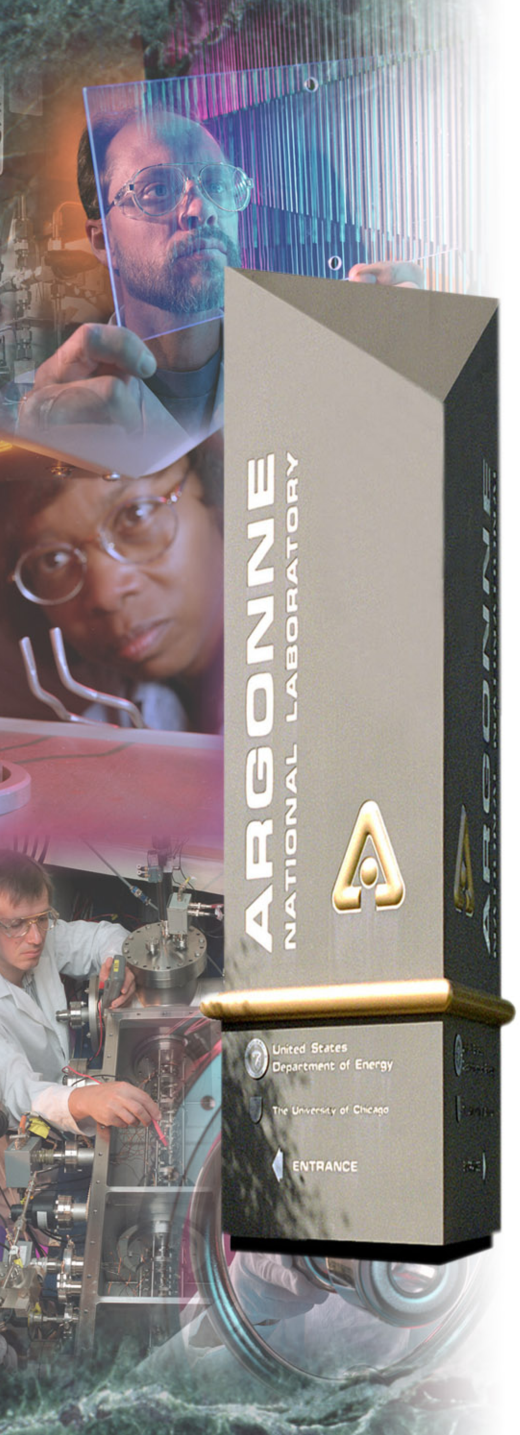

Overview of High-Brighness Electron Guns

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A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Acknowledgements

Katherine Harkay (ANL) – ongoing discussions & support

Charles Brau (Vanderbilt)
Jym Clendennin (SLAC)
Dave Dowell (SLAC/LCLS)
Klaus Flöttmann (DESY)
Fred Kiewit (Eindhoven)
Yuelin Li (ANL)
Kwang-Je Kim (ANL)
John Noonan (ANL)
John Petillo (SAIC)
John Power (ANL)
John Schmerge (SLAC)
Charles Sinclair (Cornell)
Frank Stephan (DESY-PITZ)
Todd Smith (Stanford)
Alan Todd (AES)

and many others for interesting discussions on gun design & improvement

Talk Overview

- **What I will ignore**
- **What is a high-brightness electron gun, in context?**
- **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
  - Linear colliders
  - Electron microscopes
- **Common elements**
- **Ongoing injector development efforts**

- **Conclusions and wrap-up**

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…

What is brightness? What's High-Brightness?

- **One canonical definition:**

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

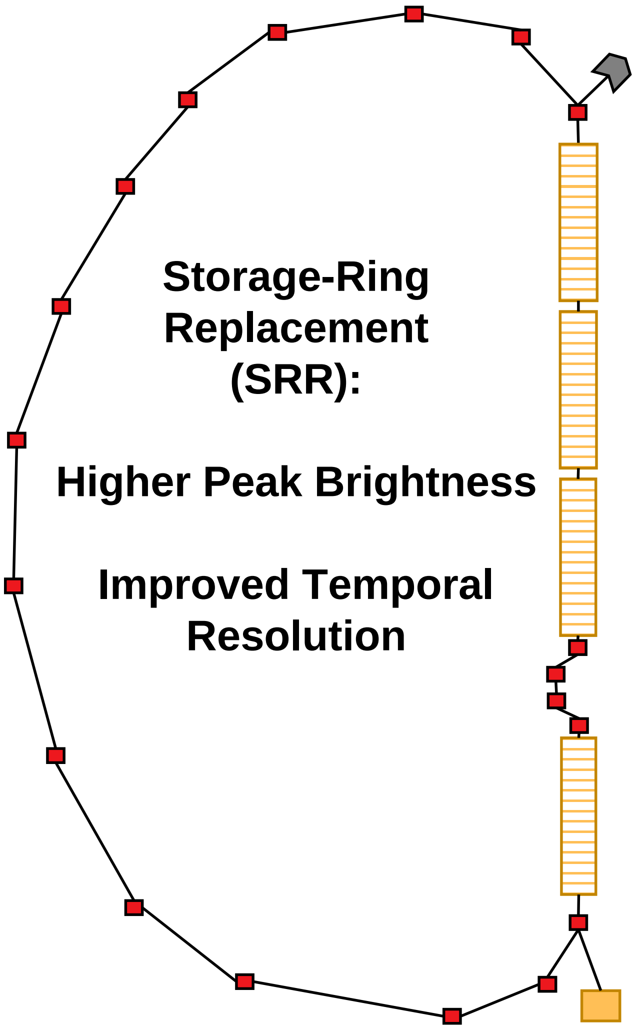
- **Another definition:**

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

- **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.**

Storage-Ring Replacements & X-FELs



Storage-Ring Replacement (SRR):

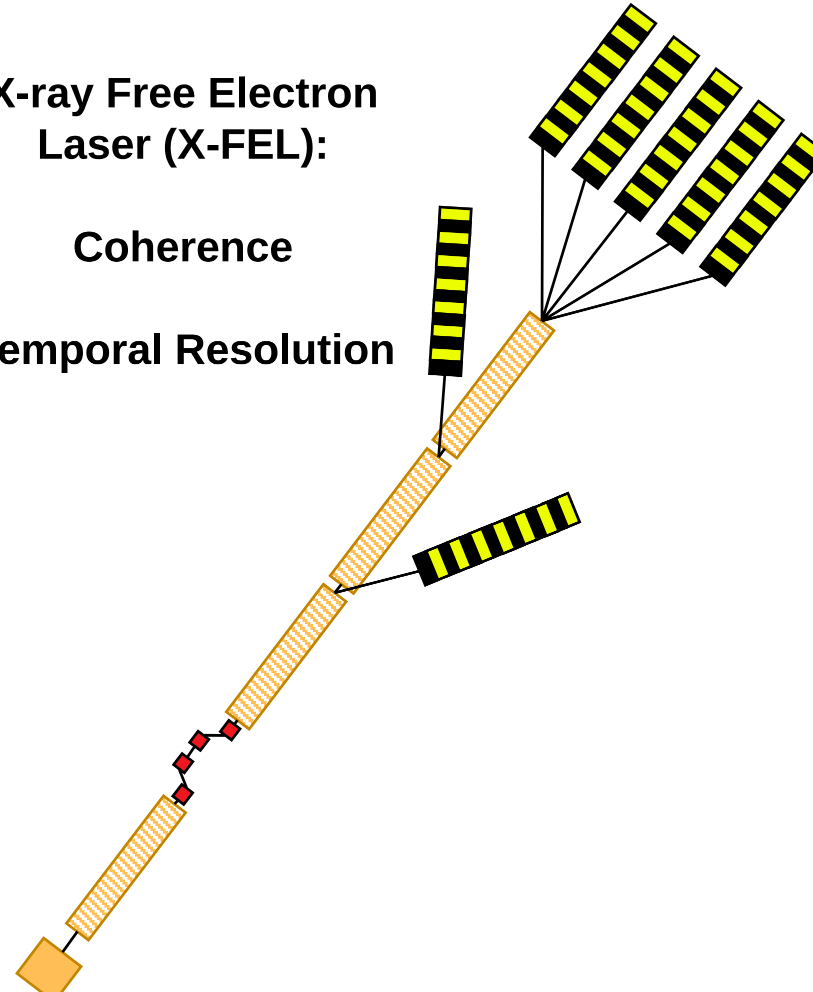
Higher Peak Brightness

Improved Temporal Resolution

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

Coherence

Temporal Resolution



"1st-generation" Linac Based Light Sources

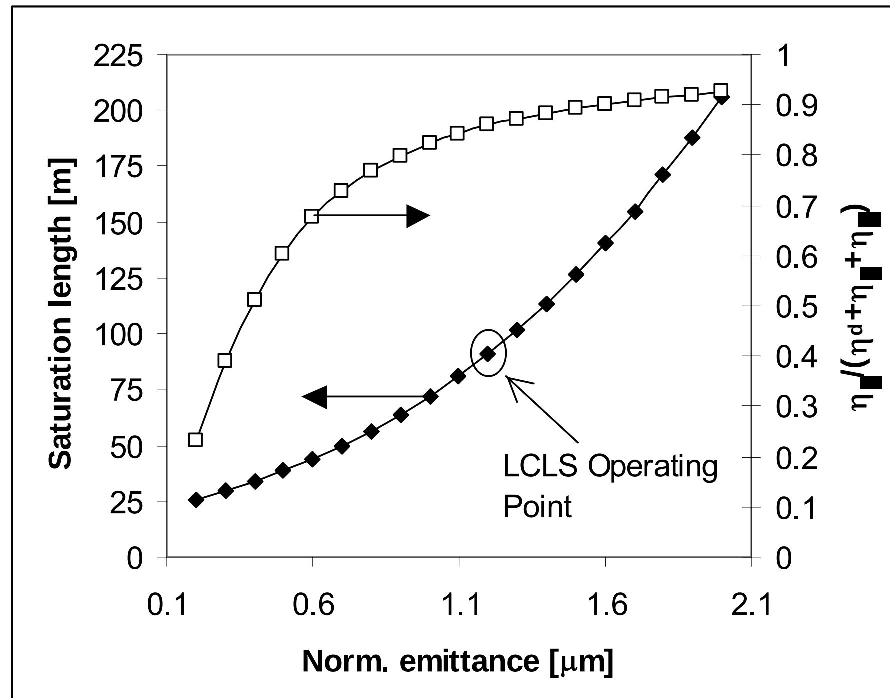
Linac-Based Light Sources

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**

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

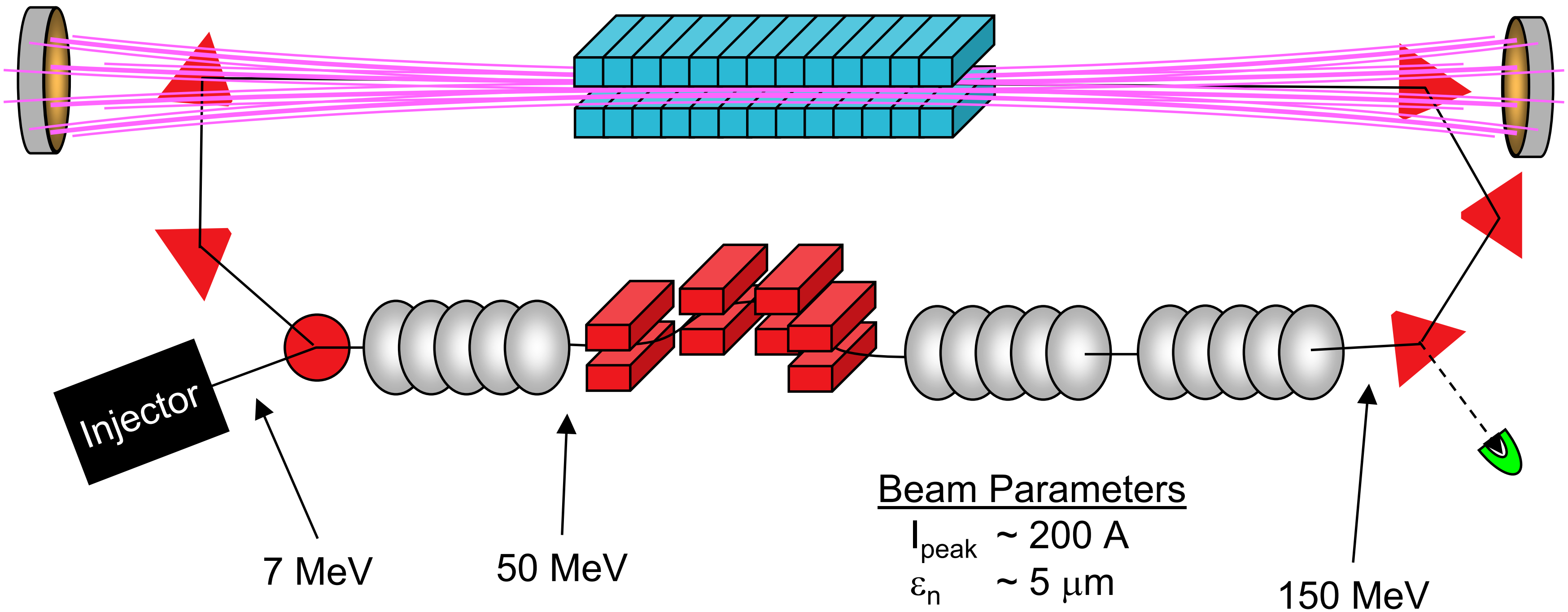
Linac-Based Light Sources – Source Specs

- **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%



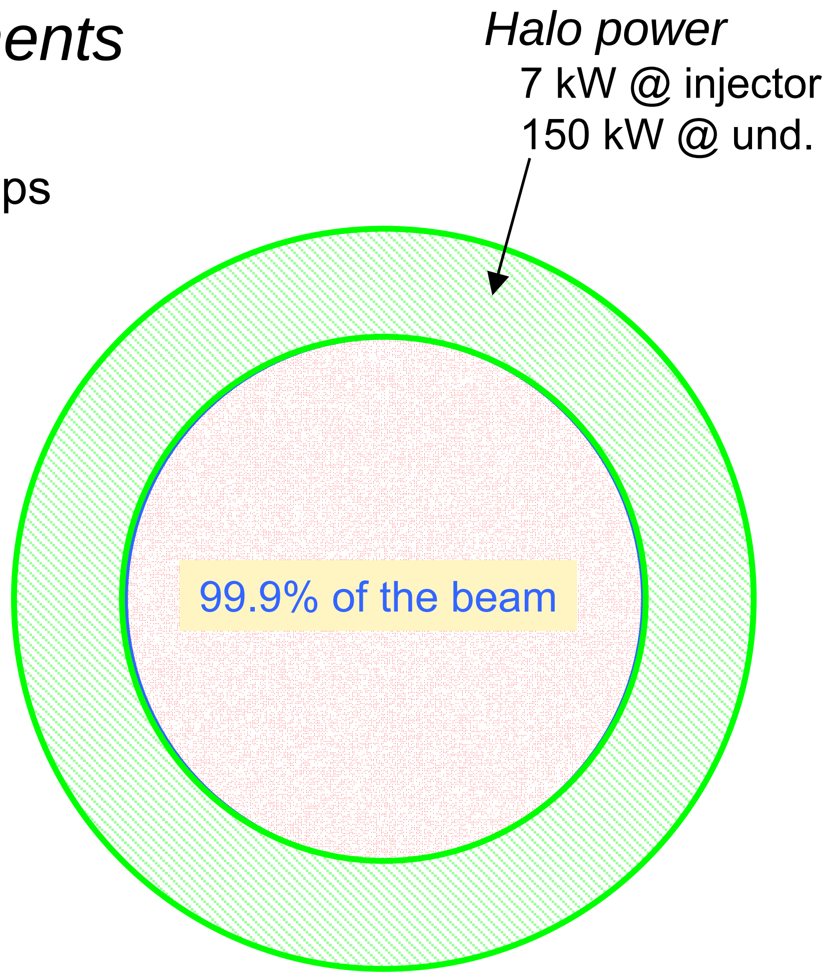
Beam Parameters

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

Linear Collider Guns

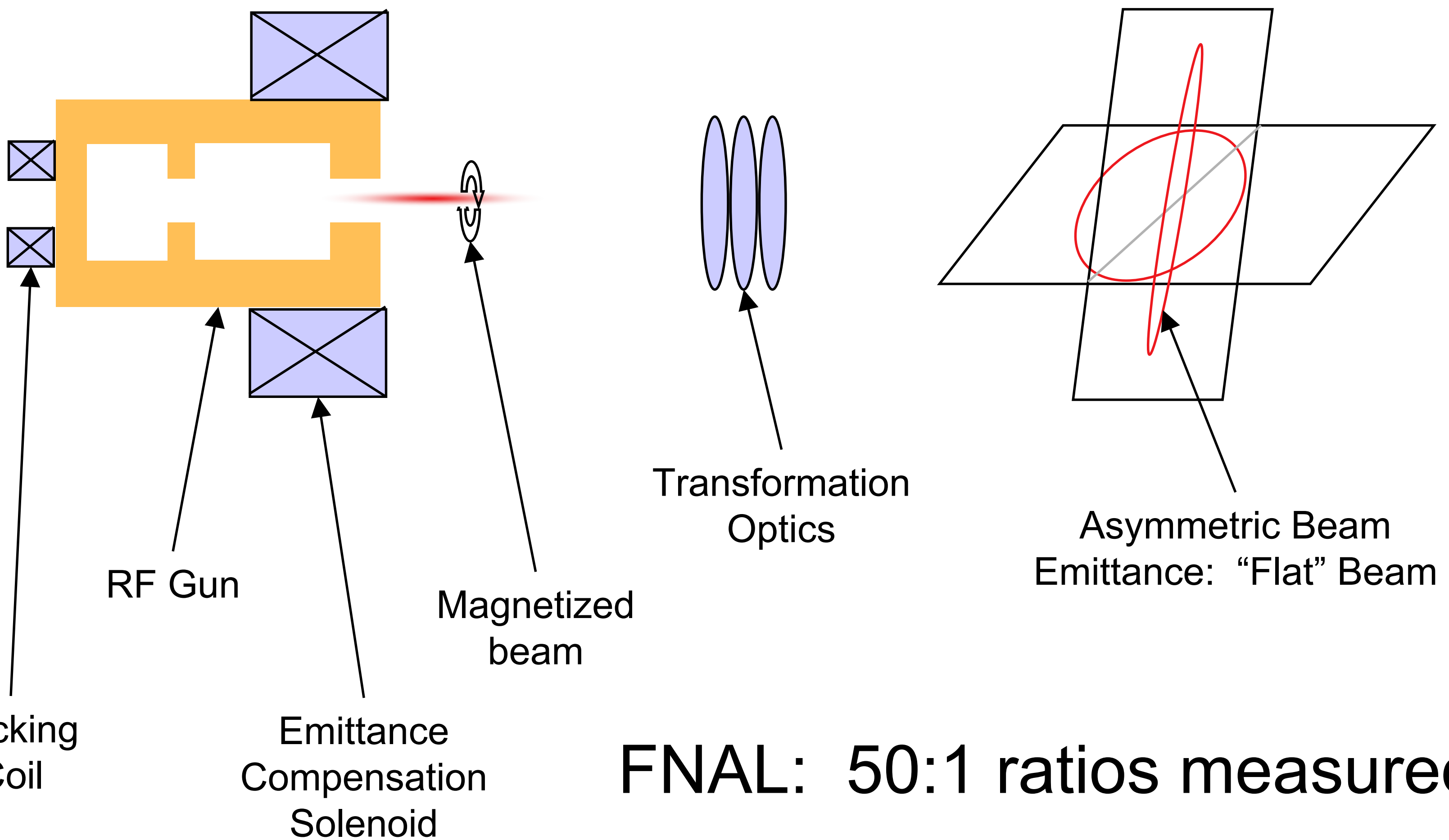
Q: Why pursue high-brighness electron guns for LCs?

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*

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**
- **1^{st}-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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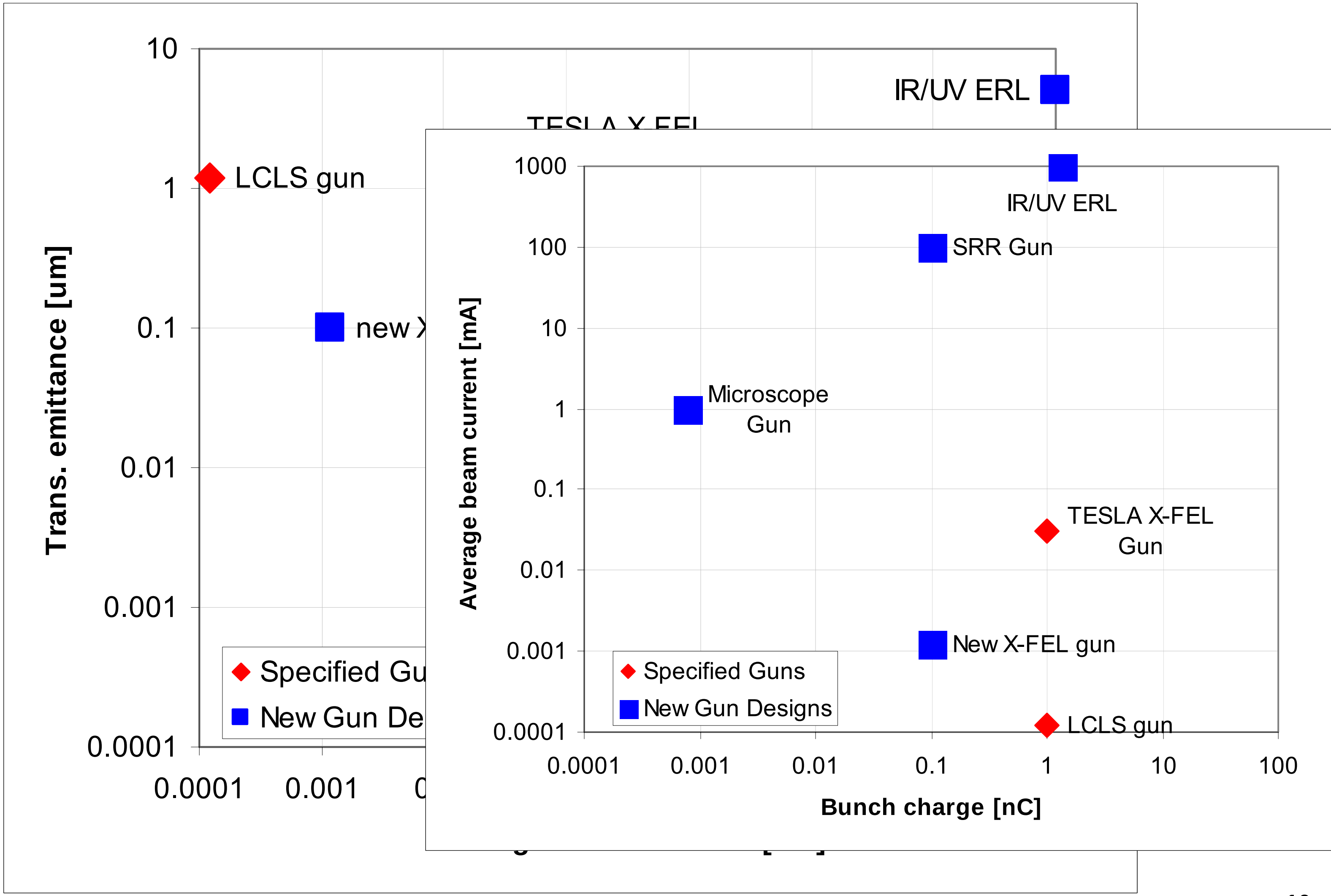
An Interim Summary…



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 Cathodes…

Drive laser requirements

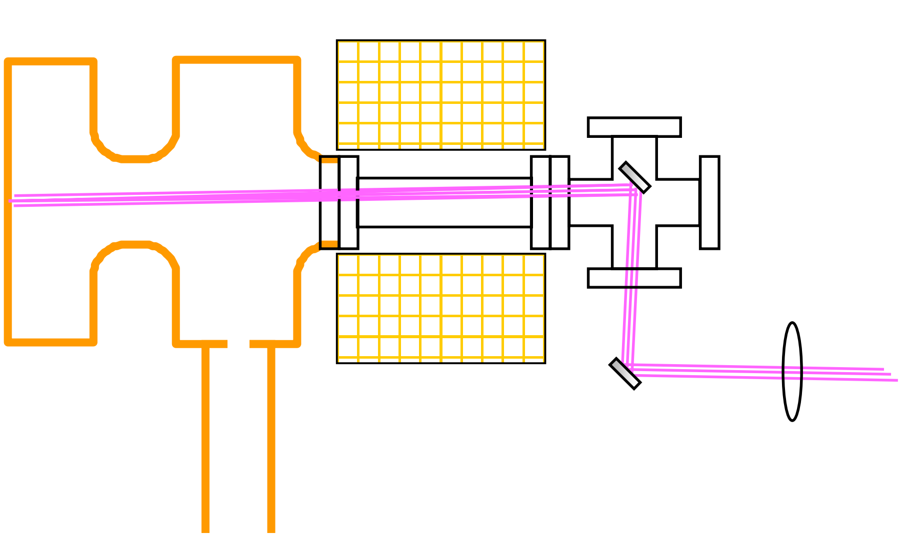
Cathode Material		Quantum Efficiency	Operating Wavelength	Harmonic laser power needed for: 10 mA	100 mA	Fundamental laser power for 100 mA
Metal	Copper	10^{-5}	266 nm	4.6 kW	46 kW	~ 750 kW
	Magnesium	$5 \cdot 10^{-5}$	266 nm	930 W	9.3 kW	~ 150 kW
CsTe		0.5%	266 nm	9.3 W	93 W	~ 1.5 kW
Alkali, NEA		5%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

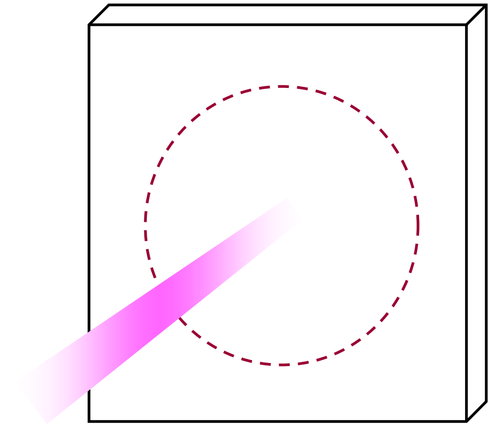
$$\varepsilon_{thermal,rms} = x_{rms} \frac{\sqrt{2 m_e E_{kin}}}{m_e c} = (1-3)\,\mu m/mm$$

Target emittance	**σ_x < …***
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

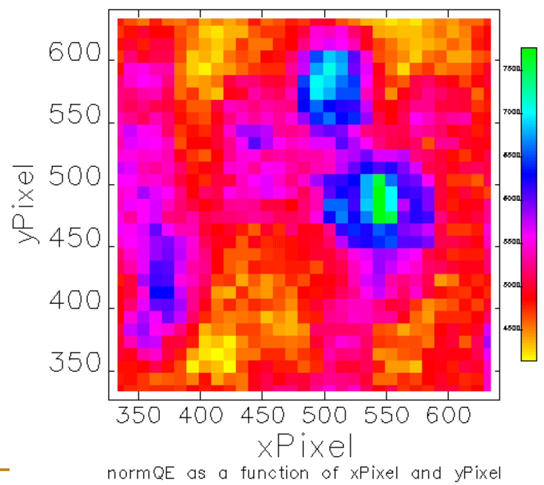
* for E_k = 1 eV; $\sqrt{2}\,\varepsilon_{th} \leq \varepsilon_{total}$

Cathode QE Uniformity

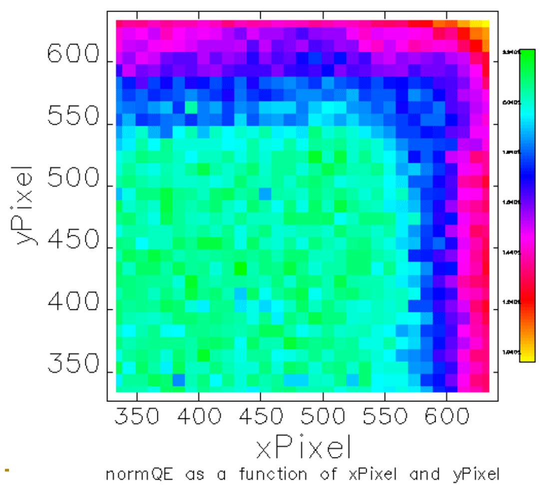




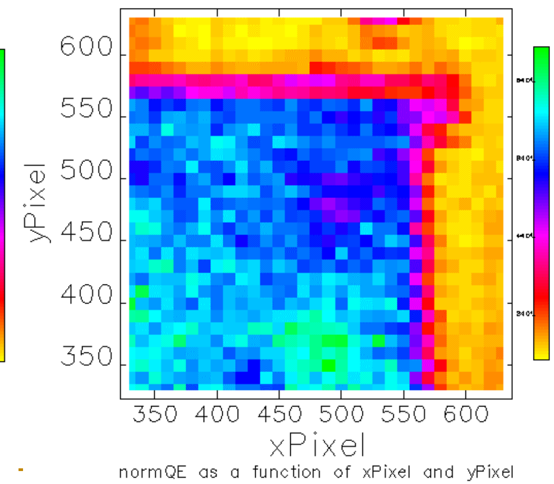
31 Oct 01 – before 1st cleaning



5 Nov 2001 - after 1st cleaning



4 Dec 2001 - after 1st cleaning



Injector Development Efforts: Simulations

- **DC guns:**
  - 0.1 μm @ 0.08 nC

- **SRF guns:**
  - ε_n ~ 1.2 nm, $\delta E/E$ ~ 2×10^{-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

Apologies…!

There are certainly other places working on injector designs and cathodes.

There are other topics and researchers worthy of mention in their own right (e.g. photonic bandgap guns at MIT, DC/RF injector designs, needle cathodes, cathode-region focusing, multimode/multifrequency guns, etc.)

But, we're just getting started and my time is almost up!

Parting thoughts

- **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**