清華大學
Tsinghua University

ACCELERATOR LABORATORY
of TSINGHUA UNIVERSITY

The Road to Achieving Ultra-low Emittance of a Photocathode RF Gun

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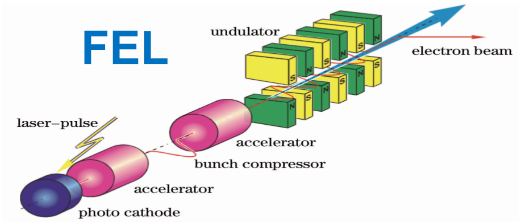
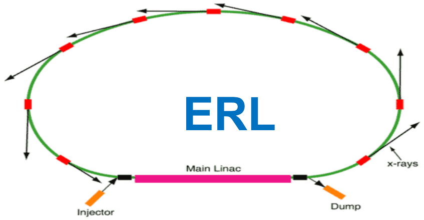
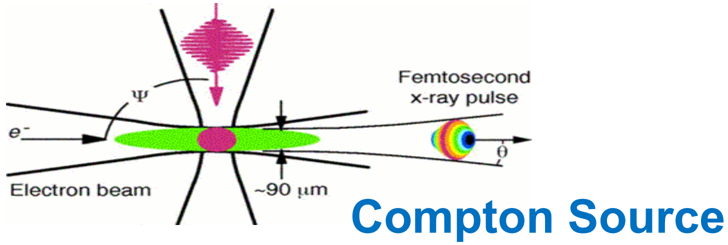
Outline

- **Introduction**
  - Motivation for low emittance electron beams
  - Research on the photocathode RF guns at Tsinghua
- **The efforts to lower the emittance of electron source**
  - photocathode
  - beam dynamics
  - gun technology
  - laser shaping
- **Summary**

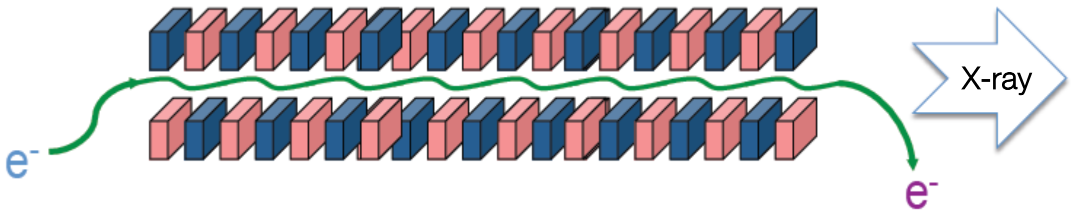
Motivation for Low emittance Electron Beams







Linac based new light sources have strong requirement for low emittance in order to operate at a certain wavelength or achieve high brightness



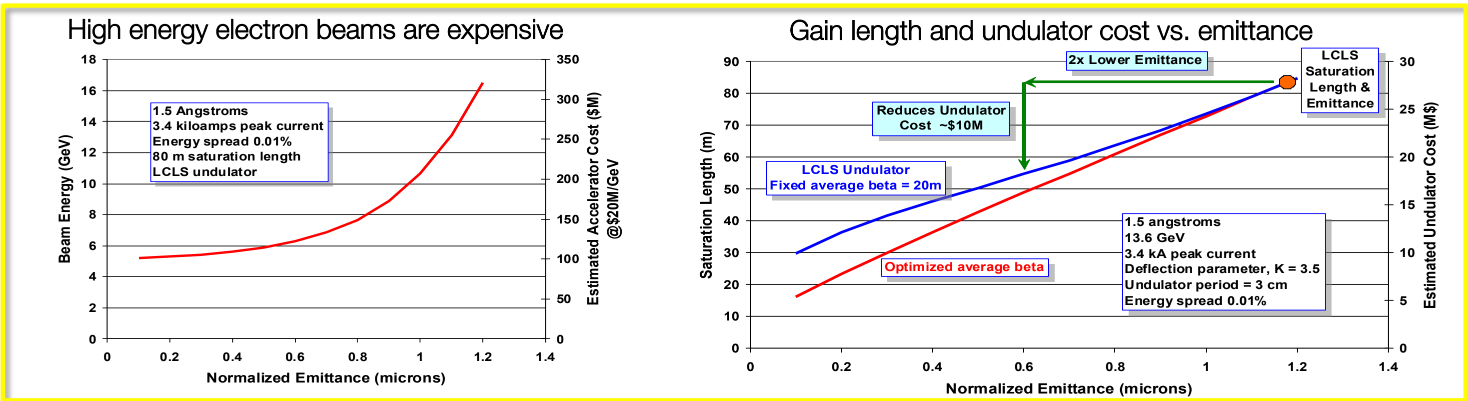
$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda_{rad}}{4\pi}$$

ε_n : normalized emittance

γ : the reduced beam energy

λ_{rad} : FEL radiation wavelength

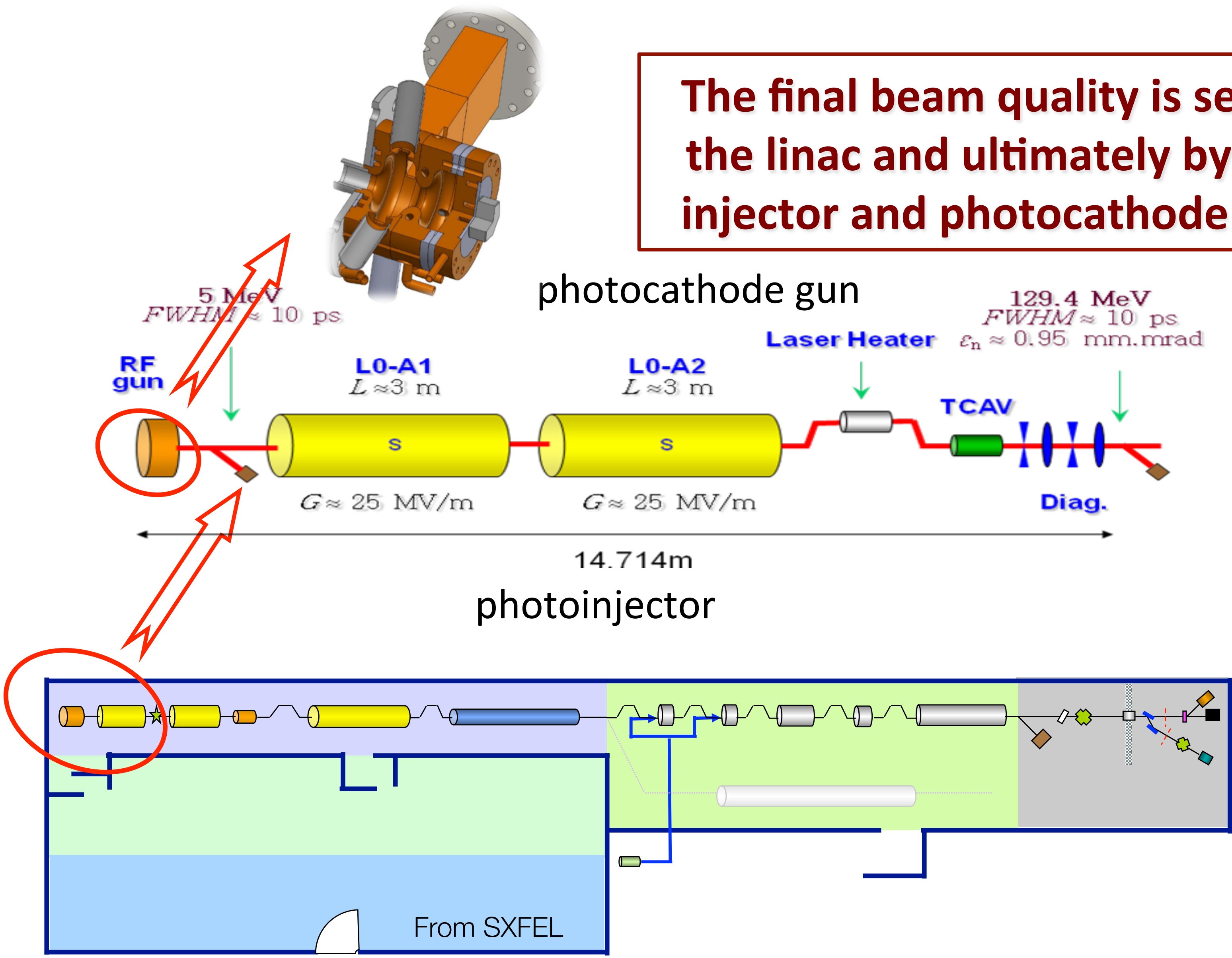
Economics of the FEL facility also demand low emittance



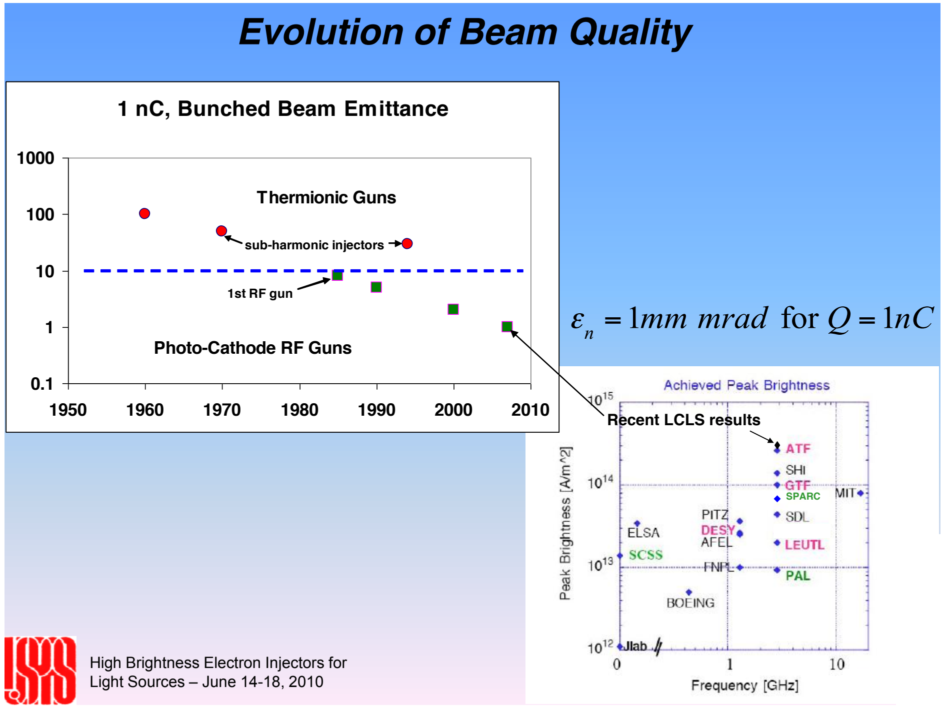
D. H. Dowell -- P3 Workshop, 2010

The Role of the Photocathode RF gun

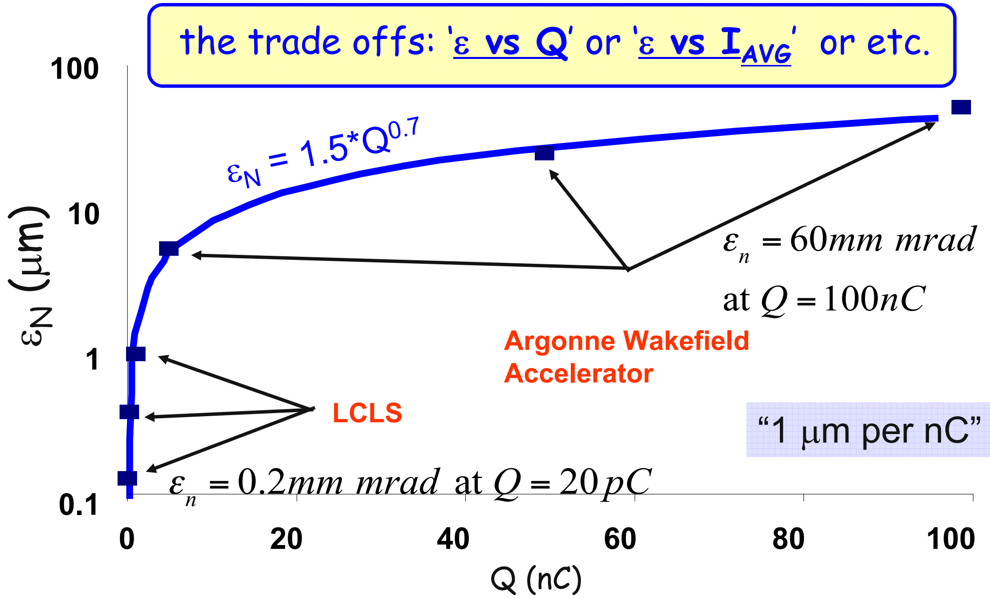
The final beam quality is set by the linac and ultimately by the injector and photocathode gun



Where we are

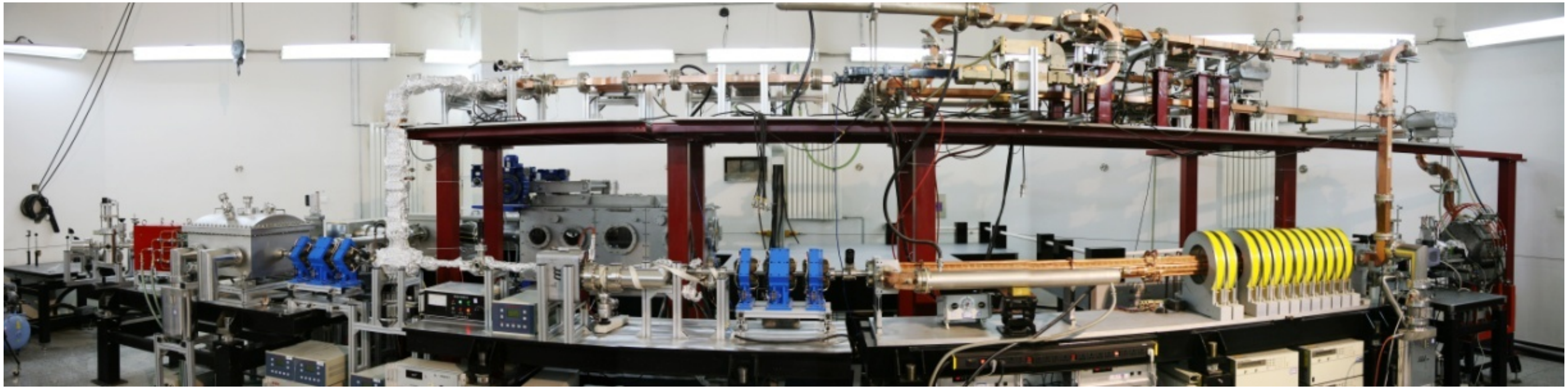


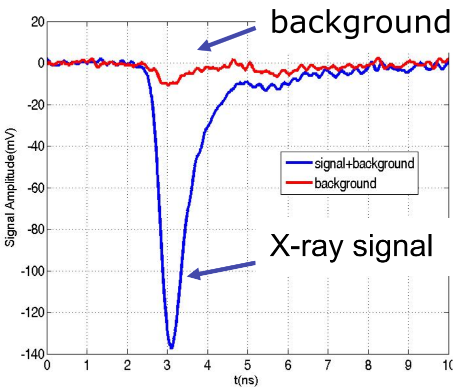
D. H. Dowell , High Brightness Electron Injectors for Light Sources-2010

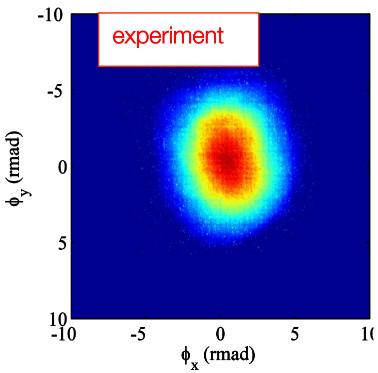


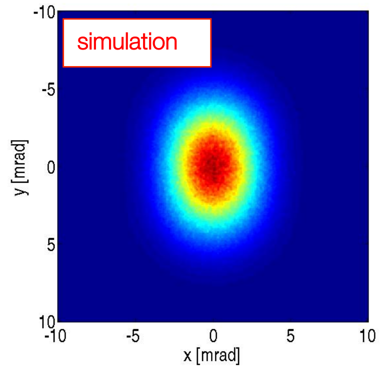
John Power, Advanced Accelerator Workshop 2010

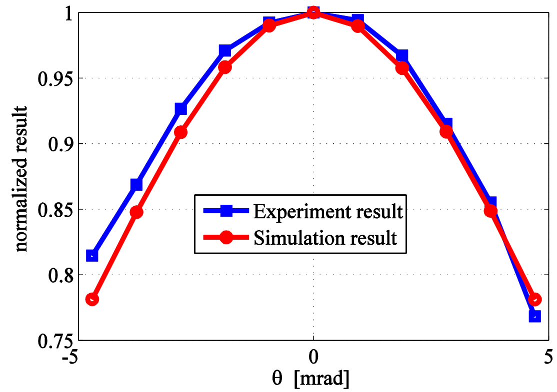
Tsinghua Thomson scattering X-ray source (TTX)









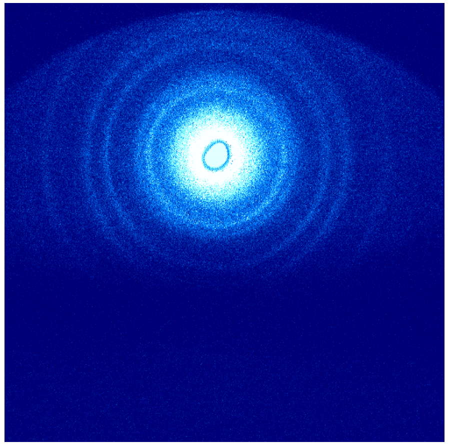


$$N_X = C_{off} \frac{N_e N_l}{2\pi} \Sigma_{th} \frac{1}{\sigma_{ex}^2 + \sigma_{lx}^2}$$

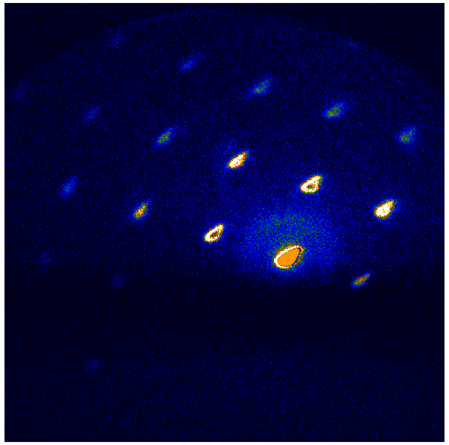
$$\boxed{B_x = \frac{3n_x \cdot 0.1\% \cdot \gamma^2}{2 \cdot 2.36\sigma_T/100fs \cdot \varepsilon_{n,x}\varepsilon_{n,y}/(1mm \cdot mrad)^2}}$$

$$\Delta u_{\perp} = \frac{\varepsilon_n}{\sigma_{ex}} \leq 0.05$$

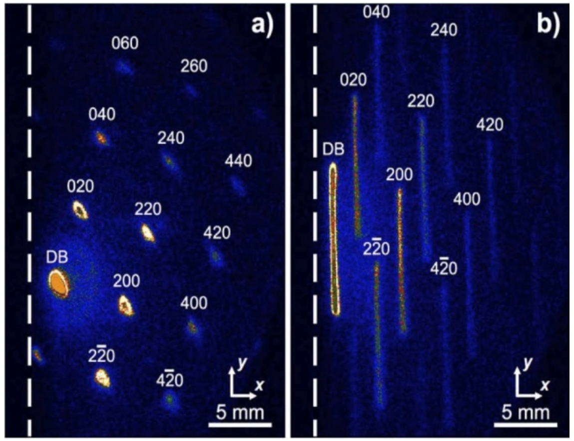
MeV ultrafast electron diffraction



single-shot diffraction pattern with Al foil sample



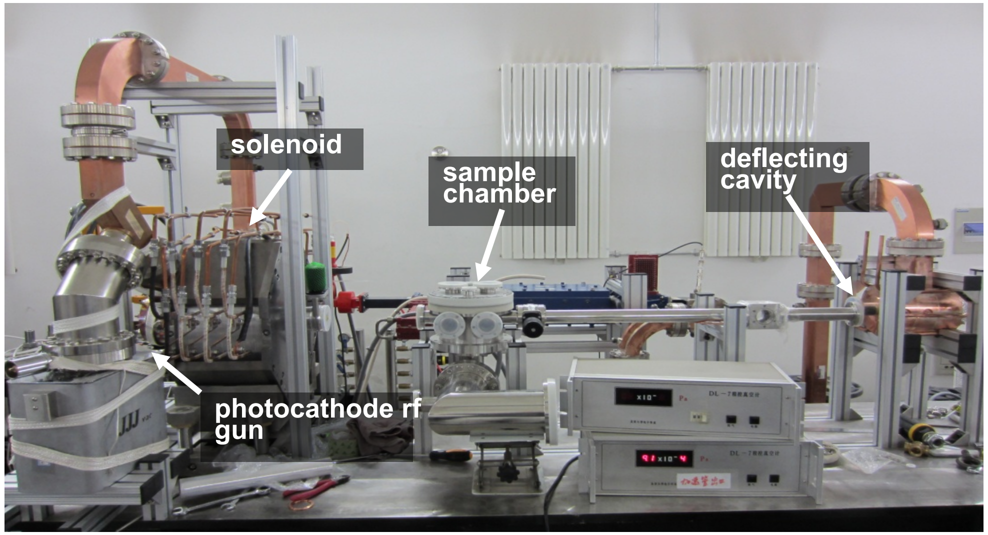
single-shot diffraction pattern with Au foil sample



Streaking an electron diffraction pattern

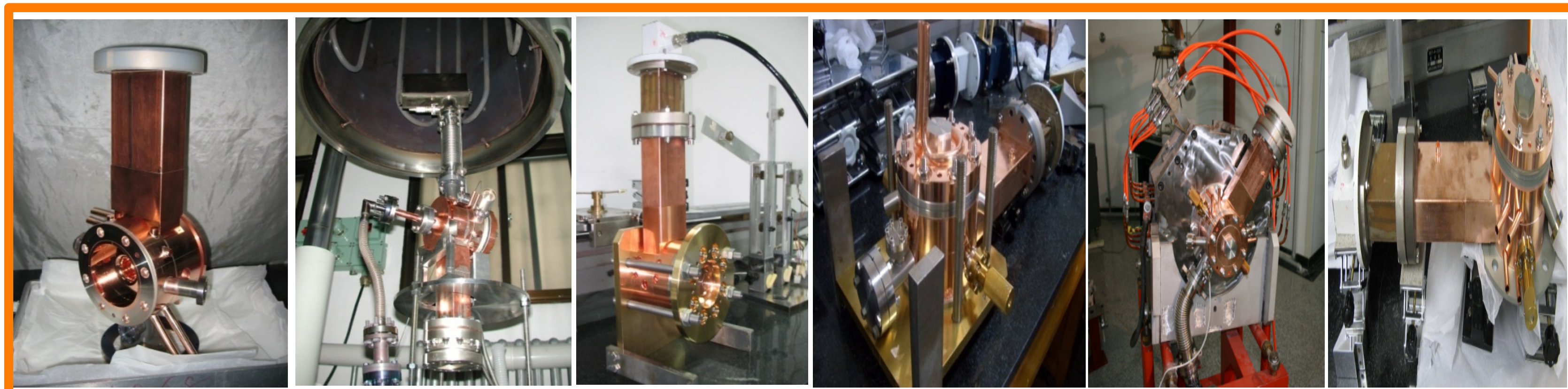
Improving resolution in diffraction patterns: low emittance beams with low charge

R&D on MeV UED at Tsinghua Univ. since 2009



a new dedicated FRED system under commissioning now

6 PC guns were developed

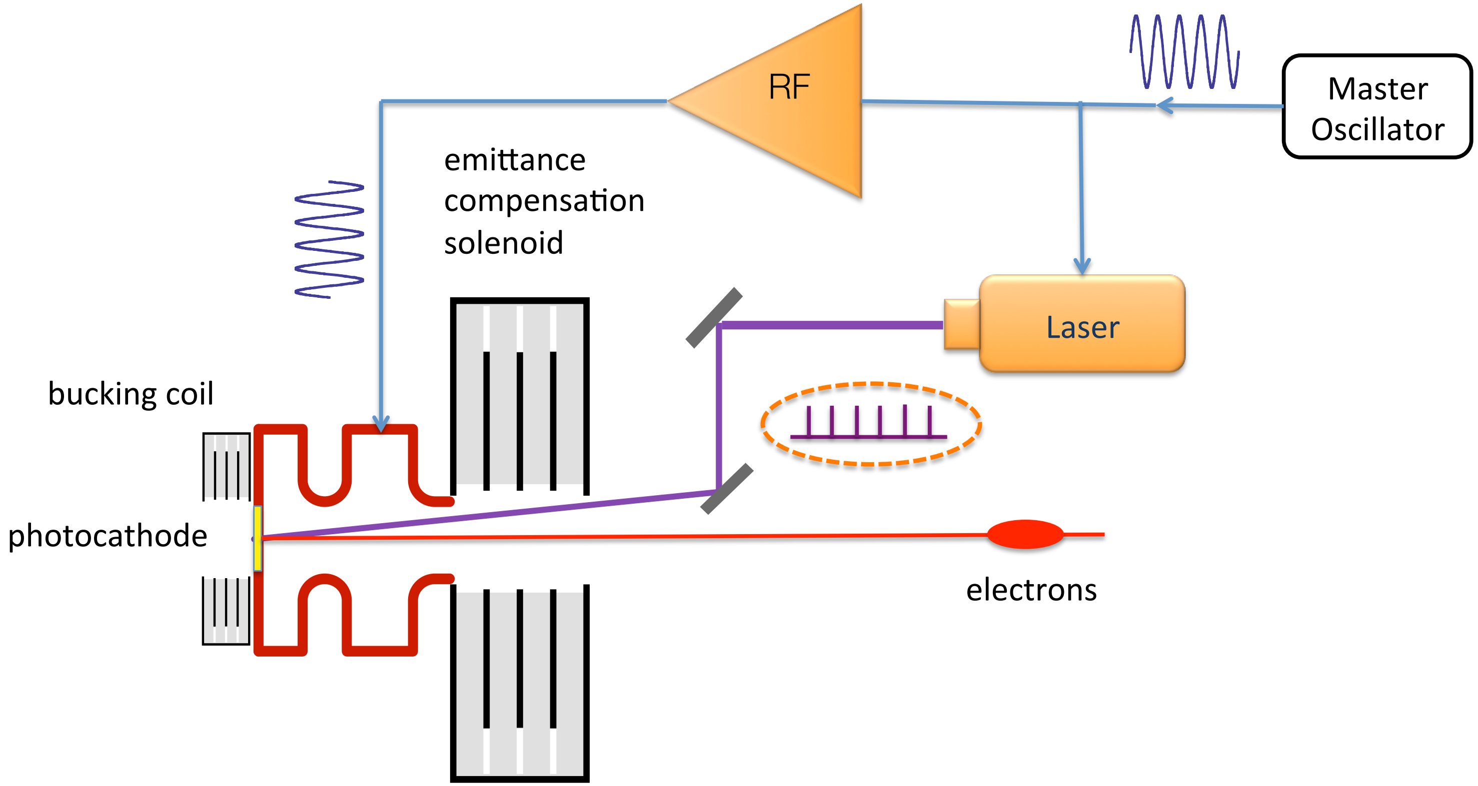


From 2002 to 2012

- TTX at Tsinghua
- DUV FEL at SINAP
- MeV UED at BNL
- High brightness beam research at University of Science and Technology of China
- MeV UED at Tsinghua

The efforts to lower the emittance of electron source

Main components of electron source using PC RF Gun



- Photocathode
- Gun cavity
- Drive laser
- Beam dynamics
- Power source
- Solenoid
- Diagnostics
- …

Commonly used photocathodes for RF guns

A good photocathode with:

- High quantum efficiency
- Better to be driven by visible light
- Long lifetime
- Low intrinsic emittance
- Vacuum robust
- Prompt response time

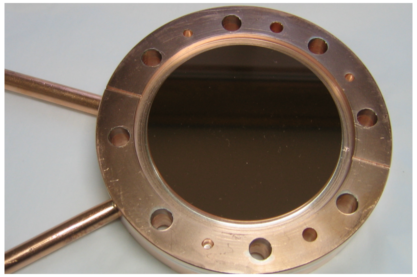
Commonly used photocathodes for RF guns

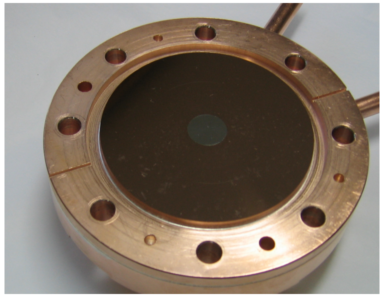
- Metals
  - Bare metal: Cu, Mg, Pb, Y,Nb, …
  - Coated metal: Cu-CsBr, Cu-MgF2, Cu-Cs, W-Cs, …
- Semiconductors
  - PEA mono-alkali: Cs_2Te, Cs_3Sb, K_3Sb, …
  - PEA multi-alkali: K_2CsSb, Na_2KTe, …
  - NEA: Cs:GaAs, Cs:GaN, Cs:GaAsP, …
- …

Not including field emitters and thermionic cathode

Metal cathodes

High peak brightness RF guns often use metal cathodes
the prominent example is Cu (simplicity) and Mg (higher QE)





Advantages

- fast response
  - fs pulse capability, application for high peak brightness beams
- long operational lifetime
  - in-situ cleaning for QE recovery: Laser, H ion or Ozone cleaning
- Tolerant of poor (nTorr) vacuum

Disadvantages

- High work function, requires UV light
- Typical QE of 10^{-5} (Cu) to 10^{-3} (Mg)

Semiconductor cathodes

The primary candidates to high average brightness photocathode RF guns

Advantages

- High QE, ~10%
- May use visible light (K_2CsSb…)
- Polarized electrons possible (GaAs)

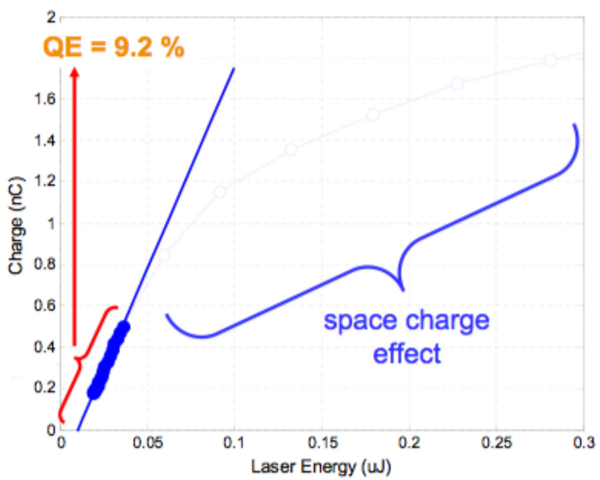
Disadvantages

- UHV conditions, 10^-10 torr
- Limited Lifetime
- Sensitive towards contamination

Examples of semiconductor cathode

Cs_2Te

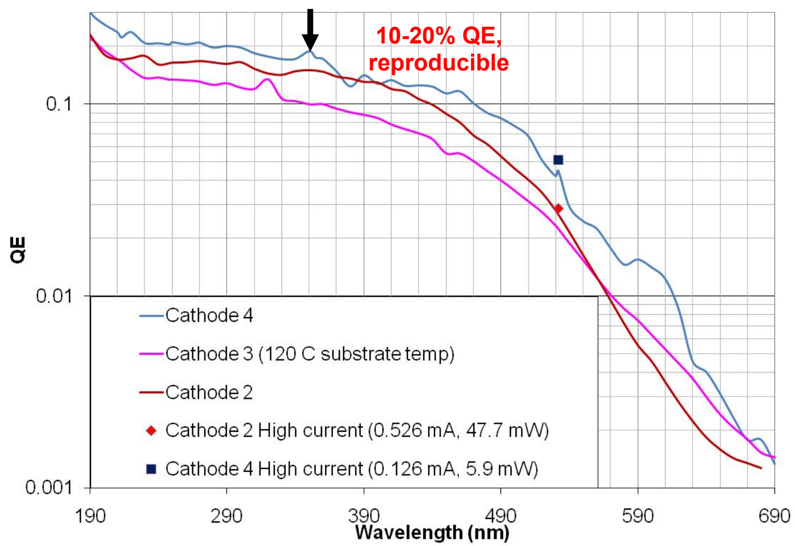
- High QE, 10% at UV
- ~ps response time
- Long life time, months with QE>1%
- Survives in high electric field
- Capable to produce high current density
- UHV conditions, 10^-9 torr
- Requires UV laser
- Sensitive to contamination



Sven Lederer, Workshop on Photocathodes for RF guns 2011

K_2CsSb

- High QE, 15% at 532 nm
- Fast response time
- RF gun tested 32 mA average beam current at 25% duty factor
- UHV conditions, 10^-10 torr
- life time, hundreds of hours
- Sensitive to contamination

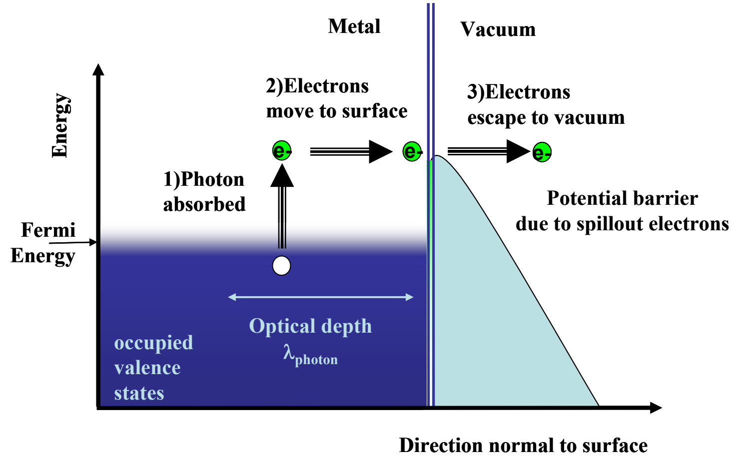


T. Rao, FLS2010

Photoemission Theory

Three-step model

1. Electron is excited with absorption of photon
2. Electron transit to surface
3. Escape from surface

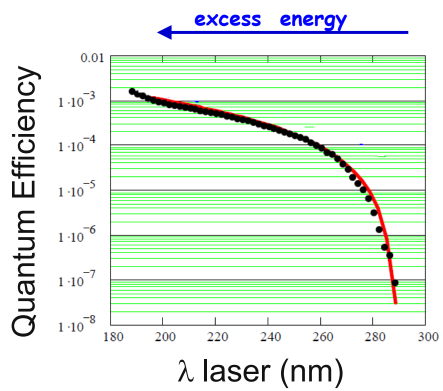


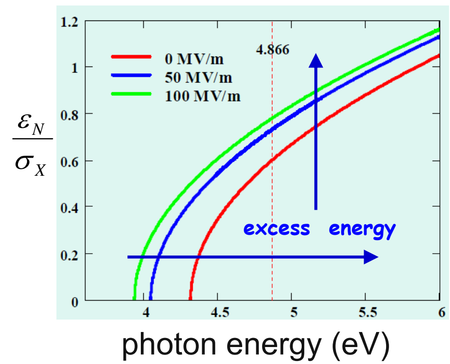
Applied to photocathode

- Predicts QE and intrinsic emittance of cathode
- in good agreement with experiment

$$QE \approx \left[\frac{1-R(\omega)}{1+\frac{\lambda_{opt}}{\bar{\lambda}_{ee}}}\right]\left[\frac{\left(E_F+\hbar\omega\right)}{2\hbar\omega}\right]\left[1-\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]^2$$

$$\frac{\varepsilon_{metal,n}}{\sigma_x} = \sqrt{\frac{\hbar\omega-\varphi_W}{3mc^2}}$$





Beyond the present Three-Step Model

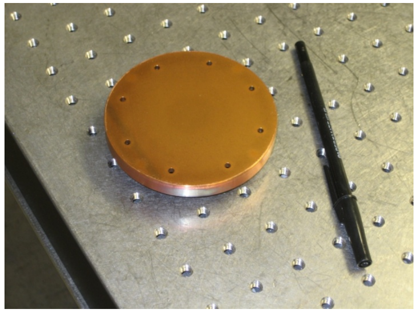
- Consider once-scattered electrons, electron heating, Space Charge, band bending effects…
- Spatial variation in reflectivity, field, work funtcion
- Incorporate dark current models
- …

Krolikowski and Spicer, Phys. Rev. 185 882 (1969)
D.H.Dowell,J.F.Schmerge,Phys.Rev.Spec.Top.Accel.Beams 12 074201 (2009)
L. Jensen et al., J. Appl. Phys. 104, 044907 (2008)

Coated metal cathodes

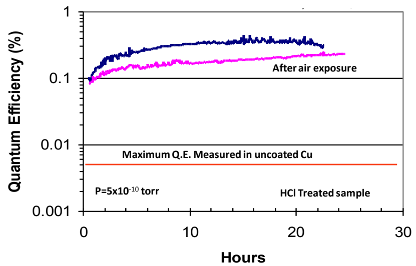
Metal cathodes with coating to lower work function or increase photon absorption

- UCLA, MgF_2 coated Cu
  - Improves scratch resistance, act as anti-reflective coating
  - Reduce reflectivity @ 800 nm from 80% to 15 %
  - Applied to multiphoton emission



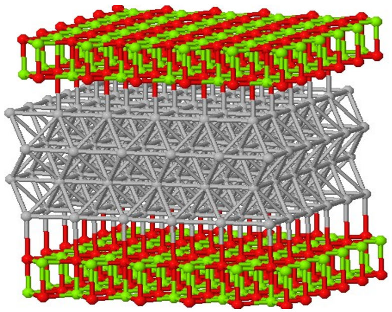
Pietro Musumeci, P3 workshop, 2010

- SLAC, CsBr coated Cu
  - 50 times higher QE
  - intrinsic emittance and QE following the 3 step model
  - survived short pulse operation without ablation



Juan R. Maldonado, P3 workshop, 2012

- ANL, MgO coated Ag(001)
  - Reduce work function from 4.64 eV to 2.92 eV
  - tune the shape of the surface bands and thus the emittance (sensitive to number of overlayers)



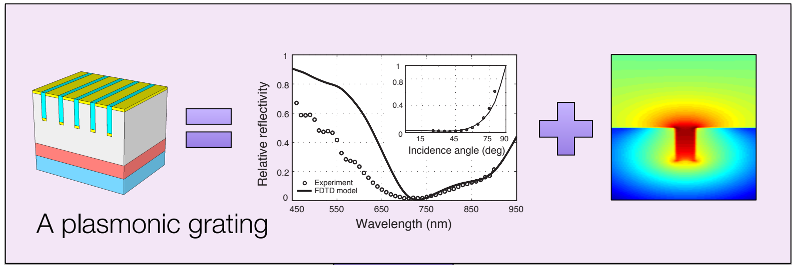
Coloring of atoms:
Mg
O
Ag

Károly Németh, P3 workshop, 2010

Novel cathode operation

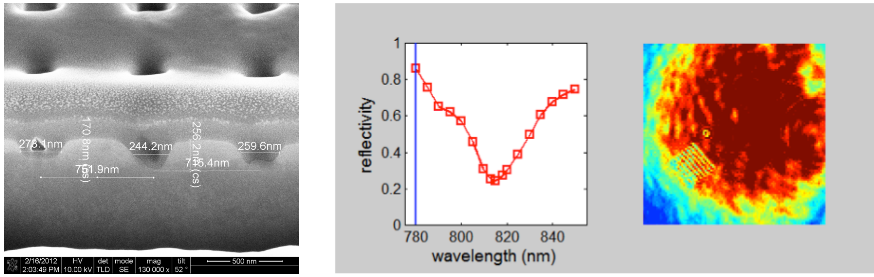
Nanostructured and plasmonic cathodes (MIT, BNL, LBNL, UCLA)

- Tunable plasmonic nanostructures for strong absorption and field enhancement

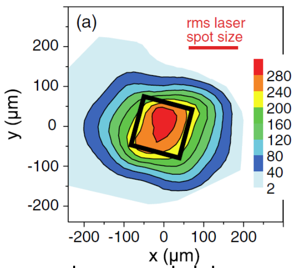


Aleksandr Polyakov, Photocathode Physics for Photoinjectors 2012

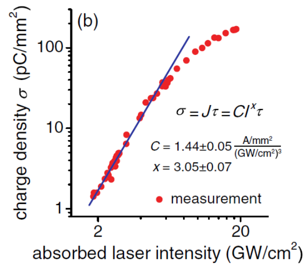
- Putting the nano-structure into a real gun



P. Musumeci and R. K. Li, Photocathode Physics for Photoinjectors 2012



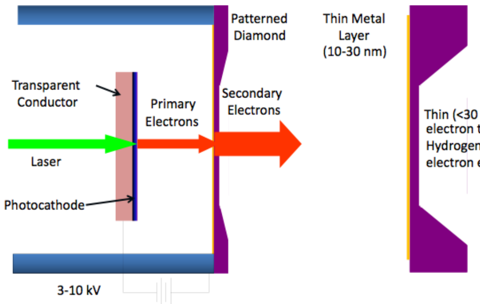
charge yield map

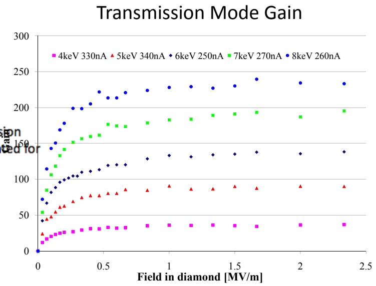


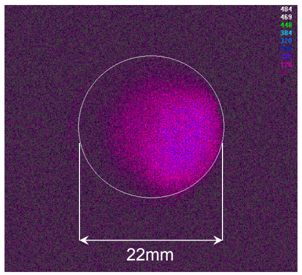
3-photon process

Diamond Amplifier cathode (BNL)

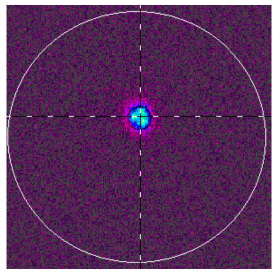
- Secondary current can be >178x primary current
- Diamond acts as vacuum barrier







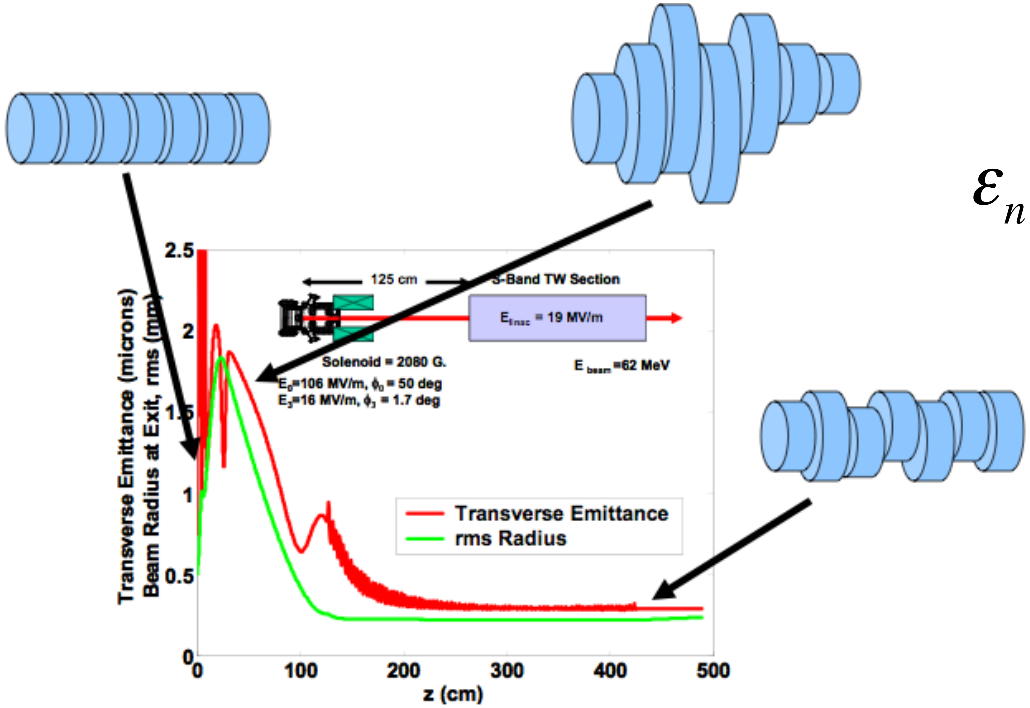
Without focusing



With focusing and reduced primary current

John Smedley, Workshop on Future Light Sources 2010

Emittance compensation



$$\varepsilon_n \approx \sqrt{\varepsilon_{thermal}^2 + \varepsilon_{dynamics}^2}$$

S. Lidia, High Brightness Electron Injectors for Light Sources,2007

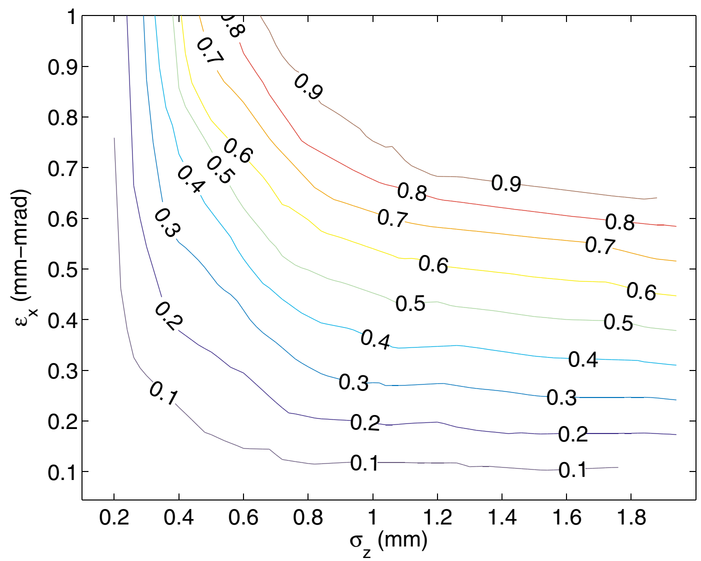
- Decrease non-linear force as small as possible
- Tune the phase of the emittance oscillation of slice by controlling the focusing parameters, reduce the project emittance due to slice depend linear force
- Place the accelerating tube in proximity of the minimum, the project emittance is frozen at its minimum value

B. E. Carlsten, Nucl. Instr. and Meth. Phys. Res., Sect. A 285, 313 (1989)
L. Serafini, and J. B. Rosenzweig, Physical Review E 55, 7565 (1997)

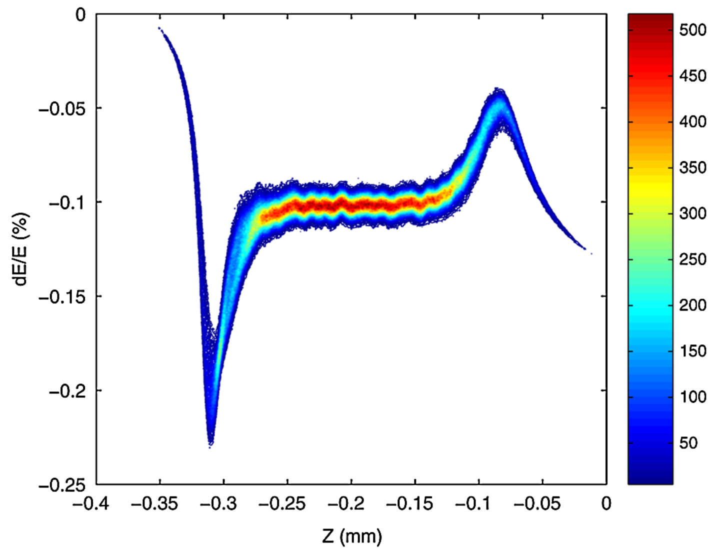
Simulation tools

- The space charge fields and RF gun components are generally nonlinear
- Accurate evaluation of nonlinear effects can be achieved only by simulation tools
- Some of commonly used codes

  ASTRA, GPT, IMPACT-T, PARMELA, HOMDYN
- Finds the globally optimal solution with Multiobjective genetic algorithms
- 1 to 1 particle representation by large numbers of particles simulation



Ivan V. Bazarov et al., Phys. Rev. ST Accel. Beams 8, 034202 (2005)

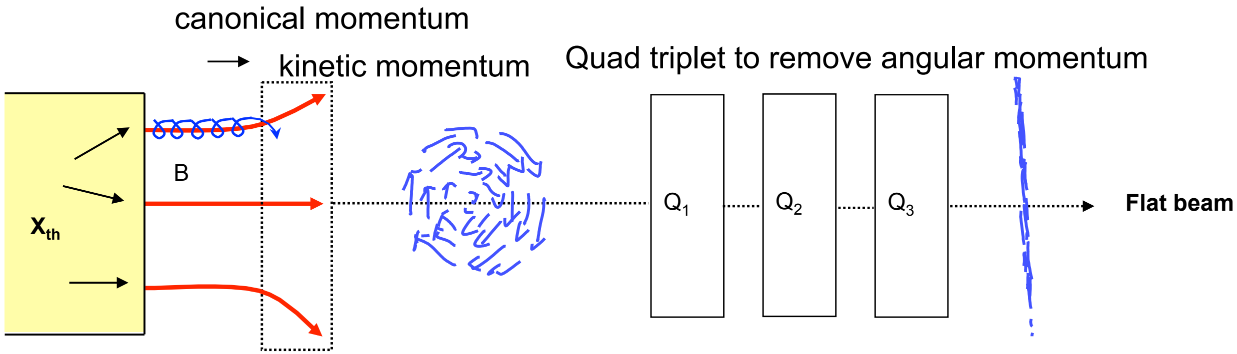


Ji Qiang et al., Phys. Rev. ST Accel. Beams 12, 100702 (2009)

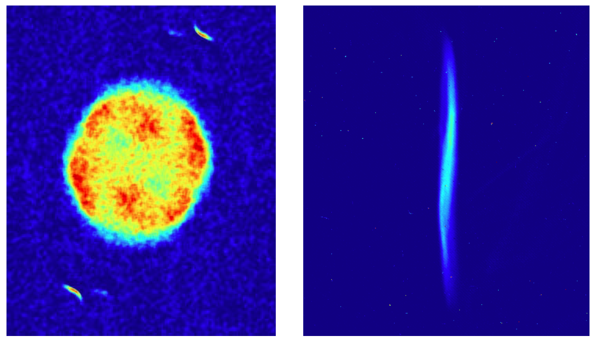
Emittance Manipulation

- The longitudinal emittance from photoinjector is much better than needed for FEL
- Make $\varepsilon_x >> \varepsilon_y$ using flat beam technique, and ε_y is small enough
- With emittance exchange equipment, make ε_x exchange with ε_z, let ε_x and ε_y both small enough

Flat Beam Generation

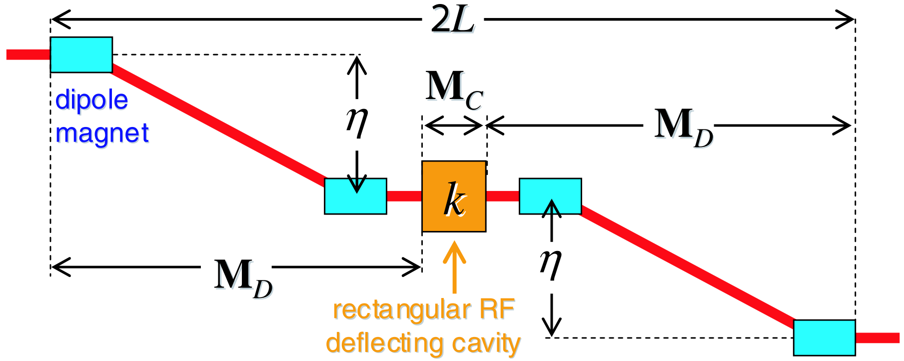


Picture from "Kwang-Je Kim, ICFA Mini-workshop on Deflecting/Crabbing Cavity and Applications, 2012"



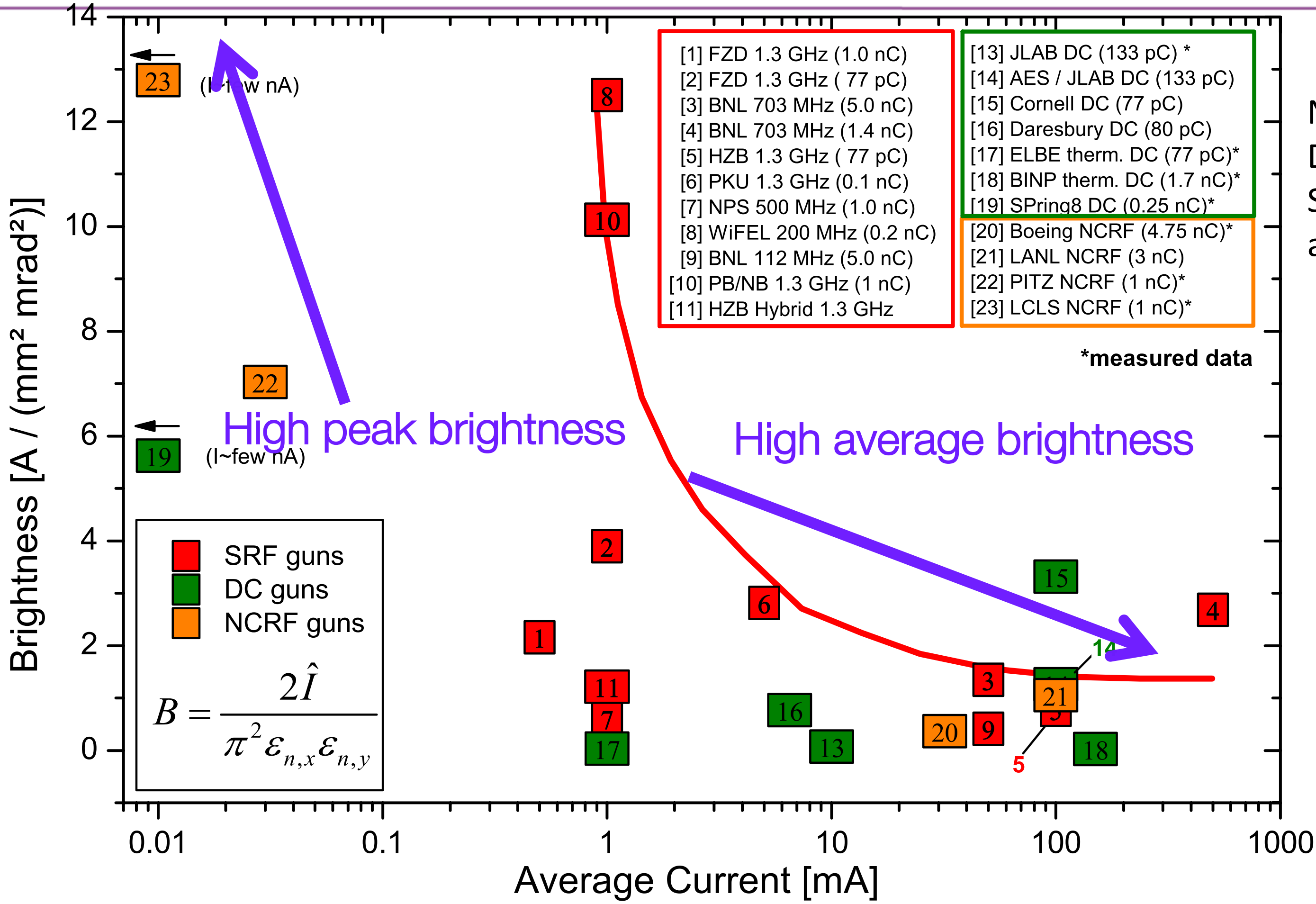
Ph. Piot et al., Phys. Rev. ST Accel. Beams 9, 031001 (2006)

Horizontal-Longitudinal Phase Space Manipulation



P. Emma et al., Phys. Rev. ST Accel. Beams 9, 100702 (2006)

Gun technology



NCRF mature for FELs
DC proved to be ERL compatible
SRF upcoming technology for FEL and ERL

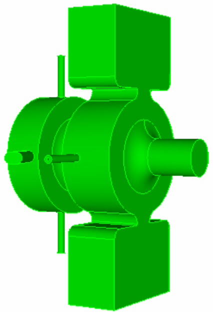
A. ARNOLD AND J. TEICHERT, Phys. Rev. ST Accel. Beams 14, 024801 (2011)

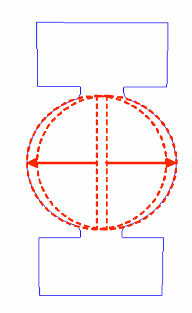
- The choice of technology depends on the application
  NCRF guns, DC guns, SRF guns
- High gradient at cathode is prefered

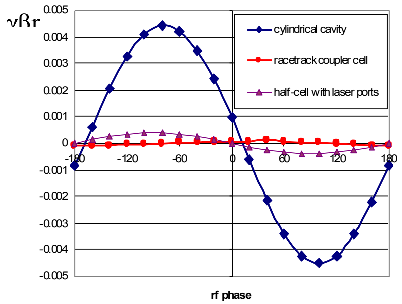
$$\frac{B_n}{f} = \frac{mc^2\varepsilon_0 E_{cathode}}{2\pi kT}$$

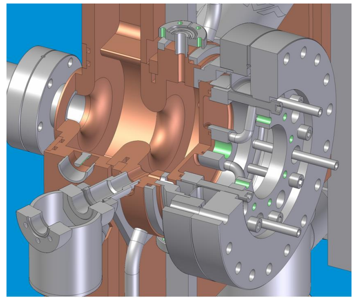
I. V. Bazarov et al., PRL102, 104801 (2009)

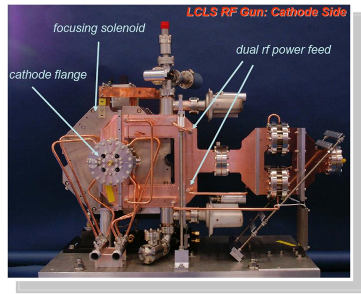
LCLS S-band RF gun











Design Features

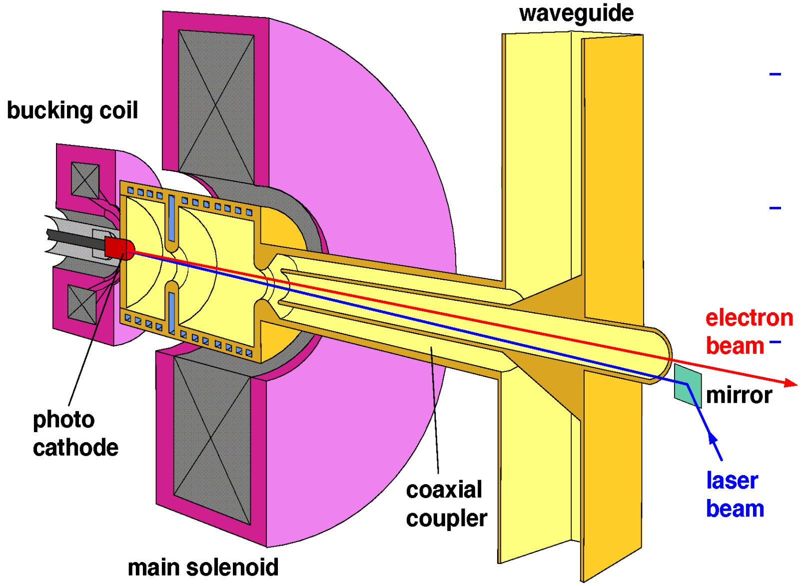
- Minimize RF mode beating with increased 0 and π mode separation
- Eliminate dipole and quadrupole RF fields with dual RF feed and racetrack shape in full cell
- Adopt z-coupling to minimize pulsed heating for long gun life
- Improved cooling for 120 Hz operation at up to 140 MV/m
- Cathode surface roughness <40 nm peak-to-peak, low dark current

Parameter[a]	20 pC	250 pC	1 nC	Unit
UV laser energy on cathode	1.5	20	250	μJ
UV spot diameter on cathode	0.6	1.2	2	mm
UV pulse duration (fwhm)	4.0	6.5	10	ps
Injector bunch length (rms)	1.3	2.5	2.8	ps
Initial peak current	5	30	100	A
Injector slice emittance	0.14	0.6	1.0	μm
Injector projected emittance	0.20	0.7	1.2	μm
Final bunch length (rms)	~3	~30	80	fs
Final peak current	~3	~3	3.4	kA
Final projected emittance	0.4	1.0	1.5	μm
FEL pulse duration (fwhm)[b]	~2	~60	230	fs
FEL peak power[b]	~400	~20	~10	GW

[a]Emittance refers to normalized emittance; fwhm stands for full width half maximum; rms stands for root mean square.
[b]Based on simulations at 1.5 Å wavelength.

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

PITZ L-band RF gun



- Developed for FLASH and European XFEL
- 1.6 cell 1.3GHz NC rf cavity with a Cs2Te photocathode, coaxial coupler
- Dry-ice sublimation-impulse cleaning to reduce dark current by a factor of ~10

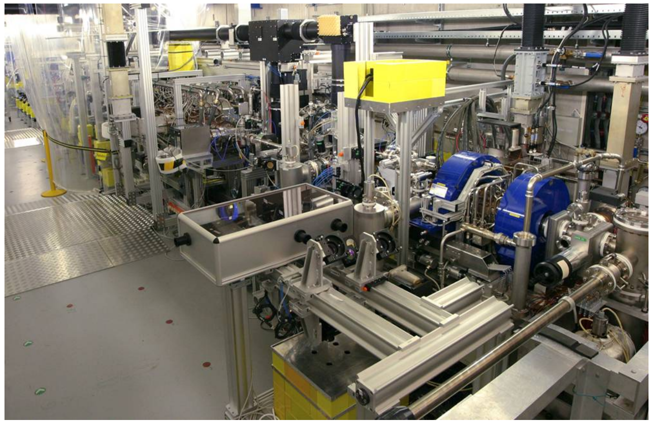
Has demonstrated key parameters for the European XFEL

- low emittance

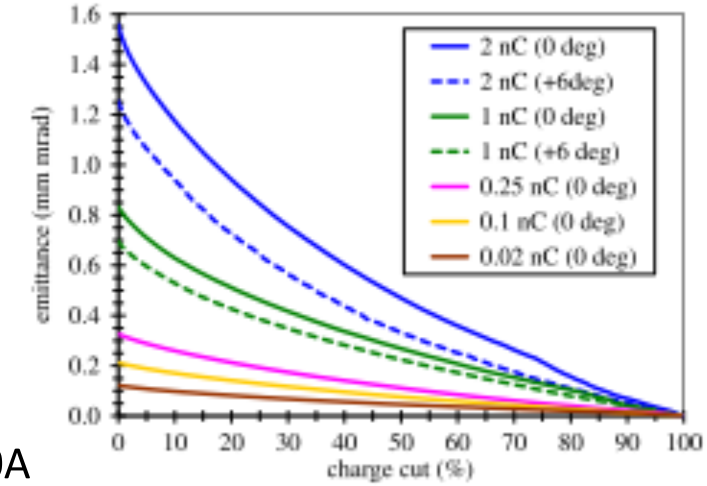
$$\varepsilon_{xy}(100\%) = (0.886 \pm 0.011)\,\text{mm mrad}$$
$$\varepsilon_{xy}(90\%) = (0.681 \pm 0.010)\,\text{mm mrad}$$
(preliminary - bunch charge 1 nC)

- high average power operation

10 Hz, 7 MW, 0.7 ms RF pulse length ~50 kW av.

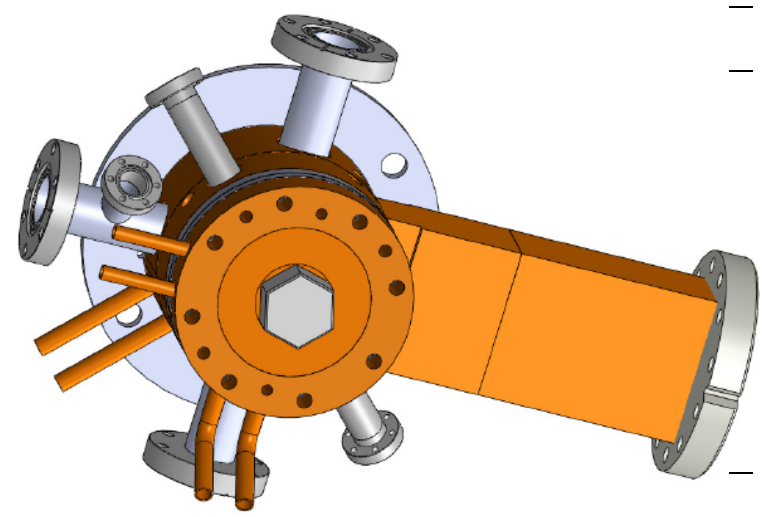


Ecath 60 MV/m, 1nC, 0.7mm-mrad, 50A



Siegfried Schreiberl, ICFA Beam Dynamics Workshop on Future Light Sources March 1-5, 2010
M. Krasilnikov et al., PRST-AB 15, 100701 (2012)

Tsinghua S-band RF gun

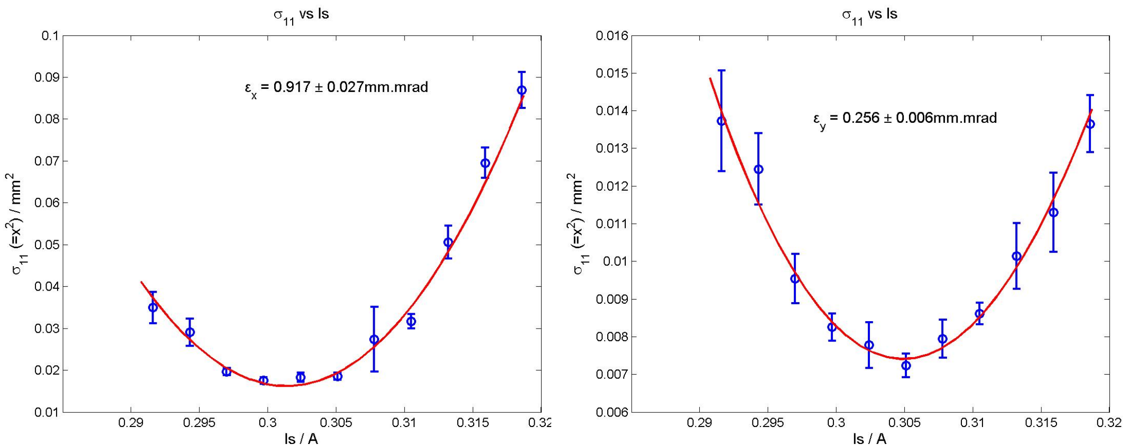


- A modified BNL type S-band photocathode RF gun
- Gun profile improvement
  - zero mode suppression
  - high Q factor

a. elliptical iris
b. curved corner
c. Larger hole

- cathode seal with matsumoto gasket
- Multipole field elimination
  - Asymmetric design of vac port for dipole field suppression
  - 4-port design for quadruple field suppression

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

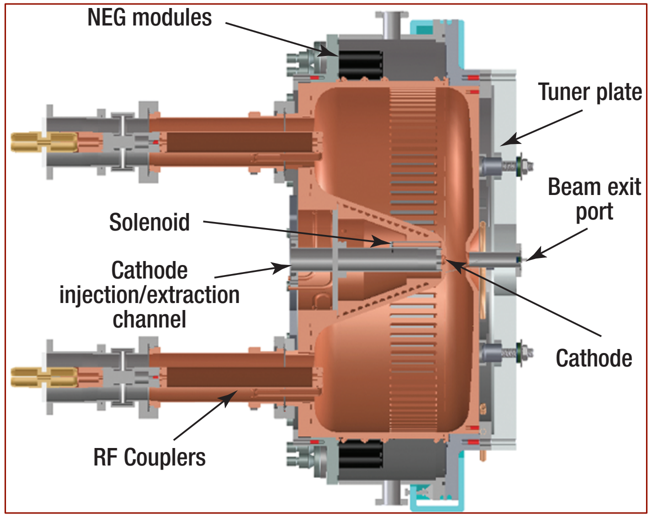


beam charge: 210pC

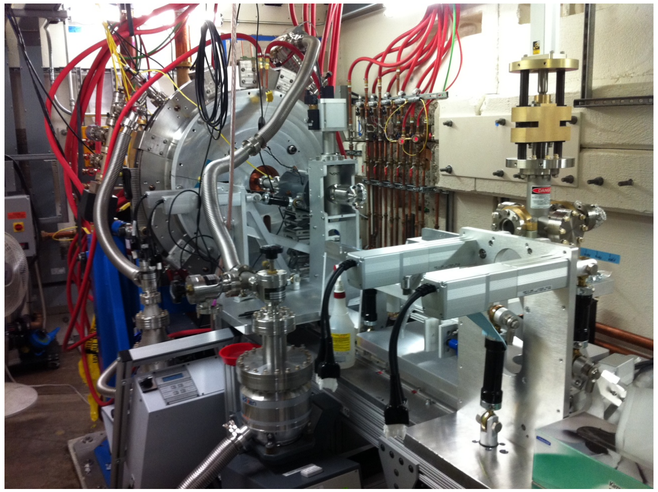
LBNL VHF RF gun

CW NCRF: the challenge is cooling for huge wall losses

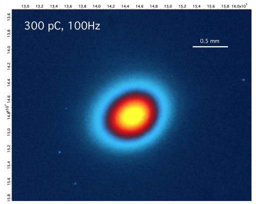
- Produce high-brightness electron beam at 1 MHz repetition rate
- Work at 187MHz, increase cooling area, plenty of pumping slots
- 10^-11 Torr vacuum capability , flexibility in photocathode materials



Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	90 kW
Stored energy	2.3 J
Peak surface field	24 MV/m
Peak wall power density	25 W/cm^2
Accelerating gap	4 cm
Diameter/Length	70/35 cm
Operating pressure	< 10^{-11} Torr



- VHF cavity is RF conditioned
- Characterization of dark current
- First beam with Cs_2Te cathode, 10kHz



John Corlett, ICFA Workshop on Future Light Sources March 5-9, 2012
D. Filippetto, PHYSICS AND APPLICATIONS OF HIGH BRIGHTNESS BEAMS,2013

SRF gun

Advantages

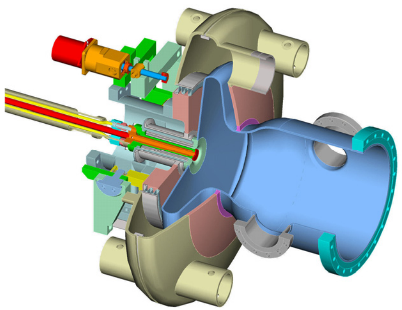
- Potential for relatively high cathode gradients (~50MV/m)
- Excellent vacuum performance which allow more cathode choices
- Produce high average current with GHz repetition rate

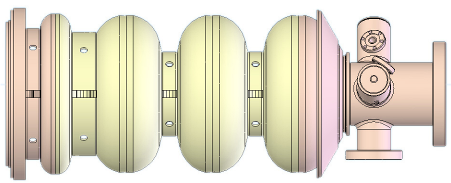
Potential limitations

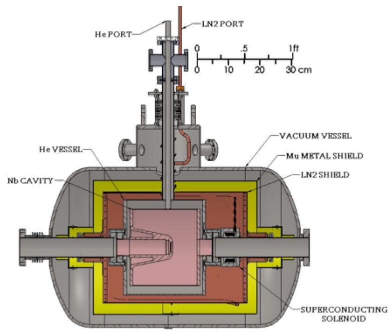
- Control the multipacting between cathode stem and cavity
- Cavity contamination from evaporated material for preparing high QE cathode
- …

Different configurations

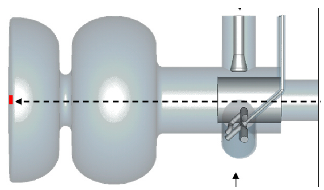
- NC cathodes + elliptical cavity
- NC cathodes + DC gap + elliptical cavity
- NC cathodes + quarter wave cavity
- Superconducting (SC) cathodes + elliptical cavity


BNL/AES cavity


PKU cavity

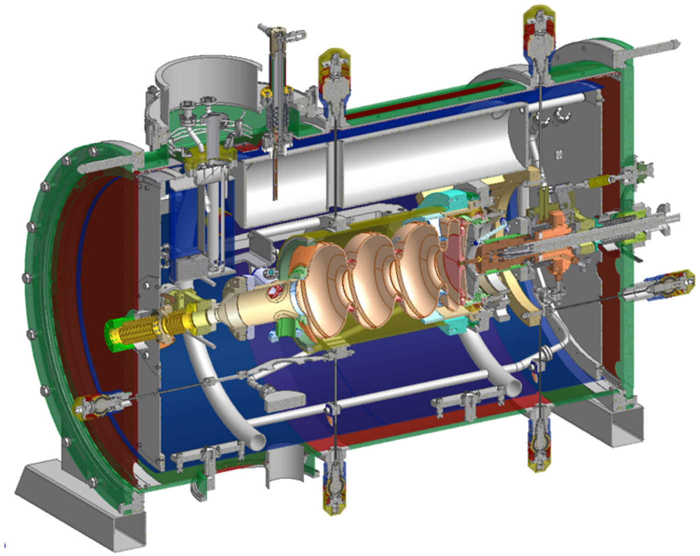


NPS cavity

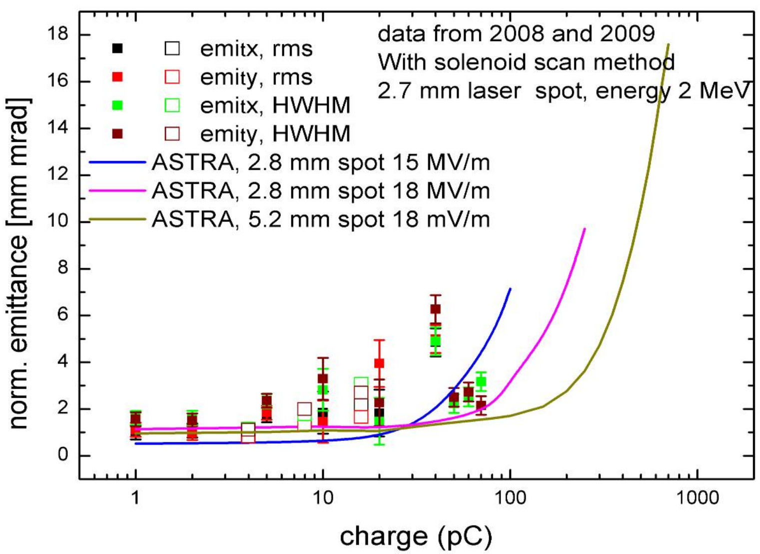

Pb/Nb hybrid SRF gun

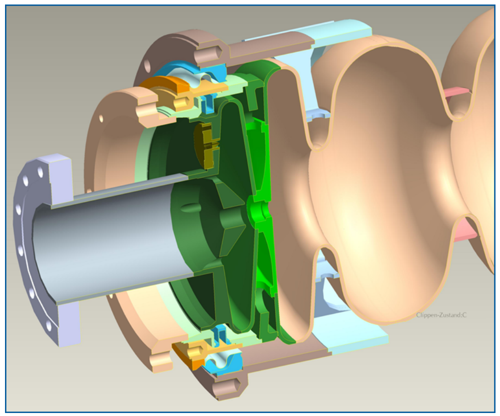
A. Arnold and J. Teichert, PRSTAB 14, 024801 (2011)

FZD SRF gun



- 1.3GHz, 3.5 elliptical cells, Cs_2Te cathode
- first beam in 2007
- Long lifetime of cathodes in SRF gun (>1 yr, total charge 35 C @ QE = 1%)
- No Q degradation since 4 years of operation
- Strong multipacting between cathode stem and cavity observed, cured by DC bias voltage and grooves
- Peak field at cathode limited by field emission to 18MV/m, gun performance not as expected
- New upgrade cavity with high gradient is ready



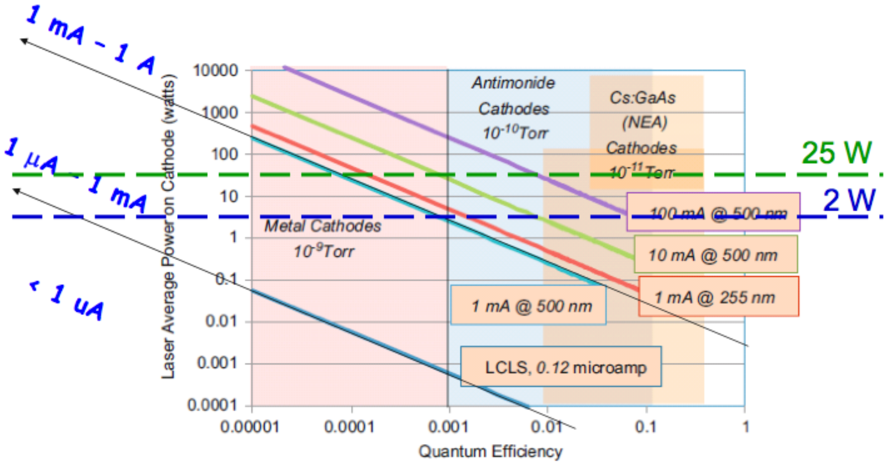


J. Teichert, ICFA Workshop on Future Light Sources March 5-9, 2012

清華大學
Tsinghua University

Drive laser for RF gun

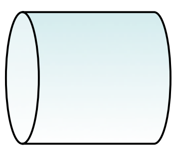
- PC guns are being driven with state-of-the-art lasers
  - 25W for near IR laser and visible,
  - 2W for UV laser



D.H. Dowell, et al., Nucl. Instr. and Meth. A (2010)
John Power, Advanced Accelerator Workshop 2010

- fundamental parameters of drive laser
  - Wavelength
    high energy for high charge, proper wavelength for low intrinsic emittance
  - limited jitters and fluctuations
  - Reliability
  - repetition rate
  - Temporal and spatial profile
    linearize the space charge forces and implement emittance compensation

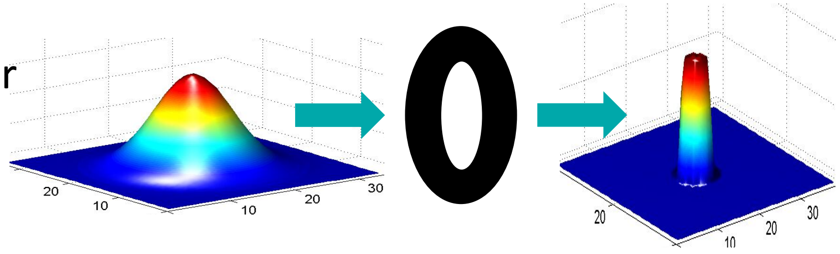
- Laser shaping for high brightness electron beam
  - optimal 3D distribution beer can or uniform filled ellipsoid



Spatial shaping

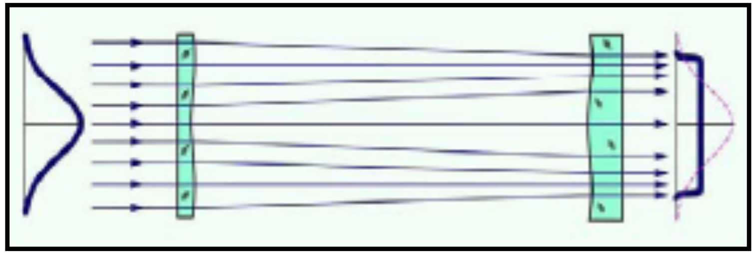
Clipped with aperture

- Overfilled aperture cuts out the inner flat part of laser beam
- lossy but simple and widespread for photoinjector application



Aspheric optics

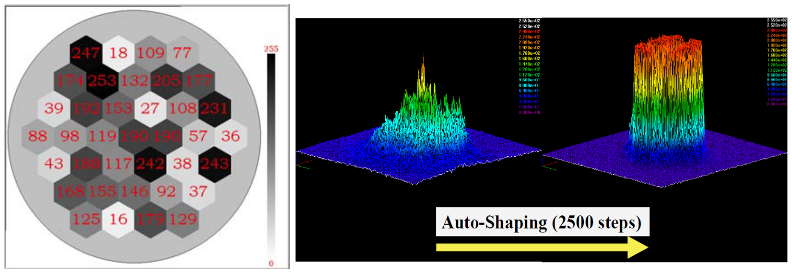
- UV Gaussian beam can be mapped into a flat-top beam by the optics system of two aspheric lens
- High transmission (90%), commercial available systems
- Very sensitive to input laser parameters

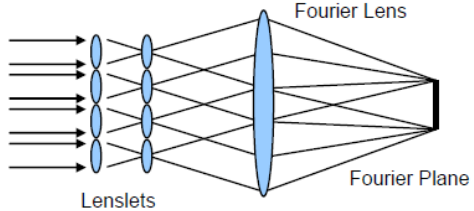


Hoffnagle et al, Appl. Opt 39, 6488 (2000)

Deformable mirror / micro-lenses array

- Deformable mirrors are formed by 2D array of movable elements , adjustable and actively controllable
- Flat-top has been demonstrated using genetic algorithm
- Reflectivity at 260 nm 70%
- Complex optimization, needs special algorithm



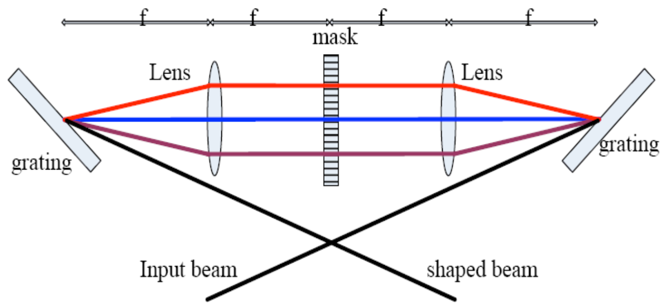


Temporal shaping

Frequency Domain Pulse Shaping

Liquid crystal mask spatial light modulator

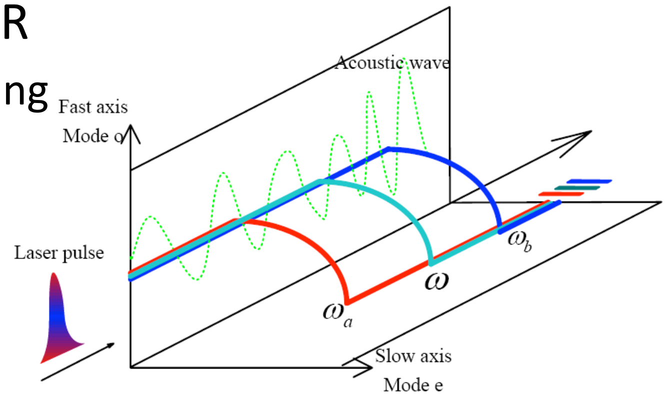
- The 4f system generates the Fourier Transform of input laser beam
- Programmable liquid crystal array placed in the Fourier plane modulate the amplitude and phase of the spectral components
- Alignment difficult and limits for tunability



A. M. Weiner, Rev. Sci. Instrum. 71, 1929 (2000).

Acusto optic programmable dispersive filter: DAZZLER

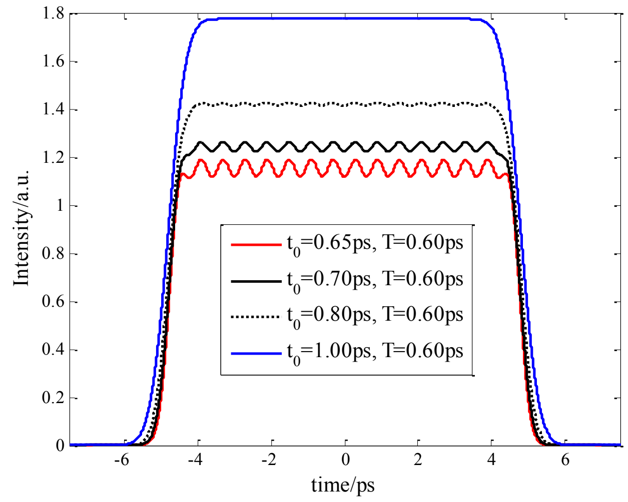
- A co-propagating acoustic generates a transient Bragg grating in a birefringent crystal (TeO_2)
- Diffraction happens at different depths for different optical wavelengths
- Optical path, or phase, is wavelength dependent
- Only up to 1kHz Rep.rate



P. Tournois et al., Opt: Comm:, 140, (1997), 245
F. Verluise et al., Opt. Lett., 25, (2000), 575

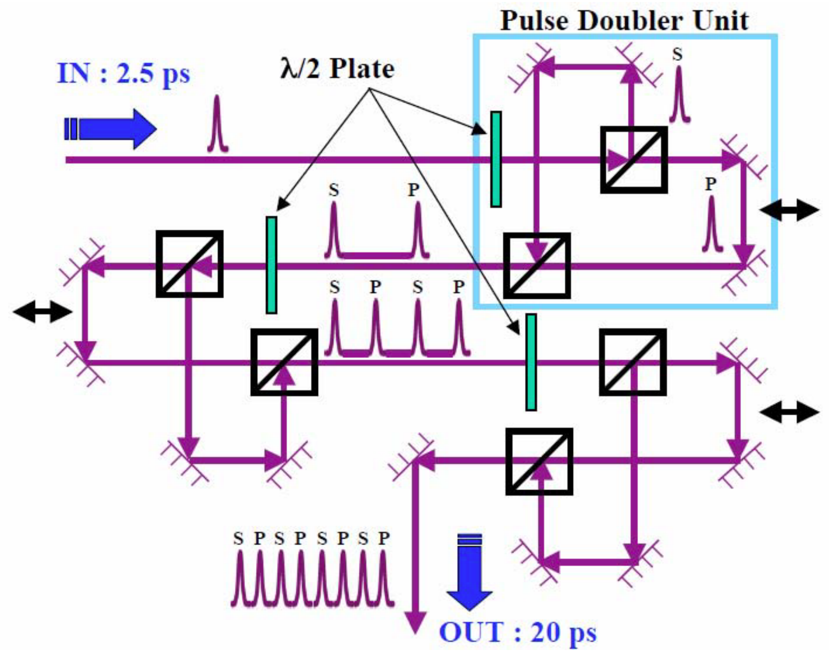
Temporal shaping

Time Domain Pulse Shaping: pulse stacking



Pulse stacking

- Split the input beam into multiple pulses, recombine and overlap them by adjusting the delay of each pulse
- The rise time and the ripples depend on the input pulse
- Interference between pulses is avoided by cross polarization



- Several "Pulse Doubler Unit" cascaded for the generation of the flat top distribution
- Alignment can be difficult

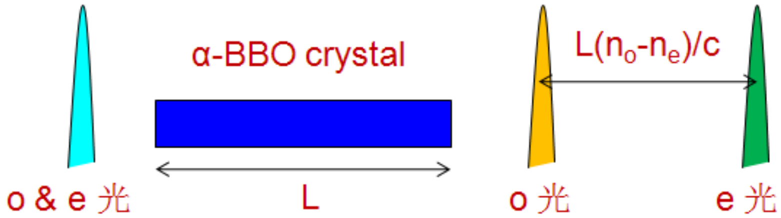
H. Tomizawa, Quantum Electronics 37, 697 (2007)

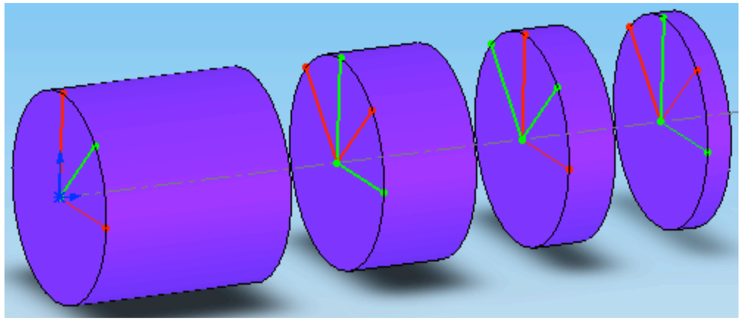
Temporal shaping

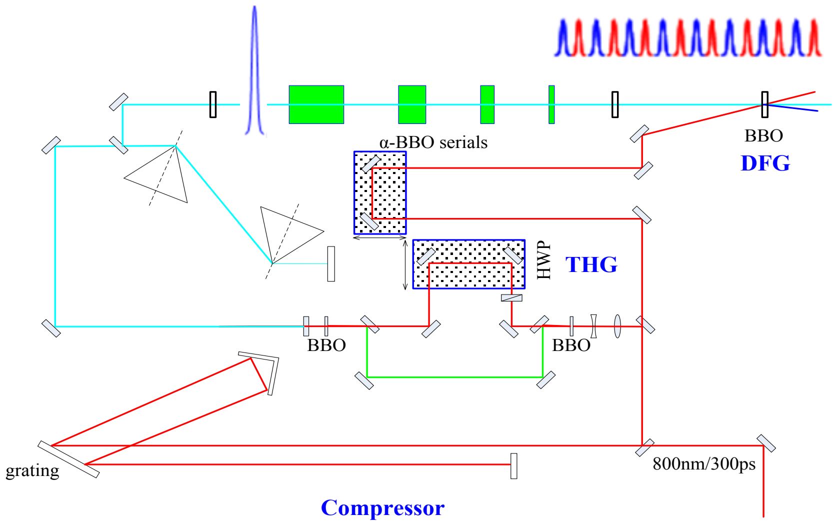
Time Domain Pulse Shaping: pulse stacking

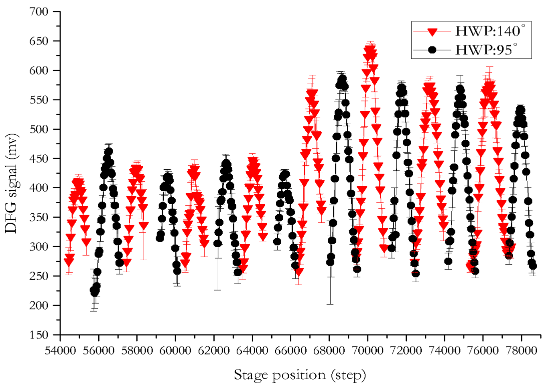
Pulse stacking

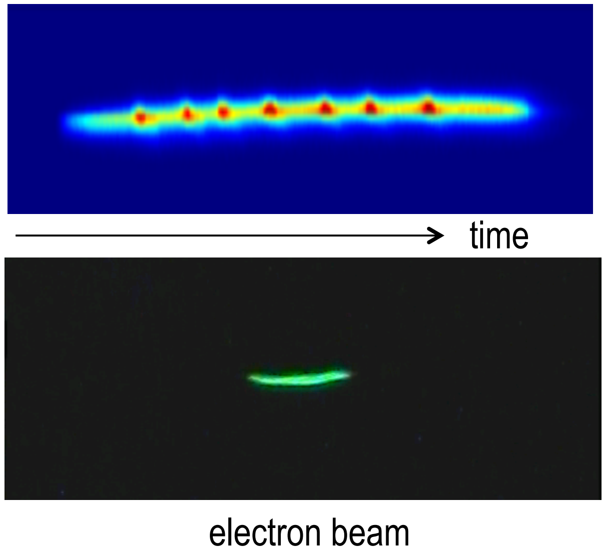
- Use birefringent crystals to generate delayed pulses along the ordinary and extraordinary axes, which reduced complexity with linear setup
- The time separation depend on the crystal length and on Δn







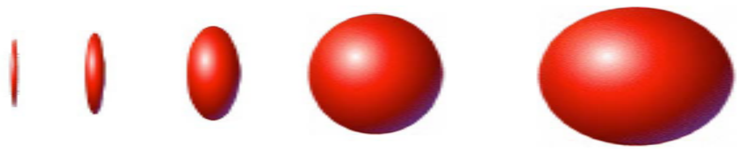




LX Yan et al., J. Plasma Physics (2012), vol. 78, part 4, pp. 429–431

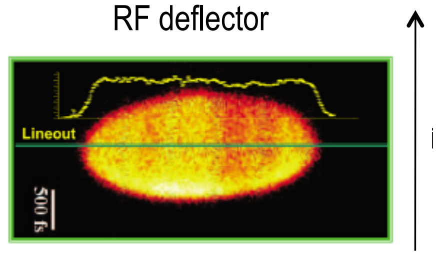
Uniformly filled ellipsoidal shaping

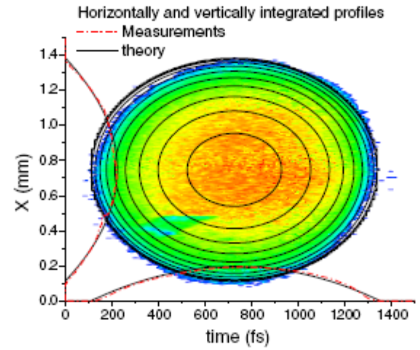
The most desired electron distribution is ellipsoidal shape



Blowout regime

- Driven with a pancake laser pulse (half-circle spatial distribution)
- Very short beam expands longitudinally under its own space charge forces, evolve into a uniform ellipsoidal beam (Serafini-Luiten)
- demonstrated up to 50 pC charge, distortion at higher charge

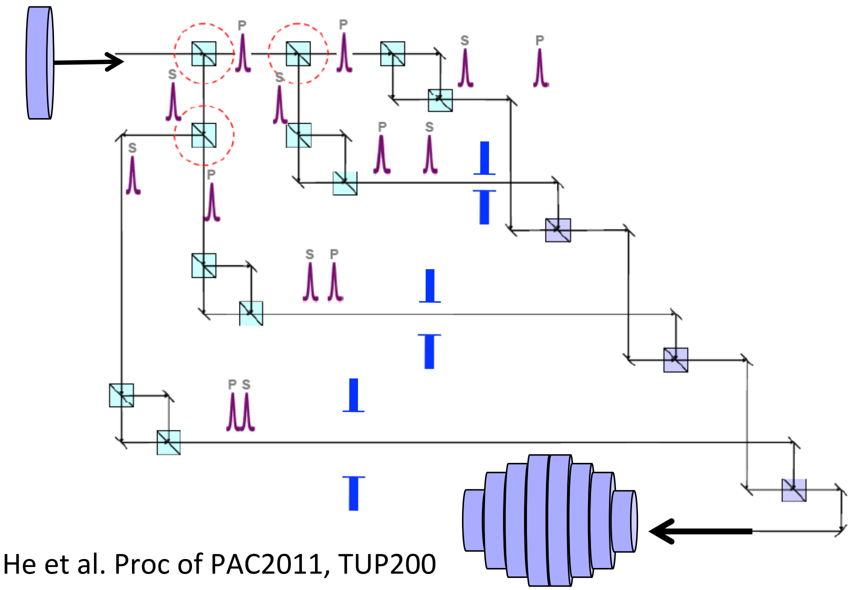




Musumeci et al., Phys. Rev. Lett. 100,

3D ellipsoid stacking

- Pulse stacking the delay laser beams that have different beam size
- Not been demonstrated yet



Z.He et al. Proc of PAC2011, TUP200

Summary

- Photocathode guns are the workhorse of new light source
- Low emittance RF guns with high average current are becoming a reality
- New technologies will lead to higher brightness beam: novel cathode, laser shaping, emittance manipulation…

Acknowledgments to:

Yingchao Du, Lixin Yan, Houjun Qian, Chuanxiang Tang(TUB)

Renkai Li(UCLA)

Gai Wei, John Power(ANL)

all members of the photocathode guns community