Energy Analyzers
June 26, 2008

USPAS - Summer 2008

Rami Kishek

Presentations

Friday, 6/27, 9:30 AM - NOON ANNAPOLIS (Breakfast Room)
10 min each, including questions (recommend 5 slides)

Sources	Carlos Maidana
Beam Monitors	Matt Hodek
Imaging	Tiago Silva
Tomography	
Solenoid	Jamie Blowers
Rotating Coil	Ed Nissen
Longitudinal Dynamics	
Energy Analyzer	Yingjie Li
Tune Measurements	Adam Lichtl
Resonances	Finn O'Shea

Motivation

Particle velocity affects its response to a given field

Lenses:

- Chromatic effects, ability to focus

Bends:

- Dispersion (different trajectories for different energy particles)
- Energy modulations $\Rightarrow$ beam bunching

  $\Rightarrow$ Coherent Synchrotron Radiation

Goal: Map the Energy Distribution – Longitudinal Phase-space

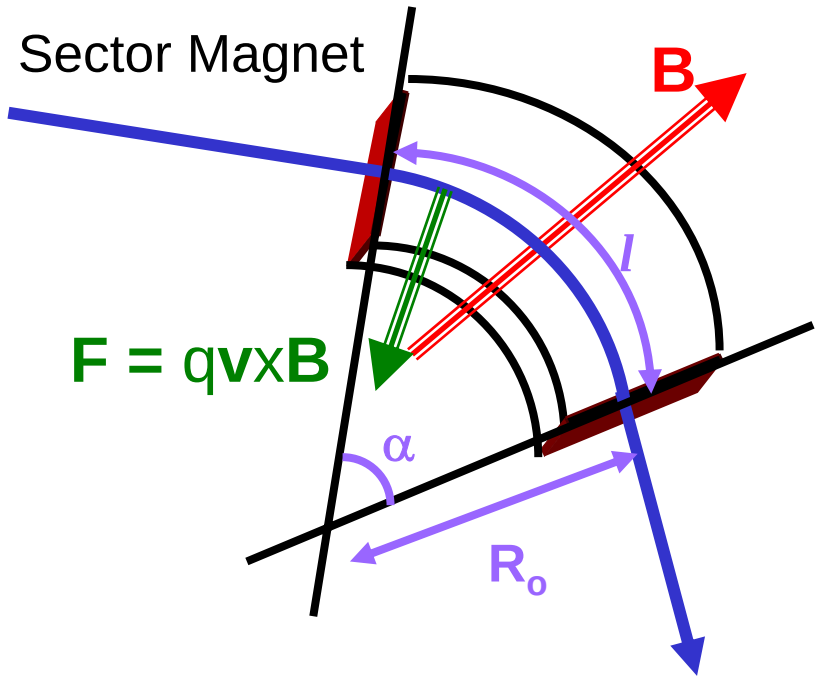
Outline

1. Measuring the Energy Distribution
2. High-Resolution Retarding Potential Energy Analyzer
3. Operation and Data-Processing
4. Space Charge Effects in EA
5. Outline of Experiment

Dipoles and Dispersion

$$\gamma m \frac{v^2}{R_o} = qvB$$

$$R = \frac{l}{\alpha}$$



$$\Rightarrow \boxed{B = \frac{\gamma\beta mc}{q}\frac{\alpha}{l}}$$

E.g., for UMER:

$\beta\gamma$ = 0.20
mc^2 = 511,000 eV
q = -e
l_{eff} = 3.85 cm
α = 10° = 0.174 rad

$\Rightarrow$ B = 15.4 Gauss

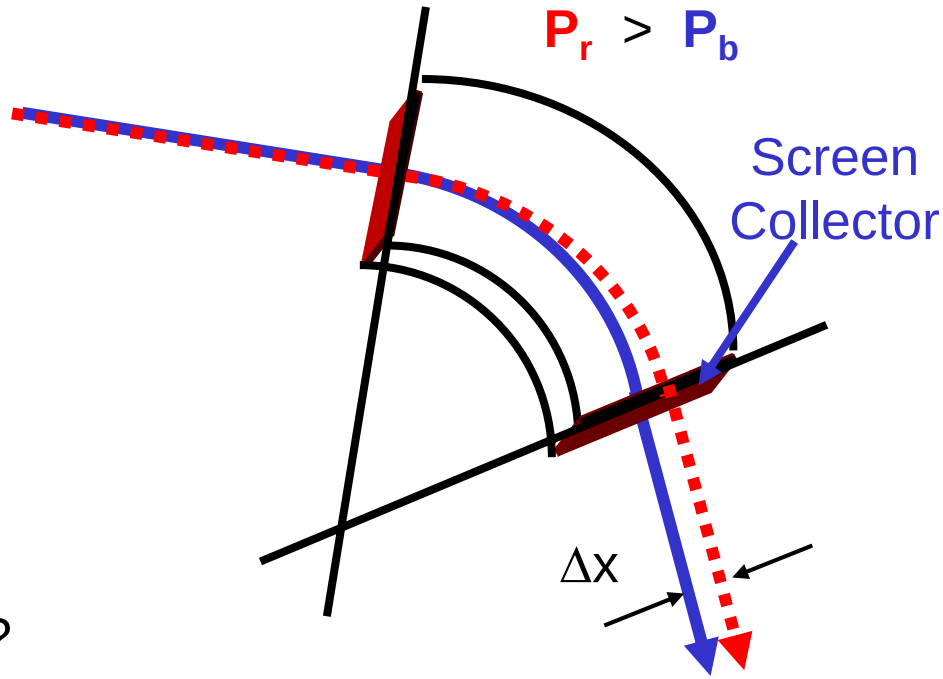
Rigidity of UMER beam = $[B\rho] = B^*l/\alpha$ = 340 G-cm/rad

Measuring the Energy Distribution – part 1

Exploit dispersion! - "mass spectrometer"

Bend radius depends on momentum

$$R = \frac{\gamma\beta mc}{qB} = \frac{P}{qB}$$



Can easily show: $\Delta R = R_o \frac{\Delta P}{P_o}$

What about transverse displacement?

In sector dipole with uniform field: $\langle \Delta x \rangle \approx \Delta R$

Highest sensitivity for 180° angle ($\Delta x = 2\,\Delta R$)

$$\frac{\Delta x}{\Delta P / P_o} = 2R_o$$

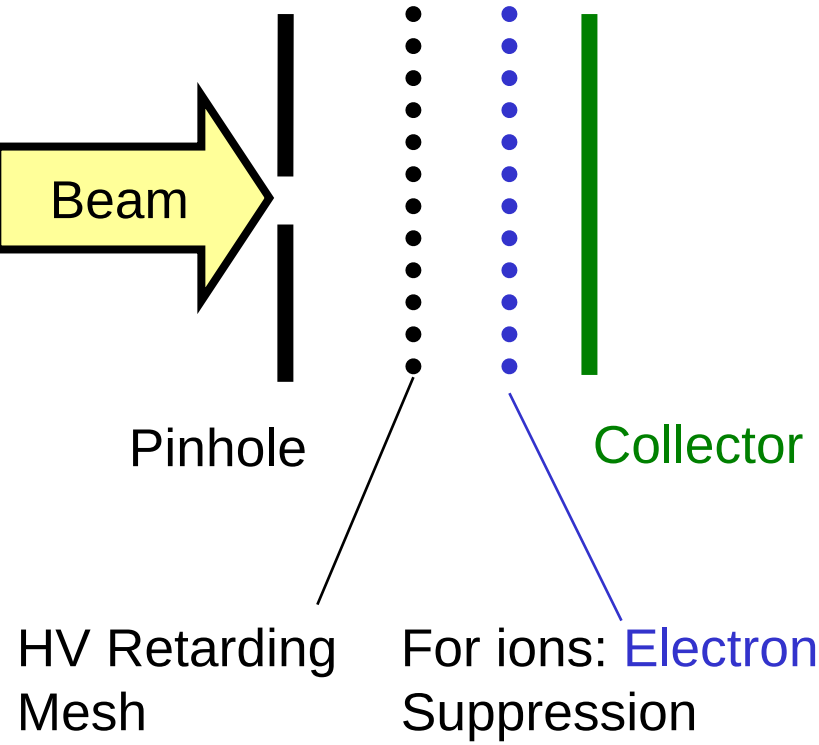
Tradeoff between size and sensitivity

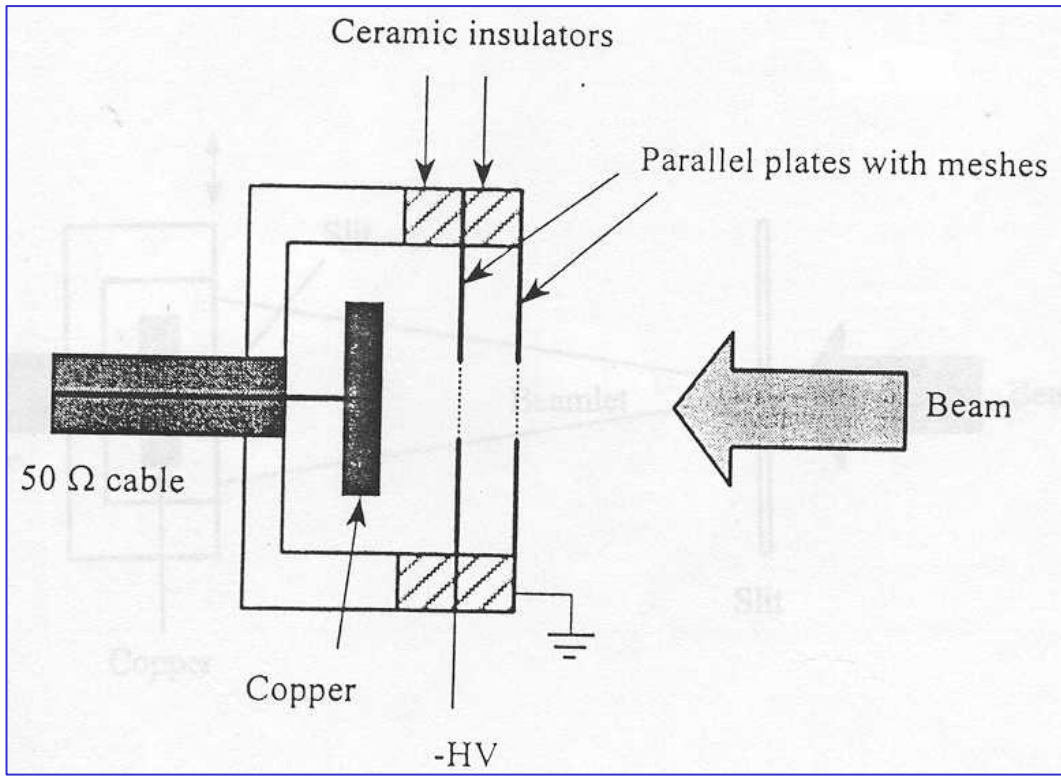
Tends to be large, but can handle high-energy beams, high resolution

Measuring the Energy Distribution – part 2

Want compact device ⇒ Retarding Potential Energy Analyzer

Parallel-Plate Design



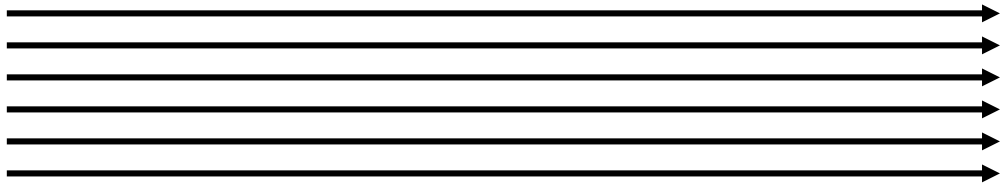


Structure of a parallel-plate energy analyzer
H. Suk, Ph.D. dissertation

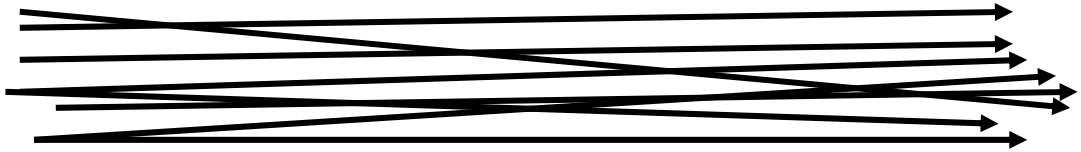
An "inverse gun"

Correlated and Uncorrelated Momentum Spread

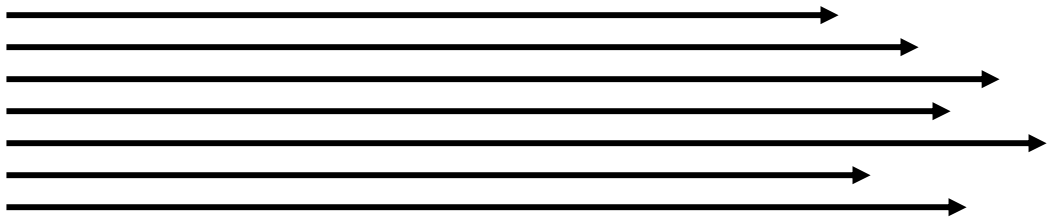
Laminar Beam (Ideal)



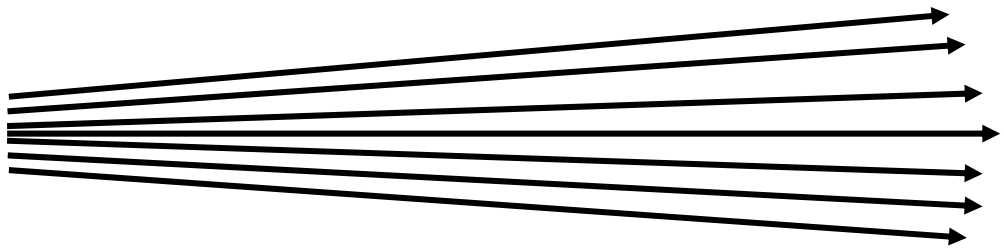
Typical beam



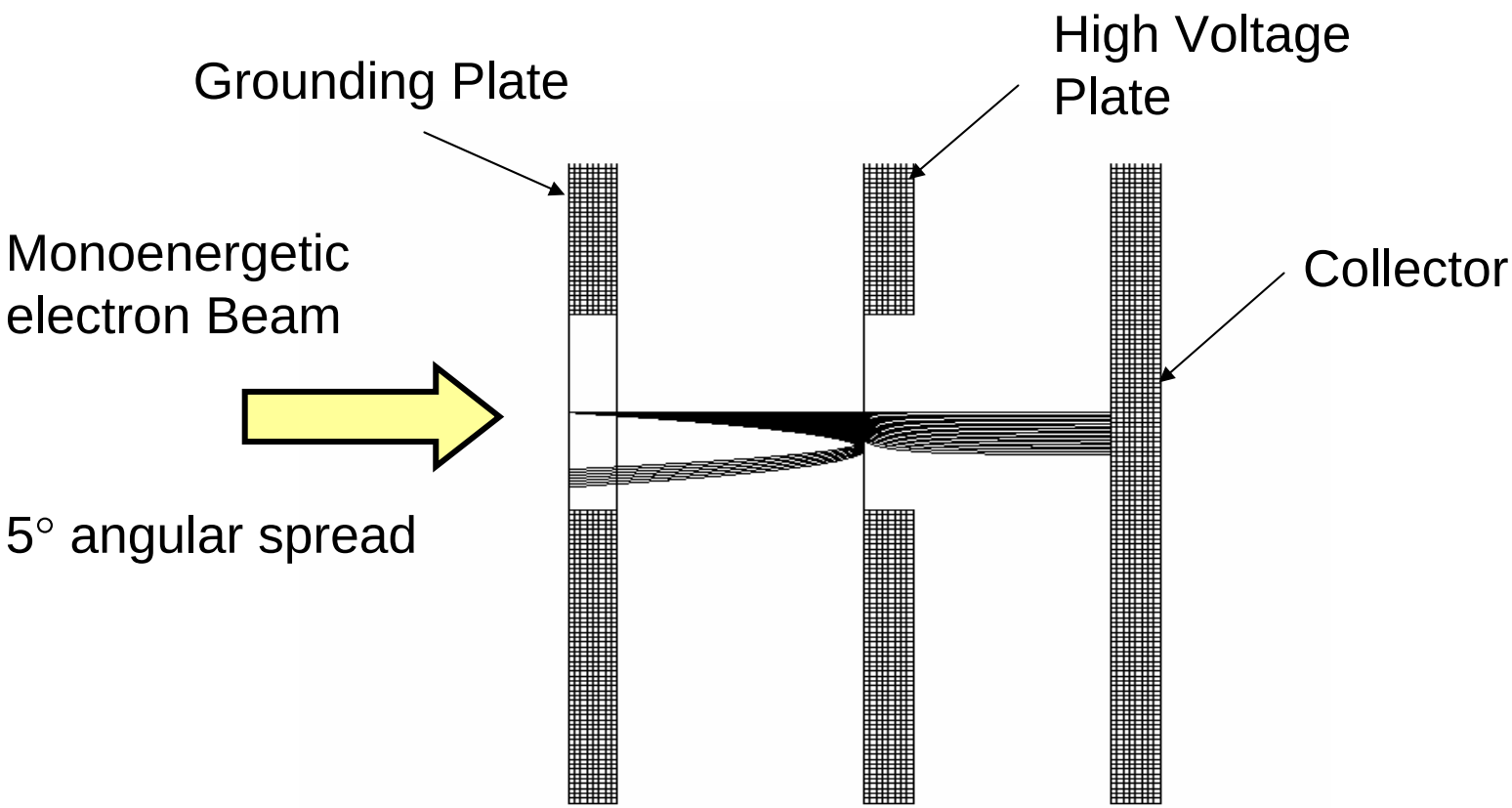
Energy spread (random)



Correlated Longitudinal Velocity Spread



Parallel-Plate EA Problem



Transverse expansion of beam causes apparently larger energy spread.

Energy Resolution Not Good (20 eV / 10 keV)

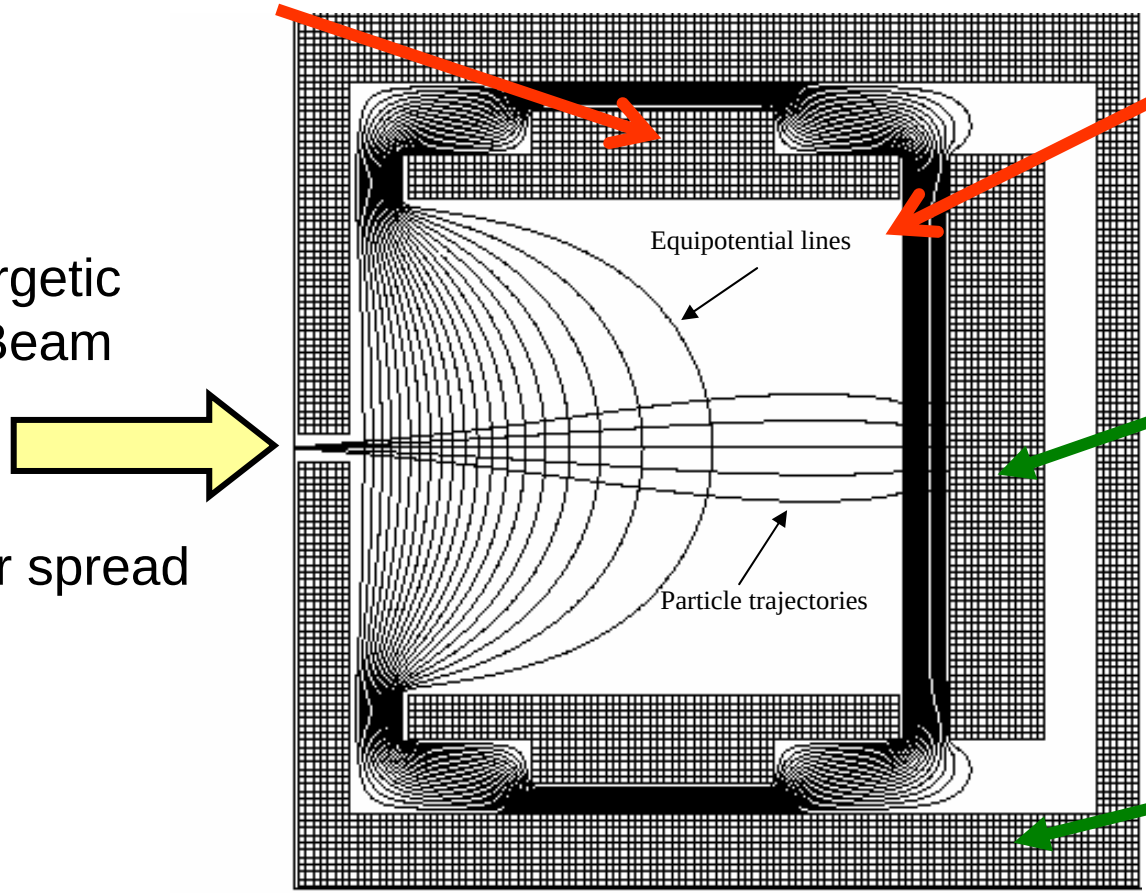
Credits: Yun Zou, SimIon simulation

High-Resolution Energy Spread Measurements

Collimating Cylinder

Retarding Mesh

Monoenergetic electron Beam



Collector

5° angular spread

Grounded Housing

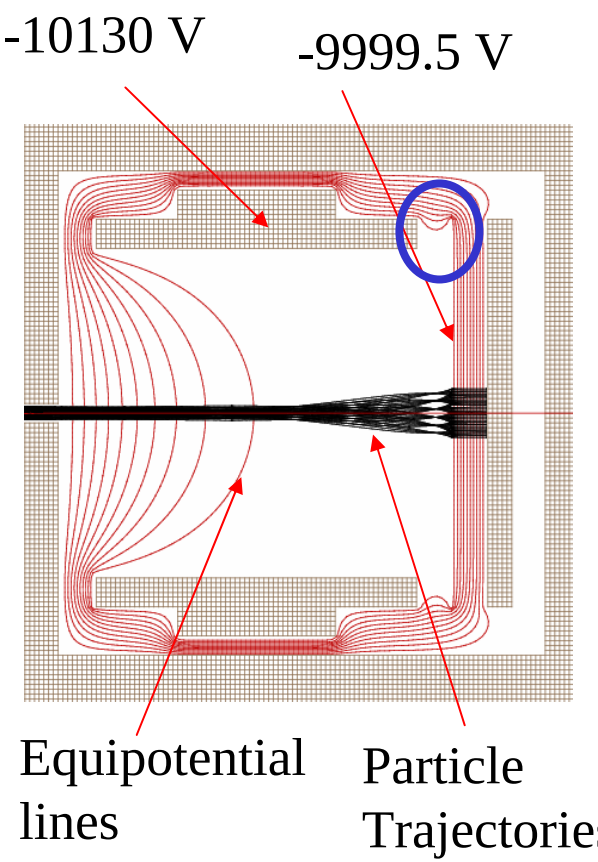
Curved equipotential lines collimate beam, so particles with tilted trajectories can overcome the retarding potential.

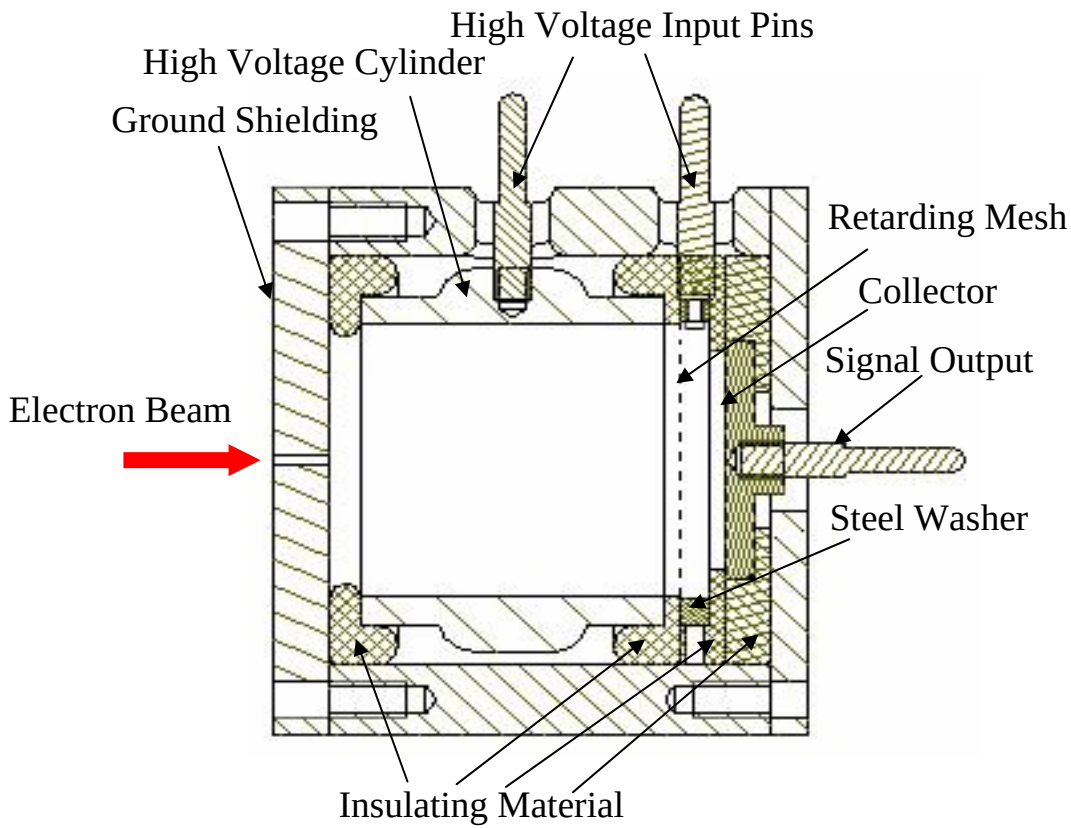
Credits: Yun Zou, SimIon simulation

2nd Generation ~ 8 eV Resolution

3rd-Generation Device Schematics

Spatial resolution: ~1 mm,
Time resolution: ~ few ns
Relative energy resolution: < 10^{-4}

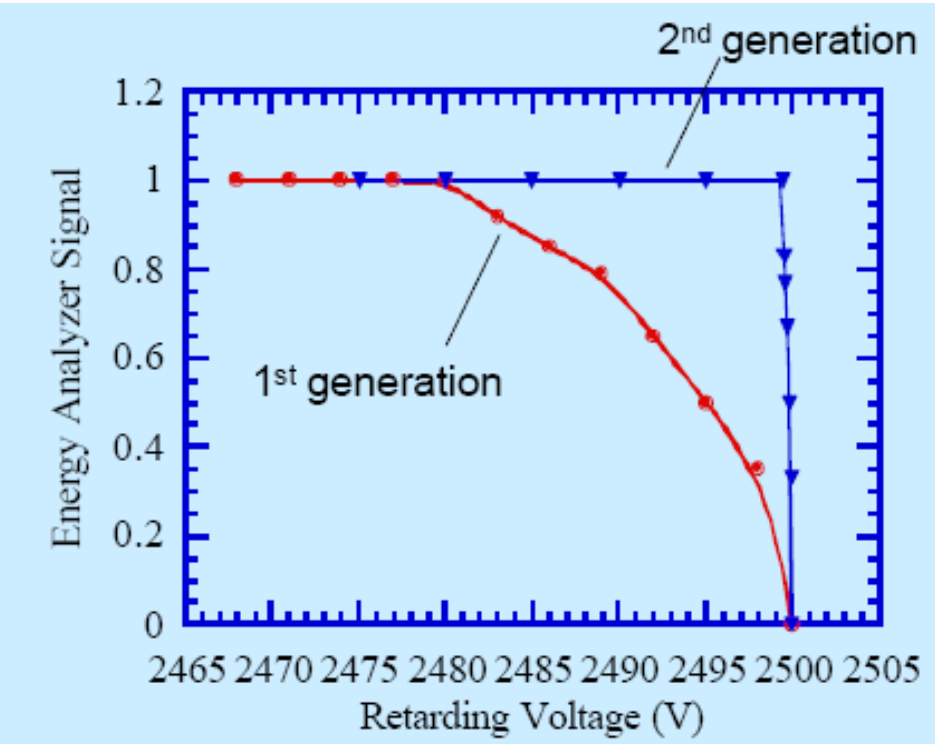


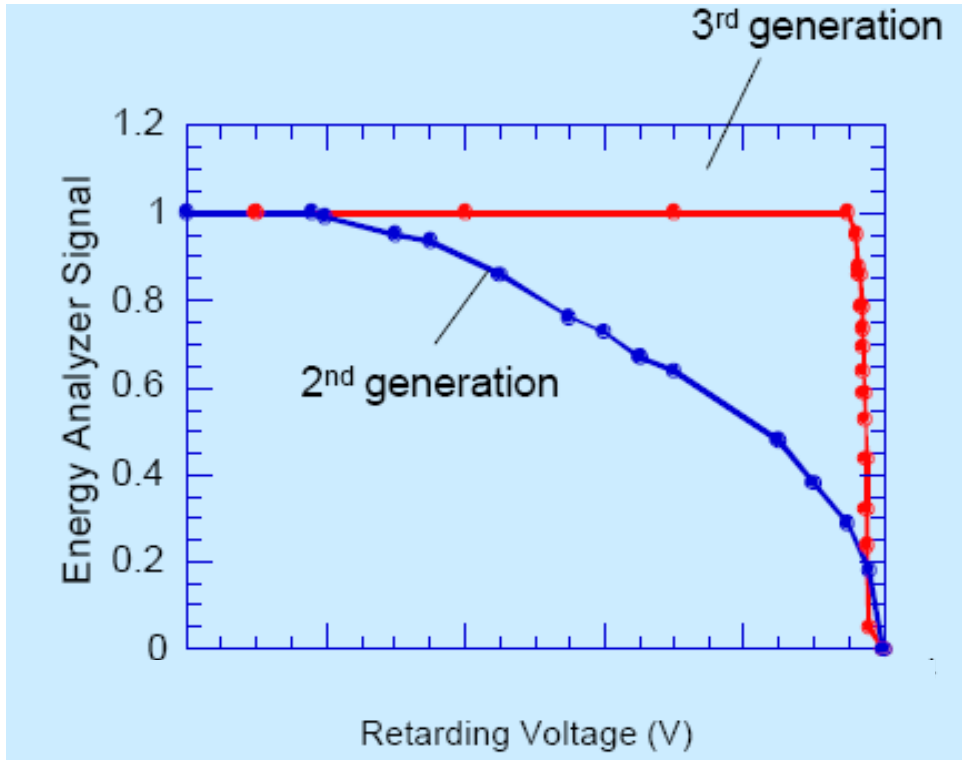


Credits: Cui Yupeng

Resolution Comparison

Simulated energy spread measurement for monoenergetic beam with initial divergence angle of 5°





Credits: Yun Zou and Yupeng Cui, SimIon simulation

References for Further Study

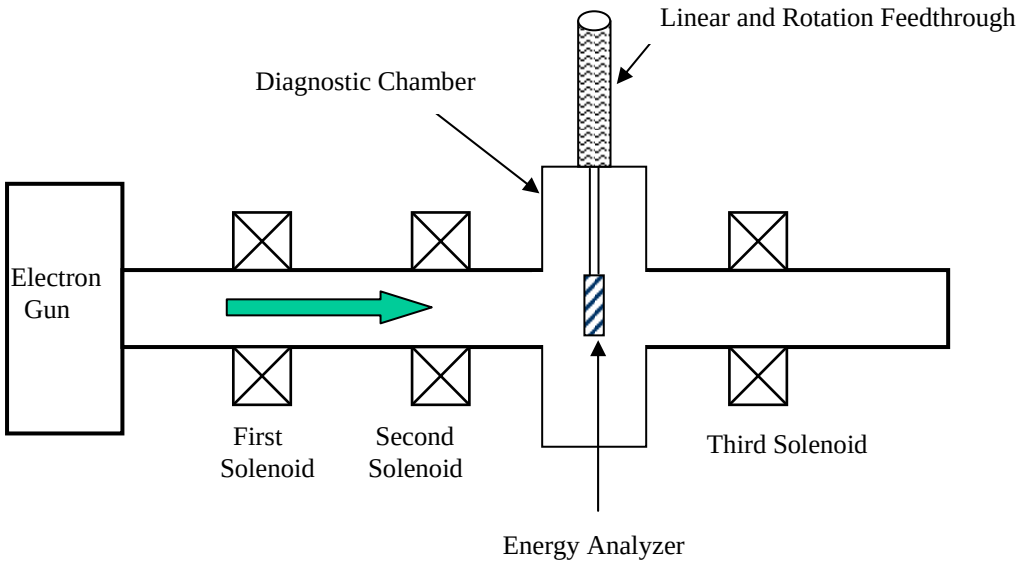
- Y. Cui, Y. Zou, A. Valfells, M. Walter, I. Haber, R.A. Kishek, S. Bernal, M. Reiser, and P.G. O'Shea, *"Design and Operation of a Retarding Field Energy Analyzer with Variable Focusing for Space-Charge Dominated Electron Beams,"* Review of Scientific Instruments **75(8)**, 2736 (2004).

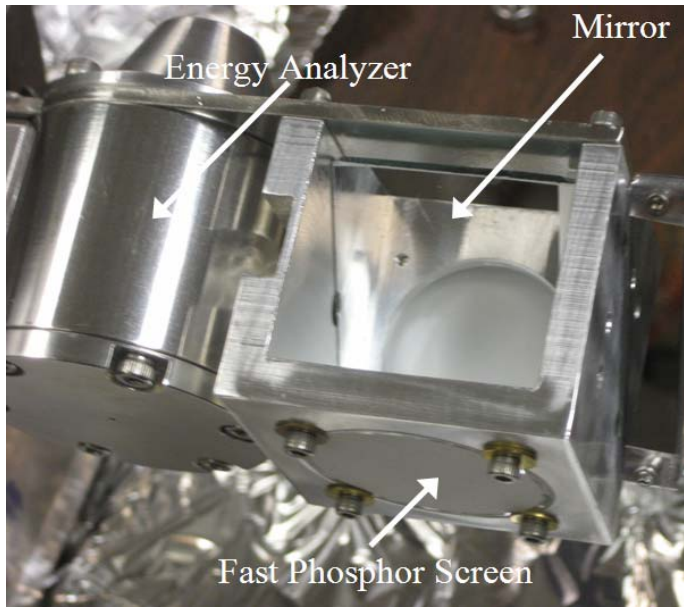
- Y. Zou, Y. Cui, V. Yun, A. Valfells, R.A. Kishek, S. Bernal, I. Haber, M. Reiser, P.G. O'Shea, and J.G. Wang, *"Compact high-resolution retarding field energy analyzer for space-charge-dominated electron beams,"* Physical Review Special Topics - Accelerators & Beams **5**, 072801 (2002).

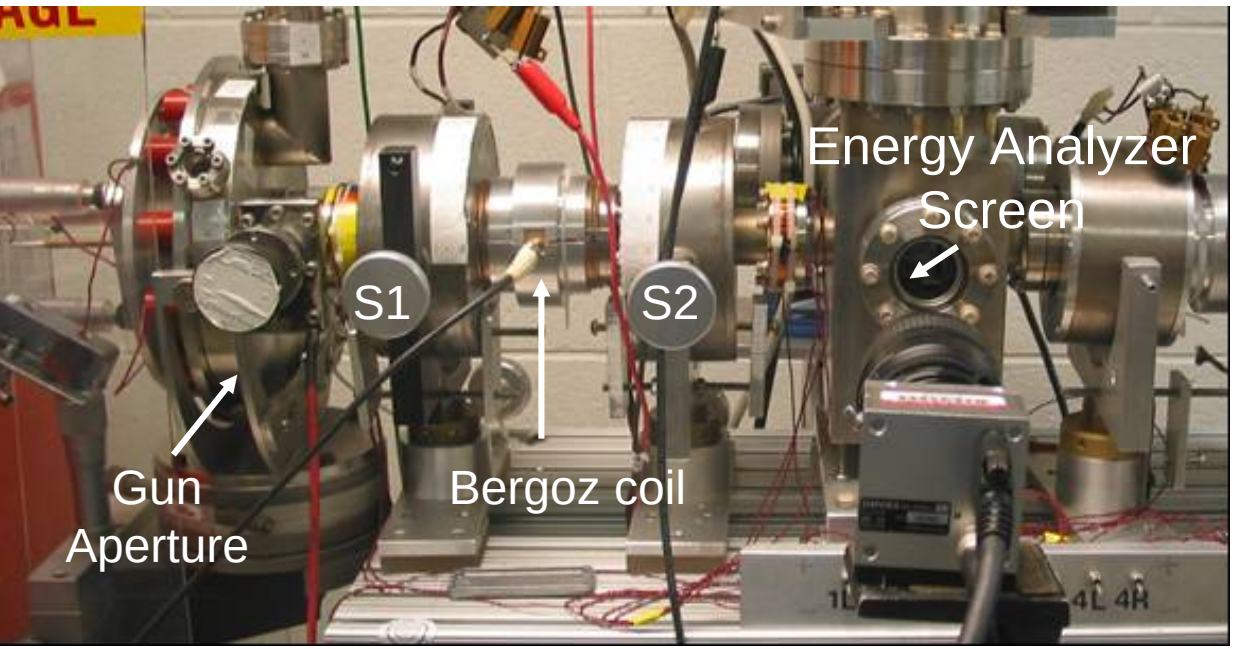
- Cui Yupeng, Ph.D. thesis:

  http://hdl.handle.net/1903/1889

Energy Analyzer and LSE Test Setup

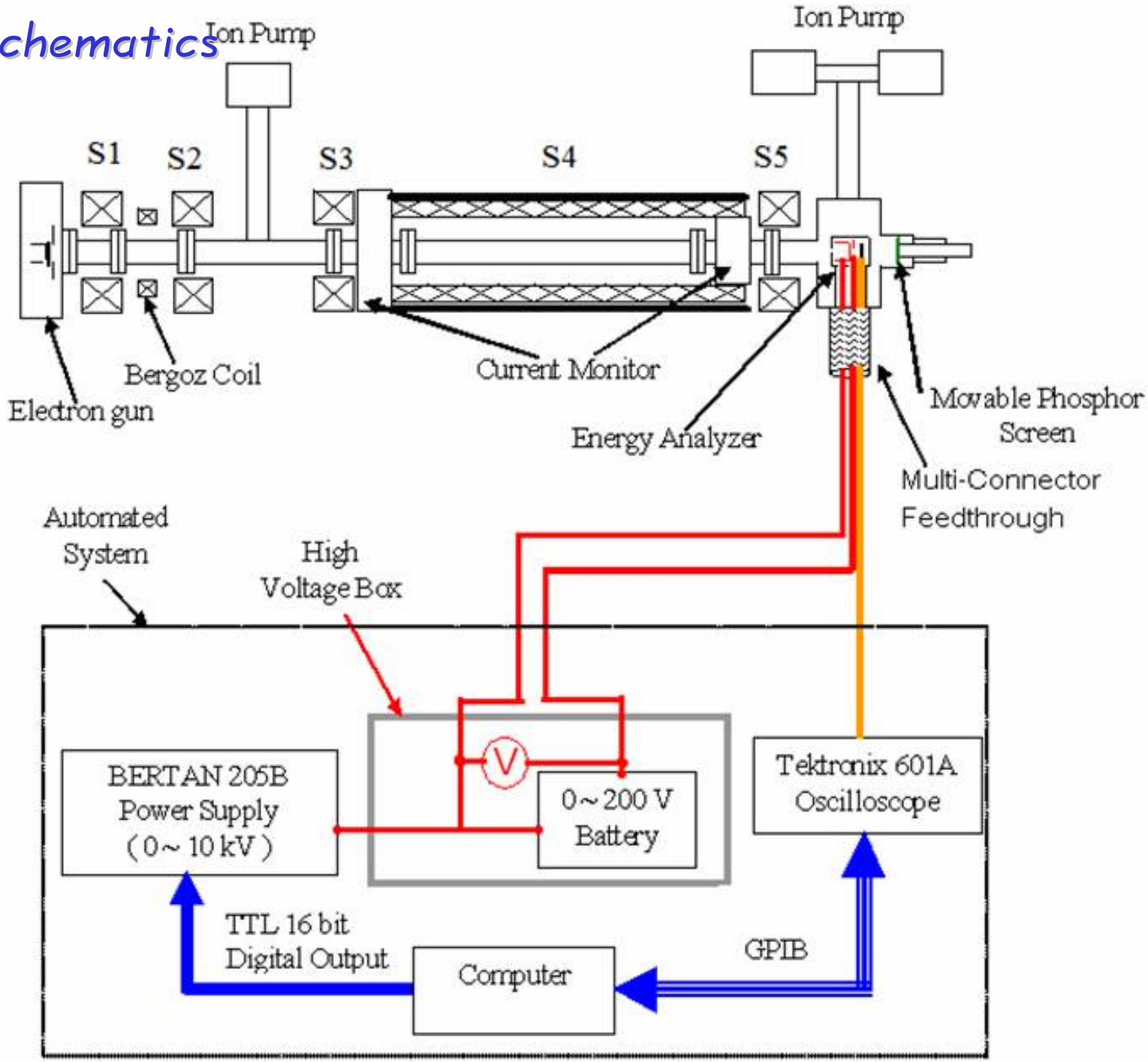






Credits: Zou, Cui, Stratakis and Tian

Electrical Schematics

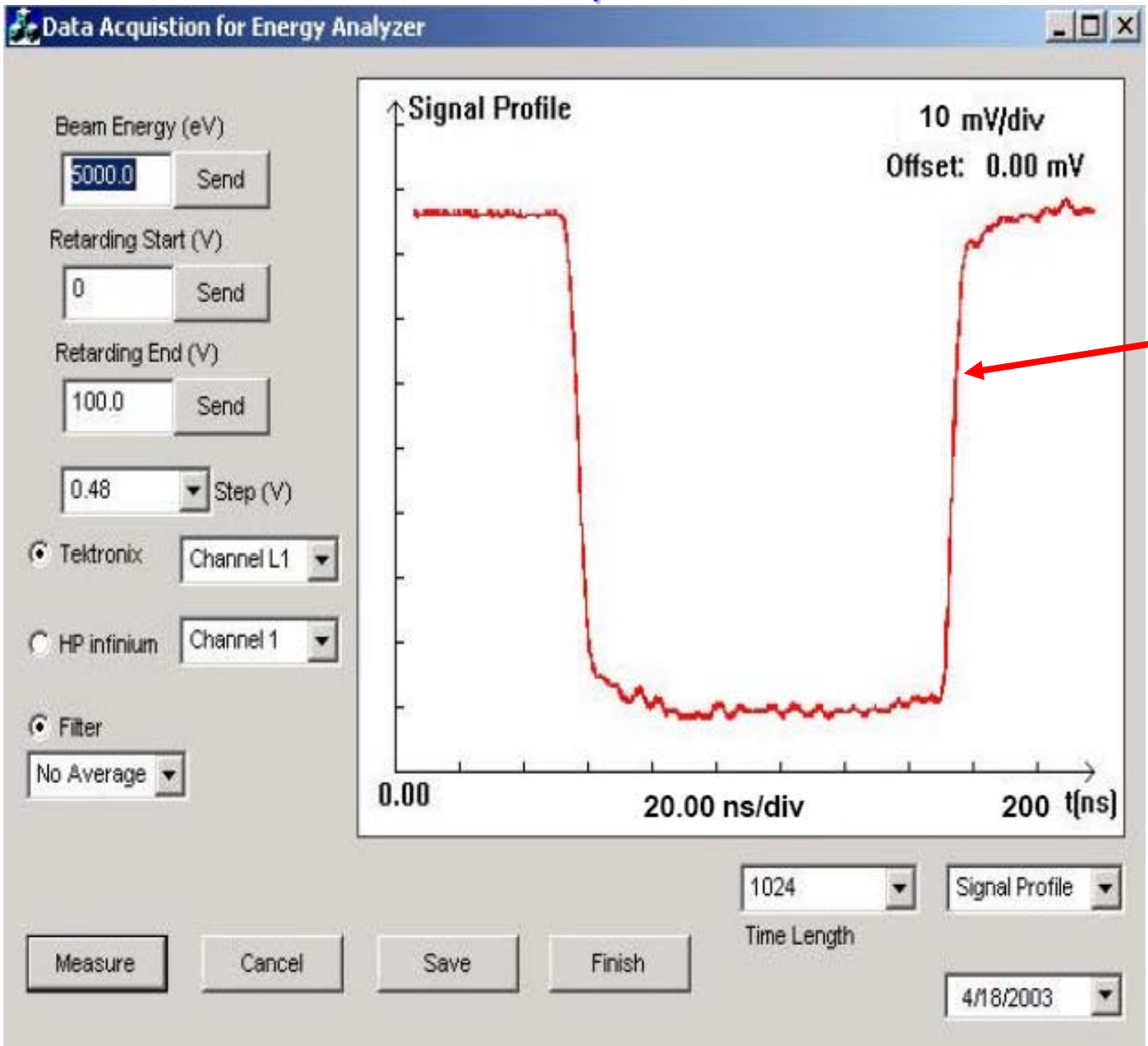


Operation and Data-Processing

- Computer Automation:
  - C++ program
  - fine steps on retarding potential (~ 0.1 eV)
  - much faster acquisition

- Computerized Processing
  - MATLAB interface

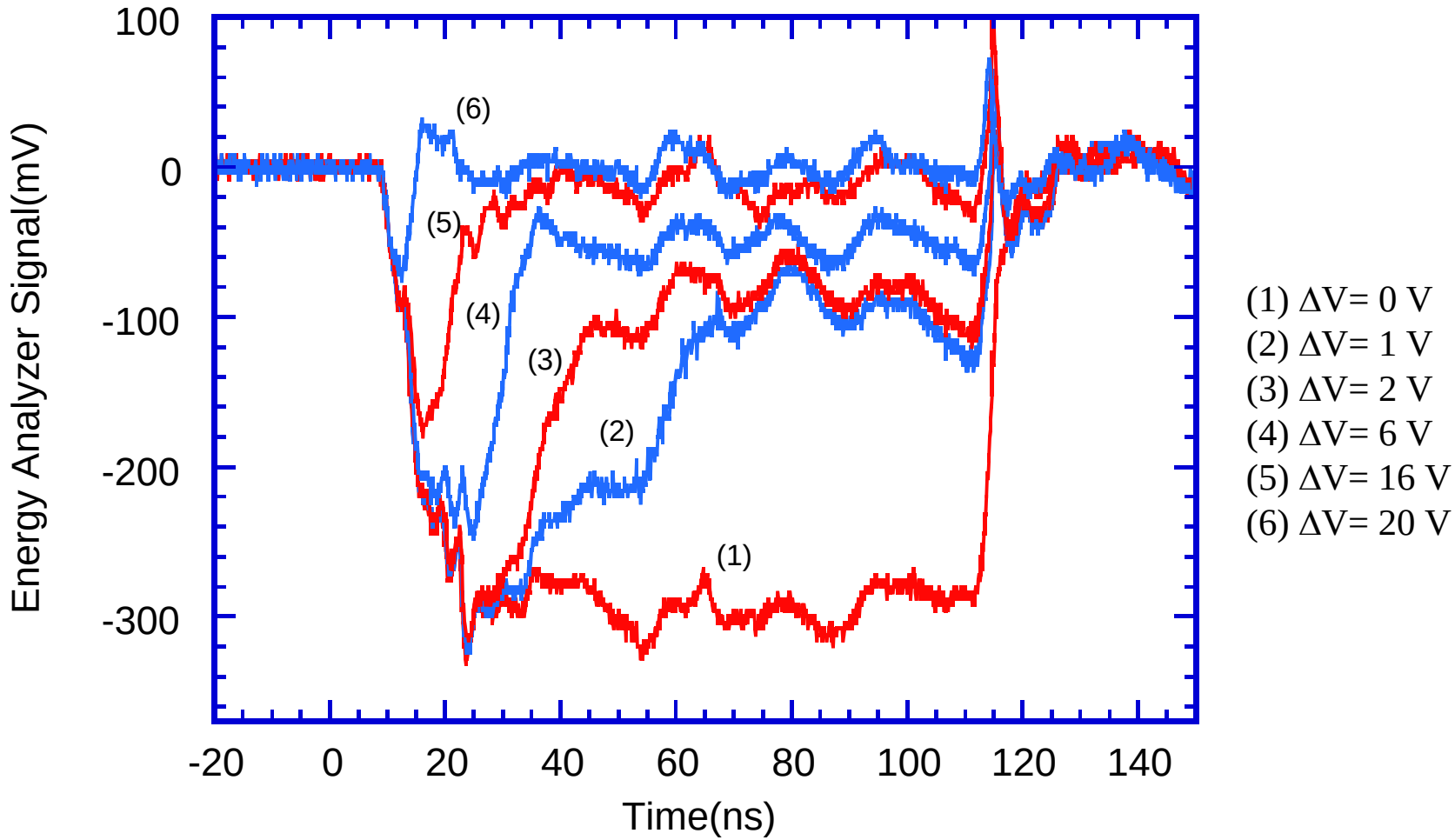
Data Acquisition Interface



Typical Signal

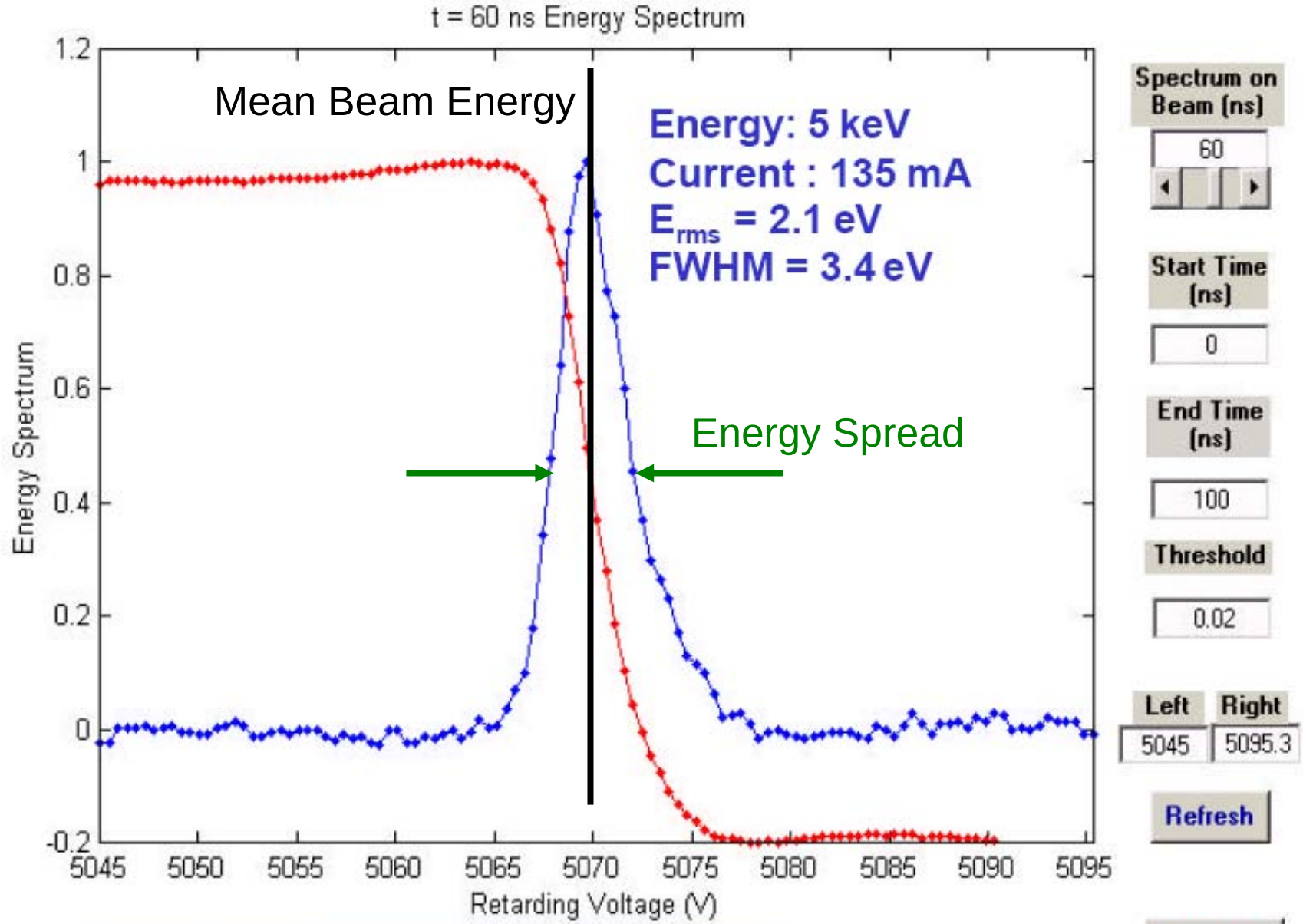
Credits: Yun Zou and Yupeng Cui, Experimental Measurement

Typical Collector Signals at Different Retarding Voltages



Credits: Yun Zou and Yupeng Cui, Experimental Measurement

Measured Energy Spectrum at one point in time (60 ns)



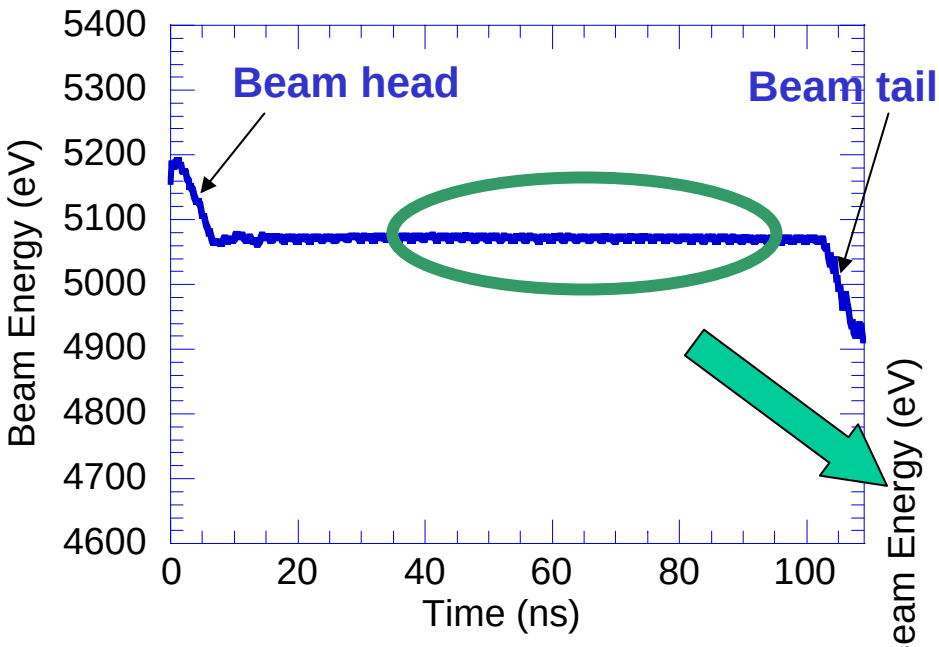
Measured beam energy spectrum

Credits: Yun Zou and Yupeng Cui, Experimental Measurement

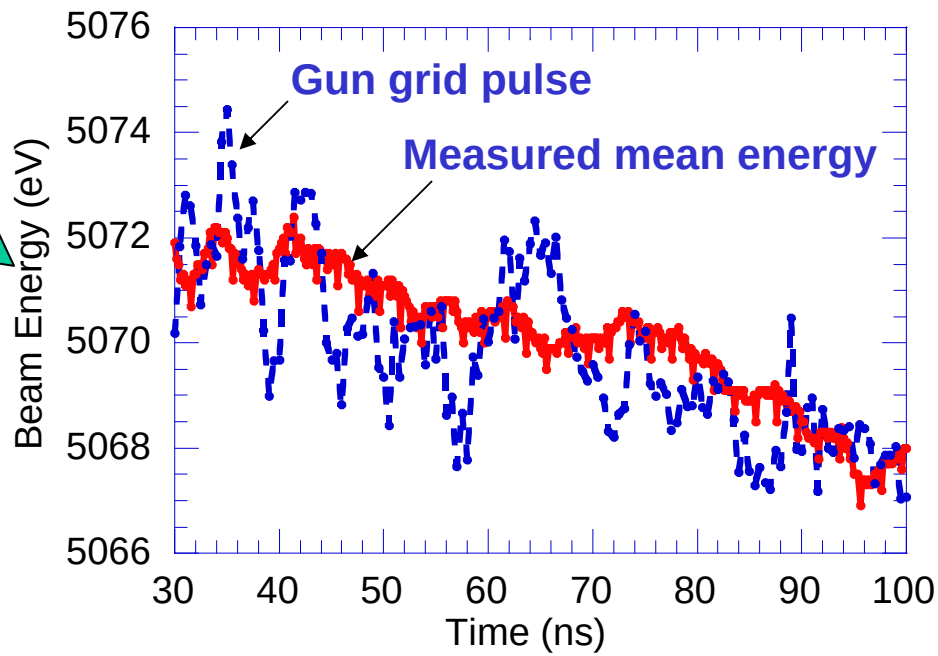
Mean Energy as a function of Time along the Pulse

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

Mean energy along the pulse



Zoom in

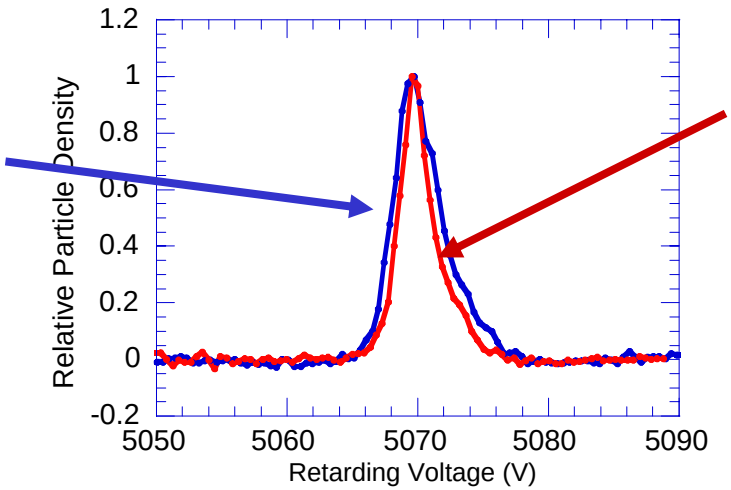


Credits: Yun Zou and Yupeng Cui, Experimental Measurement

Energy Spread as a function of time

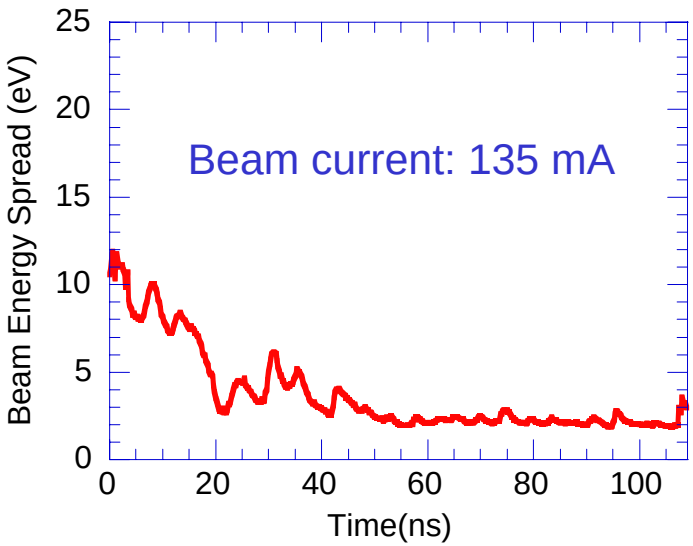
Beam Energy : 5 keV, Sampled position: 60 ns

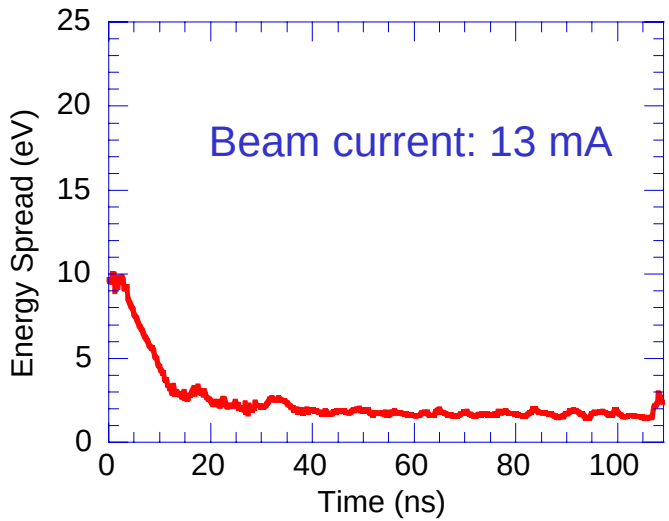
Beam current: 135 mA
Energy spread: 2.1 eV



Beam current: 13 mA
Energy spread: 1.7 eV

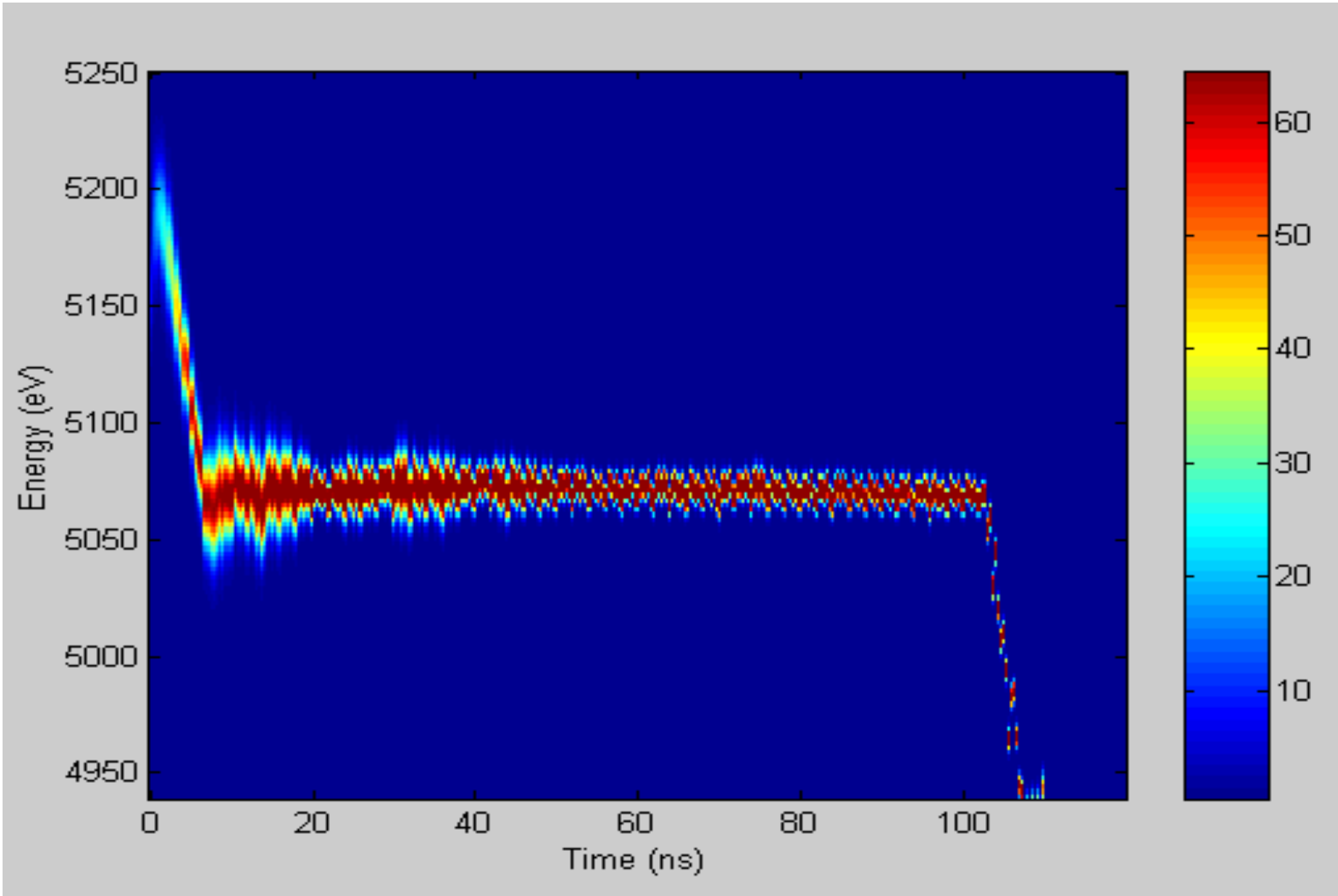
Energy spread along the pulse (time resolved)





Credits: Yun Zou and Yupeng Cui, Experimental Measurement

Longitudinal Phase-Space Mapping



Credits: Yun Zou and Yupeng Cui, Experimental Measurement

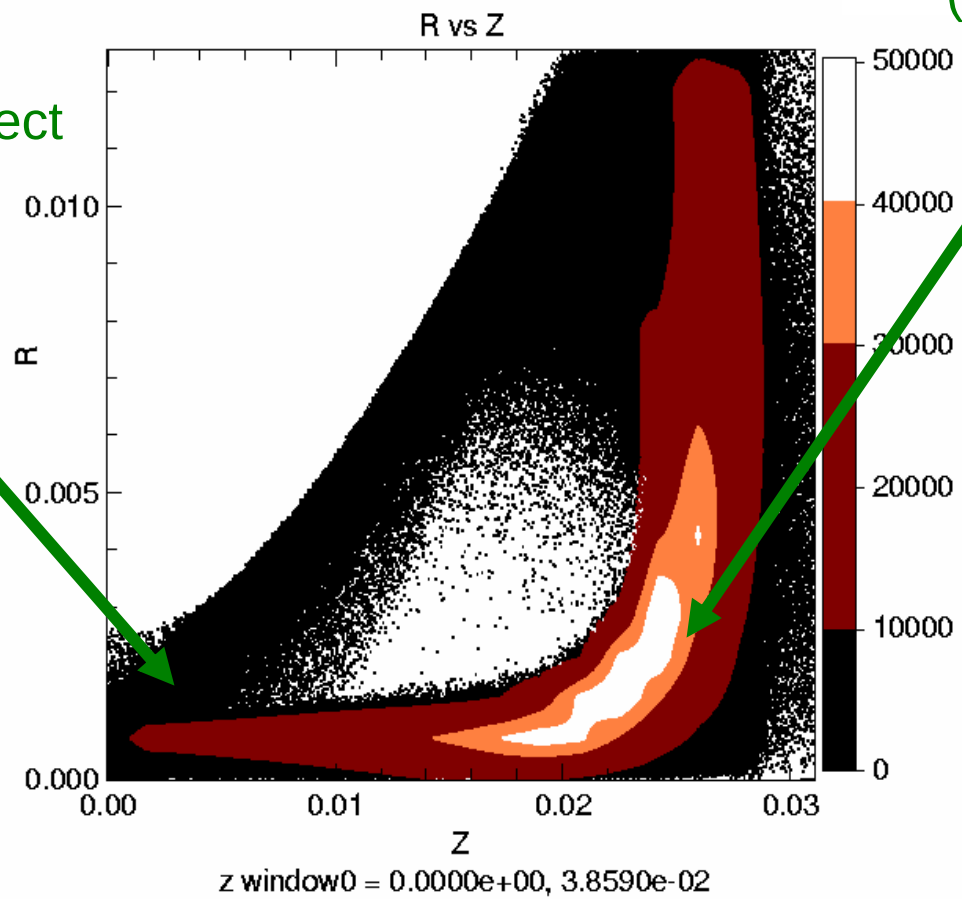
Space Charge Effects in the High-Resolution Analyzer

WARP Simulation (RZ):

Higher current density leads to complex space charge effects inside EA

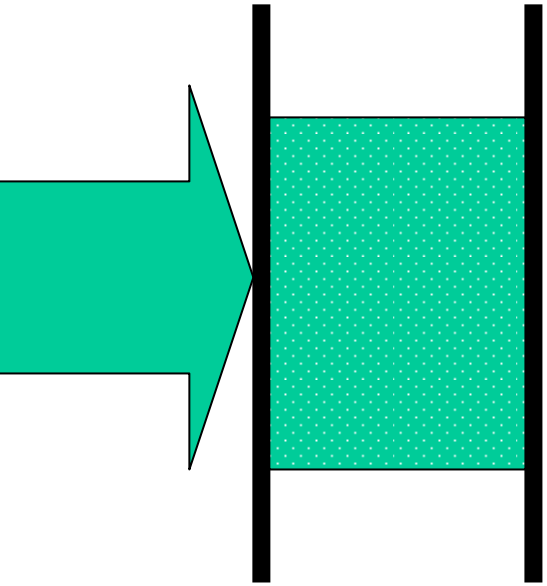
Space charges causes faster beam expansion, affecting collected signal (virtual cathode)

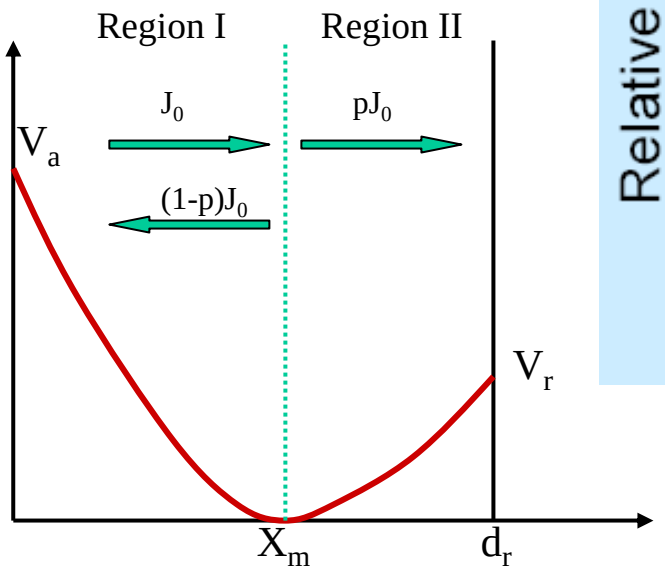
Returning particles affect incoming particles – time-dependence

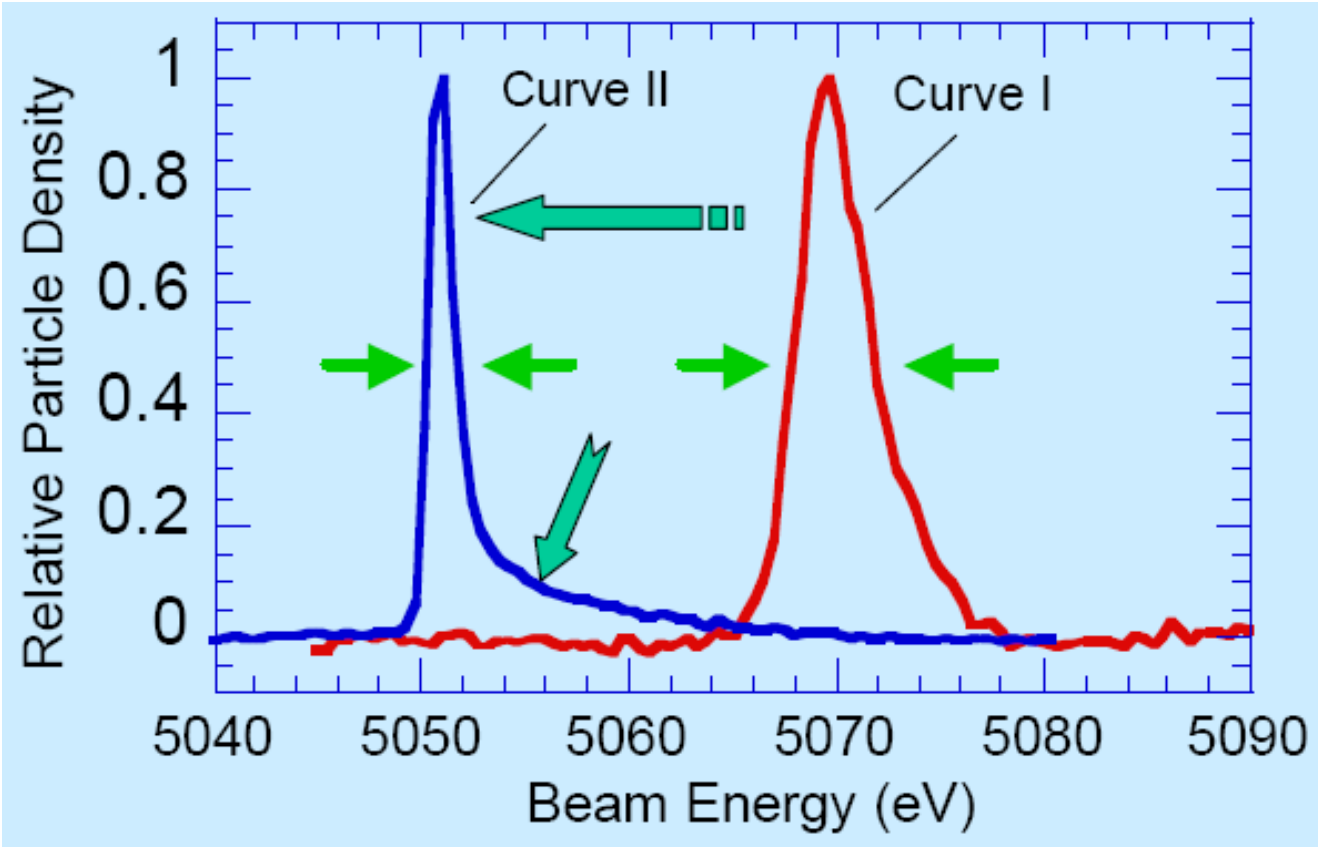


Credits: Yupeng Cui and Rami Kishek

1-D model of virtual cathode







Can derive limiting current to minimize sc effect

$$J_{\lim} = \left(\frac{4}{3}\right)^2 \frac{V_a^{3/2}}{4Cd_r^2}$$ (Child-Langmuir Law)

Credits: Yun Zou

References

- Y. Zou, Y. Cui, I. Haber, M. Reiser, and P.G. O'Shea, *"Longitudinal space-charge effects in a retarding field energy analyzer,"* Physical Review Special Topics - Accelerators & Beams **6**, 112801 (2003).

Outline of Experiment

1. Examine Collector Signal
2. Do coarse scan of retarding potential, manually
3. Run automated program to collect and then process EA data
   - mean beam energy vs. time
   - energy vs. time
   - energy distribution at middle of beam pulse