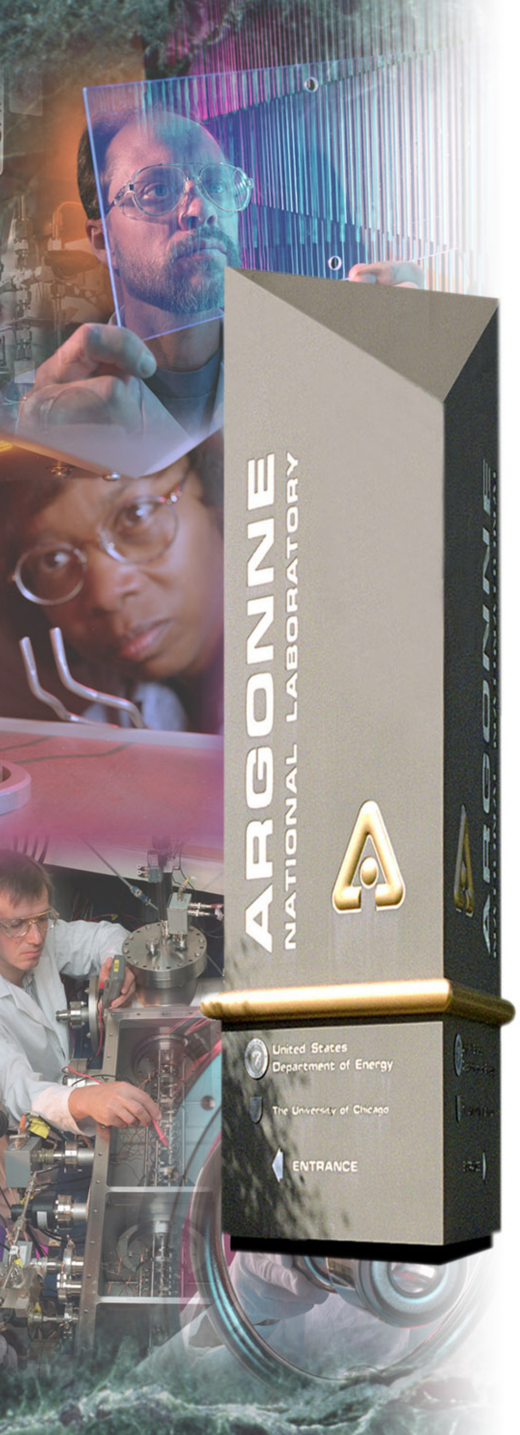

High-Brighness Electron Guns for Linac-Based Light Sources

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Office of Science Laboratory
Operated by The University of Chicago

Overview of the Talk

- **Acknowledgements & Introduction**
  - What sort of facility are we talking about?
  - SRRs vs X-FELs
  - What role does the electron gun play?
- **Source requirements**
  - Storage-ring replacement faciltiies
  - X-FEL facilities
- **Towards a realizable source design**
- **Conclusions**

Acknowledgements

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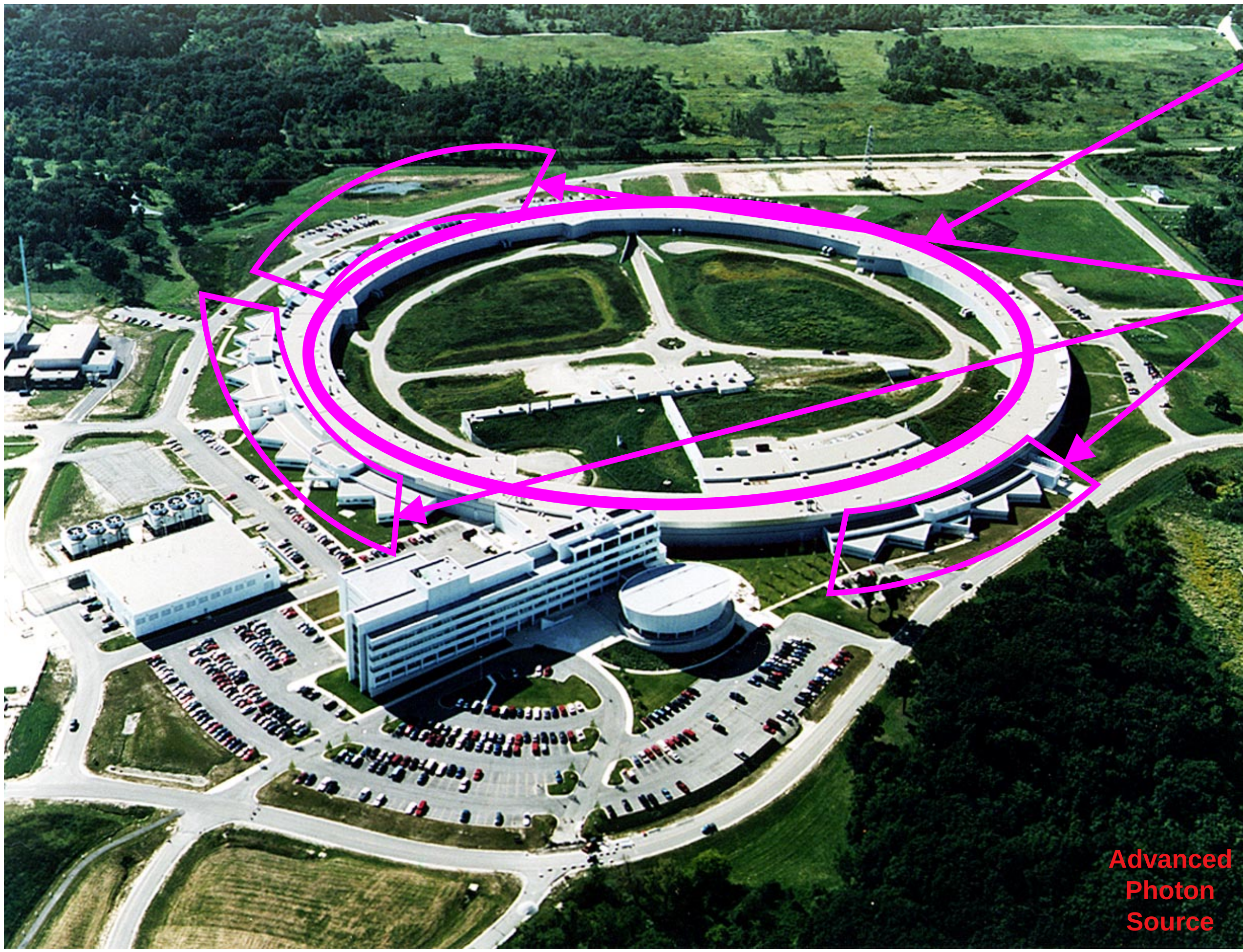
What sort & scale of facility exists now?

APS: 3rd-generation storage-ring light source



- **Circumference: ~ 1 km**

Beamlines:
~ 35 bending magnet
~ 40 undulator/ID

- **Local user group offices**

Users per year:
thousands

Scheduled run hours
per year: thousands

What improvements can be made?

- **Increase the x-ray beam flux (photons / sec unit bandwidth)**
- **Increase the x-ray beam brightness (peak or average)**
  - more “useful photons” per unit flux delivered
- **Increase the temporal resolution (shorter x-ray pulses)**
  - time-resolved phenomena
  - pump-probe experiments
- **Coherent light production**
  - “light bulb-to-laser” transition

Storage Rings vs. Linac-Based Light Sources

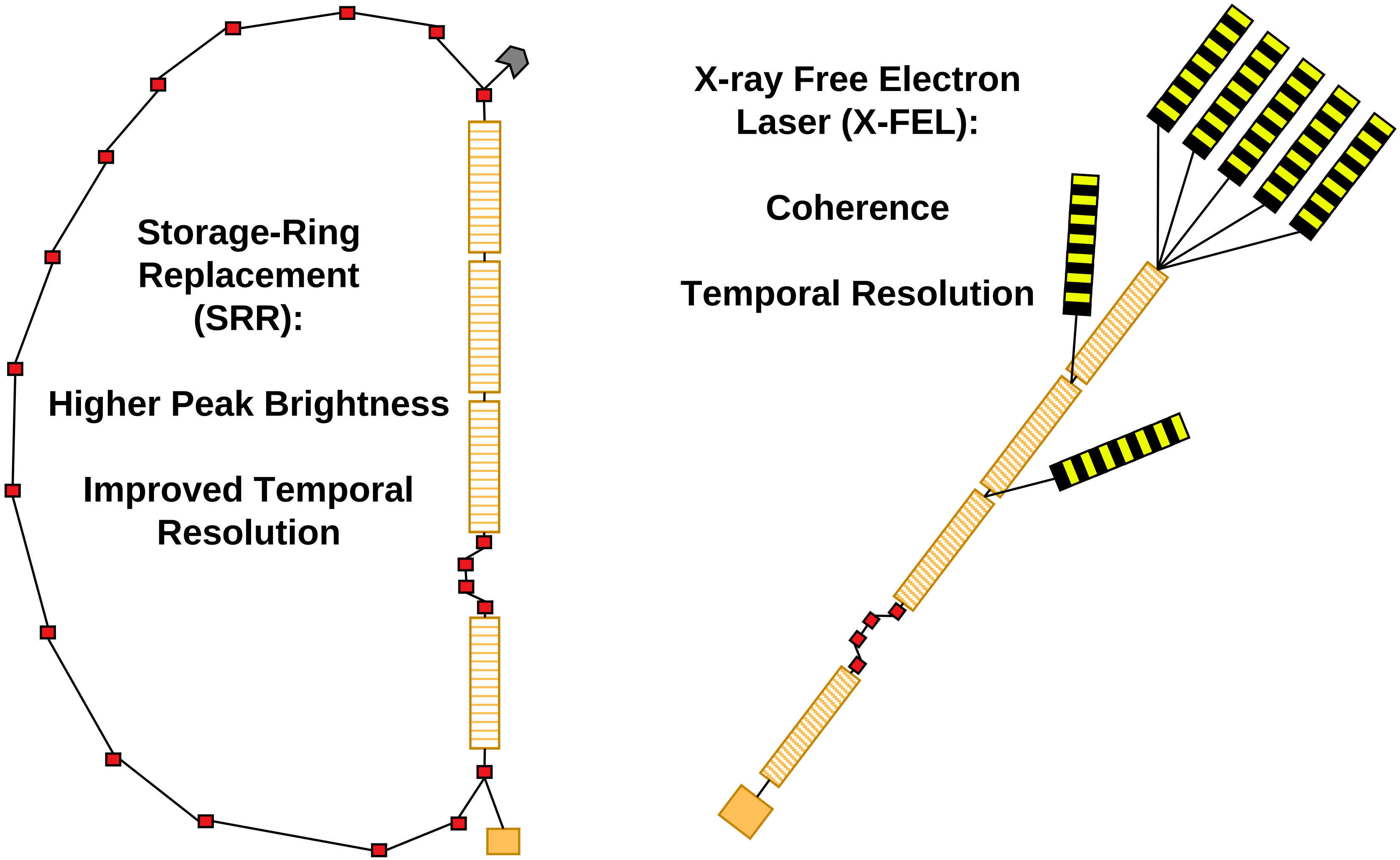
Storage Ring Light Sources

- Electrons circulate many times
- Beam power delivery = γ losses
- Electron beam properties set by the ring (injector irrelevant)

Linac-Based Light Sources

- Electrons make one pass
- Beam power delivery = $E_{beam} \cdot I_{beam}$ + γ losses
- Electron beam properties set by the linac (injector is everything)

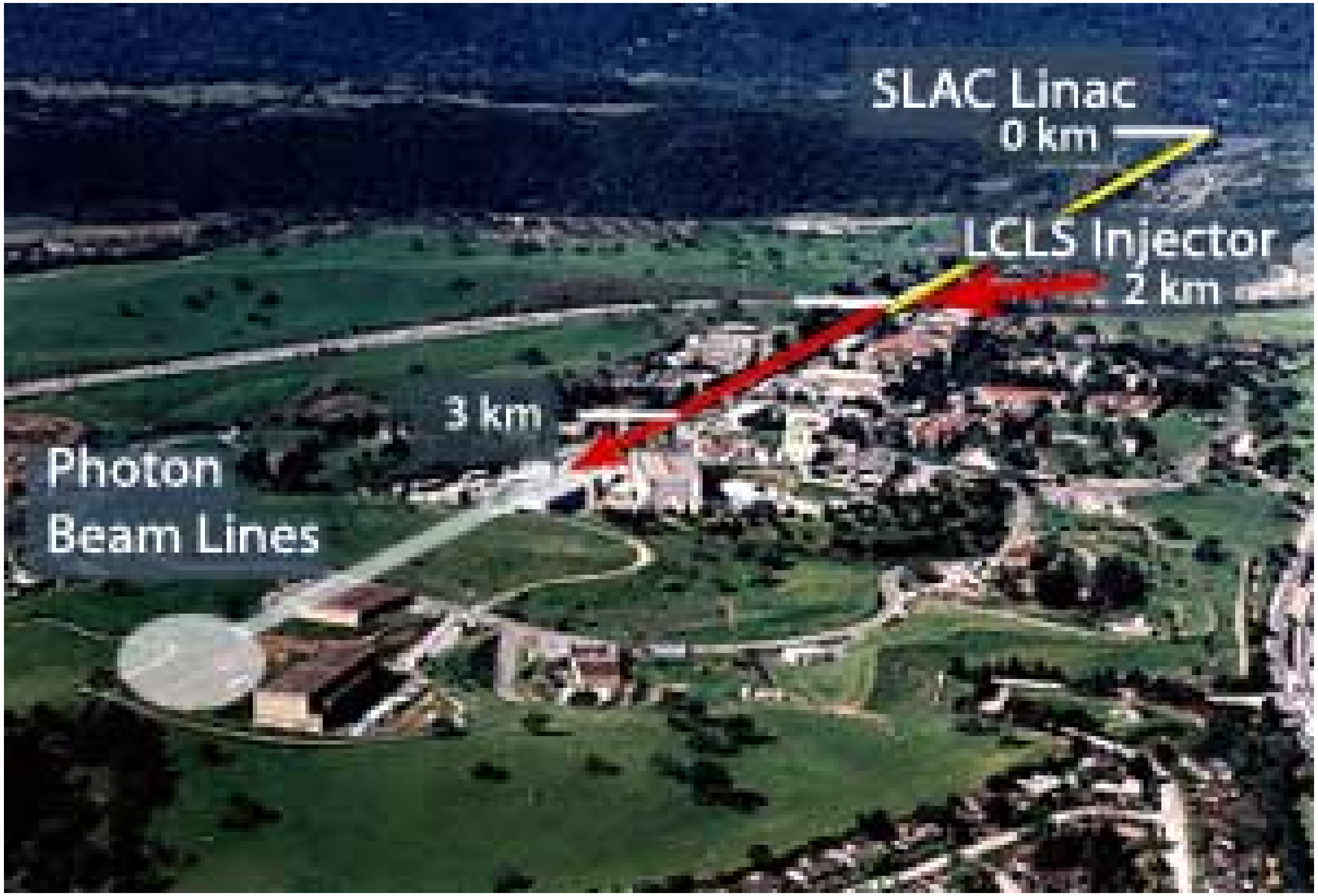
Storage-Ring Replacements & X-FELs



"1st-generation" Linac Based Light Sources

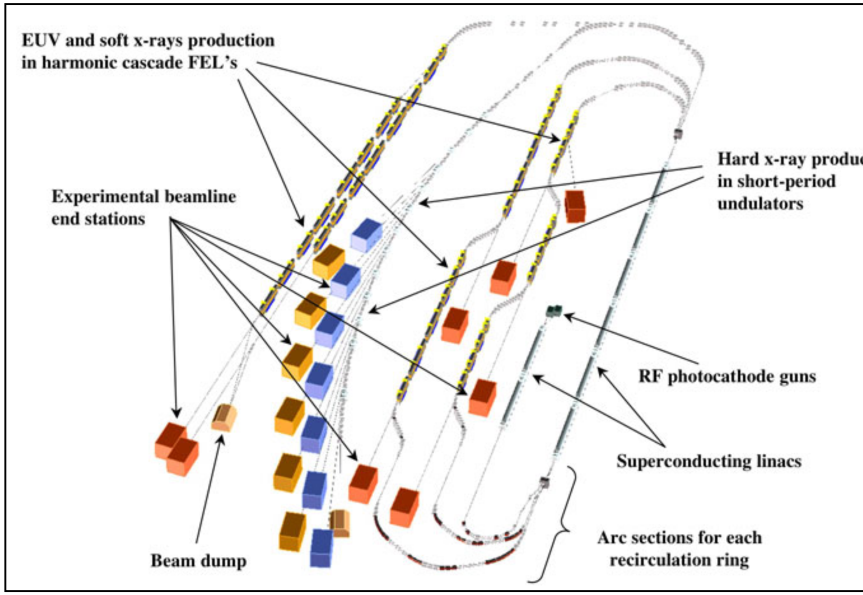
What's next in light-source development?

LCLS: 1st-Generation Linac-Based Light Source Prototype

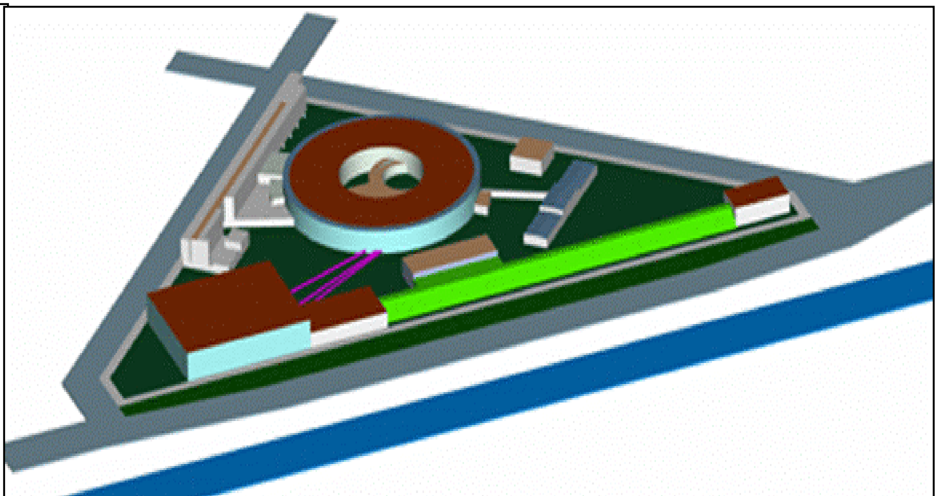


Courtesy SSRL/LCLS

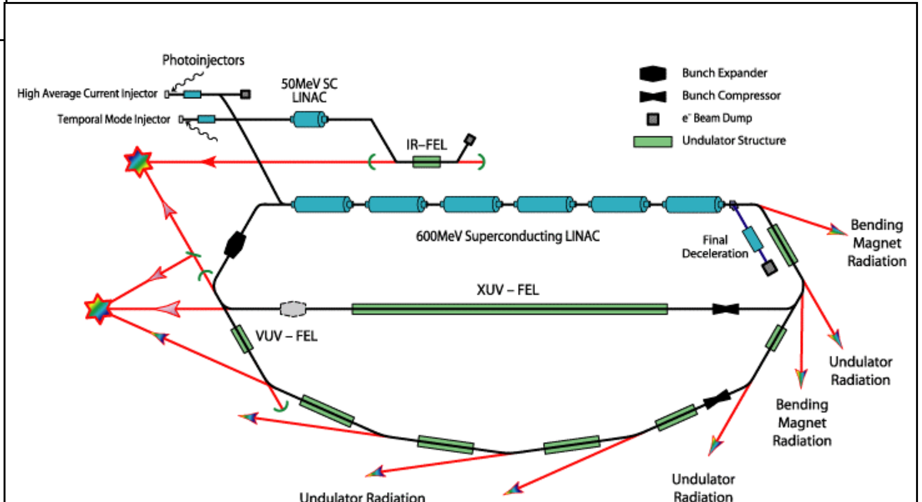
What comes after that?



LUX – Courtesy LBL



BESSY-FEL – Courtesy Bessy



4GLS – Courtesy Daresbury

2nd-generation linac-based light sources

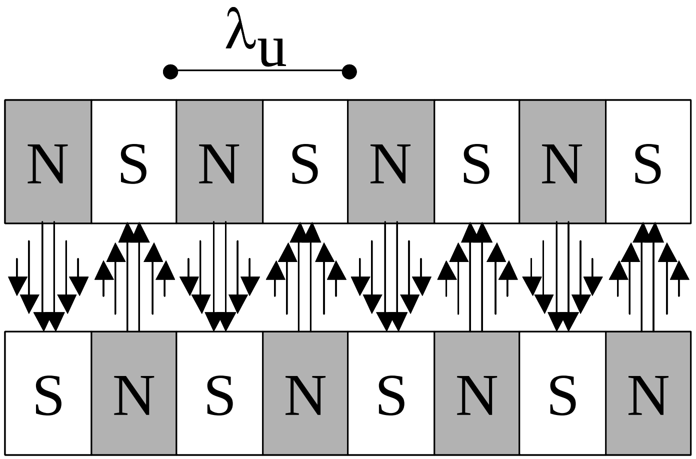
- Large, multi-user facilities.
- Combined storage-ring replacements (SRRs) and X-ray free-electron lasers (X-FELs).
- Energy-recovery linacs for high average beam currents

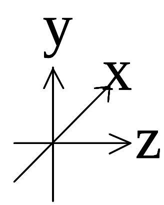
SRR – Performance Requirements

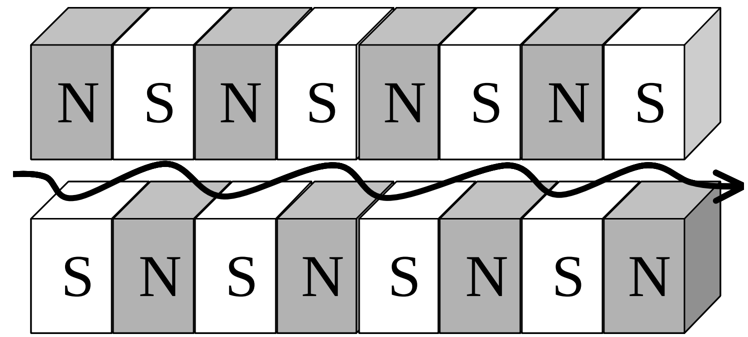
- **>10² peak brightness improvement over existing SR sources**
- **< ps temporal resolution (i.e. bunch length)**

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

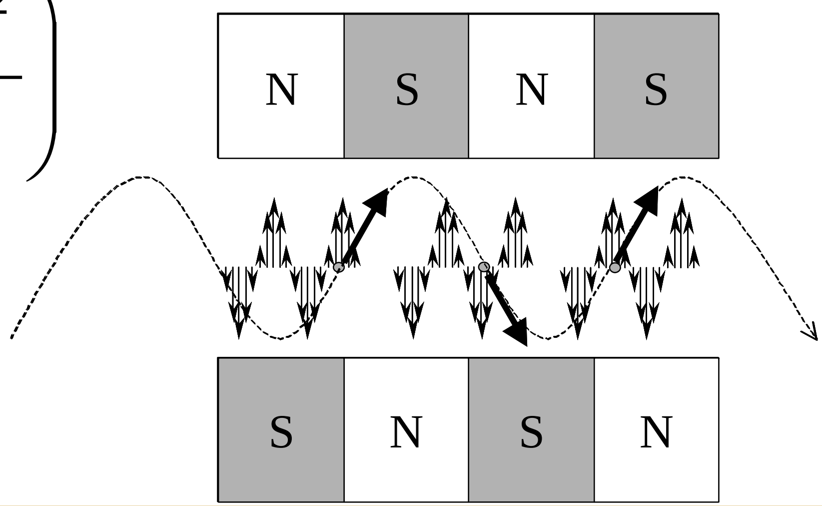
Brief Primer on FELs and SASE-FELs







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



The Pierce Parameter and X-FEL Performance

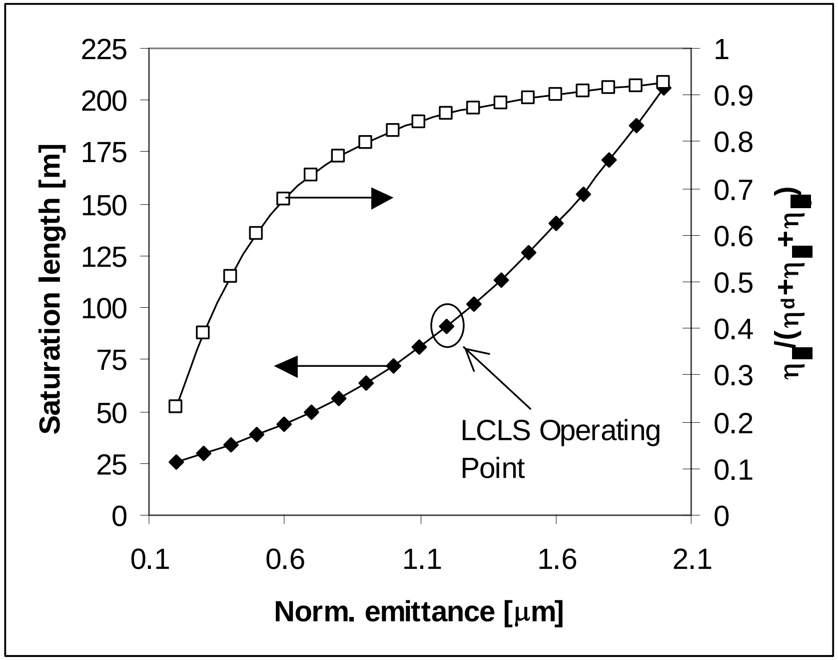
$$\rho = \sqrt[3]{\frac{I_p}{I_A}\left(\frac{\lambda_u K f_b}{2\sqrt{2}\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma}\right)^3} = \sqrt[3]{\frac{1}{I_A}\cdot\frac{\lambda_u{}^2 K^2 f_b^2}{64\pi^2\beta_x}\cdot\frac{I_p}{\gamma^2\varepsilon_{n,x}}}$$

The larger the Pierce parameter…

- the smaller the gain length
- the shorter the X-FEL undulator
- the less expensive the facility is

Emittance too big? Pump up K and λ_u … but there's a price.

$\gamma^{-2} \rightarrow \lambda_u$ for fixed λ, so slow progress



X-FEL – Performance Requirements

- **Maintain LCLS wavelength performance**
- **Minimize overall systems cost**

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

Fixed Parameter

λ = x-ray wavelength = 1.5 Å

Parameter to Minimize

γ = electron beam Lorentz factor

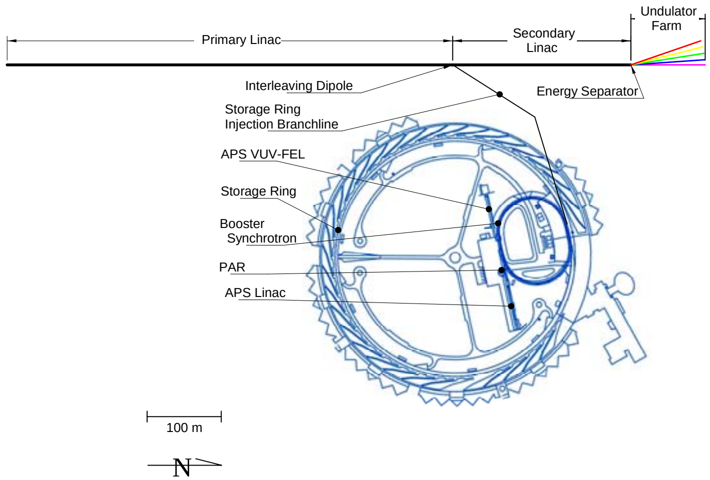
Parameters we can adjust

λ_u = undulator period > 1¼ cm

K = undulator strength ~ 1

With existing undulator technology, need about a 4 GeV beam to make 1.5 Å x-rays … assuming we can get the gain.

X-FEL Design Optimization…



Assume:

- Existing undulator technology
- Existing linac technology
- "Classic" SASE design

Towards a Realizable Source Design (I)

- **Single-bunch parameters for X-FEL and SRR sources are remarkably similar:**
  - ~ 0.1 μm normalized emittance
  - ~ 1 kA peak beam current (post-compressor)

- **SRR will need 10 – 100 mA beam current to maintain reasonable average brightness**

- **X-FELs might want long inter-pulse spacing to change out samples**

- **Therefore, two quasi-separable research tasks:**
  - Meeting the single-bunch design requirements
  - Moving towards high-average-current requirements

Single-Bunch Performance: Getting to 0.1 μm

- **DC guns:**
  - 0.1 μm @ 0.08 nC
- **SRF guns:**
  - 0.1 μm @ 0.05 nC (no drive laser needed, FE cathode)
- **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!

Bunch Train Operation

- **DC guns**
  - JLab FEL injector (operational): 10 mA, 9 μm
- **Normal-conducting RF guns**
  - DESY-Zeuthen: PITZ injector, 1.1 ms, 10 Hz → 1.1% duty factor (operational)
    - *limited by water cooling*
    - *40 MV/m gradients*
  - Boeing injector: 25% duty factor, had operated
  - AES / LANL prototype: CW operation
- **Superconducting RF guns**
  - Rossendorf / Drossel Collaboration
  - AES / BNL

Conclusions

- **SRRs and X-FELs have similar single-bunch requirements**
  - natural path towards integrated facilities
  - shared linac leverages cost, local talent
- **Good simulation progress towards single-bunch parameters**
  - yet to be demonstrated in practice
  - thermal emittance still a very real concern
  - cathode research is essential
- **Long-pulse / CW operation**
  - DC guns operating at low bunch charges
  - Normal-conducting RF guns showing good progress
  - Superconducting RF guns are showing exciting results