Thermal emittance measurements for a RF photoinjector

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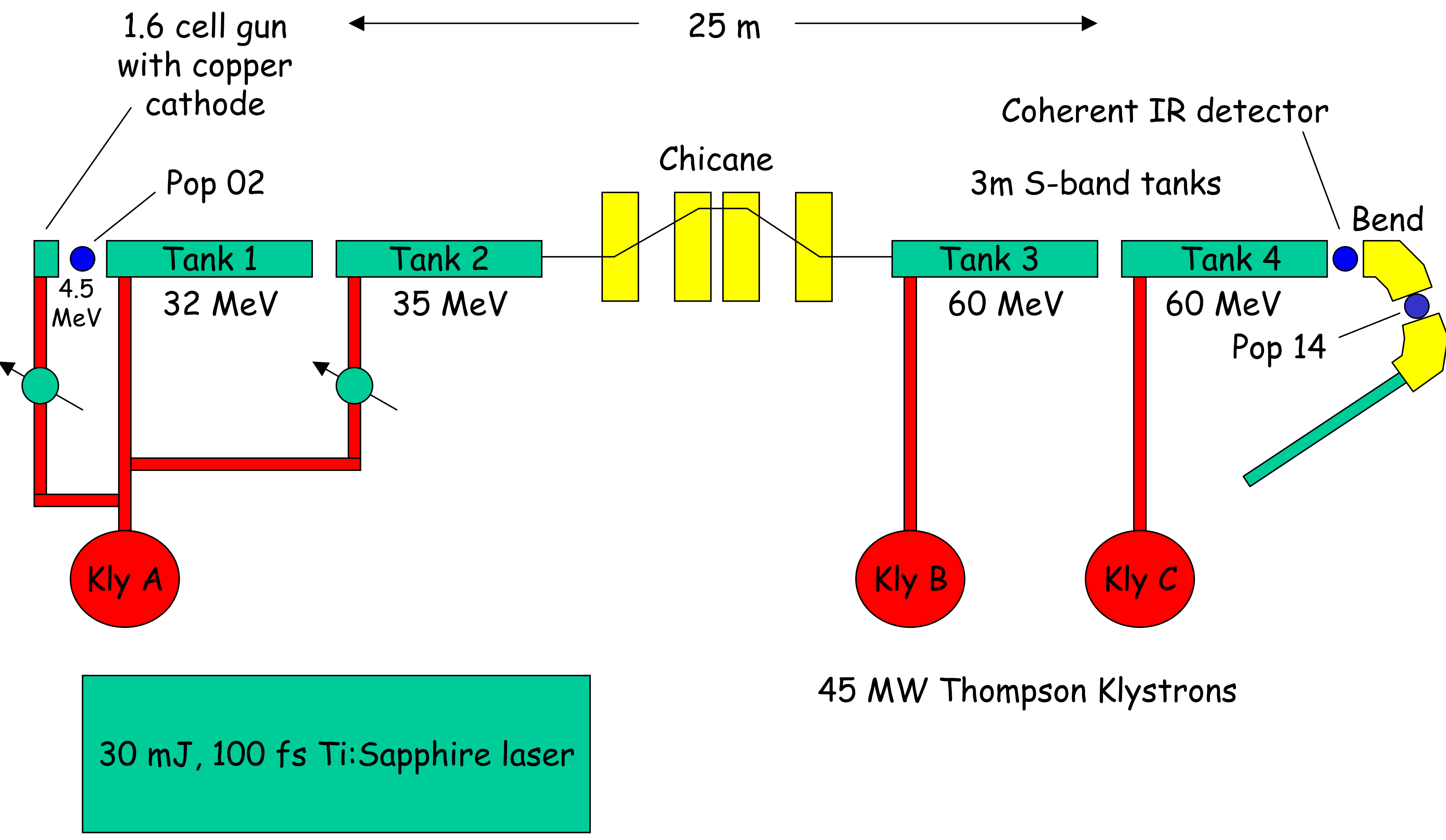
Outline

- Introduction to BNL's DUVFEL
- Thermal emittance and RF gun studies
- Beam based studies of photoinjector fields
- Experimental/instrumentation issues
- Thermal emittance scaling measurement

DUVFEL Accelerator



DUVFEL Photoinjector

1.6 cell BNL/SLAC/UCLA Gun IV	
Cathode material	Copper
Kinetic energy	4.0 MeV
Loaded Q	7100
Unloaded Q	13500
RF pulse length	2.5 us
Quantum efficiency	~2e-5
Vacuum	~8e-9 torr
Phase jitter	< 1ps

Titanium:Sapphire Laser	
IR laser energy	30 mJ
UV laser energy	2 mJ
Laser pulse length	2-6 ps FWHM

Normal incidence in-vacuum mirrors

Laser pulse length in IR is adjustable from 100 fs to 10 ps. UV output limited to narrow pulse length range due to BBO harmonic crystals.

Envelope equation

$$\sigma_x'' = \underbrace{\frac{\gamma'}{\gamma^3\beta^2}\sigma_x'}_{\text{Acceleration}} - \underbrace{\frac{\sigma_x}{2\gamma\beta^2 mc^2}\left(E_z' \sin\phi + \frac{\omega_{rf}\beta}{c} E_z \cos\phi + B_z^2 \right)}_{\text{Applied E and B fields}} + \underbrace{\frac{Q}{\gamma^3\beta^2\sigma_x\sigma_z} h_x}_{\text{Space charge}} + \underbrace{\frac{\varepsilon_{xN}^2}{\gamma^2\sigma_x^3}}_{\text{Emittance}}$$

Different time slices of beam experience different forces due to RF sinusoid and space charge.

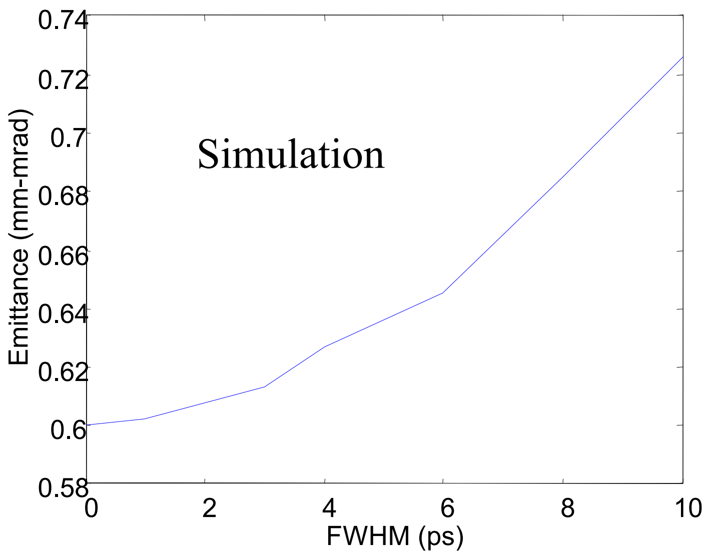
Emittance compensation is the process of untwisting the time slices so that they align.

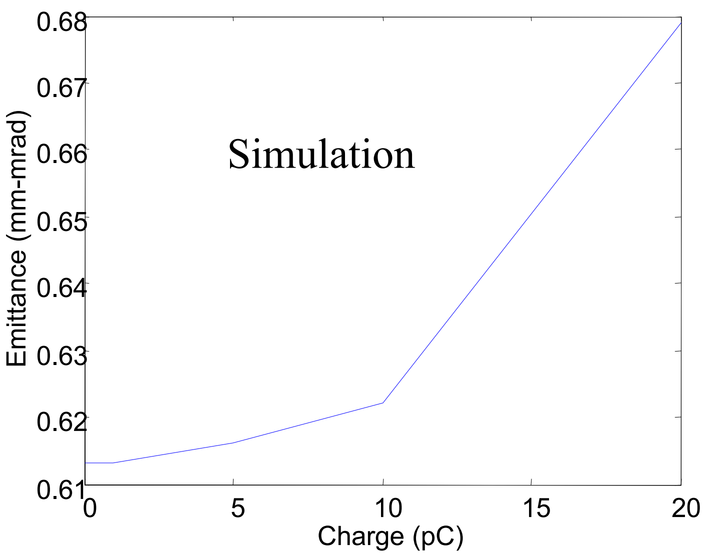
Nonlinear fields cause irreversible slice emittance growth (not time correlations).

We avoid these effects by working with short, low charge beams transported over short distances.

Projected emittance vs charge and FWHM

Use HOMDYN simulations to estimate limits on maximum bunch length and charge. Choose working parameters of 2 pC, 2 ps FWHM.



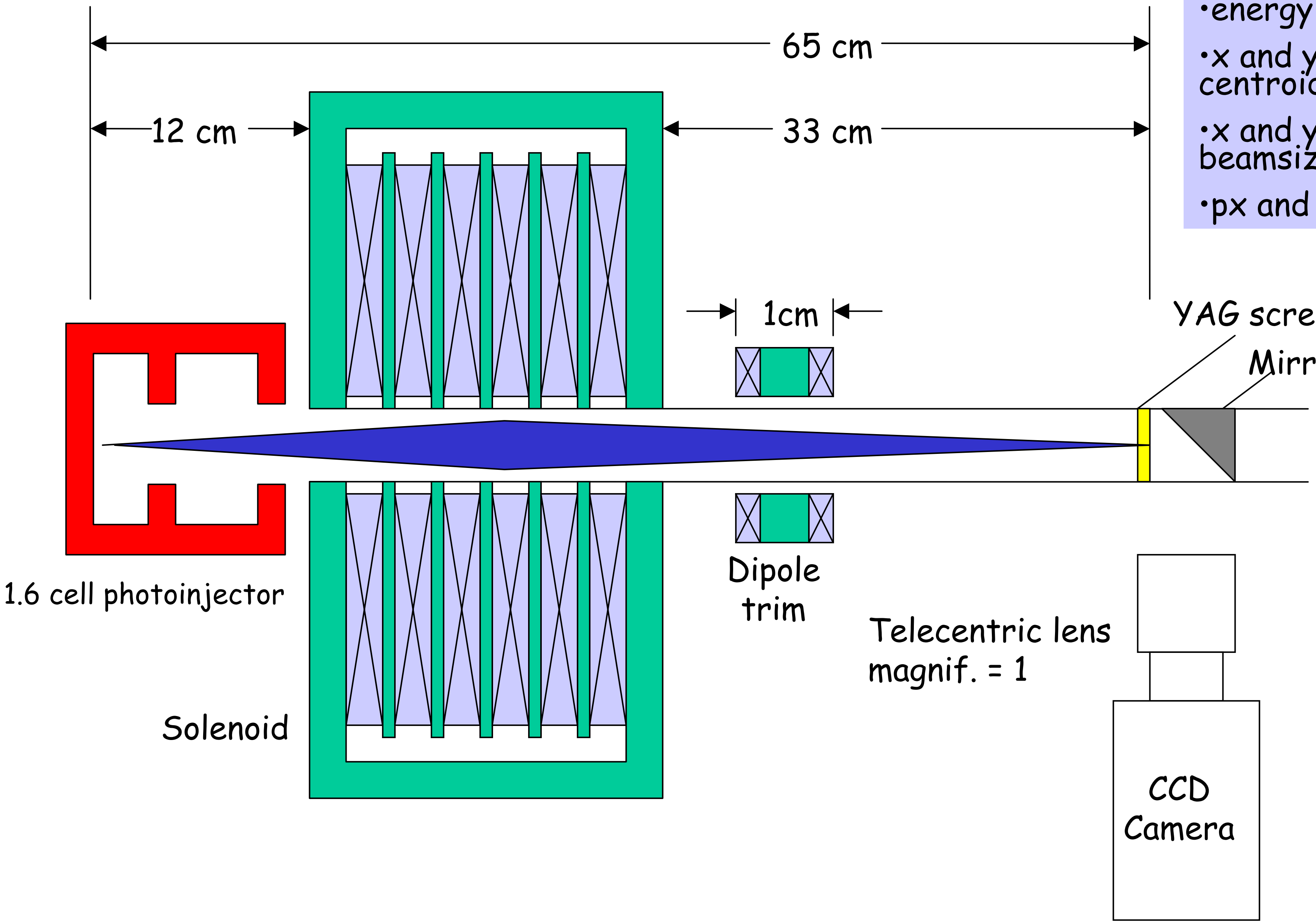


Charge	2 pC
Energy	3.7 MeV
Laser spot	0.5 mm RMS

FWHM	2 ps
Energy	3.7 MeV
Laser spot	0.5 mm RMS

Solenoid Scan Layout

Can measure
- charge
- energy
- x and y centroid
- x and y beamsize
- px and py



Solenoid Scan Equations

Usual transport equation is

$$\sigma_1 = R\sigma_0 R^T$$

where σ and R are 4x4 matrices.

Desire to decouple x and y so that

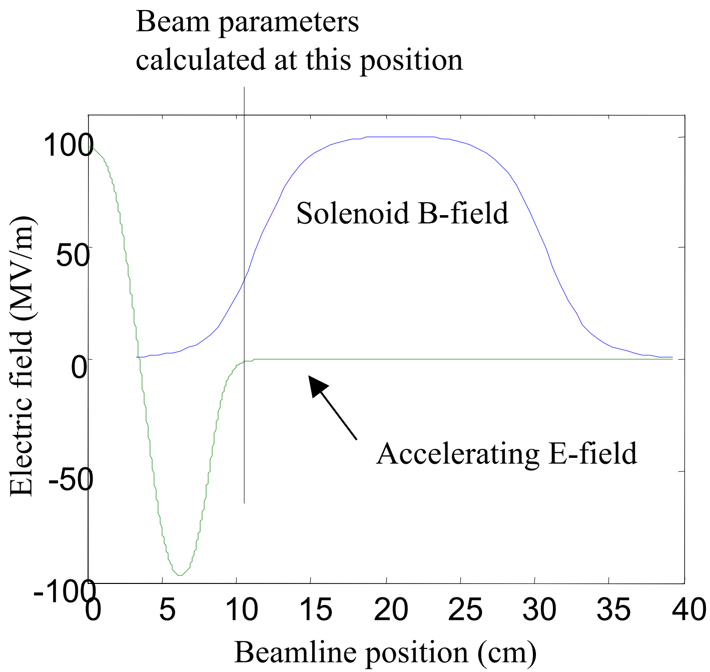
$$\langle x_1^{\ 2}\rangle = R_{11}^{\ 2}\langle x_0^{\ 2}\rangle + 2R_{11}R_{12}\langle x_0 x_0^{\prime}\rangle + R_{12}^{\ 2}\langle x_0^{\prime 2}\rangle$$

Multiply by rotation matrix *T* to decouple *R*-matrix and "unrotate" beam projections.

$$R \rightarrow TR$$
$$\sigma \rightarrow T\sigma$$

$$T = \begin{pmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$\theta = \frac{eBL}{2\gamma mc^2} = \arctan\frac{R_{31}}{R_{11}}$$

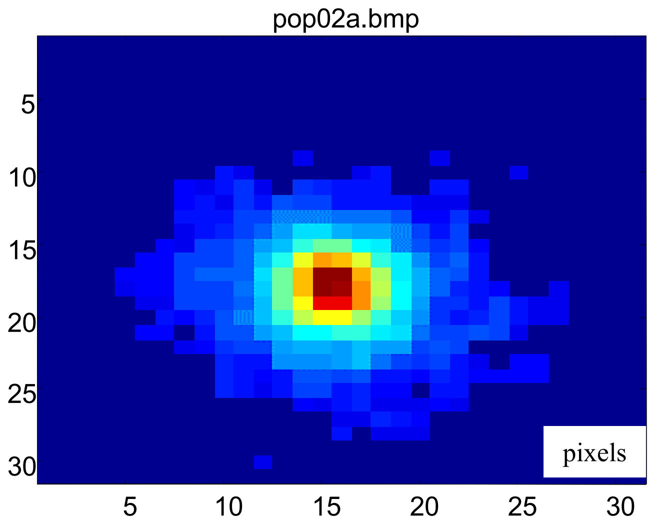


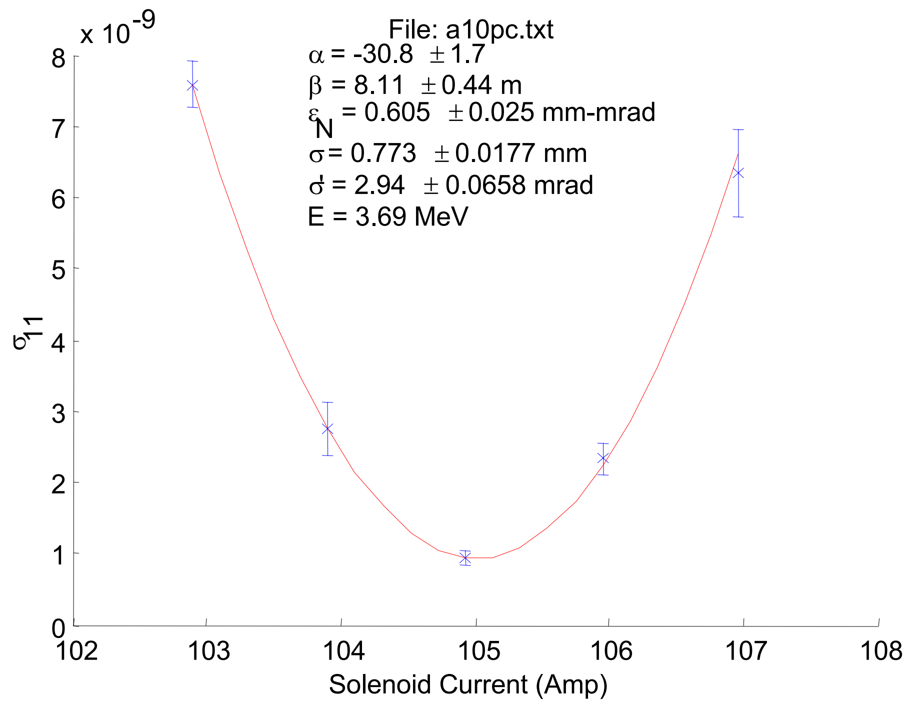
Break solenoid into 40 slices for accurate field profile.

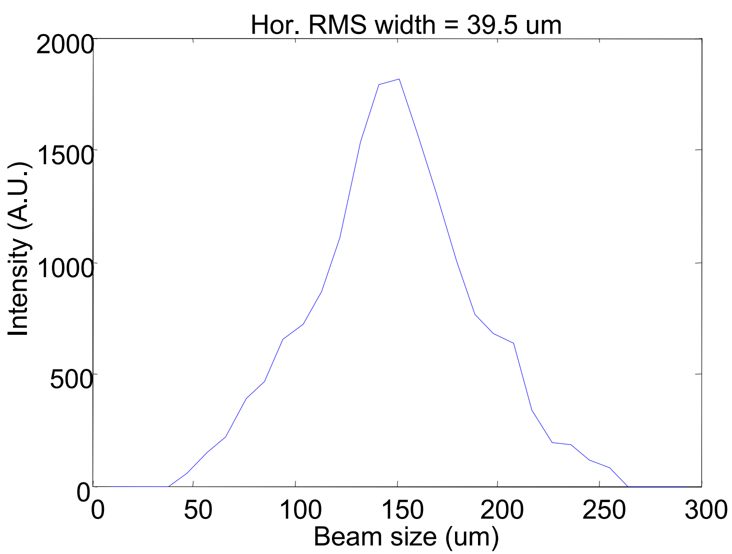
Build transport matrix by summing slices.

Use MAD and Matlab.

Solenoid Scan







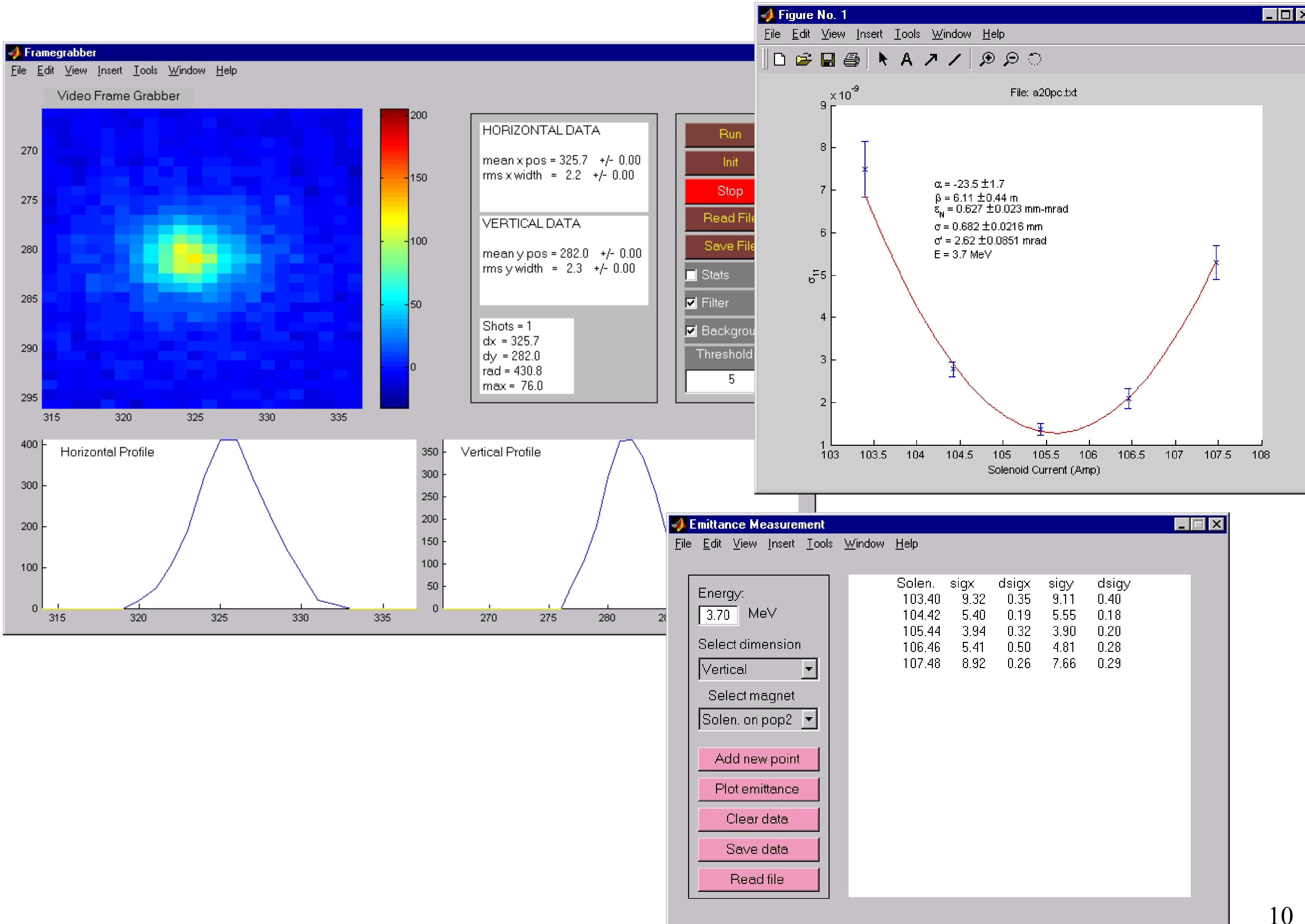
<u>Video processing</u>

- 3x3 median filter applied.
- Dark current image subtracted.
- Pixels < 10% peak are zeroed.

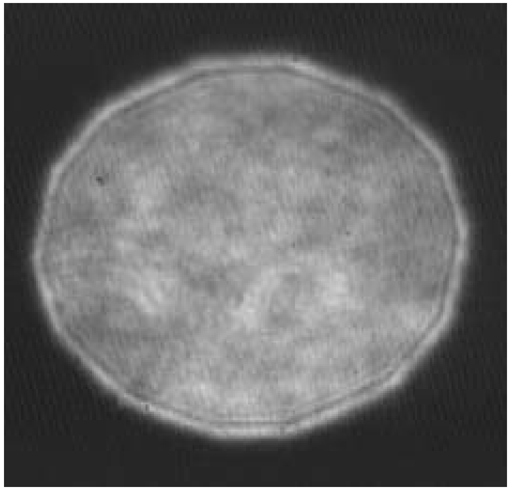
<u>Error estimates</u>

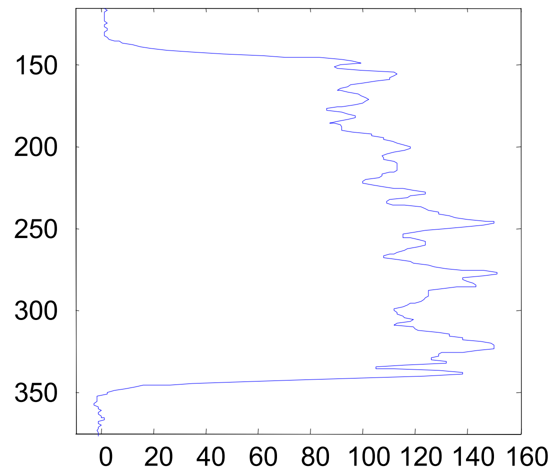
Monte Carlo method using measured beam size jitter.

User Interface



Laser spatial and time profiles

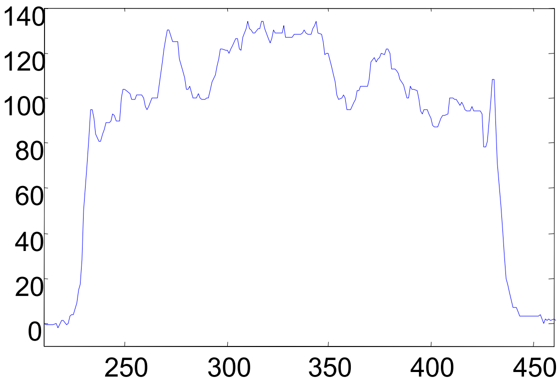




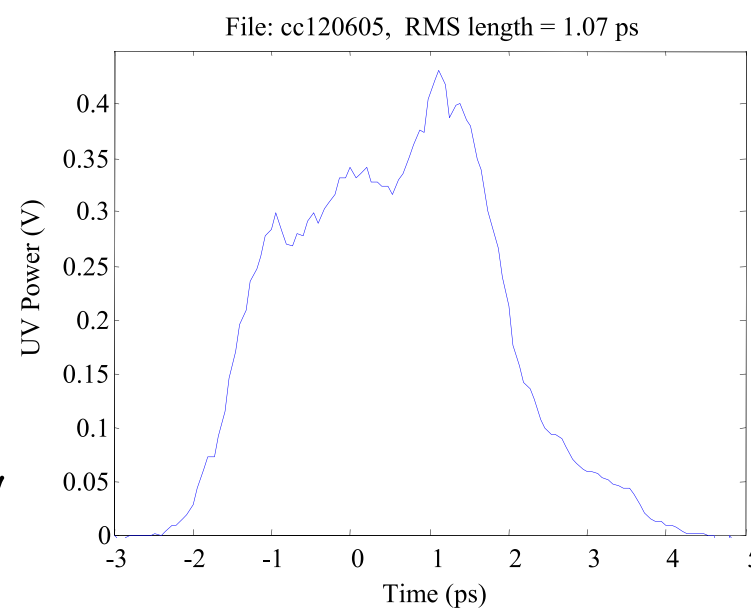
Vertical lineout

UV light is spatially filtered and apertured.

Transport calculations depend only on 2nd moments, not on spatial shape.



Horizontal lineout

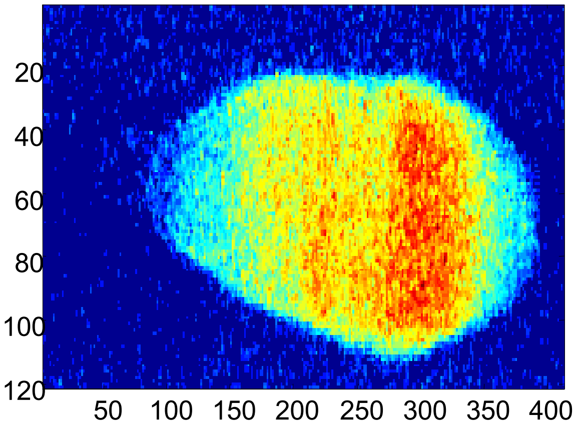


Cross-correlation measurement of UV time profile.

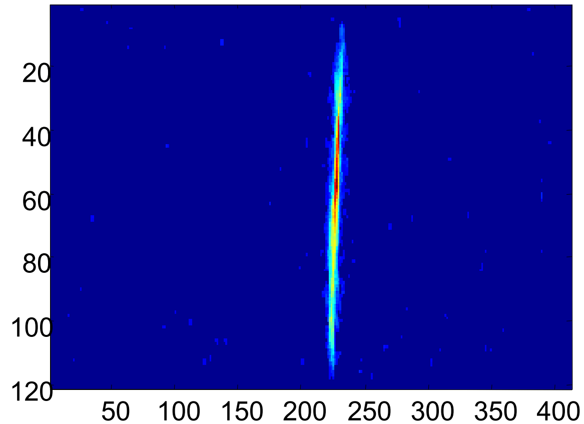
RF zero phasing electron bunch length measurement

Energy = 75 MeV, Charge = 20 pC, Tank 4 energy gain = 11 MeV

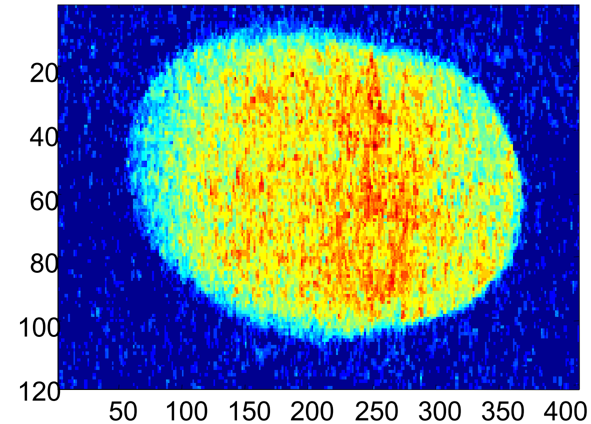
RF phase = -90 degrees



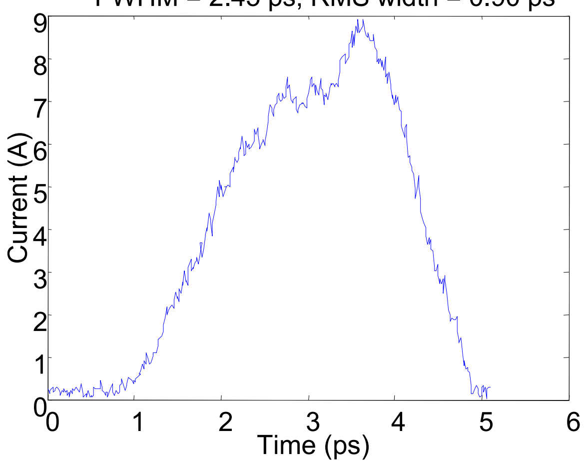
RF is off



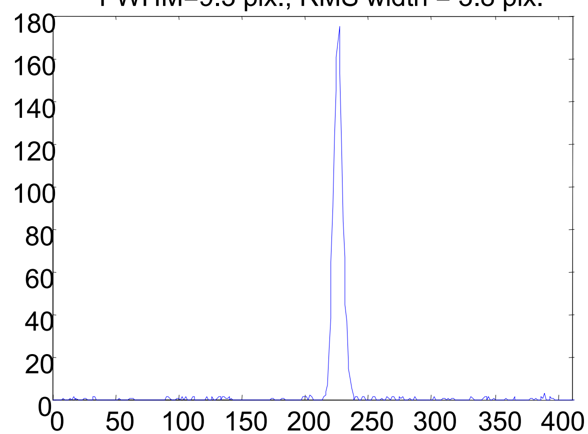
RF phase = +90 degrees



FWHM = 2.45 ps, RMS width = 0.90 ps

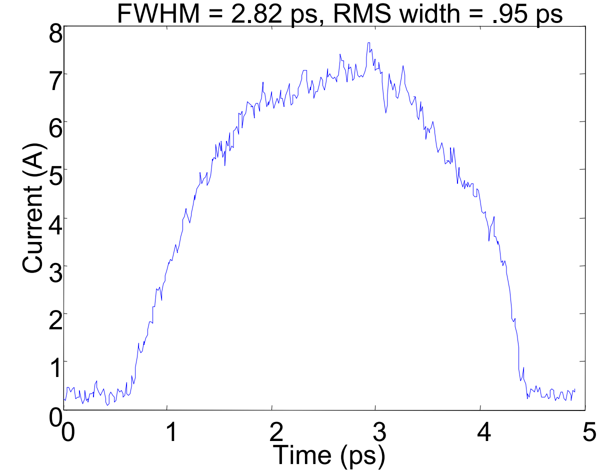


FWHM=9.3 pix., RMS width = 3.8 pix.

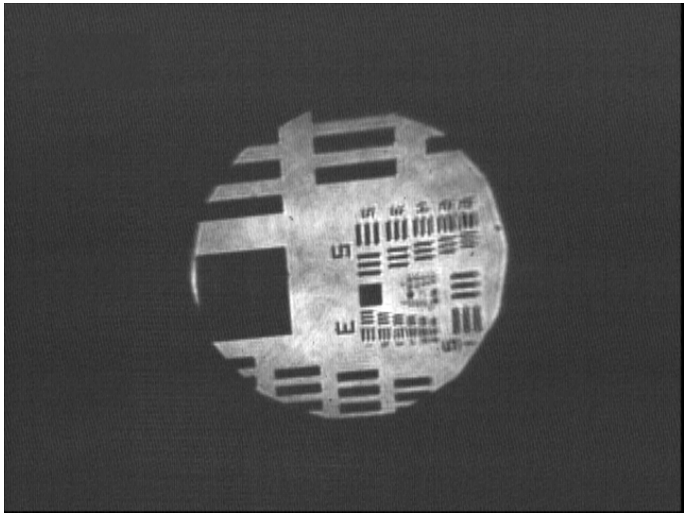


RMS energy spread = .01%

FWHM = 2.82 ps, RMS width = .95 ps

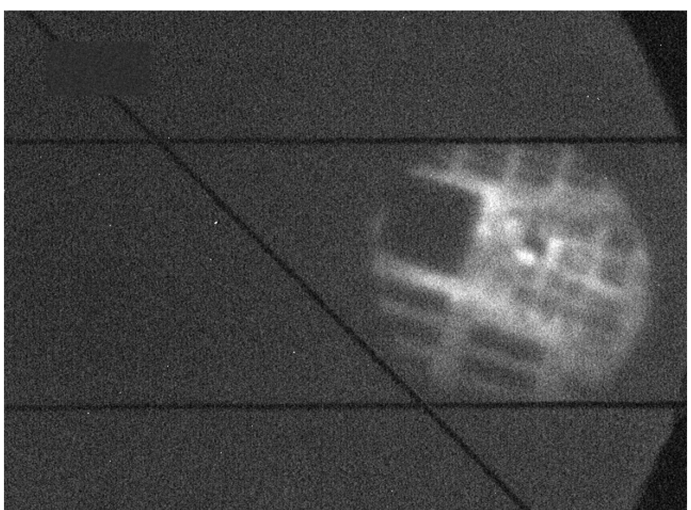


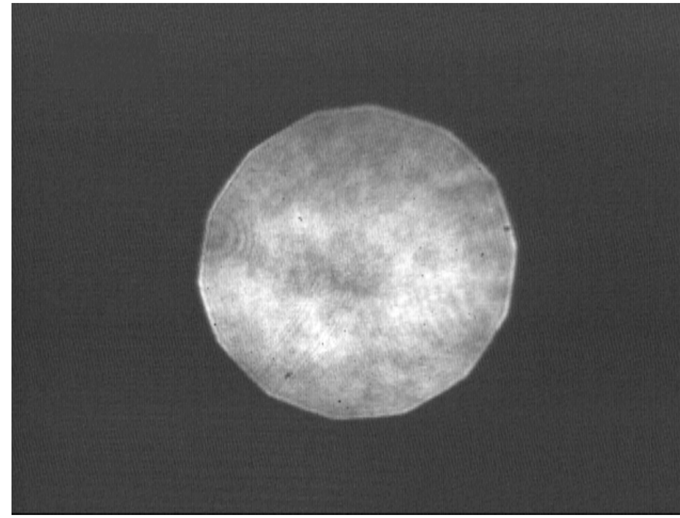
Laser masking of cathode image



Above: Laser cathode image of air force mask in laser room.

Below: Resulting electron beam at pop 2.





Above: Laser cathode image with mask removed showing smooth profile.

Below: Resulting electron beam showing hot spot of emission.

Thermal Emittance

The normalized emittance is

(1) $$\varepsilon_{xN} = \gamma\beta\sqrt{\langle x^2\rangle\langle x'^2\rangle} = \gamma\beta\sigma_x\sigma_{x'}$$

Use Lawson's expression for the RMS width of the momentum distribution of a thermalized beam

(2) $$\sigma_{x'} = \sqrt{\frac{E_k}{mc^2}}$$
$$\Rightarrow \varepsilon_N = \sigma_x\sqrt{\frac{E_k}{mc^2}}$$

(3) $$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf}E_{rf}\sin\theta_{rf}},$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}} \qquad h\upsilon = 4.67 \text{ eV} \qquad \Phi_{Cu} = 4.59 \text{ eV}$$

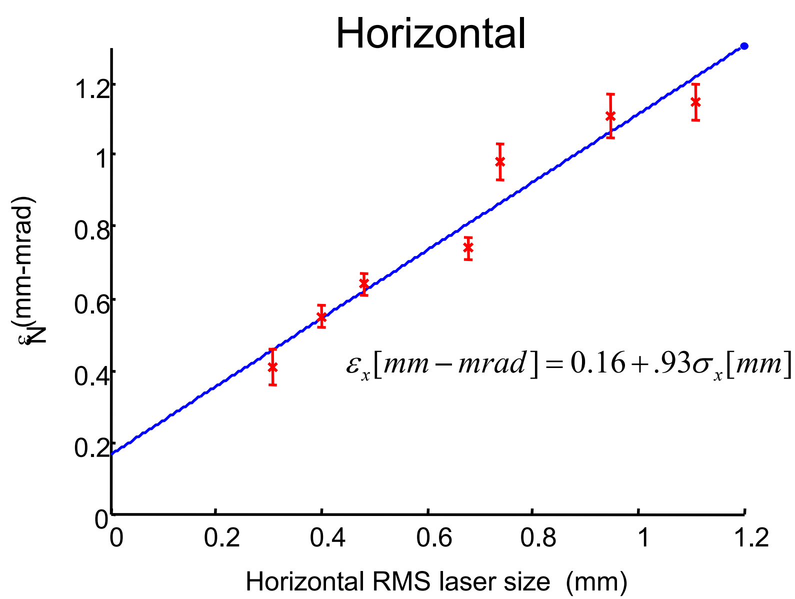
E_{rf} = 78 MV/m θ_{rf} = 30 degrees

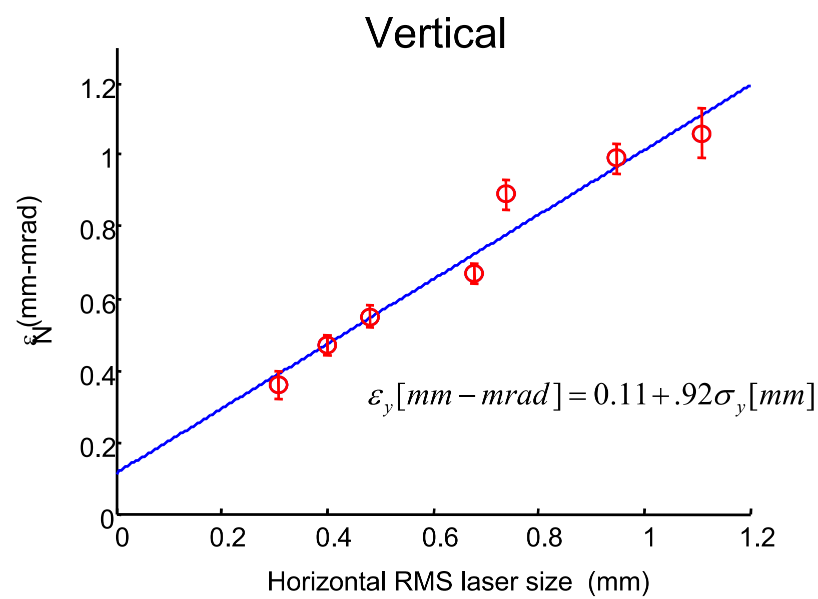
Field enhancement factor: β_{rf}

β_{rf} accounts for field variation at the cathode surface due to roughness, impurities, grain boundaries, etc.

Estimate $3 < \beta_{rf} < 10$ for a highly polished ($\lambda/2$), clean surface.

Emittance vs laser size





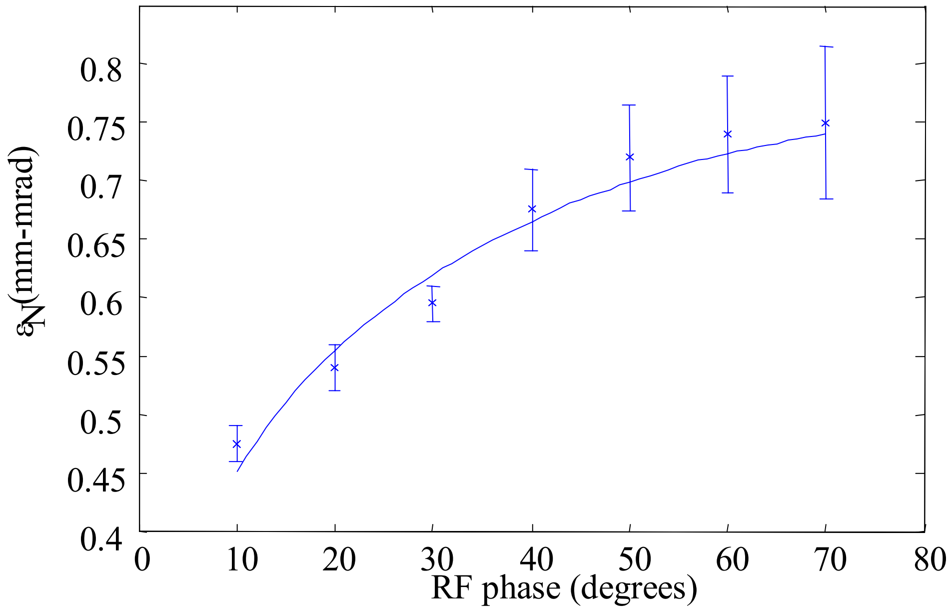
Emittance shows expected linear dependence on spot size.

Small asymmetry is always present.

FWHM	2.6 ps
Charge	2.0 pC
Gradient	78 MV/m
RF phase	30 degrees

$$\text{Average kinetic energy } E_k = mc^2\left(\frac{d\varepsilon_N}{d\sigma_x}\right)^2 = \mathbf{0.43\ eV}$$

Emittance vs RF phase



$$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf} E_{rf} \sin\theta_{rf}},$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}}$$

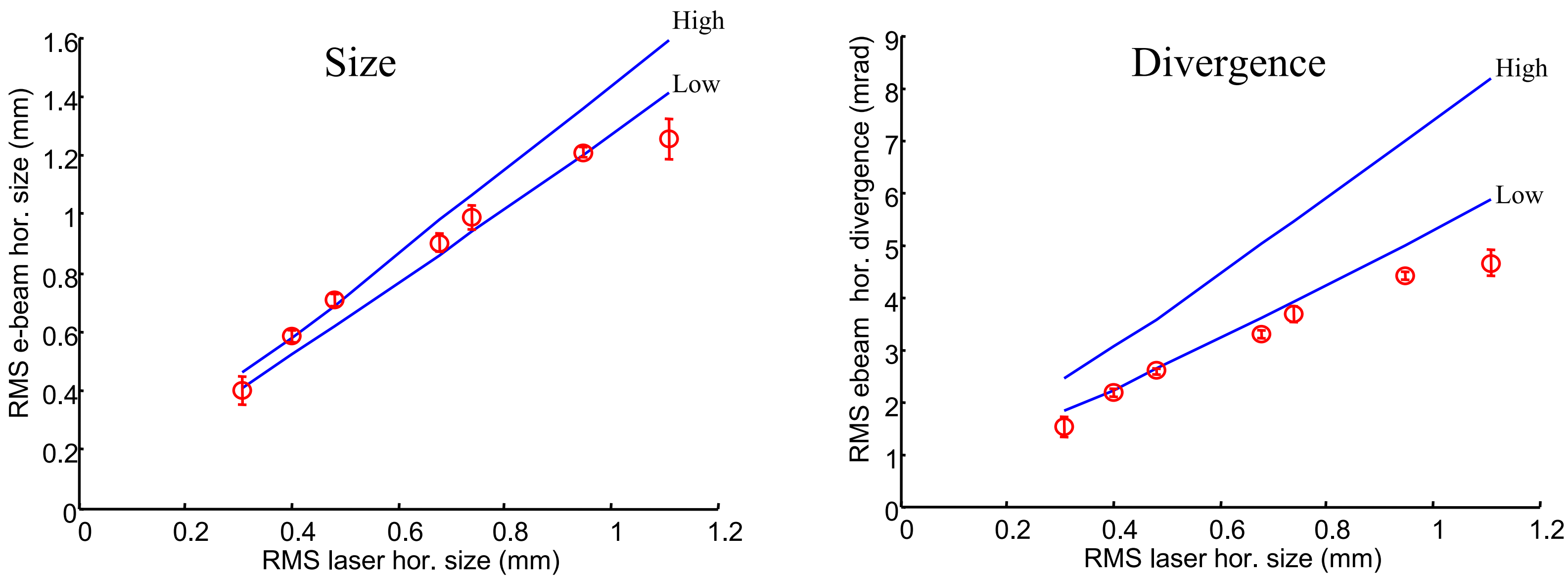
$$\varepsilon_N = \sigma_x \sqrt{\frac{E_k}{mc^2}}$$

Error bars are measured data points.

Curve is nonlinear least squares fit with β_{rf} and Φ_{cu} as parameters: $\boldsymbol{\beta_{rf}}$ **= 3.10 +/- 0.49** and $\boldsymbol{\Phi_{cu}}$ **= 4.73 +/- 0.04 eV**.

The fit provides a second estimate of the electron kinetic energy $\boldsymbol{E_k}$ **= 0.40 eV**, in close agreement with the estimate from the radial dependence of emittance.

Beam size and divergence vs laser spot size



$$\sigma_{x1}[mm] = 0.12 + 1.1\sigma_{x0}[mm]$$

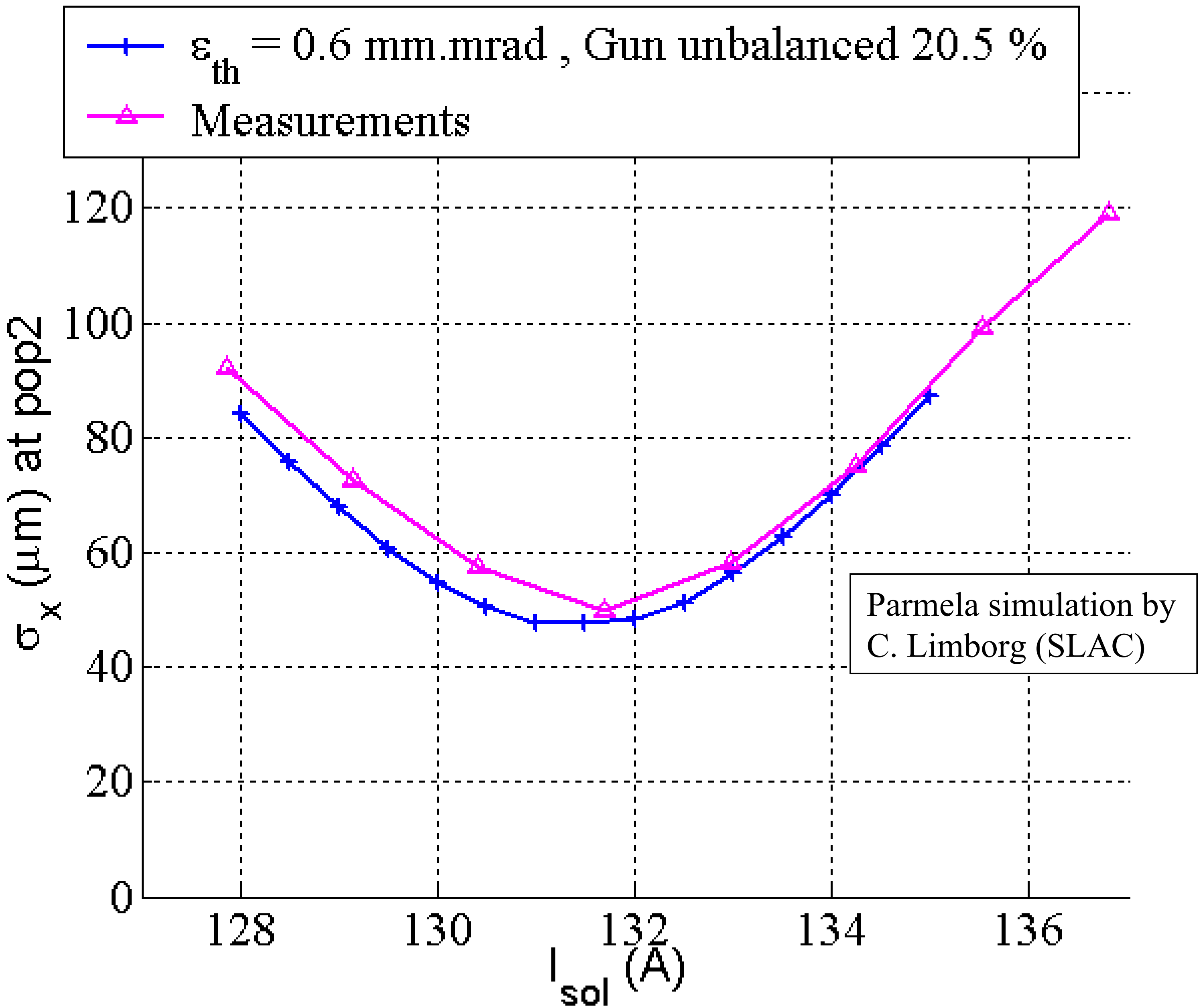
$$\sigma_x'[mrad] = 0.9 + 3.5\sigma_{x0}[mm]$$

Error bars are measured data.

Blue lines are from HOMDYN simulation using RF fields from SUPERFISH model and measured solenoid B-field.

Upper blue line has 1/2 cell field 10% higher than full cell.

Lower blue line has 1/2 cell field 10% lower than full cell.



ε_{th} = 0.6 mm.mrad , Gun unbalanced 20.5 %
Measurements
120
100
80
60
40
20
0
σ_x (µm) at pop2
128
130
132
134
136
I_{sol} (A)
Parmela simulation by
C. Limborg (SLAC)

Summary

•Measured beam dynamics show good agreement between theory and experiment in the low charge, short bunch limit.

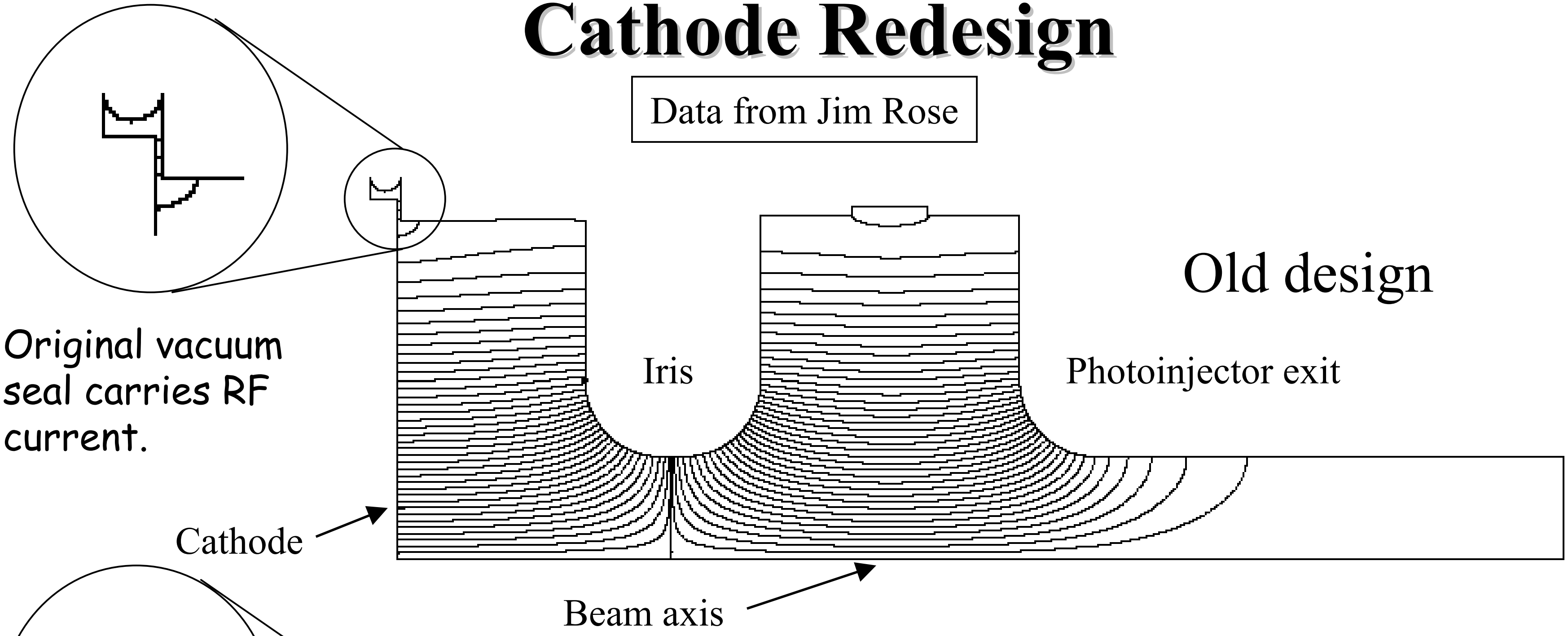
•First measurements of thermal emittance are in good agreement with theory.

•Knowledge of actual experimental parameters is important.

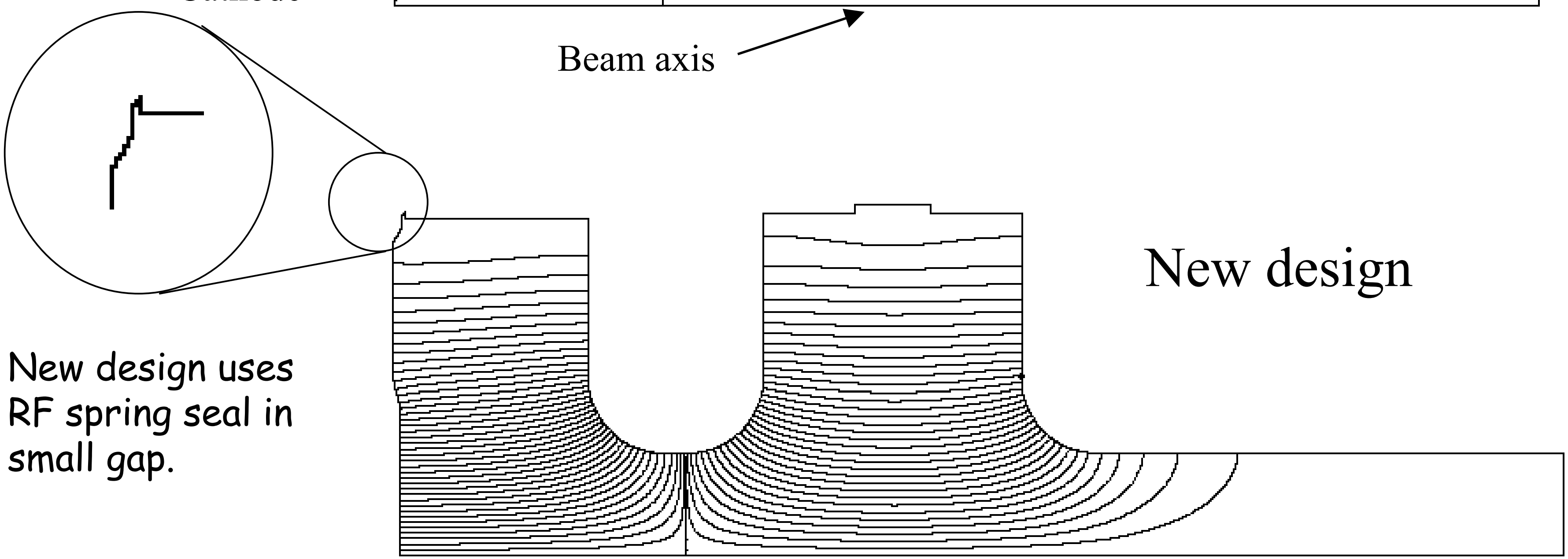
•Beam-based method of characterizing photoinjector fields can be widely used.

Cathode Redesign

Data from Jim Rose

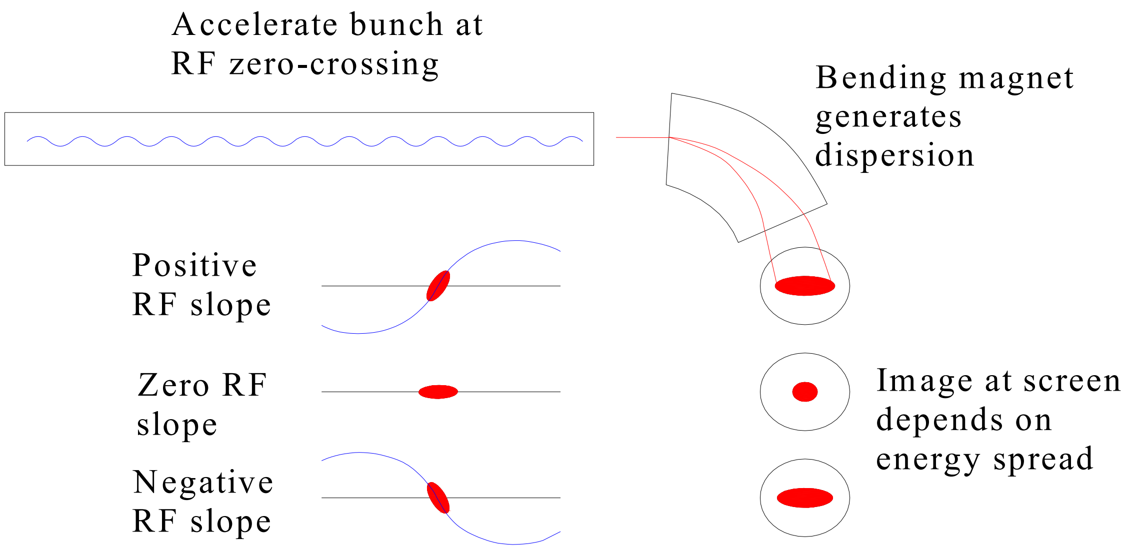


Original vacuum seal carries RF current.



New design uses RF spring seal in small gap.

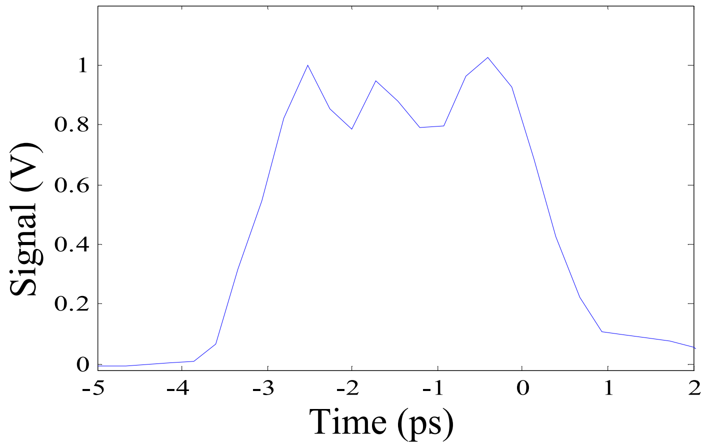
RF Zero Phase



Measure bunchlength by using linac to “streak” beam on profile monitor.

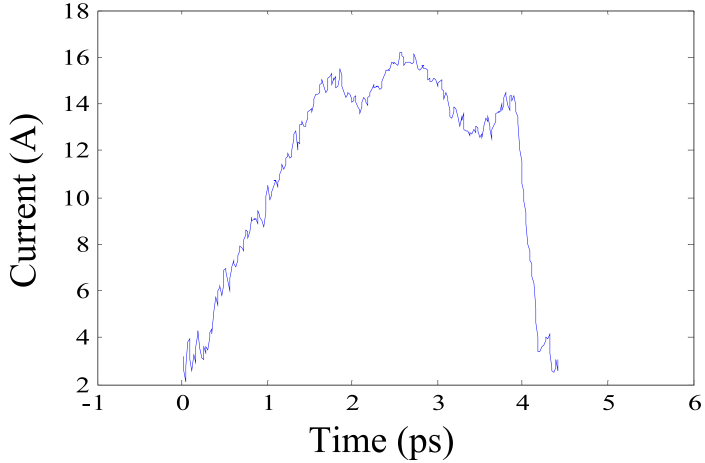
At DUVFEL, use tank3 to remove correlations from compression, tank 4 to produce chirp.

Modulations on photoinjector drive laser may seed CSR microbunching.



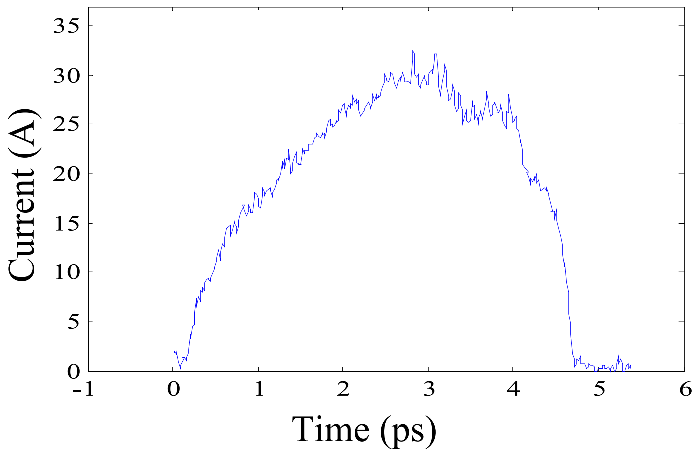
UV laser time profile

Resolution = 200 fs, RMS length = 0.97 ps



Uncompressed e-beam time profile (50 pC)

Resolution = 200 fs, RMS length = 1.05 ps.



Uncompressed e-beam time profile (100 pC)

Resolution = 200 fs, RMS length = 1.13 ps.

Time modulations on UV laser pulse

Phase matching angle of harmonic generation crystals used to produce UV affects time and spatial modulations.