APEX: A Normal-Conducting Low-Frequency RF Photo-Injector for the Next Generation Light Source

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OUTLINE

• **Accelerator based light sources:**
The story of one of the most successful tools for science.

• **Free Electron Lasers (FEL), the revolution continues…**

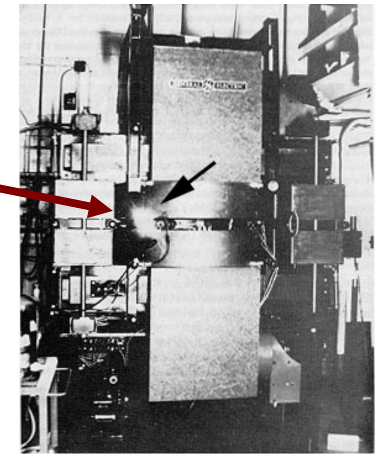
• **NGLS: The Next Generation Light Source.**
The LBNL FEL proposal for the next performance leap.

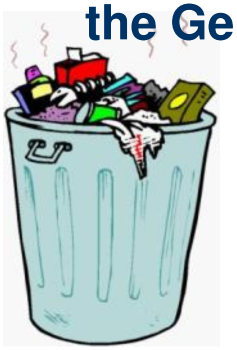
• **APEX: The Advanced Photo-injector EXperiment.**
A necessary step towards the NGLS.

THE EARLY TIMES

- Electron accelerators were initially developed to probe (subnuclear) particles in fundamental particle physics.

• The first time synchrotron radiation (SR) was observed in an accelerator was in 1947 from a 70 MeV electron beam at the General Electric Synchrotron in New York State.





• Initially, synchrotron radiation was just considered as a waste product draining energy and limiting the performance achievable by lepton colliders.

- However, it was soon realized that synchrotron radiation represented the brightest source of light from infrared to x-rays, and that it could be very useful in a large variety of scientific applications.

• Light sources were born and in ~ 60 years would undergo a dramatic evolution:

– *1st generation*: "parasitic" SR sources from dipoles in colliders.

– *2nd generation*: dedicated storage rings with light ports in dipoles

– *3rd generation*: dedicated storage rings with insertion devices

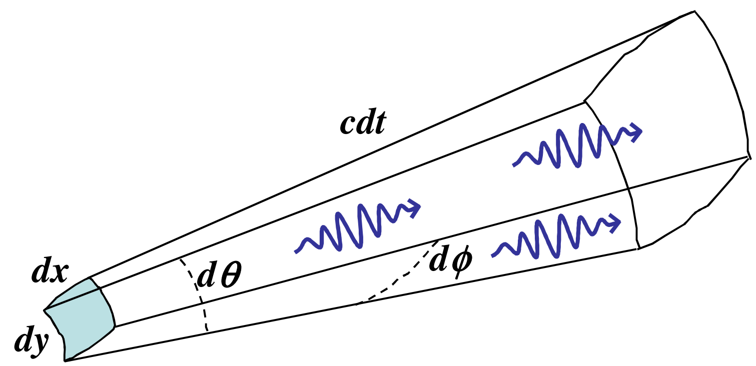
– *4th generation*: free electron lasers, energy recovery linacs, …

BRIGHTNESS: THE ULTIMATE QUALITY FACTOR FOR A LIGHT SOURCE

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

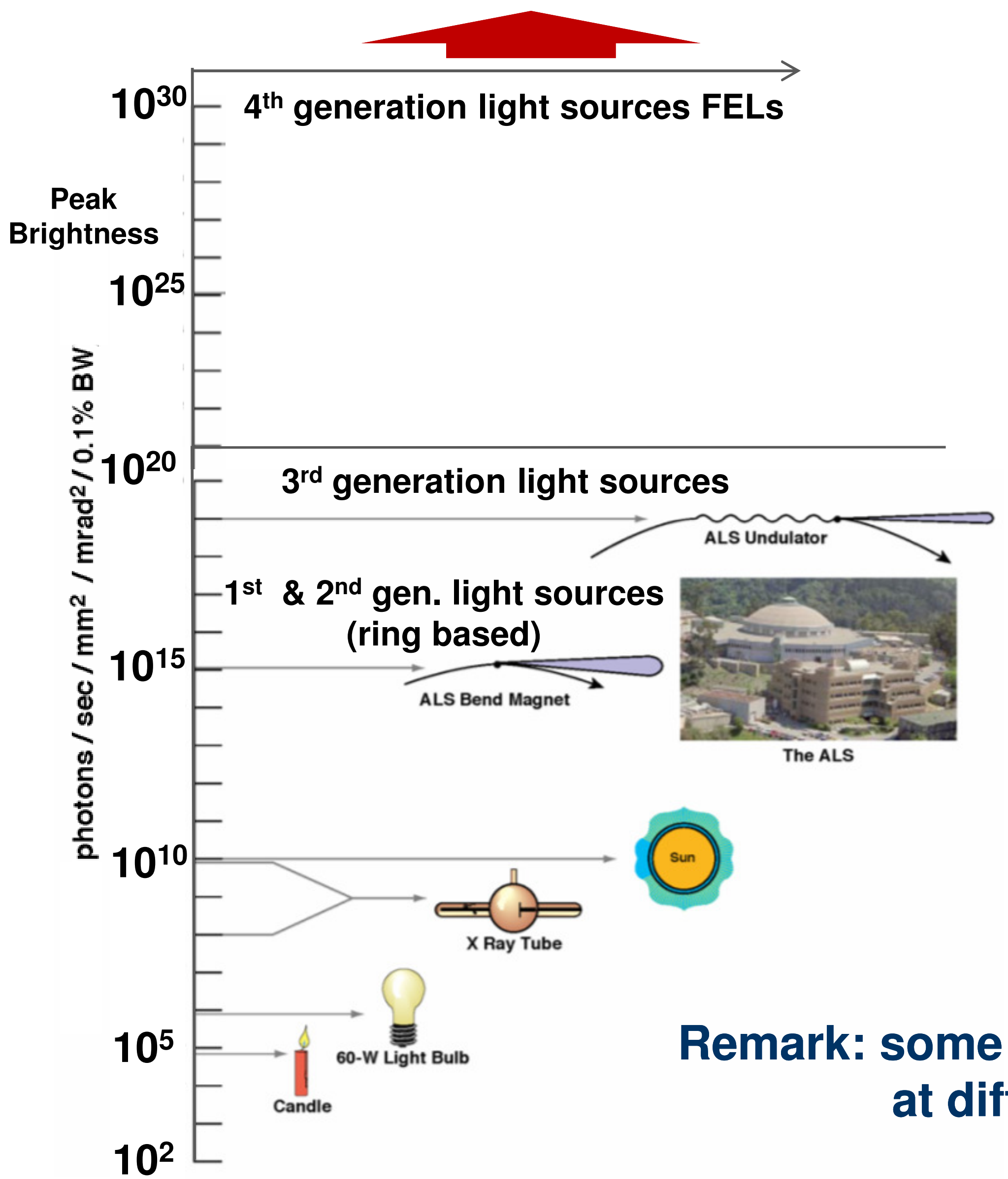
- Brightness is defined as *the density of photons in the 6-D phase space*.

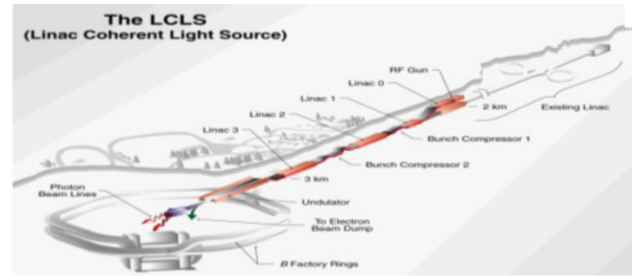
$$\text{Brightness unit} = \frac{\#\text{ of photons in } 0.1\%\ \Delta\lambda/\lambda}{\text{s mrad}^2\ \text{mm}^2}$$

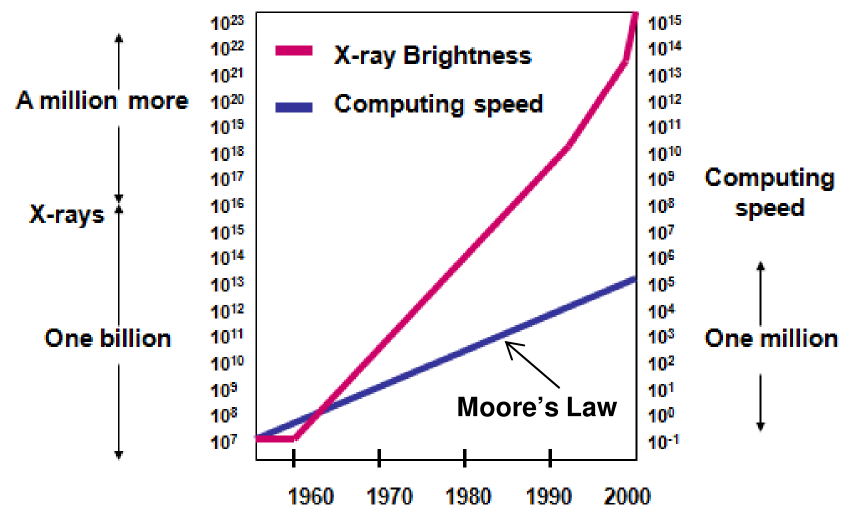


- **High brightness is strongly desirable:**
faster experiments, higher coherence, improved spatial, time and energy resolutions in experiments, …

LIGHT SOURCE BRIGHTNESS



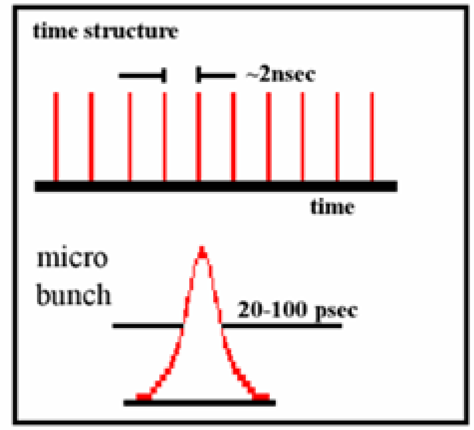




Remark: some of the sources are compared at different wavelengths!

3rd VS. 4th GENERATION LIGHT SOURCES

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



- High brightness and flux
- Highly polarized
- Short pulses (>~ ps) —4th Generation→ • Much shorter pulses (~fs)

3rd generation light sources offers many characteristics of visible lasers but in the x-ray regime!

- Large energy tunability —4th Generation→ • Large energy tunability
- Partial transverse coherence —4th Generation→ • Full transverse coherence and full longitudinal in some schemes
- High stability —4th Generation→ • Slightly reduced stability

FELs offers most (all) the characteristics of visible lasers in the x-ray frequency range!

NEW SCIENCE OPPORTUNITIES!

- Medicine
- Biology
- Chemistry
- Material Science
- Environmental Science
- Atomic Physics
- ...

FEL BASICS: THE NECESSARY COMPONENTS

- The Free Electron Laser Inventor (John Madey, 1970) or some of his representatives,

+

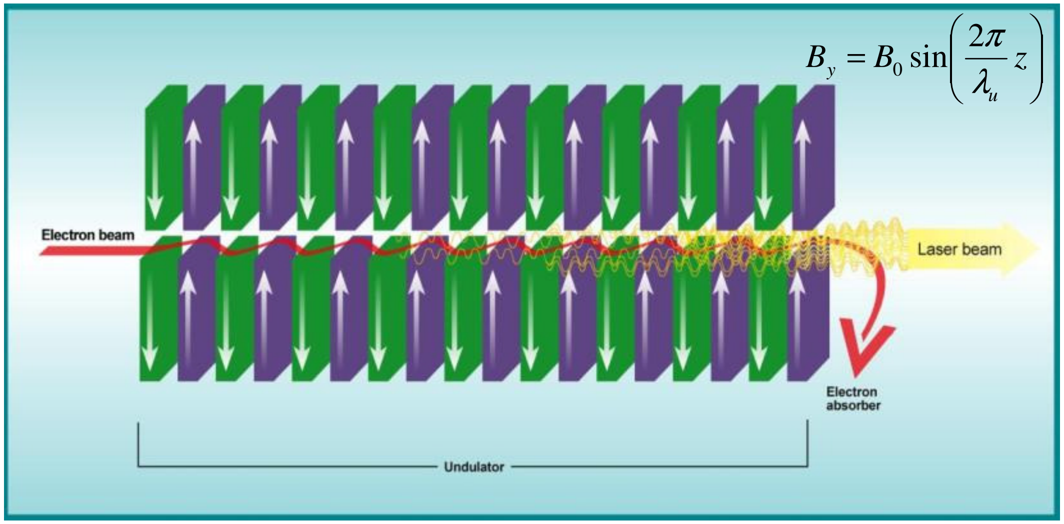
- An accelerator (linear for x-rays) capable of generating at the proper energy a “high quality” electron beam,

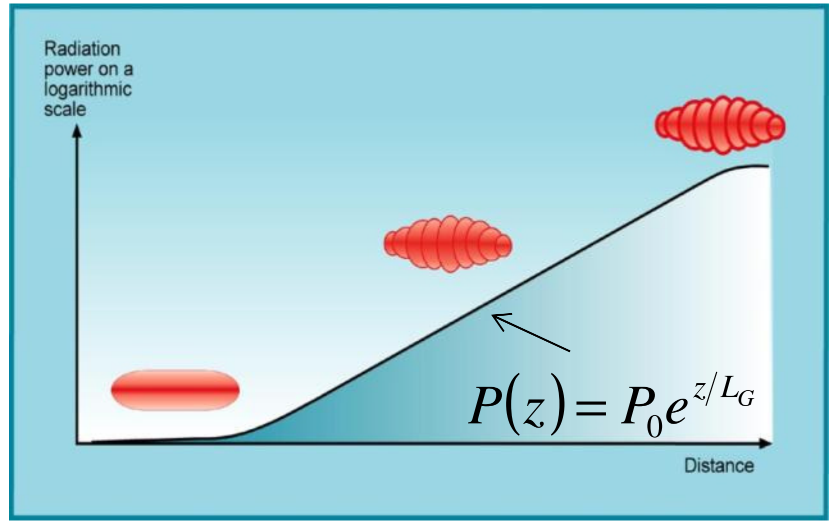
+

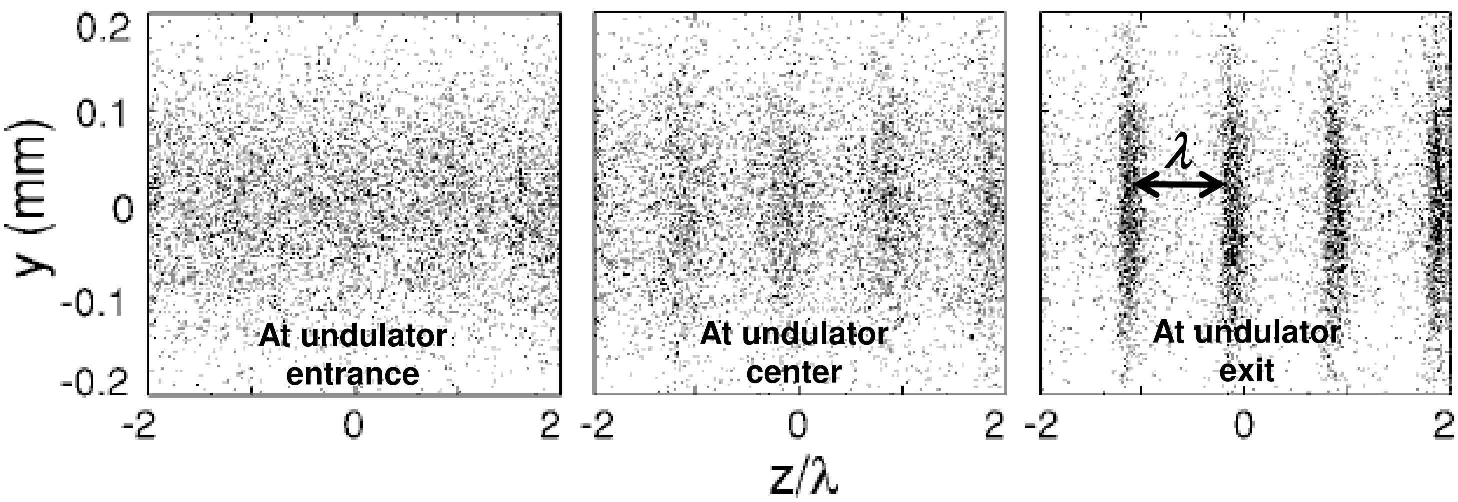
- At least one undulator.

- The electron beam is sent inside the undulator and …

FELS EXPLOIT COHERENCE





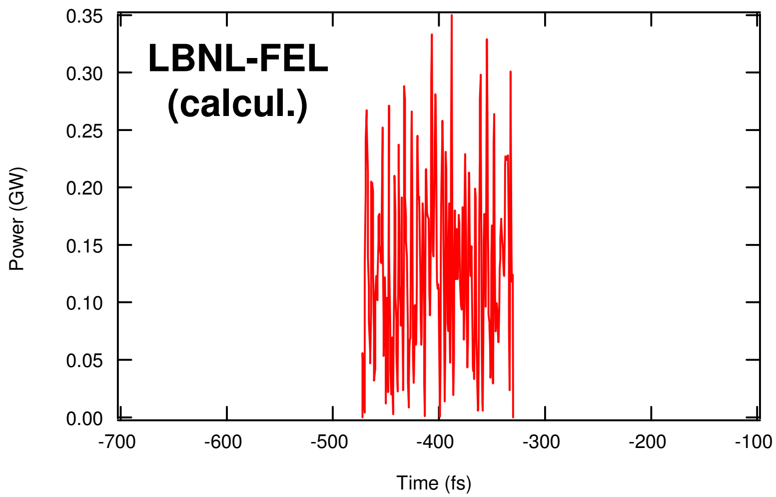


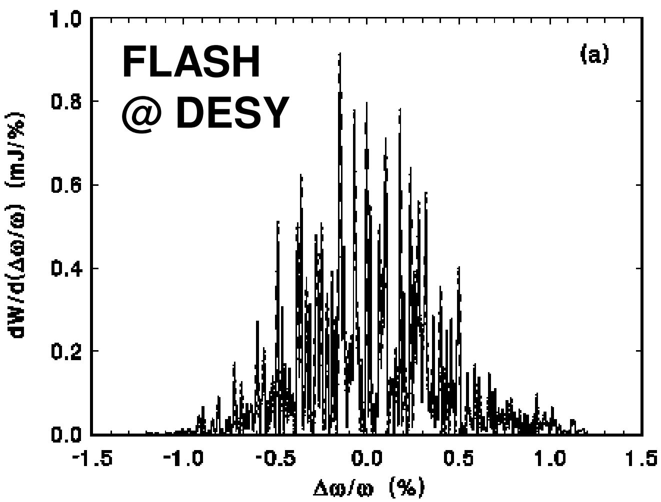
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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

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:





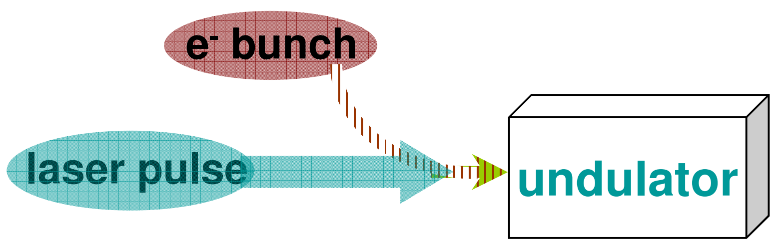
- SASE pulses are transversely coherent but longitudinally incoherent.
- The stochastic time and spectral nature of SASE can represent an issue to some experiments…

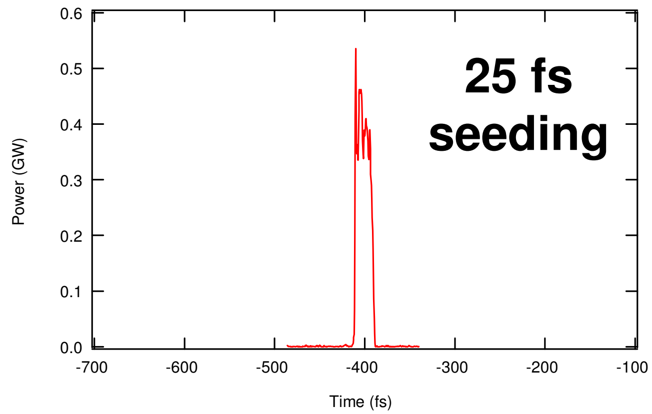
SEEDED FEL SCHEMES

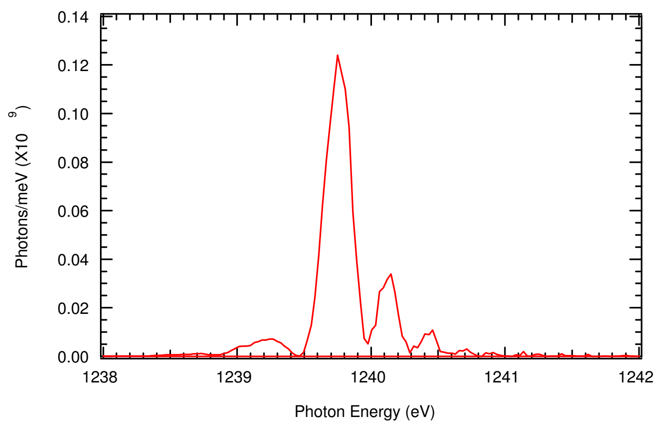
If the role of spontaneous undulator radiation used in the SASE scheme is played by **a laser pulse** with well defined pulse length, amplitude and wavelength:

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

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 can approach the *Fourier Transform Limit*

SEEDED FEL SCHEMES

The seeding previously described, requires a laser with wavelength λ. For short wavelengths this can represent a difficult requirement.

Remarkable developments in laser High Harmonic Generation (HHG) are making UV/soft X-ray seeding more realistic.

Several alternative schemes have been developed to create and exploit higher harmonic contents in the electron beam microbunching to radiate at higher photon energies.

Notable examples include:

- **Self-seeding**
- **High Gain Harmonic Generation (HGHG)**
- **Echo Enabled Harmonic Generation (EEHG)**

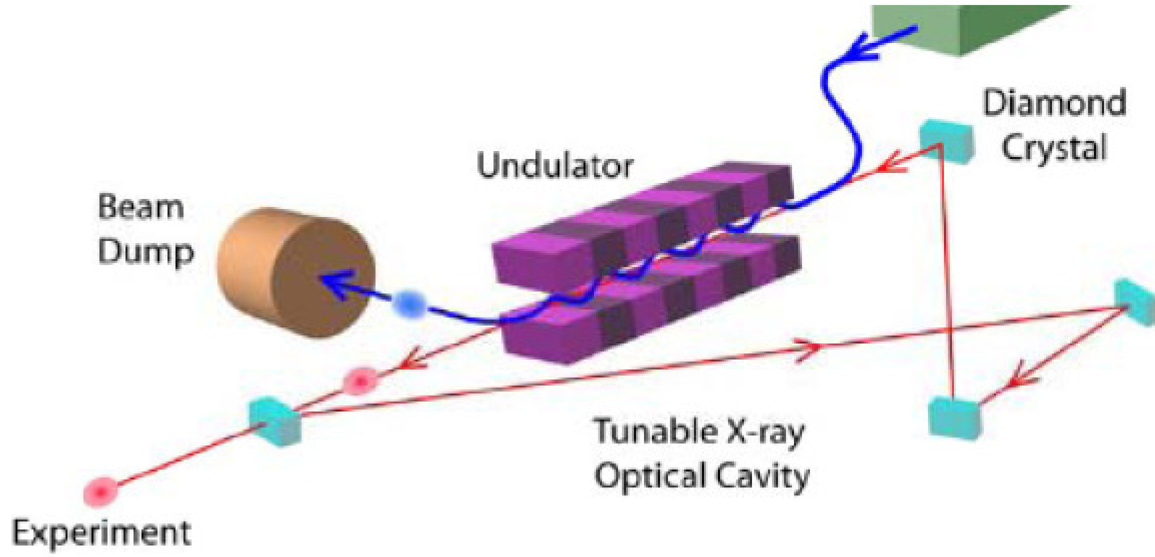
SHORT WAVELENGTH FEL OSCILLATORS

• 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 hard x-ray region.



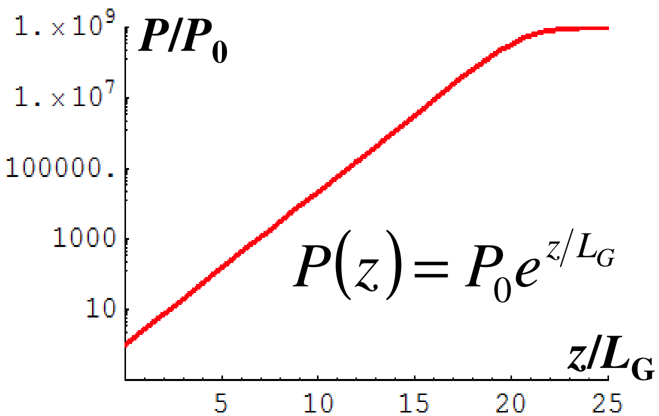
Argonne hard X-ray FEL Oscillator

ELECTRON BEAM QUALITY REQUIREMENTS

The 1D FEL theory* defines the FEL parameter ρ :

$$\rho = \frac{1}{\gamma}\left[\frac{1}{64\pi^2}\frac{I_e}{I_A}\frac{1}{\varepsilon_x \beta_x}\lambda_u^2 K^2 JJ^2\right]^{1/3}$$

emittance = beam phase space area



$$L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho} \quad gain\ \ length \qquad L_S \approx 20 L_G$$

$$P_{saturation} \approx \rho \langle I_{beam} \rangle E_{[eV]}$$

Energy spread condition matching: $\frac{\sigma_E}{E} <\sim \rho$

Large ρ are desired ➜ **large** $\frac{I_e}{\varepsilon_x} \propto electron\ brightness$

***3D effects reduce the FEL performance predicted by the 1D model.**

ELECTRON BEAM QUALITY REQUIREMENTS

Photon-electron emittance matching: $$\varepsilon_w = \frac{\varepsilon_{nw}}{\gamma} <\sim \frac{\lambda}{4\pi} \qquad w = x, y$$

The normalized emittance ε_{nw} is ultimately set by the injector performance.
For a given wavelength the electron beam energy is set by the above relation.

X-ray FELs with their short wavelengths and with the presently available injectors ($\varepsilon_n \sim 1\ \mu\text{m}$) require GeV class accelerators.

For X-ray FELs $\rho \sim 10^{-3}$

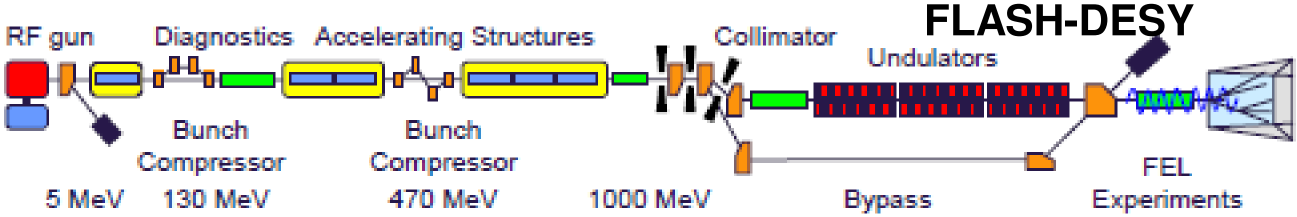
At the same time, the proper undulator technology must satisfy the resonance condition

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

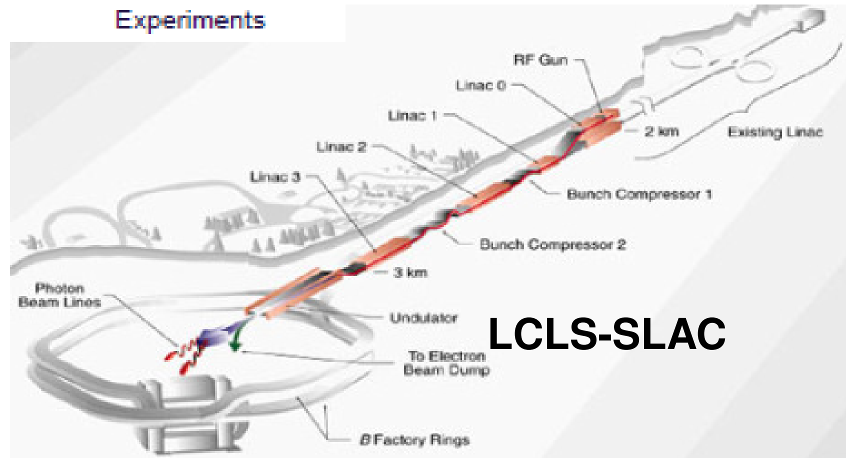
FROM THEORY TO REAL X-RAY FELS!

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

FLASH-DESY

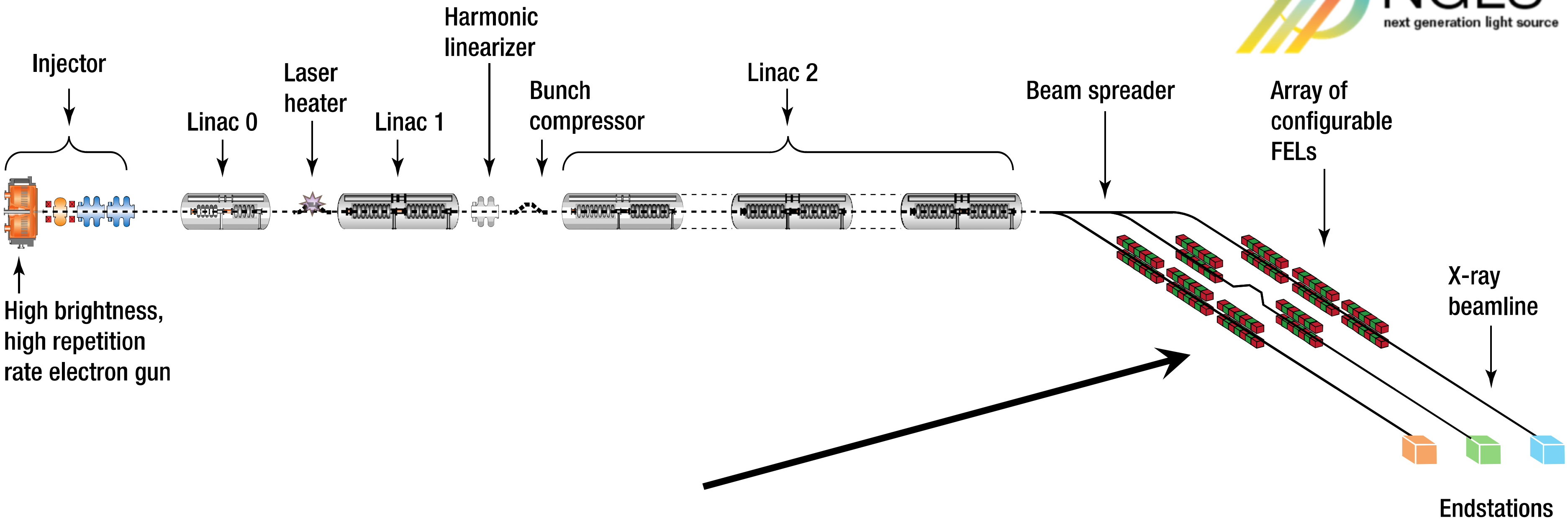


LCLS-SLAC



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

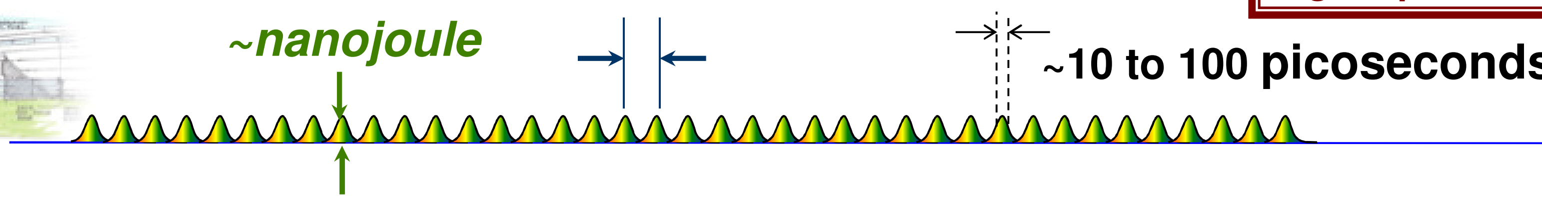
THE NGLS: THE BERKELEY CONCEPT FOR A X-RAY FEL



- **High repetition rate array of FELs (mostly seeded, initially 3, ultimately 10)**
  - X-ray energy range ~0.25 – 1.0 keV on fundamental
  - Harmonics (third and fifth) to extend photon energy up to 5 keV.
  - Pulse length ~0.25 – 250 fs
  - Bandwidth 5×10^{-5} – ~1% (FWHM at ~1 nm)
  - Peak power ≤1 GW
  - Average power ≤100 W

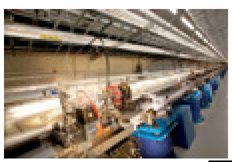
NGLS IN COMPARISON WITH EXISTING LIGHT SOURCES

Today's storage ring x-ray sources



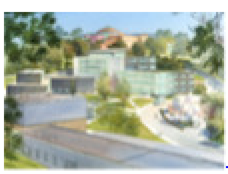
Weak pulses at high rep rate

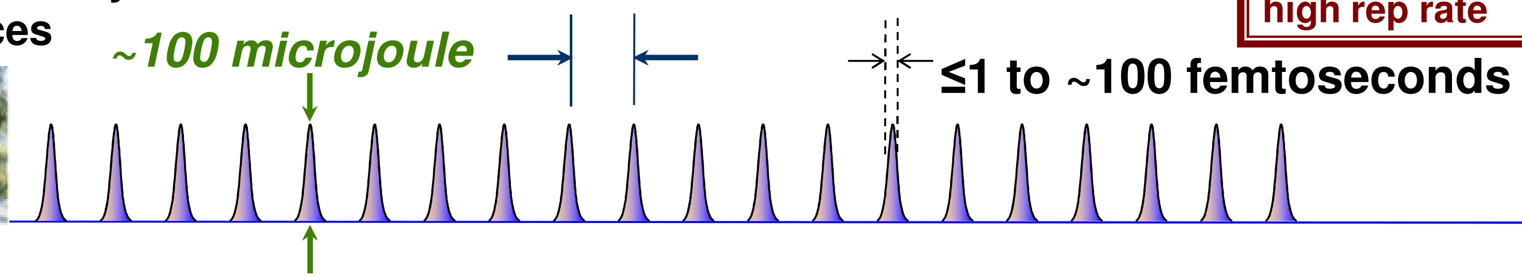
Today's x-ray laser sources



Intense pulses at low rep rate

Tomorrow's x-ray laser sources





Intense pulses at high rep rate

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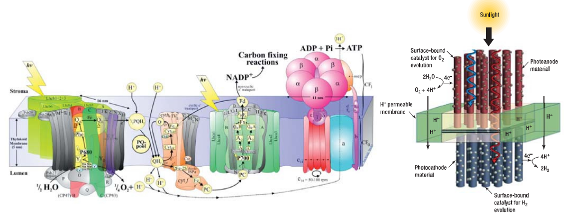
A SCIENCE DRIVEN FACILITY

We have worked with a broad community over four years to develop the scientific case for a Next Generation Light Source

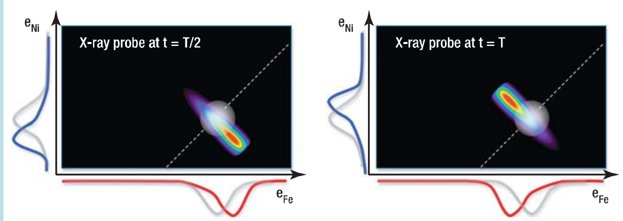
BROAD RANGE OF ENERGY SCIENCE UNIQUELY ENABLED BY NGLS

APEX: An Injector For The NGLS (F. Sannibale)

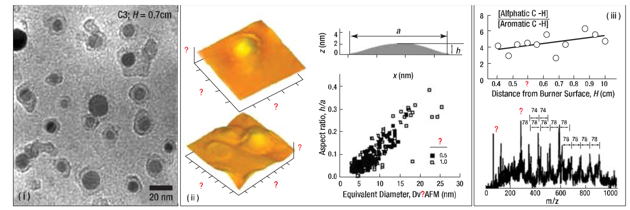
Natural and Artificial Photosynthesis



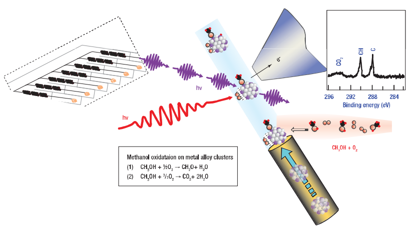
Fundamental Charge Dynamics



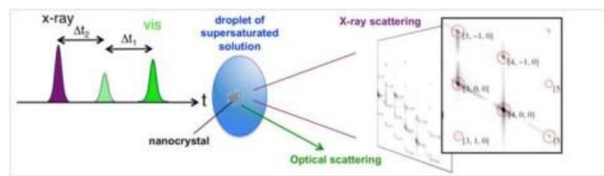
Advanced Combustion Science



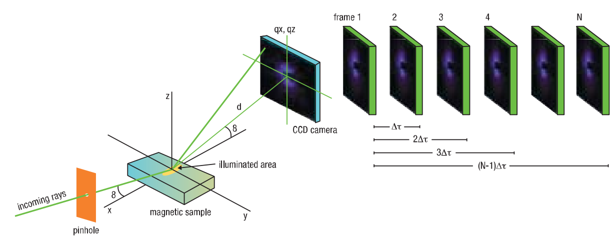
Catalysis



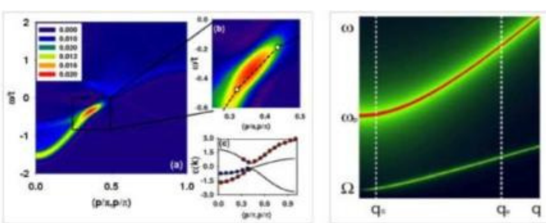
Nanoscale Materials Nucleation



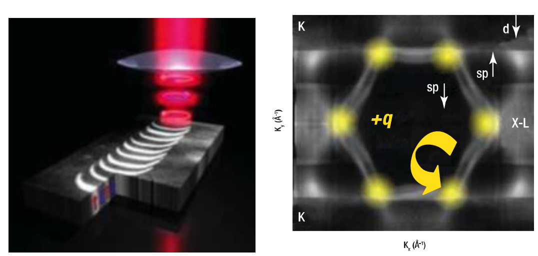
Dynamic Nanoscale Heterogeneity



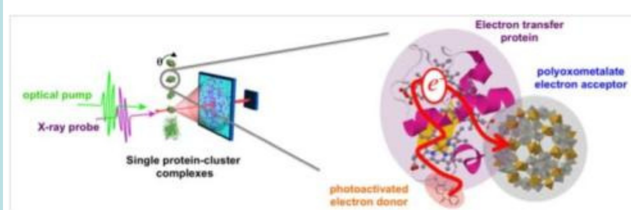
Quantum Materials

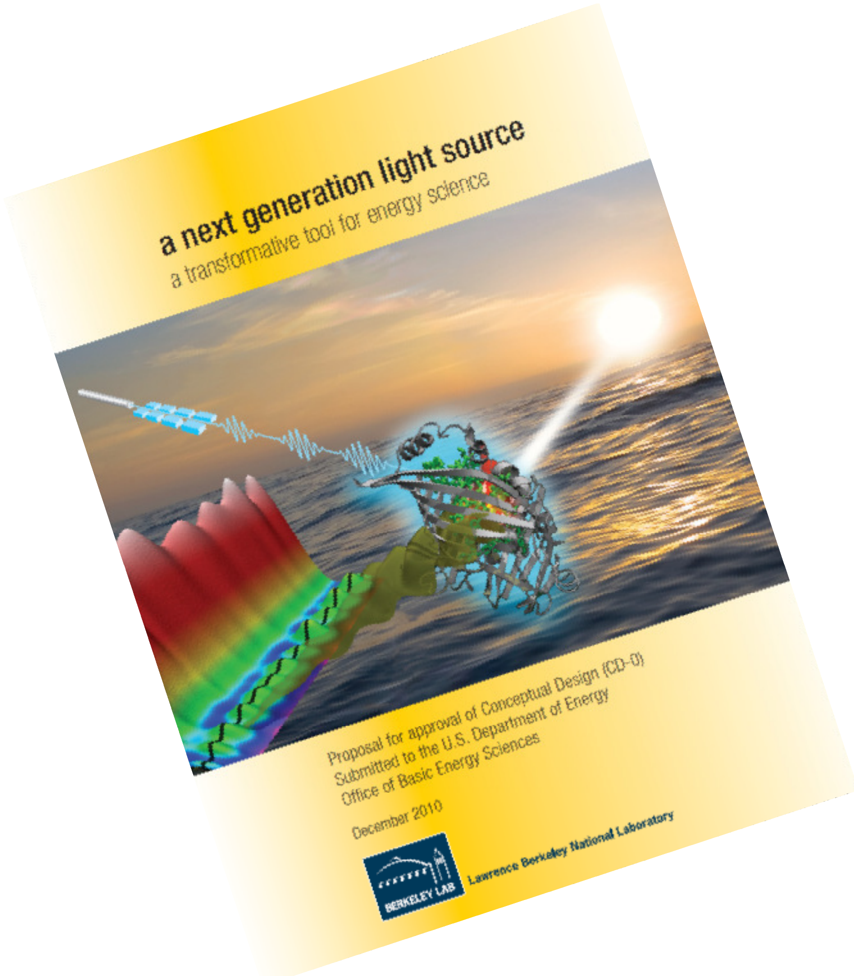


Nanoscale Spin and Magnetization



Bioimaging: Structure-to-Function





- Submitted December 2010
- More than 150 contributors
- Representing >40 national and international research institutions

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NGLS APPROVAL STATUS

- **LBNL submitted a CD-0 proposal in December 2010**
- **DOE approved "Mission Need" for the Next Generation Light Source**
- **Currently no DOE budget to pursue a Project**
- **LBNL is**
  - **Fully committed to NGLS**
  - **Performing Accelerator and Detector R&D**
  - **Performing feasibility studies which will inform a Conceptual Design**

The Deputy Secretary of Energy
Washington, DC 20585

April 5, 2011

MEMORANDUM FOR WILLIAM F. BRINKMAN
DIRECTOR
OFFICE OF SCIENCE

FROM: DANIEL B. PONEMAN

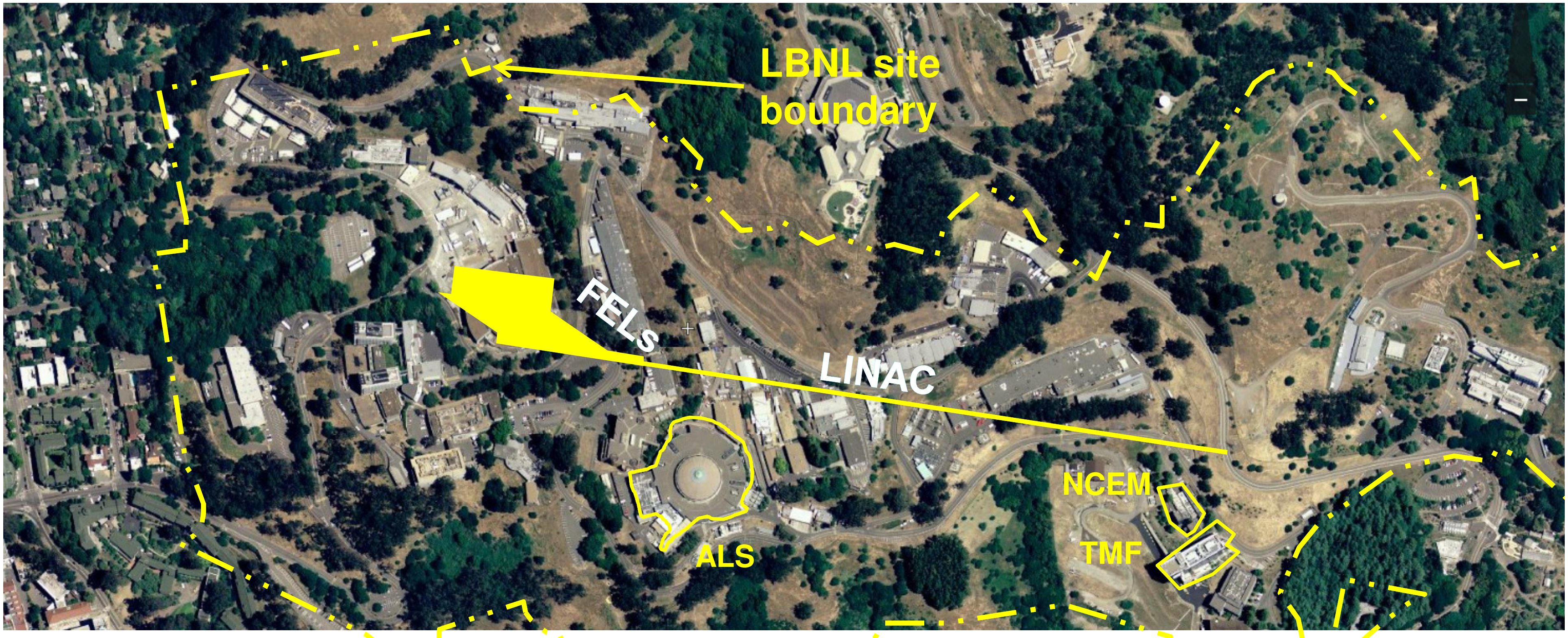
SUBJECT: Approval of Critical Decision-0 for the Next Generation Light Source

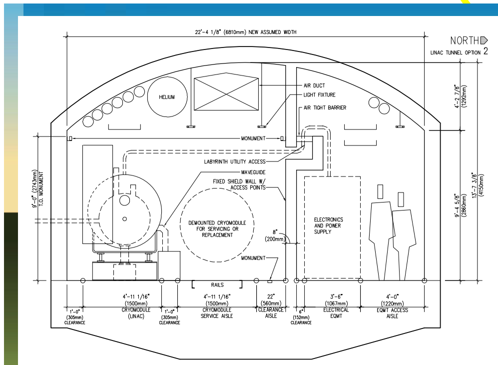
In accordance with Department of Energy Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, the Next Generation Light Source project has met Critical Decision (CD)-0 (Approve Mission Need) requirements. As the Secretarial Acquisition Executive, based on the recommendation of the Energy Systems Acquisition Advisory Board, I approve CD-0. The rough order of magnitude cost range is $0.9 billion to $1.5 billion.

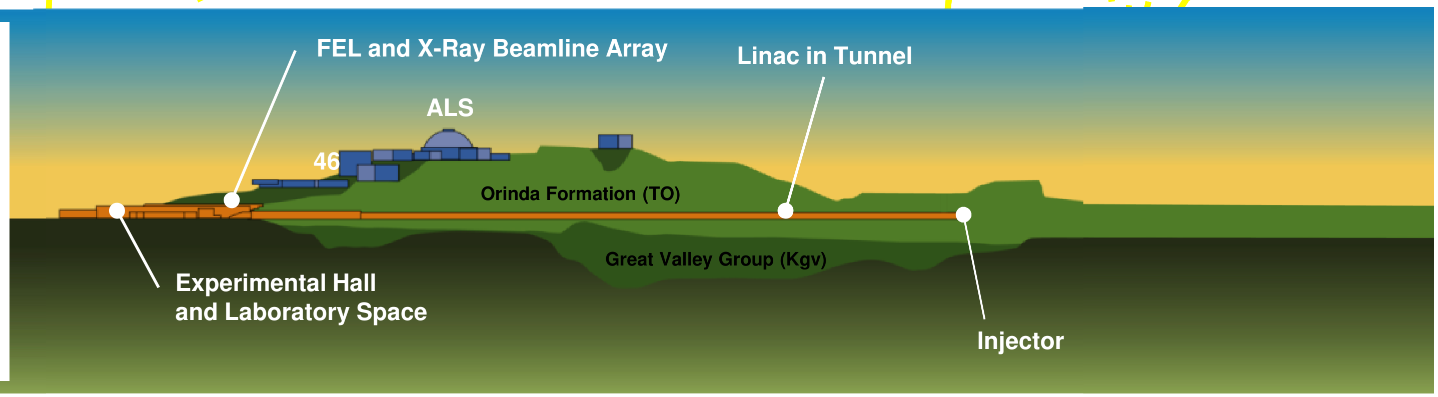
Please continue to work with the Office of Engineering and Construction Management as you progress to Critical Decision-1 (Alternative Selection and Cost Range).

cc:
Steven E. Koonin, S-4
Ingrid Kolb, MA-1
Paul Bosco, MA-50
Sean Lev GC-1
Associate Director, Office of Basic Energy Sciences, SC-22
Director, Office of Project Assessment, SC-28

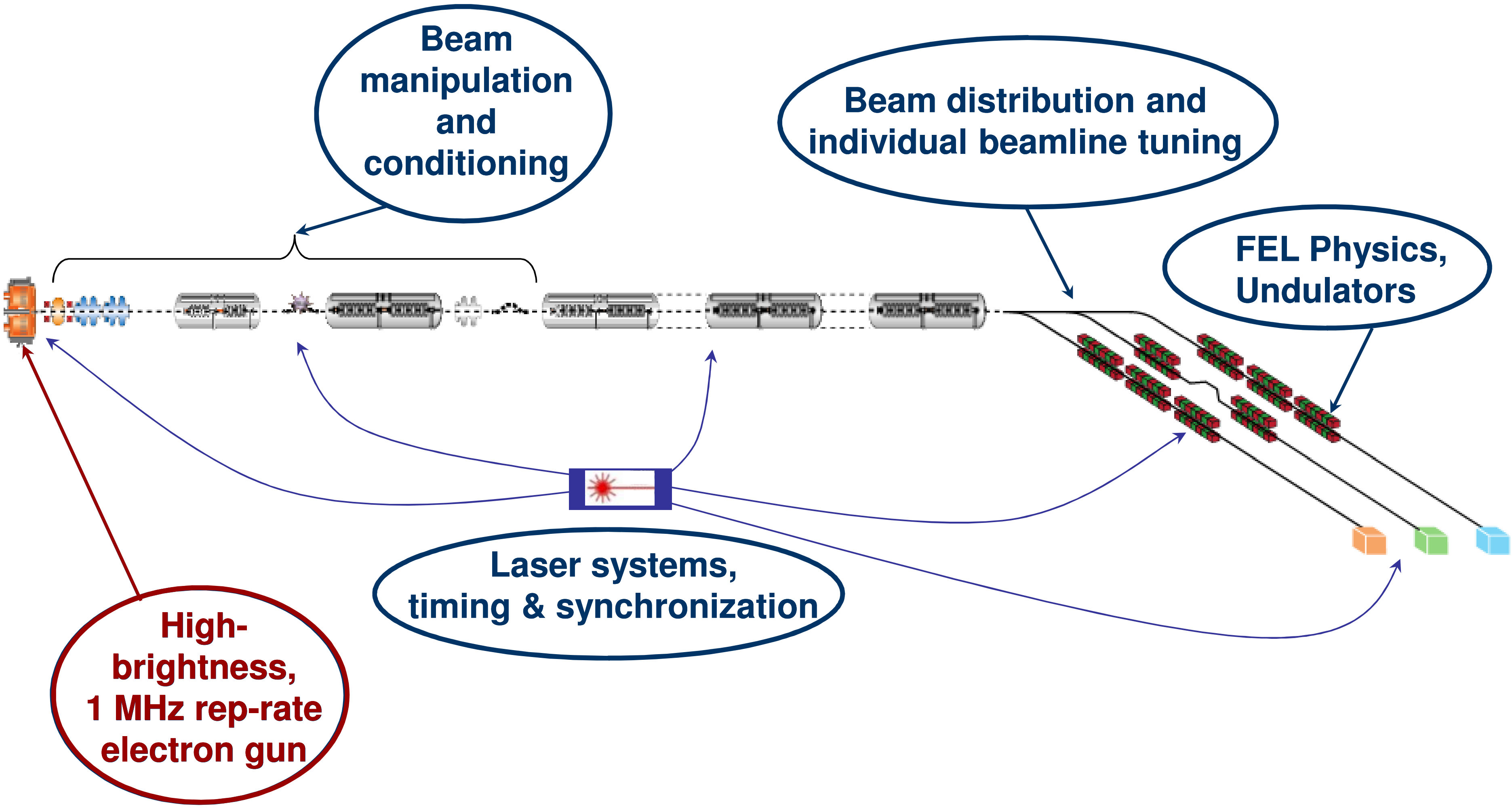
NGLS SITE AT LBNL







R&D AREAS TO BE PURSUED



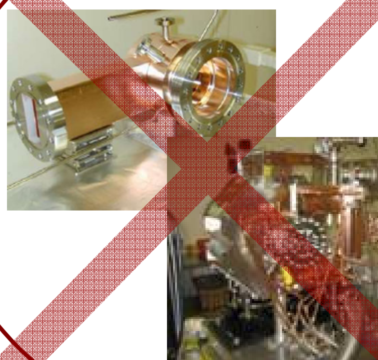
REQUIREMENTS FOR THE NGLS INJECTOR

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

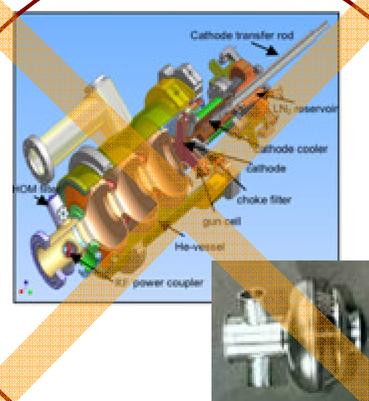
To achieve the NGLS goals, the electron source should simultaneously allow for:

- **MHz-class repetition rates.**
- **charge per bunch from few tens of pC to ~ 0.3 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.**

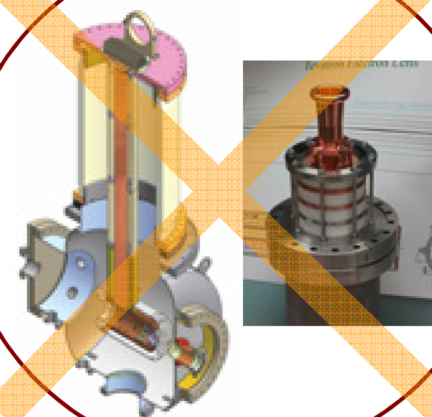
AVAILABLE TECHNOLOGIES



High frequency (> 1 GHz)
normal-conducting RF



Super-conducting RF



DC gun

Not usable

R&D required

An electron gun to operate the NGLS presently does not exist!

THE LBNL CONCEPT

CBP Tech Note 366

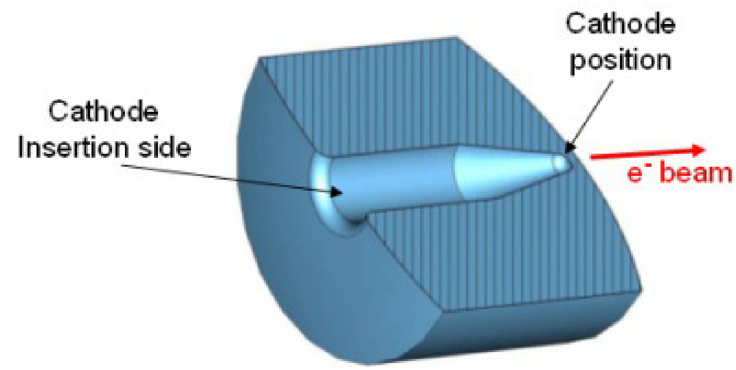
VHF-band Photoinjector

J. Staples, F. Sannibale, S. Virostek
Lawrence Berkeley National Laboratory

26 October 2006

Introduction

New generation accelerator-based x-ray light sources require high quality electron beams. Parameters such as transverse emittance (projected or "sliced"), energy spread and bunch length for beams in the nC charge range, need to be pushed beyond their present limits for the successful operation of light sources such as Energy Recovery Linacs (ERL) and Free Electron Lasers (FEL). At the same time, the demand for a high average brightness is also driving towards technologies capable of very high repetition rate operation. The overall performance is greatly determined at the accelerator injector and in particular, at the electron gun.



Originally it was a "spoke cavity" that became gradually a quarter wave structure and finally a "reentrant nose" cavity. The initial frequency was 65 MHz and…

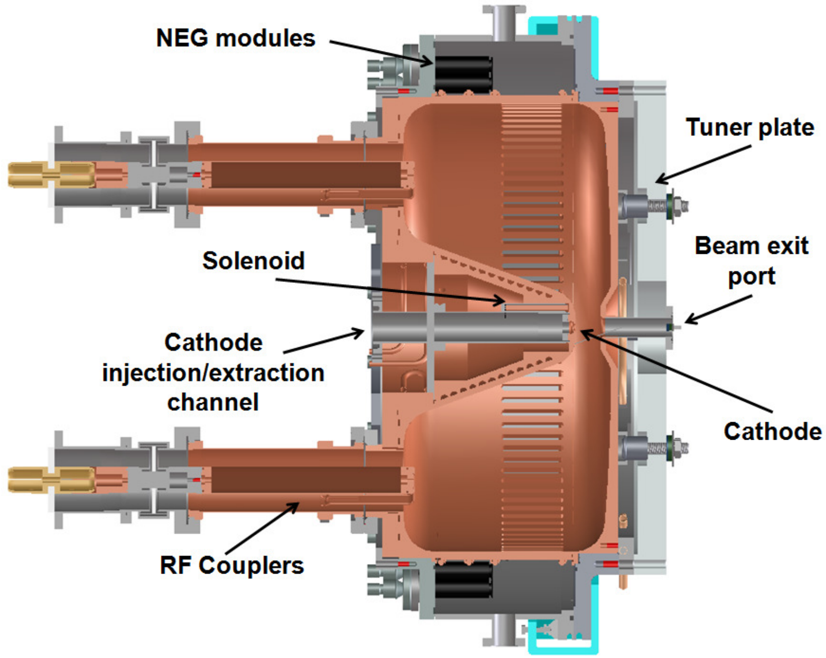
THE APEX TEAM

F. Sannibale, B. Bailey, K. Baptiste, J. Byrd, M. Chin, D. Colomb, J. Corlett, C. Cork, S. De Santis, L. Doolittle, J. Doyle, J. Feng, D. Filippetto, G. Huang, H. Huang, T. Kramasz, S. Kwiatkowski, W. E. Norum, H. Padmore, C. Papadopoulos, G. Penn, C. Pogue, G. Portmann, J. Qiang, D. Garcia Quintas, J. Staples, T. Vecchione, M. Venturini, M. Vinco, W. Wan, R. Wells, M. Zolotorev, F. Zucca, … .

Most of people is part time on APEX

THE LBNL VHF RF GUN

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



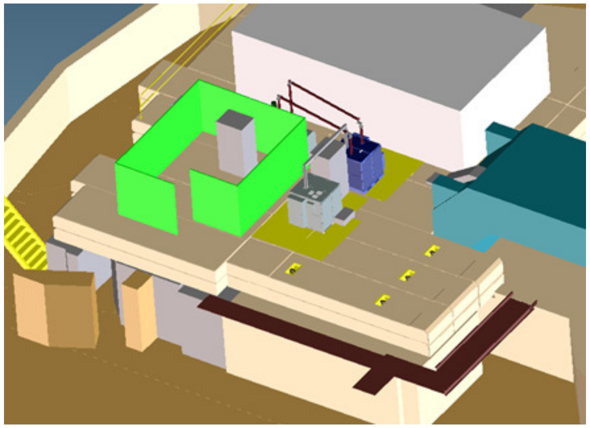
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

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

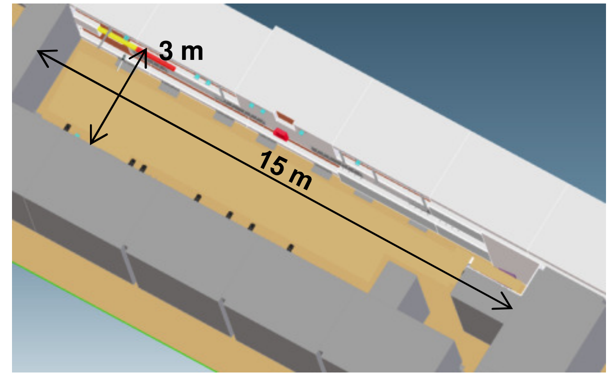
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-11} Torr

- 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**.
- 186 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.

APEX: THE ADVANCED PHOTO-INJECTOR EXPERIMENT



Located in the Beam Test Facility (BTF) at the ALS.



Main Goal:

Demonstrate the high-brightness high-repetition rate capability of an injector based on the LBNL VHF Gun.

Additional Goals:

***Cathode physics*: selection of the best cathode for NGLS.**

***Diagnostics*: demonstrate diagnostics systems for NGLS.**

***Dark current* characterization**

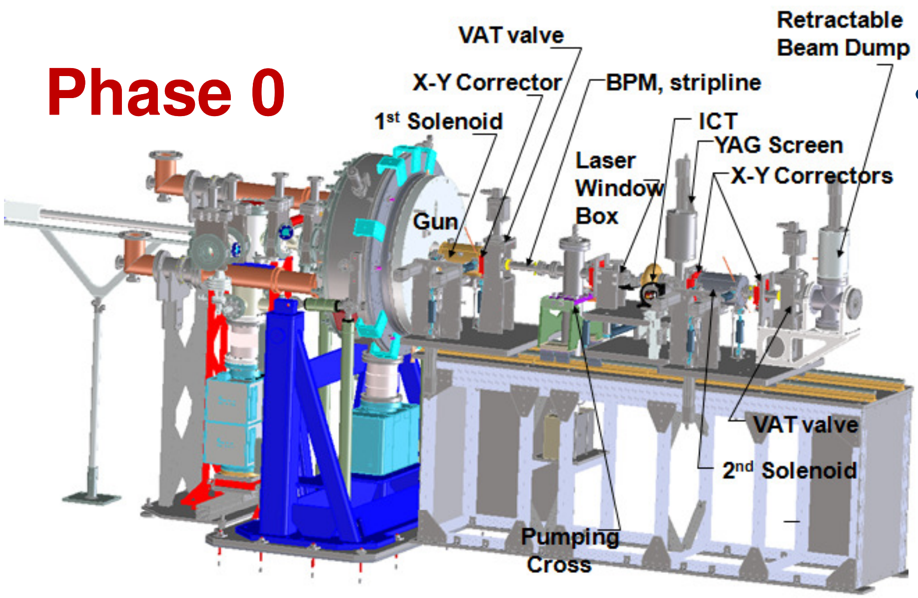
….

Low energy *collimation* schemes

***Active radiation interlock* system test (?)**

***New undulator technology* demonstration (depending on funds)**

APEX: PHASES 0 & I



Phase 0 scope:

- Demonstration of the RF performance at full repetition rate.
- Vacuum performance demonstration.
- Dark current characterization.
- High QE cathode physics (QE and lifetime measurements)

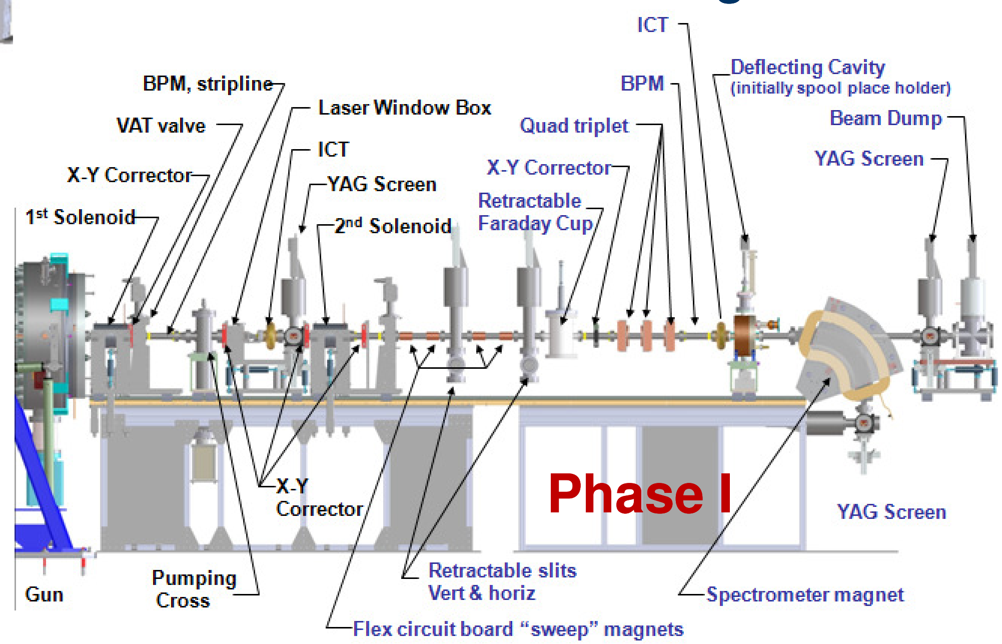
Funded.
Under commissioning

Phase I scope:

(Phase 0 + extended diagnostics)

- High QE cathode physics (Intrinsic emittance measurements)
- Diagnostics systems tests.
- Low energy beam characterization

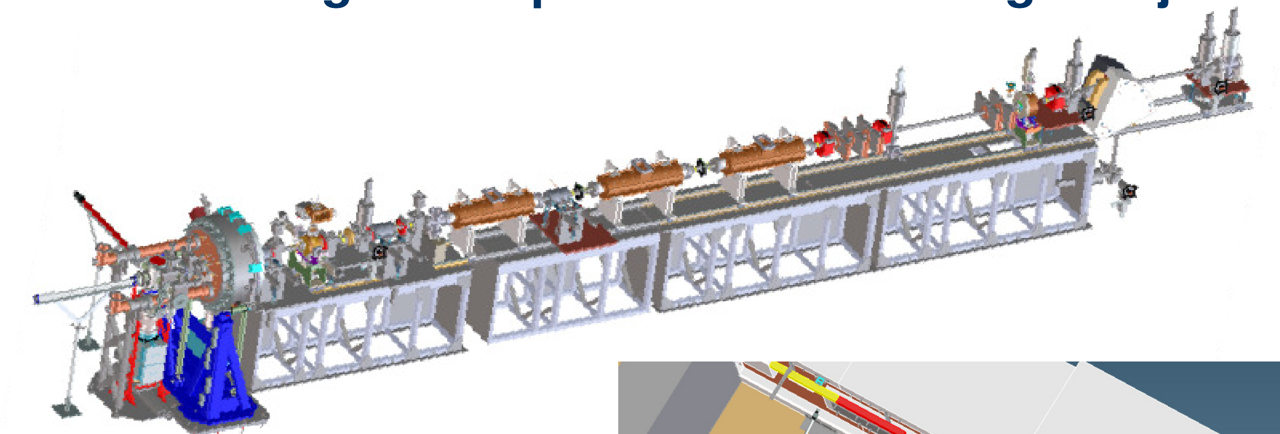
If funding confirmed operation in late 2012



APEX: PHASE II

At the Phase 0 and I energies, space charge forces (Coulomb interaction between particles) are strong and dominate the beam dynamics.

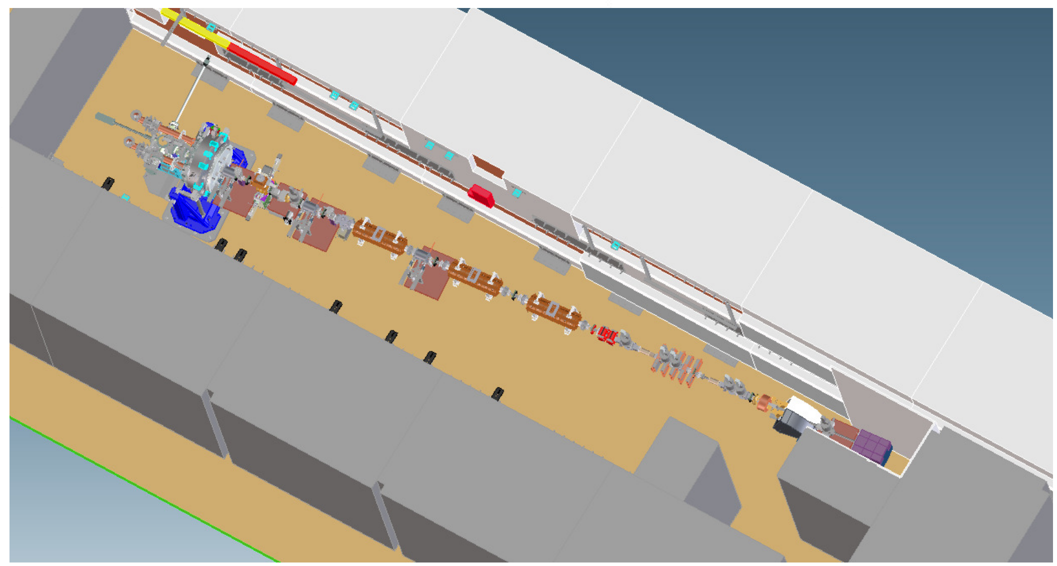
The beam needs to be accelerated at higher energies (space charge forces scales as γ^{-2}) while carefully "manipulated" to be able to demonstrate the actual brightness performance of the gun/injector.



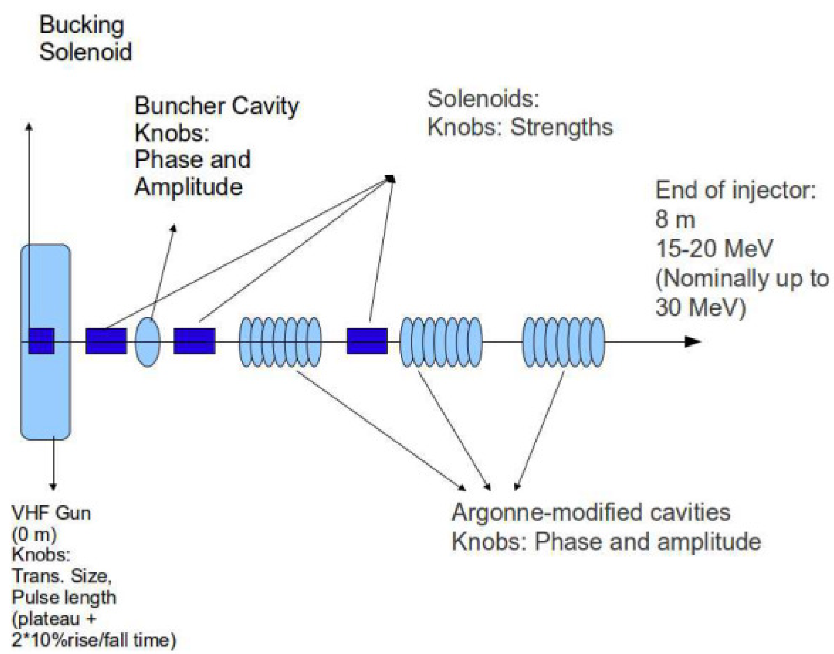
Phase II scope:

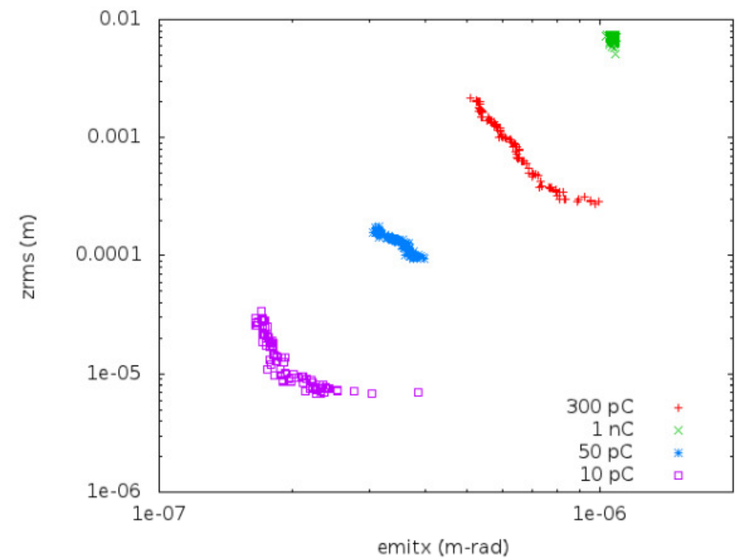
- **Demonstration of the brightness performance at ~ 30 MeV at low repetition rate* (*BTF shielding limited)**

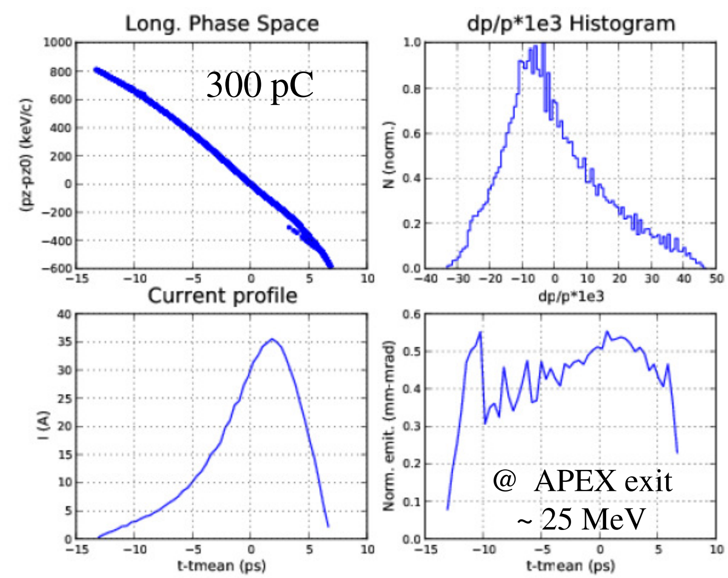
If funding confirmed commissioning in early 2014.



APEX BEAM DYNAMICS







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

APEX COLLABORATIONS

"Do not reinvent the wheel!
Use the good stuff that already exists!"

- **LLNL/UCB**. Photocathode laser.
- **ANL-AWA**. Linac accelerating sections.
- **Cornell University**. Beam diagnostics and RF components.
- **INFN-Milano LASA**. Cs_2Te cathodes.
- **BNL**. Diamond amplifier cathodes.

…

Also help from: L'OASIS, SLAC (LCLS, SSRL), DESY-PITZ, …

…

STTR with QPeak

APEX PROJECT REVIEWS

- Phase 0: reviewed by external/internal committee in Jan. & May 2009. (Dave Dowell chair)
- Phase II: first reviewed on Nov. 28, 2011 by an external/internal committee (Phase I diagnostics beamline included)

Phase II Committee

Ivan Bazarov, Cornell Univ., Chair
John Power, ANL
Richard, Konecny, ANL
Michael Zisman, LBNL,
Alex Ratti, LBNL
Steve Virostel, LBNL

The committee endorsed the strategy and plan for the project and a number of useful suggestion and comments were given.

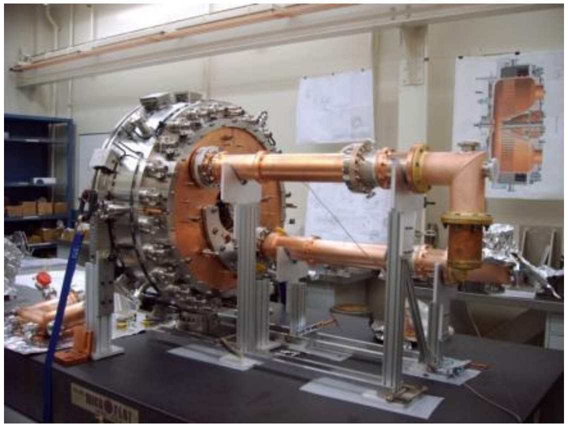
"The proposed plan is well thought out and mature, and the group is commended on the progress they have demonstrated to date, especially given the constrained fiscal climate."

"In general, we believe that the proposed plan will provide good confidence in the ability to reach NGLS parameters."

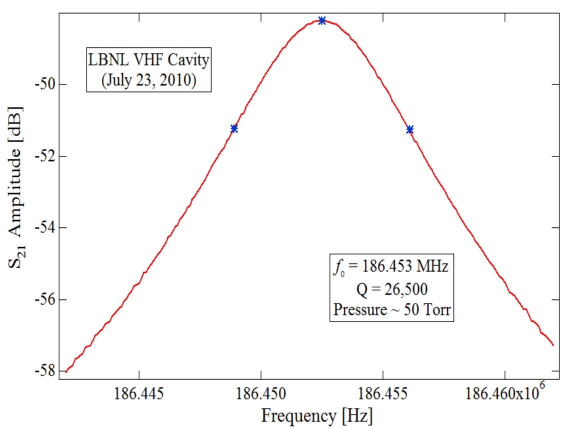
"We are supportive of the plan to purchase the RF power system as an integrated package, and we commend the group for this approach."

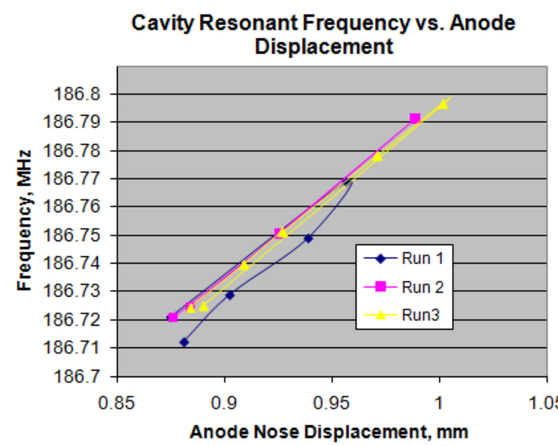
"We were pleased to see the attention to detail given to this aspect (beam diagnostics) in the planning. There were a few minor holes in the plan that we suggest be addressed by the project team."

GUN FABRICATION COMPLETED
(~90% at LBNL Shops)



Successful low power RF test



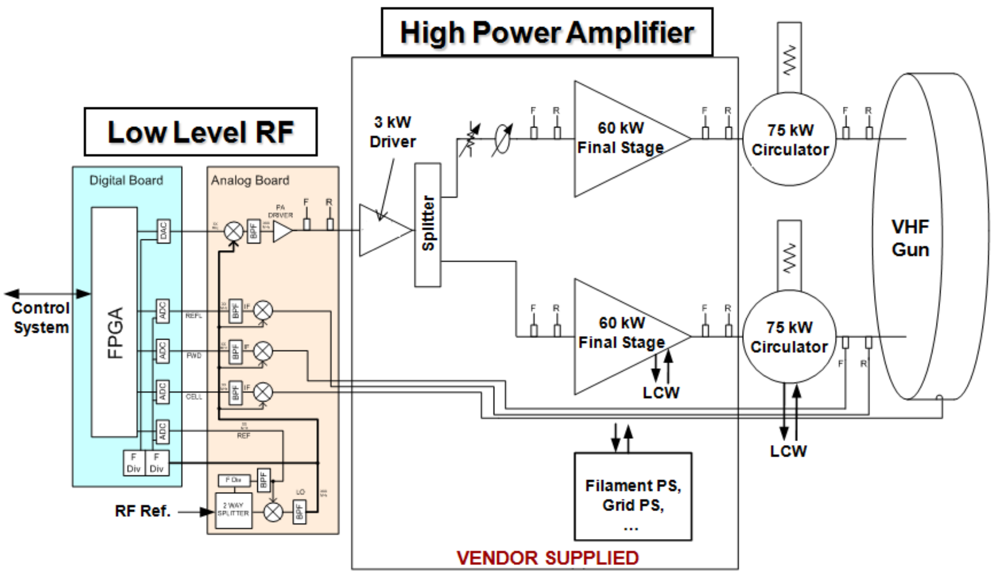


Tuning mechanism principle tested.

1.2 10^{-9} Torr achieved with 1 (out of 20) NEG pump and no baking.

THE GUN RF SOURCE

- The 120 kW CW 187 MHz RF amplifier required to operate the VHF gun has been manufactured by a local company.

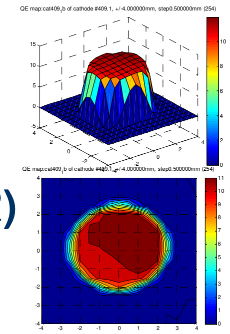


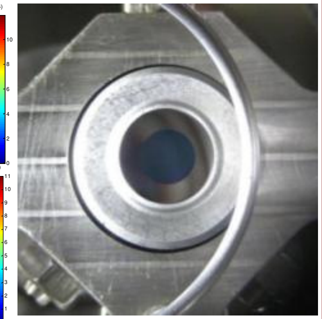
- Acceptance test completed at LBNL in May 2011. Fully operational.

PHOTO-CATHODES FOR APEX

PEA Semiconductor: Cesium Telluride Cs_2Te (In collaboration with INFN-LASA)

- <~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/4th harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required

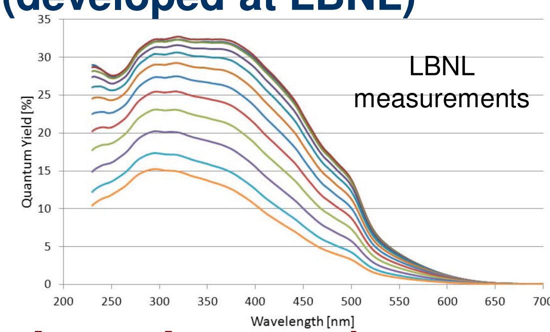




First 3 cathodes successfully developed at INFN/LASA and delivered to LBNL.

PEA Semiconductor: Alkali Antimonides CsK_2Sb, (developed at LBNL)

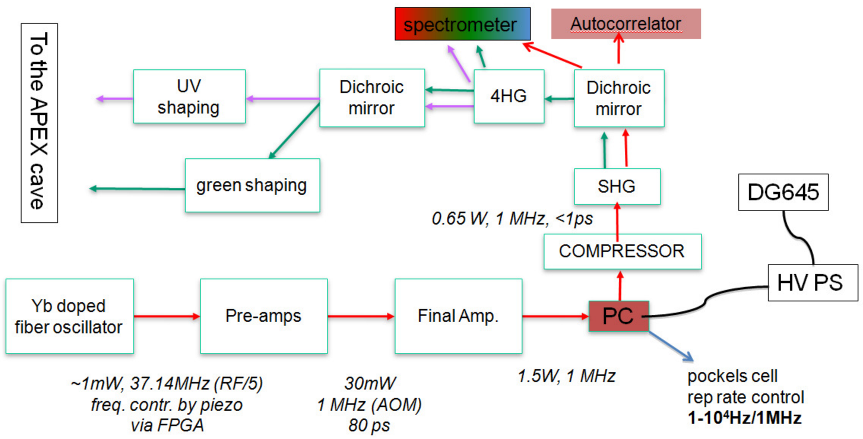
- <~ps pulse capability
- reactive; requires ~ 10^{-10} Torr pressure
- high QE > 1%
- requires green/blue light (eg. 2nd harm. Nd:YVO4 = 532nm)
- for nC, 1 MHz reprate, ~ 1 W of IR required



Cathodes under development at LBNL (H. Padmore's group).
Promising lifetime and intrinsic emittance results (Cornell and LBNL).
Transfer chamber from preparation chamber to VHF gun in fabrication.

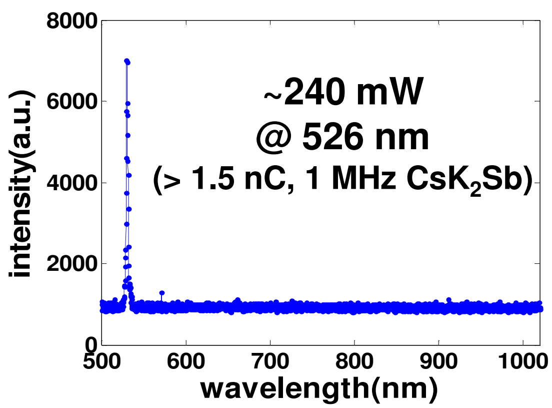
Collaboration with BNL for diamond amplifier testing

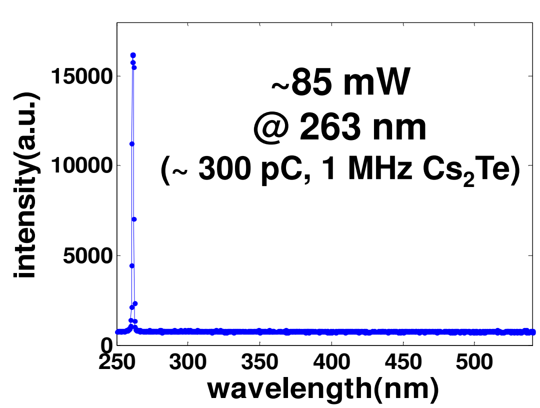
PHOTO-CATHODE LASERS

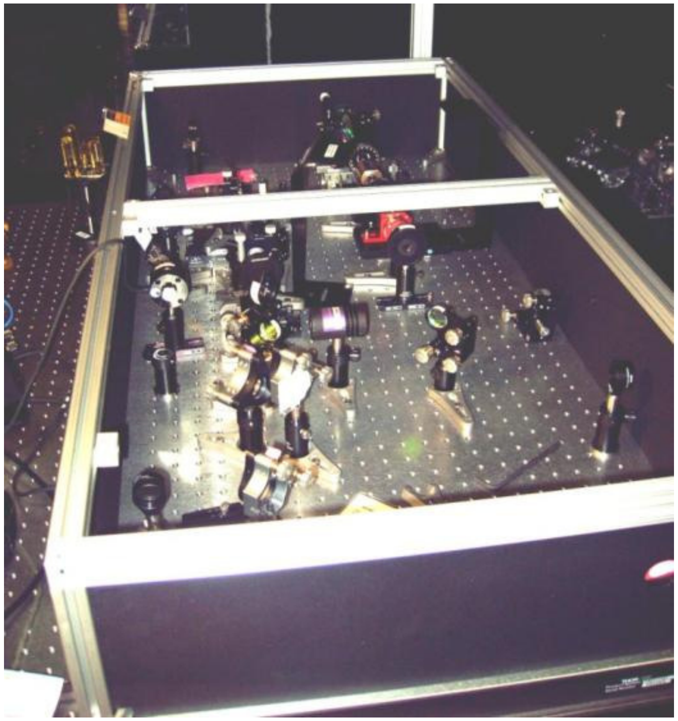


LASER 1: 1 MHz reprate Yb fiber laser from a LLNL/UCB/LBNL collaboration.

Present: 0.7 W at ~1052 nm. Margin for improvement.



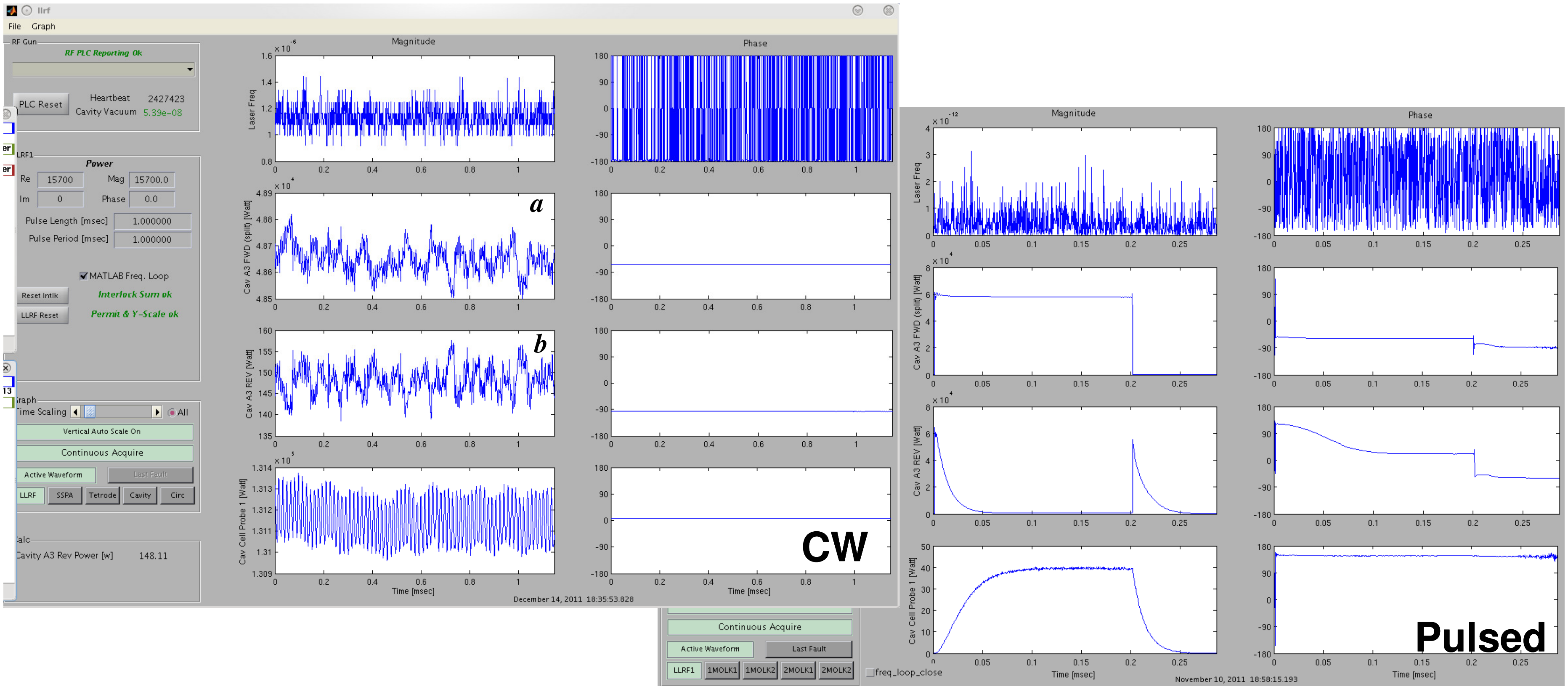




LASER 2: Commercial 1 MHz 2 W Calmar 1052 nm tested & available.

RF CONDITIONING

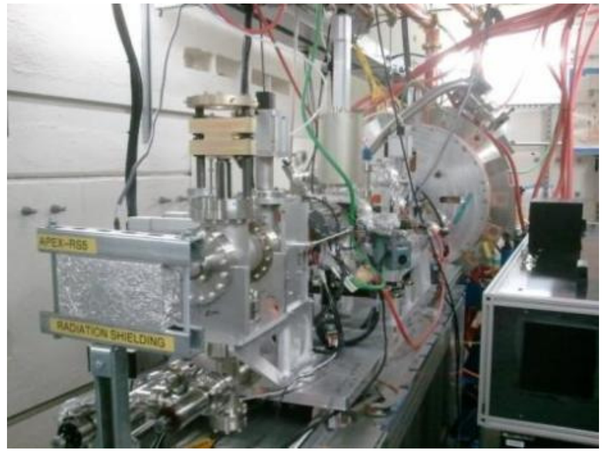
Gun RF conditioning started on November 7, 2011

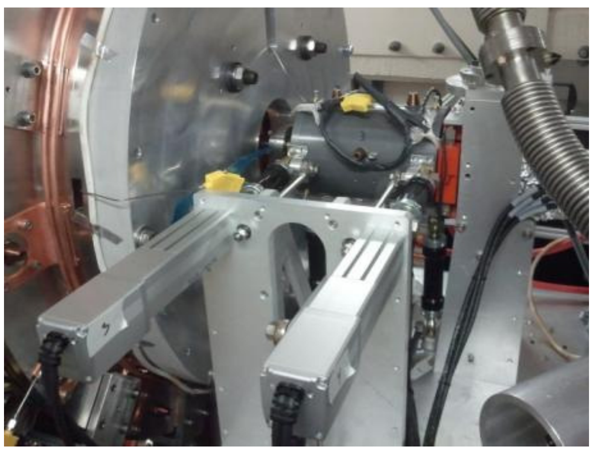
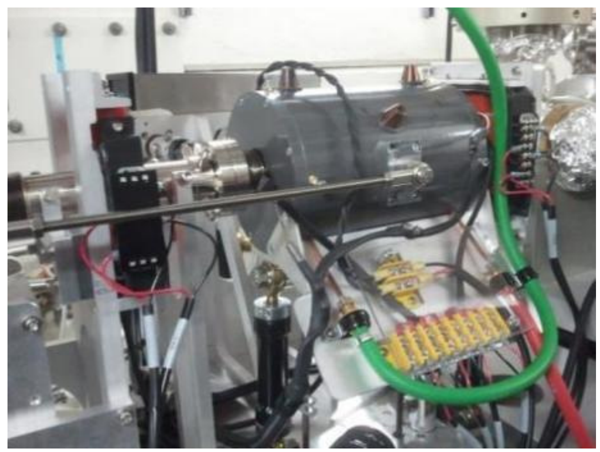
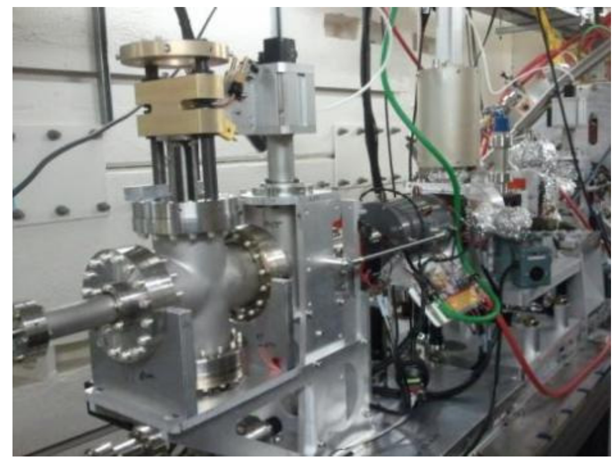


On Dec. 15, 2011 after < 120 integrated hours of conditioning achieved more than 12,5 hours run without faults in CW mode at nominal power (100 kW). Results reconfirmed the day after (> 24 hours no fault).

RF conditioning completed!

PHASE 0 BEAMLINE INSTALLED

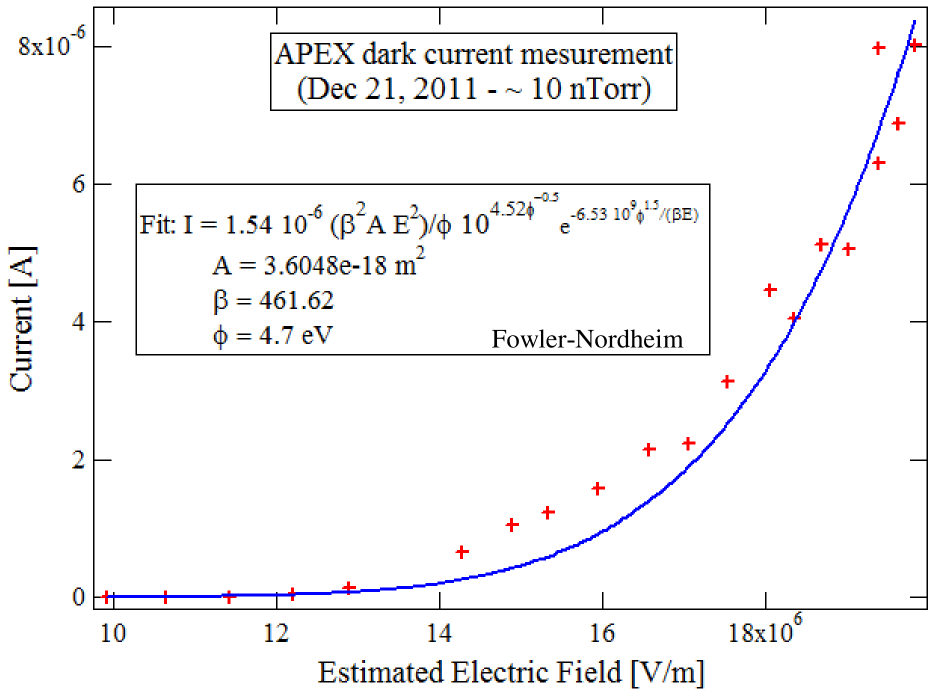



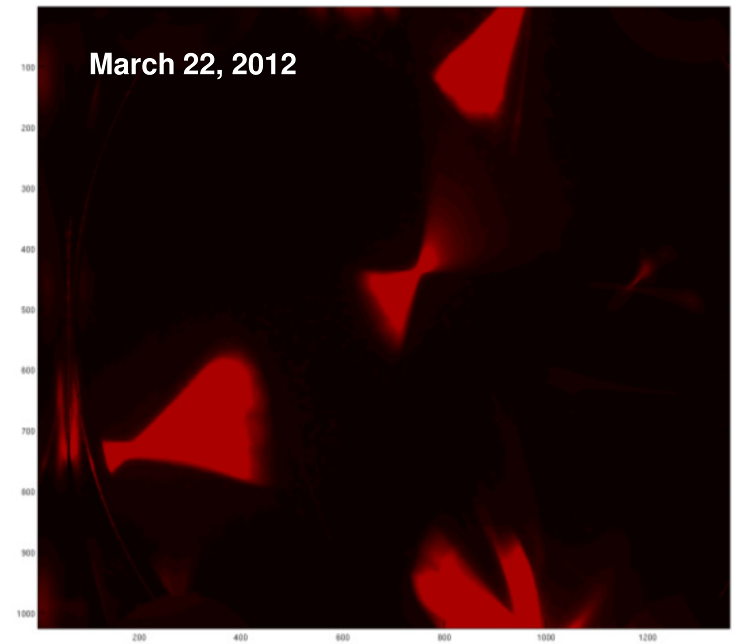





Beamline installation completed.

DARK CURRENT

Dark current is an undesired phenomenon. High fields inside the gun generate electron field emission. Dark current if excessive can induce quencing in the super-conducting linac and larger radiation doses along the facility.



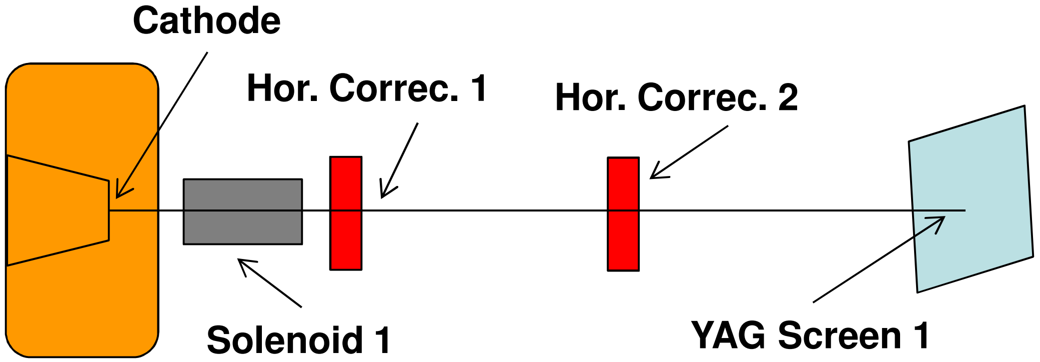


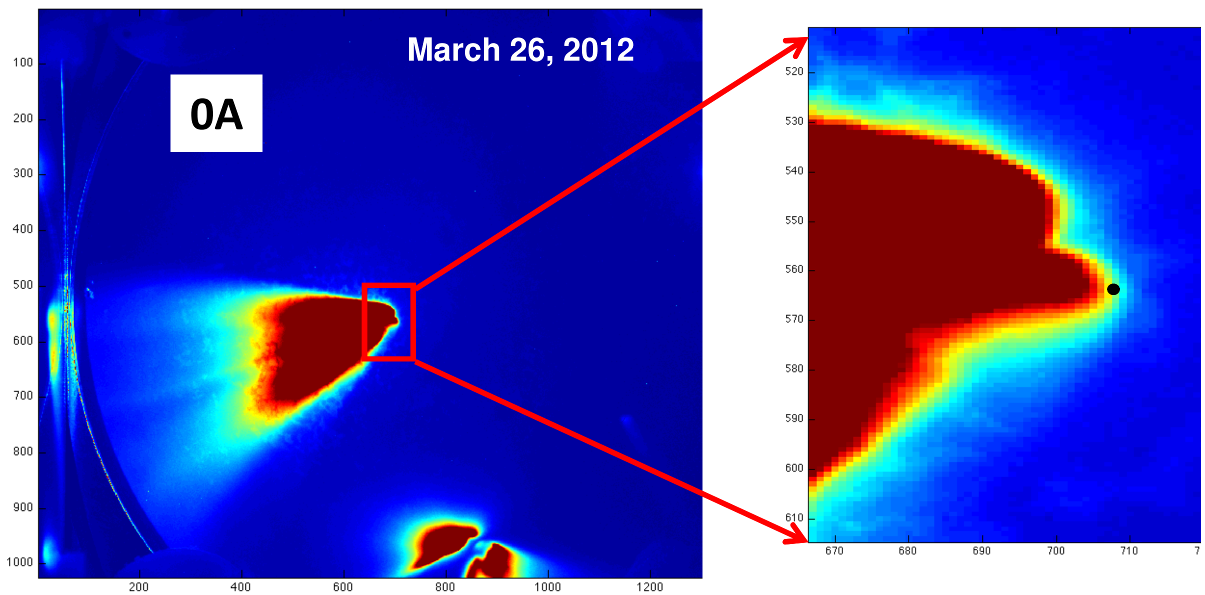
The dark current image on a YAG screen reveals several "butterflies" indicating the presence of "hot" tips on the temporary "dummy" plug.
No evidence of field emission in the plug/gun contact area.

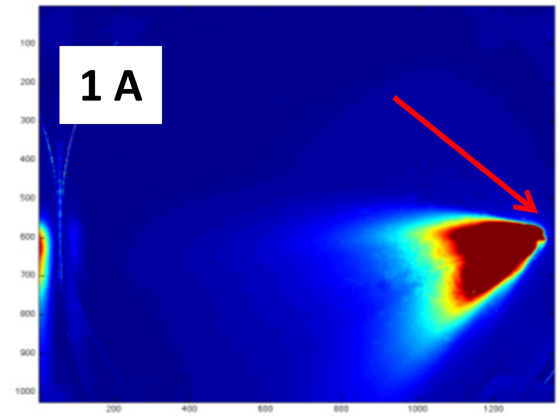
Measured values in line with data from others guns in operation.

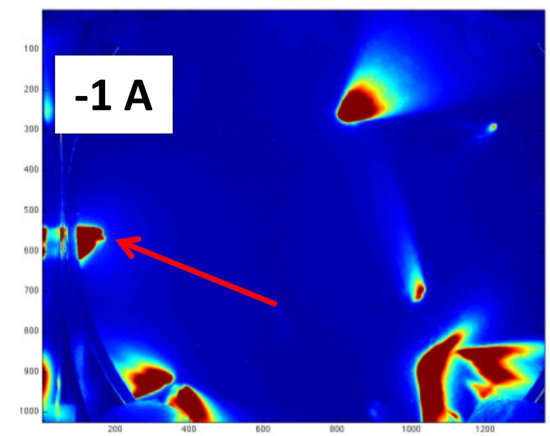
Energy Measurement by Dark Current

Nominal RF Power. Solenoid 1 ON to focus dark current on screen. Corrector 1 OFF. Corrector 2 current scanned for the measurement.



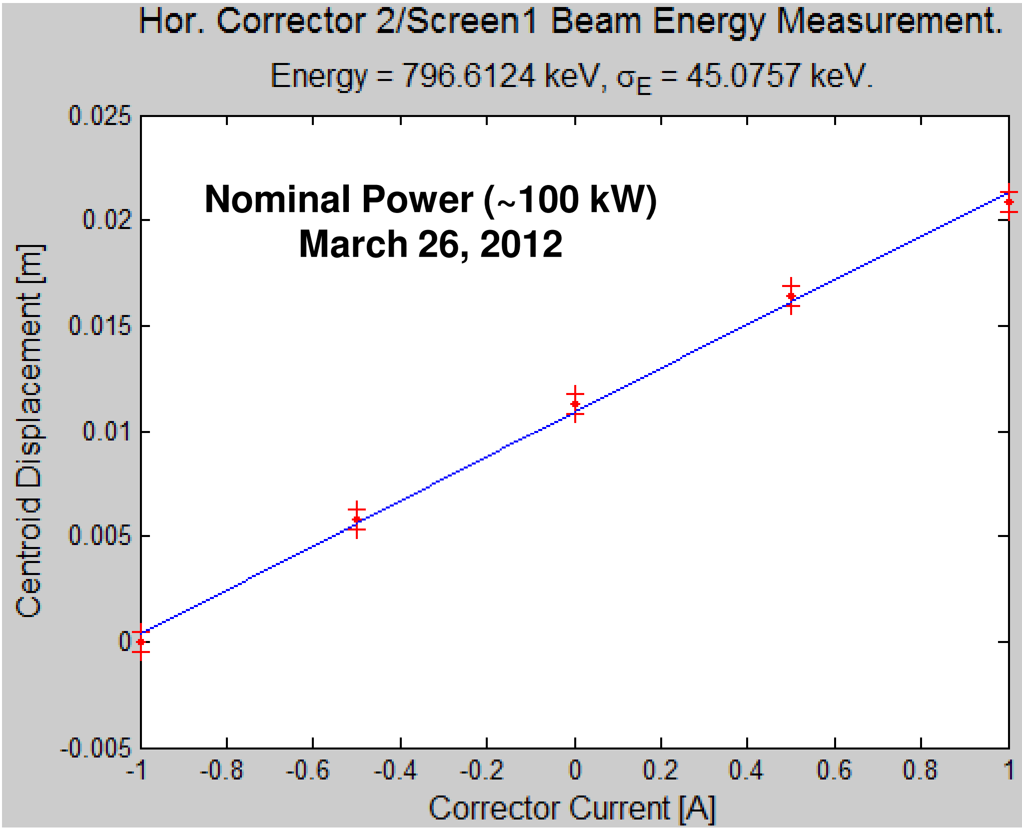






BEAM ENERGY MEASUREMENT BY DARK CURRENT

The fit slope is proportional to the particle momentum

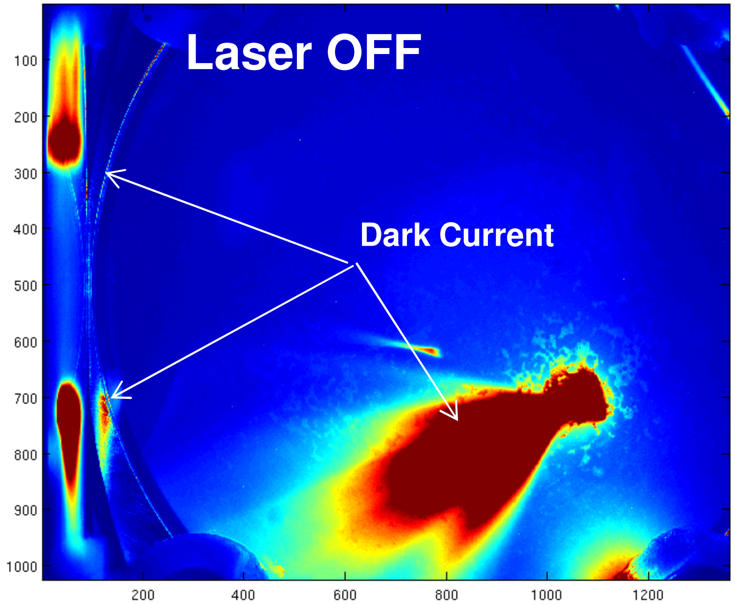


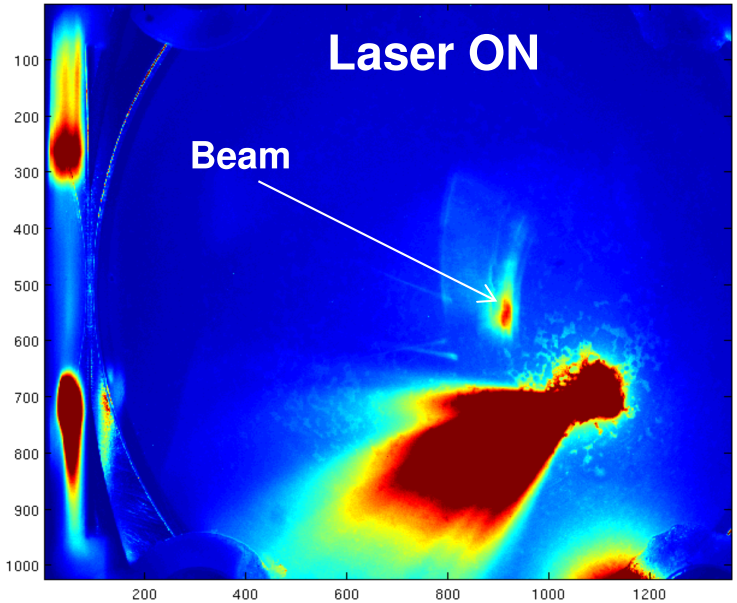
$$E = 797 \text{ keV}$$
$$\sigma_E = 45 \text{ keV}$$

Expected value at nominal power: 750 keV.
The slight discrepancy (in the good direction!) probably due to calibration accuracy of the RF probes.

FIRST BEAM!

On March 30, 2012 we were able to synchronize the laser to the gun RF and measure the first photo-emitted beam by the dummy cathode plug presently installed in the gun.





Laser average power at the cathode: ~ 30 mW at ~ 266 nm.
Cathode: Molybdenum plug, QE ~ 10^{-6}
Expected charge per bunch : ~ 6 fC (!!!)
Expected average current at 1 MHz: ~ 6 nA (dark current ~ 100 nA)
RF power: ~ 86 kW CW (~750 keV); RF phase: ~ 120 RF deg

Full cross-check of the photo-gun functionality!
"Serious" cathodes to be tested in the near future…