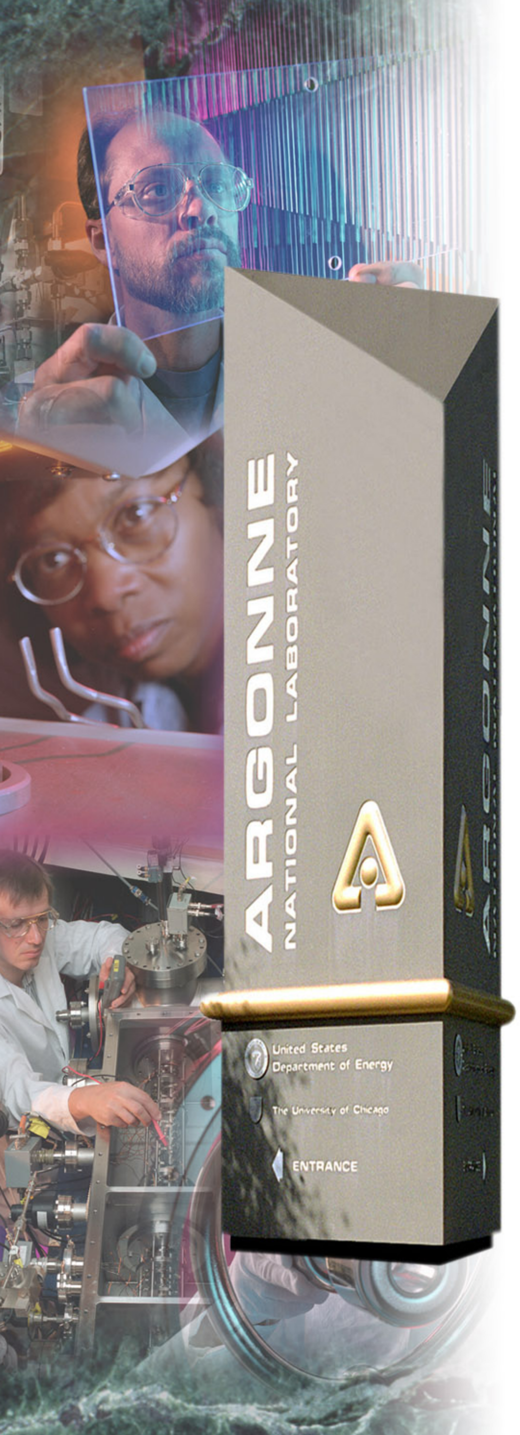

Directions for Electron Beam Injector Development

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Office of Science
U.S. Department of Energy

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Operated by The University of Chicago

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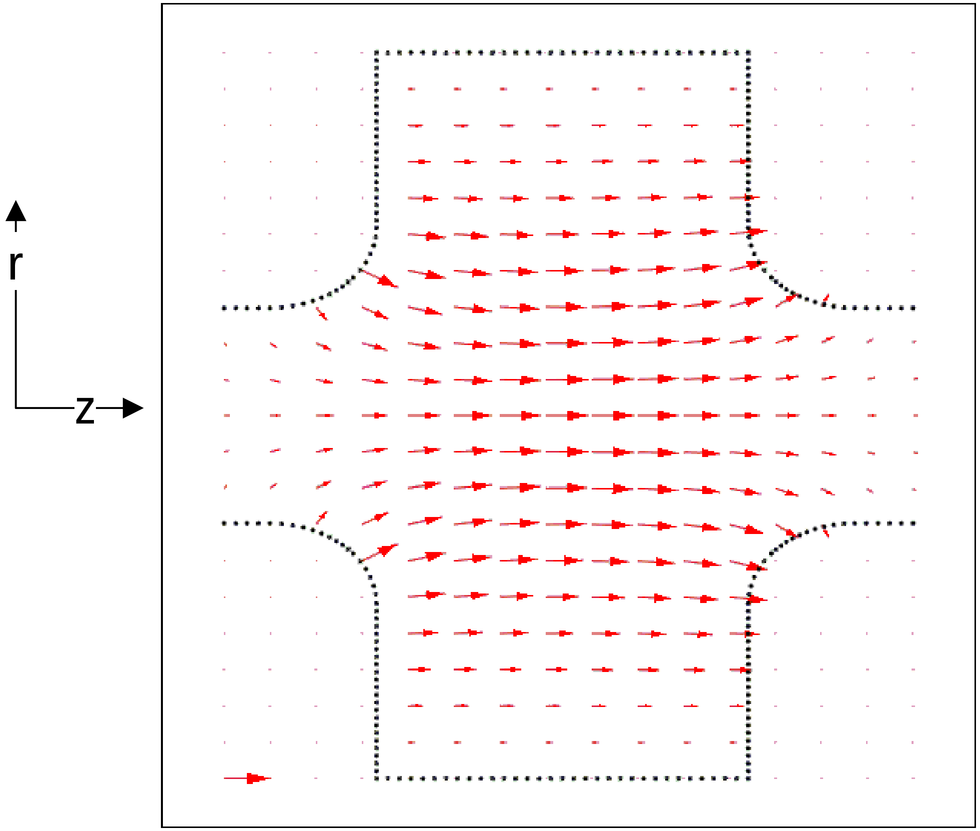
Alan Todd (AES)

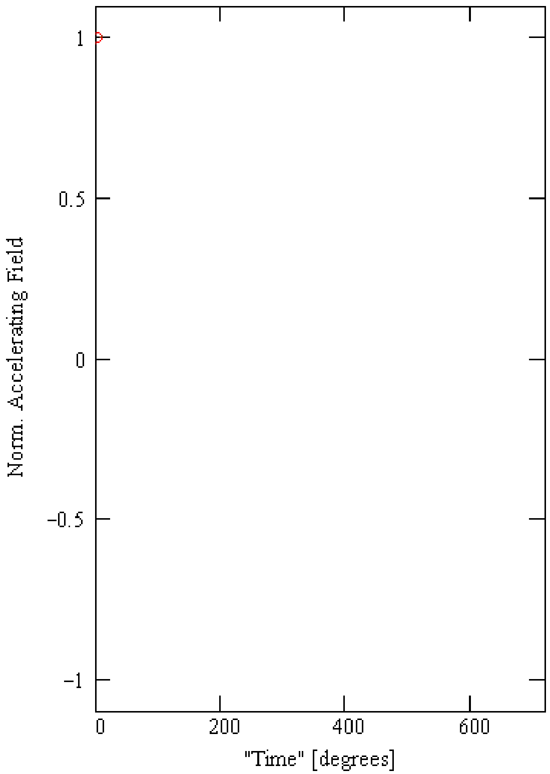
and many others for interesting discussions on gun design & improvement

Talk Overview

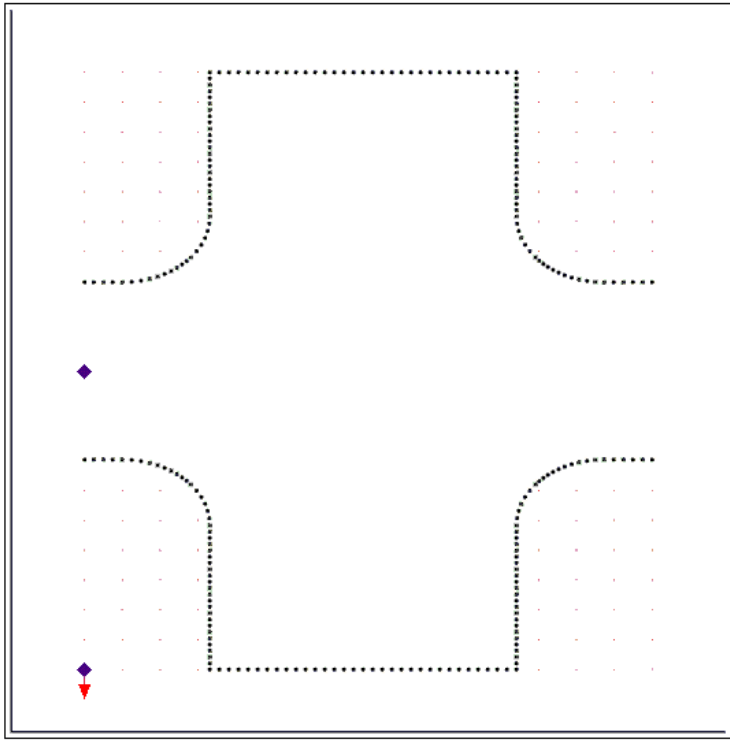
- What is a high-brightness electron gun, in context?
- What I will ignore
- Areas of interest for new source development
  - Linac-based light sources
    - *X-ray free-electron lasers (X-FELs)*
    - *Storage-ring replacements (SRRs)*
  - IR and UV free-electron lasers
  - Electron microscopes
- Common elements
- Ongoing injector development efforts
- Desktop Accelerator Development
- Conclusions & Wrap-Up

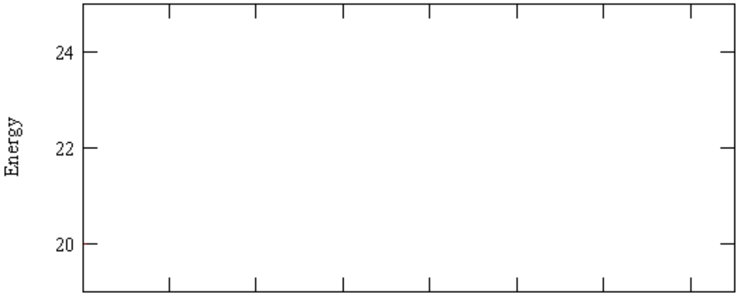
RF Cavity – Accelerator Building Block



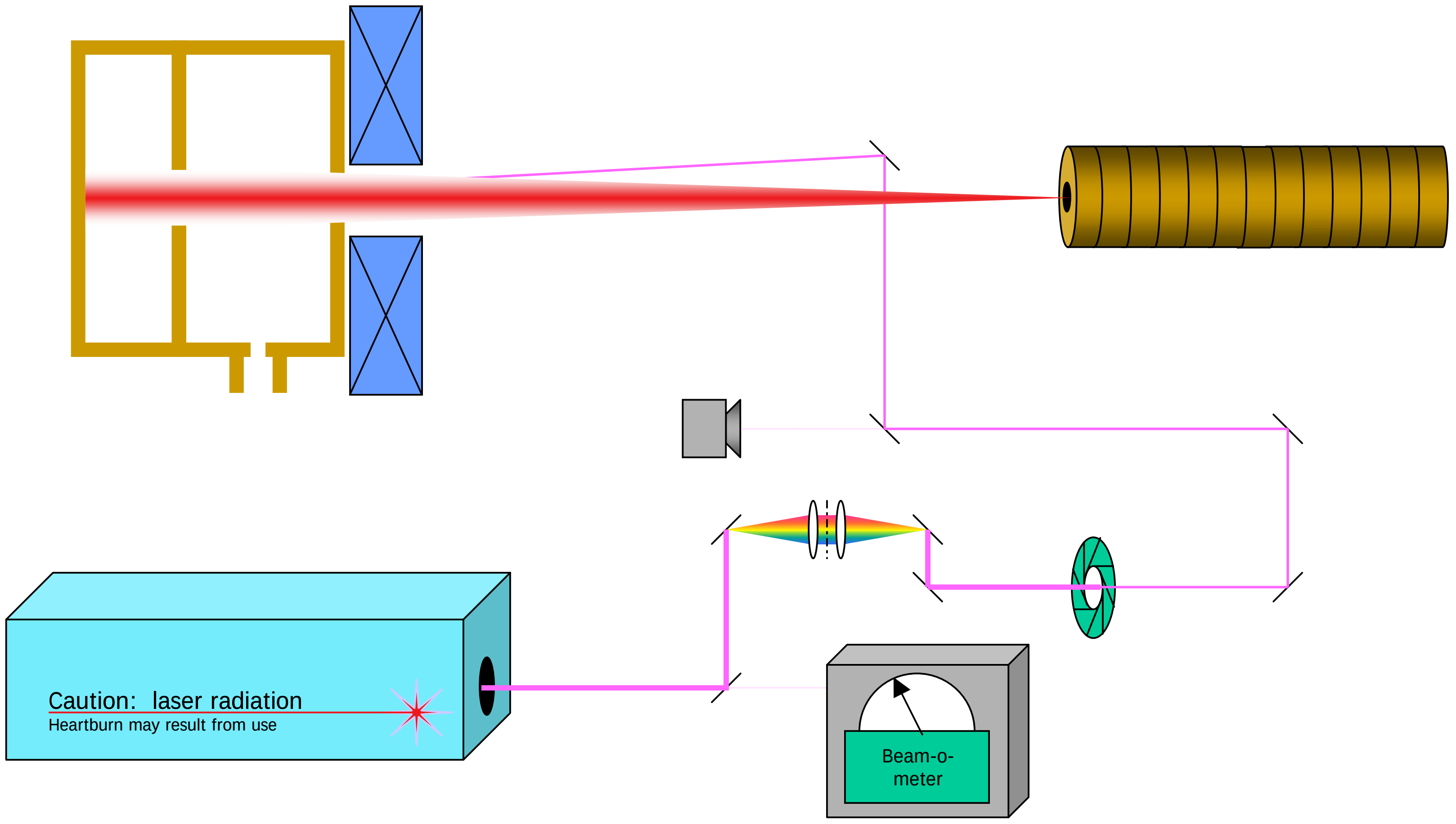


Particle Acceleration



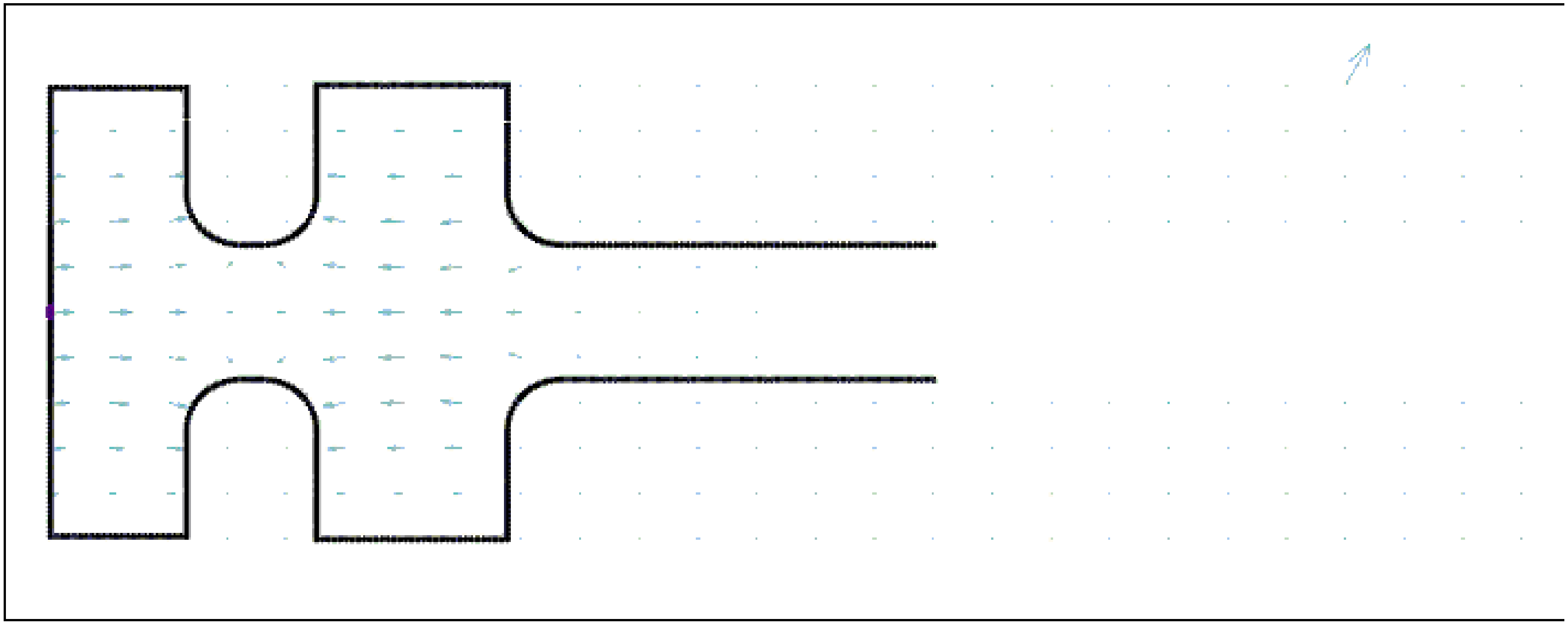


What is an RF Photoinjector?



RF Gun Beam Dynamics

$\gamma = 1$



Launch phase ~ 35°
Gradient ~ 120 MV/m
No space charge included
No solenoid focusing included

Why an RF gun? (Or: Why not DC guns?)

- **Desired beam properties**
  - high bunch charge
  - good transverse quality
  - short bunches

- **High bunch charge → strong space charge**

- **Strong space charge → poor beam quality**

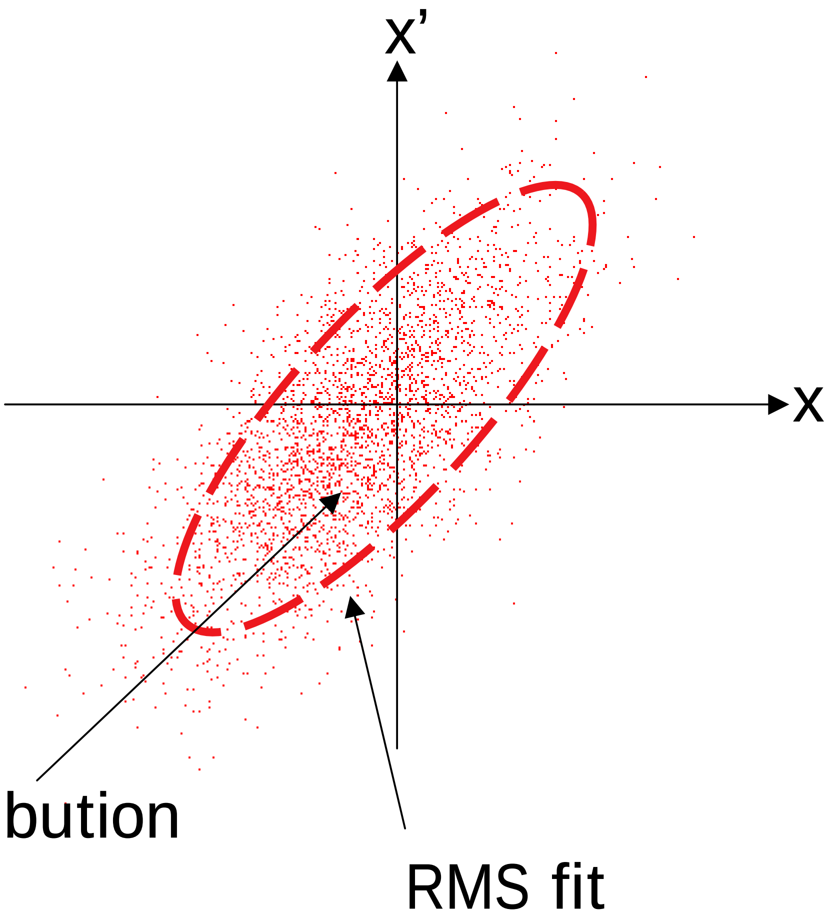
- **Higher gradients → more rapid acceleration → less time for space charge to act**

- **RF guns are very good at providing high gradients … at a price.**

What is emittance?

- Transverse beam quality
- ~ product of spot size and divergence
- Phase space area
- Smaller is better

$$\varepsilon_{x,n} = \sqrt{\langle x^2 \rangle \langle p_x{}^2 \rangle - \langle x \cdot p_x \rangle^2}$$



What is brightness? What's High-Brightness?

- **One canonical definition:**

$$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

- **Another definition:**

$$\rho = \left[\alpha \cdot \frac{I}{\sigma_x^2}\right]^{1/3} \propto \left[\frac{I}{\varepsilon_n}\right]^{1/3}$$

- **The actual characteristics of a beam, relative to those which are of interest for the task we wish to perform with the beam**

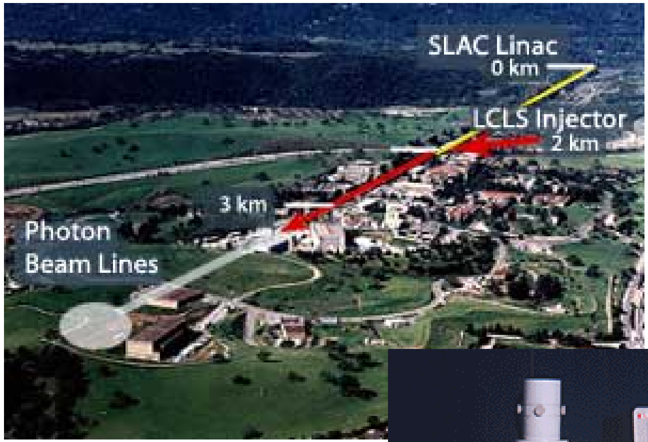
- **In useful terms, brightness is situational.**

Important but ignored (by this talk)

- **Drive laser development efforts**
- **High-brightness beam diagnostics (e.g. emittance measurement)**
- **Operational reliability – transition from laboratory curiosity to facility keystone**
    - service & maintenance features
    - mean time between failures
    - soft vs. hard failure modes
    - etc…

Directions for Injector Development

- "Big Iron" accelerators
  - Linear colliders
  - Next-generation x-ray light sources
- "Desktop" accelerators
  - Electron microscopy
  - Electron beam lithography
  - Small laboratory experiments
- "Mini-Me" accelerators
  - Radioisotope generation
  - High-power free-electron lasers
  - Slow positron production
  - Pulse radiography



Courtesy SLAC/LCLS

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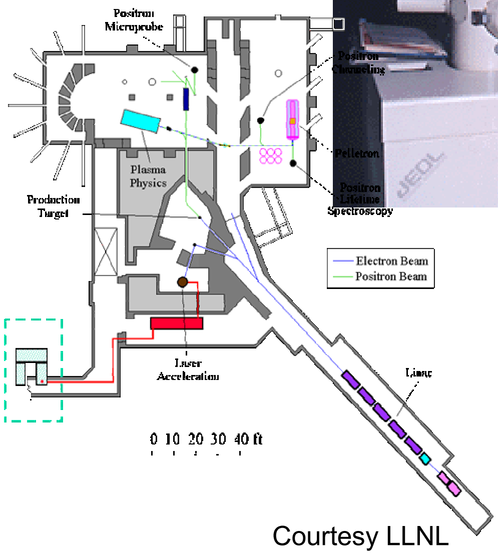
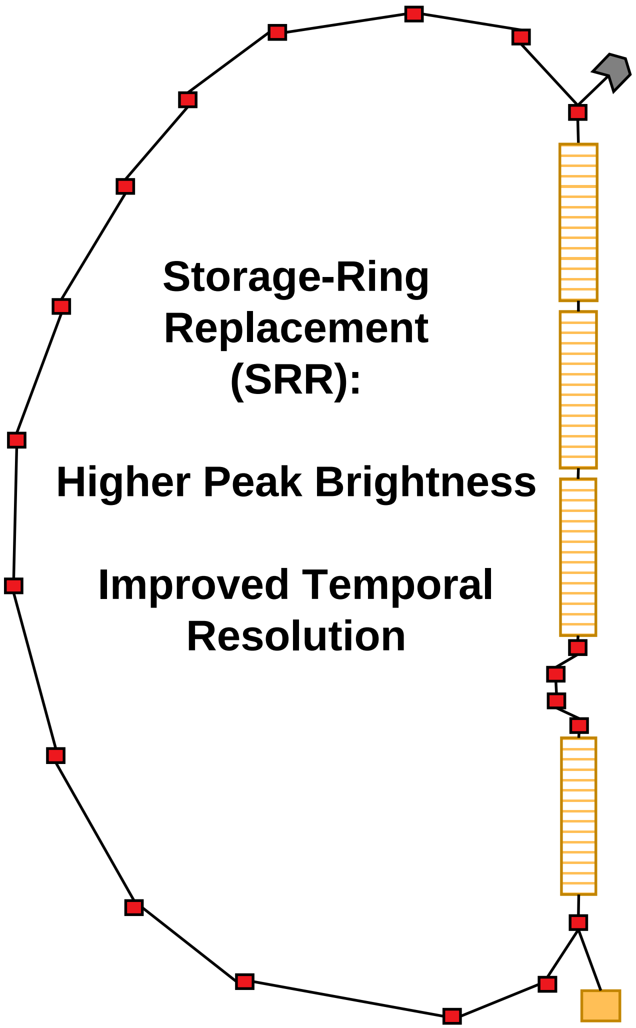


Courtesy LLNL

Storage-Ring Replacements & X-FELs



Storage-Ring Replacement (SRR):

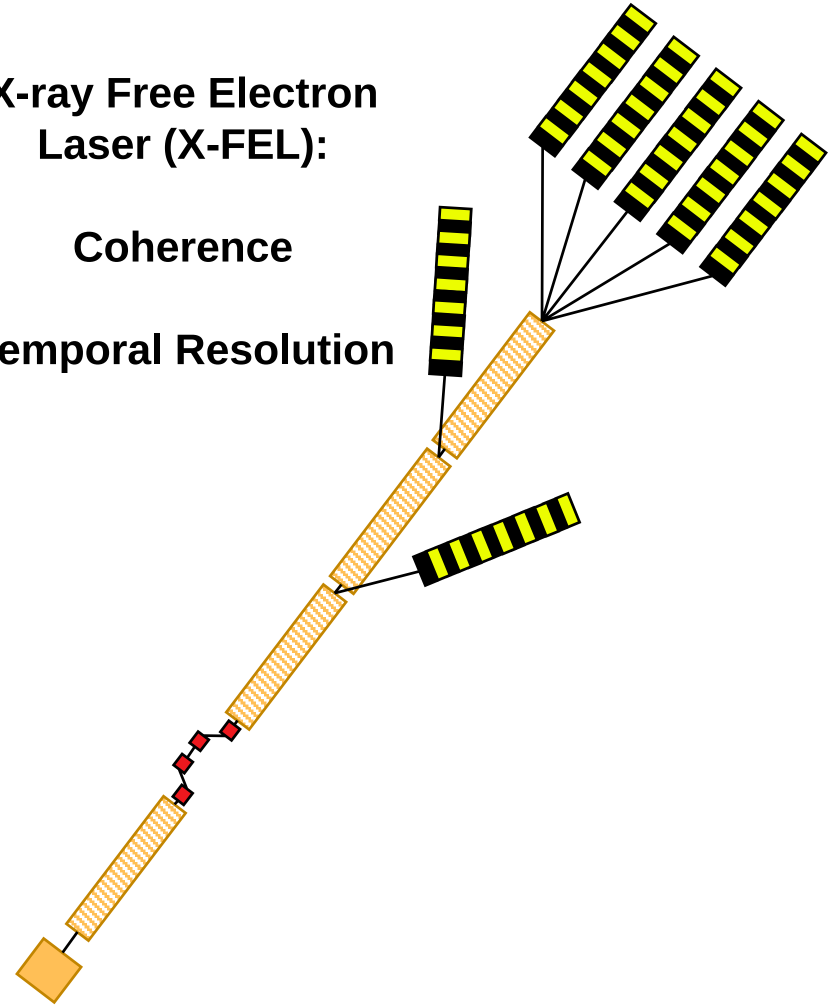
Higher Peak Brightness

Improved Temporal Resolution

X-ray Free Electron Laser (X-FEL):

Coherence

Temporal Resolution



"1st-generation" Linac Based Light Sources

Linac-Based Light Sources – Source Specs

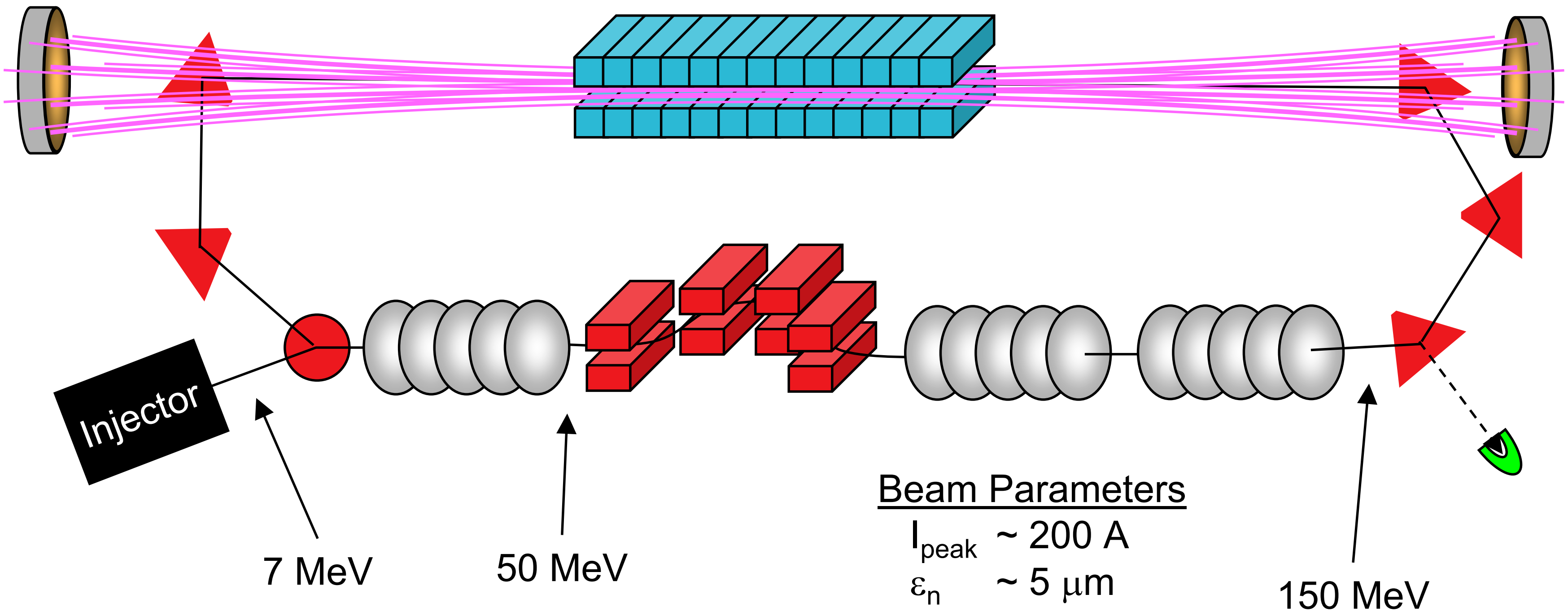
- **Single-bunch requirements**
  - 0.1 μm normalized transverse emittance
  - 0.1 nC
  - 500 – 1500 A peak current (after linac compressor)
  - 0.025% relative energy spread

- **Duty factor requirements**
  - 10 – 100 mA (SRR gun)
  - 120 Hz – 10 kHz (X-FEL gun)

High-power IR and UV FELs

Average beam current: 1A
Electron beam power: 150 MW
Optical beam power: 1 - 2 MW

RF power used: 7 MW (to dump)
: 2 MW (FEL)
Wallplug efficiency: ~ 10 – 20%



Beam Parameters

I_{peak}	~ 200 A
ε_n	~ 5 μm
$\delta E/E$	~ 0.1%

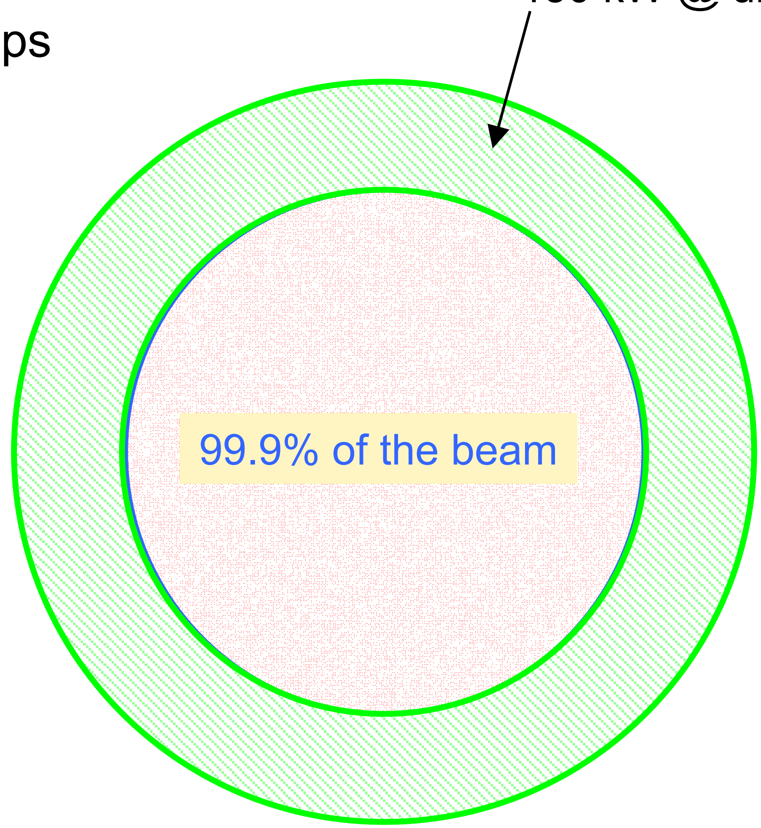
High-power IR and UV FELs

Injector performance requirements

Transverse emittance:	3 – 5 μm
Longitudinal emittance:	< 100 keV ps
Average beam current:	~ 1 A
Single-bunch charge:	1 – 1.5 nC

Some other considerations…

- Energy gain per gun cavity: < 2 MeV
- Beam break-up modes
- Drive laser power requirements
- Beam halo



Electron Microscope Guns

Linac Injector Gun

- 1 – 5 MeV (kinetic)
- 0.1 – 1 nC / bunch
- nA – mA
- ~ 1 μm norm. emittance
- ~ 1% rms energy spread
- 1st-order optics (solenoid)

Electron Microscope

- 10 – 50 keV (kinetic)
- Bunches? What bunches?
- few mA
- ~ 1 nm norm. emittance
- ~ 10^{-5} rms energy spread
- High-order optical corrections

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Directions of exploration...

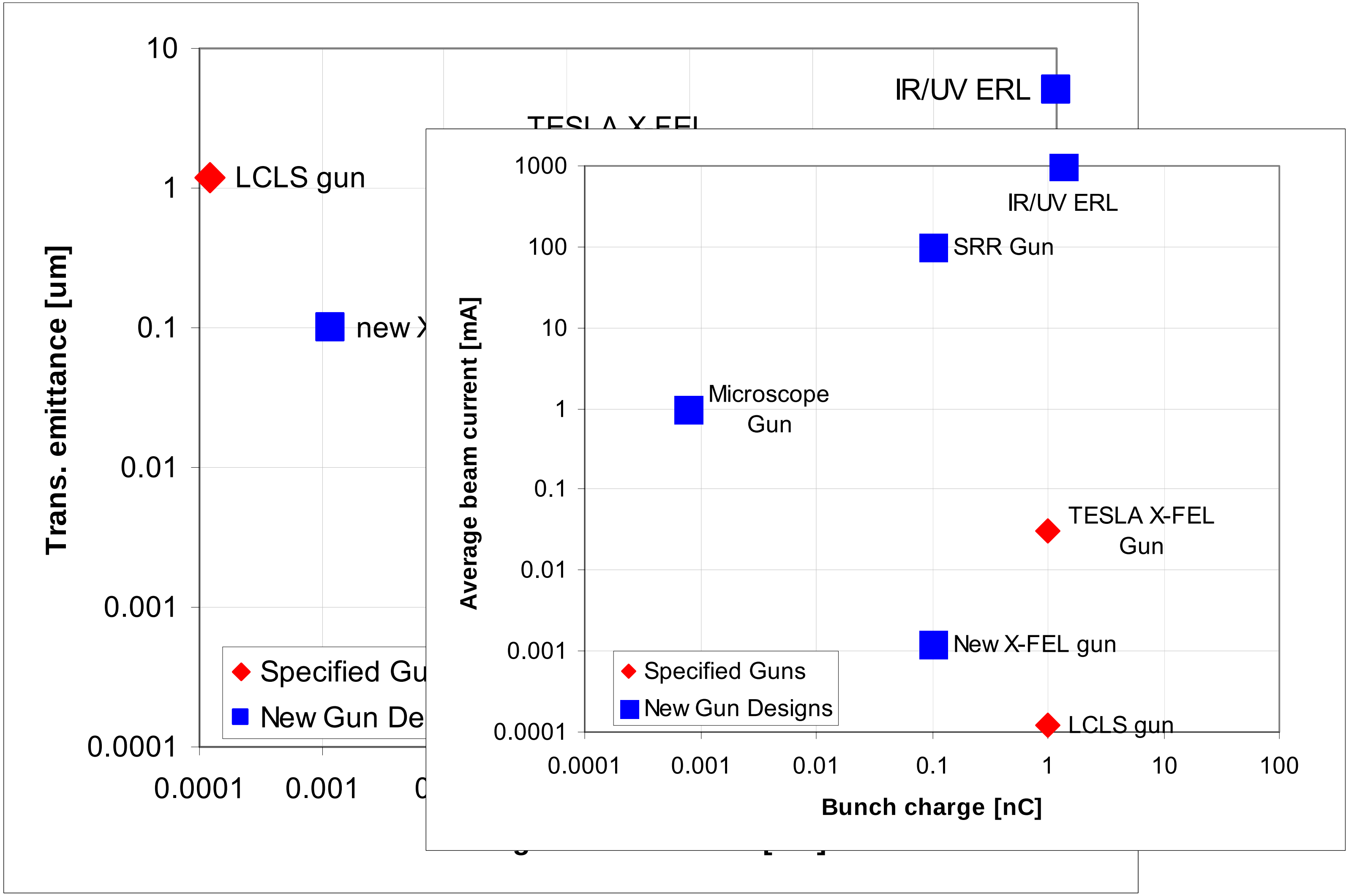
Some different requirements

- **"Big Iron"**
  - lower emittance (10x)
  - higher peak currents (5x)
  - emittance aspect ratio control
- **"Desktop"**
  - ultra-low emittance (10^3x)
  - very low energy spreads (10^{-5})
- **"Mini-Me"**
  - (usually) modest beam quality (e.g. we can sometimes get there today)
  - high average power (e.g. 1 MW from the gun for FEL)
  - at least quasi-CW operation
  - beam halo is a critical issue

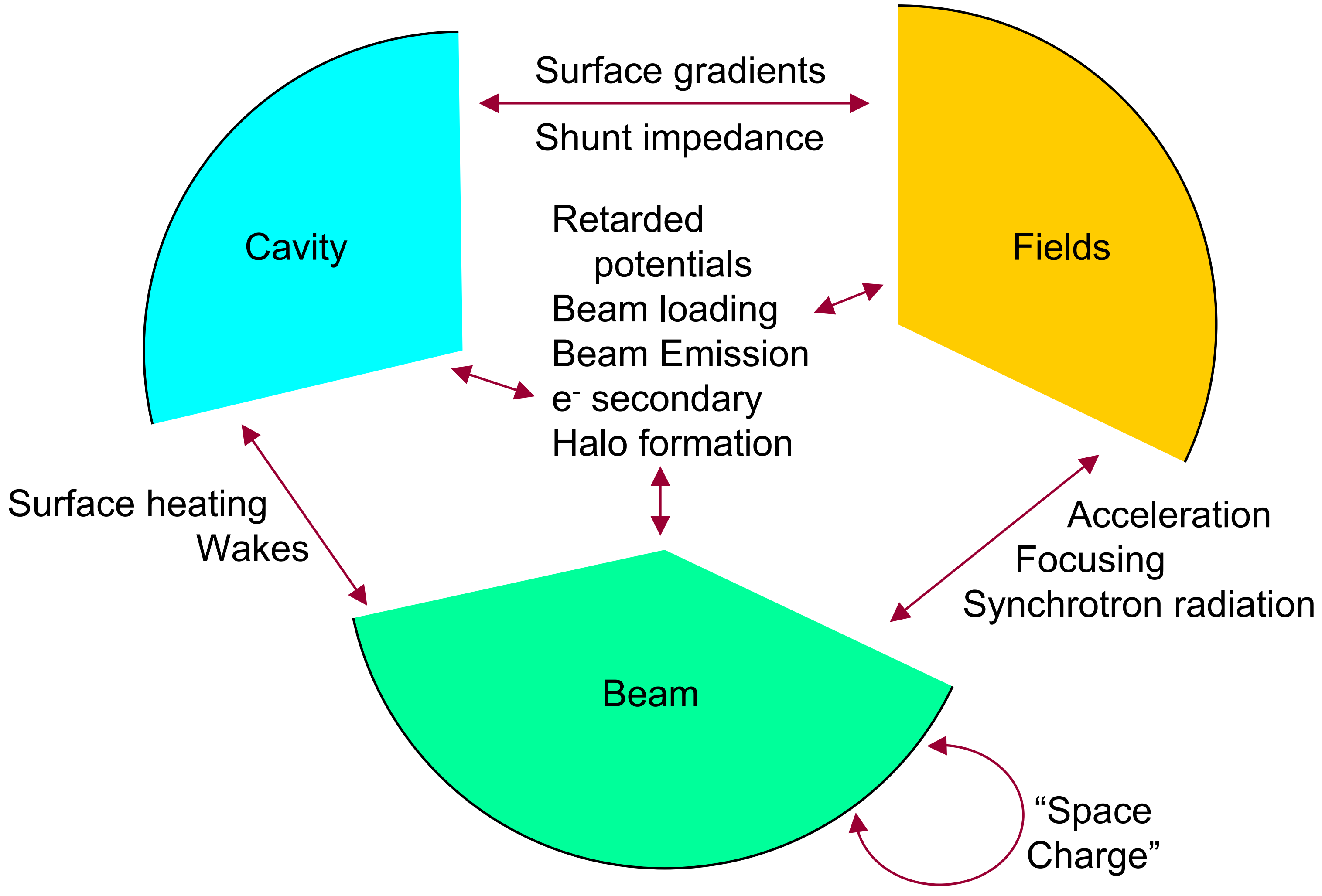
Some common themes

- Higher performance levels than are routinely achieved today are demanded
- With few exceptions, the injector is a quasi-standalone component
- Injector reliability is key to the uptime of the entire facility
- Backup injector capability would be a large benefit
- "Beyond the beam physics" issues are very important

An Interim Summary…



What is being modeled?



Common Elements

Performance Figures
- Better cathodes
- Higher duty factors
- Better beam quality

Fabrication Issues
- Improved symmetrization
- Thermal issues (cooling, transients)
- Higher-capacity power couplers
- Routine maintenance

R&D Requirements
- Cathode research
- Extended injector theory
- Expanded & improved simulation codes
  - cavity / beam interactions
  - wakefields
  - HOM effects
  - Beam halo

A Word on Photocathodes…

Drive laser requirements

Cathode Material		Quantum Efficiency	Operating Wavelength	Harmonic laser power needed for: 10 mA	100 mA	Fundamental laser power for 100 mA
Metal	Copper	10^{-5}	266 nm	4.6 kW	46 kW	~ 750 kW
	Magnesium	$5 \cdot 10^{-5}$	266 nm	930 W	9.3 kW	~ 150 kW
CsTe		0.5%	266 nm	9.3 W	93 W	~ 1.5 kW
Alkali, NEA		5%	532 nm	0.46 W	4.6 W	~ 20 W

$$\varepsilon_{thermal,rms} = x_{rms} \frac{\sqrt{2 m_e E_{kin}}}{m_e c}$$

$$= (1-3)\,\mu m/mm$$

Target emittance	$\sigma_x < \ldots^*$
5 μm (IR, UV FEL)	1.8 mm
1 μm (LCLS)	0.36 mm
0.1 μm (SRR, X-FEL)	36 μm
1 nm (E-microscope)	0.36 μm

* for $E_k = 1$ eV; $\sqrt{2}\,\varepsilon_{th} \leq \varepsilon_{total}$

Injector Development Efforts: Simulations

- **DC guns:**
  - 0.1 μm @ 0.08 nC
- **SRF guns:**
  - ε_n ~ 5 nm, $\delta E/E$ ~ $5x10^{-5}$, E_k ~ 1.7 MeV, I_{avg} ~ 90 μA
  - ε_n ~ 0.1 μm @ 0.05 nC
  - ε_n ~ < 5 μm @ 1 A
- **NC guns:**
  - needle cathode: 0.05 μm @ 0.02 nC
  - planar focusing cathode: 0.13 μm @ 0.1 nC

Simulation Results:

- ***No thermal emittance included!***
- ***Single-bunch performance only!***

Injector Development Efforts: Who & What?

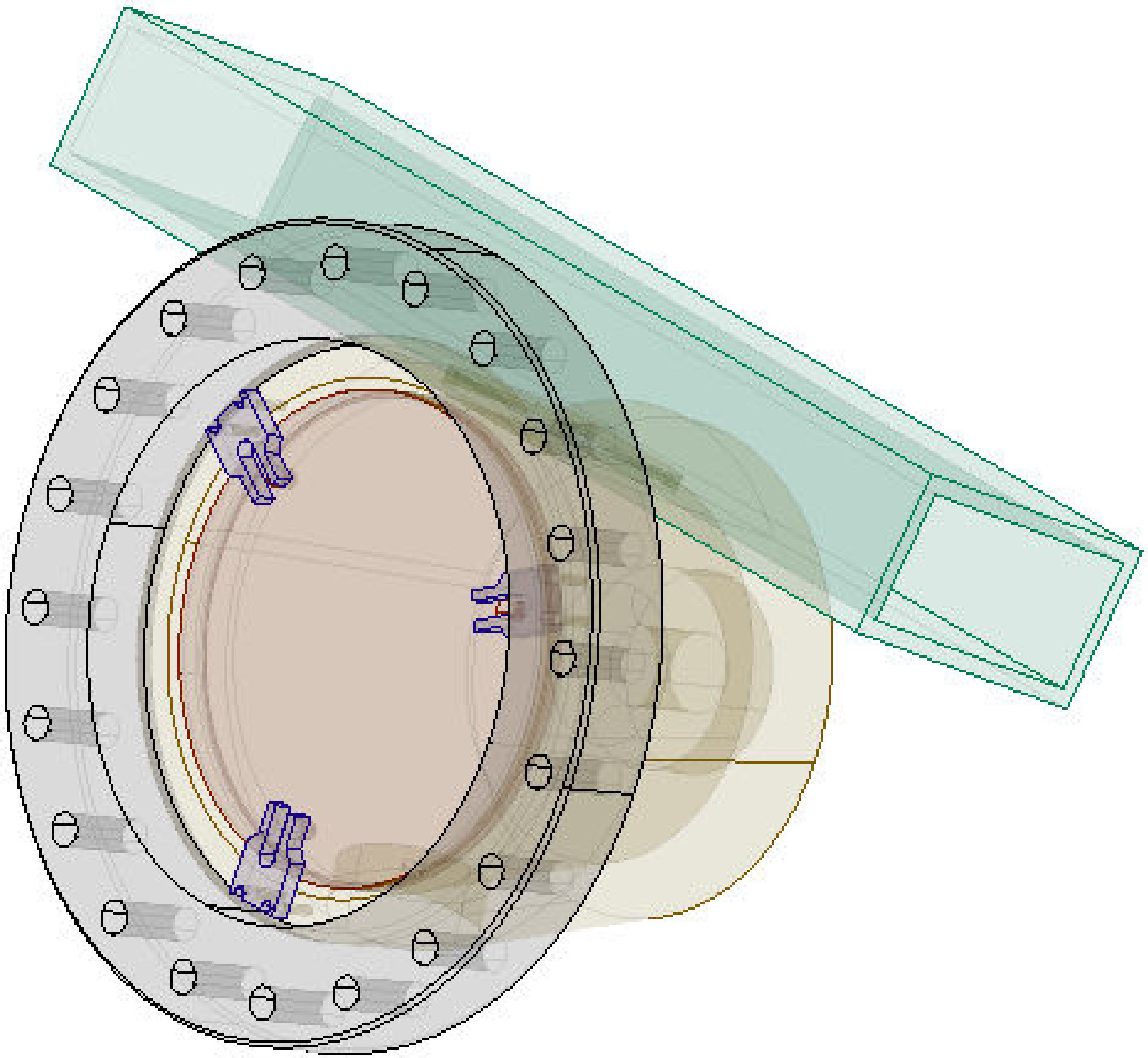
- **Cornell**
  - DC guns for ERLs
  - massive concurrent processing & optimization using ASTRA
- **Advanced Energy Systems**
  - DC/SRF hybrid with JLab
  - NC-CW for IR-FEL with LANL
  - SRF CW with BNL and JTO
  - High-duty-factor with SLAC
  - Polarized source studies
- **SPring-8 / Riken / KEK**
  - DC gun for FEL
- **LBNL**
  - High-rep-rate NC guns
- **TU-Eindhoven**
  - DC/RF hybrid NC guns
- **Vanderbilt**
  - Needle cathodes
- **LANL**
  - high-power CW NC guns
- **Stanford / SLAC**
  - Polarized-beam gun
  - High-duty-factor NC operation
  - Multifrequency gun designs
- **BNL**
  - SRF gun with AES & Rossendorf
  - Electron cooling injectors
- **DESY & PITZ**
  - High-rep-rate NC guns
  - Next-generation injector research
- **FNAL**
  - Flat-beam production
  - LN_2-cooled NC guns
- **Rossendorf**
  - fully SRF gun development w/ novel focusing
- **ANL**
  - high-power CW NC & SRF guns
  - e-microscope guns (just starting)

Injector Development Efforts: Cathodes

- **Brookhaven National Laboratory**
  - Nb cathodes (“native” SRF gun cathodes)
  - Diamond-plate secondary-emission cathode
- **U. Maryland & Naval Research Laboratory**
  - Thermionic-assisted photocathodes
  - General cathode emission theory
- **SPRING-8**
  - DC gun cathodes
- **SLAC**
  - Polarized electron cathode for RF guns

Parting thoughts – Part 1

- **Injector development is proceeding in many directions.**
- **Many designs begin to approach materials & technological limits (e.g. thermal emittance, rf coupler power handling).**
- **Many common themes unite the work, including:**
  - need for more cathode research for better cathodes (lifetime, QE, $\varepsilon_{thermal}$), and
  - need for theory & simulations with expanded capabilities to take into account new design features.
- **This is an exciting time to be working on injector design**



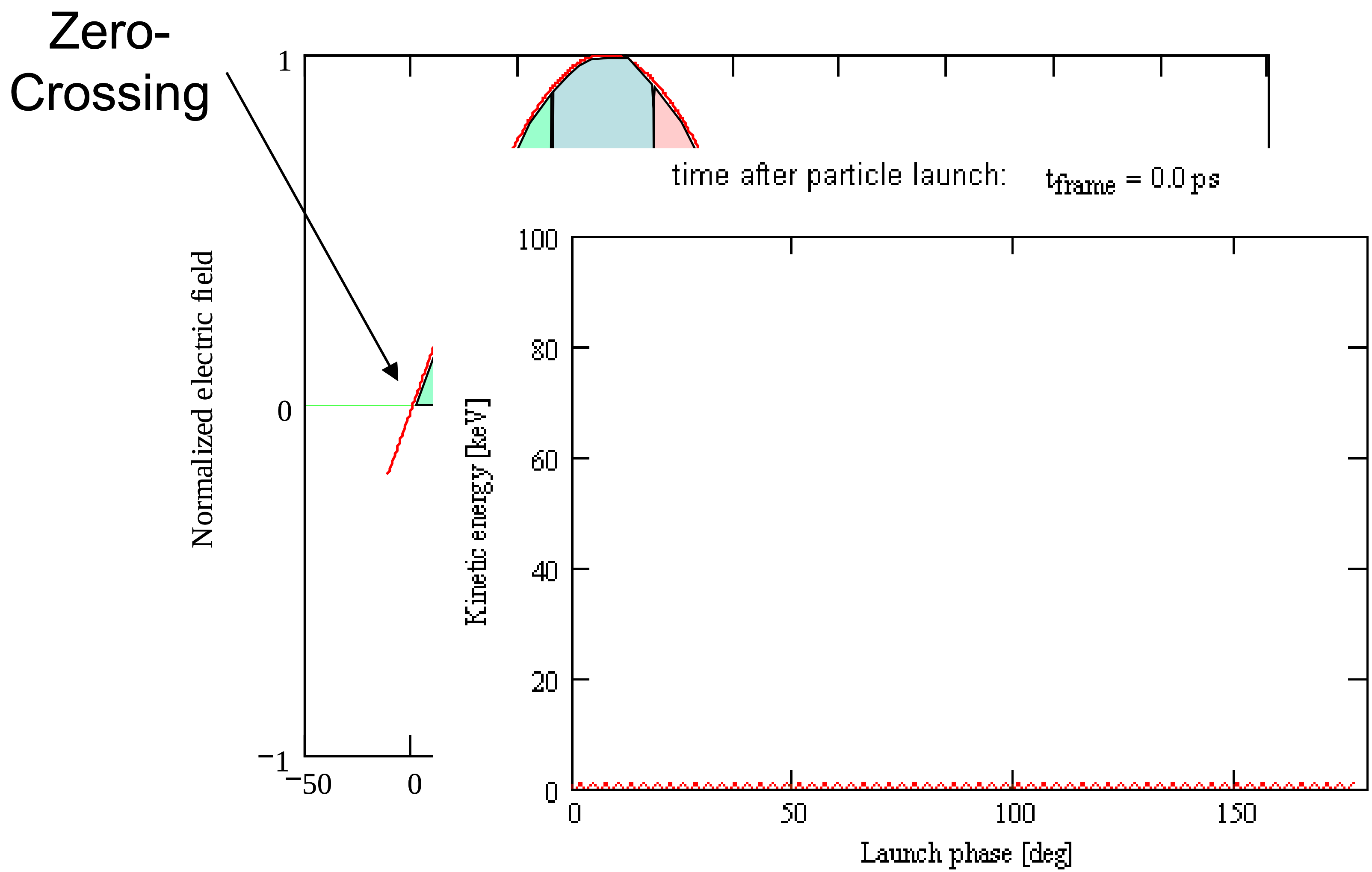
Desktop Accelerator Development

- **Interesting things to do with just a gun**
- **Choices for cathodes**
- **General limitations**
  - Duty factor
  - Drive laser
- **Losing the laser**
- **Some performance calculations**
- **Concluding remarks and thoughts**

Fun Gun Things (no linacs required)

- **Particle beam & accelerator physics**
  - basic beam physics measurements
  - beam manipulation
  - diagnostics development
- **Applications**
  - Electron microscopy
  - Long-wavelength radiation generation
  - E-beam welding
  - Cancer therapy
  - Etc…
- **Teaching**

Beam Emission Timing



Cathode Overview

"Ideal" Cathode Checklist:

- ✓ **Long lifetime**
- ✓ **Rapidly switchable on/off**
- ✓ **Damage resistant**
- ✓ **High charge density**
- ✓ **Cryogenic compatible**
- ✓ **Simple operation**

Photocathodes

Emission mechanism: Use laser pulse to excite electrons off the cathode surface

Advantages:
- ✓ Rapidly switchable
- ✓ High charge density

Disadvantages:
- × Efficiency-lifetime tradeoffs
- × External drive laser required

Thermionic cathodes

Emission mechanism: heat the cathode to "boil" the electron sea in the metal

Advantages:
- ✓ Long lifetime
- ✓ Robust
- ✓ Simple to operate

Disadvantages:
- × Not rapidly switchable
- × High temperature required

Field-emission cathodes

Emission mechanism: Electric field pulls electrons from cathode surface

Advantages:
- ✓ Very simple
- ✓ High charge density
- ✓ Rapid turn-on/off

Disadvantages:
- × Problematic gating (for rf app.)
- × Damage questions

Limitations on Electron Gun Performance

- **Duty factor**
  - Field gradients of 10 – 100 MV/m, over 10s of cm, desired
  - Cu cavity guns: max. duty factor 25% to date
    - *low-frequency*
    - *anything but compact*
  - SRF gun developments promise true CW operation

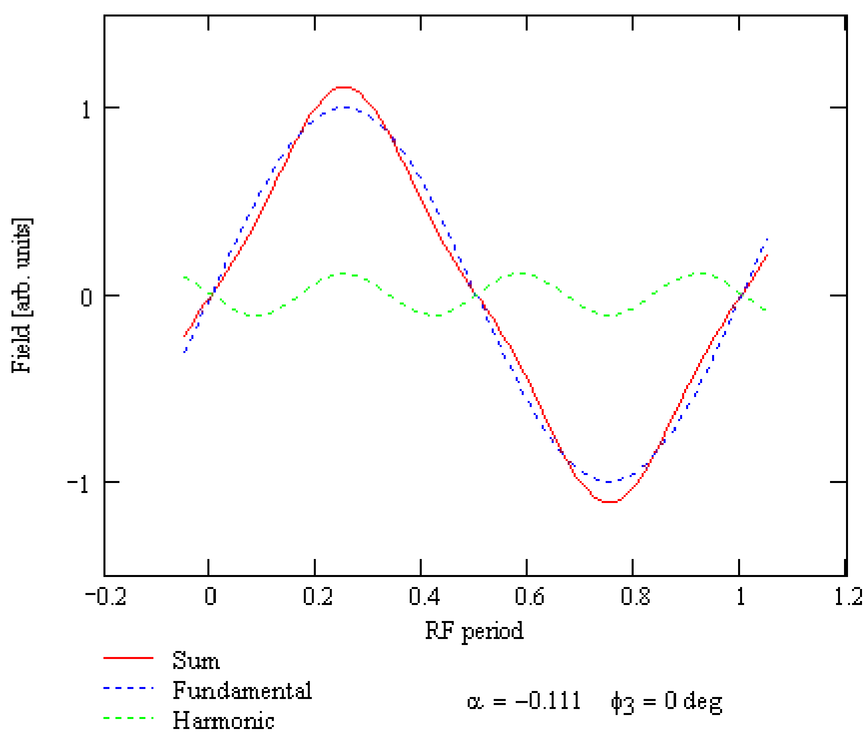
- **Drive laser**
  - Laser rep rates often lower than gun rf frequencies
    - *higher charge per pulse for same <I>*
    - *higher laser energies required*
  - Unobtainium cathodes needed for true CW & long-life operation

Field Emission Cathode Gating Scheme

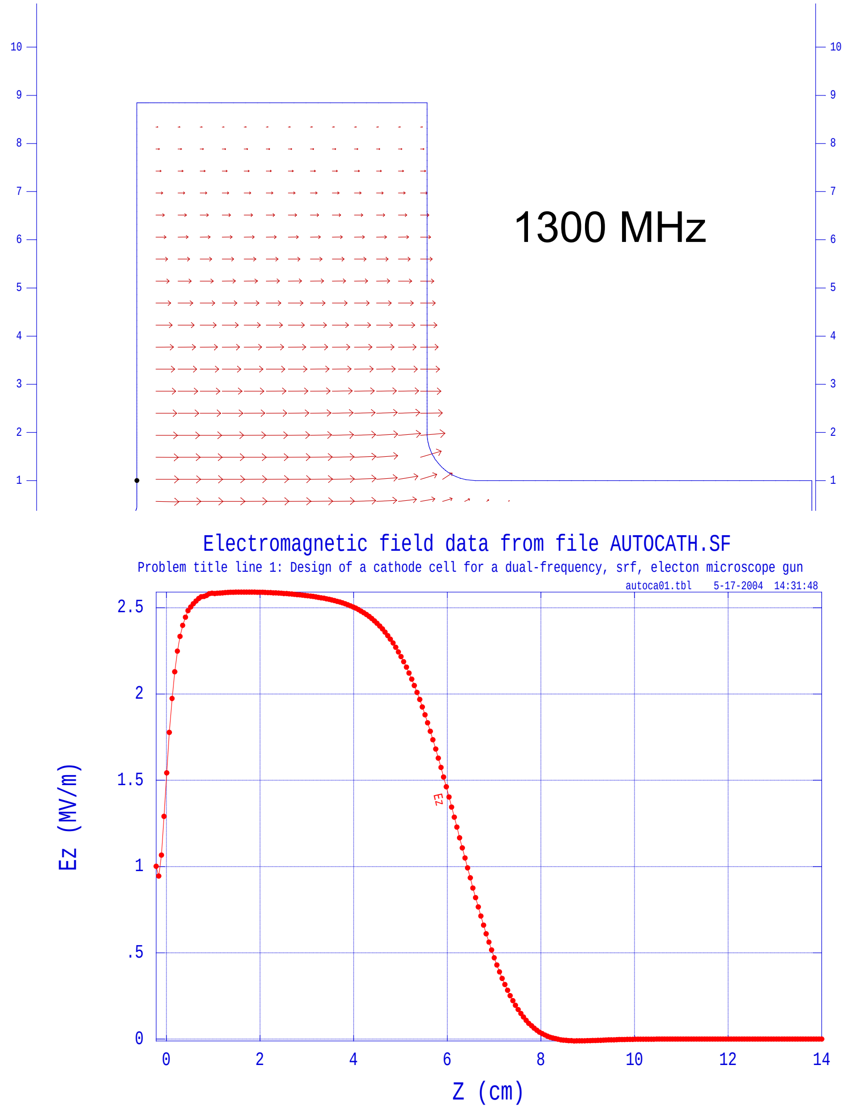
FE cathodes emit electrons when the field is high enough

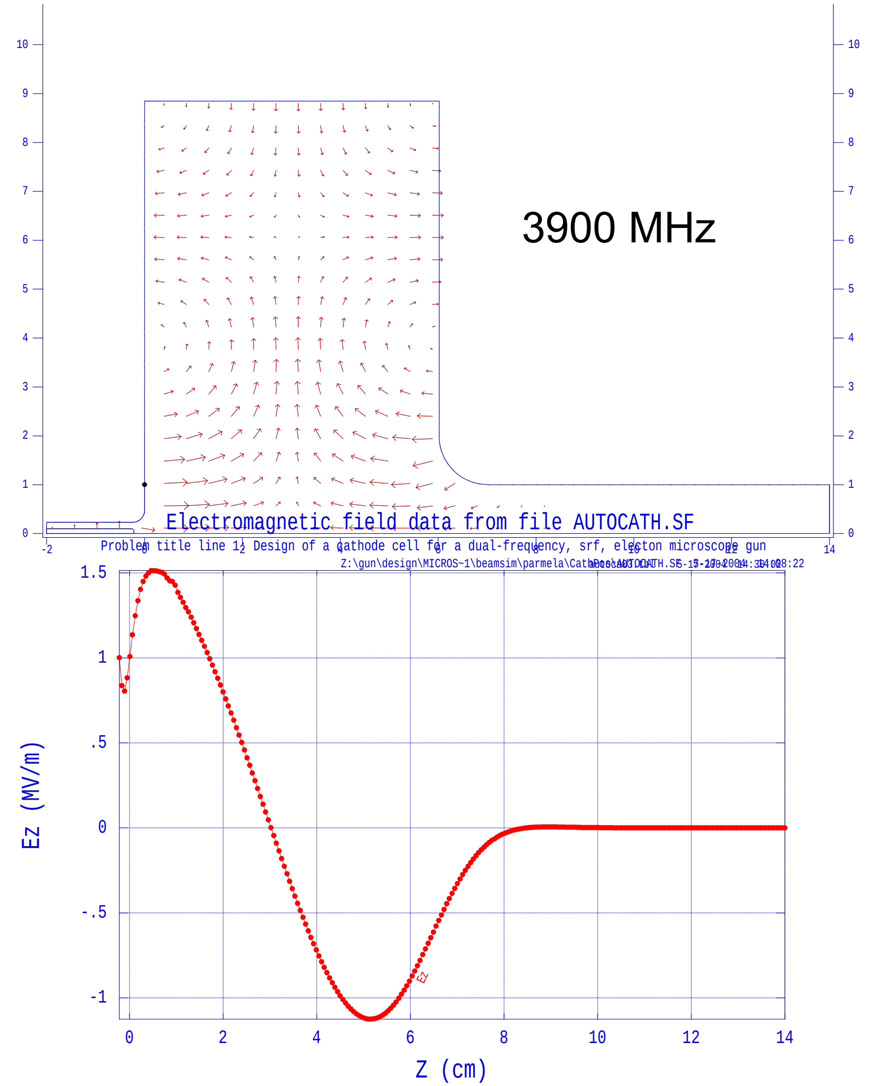
- **operate at low temperature (unlike thermionic cathodes)**
- **emit only under "internal" influences (unlike photocathodes)**

$$\text{Sum} = E_0 \cdot \sin(2 \cdot \pi f \cdot t) + \alpha \cdot E_0 \cdot \sin(2 \cdot \pi \cdot 3 \cdot f \cdot t + \phi_3)$$



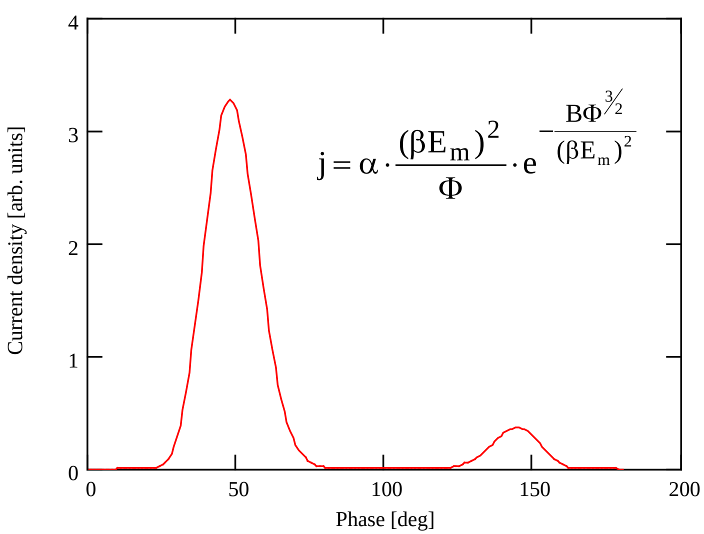
Can these fields be realized?

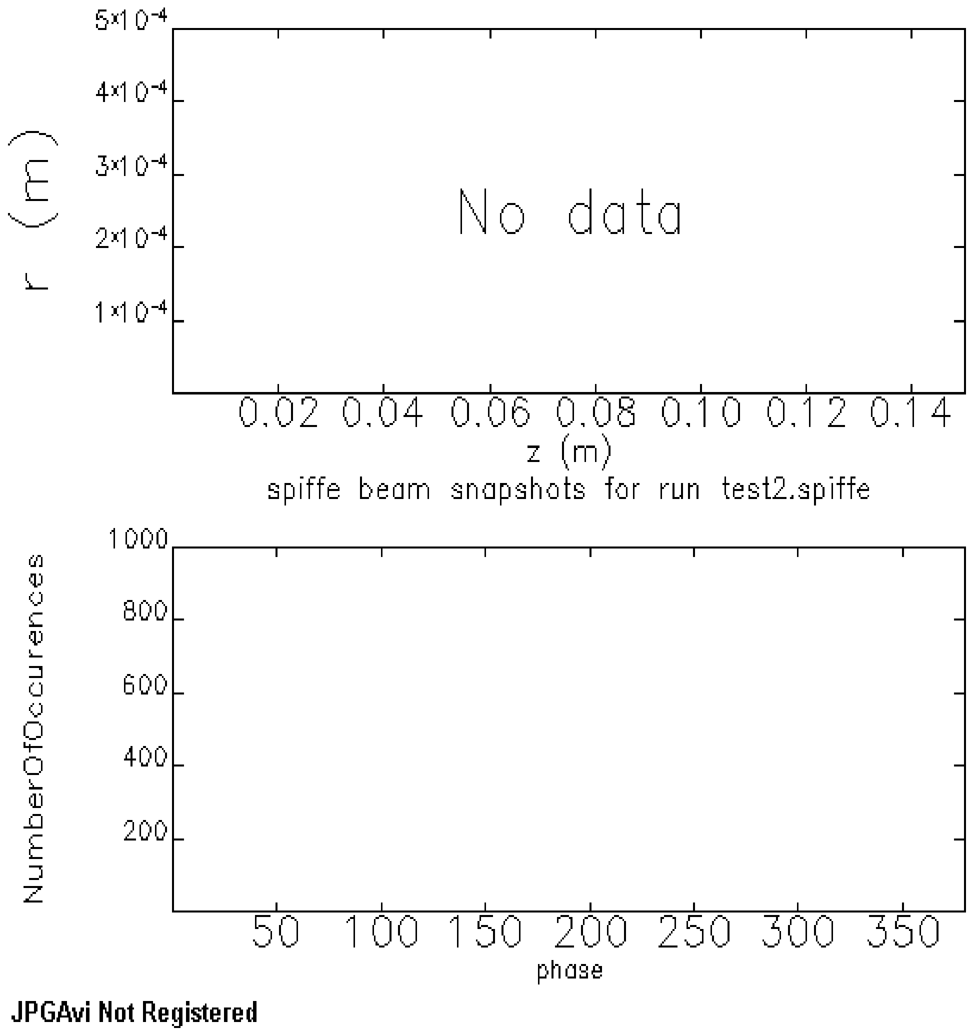




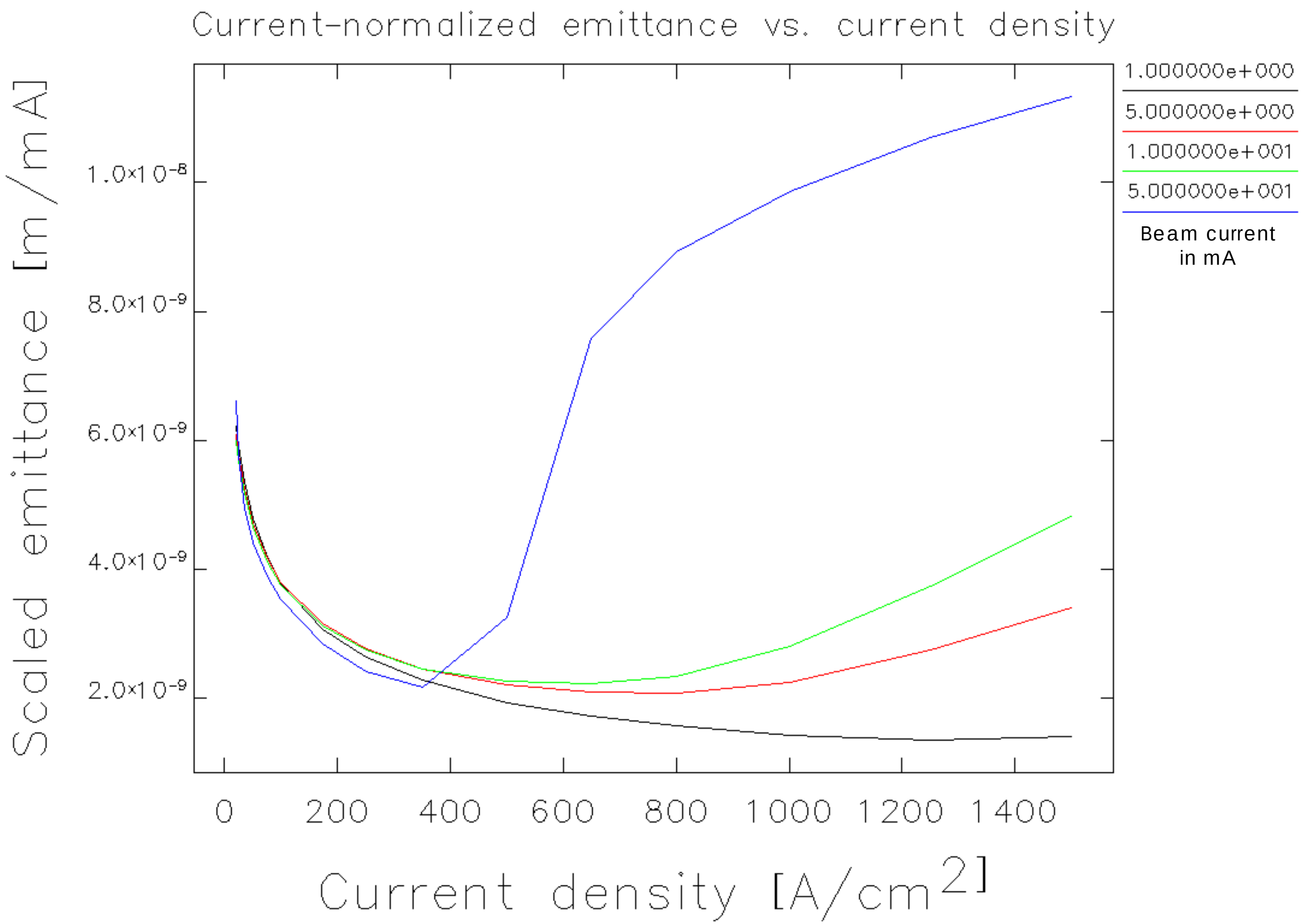
Will it work?

- **Simulation:**
  - Incorporated the Shottky emission model directly
  - Also includes space-charge effects

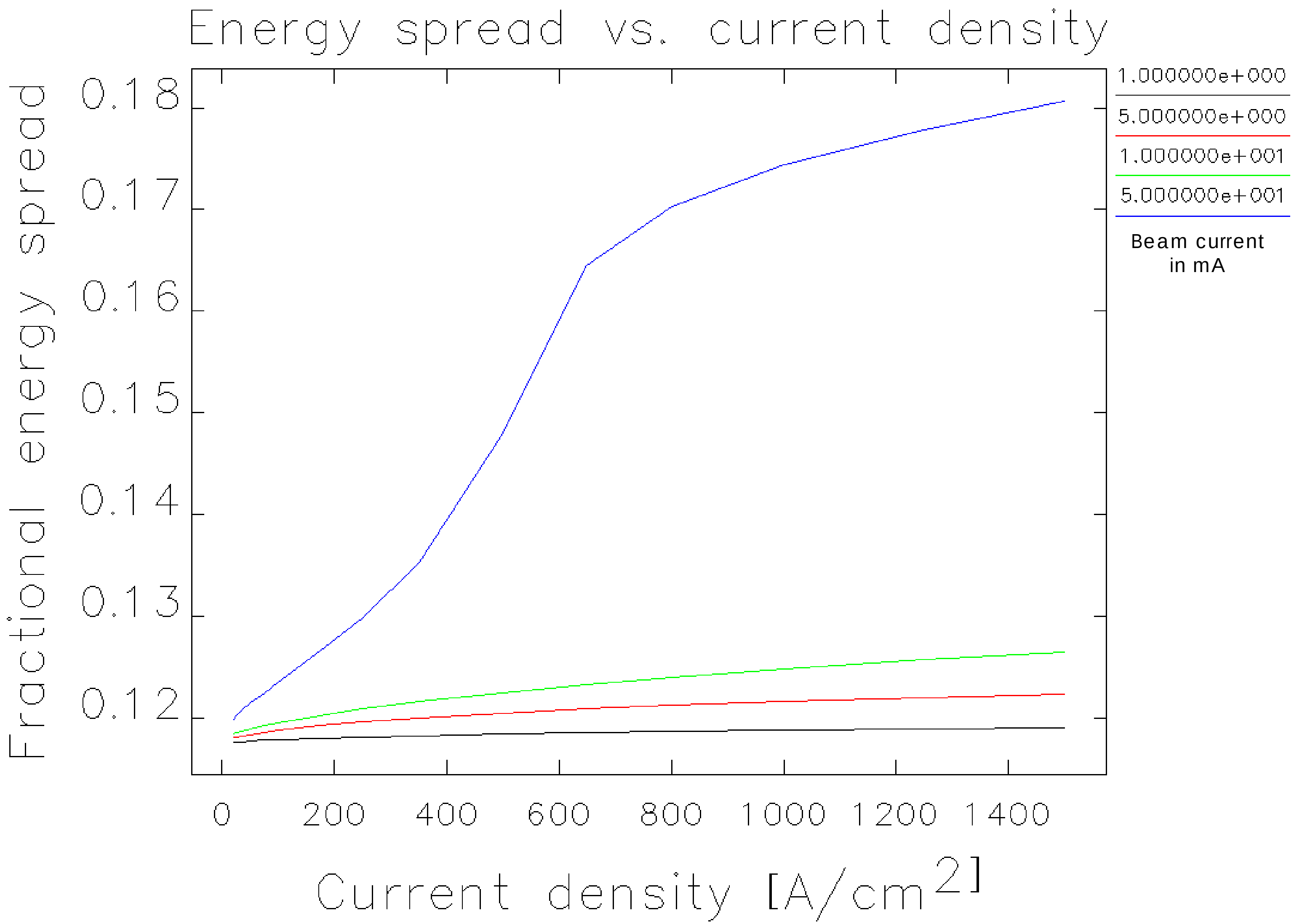




Expected scaling – emittance

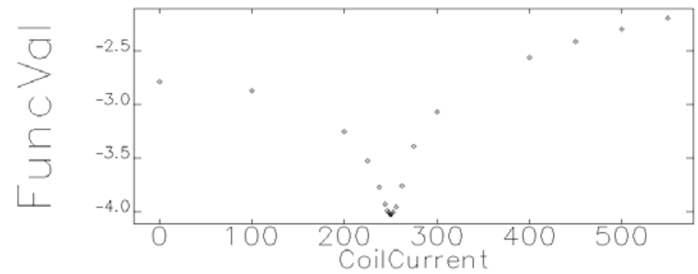


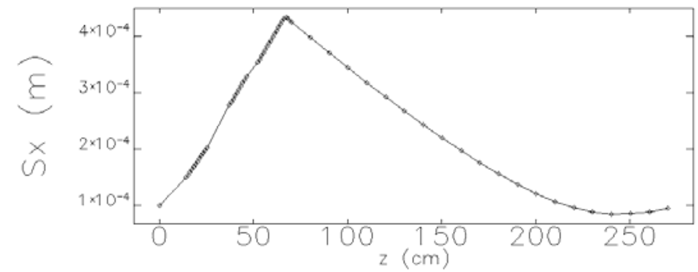
Expected scaling – energy spread

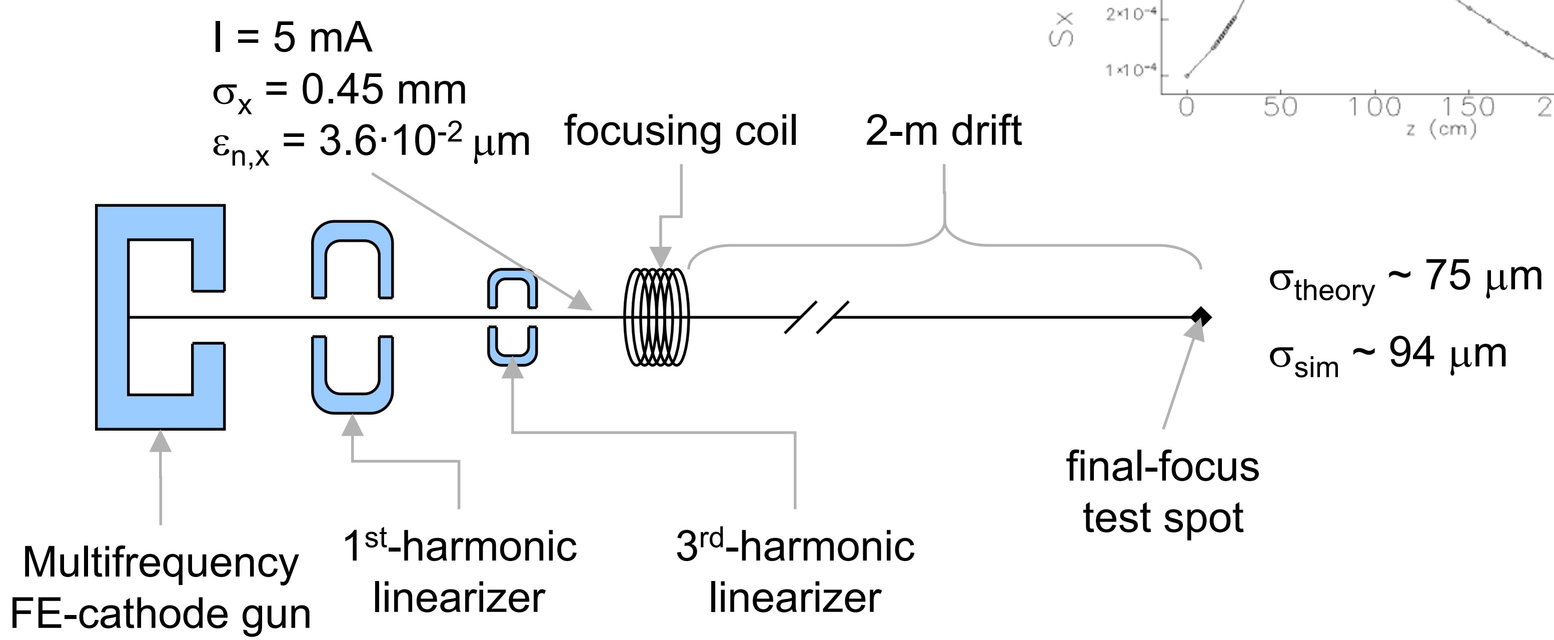


Sample calculation #1 – e-beam welder

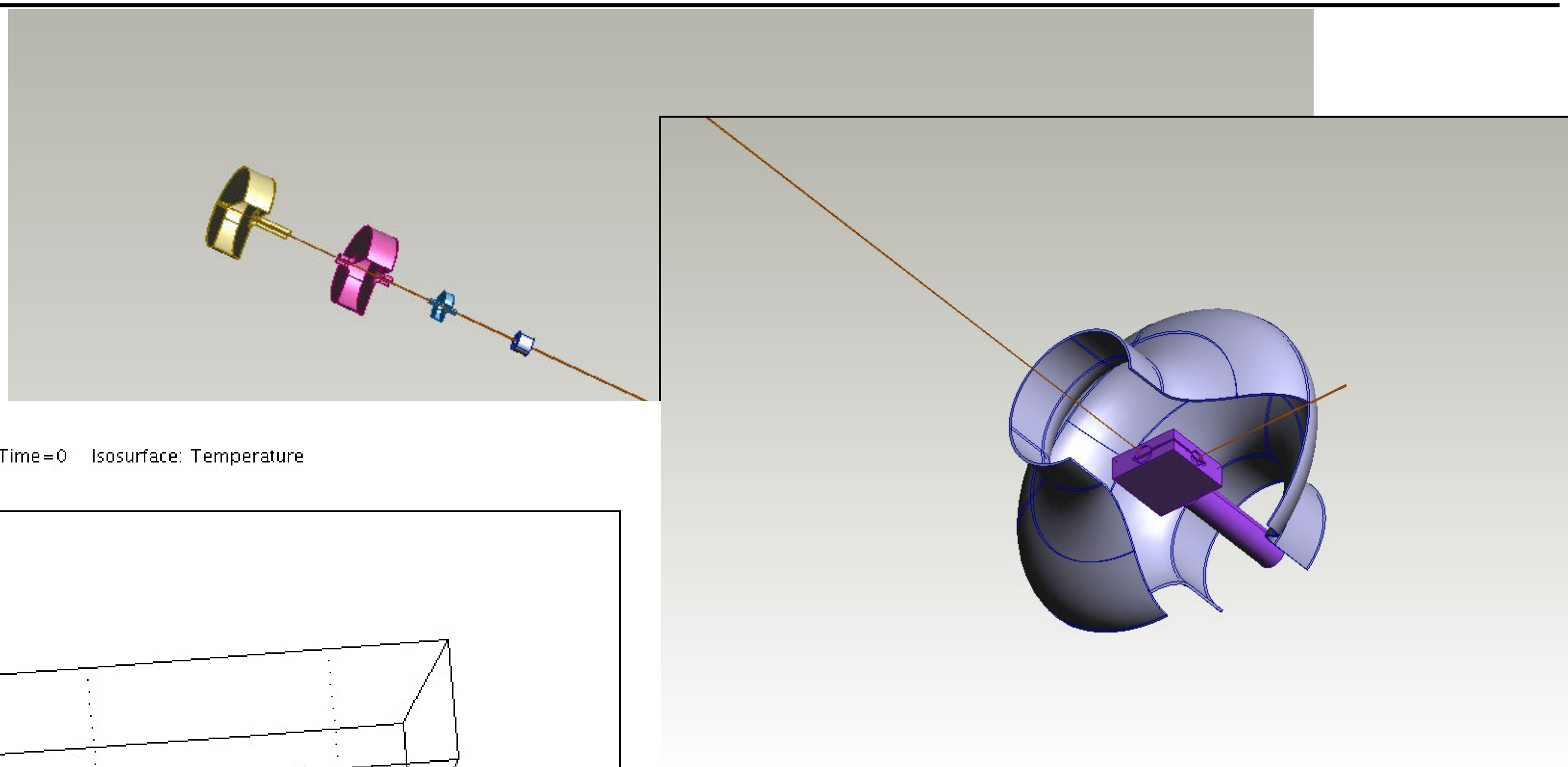
- **Requirements**
  - Modest beam quality
  - High beam power density
  - Long depth-of-focus

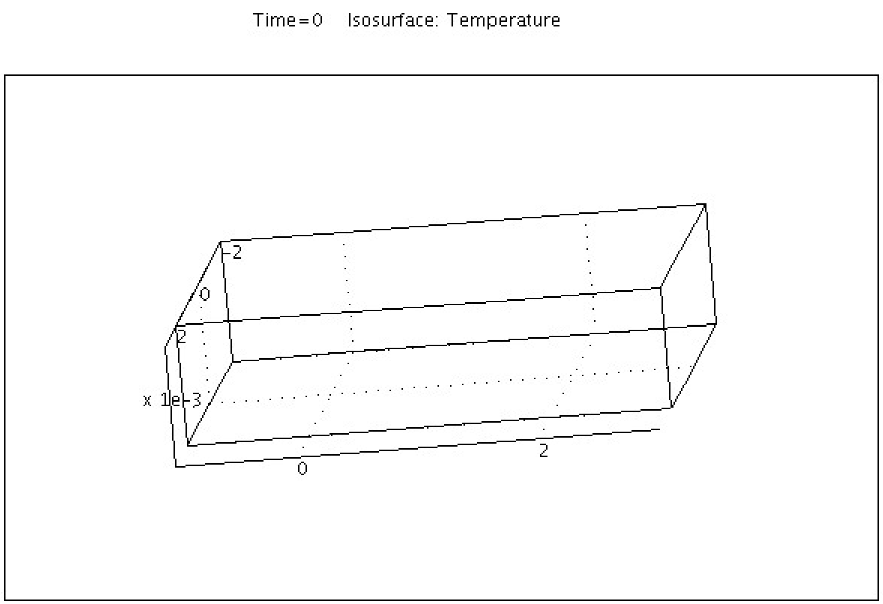






Scale drawing of welder system



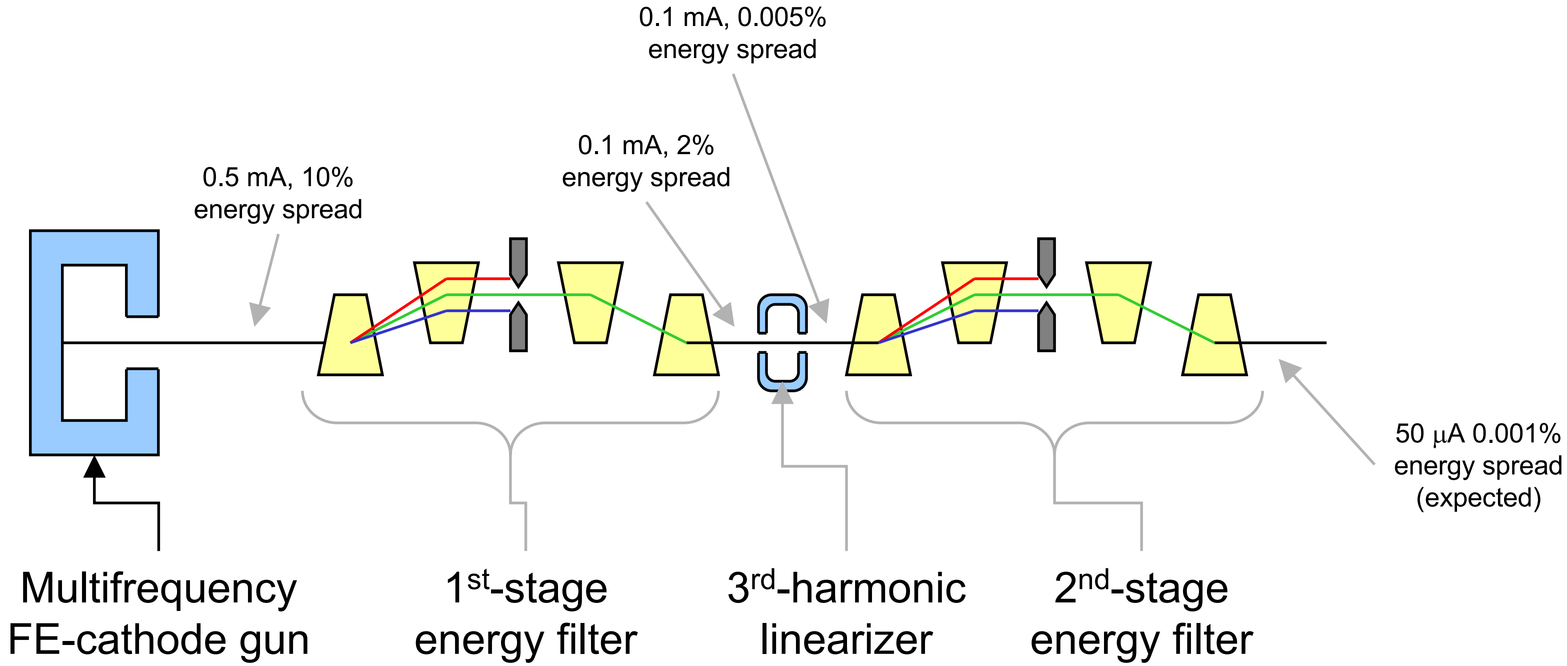


Sample calculation #2 – microscope front-end

- **Requirements:**
  - low energy spread beam
  - high transverse quality

After 3rd-harmonic linearizer:

- $\varepsilon_{n,x} = 3.1 \cdot 10^{-3}\ \mu m$
- $\varepsilon_{n,y} = 6.3 \cdot 10^{-3}\ \mu m$
- $\delta E = 110\ V$



Towards a High-Voltage Electron Microscope?

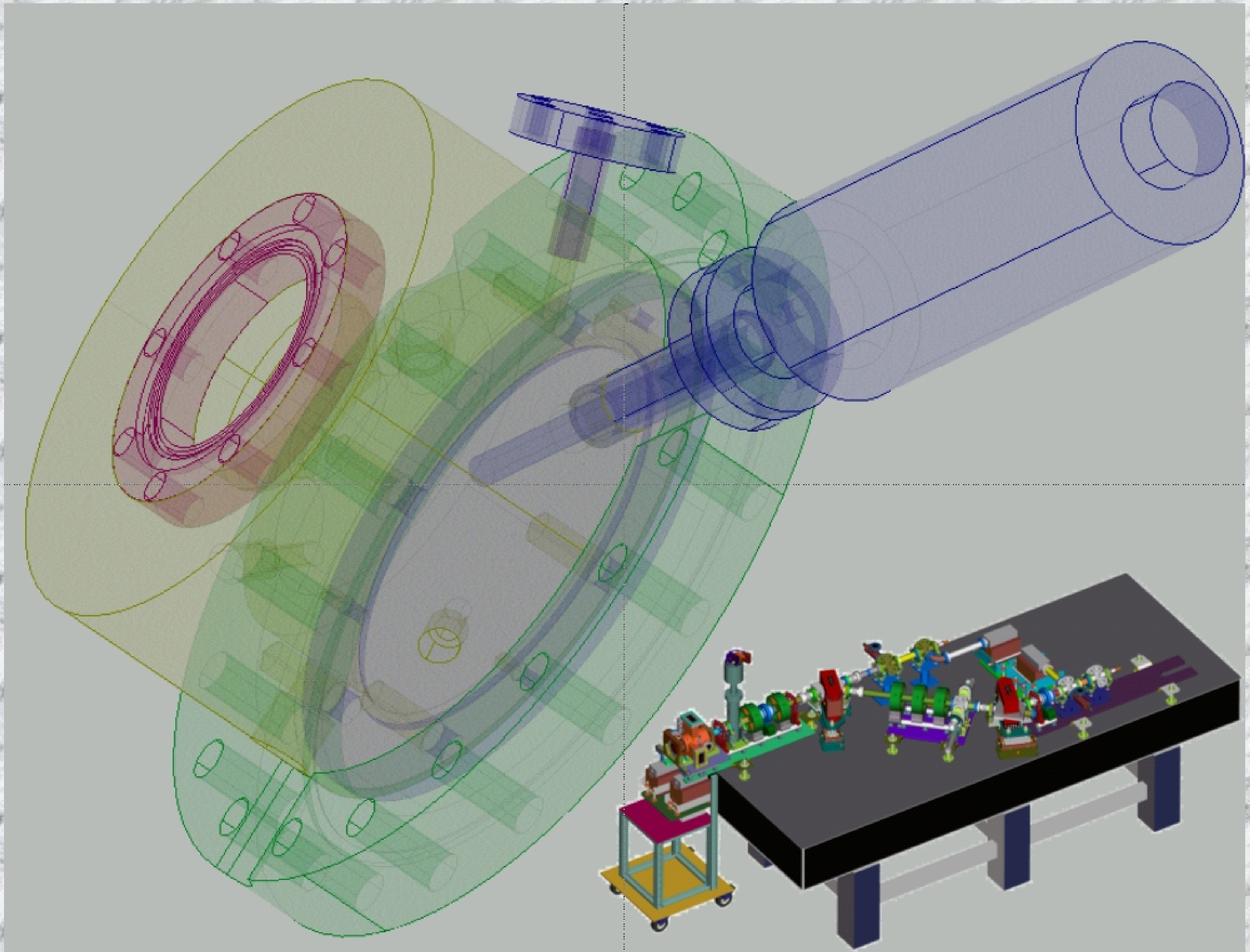
- **Cavity design can be improved**
  - "Mark I" design used for example
  - Not optimized for lowest possible emittance
- **Alternate means of reducing energy spread**
  - Add more harmonics to further flatten pulse?
  - Different beamline geometries to better preserve emittance
- **Focusing system & abberation correction – study needed**
- **Present design represents about 6 months of part-time effort from one accelerator physicist and one vacuum engineer.**

Recap & Concluding Thoughts

- **Field emission cathodes hold great promise for future “desktop” injector development**
  - lower maintenance & upkeep than drive lasers
  - modest bunch charge for low emittance
  - high average beam currents for high-power operation

- **Several applications immediately suggest themselves**
  - microscope gun
  - e-beam welder

- **Some advanced applications also interesting**
  - THz radiation source
  - cancer therapy



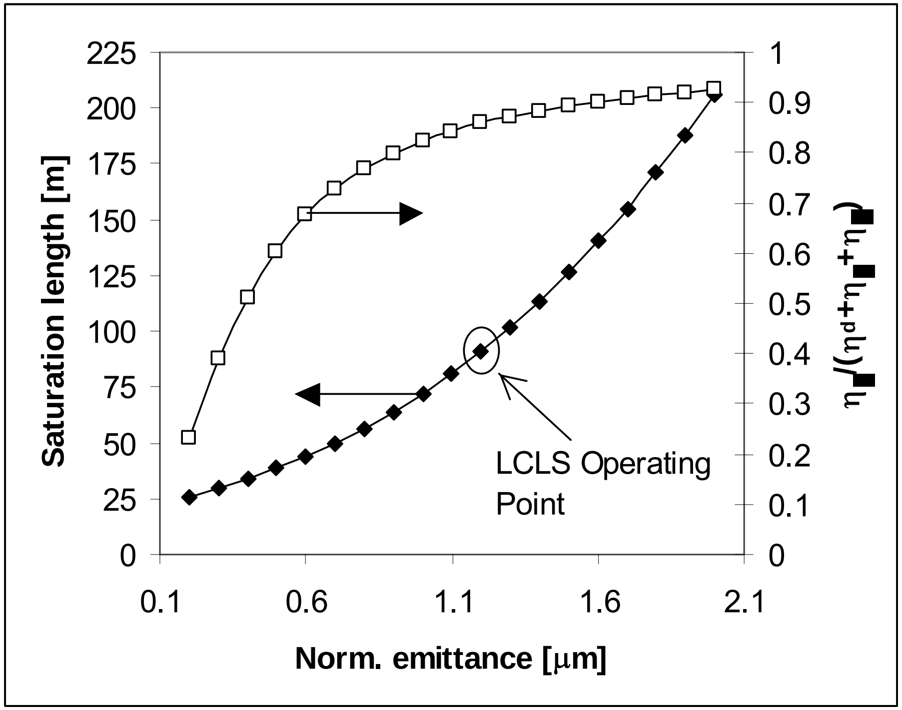
Linac-Based Light Sources

X-FELs: Minimize size of linac and undulator

- **lowest possible beam energy for a given wavelength**
- **saturation length "balanced" between emittance, energy spread and diffraction**

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

4 GeV for 1.5 Å



Linac-Based Light Sources - SRRs

- **Obtain > 100x peak brightness over 3rd-generation facilities**
- **Obtain ps-scale or better bunch durations**

$$B_{\Delta\omega/\omega} \propto \frac{\gamma^2 N^2 I}{\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}}$$

Source	**Norm. Transverse Emittance [μm]**	**Bunch Charge [nC]**	**Bunch Length [ps]**	**Peak Current [A]**	**Peak Brightness Enhancement**	**Avg. Brightness Enhancement**
APS	43 x 0.5	3 – 18	20 - 40	300	1	1*
S-band Gun	1 x 1	1.0	0.33	3000†	45	45*
New Gun (I)	0.1 x 0.1	0.1	0.1	1000†	135	135*
New Gun (II)	0.1 x 0.1	0.1	0.1	1000†	135	13.5‡

† **With linac-based bunch compressor**
‡ **Assuming 10 mA average beam current**
* **Assuming 100 mA average beam current**

Linear Collider Guns

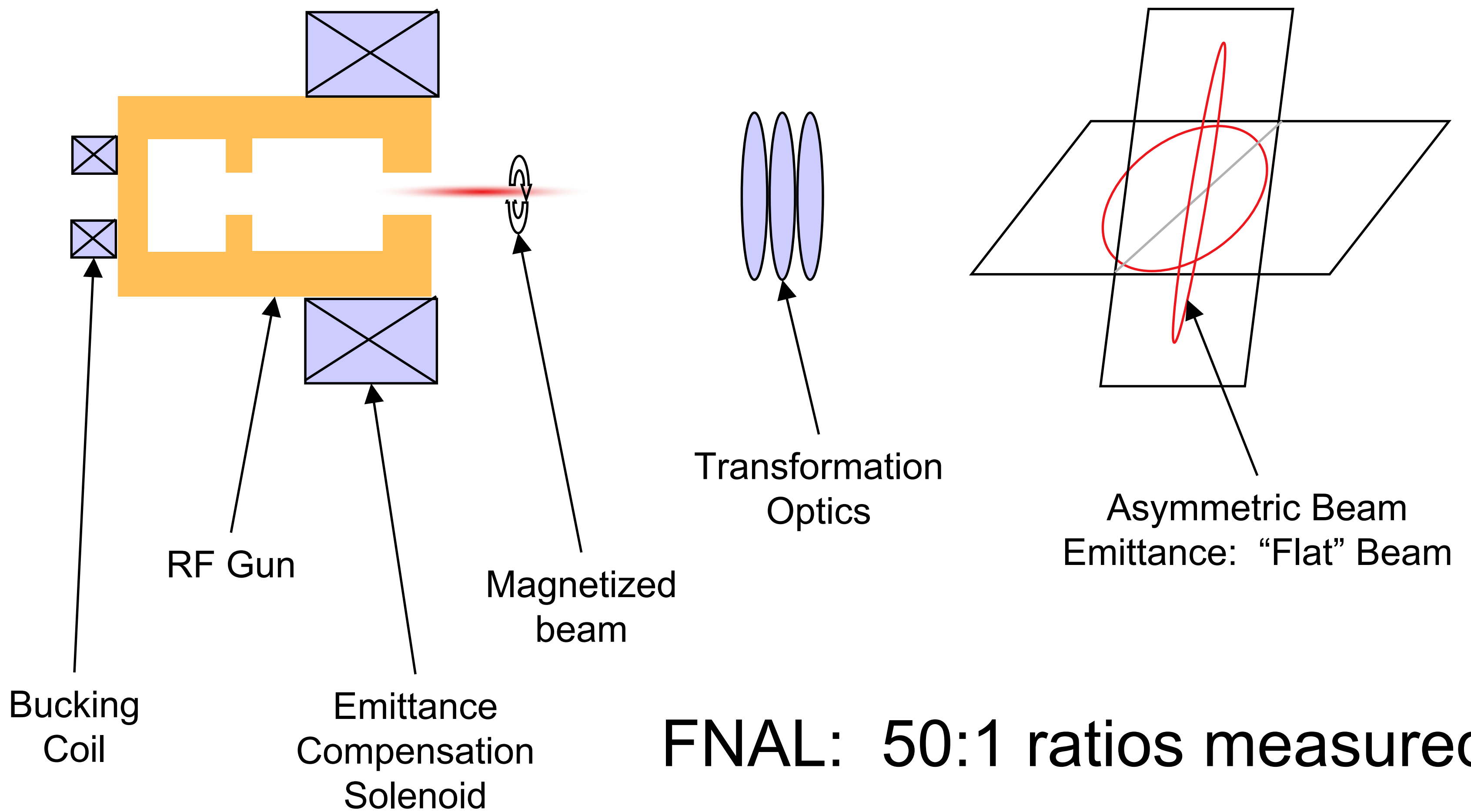
Q: Why pursue high-brighness electron guns for LCs?

A: Damping rings are very expensive; potential payoff is great

What are the basic requirements for a LC gun?

- **Capable of generating polarized electron beams**
- **Capable of generating “flat” beams**
  - damping ring elimination would be ideal
  - reducing damping ring complexity (size, cost) still worthwhile

Linear Collider Guns – Flat Beam Production



FNAL: 50:1 ratios measured

Polarized Electron Beam Production

- **Method: Use a “strained” semiconductor cathode with NEA surface to generate polarized electrons**

- **Successfully used with DC guns**

- **Issues**
  - Lifetime
    - *RF gun vacuum environment*
    - *back-bombardment ions* ***and electrons***
  - Dark current
    - *NEA surface, high gradient fields*

A Word on Cathodes…

Drive laser requirements

Cathode Material		Quantum Efficiency	Operating Wavelength	Harmonic laser power needed for:		Fundamental laser power for 100 mA
				10 mA	100 mA	
Metal	Copper	10^{-5}	266 nm	4.6 kW	46 kW	~ 750 kW
	Magnesium	$5 \cdot 10^{-5}$	266 nm	930 W	9.3 kW	~ 150 kW
CsTe		0.5%	266 nm	9.3 W	93 W	~ 1.5 kW
Alkali, NEA		5%	532 nm	0.46 W	4.6 W	~ 20 W

$$\varepsilon_{thermal,rms} = x_{rms} \frac{\sqrt{2 m_e E_{kin}}}{m_e c} = (1-3)\,\mu m/mm$$

Target emittance	$\sigma_x < \ldots^*$
5 μm (IR, UV FEL)	1.8 mm
1 μm (LCLS)	0.36 mm
0.1 μm (SRR, X-FEL)	36 μm
1 nm (E-microscope)	0.36 μm

* for E_k = 1 eV; $\sqrt{2}\,\varepsilon_{th} \leq \varepsilon_{total}$