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Paper No: MO2A04

Low Emittance and High Current Electron Linac Development at Tsinghua University

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Outline

- High Brightness Electron Beam
- Photocathode RF Gun Development at THU
- Tsinghua Thomson Scattering X-ray Source (TTX)
- Coherent THz Radiation of an electron bunch train generated by NSCO
- Summary

Brightness of an electron beam

The brightness distribution B is the density in 6-D phase space

$$(x, p_x, y, p_y, t, E)$$

where *t* is the arrival time, *E* is the kinetic energy canonical to *t*. When the system has a Hamiltonian, B is invariant along each particle trajectory in an accelerator.[*]

If the electron beam is axis symmetry, its brightness can be written as:

$$B_n = \frac{2I}{\varepsilon_n^{\ 2}}$$

Peak current

Normal Emittance

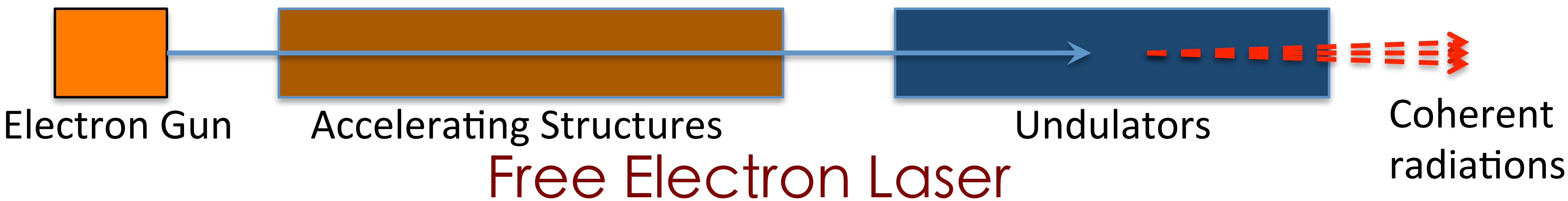
High Current

Low Emittance

High Brightness

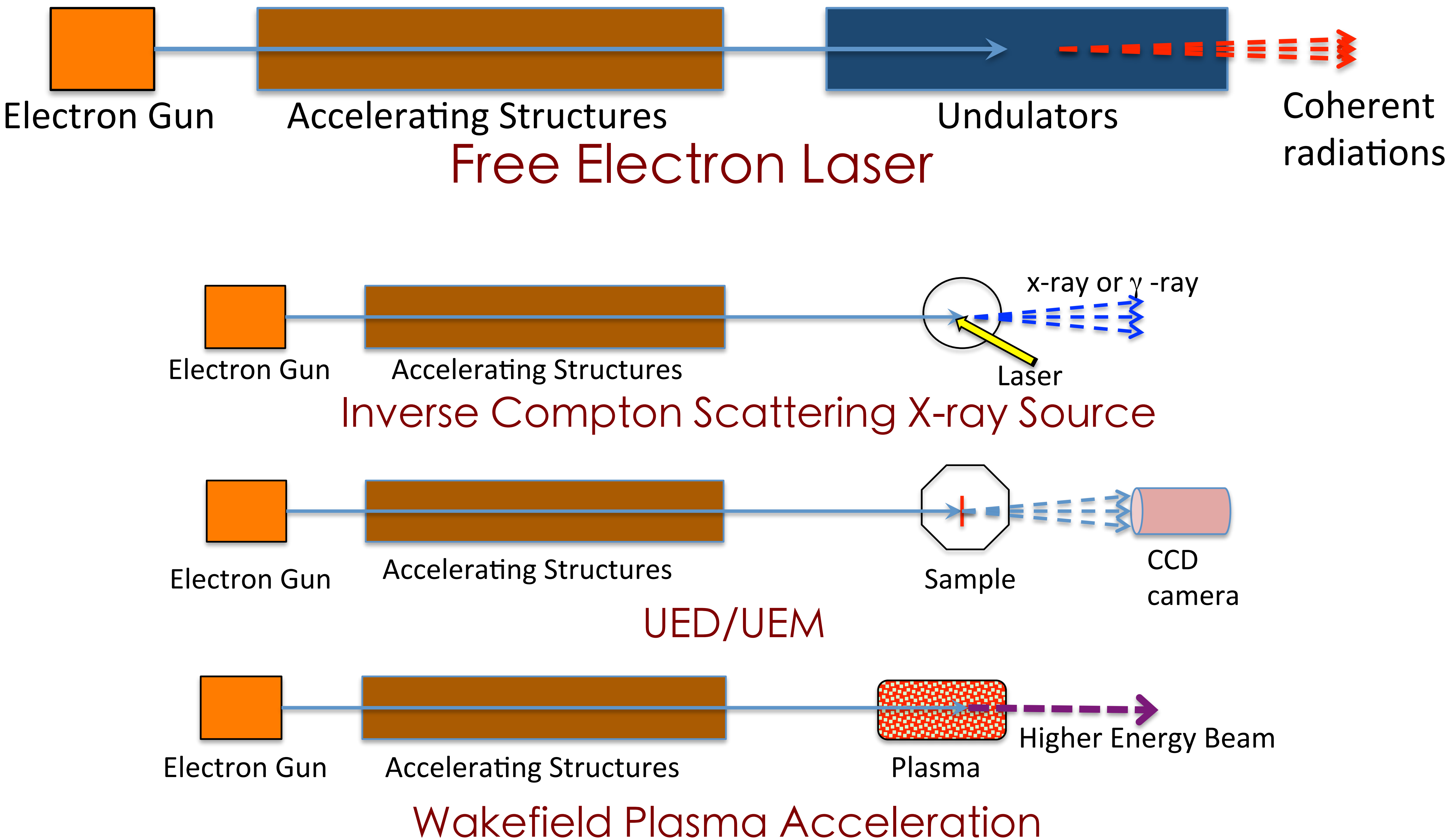
* Handbook of Accelerator Physics and Engineering, 2nd Edition. P318. “Brightness” , P. Elleaume, KJ Kim.

High brightness electron beam

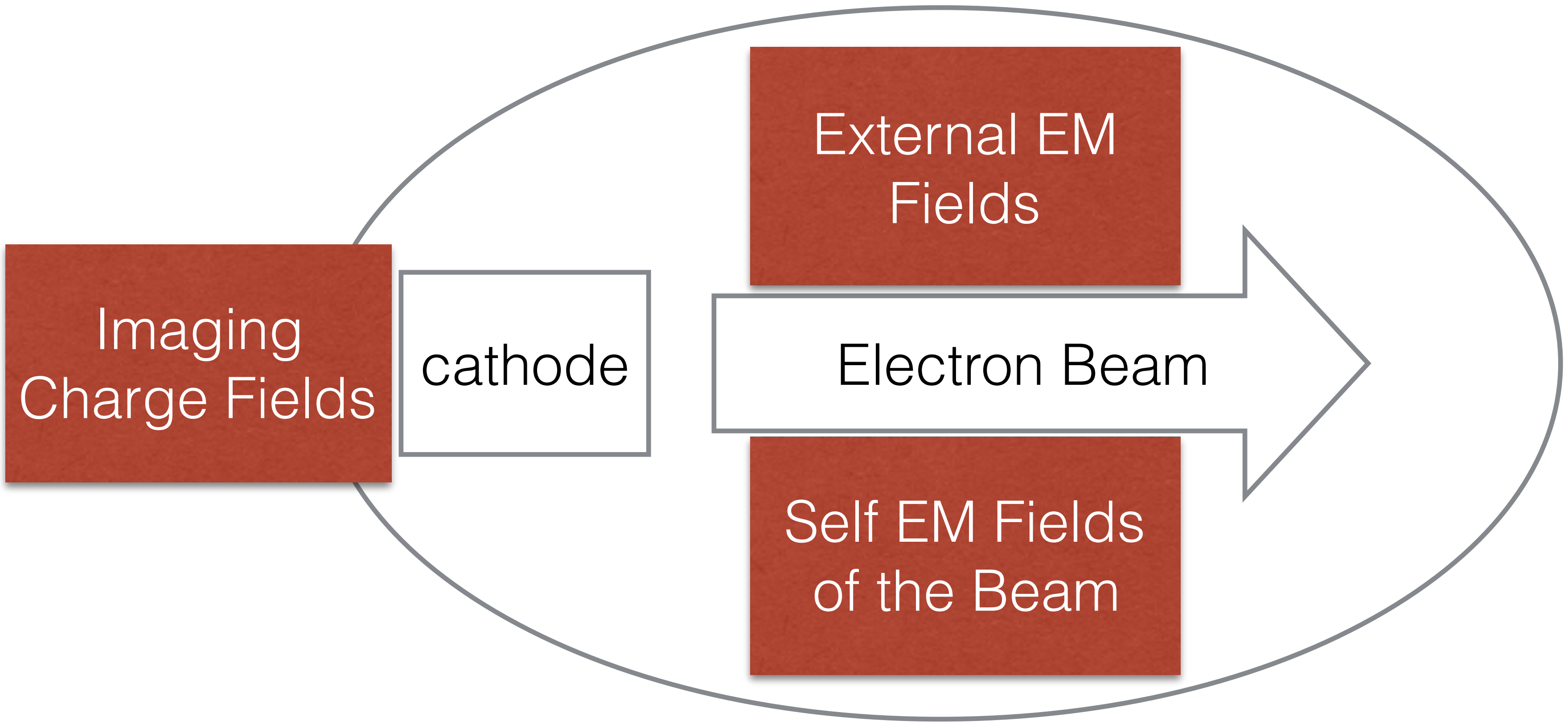


Free Electron Laser

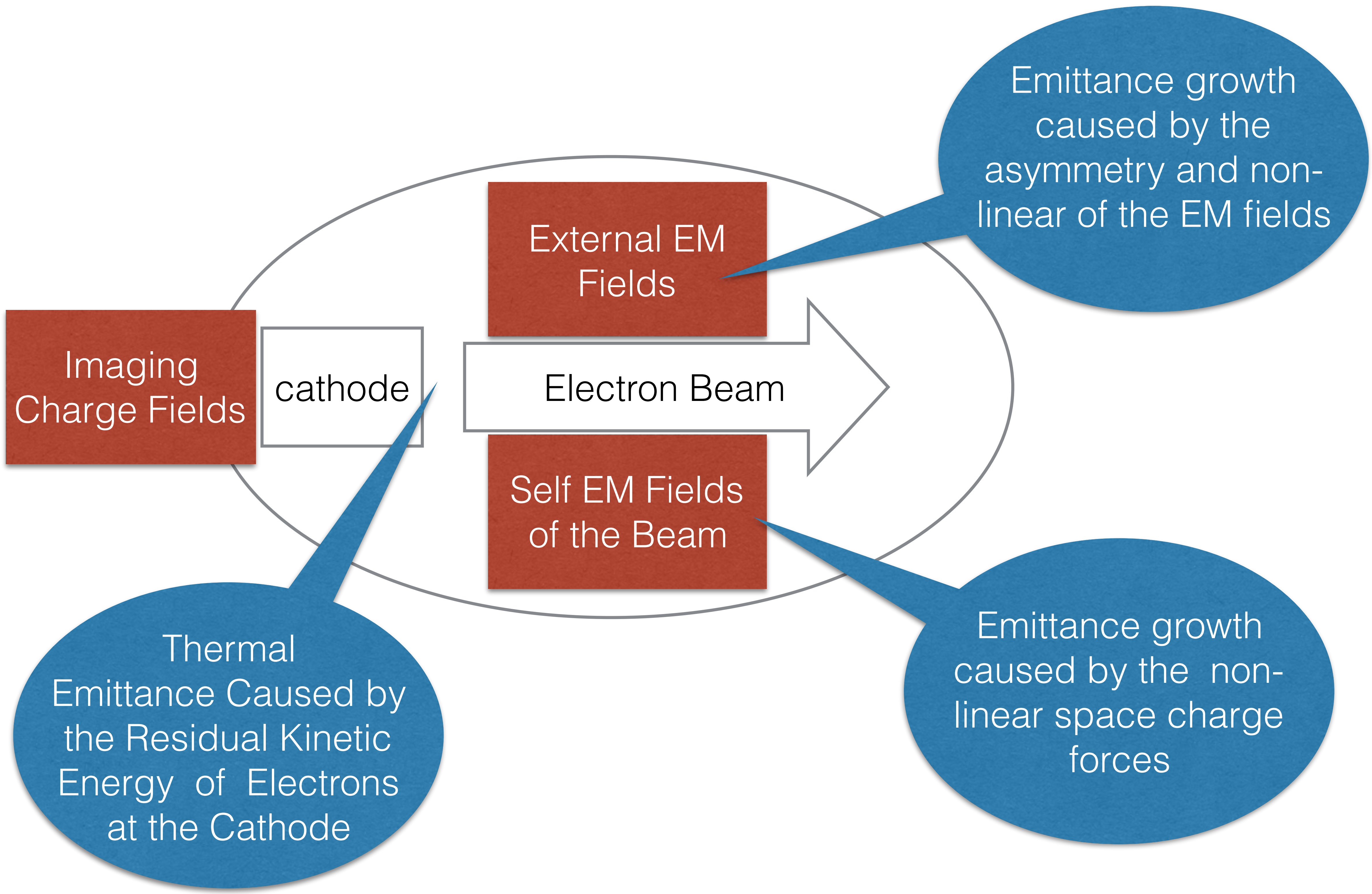
High brightness electron beam



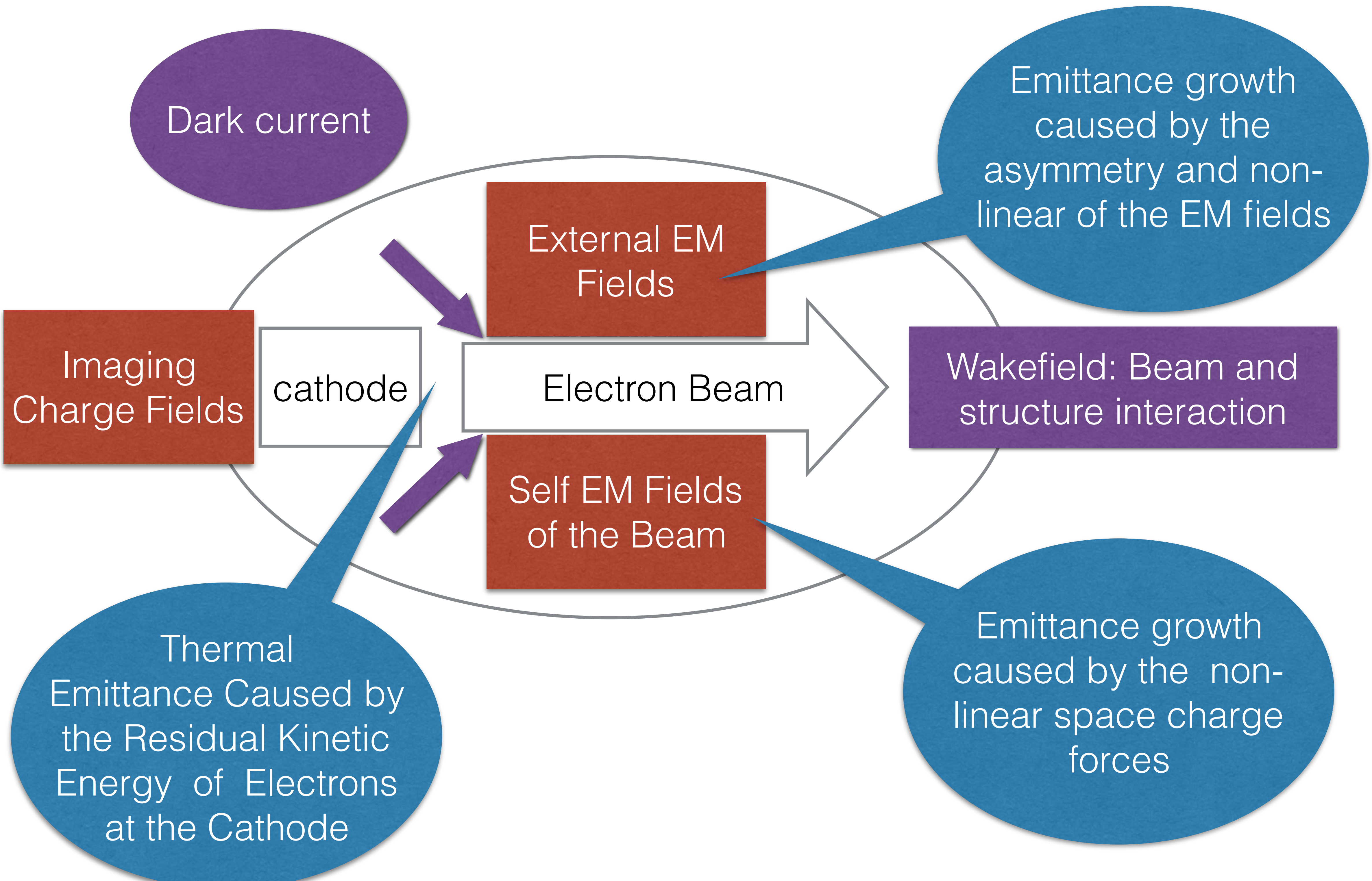
Electron gun is the most important part of a linac for high brightness electron beams



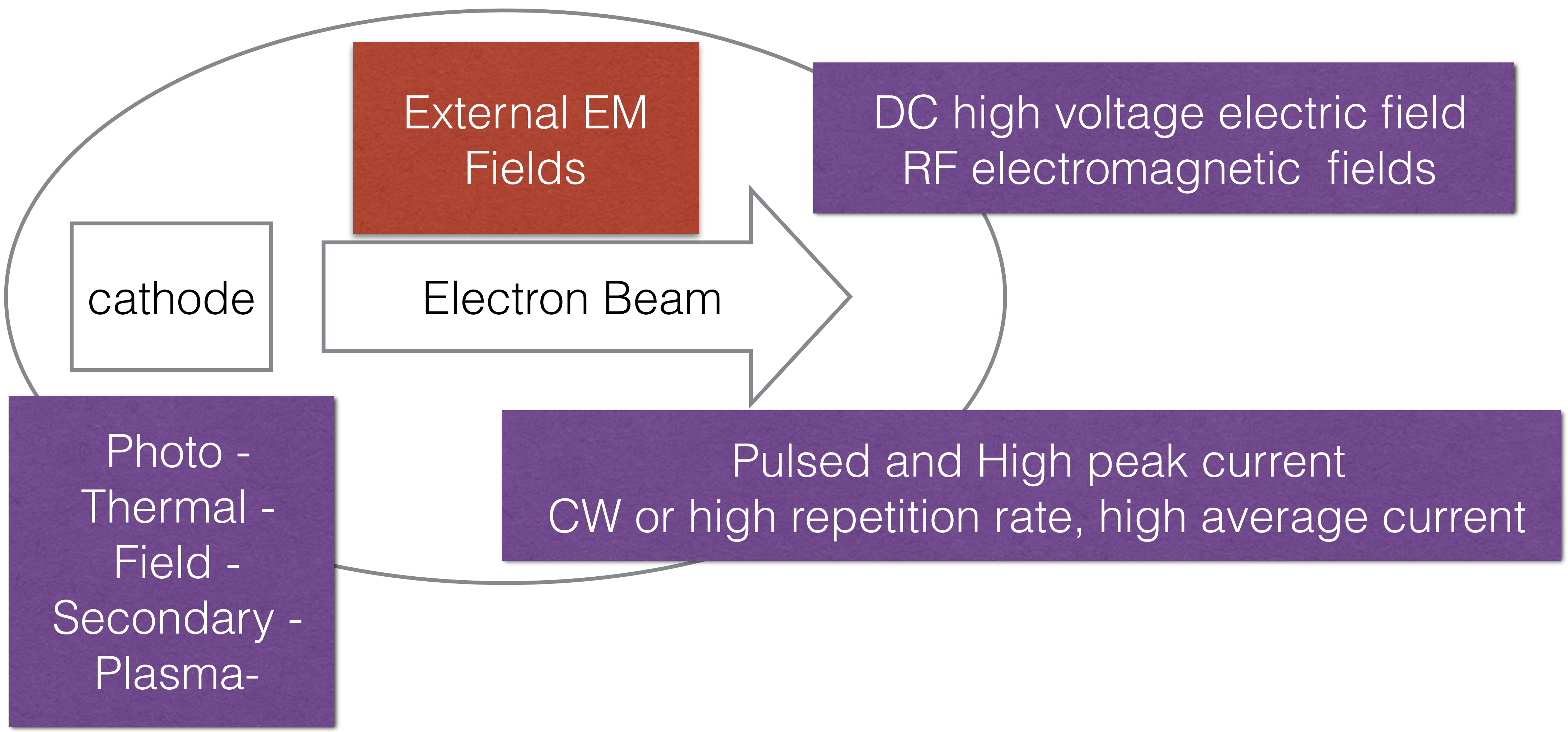
Emittance growth inside an electron gun



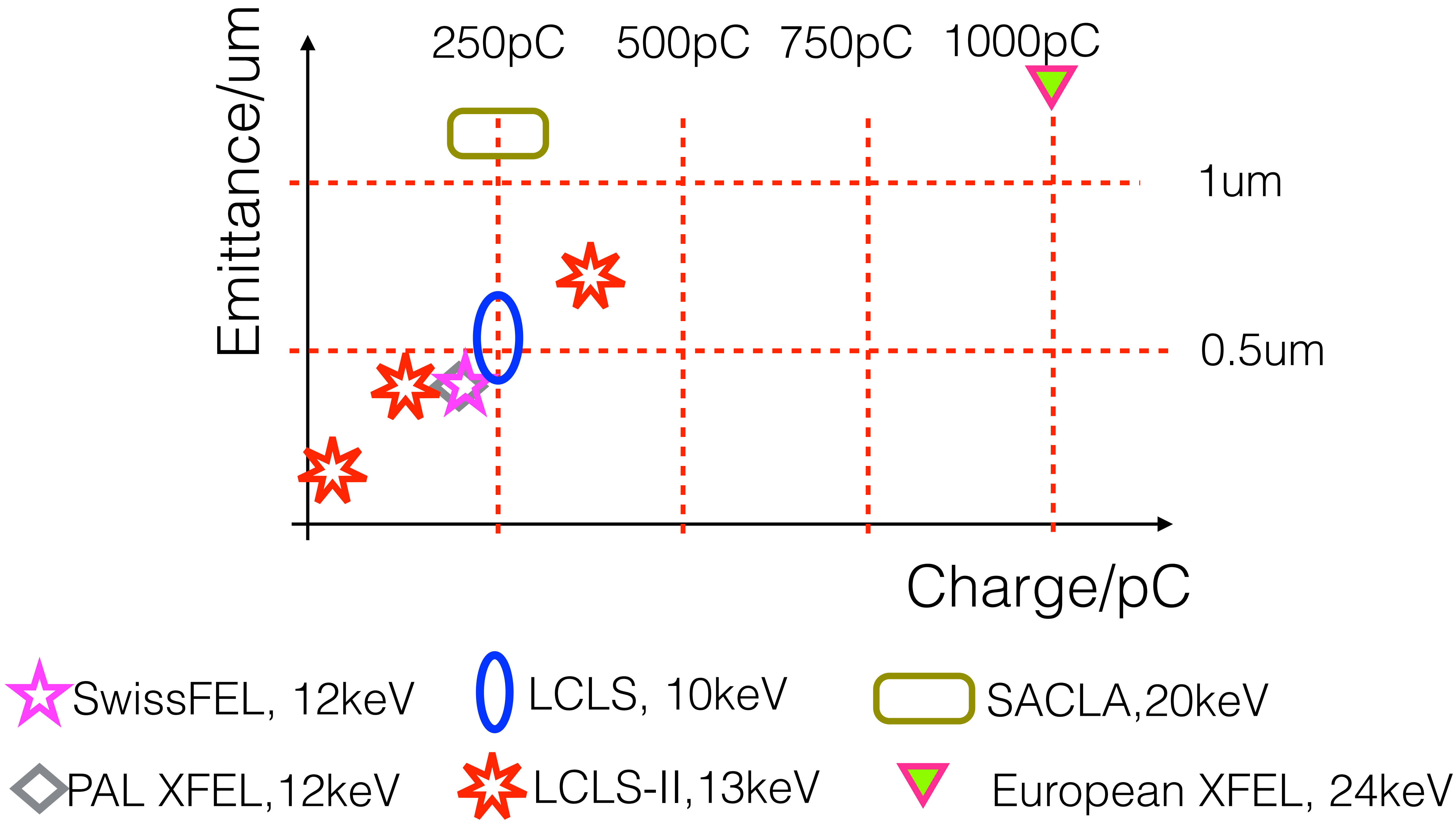
Other effects need to be considered inside an electron gun



Kinds of electron guns

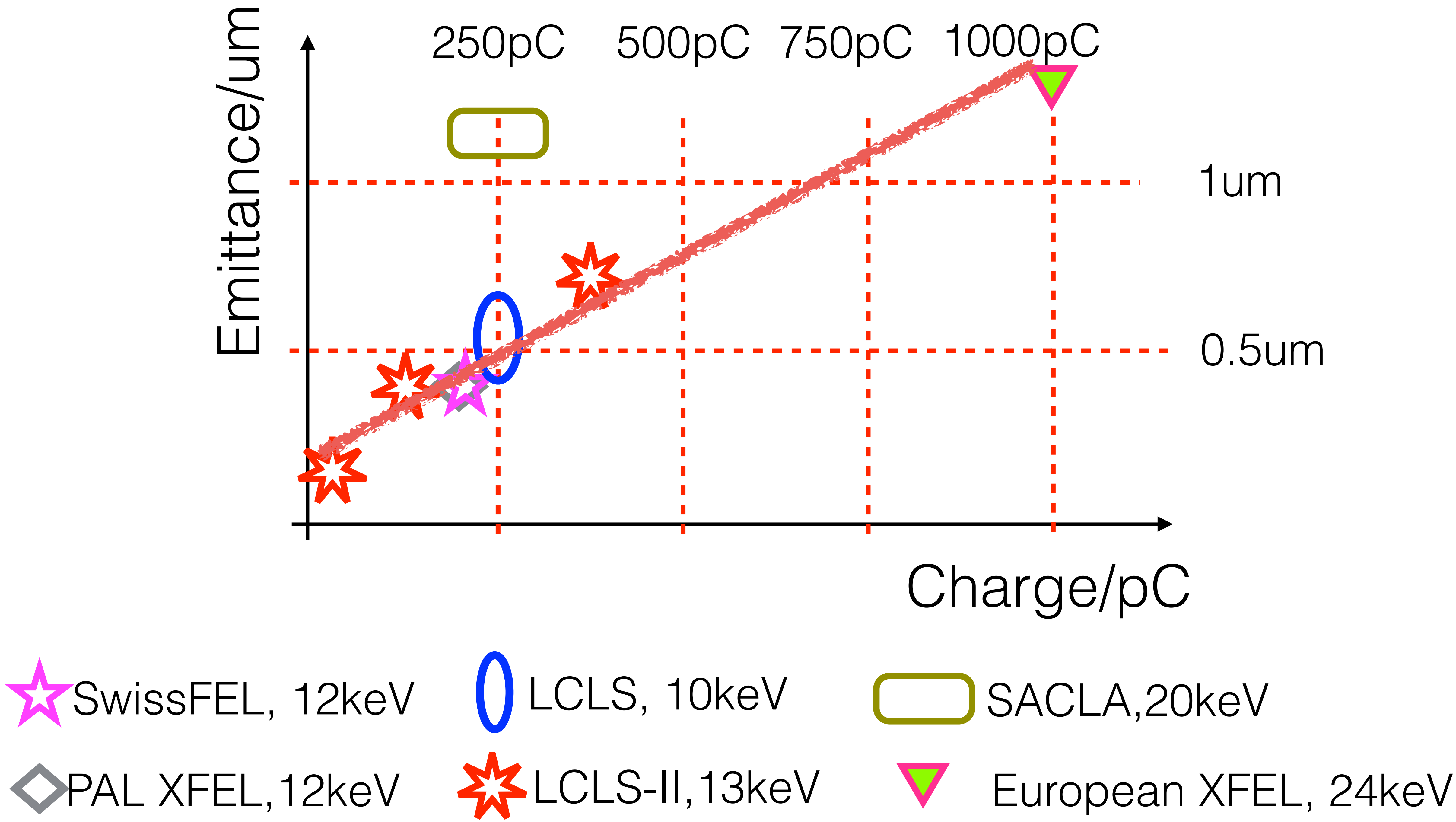


The XFELs and Their Electron Guns



David H. Dowell, ICFA Beam Dynamics Workshop on Future Light Sources, March 1-5, 2010
R. Akre et al., PRST-AB (2007)
Y. Ding et al., PRL 102, 254801(2009
FEL2014-THP011, IPAC2014-THPRO034, Nature Photonics 2012141.
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 020703 (2007)

The XFELs and Their Electron Guns



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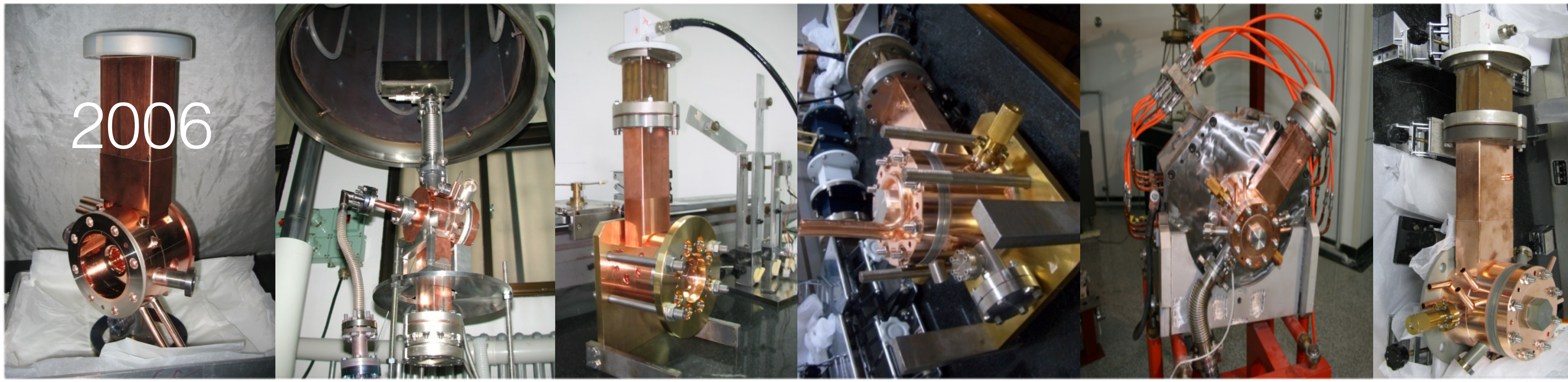
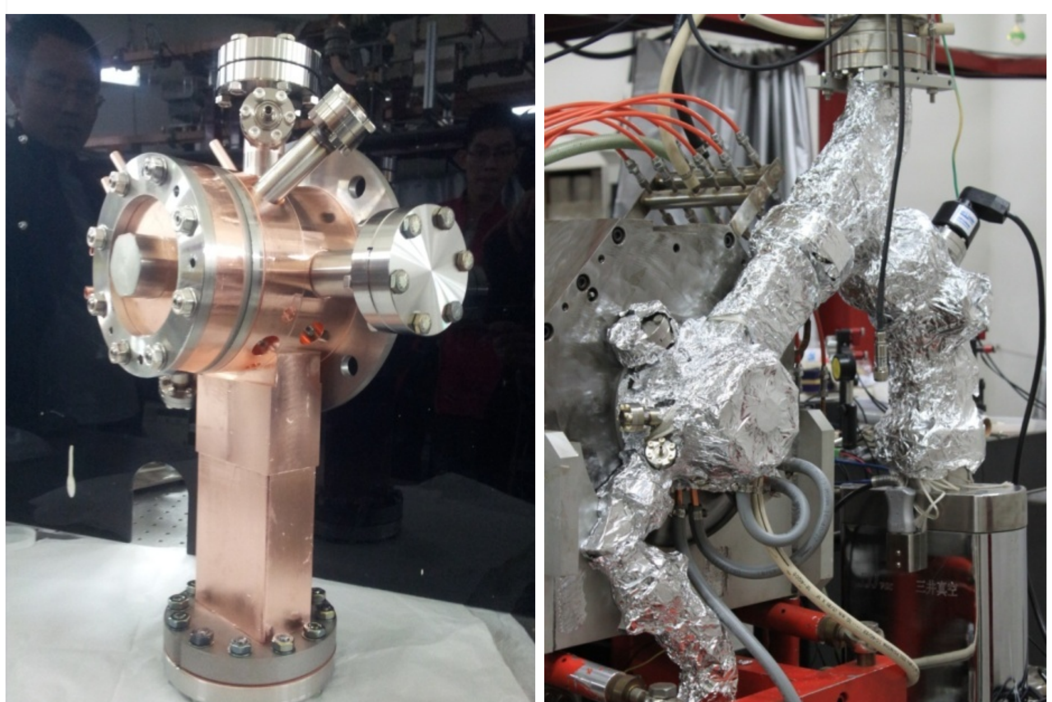
FEL2014-THP011, IPAC2014-THPRO034, Nature Photonics 2012141.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 020703 (2007)

Photocathode RF Gun Development at THU

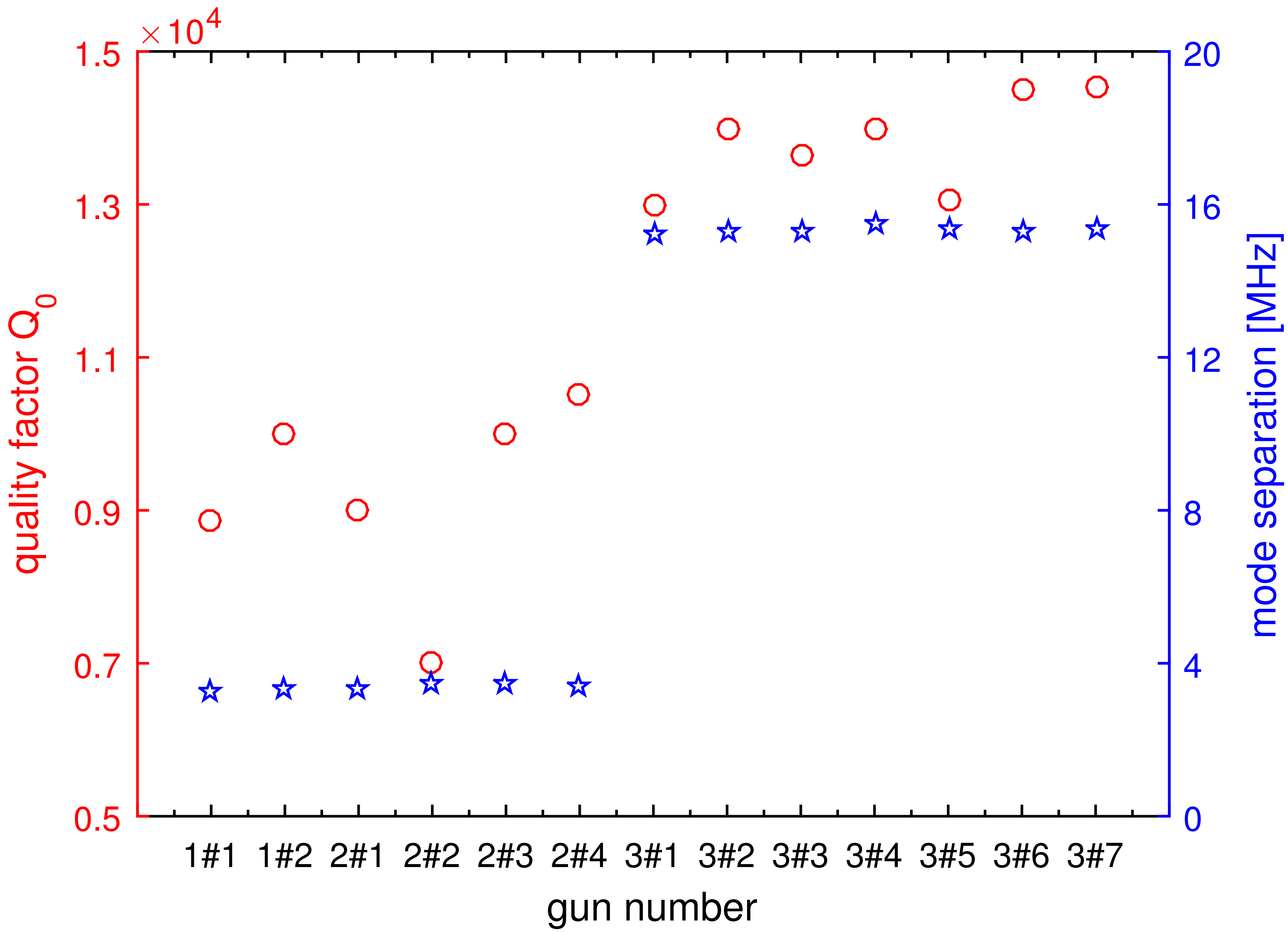


2011



Parameters	*Value*	*Unit*
PI mode frequency	2856	MHz
Quality factor Q_0	14000	
Coupling factor β	1.3	
Electric field on cathode	120	MV/m
RF pulse width	1.7	µs
Repetition rate	10	Hz
Peak power of wall heat loss	9.4	MW
Input RF peak power	11.3	MW
Cathode material	Copper	
QE	4×10^{-5}	
dark current at 120 MV/m	< 250	pC/pulse

The unloaded quality factors and 0-pi mode separations of the three generations of the photocathode rf gun developed by THU



1st generation:
- silver copper brazing

2nd Generation:
- gold copper brazing
- Optimized vacuum pump hole

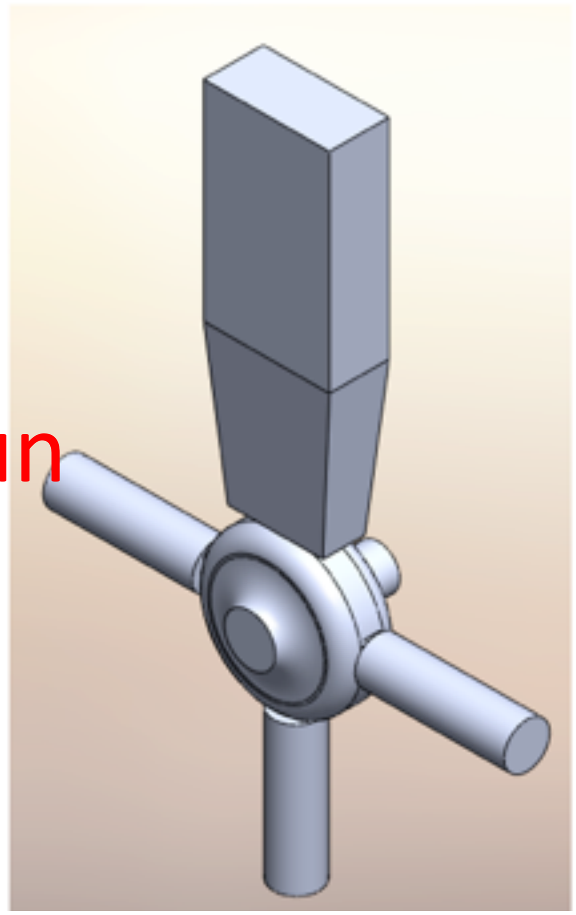
3rd Generation:
- gold copper brazing.
- optimized vacuum pump hole.
- added another two holes to eliminate quadruple.
- thin and ellipse iris.
- no Helico flex.
- dry ice cleaned cathode
- round corner.

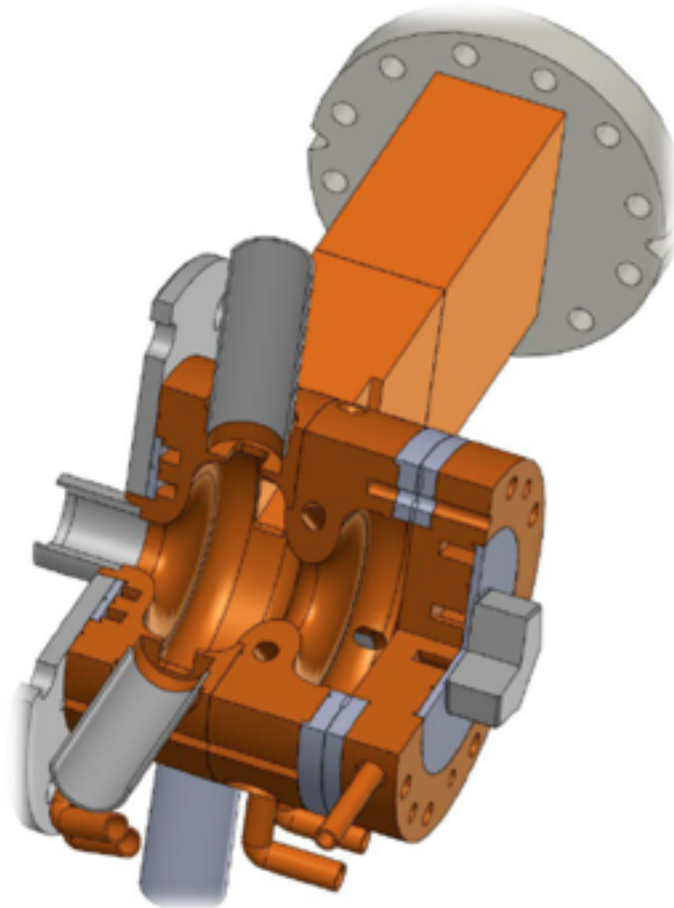
…

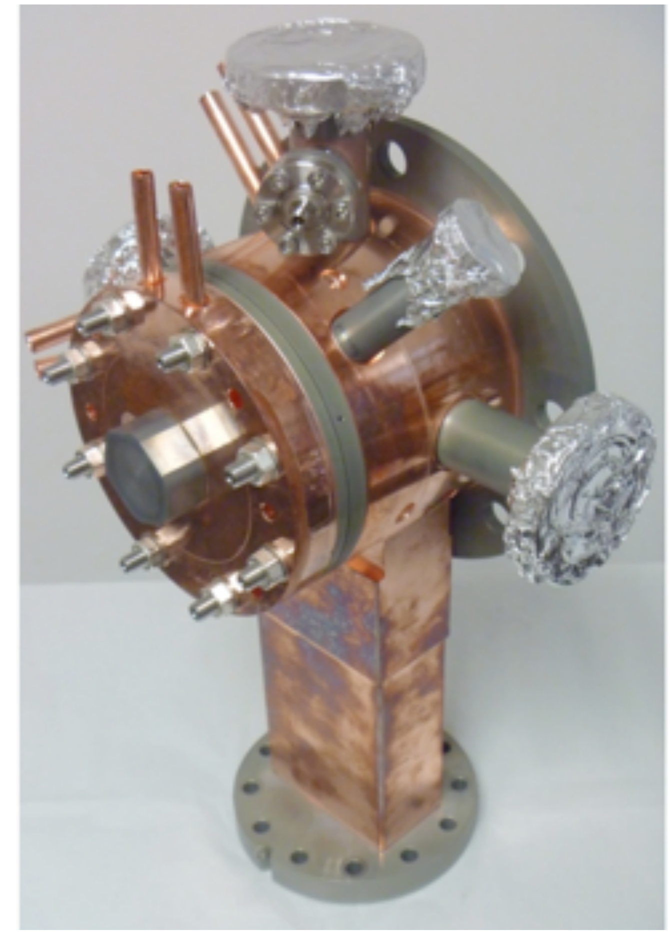
L. M. Zheng *et al*., Nucl. Instrum. Methods Phys. Res Sect. A 834, 98-107 (2016)
H. Qian *et al*., in the proceedings of FEL 2012
H.Qian *et al*., in the proceedings of IPAC2011

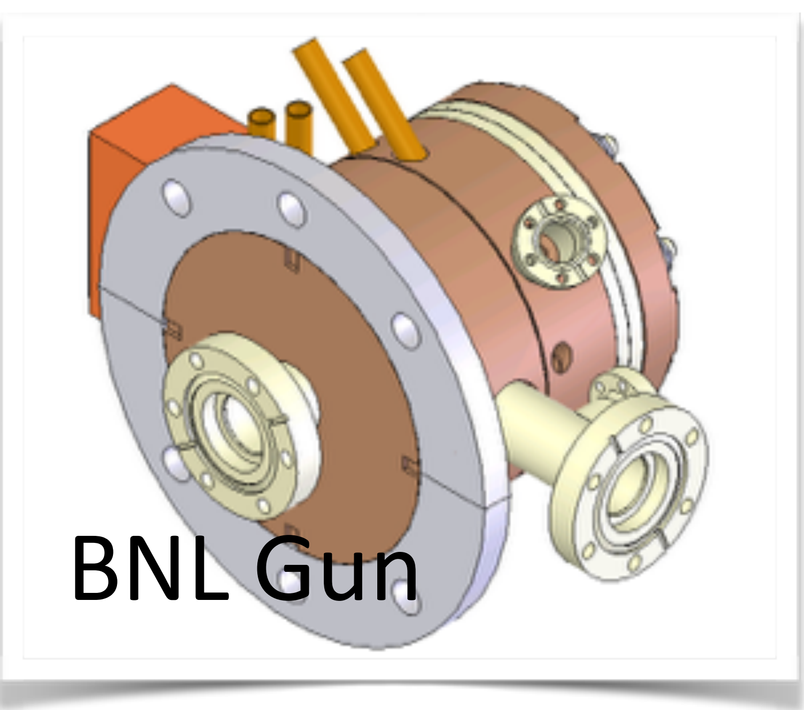
The gun designed to eliminate the multiple modes

THU Gun



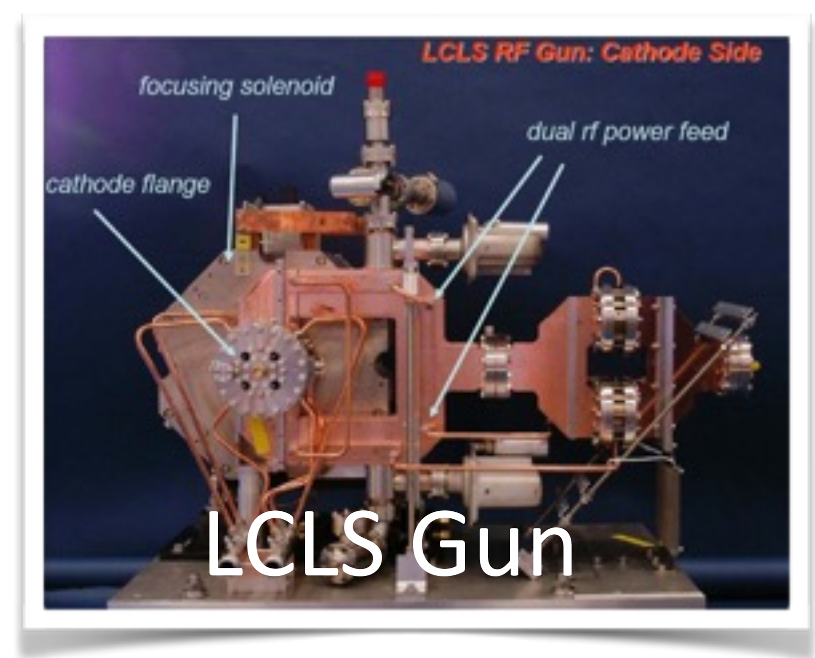






	Dipole	Quadruple
BNL	2E-03	2E-02
LCLS	9E-06	5E-05
THU	7E-05	1E-05

*CST simulation, H_{ϕ} analysis @ r=10mm

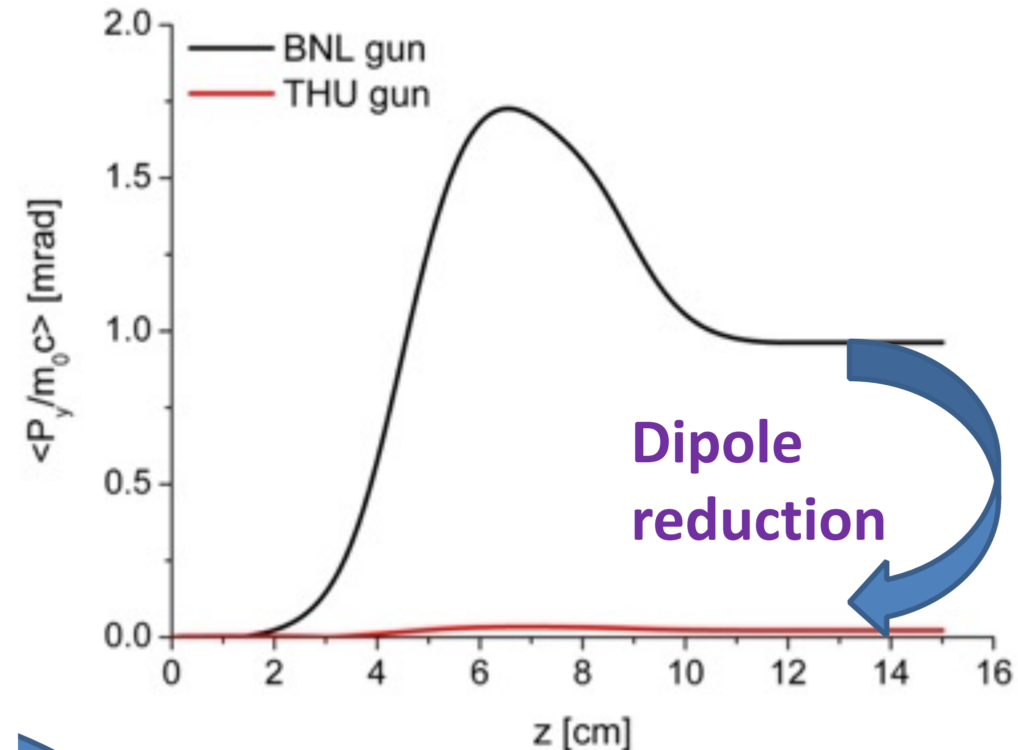


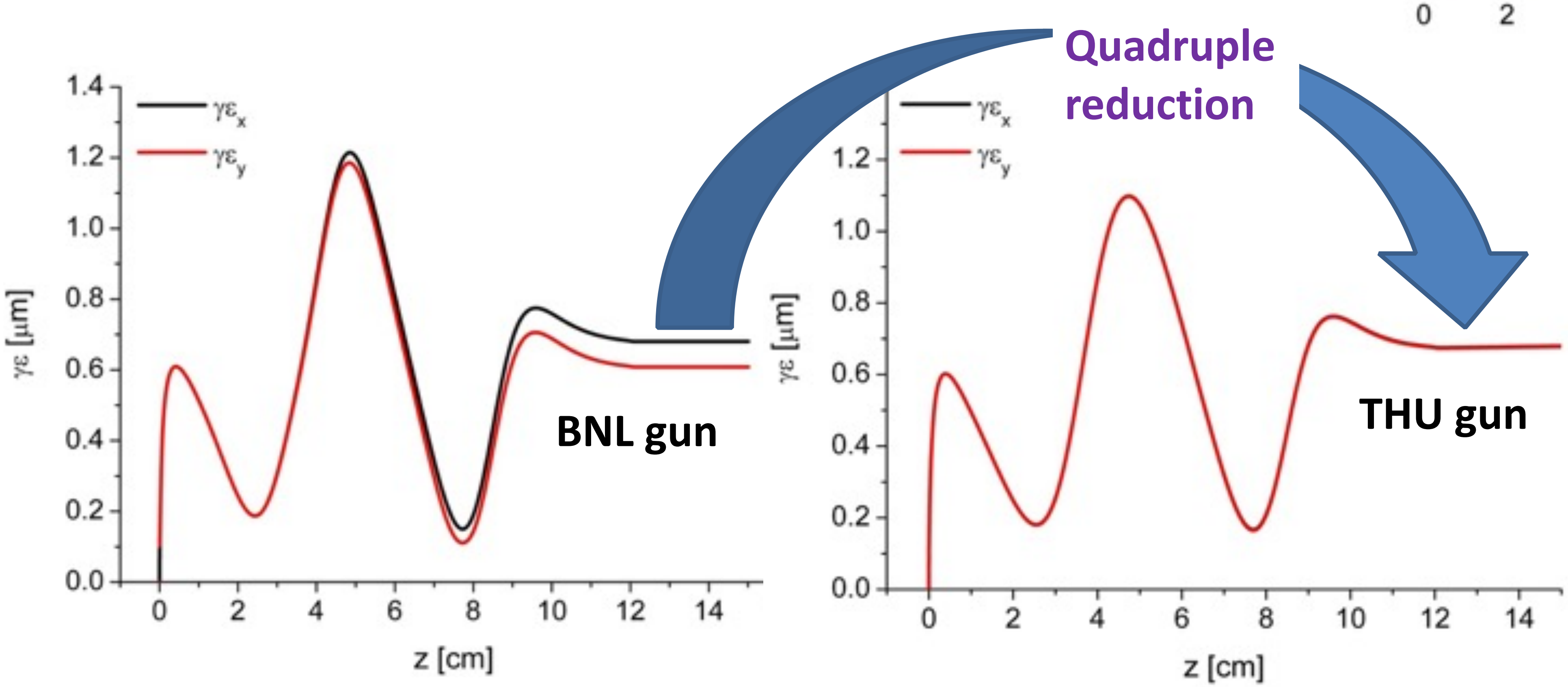
Emittance caused by the multipole modes

- Multipole field elimination

Dipole elimination ($\sim 10^{-2} \downarrow$)
tuning vac port length
(opposite RF coupling hole)

Quadruple elimination ($\sim 10^{-4} \downarrow$)
4-port design





Cathode Physics is important for ultra-low emittance electron beam

$$\varepsilon_n \sim \sqrt{\varepsilon_{th}^2 + \varepsilon_{sc}^2 + \varepsilon_{rf}^2 + \varepsilon_{mp}^2 + \varepsilon_{Bz}^2 + 2\eta\varepsilon_{sc}\varepsilon_{rf}^2}$$

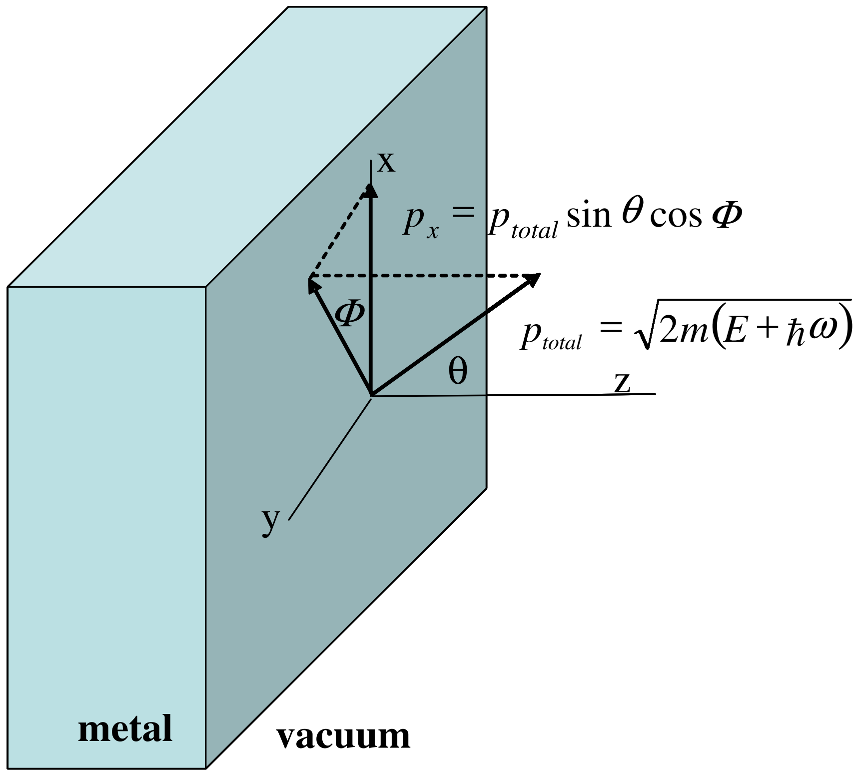
★ ε_{th}	Initial Emittace or Thermal Emittance
ε_{sc}	Space Charge Emittance
ε_{rf}	RF Emittance
ε_{mp}	Multi-pole mode of RF field caused Emittance
ε_{Bz}	Emittance because of Magnetic field Bz at cathode surface
η	Coupling between space charge effect and RF effect

★ Emittance at the Cathode:

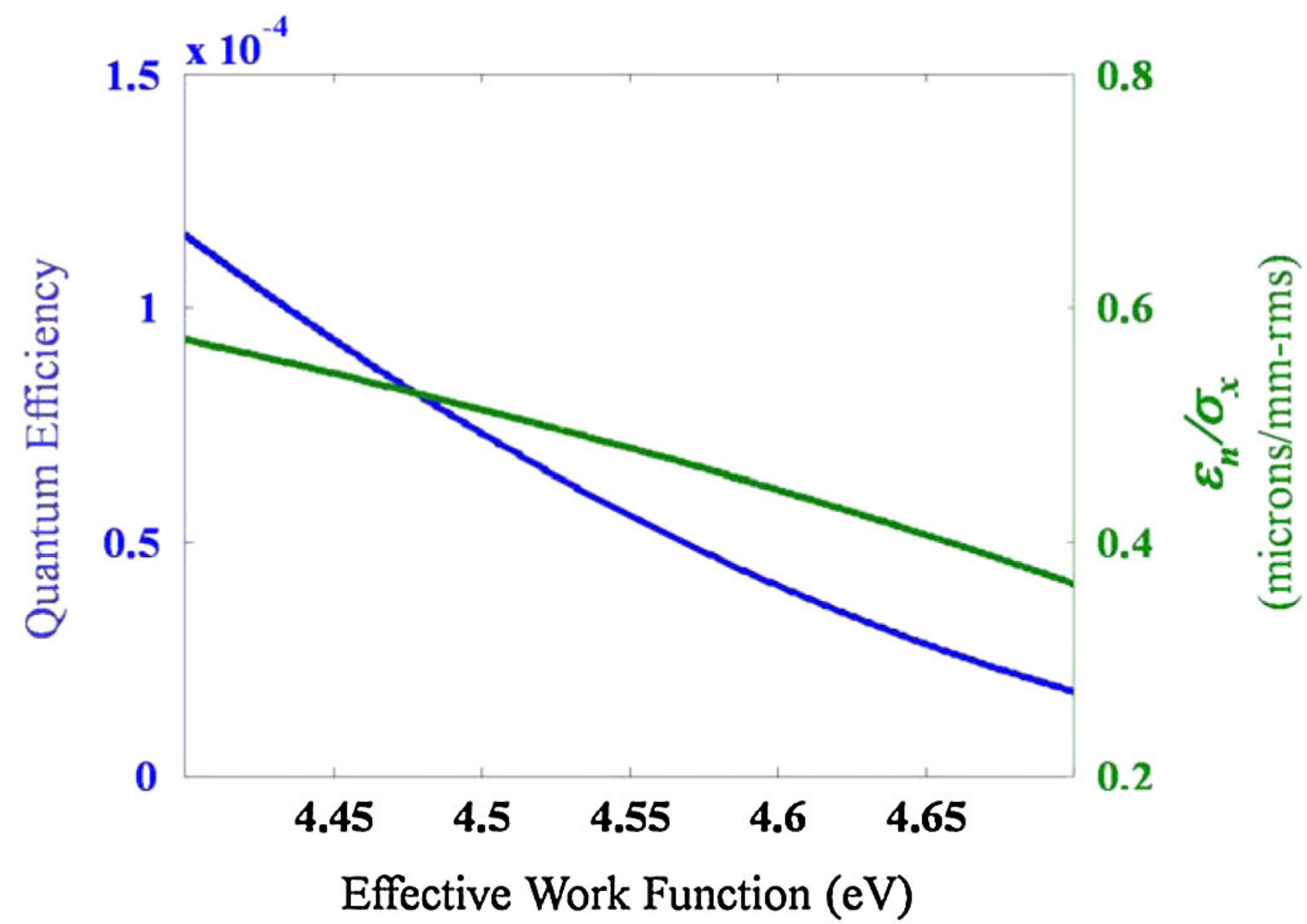
thermal emittance

emittance caused by the roughness

Thermal emittance of metal photocathode



$$\varepsilon_n = \sigma_x \sigma_{p_x} = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{\text{eff}}}{3mc^2}}.$$



$$\mathrm{QE}(\omega) \approx \frac{1 - R(\omega)}{1 + \frac{\lambda_{\text{opt}}(\omega)}{\bar{\lambda}_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{\text{eff}})^2}{8\phi_{\text{eff}}(E_F + \phi_{\text{eff}})}.$$

D. Dowell, et al , Nucl. Instrum. Methods Phys. Res. A **622**, 685 , 2010.

David H. Dowell and John F. Schmerge , PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12, 074201 (2009)

Roughness caused thermal emittance

HJ Qian et al, PRST Vol.15 Issue:4, 2012

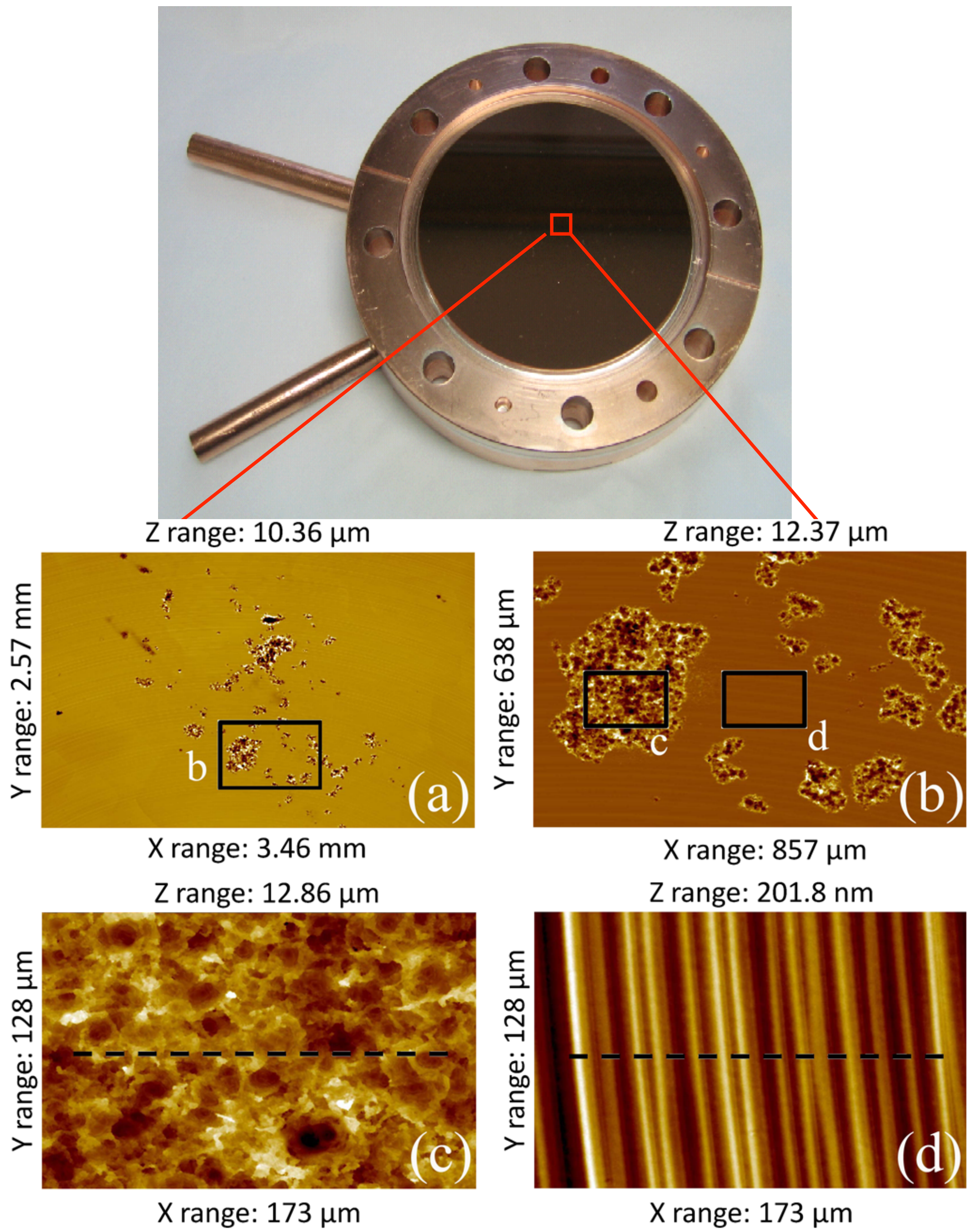
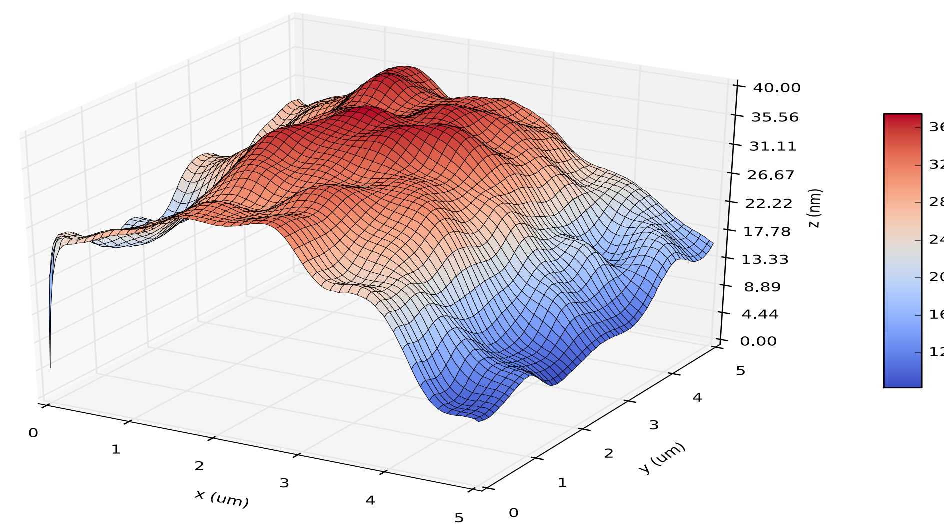


FIG. 7. Cathode surface morphology measured by a white light interferometer, and rms roughnesses are (a) 233 nm, (b) 653 nm, (c) 1420 nm, and (d) 36.5 nm.

item	$\gamma\varepsilon^{95\%}$	$\gamma\varepsilon^{100\%}$
$\hbar\omega-\phi_w$	0.44 eV	0.88 eV
β	0.92	3.62
Surface roughness emittance @ 50 MV/m	0.87 μm/mm	1.11 μm/mm



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The 3D random surface model gives the influence of the surface roughness to the emittance growth is much smaller than expected.

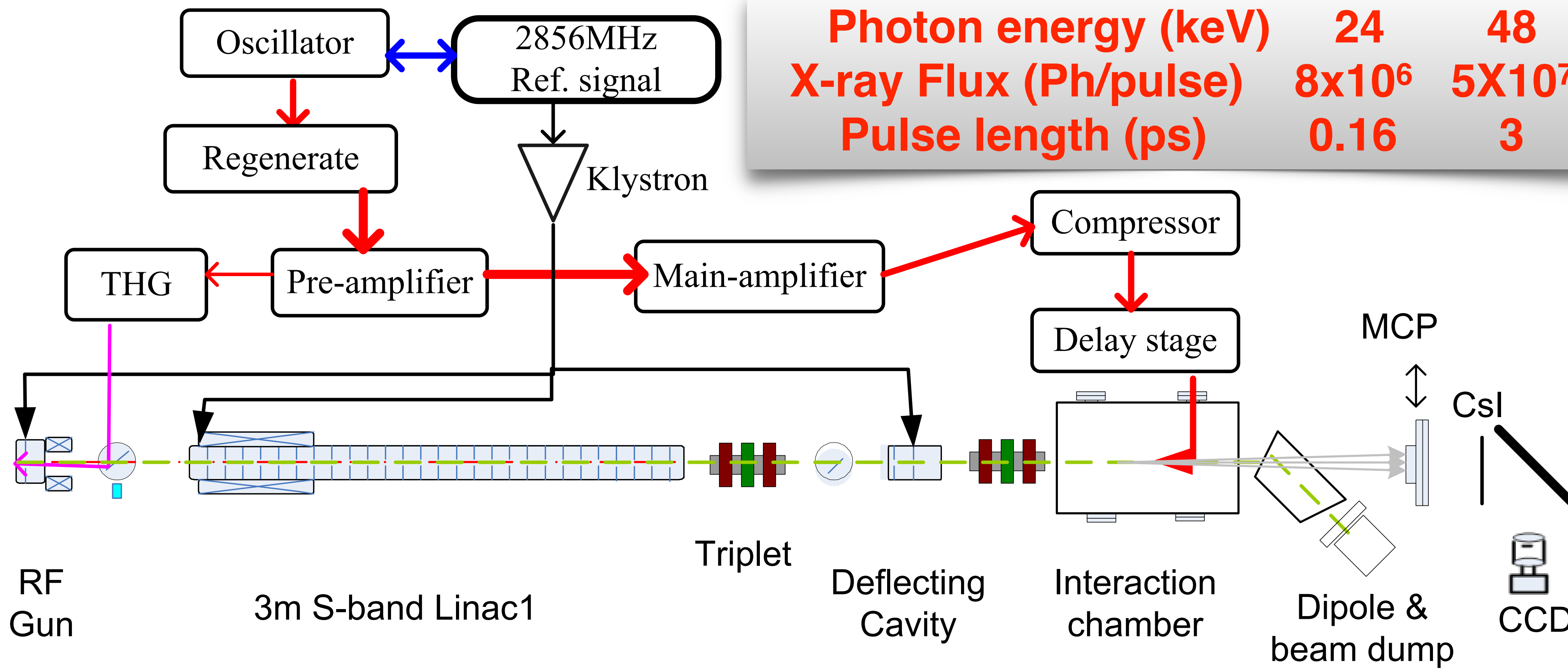
X.Z.He,C.X.Tang,W.H. Huang andY.Z.Lin, High Energy Phys. Nucl. Phys. 28, 1007 (2004).
Z. Zhang and C. X. Tang, Phys. Rev. ST Accel. Beams 18, 053401 (2015).

Tsinghua Thomson scattering X-ray source (TTX):

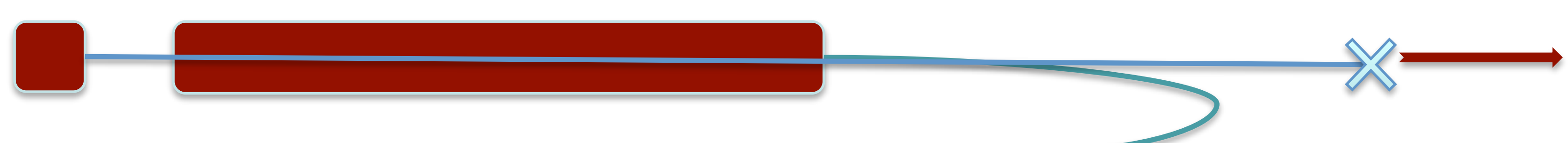
TTX-I is operating, TTX-II is under technical design.

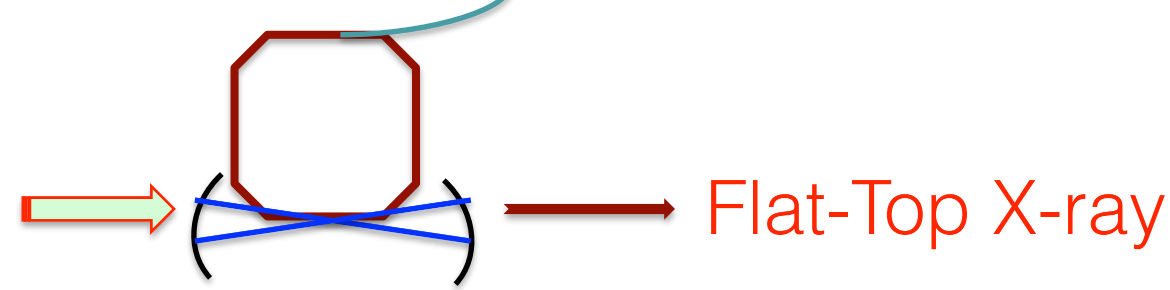
Photon energy (keV)	24	48
X-ray Flux (Ph/pulse)	8×10^6	5×10^7
Pulse length (ps)	0.16	3

TTX-I



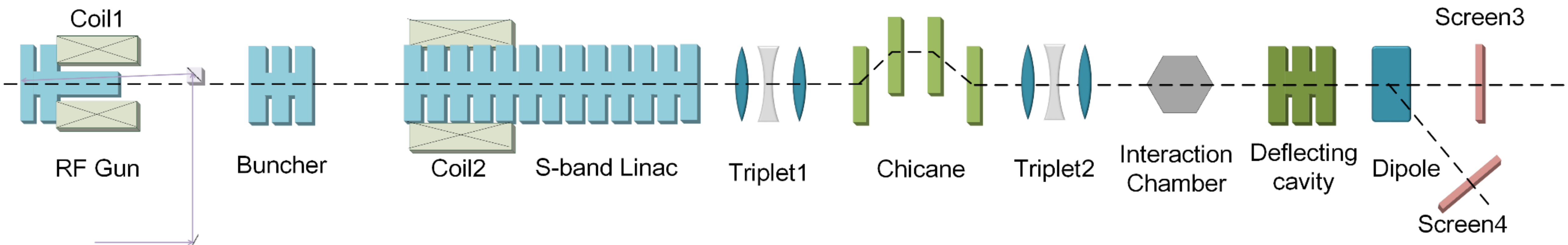
TTX-II



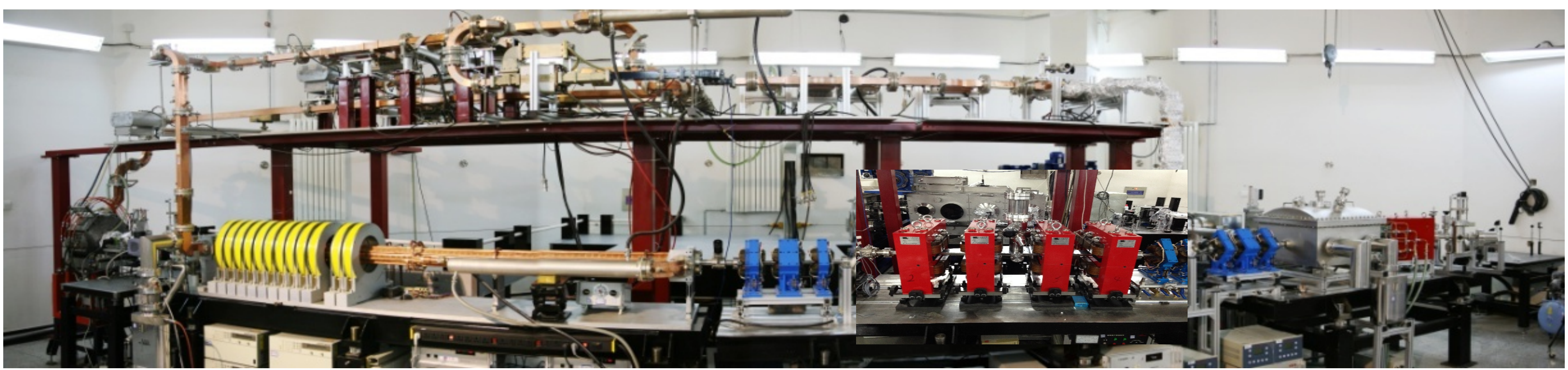


Circumference	4.8 m
Electron energy	50MeV
RF frequency	500MHz
X-ray Flux	$\sim10^{10}$ph/s

The 50MeV Electron linac beam line of TTX

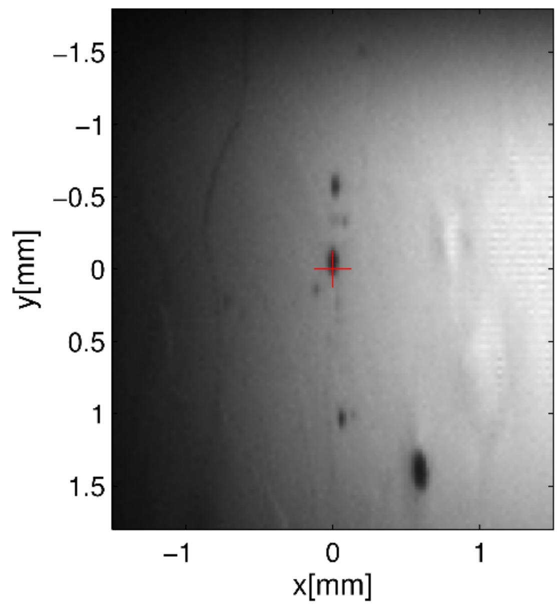


- The maximum gradient of the gun is ~110MV/m and the bunch charge from a few pC to ~1nC.
- An S-band TW cavity was installed for ballistic bunching before the acceleration.
  - ☑ The acceleration phase is set at ~-90° to introduce an energy chirp
  - ☑ Simulations show the emittance can be preserved when compression factor $C<3$
- A 4-dipole chicane has been installed after the linac
  - ☑ The bend angle can be varied up to ~15°.
- The combination of ballistic bunching and magnetic compression enable us to generate ultrashort (rms<20fs) and high-intensity (~10kA) electron beam.

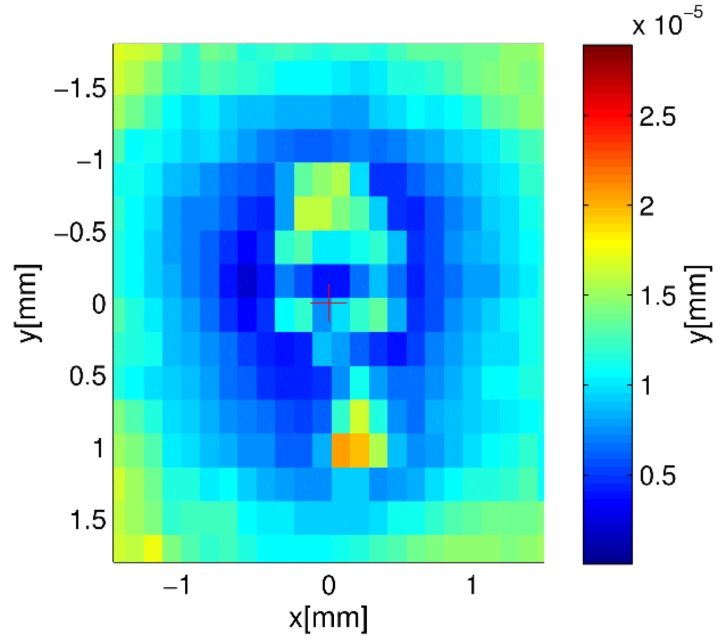


Emittance optimization of the TTX linac

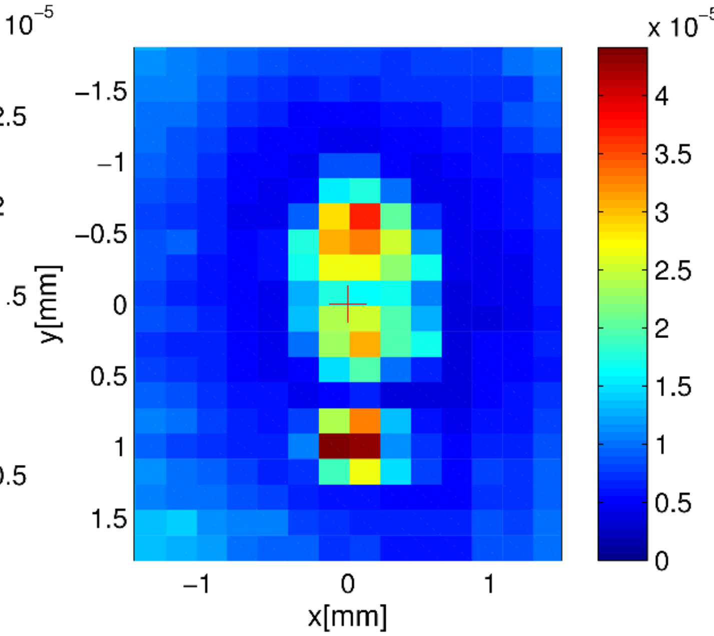
- QE map of the cathode area



Cathode image
with white light



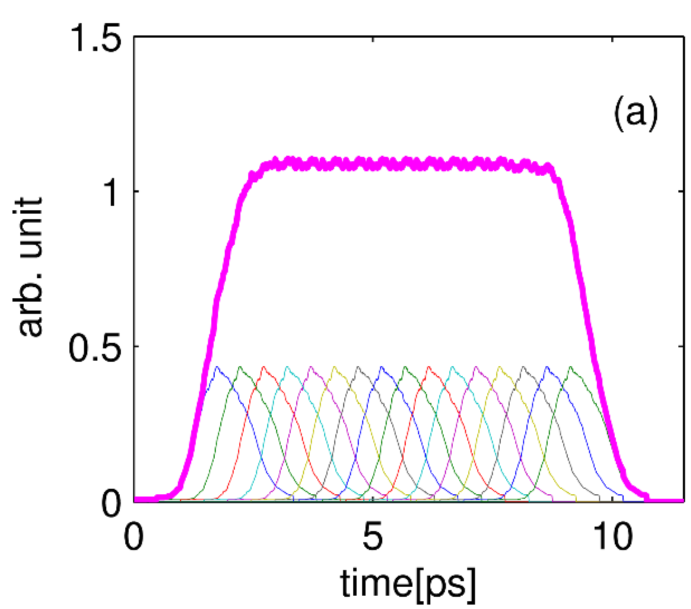
QE map with laser
normal incidence

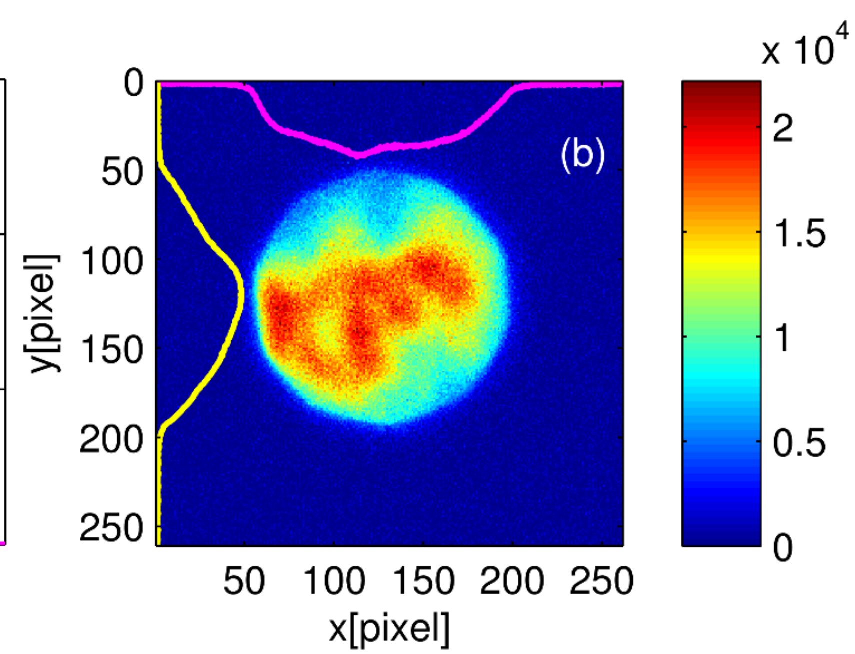


QE map with laser
oblique incidence

- Longitudinal and transverse shaping of the driven UV laser

4 α-BBO crystals to get flat-top laser profile

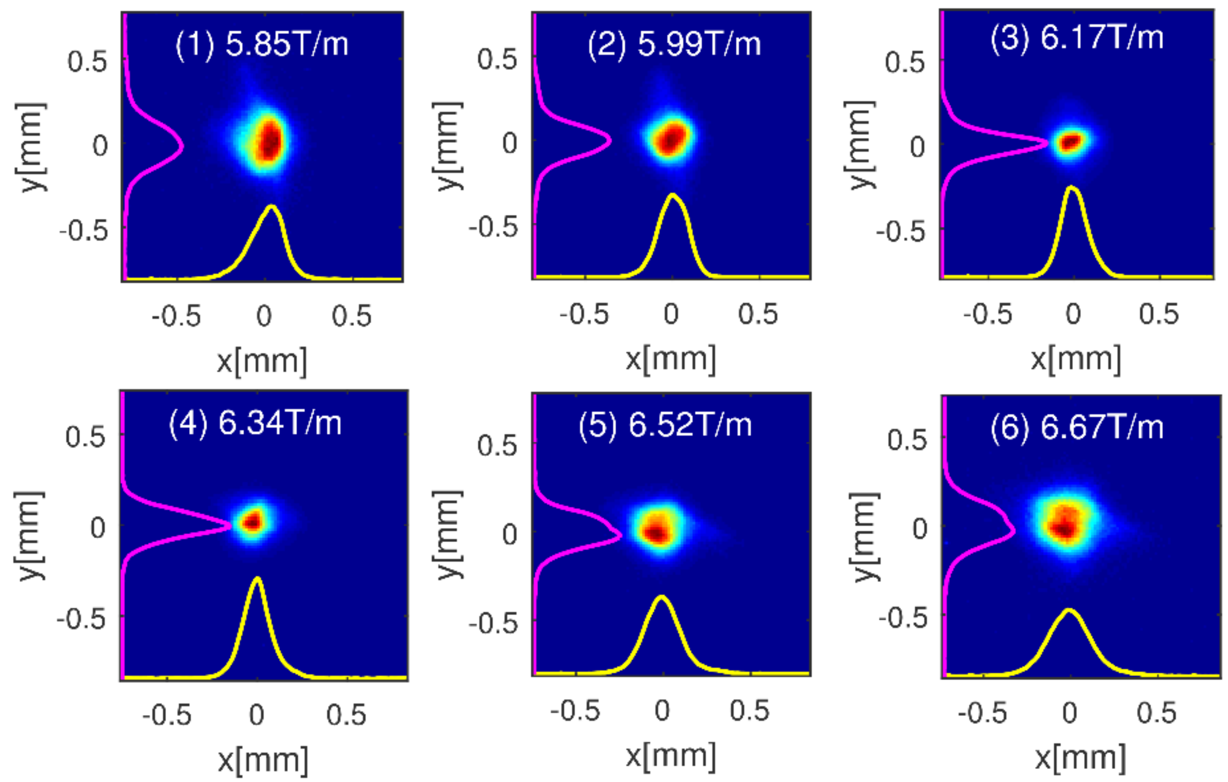


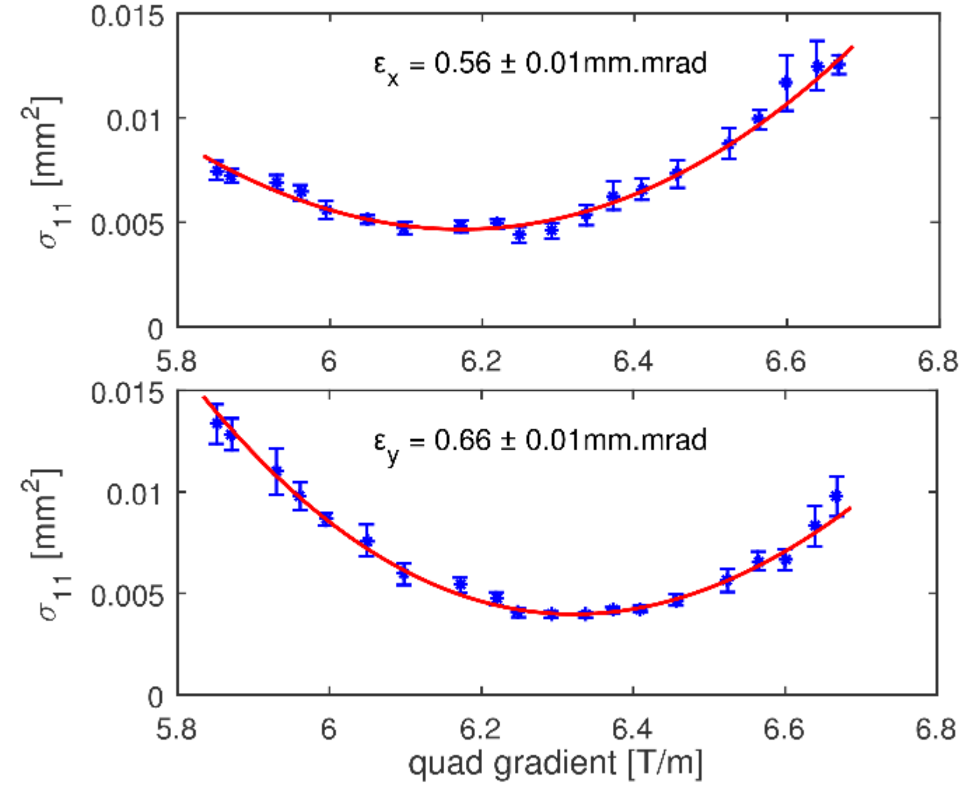


Gaussian truncate and image transfer system

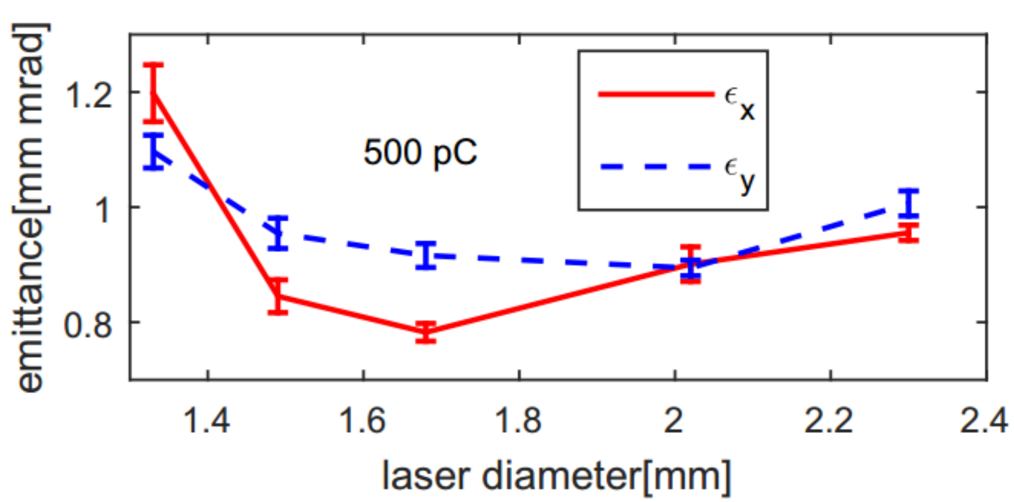
Emittance measurement and optimization

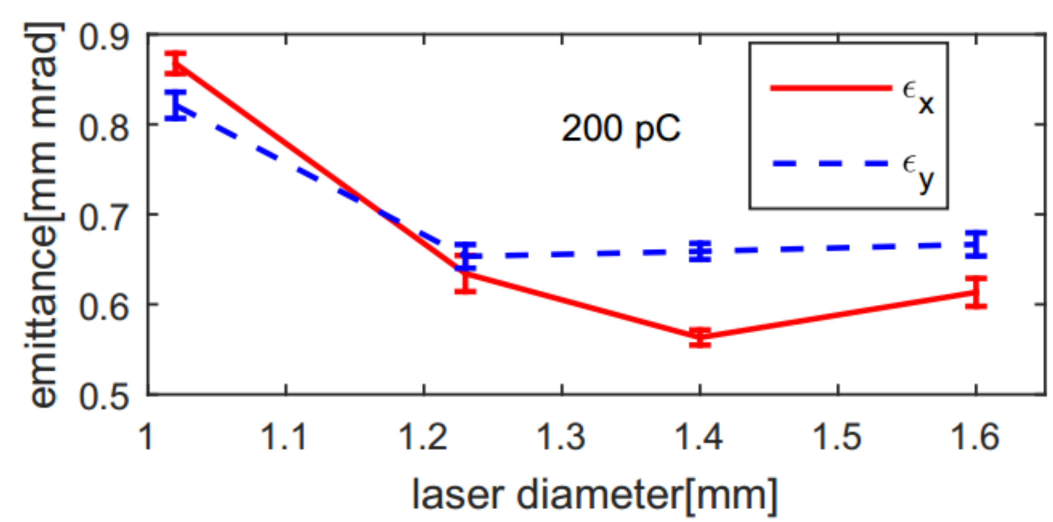
- Quad-scan technique to measure the beam emittance



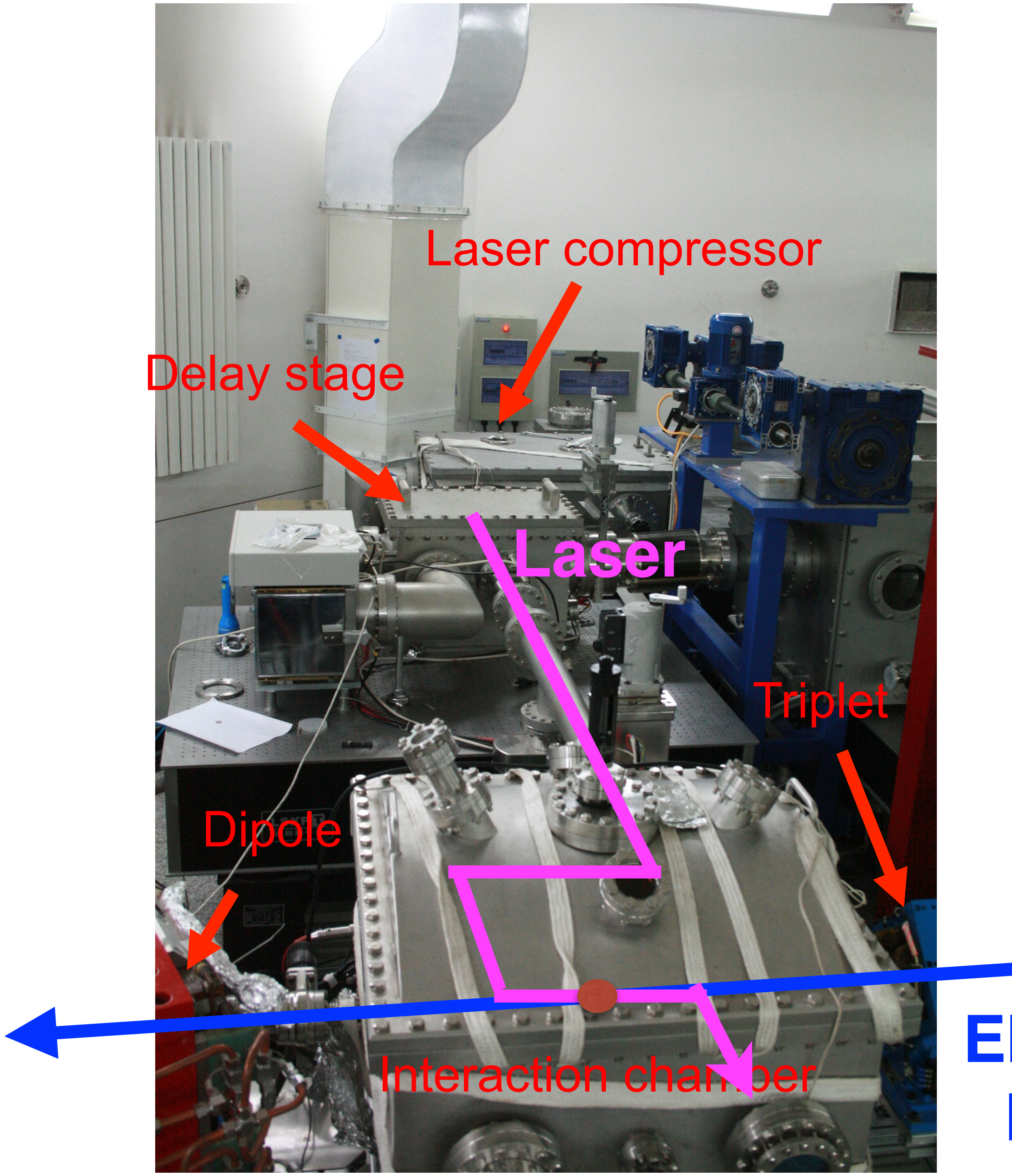


- Emittance optimization results for beam charge 200pC and 500pC

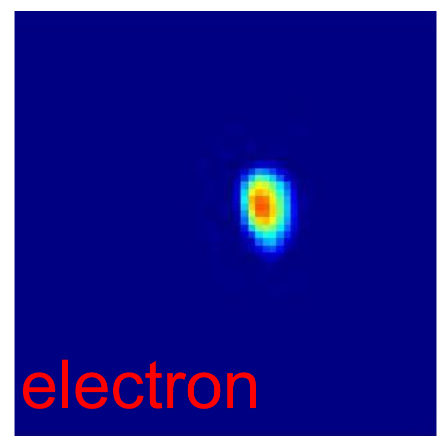


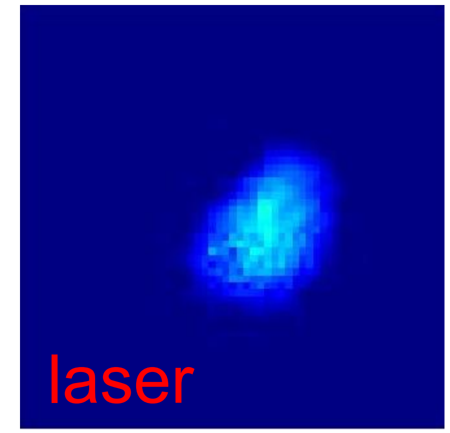


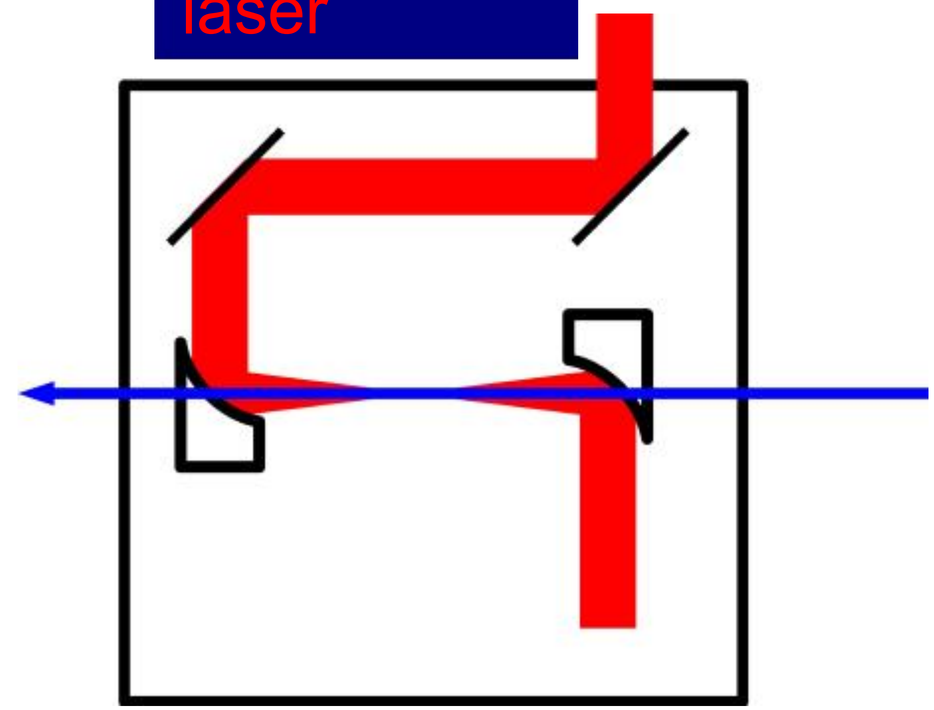
The 20TW 800nm laser pulse interacted with the electron beam at TTX



Electron Beam

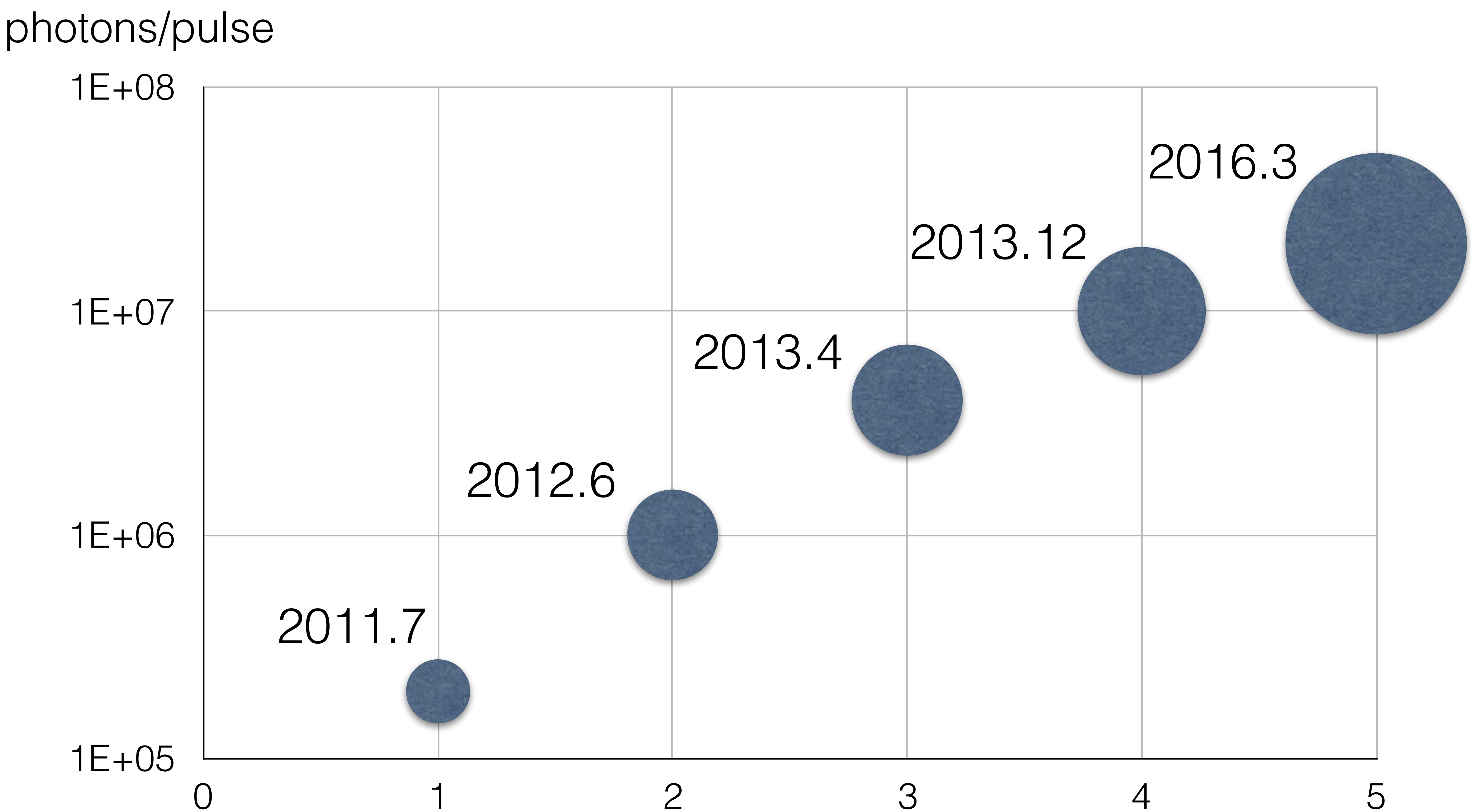






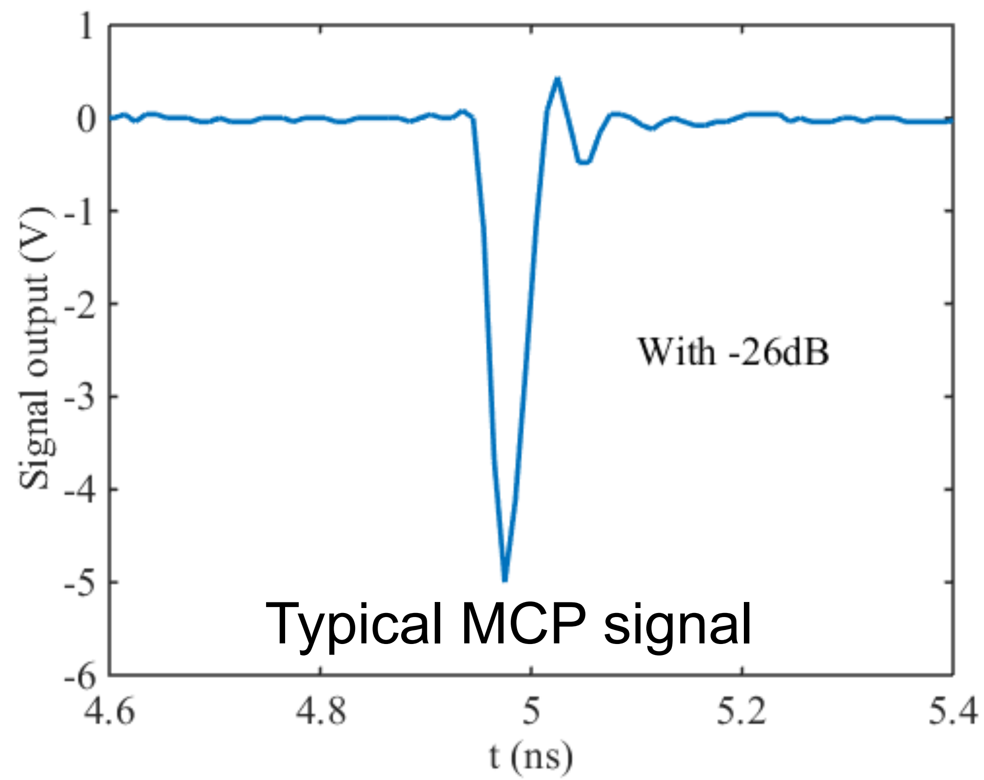
The laser is focused by a parabolic mirror with 4mm hole in center

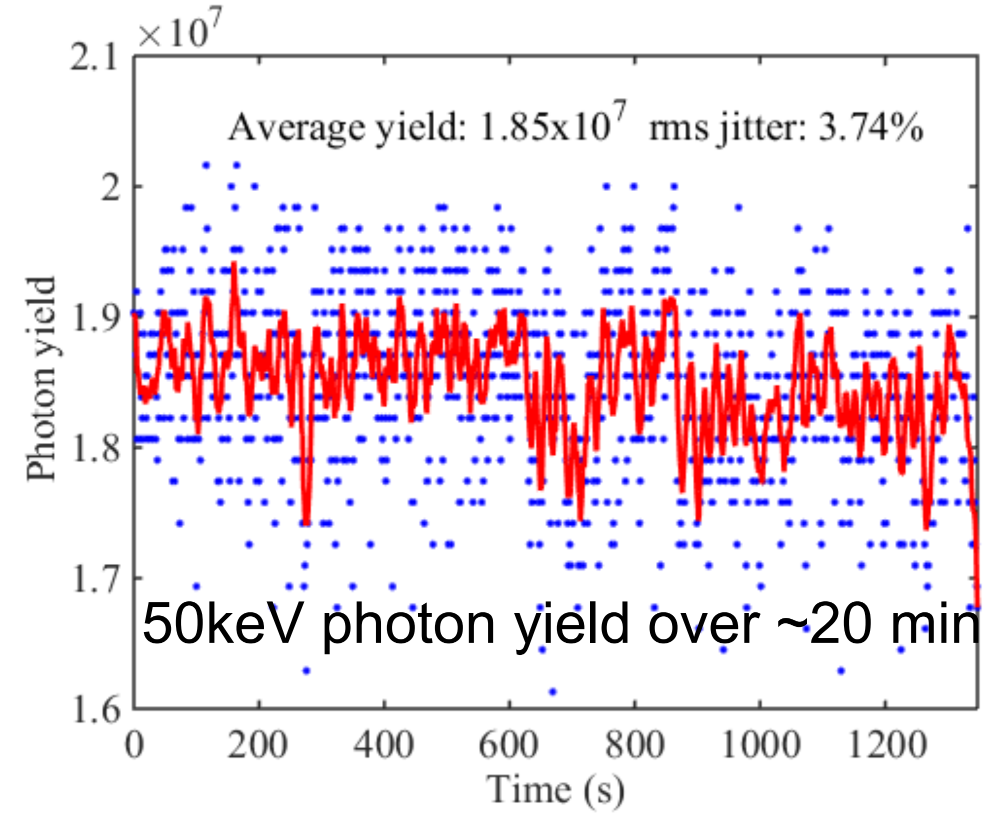
Photon flux of TTX-I

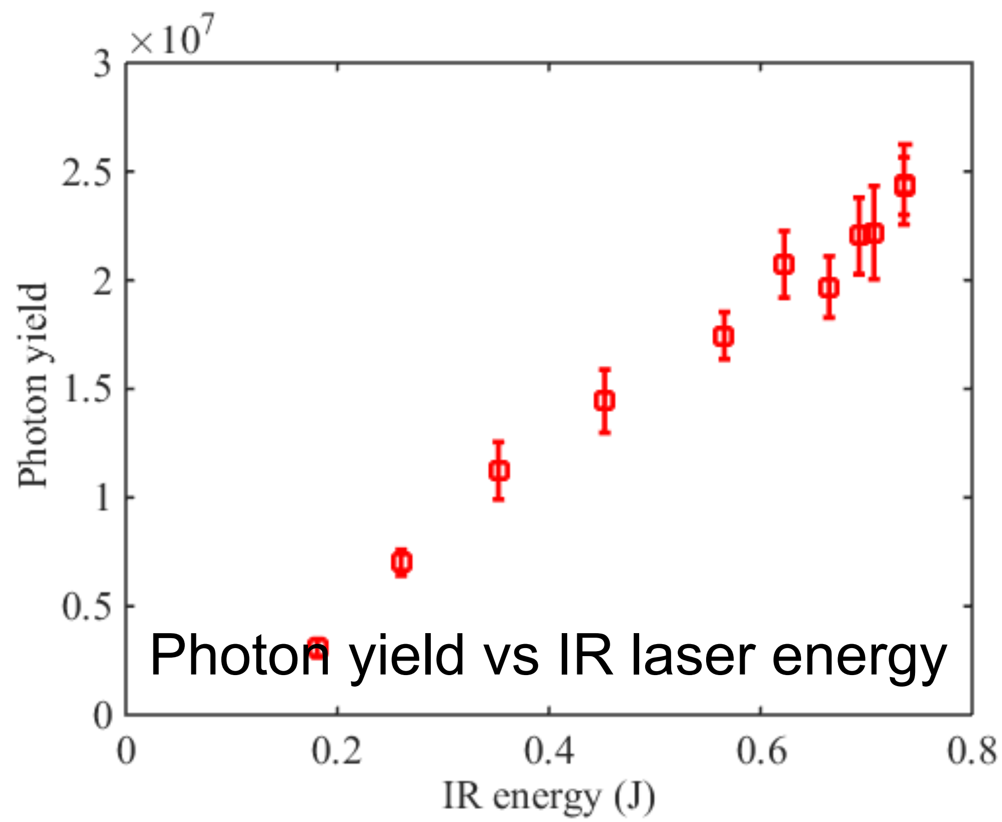


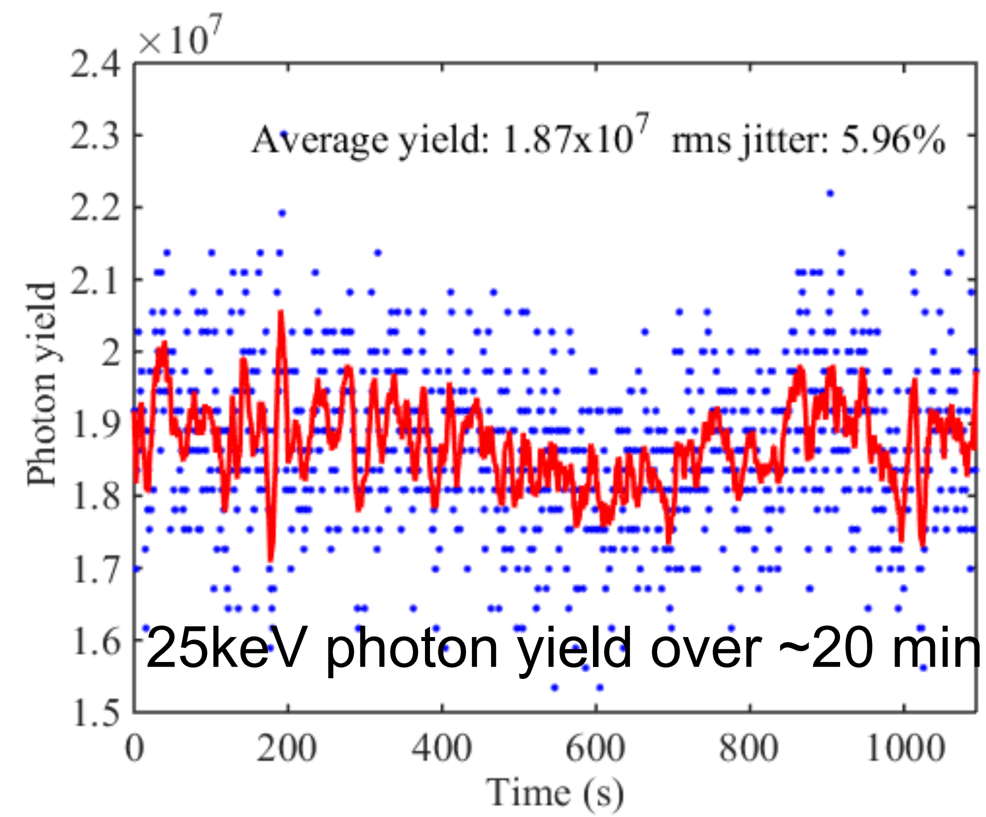
NIM A 608 (2009), NIM A637(2011), RSI 84, 053301(2013)

Photon yield measurements with an MCP

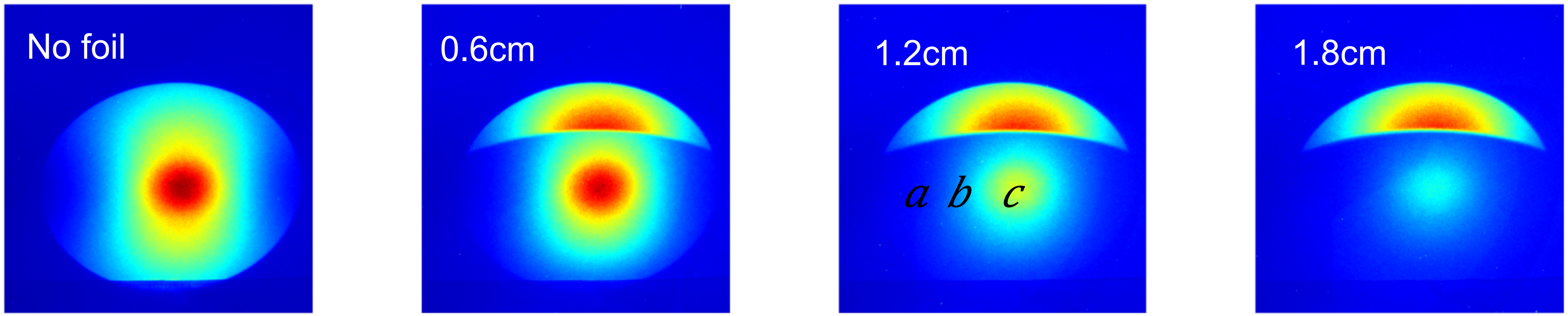


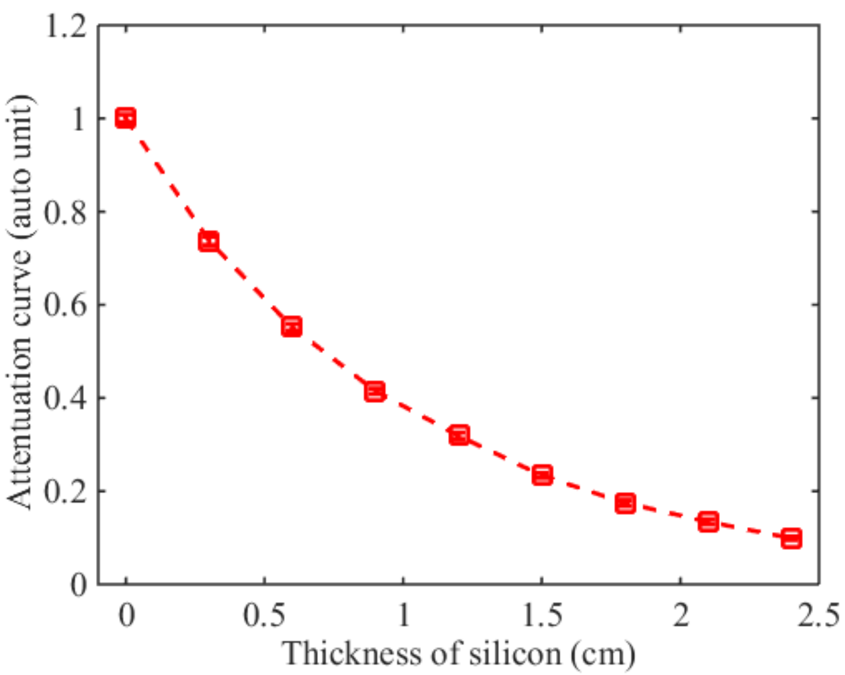




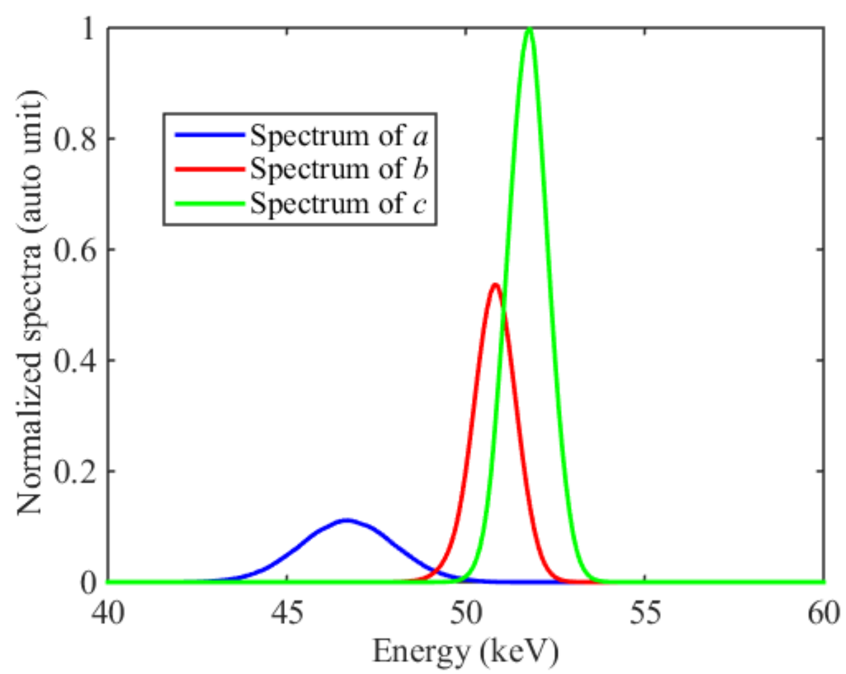


Reconstruct the spectra of scattered X-rays by the attenuation curve over silicon foils

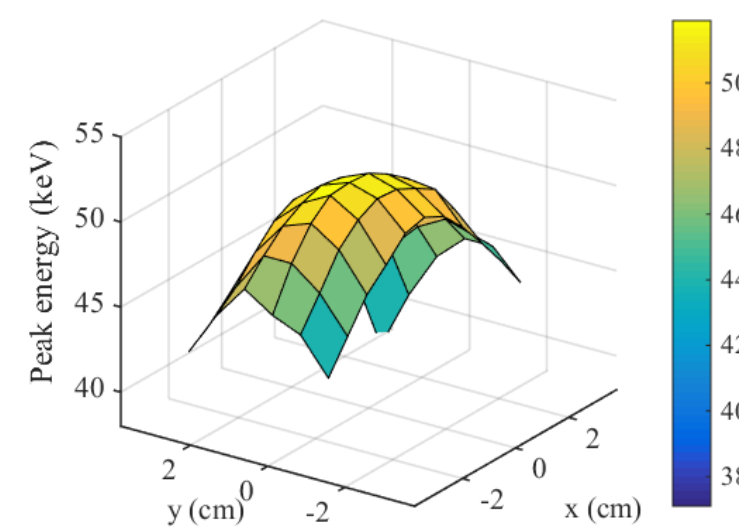




Attenuation curve

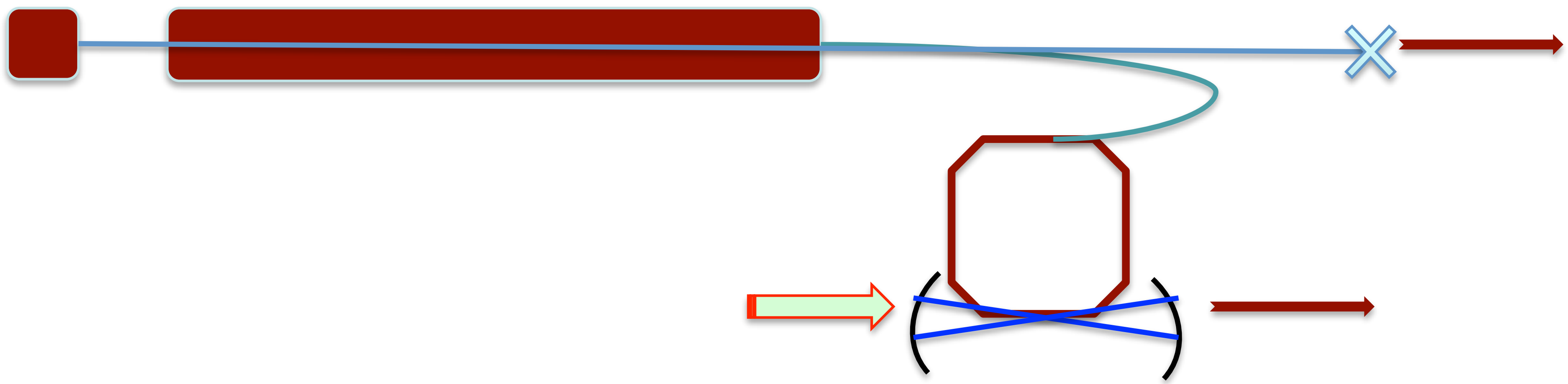


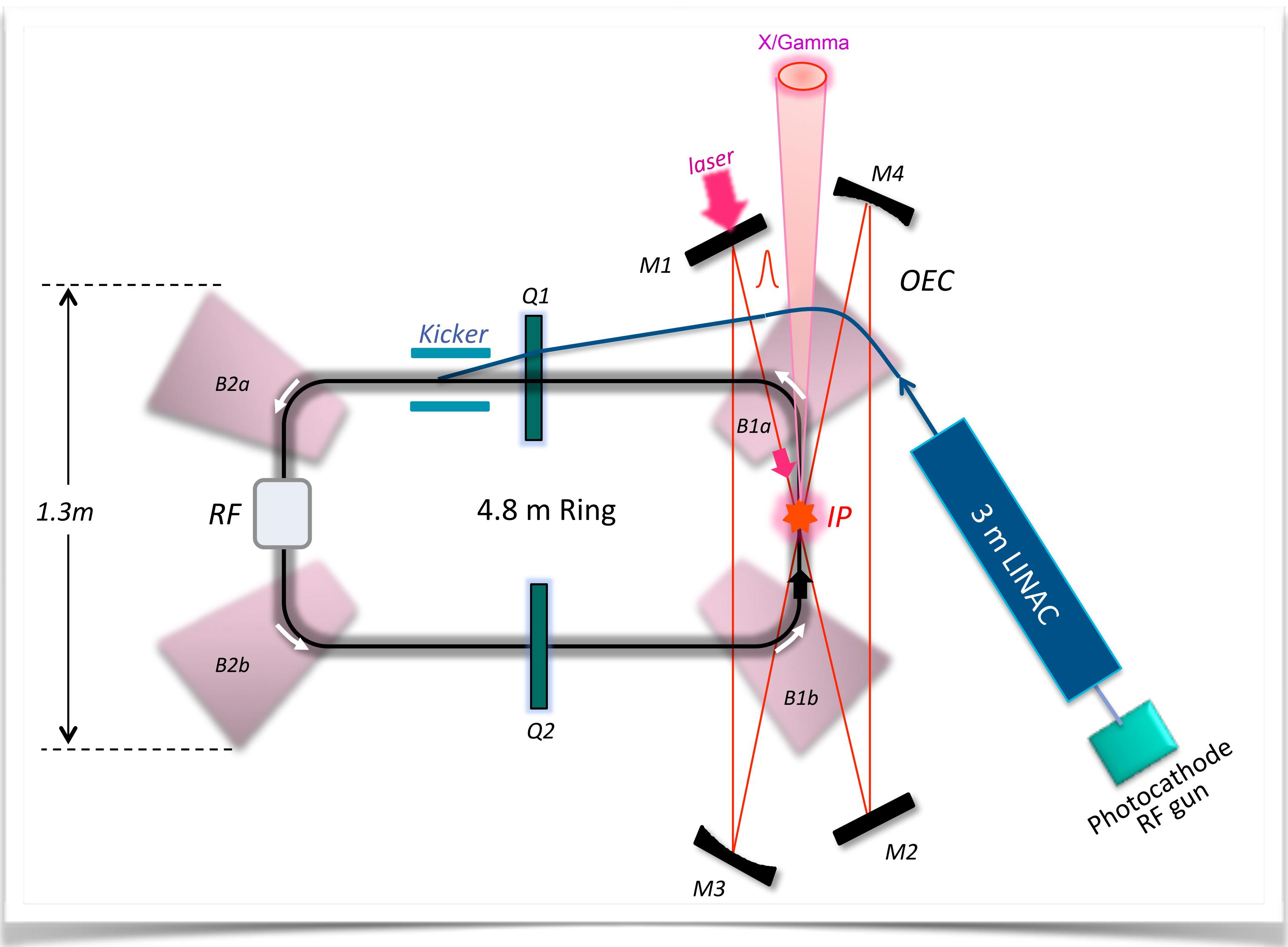
Reconstructed spectra of the points a,b,c on the x-ray spot



Peak energy distribution of the x-ray profile

TTX-II with LESR and Optical Cavity



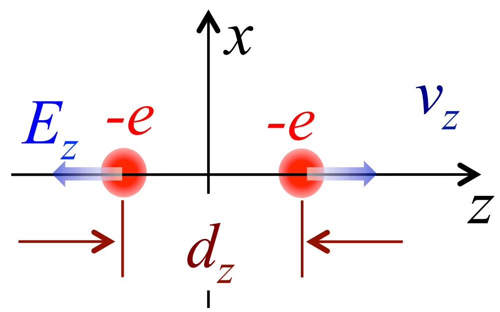


Circumference	4.8 m
Electron energy	50MeV
RF frequency	500MHz
X-ray Flux	~10^{10}ph/s

By HS Xu and Y.You

Nonlinear longitudinal space charge oscillation (NSCO)

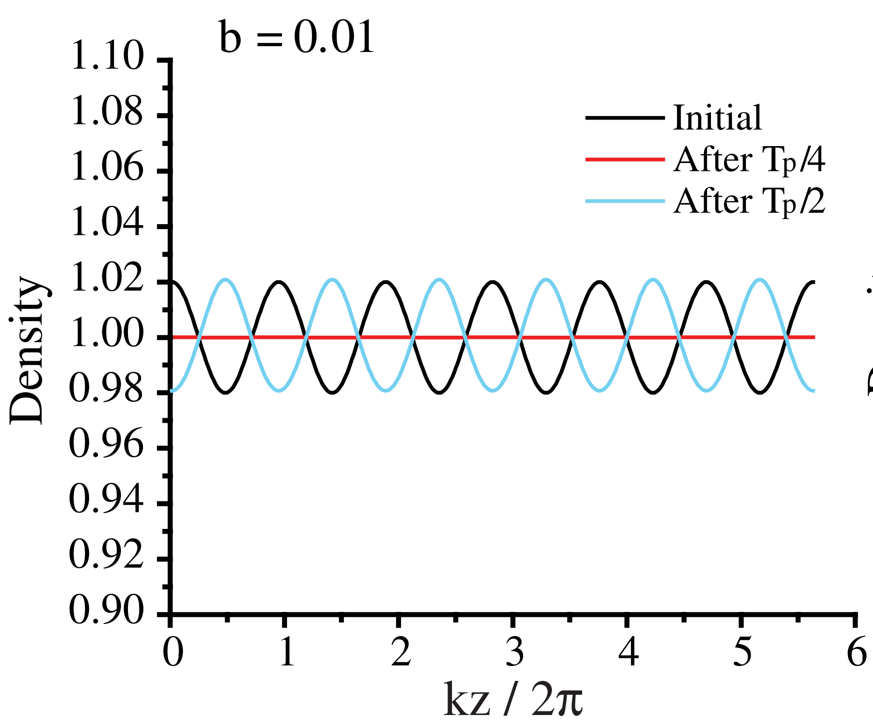
$$\partial_t \Delta\gamma + c\frac{\Delta\gamma}{\gamma^3}\partial_z \Delta\gamma = -\frac{eE}{mc},$$

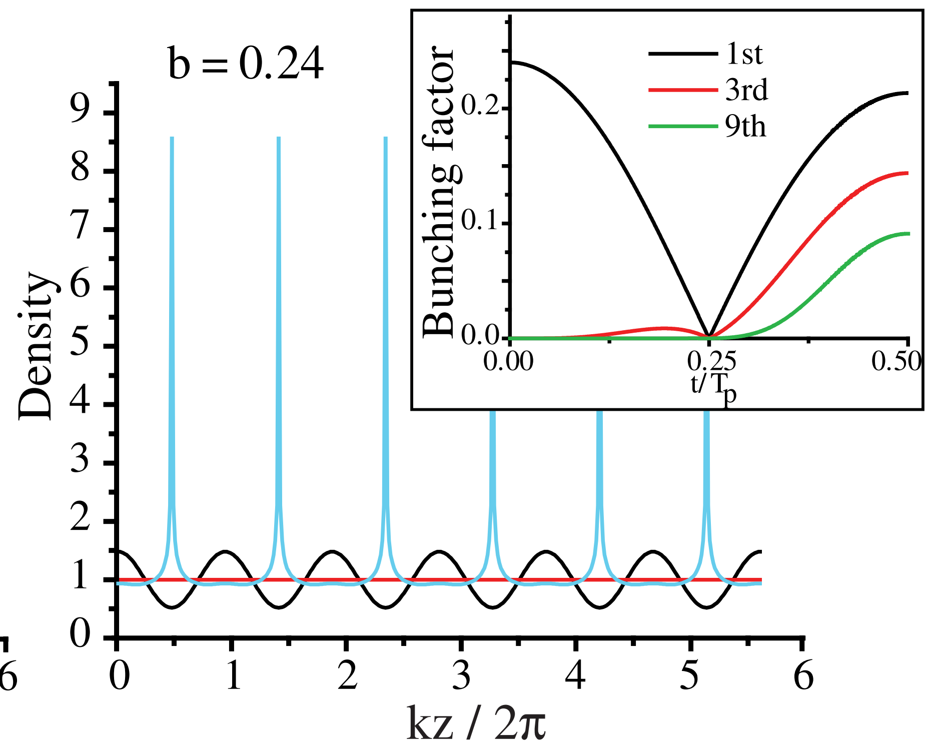


$$\partial_z E = -\frac{en}{\epsilon_0},$$

$$\partial_t n + c\partial_z n\frac{\Delta\gamma}{\gamma^3} = 0,$$

where the three unknown functions $n(z,t)$, $\Delta\gamma(z,t)$ and $E(z,t)$ describe the electronic density, the deviation from the reference energy and the longitudinal space-charge field, respectively





The initial electron density distribution

$$n(z,0) = n_0(1 + 2b\cos(kz))$$

$$\omega_p = \sqrt{e^2 n_0 / m\epsilon_0\gamma^3}$$

$$T_p = 2\pi/\omega_p$$

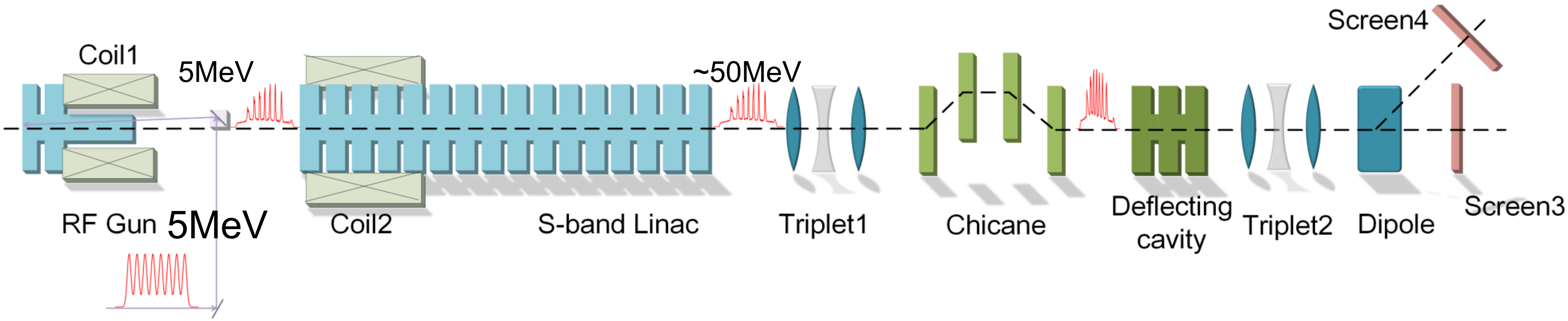
$$\omega_{p3D} = \frac{2D}{1+2D}\omega_p$$

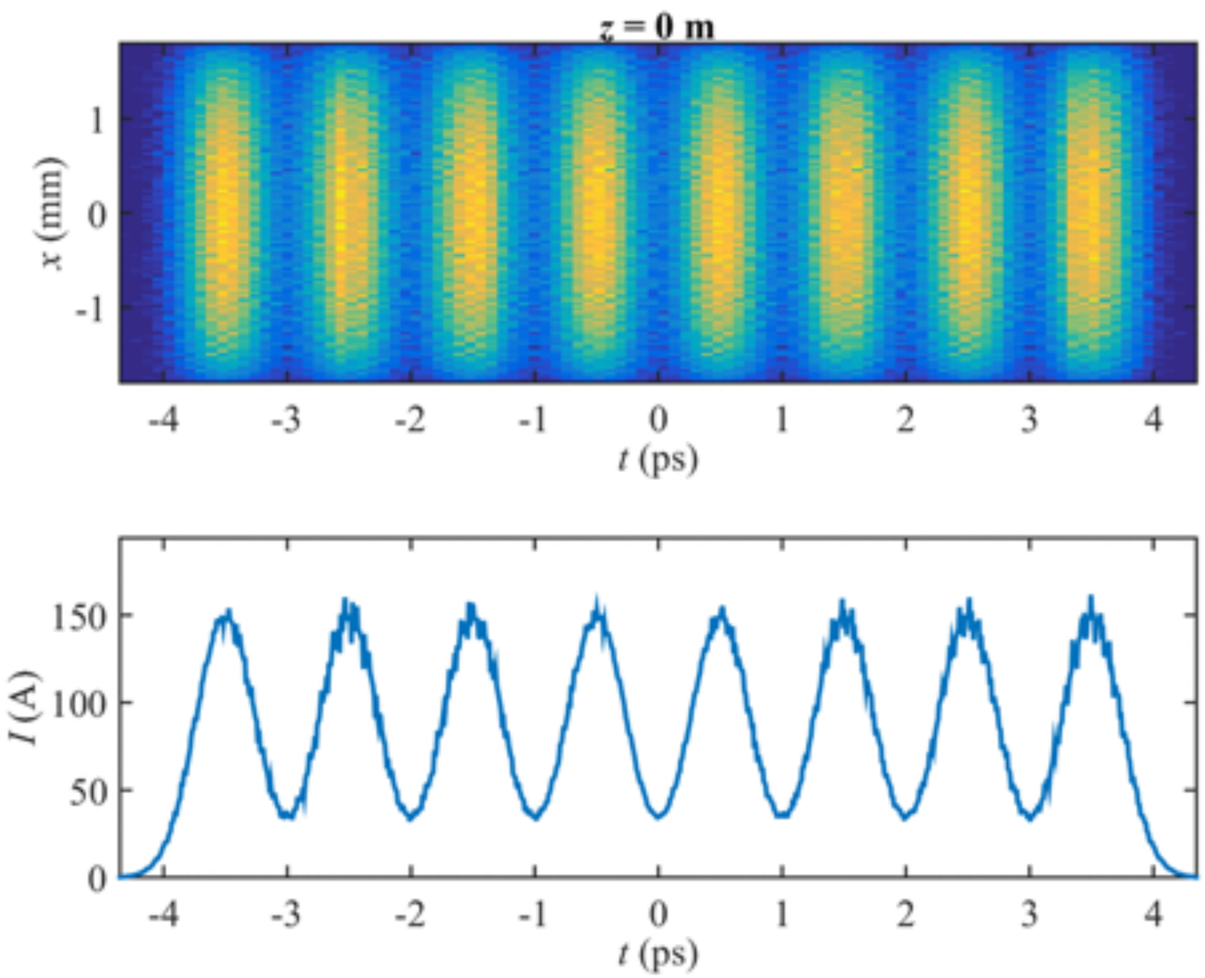
$$D = k\sigma_x/\gamma < 1$$

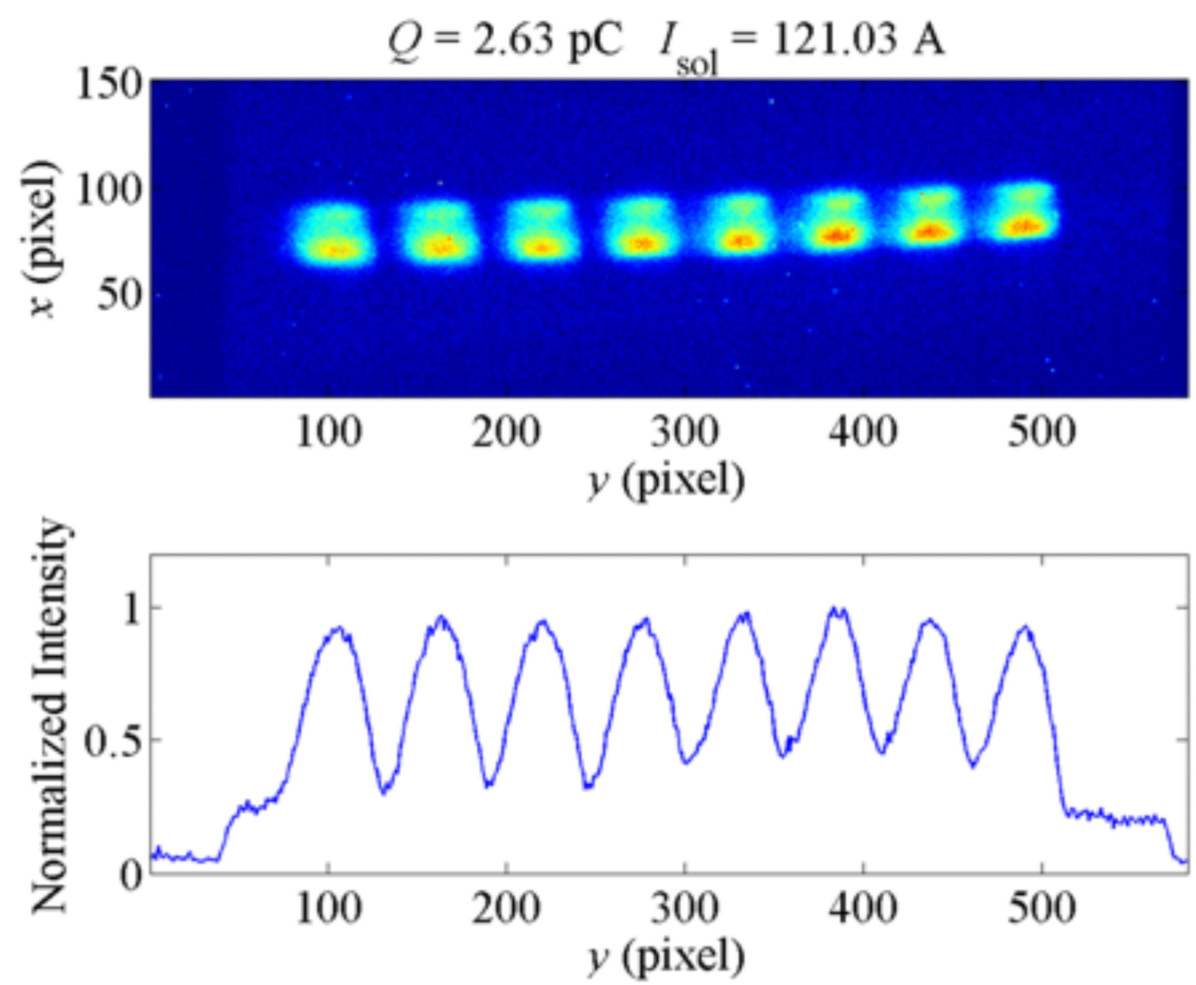
P. Musumeci et al., PRL 106, 184801 (2011)

P. Musumeci et al., PRST-AB 16, 100701 (2013)

Demonstration of NSCO at TTX beam line





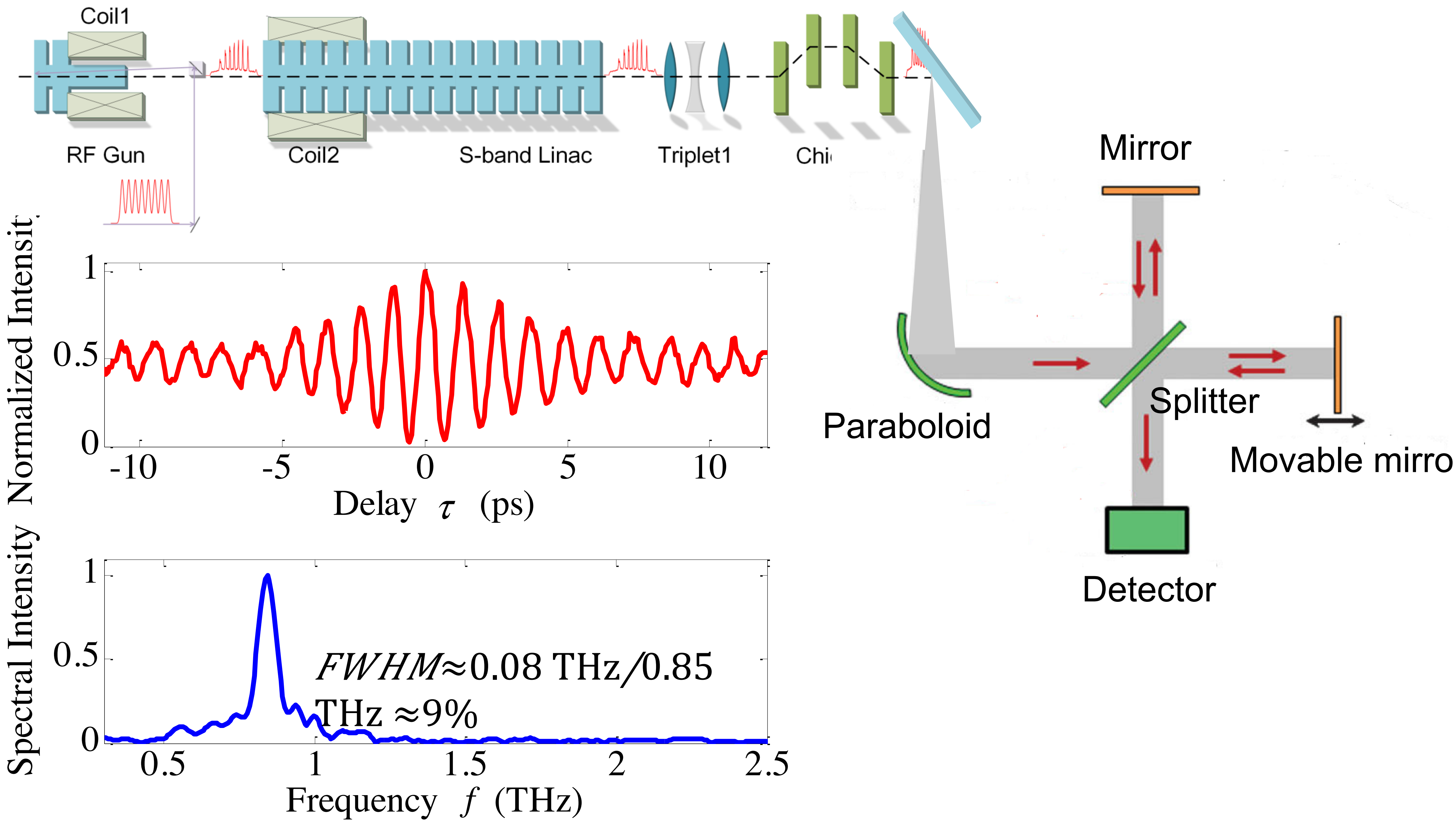


Simulation

Experiment

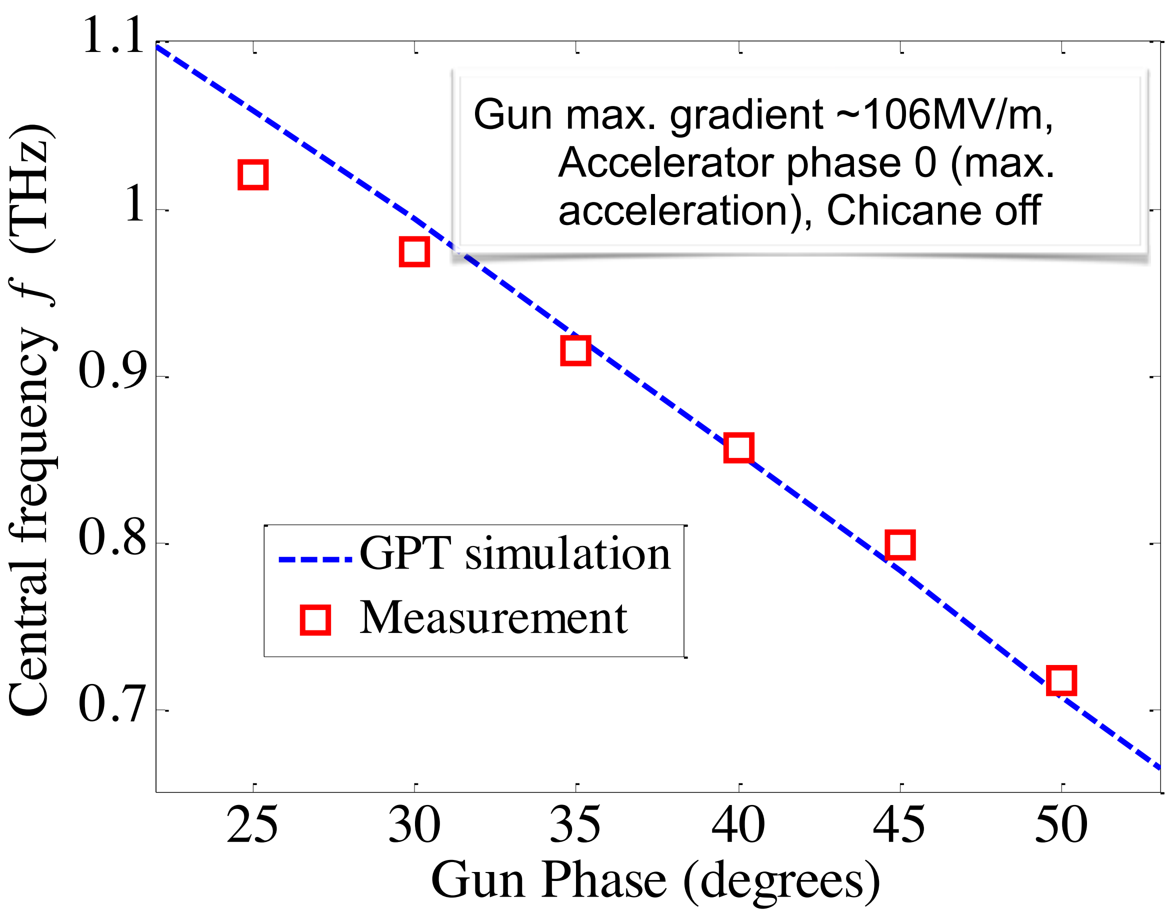
THz Autocorrelation Measurement

The electron bunch trains are used to generate THz radiation by CTR and the spectra are solved through the autocorrelation in the interferometer.

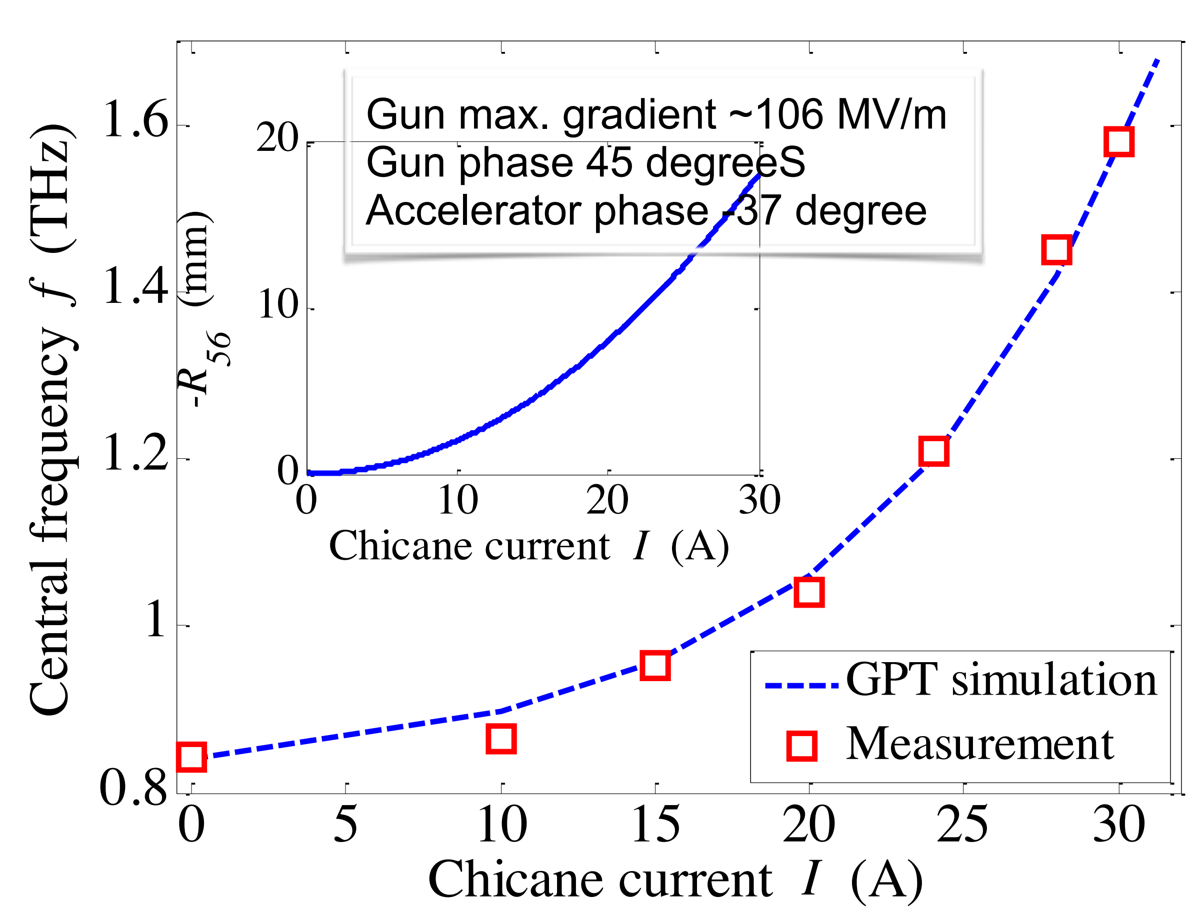


Tunable bunch train spacing and the frequency tuning of THz radiation

The bunch train spacing can be controlled by the velocity bunching of the RF gun and the accelerator, or by the magnetic compression.



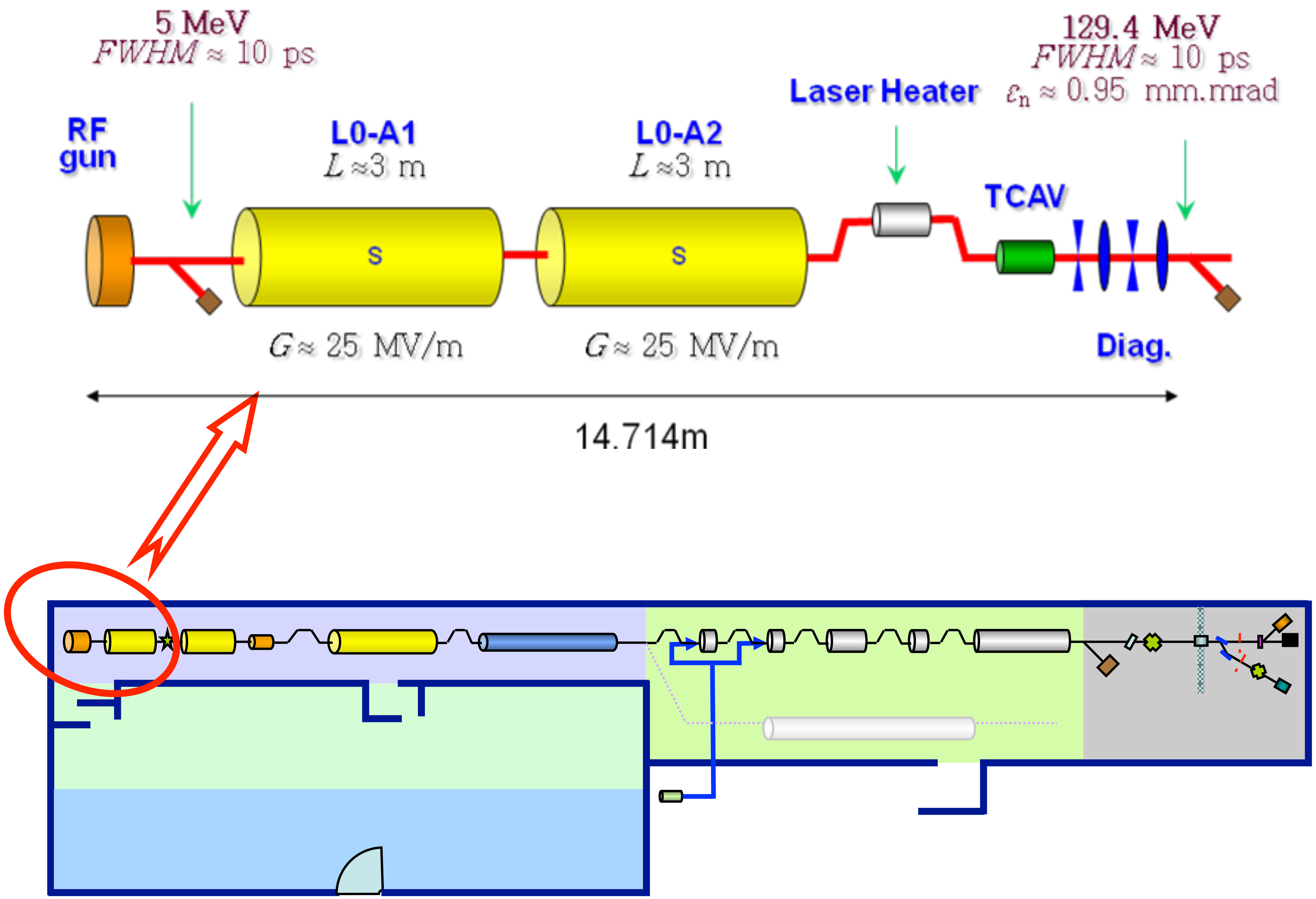
Velocity bunching according to the phase of the gun



Magnetic compression by the CHICANE

PRL 116, 18, 2016

The photo-injector for SXFEL in Shanghai



Summary

- NC Photocathode rf guns have been developed, the gradient on cathode is about 120MV/m, and around 1um, 0.5um emittance can be got with the gun at charge of 500pC and 200pC.
- A 50 MeV linac has been running for ICS x-ray, THz radiation and other applications.
- New projects with high brightness electron linacs are under construction, such as gamma ray source XGLS and the photo injector of SXFEL .

Thanks!