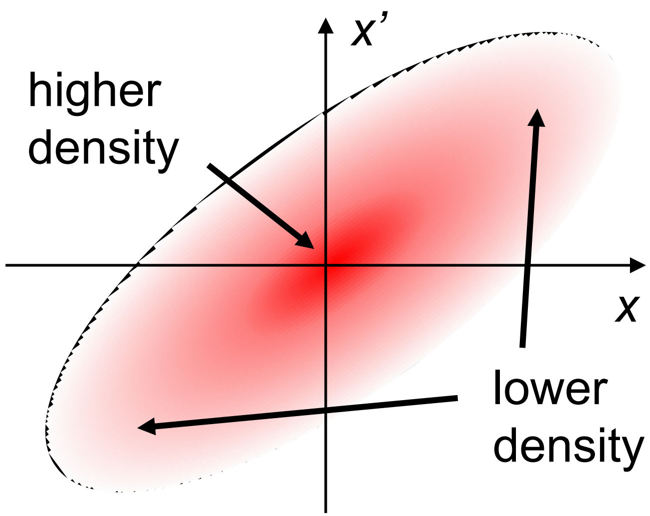
'Good' and 'bad' electrons? The bad ones make the others better.

a circular collimator pick the center 50% beam



Collimation can improve the brightness

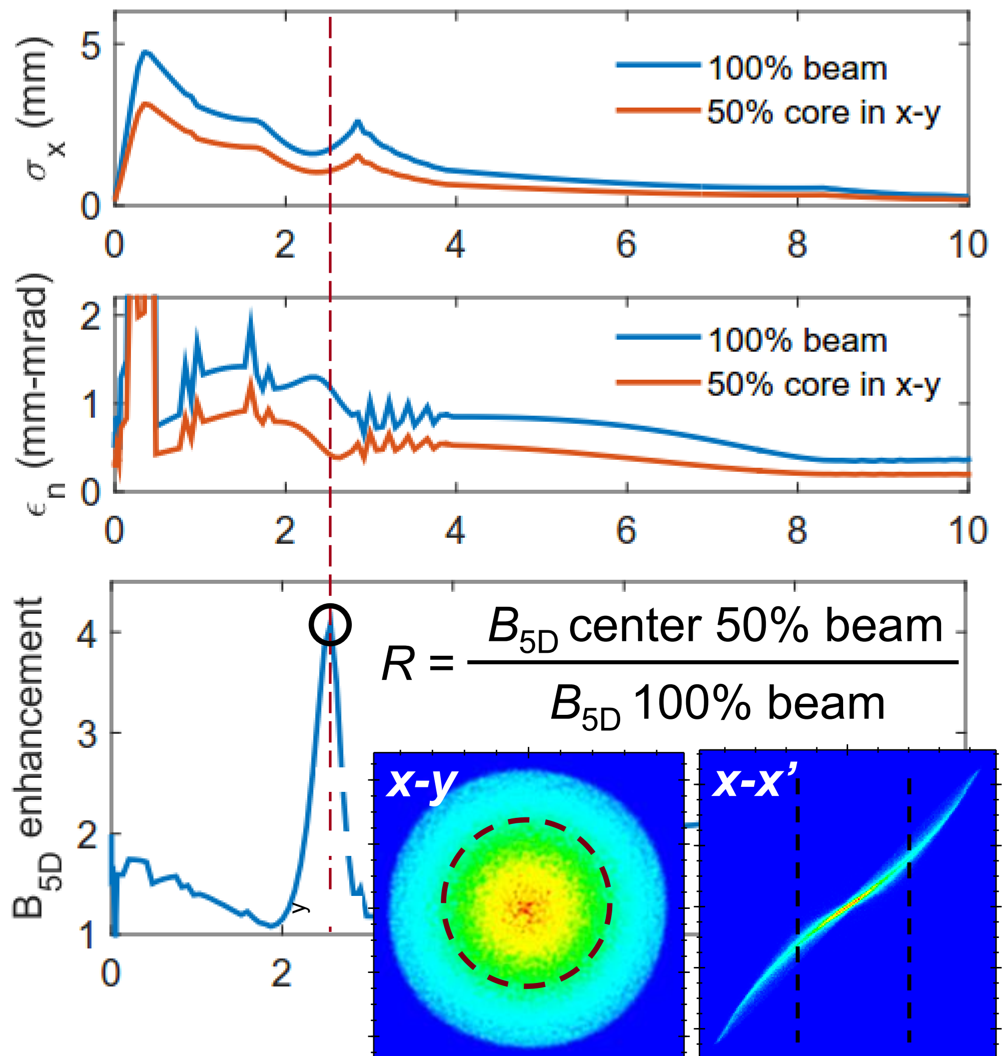
- Part of the beam (always) has higher phase-space density



- outside electrons help maintain the high density in the core

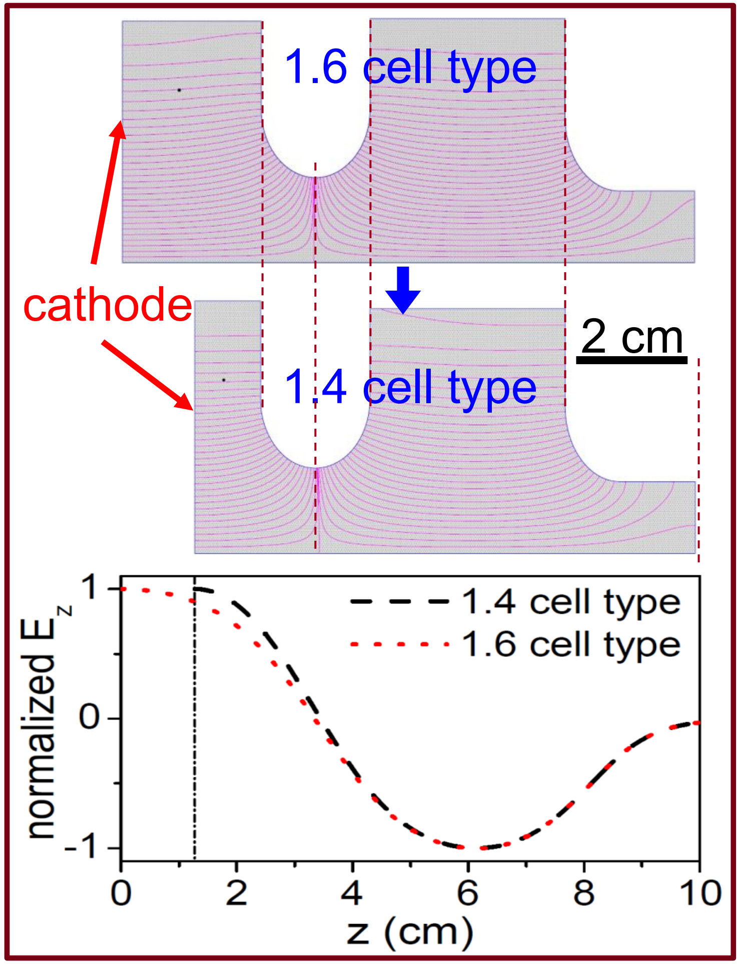
'Good' and 'bad' electrons? The bad ones make the others better.

a circular collimator pick the center 50% beam



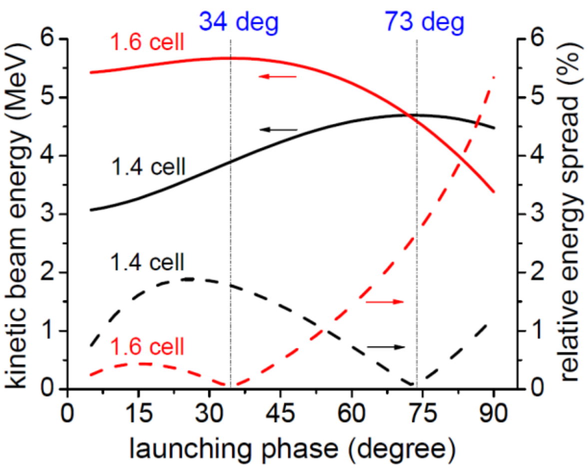
Higher extraction field - new gun geometry

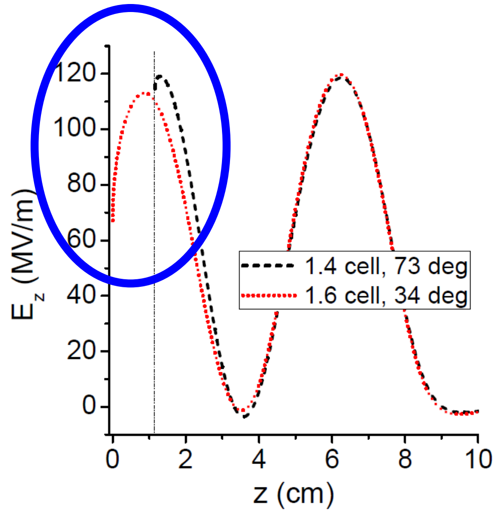
- Brightness depends on E_0: $B_{5D} \propto E_0$ (pancake) and $B_{5D} \propto E_0^{3/2}$ (cigar)
- Higher E_0 allows more emission, also suppresses SC induced emittance growth



- 1.6 cell to 1.4 cell shifts the launching phase from 30° to 70°. Note sin(70°)=0.94.
- E_0 roughly x2 times higher

R. K. Li and P. Musumeci, PRApplied 2, 024003 (2014)





Intrinsic emittance

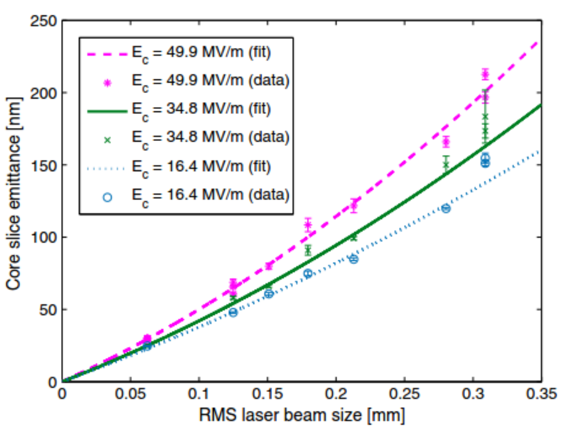
Thermal emittance	$\epsilon_n = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{\text{eff}}}{3mc^2}}$
Quantum efficiency	$\text{QE}(\omega) \propto (\hbar\omega - \phi_{\text{eff}})^2$

Minimzing $\hbar\omega - \phi_{\text{eff}}$ can reduce ϵ_n, but at the cost of QE

Dowell and Schmerge, PRST-AB 12, 074201 (2009)

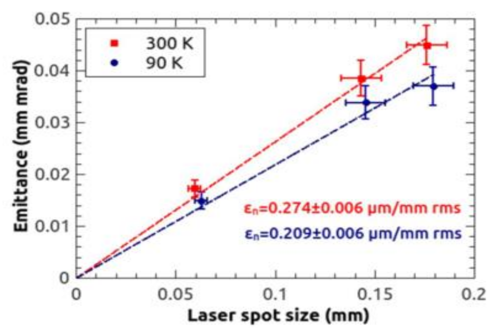
Cu: 0.35 mm-mrad/mm w/ mid-10^{-5} QE @ PSI

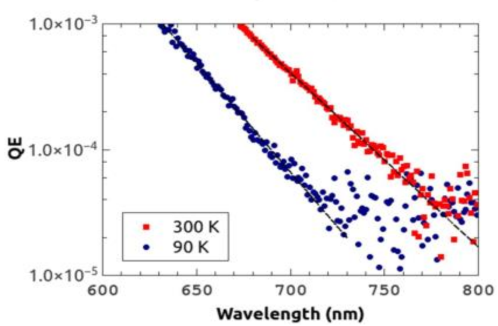
Cathode field MV/m	Quadratic component nm/mm²	$\varepsilon_{\text{int}}/\sigma_l$ nm/mm
49.9	724 ± 84	428 ± 16
34.8	505 ± 137	370 ± 25
16.4	321 ± 105	346 ± 25



Prat, PRST-AB 18, 063401 (2015)

Cs_3Sb: 0.21 mm-mrad/mm w/ 7×10^{-5} QE @ Cornell





Cultrera, arXiv:1504.05920

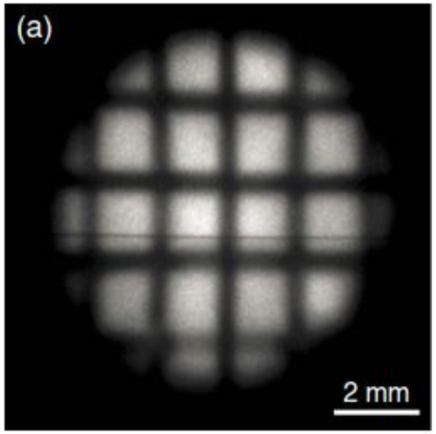
- Effects of surface roughness
- Tuning extraction field and photon energy independently
- Limitation due to laser damage of the cathode and demand on laser power
- Explore more exotic emission mechanism
- Don't forget the temporal response of the photo-emission

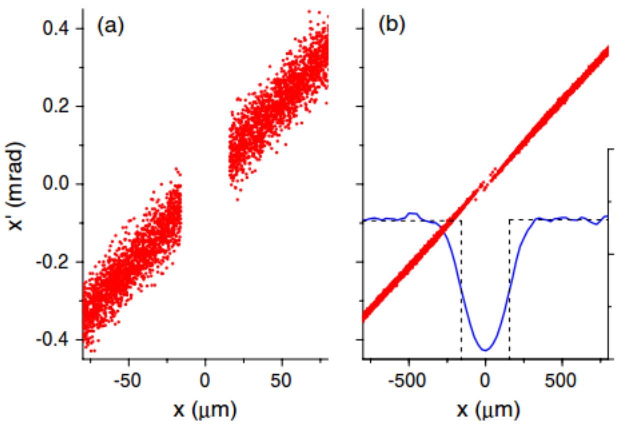
Measure nanometer emittance

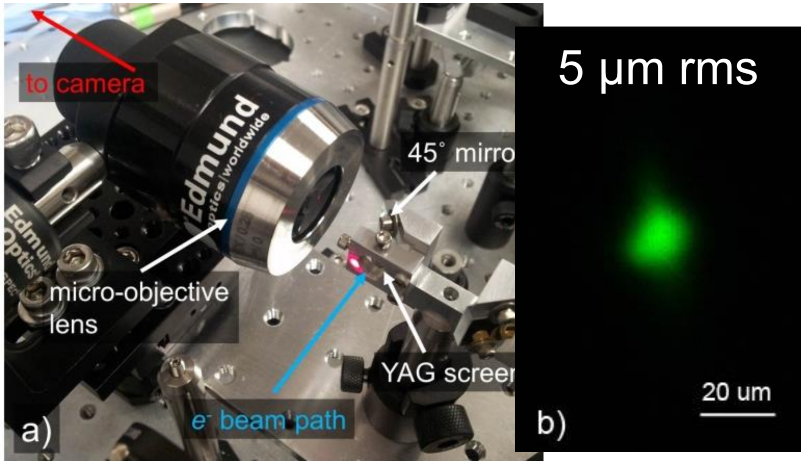
Knife-edge, single-shot emittance measurement

R. K. Li et al., PRST-AB 15, 090702 (2012)

Relies on high spatial-resolution measurement of low charge beams



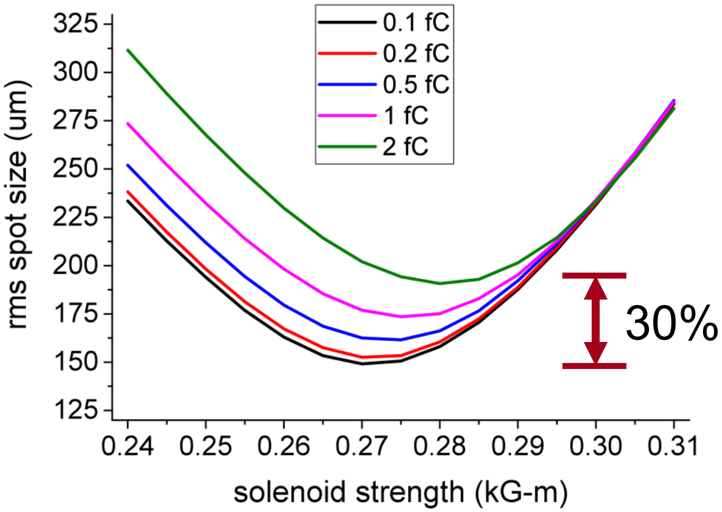




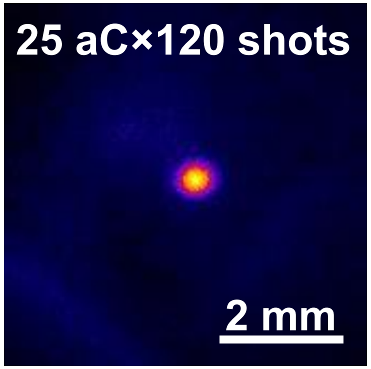
- Low charge ≠ low charge density
- SC effects should be carefully evaluated

$$R_0 = \frac{I\sigma_0^2}{2I_0\gamma\epsilon_n^2}$$

S. G. Anderson et al., PRST-AB 5, 014201 (2002)



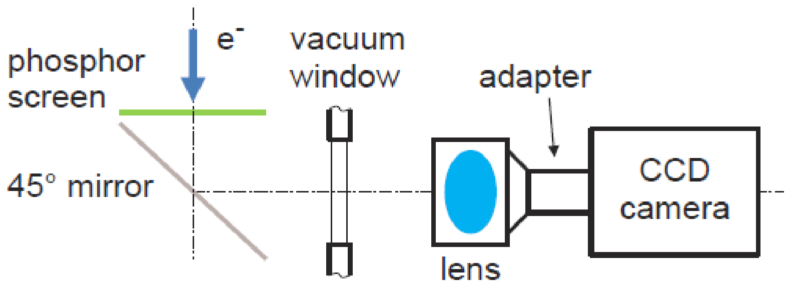
Solenoid scan using very low charge

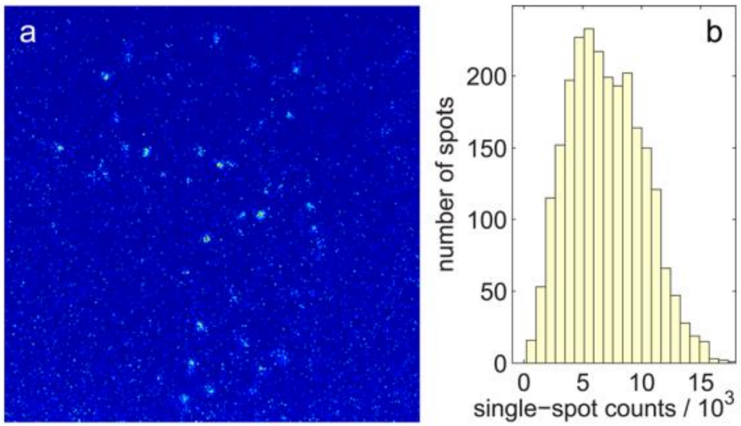


Imaging single electrons

SLAC

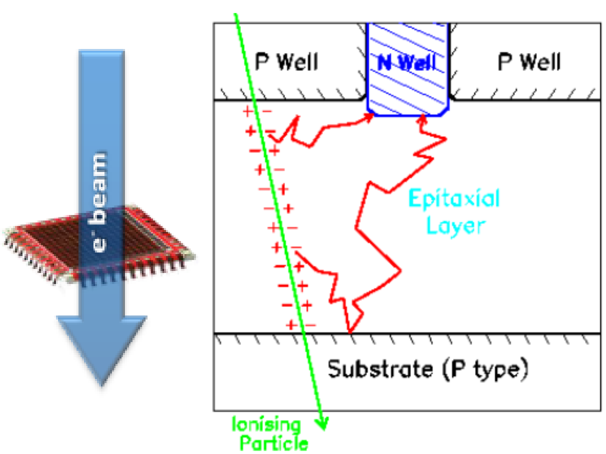
Optimized phosphor screen + high collection optics + Electron Multiplying CCD (EMCCD).
Achieved Single electron detection capability !





R. K. Li et al., J. Appl. Phys. 110, 074512 (2011)

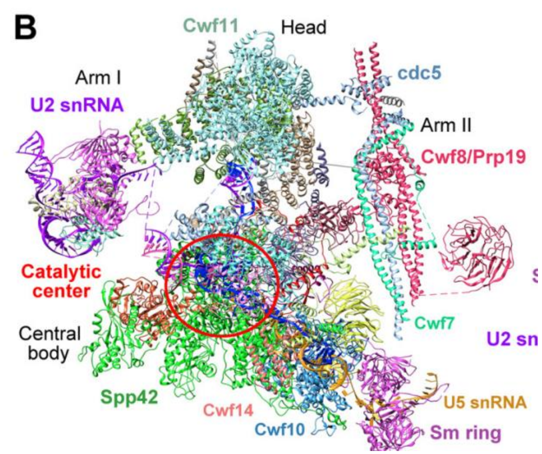
CMOS direct detection detector



- Single e- sensitivity
- Excellent PSF (<10 um)
- Fast readout (>400 fps)
- Radiation hard (yrs lifetime) at 300 keV
- Commercialized for electron microscope

Courtesy of D. Contarato & P. Denes

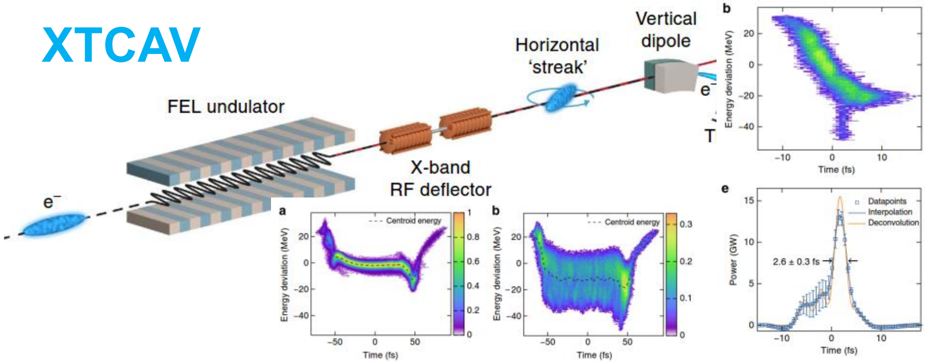
Revolutionary impact on cryo-EM



Y. G. Shi et al., 10.1126/science.aac7629

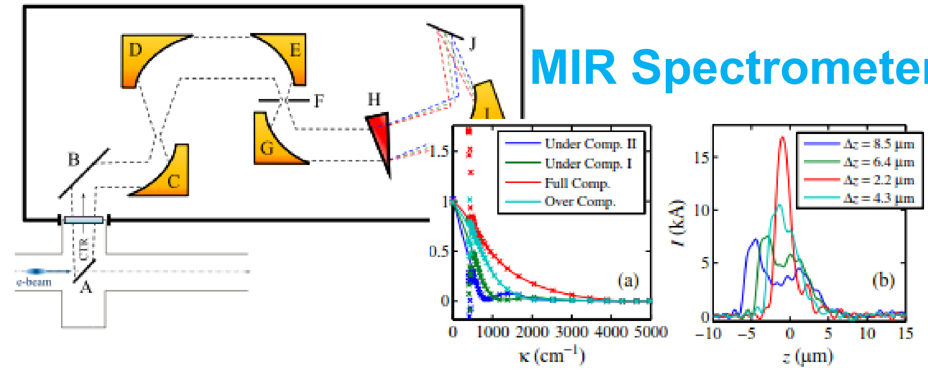
Femtosecond bunch length measurement

XTCAV



C. Behrens et al., Nature Commun. 5, 3762 (2014)

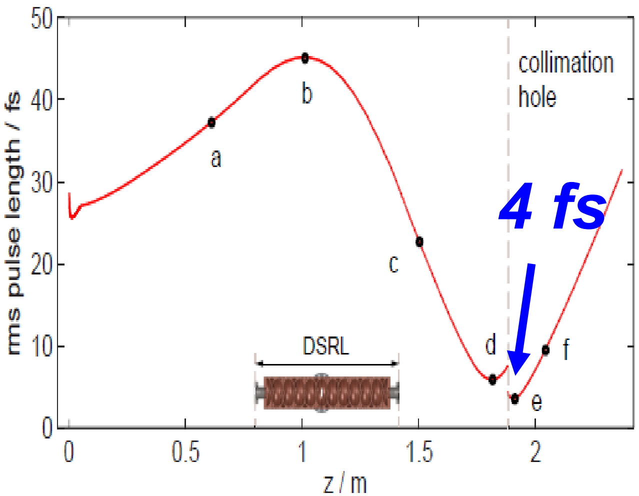
MIR Spectrometer



T. J. Maxwell et al., PRL **111**, 184801 (2013).

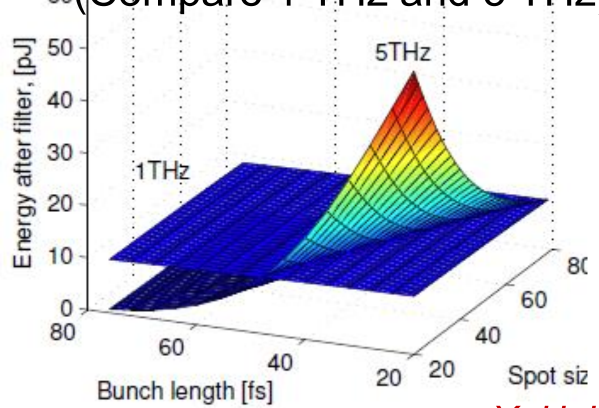
How to measure only 5 MeV, <10 fs beams?

- 10 fs UED, external injection
- Beam is only short within a few cm



R. K. Li et al., JAP 110, 074512 (2011)

Study the spectrum of CTR
(Compare 1 THz and 5 THz)

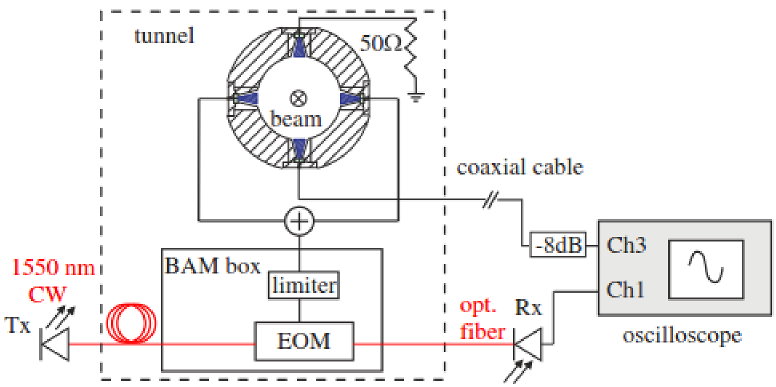


- Use Bolometer
- Strong dependence on transverse spot size
- Can be limited by rf phase and amplitude jitter

X. H. Lu et al., PRST-AB 8, 032802 (2015)

Time-of-Arrival monitor

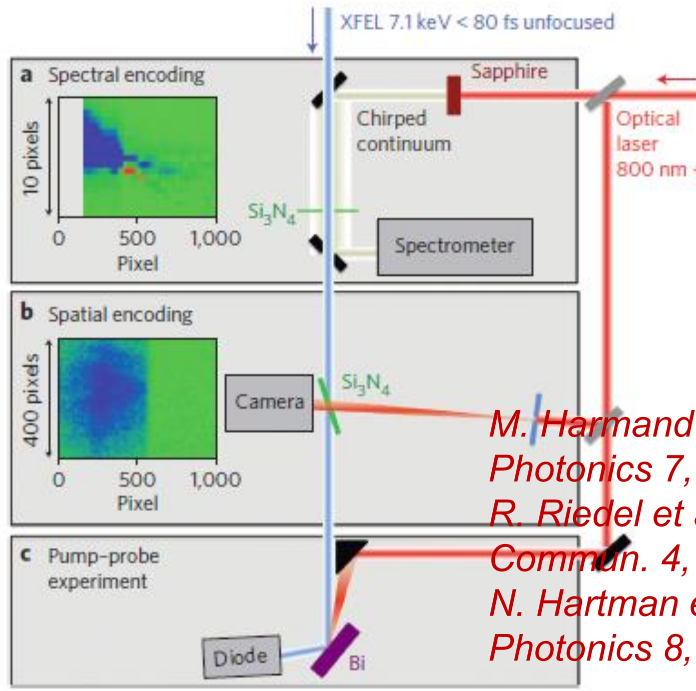
Bunch arrival-time monitor (BAM)



A. Angelovski et al., PRST-AB18, 012801 (2015)

- sub-10 fs for 20 pC beams (FLASH, ELBE, and SwissFEL), similar BAM at LCLS
- Cone-shape can be optimized for lower beam charge (REGAE)
- But, there is extra jitter due to the regen and user laser

Optical cross-correlation



M. Harmand et al., Nat. Photonics 7, 215 (2013). R. Riedel et al., Nat. Commun. 4, 1731 (2013). N. Hartman et al., Nat. Photonics 8, 706 (2014).

- Direct measurement between pump (optical laser) and probe (x-ray).
- Same principle could work for e-beams. (Cesar & Musumeci et al.)

Using ultralow charge beams for FELs

SLAC

FELs enabled by a few pC, <30 nm-rad, kA electron beams

- Single-spike SASE $\sigma_z \sim 2L_c$: sub-fs pulses
- Compact FELs

1 pC-case studies

Contents lists available at Scien

Nuclear Instruments and
Physics Research

journal homepage: www.elsevier.co

ELSEVIER

Generation of ultra-short, high brightness elect
SASE FEL operation

J.B. Rosenzweig [a,*], D. Alesini [c], G. Andonian [a], M. Boscolo [c], M. Dunning [a], L. Faillace [b,c], M. Ferrario [c], A. Fukusawa [a], L. Giannessi [e], E. Hemsing [a], G. Marcus [a], A. Marinelli [b,c], P. Musumeci [a], B. O'Shea [a], L. Palumbo [b,c], C. Pellegrini [a], V. Petrillo [d], S. Reiche [a], C. Ronsivalle [e], B. Spataro [c], C. Vaccarezza [c]

[a] UCLA Department of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095, USA
[b] Universita degli Studi di Roma La Sapienza, Via Antonia Scarpa 14, Rome 00161, Italy
[c] INFN-LNF, via E. Fermi, 40- 00044 Frascati, Rome, Italy
[d] INFN-Milano, Via Celoria 16, 20133 Milan, Italy
[e] ENEA, via E. Fermi, 00044 Frascati, Rome, Italy

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Development of ultra-short pulse, single coherent spike for SASE X-ray FELs

S. Reiche *, P. Musumeci, C. Pellegrini, J.B. Rosenzweig

UCLA, Department of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095, USA

Y. Ding's talk, TUA01, Generating Femtosecond to Sub-Femtosecond X-Ray Pulses at Free Electron Lasers

- more challenging diagnostics and beam control (especially at existing facilities)
- Consider collective effects: wakefields, LSC, CSR ($\delta_{CSR} \propto I\sigma_z^{-1/3}$)

Acknowledgement

- Many of the works done at UCLA with P. Musumeci
- Colleagues at SLAC, UCLA, and Tsinghua University
- Y. Ding, V. Dolgashev, P. Emma, D. Filippetto, J. Frisch, Z. Huang, T. Maxwell, T. Raubenheimer, J. Rosenzweig, J. Schmerge, C. X. Tang, T. Vecchione, L. Wang, X. J. Wang, and F. Zhou for helpful discussions
- Work supported by U.S. Department of Energy

Summary and outlook

- We can produce ultrahigh brightness with ultralow beam charge
- Charge density still high – require beam shaping and collimation
- Control the photoemission process – emittance and current density
- New techniques/detectors to measure these beams – both in x-y and in time
- Energy spread not discussed here but critical for micro-bunching and harmonic-generation for FELs, and chromatic effects in UEMs
- Merging FEL and TEM beams – ultrafast, ultra-narrow and ultra-stable
- *High brightness, high precision frontier of photoinjectors*
- Understand and control each *e*- nicely, and use it for good science.

Thank you for your attention!