Review of SOME experiments on bright e-beam photo-production

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Introductions / Comments

Photo-emission, thermal emittance

RF-guns (11 Ghz, S, L bands, and 144 Mhz)

DC-guns

R&D SRF guns, polarized RF-gun

Conclusion + discussions

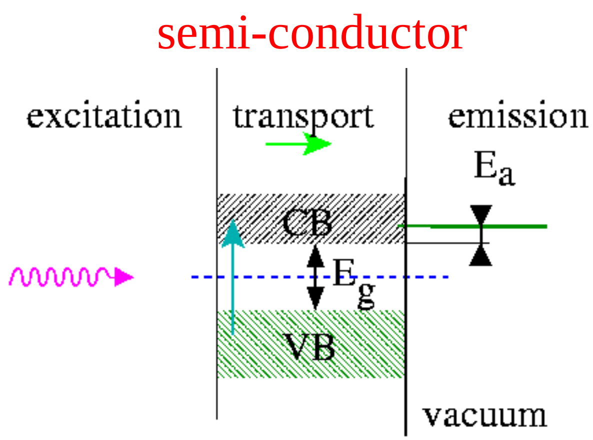
(talk very similar to the one I gave at 2002 ICFA workshop on high brightness beam)
see report DESY M-02-02 December 2002 available from DESY Hamburg at:
http://www.desy.de/~ahluwali/mreports/2002/02-02.pdf

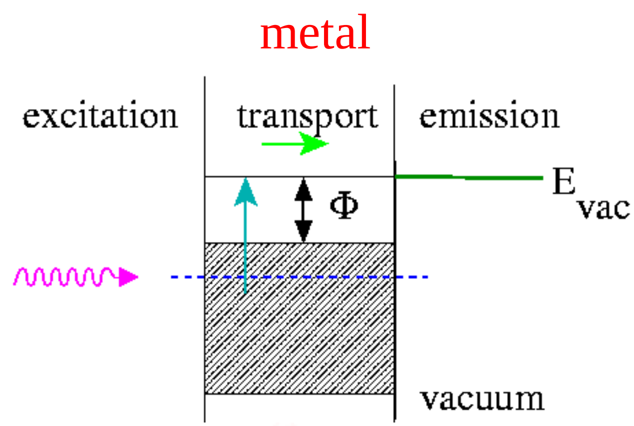
Introduction

- Application of high-brightness photo-injectors:
  - high energy linear colliders (needs flat beam $\varepsilon_y/\varepsilon_x \ll 1$)
  - radiation sources (FELs, short pulse , high power)
  - X-rays production (XTR, Thomson)
  - plasma-based electron sources-drivers,
  - etc
- Many accelerator test facilities in operation based on photo-injectors:
  - dedicated to beam physics (BNL, UCLA, DESY-Z, NERL...)
  - drive user-facility (ATF, Jlab, DESY-HH,…)
- Figure-of-merit: emittance (FELs requires $\varepsilon<\lambda$) , peak current, average current (photon flux), local energy spread, bunch length (e.g. for probing ultra-fast phenomena)…

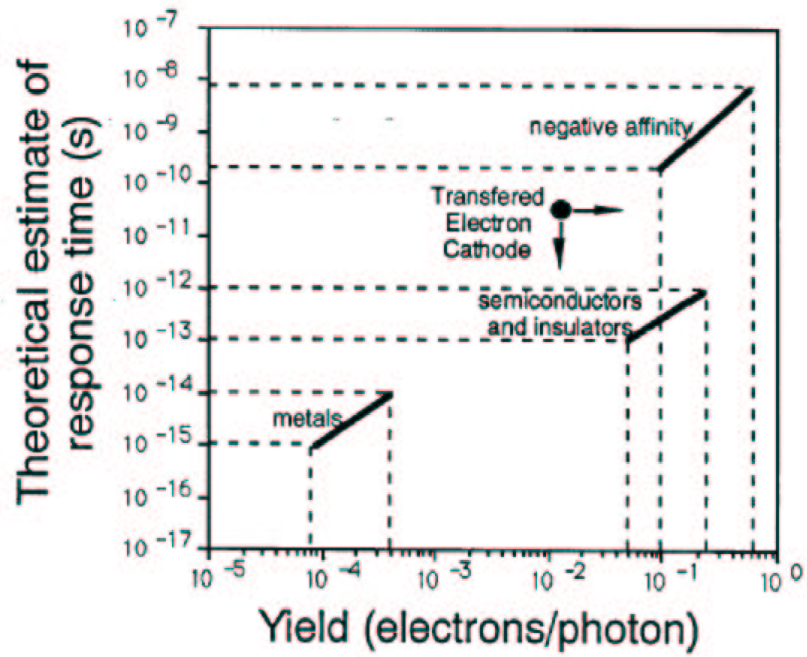
Beam brightness: $$B = \frac{Q}{\tau_6} \simeq \frac{Q}{\varepsilon_x \varepsilon_y \varepsilon_z}$$

Photo-emission from metals and semi-conductors





Material	QE Range (%)	λ (nm)	Lifetime	Required Vacuum (T)
Metal	0.02-0.06	260	Months	1E-7
CsK_2Sb	10-14	527	-	1E-10
Cs_2Te	10-14	260	Months	1E-9
LaB_6	0.1	355	Months	1E-7
GaAs (Cs)	1-5	527	Days	1E-11



(from Spicer et al. SLAC-PUB 6306)

Few words on Lasers

$$Q_{bunch} = \eta \frac{e\lambda_{laser}}{hc} E_{laser} \rightarrow Q[nC] \simeq \eta \frac{\lambda_{laser}}{1.24} E_{laser}[\mu J]$$

Quantum efficiency

- For metal, typical laser energy required: ~5-500 μJ/pulse
- For semi-conductor: ~0.5 μJ/pulse
- Metallic cathodes are bad candidates for high-average power machine [namely the drive-laser is a big challenge and one might need an FEL-based photo-cathode laser to have 100 W level in the UV.]

Thermal Emittances

Electrons are emitted with a kinetic energy E_k

$$\Rightarrow \varepsilon_{th} = \frac{r}{2}\sqrt{\frac{E_k}{m_e c^2}}$$

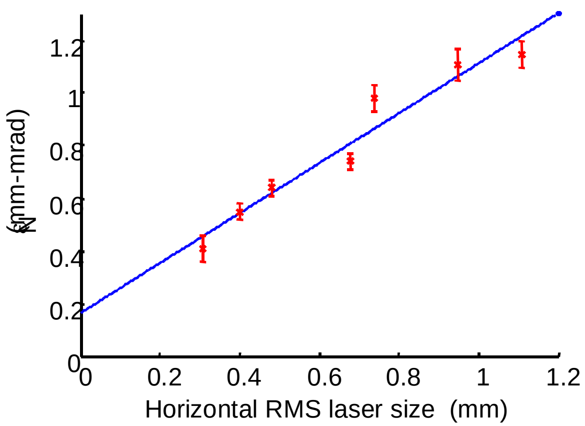
Uniform laser spot with radius r

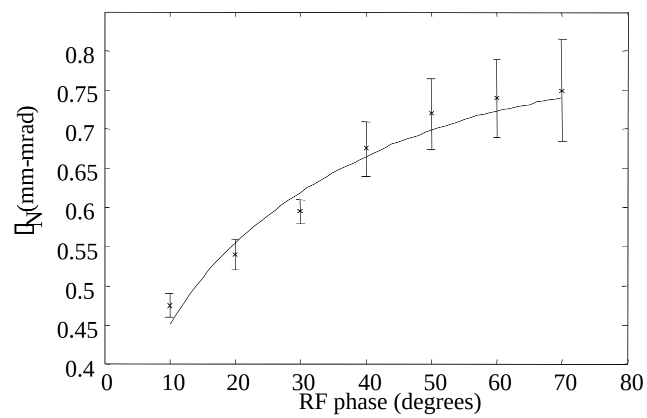
$$\Rightarrow \delta E_{th} \simeq \langle E_{kin}^2 \rangle^{1/2} \ll \sigma_E$$

$$E_k = h\nu - \Delta + \alpha\sqrt{\beta_{RF} E_{RF} \sin\vartheta_{rf}} \qquad \Delta = \Phi \text{ ,or } E_G + E_A$$

Example of measurement for Cu-cathode

(Courtesy of W. Graves)





Linear fit gives E_k=0.43 eV

Nonlinear fit gives β_{rf}=3.1+/-0.5, Φ_{cu}=4.73+/-0.04 eV, and E_k=0.40 eV

Thermal Emittance

To date no thermal emittance measurement for Cs_2Te cathodes has been performed [plan at INFN Milano are underway]

Several groups have measured thermal emittance of GaAs:

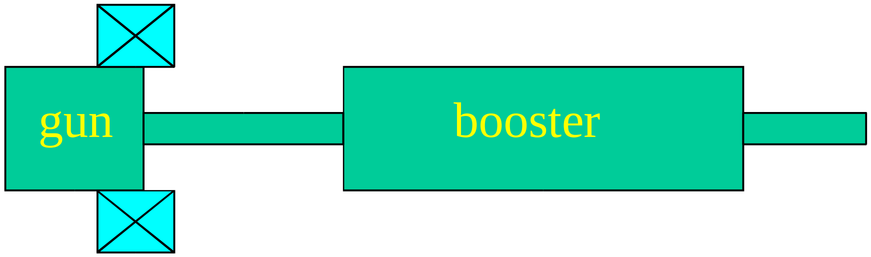
* Duhnam et al., on the Illinois/CEBAF polarized beam (PAC1993) at room temperature

* Orlov et al., at Heidelberg (Appl. Phys. Lett. 78: 2171 (2001)) at 70 K

The measurements indicate that a reduction of the cathode temperature results in a lower transverse kT for the emitted e-. This is particular to NEA cathodes where electrons from thermalized population can escape.
The price to pay is the long emission time of 10-20ps

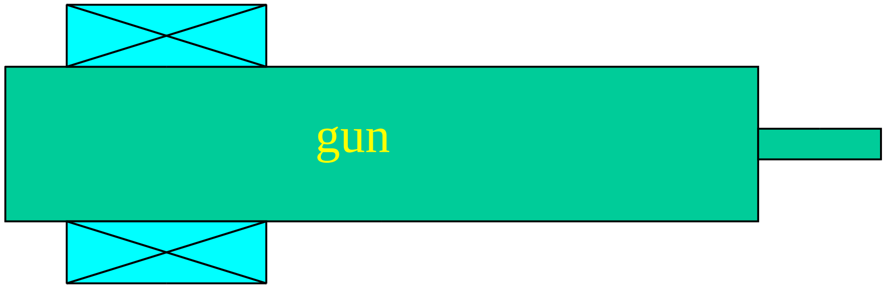
Generic photo-injectors

Split injectors



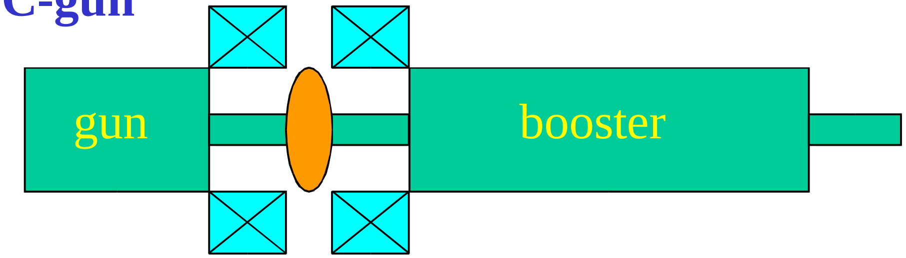
- 1-1/2, 2-1/2 cell cavity with high E-field
- booster section downstream of the gun
- E.g. BNL-gun, FNAL, AWA, DESY,…

Integrated injectors



- typically 10-1/2 cell cavity with moderate E-field
- long solenoid lens
- E.g. AFEL, PEGASSUS

DC-gun



- DC column with HV 500 kV and higher achieved
- Solenoids + rf-buncher
- Booster section
- E.g. IR-Demo

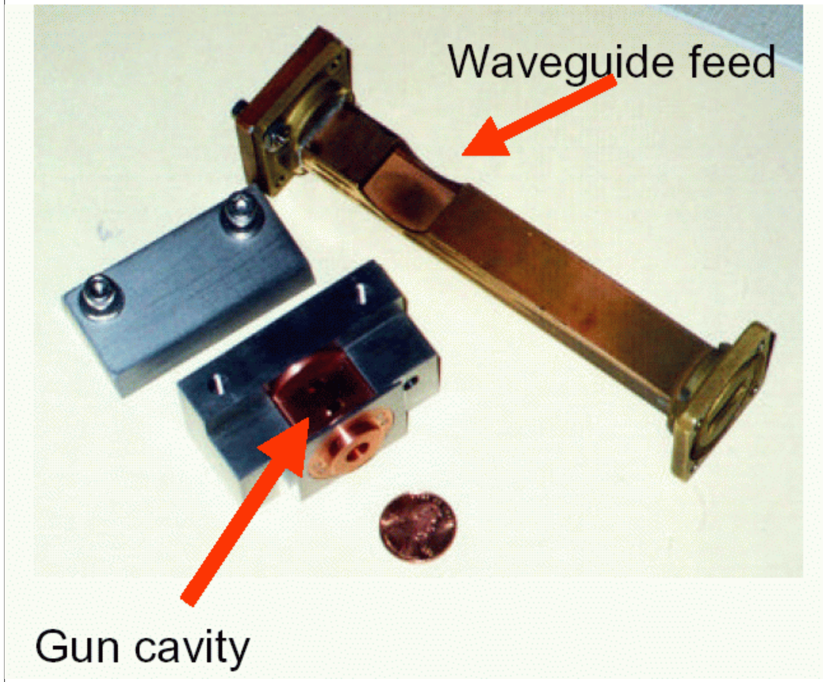
Frequency Scaling of photo-injectors

(Rosenzweig and Colby PAC95 Also L C.-L. Lin et al., PAC95)

PARAMETER	SCALING
Cavity dimension	ω^{-1}
Accelerating field	ω^{1}
Peak current	ω^{0}
Bunch charge	ω^{-1}
Bunch energy	ω^{0}
Bunch emittance	$\sim\omega^{-1}$
Bunch brightness	$\sim\omega^{2}$

- If the operating parameters are scaled following the Table, one would expect:
  Brightness~ ω^2
- this assumes: **E-field~ ω^1**
- Naively scaling the present BNL gun (120 MV/m) e.g. to 17 GHz would imply:
  E-field~ 720 MV/m!!!

MIT 17 GHz gun



(PRSTAB vol. 4:083501 (2001))

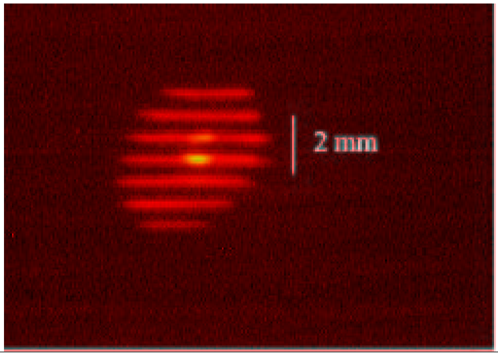
Mission: Advanced ultra-bright accelerator developments

1/ has commissioned a 1.5 cell gun

2/ work on a 2.4 cell gun (>2 MeV)

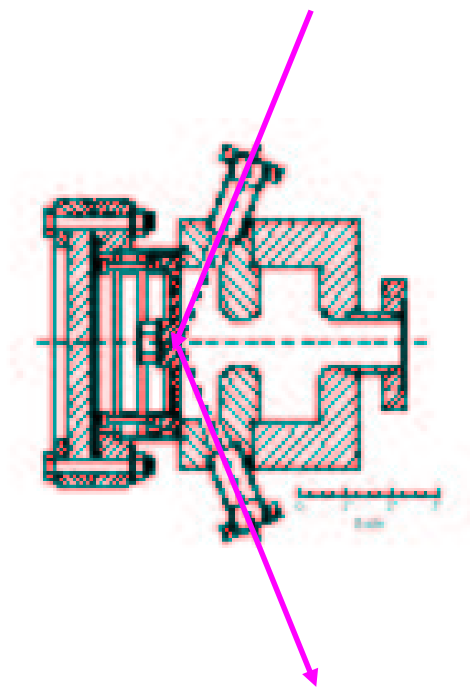
	Achived values
Frequency	17 GHz
Charge/bunch	0.1nC
Field on cathode	200 MV/m
RF pulse length	50 ns to 1 μs
Input power	4 MW coupled in
Laser radius	0.5 mm
Laser length	1 ps
Beam energy	1.05 MeV

- Measured emittance at 50 pC to be 1mm-mrad at the gun exit
- Trans. Brightness ~80 A/(mm-mrad)^2
- It will be boosted to ~800 A/(mm-mrad)^2 after emittance compensation



BNL/UCLA/SLAC gun

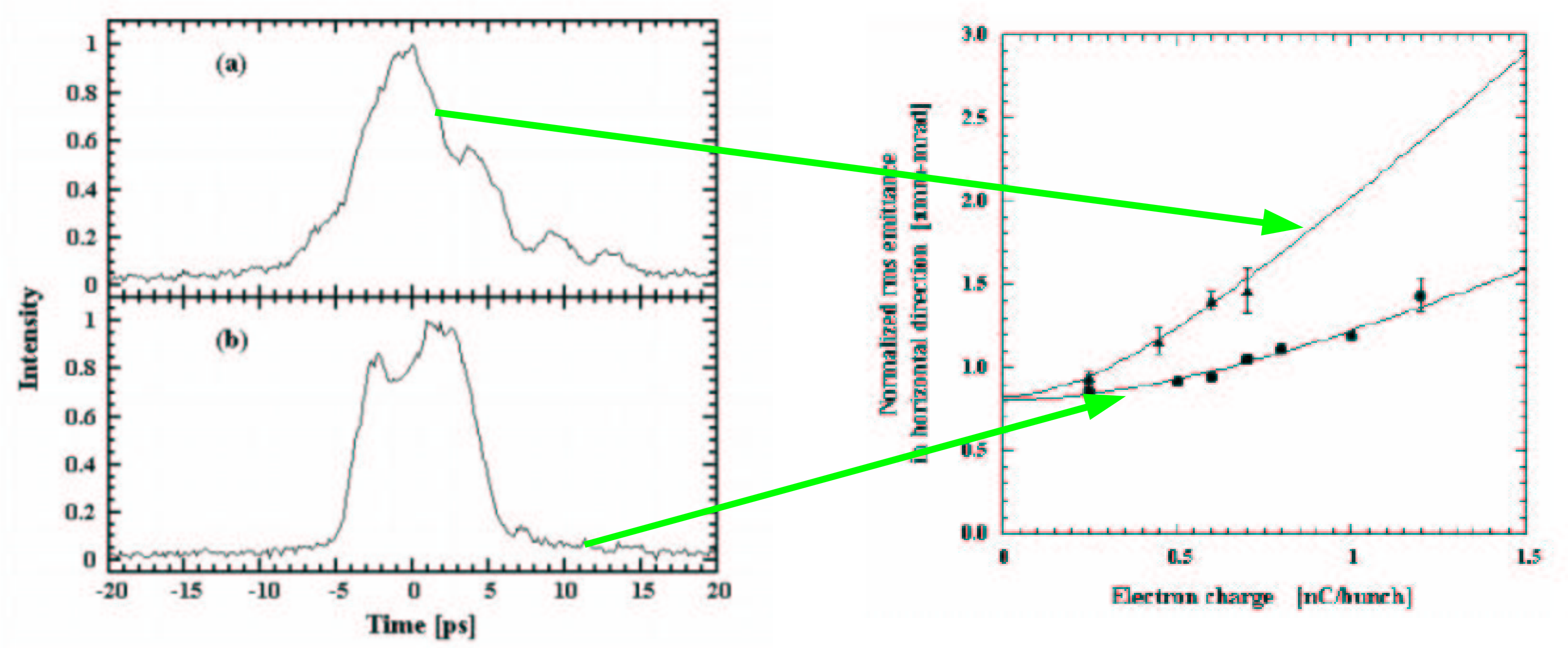
•Popular design, used at BNL (ATF & SDL), SLAC (GTF), ANL (LEUTL), Tokai (NERL),…
•Since its first design the gun has undergone improvements; latest foreseen are: a mode-lock system and a split symmetric RF input coupler



	LCLS Goal / achieved
Charge/bunch	1 nC / 1 nC
Field on cathode	140 MV/m / 120 MV/m
RF pulse length	3 μs / 3 μs
Rep. rate	120 Hz / 10 Hz
Input power	14 MW/ -

Impact of laser time shape on emittance (Sumitomo heavy industry, Japan)

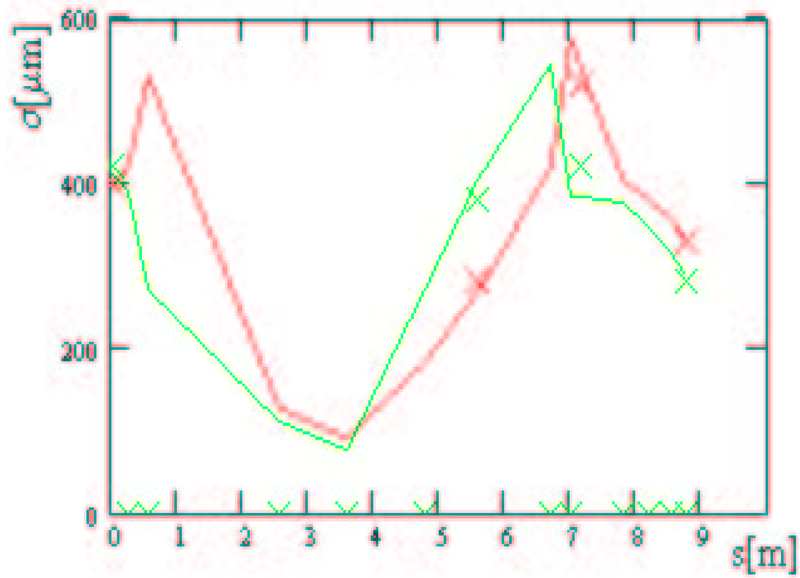
- Emittance measurements at 14 MeV using a quadrupole scan technique
- Transverse beam profile were fitted with Gaussian distribution
- Measured emittance of 1.2 mm-mrad at 1 nC with a square pulse length of 9 ps FWHM



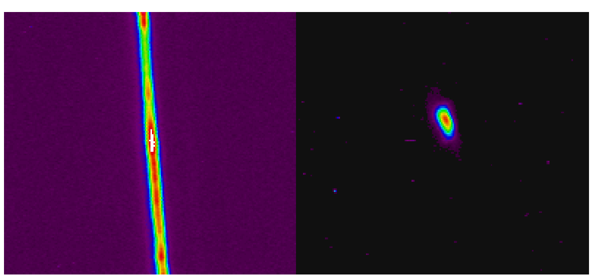
Generation of micron-sizes beam (ATF, BNL)

- Beam based alignment of quad to center beam in the TWS
- Optimized optics (with a high-β) to overcome problems inherent to the screen resolution
- Measured beam emittance using the multi-monitor technique
- Obtained: ε=0.8 mm-mrad [ERROR BARS?] for Q=0.5nC and I=200 A

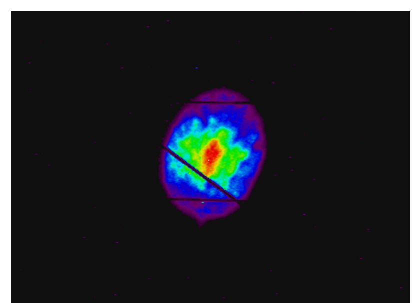
Example of fitted envelope at 70 MeV

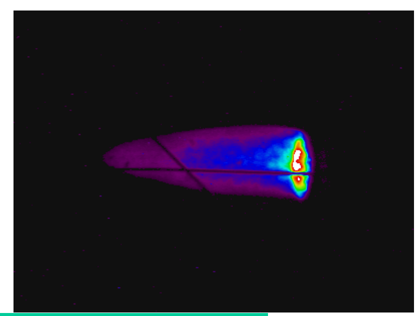


30 um wire focused spot



centered beam mis-steered beam

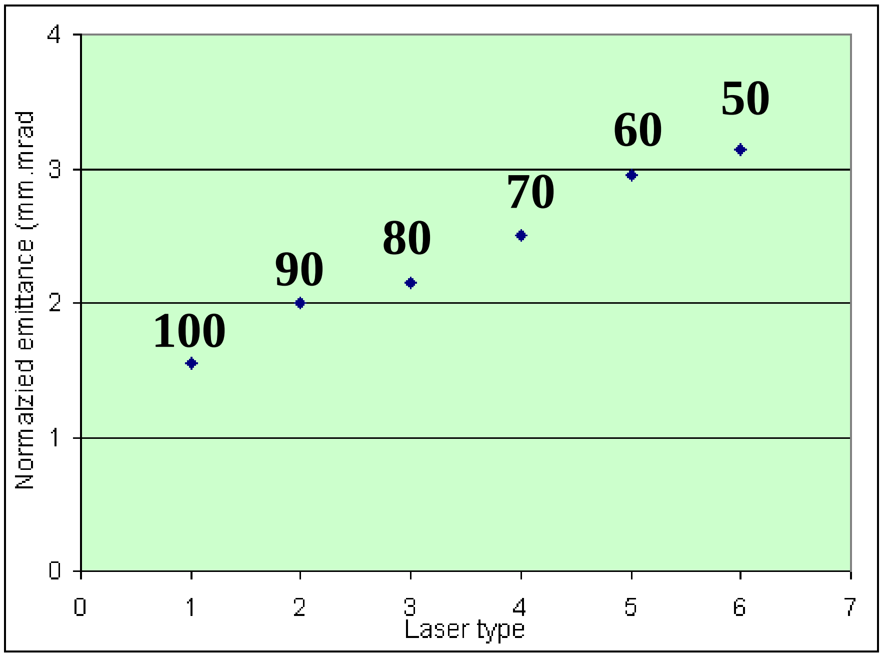




(Courtesy of V. Yakimenko)

Impact of non uniform laser spot (ATF, BNL)

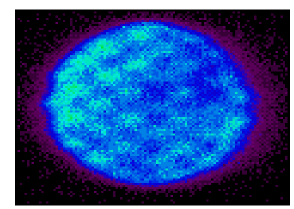
(extracted from ATF News Letter 03/2002)



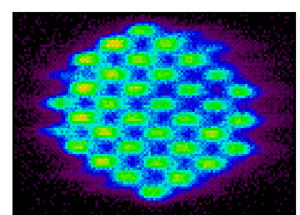
- Measurement of impact of transverse non-uniformity on emittance
- Used a mask
- Q=0.5 nC (kept constant)
- Emittance for uniform beam is about 1.5 mm-mrad
- Long. Length is 3 ps FWHM

100 %

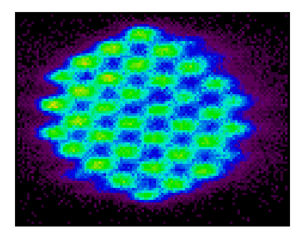
90 %



60 %

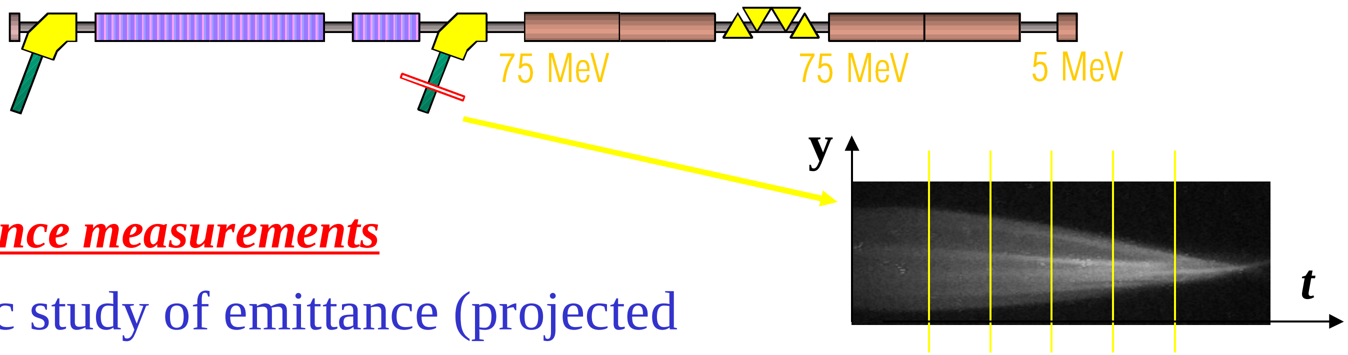


50 %



- As predicted by simulation, uniform beam gives the best emittance
- Emittance doubles for the 50 % modulation case

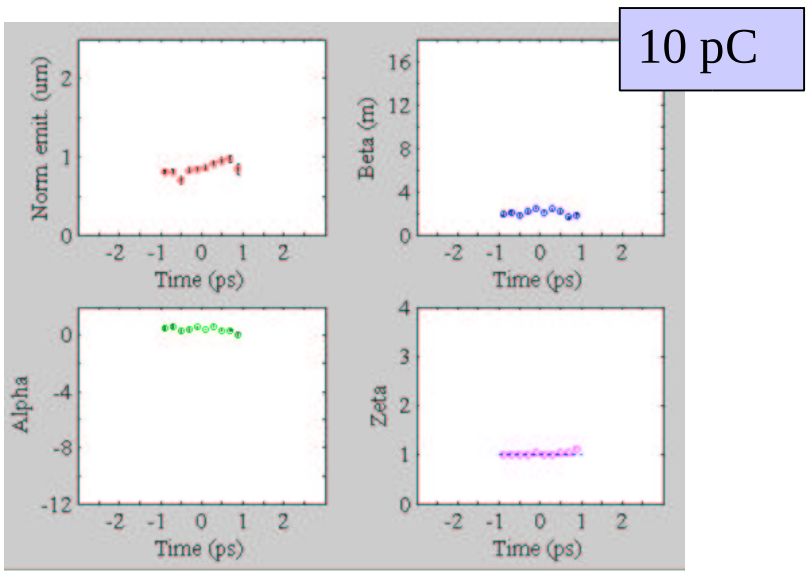
Slice emittance measurements at SDL, BNL

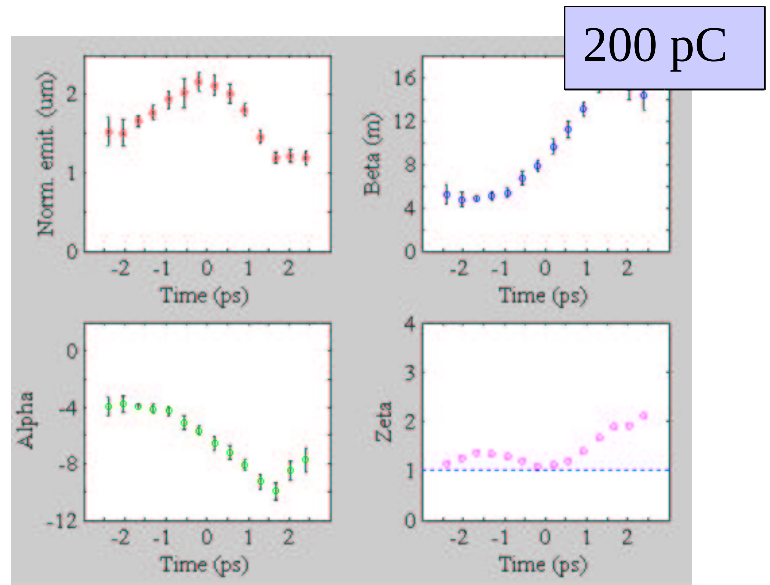


(Courtesy of W. Graves et al.)

Slice emittance measurements

- Parametric study of emittance (projected + slice) vs various parameters
- Data indicate brightness improves as charge is decreased

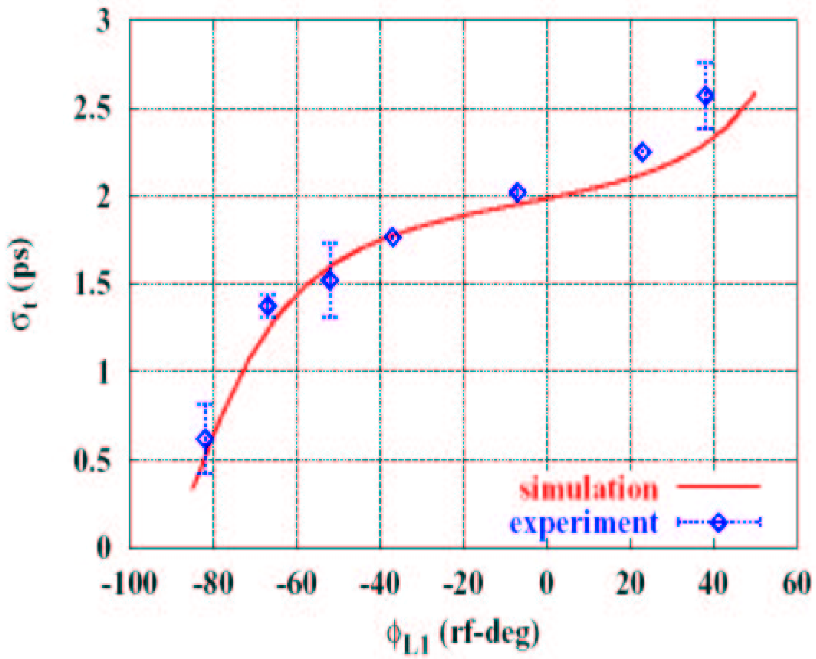


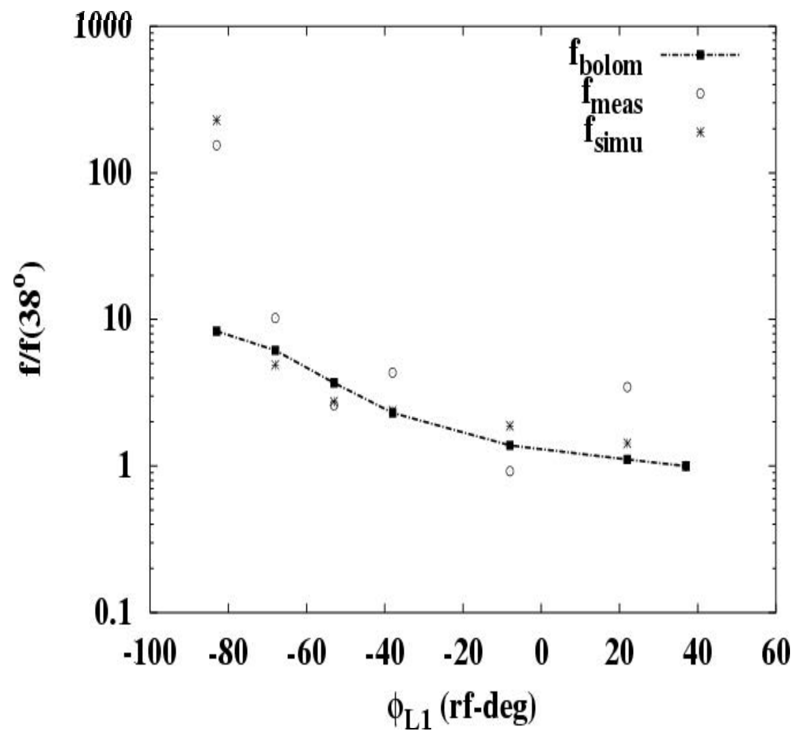


Rf-based bunching from SDL, BNL

Sub-picosecond compression by velocity bunching

- Used the TWS tank downstream of the rf-gun as a buncher (operated far off-crest)



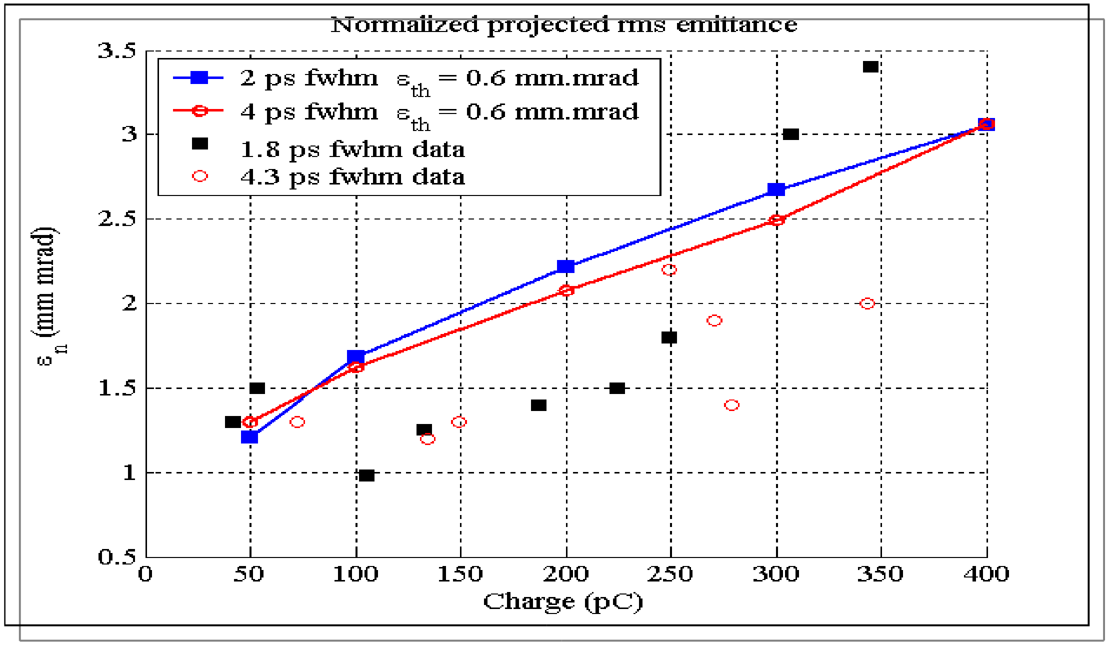


- Measurement were performed using both frequency- and time-domain technique

Longitudinal space charge-induced modulation

- See talk from W. Graves (Wednesday)

Recent results GTF, SLAC



•Longitudinal phase space study

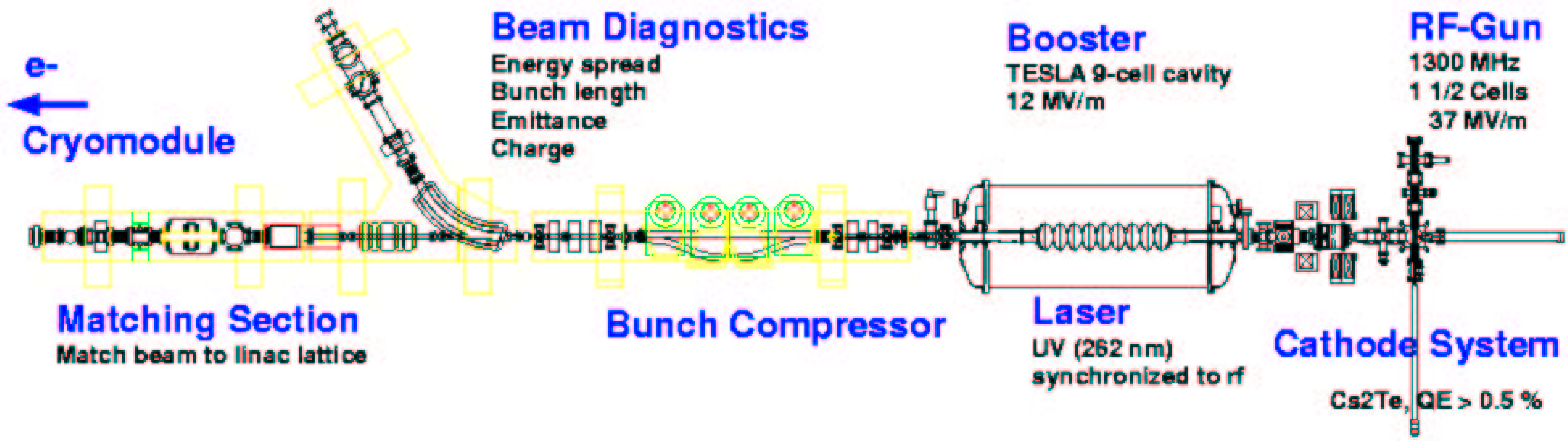
Q(nC)	15	190
σ_t (ps)	0.0108	0.0635
σ_e (keV)	2.62	8.04
ε_t (keV-ps)	0.924	12.5
I_p (A)	9	80

(Courtesy of J. Schmerge)

•Parametric study of emittance versus bunch charge

•Achieved LCLS project parameters (1.5 mm-mrad for I~100 A) for low charge scenario

DESY TTF injector II (decommissioned)



typical parameters for TTF 1-FEL:

repetition rate: 1 Hz

pulse train length: 1-800 μs

bunch frequency: 1-2.25 MHz

bunch charge: 1-3 nC

bunch length (rms): ~3 mm (1 nC, after booster)

norm. Emit., x,y: 3-4 μm (@ 1nC)

dpp: 0.13 % rms (@ 17 MeV)

injection energy: 17 MeV

(Schreiber et al. EPAC2002)

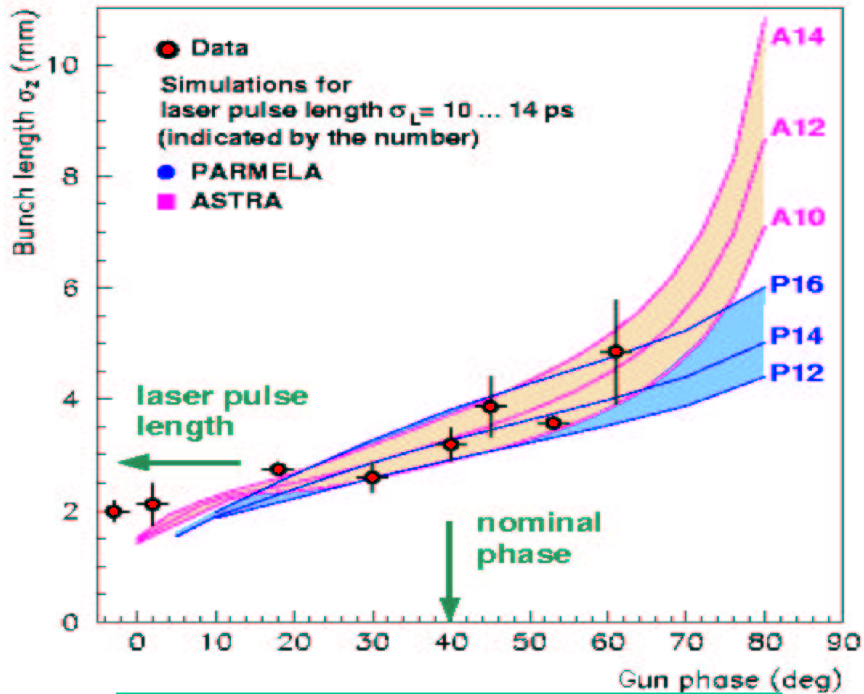
Results at TTF Injector 2 (1nC setup)

Emittance measurements

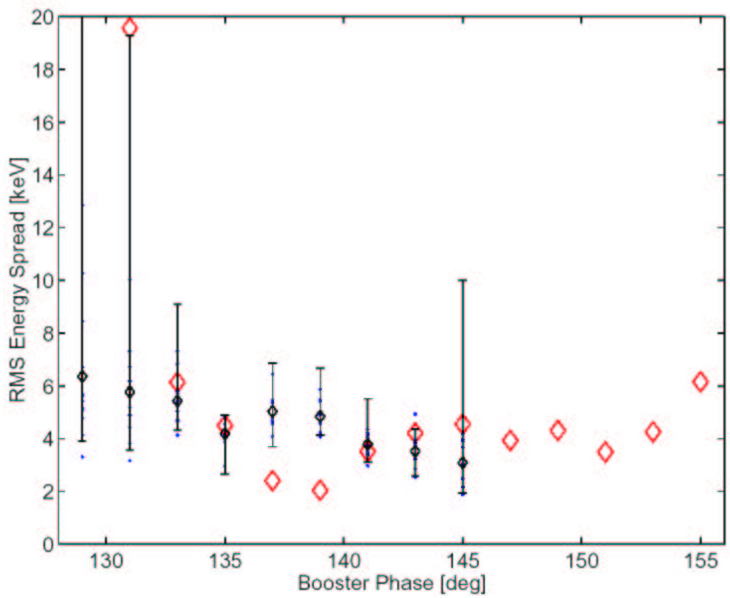
sol. 1/2	emit. x	emit. y
200 / 104	4.19 ± 0.13	4.58 ± 0.15
220 / 104	**3.02 ± 0.17**	**3.47 ± 0.12**
240 / 104	4.08 ± 0.57	4.52 ± 0.47

(Schreiber et al. PAC2001)

Bunch length measurement (streak cam.)



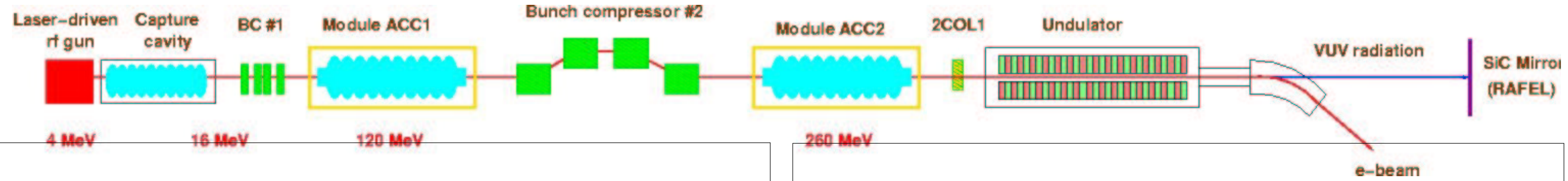
(Honkaavara et al. PAC2001)

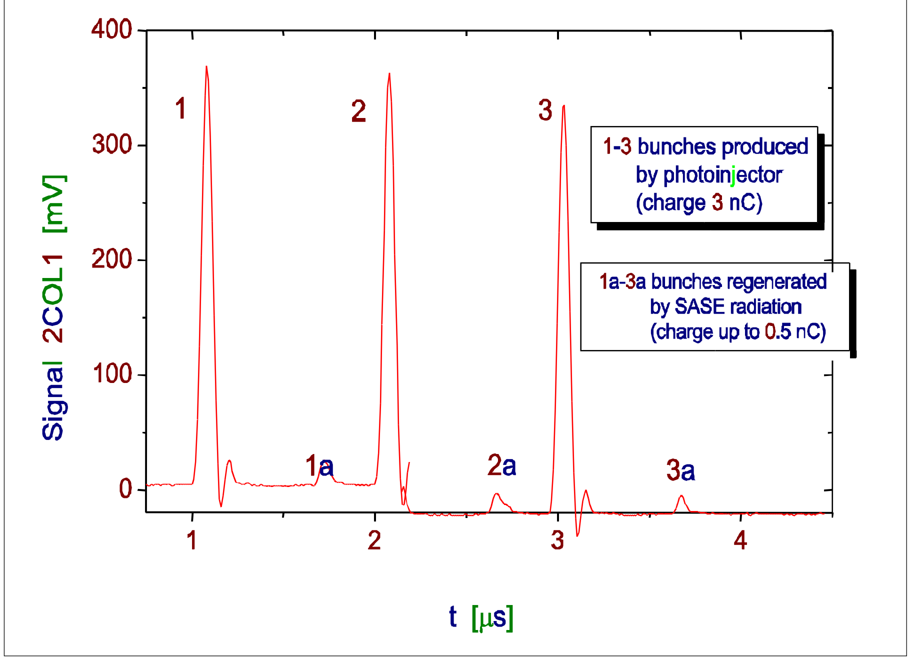


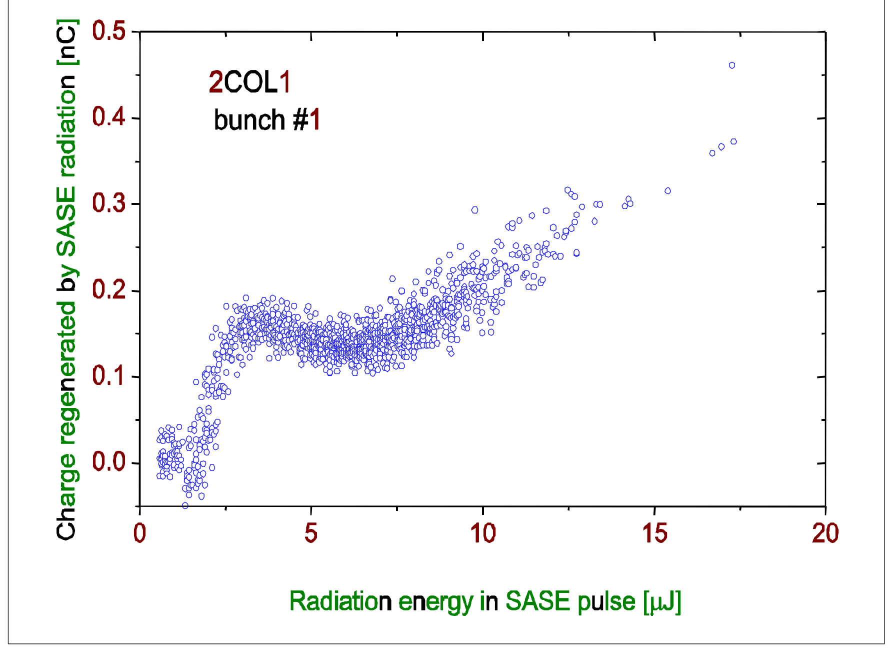
(Huening Schlarb PAC2003)

- 1nC tranverse emittance ~ 3 mm-mrad
- dp/p uncorrelated ~ 3 keV for 4 nC!
- Both consistent with simulations

SASE-driven rf-gun



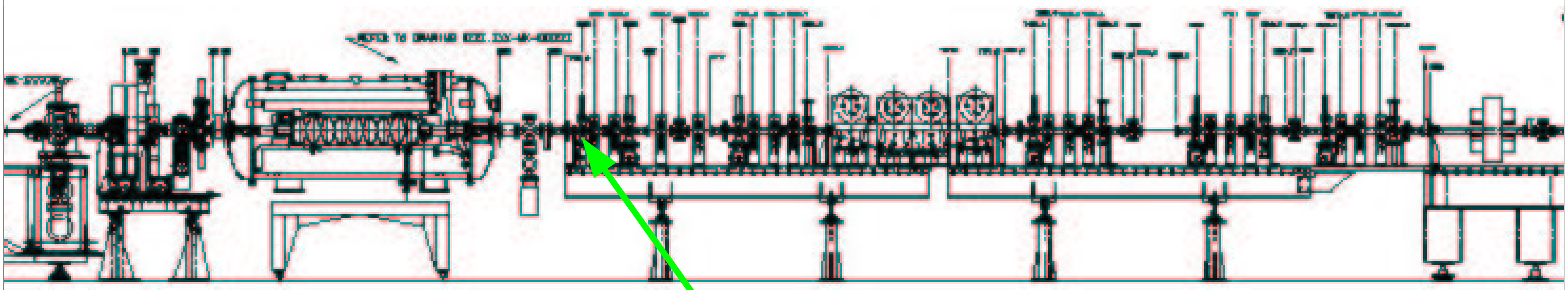


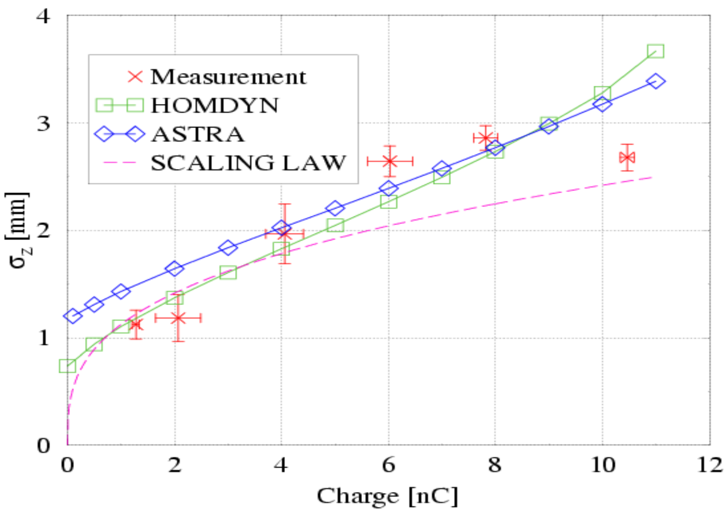


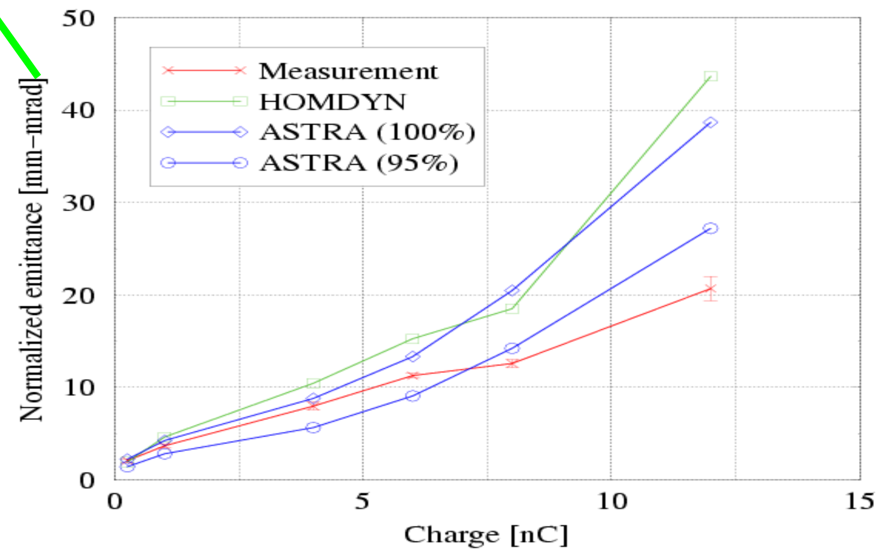
- Primary electron bunch (Q=3 nC) a produced by a laser-driven rf-gun
- During single pass in undulator primary bunch produces VUV radiation (λ=95 nm)
- Radiation is reflected by planar SiC mirror and it directed back to the photocathode
- Electron bunch photo-produced by the SASE radiation (Q=0.5nC) is accelerated

(Faatz et al. FEL2002)

Results at FNPL, FNAL







•Systematic optimization of rf-gun parameters (solenoids, laser radius) vs charges
•Estimate of brightness indicates it improves with decreasing charge

(Courtesy of J.-P Carneiro)

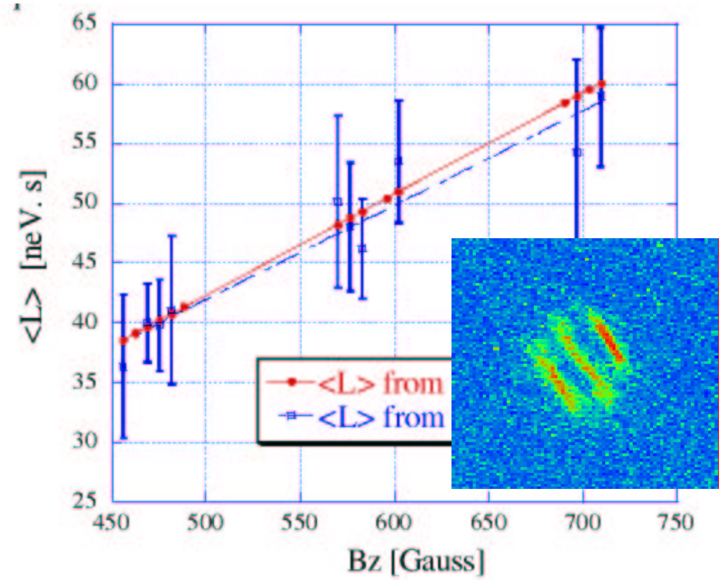
Photo-injector production of flat beam

➔ Photo-cathode is immersed in a Bz-field

➔ Solenoid fringe field ⟶ beam acquires an angular momentum (x-y coupled motion)

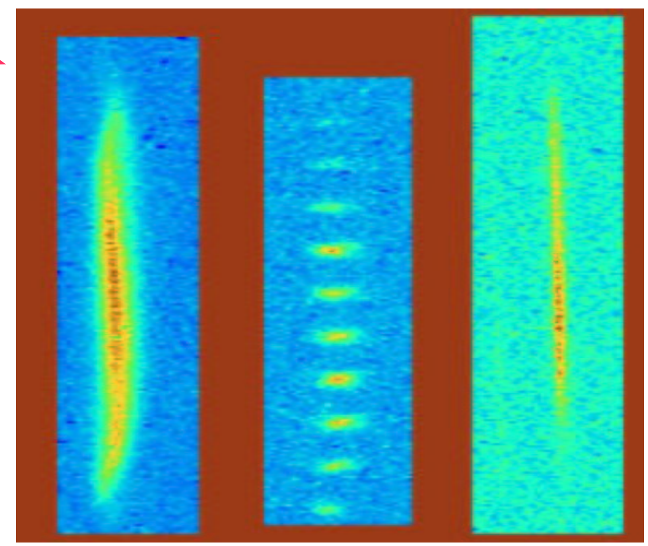
➔ A skew quad. Channel decouples the motion and yields a beam with a high transverse emittance ratio :

$$\frac{\varepsilon_x}{\varepsilon_y} - 1 \propto B_z^2 \frac{\sigma_r^2}{\sigma_{r'}^2}$$

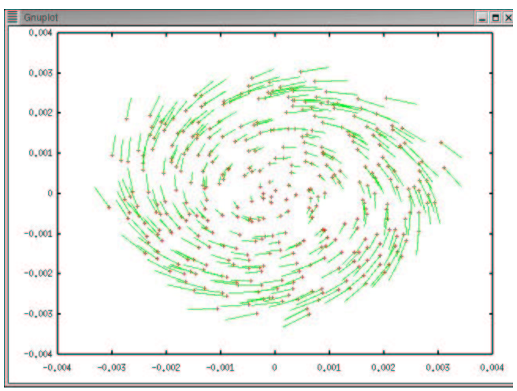


Proof-of-principle experiment done obtained a ratio of ~40

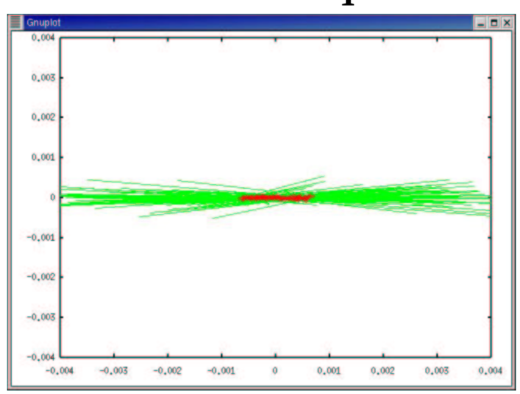
SPOT YMS XMS



After solenoid

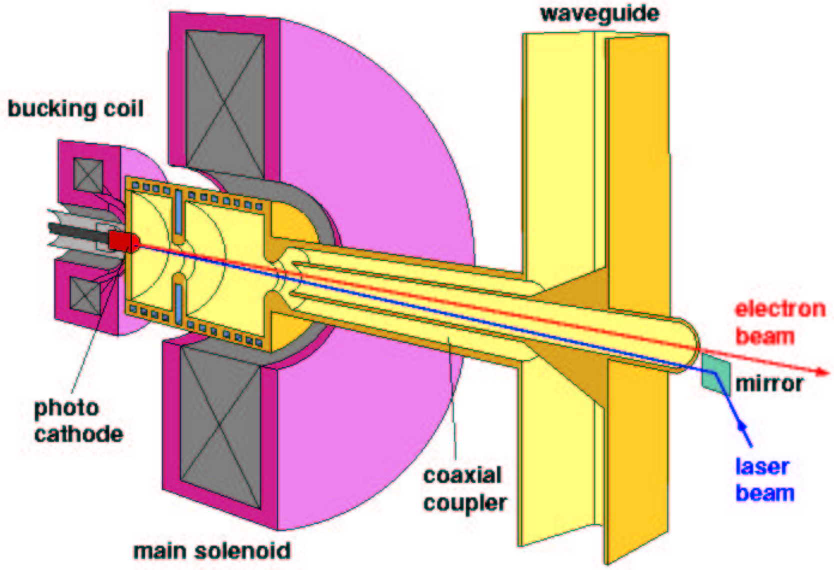


After skew quads

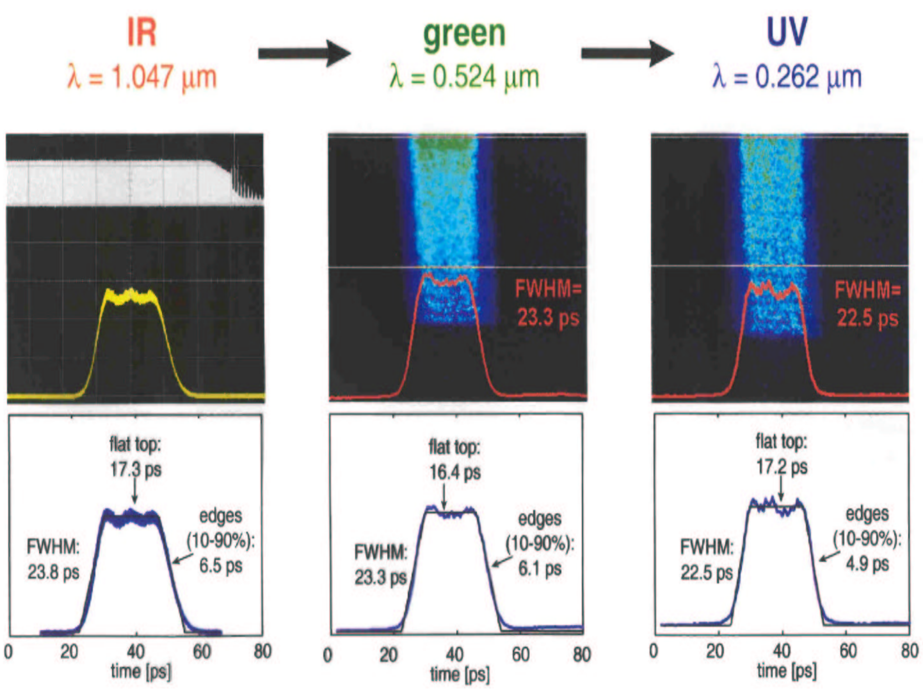


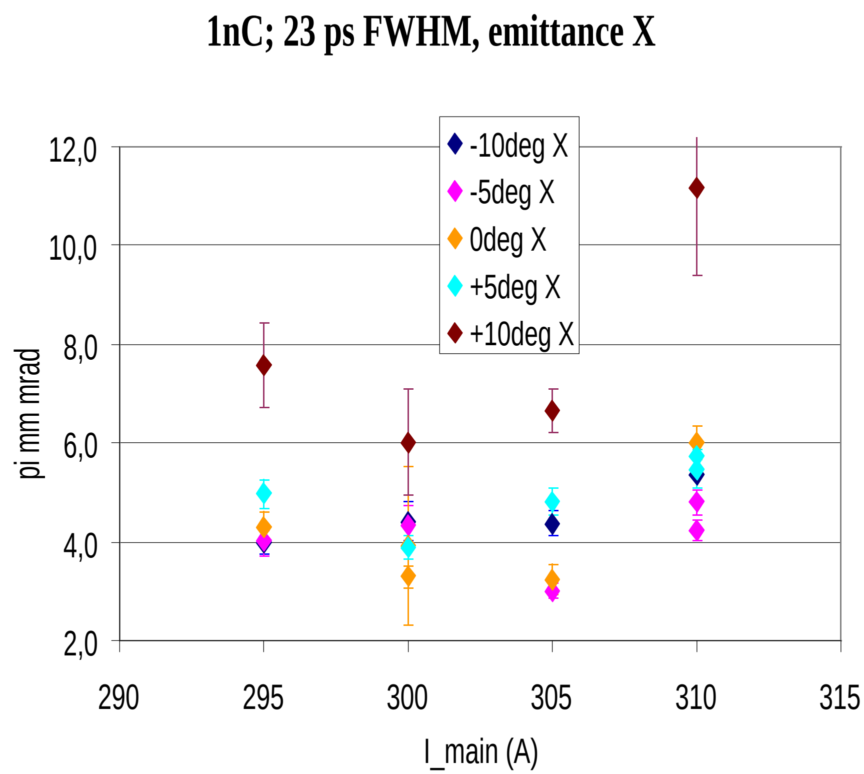
(Courtesy of Y.-E. Sun et al.)

DESY 1.3 GHz gun



- Second generation of gun for TTF/TESLA FEL user facilities
- Fully symmetrized cavity using a coaxial input-coupler

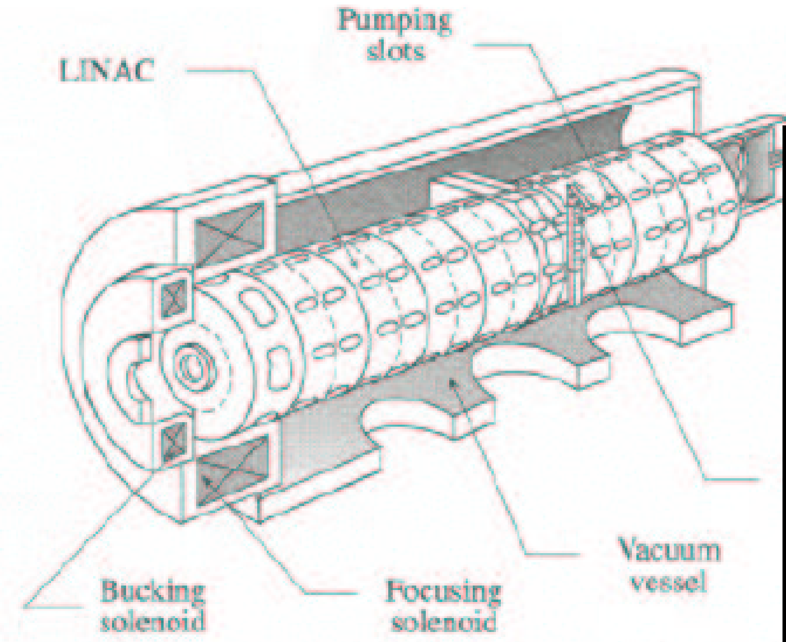




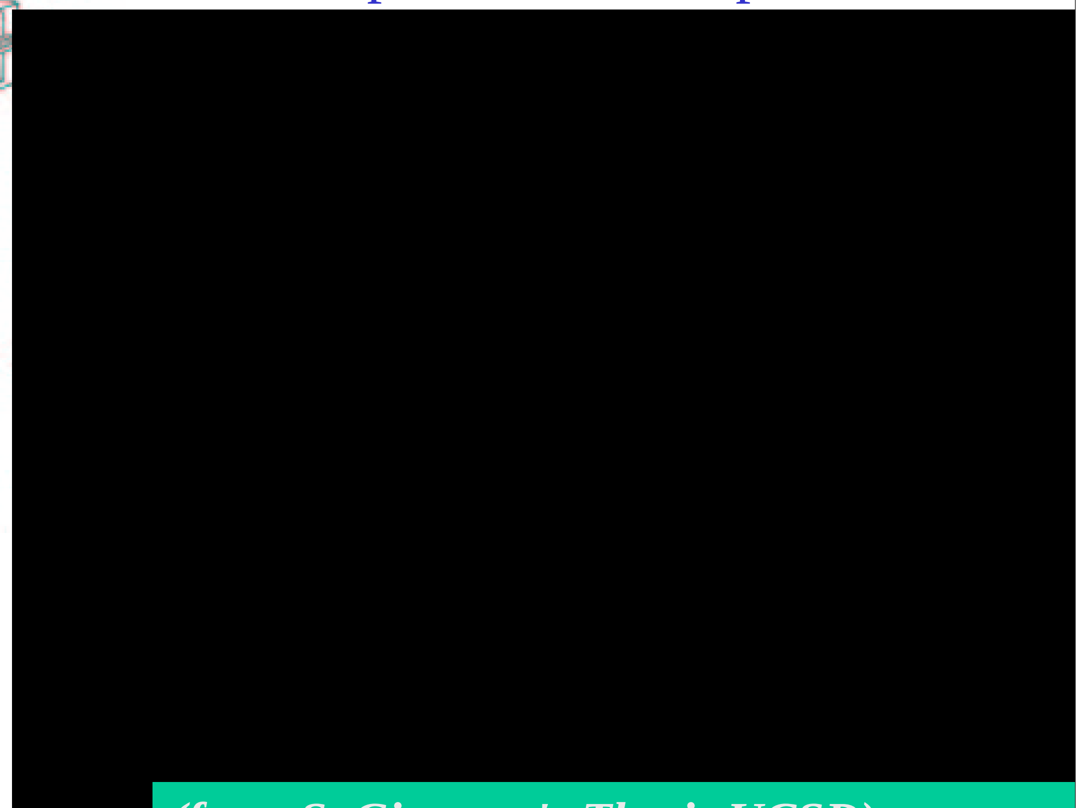
LANL AFEL Facility

Mission: **Advanced free-electron laser experiment at Los Alamos. The gun has driven a IR SASE-FEL**

- 1.3 GHz, 10+1/2 cells
- E-field=20 MV/m
- Typical charge 1 to 4 nC
- Exit energy 15-20 MeV
- Macropulse current up to 400 mA



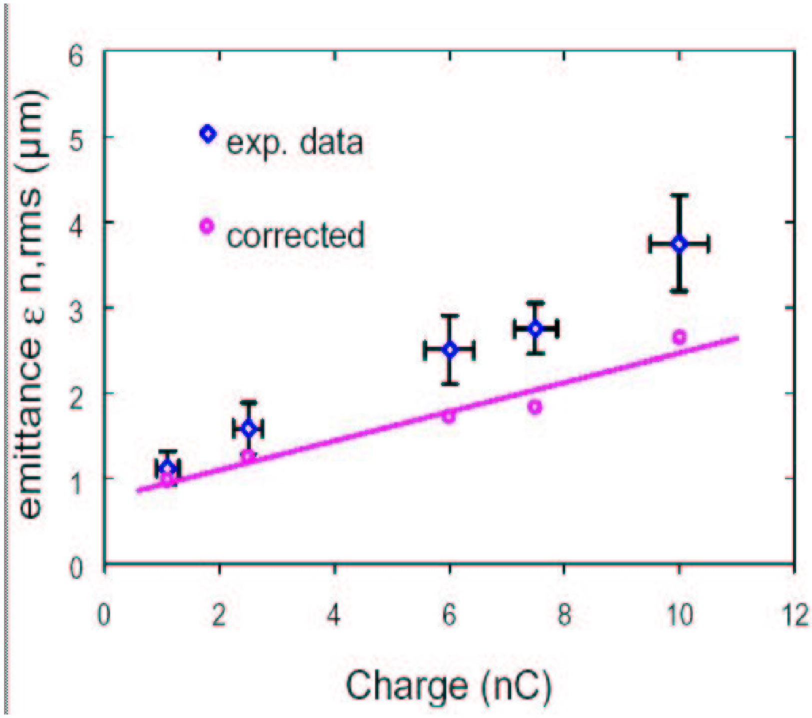
(from Nguyen's talk at PERL workshop BNL, Jan 2001)

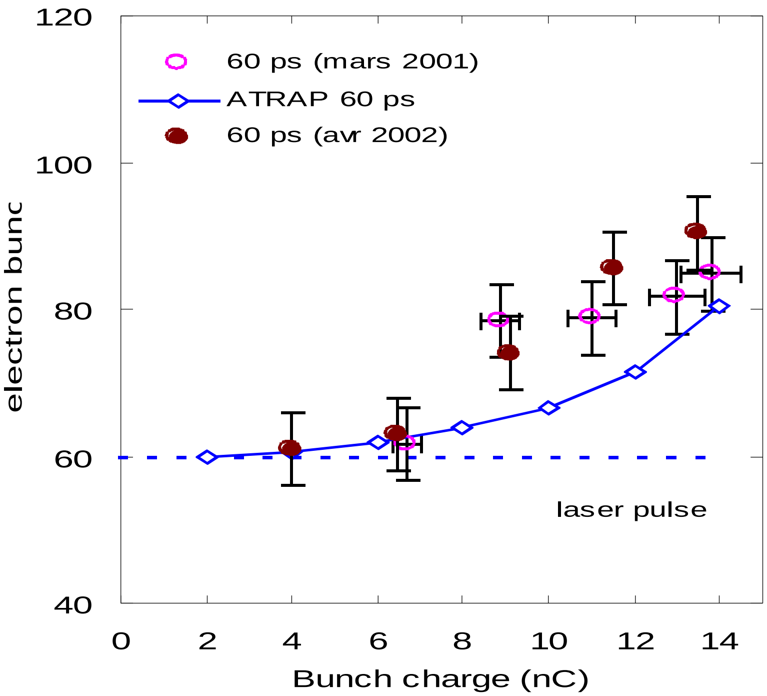


(from S. Gierman's Thesis UCSD)

Lowest frequency gun ELSA-2 Bruyeres-le-chatel

- 0.144 GHz, 2 cells
- E-field=25 MV/m
- Typical charge 1 to 10 nC
- Exit energy ~2.6 MeV
- Laser: 60 ps (FWHM), 4 mm radius

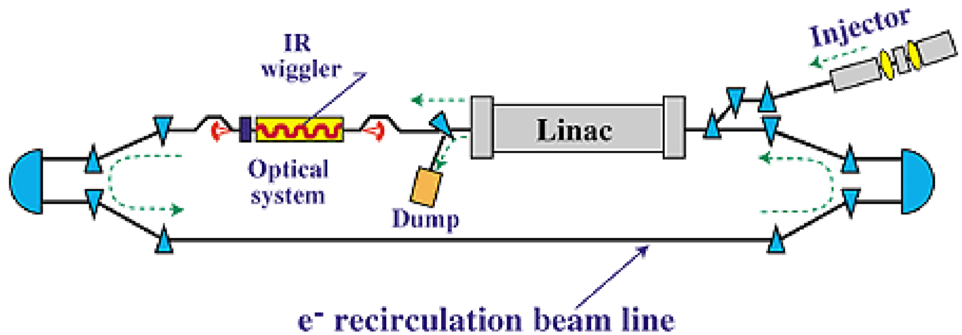


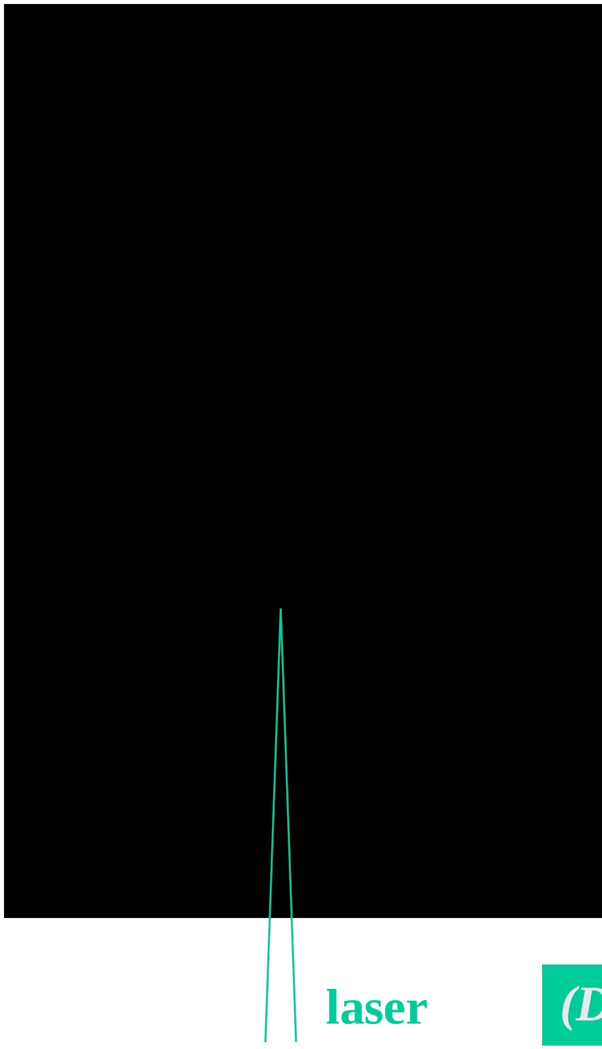


- Macropulse frequency: 10 Hz
- Macropulse length: 150 μs
- Micropulse frequency: 14.4 MHz

(Courtesy of Ph. Guimbal)

DC-GUN, JLab IR-Demo

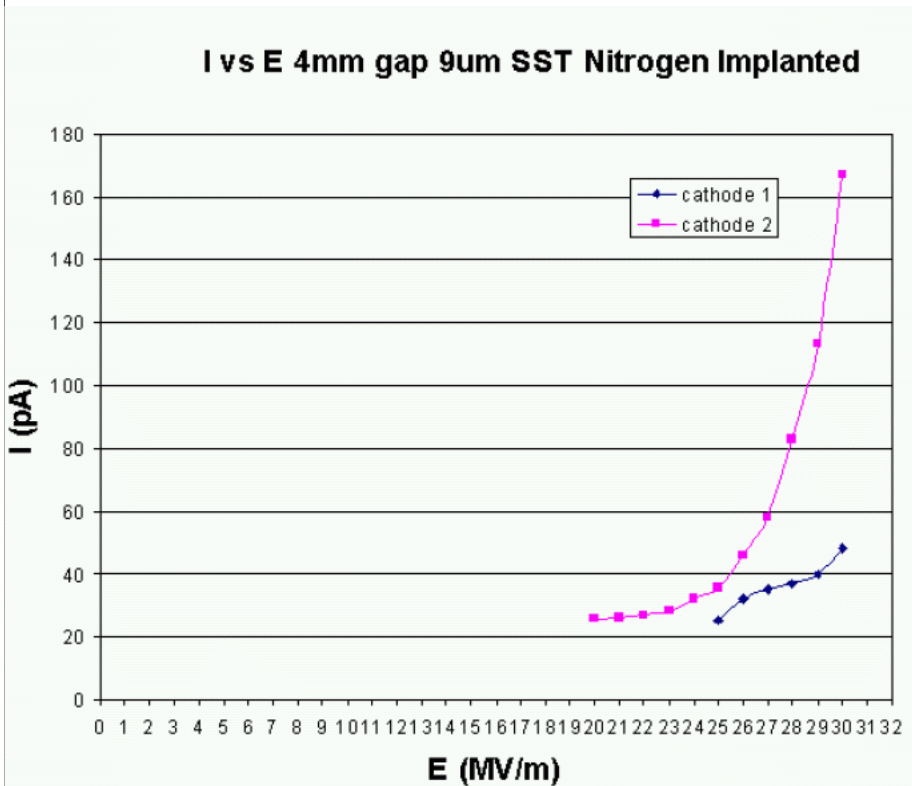




- DC gun with GaAs photo-cathode
- Buncher needed despite the 20 ps laser
- In the Ir-Demo gun is coupled to a ¼ cryounit (2 CEBAF-type 5-cell SRF cavities at 10 and 9 MV/m)
- advantage: ran CW at 75 MHz (1/80th of 1497 MHz)
- Recently developed laser (M. Poekler PAC 2001) allows CW ope. @ 1.5GHz

(D. Engwall et al. PAC1997, Ph. Piot et al. EPAC1998)

DC-GUN, JLab IR-Demo



- High voltage operation of DC-gun limiter by field-emission
- Collaboration Jlab + College of William & Mary: study reduction of field-emission by Nitrogen ions implantation on the electrodes
- Experiment performed in a test chamber demonstrate the benefits of ion implantation: up to 25 MV/m DC-field could be achieved with less than 40 pA "dark" current.

(C.K. Sinclair et al. PAC2001)

SRF gun (DROSSEL collaboration)

(Courtesy of P. Michel & P. Etuvensko)

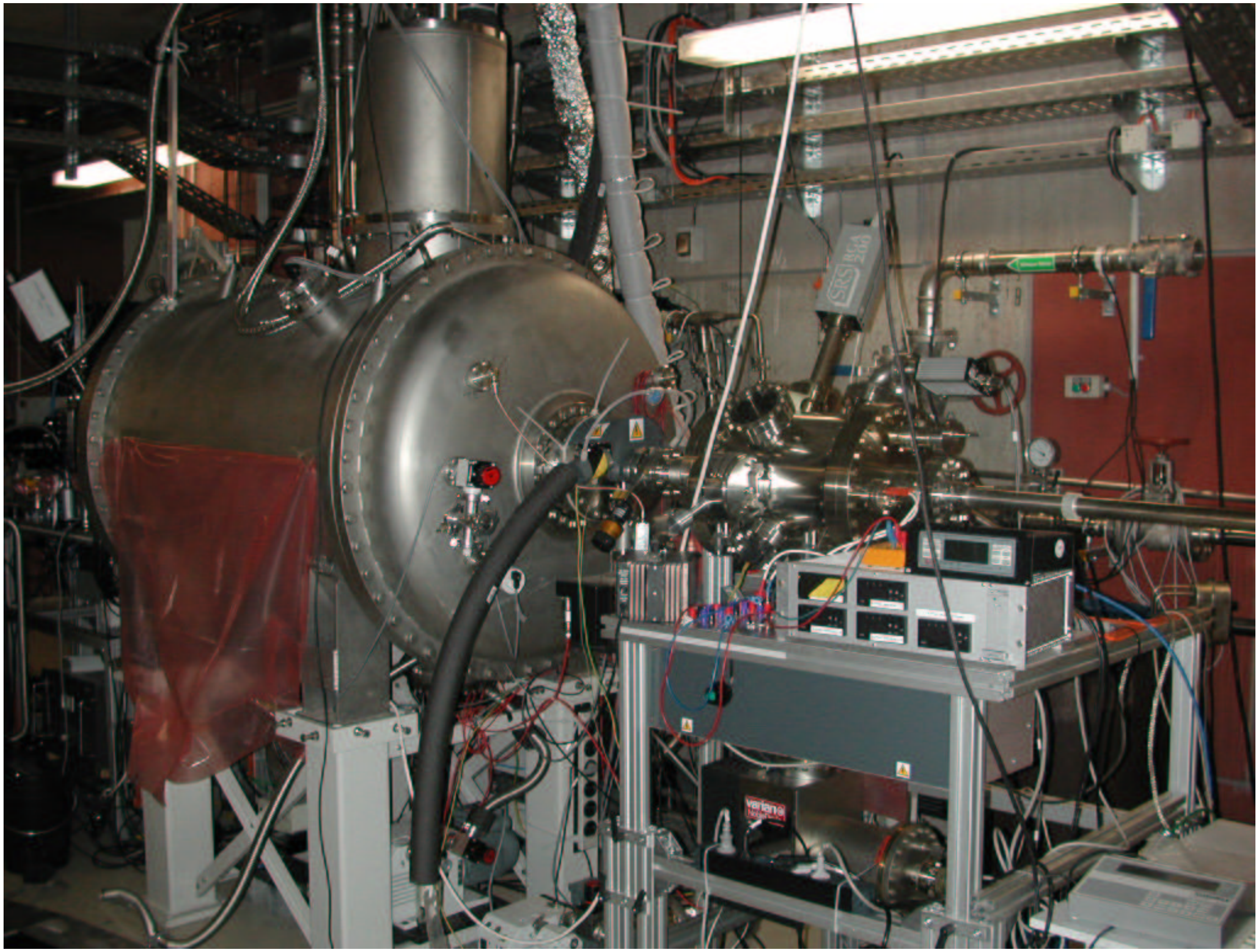
First phase: proof-of-principle: observe photo-emission of a cathode in a superconducting rf-cavity

Later: built a "real" gun that could be used for CW operation of the ELBE free-electron laser based at Forschungszentrum Rossendorf

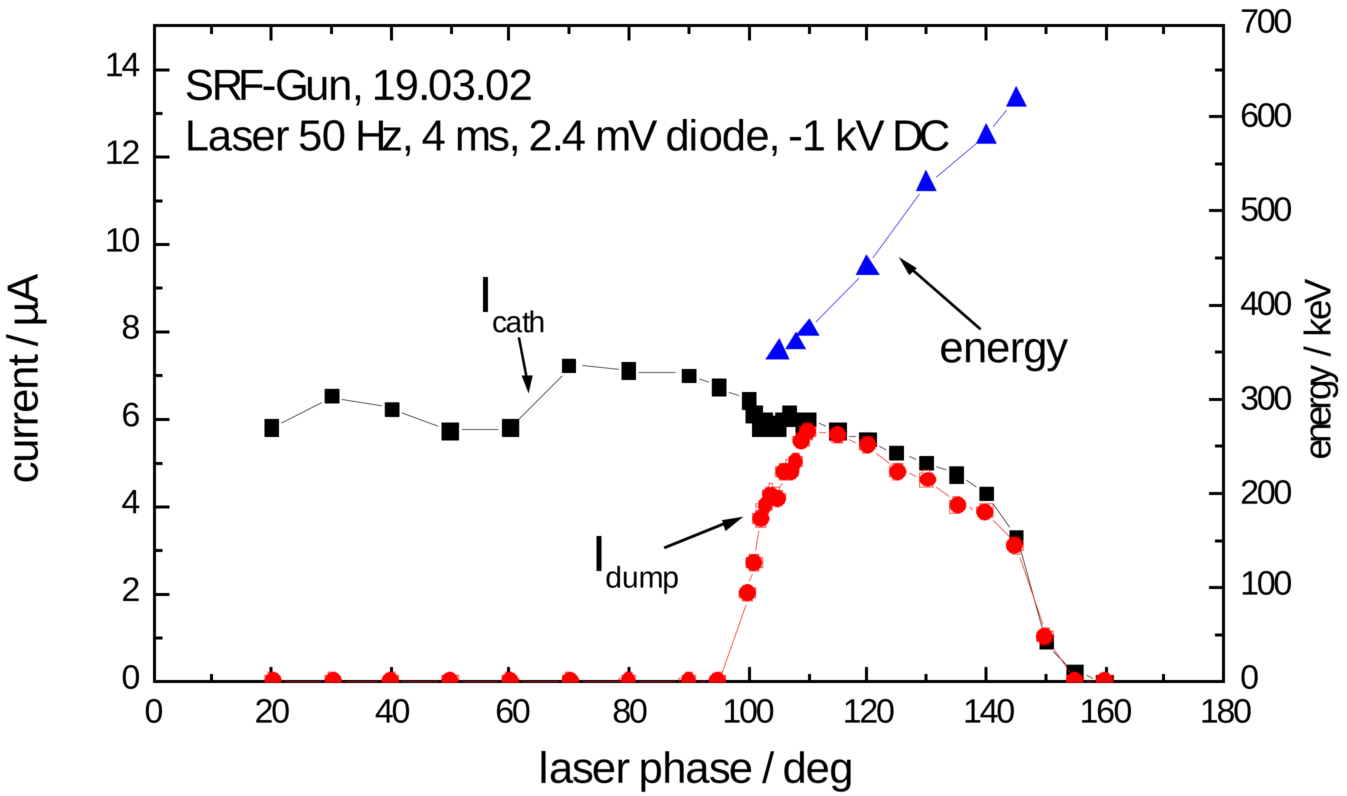
on-going collaboration between Rossendorf, Jlab, and University of Pekin

- Frequency=1.3 Ghz
- Number of cell~ 0.5
- Half-cell is a TESLA cavity shape with a shallow cone
- Use a Cs_2Te
- No solenoid => focusing provided by rf (conic-shaped back plate)
- First photo-electrons observed 03/02

SRF gun (DROSSEL collaboration)



SRF gun (DROSSEL collaboration)

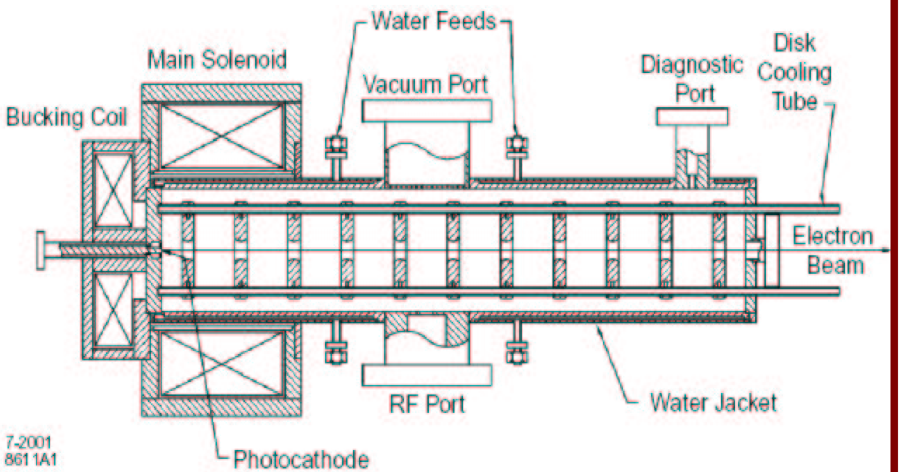


(Courtesy of P. Janssen et al.)

The path toward polarized electron beam

- To date polarized electron beams are produced from NEA GaAs photocathode
- The vacuum required is 1E-12 Torr
- Typical vacuum level in rf-gun is 1E-9 Torr
- Work initially started at Novosibirsk in a standard 1+1/2 rf-gun

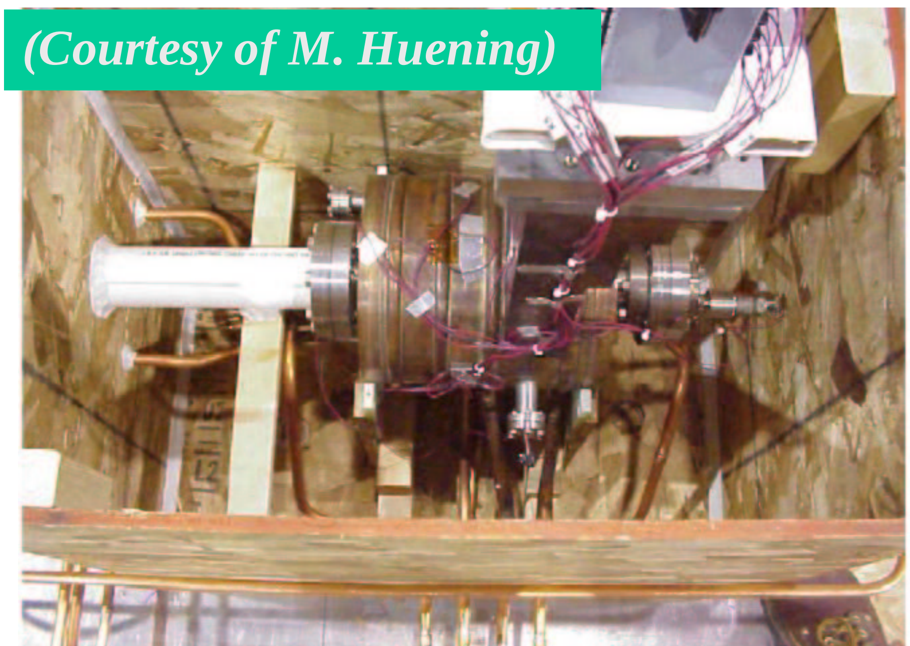
SLAC proposed the use of open structure (PWT) with high vacuum conductance



(Clendemin et al. SLAC-PUB-8971)

FNAL proposed to use cryogenic-operated copper gun 1+1/2 cell

(Courtesy of M. Huening)



-> vacuum test underway

Conclusions I

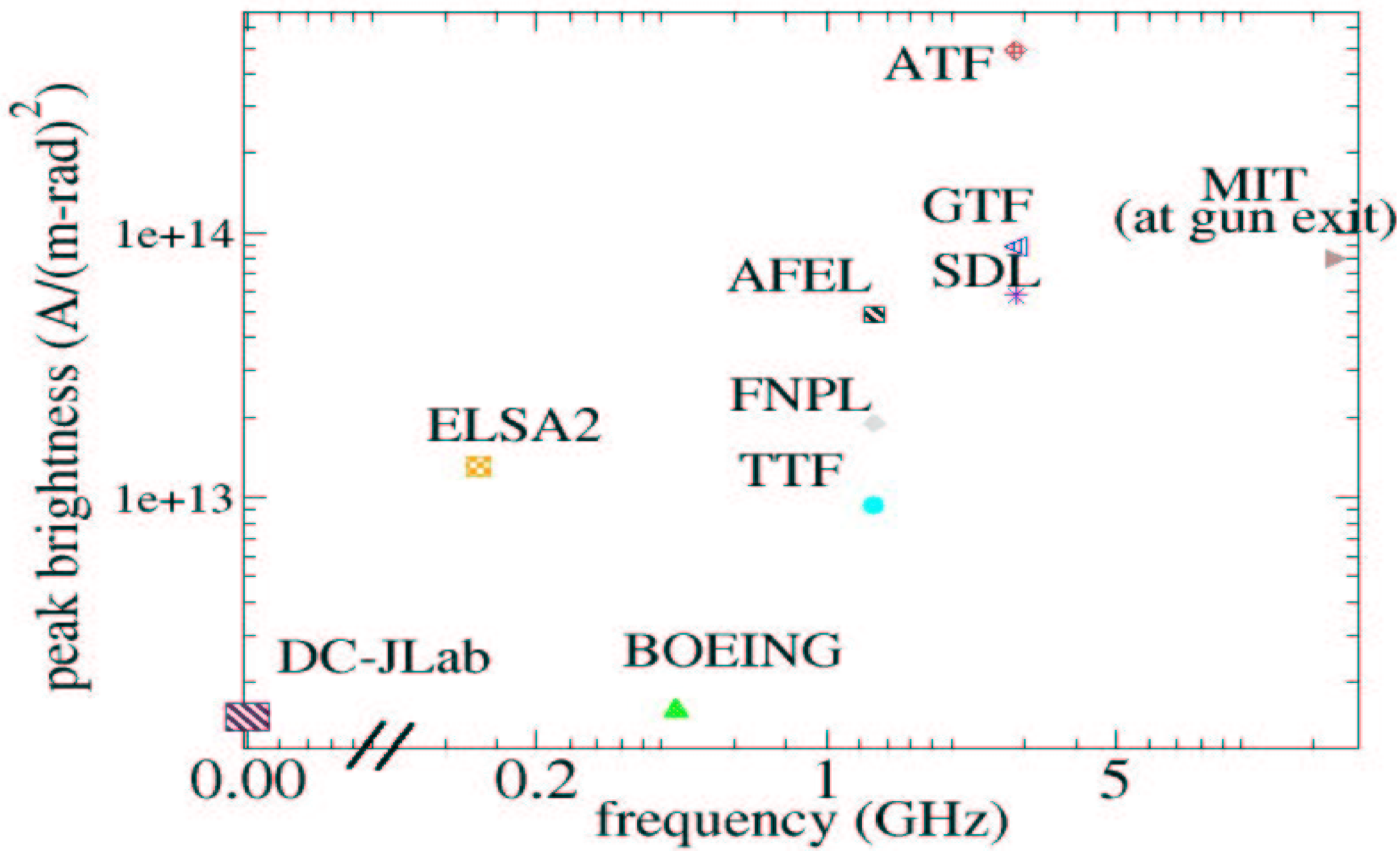
- Smitomo Heavy industry in Japan has set new record in brightness

- Both BNL-type and DESY-type gun have driven short wavelength single-pass FELs to saturation (LEUTL, TTF-1).

- Presently achieved performances with a DC gun are comparable to rf-gun running with high duty cycle (in term of brightness).
  - better candidate to drive high photon-flux based on ERL?
  - largest average brightness
  - and E-field of 25 MV/m have been achieved in experiment

- Many other developments I have not addressed (hybrid DC/RF guns, hybrid plasma/photo-emission guns, needle cathodes, etc…)

Conclusions II: Comparison of peak transverse brightness



Comment: Notes on transverse emittance

Canonical emittance (Liouvillian invariant under linear force)

What codes give

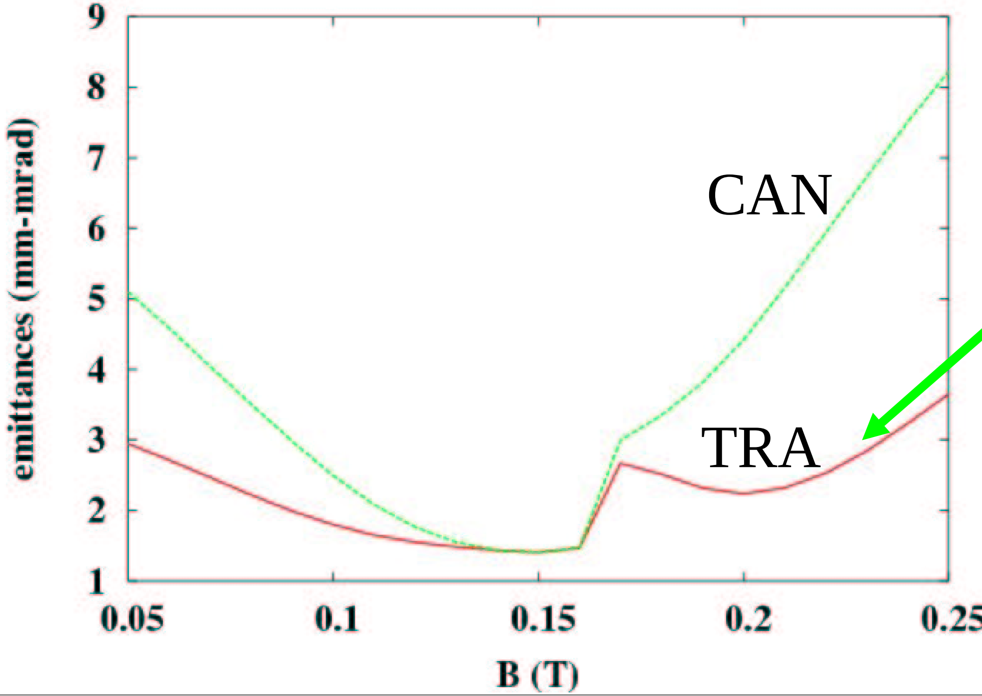
$$\varepsilon_{CAN} = \frac{1}{m_e c} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2}$$

$$\varepsilon_{CAN} = \frac{\langle p_z \rangle}{m_e c} \sqrt{\langle x^2 \rangle \langle (1+\delta)^2 x'^2 \rangle - \langle (1+\delta) x x' \rangle^2}$$

Trace-space normalized emittance (experimental observable)

$$\varepsilon_{TRA} = \beta \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

Might be different if large fractional momentum spread



What one would measure 1 m downstream of TTF-2 gun

See also K. Floettmann PRSTAB 6:03420 (2003)