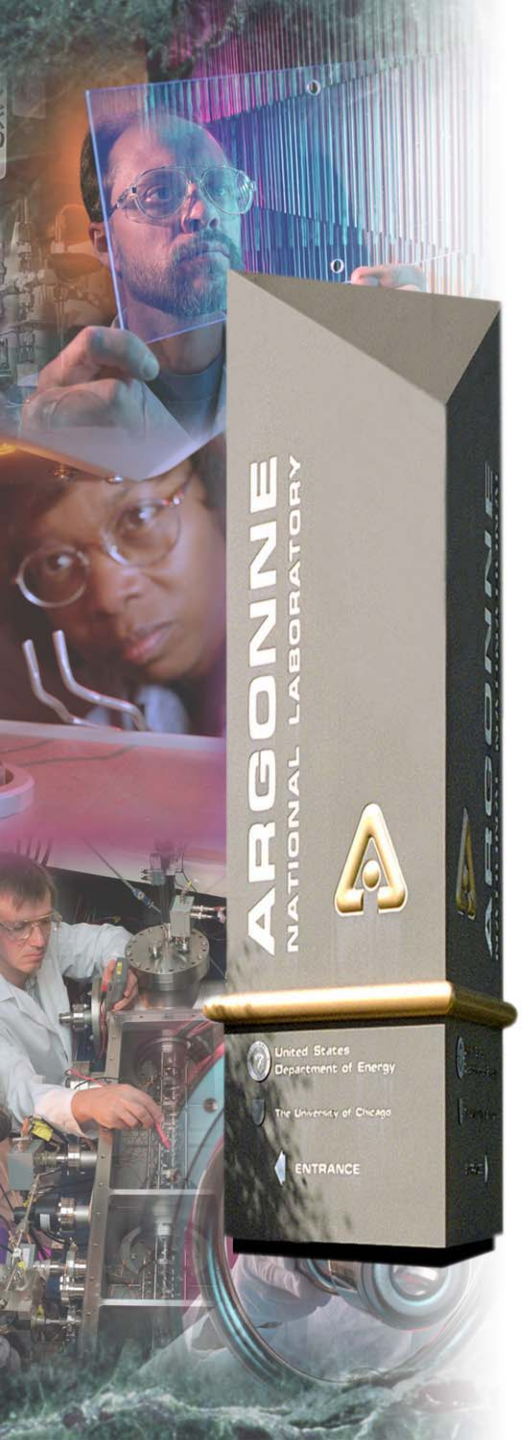

High-Brightness Gun Development

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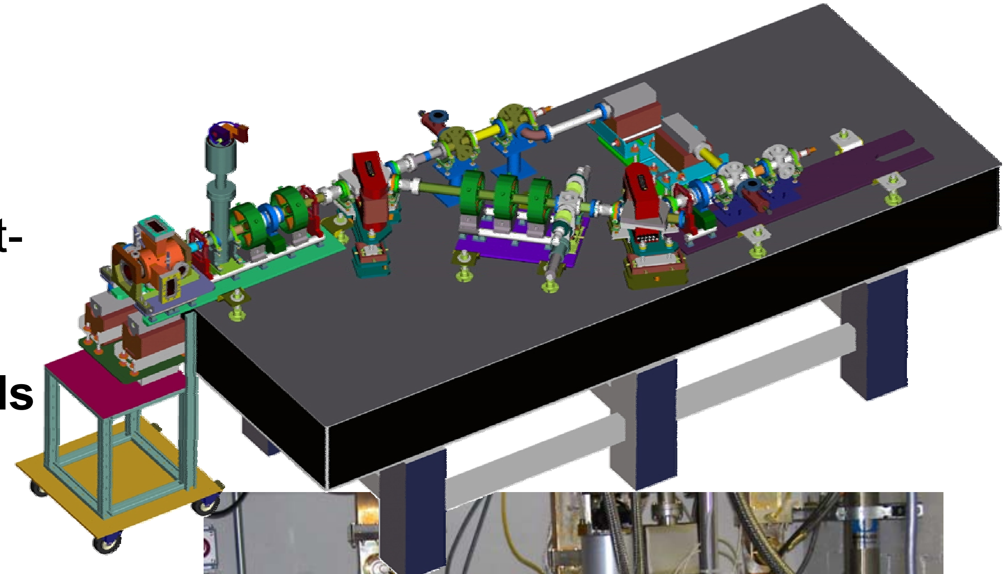
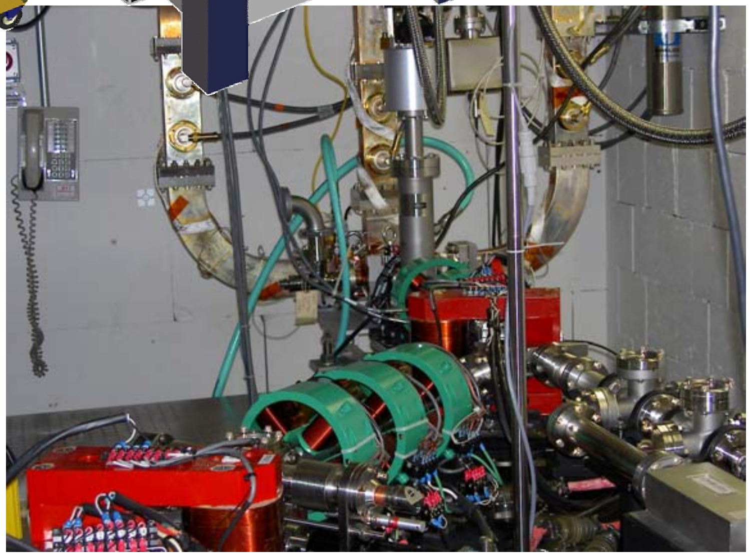
Outline

- **Introduction**
  - What is an an injector?
  - What is beam brightness?
- **The “Canonical” High-Brightness RF Gun Design**
- **Alternate Paths Towards High Brightness**
  - Longitudinal phase space control
  - Needle cathodes
  - Novel cavity designs
  - Hybrid gun designs
- **Experiments in Progress**
- **Cathodes – The Next Advance?**
- **Conclusions**

Why Injector Research? Why Here?

- **APS Current Operational Needs**
  - Storage ring injector repair and validation
  - Operator training facility
  - Hardware and software test-bed without operations risk
- **APS Future Operational Needs**
  - Direct, single-bunch, high-charge booster injection
  - Possibly, support for a free-electron user facility “beamline”
- **APS Injector Test Stand**
  - Performs the above tasks
  - Platform for testing new high-brightness gun designs





How Necessary Is It, Really?

"The BESAC Subcommittee recommends that development in the following areas be a priority: electron gun technology, detector technologies, ..."

"Critical areas that need improvement include gun technology..."

"The critical enabling technology to advance linac-based light sources is the electron gun. ... Performance enhancements in RF photocathode guns are crucial to advanced FELs and extended capability undulator sources such as LUX. ... "

"These order of magnitude improvements in electron guns (DC, RF, and superconducting RF) will allow qualitative advances in light sources capabilities at reduced costs. They are the highest-leveraged technology for next generation light sources. The BESAC Subcommittee recommends that DOE BES strongly support and coordinate research and development in this unique and critical technology."

- **BESAC Subcommittee Workshop Report on 20-Year Basic Energy Sciences Facilities Roadmap**

  http://www.er.doe.gov/production/bes/BESAC/20%20year%20report.pdf

What Is an Injector?

- **In general:**
  - supplies beam to a post-injector device
  - often sets the “best” beam quality for the system as a whole
  - upgradeable
- **For this talk:**
  - an electron gun
  - an electron gun + one or two linac sections

What is Beam Brightness?

- **Canonically, it is:** $$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$
- **Practically, it is the measure by which one judges an injector's performance for a specific application:**

$$B_{e^+} \propto Q_{bunch} \cdot I_{average}$$ **…for a positron-production linac**

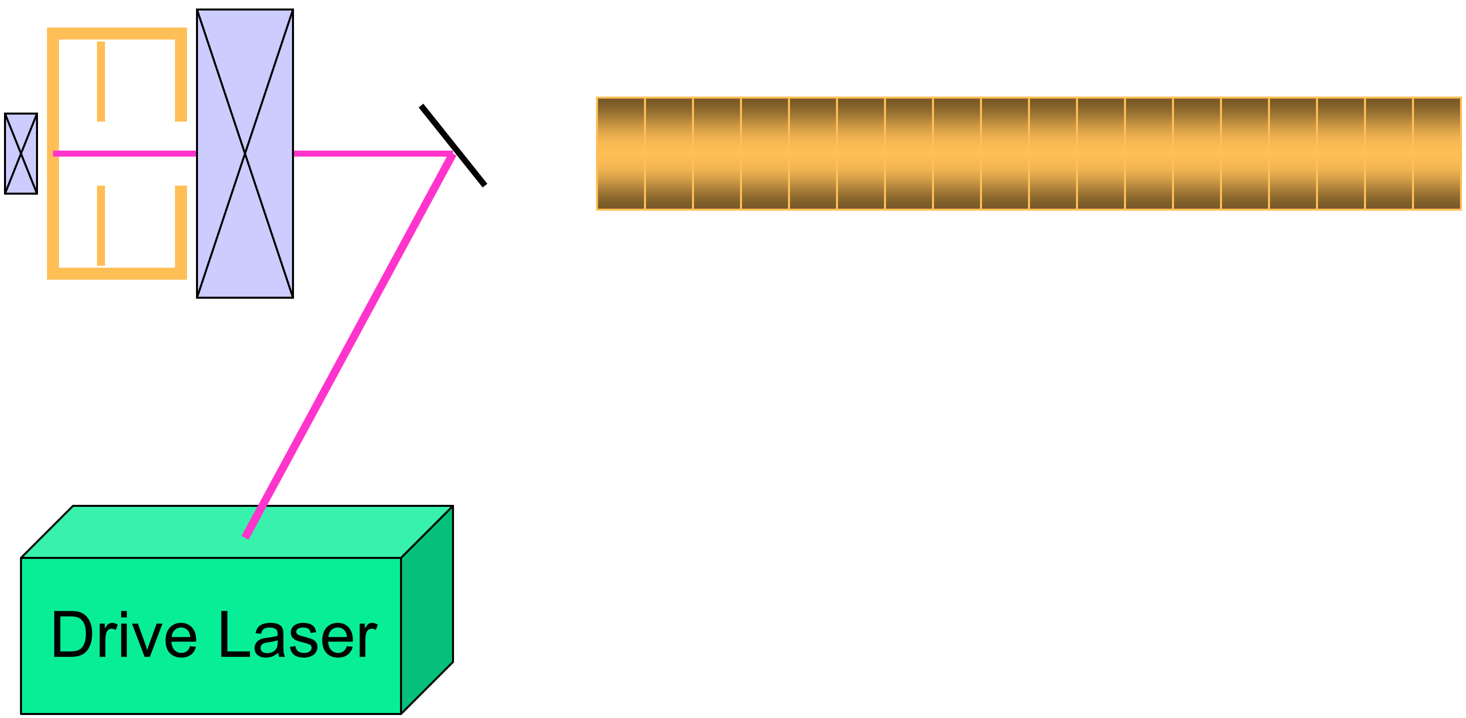
$$B_{topup} \propto \Phi\left(\frac{I}{I_{topup}} - 1\right)$$ **…for the APS injector**

$$B_{SASE} \propto \left(\frac{I_{peak}}{\varepsilon_n}\right)^{1/3}$$ **…for SASE-FELs**

The beam brightness determines whether the machine will work as intended or not

The Canonical High-Brightness Injector

- Coupled-cavity high-gradient gun (~100 Mv/m @ S-band)
- Drive laser to gate electron emission (~ 2 – 20 ps)
- Solenoid for emittance compensation (ε_n ~ 1 – 5 μm)
- Linac to capture & damp beam



Why Do Something Else?

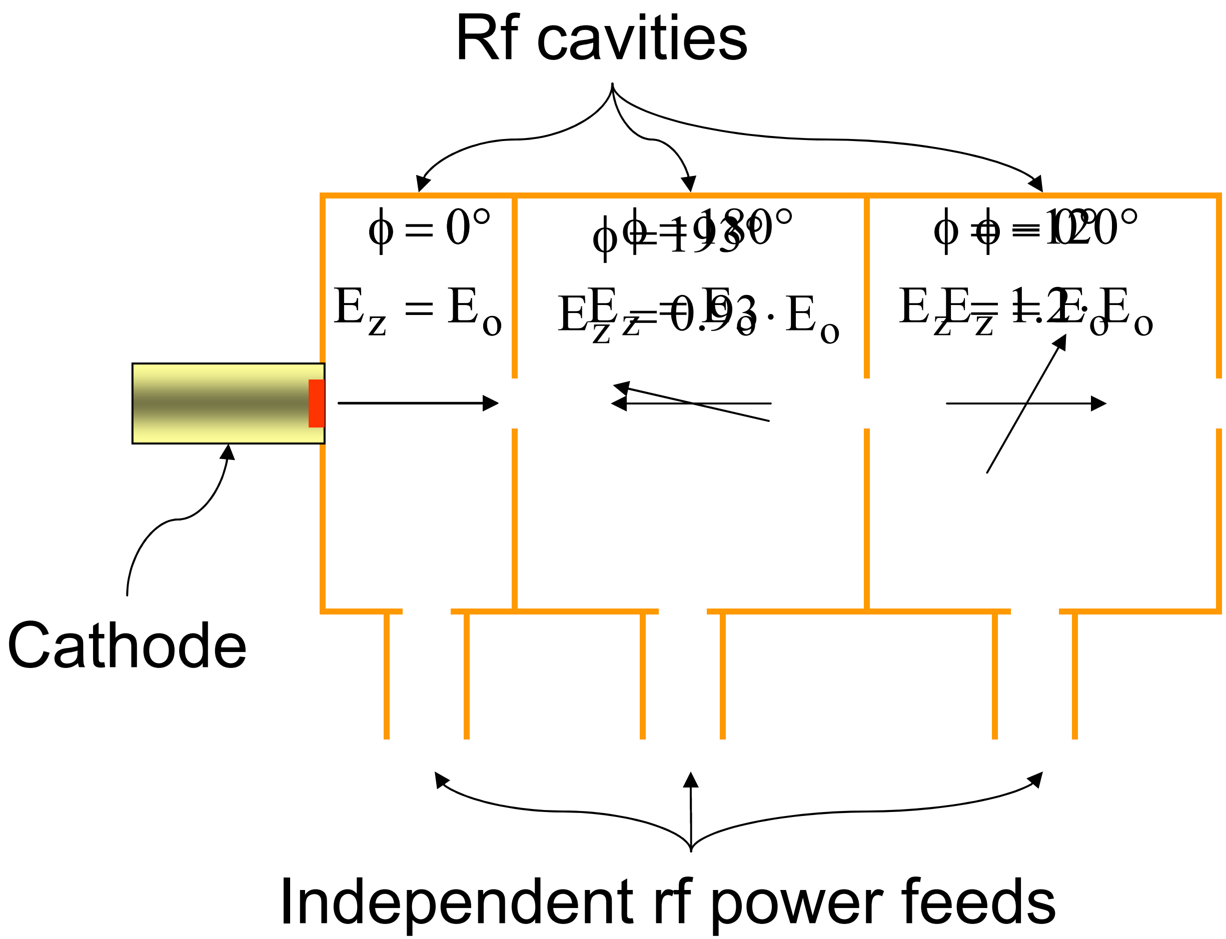
- **The canonical design…**
  - Is starting to approach theoretical limits
  - Has proven very difficult, in practice, to get to work at optimal performance over extended periods of time
  - Is, in essence, a “Jack-of-all-trades” design

- **Other factors:**
  - Maintenance & fabrication issues
  - Diagnostics & precise beam control
  - Cathode lifetime vs. laser energy
  - Better performance is required for operational facilities

Alternate Paths Towards High Brightness

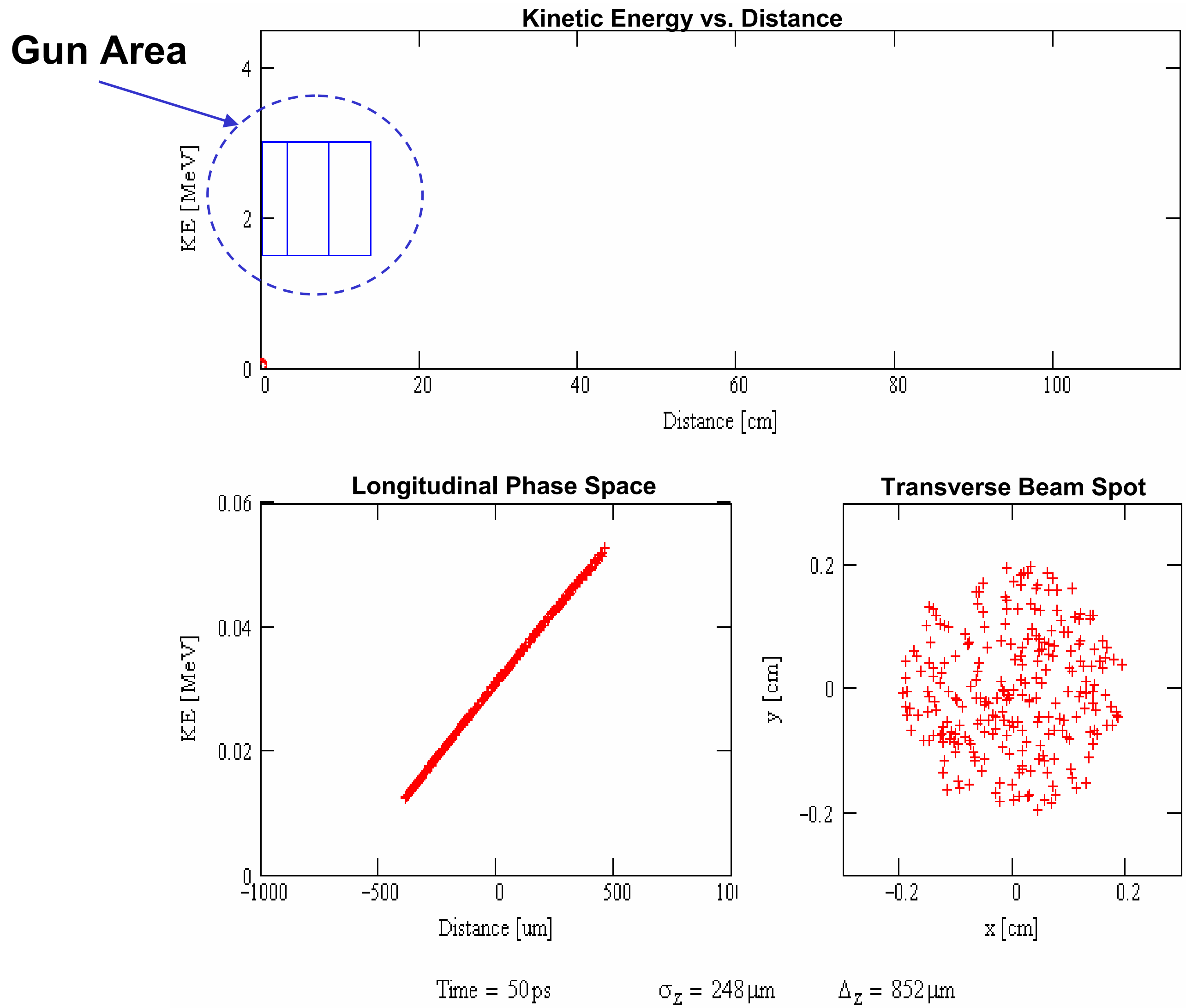
- **Better control over longitudinal dynamics: the ballistic bunch compression (BBC) gun (design and experiment)**
- **Reduced emission area for less thermal emittance and higher gradients: the needle-cathode gun**
- **Improved robustness, simplified design, and easily upgraded: the higher-order mode gun**
- **Ultrahigh gradients for reduced space-charge effects: the DC/rf hybrid gun design**

Longitudinal Control: The BBC Gun



"Tailor" the beam longitudinal phase space for self-compression and linac capture

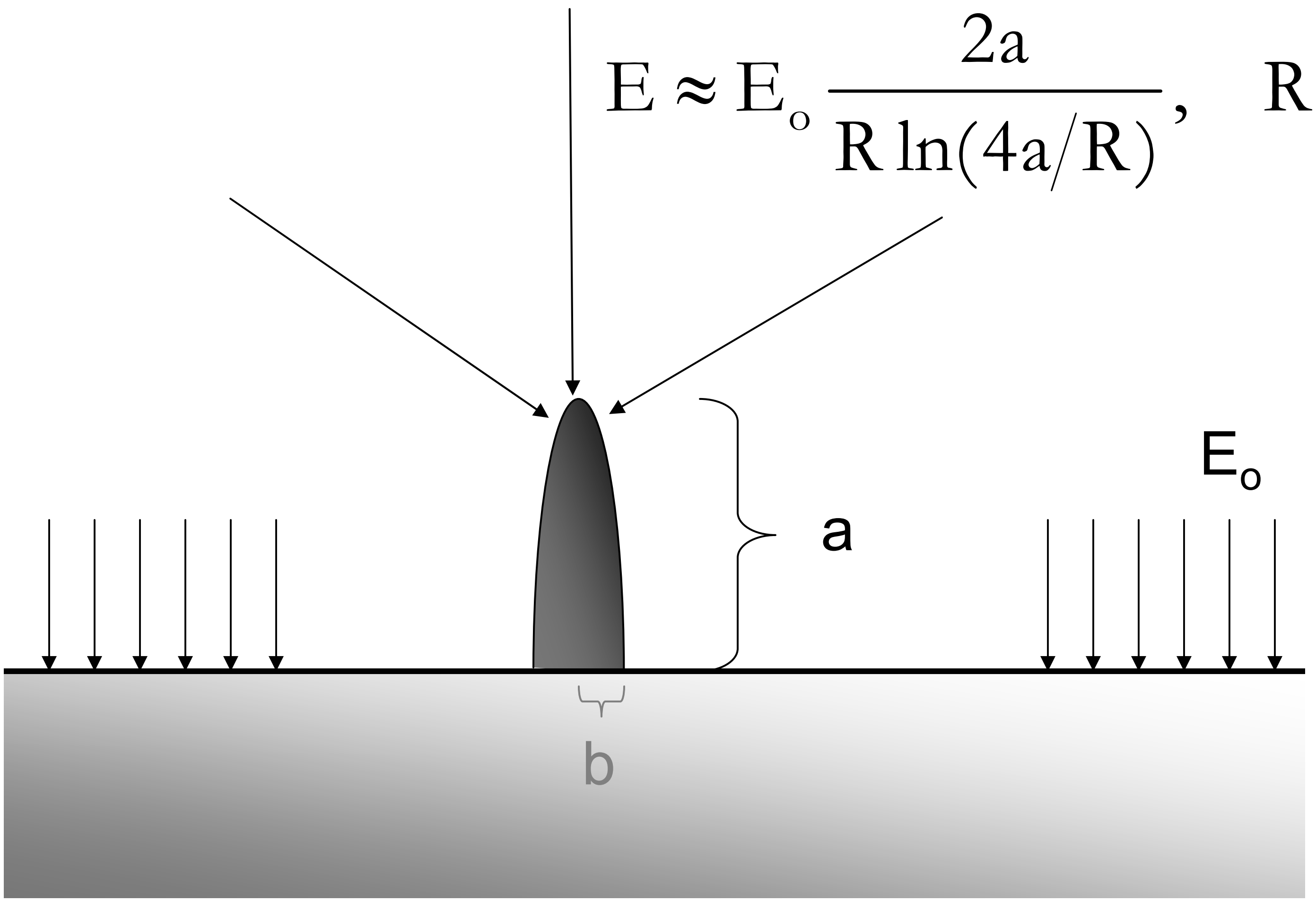
Ballistic Compression In Action



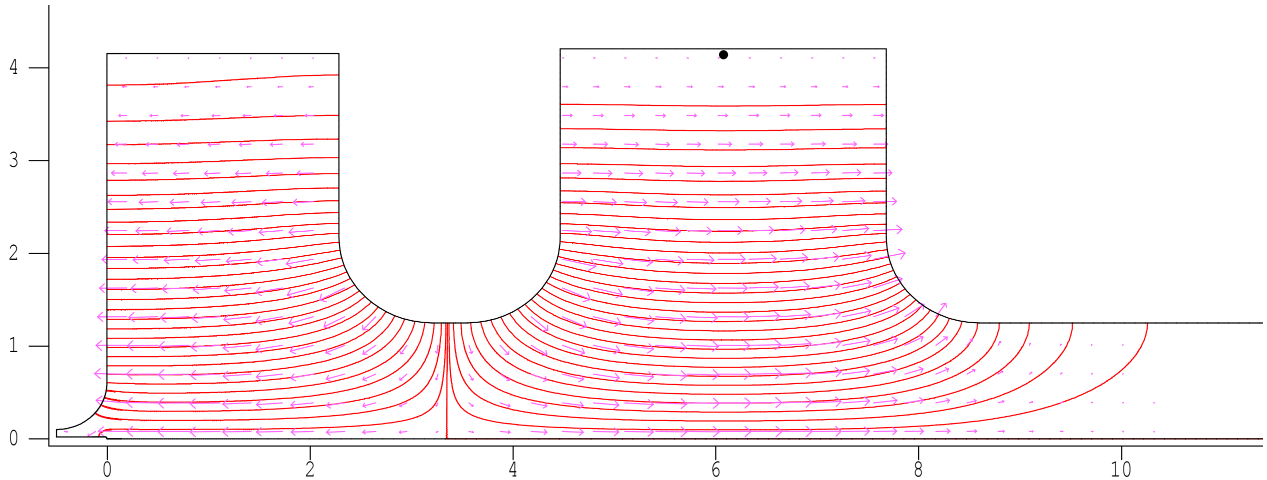
- **Limited Particle Count**
- **No Space Charge**
- **No Focusing**

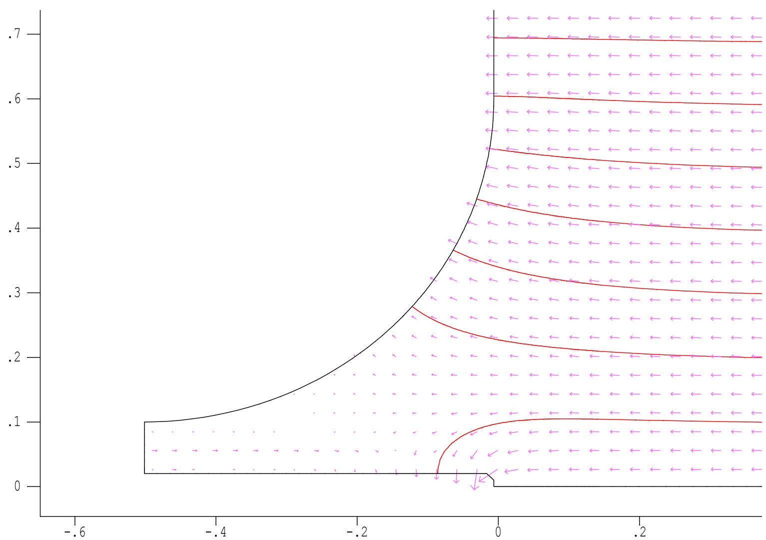
Needle Tip Field Enhancement

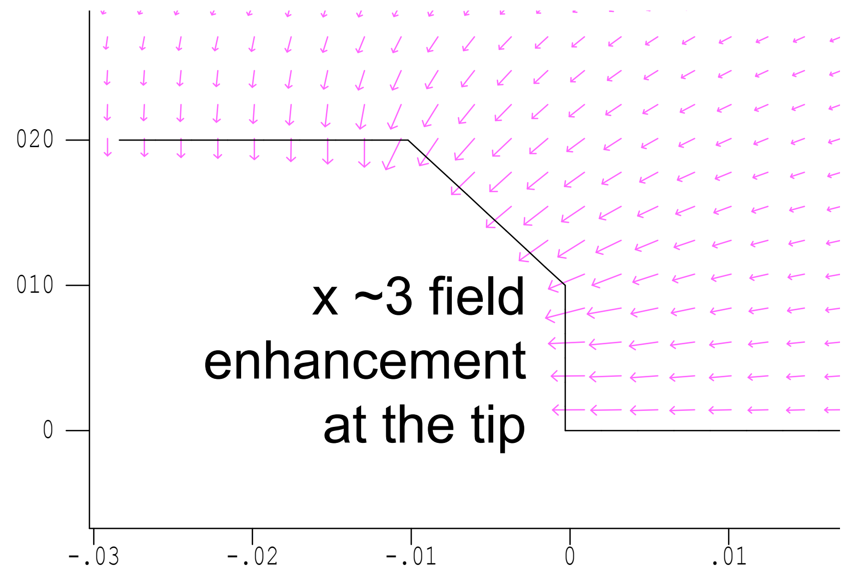
$$E \approx E_o \frac{2a}{R \ln(4a/R)}, \quad R = \frac{b^2}{a}$$



“Blunt” Needle Cathode – Cavity Design







“Blunt” Needle Beam Simulation

“Conventional” Gun

$Q \sim 1$ nC
$\tau_b \sim 10$ ps
$\varepsilon_n \sim 1\ \mu$m

$$B_n \approx 20 \frac{A}{\mu m^2}$$

$$\left(\frac{\rho}{\alpha}\right)^3 = 100 \frac{A}{\mu m}$$

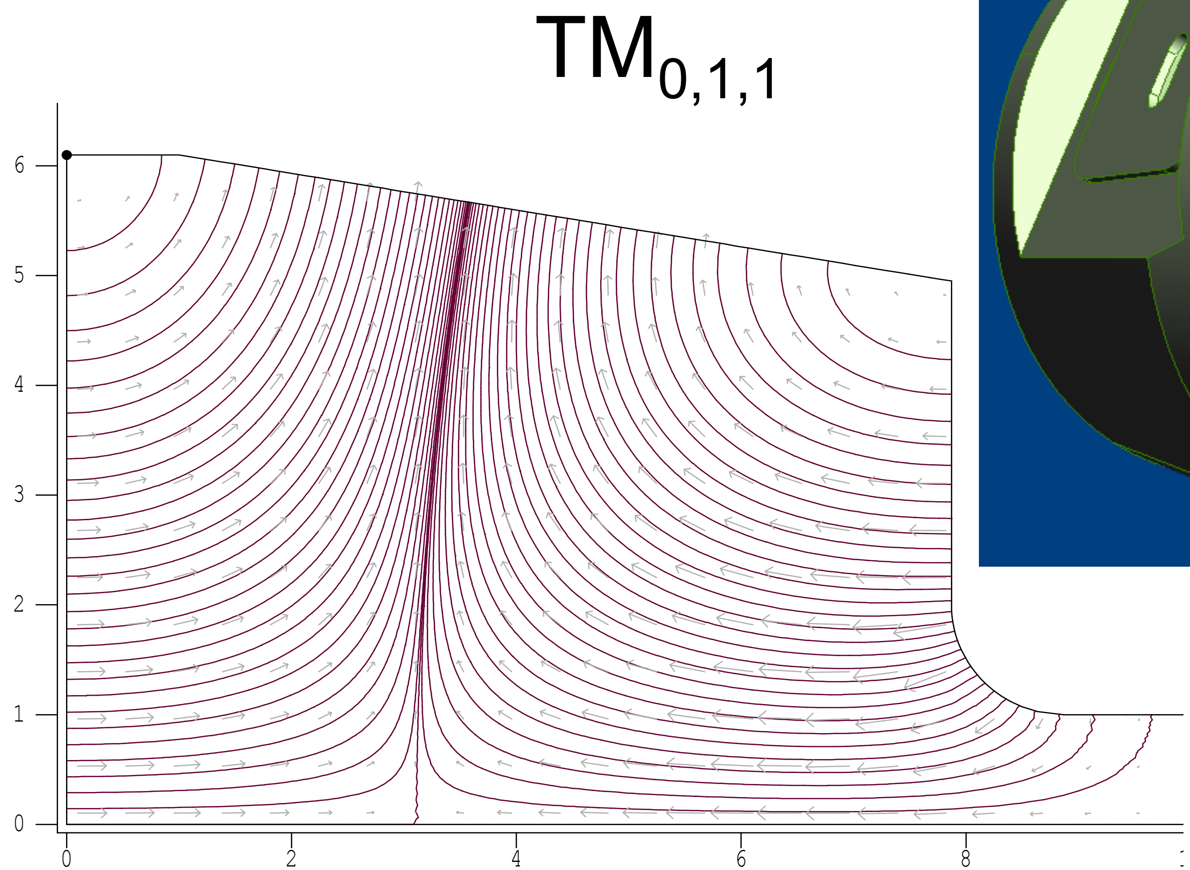
“1st-cut” Needle Gun

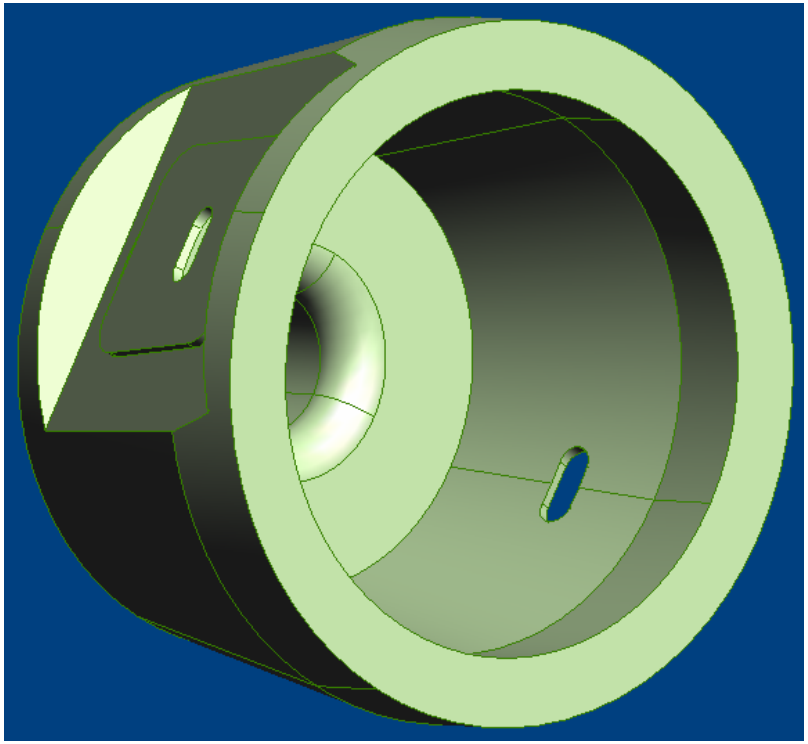
$Q \sim 20$ pC
$\tau_b \sim 4$ ps
$\varepsilon_n \sim 0.11\ \mu$m

$$B_n \approx 83 \frac{A}{\mu m^2}$$

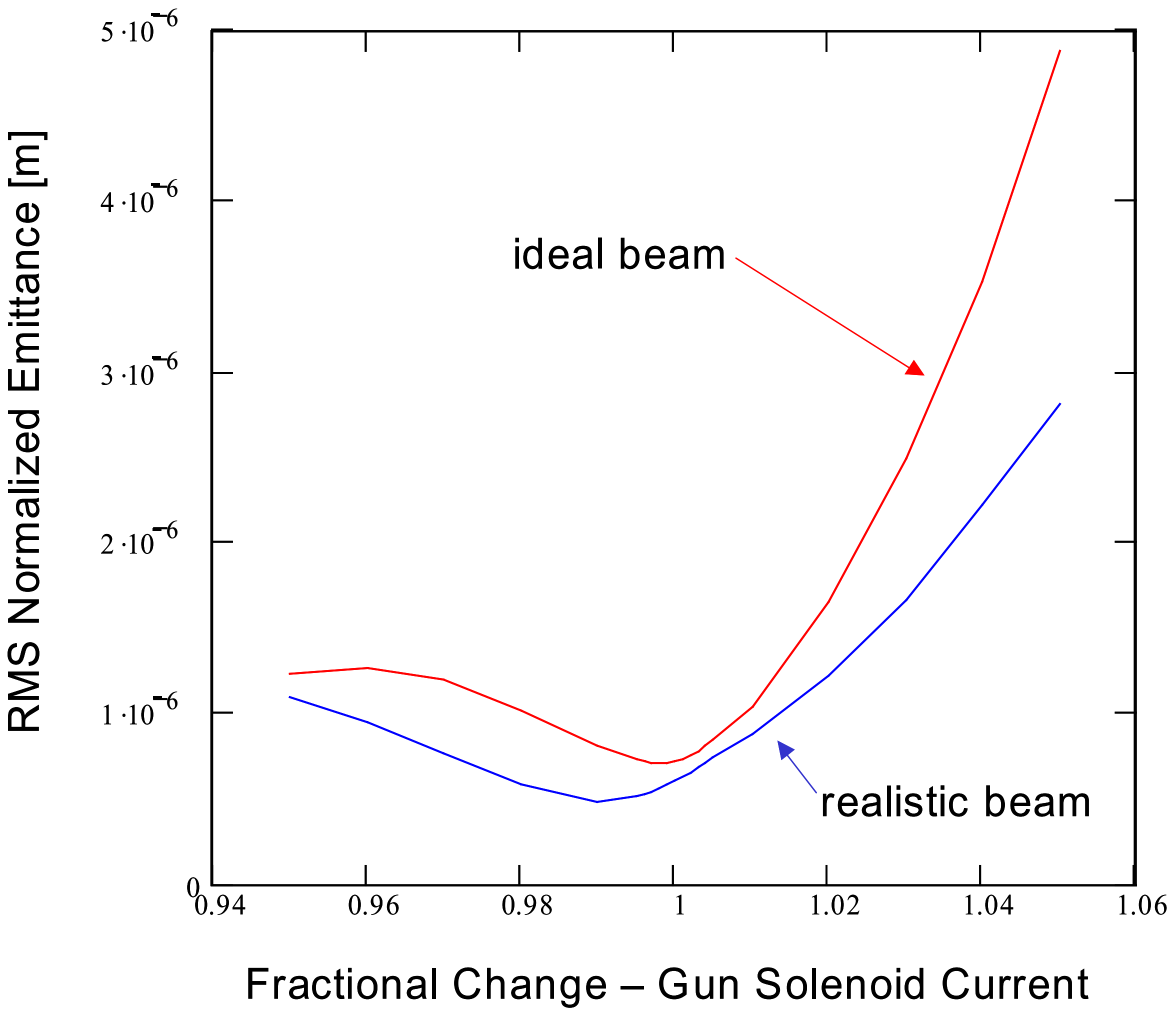
$$\left(\frac{\rho}{\alpha}\right)^3 = 45 \frac{A}{\mu m}$$

What Is a Higher-Order Mode (HOM) Gun?





HOM Gun – Simulation Performance



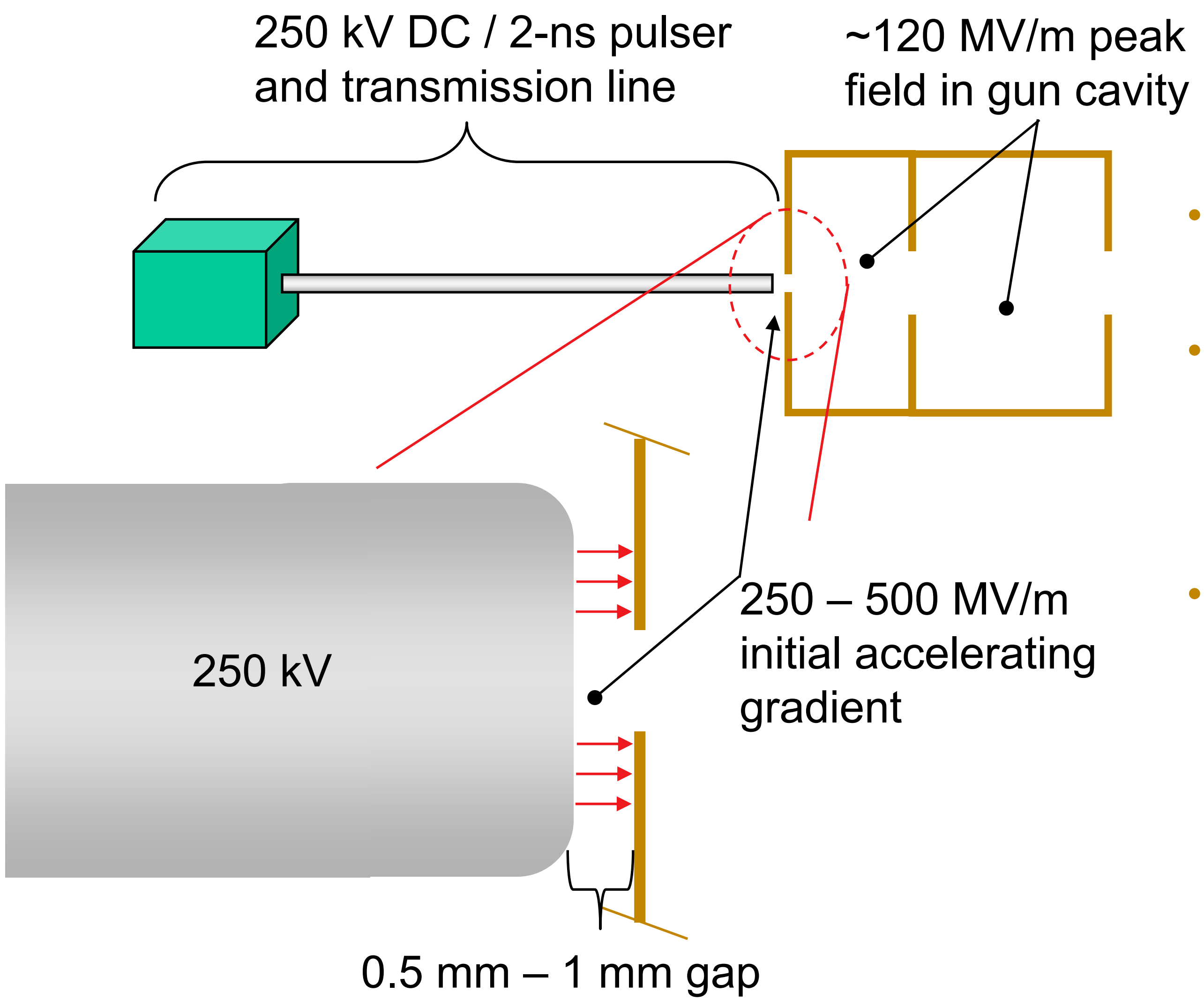
"Ideal" beam:
- **1-nC bunch charge**
- **Transverse & longitudinal flat-top**

"Realistic" beam
- **300-pC bunch charge**
- **Transverse Gaussian, clipped at 1σ**
- **Longitudinal Gaussian, clipped at 2.5σ**

HOM Gun – Good Research Platform

- **Very insensitive to small geometry changes**
  - Needle cathode doesn't perturb bulk fields
  - Insensitive to disassembly/reassembly
- **Other modes suggest interesting concepts**
  - Use $TM_{0,1,2}$ mode to support field-emitter cathode
  - Use TE modes for in-cavity deflection scheme
- **Current design can resonate at 2.856 GHz and 3 GHz**
  - Easier collaboration among American and European laboratories
  - With care, will permit frequency-scaling of performance parameters to be verified with a single gun

Hybrid Gun Designs

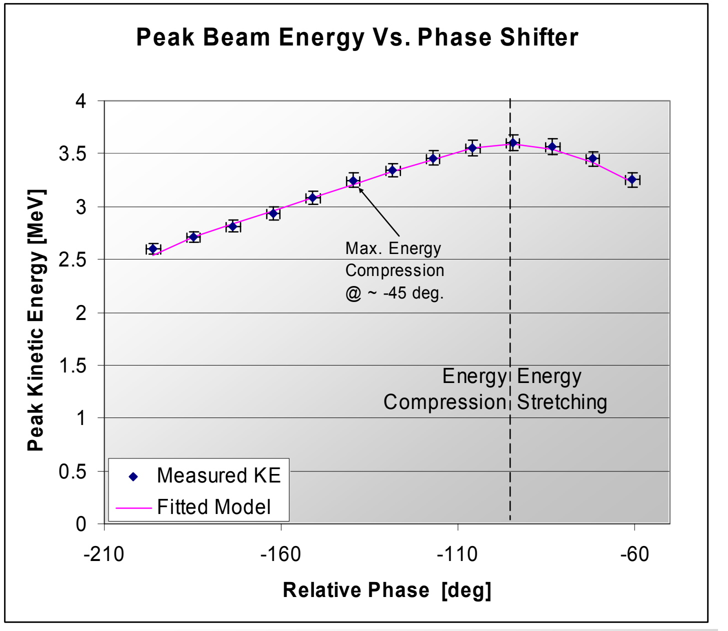


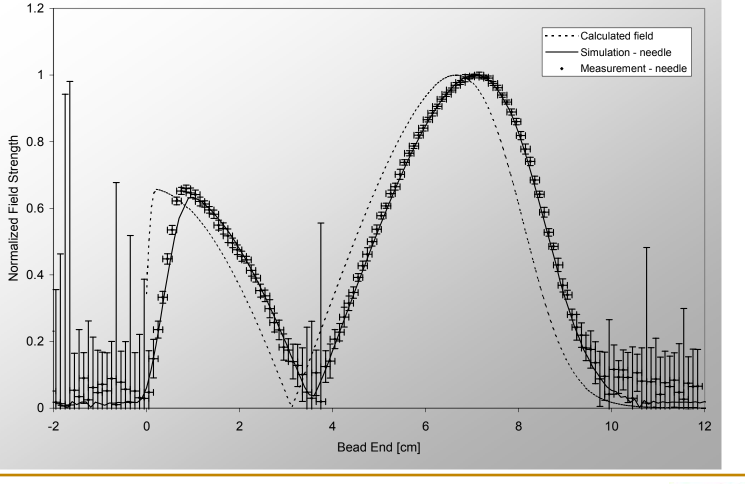
- Convential gun limited in gradient
- Initial acceleration is the most critical for beam property preservation
- “No time for breakdown” DC pulse allows extreme initial gradients

Experiments in Progress

- **BBC gun**
  - Initial longitudinal dynamics studies have started
  - Long-pulse drive laser tests are being planned

- **Higher-order mode photoinjector**
  - Cold-test model characterizations completed
  - Copper cold test model tests in progress





Conclusions & Final Thoughts

- The "canonical" BNL-type high-brightness injector is a "jack-of-all-trades" design; better designs will be required soon
- Injector research at the APS has focused on cavity design and on specific areas of improvement, e.g., longitudinal phase-space control or increased initial gradients
- The experimental program is in its early stages; early results are encouraging
- We hope to start also branching out into cathode research, as that is the other main ingredient for high-performance guns
- Overall injector research review scheduled for 9-10 October