10 Femto-seconds Kilo-ampere Electron Beam Generation

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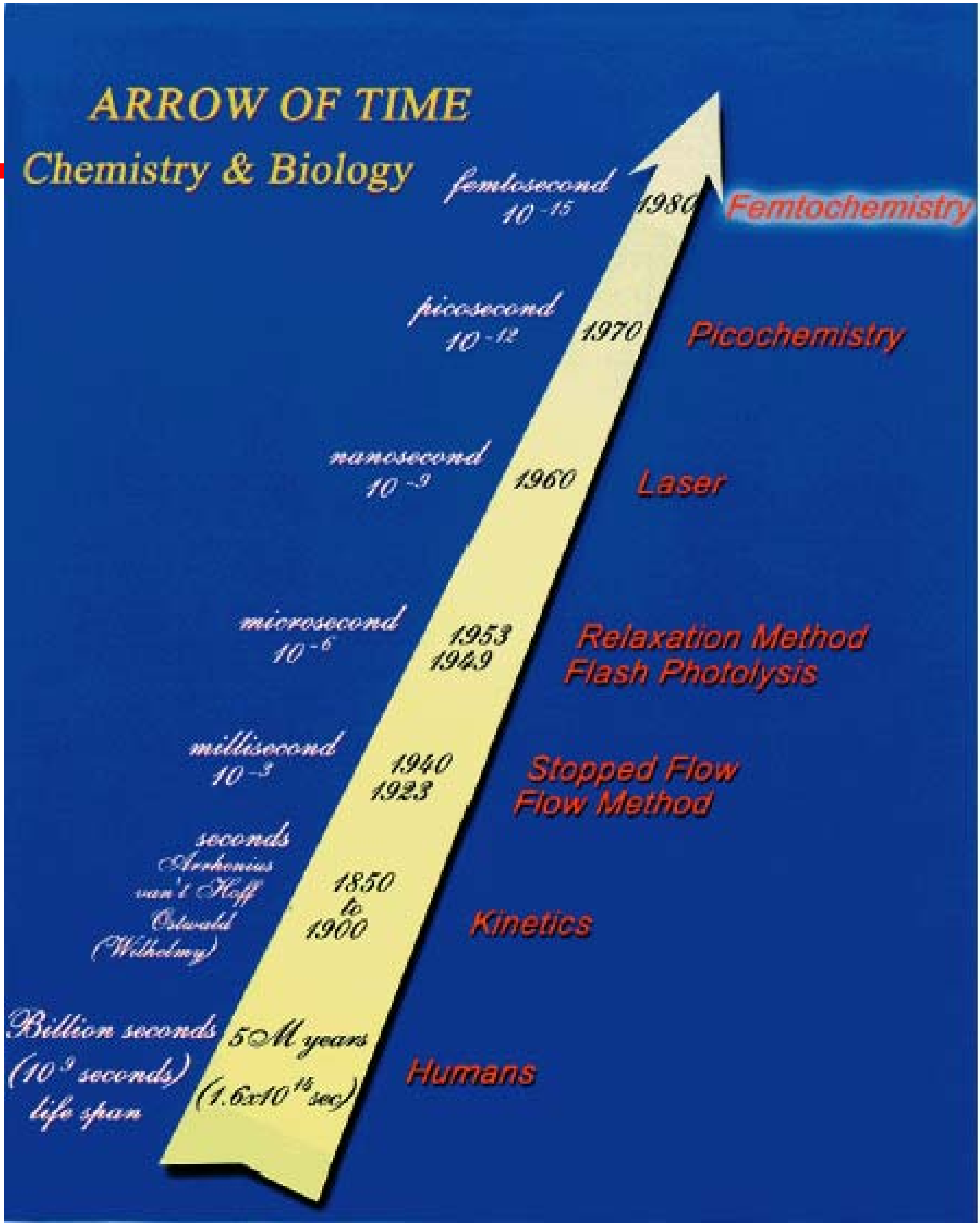
- Introduction:issues in fs beam generations.
- 6-D beam quality optimization in photoinjector - Longitudinal Emittance Compensation.
- Three steps electron bunch compression

  1. **RF gun – quarter wave buncher and Energy chirp (10 ps).**
  2. **Drift space – velocity bunching (ps)**
  3. **Off crest acceleration – femto-second velocity bunching.**

- Initial experimental results: old and new

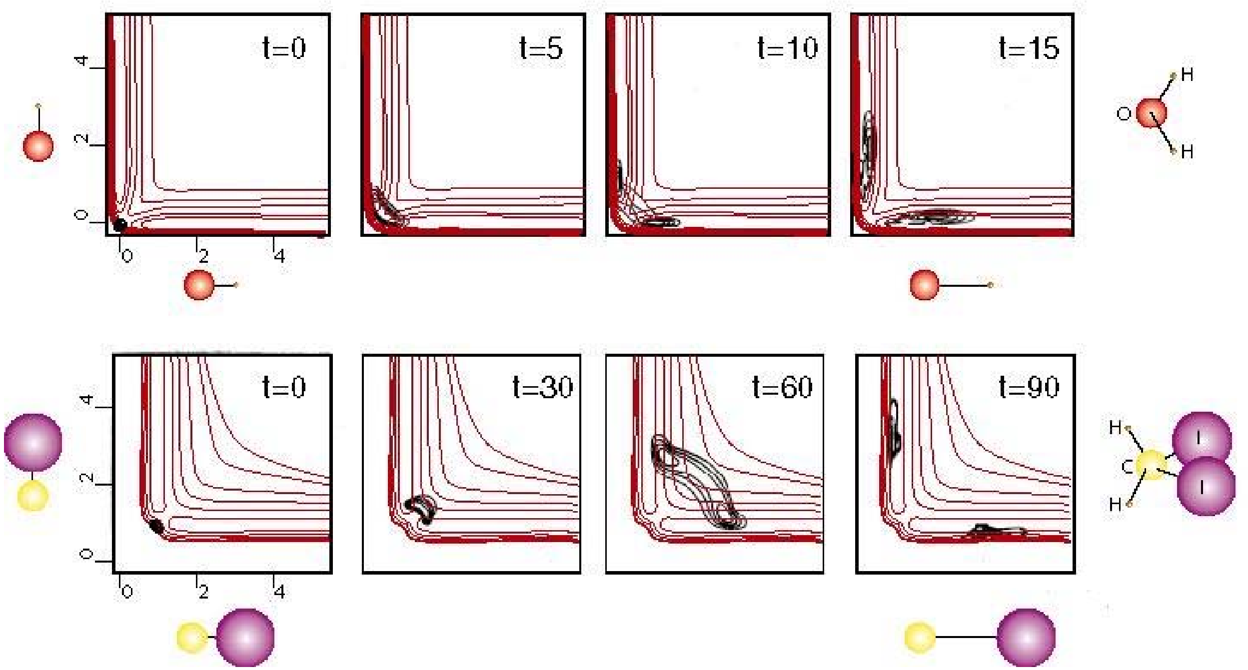
A.H. Zewail


ARROW OF TIME
Chemistry & Biology
femtosecond
10 -15
1980
Femtochemistry
picosecond
10 -12
1970
Picochemistry
nanosecond
10 -9
1960
Laser
microsecond
10 -6
1953
1949
Relaxation Method
Flash Photolysis
millisecond
10 -3
1940
1923
Stopped Flow
Flow Method
seconds
Arrhenius
van't Hoff
Ostwald
(Wilhelmy)
1850
to
1900
Kinetics
Billion seconds
(10 9 seconds)
life span
5 M years
(1.6x10 14 sec)
Humans

Temporal and Spatial Scales

$H_2O \rightarrow OH + H$

$CH_2I_2 \rightarrow CH_2I + I$



LIGHT & FAST

SLOW & HEAVY

$$\tau \approx \hbar / kT \approx 100 \quad fs$$

Time in femtoseconds, distance in Å

from LCLS scientific cases

Space charge effect

$$x''+k\ (s)x-\frac{2r_e N/\ell}{a^2\gamma^3}x=0$$

$$z'=\frac{\delta}{\gamma^2}$$

$$\delta'=\frac{3r_0N}{\gamma^3\beta^2\ell_b{}^3}f(a,b)z$$

Energy is the most effective reduce space charge effect, asymmetry in transverse and longitudinal space charge effect must be kept in mind all time.

Transverse Emittance and Energy Spread Effect on the Short Bunch Production

To generate and preserve the femto-second electron bunch, trnasverse emittance and energy spread are important:

$$\Delta\ell = \frac{L}{2}(x'^2 + y'^2)$$

$$for\ x' = y' = 10\,mrad,\ L = 1\,m,\quad \Delta\ell = 0.1\quad mm = 333\,fs!!$$

$$\Delta\ell = \frac{L}{\gamma^2}\frac{\Delta\gamma}{\gamma}$$

$$for\quad \gamma = 10,\quad \frac{\Delta\gamma}{\gamma} = 1\%,\quad L = 1\,m,\quad \Delta\ell = 333\ fs$$

Transverse Emittance

- Are all emittance uncorrelated?

$$\varepsilon = \sqrt{\varepsilon_{ther} + \varepsilon_{rf} + \varepsilon_{sc}}$$

K-J.'s theory:

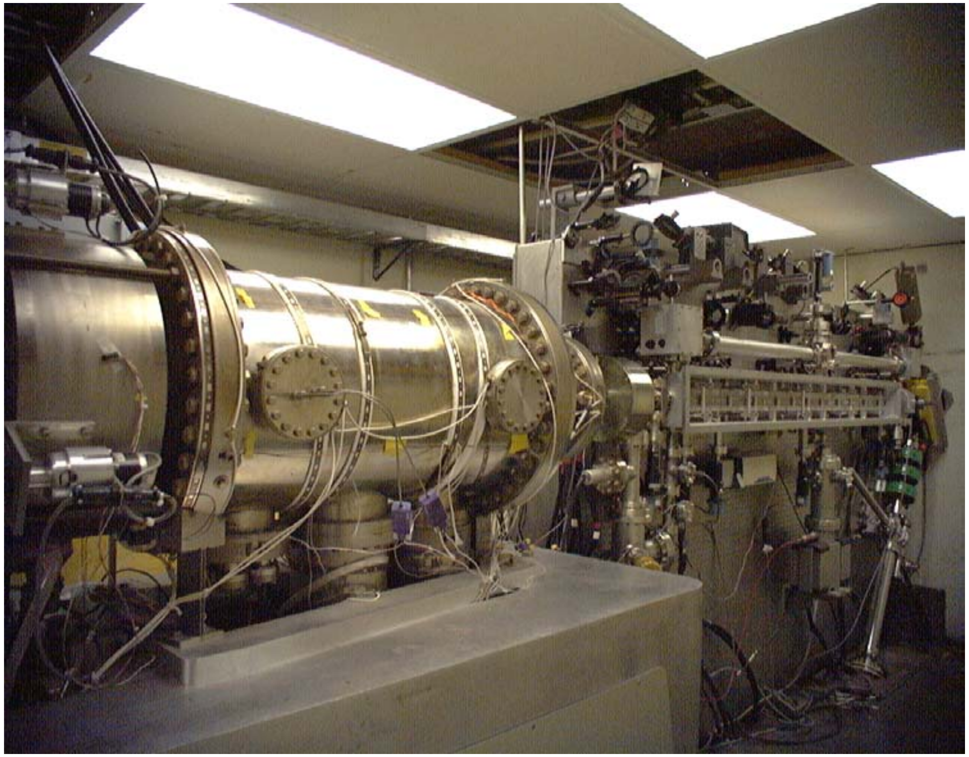
$$\varepsilon_{nx}^{sc} = \frac{\pi}{4}\frac{1}{\alpha k}\frac{1}{\sin\phi_0}\frac{I}{I_A}\mu_x(A)$$

Emittnace growth (Rieser):

$$\frac{\varepsilon_{nf}}{\varepsilon_{ni}} = \left[1 + \frac{N r_c \tilde{x}}{15\sqrt{5}\gamma_0 \varepsilon_{ni}^2}\frac{U}{w_0}\right]^{1/2}$$

The Advanced FEL Photoinjector Operates at 20 MV/m Gradient and 200 mA Average Current

- 1300 MHz
- E_b = 15-20 MeV
- $\bar{I}_{macro}$ = 100-400 mA
- Q = 1-4 nC
- ε_{rms} = 1.6 mm-mrad
- $\Delta\gamma/\gamma$ = 0.2%
- Injection $\phi = 30^o$
- Solenoid = 300A
- Bucking Sol. = 310A



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

Typical operating parameters

** determined in the RF gun with a picosecond Nd:YAG laser **

(1) Laser injection phase in RF gun : 30°

⇒ *for a maximum energy with low emittance*

(2) Linac RF phase : 47°

⇒ *for a minimum energy spread*

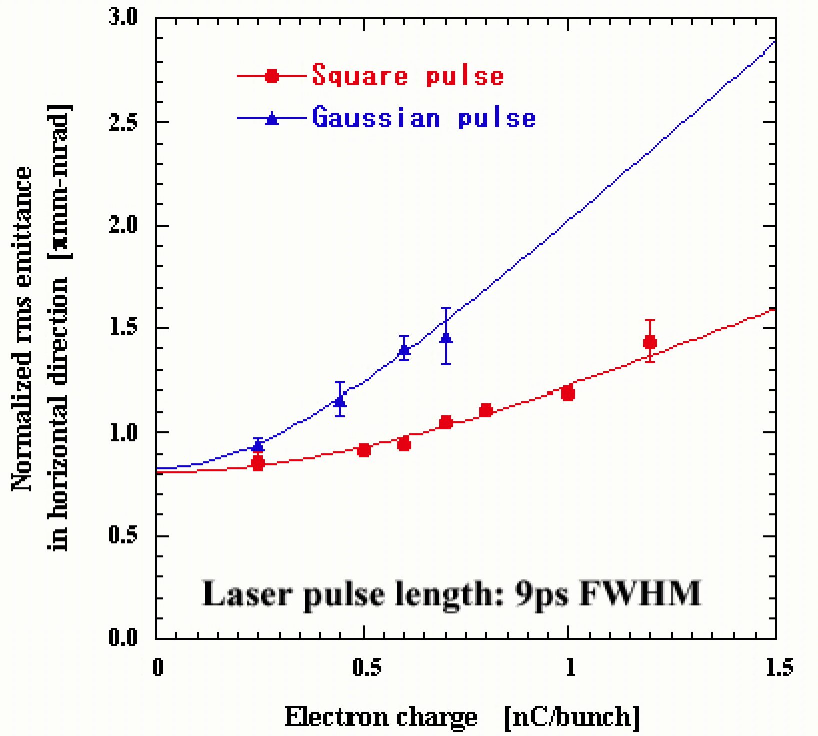
(3) Solenoid magnetic field : 1.57kG

⇒ *For an optimal emittance compensation at 0.6nC, 14MeV*

FESTA

Sumitomo Heavy Industries, Ltd.

Emittance measurements for gaussian and square laser pulse shapes



$$\varepsilon_n = \sqrt{(a'\cdot Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	πmm-mrad/nC	πmm-mrad
Gaussian(9ps)	1.85±0.13	0.83±0.05
Square (9ps)	0.92±0.05	0.81±0.03

The reduction of the linear space-charge emittance for the square pulse shape:
~50%.

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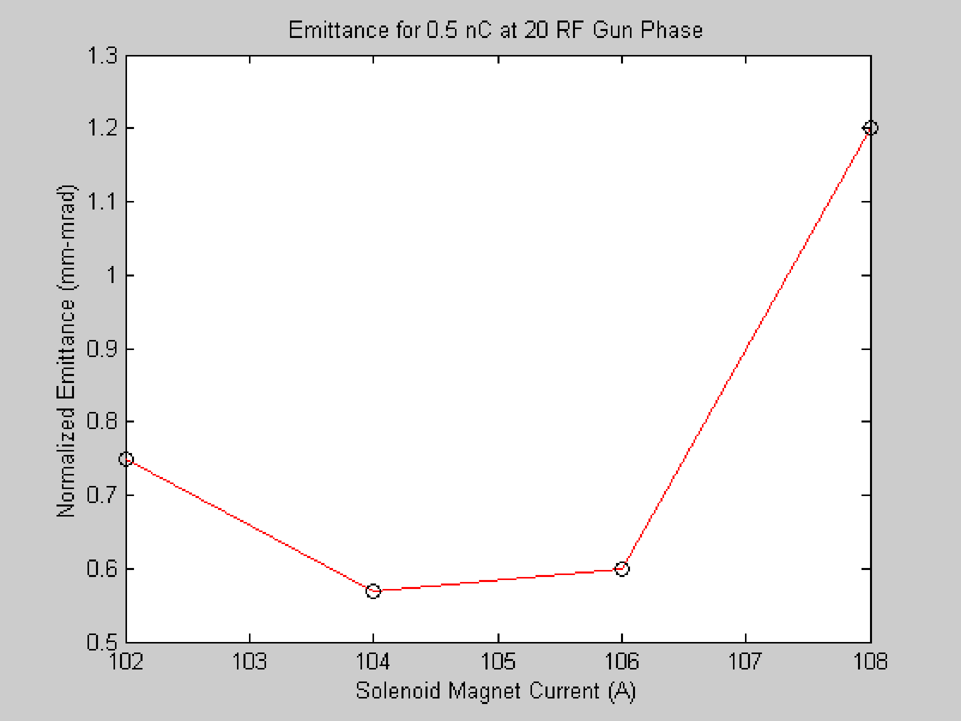
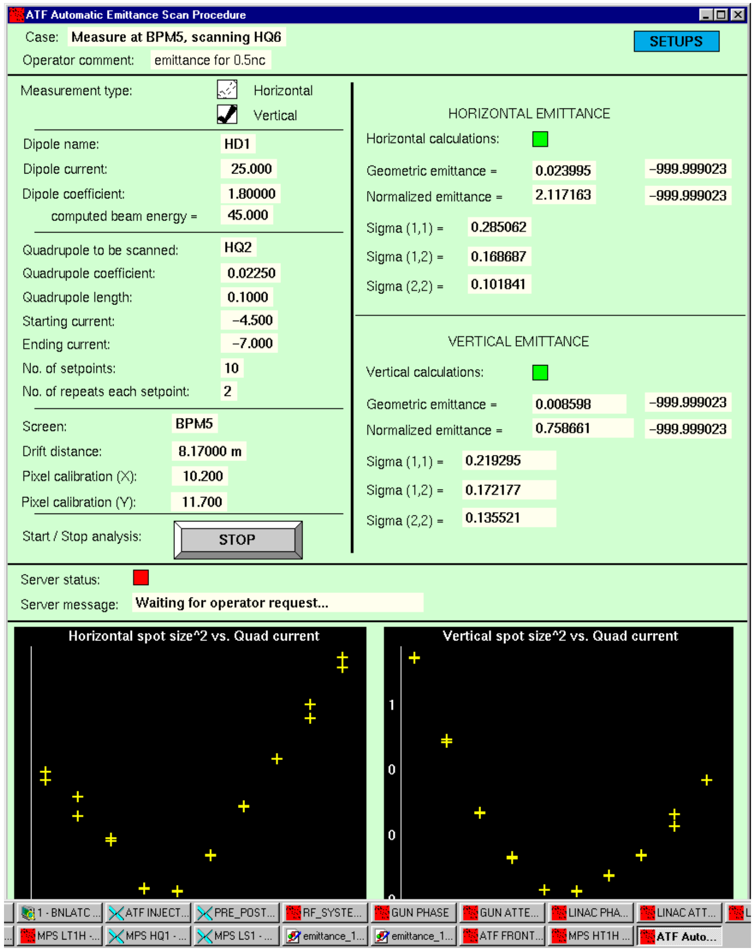
FEL 2002, ANL, Chicago

Emittance Optimization at the BNL ATF





Case: Measure at BPM5, scanning HQ6
Operator comment: emittance for 0.5nc

Measurement type: ☐ Horizontal ☑ Vertical

Dipole name: HD1
Dipole current: 25.000
Dipole coefficient: 1.80000
computed beam energy = 45.000

Quadrupole to be scanned: HQ2
Quadrupole coefficient: 0.02250
Quadrupole length: 0.1000
Starting current: −4.500
Ending current: −7.000
No. of setpoints: 10
No. of repeats each setpoint: 2

Screen: BPM5
Drift distance: 8.17000 m
Pixel calibration (X): 10.200
Pixel calibration (Y): 11.700

Start / Stop analysis: STOP

HORIZONTAL EMITTANCE

Horizontal calculations: 🟩
Geometric emittance = 0.023995 −999.999023
Normalized emittance = 2.117163 −999.999023
Sigma (1,1) = 0.285062
Sigma (1,2) = 0.168687
Sigma (2,2) = 0.101841

VERTICAL EMITTANCE

Vertical calculations: 🟩
Geometric emittance = 0.008598 −999.999023
Normalized emittance = 0.758661 −999.999023
Sigma (1,1) = 0.219295
Sigma (1,2) = 0.172177
Sigma (2,2) = 0.135521

Server status: 🟥
Server message: Waiting for operator request...

Thermal Emittance

Electrons are emitted with a kinetic energy E_k

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

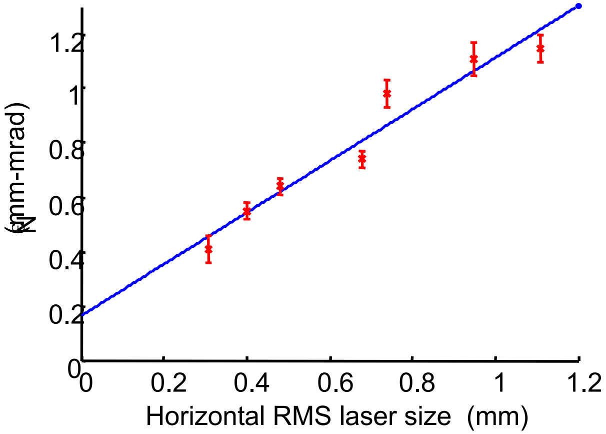
laser spot assumed uniform with radius r

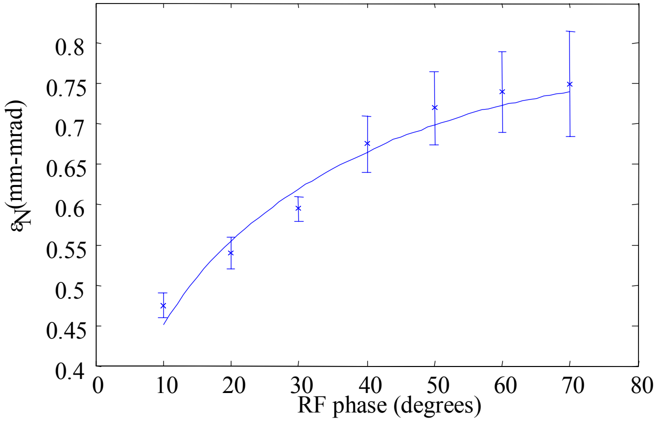
$$E_k = h\nu - \Delta + \alpha\sqrt{\beta_{RF} E_{RF} \sin\theta_{RF}}$$

$$\Delta = \Phi \text{ , or } E_G + E_A$$

Example of measurement for Cu-cathode

(Courtesy of W. Graves)

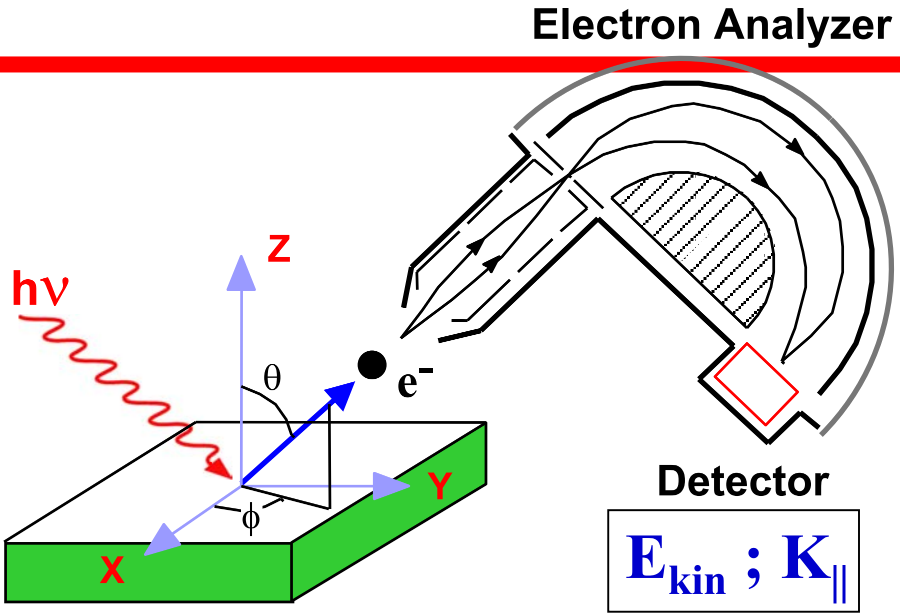


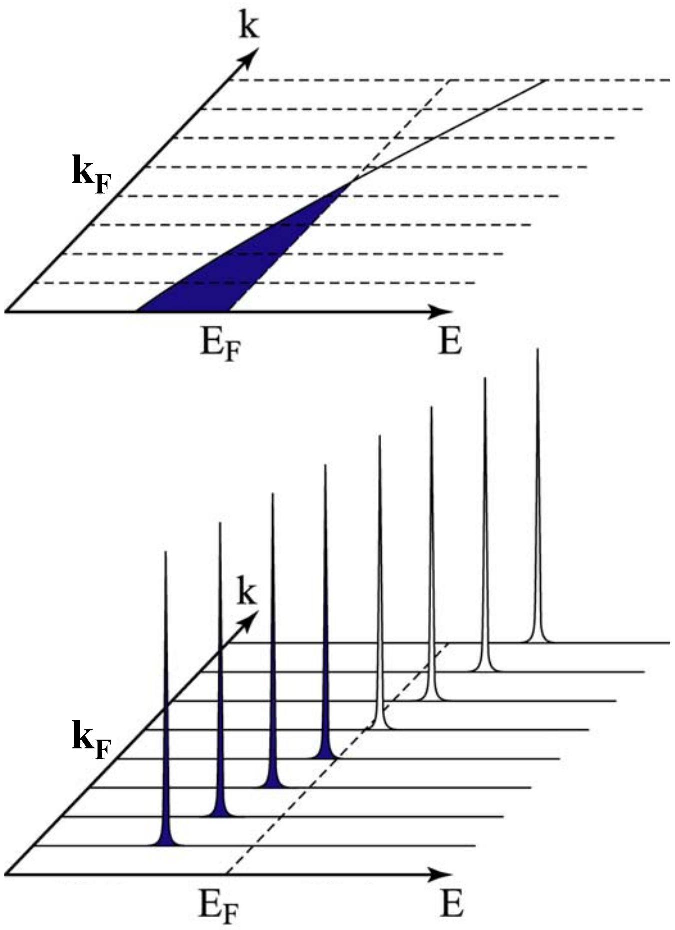


Linear fit gives E_k=0.43 eV

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

Angle-Resolved Photoemission Spectroscopy





Energy Conservation

$$E_B = h\nu - E_{kin} - \Phi$$

Momentum Conservation

$$K_{||} = k_{||} + G_{||}$$

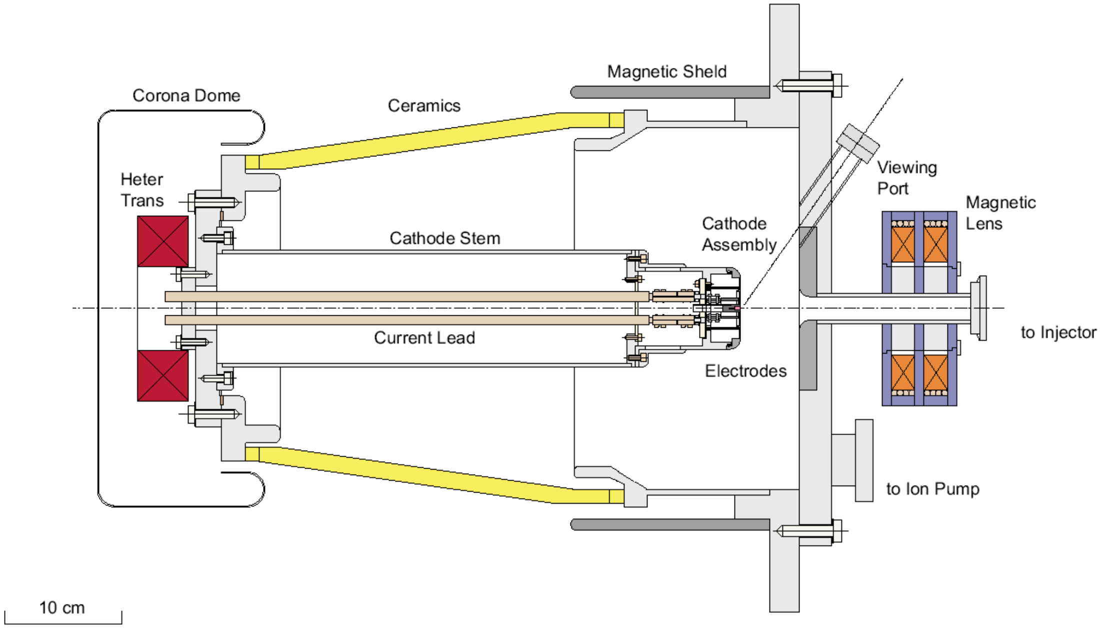
Femto-seconds Electron Beam Production

- Femto-seconds pulse train using IFEL and SASE FEL.
- Single pulse femto-second pulse production:

A) Direction Generation – Photoinjector, DC Pulse gun plasma accelerators.

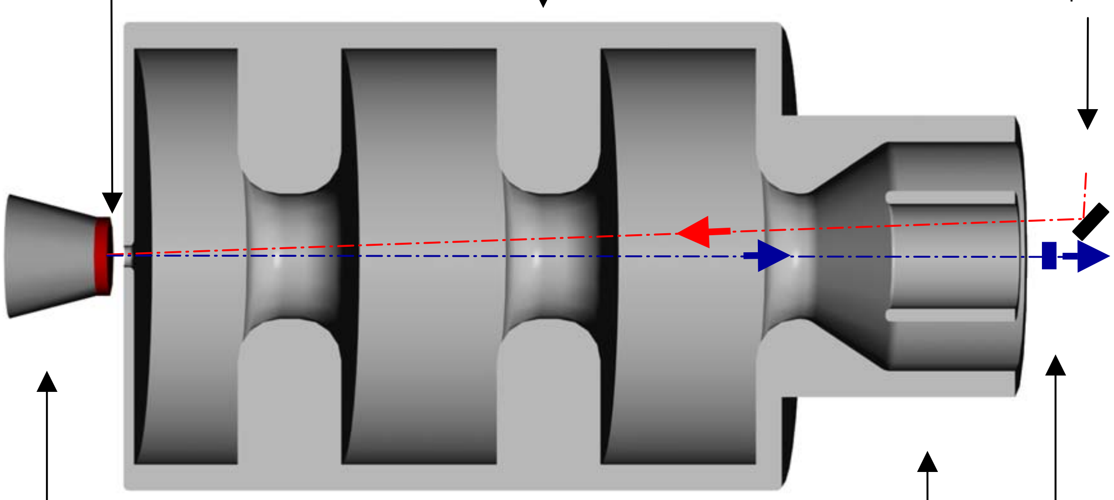
B) Magnetic Compressor – chicane and undulator.

500 kV SCSS electron Gun



DC gun (500 keV, 10 MV/m) to RF gun (5 MeV, 100 MV/m) lead to pulse length from ns to ps, peak current from several Ampere to ≈100 A. Does present technology allows us to produce kilo-ampere, femto-second electron beam directly?

TUE-Pulser



Cu photocathode

3 GHz, 100 MV/m
cavity

Laser pulse
50 fs, 100 μJ,
260 nm

HV pulser
2.5 MV , 1 ns

Coaxial incoupling
10 MW RF

Microbunch
Goal:100 pC, 100 fs,
10 MeV

A Plasma Electron-gun

Lanex film ⟶

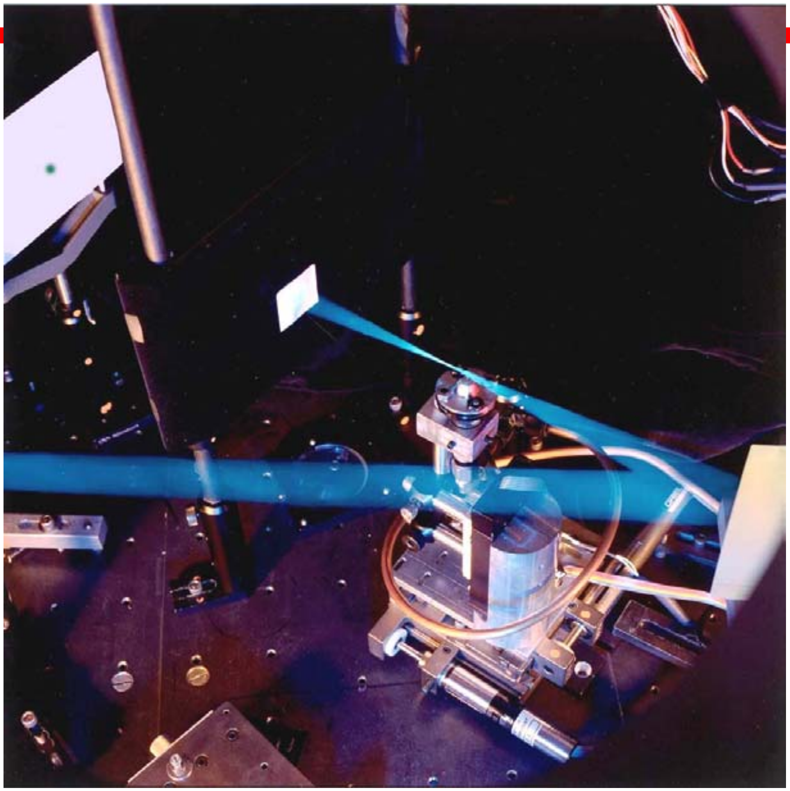
$a_0 = 3.0$

$\tau = 400$ fs

100 MeV/mm

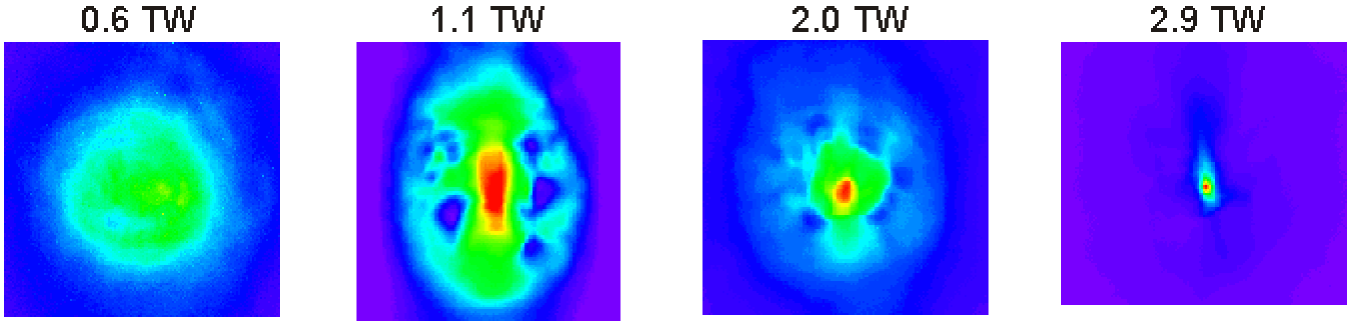
10^{10} e^-/shot

D. Umstadter *et al.*, *Science* **27**3, 472 (1996).
S.-Y. Chen *et al.*, *Phys. of Plasmas*, **7**, 403 (2000).



$I = 10^{19}$ W/cm^2

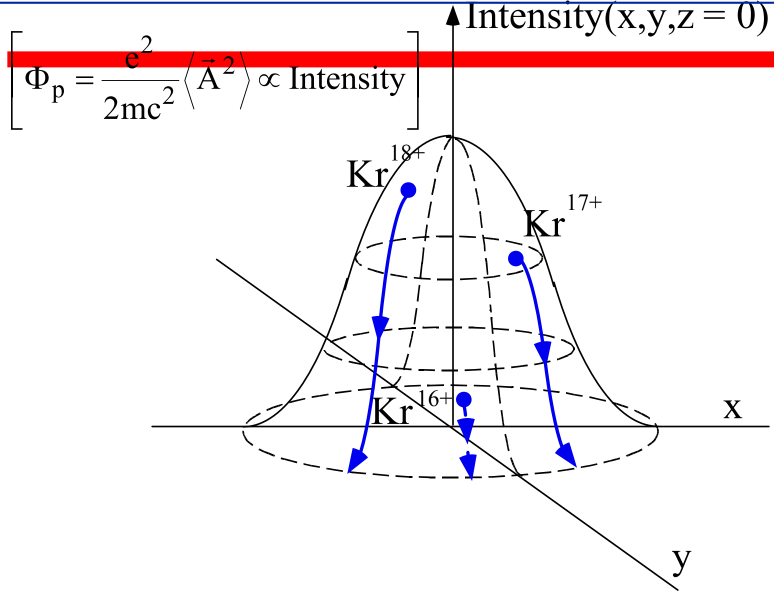
$n = 10^{19}$ cm^{-3}



$\Delta\Theta = 1°$ ←

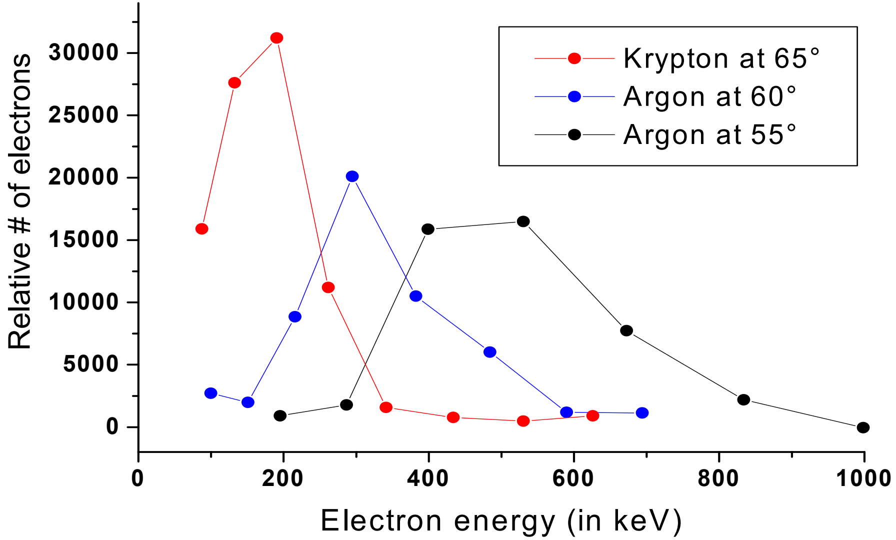
$\varepsilon_t = 0.06\ \pi$ mm mrad

LIPA injector for laser based accelerators



$$\Phi_p = \frac{e^2}{2mc^2}\left\langle \vec{A}^2 \right\rangle \propto \text{Intensity}$$

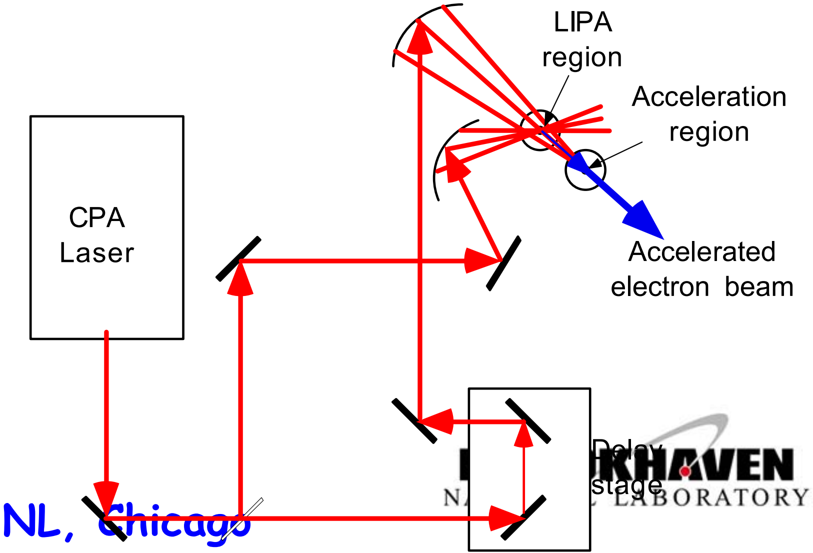
Electron spectra from LIPA injector



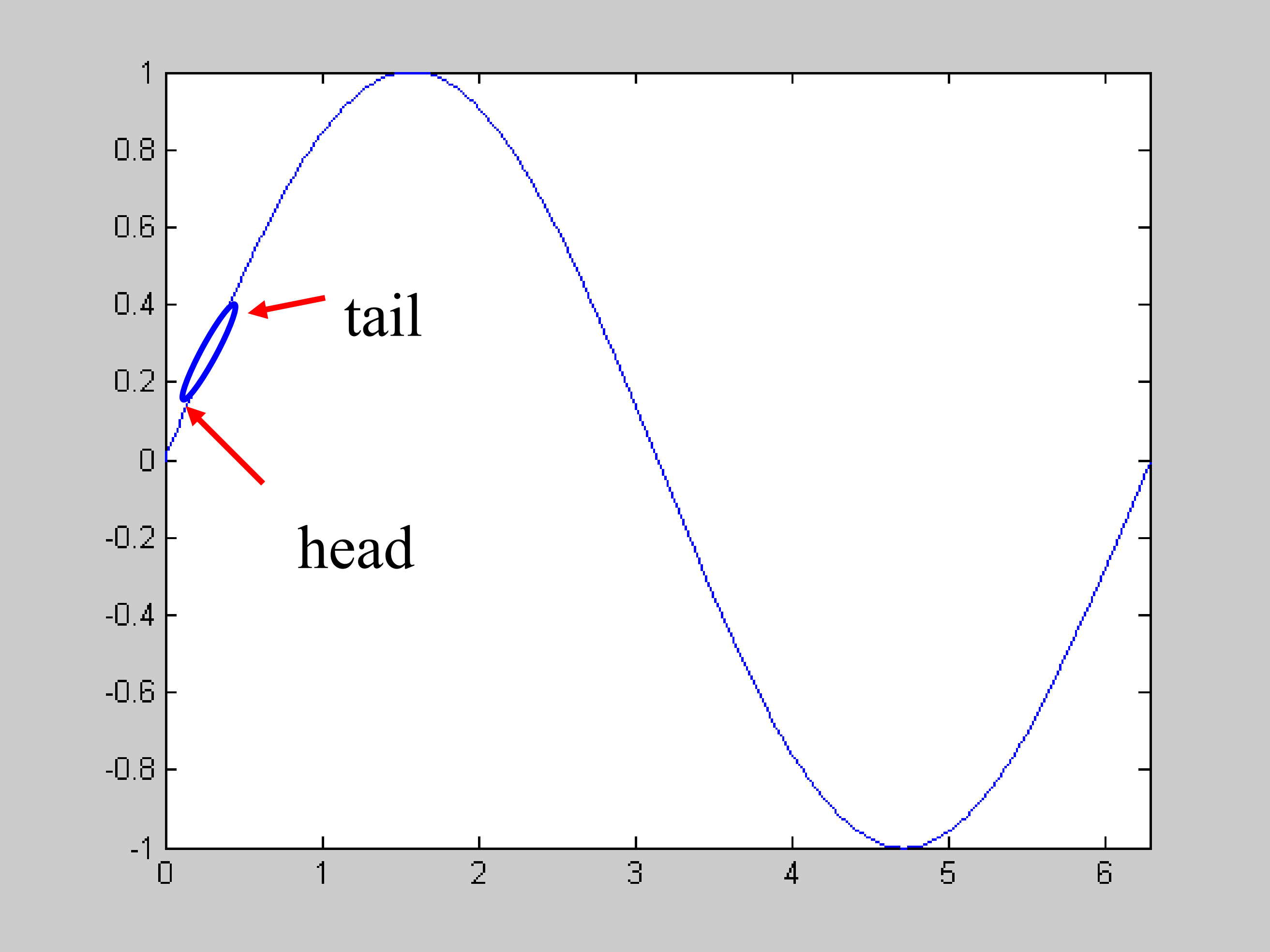
- LIPA -- Laser Ionization and Ponderomotive Acceleration.
- Tightly bound electrons ionize at high laser intensities and acquire large ponderomotive energy.
- LIPA electrons are synchronized for precise injection in laser driven accelerators.
- Energy dependent ejection angles of LIPA electrons allow energy selection.
- LIPA electron pulse is shorter than the ionizing laser pulse.
- Experiment demonstrated $>10^7$ electrons at 500 keV.

C.I. Moore, et al, PRL, 82, 1688 (1999)

LIPA injected electron accelerator

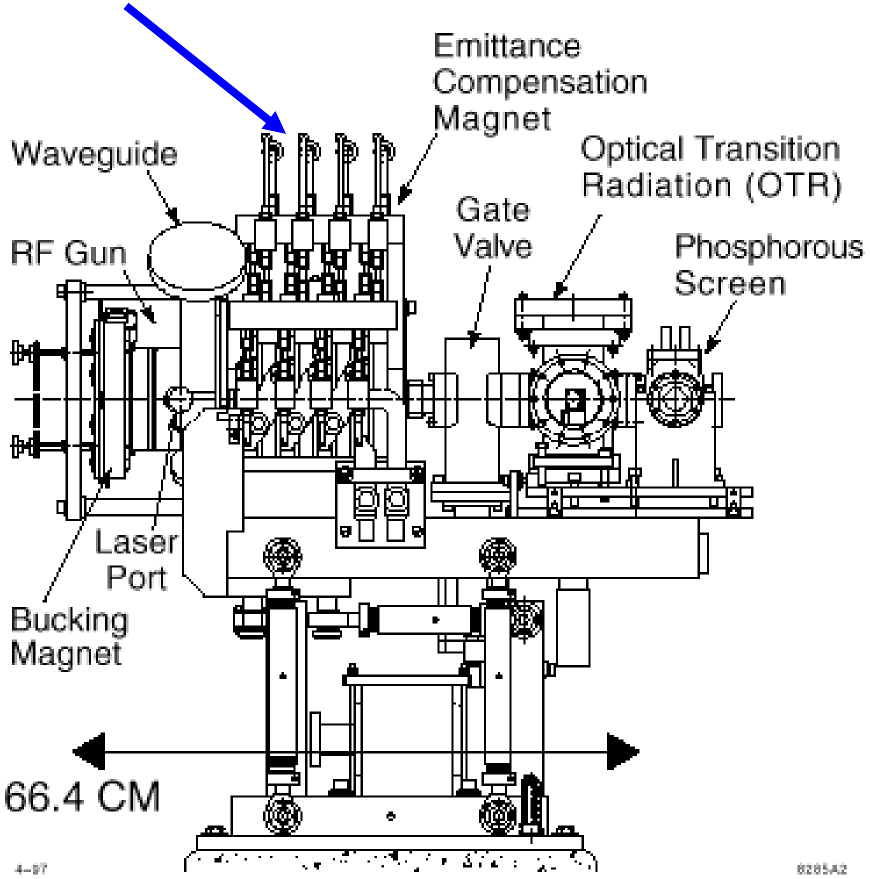


Traveling wave linac as a Buncher



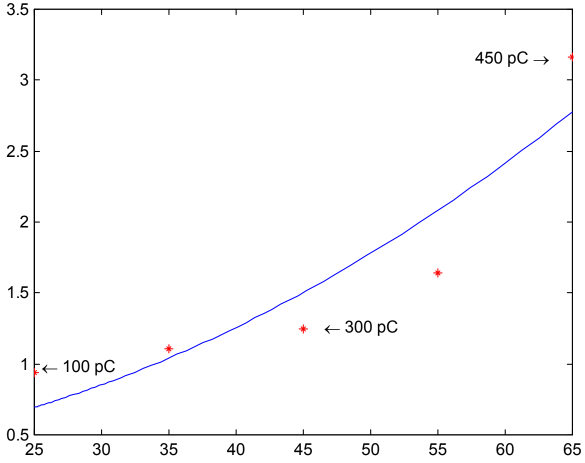
Photocathode RF Gun Injector System

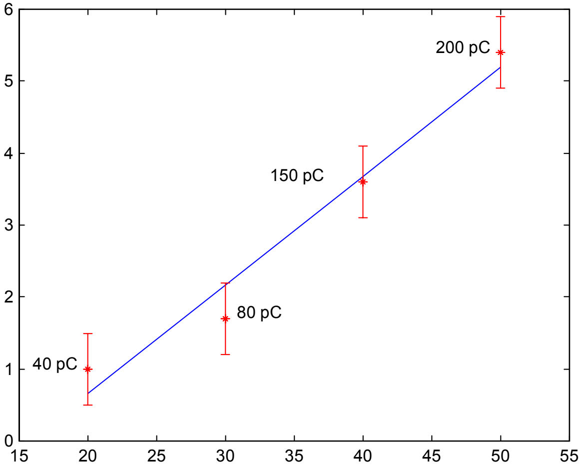
1. RF Gun.
2. Driving Laser system.
3. Solenoid Magnet.
4. Beam diagnostics.
5. RF gun Operating principle.

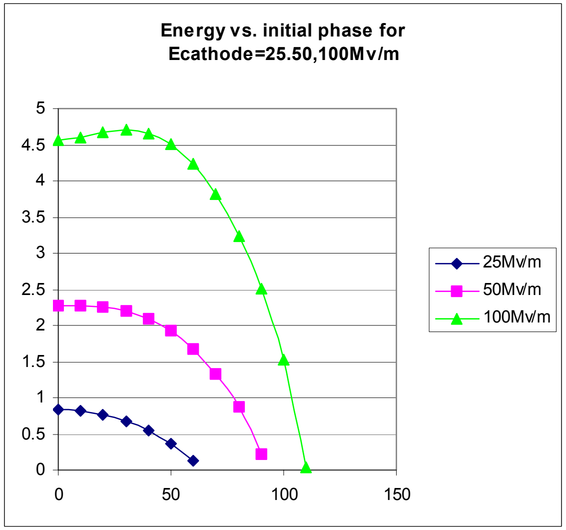


Longitudinal Emittance Compensation

- Space charge.
- Emittance.

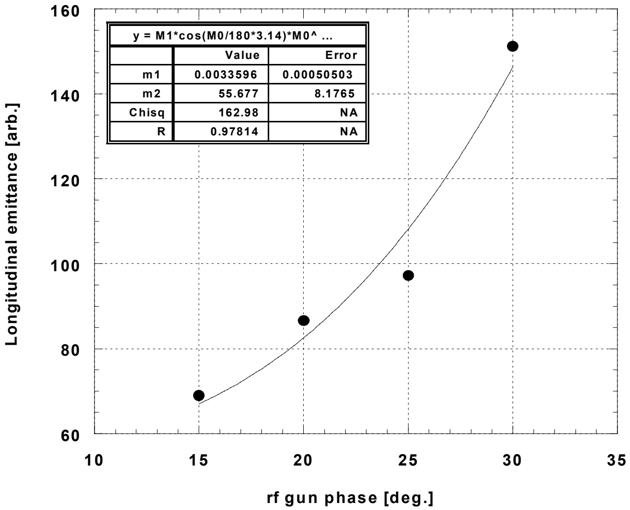




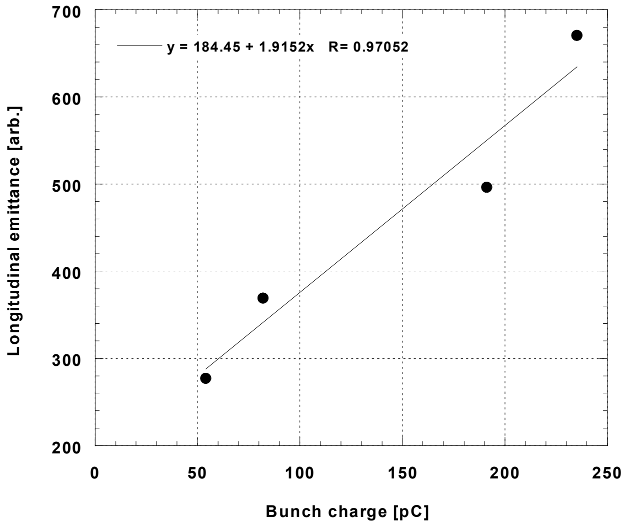


Longitudinal Emittance

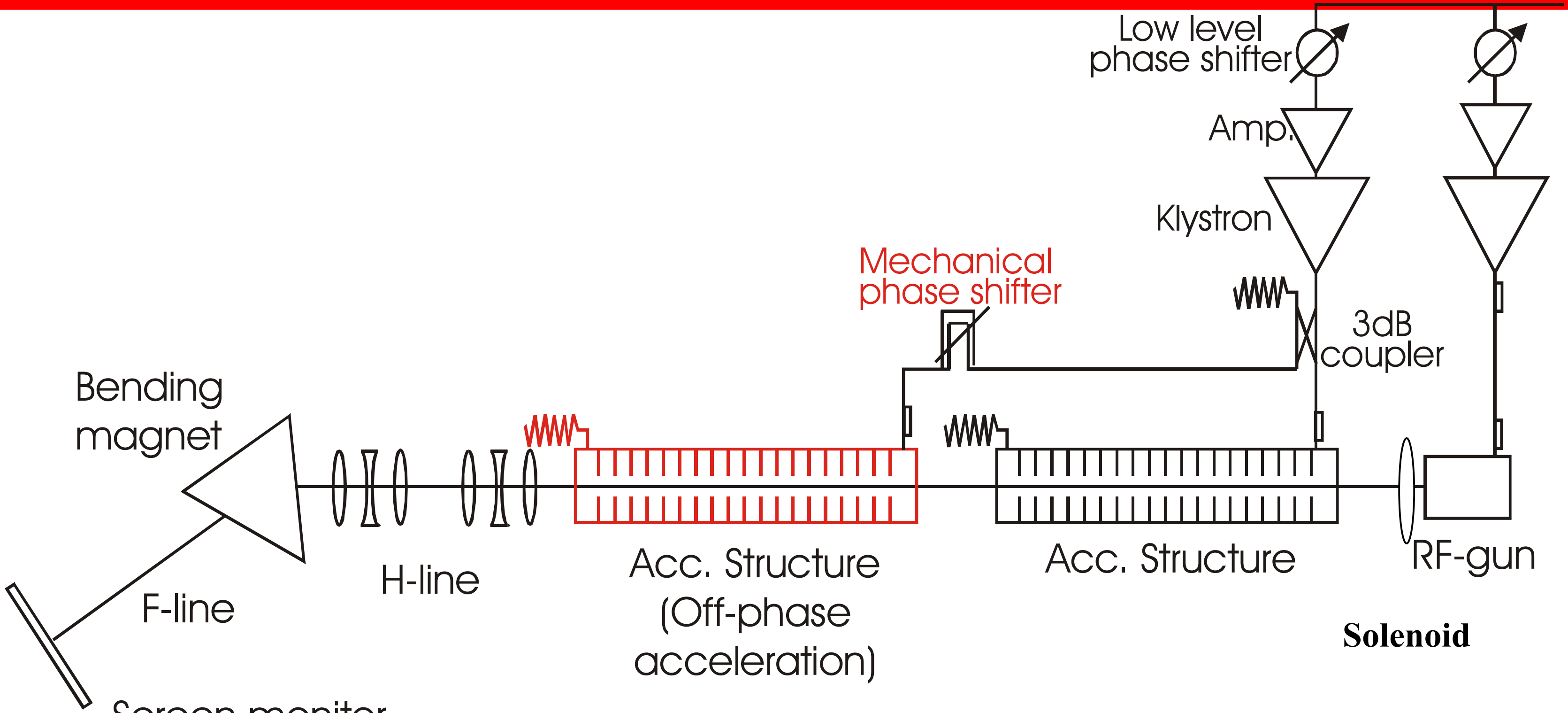
$$\varepsilon_{\phi} \approx \frac{1}{2}\sigma_{\phi}{}^{3}\cos(\phi_0)$$



y = M1*cos(M0/180*3.14)*M0^ ...		
	Value	Error
m1	0.0033596	0.00050503
m2	55.677	8.1765
Chisq	162.98	NA
R	0.97814	NA



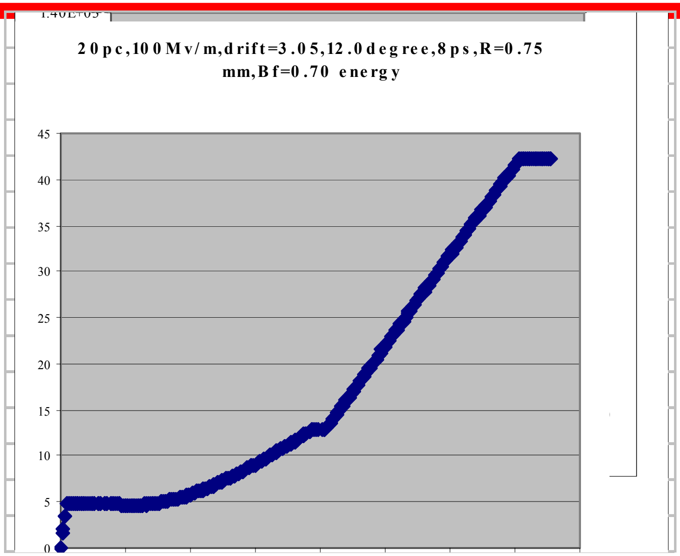
ATF Accelerator System

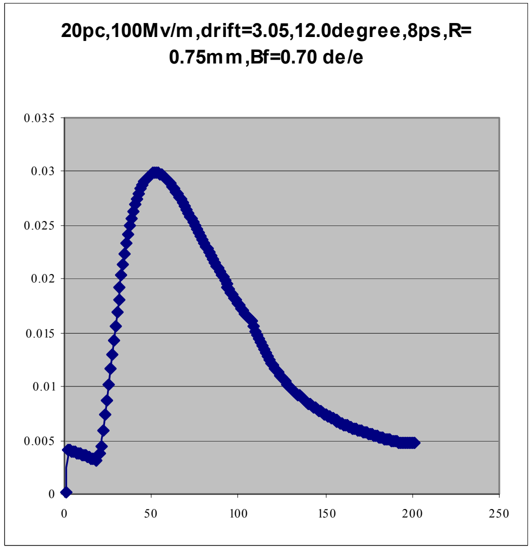


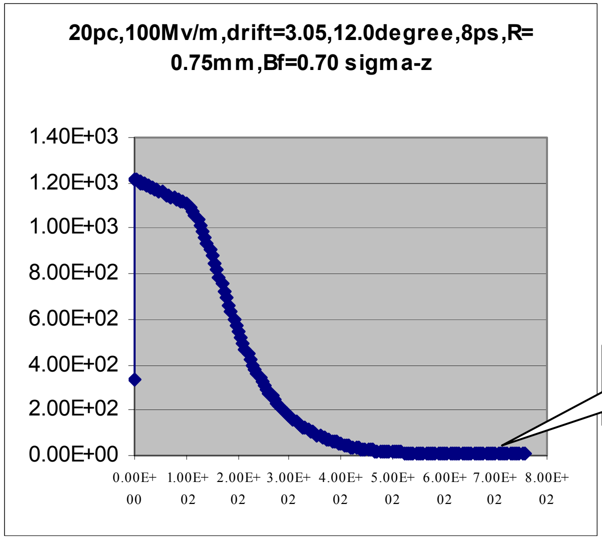
Screen monitor

Solenoid

10 fs kilo-Ampere
Electron beam generation



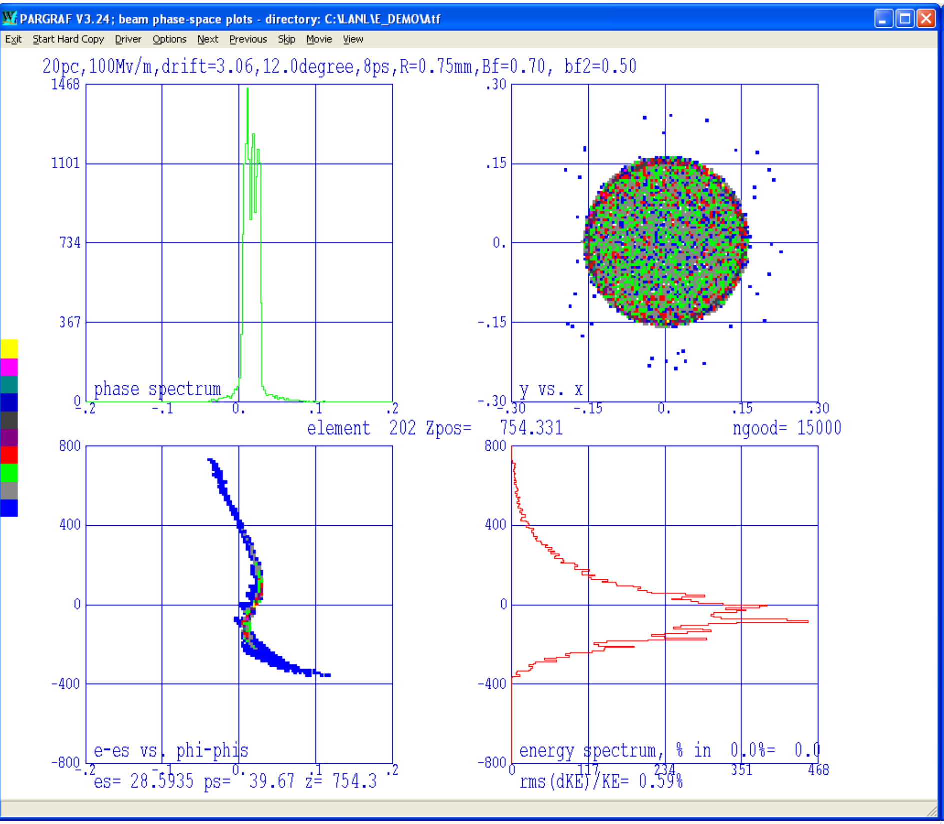




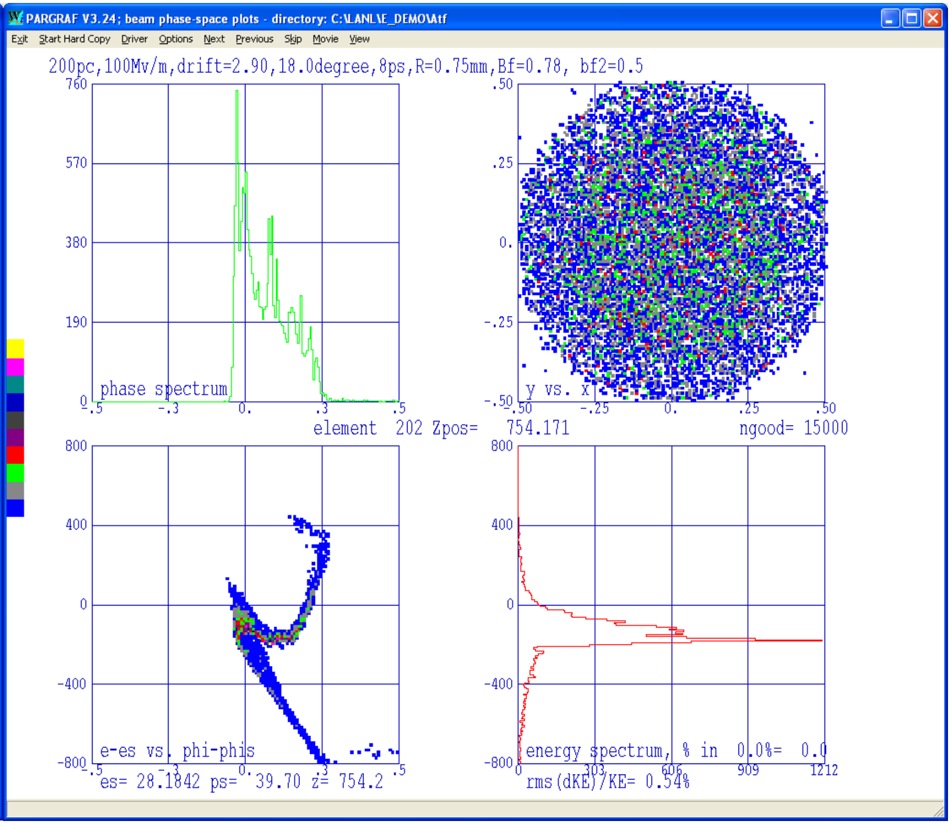
10. 8 fs

10 fs Kilo-Ampere Electron Beam Phase Space distribution

20 pC



200 pC



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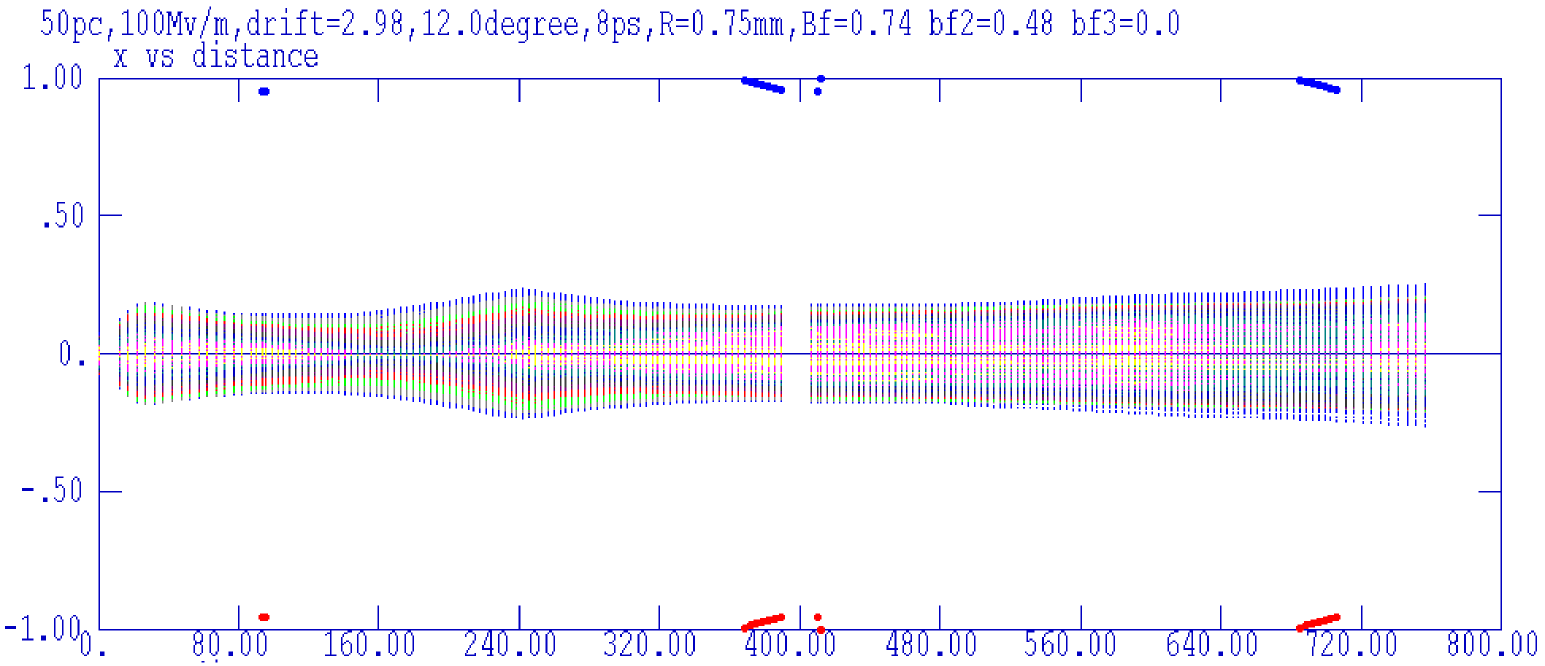
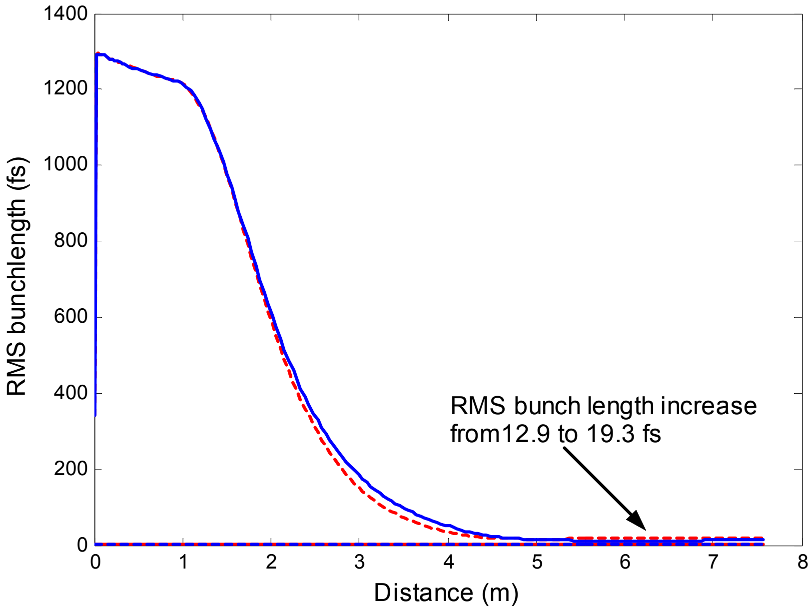
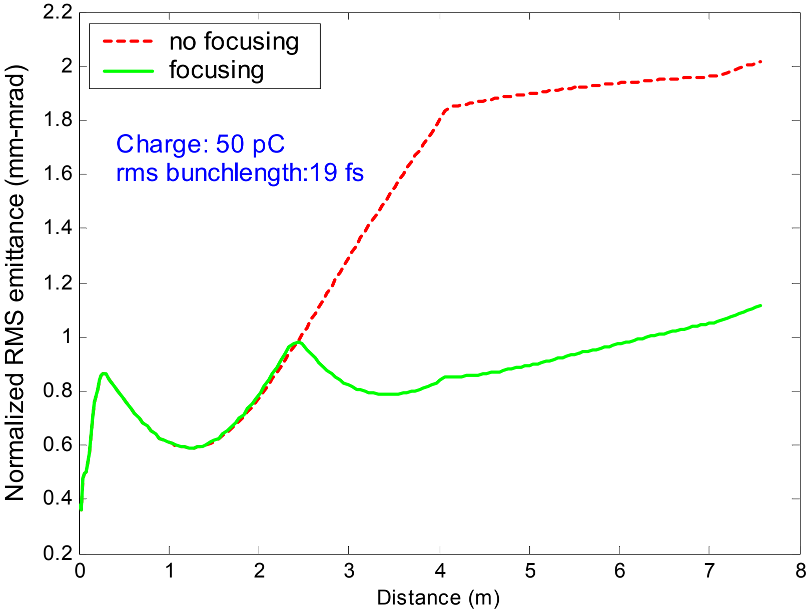

50pc,100Mv/m,drift=2.98,12.0degree,8ps,R=0.75mm,Bf=0.74 bf2=0.48 bf3=0.0
x vs distance
1.00
.50
0.
-.50
-1.00
0.
80.00
160.00
240.00
320.00
400.00
480.00
560.00
640.00
720.00
800.00

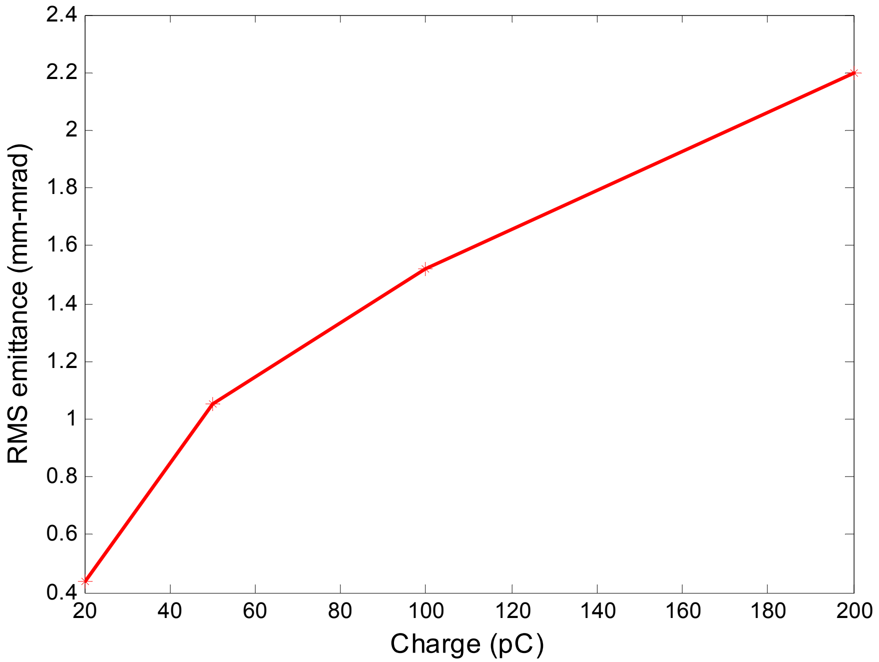


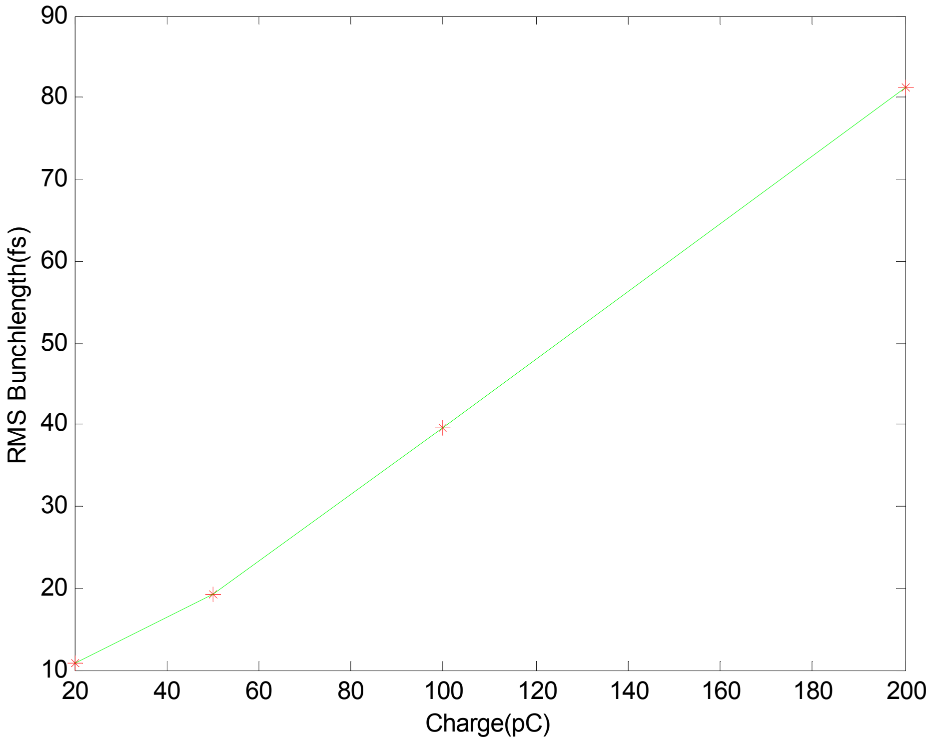
RMS bunch length increase
from12.9 to 19.3 fs



Charge: 50 pC
rms bunchlength:19 fs

Electron Beam Properties as function of the Charge





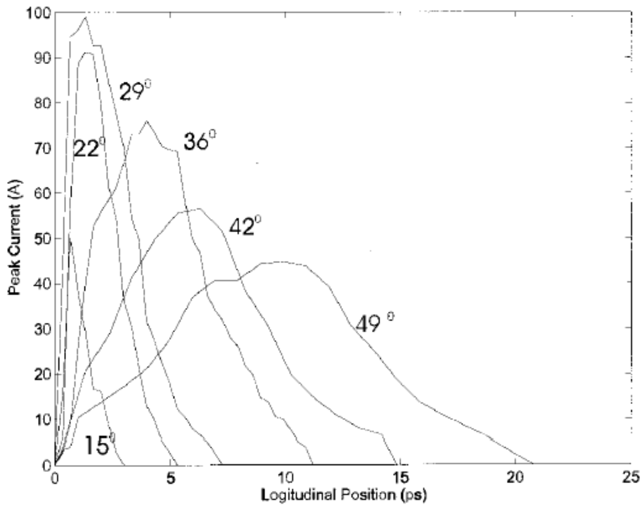
PHYSICAL REVIEW E VOLUME 54, NUMBER 4 OCTOBER 1996

Experimental observation of high-brightness microbunching in a photocathode rf electron gun

X. J. Wang, X. Qiu, and I. Ben-Zvi
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973

(Received 13 February 1996)

We report the measurement of very short, high-brightness bunches of electrons produced in a photocathode rf gun with no magnetic compression. The electron beam bunch length and the charge distribution along the bunch were measured by passing the energy chirped the electron beam through a momentum selection slit while varying the phase of the rf linac. The bunch compression as a function of rf gun phase and electric field at the cathode were investigated. The shortest measured bunch is 370±100 fs (at 95% of the charge) with 2.5×10^8 electrons (170 A peak current); the normalized rms emittance of this beam was measured to be 0.5π mm mrad and the energy spread is 0.15%. [S1063-651X(96)51110-4]



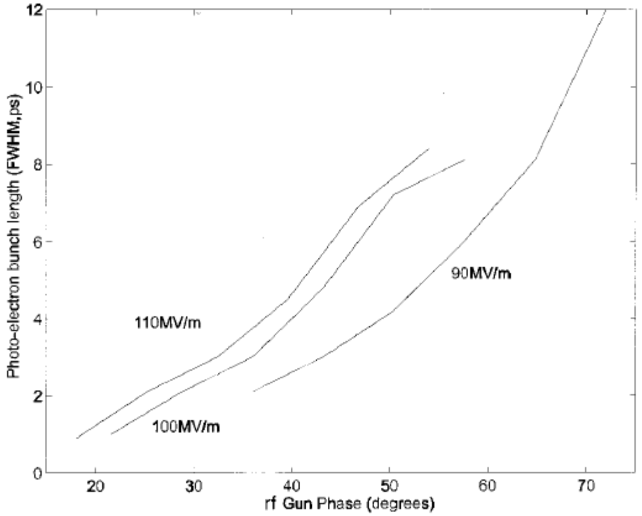
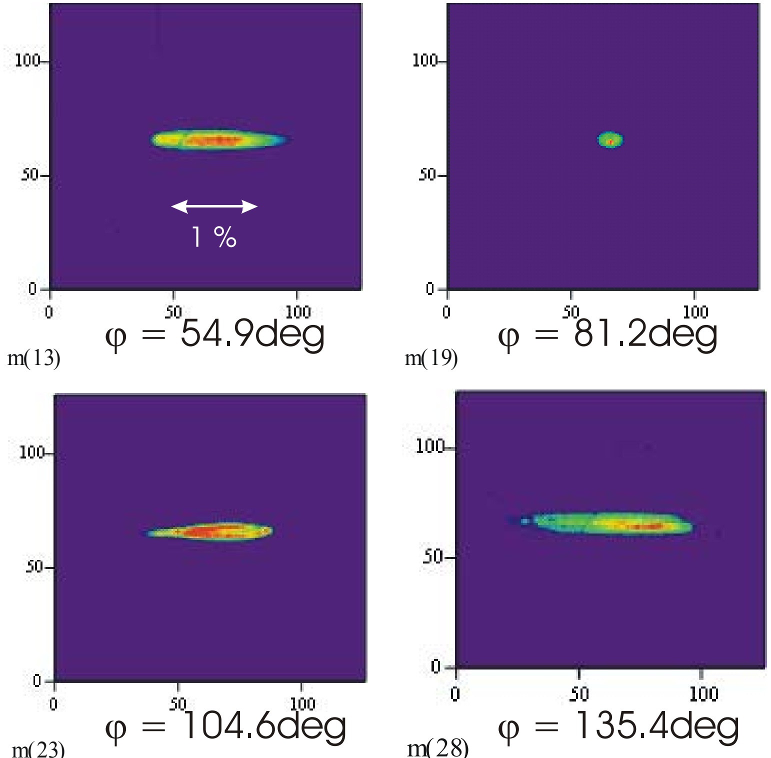
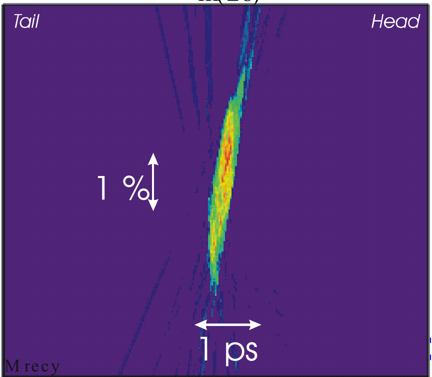
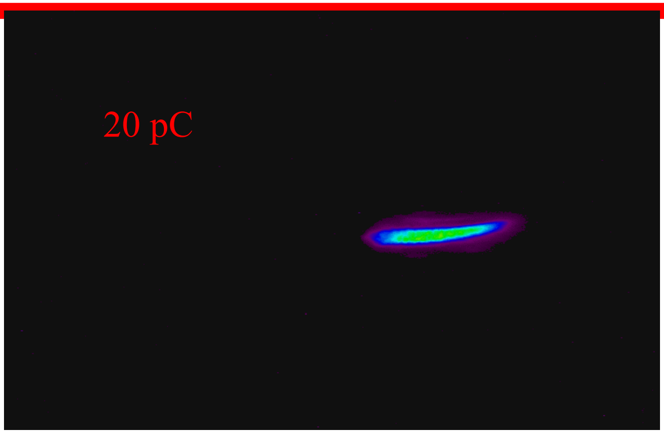


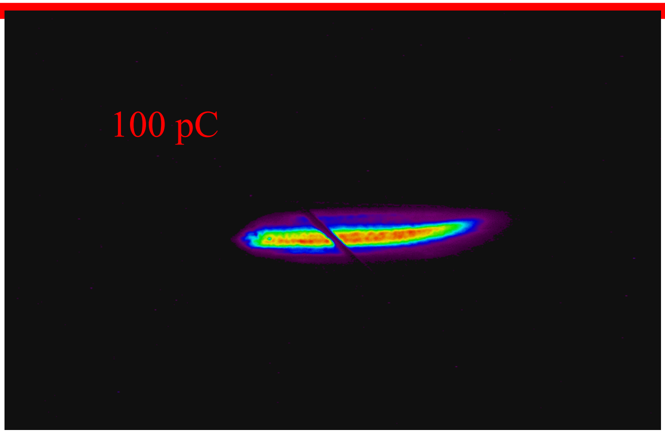
PHOTO-ELECTRON BEAM LONGITUDINAL PHASE SPACE TOMOGRAPHY STUDIES AT THE ATF

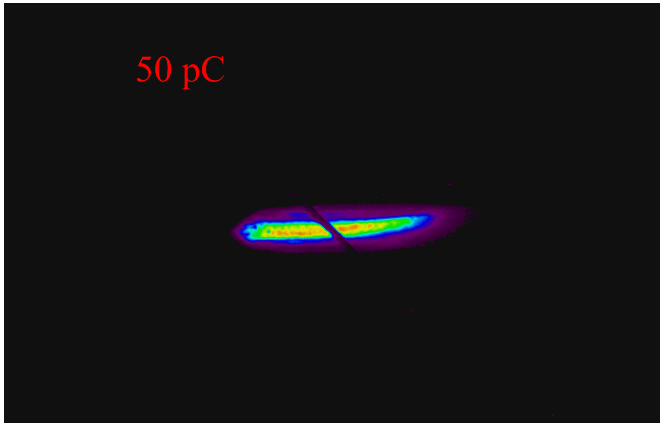
S. Kashiwagi, M. Washio, Waseda University, Tokyo, 169-8555, Japan
X. J. Wang, I. Ben-Zvi, R. Malone, V. Yakimenko, BNL, NY, 11973, USA

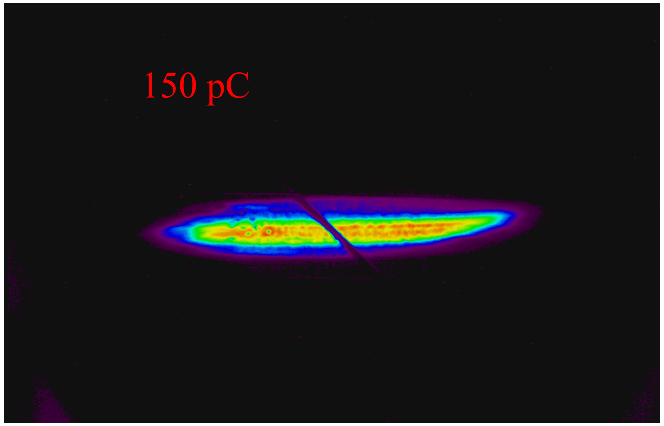




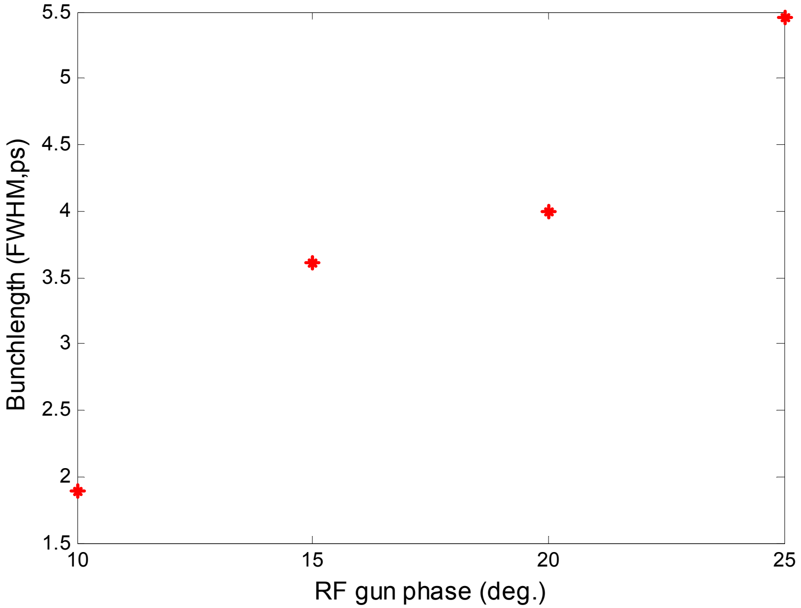

20 pC

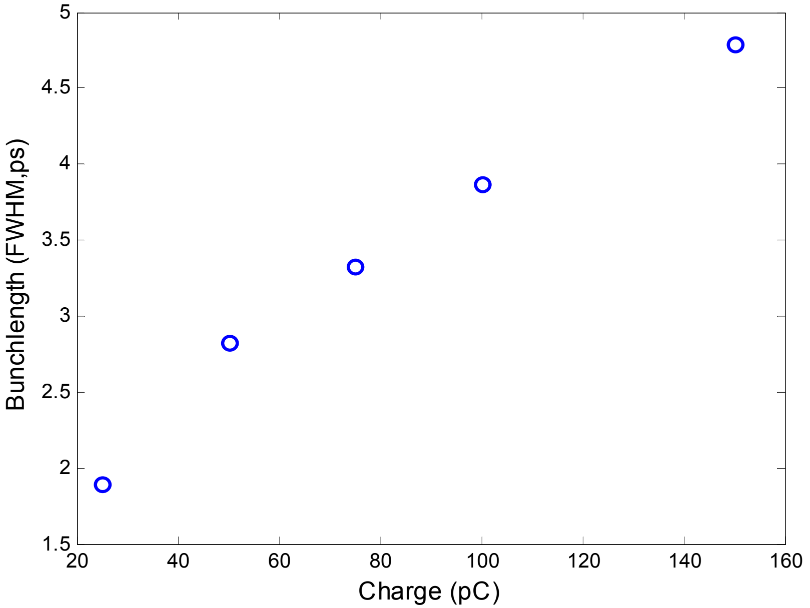

100 pC

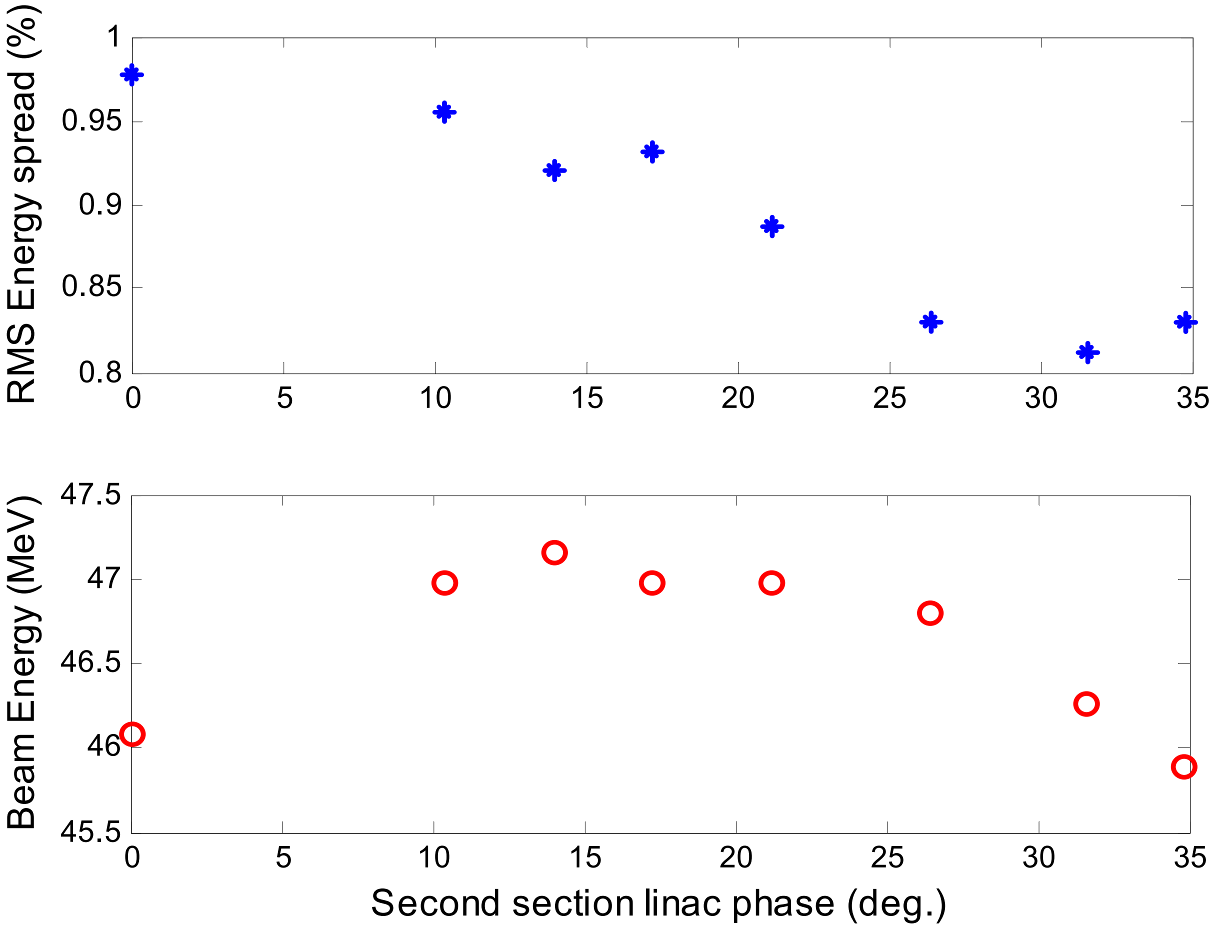

50 pC

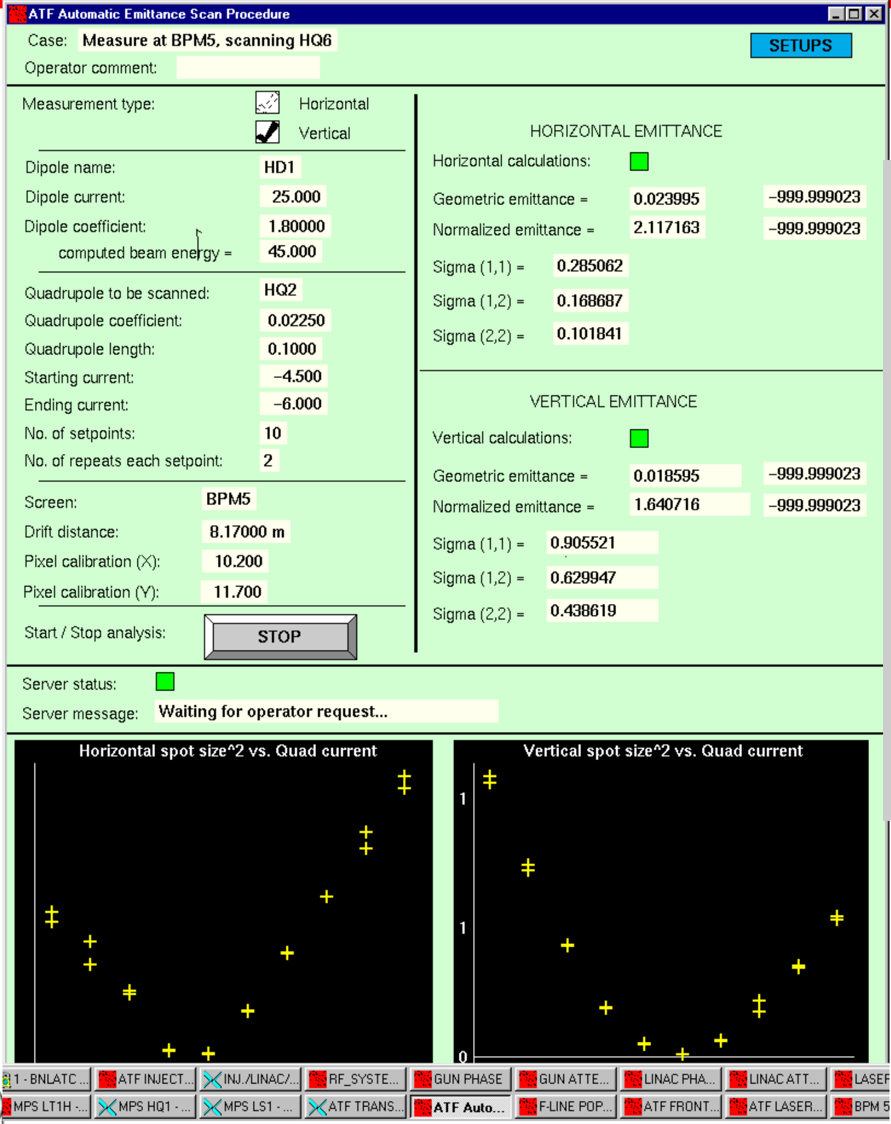

150 pC

Bunch length as RF gun phase and charge






RMS Energy spread (%)
1
0.95
0.9
0.85
0.8
0
5
10
15
20
25
30
35
Beam Energy (MeV)
47.5
47
46.5
46
45.5
0
5
10
15
20
25
30
35
Second section linac phase (deg.)



ATF Automatic Emittance Scan Procedure

Case: Measure at BPM5, scanning HQ6

Operator comment:

Measurement type: ☐ Horizontal ☑ Vertical

Dipole name: HD1
Dipole current: 25.000
Dipole coefficient: 1.80000
computed beam energy = 45.000

Quadrupole to be scanned: HQ2
Quadrupole coefficient: 0.02250
Quadrupole length: 0.1000
Starting current: −4.500
Ending current: −6.000
No. of setpoints: 10
No. of repeats each setpoint: 2

Screen: BPM5
Drift distance: 8.17000 m
Pixel calibration (X): 10.200
Pixel calibration (Y): 11.700

Start / Stop analysis: STOP

HORIZONTAL EMITTANCE

Horizontal calculations: 🟩

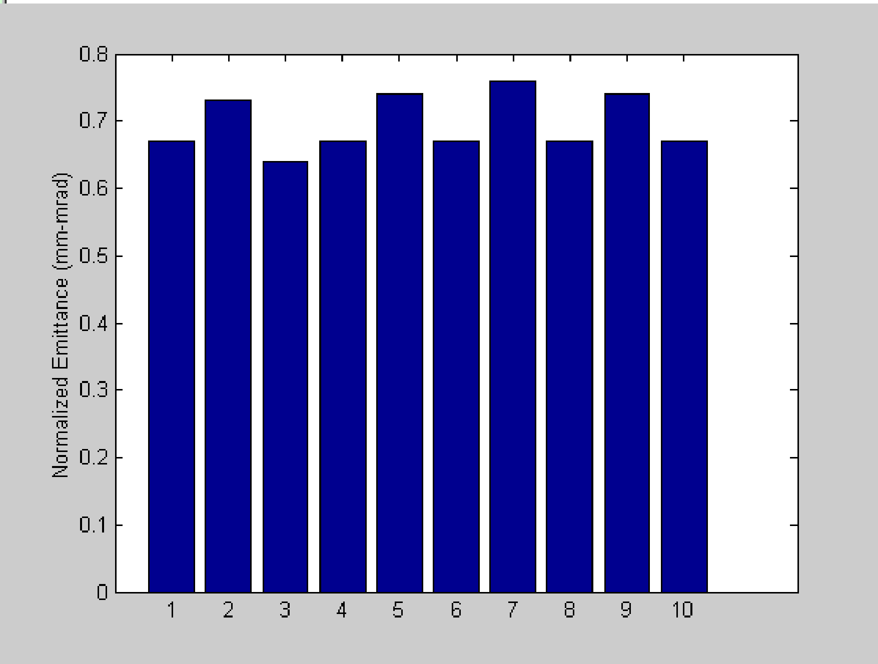
Geometric emittance = 0.023995 −999.999023
Normalized emittance = 2.117163 −999.999023
Sigma (1,1) = 0.285062
Sigma (1,2) = 0.168687
Sigma (2,2) = 0.101841

VERTICAL EMITTANCE

Vertical calculations: 🟩

Geometric emittance = 0.018595 −999.999023
Normalized emittance = 1.640716 −999.999023
Sigma (1,1) = 0.905521
Sigma (1,2) = 0.629947
Sigma (2,2) = 0.438619

Server status: 🟩
Server message: Waiting for operator request...



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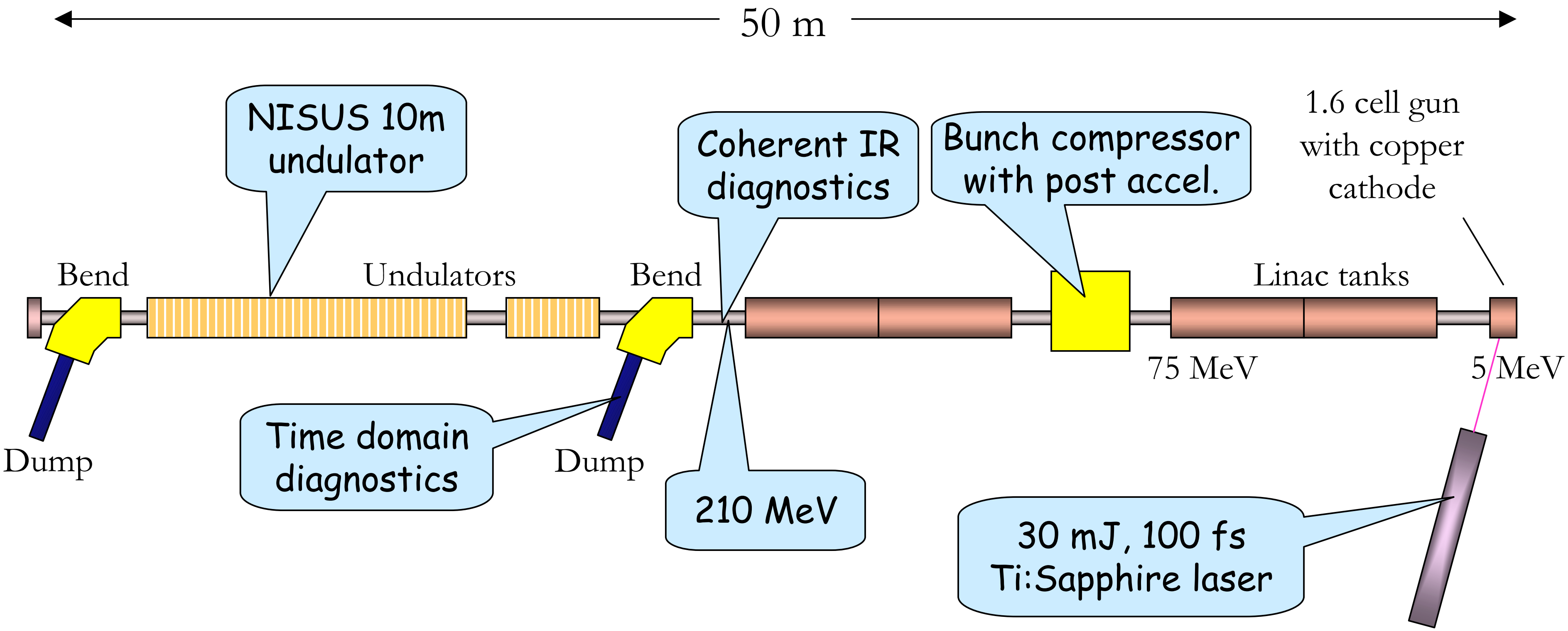
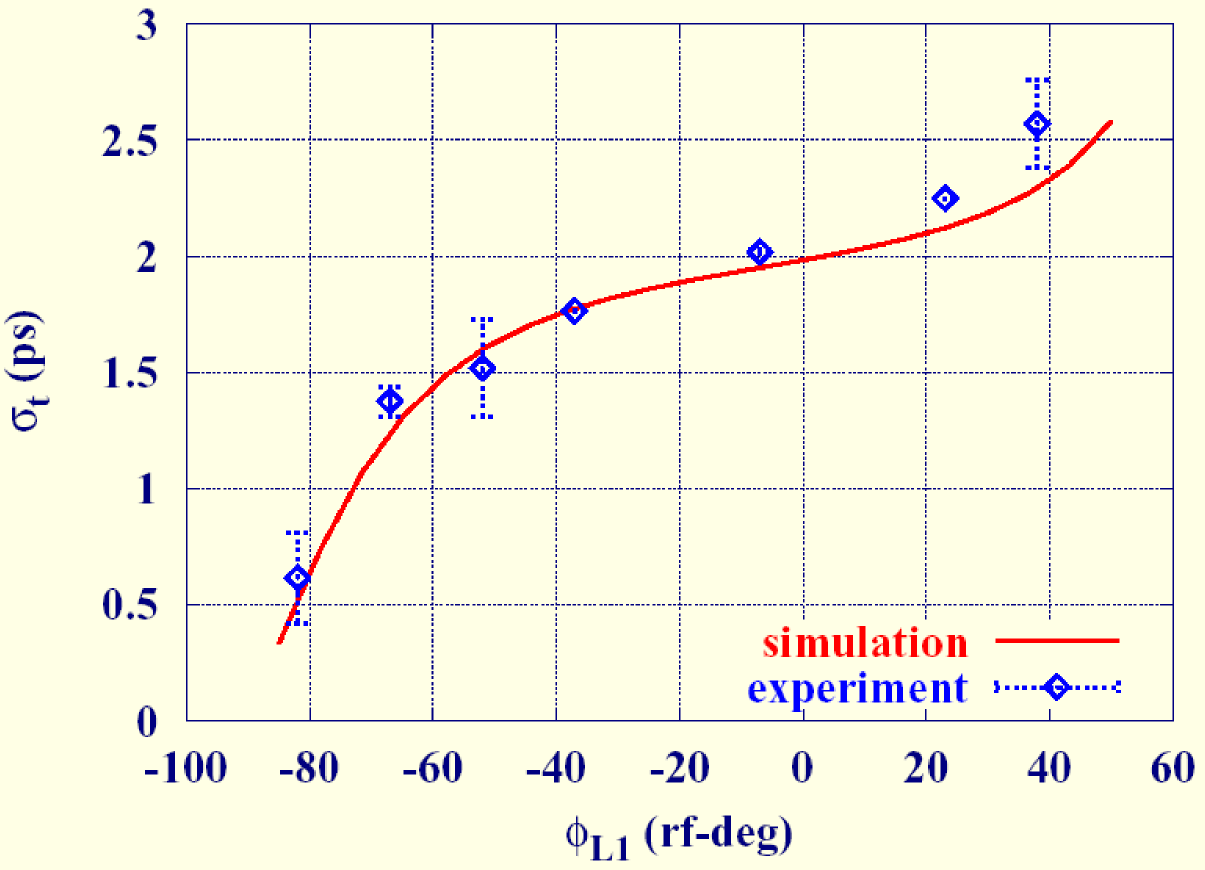
DUV-FEL Facility



Bunch length versus phase of L1

- phase of linac section L1 is varied + L2 kept on-crest



Summary

- We have shown that, by taking advantage of the longitudinal emittance compensation, it is possible to produce 10 fs Kilo-Ampere electron beam with emittance less than 1 mm-mrad.
- Preliminary experimental results are very promising, 200 MeV linac at the Brookhaven DUV-FEL and associated diagnostic tool will be a perfect fit with additional solenoid magnet.