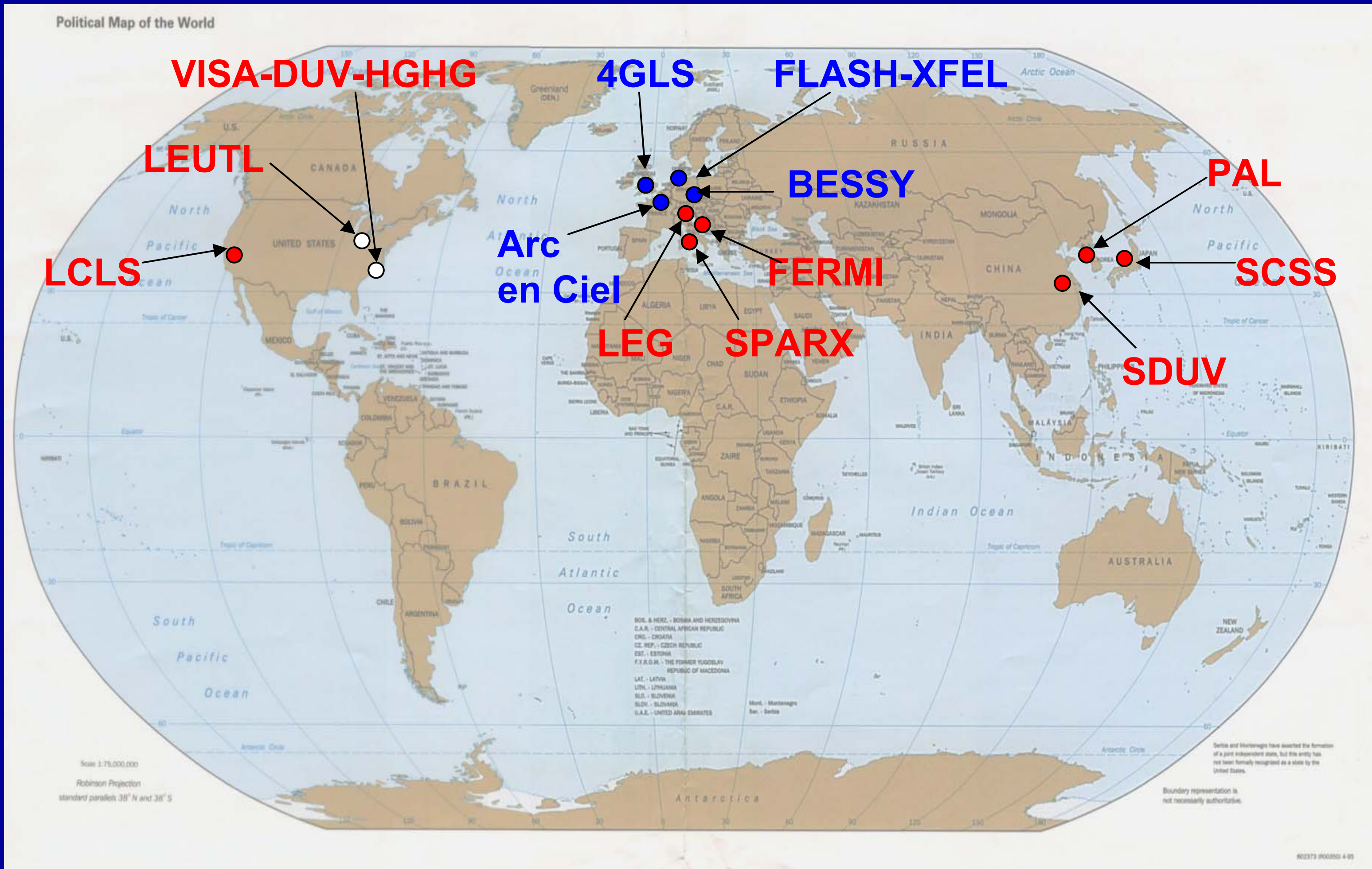
Overview of FEL injectors

Massimo Ferrario
INFN - LNF



SASE FEL Electron Beam Requirement: High Brightness $B_n > 10^5\ A/m^2$

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

Bunch compressors

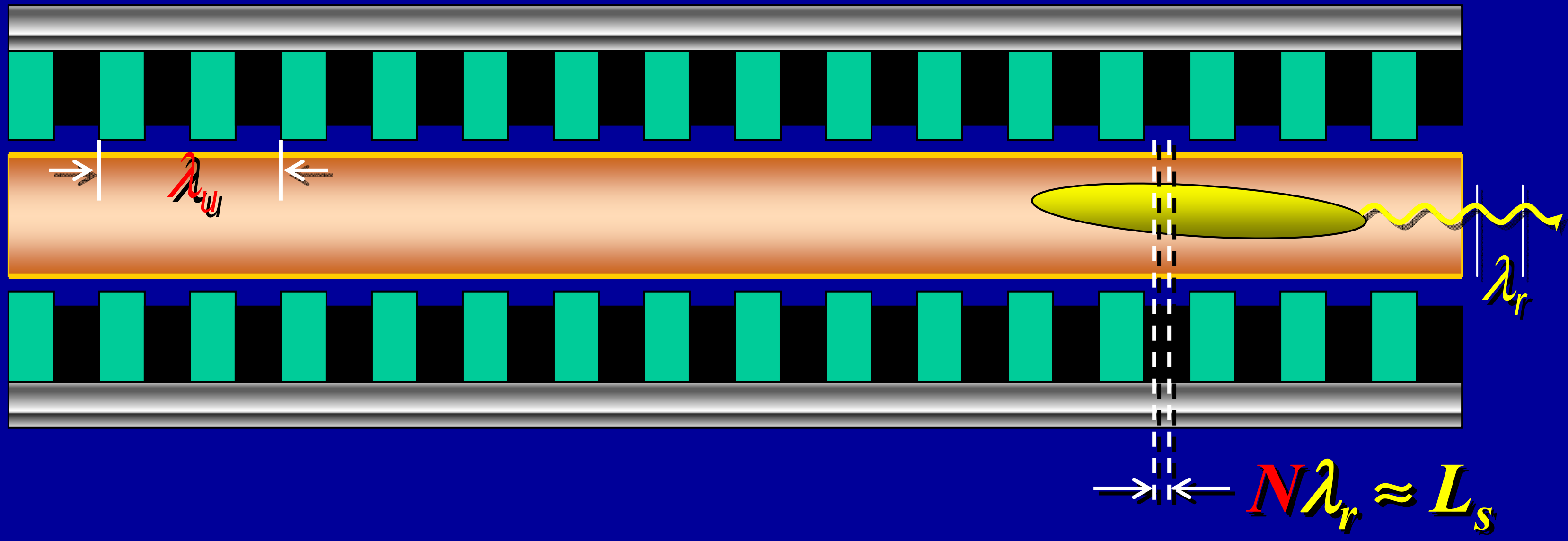
RF & magnetic

Cathode emittance

Pulse shaping

Emittance compensation

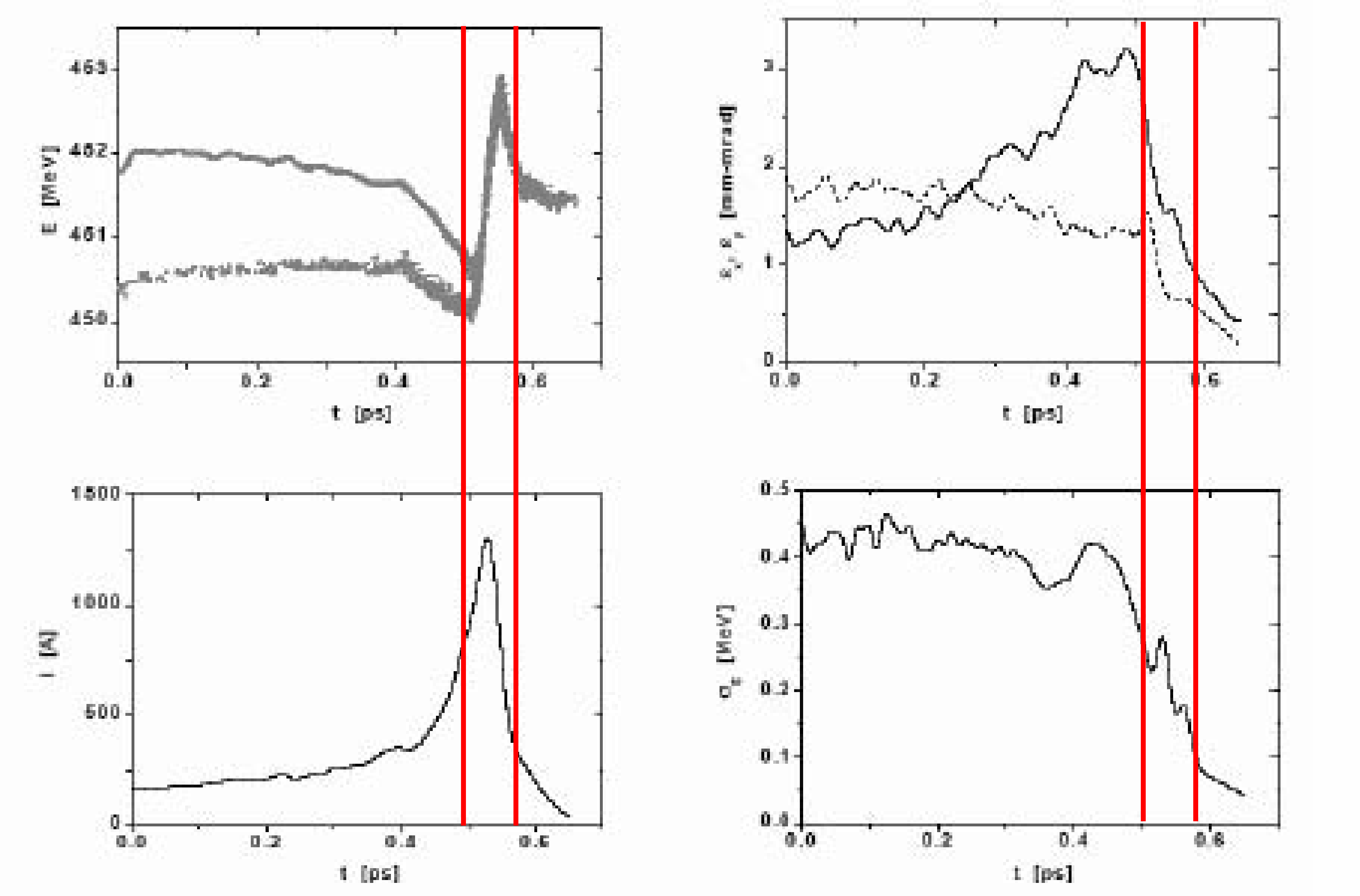
FEL resonance condition implies that e^- slips back in phase w.r.t. photons by λ_r per period λ_u



Amplification occurs over slippage length L_s
==> '*slice*' parameters are important

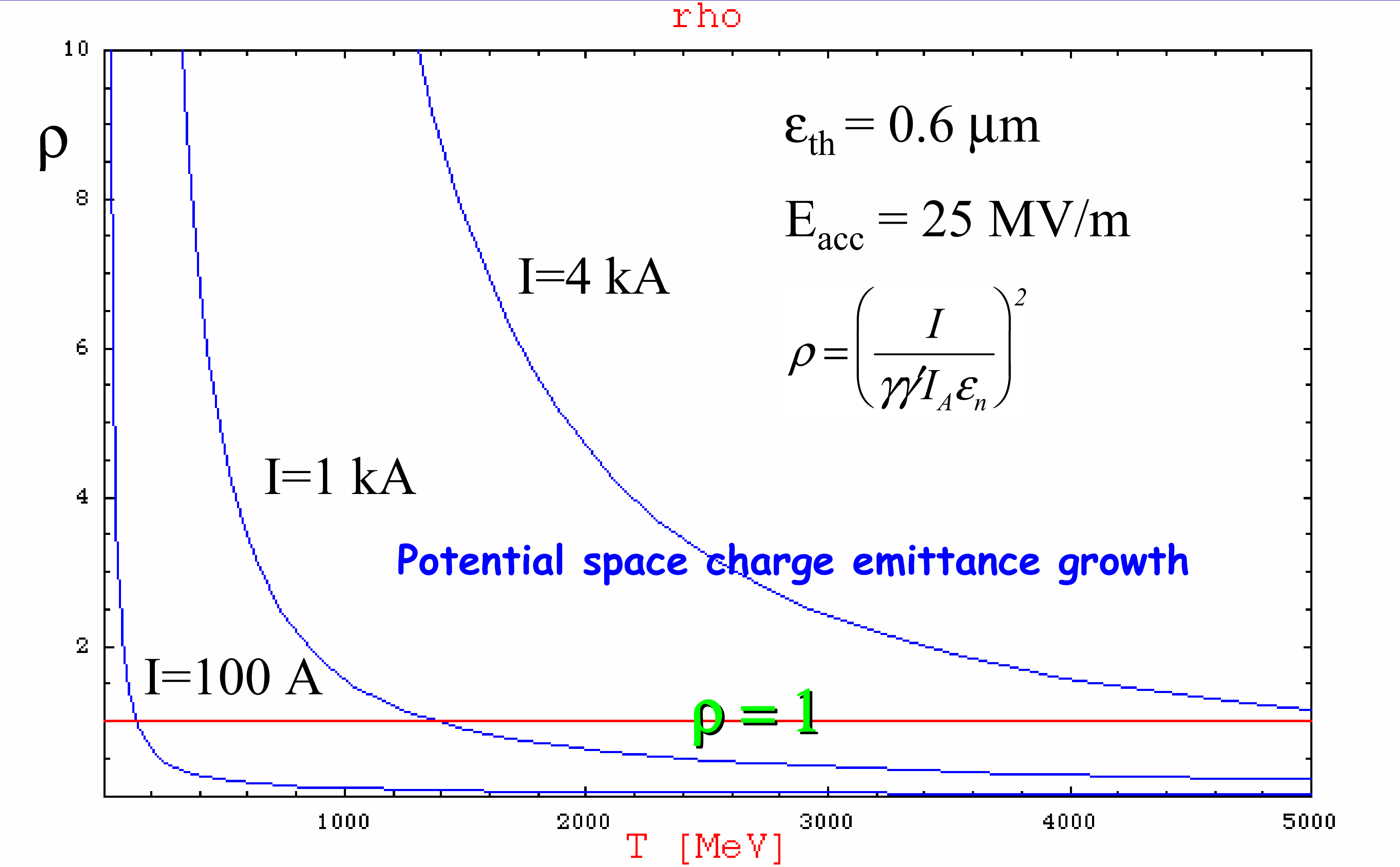
Courtesy Paul Emma - SLAC

FLASH @ 13 nm



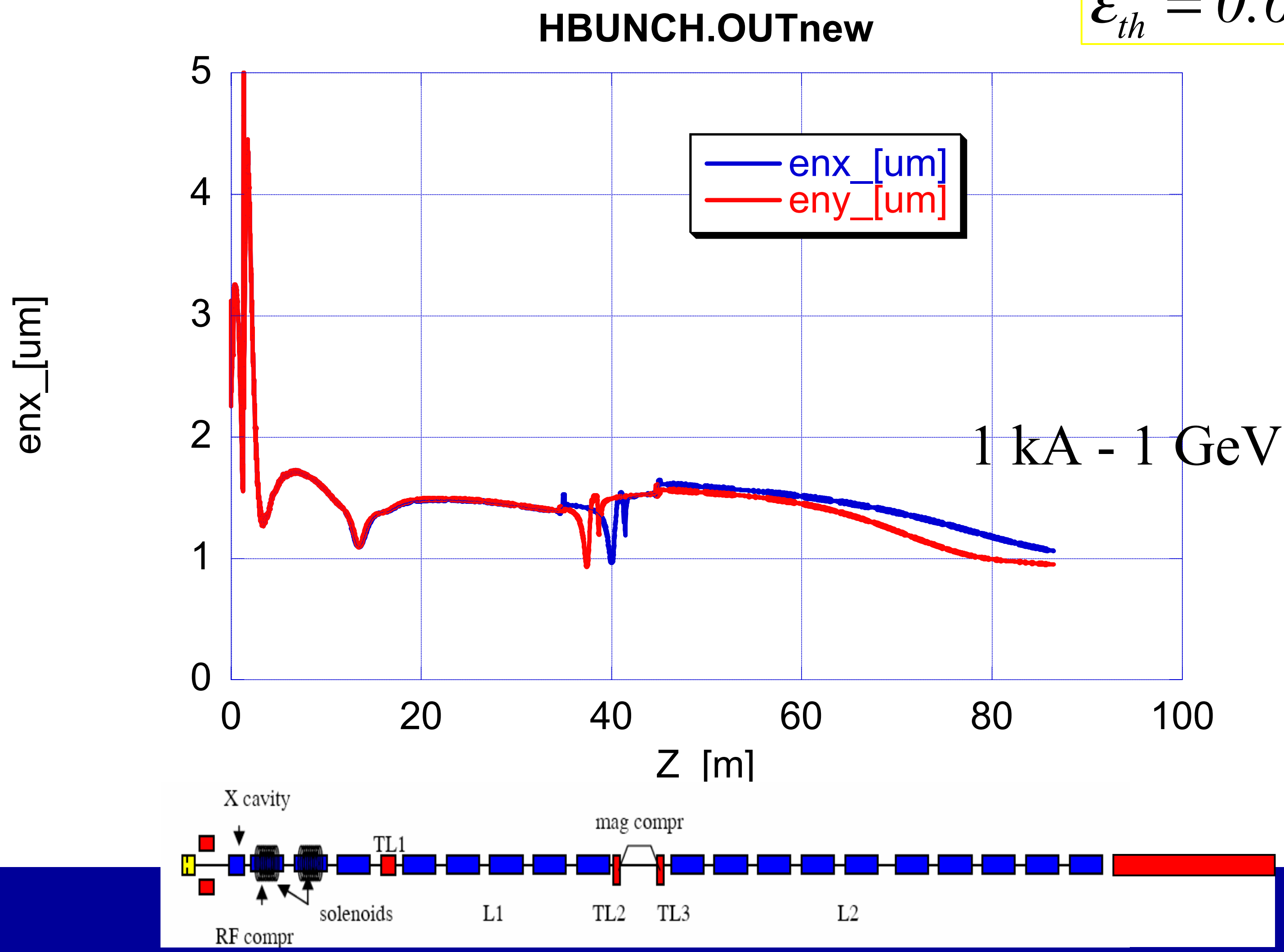
$$B_n \approx 10^{15} \; \left[A/m^2 \right]$$

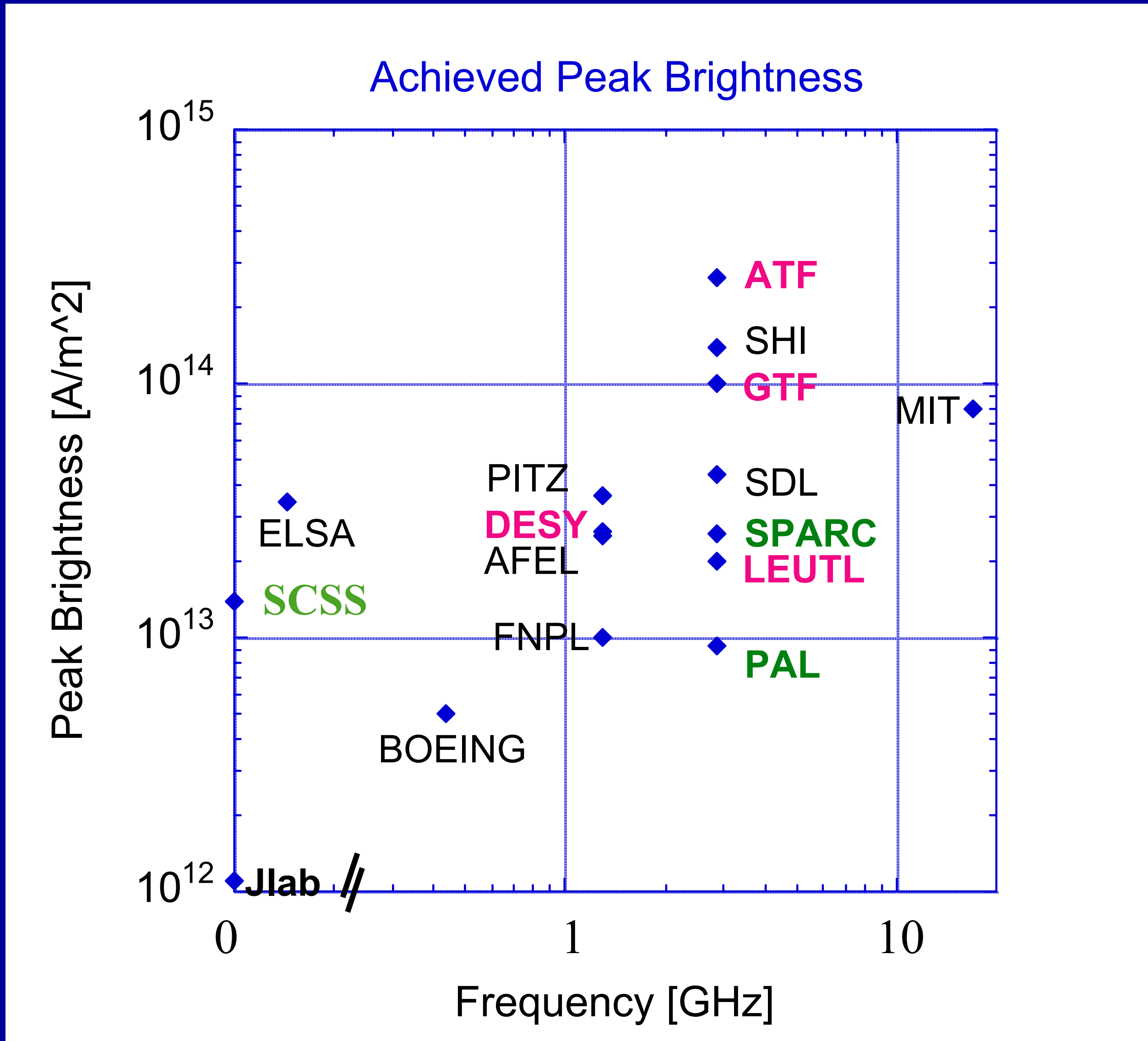
Emittance Compensation
==> Controlled Damping of Space Charge Effects



==> propagation close to the "invariant envelope"

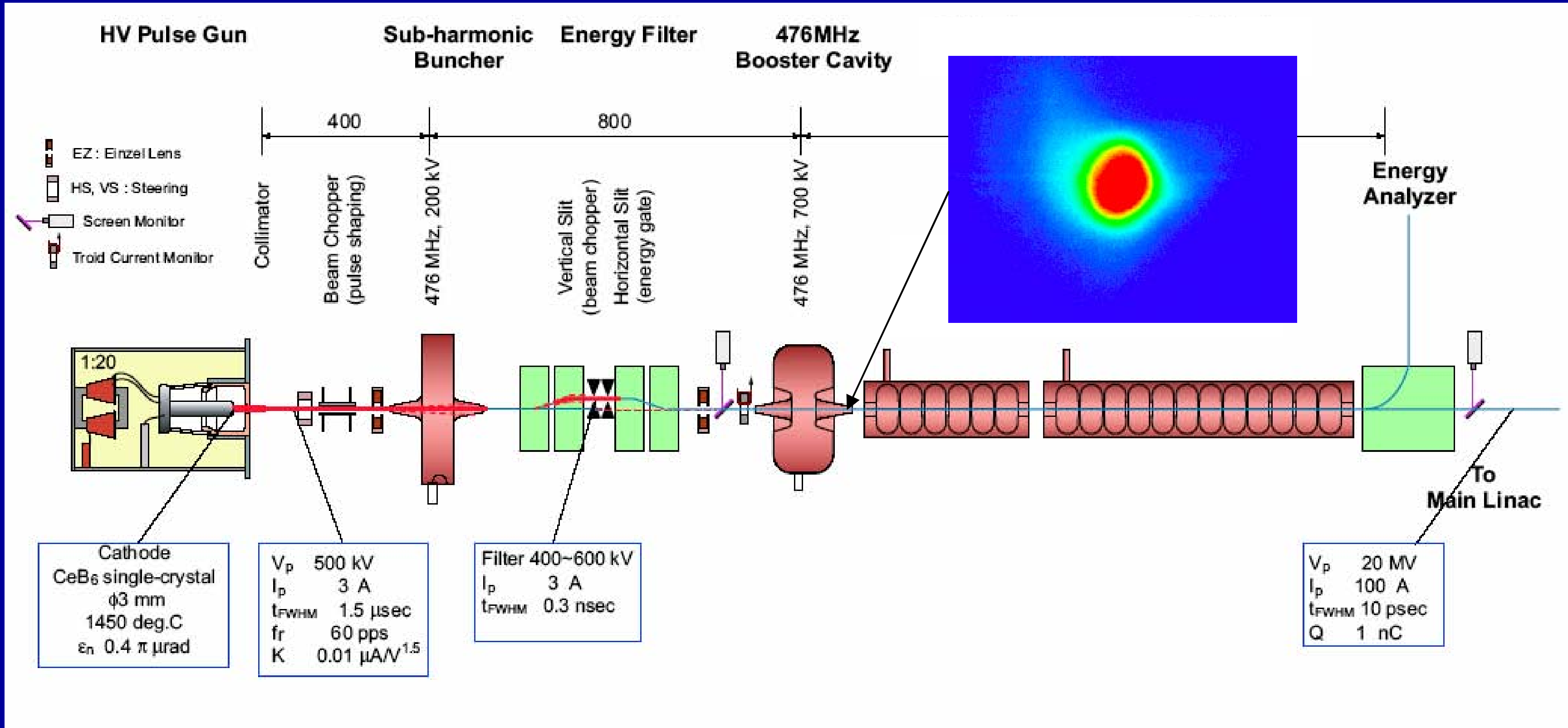
$\varepsilon_{th} = 0.6\mu m$





Achieved Peak Brightness
Peak Brightness [A/m^2]
Frequency [GHz]
10^15
10^14
10^13
10^12
0
1
10
ATF
SHI
GTF
MIT
PITZ
DESY
AFEL
SDL
SPARC
LEUTL
ELSA
SCSS
FNPL
PAL
BOEING
Jlab

500 kV pulsed thermionic gun for SCSS



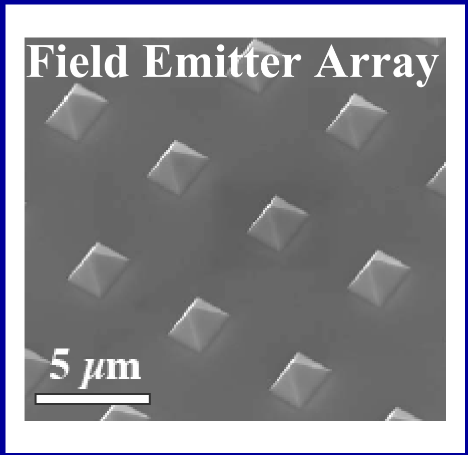
Stable operation with uniform beam quality

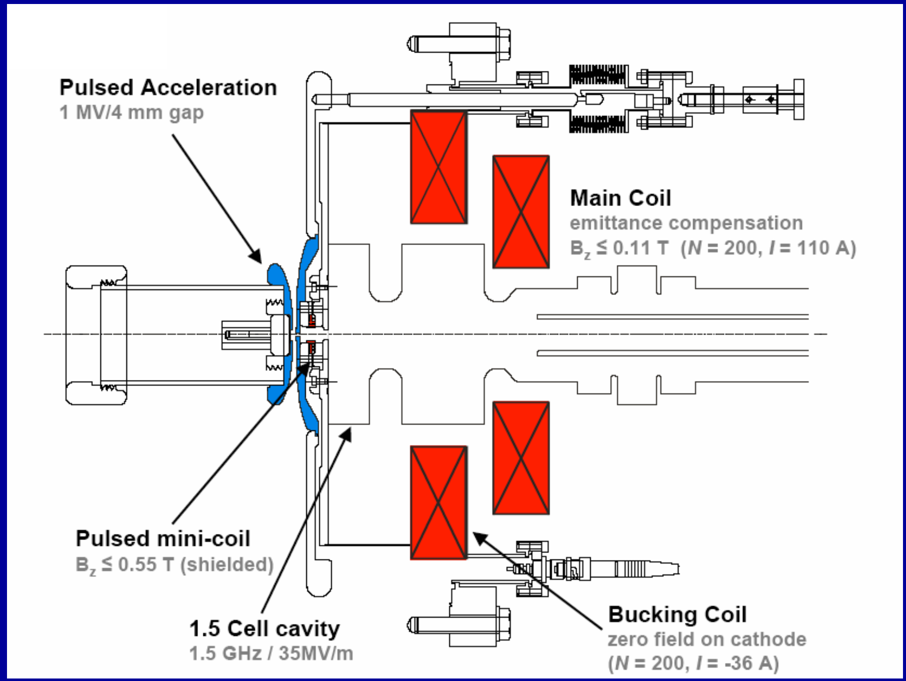
Low thermal emittance single crystal CeB_6 (Cerium Hexaborite)

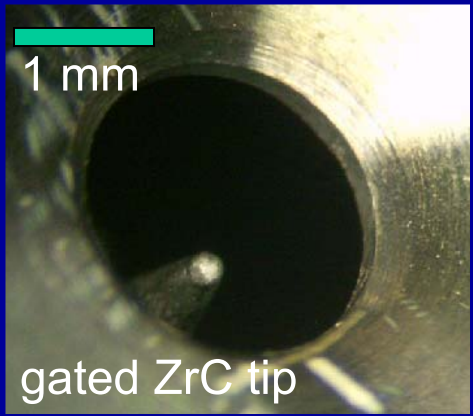
Low accelerating gradient (10 MV/m) ==> Low charge density ==> Free from dark current

Ulta-Low slice emittance gun

==> 0.05 µm @ source (0.1 µm @ undulator)







Frequency	1x10 Hz (macro pulse)	-
Peak field at cathode	6 GeV/m	> 6 GV/m
Charge per bunch	200 pC	> 1 nC (long pulses)
Rms norm. emittance	0.05 mm mrad (at cathode)	< 0.1 mm mrad (I < 0.6 A)
Peak Current	5.5 A (at cathode)	0.6 A
Average Current	2 nA	> 5 µA (long pulses)

Photo-Injector Test Facility at Zeuthen

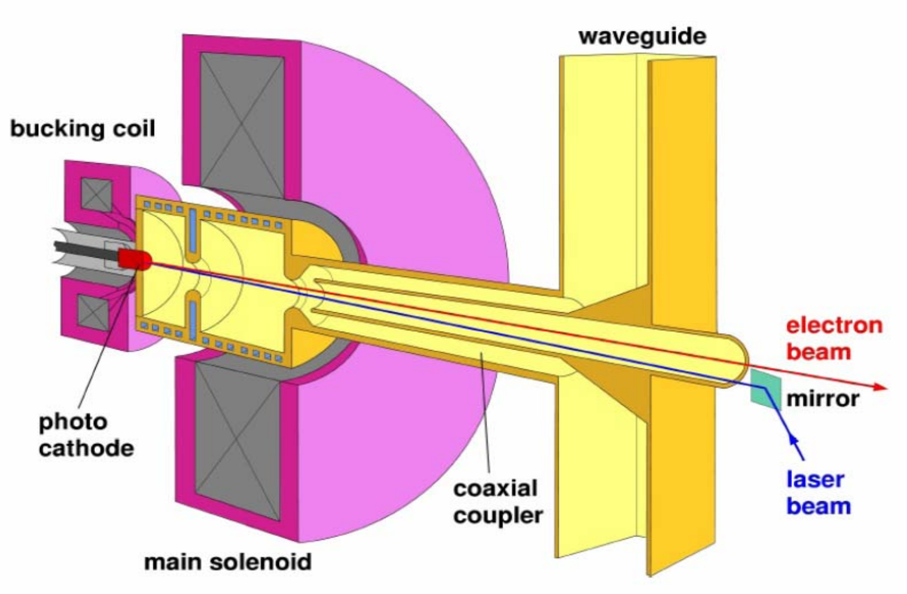
PITZ
Photo Injector Test Facility Zeuthen

Goals of PITZ

- test facility for FELs: FLASH, XFEL
  - ⇒ **small transverse emittance (1 mm mrad @ 1 nC)**
  - ⇒ **long RF pulses => high average power**
  - ⇒ **long laser pulse trains**
  - ⇒ **high QE cathode Cs_2Te**
- PITZ2 features:
  - ⇒ **higher gun gradient (~60MV/m)**
  - ⇒ **flat-top cathode laser profile with shorter rise/fall time**
  - ⇒ **emittance conservation with booster cavity**

Several gun cavities (1.5-cell, L-band, 1.3 GHz) have been conditioned and operated: PITZ-*guns1,2,3, BESSY-gun*.

Currently, *gun3* cavity is under characterization

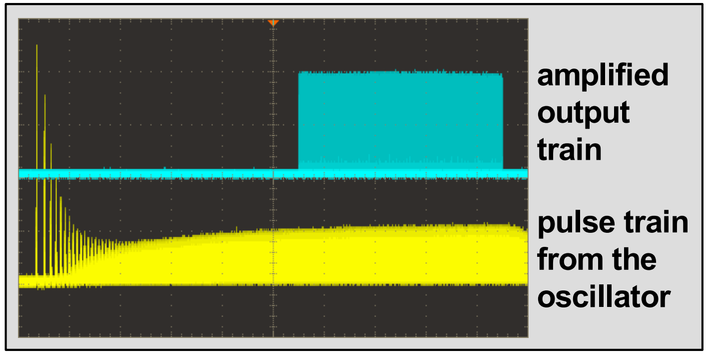


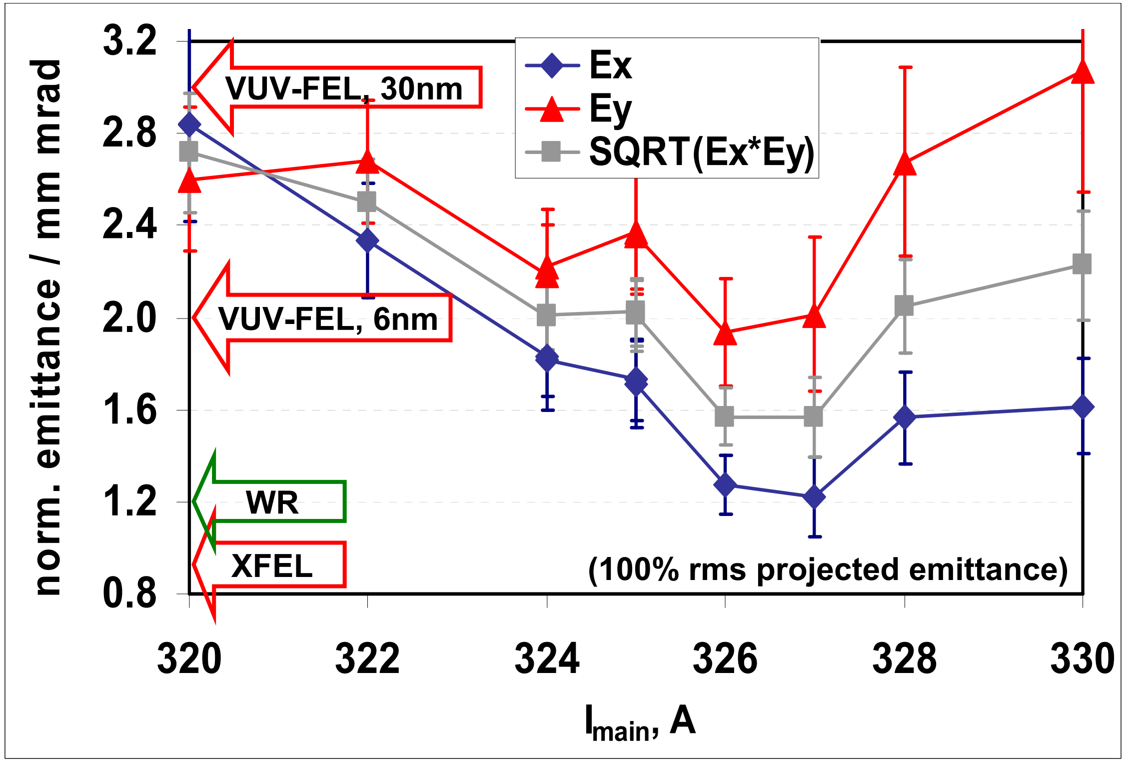
Emittance measurements of PITZ Gun

PITZ
Photo Injector Test Facility Zeuthen

<u>measured @ PITZ:</u> p = 5.2 MeV/c, Q = 1 nC,

The PITZ RF gun is developed for the operation with long RF pulses and long laser pulse trains, e.g.





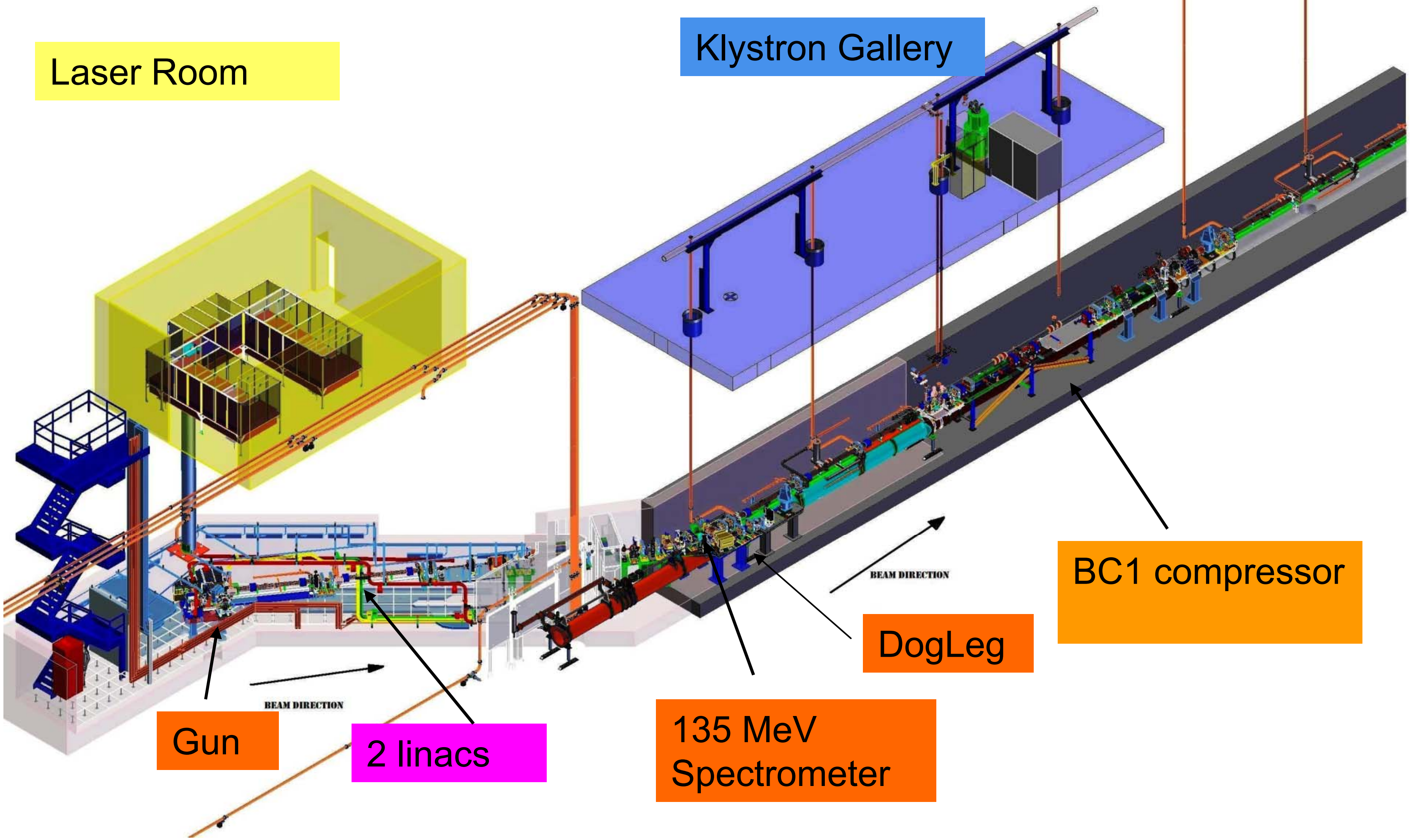
<u>measured @ VUV-FEL(FLASH):</u> p = 127 MeV/c, Q = 1 nC

- regularly obtain **2.1 mm mrad** (100% rms projected emittance)
- minimum **1.1 mm mrad** (90% rms projected emittance)

LCLS Injector

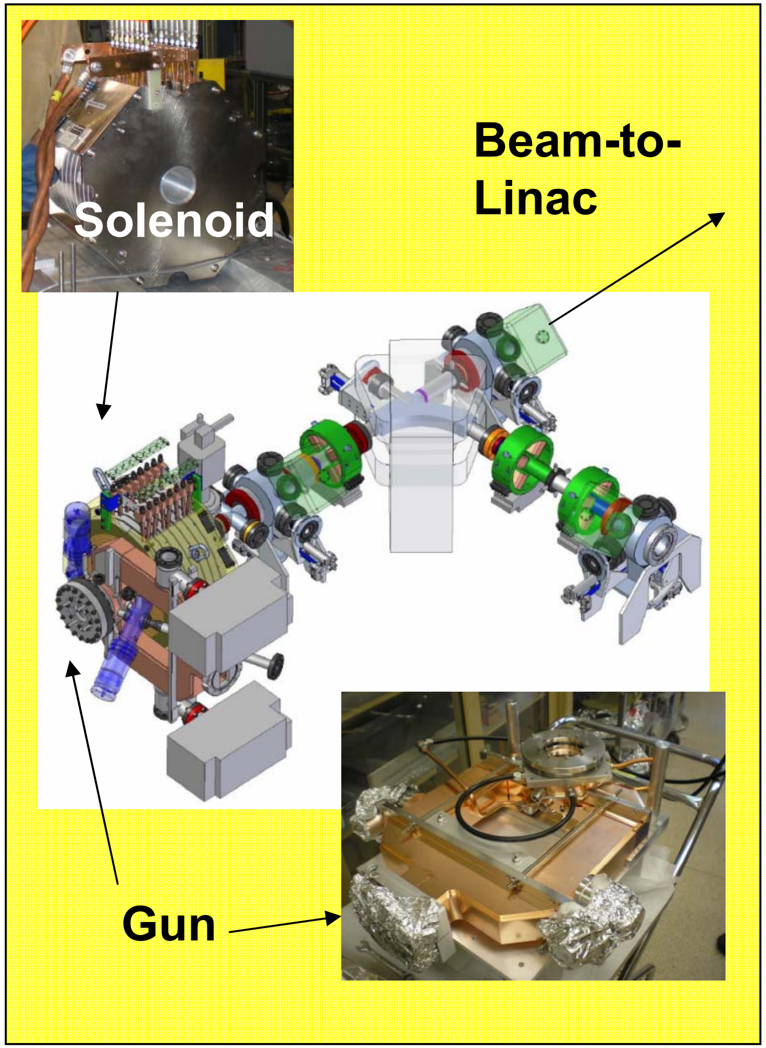
Courtesy : C.Limborg-Deprey, D.Dowell

Under Construction – Commissioning starts January 2007



LCLS Injector Parameters

Parameter	Value
Peak Current	100 A
Charge	1 nC
Normalized Transverse Emittance: Projected/Slice	< 1.2 / 1.0 micron (rms)
Repetition Rate	120 Hz
Energy	135 MeV
Energy Spread@135 MeV: Projected/Slice	0.1 / 0.01 % (rms)
Gun Laser Stability	0.20 ps (rms)
Booster Mean Phase Stability	0.1 deg (rms)
Charge Stability	2 % (rms)
Bunch Length Stability	5 % (rms)

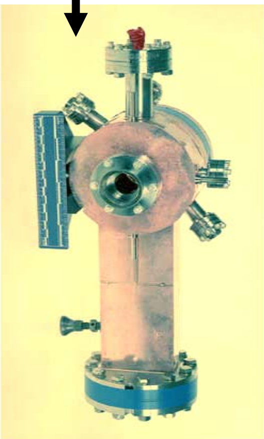


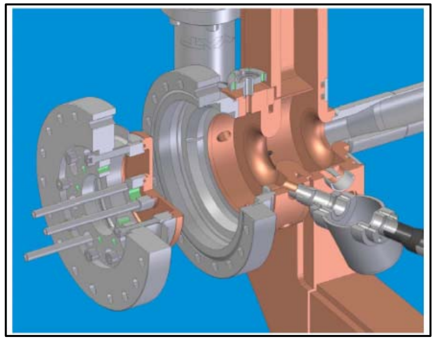
LCLS Gun

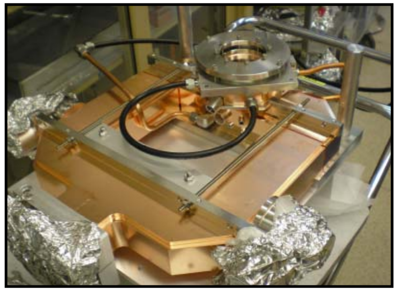
Modified from

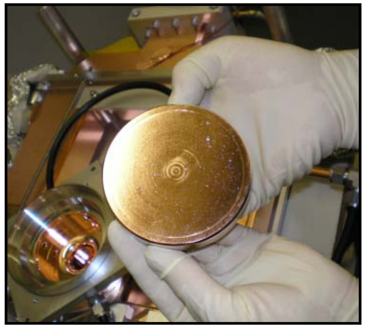
BNL/SLAC/UCLA version

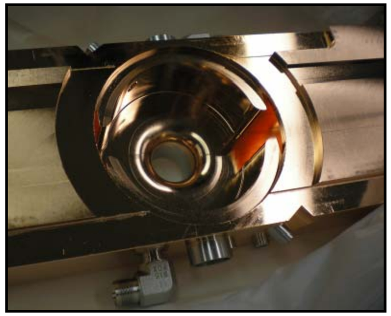
S-Band (2.856 MHz)
1.6 cell











LCLS version

•RF Dipole suppressed with dual feed
  • Quadrupole suppressed with racetrack shape
• Solenoid Quadrupole component compensated
• Laser axial injection
• Mode separation 15MHz instead of 3.5 MHz

INFN Istituto Nazionale di Fisica Nucleare

ENEA

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

ULTRAS INFM NATIONAL LABORATORY FOR ULTRAFAST AND ULTRAINTENSE OPTICAL SCIENCE

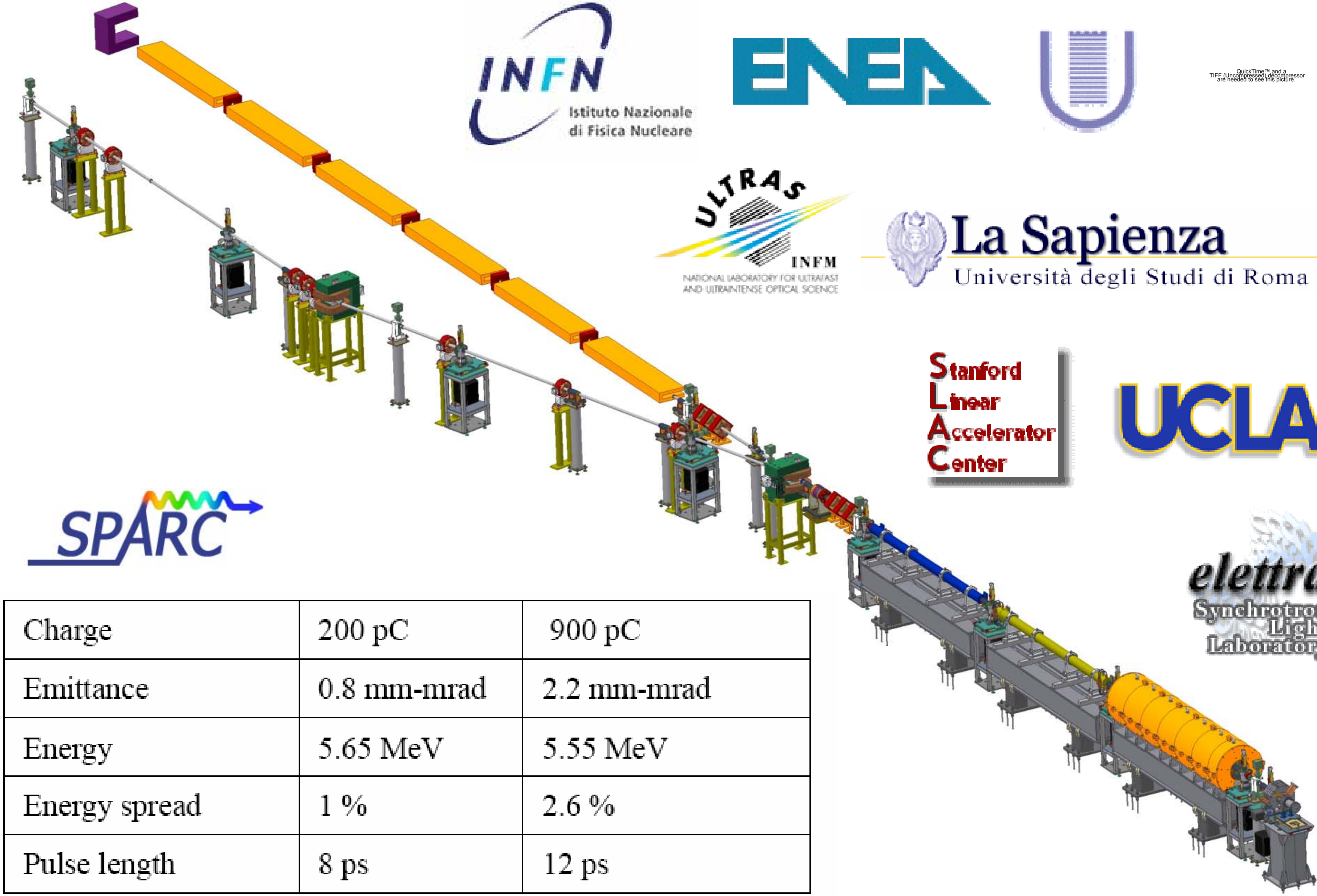
La Sapienza Università degli Studi di Roma

Stanford Linear Accelerator Center

UCLA

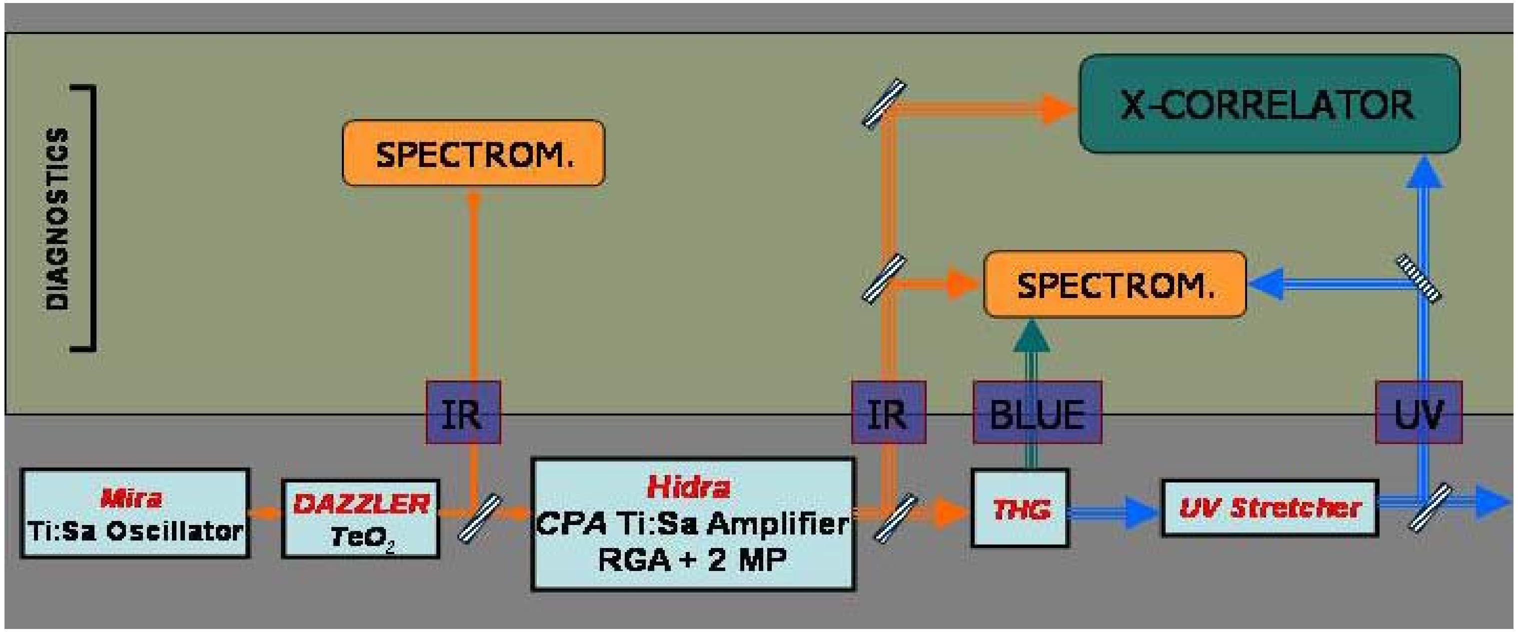
SPARC

elettra Synchrotron Light Laboratory



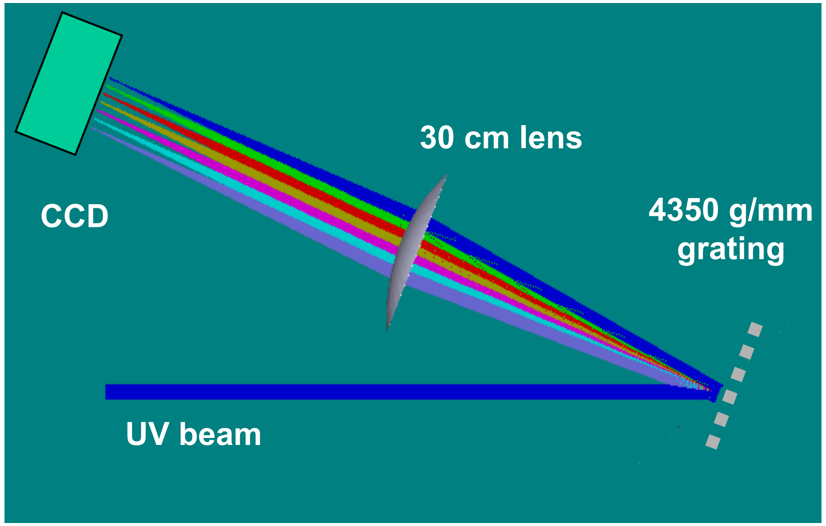
Charge	200 pC	900 pC
Emittance	0.8 mm-mrad	2.2 mm-mrad
Energy	5.65 MeV	5.55 MeV
Energy spread	1 %	2.6 %
Pulse length	8 ps	12 ps

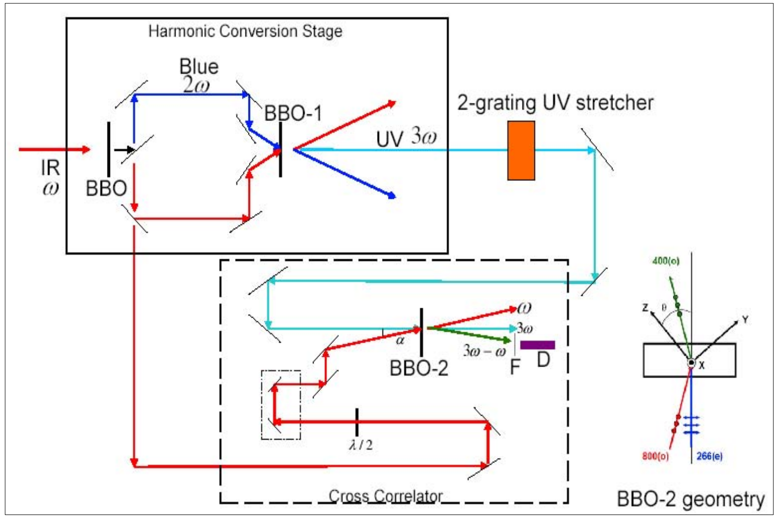
Ti:Sa LASER system

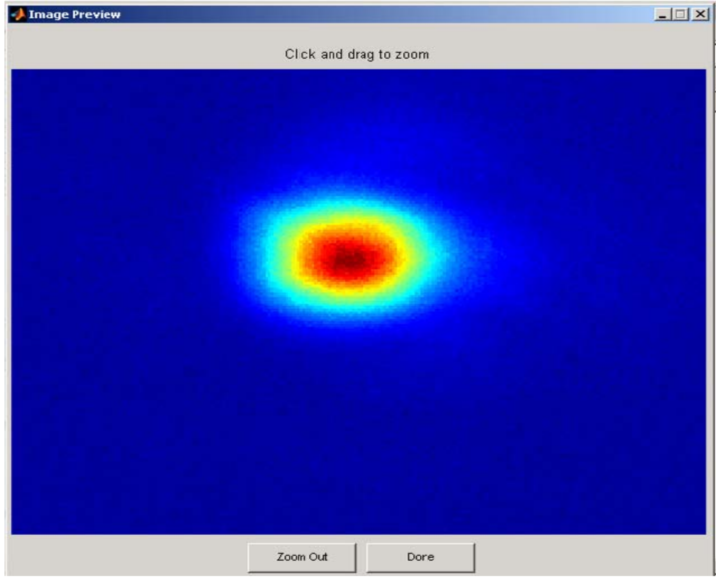


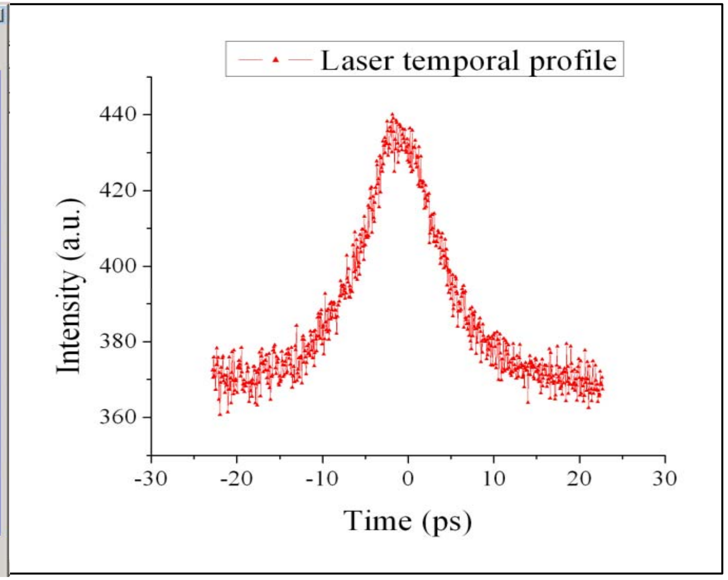
0.02 nm resolution spectrometer

200 fs resolution UV xcorrelator

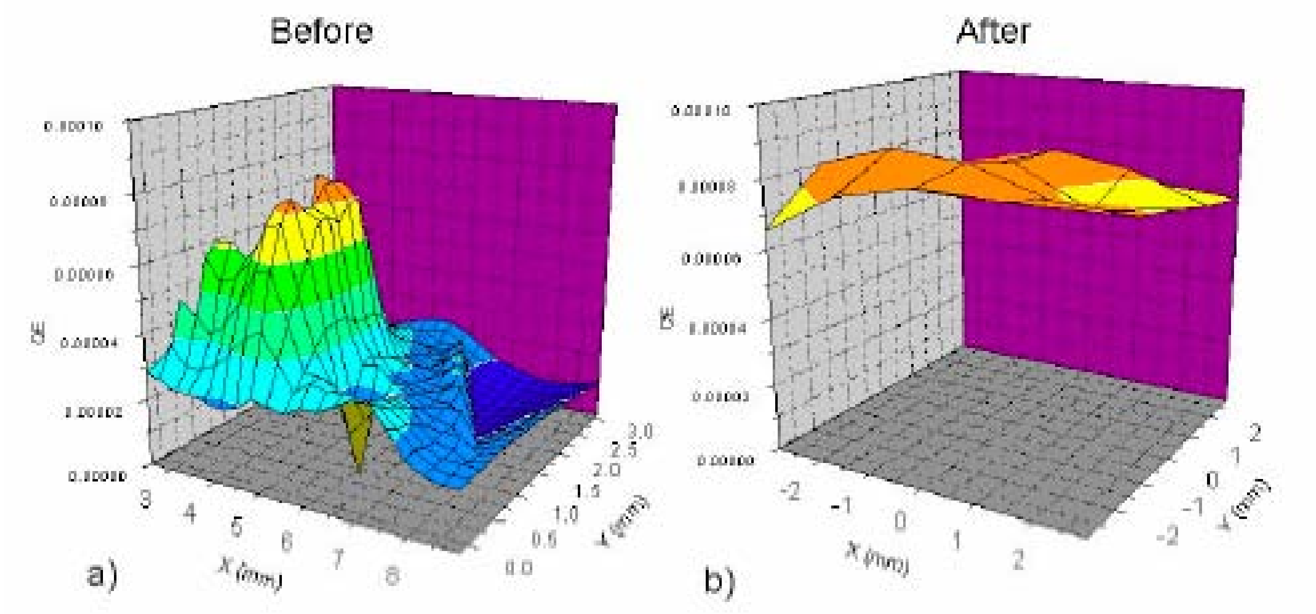




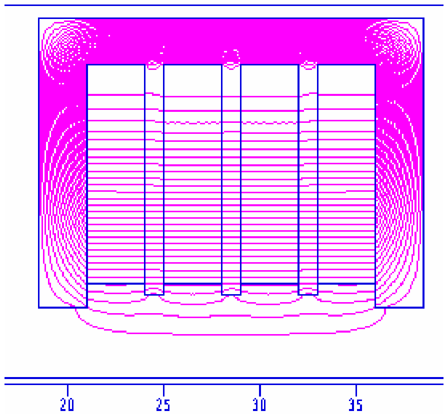




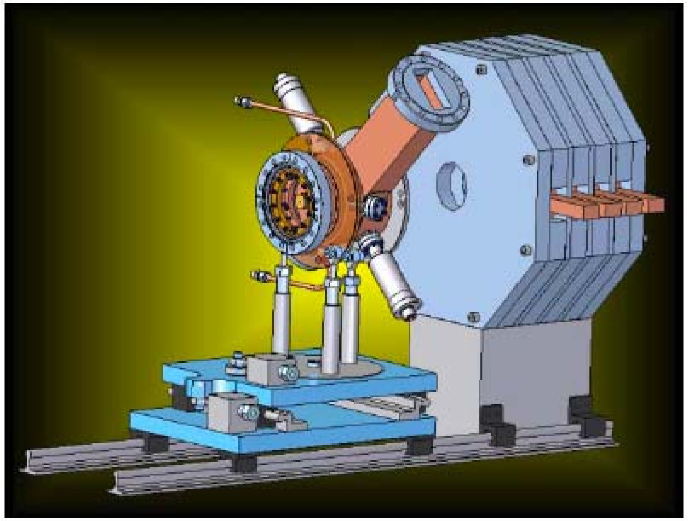
Cu Cathode QE ~ 10^{-4} improved by laser cleaning

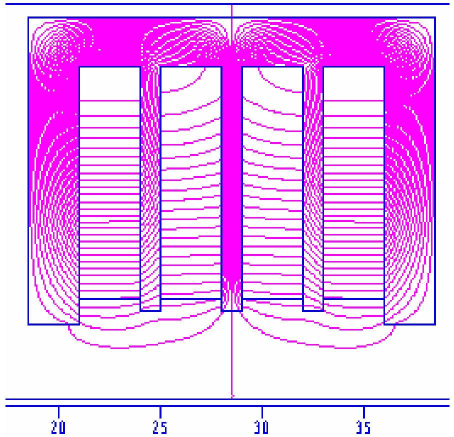


Coils Current Configuration

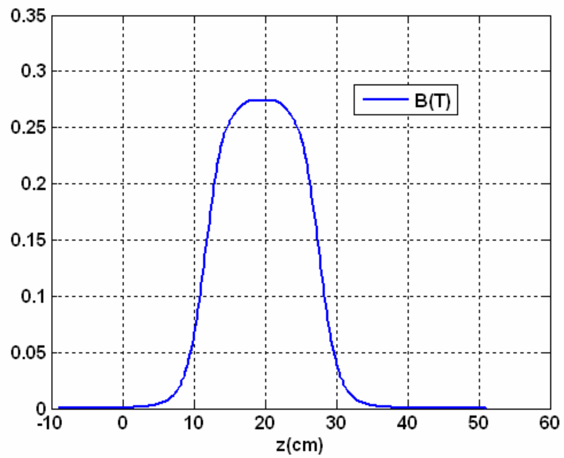


Beam rotation ~60°



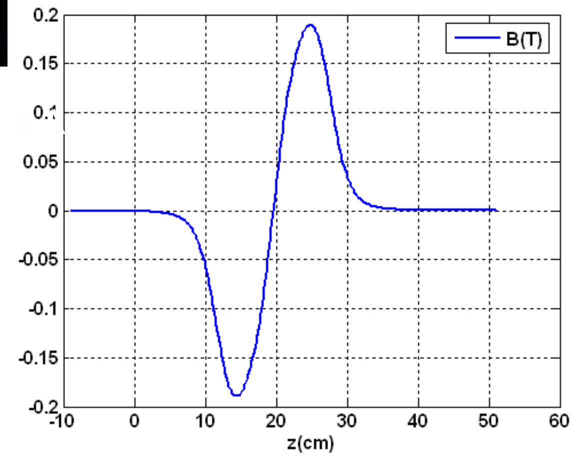


Beam rotation ~0°



$$r'' = -\left(\frac{eB(z)}{2\gamma m\beta c}\right)^2$$

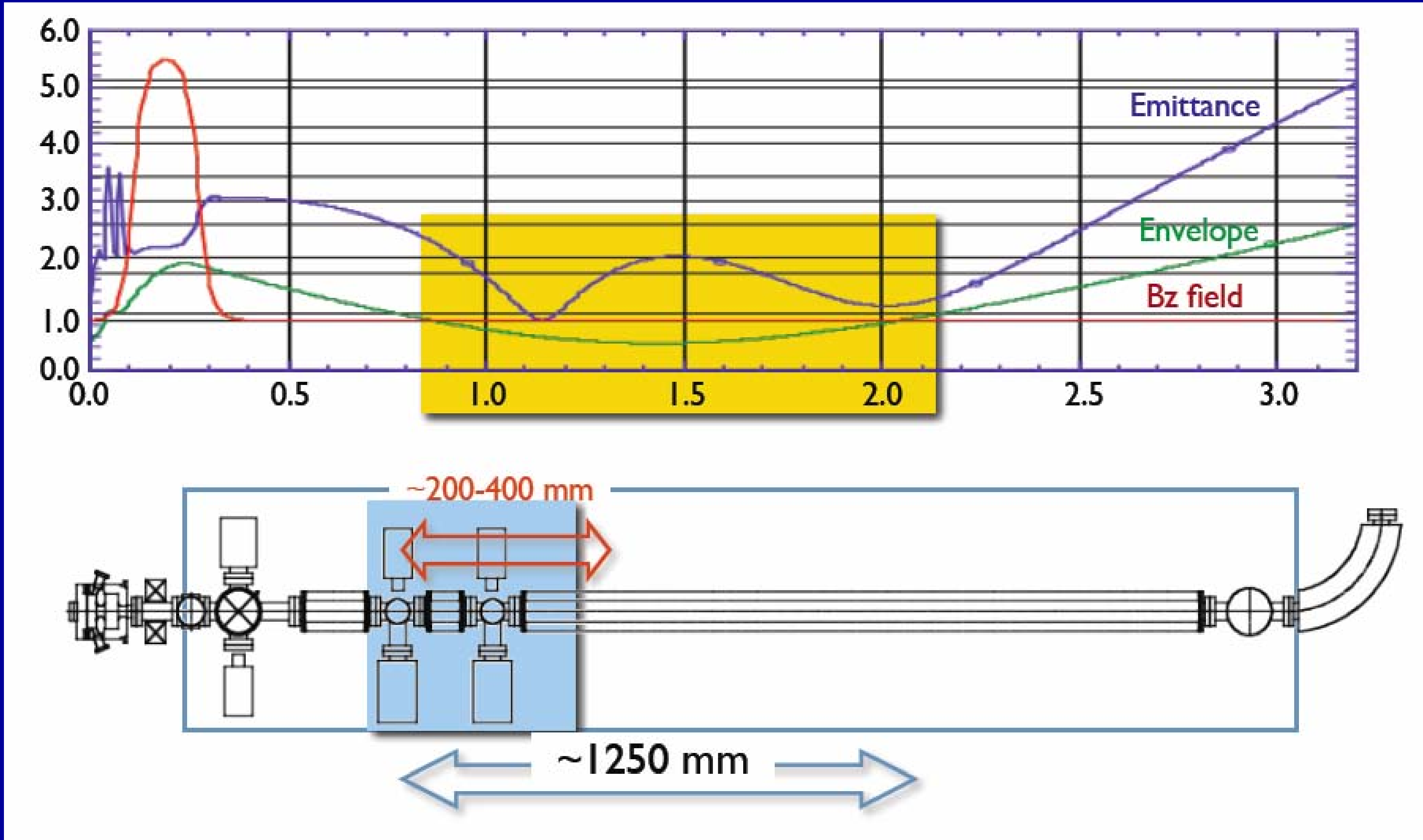
$$\vartheta' = -\frac{eB(z)}{2\gamma m\beta c}$$



I(A)=+140 ,+140, +140,+140

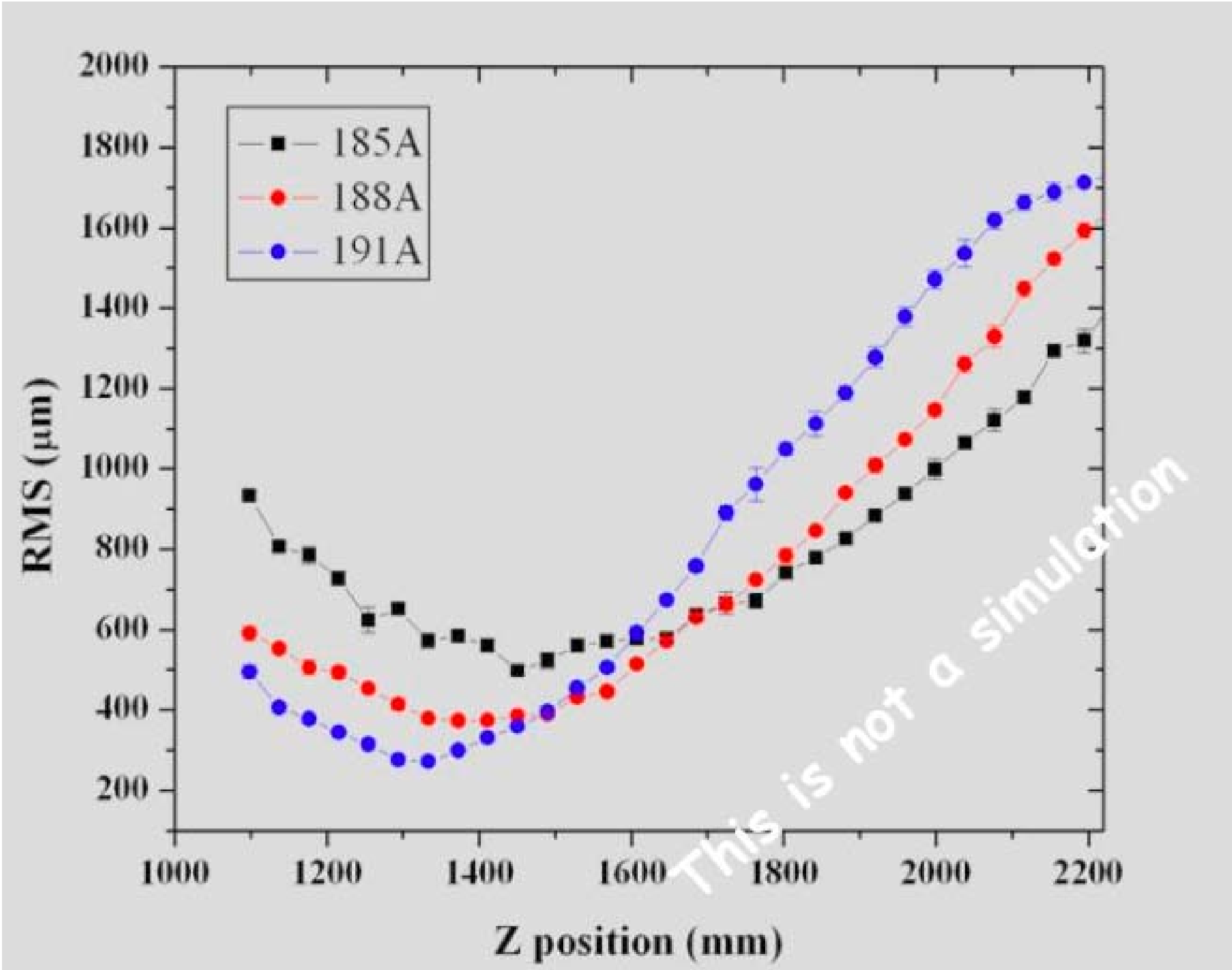
I(A)=-140 ,-140, +140,+140

Movable Emittance-Meter

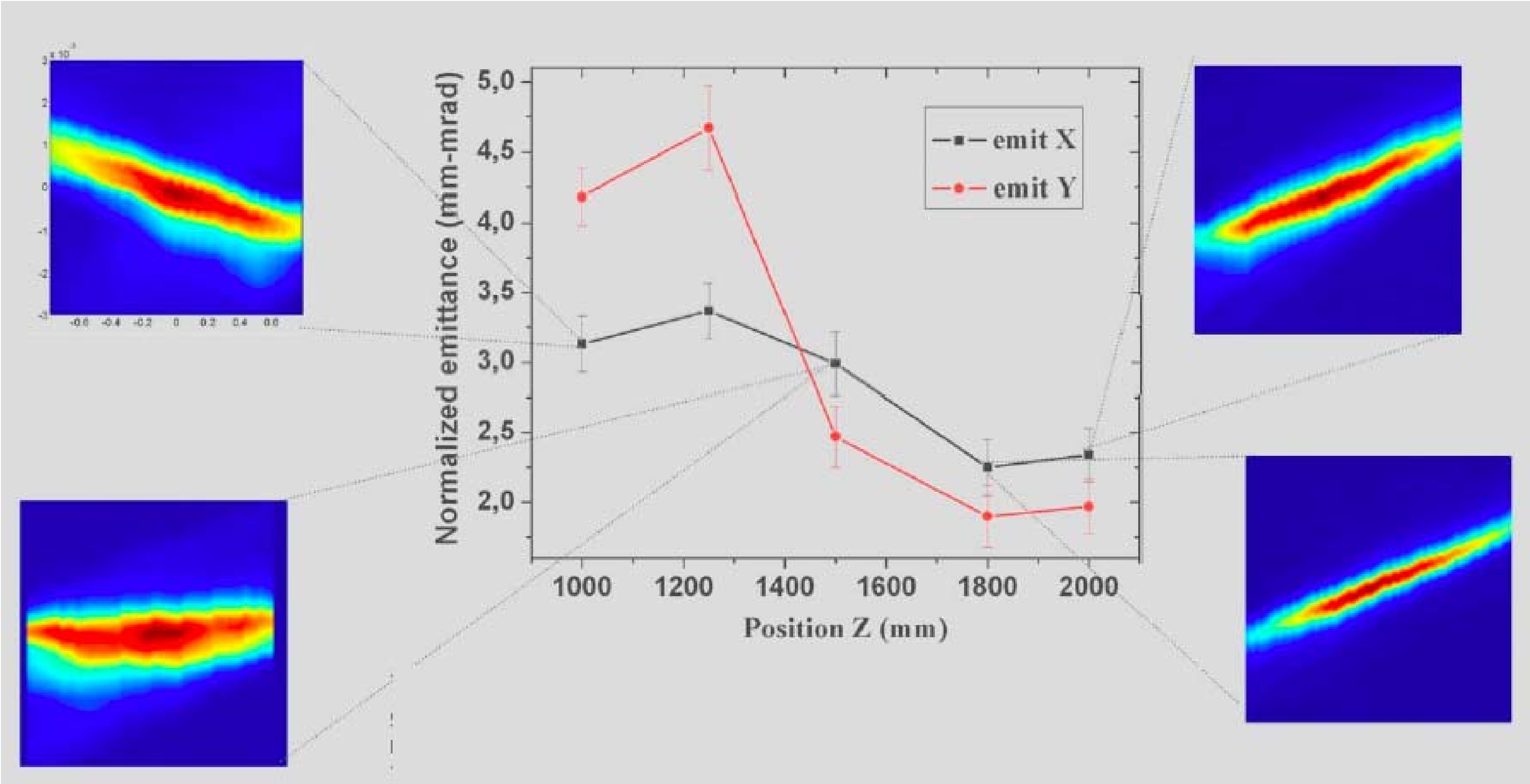


Gun and emittance meter in the SPARC bunker

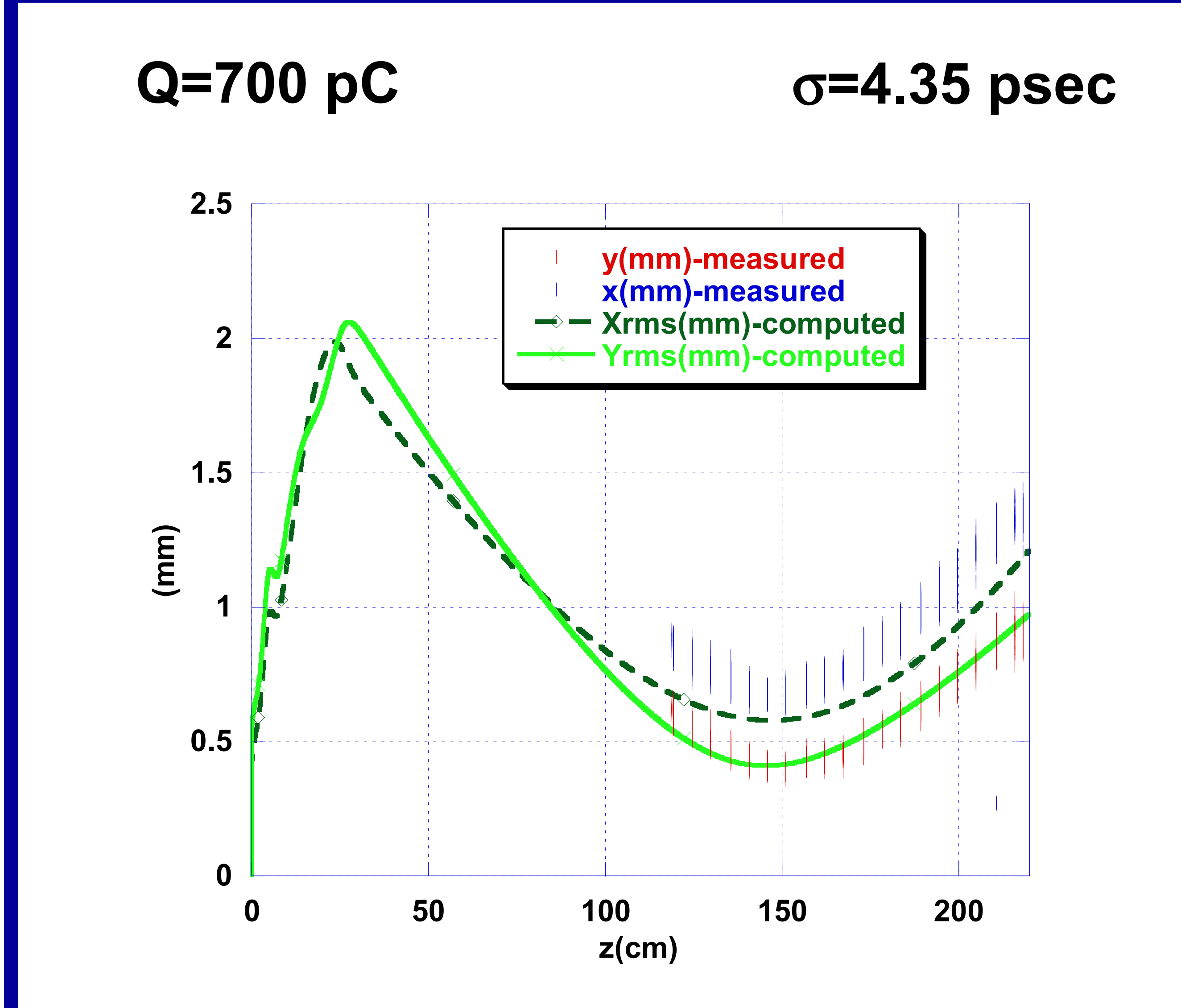
Beam envelope along the drift

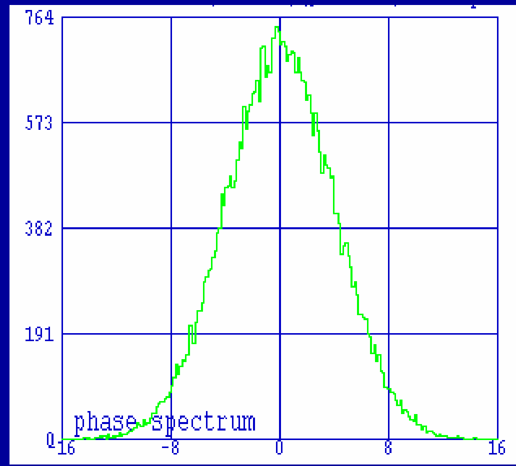


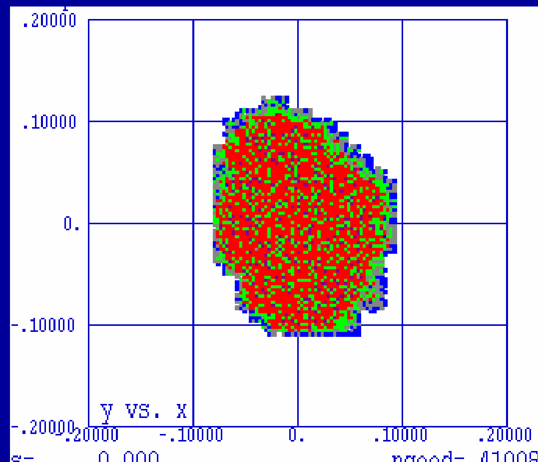
Beam rms norm. emittance along the drift



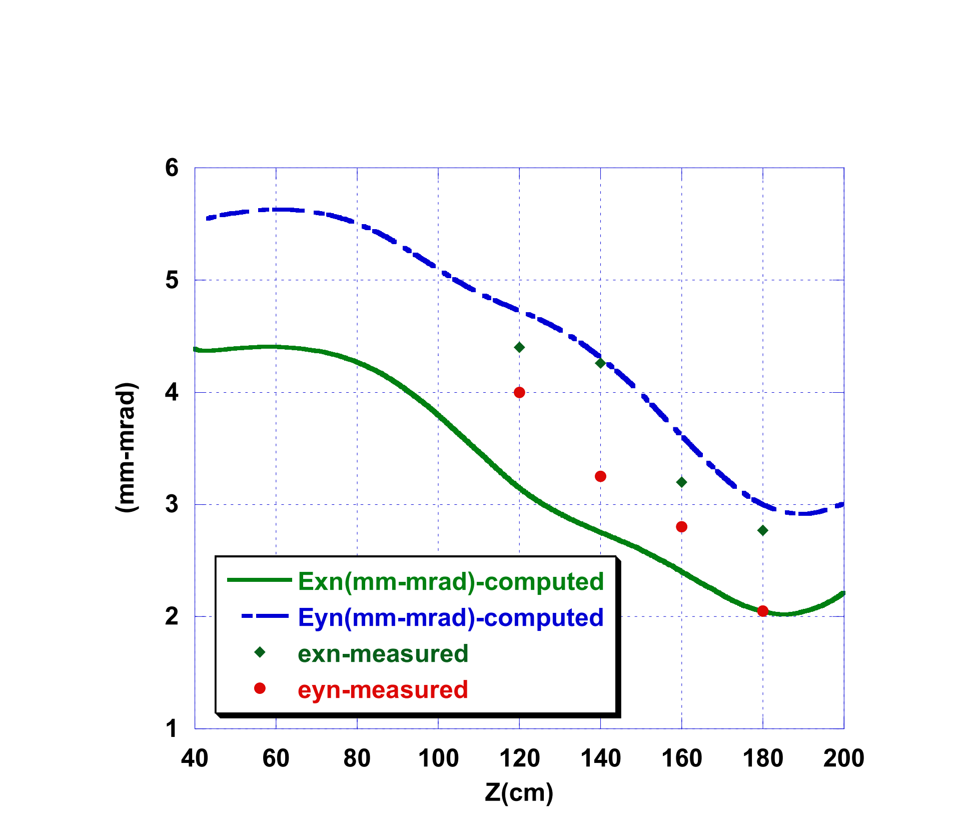
Comparison measurements-computations:envelopes

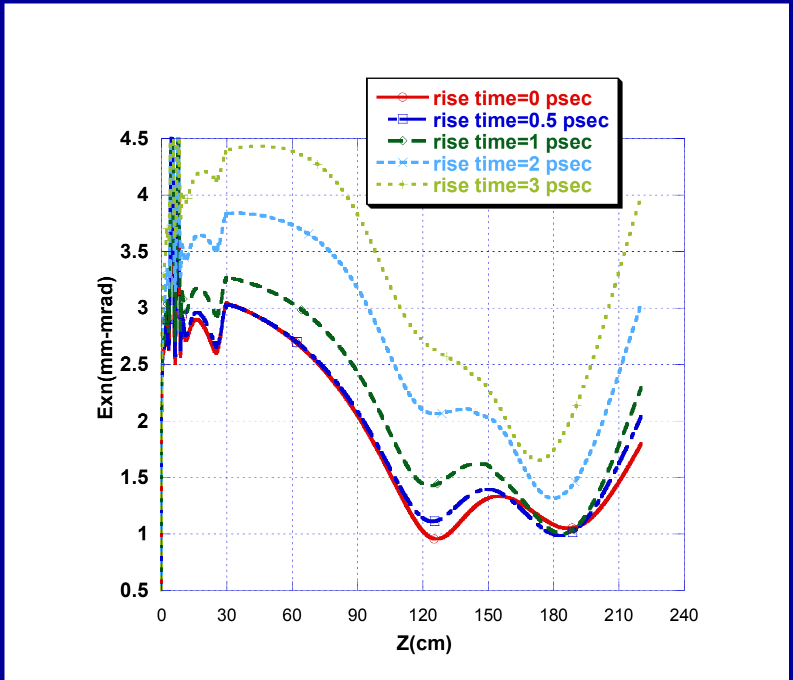




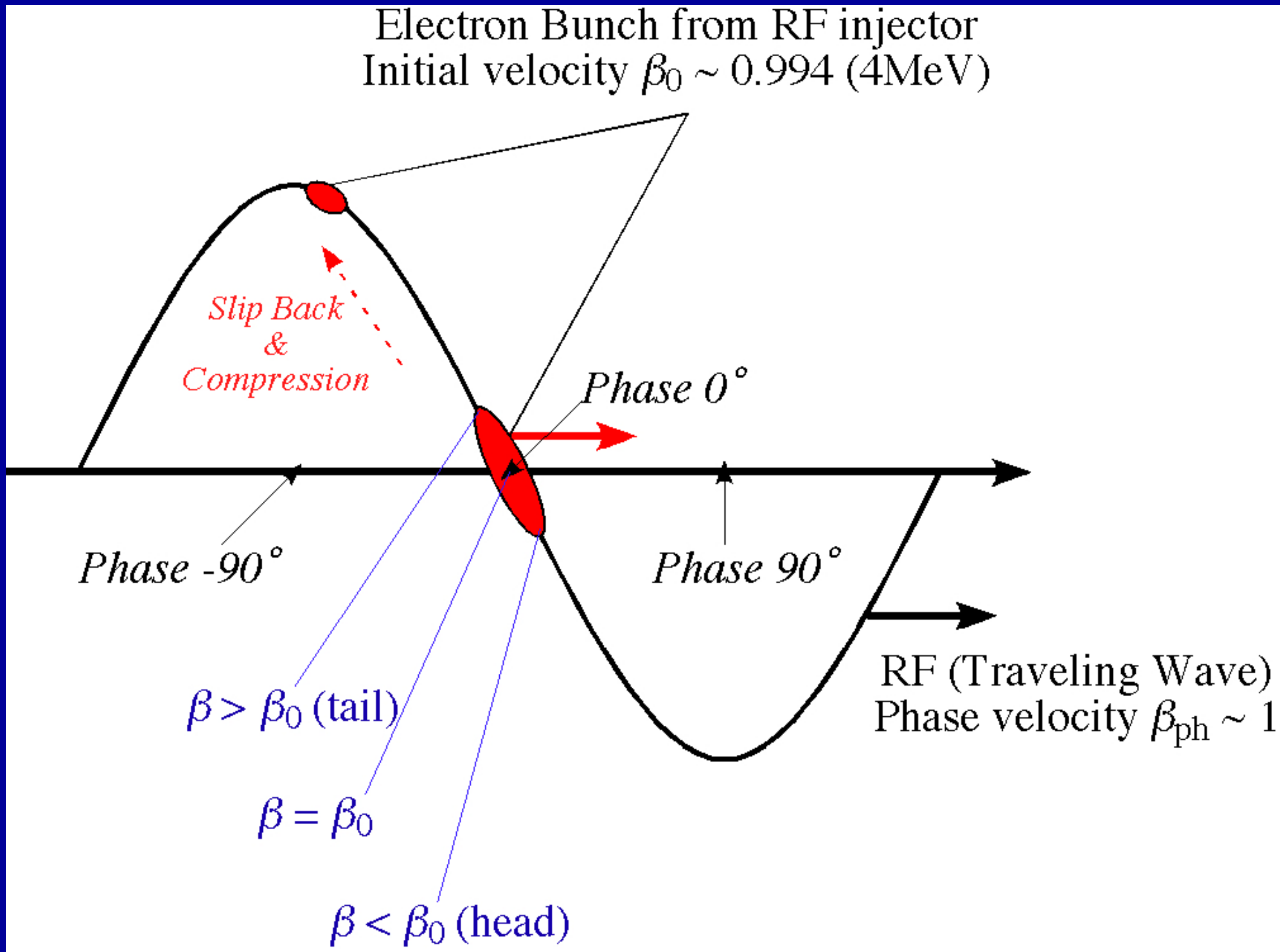


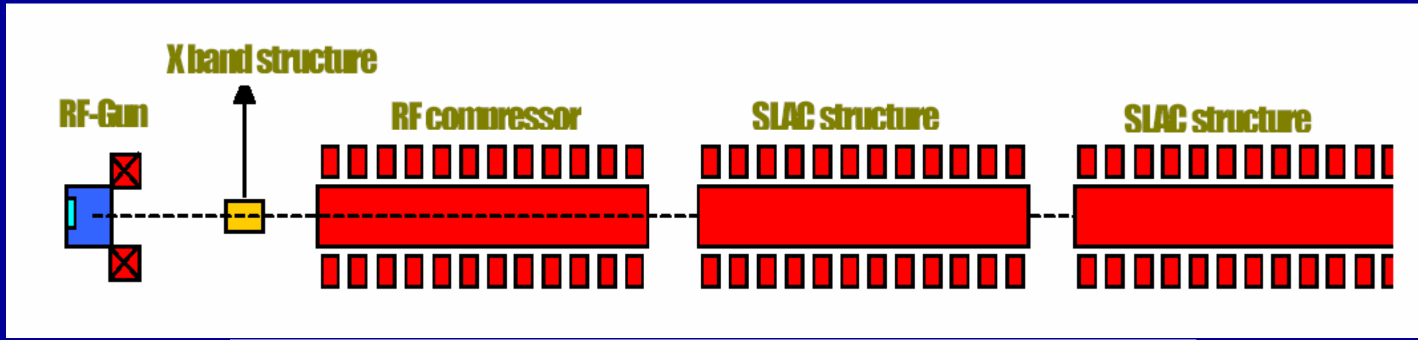
Comparison measurements-computations:emittance

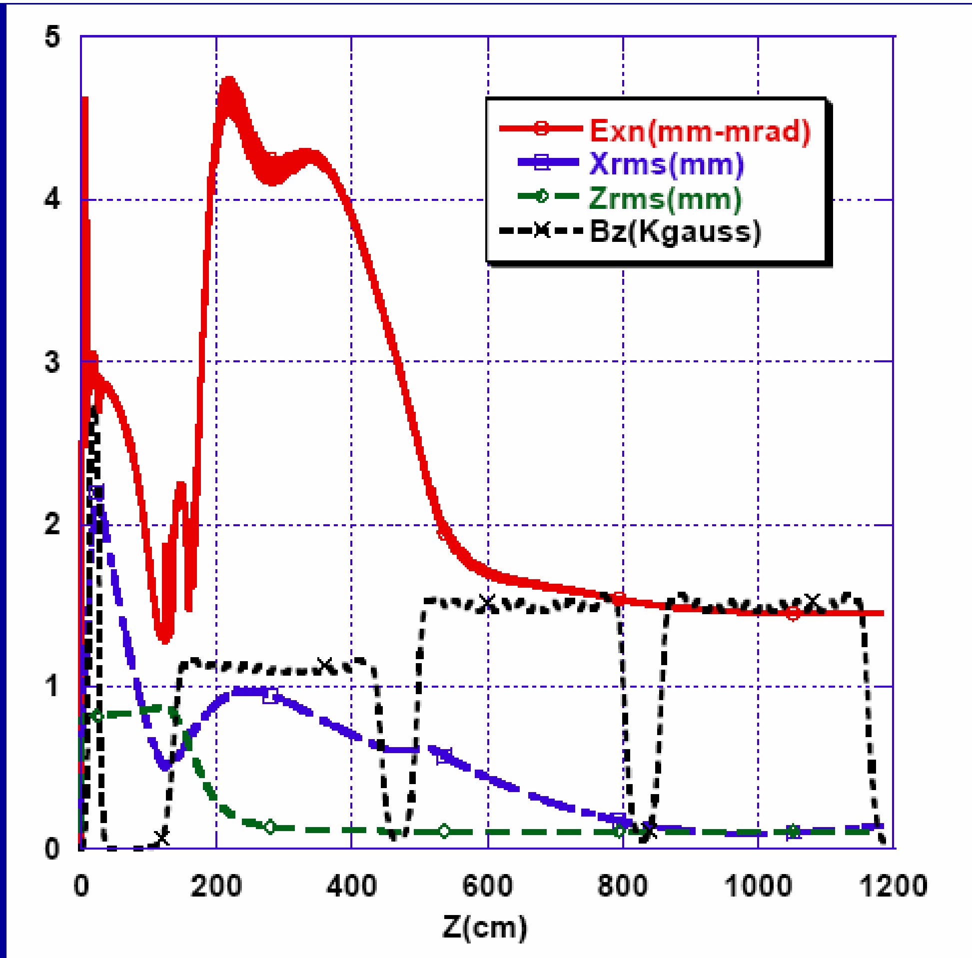




Velocity bunching concept







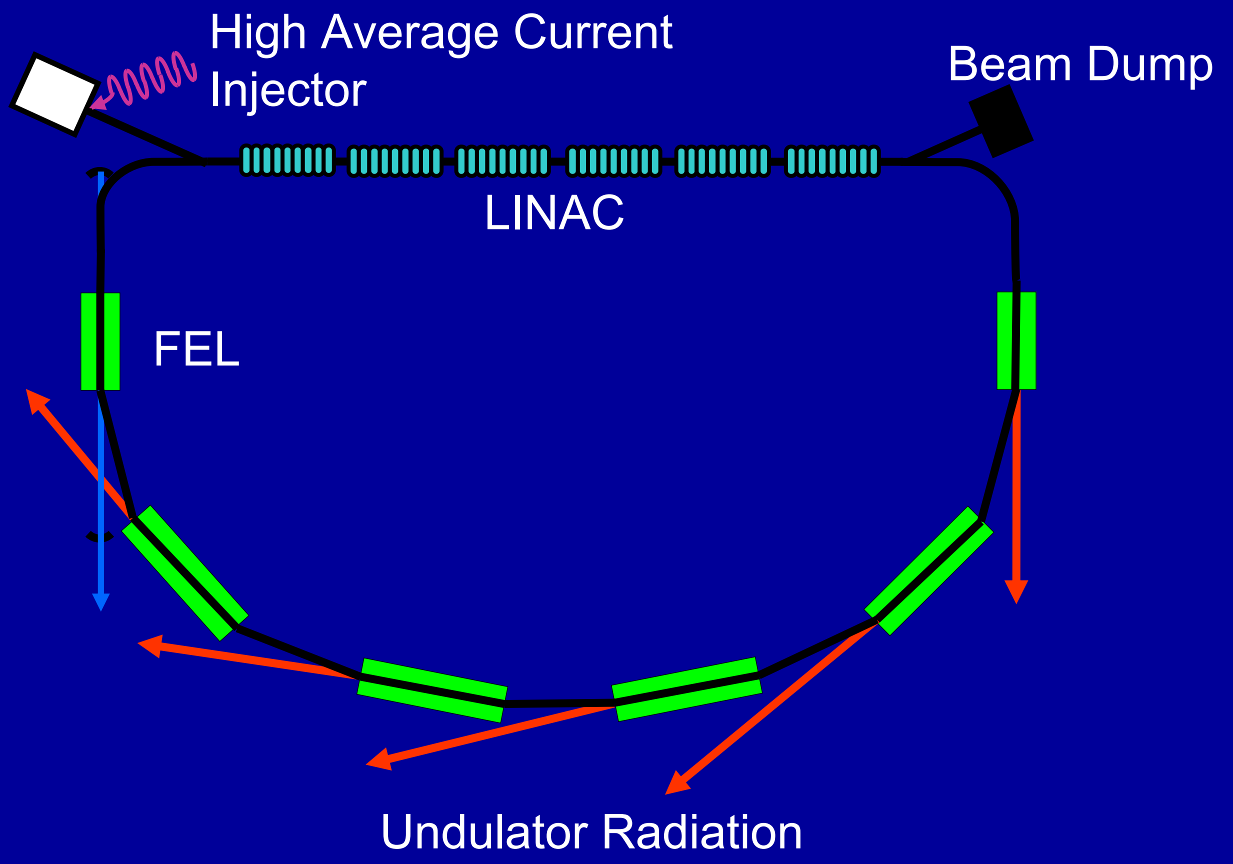
$\langle I \rangle = 860$ A

$\varepsilon_{nx} = 1.5\ \mu m$

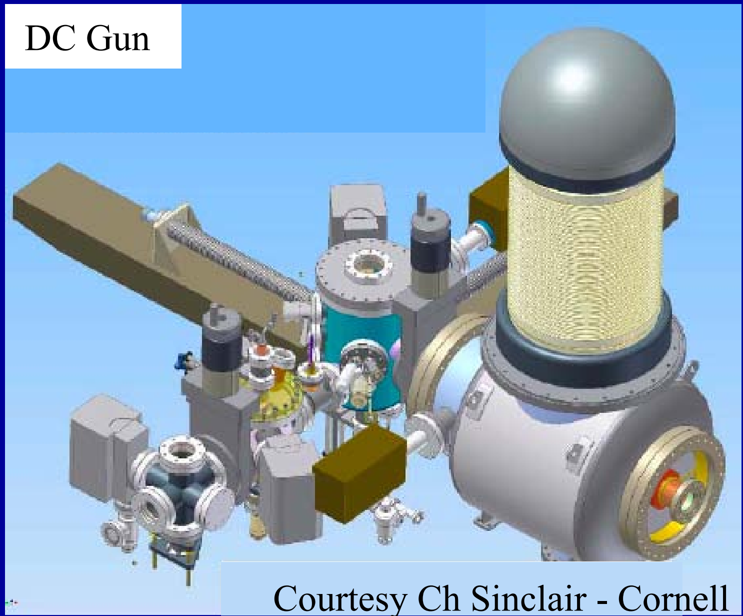
Rectilinear Bunching Experiments

	BNL	UCLA	BNL-DUVFEL	UTNL-18L	LLNL
Methode	Ballistic	Ballistic	Velocity Bunching	Velocity Bunching	Velocity Bunching
Acc. Structure	S-band	PWT	4 S-band	1 S-band	4 S-band
Measurement	zero-phasing method	CTR	zero-phasing method	Femotsecond Streak Camera	CTR
Charge	0.04 nC	0.2 nC	0.2 nC	1 nC	0.2 nC
Bunch width	0.37 ps (rms)	0.39 ps (rms)	0.5 ps (rms)	0.5 ps (rms)	< 0.3 ps
Comp. Ratio	6	15	> 3	> 13	10
Solenoid field	No	No	No	Yes	Yes

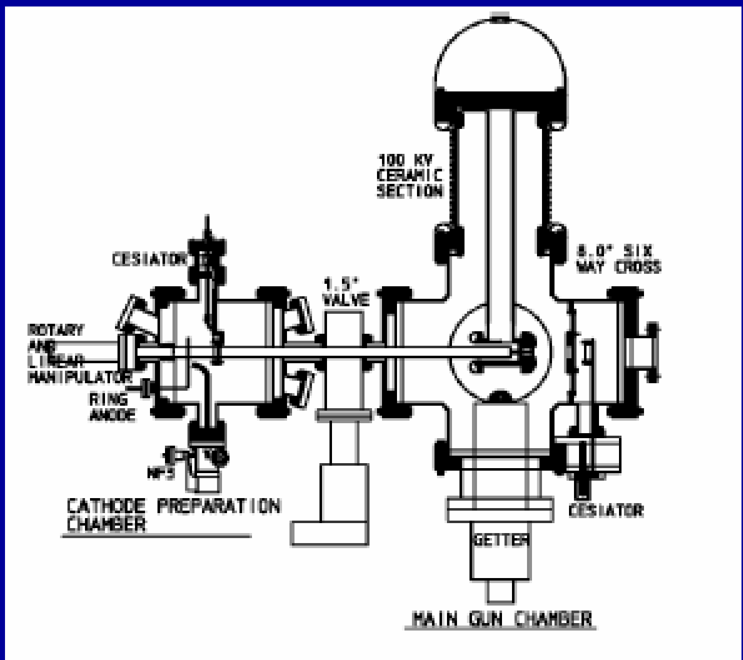
High average current sources



DC photo-electron source



Courtesy Ch Sinclair - Cornell



operation mode	
pulsed / CW	CW
single bunch charge	122 pC
single bunch rep rate	75 MHz
DC voltage / gap	350 kV / 10.57 cm
average current	9.1 mA
norm. trans. emittance (rms)	~ 8-10 mm mrad @ 10 MeV

Long operating experience

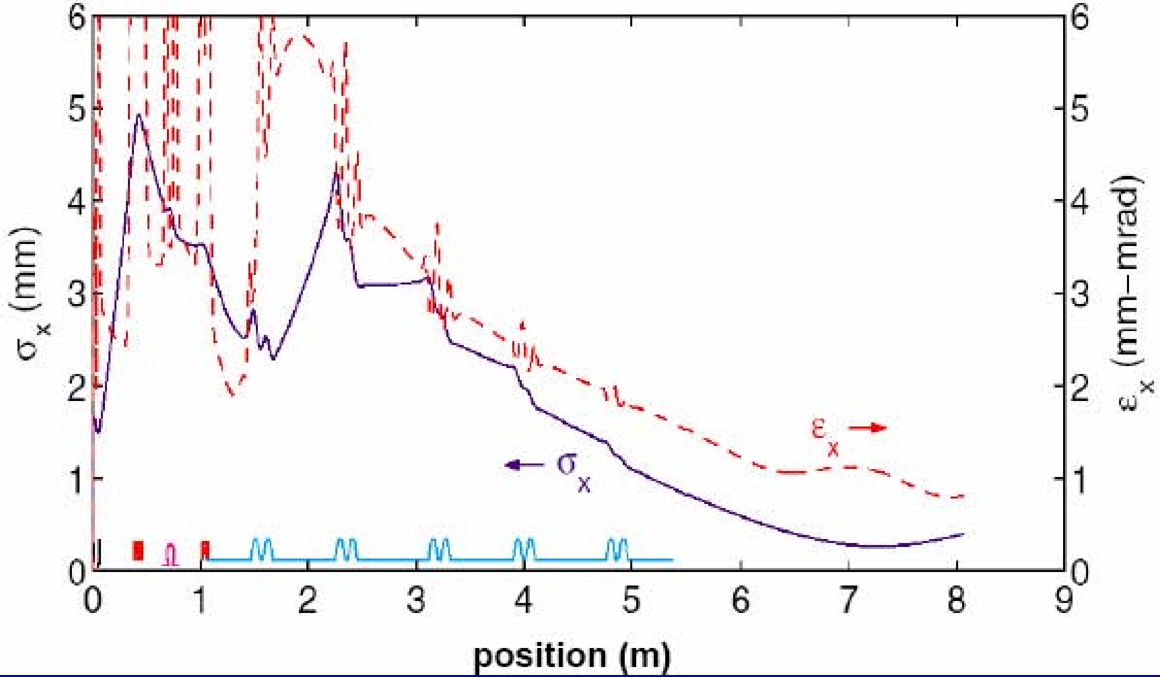
High average current

Low accelerating gradient

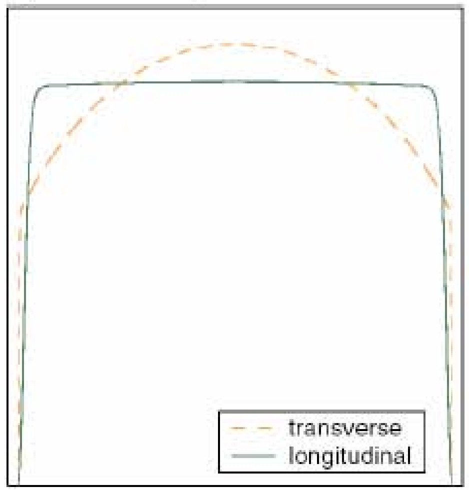
==> Low charge density

Multivariate Optimization of Cornell Injector

Results for 800 pC:



opt. laser parameters:



1.6 mm rms spot size

17 ps rms pulse duration

Superconducting RF photoinjectors

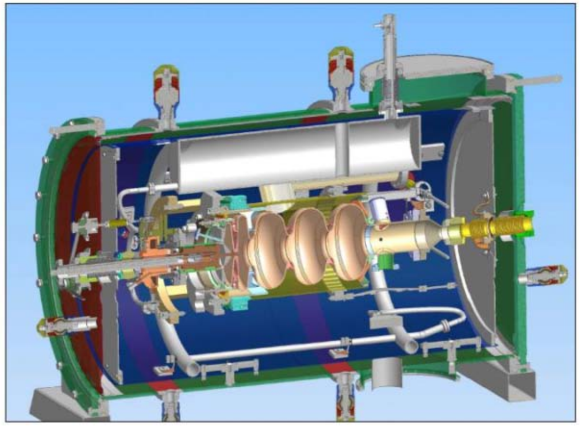
Main Advantage:

Low RF Power Losses & CW Operation

Problems and Open Questions:

- **Emittance Compensation ?**
- **High Peak Field on Cathode ?**
- **Cathode Materials and QE ?**

FZR (since 1998)

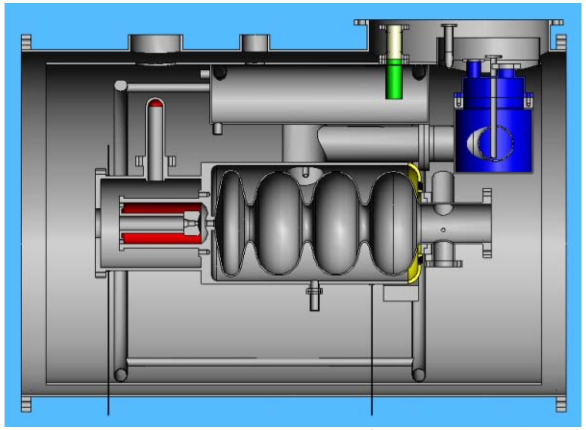


Courtesy of Dietmar Janssen

f =1.3 GHz

Cs_2Te ◄ E_{RF}

IHIP PU (since 2001)



Courtesy of Hao Jiankui

f =1.3 GHz

Cs_2Te ◄ E_{DC}

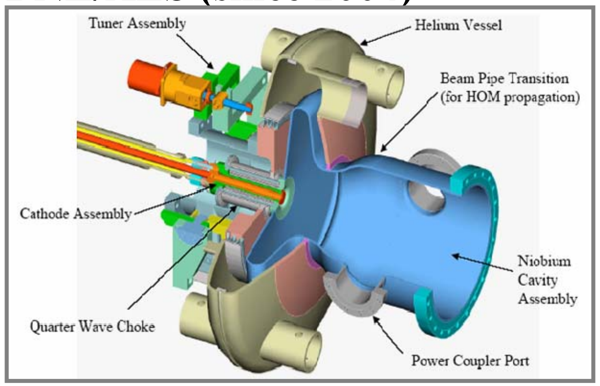
BNL (since 2002)

Courtesy of Triveni Rao

f =1.3 GHz

Nb ◄ E_{RF}

BNL/AES (since 2004)



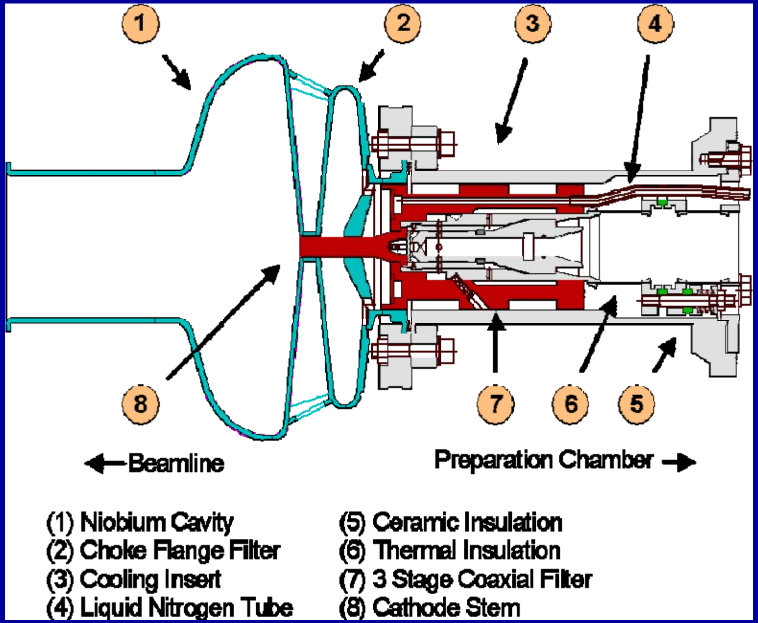
Courtesy of Alan Todd

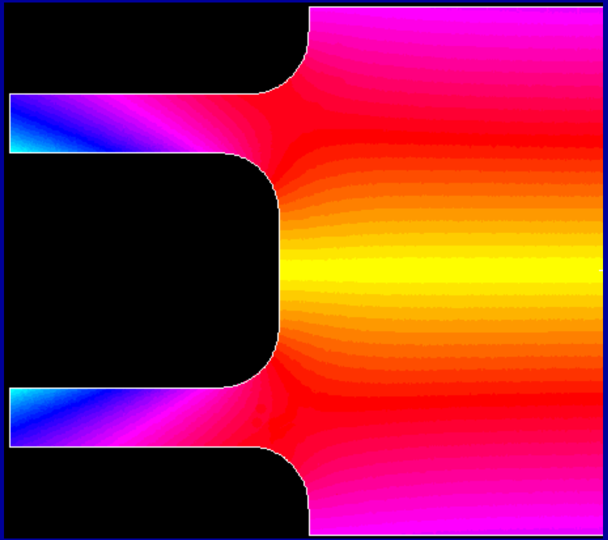
f =703.75 MHz

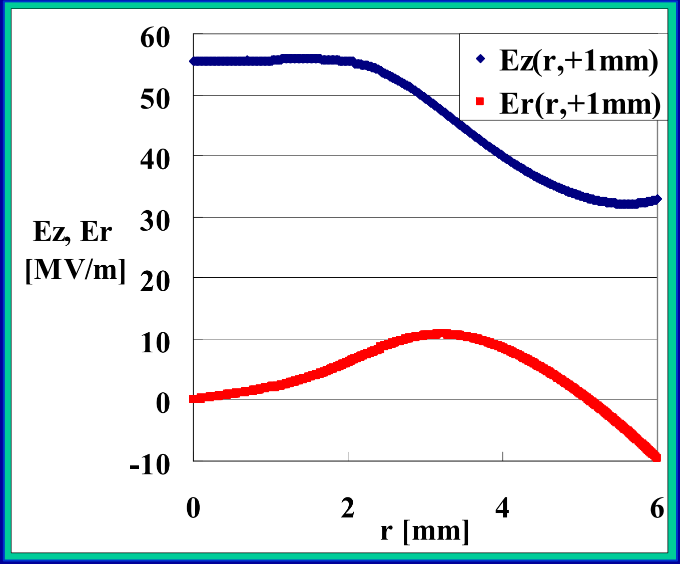
Alkali+ ◆ ◄ E_{RF}

FZR Rossendorf

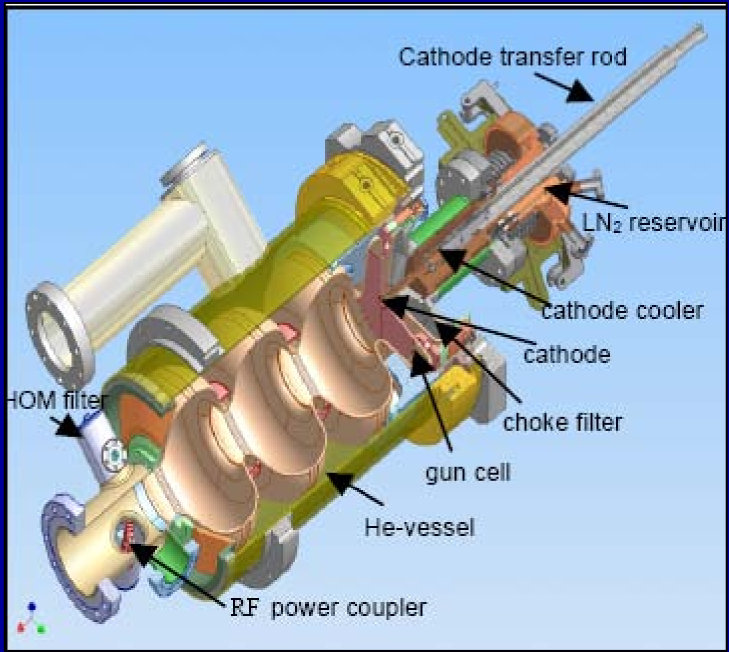
normal-conducting cathode inside SC cavity







pulsed / CW	CW
single bunch charge	1-20 pC
single bunch rep rate	26 MHz
length of bunch train	-
bunch train rep rate	-
average current	≤ 130 μA
norm. trans. emittance (rms)	2.5 mm mrad @ 4 pC, 900 keV



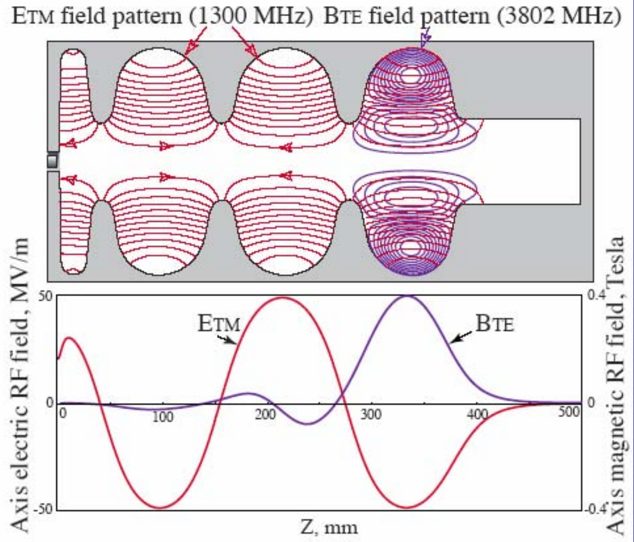
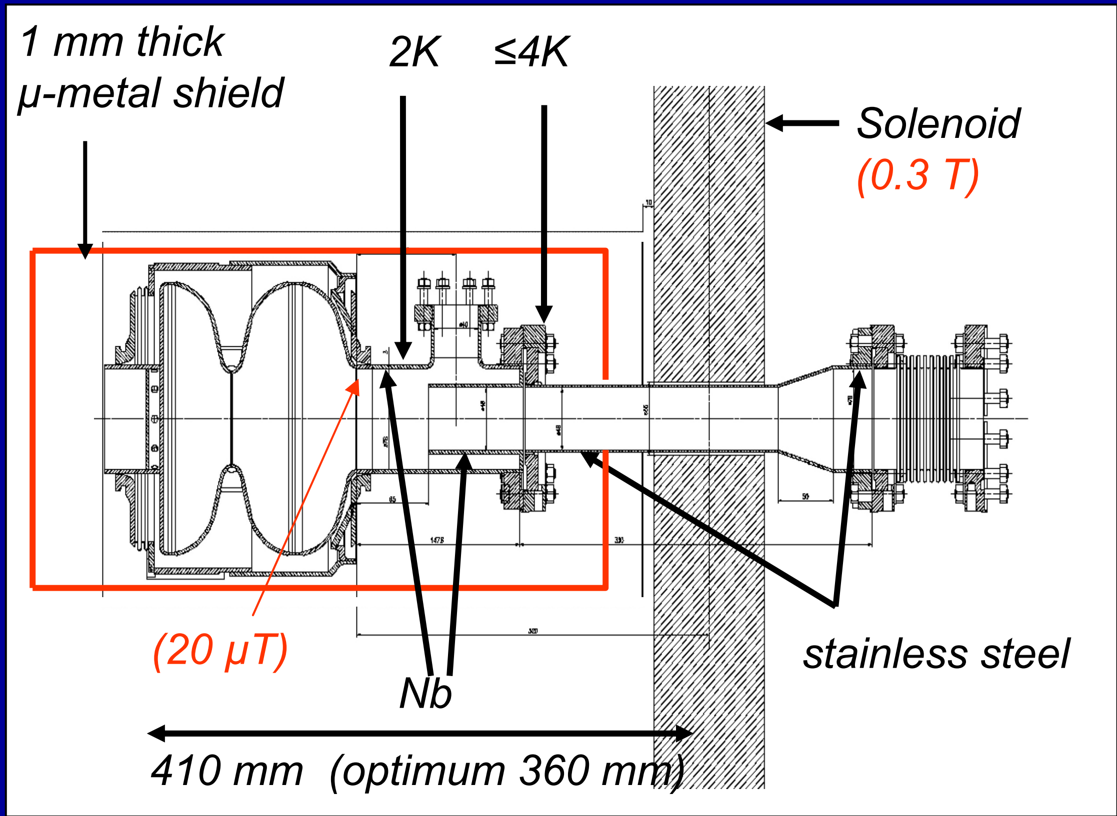


Figure 2: a) RF field pattern of E_{TM010} 1300 MHz and B_{TE021} 3802 MHz. b) Axis fields of the RF modes.(Color picture)

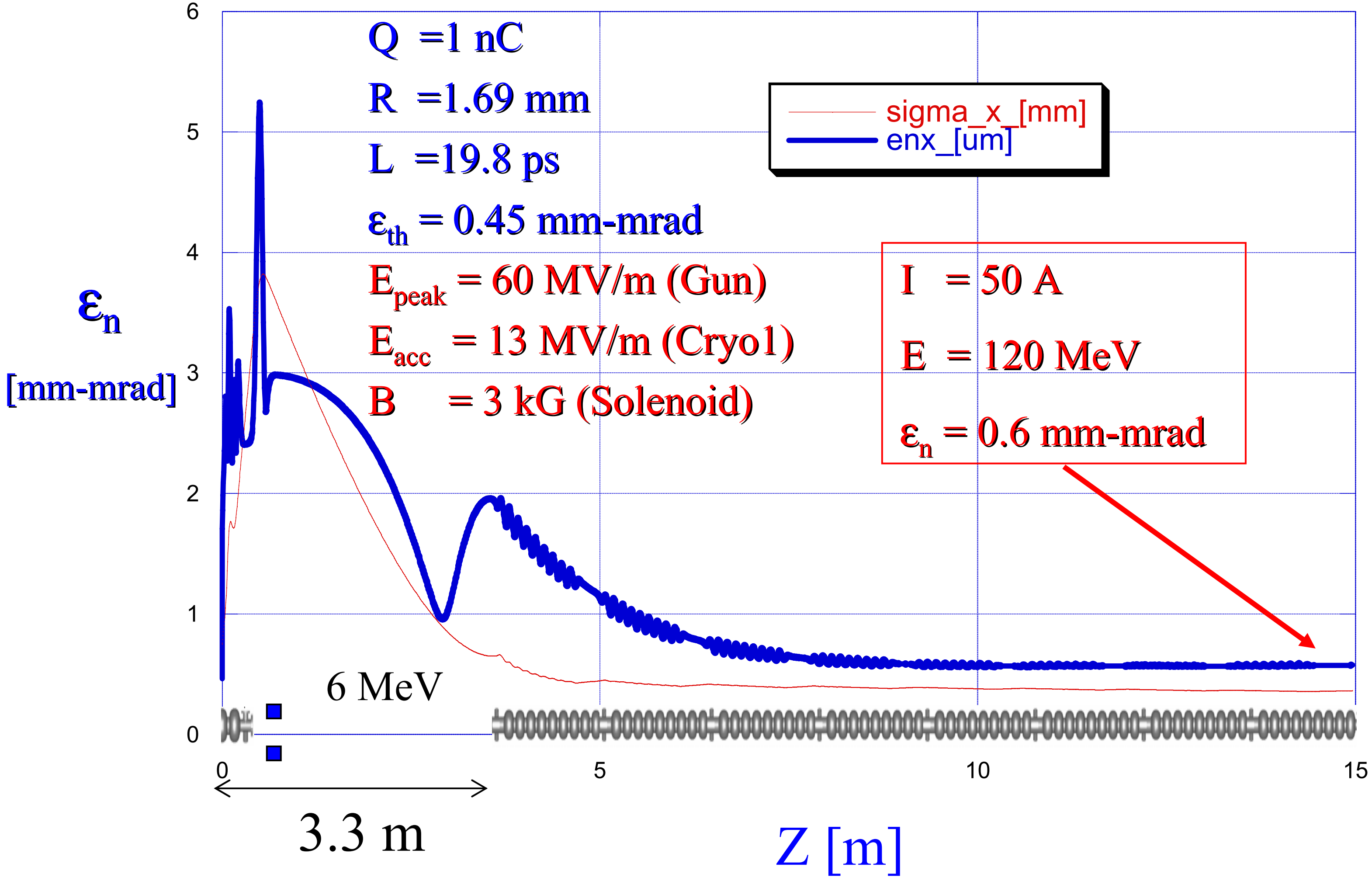
gun type	3.4 cell gun, Goals	
operation mode	ELBE	high charge
pulsed / CW	CW	CW
single bunch charge	77 pC	1 nC
single bunch rep rate	13 MHz	1 MHz
average current	1 mA	1 mA
norm. trans. emittance (rms)	1.5 mm mrad @ 9.5 MeV	2.5 mm mrad @ 9.5 MeV
rf frequency	1.3 GHz	1.3 GHz

Splitting Acceleration and Focusing

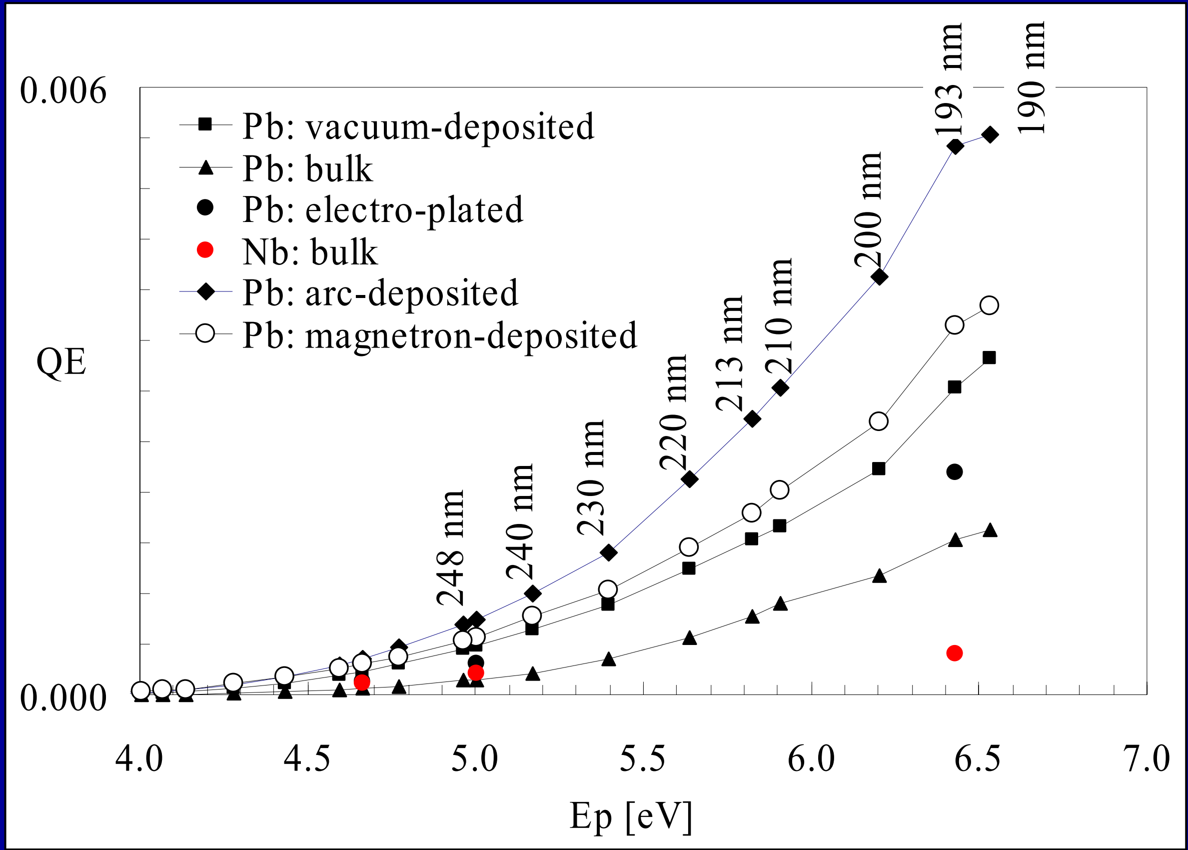


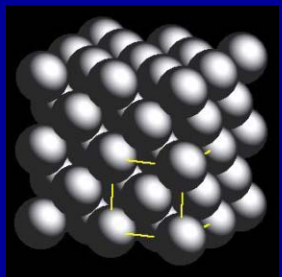
- The Solenoid can be placed downstream the cavity
- Switching on the solenoid when the cavity is cold prevent any trapped magnetic field

HOMDYN Simulation

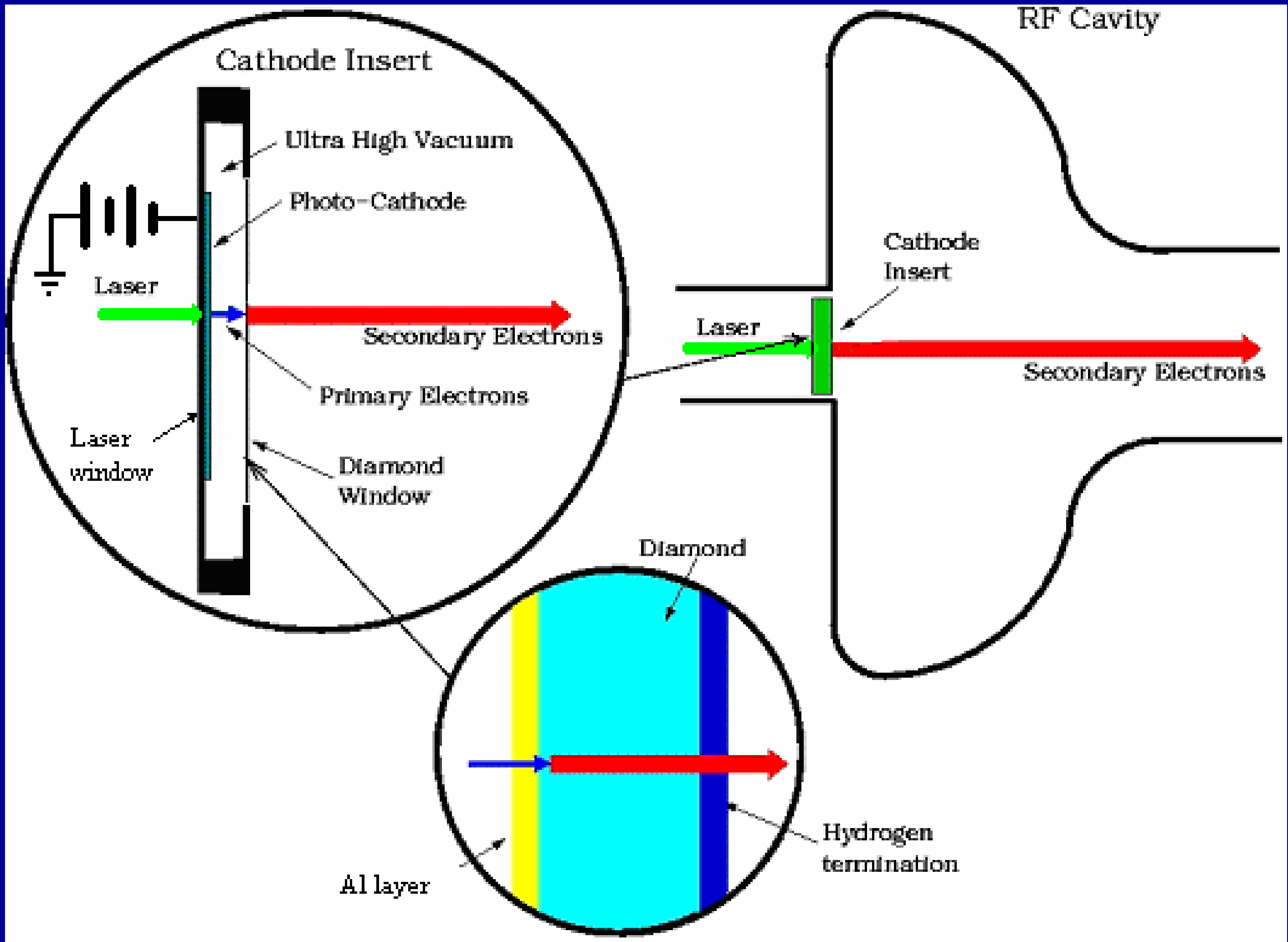


Quantum Efficiency of Lead at 300 K measured @ BNL





Schematic diagram of a secondary emission amplified photoinjector



Conclusions

Lot of ***R&D*** ongoing on *technical issues*: Laser and Cathodes, Advanced Diagnostic, High duty, quasi-CW operations, SC RF gun, higher frequencies ultra-high gradients (X and W-band)

Within next year *more experimental data* will be available on RF compression and pulse manipulation for Ellipsoidal Beam and Blow Out Regime

Progress in plasma inj