Overview of Photoinjectors

→ Part tutorial
→ Part recent progress

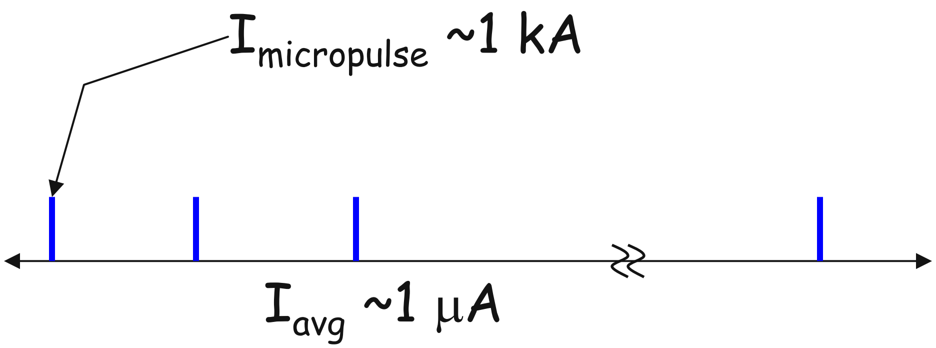
John Power
Argonne Wakefield Accelerator Group
Argonne National Laboratory

Advanced Accelerator Workshop 2010
Annapolis, MD
June 13-19, 2010

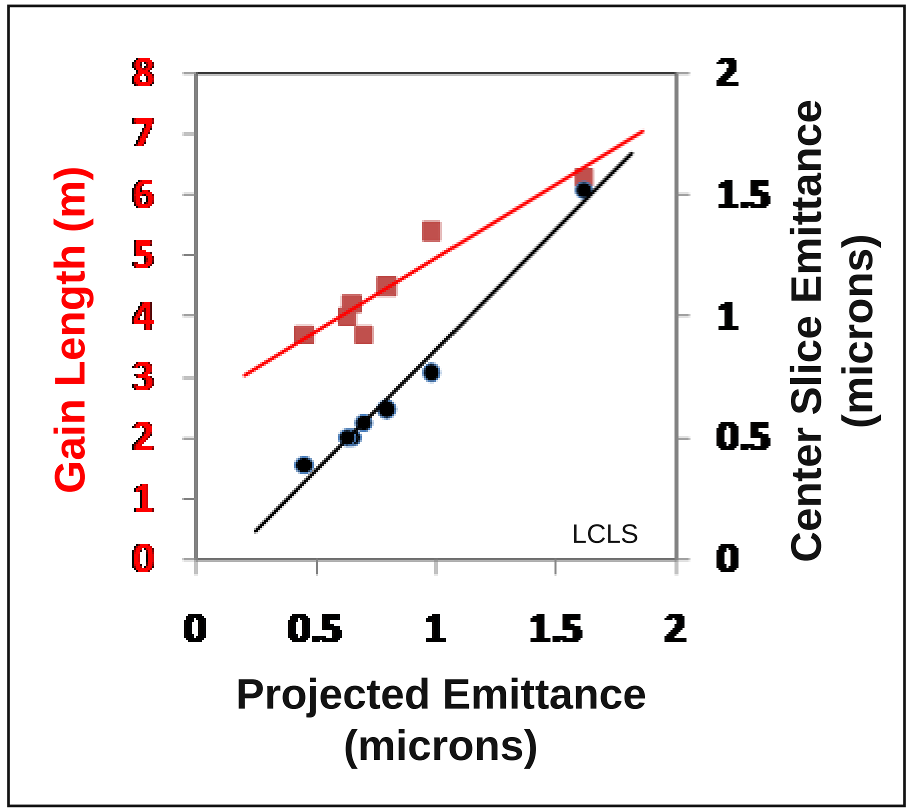
The ideal electron source…

…depends on your application

SASE FEL→ High peak current & low emittance



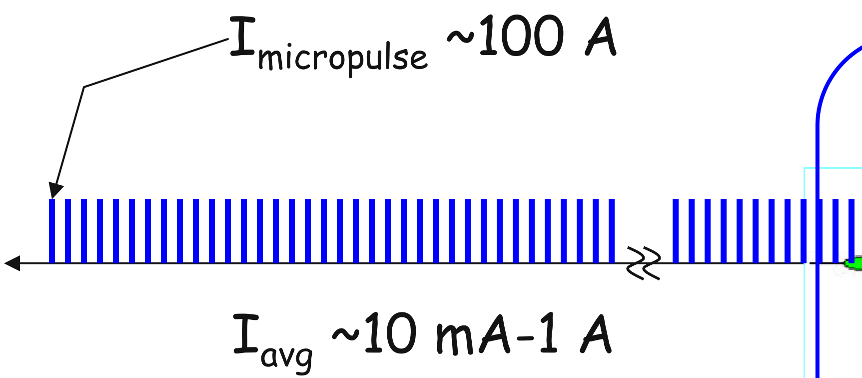
High Peak Brightness

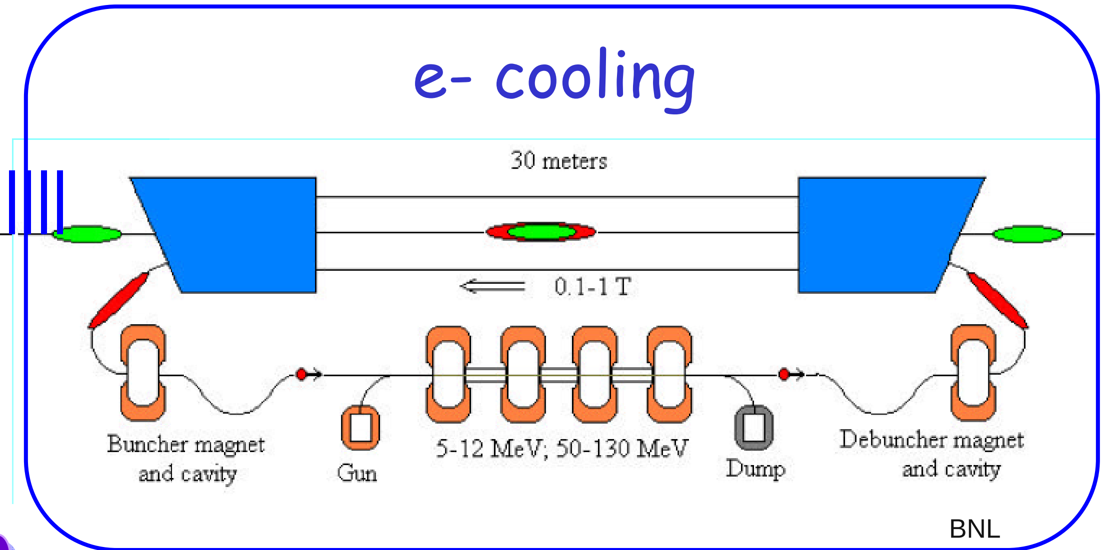


The ideal electron source…

…depends on your application

High Average Current → ERL & IR-FEL



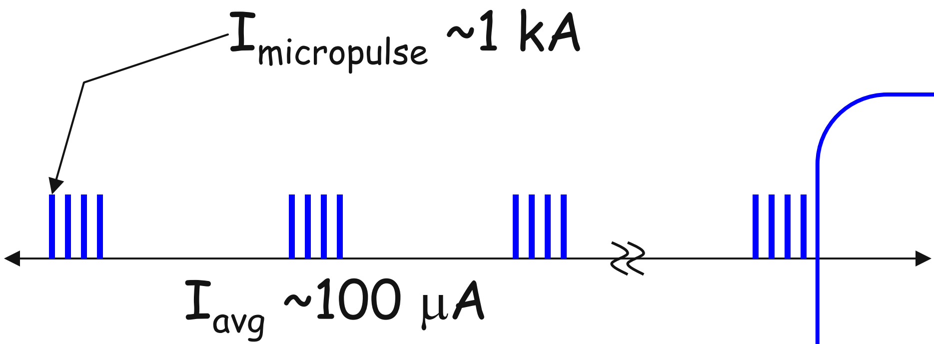


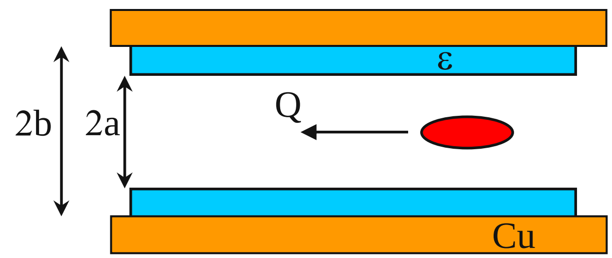
High Average Brightness

The ideal electron source…

…depends on your application

High Pulsed Current → Wakefield Acceleration





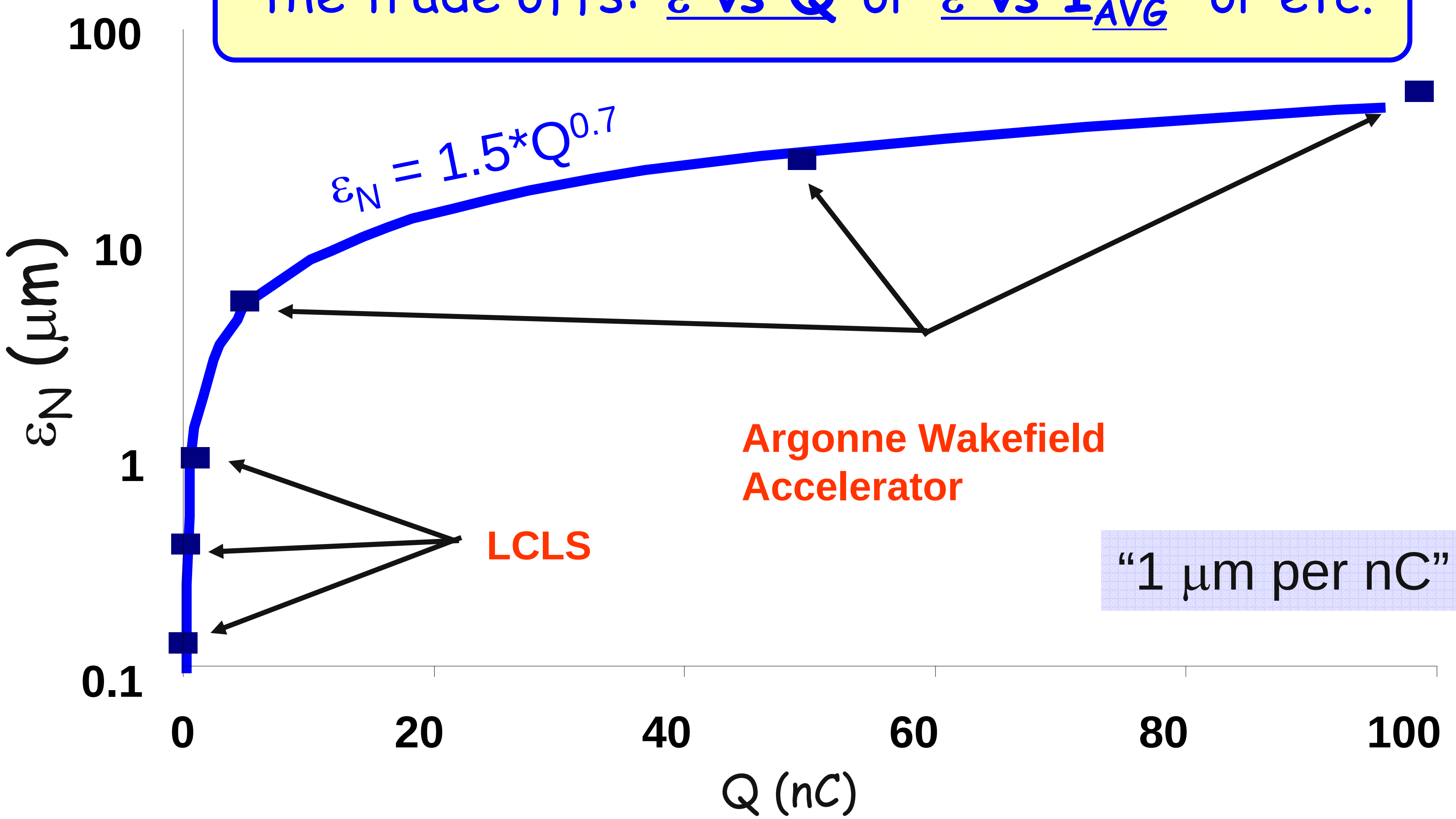
dielectric wakefield acceleration

High Pulsed Current

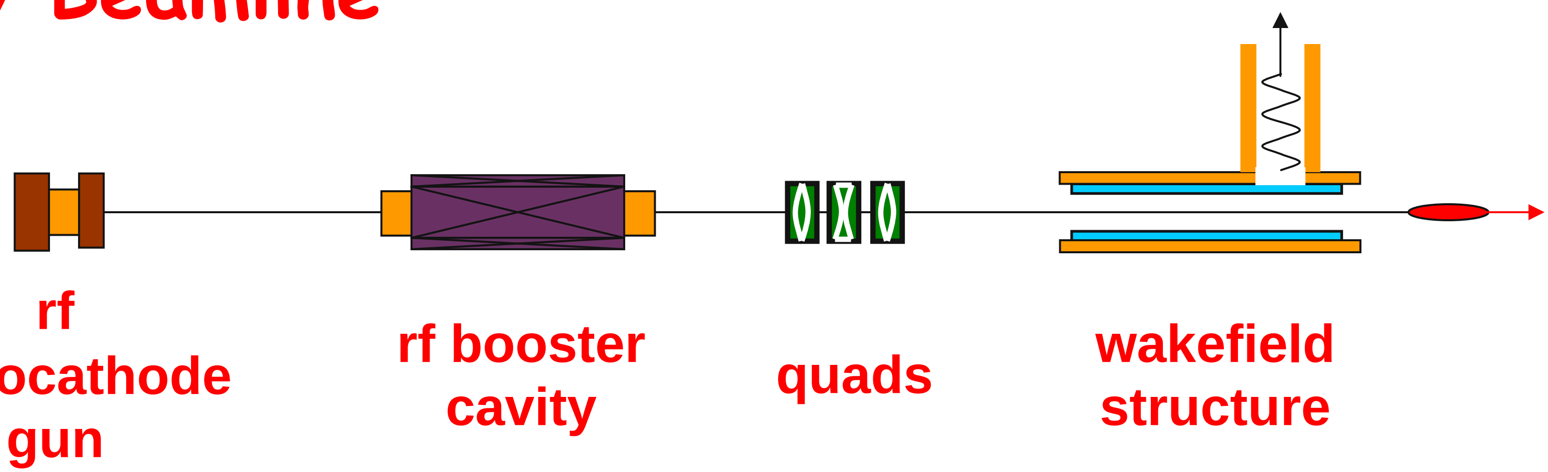
The ideal electron source...

Match application ⟷ source

the trade offs: 'ε vs Q' or 'ε vs I_{AVG}' or etc.



The Argonne Wakefield Accelerator (AWA) Facility Beamline

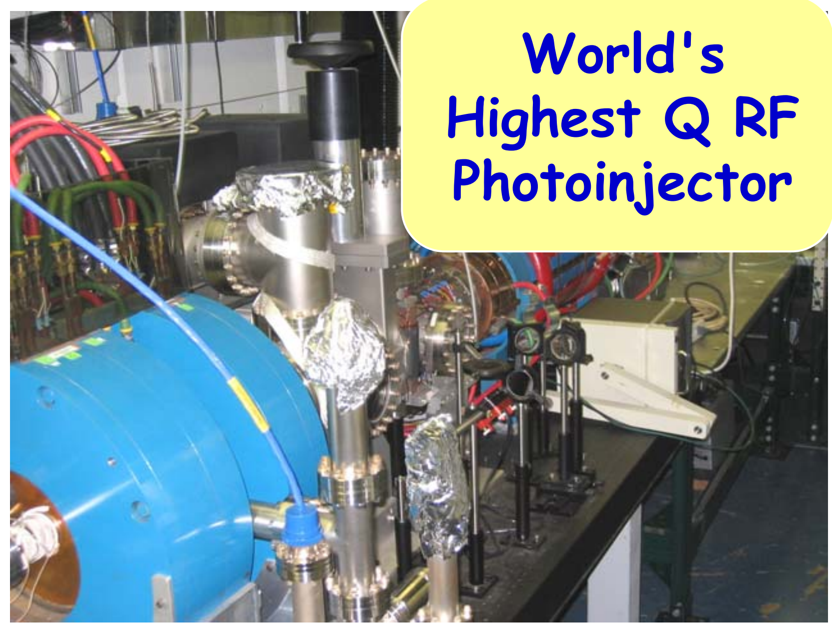


Single bunch operation

1. **Q=100 nC**
2. **Current = 10 kAmp**
3. **Energy=15 MeV**

Bunch train operation

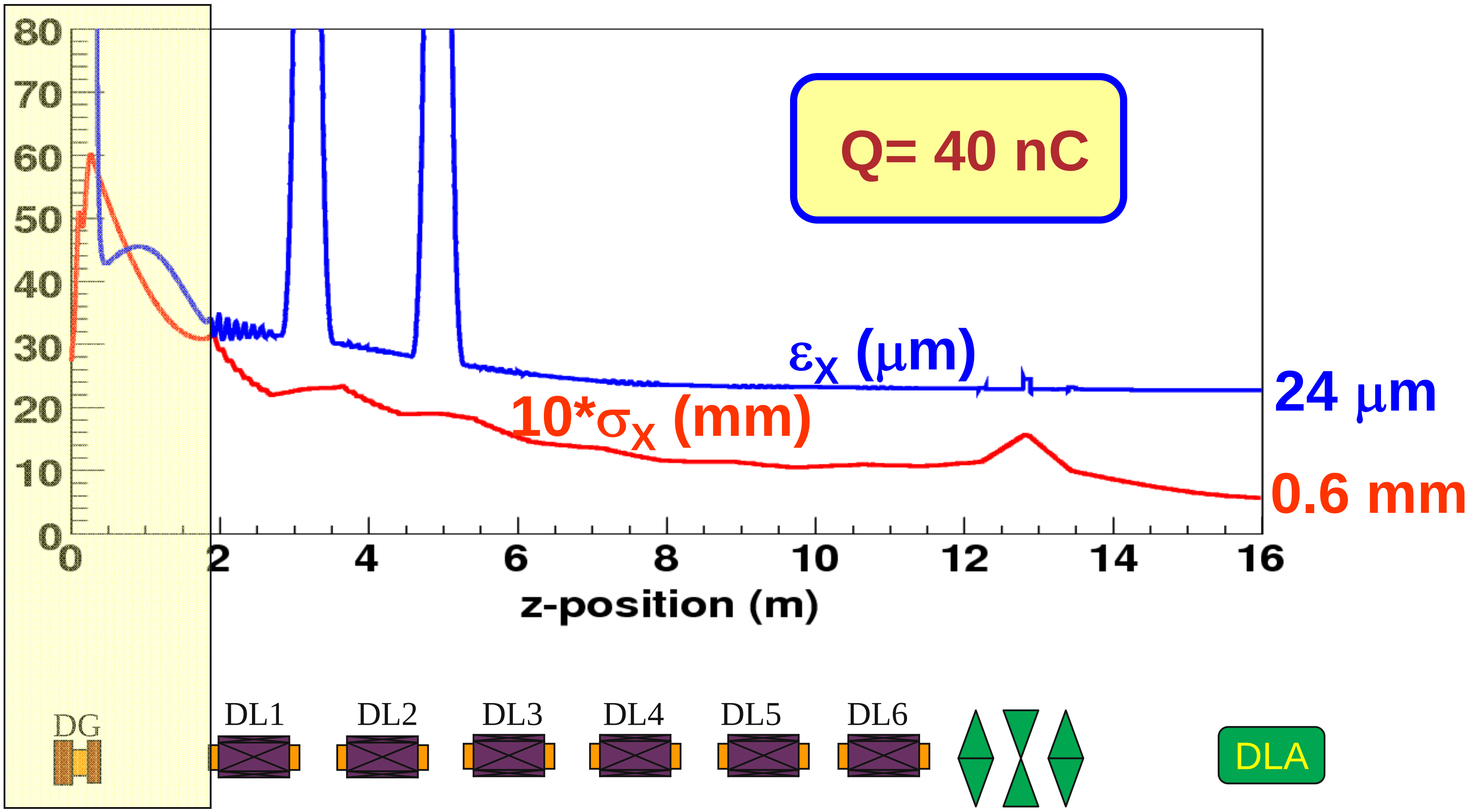
1. **4 bunches x 25 nC (3 ns, present)**
2. **16 bunches x 5 nC (12 ns, present)**
3. *32 bunches x 40 nC (25 ns, future)*



World's Highest Q RF Photoinjector

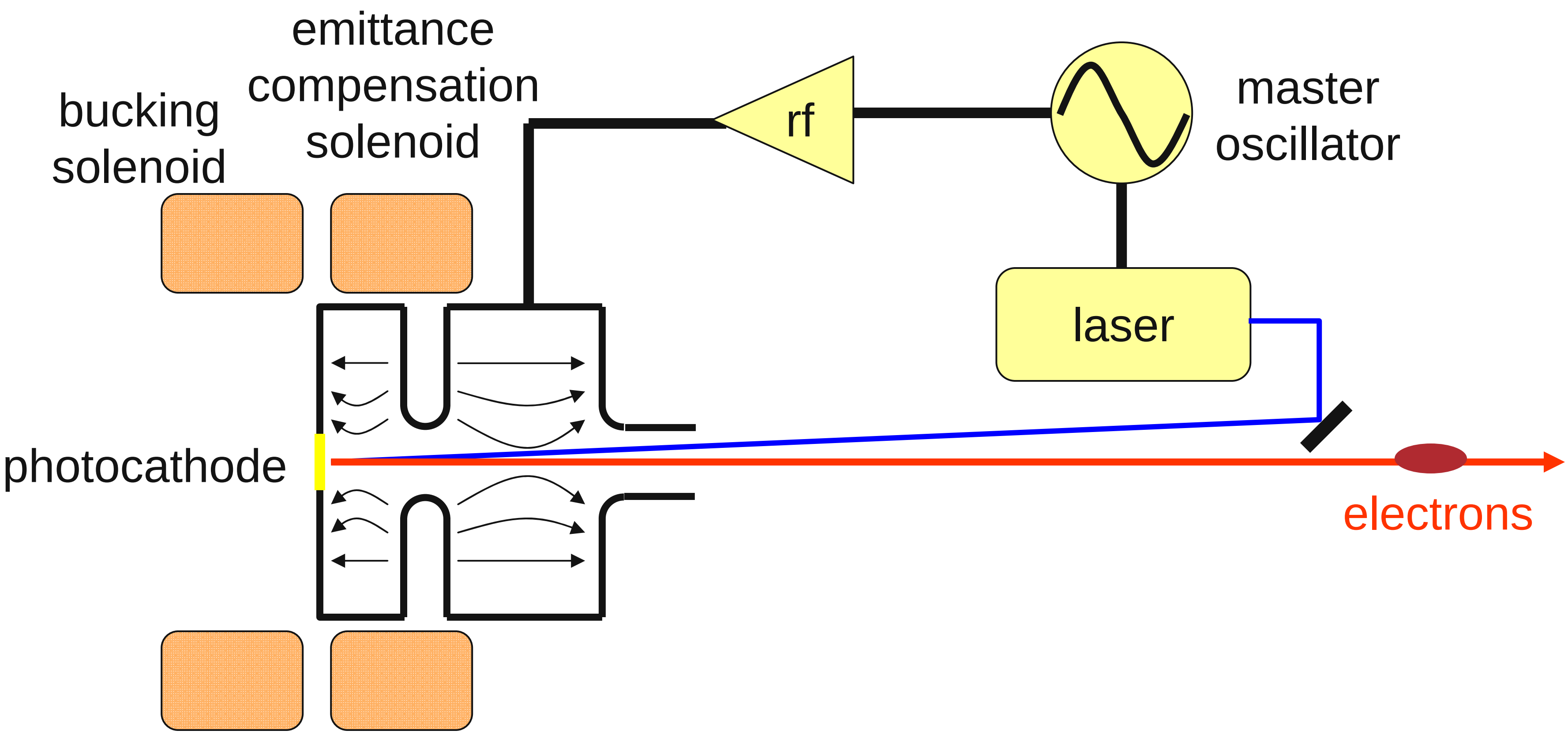
(Typical) Photoinjector Facility

The Argonne Wakefield Accelerator (Upgrade)

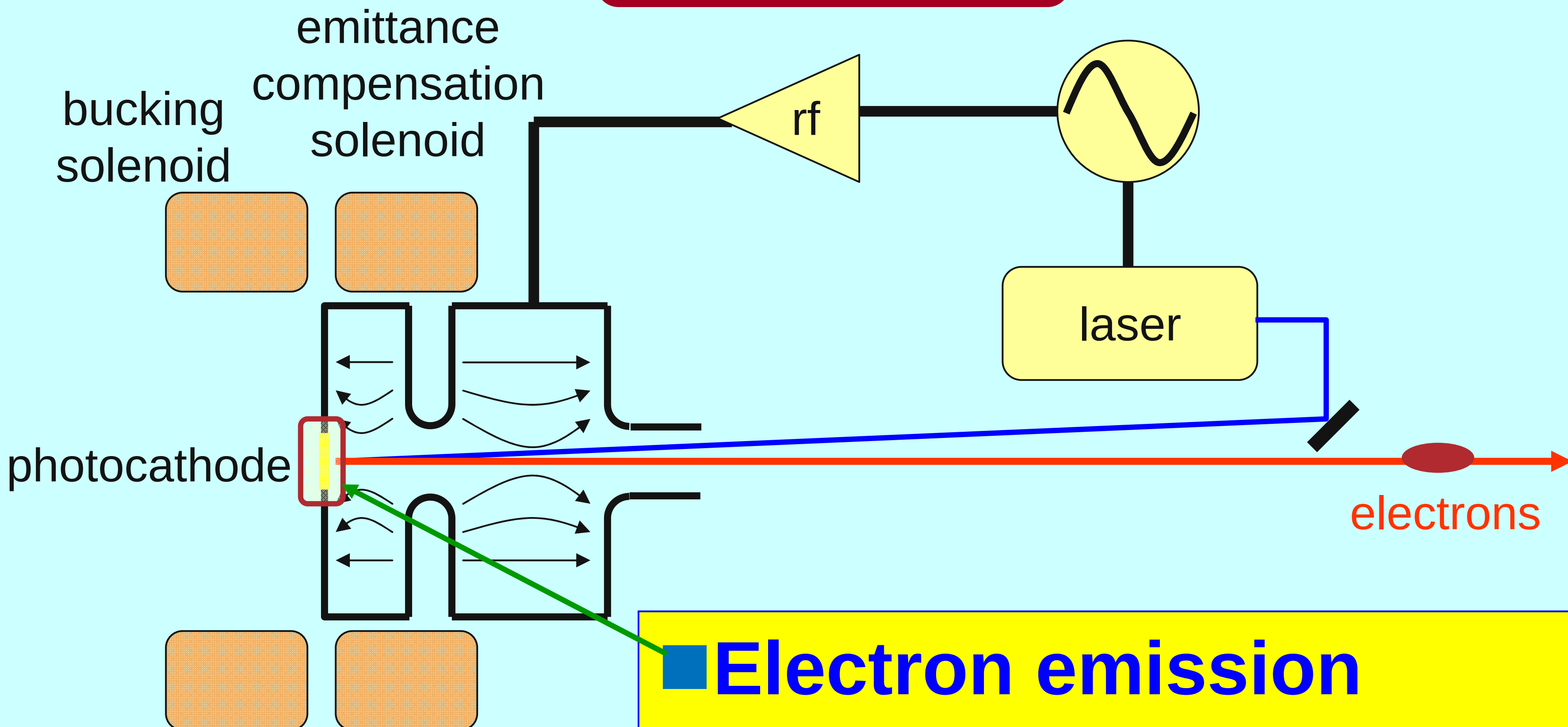


Today's focus

Anatomy of an rf photoinjector



outline



■ Electron emission

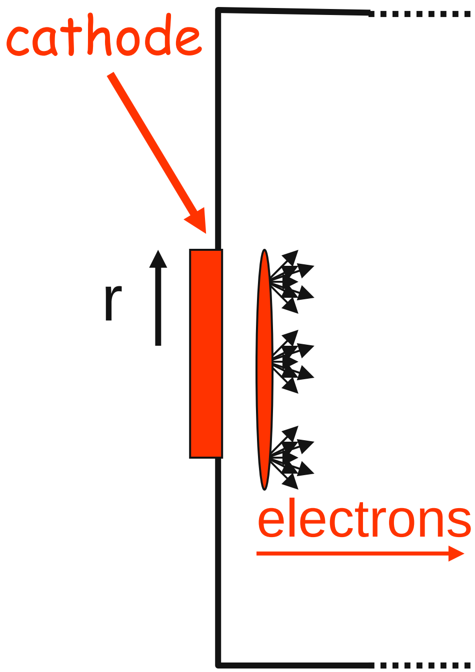
- Dynamics (Theory & Simulations)
- The drive laser
- The guns
- Beam characterization

Disclaimers

→biased: NCRF guns with metal photocathodes

→selective: picked a few representative examples

Adopt a standard for comparing cathodes



$$\varepsilon_N = \sigma_x \sigma_{p_X} \quad [m - rad]$$

assume e- have no momentum-position correlation at emission

$$\sigma_{p_X} = \frac{\sqrt{\langle p_X^2 \rangle}}{mc}$$

intrinsic momentum spread

$$\sigma_x = \frac{r}{2}$$

Position spread (we control)

- **Normalized intrinsic emittance of cathode per unit beam size**

$$\frac{\varepsilon_N}{\sigma_X} = \frac{\sqrt{\langle p_X^2 \rangle}}{mc} = \sqrt{\frac{E_{\text{int}}}{mc^2}}$$

e.g.

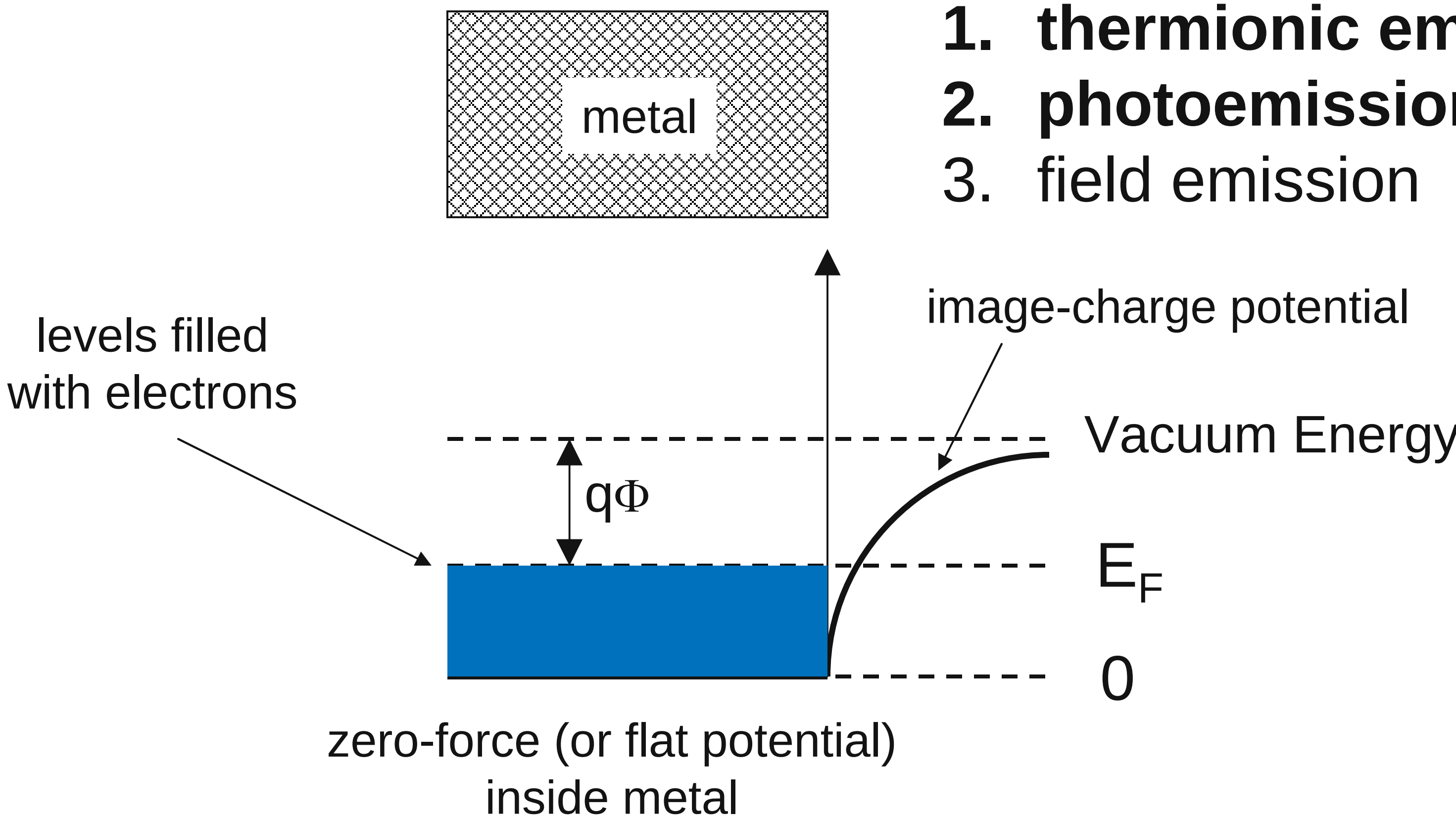
E_{int} = 1eV

ε_N/σ_X = 1.4 microns/mm(rms)

D.H. Dowell, et al., Nucl. Instr. and Meth. A (2010)
doi:10.1016/j.nima.2010.03.104

How to get the electrons out of the box?

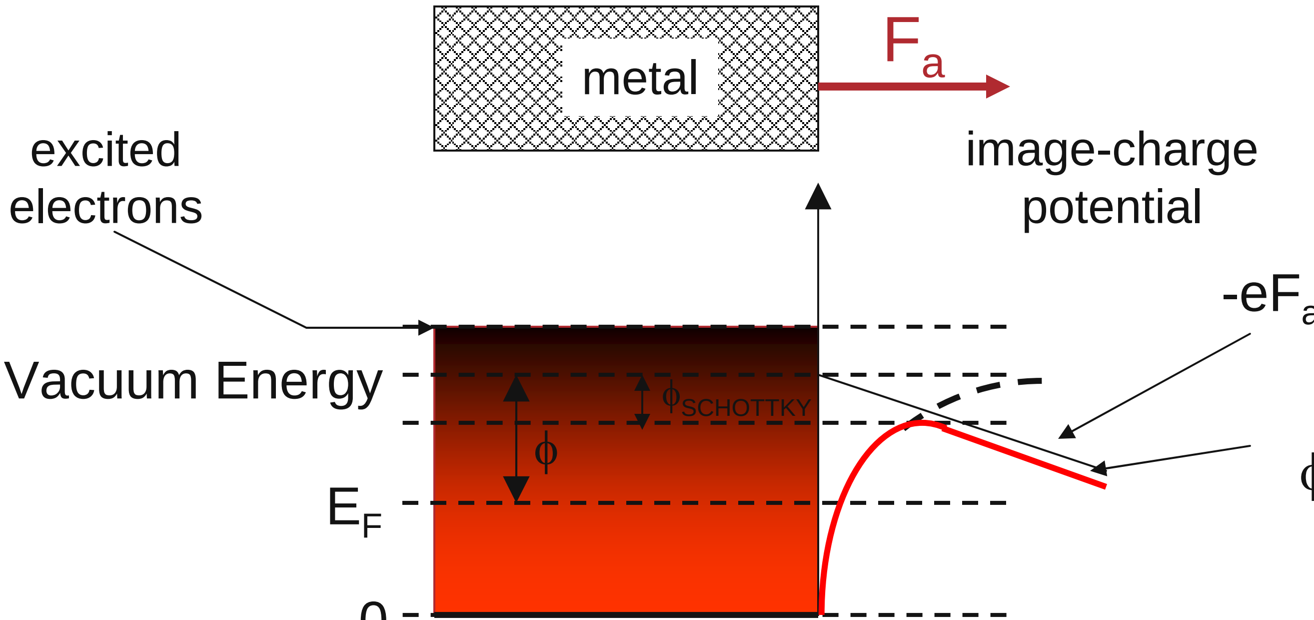
- free electrons are trapped in a potential well
- electrons must overcome the work function = (qΦ)



1. **thermionic emission**
2. **photoemission**
3. field emission

thermionic emission

heat electrons up until they go over the barrier



zero-force (or flat potential) inside metal

$$\phi_{\rm eff} \equiv \phi_w - \phi_{\rm Schottky} = \phi_w - e\sqrt{\frac{eF_a}{4\pi\varepsilon_0}}$$

current density → $J = AT^2 \exp\left(-\phi_{eff}/k_b T\right)$

thermal energy → $E_k = k_b T$

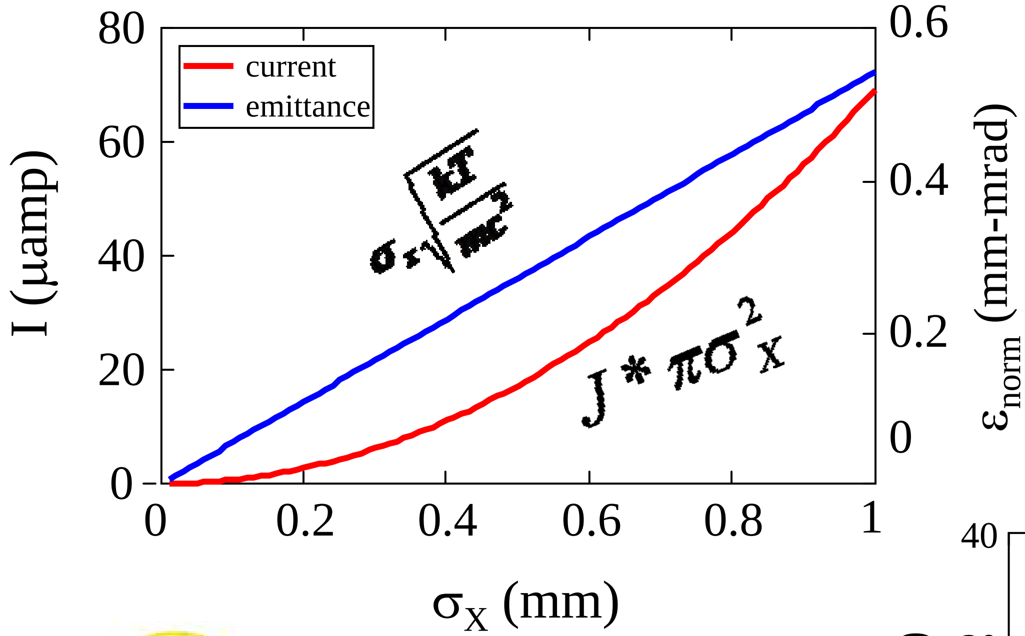
intrinsic emittance → $\dfrac{\varepsilon_N}{\sigma_X} = \sqrt{\dfrac{E_k}{mc^2}}$

EXAMPLE: T=1740 K & F_a=20MV/m

- J =17 A/cm^2
- E_k=0.150 eV
- ε_N/σ_X = 0.54 μm/mm(rms)

J_{th} ~ (10-100) A/cm^2

thermionic emission

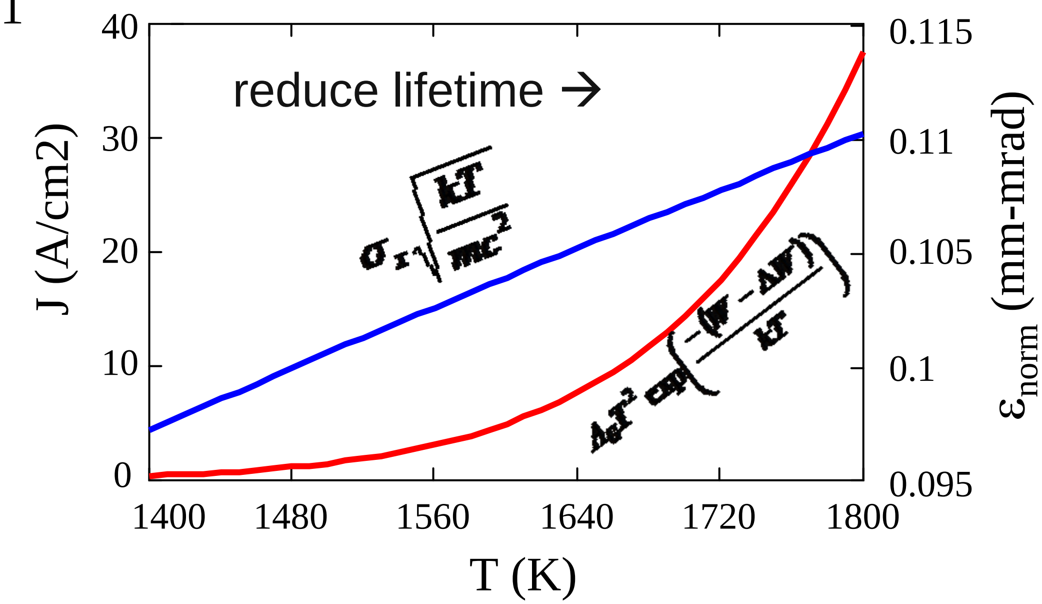


The High Brightness Dream:

Can we have high current
&
low (thermal) emittance?

NO!

Higher current means higher emittance



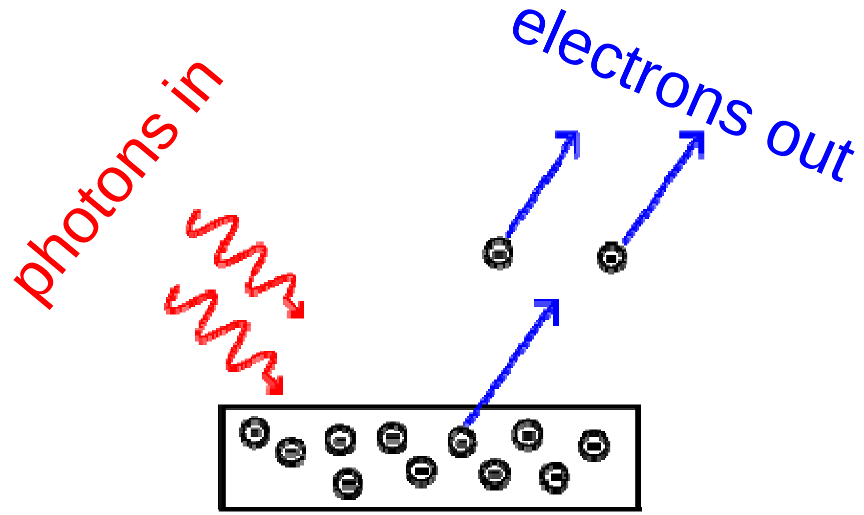
→for this example: CeB6 (W=2.39 eV); F=20MV/m; σ_x=0.2 mm; T=1743 K

photoemission

Quantum Efficiency (QE)

$$QE = \frac{\text{Number of photoelectrons}}{\text{Number of photons}}$$

$$Q[nC] = QE[\%] * E_{laser}[\mu J] * \frac{\lambda_{laser}[nm]}{124}$$



Classes of photoemitters

- **metallic photocathode**
  - **Cu, Mg, Pb, Nb (bare metal)**
  - **CsBr:Cu, CsBr:Nb (coated metal)**
- **semiconductor photocathode**
  - **Cs_2Te, Cs_3Sb, K3Sb, (PEA, mono-alkali)**
  - **K_2CsSb, Na_2KSb, (PEA, multi-alkali)**
  - **GaAs(Cs), GaN(Cs), (NEA)**

Ideal Photocathode

1. **high QE**
2. **low intrinsic emittance**
3. **fast response time**
4. **vacuum robust**

photoemission theory

Spicer's 3 step model

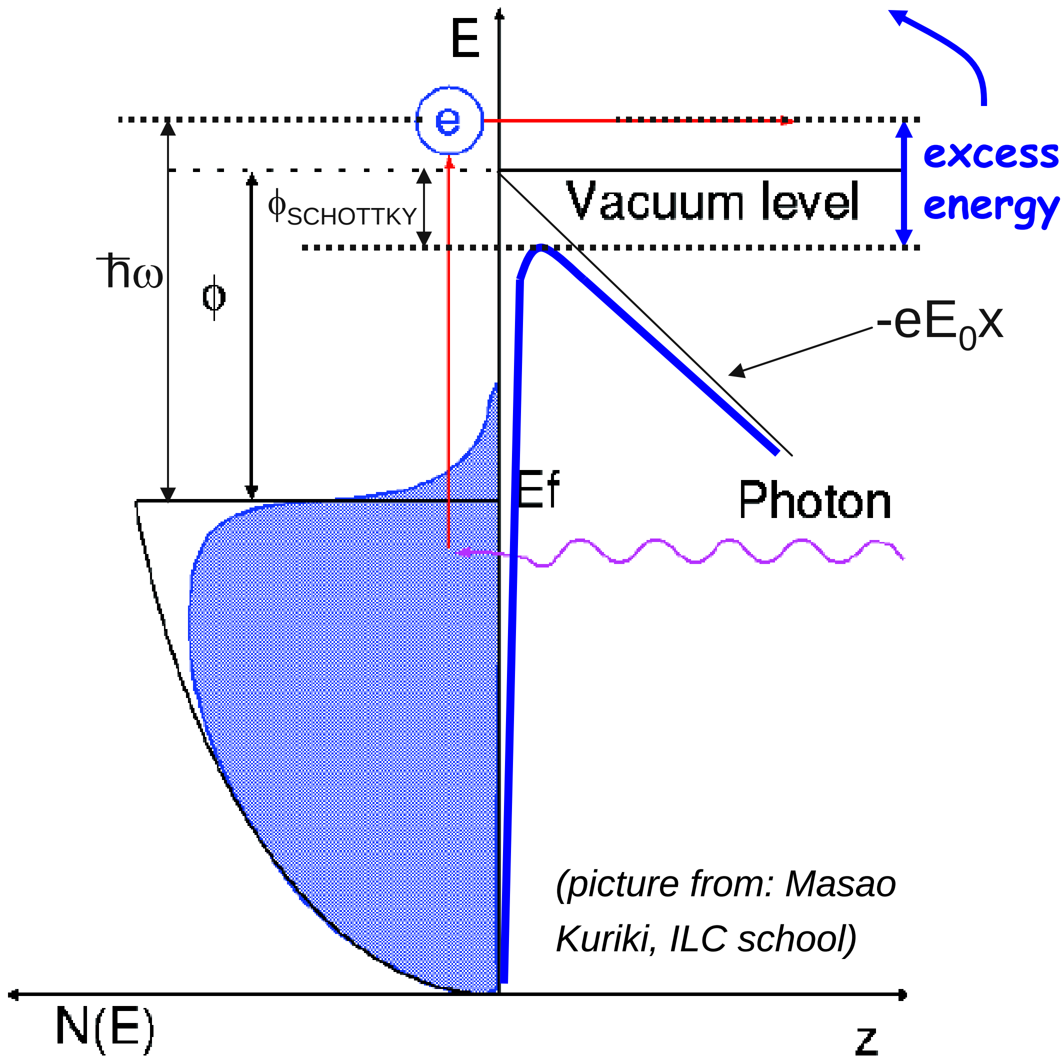
1. A photon is absorbed and an electron is excited
2. Electron migrates to the surface
3. Escape through the barrier

Spicer does not do emittance

3 step model applied to photoinjectors…

1. **Dowell and Schmerge[1]**
   1. metals (zero field and temp)
   2. predicts $\varepsilon_{INTRINSIC}$ and QE
2. **Jensen[2]**
   1. metal and semiconductors
   2. predicts $\varepsilon_{INTRINSIC}$ and QE
   3. thermionic, photo, and field emission

$E_{excess,\,metal} = \hbar\omega - \phi_{eff}$

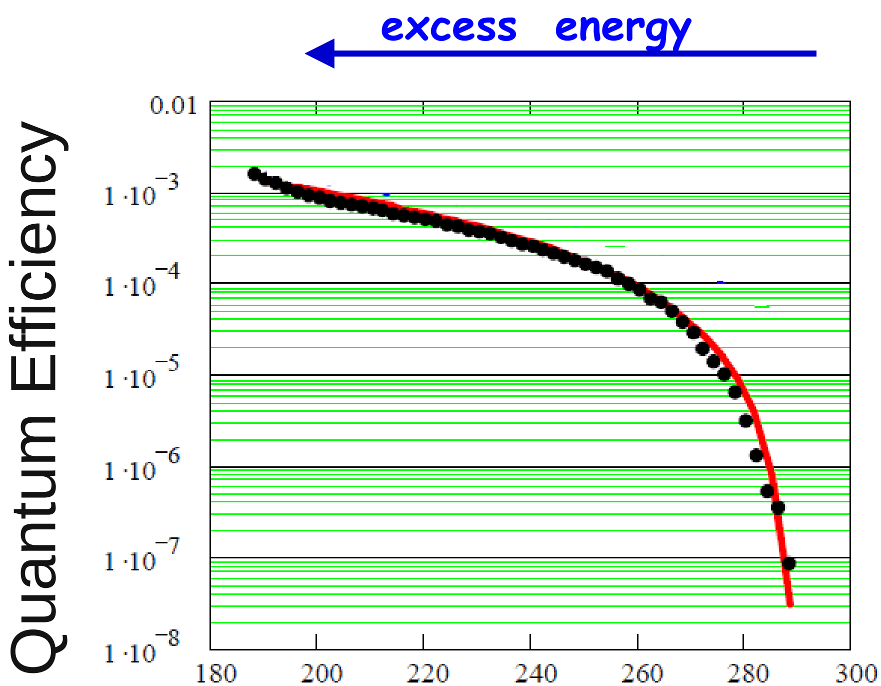


(picture from: Masao Kuriki, ILC school)

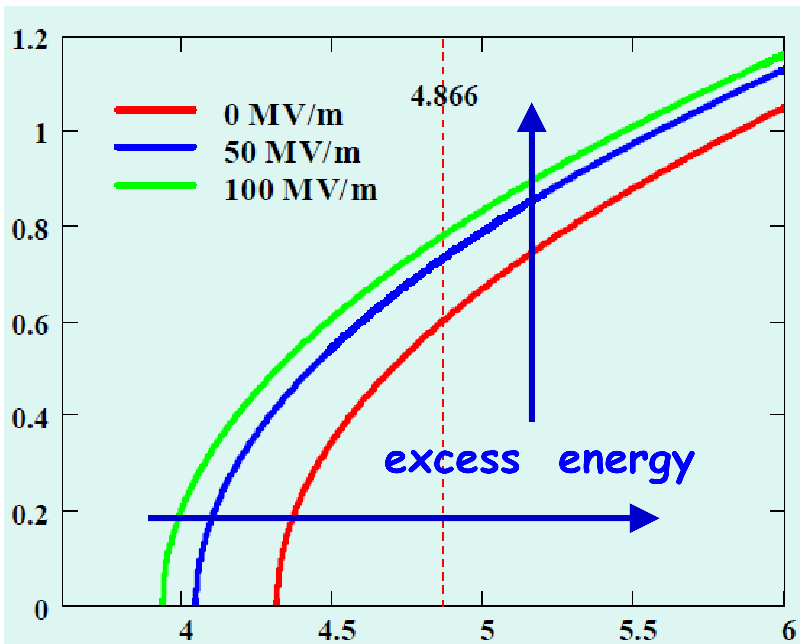
[1]D.H.Dowell,J.F.Schmerge,Phys.Rev.Spec.Top.Accel.Beams 12 074201 (2009)
[2]K.L. Jensen et al., J. Appl. Phys. 104, 044907 (2008)

photoemission in metals
[Dowell and Schmerge]

- Theory predicts '**Quantum Efficiency**' and '**Normalized intrinsic emittance of cathode per unit beam size**'
- is in good agreement with experiment



λ laser (nm)



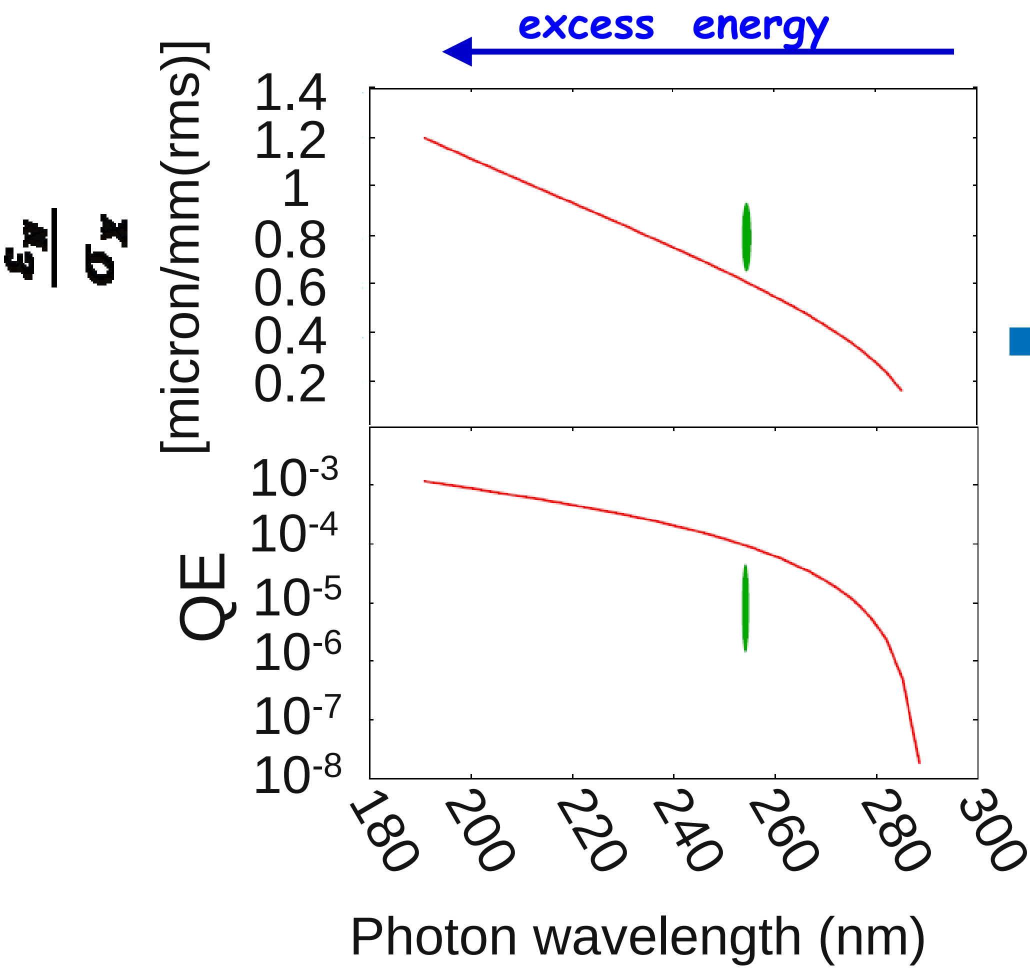
$\frac{\varepsilon_N}{\sigma_X}$

photon energy (eV)

photoemission in metals
[Dowell and Schmerge]

The High Brightness Dream:

Can we have high QE
&
low intrinsic emittance?



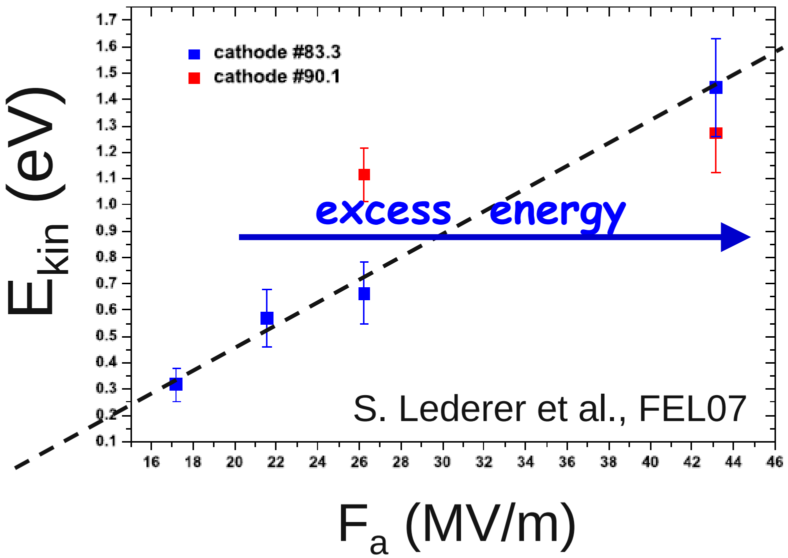
- No → High QE means high emittance

- Yes → Can increase charge with laser intensity

photoemission in semiconductors

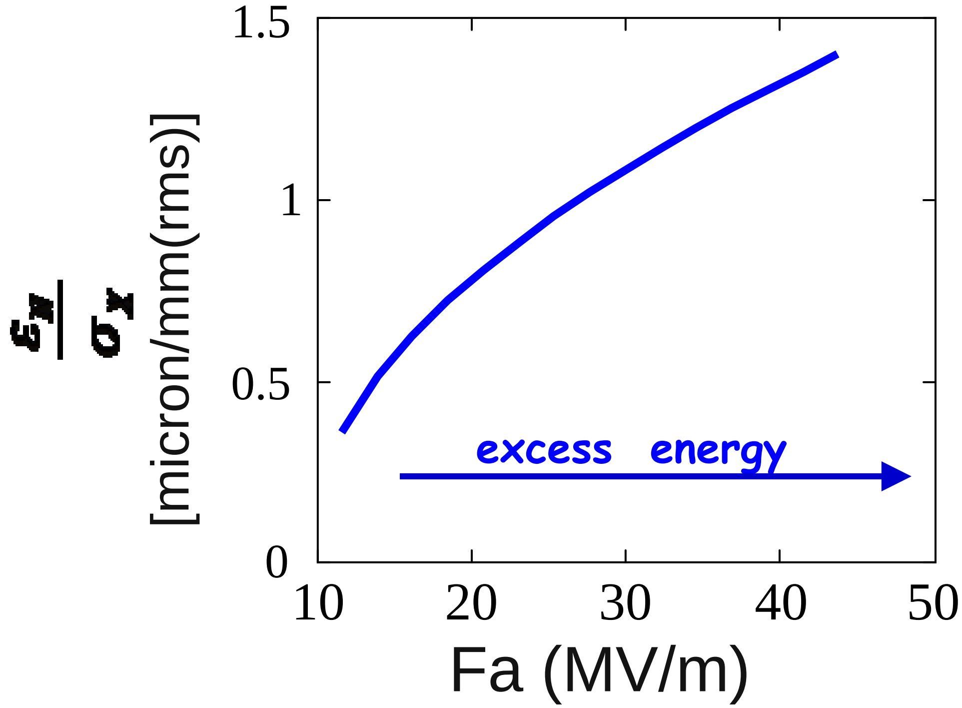
[e.g. CsTe]

$$\frac{\varepsilon_N}{\sigma_X} = \sqrt{\frac{2E_k}{3mc^2}}$$



$$E_k = \frac{1}{2}\left(\bar{h}\,\omega - E_G - E_A - \phi_{eff}\right)$$

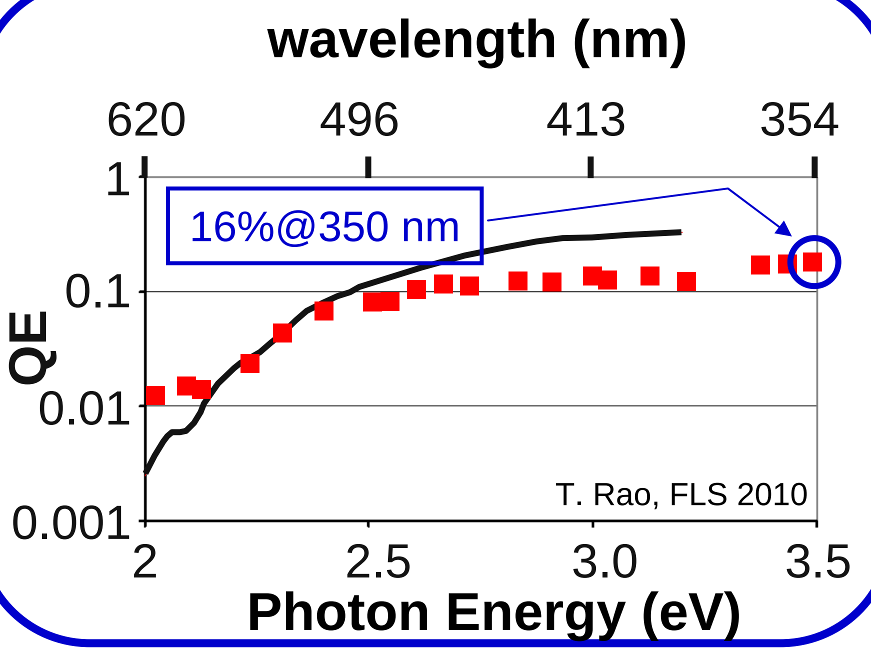
excess energy



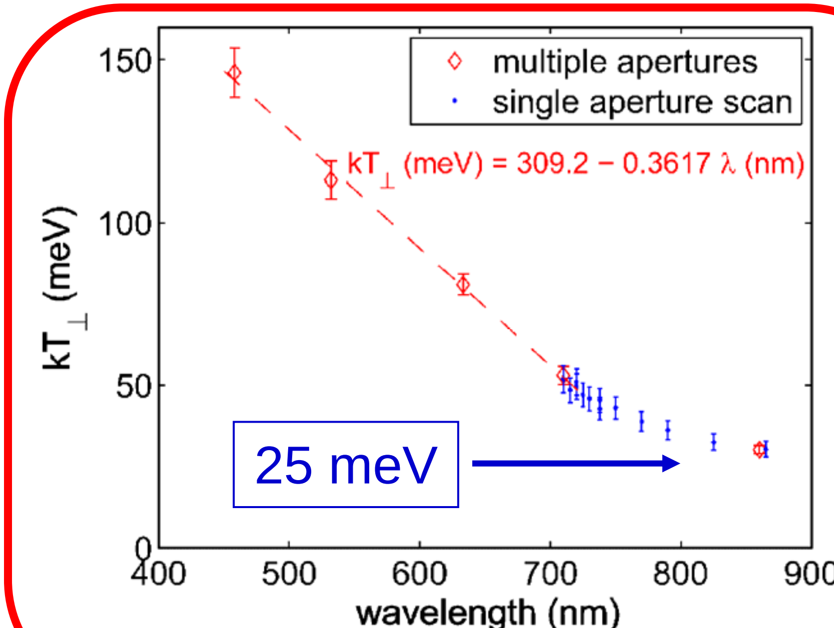
The ideal cathodes:
High QE + visible/IR lasers

--challenge-- vacuum robustness

- **K_2CsSb**
- Successfully used in rf gun (Boeing Gun: still holds record for highest average I)
- 10% at 543 nm



- **GaAs:Cs**
- used in DC guns
- ultra-low thermal emittance (0.22 μm/mm(rms)) near bandgap (880 nm), but slow response
- 5.6% at 532 nm (fast response!)



[I. Bazarov, J. Appl. Phys. 103, 054901 (2008)]

Properties of Photocathodes

QE

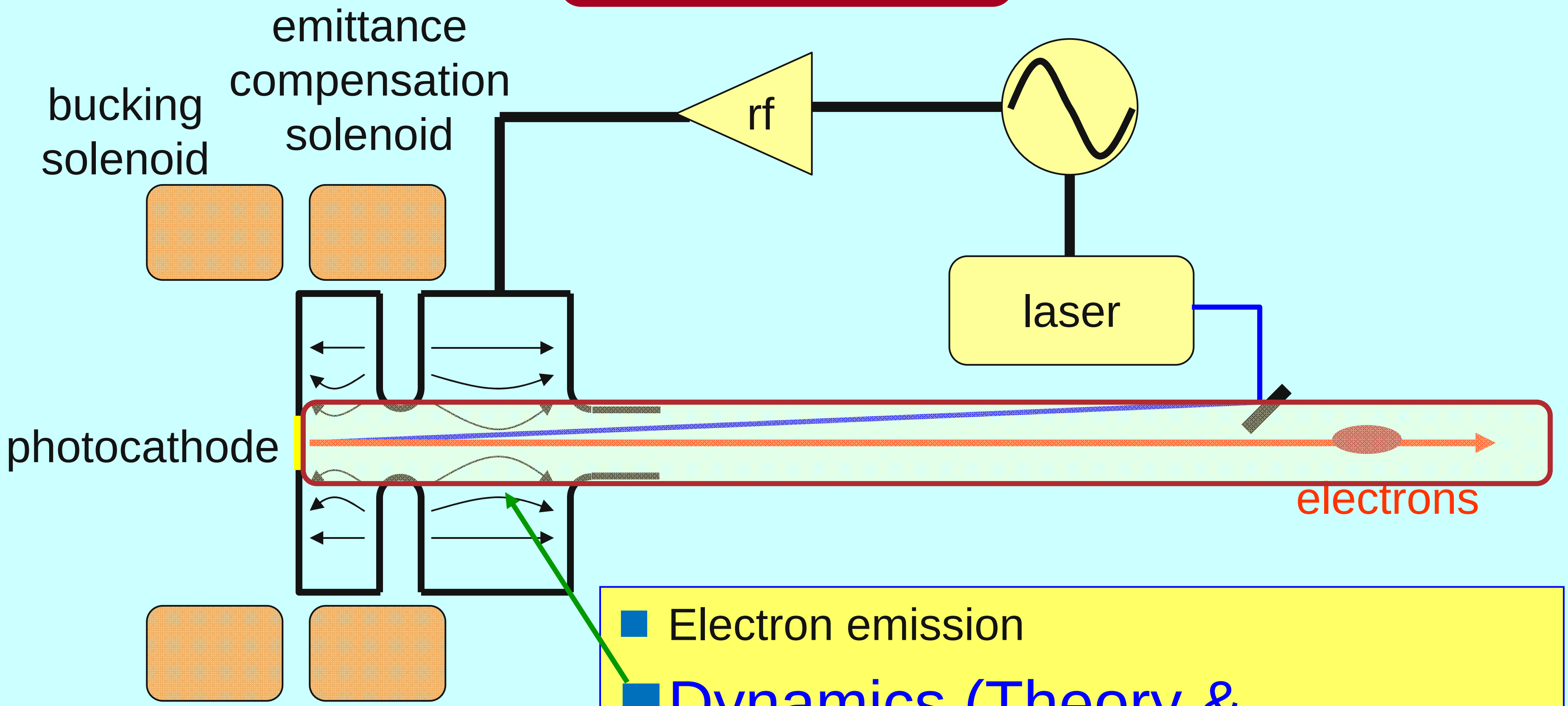
Normalized intrinsic emittance of cathode per unit beam size

Metal cathodes	Wavelength & energy: λ_{opt} (nm) $\hbar\omega$ (eV)		Vacuum for 1000 h operation (Torr)	Work functio[n] ϕ_W (eV)		
Bare metal						
Cu	250, 4.96	1.4×10^{-4}	10^{-9}	4.6 [34]	0.5	1.0 ± 0.1 [39] 1.2 ± 0.2 [40] 0.9 ± 0.05 [3]
Mg	266, 4.66	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4 ± 0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	$\sim2\times10^{-5}$	10^{-10}	4.38 [34]	0.6	?
Coated metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

Cathode type	Cathode	Typical wavelength & energy, λ_{opt} (nm), (eV)	Quantum efficiency (electrons per photon)	Vacuum for 1000 h (Torr)	Gap energy+ electron affinity, E_G+E_A (eV)	Thermal emittance (microns/ mm(rms))	
						Eq. (7)	Expt.
PEA: mono-alkali	Cs_2Te	211, 5.88	0.1	10^{-9}	3.5 [42]	1.2	0.5 ± 0.1 [35]
		264, 4.70	–	–	"	0.9	0.7 ± 0.1 [35]
		262, 4.73	–	–	"	0.9	1.2 ± 0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6+0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1+1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1+2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_3KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+ < 1.1[42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33	0.1	?	1.4 ± 0.1[42]	0.8	0.44 ± 0.01[44]
		860, 1.44	0.1	?		0.2	0.22 ± 0.01[44]
	GaN(Cs)	260, 4.77	0.1	?	1.96+?[44]	1.35	1.35 ± 0.1[45]
	GaAs$(1-x)$Px $x\sim0.45$ (Cs,F)	532, 2.33	0.1	?	1.96+?[44]	0.49	0.44 ± 0.1[44]
S-1	Ag–O–Cs	900, 1.38	0.01	?	0.7[42]	0.7	?

D.H. Dowell, et al., Nucl. Instr. and Meth. A (2010)
doi:10.1016/j.nima.2010.03.104

outline



- Electron emission
- **Dynamics (Theory & Simulations)**
- The drive laser
- The guns
- Beam characterization

Transverse emittance growth

$$\varepsilon_N = f\left(\varepsilon_{THERMAL}, \varepsilon_{rf}, \varepsilon_{sc}\right) \approx \sqrt{\varepsilon^2_{THERMAL} + \varepsilon^2_{DYNAMICS}}$$

ε_{TH} {Lowest possible emittance}

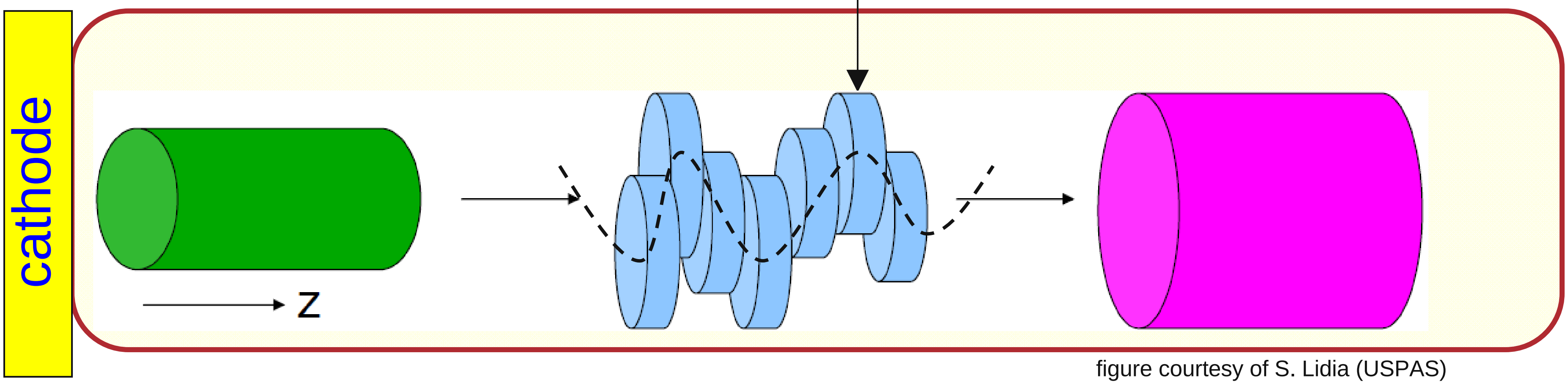


figure courtesy of S. Lidia (USPAS)

The Dynamics Lesson

- **linearize all forces and apply emittance compensation**
  [B. E. Carlsten, NIM, A285, 313 (1989)]

- nonlinear forces (rf mutlipole fields, rf curvature, solenoidal aberrations, nonlinear space charge, etc.) dilute slice emittance

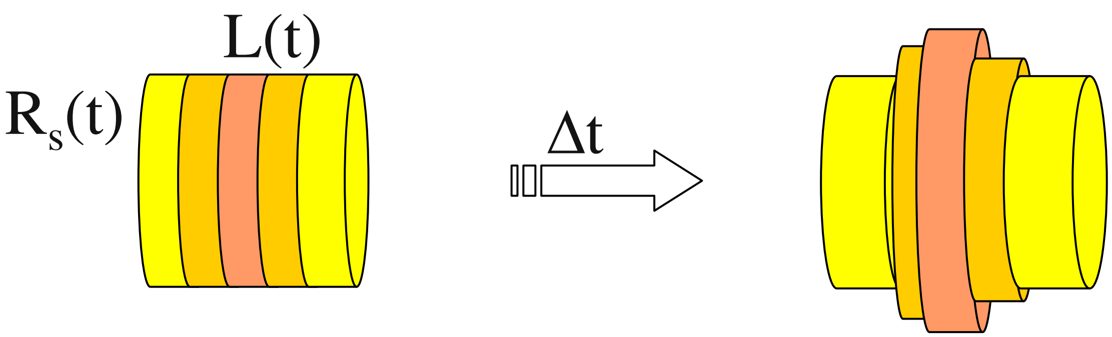
Emittance compensation →

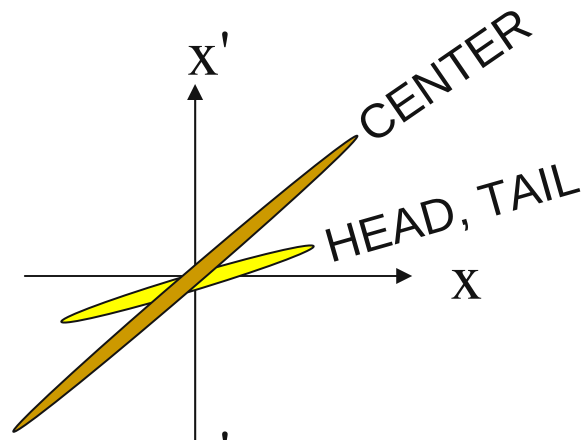
reduces projected emittance due to slice-dependent linear focusing forces

Examples…

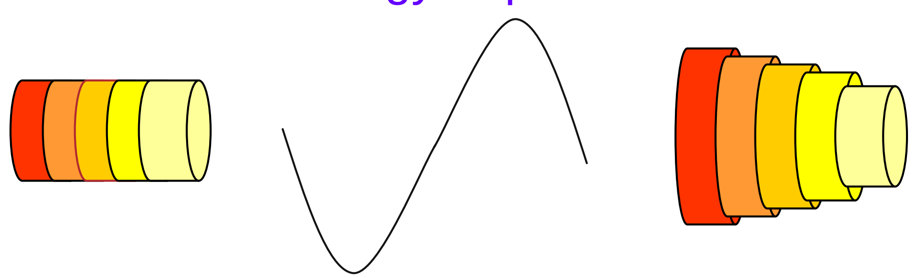
Projected Phase Space

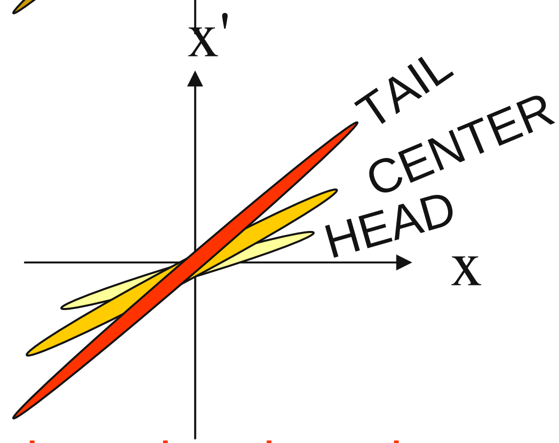
1. linear space-charge forces (dominant)





2. linear rf energy-dependent forces



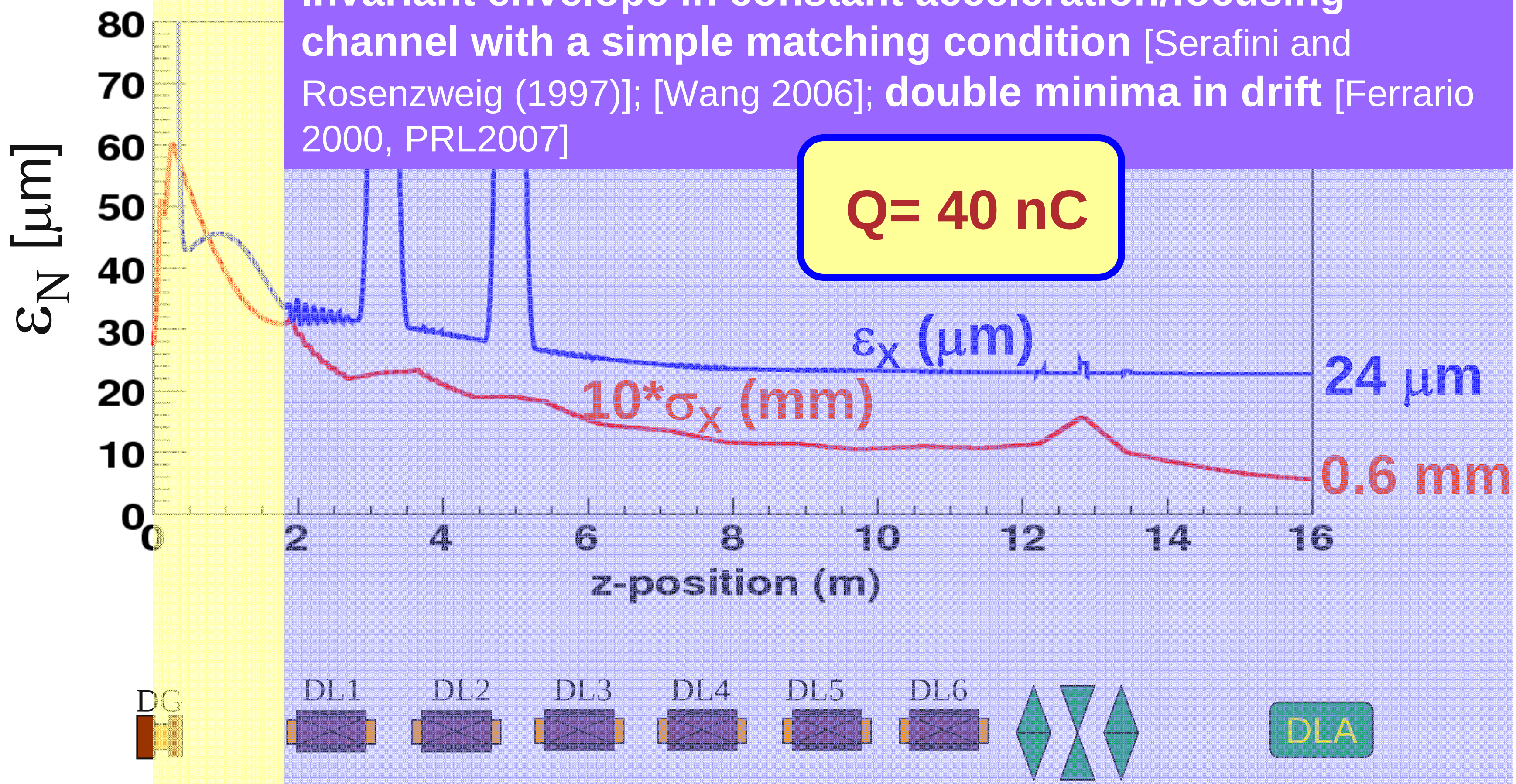


Note → most guns operate in the space charge dominated regime since we are interested in high charge applications

Beam envelope theories for photoinjectors
for the optimized AWA drive beamline

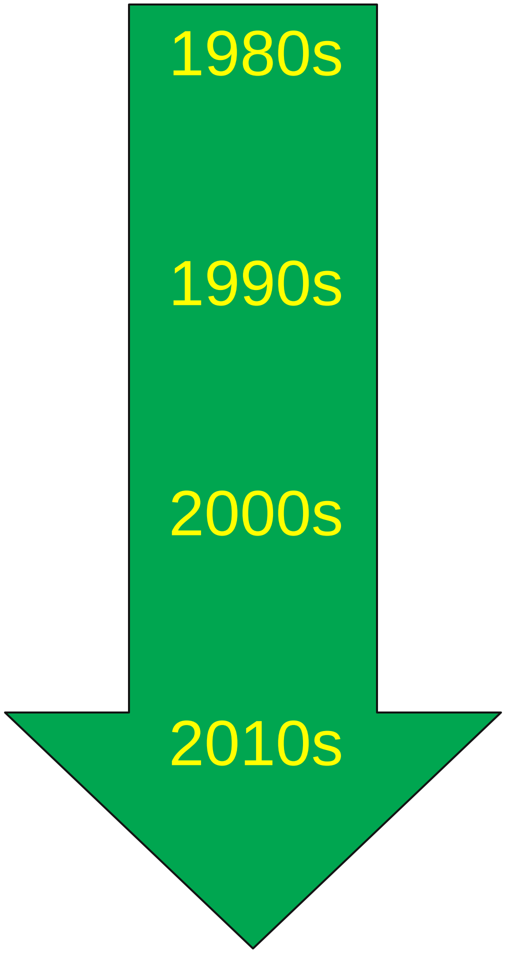
Emittance compensation in space-charge regime [Carlsten 1989],
General envelope theory with newly found criteria [Wang et al. 2007]

Invariant envelope in constant acceleration/focusing channel with a simple matching condition [Serafini and Rosenzweig (1997)]; [Wang 2006]; **double minima in drift** [Ferrario 2000, PRL2007]



simulations for photoinjectors

- Simulations are the workhorse of the photoinjector field



•1000’s of macroparticles

•Searched for solutions by hand

•100,000s of macroparticles

•Local optimizers

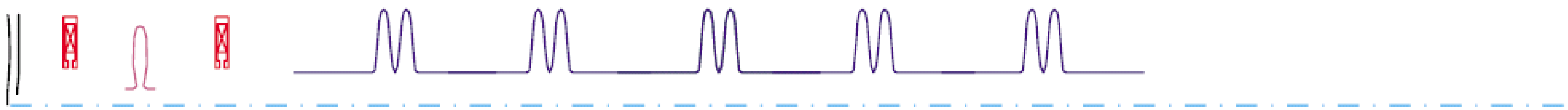
•Global Optimizers

•Realistic laser profiles

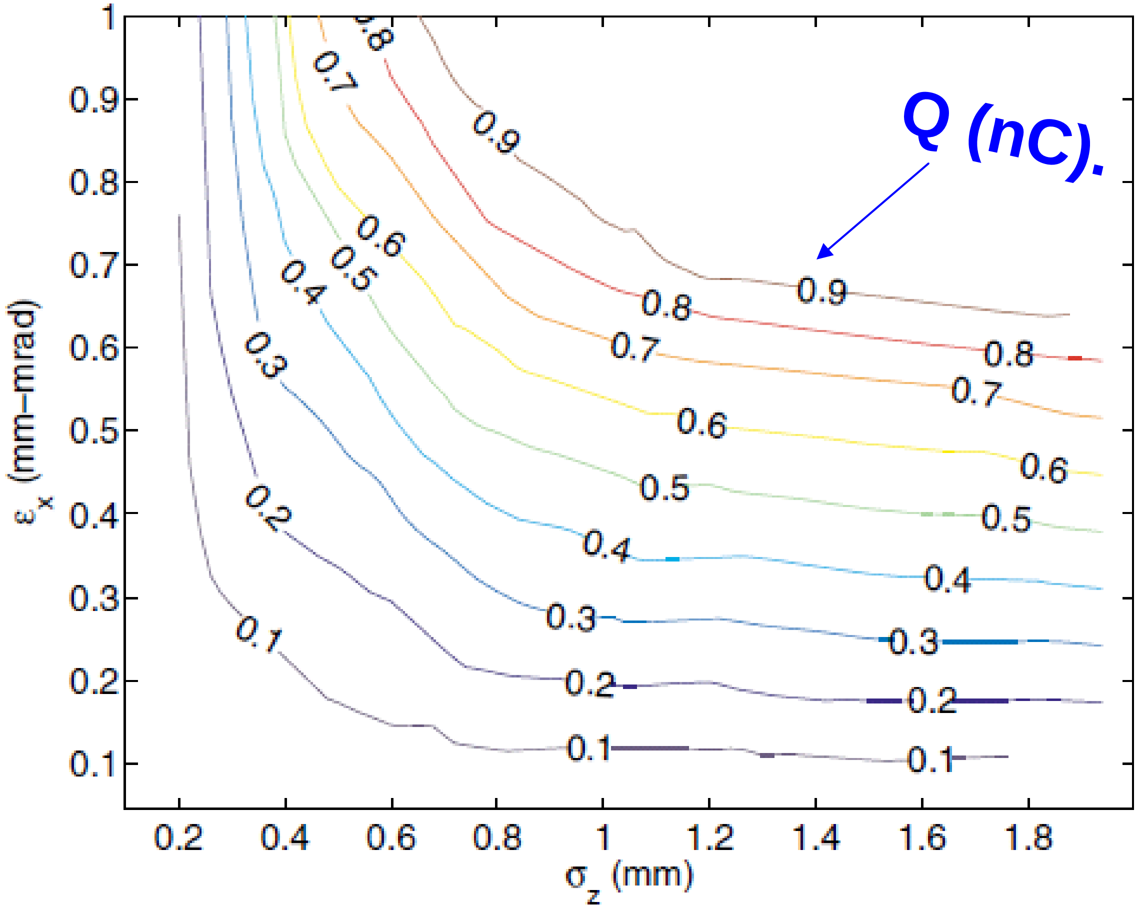
•Parallel Codes (1:1 particle)

Global Optimizers

Multiobjective genetic algorithms



Schematic of the dc gun injector layout.

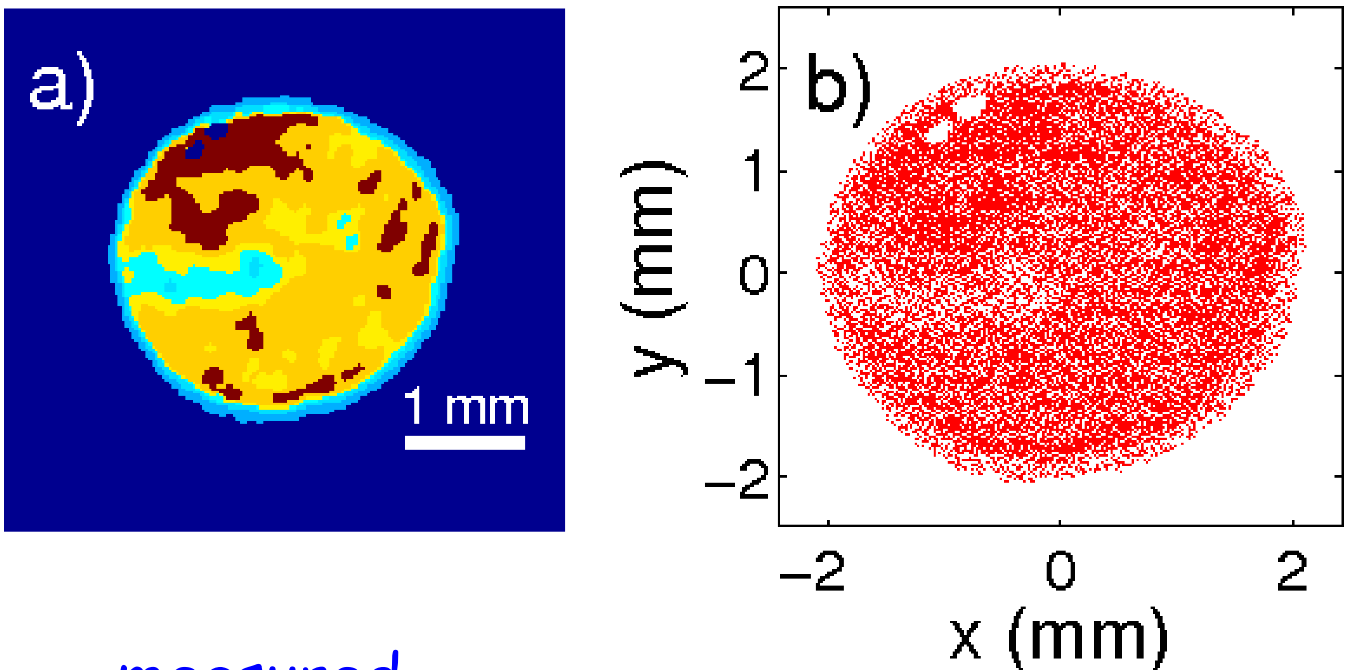


22 parameters scanned

{longitudinal positions, accelerating gradients and phase, dc gun voltage, solenoid fields, buncher cavity gradient,
laser spot size and length, bunch charge}

Realistic Laser Profiles

- More accurate simulations → better understanding → improved beams

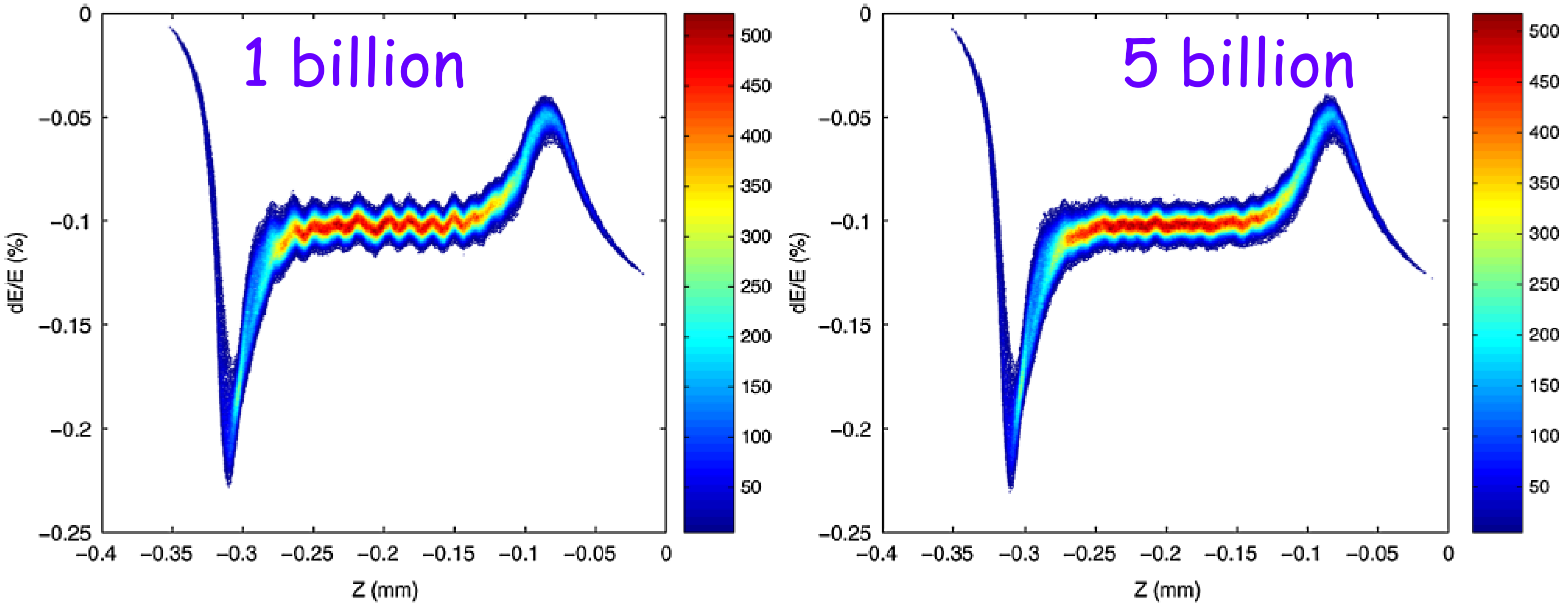


measured
laser profile

Monte carlo generated
macroparticle distribution

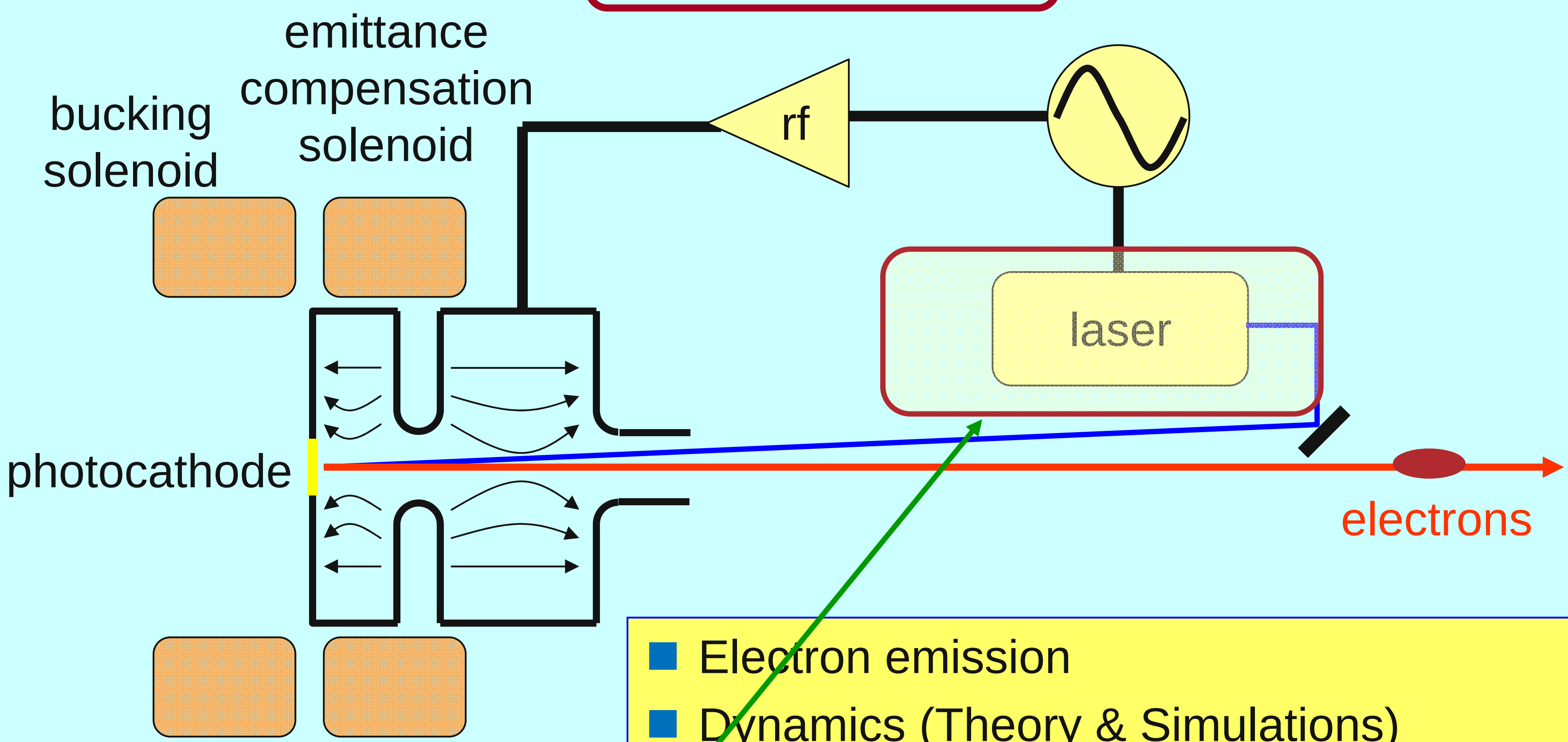
Parallel Sims
1:1 particle rep

simulations with billions of particles are now achievable



large numbers needed to control the numerical shot noise and avoid overestimating the microbunching instability

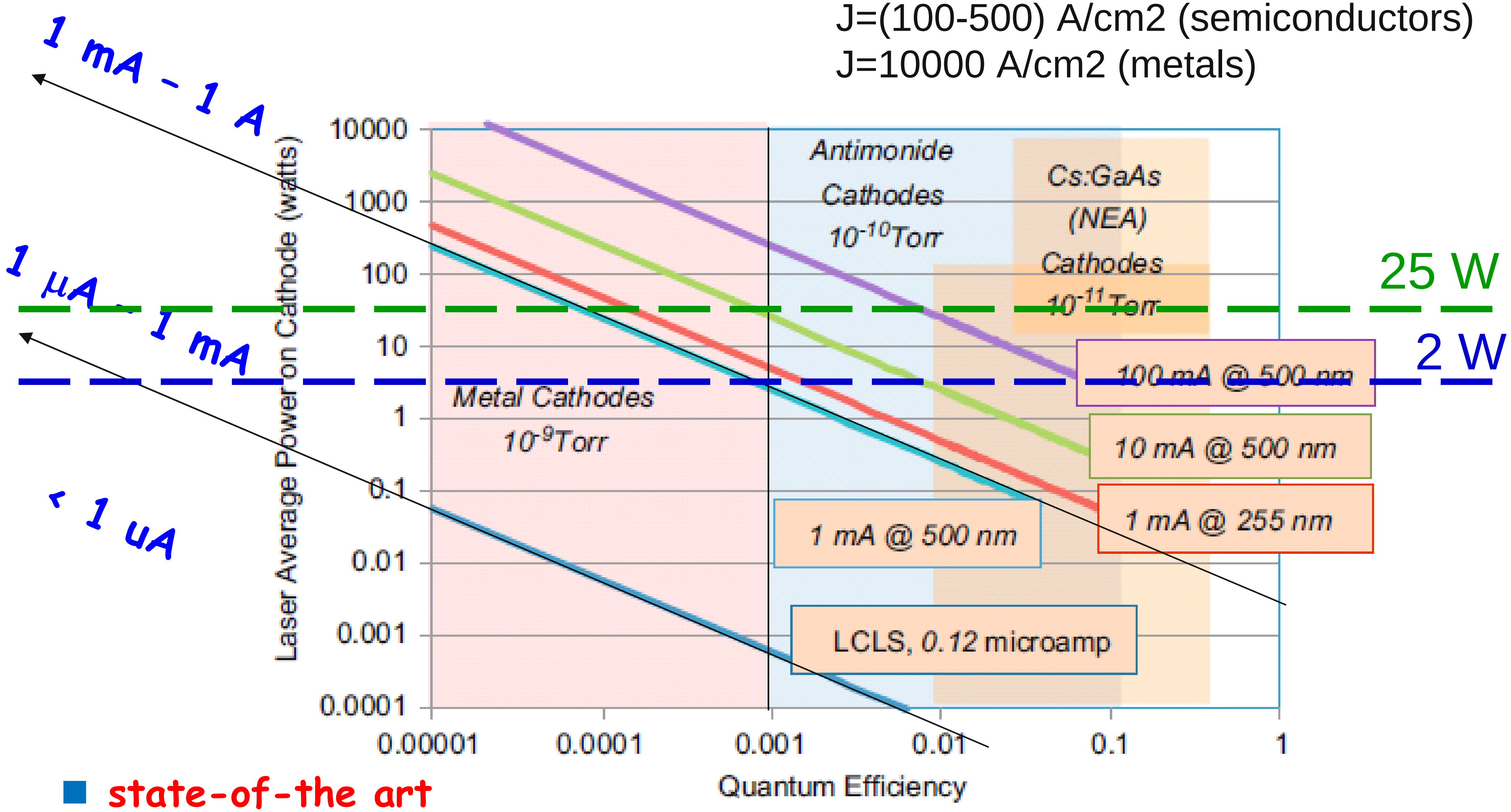
outline



- Electron emission
- Dynamics (Theory & Simulations)
- **The drive laser**
- The guns
- Beam characterization

The trade-off: cathodes and lasers

J=(100-500) A/cm2 (semiconductors)
J=10000 A/cm2 (metals)



- **state-of-the art**
  - near IR laser and visible = 25 W
  - UV laser = 2W

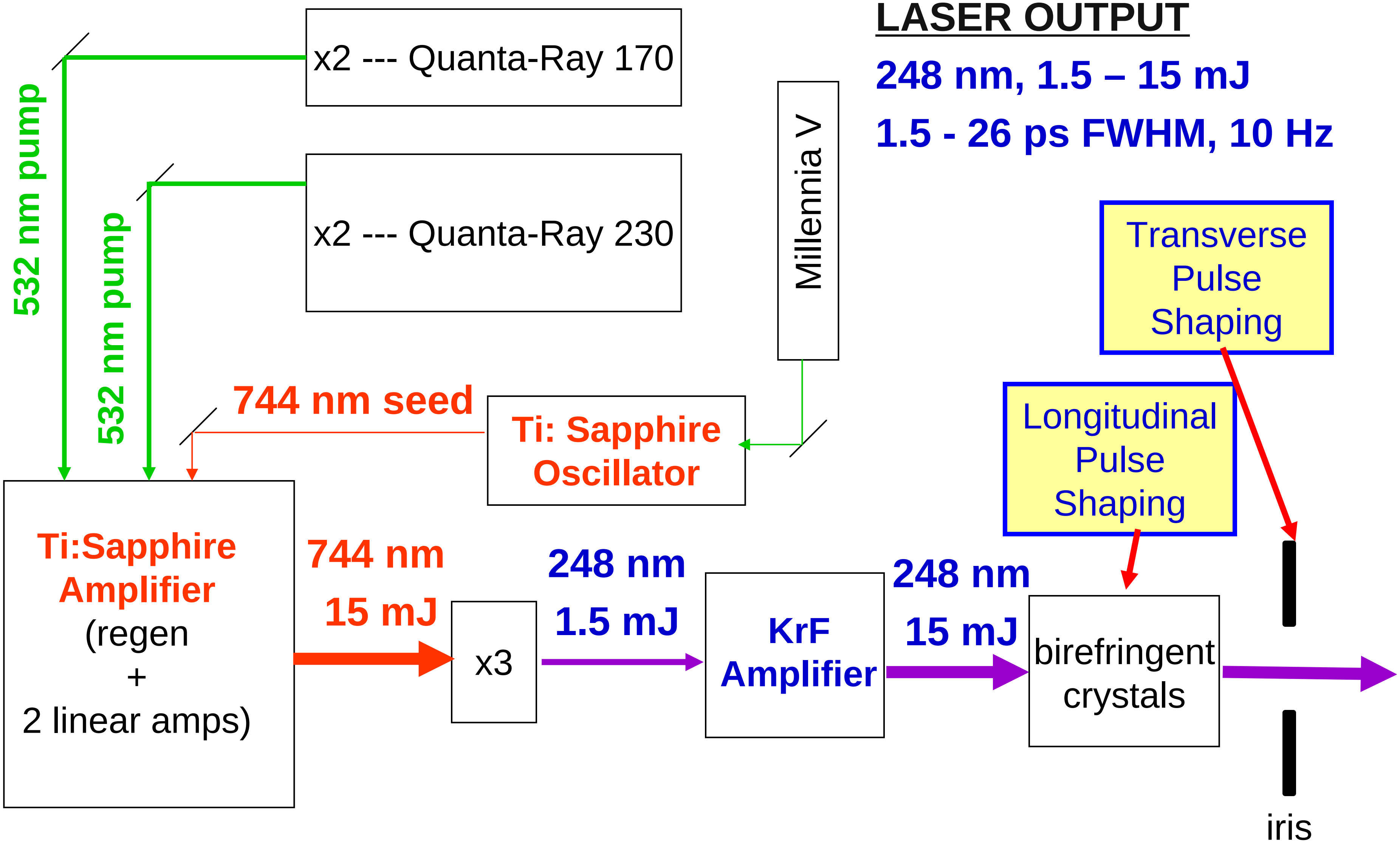
Ti:Sa CPA x3 + excimer + shaping

The AWA Drive Laser

LASER OUTPUT

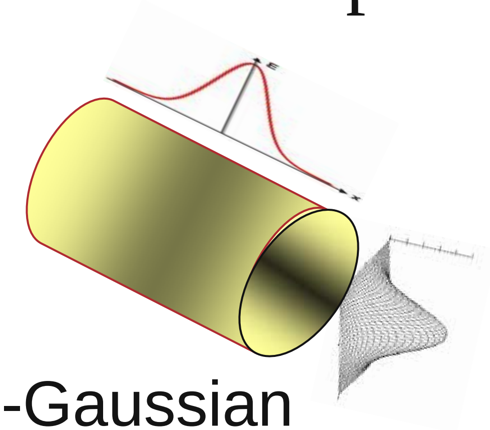
248 nm, 1.5 – 15 mJ

1.5 - 26 ps FWHM, 10 Hz

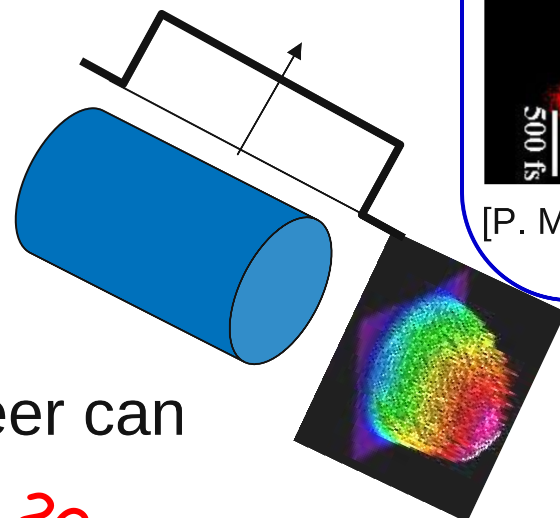


laser pulse shaping

linearize the space charge forces

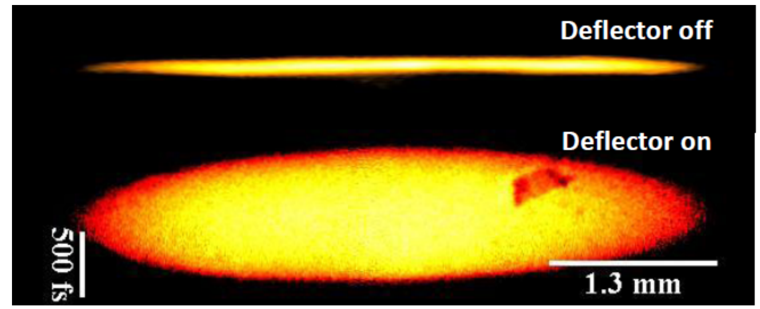


tri-Gaussian

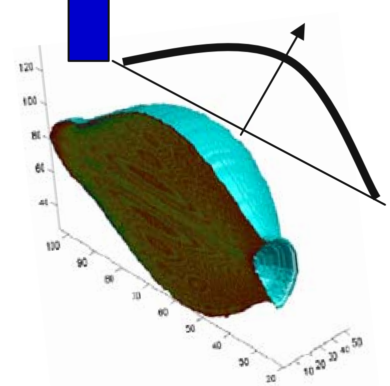


beer can

Generated ellipsoidal beam in blowout regime
Q=20 pC (35 fs → 300 fs)



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



ellipsoidal

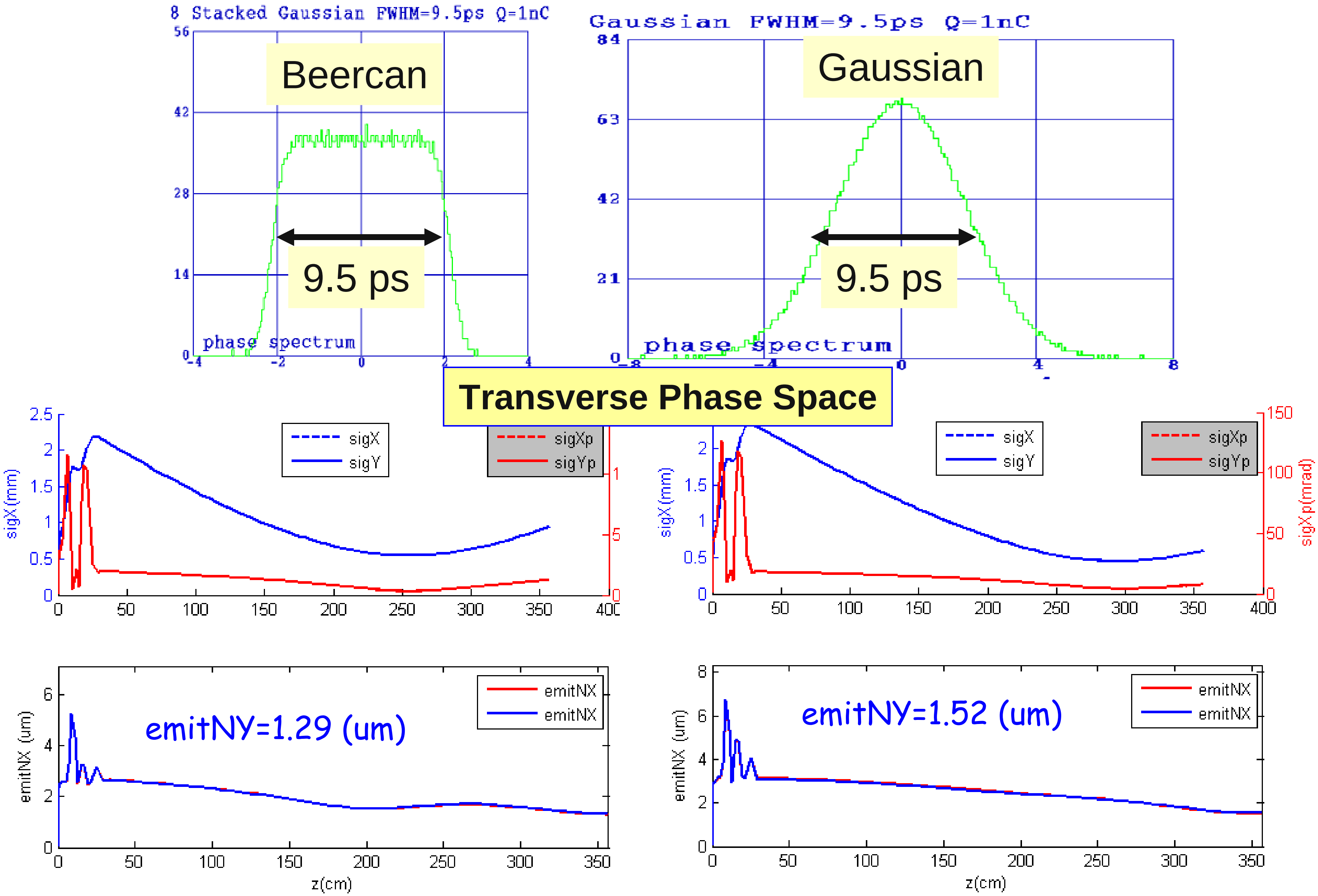
1990s

2000s

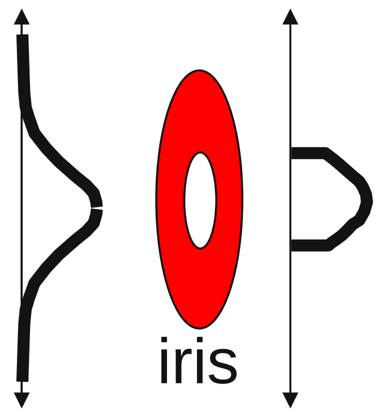
2010s

evolution of pulse shaping

Flat-top for low emittance at the AWA

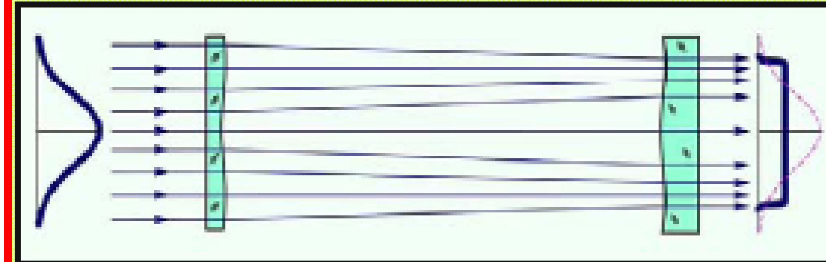


Spatial Profile: Beercan



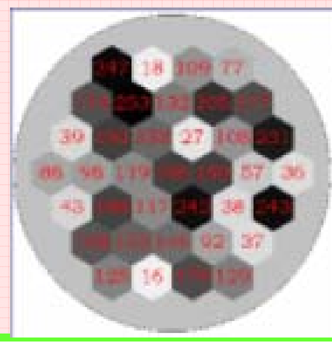
- **Clipped Gaussian**
  - simple
  - flexible
  - lossy

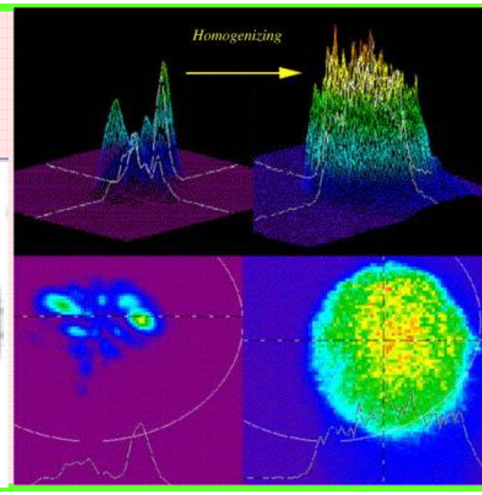
- **Π-shaper**
  - simple
  - fixed
  - low loss (5%)



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

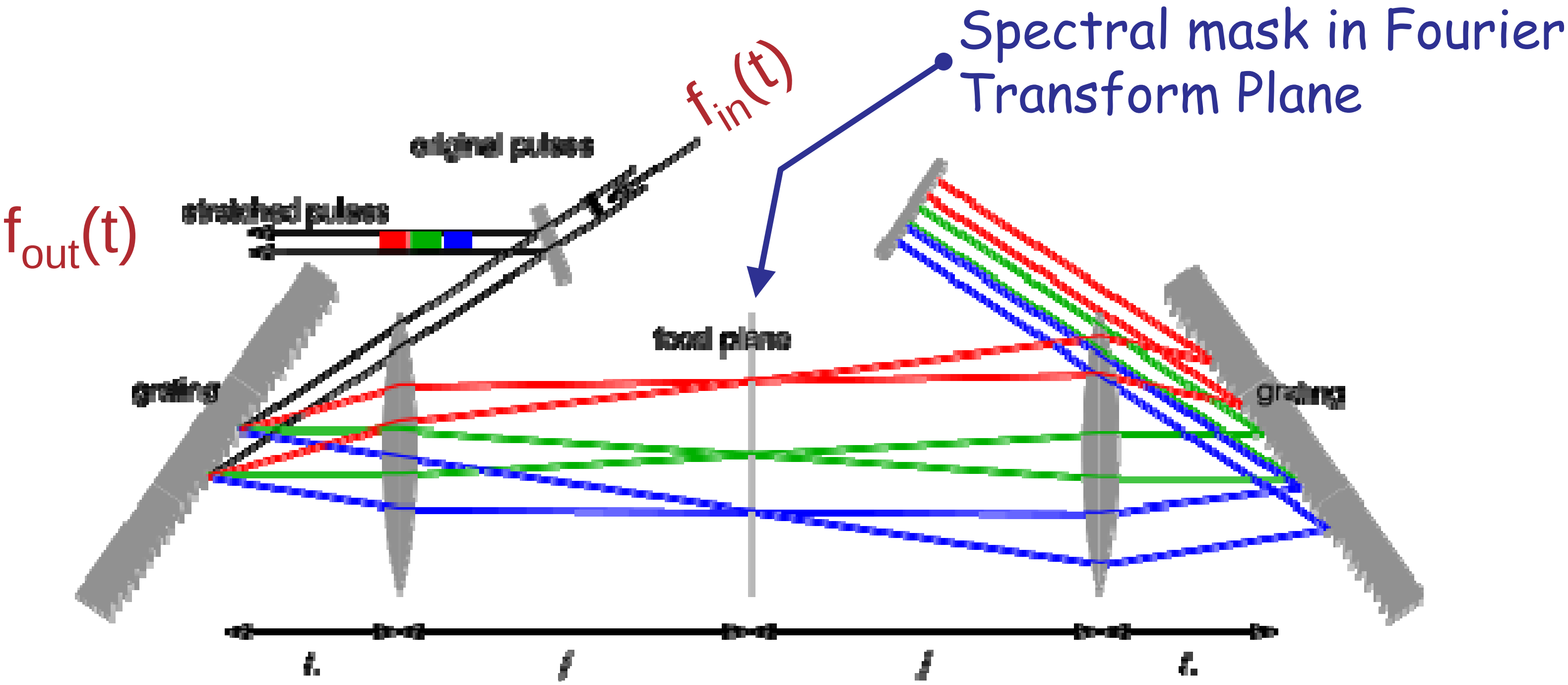
- **Deformable Mirror/ Microlens array**
  - complex (computer genetic algorithm, $$)
  - flexible
  - low loss





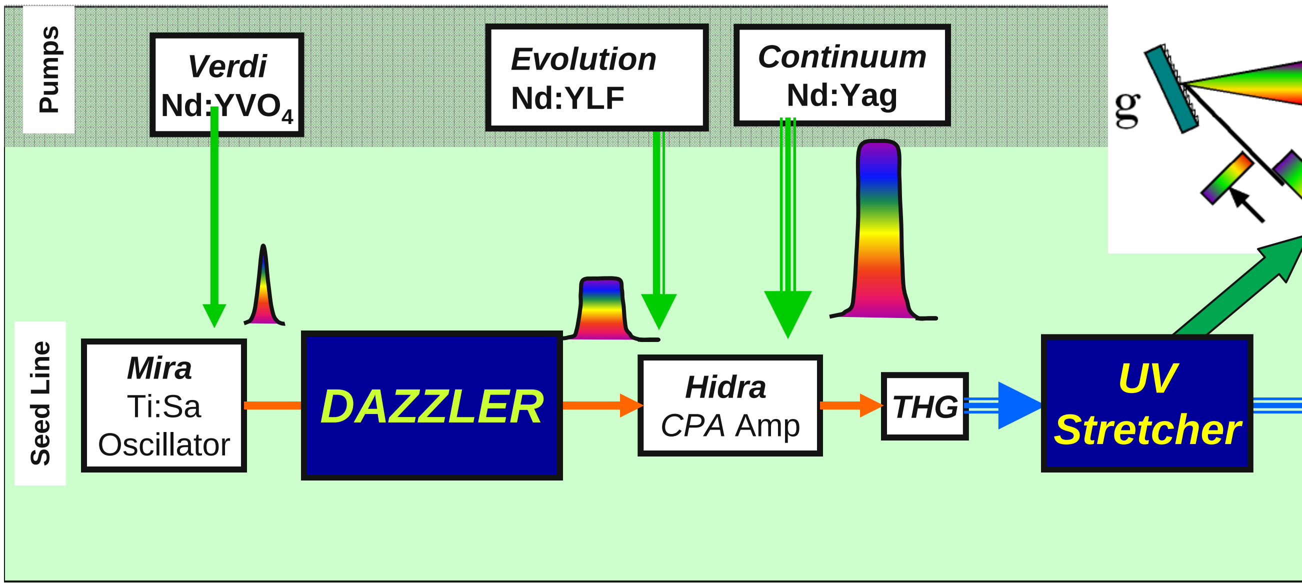
H. TOMIZAWA, SPring-8

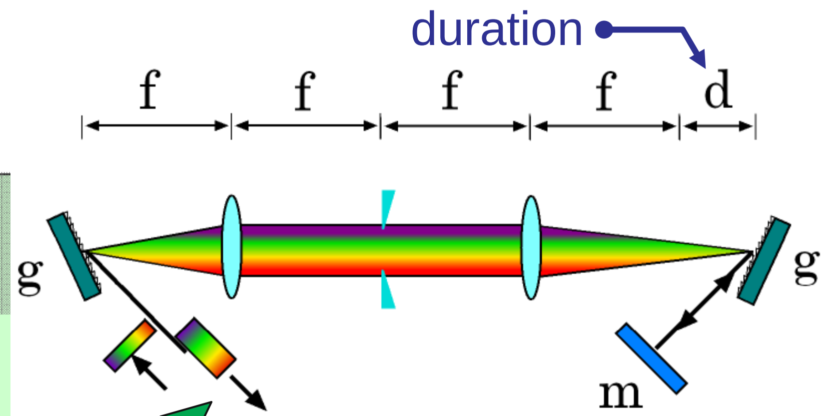
Longitudinal Pulse Shaping (frequency domain)

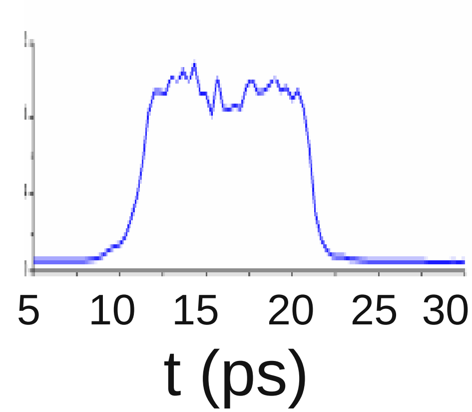


- **How it works:**
  1. The stretcher generates the Fourier Transform of the input pulse
  2. A mask is used to <u>**modulate the amplitude and phase**</u>

SPARC: Shaping in IR (Dazzler) + Stretching in UV





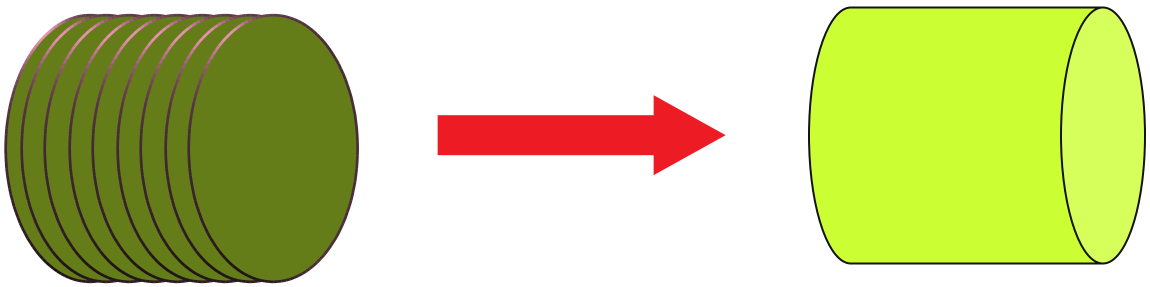


- IR Dazzler (Acousto-optic Programmable Dispersive filter) adopted by many photoinjector projects: LCLS, TESLA X-FEL, SPARC:
  - limited rise time in UV ~3 ps (finite bandwidth of the non-linear crystals)
- IR Dazzler + UV Stretcher
  - Fastest Rise time in UV ~1.4 ps

C. Vicario, SPARC-LS-09/001

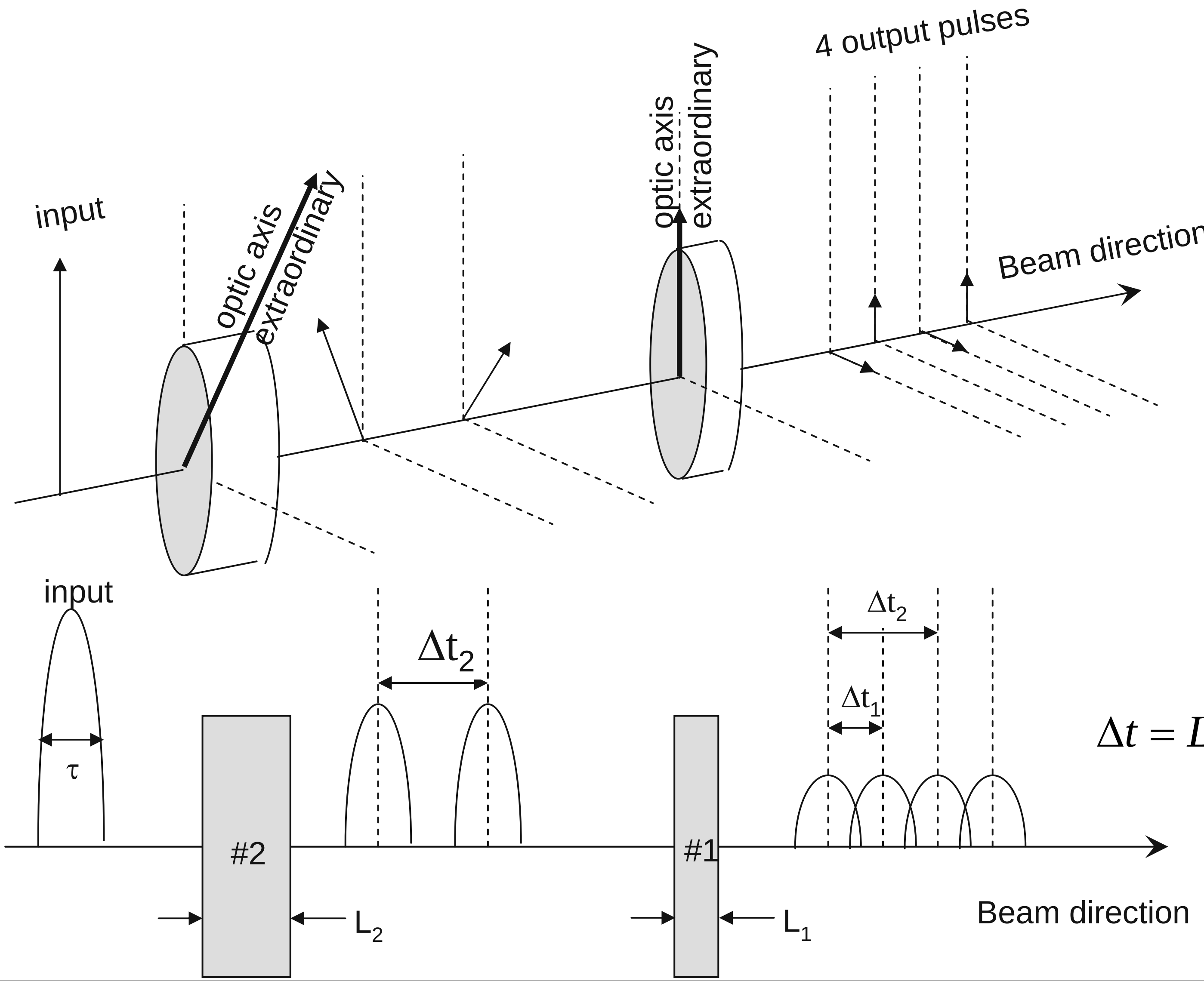
Longitudinal Pulse Shaping (Time Domain)

- A series of short discs can be stacked together to make a long cylinder



- Rise time limited by the "seed", typically very short

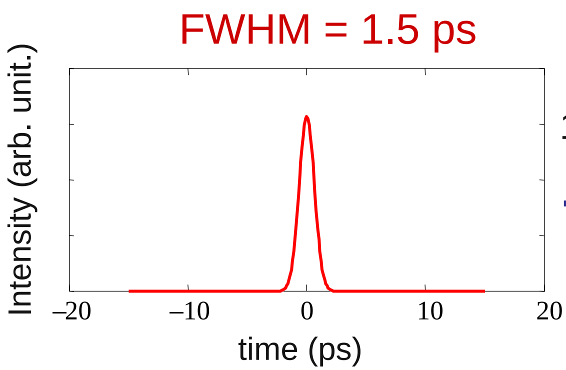
Pulse Stacking with birefringent crystals

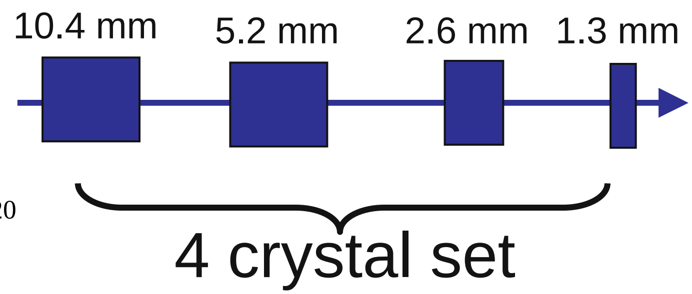


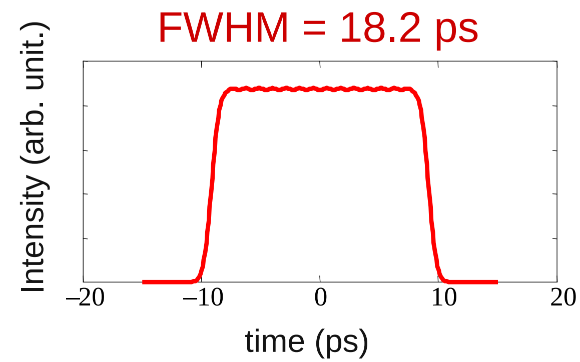
2^n pulses for n crystals

$$\Delta t = L\left(\frac{1}{v_{ge}} - \frac{1}{v_{g0}}\right) = L\frac{\Delta n_g}{c}$$

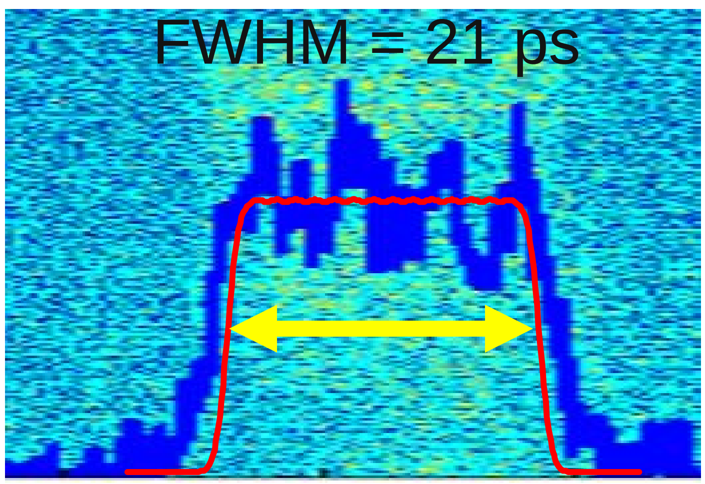
Flat-top for low emittance at the Argonne Wakefield Accelerator



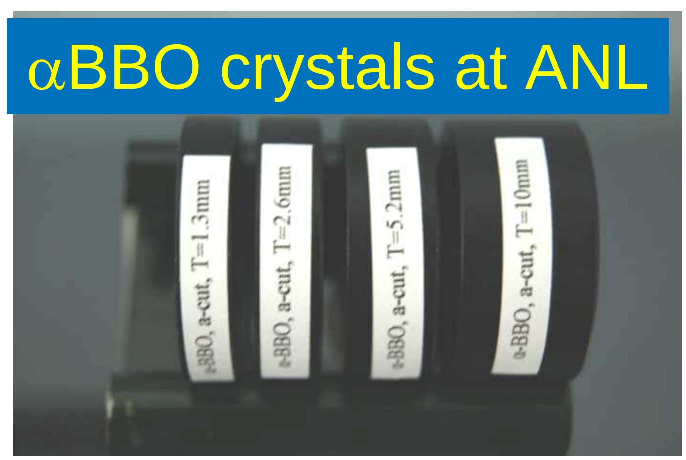




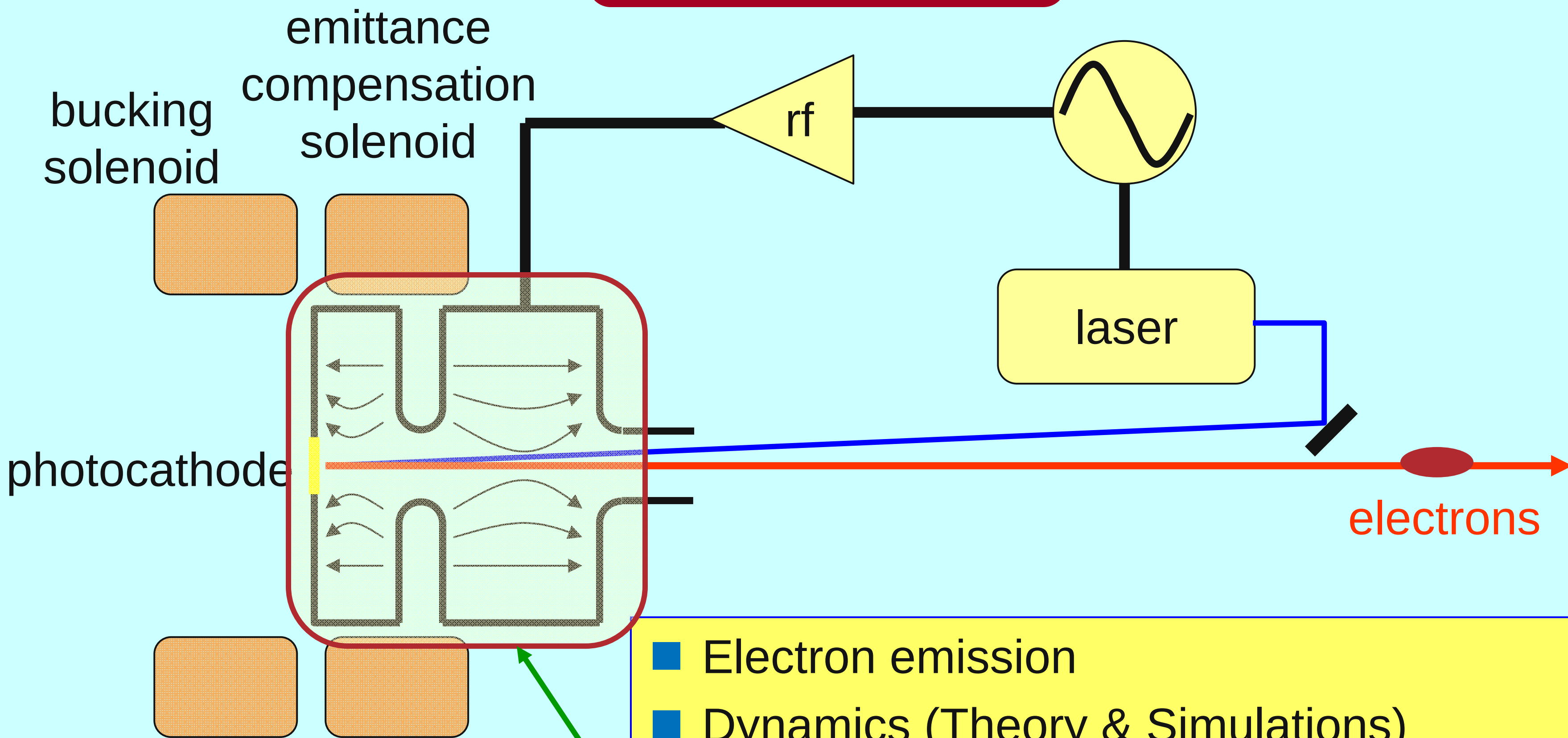
16 stacked Gaussians



streak camera measurement

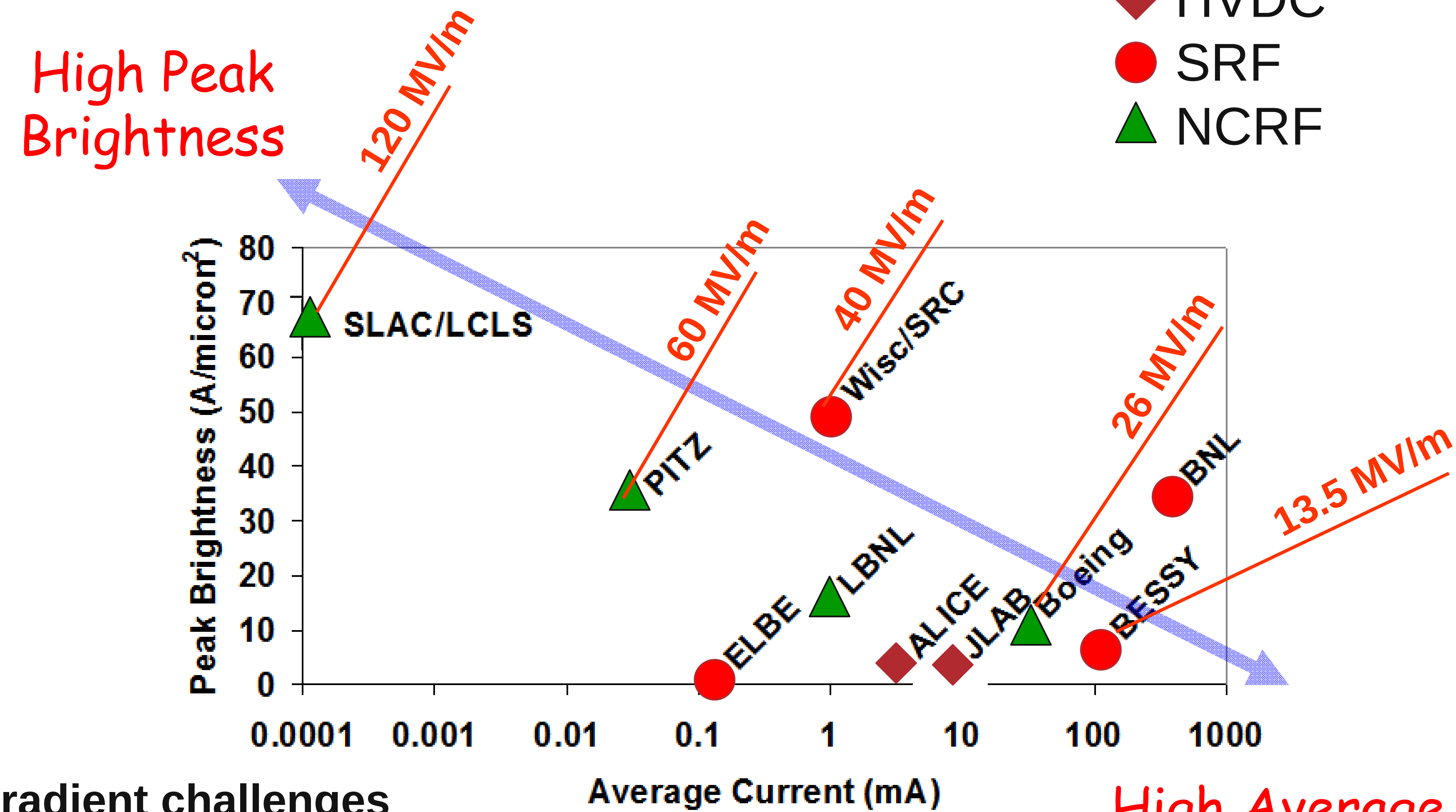


outline



- Electron emission
- Dynamics (Theory & Simulations)
- The drive laser
- **The guns**
- Beam characterization

The peak vs average trade-off



gradient challenges

NCRF → cooling

HVDC → field emission

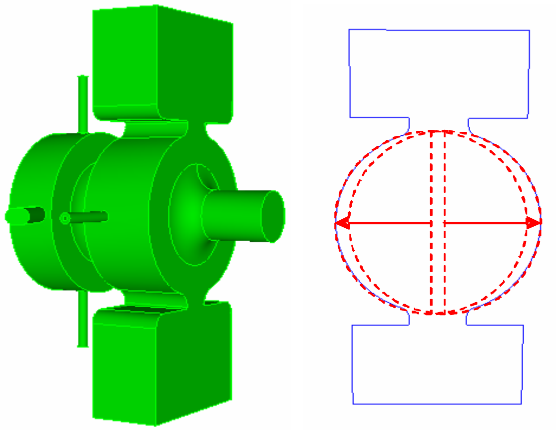
SRF → ~50 MV/m (*potential*)

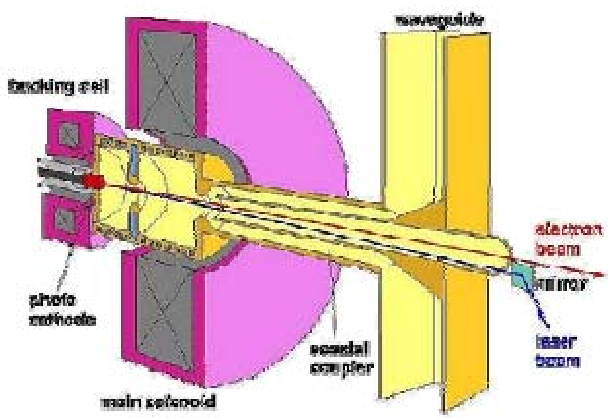
classes of photocathode guns:

NCRF

low duty cycle guns

Gun dynamics → *Modern guns realize nearly perfect rf and magnetic fields*





- **LCLS**
  1. Eliminates the **dipole and quadrupole rf fields** (Dual RF feed and racetrack shape)
  2. Eliminated **beating between 0 and π modes** during rf fill
  3. Eliminated **quadrupole fields in solenoid**
- **PITZ**
  1. **Coaxial coupler:** a fully symmetric design of cavity and RF coupling
  2. a careful **laser pulse shaping** (transversely and temporally)

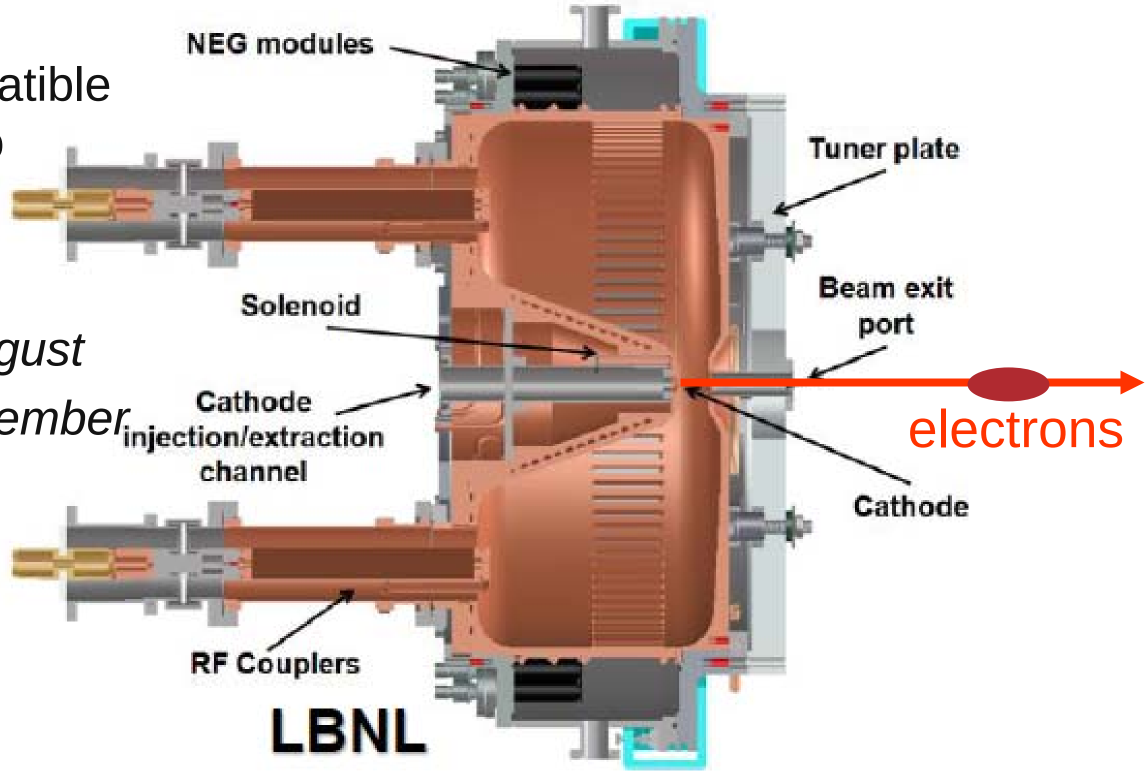
classes of photocathode guns:

NCRF

CW guns

Challenge for CW NCRF gun: **cooling** (wall losses)

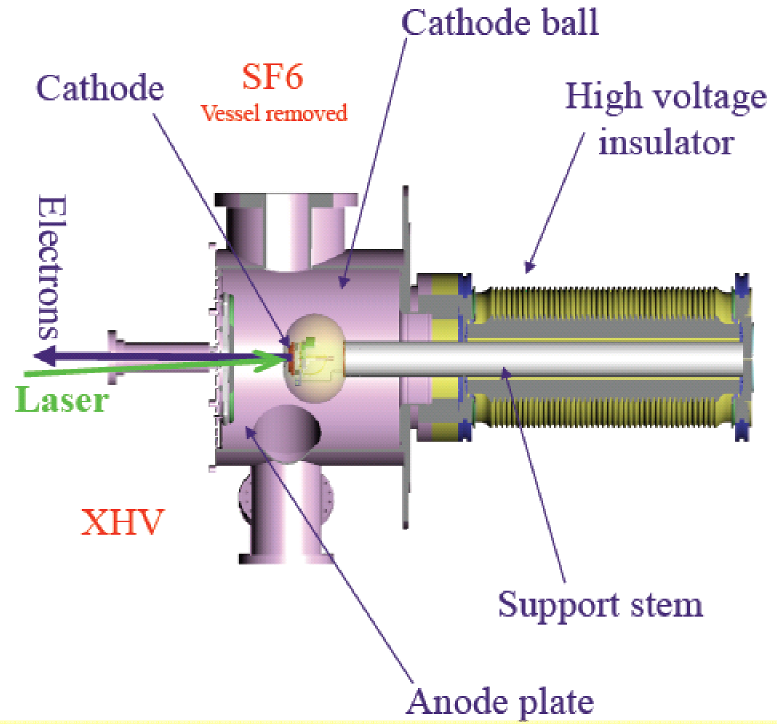
- **VHF gun (LBNL)**
  1. **187 MHz** (20 MV/m)
  2. **excellent vacuum: c**ompatible with most cathodes due to
  3. **status**
     1. *gun is fabricated*
     2. *rf conditioning late August*
     3. *first cathodes by September*



classes of photocathode guns:

HVDC

- **State of the art**
  - High Current capabilities (>10 mA)
  - exceptional vacuum (allows GaAs:Cs cathodes)
- **Future directions**
  - **higher Q** → Increase Ecathode;
  - >10 MV/m (or >500 kV) → 1 nC



Darsbery/ALICE

- 350 kV
- Iavg=6.5 mA
- ε_{XN}=1.5 μm @ Q=80 pC

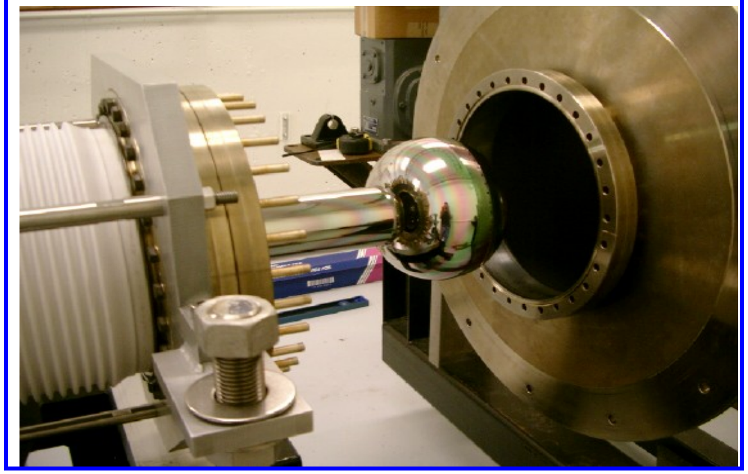
classes of photocathode guns:

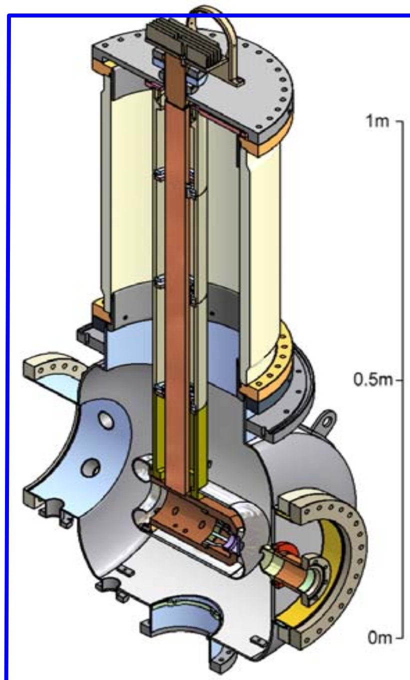
HVDC

photocathode: GaAs

Jlab (C. Hernandez-Garcia)

Q>7000 Coulombs with a single GaAs wafer (at 1-8.5 mA CW; 2004-07)

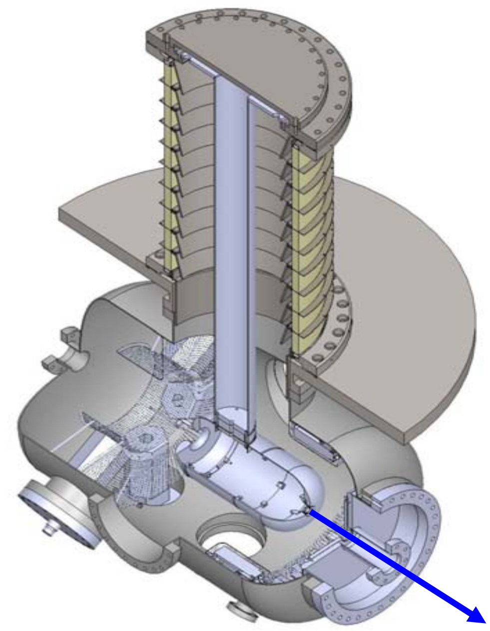




Cornell (I. Bazarov)

Iavg=20 mA DC

300 kV



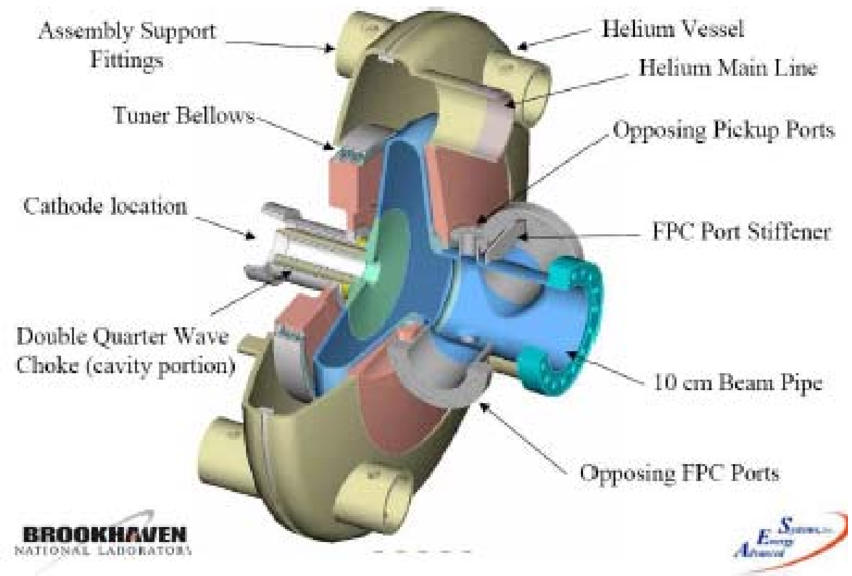
JAEA/KEK

>500 kV (a segmented insulator to mitigate field emission problem)

classes of photocathode guns: SRF

- **Potentially the best of both worlds**
  - **Higher gradient** than HVDC (~50 MV/m)
  - **Excellent Vacuum** (may allow more cathode choices)

- **Challenges**
  - **No magnetic field near cathode** (emittance compensation solenoid)
  - warm (LN2 temperature) **normal conducting photocathode** in an SRF environment
  - **Cathode contamination** onto superconducting surface



(BNL) ERL R&D Gun (I. Ben-Zvi)

Iavg=0.5 A

704 MHz, T=2.5MeV

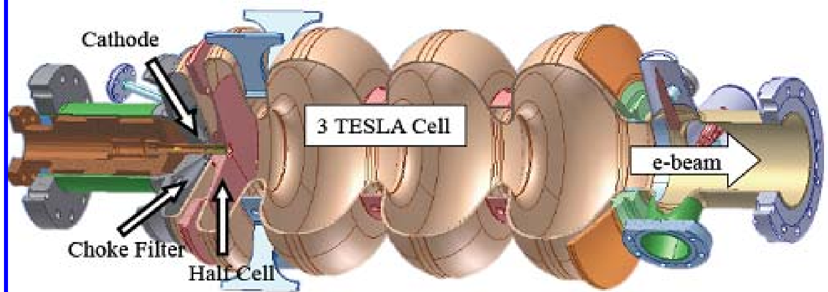
Q=0.7 nC → ε_{XN}=1.4 µm, σ_Z=6mm

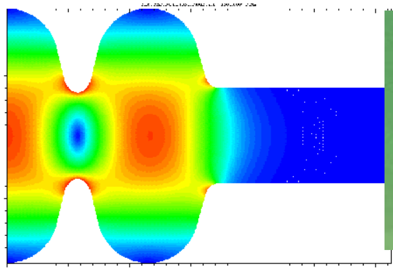
classes of photocathode guns: ● SRF

Rossendorf/ELBE (J. Teichert)

I = 1 μA (**demonstrated**)

Cs2Te in SRF gun (**demonstrated**)

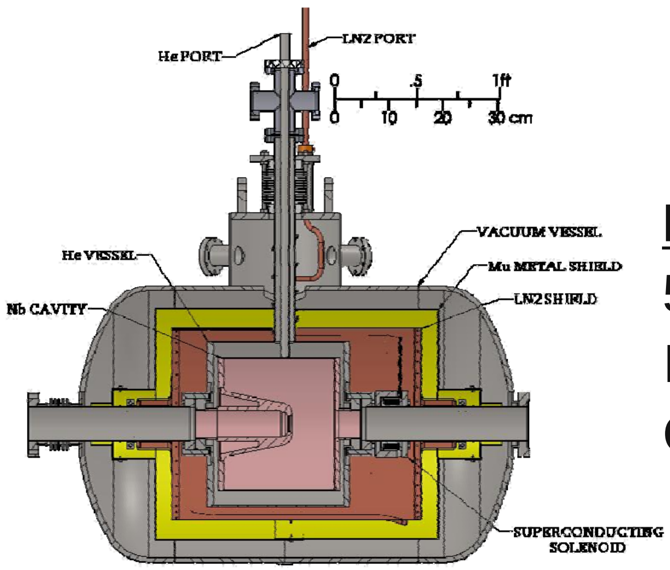




HZB/BERLinPro gun (T. Kamps)

initial: Pb/Nb cathode, Iavg=15 μA

final: CsK2Sb cathode , Iavg=100 mA



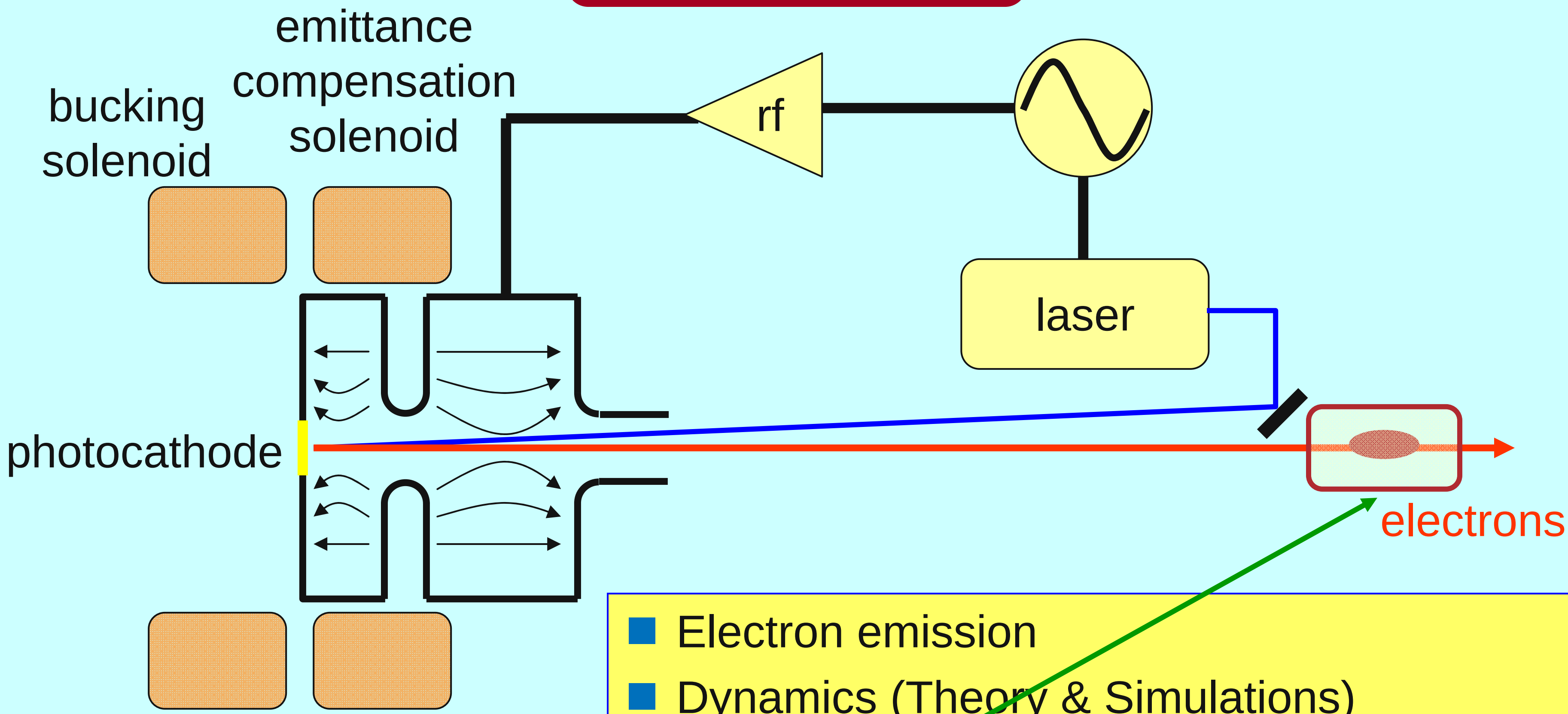
Naval Post Graduate School Prototype

500-MHz quarter-wave cavity (J. Lewellen)

Iavg=10 mA, T=1.2 MeV, Q=10 pC-1 nC

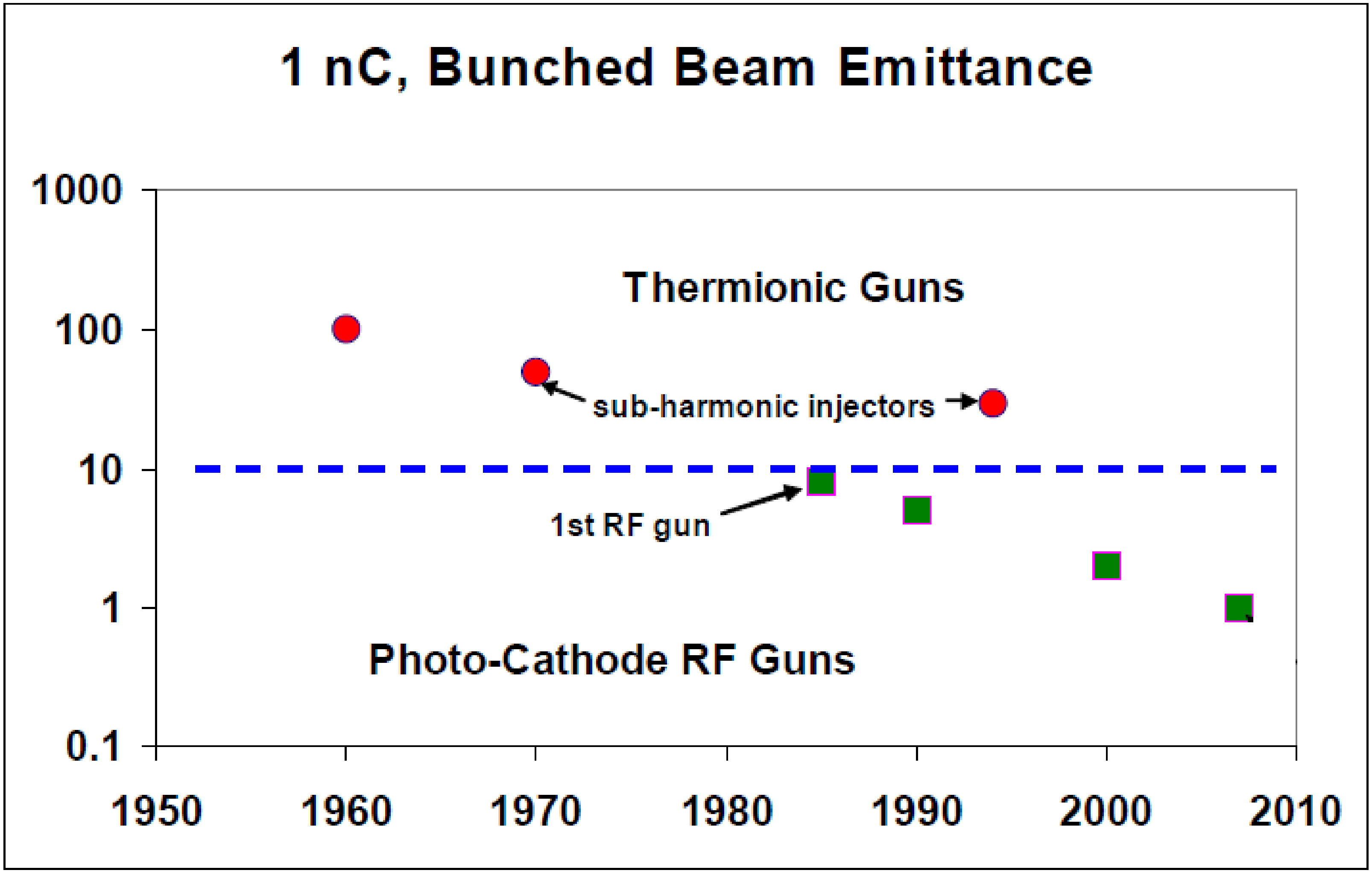
Commissioning soon??

outline



- Electron emission
- Dynamics (Theory & Simulations)
- The drive laser
- The guns
- **Beam characterization**

Evolution of beam quality

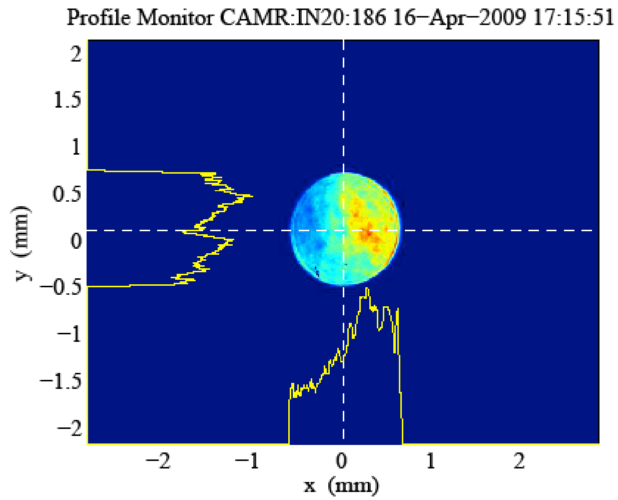


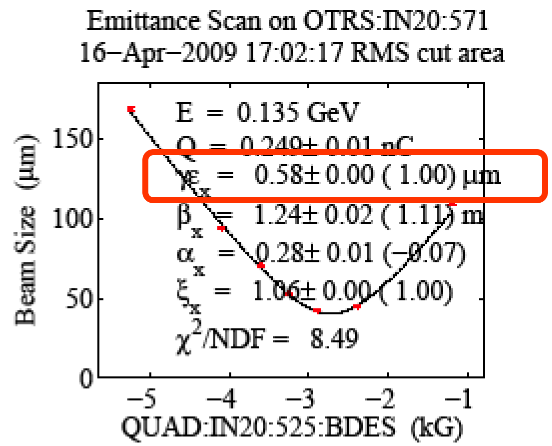
LCLS transverse emittance

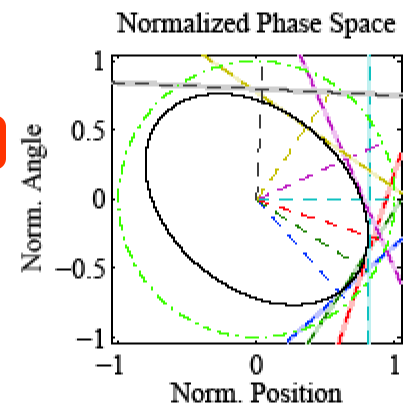
Asymmetric UV beam on the cathode → creates a tail on the e-beam in the injector → degrades the emittance

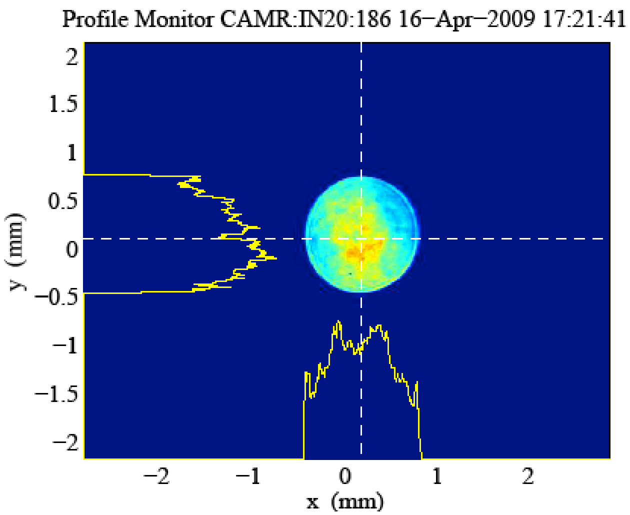
Q=250pC

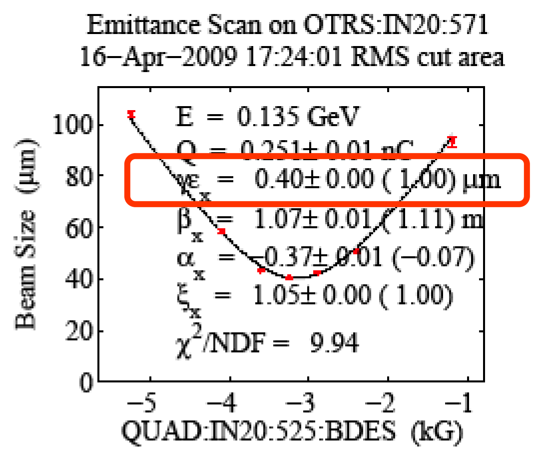
ε_X: 0.58 → 0.4 μm

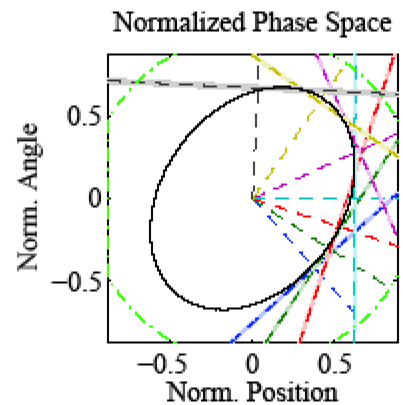








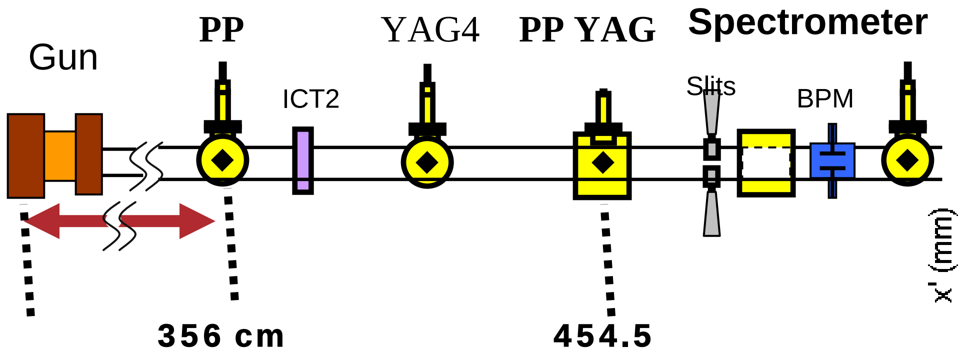


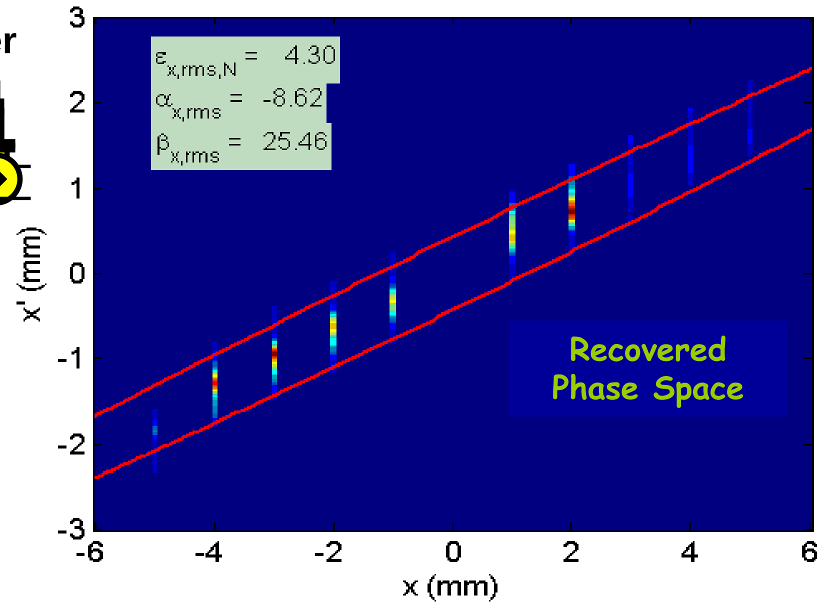


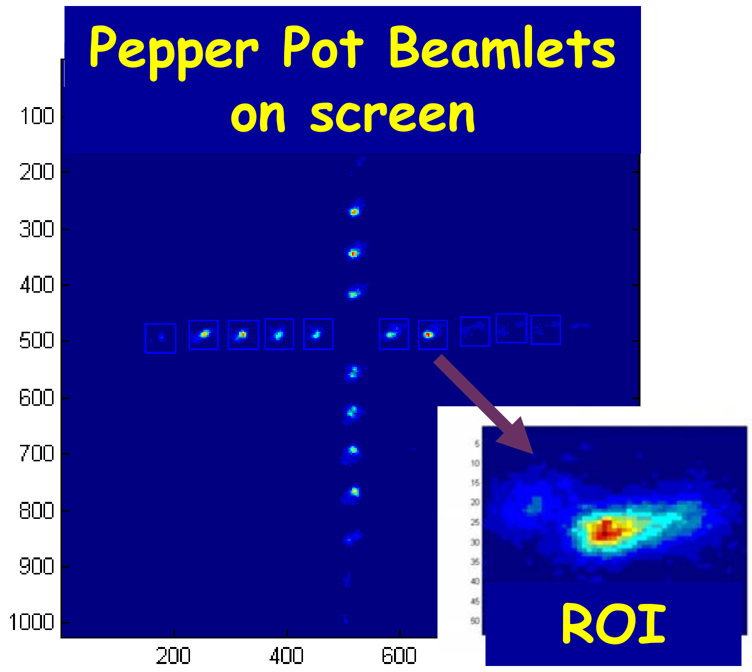
*Measured at 135 MeV with Quad Scan technique
*courtesy P. Hering & B. White

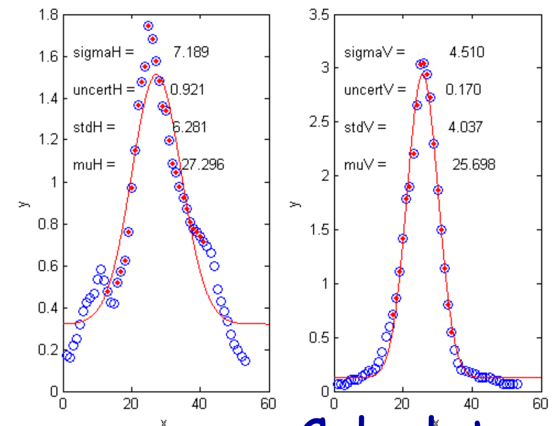
Pepper pot phase space measurements at AWA

-Measuring the emittance directly out of injector
-Single shot measurement







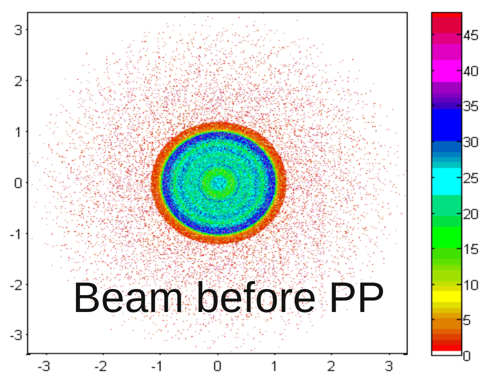


Calculate rms size

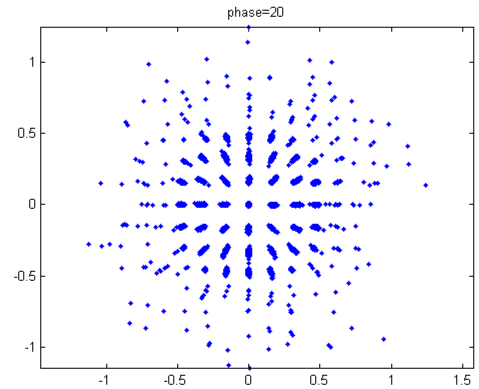
4D phase space measurement at AWA

-Simulation of Pepper Pot diagnostic, 10 million particles

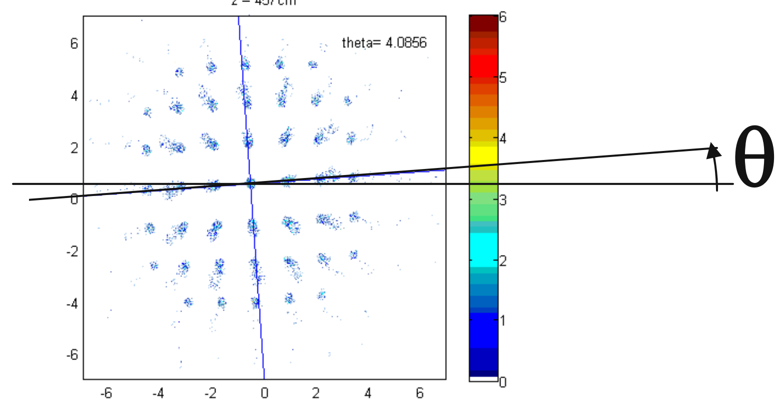
Pattern rotation indicates X-Y coupling

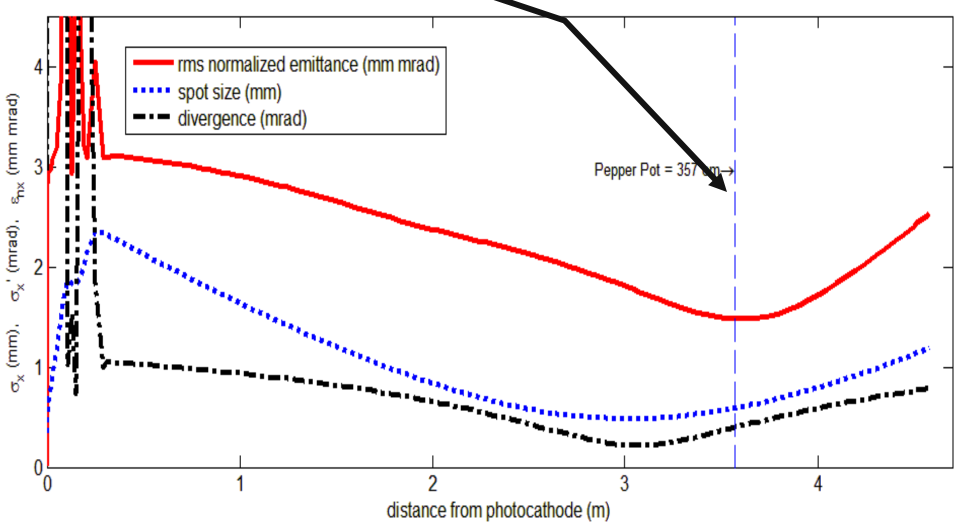


$B_{cathode}$=0



$B_{cathode}$=0.01T



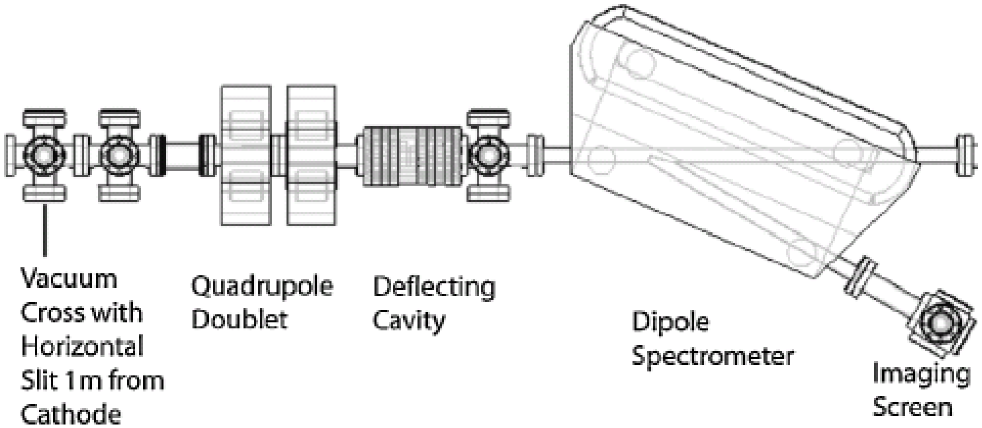


Non-zero off block diagonal terms indicates X-Y coupling

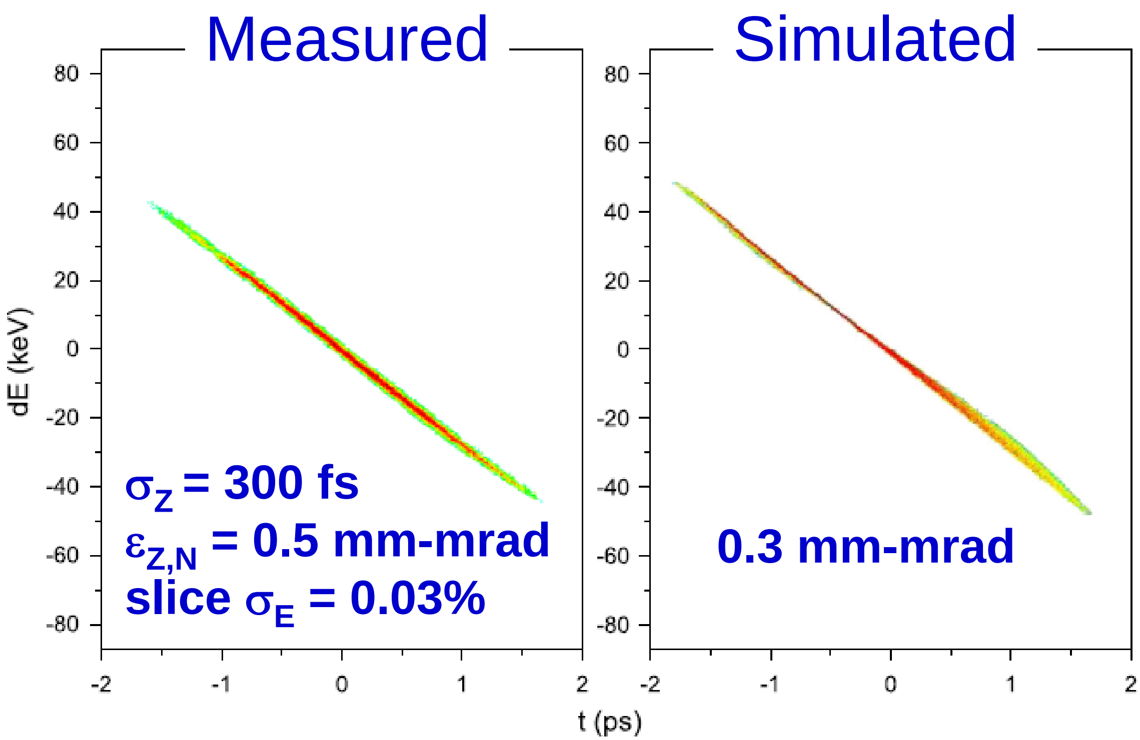
$$\Sigma_{4D} = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle y^2 \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'^2 \rangle \end{pmatrix} = \begin{pmatrix} \sigma_{xx'} & \sigma_{xyx'y'} \\ \sigma_{xyx'y'} & \sigma_{yy'} \end{pmatrix}$$

$$\varepsilon_{4D} = \sqrt{\det(\Sigma)}$$

Longitudinal Phase Space measurements



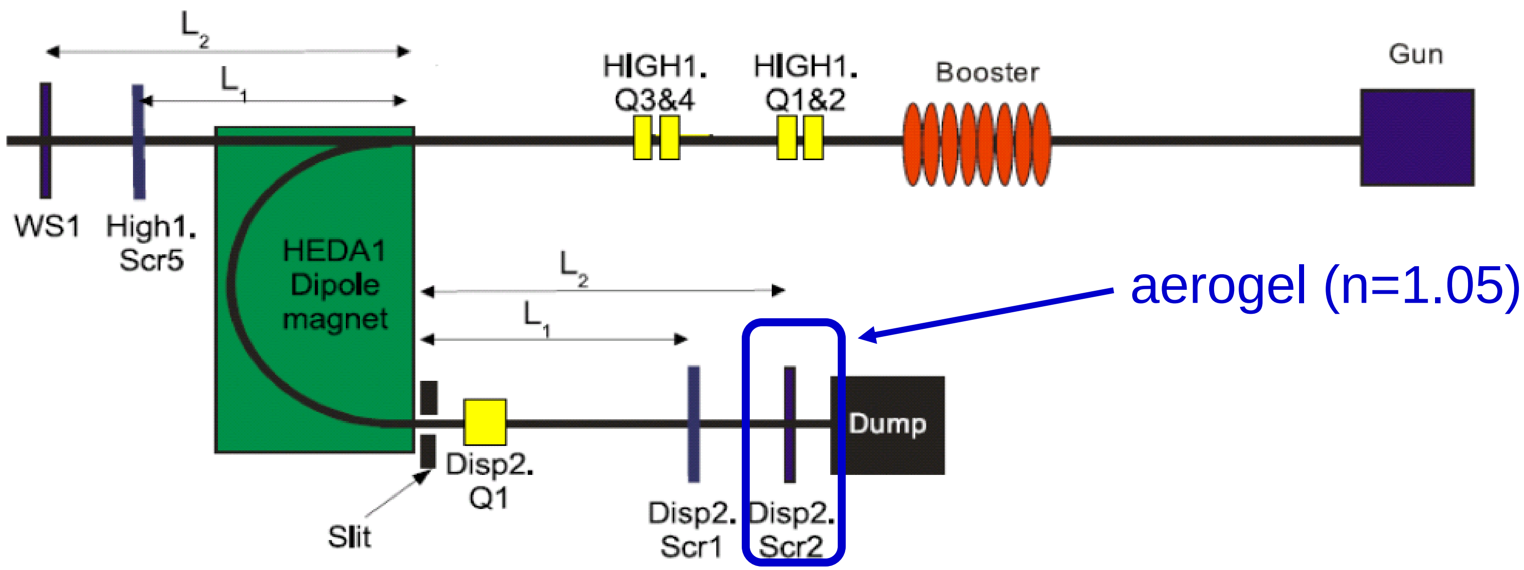
- **Deflecting cavity**
  - streaks vertically
  - resolution = 50 fs
- **Spectrometer**
  - disperses horizontally
  - resolution 1 keV



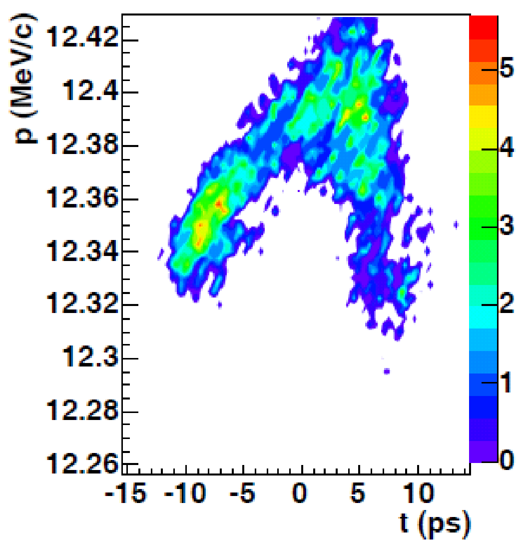
Q=20 pC

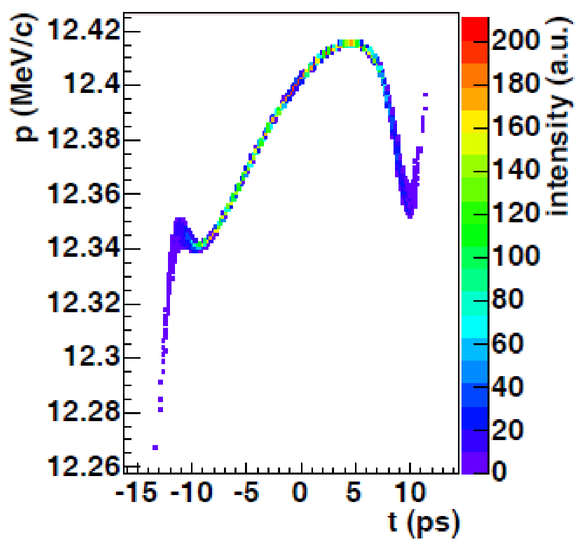
J. T. Moody et al., PRSTAB 12, 070704 (2009)

Longitudinal phase space measurements



- **Spectrometer**
  - disperses vertically
- **Aerogel**
  - prompt light
  - resolution = streak camera (2 ps) + optical transmission line





J. Ronsch, DIPAC09

→streak camera resolution limited←

Where we've been…

- **Photoinjectors are now in use at major user facilities:** LCLS, FLASH, XFEL,
- **Rapid improvement in all major subsystems:** Cathodes, Theory and simulation, Laser technology, Gun, Diagnostics

Looking forward…

- **High average current guns beginning to turn on**: {SRF guns VHF guns}
- **New brightness frontiers** {Laser Beam shaping, New photocathodes}

acknowledgements

I. Ben-Zvi (BNL), J. Smedley (BNL), D. Dowell (LCLS), K.-J. Kim (ANL), C.-X. Wang (ANL), J. Lewellen (NPS), T. Kamps (HZB), T. Rao (BNL), F. Stephan (PITZ), F. Sannibale (LBLN), C. Garcia-Hernandez (JLab), P. Piot (NIU), D. Mihelica (FNAL), W. Gai (AWA), M. Conde (AWA), J. Schmerge (SLAC), Z. Yusof (AWA), S. Lederer (PITZ), I. Bazarov (Cornell),