A normal conductive RF photo-injector for high repetition rate X-ray free electron lasers

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Outline

FEL Basics

The LBNL FEL Vision

An R&D towards the FEL

Electron Sources Schemes and Limitations

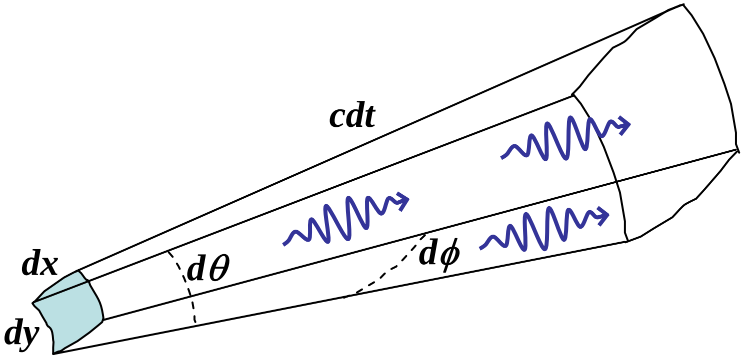
The LBNL Normal-Conductiong CW RF Photo-Injector

Brightness: A Defining Factor

- **Brightness** is the main parameter for the characterization of a light source.

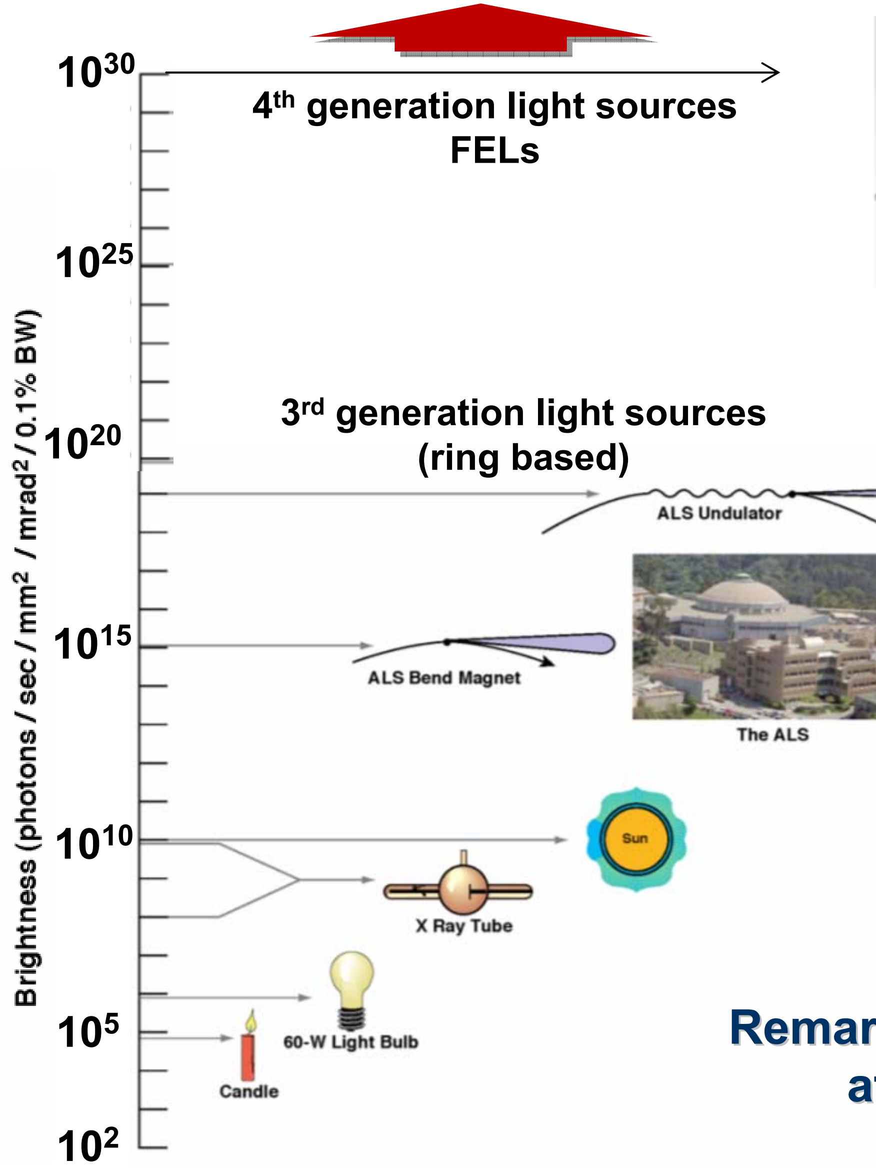
- Brightness is defined as *the density of photons in the 6-D phase space*.

$$\frac{\text{Brightness}}{\text{unit}} = \frac{\text{\# of photons in } 0.1\% \, \Delta\lambda/\lambda}{\text{s mrad}^2 \text{ mm}^2}$$



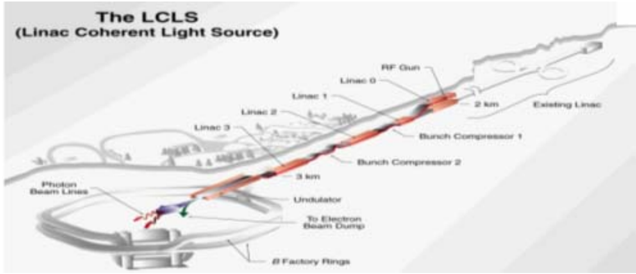
- **High brightness is strongly desirable**:
faster experiments, higher coherence, improved time and energy resolution in experiments, …

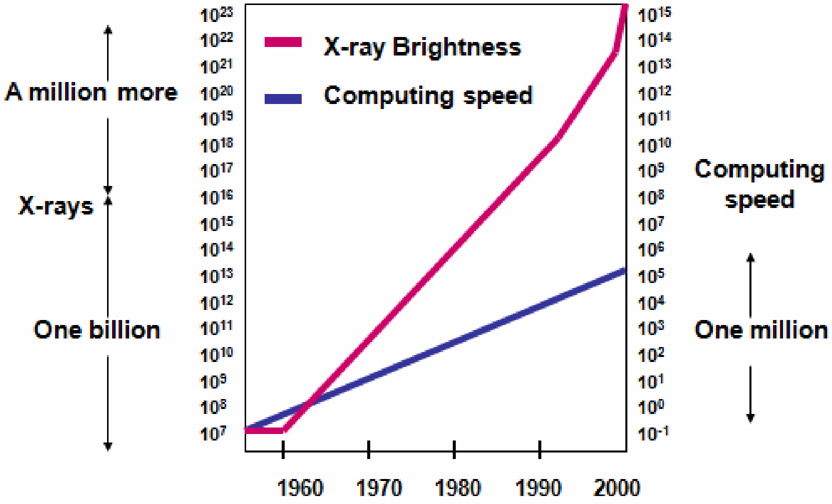
Light Source Brightness



4th generation light sources
FELs

3rd generation light sources
(ring based)

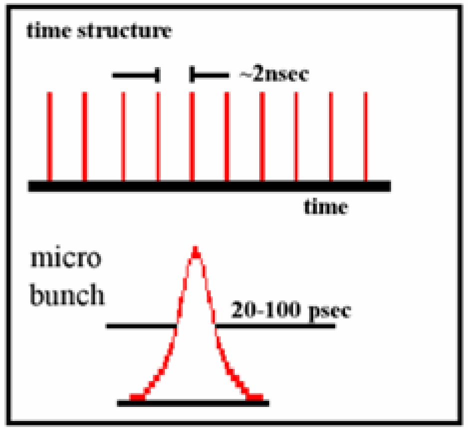




Remark: the sources are compared at different wavelengths!

3rd Vs. 4th Generation

The main properties of synchrotron radiation from 3rd generation light sources:

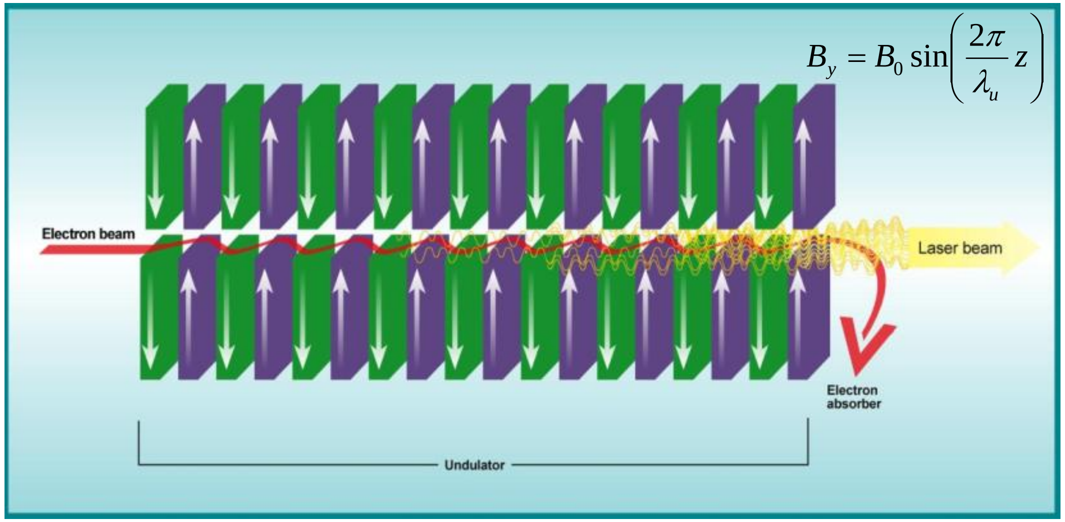


- High brightness and flux
- Highly polarized
- Short pulses (>ps) $\xrightarrow{\text{4th Generation}}$ • Much shorter pulses (~fs)

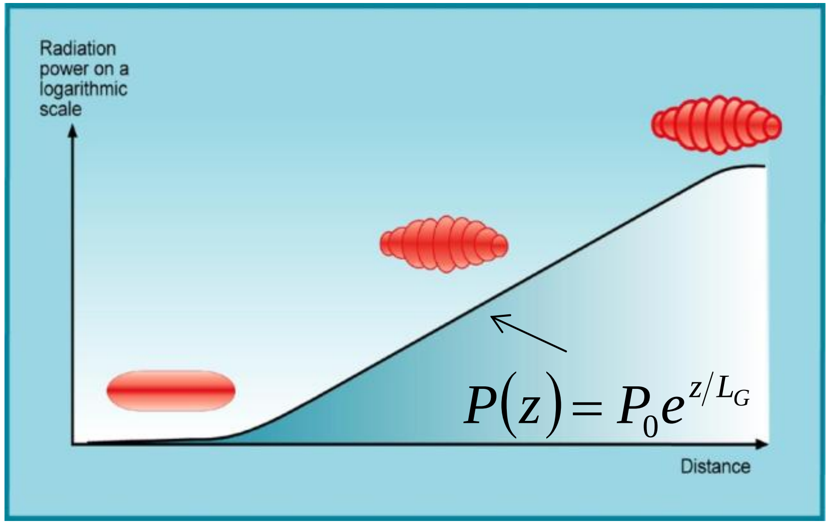
SR offers many characteristics of visible lasers but into the x-ray regime!

- Large energy tunability $\xrightarrow{\text{4th Generation}}$ • Large energy tunability
- Partial transverse coherence $\xrightarrow{\text{4th Generation}}$ • Full transverse coherence and full longitudinal in some schemes
- High stability $\xrightarrow{\text{4th Generation}}$ • Worse stability

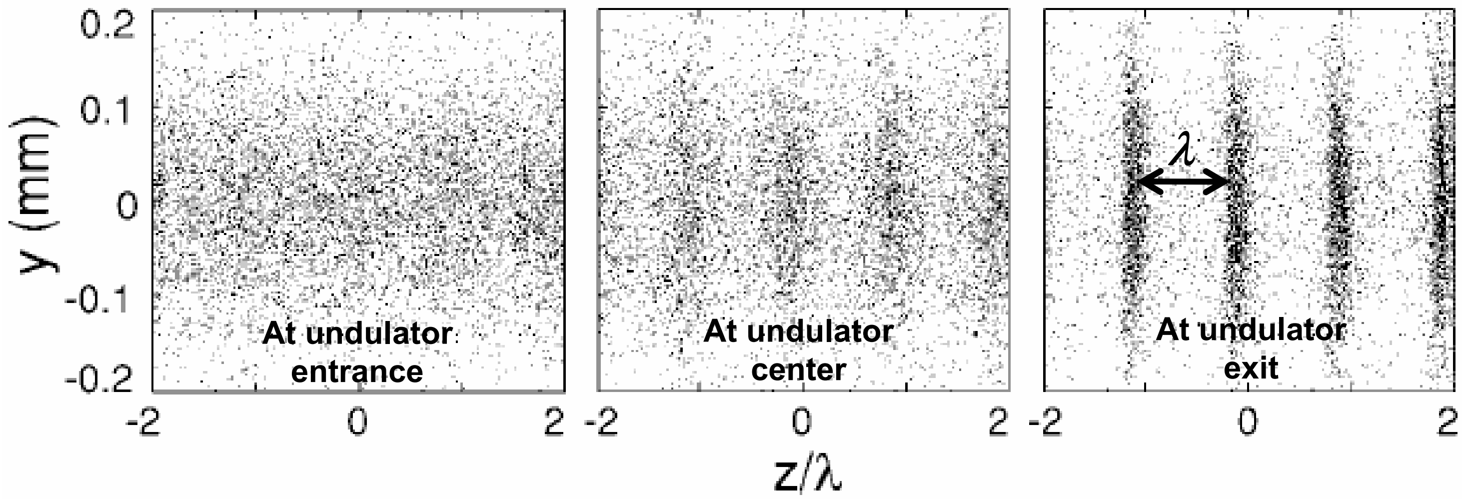
FELs Exploits Coherence



$$B_y = B_0 \sin\left(\frac{2\pi}{\lambda_u} z\right)$$



$$P(z) = P_0 e^{z/L_G}$$

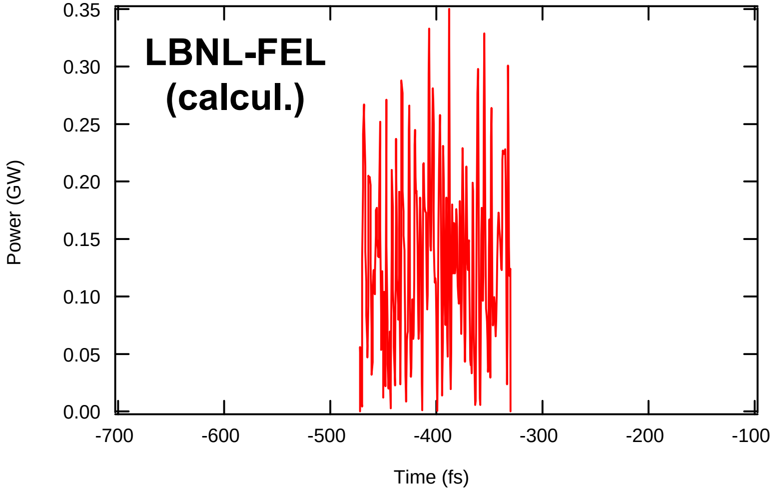


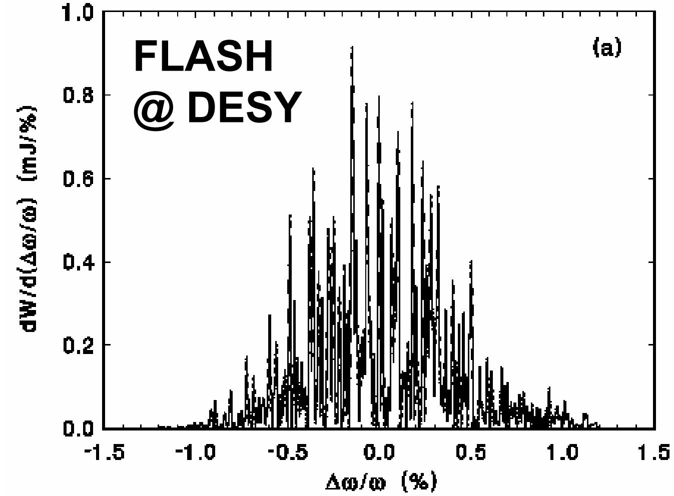
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{e}{2\pi m_0 c}\lambda_u B_0$$

SASE FELs

- **The FEL scheme described before is commonly referred as SASE, which stays for Self-Amplified Spontaneous Emission.**
- **The spontaneous emission from an undulator that randomly starts from a micro-modulation of the beam (noise) is amplified by the FEL gain mechanism.**
- **The randomness of the process has two important consequences:**





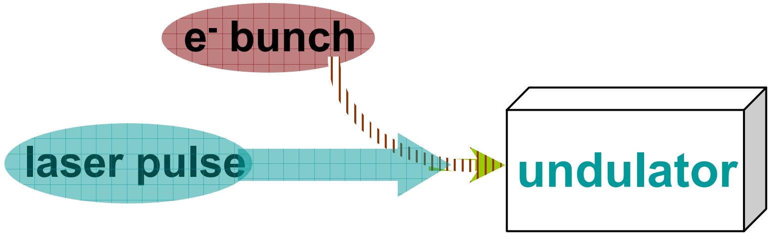
- **SASE pulses are transversely coherent but longitudinally incoherent.**
- **The stochastic time and spectral nature of SASE can represent an issue to some experiments…**

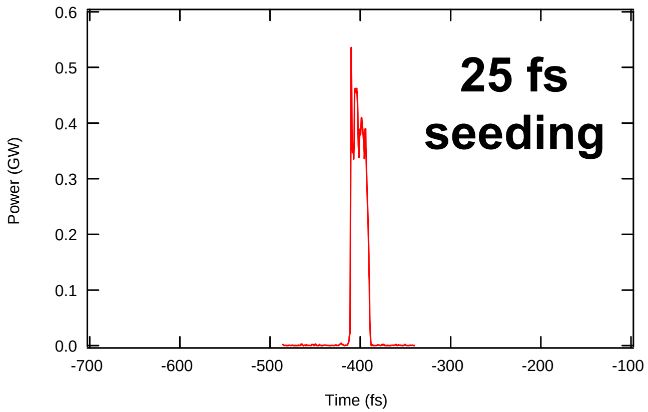
Seeded FEL Schemes

If the spontaneous undulator radiation used in the SASE scheme is replaced by a laser pulse of well defined pulse length, proper amplitude and with wavelength:

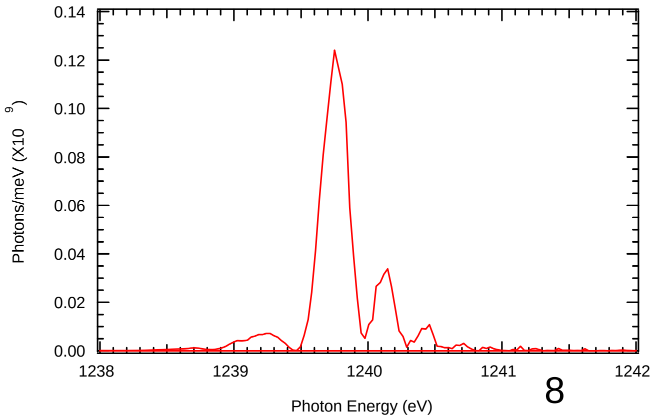
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

then the FEL process will not start anymore from noise but will be seeded by the laser.





Respect to the SASE case, seeding allows for a much better control of the pulse length and spectrum of the radiated pulse. Indeed, the pulse will have about the length of the laser pulse and the spectrum will approach the *Fourier Transform Limit*

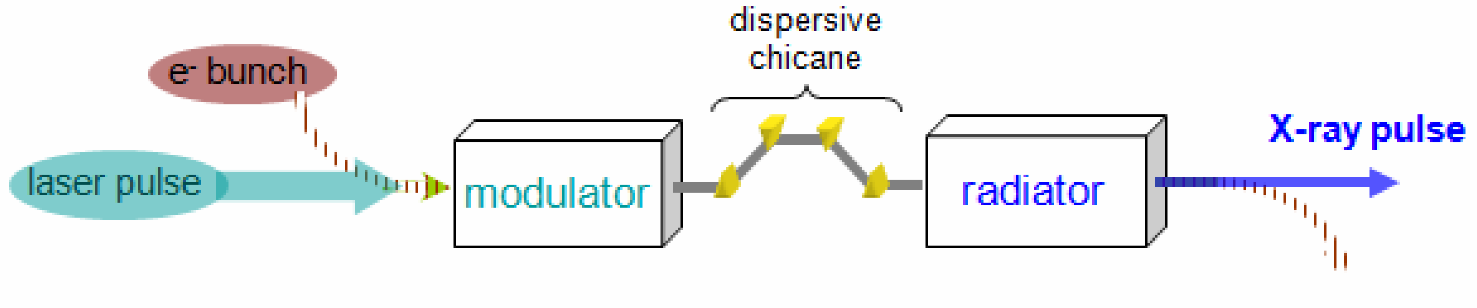


Seeded FEL Schemes

The seeding previously described requires the existence of a laser with wavelength λ. For short wavelengths this can represent a quite difficult requirement.

Several different schemes have been developed that exploit the higher harmonics present in an undulator to overcome such a difficulty.

The next example is called High Gain Harmonic Generation (HGHG) and uses two undulators (modulator and radiator) in cascade separated by a magnetic chicane



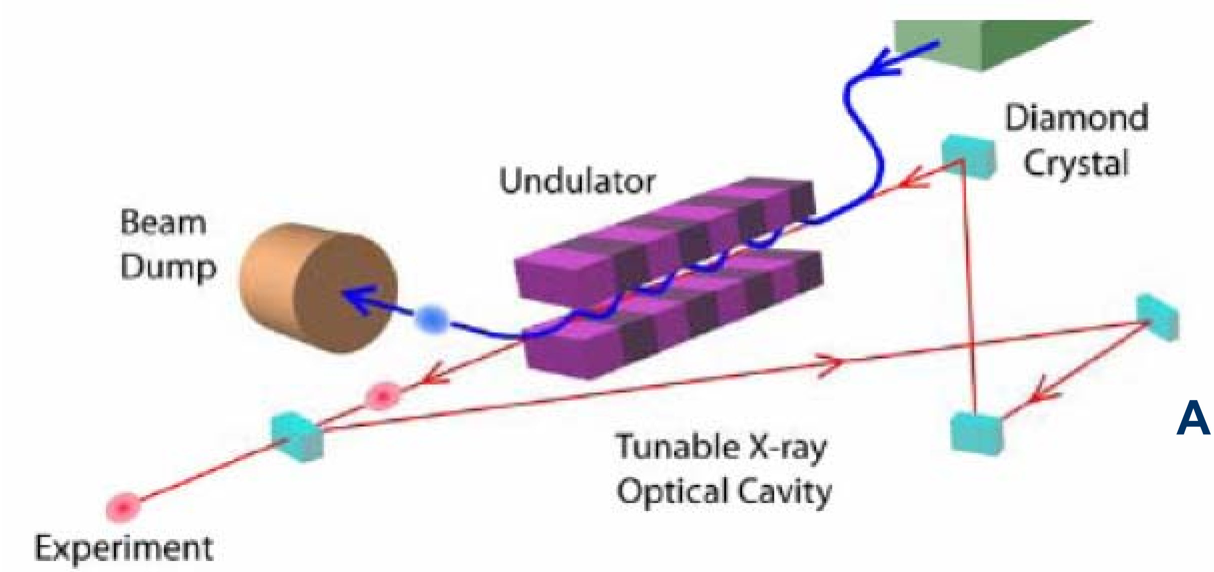
$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Relatively recently novel scheme has been proposed, the Echo Enabled Harmonic Generation with the potential of efficiently generating very high harmonics

Short-Wavelength FEL Oscillators

- **In an oscillator scheme the undulator is included between two (or more) mirrors and the radiation interacts for many passages with the electron beam. The scheme allows for relatively compact FELs with very narrow bandwidth.**
- **Realistic FEL oscillators require high quality mirrors with high reflectivity at large reflection angles.**
- **For frequencies above the near UV such mirrors become hard to fabricate. FEL oscillators presently in operation radiates in the IR, visible and near UV.**
- **Recently a scheme using high purity diamond crystals as mirrors have been proposed in an oscillator scheme radiating in the X-ray region.**

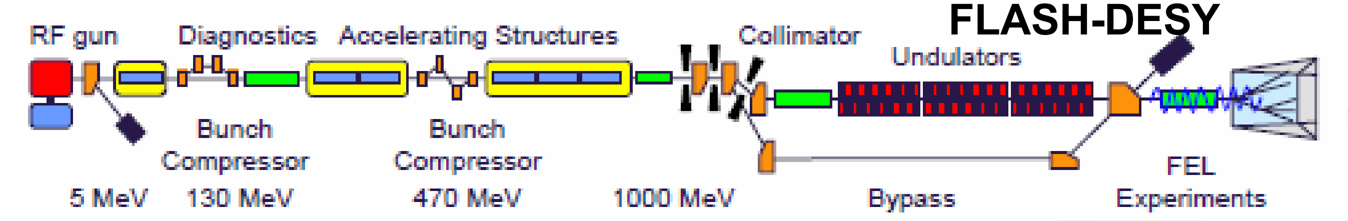


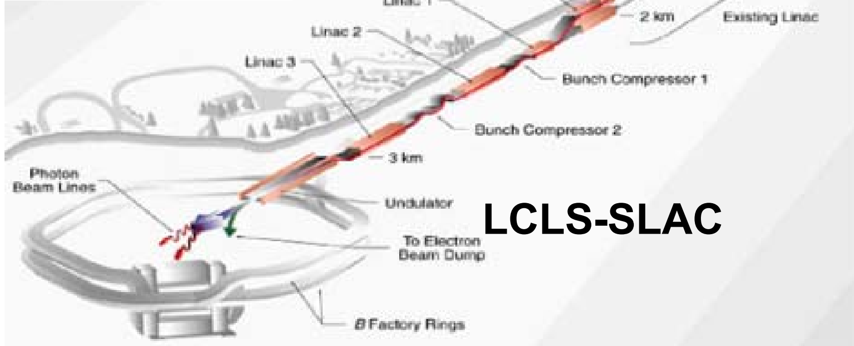
Argonne hard X-ray FEL Oscillator

From Theory to Real X-ray FELs!

A number of X-ray FELs are being proposed, in construction phase and in operation. For example:

FLASH-DESY





LCLS-SLAC

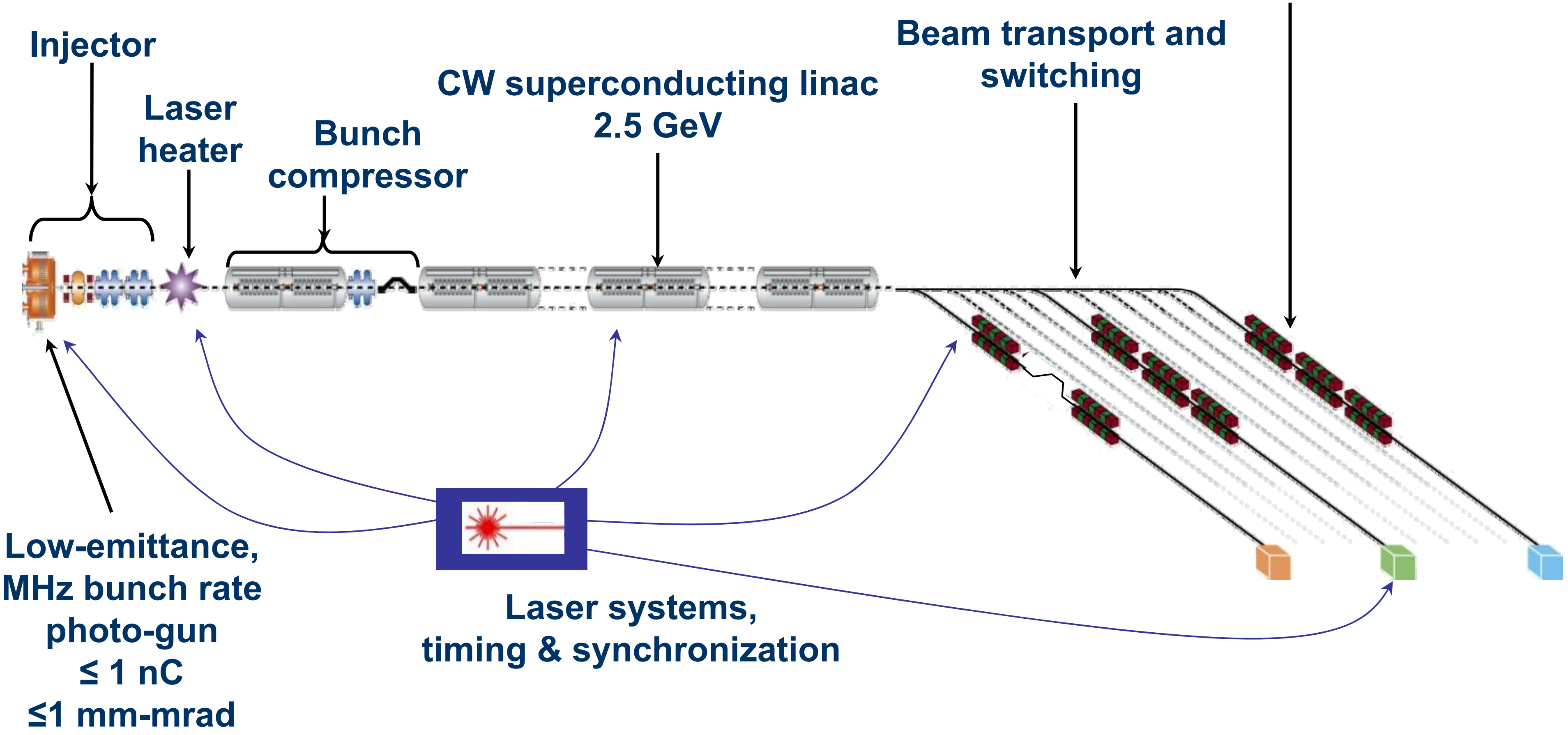
- 2011-60 p/s
- SPring-8 Compact SASE Source (SCSS)

- European XFEL Facility (XFEL)
- 2014 - 30 000 p/s

And after the spectacular success of FLASH and LCLS, there is the experimental evidence of the capability of such schemes!

The LBNL FEL Scheme

Array of 10 configurable FEL beamlines, up to 20 X-ray beamlines
100 kHz CW pulse rate, capability of one FEL having MHz rate
Independent control of wavelength, pulse duration, polarization
Each FEL configured for experimental requirements;
seeded, attosecond, ESASE, mode-locked, echo effect, etc



Injector

Laser heater

Bunch compressor

CW superconducting linac 2.5 GeV

Beam transport and switching

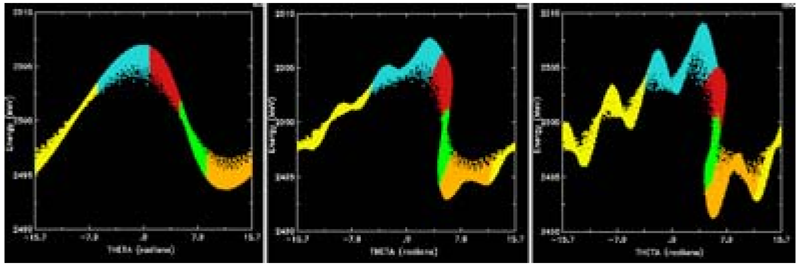
Low-emittance, MHz bunch rate photo-gun ≤ 1 nC ≤1 mm-mrad

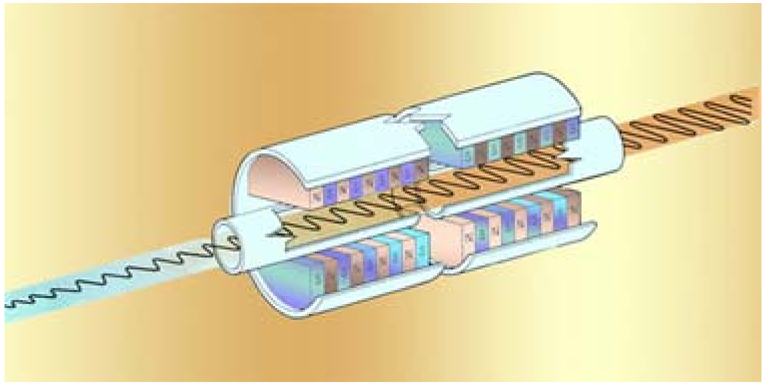
Laser systems, timing & synchronization

A Science Driven Facility

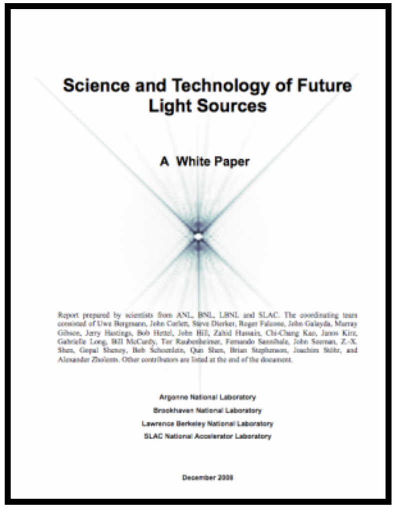
Science for a New Class of Soft X-ray Light Sources
Workshop on October 8 - 10, 2007 | Berkeley, California

1. Atomic, Molecular and Optical Physics
2. Chemical Physics
3. Correlated Materials
4. Magnetization and Spin Dynamics
5. Nanoscience and Coherence





And Many More…



Science and Technology of Future Light Sources

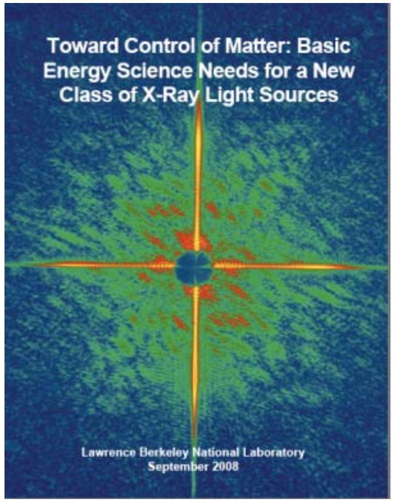
A White Paper

Report prepared by scientists from ANL, BNL, LBNL and SLAC. The coordinating team consisted of Uwe Bergmann, John Corlett, Steve Dierker, Roger Falcone, John Galayda, Murray Gibson, Jerry Hastings, Bob Hettel, John Hill, Zahid Hussain, Chi-Chang Kao, Janos Kirz, Gabrielle Long, Bill McCurdy, Tor Raubenheimer, Fernando Sannibale, John Seeman, Z.-X. Shen, Gopal Shenoy, Bob Schoenlein, Qun Shen, Brian Stephenson, Joachim Stöhr, and Alexander Zholents. Other contributors are listed at the end of the document.

Argonne National Laboratory
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
SLAC National Accelerator Laboratory

December 2008

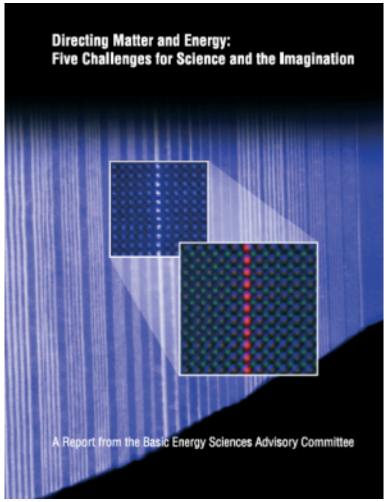
4 Lab Report



Toward Control of Matter: Basic Energy Science Needs for a New Class of X-Ray Light Sources

Lawrence Berkeley National Laboratory
September 2008

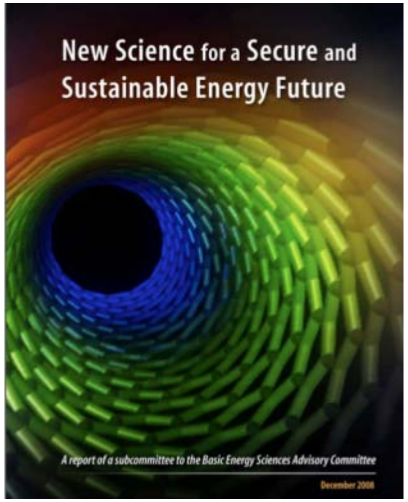
LBNL Workshop



Directing Matter and Energy:
Five Challenges for Science and the Imagination

A Report from the Basic Energy Sciences Advisory Committee

Grand Challenges

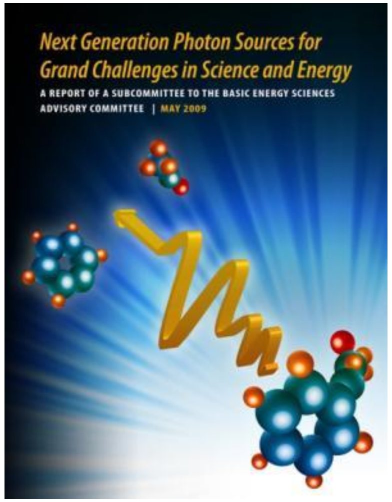


New Science for a Secure and Sustainable Energy Future

A report of a subcommittee to the Basic Energy Sciences Advisory Committee

December 2008

New Era Report



Next Generation Photon Sources for Grand Challenges in Science and Energy

A REPORT OF A SUBCOMMITTEE TO THE BASIC ENERGY SCIENCES ADVISORY COMMITTEE | MAY 2009

“Crabtree” Report

The Future of Ultrafast Soft X-ray Science

November 30 – December 3, 2009

■ ■ ■

Requirements for a Soft X-Ray/VUV Light Source

Ultrafast Time resolution and Synchronization

Required for all dynamics studies
Freezing atomic motion, femtosecond dynamics

250 as – 500 fs pulses

Tunable X-rays

Elemental specificity, spatial resolution, penetrating power, inner-shell atomic physics

100 eV – 1 keV
harmonics to 5 keV

Controlled, intense pulses

Single-shot applications, nonlinear effects
Limit flux/pulse
Avoid sample damage

50 µJ in 50 fs = 1 GW
50 µm focus = $4x10^{13}$ W/cm^2

1 µJ in 50 fs = 20 MW
50 µm focus = $8x10^{11}$ W/cm^2

High Repetition Rate

High average X-ray power without sample damage
Signal averaging

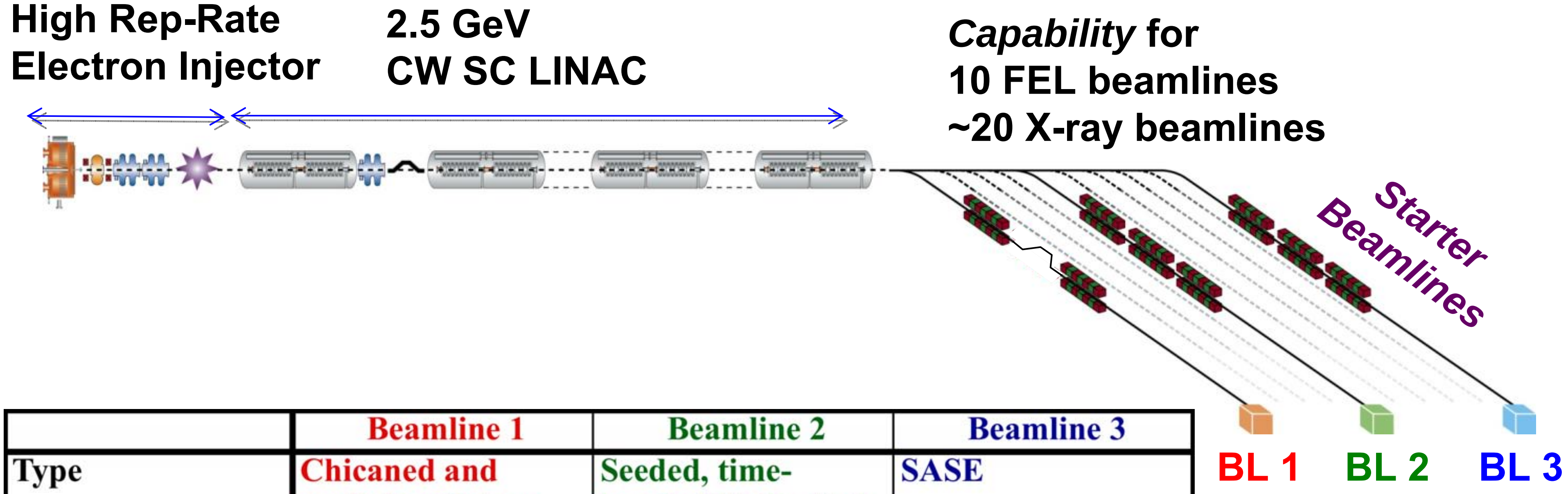
10-100 kHz
1-100 MHz
<1 W to 100 W

Coherence

Monochromatic source
Transverse coherence for small focus
High degeneracy ($N_{photons}$ per optical mode)

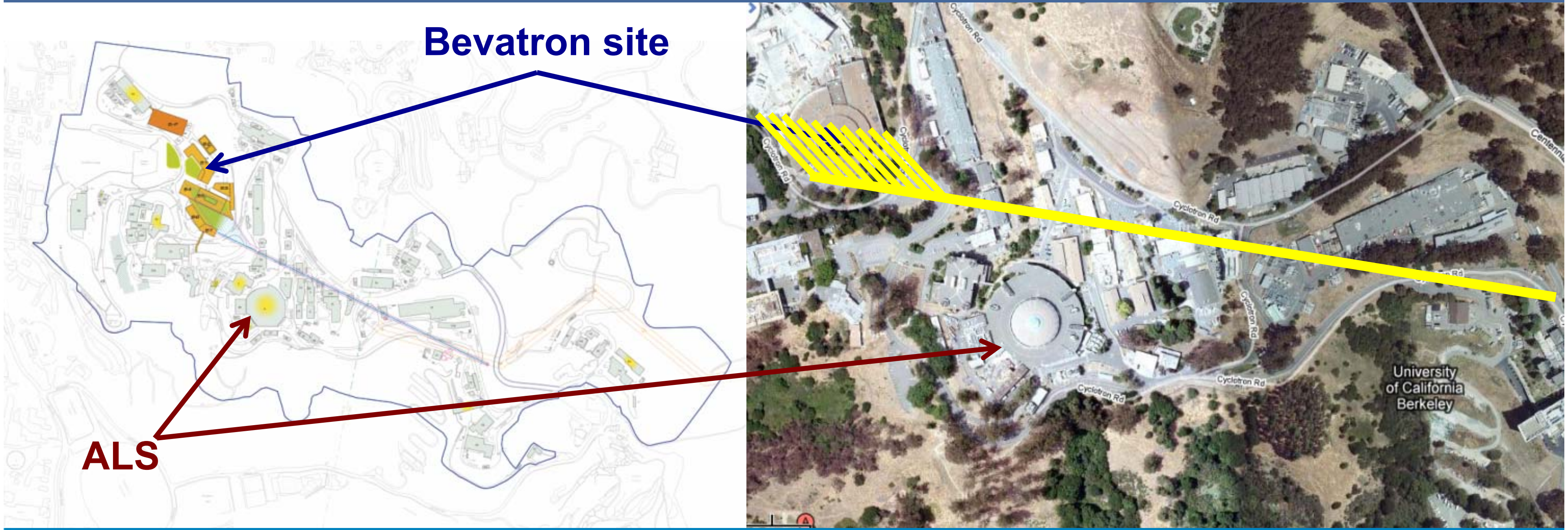
Close to Fourier transform limit

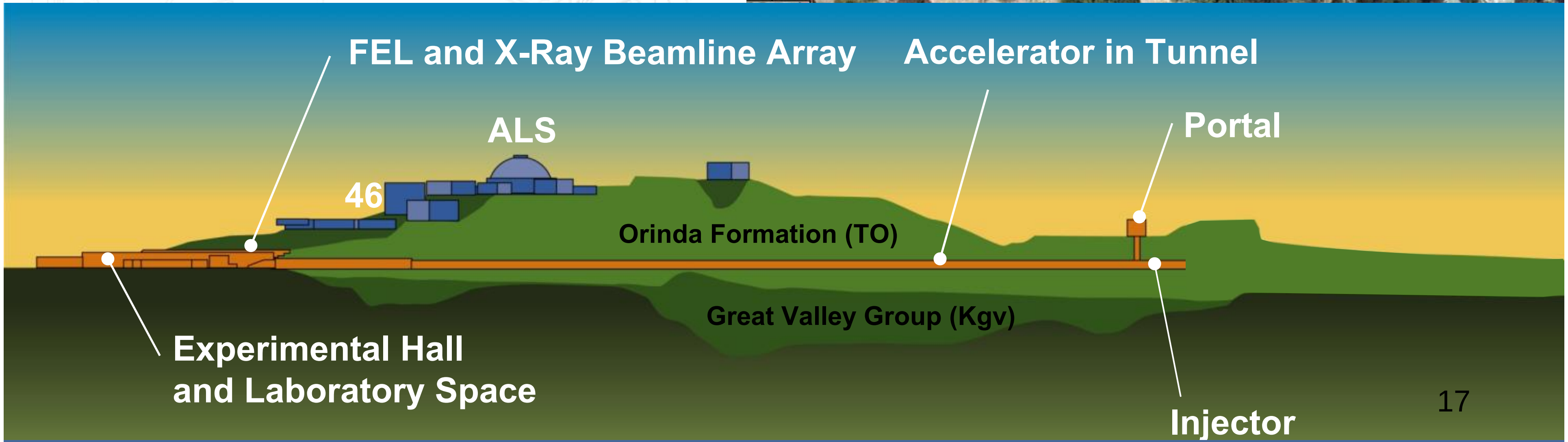
Example NGLS Initial Facility



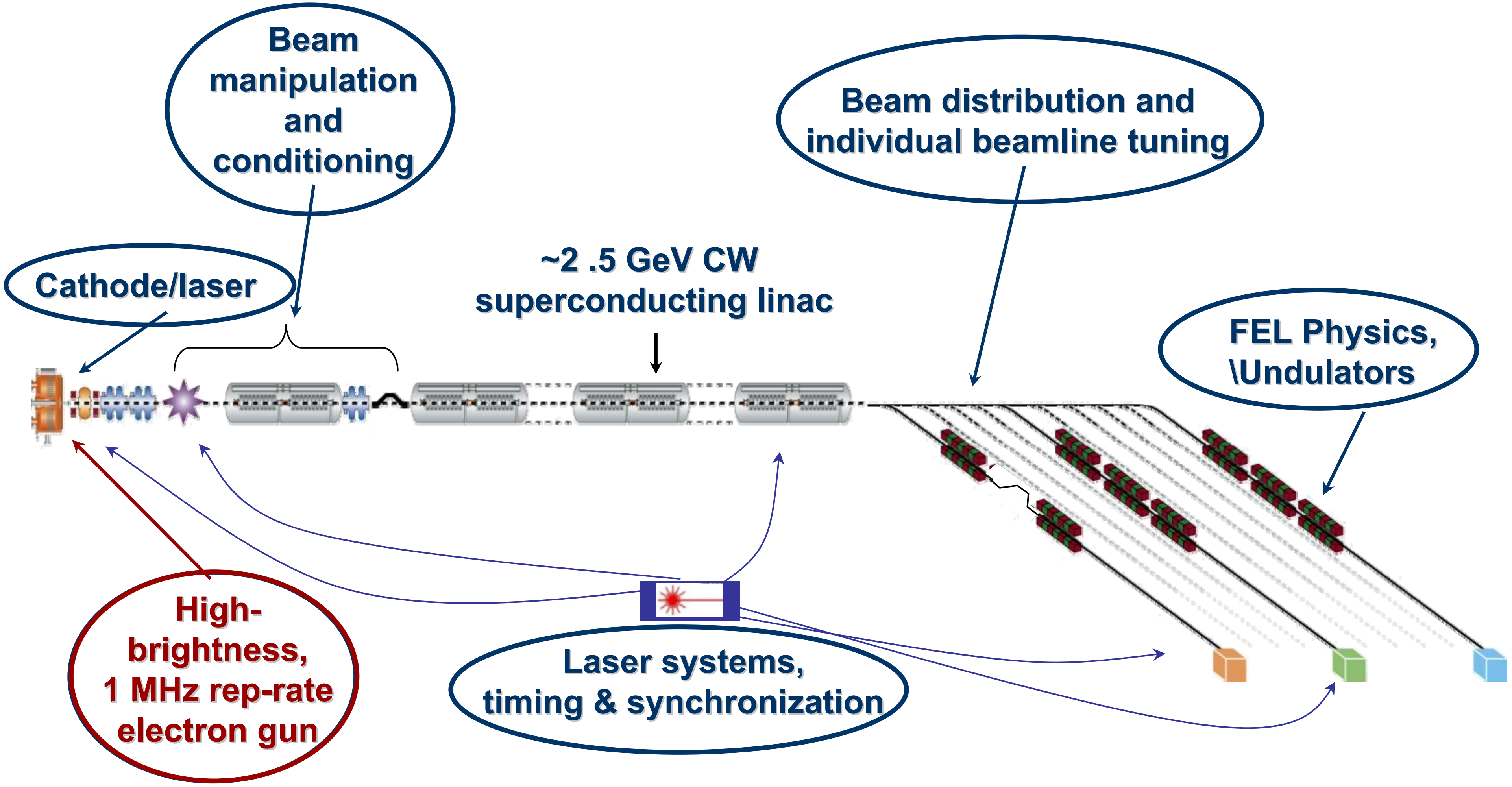
	Beamline 1	Beamline 2	Beamline 3
Type	Chicaned and seeded radiators	Seeded, time-bandwidth-limited	SASE
Feature	2-color X-ray pump/probe with fs resolution	Short pulse, pump/probe with adjustable delay (THz - UV pump)	High average flux and brightness
Pulse duration	250 as - 25 fs	250 as - 50 fs (30 meV BW)	1 - 50 fs
Photon energy	250–1000 eV	250–1000 eV	250–1000 eV
Repetition rate	10–100 kHz	10–100 kHz	100 kHz–1 MHz
Photons per pulse	~10^{8}–10^{10}	~10^{9}–10^{11}	~10^{10}–10^{11}
Pulse energy	~0.01–1 μJ	~0.1–10 μJ	~1–10 μJ
Average power	~0.1–100 mW	~0.1–1 W	0.1–10 W

NGLS Site at LBNL





An R&D Program and Studies for the Critical Parts



Beam manipulation and conditioning

Beam distribution and individual beamline tuning

Cathode/laser

~2 .5 GeV CW superconducting linac

FEL Physics, \Undulators

High-brightness, 1 MHz rep-rate electron gun

Laser systems, timing & synchronization

Most of such R&D areas are funded

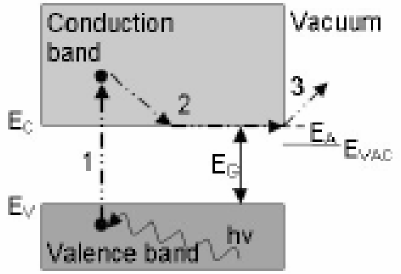
Electron Source Requirements

In a FEL the electron beam quality is defined at the gun/injector

To achieve the LBNL FEL goals, the electron source should simultaneously allow for:

- **repetition rates up to ~ 1 MHz**
- **charge per bunch from few tens of pC to ~ 1 nC,**
- **sub 10^{-7} (low charge) to 10^{-6} m normalized beam emittance,**
- **beam energy at the gun exit greater than ~ 500 keV (space charge),**
- **electric field at the cathode greater than ~ 10 MV/m (space charge limit),**
- **bunch length control from tens of fs to tens of ps for handling space charge effects, and for allowing the different modes of operation,**
- **compatibility with significant magnetic fields in the cathode and gun regions (mainly for emittance compensation)**
- **10^{-9} - 10^{-11} Torr operation vacuum pressure (high QE photo-cathodes),**
- **“easy” installation and conditioning of different kind of cathodes,**
- **high reliability compatible with the operation of a user facility.**

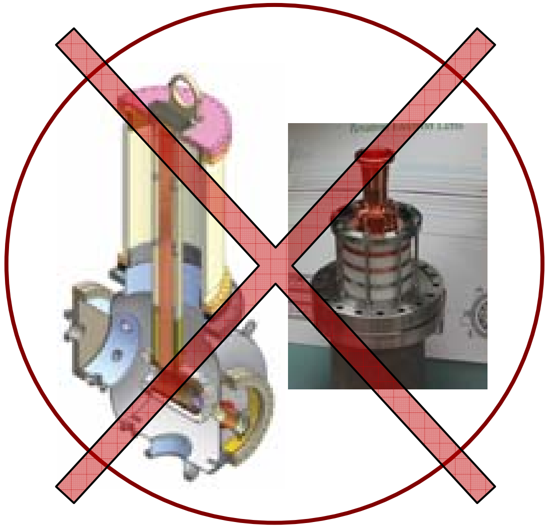
Available Gun Technologies



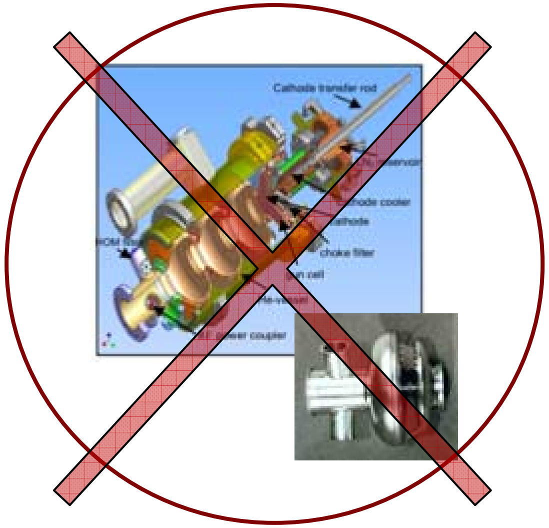
Low emittance, high quantum efficiency photo-cathodes
(for high repetition rates)

High charge, low emittance require photo guns

Photocathode laser systems including pulse shaping



DC gun



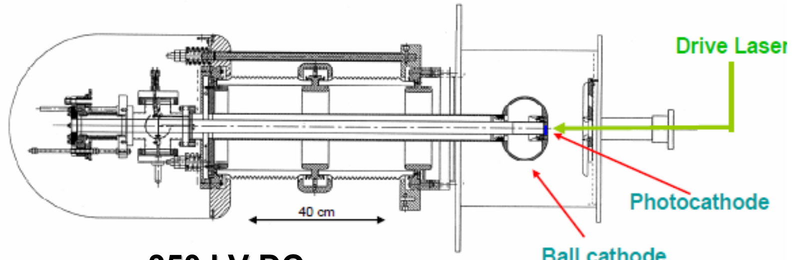
Super-conducting RF

High frequency (> 1 GHz) normal-conducting RF

DC Guns

Pros:

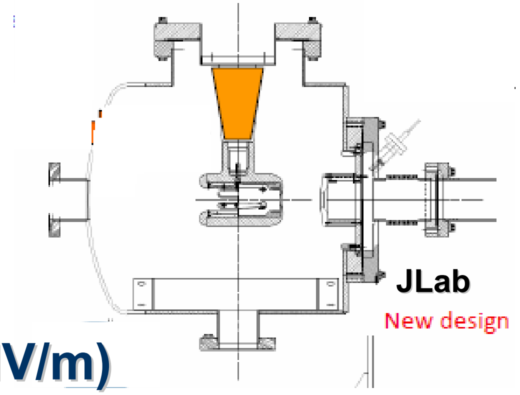
- DC operation
- DC guns reliably operated at 350 kV (JLAB) for many years, ongoing effort to increase the final energy (Cornell, Daresbury, Jlab, …).
- Extensive simulations (Cornell, …) "demonstrated" the capability of sub-micron emittances at ~ 1 nC, if a sufficient beam energy is achieved
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes. (The only one operating GaAs cathodes)



350 kV DC gun

Challenges:

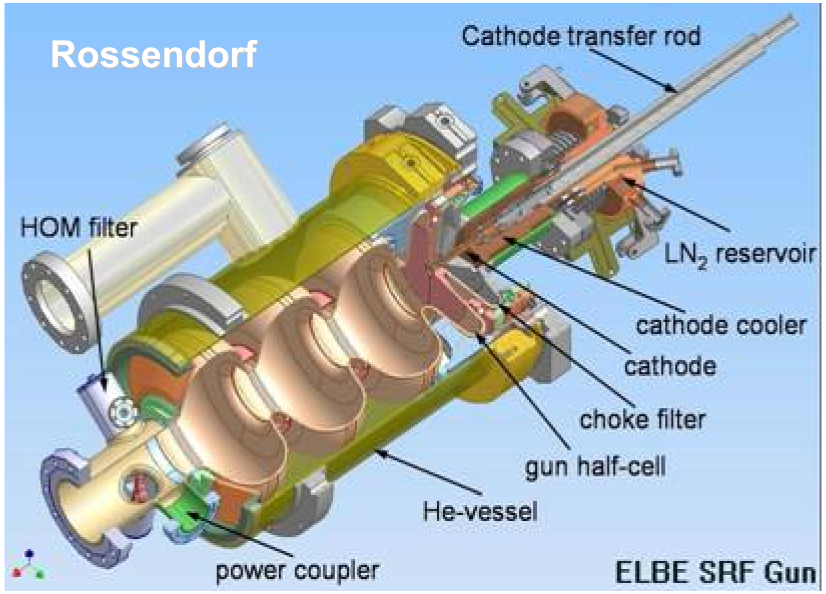
- Higher energies require further R&D and significant technology improvement.
- In particular, improvement of the high voltage breakdown ceramic design and fabrication.
- Minimizing field emission for higher gradients (>~ 10 MV/m)
- Developing and test new gun geometries (inverted geometry, SLAC, JLab) Very interesting results from a "pulsed" DC gun at Spring-8.



Super-Conducting Guns

Pros:

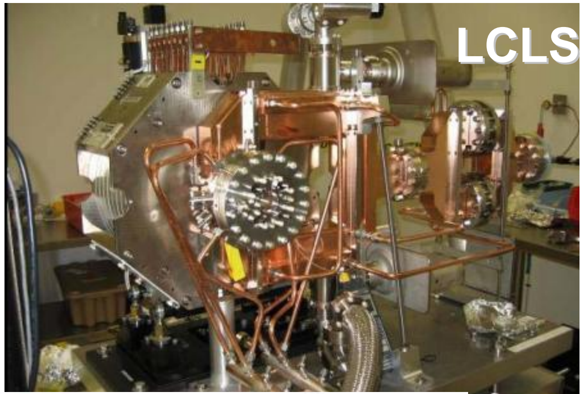
- Potential for relatively high gradients (several tens of MV/m)
- CW operation
- Excellent vacuum performance.

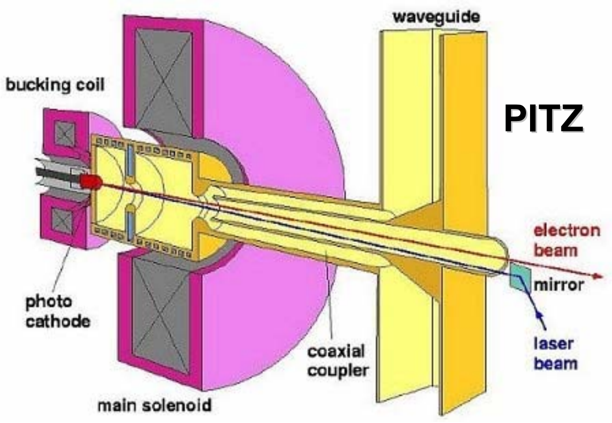


Challenges:

- Move technology from R&D to mature phase
- Evaluate and experimentally verify cathode compatibility issues (Promising results with Cs_2Te at Rossendorf, DC-SRF Peking approach)
- Develop schemes compatible with emittance compensation ("cohabitation" with magnetic fields, HOM schemes, …).

Normal Conducting High Frequency RF Guns





L band (~ 1 to 2 GHz) and S band (~ 2 to 4 GHz)

Pros:

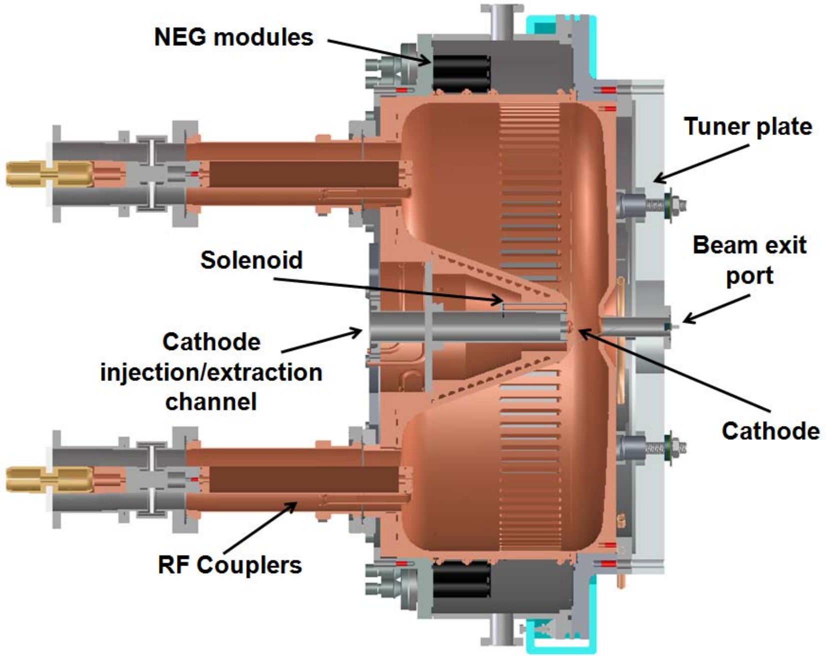
- **High gradients ~50 to ~140 MV/m**
- **“Mature” technology.**
- **Full compatibility with magnetic fields.**
- **Compatible with most photocathodes**
- **Proved high-brightness performance.
(LCLS and PITZ)**

Challenges:

- **High power density on the RF structure (~ 100 W/cm^2) limits the achievable repetition rate at high gradient to ~ 10 kHz (LUX).**
- **Relative small volume and small apertures can limit the vacuum performance.**

The LBNL VHF RF Gun

The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.



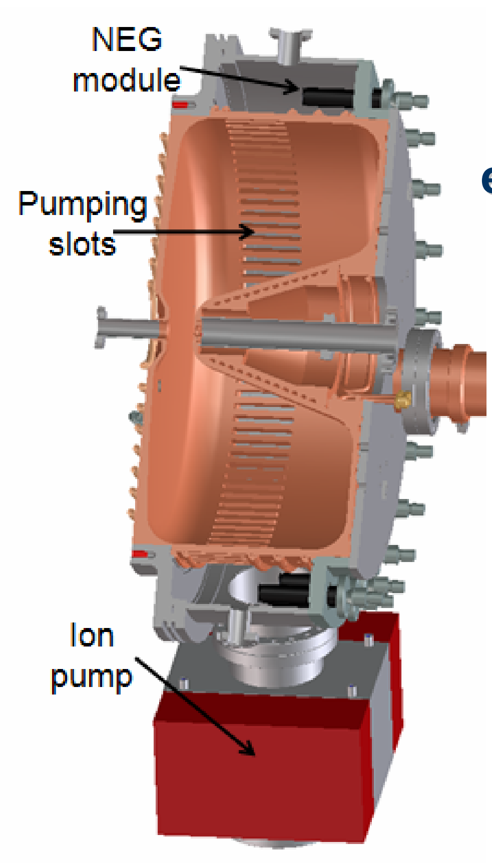
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter	69.4 cm
Total length	35.0 cm

- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.
- 187 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.

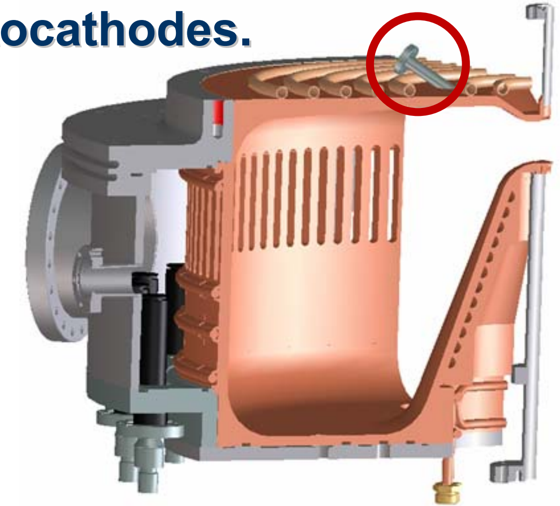
A Cathode Test Facility



- The **long RF wavelength** allows for **large apertures** and for **high vacuum conductivity**. The vacuum system has been designed to achieve an operational vacuum pressure down into the low **10^{-11} Torr range.** NEGs pumps are used (very effective with H_2O and O_2). This arrangement will allow testing a variety of cathodes including "delicate" multi-alkali and/or GaAs cathodes.

- Cathode area designed to operate with a **vacuum load-lock mechanism** for an easy in-vacuum replacement or "in situ" reconditioning of photocathodes.

The nominal laser illumination configuration for the cathode is quasi-perpendicular with laser entrance in the beam exit pipe.



An additional 30 deg laser entrance port has been added to allow testing of more exotic cathodes (surface plasma wave cathodes, ...)

Cathodes

- **Cathodes are obviously a fundamental part of electron sources. The gun performance heavily depends on cathodes**

- **The ideal cathode should allow for high brightness (have a low thermal/intrinsic normalized emittance, low energy spread, high current density) full control of the bunch distribution, and long lifetimes.**

- **In the low charge regime (tens of pC/bunch) the ultimate emittance performance is set by the cathode thermal emittance**

- **Photo-cathodes (most of present injector schemes)**

- **Thermionic cathodes can in some cases, offer low thermal emittances but require sophisticate compression schemes.**
  (CeB_6 at SCSS-Spring 8, XFELO-ANL)

Metal cathodes are robust but show low QE (<~ 10^{-4}). In high-repetition rates photo-sources high quantum efficiency photo-cathodes (QE>~ 1 %) are required to operate with present laser technology.

Other cathodes under study (photo-assisted field emission, needle arrays, photo-thermionic, diamond amplifiers)

Examples of Photo-Cathodes & Lasers

PEA Semiconductor: Cesium Telluride Cs_2Te (used at FLASH for example)

- <~ps pulse capability
- relatively robust and un-reactive (operates at ~ 10^{-9} Torr)
- successfully tested in NC RF and SRF guns
- high QE > 1%
- photo-emits in the UV ~250 nm (3rd or 4th harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required

Pursued by LBNL

NEA Semiconductor: Gallium Arsenide GaAs (used at Jlab for example)

- tens of ps pulse capability
- reactive; requires UHV <~ 10^{-10} Torr pressure
- high QE (typ. 10%)
- Photo-emits already in the NIR,
- low temperature source due to phonon scattering
- for nC, 1 MHz, ~50 mW of IR required
- operated only in DC guns at the moment
- Allow for polarized electrons

PEA Semiconductor: Alkali Antimonides eg. $SbNa_2KCs$, CsK_2Sb, …

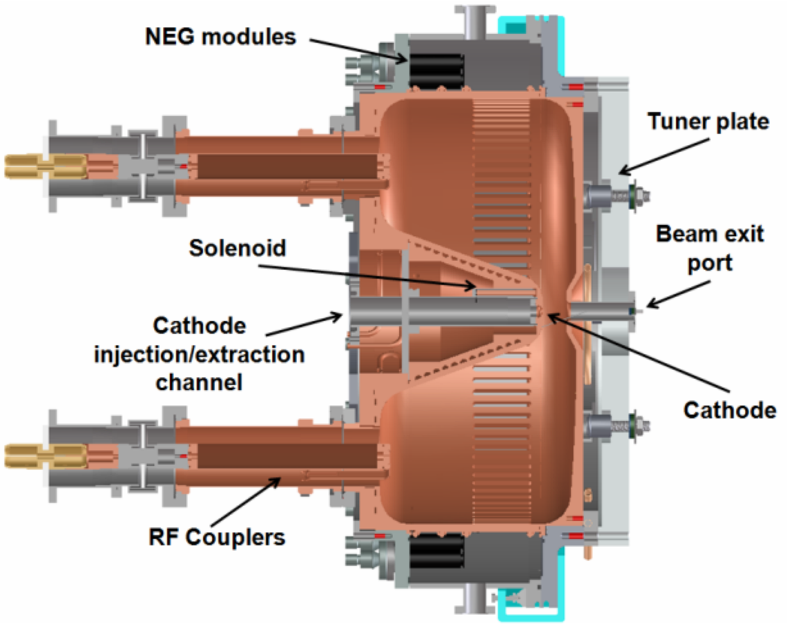
- <~ps pulse capability (studied at BOING, INFN-LASA, BNL, Daresbury, LBNL, ….)
- reactive; requires ~ 10^{-10} Torr pressure
- high QE > 1%
- requires green/blue light (eg. 2nd harm. Nd:YVO4 = 532nm)
- for nC, 1 MHz reprate, ~ 1 W of IR required

Pursued by LBNL

In Summary:
The LBNL NC CW VHF RF Gun

Pros:

- Can operate in CW mode
- Beam Dynamics similar to DC but with higher gradients and energies
- Based on mature RF and mechanical technology.
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes
- Potential for excellent vacuum performance.



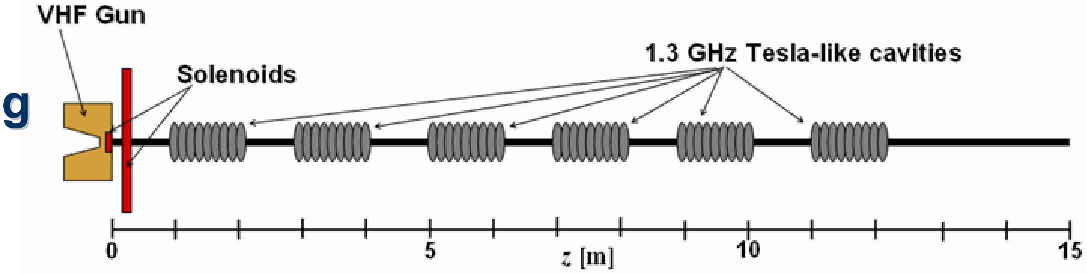
Challenges:

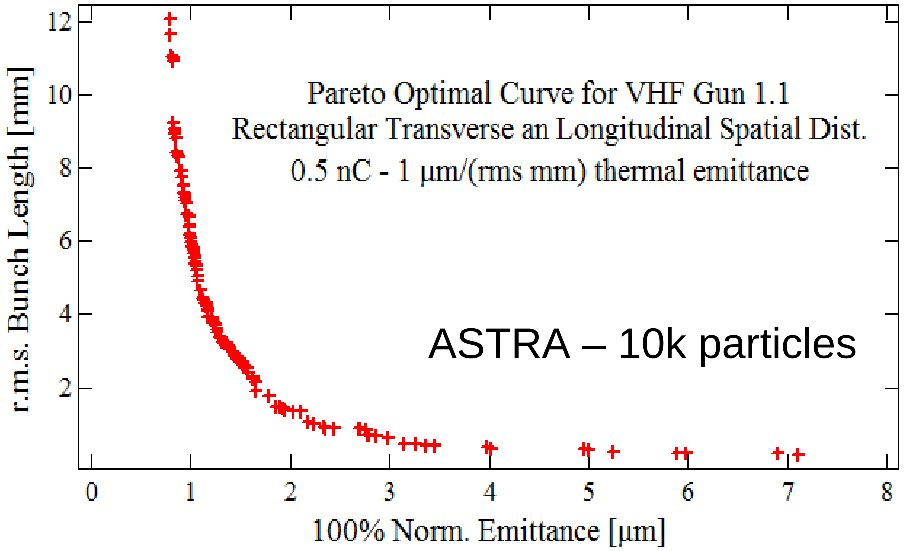
- Gradient and energy increase limited by heat load in the structure
- CW high brightness performance still to be proved

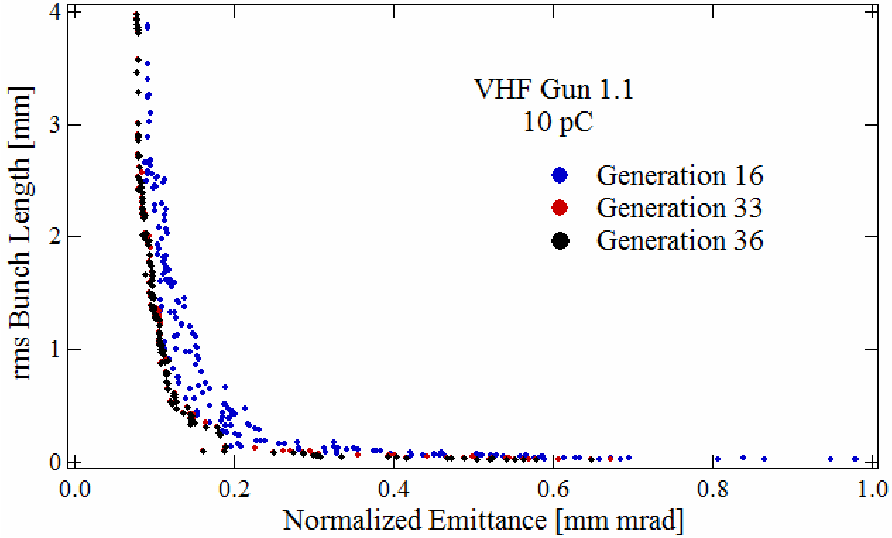
Ongoing Beam Dynamics Studies

- **EXAMPLE: No pre-buncher or buncher. Just main linac cavities**
- **Velocity bunching by de-phasing the first cavity**
- **Emittance compensation by a single solenoid (plus embedded bucking coil)**

- **Multi-Objective Genetic Algorithms optimization, trading between final emittance and bunch length.**







- **Work in progress but already showed the VHF gun capability to operate in a FEL scheme**

CW or Quasi-CW RF Guns

A VHF (144 MHz) gun is used at the ELSA 19 MeV linac and produces high charge-low emittance beams within a 150 μs macropulse at 10 Hz repetition rate.

R. Dei-cas, *et al.*, NIM A, **296**, pp. 209 (1990).
R. Dei-cas, *et al.*, NIM A, **331**, pp. 199 (1993).
J.-G. Marmouget, *et al.*, EPAC 2002, Paris, France, June 2002, p. 1795.
D. Guilhem, *et al*., EPAC 2006, Edinburgh, Scotland, July 2006, p. 1927.

The Boeing gun has achieved 25% duty cycle operation at 433 MHz.

D. Dowell, *et al*., Appl. Phys. Lett., **63** (15), 2035 (1993).

A Los Alamos/AES completed the RF test of a 700 MHz normal-conducting RF gun where a sophisticated and state of the art cooling system allows the gun to operate in CW mode.

S.S. Kurennoy, *et al.*, NIM A **528**, 392 (2004).

A 700 MHz CW normal conducting gun was studied at JLAB.

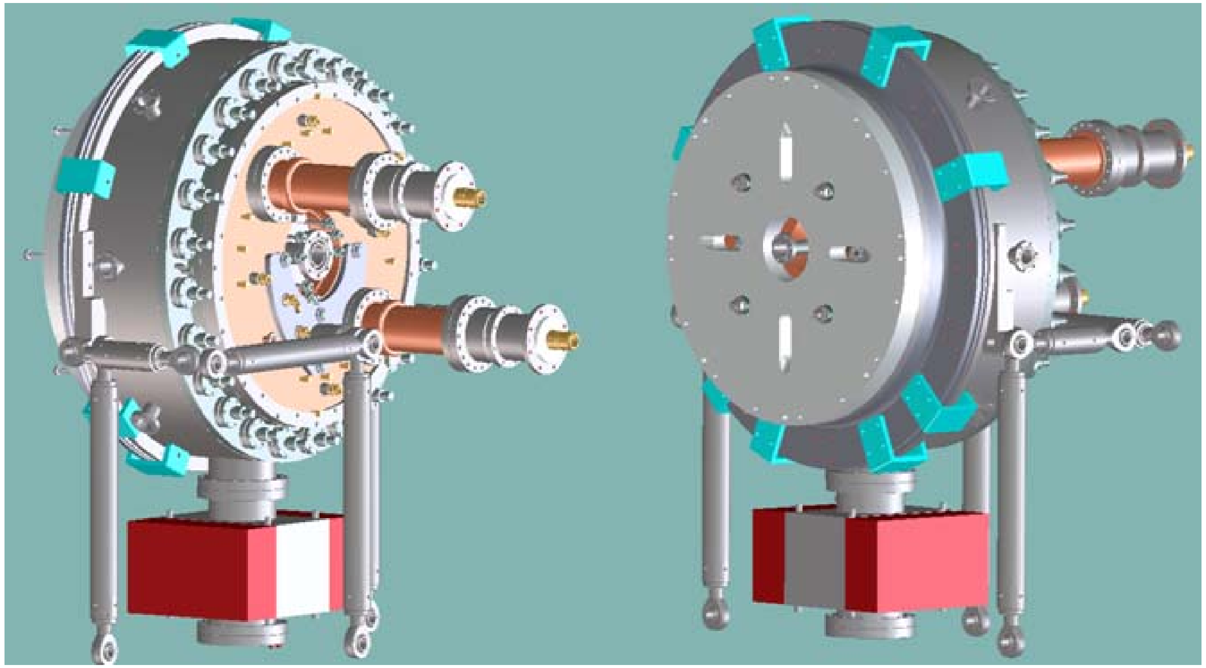
R. A. Rimmer, PAC05, pag. 3049.

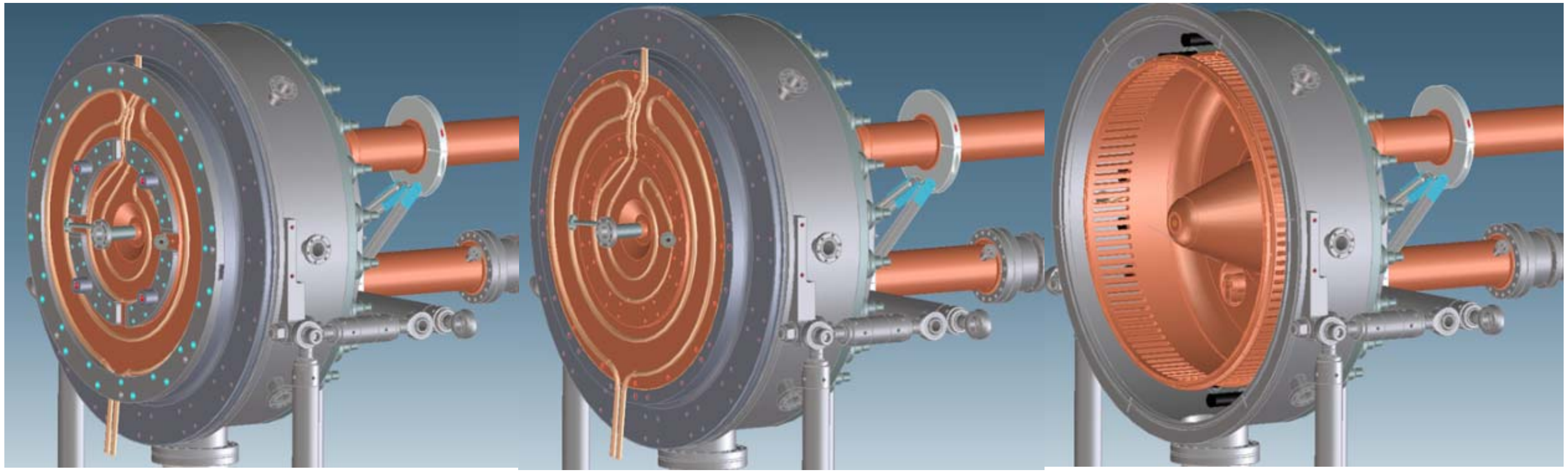
A 144 MHz CW normal conducting gun was studied at BNL.

X. Chang, *et al.*, PAC07, pag. 2547.

Cavity Engineering Design Completed

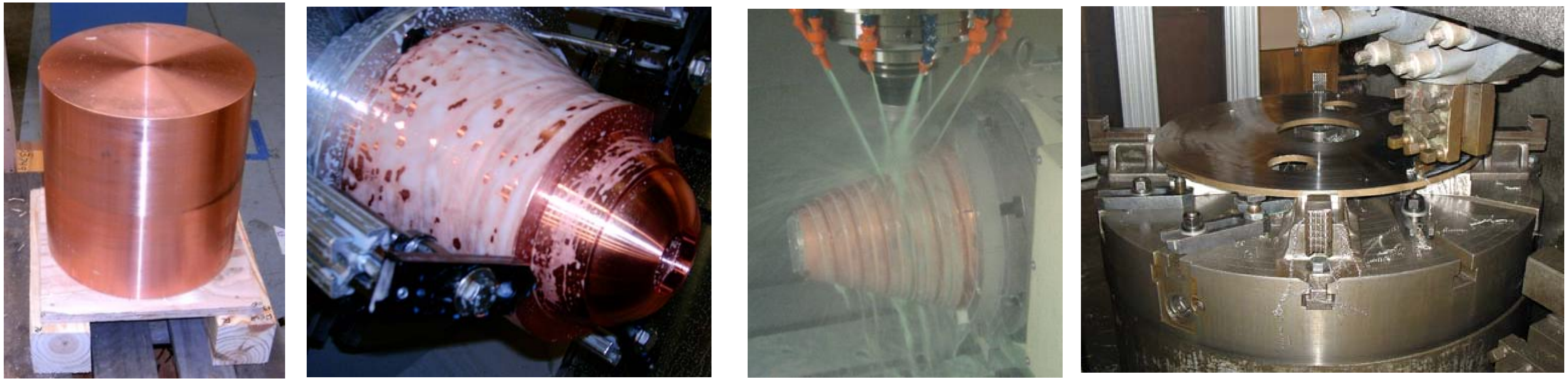
- **The cavity design finalized**

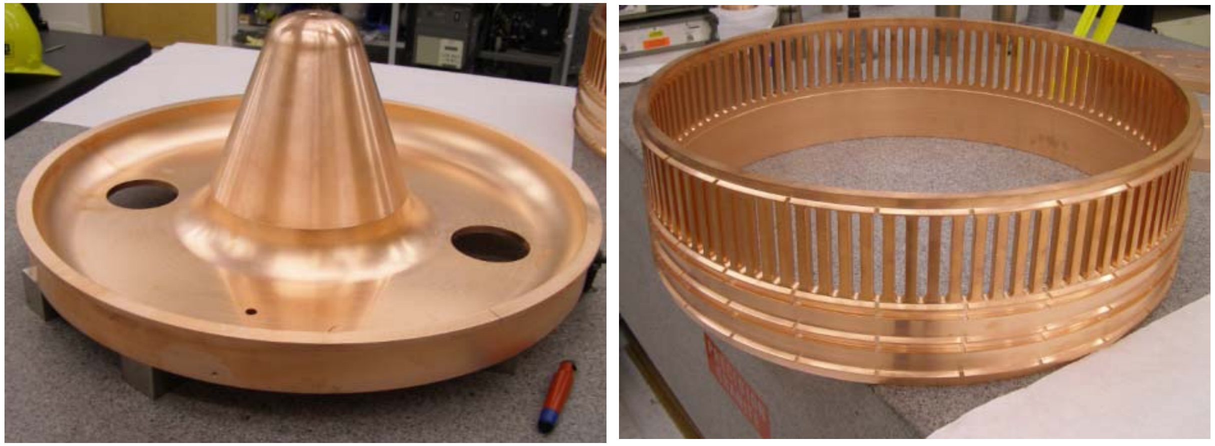




And We Are Actually Constructing It!

- **Most of the cavity is being fabricated at the LBNL mechanical shop**

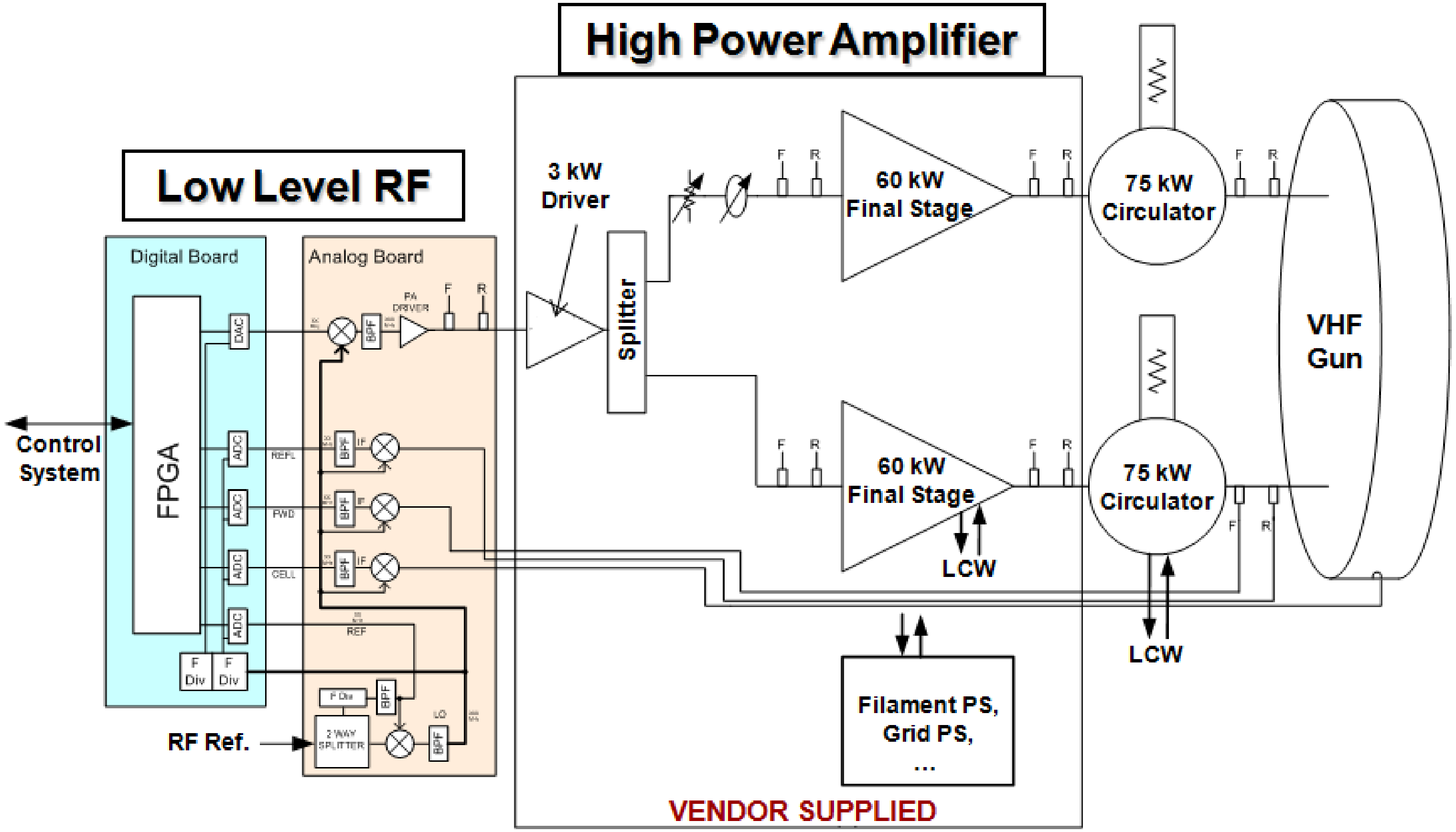




- **Fabrication completion in early spring 2010.**
  - **First cold RF test succesfully performed.**

The RF Power Source

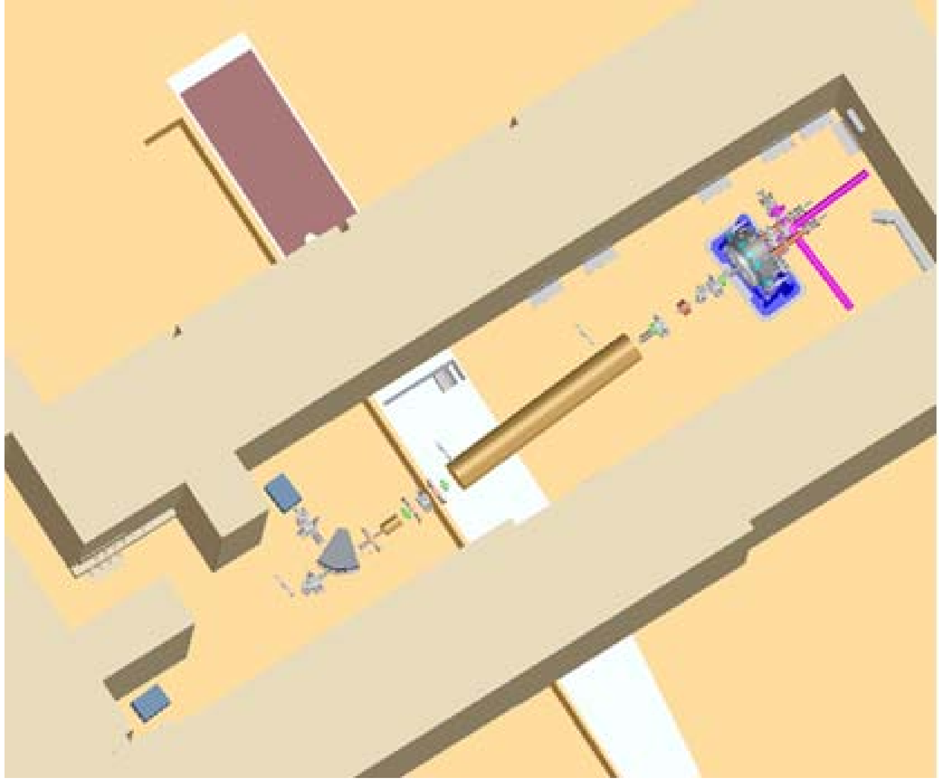
- **The 120 kW CW RF amplifier required to operate the VHF gun is being developed and manufactured by ETM Electromatic.**

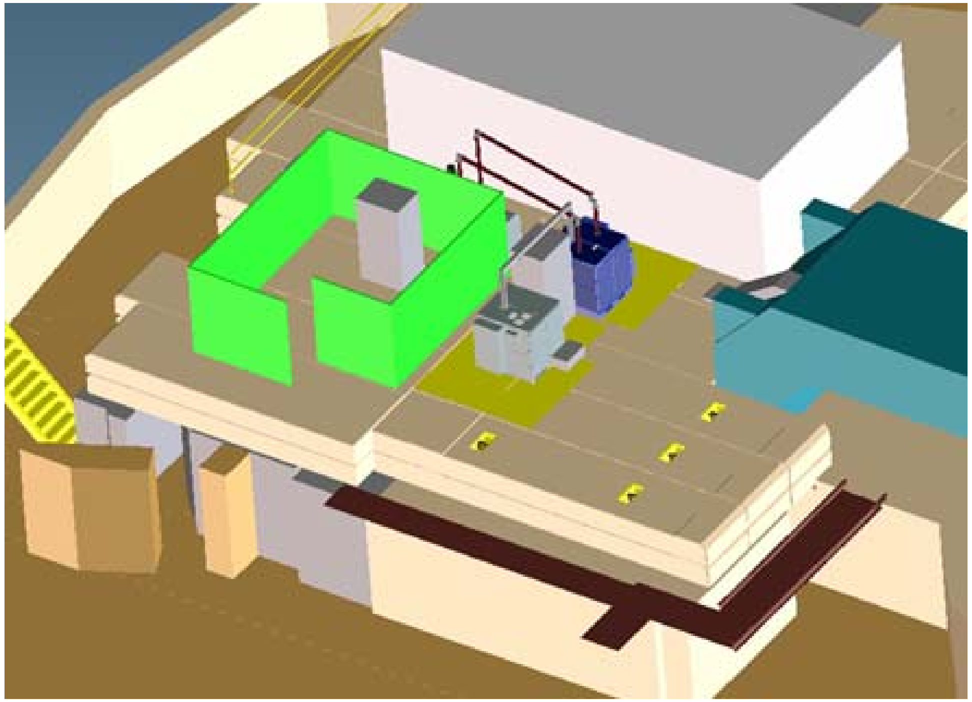


- **Expected delivery at LBNL in March 2010**

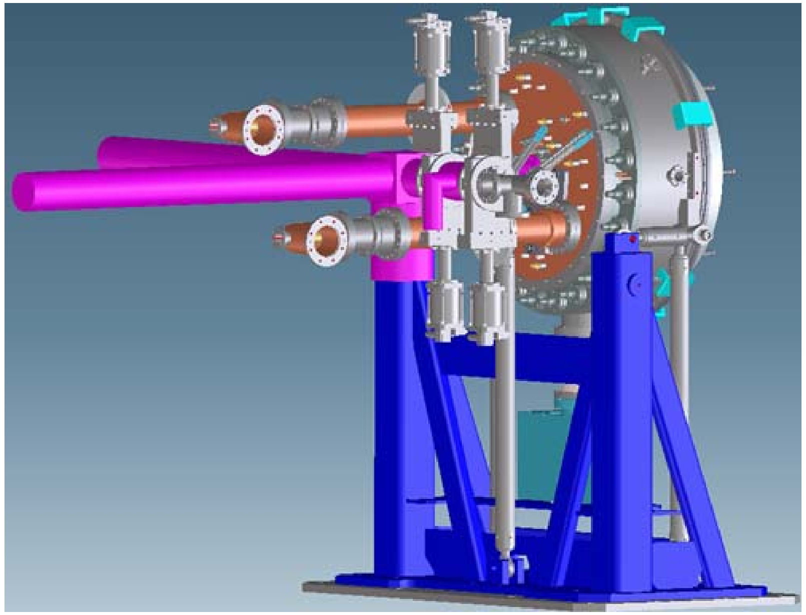
The VHF Gun Test Facility

All the photo-injector system will be accommodated in the existing ALS Beam Test Facility (BTF) for full characterization.
The BTF footprint is large enough to accommodate also the structures to accelerate the beam to few tens of MeV.





Phase I Test Plan



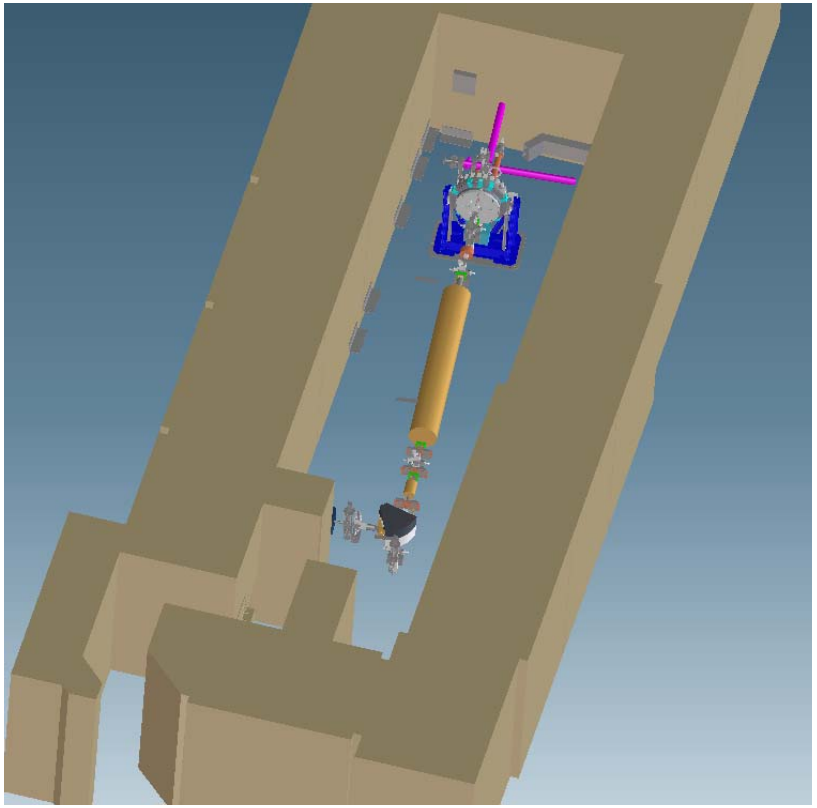
In phase I, only the gun, the vacuum load lock system and a low energy beam diagnostics installed in the BTF

Fully funded (to be completed by 2010)

- **Perform cold and full power RF tests of the VHF cavity**
- **Demonstrate the system vacuum performance**
- **Install and characterize the first generation cathode.**
- **Characterize the electron beam at the gun energy (750 kV) at full repetition rate**

Phase II Test Plan

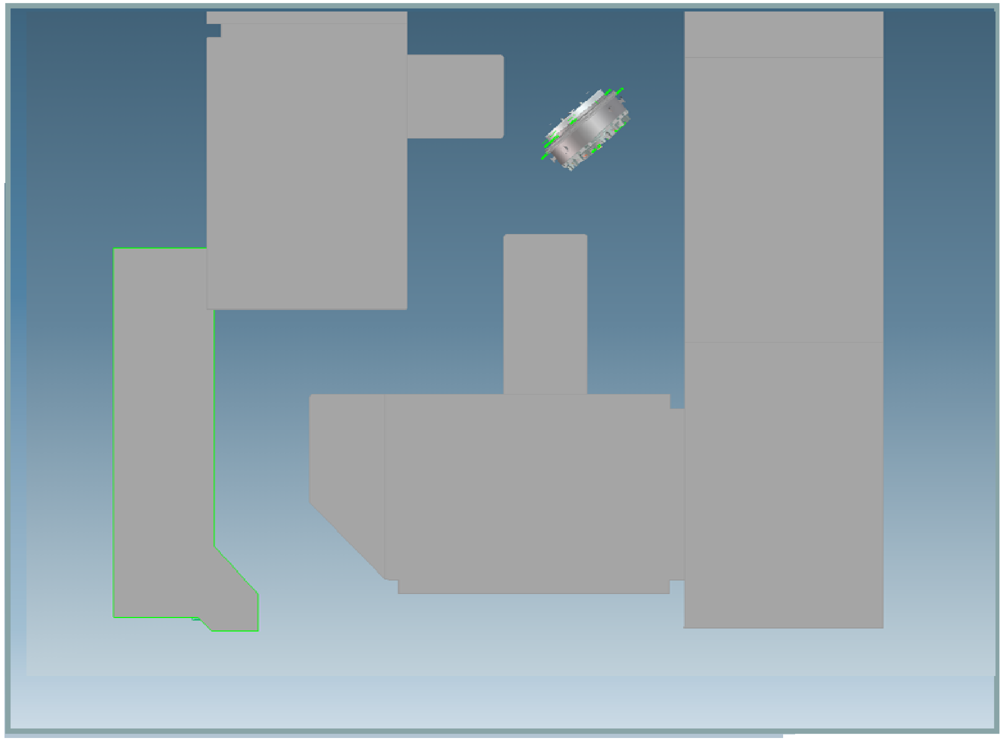
Requires funding continuation



- **Develop and install accelerating section for few tens of MeV energy**
- **Develop and install high energy diagnostic beamline**
- **Perform full characterization of the beam parameters at high energy (probably at low repetition rate)**

Fundamental Question

Does the cavity go through the door?



Yes, it does!!!

The LBNL
VHF Injector Team

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**Contributions: J. Byrd, T. M. Huang,
D. Li, S. Lidia, J. McKenzie, S. Virostek, W. Waldron, ...**

The LBNL VHF Gun
References

J. Staples, F. Sannibale, S. Virostek, "VHF-band Photoinjector", CBP Tech Note 366, October 2006

S. Lidia, et. al., ”Development of a High Brightness VHF Electron Source at LBNL”, Proceedings of the 41st Advanced ICFA Beam Dynamics Workshop on Energy Recovery Linacs, Daresbury Laboratory, UK, May 21-25, 2007.

J. W. Staples, et al., "Design of a VHF-band RF Photoinjector with MegaHertz Beam Repetition Rate". 2007 Particle Accelerator Conference, Albuquerque, New Mexico, June 2007.

K. Baptiste, et al., "The LBNLnormal-Conducting RF gun for free electron laser and energy recovery linac applications", NIM A **599**, 9 (2009).

K. Baptiste, et al., Status of the LBNL normal-conducting CW VHF photo-injector, Proceedings of the 2009 Particle Accelerator Conference, Vancouver, Canada, May 2009.

K. Baptiste, et al., Status and plans for the LBNL normal-conducting CW VHF photo-injector, Proceedings of the 2009 Free Electron Laser Conference, Liverpool, UK, August 2009.

Back-up Viewgraphs

The LBNL FEL TEam

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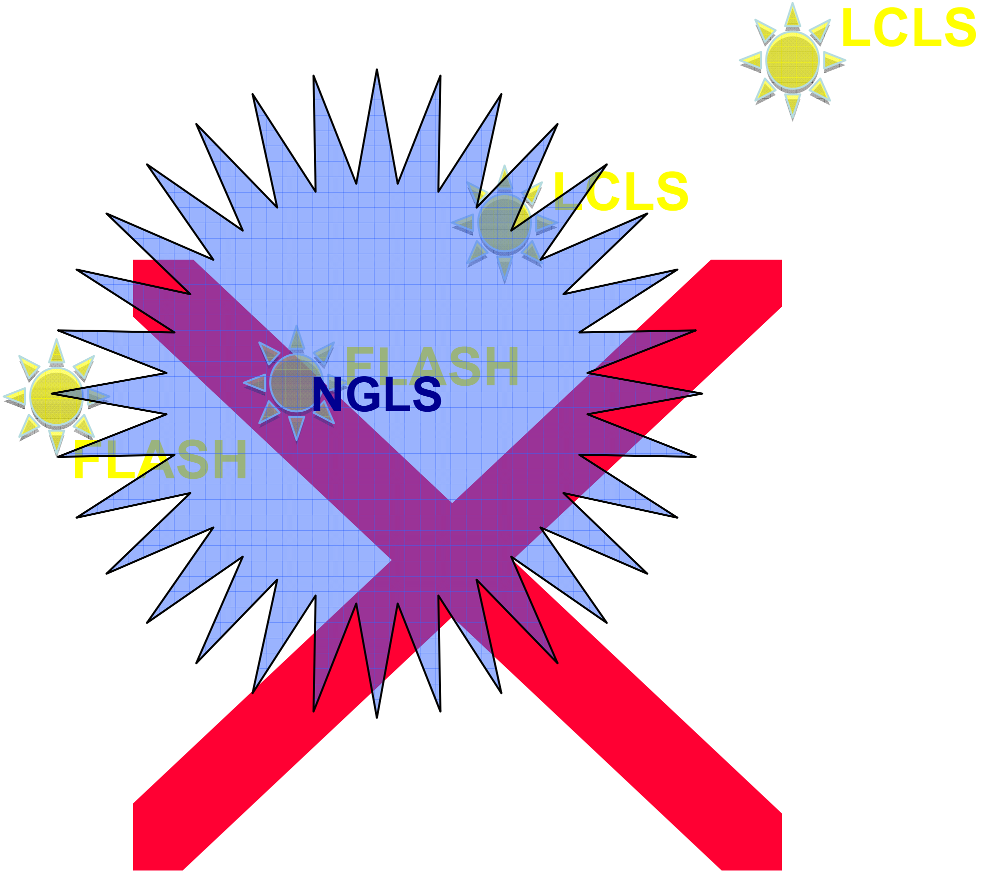
Max Zolotorev

Peak Brightness



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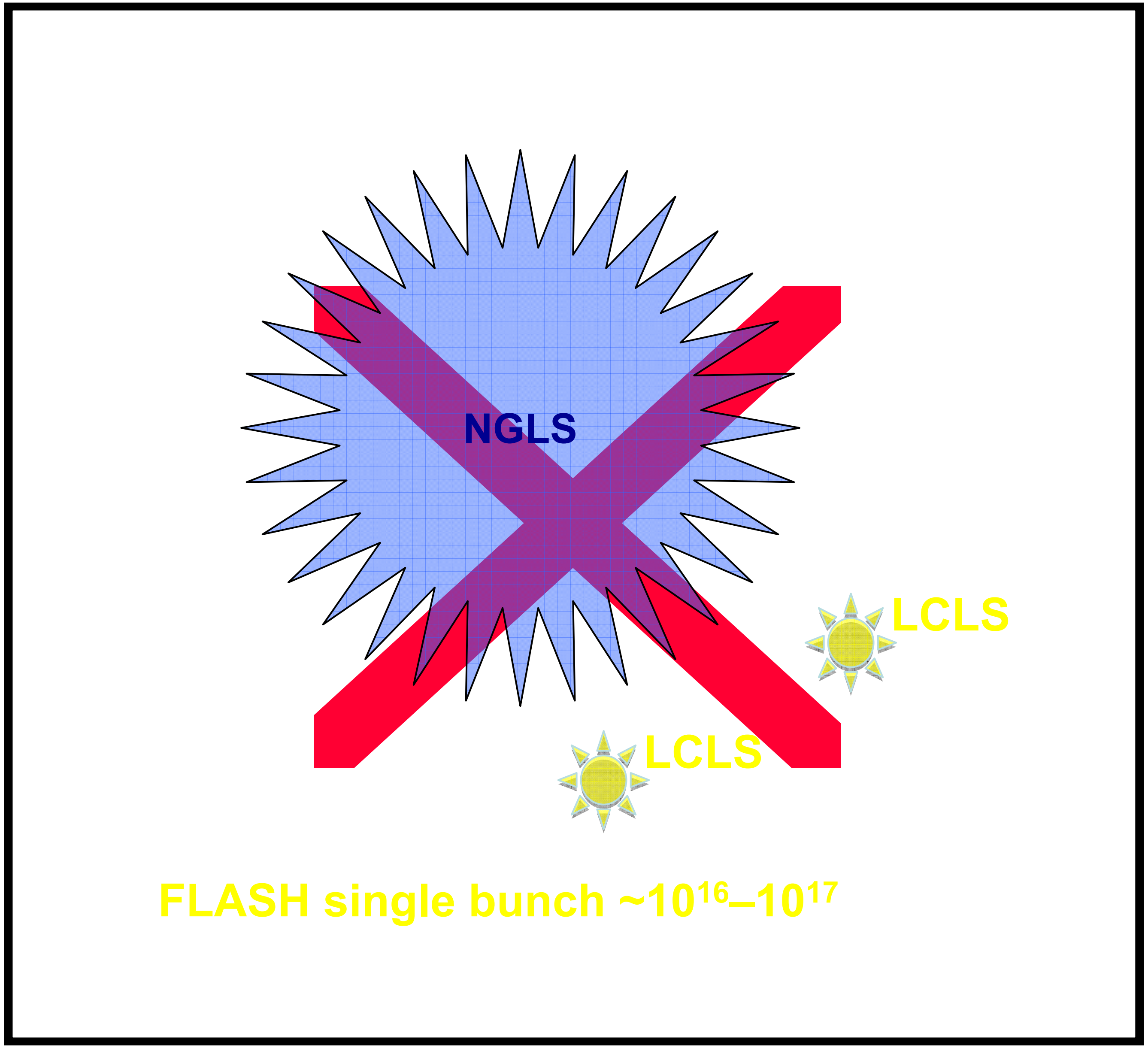
BNL-81895-2008
LBNL-1090E-2009
SLAC-R-917

Average Brightness



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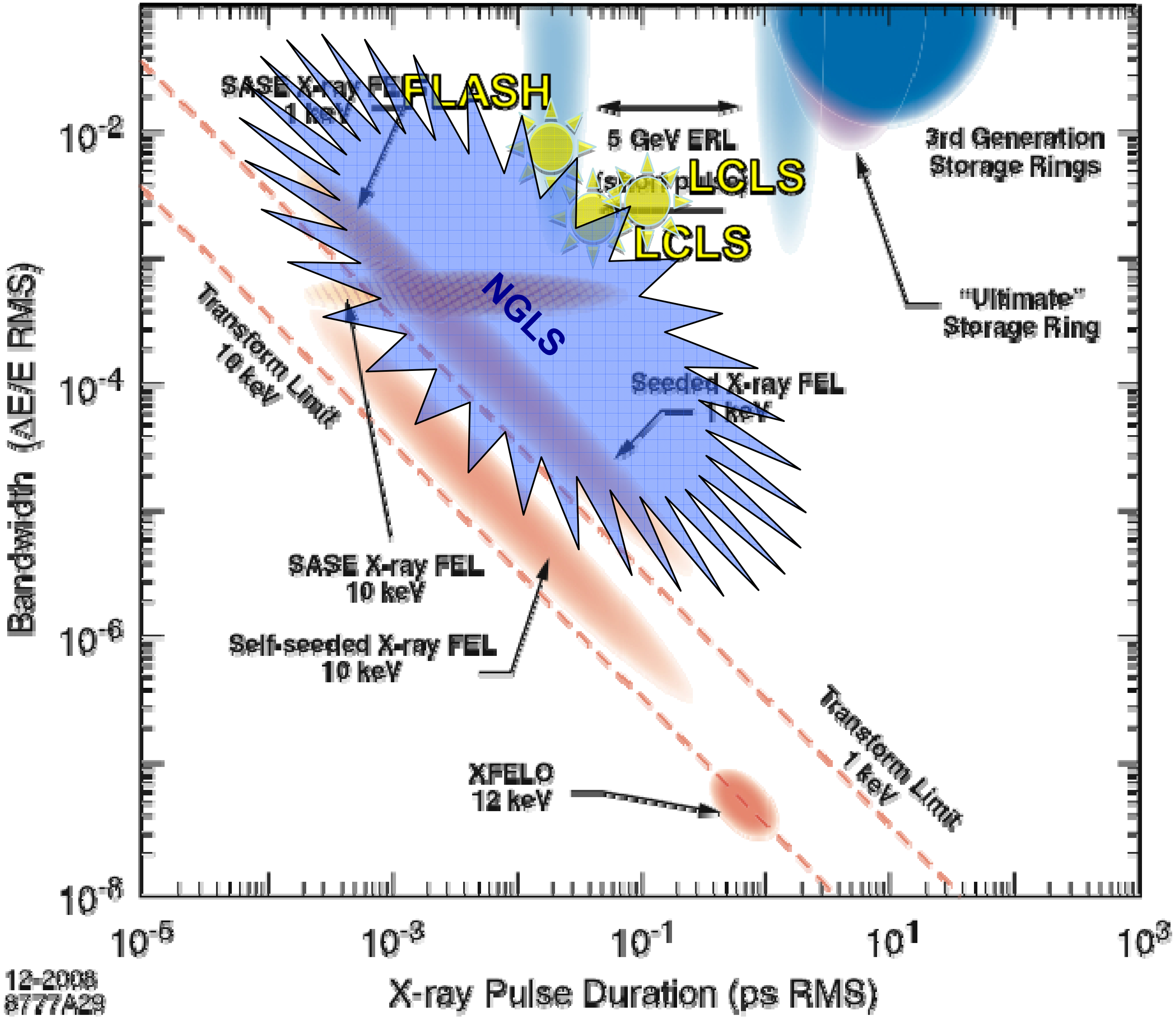
SLAC-R-917

Bandwidth / Coherence



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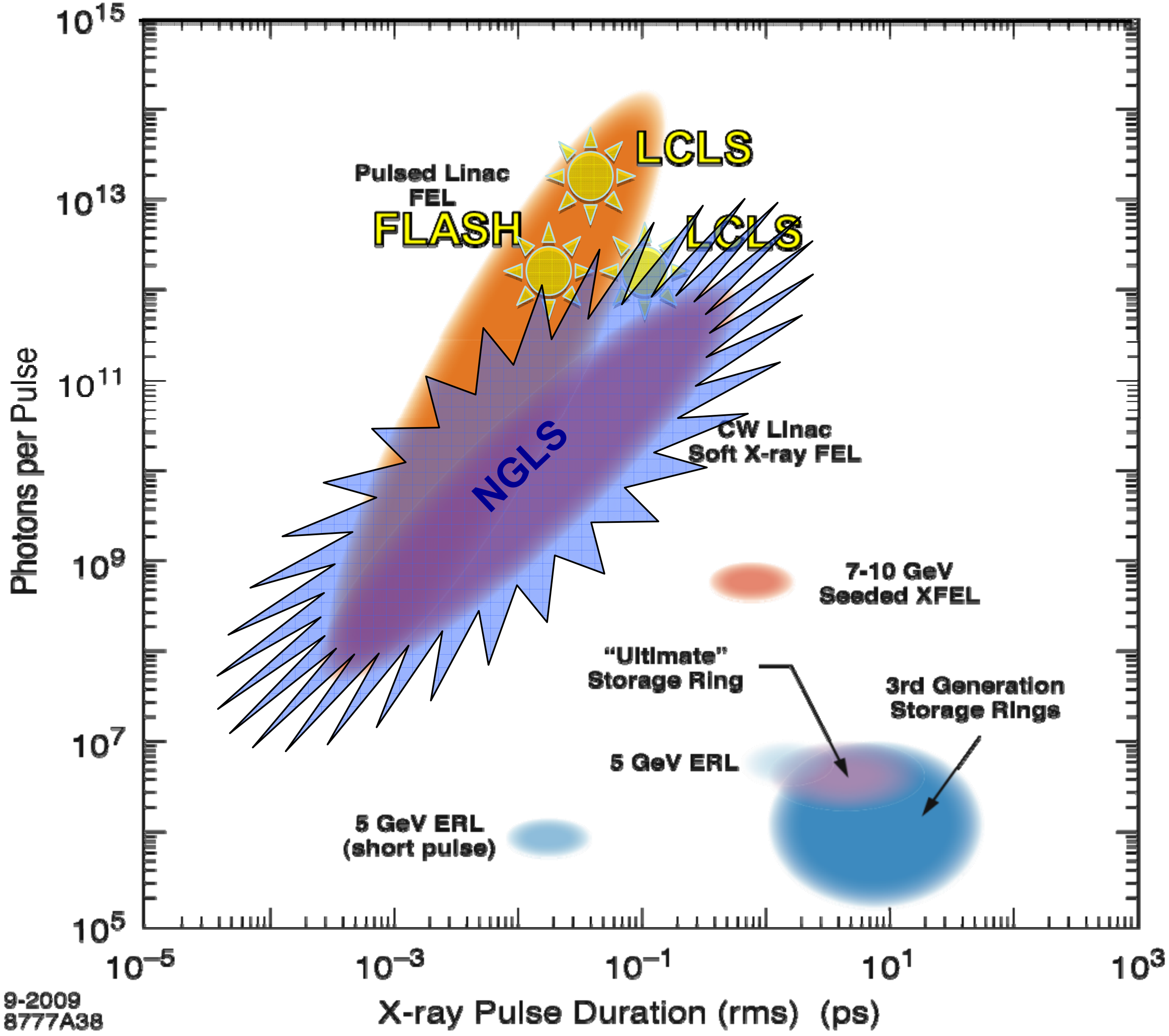
Photons per Pulse



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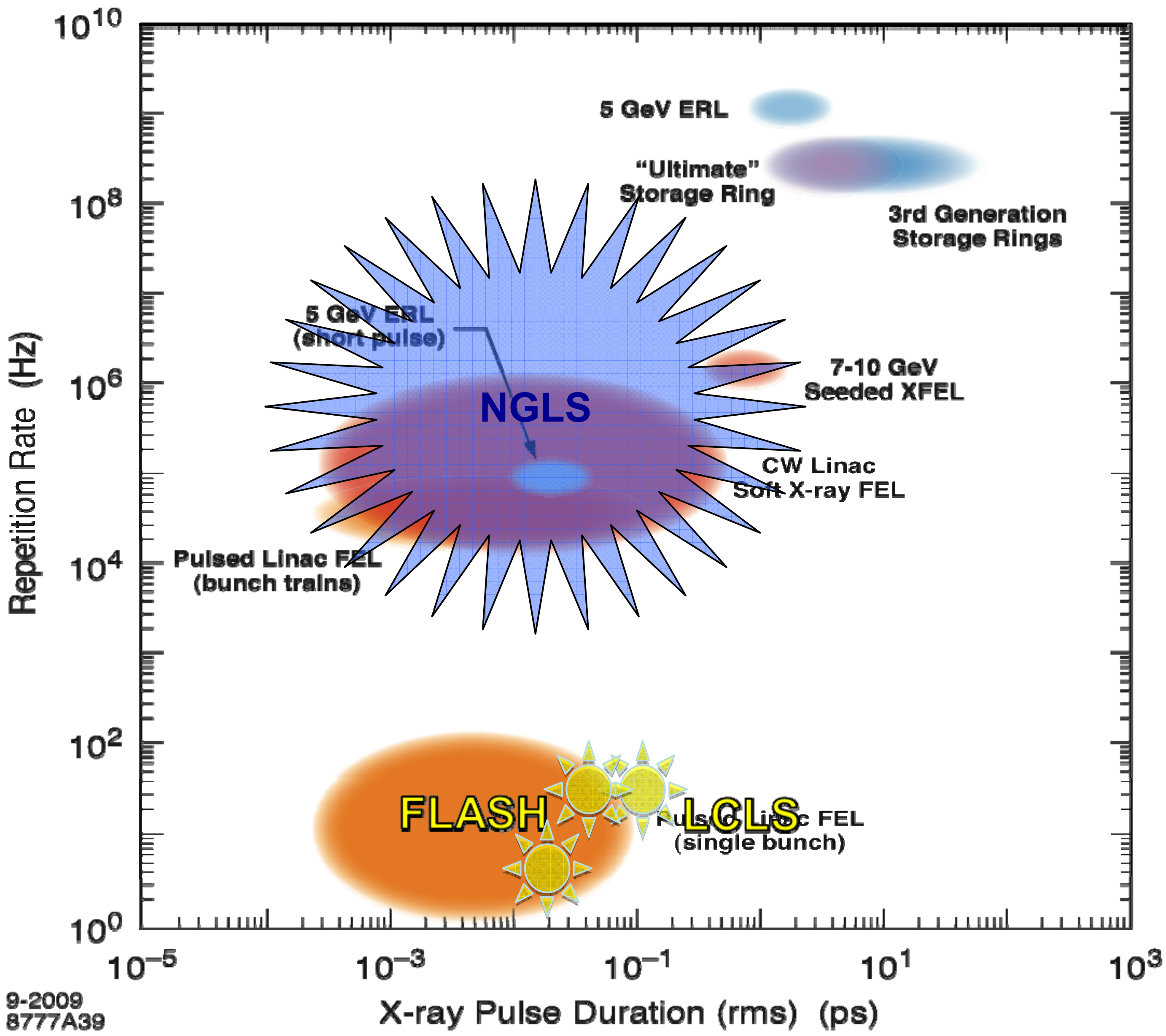
Repetition Rate



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