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Cathode R&D for ERL

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Accelerator R&D Workshop

3-Way Meeting

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UChicago Argonne LLC

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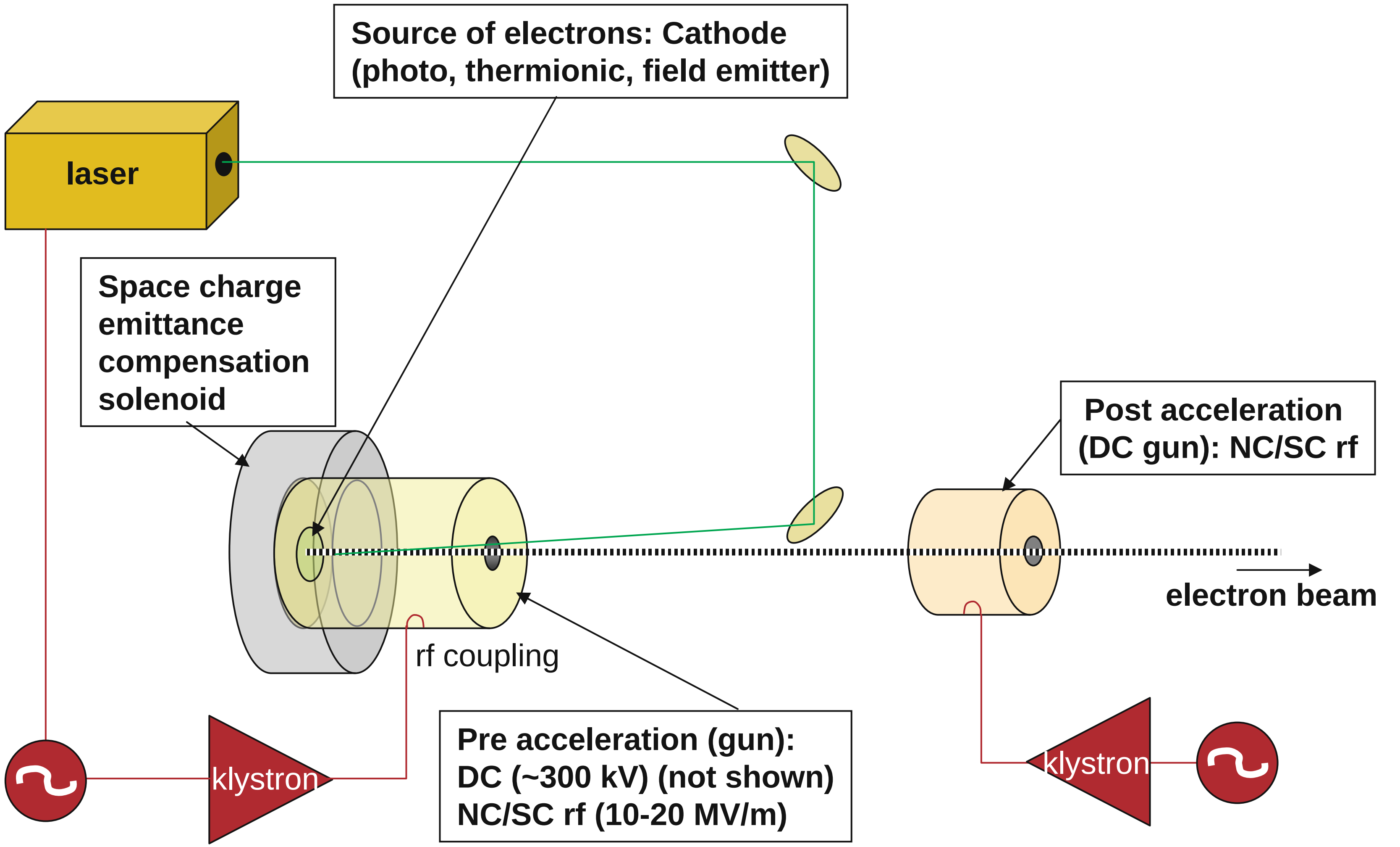
Introduction

- ERL requirements ***very*** demanding on electron gun
- Grand challenges:
  - Extremely low emittance AND
  - High average current
- Physics and engineering of high brightness guns have long been pursued – performance achieved but at low duty factors
- Interest in high-average-power FELs and ERLs is driving a vigorous CW gun R&D effort world-wide

Anatomy of an ERL gun/injector



Schematic adapted from D.C. Nguyen

Cornell ERL Parameters[1] Scaled to 7 GeV

	APS	ERL		
	now	High flux	High coherence	Ultrashort pulse
Average current (mA)	100	100	25	1
Repetition rate (MHz)	0.3~352	1300	1300	1
Bunch charge (nC)	0.3~60	0.077	0.019	1
Emittance (nm)	3.1 x 0.025	0.022 x 0.022	0.006 x 0.006	0.37 x 0.37
Rms bunch length (ps)	20 ~ 70	2	2	0.1
Rms momentum spread (%)	0.1	0.02	0.02	0.3
Normalized emittance, εγ (μm)			**0.08**	**5**

Target values for X-FELO

Pulsed dc source a potential option

[1] G. Hoffstaetter, FLS 2006 Workshop, DESY

Challenge: ERL Injector Requirements

- Unlike a storage ring, the minimum ERL emittance is determined by the electron source, which must operate continuously
- The highest-brightness existing state-of-the-art (SOA) electron sources are low rep-rate sources developed for FELs (1 nC bunch charge, 1-2 μm emittance, and 1-2 ps duration)
  - Photocathode, room-temperature rf gun sources (LCLS, FLASH)
  - Thermionic cathode, pulsed DC sources (SPring-8 FEL)
- ERL requires a electron source with an order of magnitude smaller emittance than that achieved in SOA injectors (latter required 10 yrs R&D)
- Operational ERL x-ray source must be reliable, requiring cathodes that are robust with long lifetime (consistent with design criteria for SCSS FEL at Spring-8)

Intrinsic emittance and quantum efficiency (QE)

- ERL source emittance requirement (~0.1 μm) is on the order of the intrinsic ("thermal") emittance of a photocathode, which sets the lower limit of the achievable emittance
- Representative ε_n^{th} (in units of μm per mm σ)
  - Cornell: (Cs:GaAs) 0.2-0.4 μm/mm
  - BNL: (Cu) 1 μm/mm
  - PITZ: (Cs_2Te) 0.4-0.7 μm/mm

$$\varepsilon_n^{th} = \sigma_{laser} \sqrt{\frac{\langle E_k \sin^2 \theta \rangle}{mc^2}}$$

- Critical physics near the cathode surface related to intrinsic emittance is poorly understood

$$E_k = h\nu - \phi + \sqrt{\frac{e}{4\pi\varepsilon_0} \beta_{rf} E_{rf} \sin\theta_{rf}}$$

- Pushes to small spots: σ = 100-300 μm
- QE also pushes limits

Thermal emittance model (cont).

J.D. Lawson, *The Physics of Charged Particle Beams*, Oxford Science Publications, p. 210 (1988). (1st edition 1977)

Assumption:

- Non-laminar beam w/o collisions
- Maxwellian transverse velocity distrib.
- Thermal beam is in a focusing channel with linear external focusing

W.S. Graves et al., Proc. 2001 PAC, 2227 (2001).

We assume a thermalized distribution of electrons is emitted from the copper surface. There is no correlation among momentum and position so that the normalized emittance is given by

$$\varepsilon_{xN} = \gamma\beta\sqrt{\langle x^2\rangle\langle x'^2\rangle} = \gamma\beta\sigma_x\sigma_{x'} \qquad \textbf{(1)}$$

Lawson's expression [1] for the width of the momentum distribution of a thermalized beam is

$$\sigma_{x'} = \sqrt{\frac{E_k}{mc^2}} \Rightarrow \varepsilon_{xN} = \sigma_x\sqrt{\frac{E_k}{mc^2}} \qquad \textbf{(2)}$$

where the kinetic energy of the electrons after emission is

$$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf}E_{rf}\sin\theta_{rf}}\,, \qquad \textbf{(3)}$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}},\ h\upsilon = 4.67\ \text{eV},\ \Phi_{Cu} = 4.59\ \text{eV}.$$

R&D Addresses Key Physics

- **Physics optimization**
  - Perform optimization study of laser-photocathode system to set boundaries on minimum QE and maximum intrinsic emittance
- **Advanced surface analysis**
  - Systematically characterize the intrinsic emittance for a variety of cathodes using advanced surface analysis to measure the emission momentum distribution (ARPES) and spatially-resolved cathode composition and surface geometry (e.g., SEM, scanning Auger)
- **Improved emission models** for use in cathode injector design
  - Benchmark improved physics models based on these data in a test injector
  - Evaluate and/or design novel cathodes with optimized characteristics
- **Cathode lifetime**
  - Study lifetime improvement and develop load-lock system to allow quick cathode exchange
- **Injector design**
  - Carry out design study for cw operation, high-coherence mode

R&D resources

- Injector Test Stand and photocathode drive laser
  - High-QE cathode characterization (ext. collab)
  - Novel RF gun design & test (ext. collab)
  - Support of LCLS BPM tests
- Shared labs & collaborations
  - Laser labs in XSD and Argonne Chemistry Division (pulse shaping to linearize space charge, Y. Li)
  - XSD surface analysis lab (R. Rosenberg) (site of proposed Cathode Test Stand)
- Parallel computing clusters
  - "apex" and "weed"
- Ultra-low emittance beam characterization
  - PITZ, DESY Zeuthen hosting mini-workshop (May 2008)

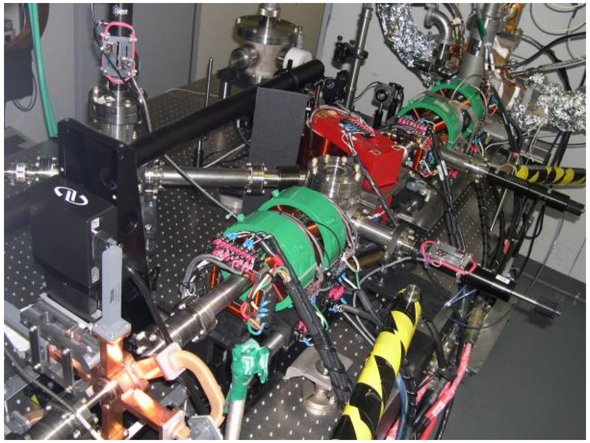
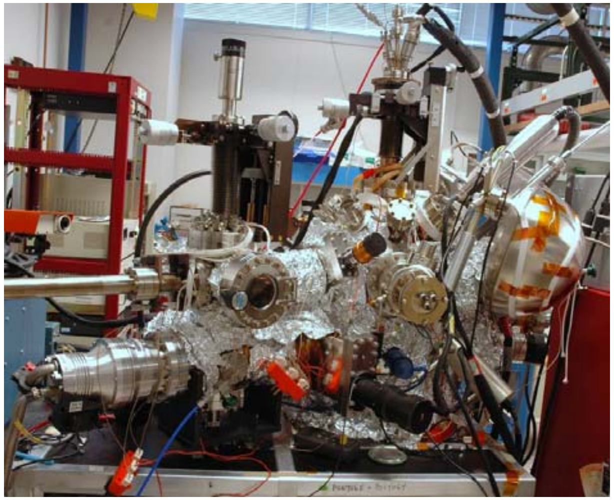


photo: Y.-e Sun

photos: M. White



courtesy R. Rosenberg

Cathode Test Stand (CATS)

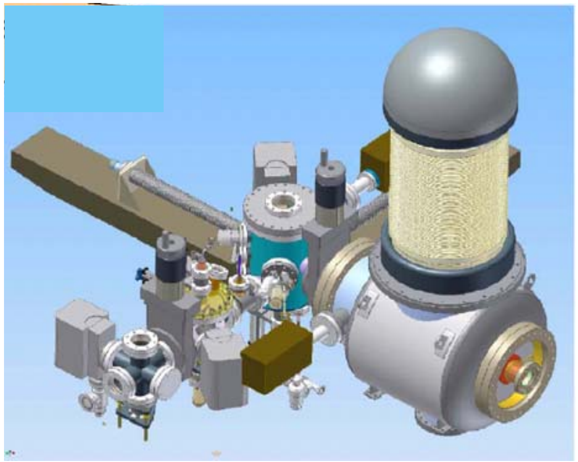
- Leverage capabilities in existing surface analysis laboratory (SAL) (R. Rosenberg, XSD) to test photocathode properties
  - Cathode chemical composition (XPS)
  - Spatially-resolved cathode composition and surface geometry (low-resolution SEM, scanning Auger)
  - Heat/cool samples
- Upgrade to add ARPES and improved electron detector to allow measurement of momentum distribution and intrinsic emittance
  - Low-power laser and 2D-array electron detector to measure very low energy photoelectrons
- Collaborate with ARPES experts world-wide

Injector Test Stand (ITS)

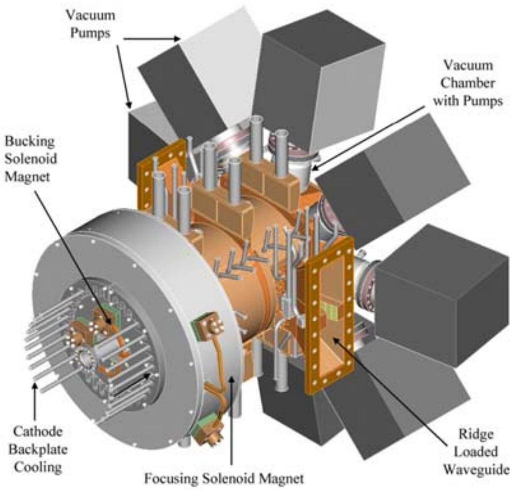
- Leverage existing capabilities: upgraded photocathode drive laser, diagnostics
- Upgrade: improve laser transport line and add second L-band beamline to test cathodes & load lock in prototype cw rf gun (e.g., emittance, lifetime, QE)

ERL Injector Design

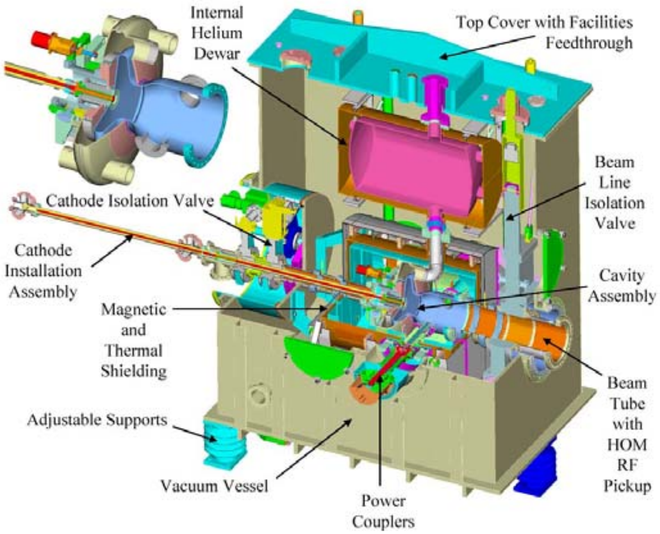
- Three main technologies are candidates for cw ERL source: dc, room-temperature (RT) rf, and superconducting (SC) rf – too early to decide best
- Significant technology challenges remain for all three: build on successes at other facilities. Design criteria significantly different from FEL guns.
- Goal is to develop and test optimized gun designs for physics regime of ERL injector, high-coherence mode, to be tested in ERL prototype



Cornell DC gun (S. Gruner)



LANL/AES RT cw rf gun (D. Nguyen)



AES/BNL SC rf gun (A. Burrill et al)

Summary

- ERL cw guns extremely challenging: pushing significantly beyond present state-of-the-art
- R&D at APS underway (LDRD)
  - Preparations to characterize intrinsic emittance of candidate cathodes
  - Develop “designer” cathodes with optimum properties

- Benchmarks of experimental data and numerical results critical but relatively few (e.g., PITZ, ITS, AWA). Collaborate with others to validate numerical models for ultralow emittance and develop emittance measurements for required resolution.

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Marion White

Hope to broaden collaboration to PITZ, SLAC, SPring-8,…