Longitudinal Beam Physics in the Cathode Region

Patrick G. O'Shea

Institute for Research in ELECTRONICS AND APPLIED PHYSICS

Research sponsored by US Department of Energy and Office of Naval Research

Outline

Longitudinal space charge effects: limits and instabilities

Controlled generation of longitudinal perturbations

Longitudinal/transverse thermal effects

Operation Of Photocathodes Near the Space Charge Limit

Fundamental issue: Unlike thermionic cathodes, photocathodes are usually operated well below the space charge limit

…and the pulse length(τ_p) << gun transit time (T_{trans})

Early work showed that instabilities occur when photocathode is operated near the SCL

P.G. O'Shea;. *Nuclear Instruments and Methods in Physics Research*, A331, pg. 62 (1993).

Subsequent work explored details of longitudinal break-up

D.H Dowell et al. Phys Plasmas, **4,** 3369 (1997)

A. Valfells et al, Phys Plasmas **9**, 2377 (2002)

Many unresolved issues

Experiments with Laser Generation of Perturbations

Three methods under investigation:

- Single laser pulse (ns)
- Single laser pulse superimposed on thermionic emission
- Multiple pulses (ps), i.e. laser pulse with structure

  - What is the critical current density for the onset of space charge instabilities?
  - What is the impact of drive laser structure

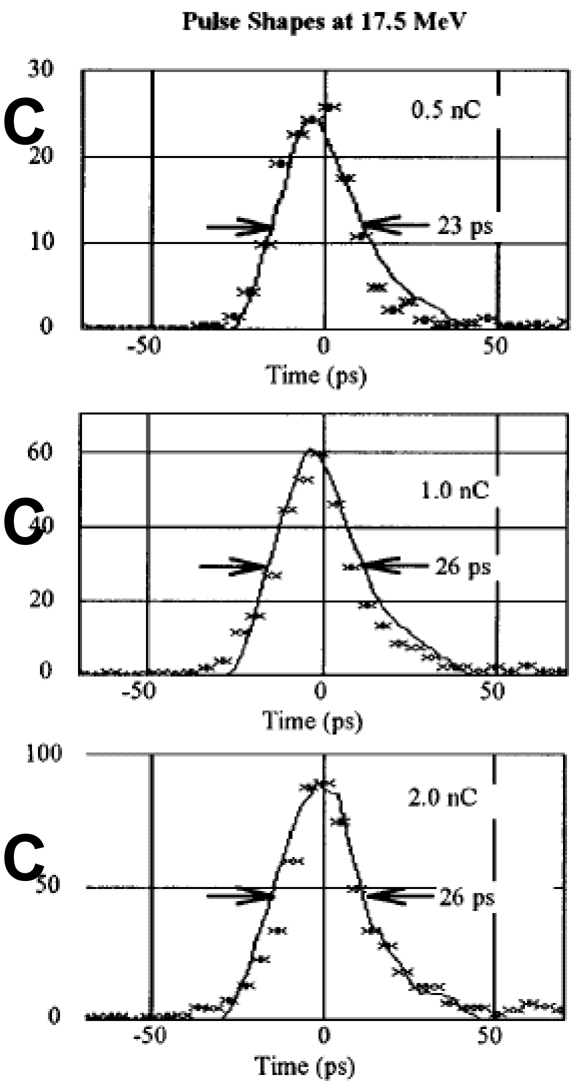
Single Pulse Experiments

D.H Dowell et al. Phys Plasmas, **4,** 3369 (1997)

0.5 nC

1.0 nC

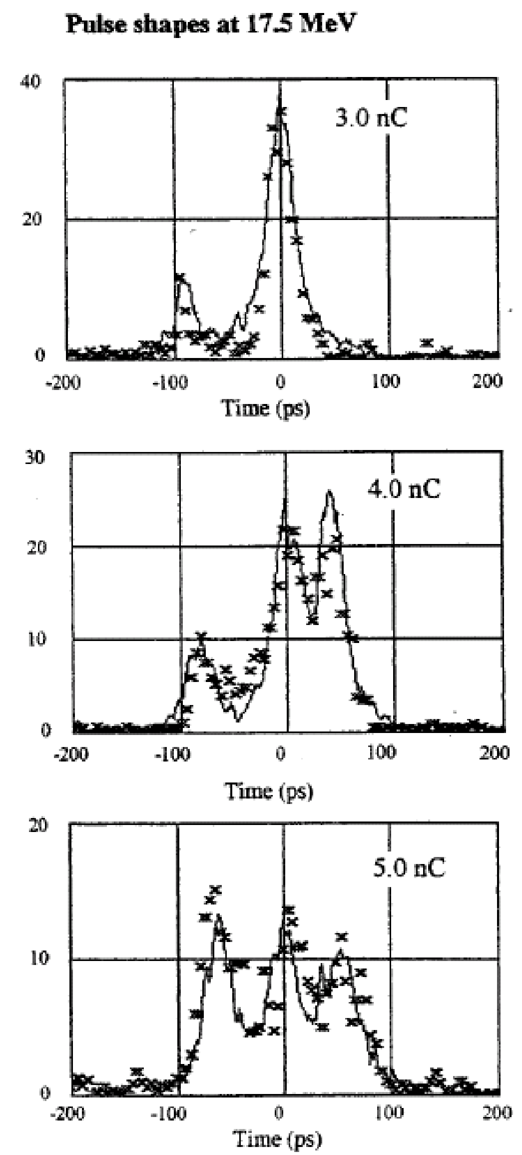
2.0 nC



3 nC

4 nC

5 nC

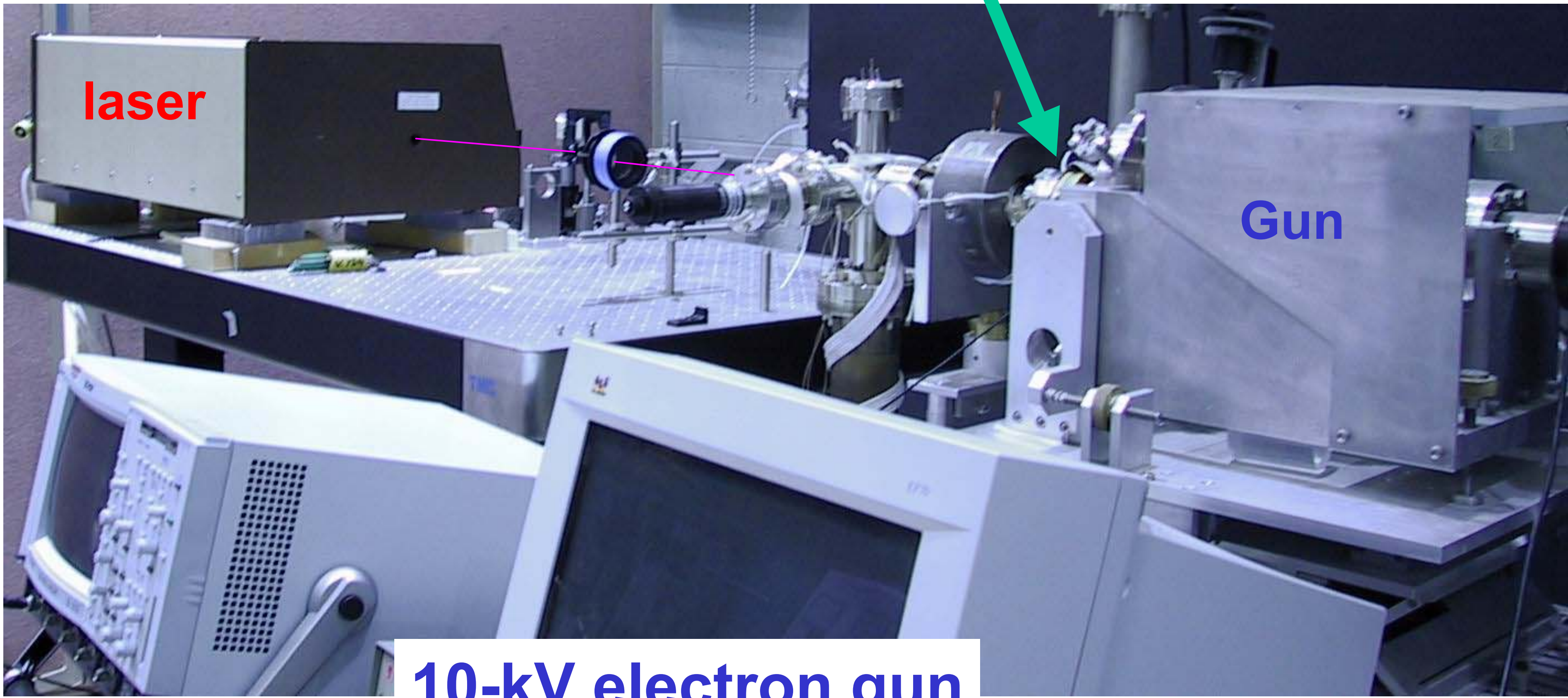


Single Pulse Experiments @ Maryland

A. Valfells D. Feldman, M. Virgo, Y.Y. Lau, P.G O'Shea,
Phys Plasmas **9**, 2377 (2002)

Photoemission from Thermionic Cathode (WBaCaO)

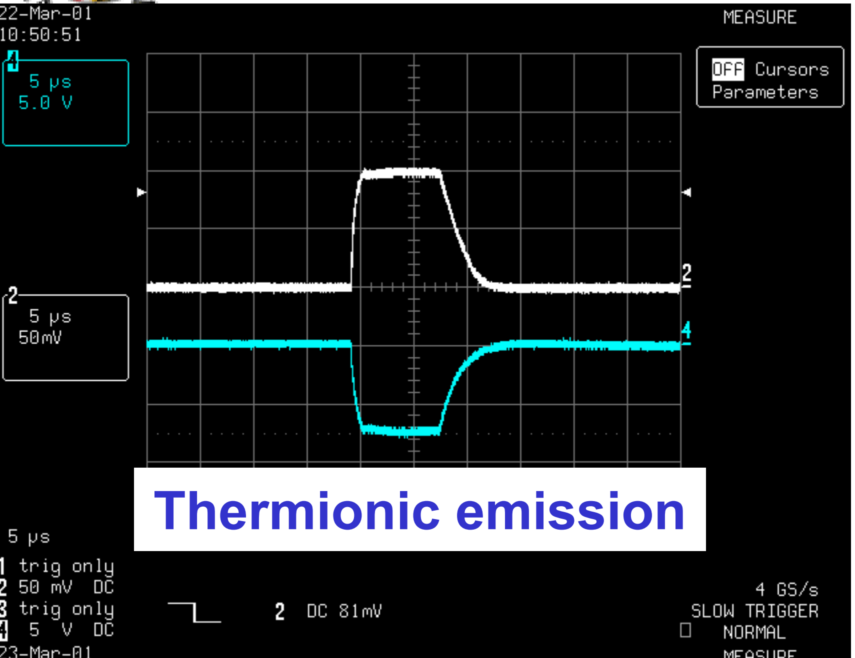
Bergoz toroid < 200 ps rise time



10-kV electron gun

Nitrogen Laser (337nm) pulse is 660 ps FWHM
several hundred μJ of UV per pulse

Types of Emission



Thermionic emission

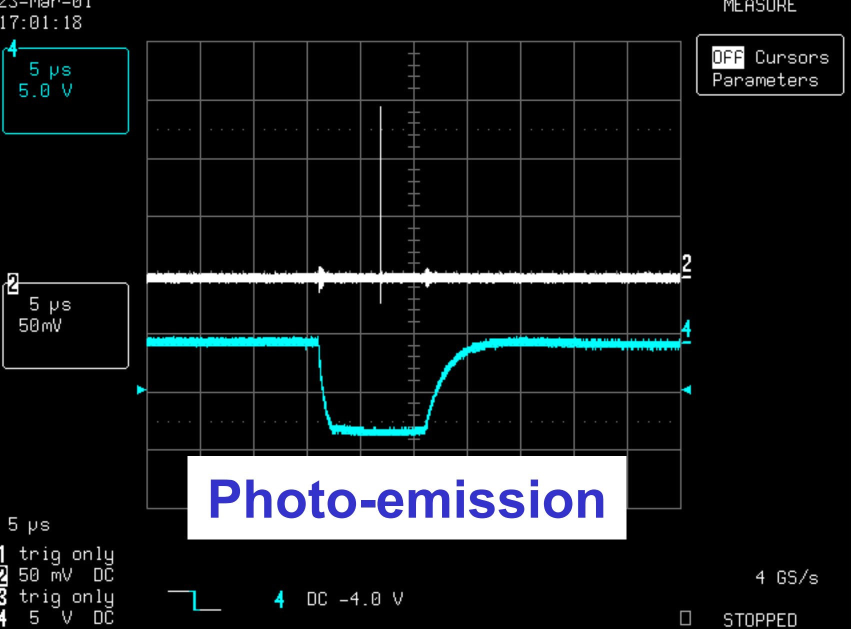
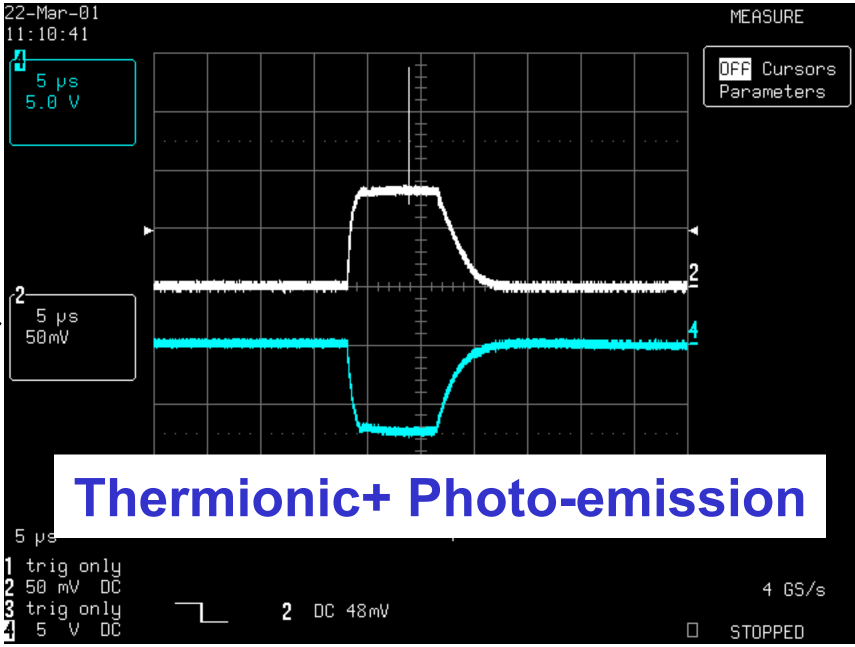


Photo-emission

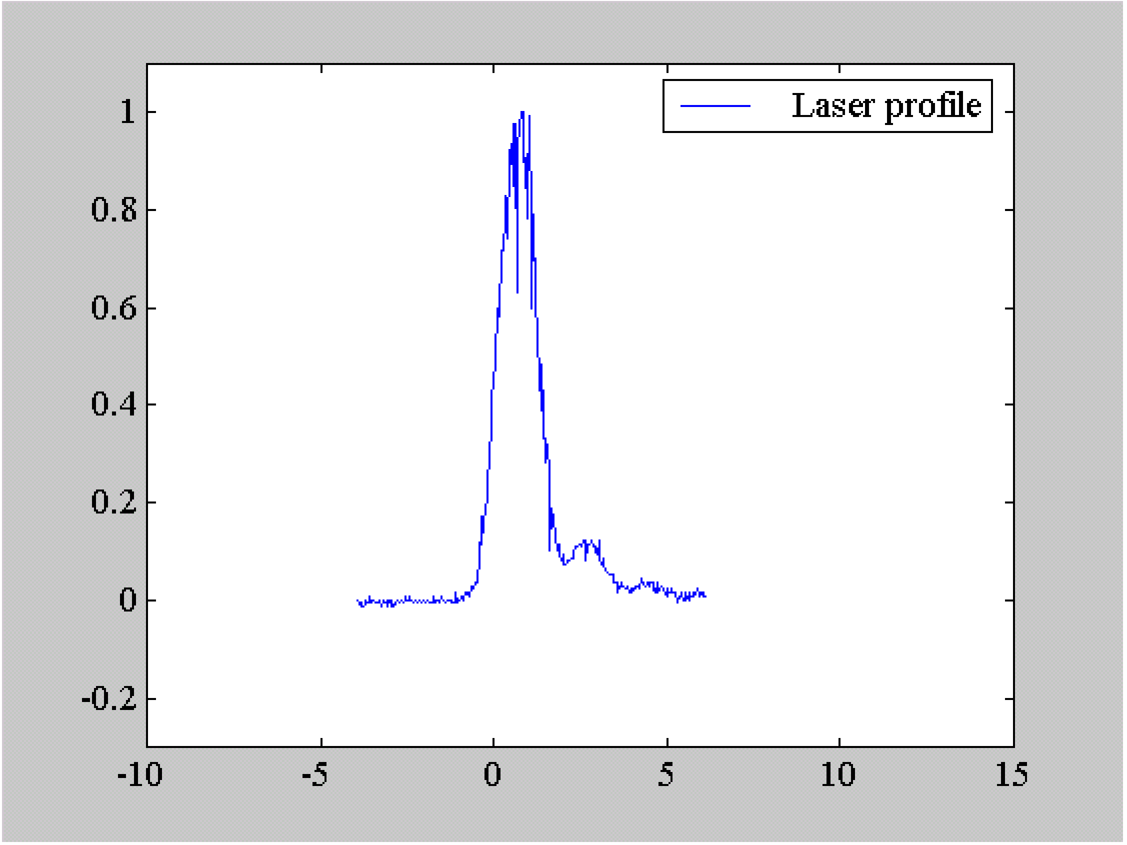
10 μs HV pulse



Thermionic+ Photo-emission

Experimental data

Laser Pulse Shape



Normalized Amplitude

Time [ns]

Details of Electron Beam Pulse Shapes

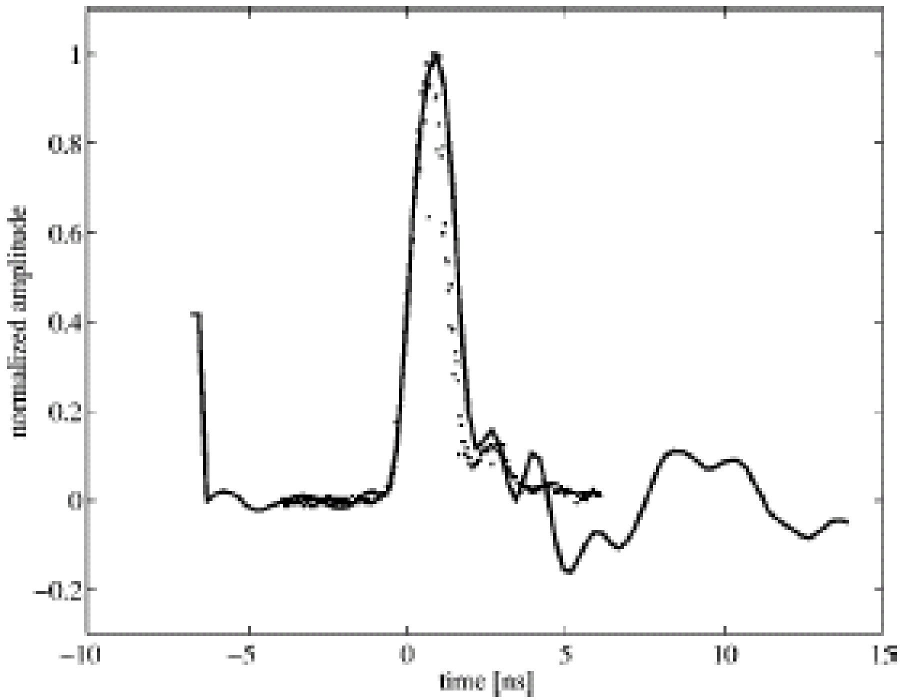


FIG. 2. Shape of the current pulse (solid line) compared with that of the laser pulse (dots) for an accelerating voltage of 9 kV, and the laser attenuated to 1% of its peak intensity.

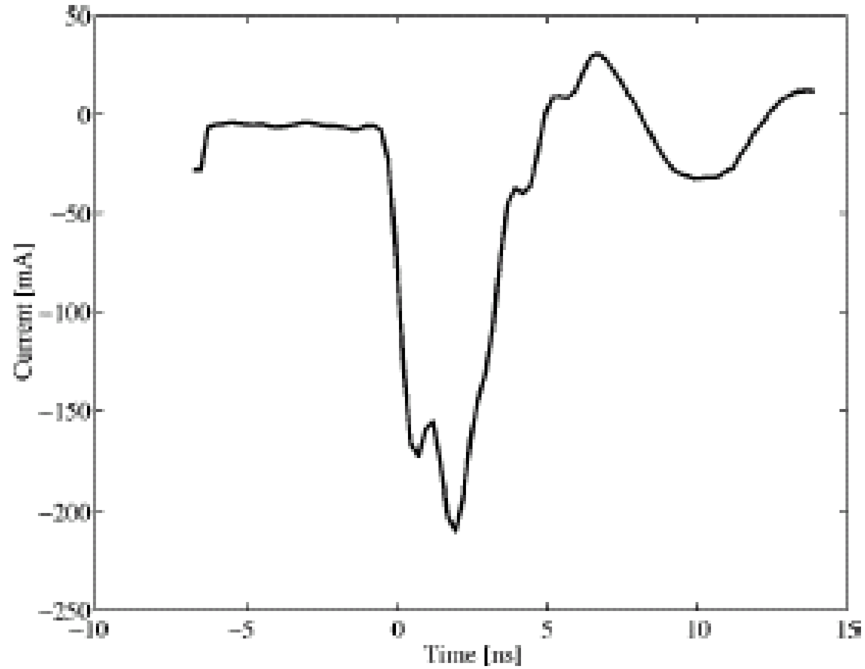
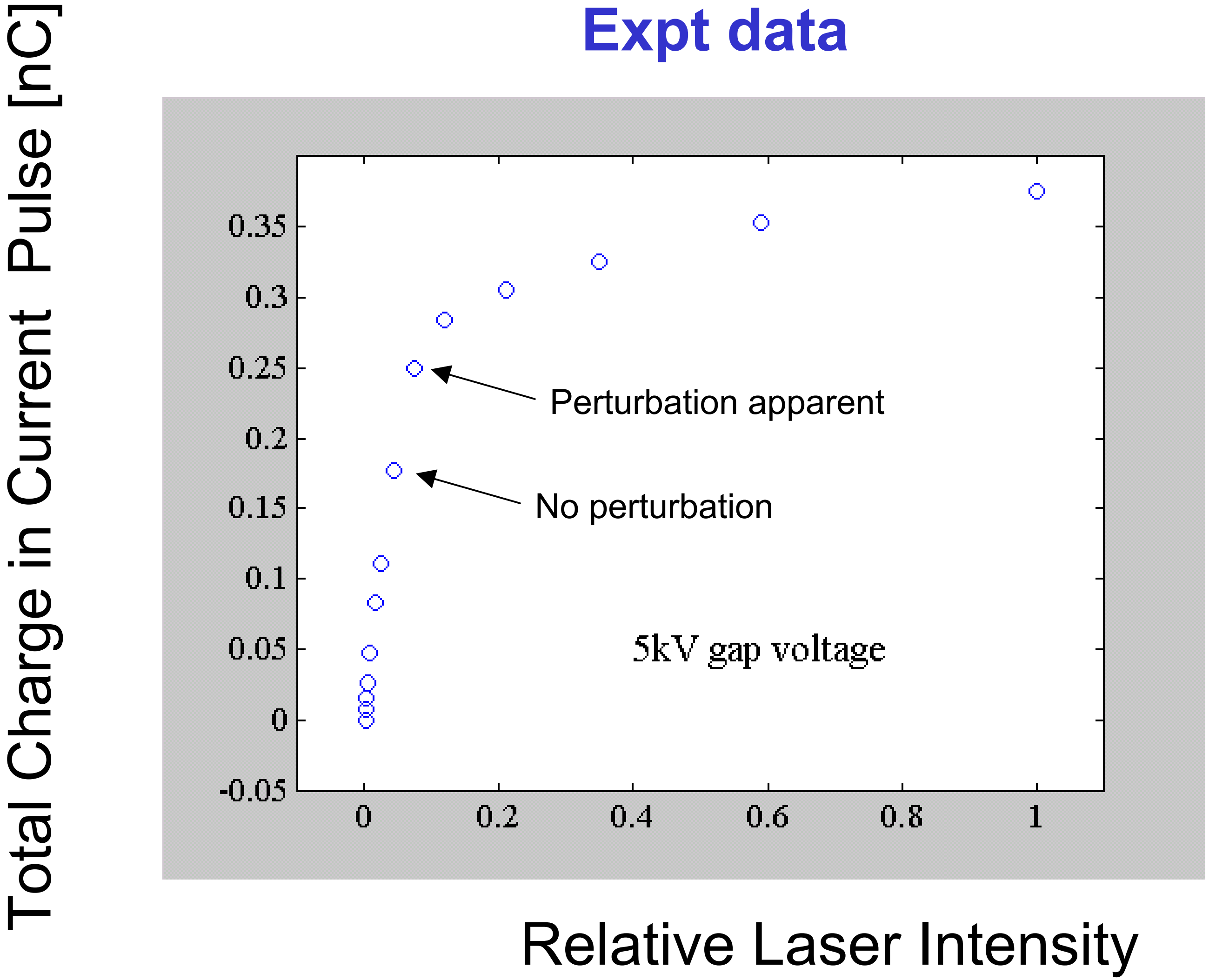


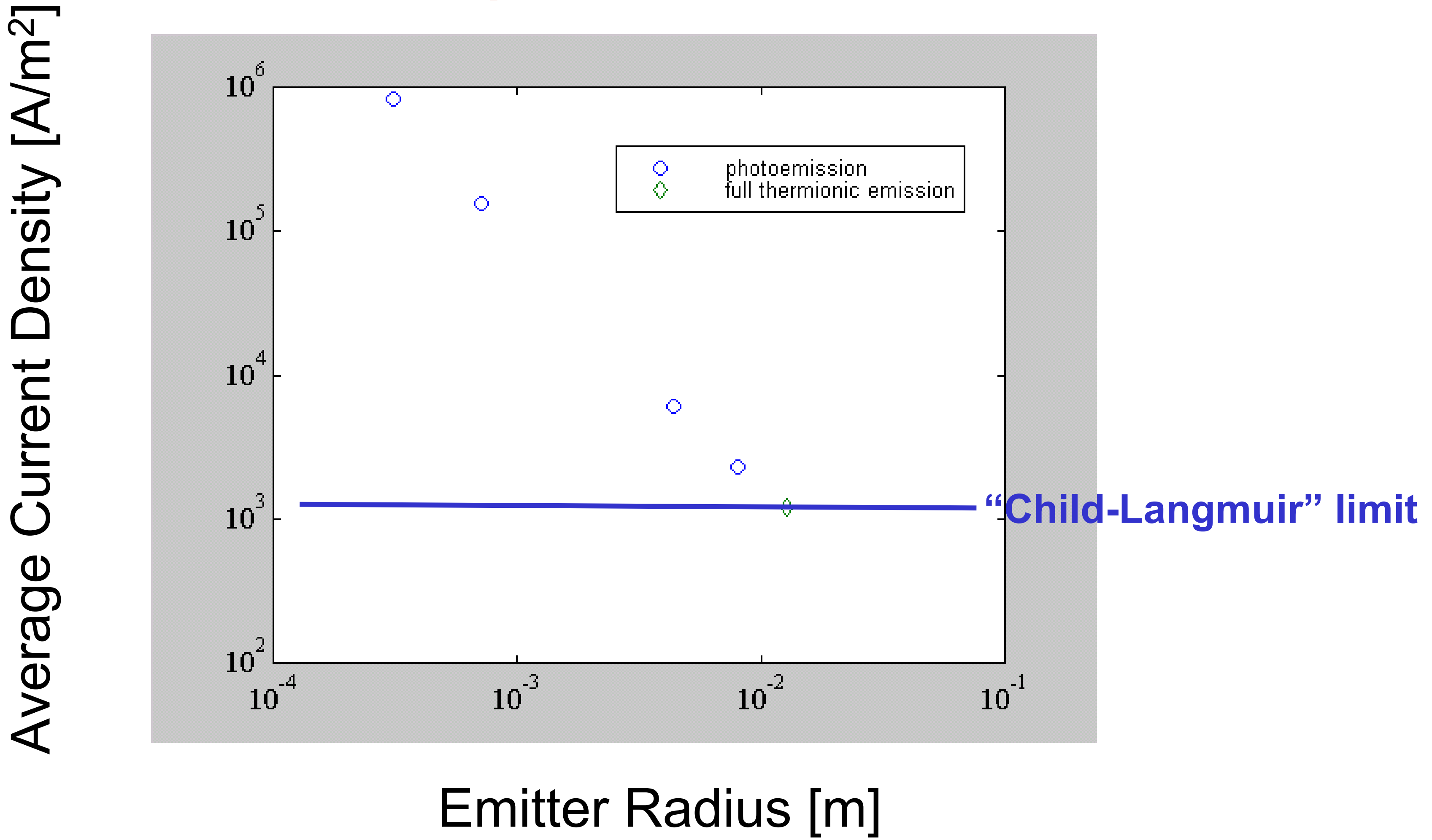
FIG. 1. Example of a current pulse with the virtual cathode manifesting itself through a dip in the pulse.

Charge per pulse vs laser intensity
Expt data



Effect of Emitter Size
Experimental data

$J \sim R^{-1.8}$

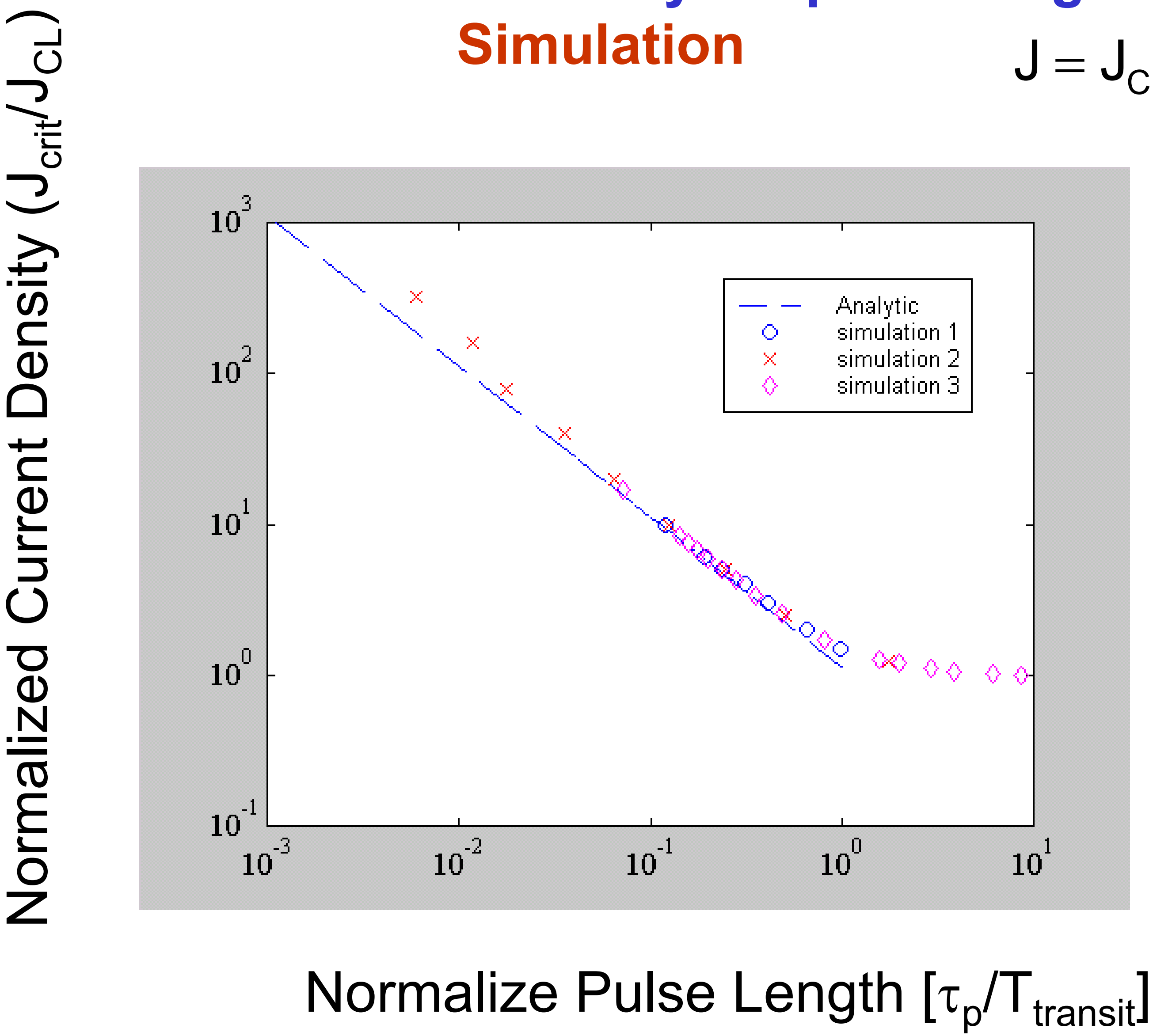


Small laser spot give big enhancement over "Child-Langmuir limit"

Critical Current Density vs. pulse length

Simulation

$$J = J_{CL}\left(\frac{\tau_p}{T_{trans}} + 1\right)$$

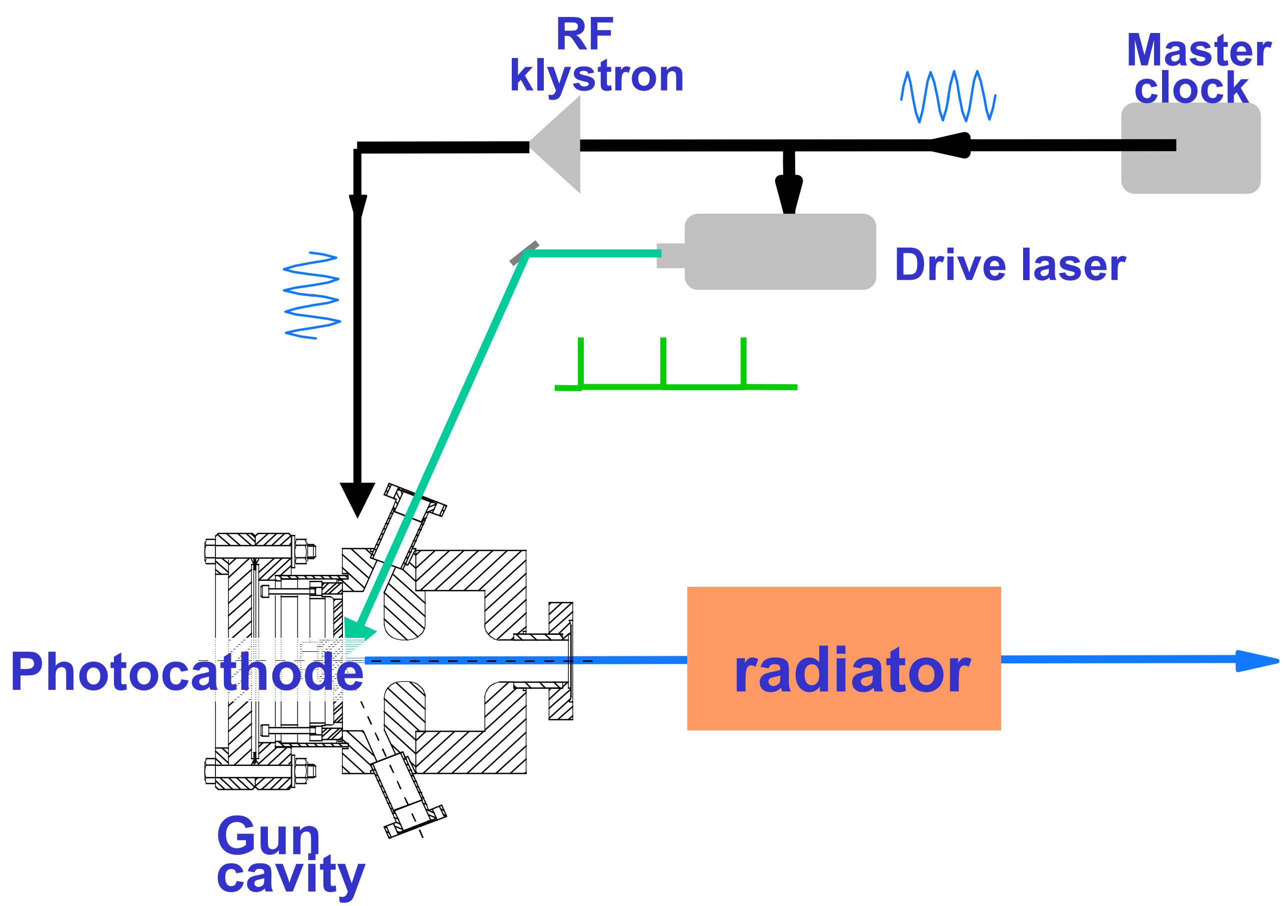


Multi-Pulse perturbations (Coherent pulse train) Collaboration with SDL at Brookhaven

J.Neumann, Ph. D student

Motivations for multi-pulse Experiments

1. Explore impact of longitudinal pulse structure on beam dynamics
2. Generate coherent radiation.

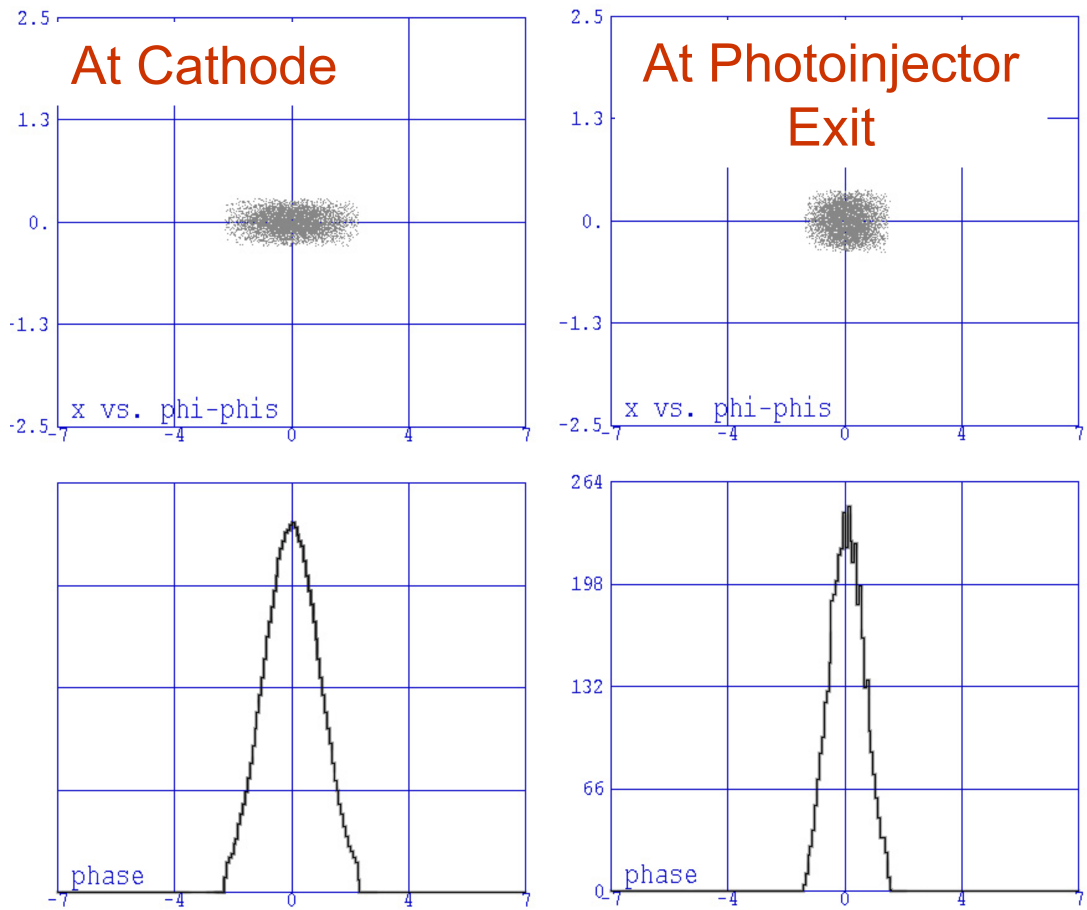


PARMELA Simulations of electron modulation (low charge control case)

Electron beam distribution at cathode and RF gun exit for a ~ 4 pS unmodulated 70 pC electron beam (Control case)

x (cm)

Electron Density



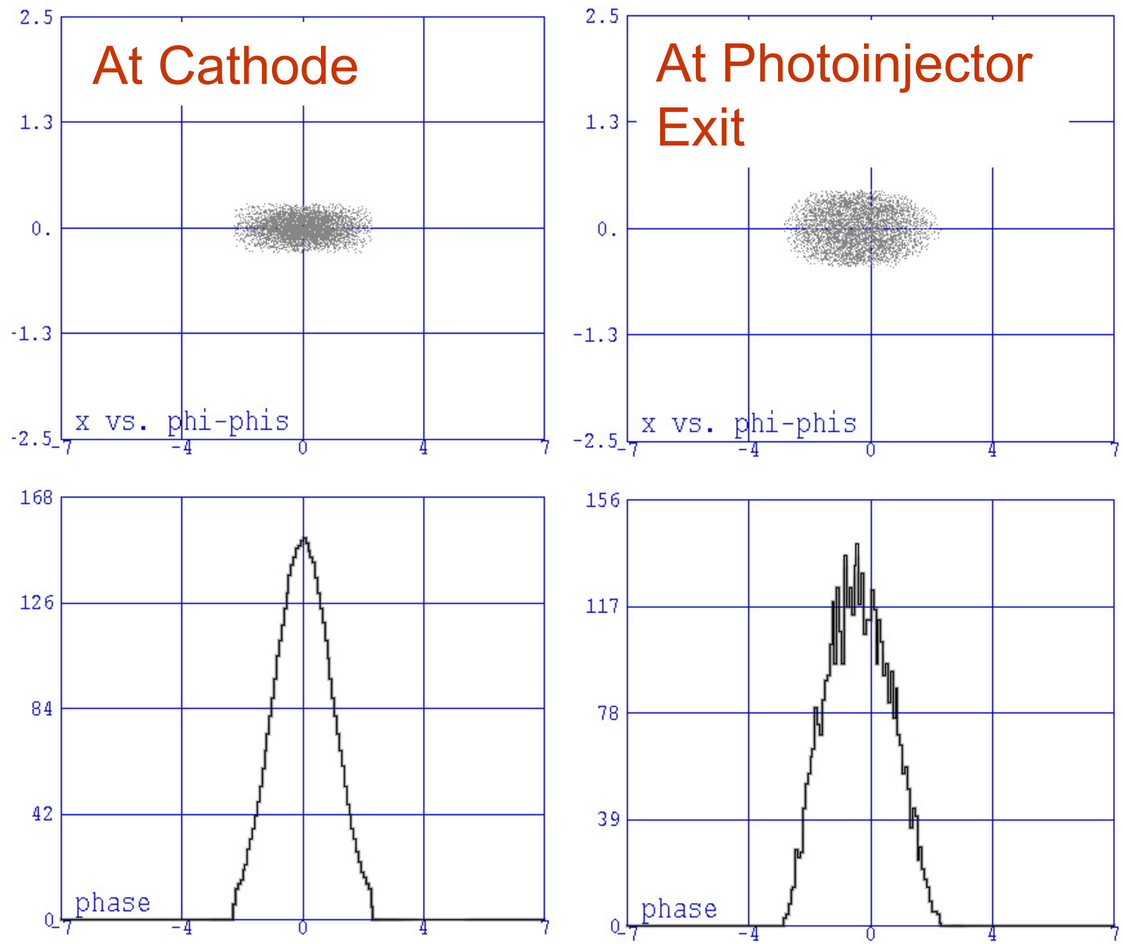
At 2856 MHz, 1° phase ≈ 1 pS, each grid line = 4°

Simulations of electron modulation
(high charge control case)

Electron beam distribution at cathode and RF gun exit for a ~ 4 pS unmodulated 1 nC electron beam (Control Case)

x (cm)

Electron Density



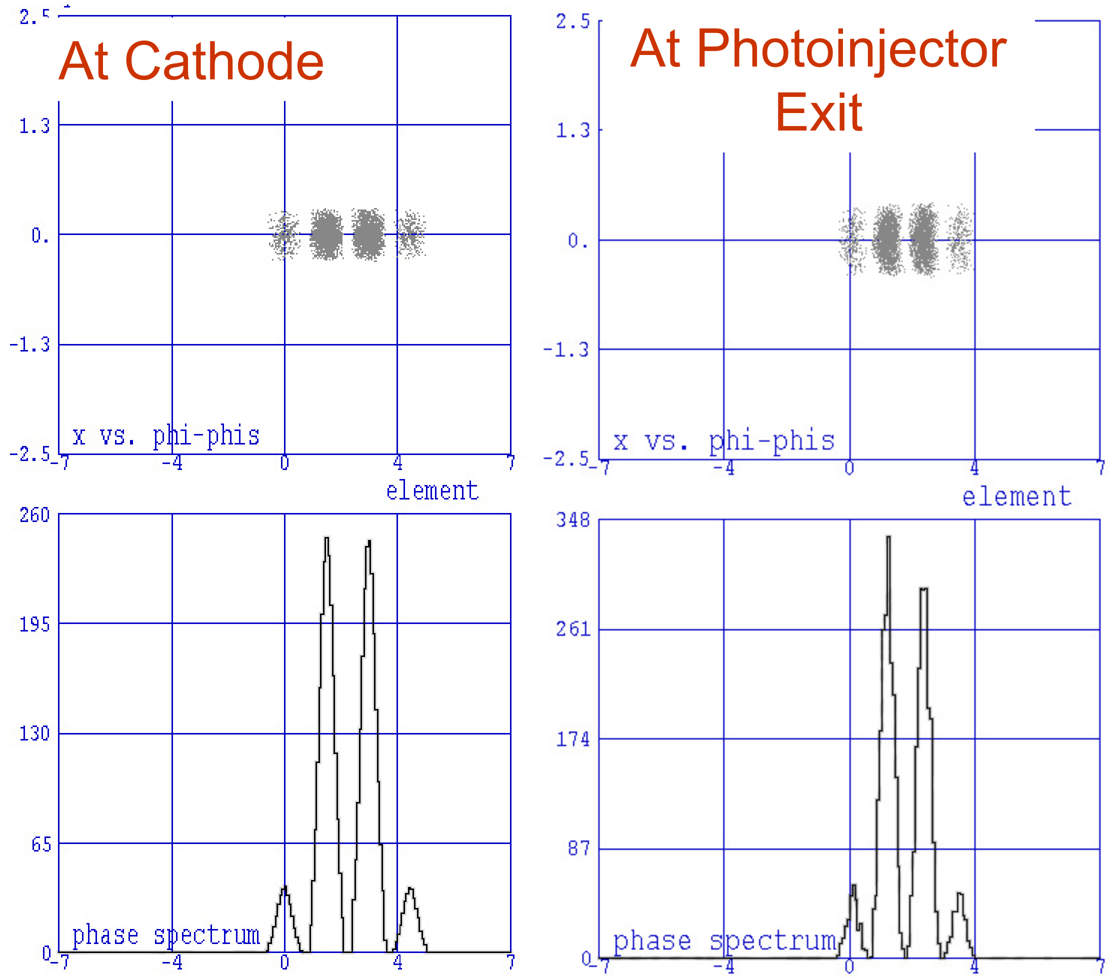
At 2856 MHz, 1° phase ⏲ 1 pS, each grid line = 4°

PARMELA Simulations with 0.8 THz Modulations (low charge case)

Electron beam distribution at cathode and RF gun exit for a **0.8 THz** modulated 70 pC electron beam

x (cm)

Electron Density



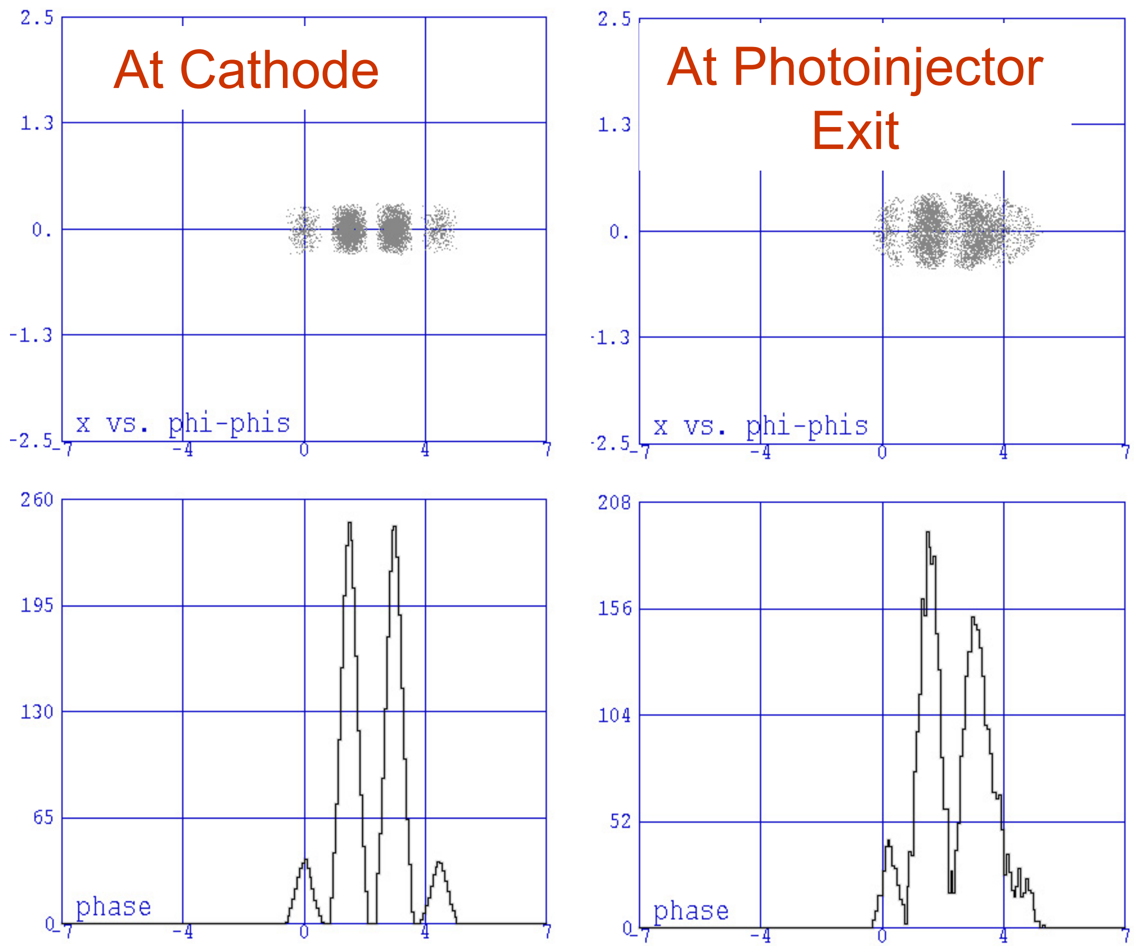
At 2856 MHz, 1° phase ⏲ 1 pS, each grid line = 4°

PARMELA Simulations with 0.8 THz Modulations (high charge case)

Electron beam distribution at cathode and RF gun exit for a **0.8 THz** modulated 1 nC electron bunch

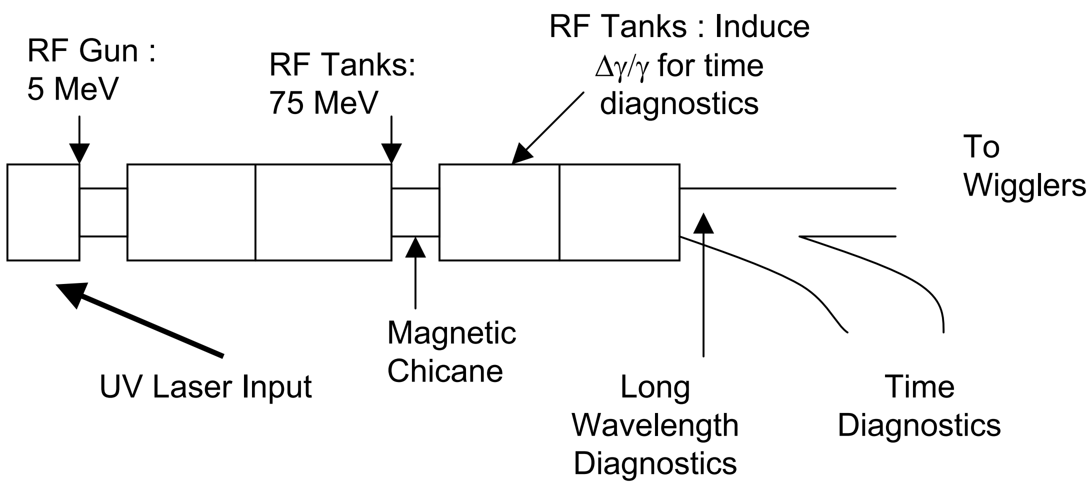
x (cm)

Electron Density



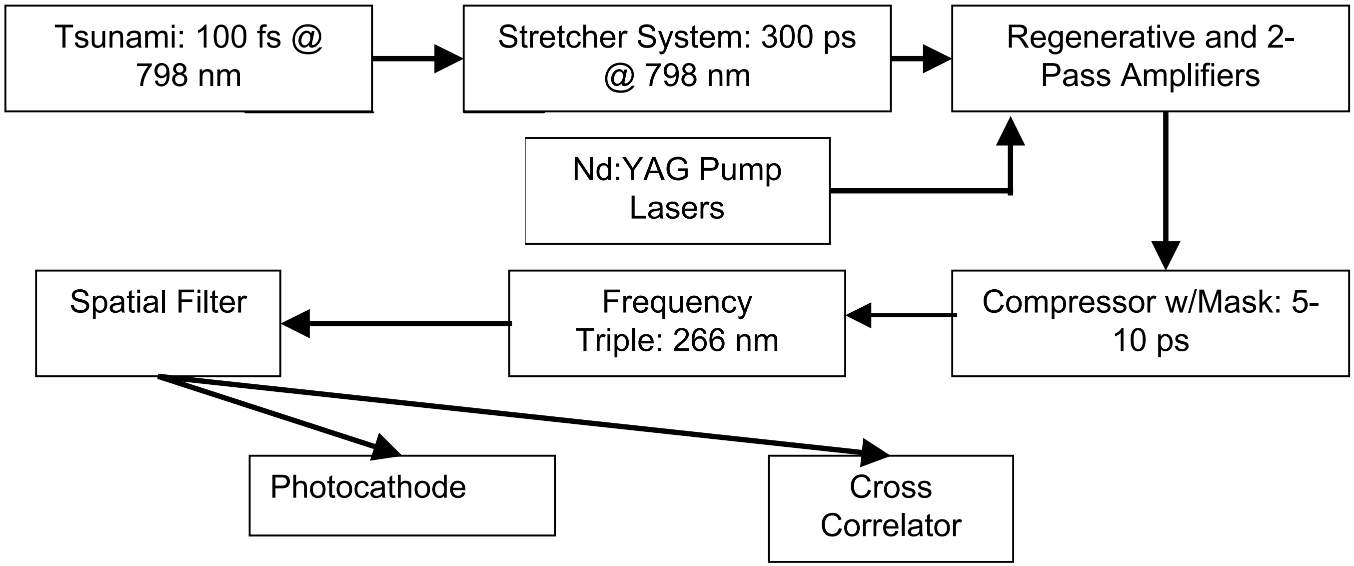
At 2856 MHz, 1° phase 🕐 1 pS, each grid line = 4°

Experimental Apparatus and Techniques



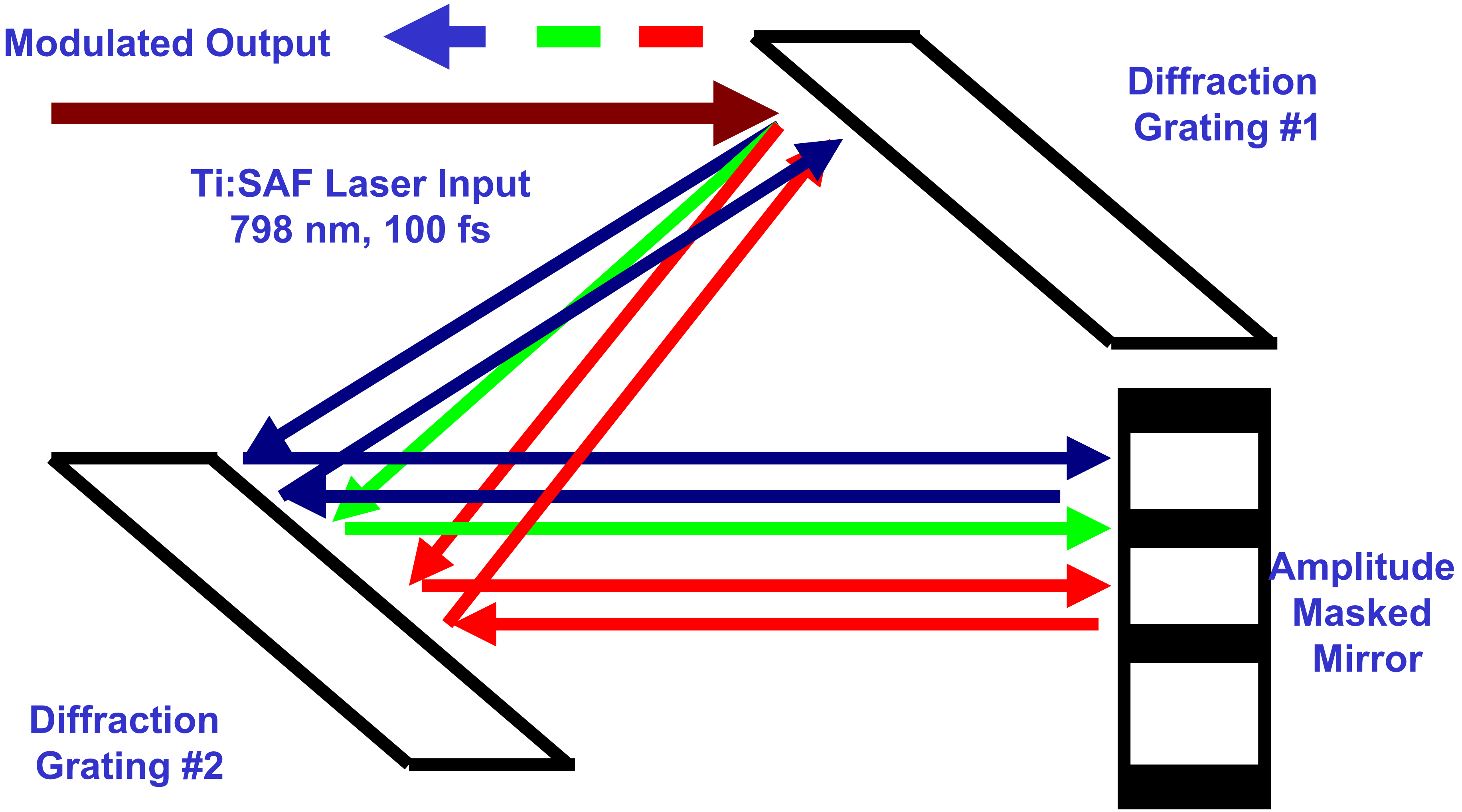
The Source Development Laboratory
at Brookhaven National Laboratory

Experimental Apparatus and Techniques



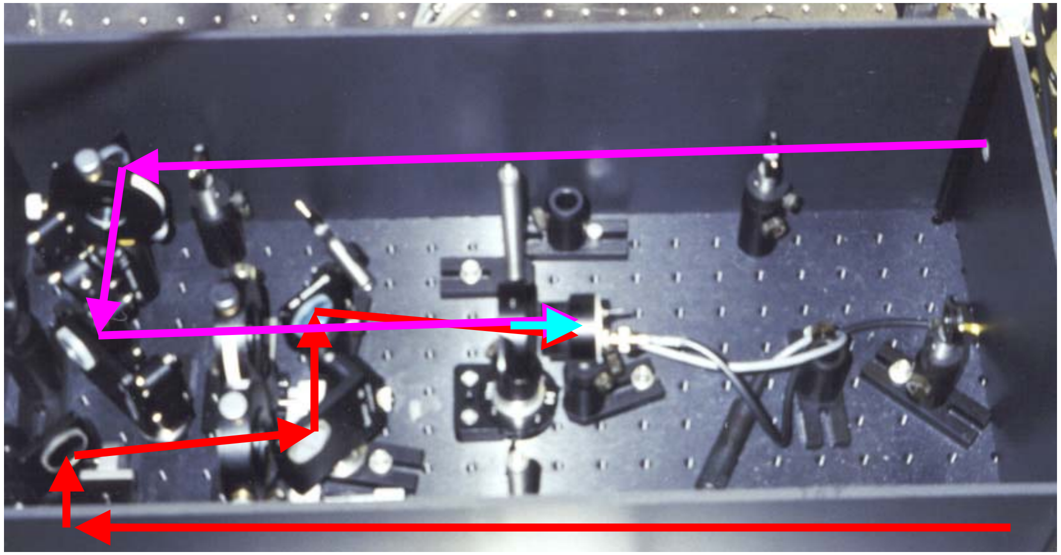
Ti:sapphire based drive laser system

Schematic Laser Modulation Technique (Spatial filtering in compressor)



This system is intended for use with the Source Development Lab at Brookhaven National Laboratory

Experimental Apparatus and Techniques



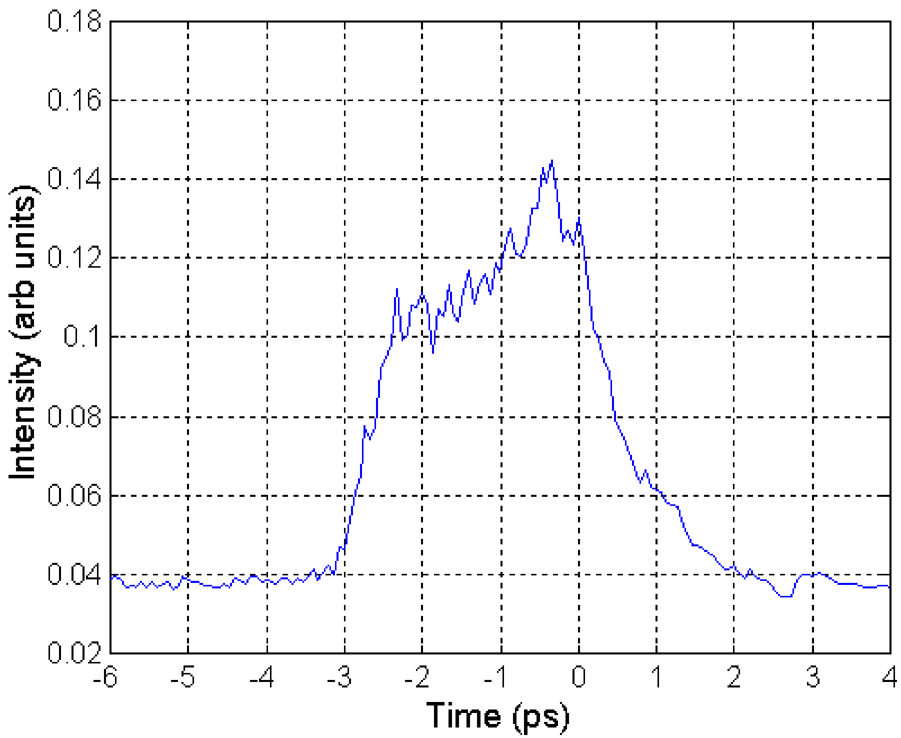
Cross Correlator

798 nm, 100 fs
266 nm
400 nm

Experimental Apparatus and Techniques

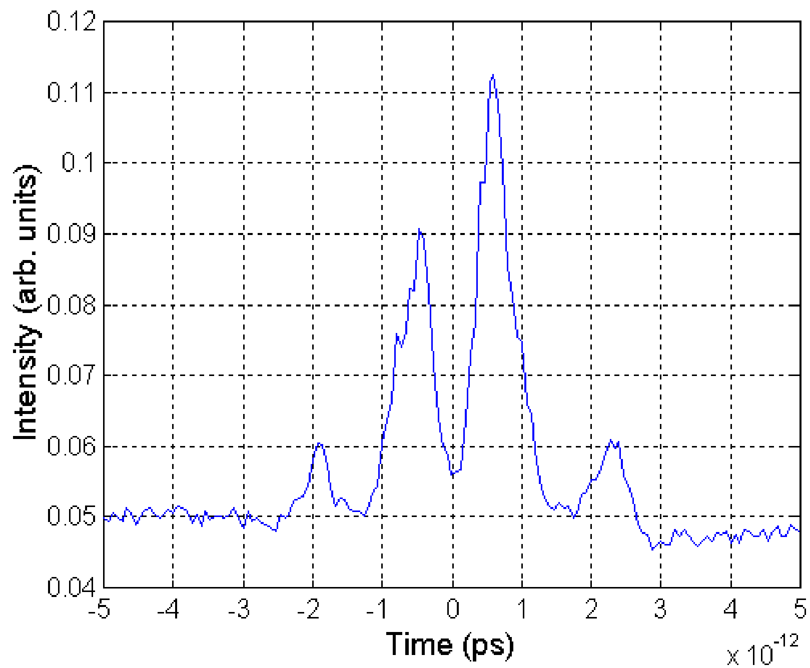
Sample Amplitude Masks Used For Pulse shaping

Experimental Results : Laser Modulation (control case: no deliberate modulation)



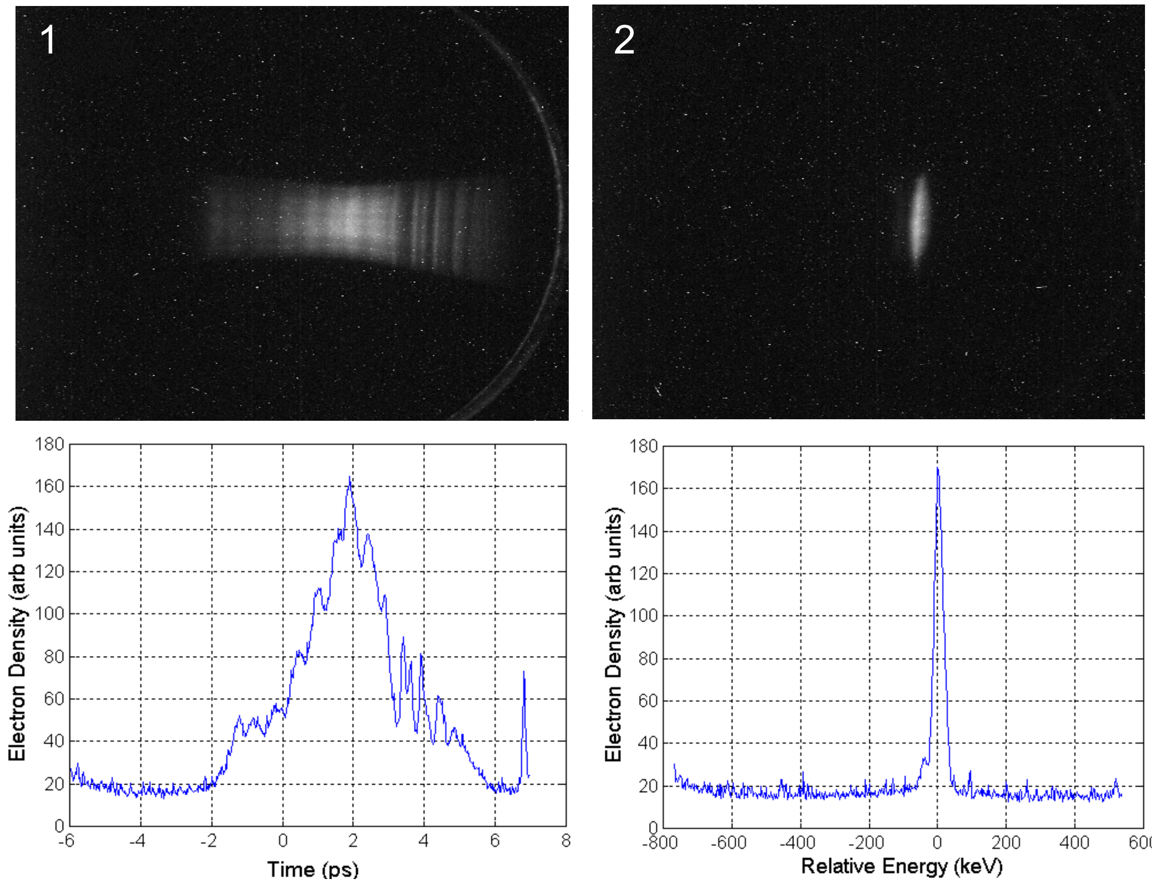
Unmodified UV Laser Time Profile (Control Case)

Experimental Results : Laser Modulation At 0.8 THz



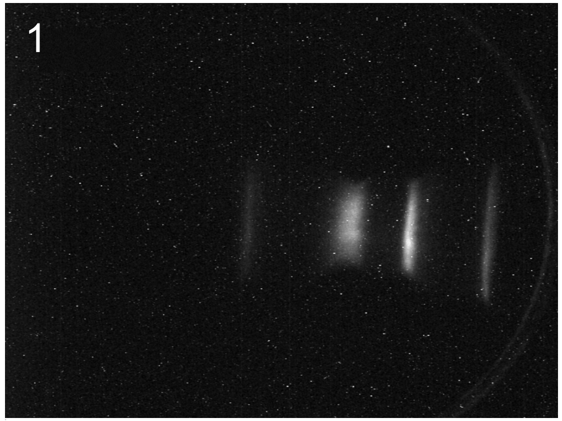
UV Laser Profile for (1.58mm) Comb Filter

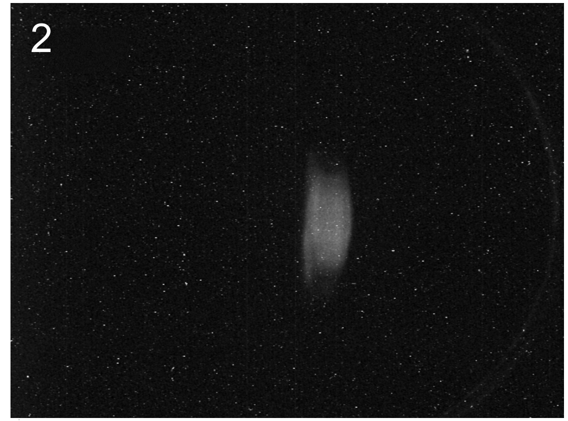
Experimental Results: Electron-beam
Control case: No deliberate laser modulation

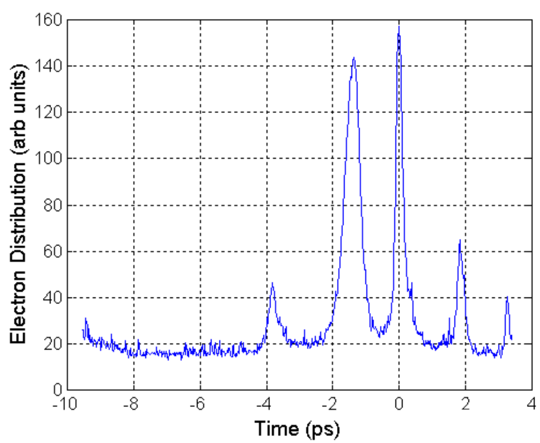


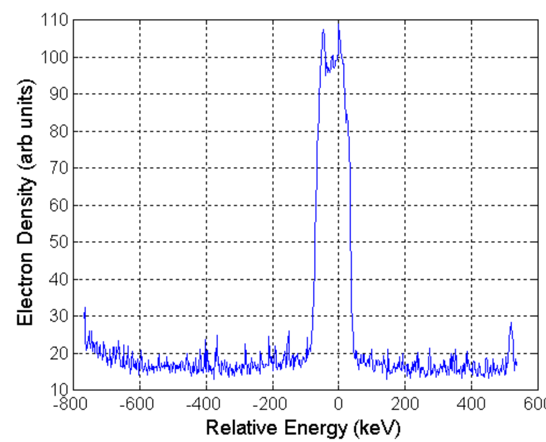
Electron Beam (1) Time structure and (2) Energy spread
(No deliberate laser modulation)

Experimental Results : Electron-Beam 0.8 THz modulation









Electron Beam Resulting From 1.58 mm Comb Filter
(1) Time structure and (2) Energy spread

Conclusions and Future Work

PARMELA Simulations:

✓ The electron beam can be deliberately modulated near 1 THz

✓ The transverse emittance is not significantly affected by the longitudinal modulation

✓ The energy spread is not significantly affected by the longitudinal modulation

Conclusions and Future Work

Drive Laser Modulation:

✓ The drive laser can be successfully modulated at 0.8 THz

✓ Longitudinal structure on drive laser control case may affect results

- No modulation faster than 0.8 THz could be experimentally verified at this time.

Conclusions and Future Work

Electron Beam Experiments:

✓ The electron beam can be successfully modulated at 0.8 THz

- In the case where the drive laser was not intentionally modulated there was still longitudinal structure on the electron beam

- No modulation faster than 0.8 THz could be experimentally verified at this time

Cathode Response Time

Prompt emission (sub ps) has two advantages and one disadvantage:

A: Allows operation in an RF gun at GHz RF frequencies

A: Allows laser pulse shaping to control temporal electron beam profile

D: Electron beam will track undesirable laser temporal fluctuations closely, i.e. little damping of instabilities

Slow emission (> ps) has one advantage and one disadvantage:

A: Cathode emission damps laser fluctuations giving a smoother electron beam

D: Difficult to use in a GHz RF gun

Note that a smooth temporal beam profile may help reduce coherent synchrotron radiation effects in magnetic bunchers and bends.

Perhaps the ideal cathode would have an emission time of a few ps to take partial advantage of the smoothing effects while still allowing operation in an RF gun.

Longitudinal energy Spread
Y. Zou and Y. Cui

Beam Cooling due to Acceleration

- **Before Acceleration:**
  - **Beam temperature is isotropic (?)**

$$k_B T_{//i} = k_B T_{\perp i} = k_B T_c$$ **~ 0.1 eV @ cathode**

- **After Acceleration:**
  - **Transverse beam temperature:**

$$k_B T_{\perp f} = \left(r_c / a \right)^2 k_B T_c$$

- **Longitudinal beam temperature:**

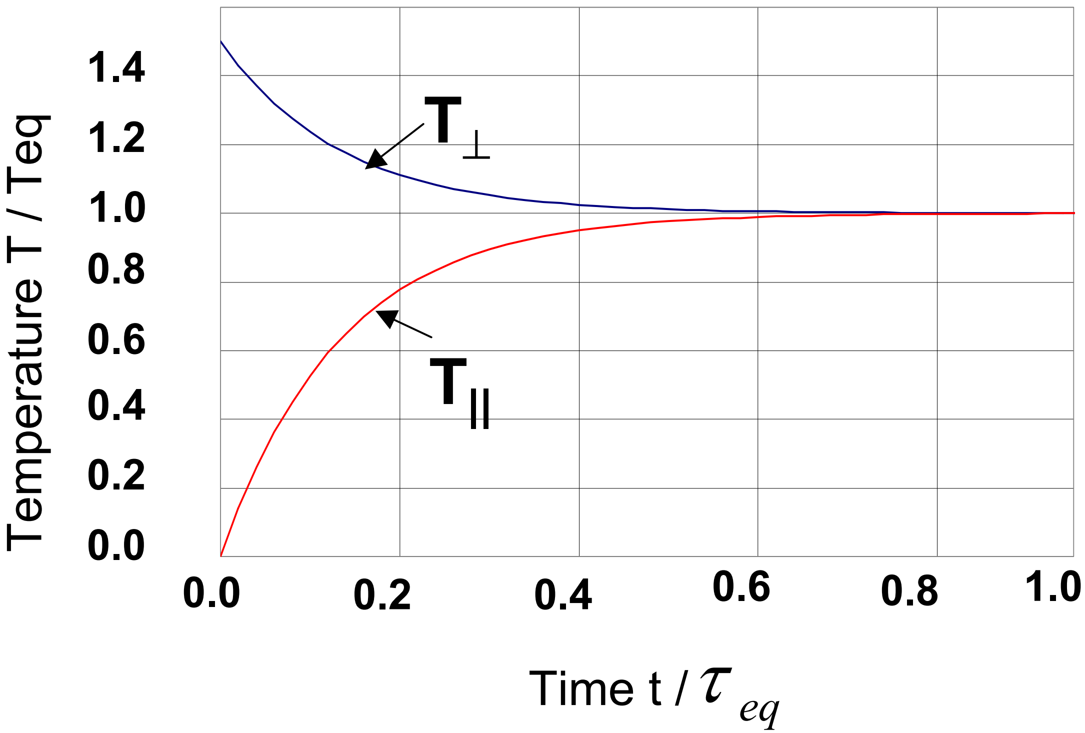
$$k_B T_{\parallel f} = \left(k_B T_{\parallel i} \right)^2 / 2\beta^2\gamma^2 mc^2$$

- **Numerical example:**

$k_B T_{||i}$ = 0.1 eV, $@$ = 10 keV, $k_B T_{||f}$ ~ 5 x 10^{-7} eV !

Energy Spread Growth in the Intense Electron Beam

- **Longitudinal-transverse relaxation due to intra beam scattering, instabilities etc (Boersch effect)[1]**
  - **Long relaxation time**



Will cause significant beam energy spread even before it reaches equilibrium

Examples: UMER qV_0=10 keV, I =100 mA, L = 10 turns (~ 110 m): Energy spread ~ 16 eV

[1] See the reviews in Chapters 5 and 6 of M. Reiser, "Theory and Design of Charged Particle Beams", John Willey & Sons, 1994.

Energy Spread Growth in the Intense Electron Beam (cont'd)

- Theoretical prediction for the longitudinal energy spread given by:

$$\Delta E_{//,rms} \approx \beta\gamma mc^2 \left(\frac{\gamma k_B T_{//}}{mc^2}\right)^{1/2}$$

$$\rightarrow \beta\gamma mc^2 \left(\frac{\gamma k_B T_{\perp}}{mc^2}\right)^{1/2}$$

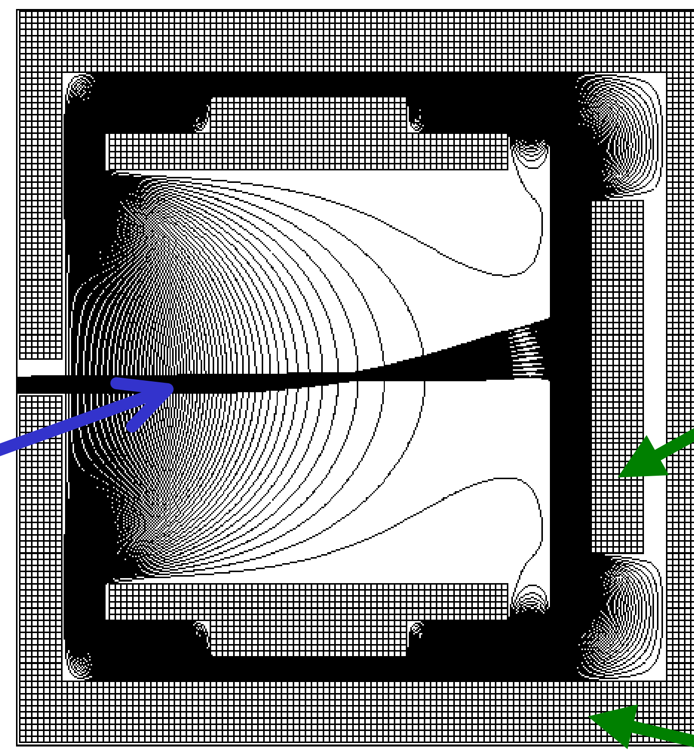
- **Also:** Longitudinal-longitudinal relaxation related to fast (nonadiabatic) acceleration [2]
  - Short relaxation time, ~ plasma period

[2] See, for instance, A. V. Aleksandrov et al. Phys. Rev. A, 46, 6628 (1992)

Experimental Study of Beam Energy Spread
Energy Analyzer Design

Y. Zou and Y . Cui

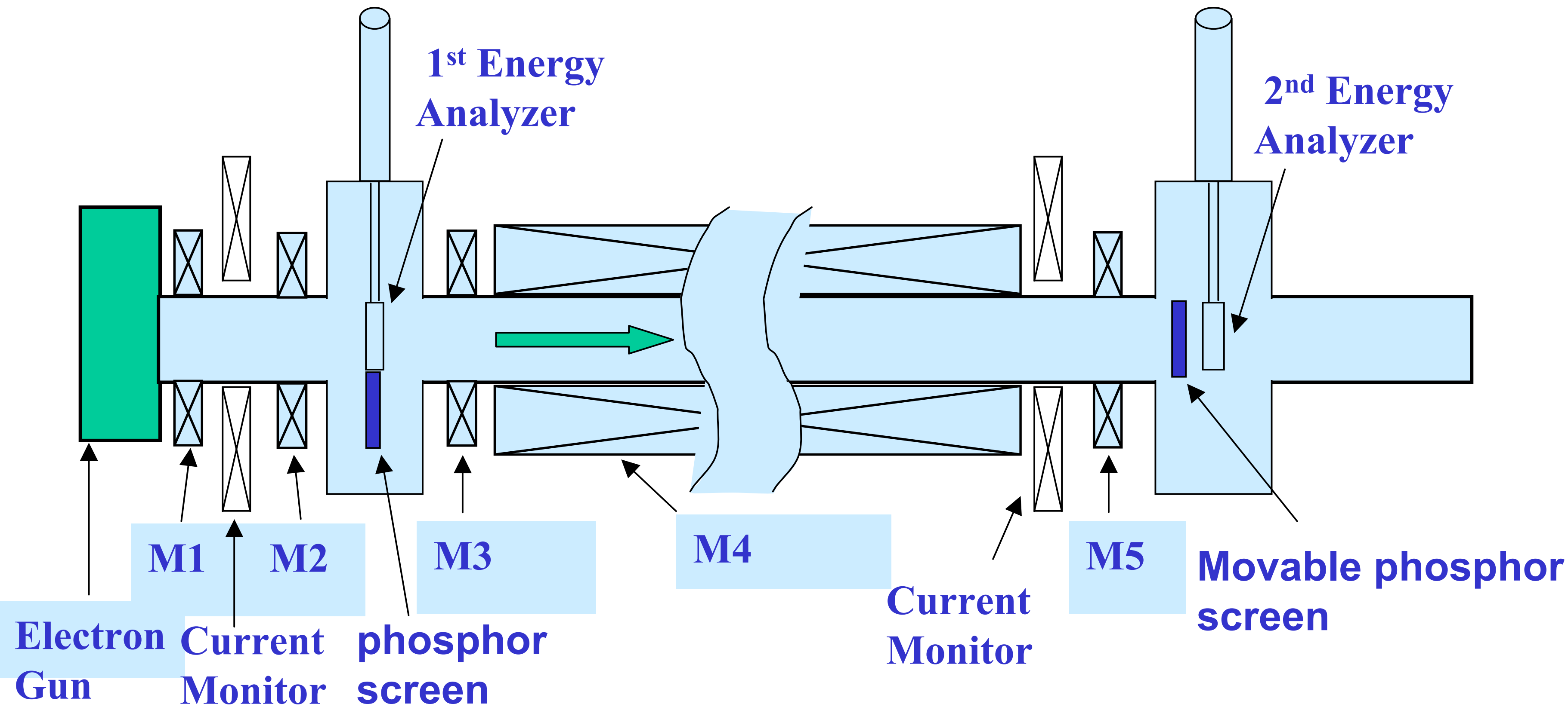
- Regarding field energy analzyer
- High resolution (< 1 eV for 10 keV beam)
- ns temporal resulation



3rd Generation: Res. < 1 eV

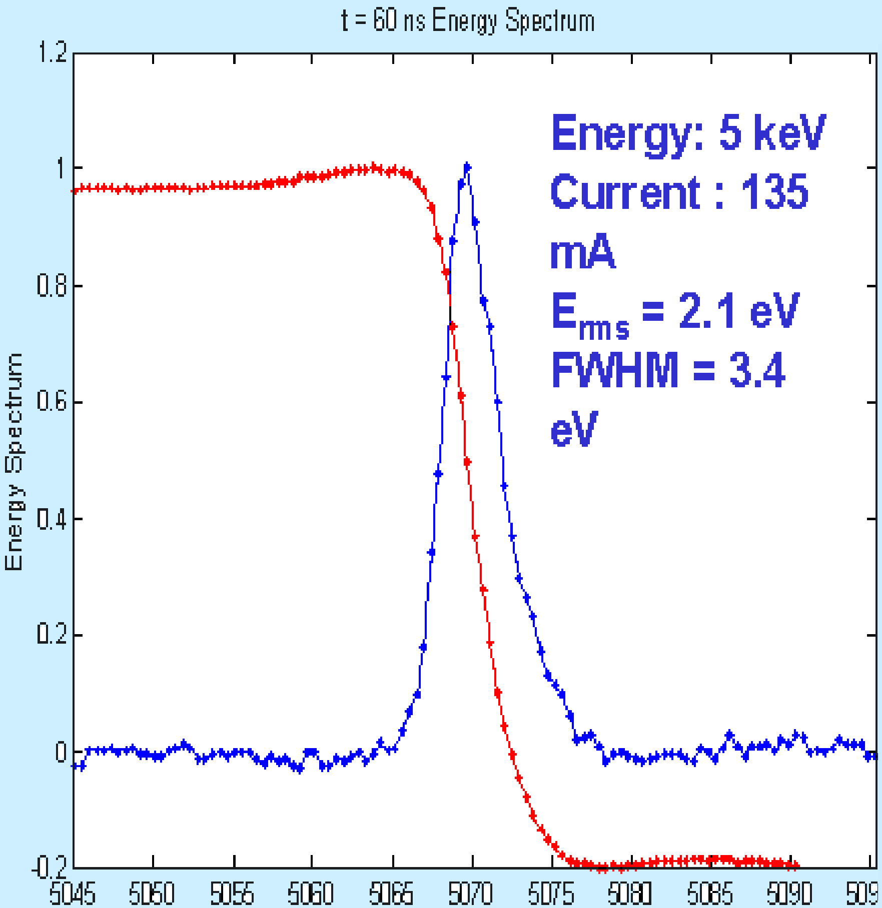
Experimental Study of Beam Energy Spread

- Long Solenoid Channel Experiment (Length: 2 m)
  - Energy analyzer test bed
  - Study the energy spread evolution in linear channel due to the intra beam scattering, mismatch, instability …
- Beam parameters:
  Energy: 1~5 keV, Current: 12 mA ~ 150 mA

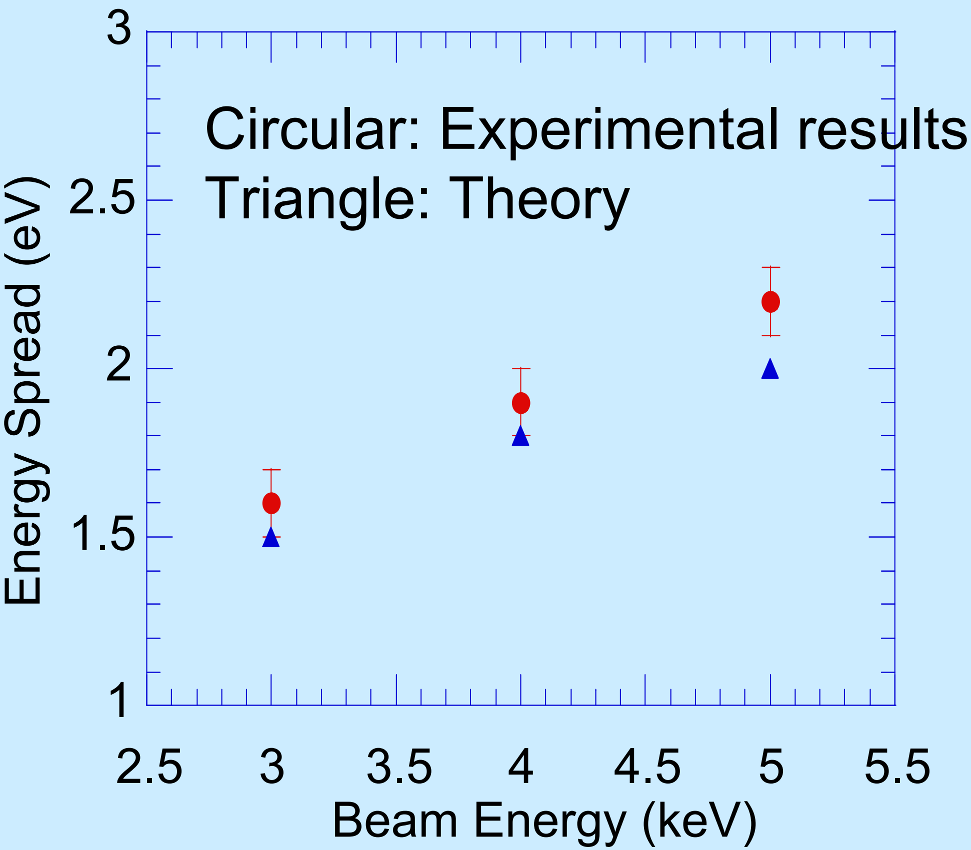


Preliminary Experimental Results

- **Location: 1st analyzer, ~25 cm from gun**

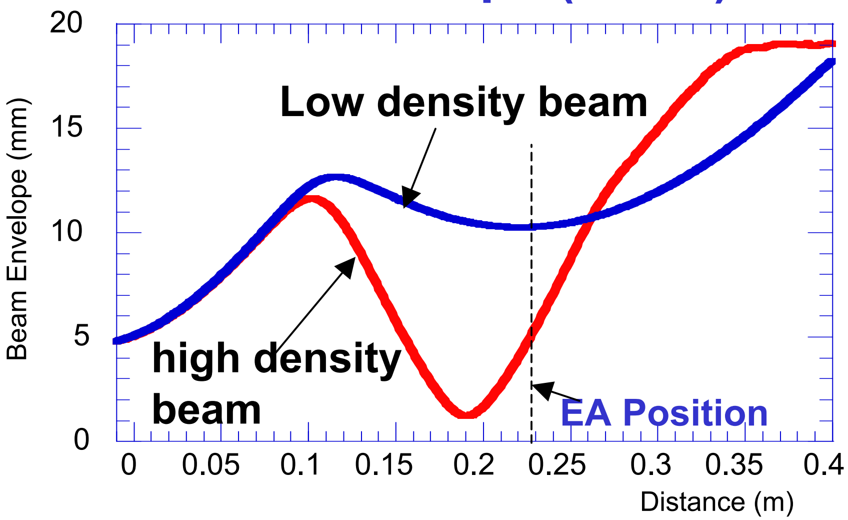


Measured beam energy spectrum

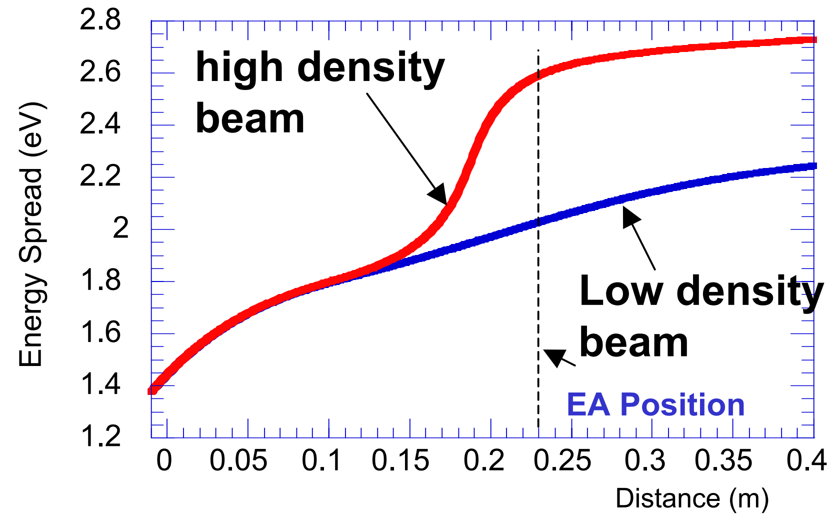


Energy Spread vs Beam Energy at Different Particle Densities

Beam envelope (5 keV)

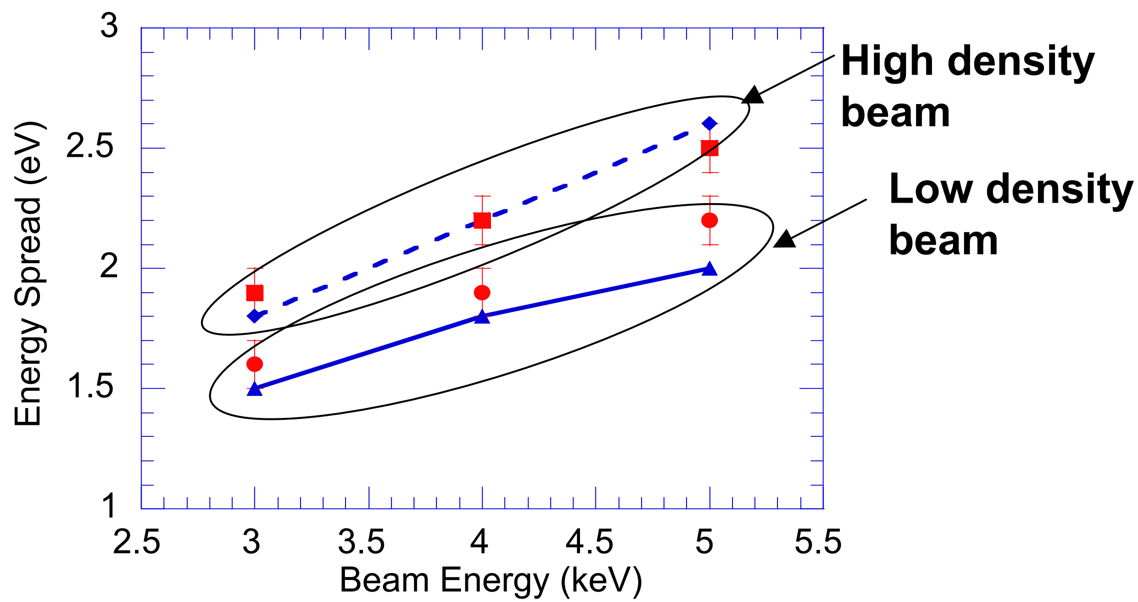


Calculated energy spread



Comparison of experimental results and theory

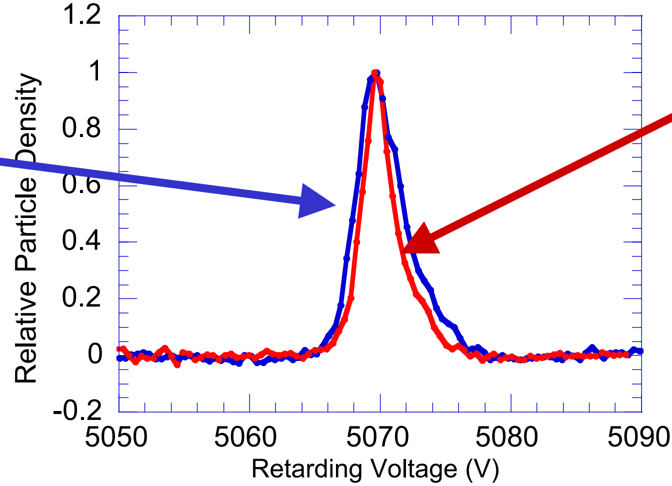
(Dots with error bars: experimental results.
Dashed curves: theoretical calculations)



Energy Spread at Different Beam Currents

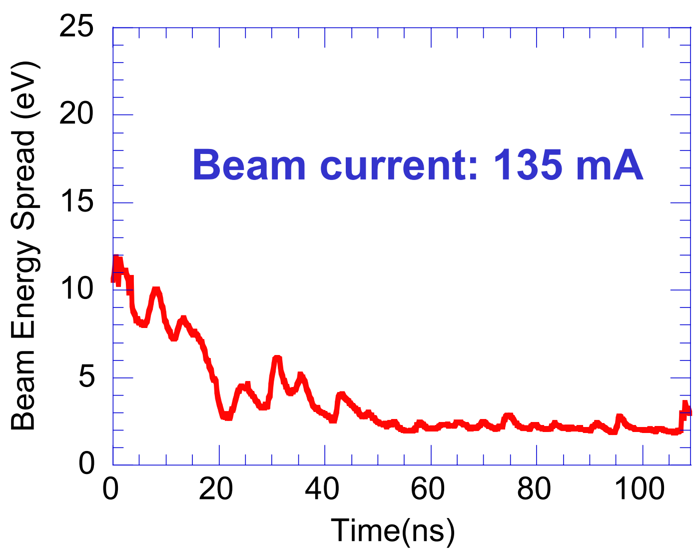
Beam Energy : 5 keV, Sampled position: 60 nS

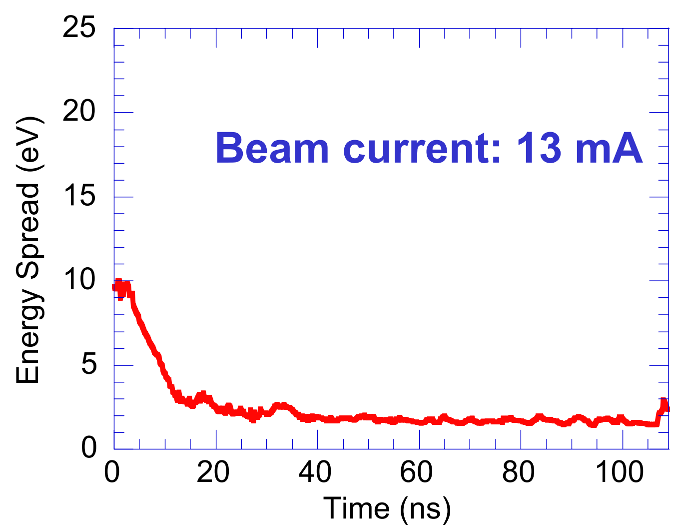
Beam current: 135 mA
Energy spread: 2.1 eV



Beam current: 13 mA
Energy spread: 1.7 eV

Energy spread along the pulse (time resolved)





Mean Energy Along the Pulse

Beam Energy : 5 keV,
Location: 25 cm from anode