JLAMP Proposed 4th Generation Soft X-ray Light Source

Tom Powers, for the JLAB Team

May 6, 2009

What are (4th) Next Generation Light Sources?

- Superconducting radio-frequency linac based, as opposed to rings
- Significantly higher brightness than existing sources
- Short pulse capability (< 100 fs)
- High transverse coherence and ideally longitudinal coherence
- Concept covers broad spectral range from THz through VUV to soft and hard X-rays but the push is toward X-rays
- Complementary capability – they do not displace 3rd generation rings!
- Configuration loosely divided into Free Electron Lasers or Energy Recovering Linacs

Third generation x-ray sources

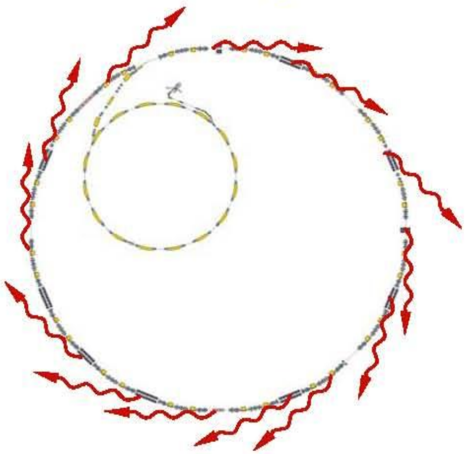
Fourth generation x-ray sources

Storage ring

$\varepsilon \sim E^2/R$

$\tau_{lifetime} >> \tau_{relaxation}$

bunch charge 1nC



- Many experiments
- Ready tunability
- High flux
- ps pulses

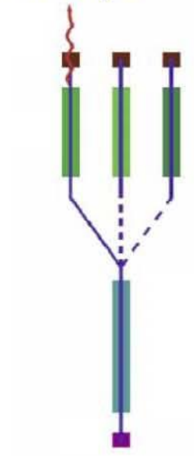
Courtesy W. Eberhardt

LINAC source (=> FEL)

$\varepsilon \sim 1/E$

$\tau_{lifetime} << \tau_{relaxation}$

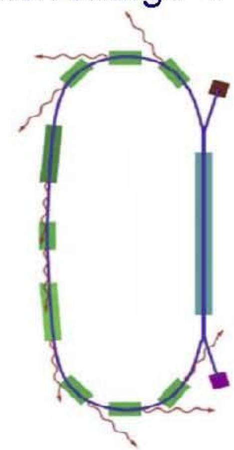
bunch charge ≤ 1 nC



- Extremely high peak brilliance
- Full spatial coherence
- Ultrashort (fs) pulses
- Temporal synchronization with seeding
- low pulse rep. Rate 10^2 to 10^5 Hz
- Few experiments

Energy-Recovery LINAC

bunch charge < 100 pC



- High avarage brilliance
- Full spatial coherence
- Many experiments
- Ready tunability
- Excellent energy resolution
- Flexible pulse characteristics
- Fs to ps pulse lengths
- 10^9 pulses/s

So why haven't CW 4th Generation sources been built?

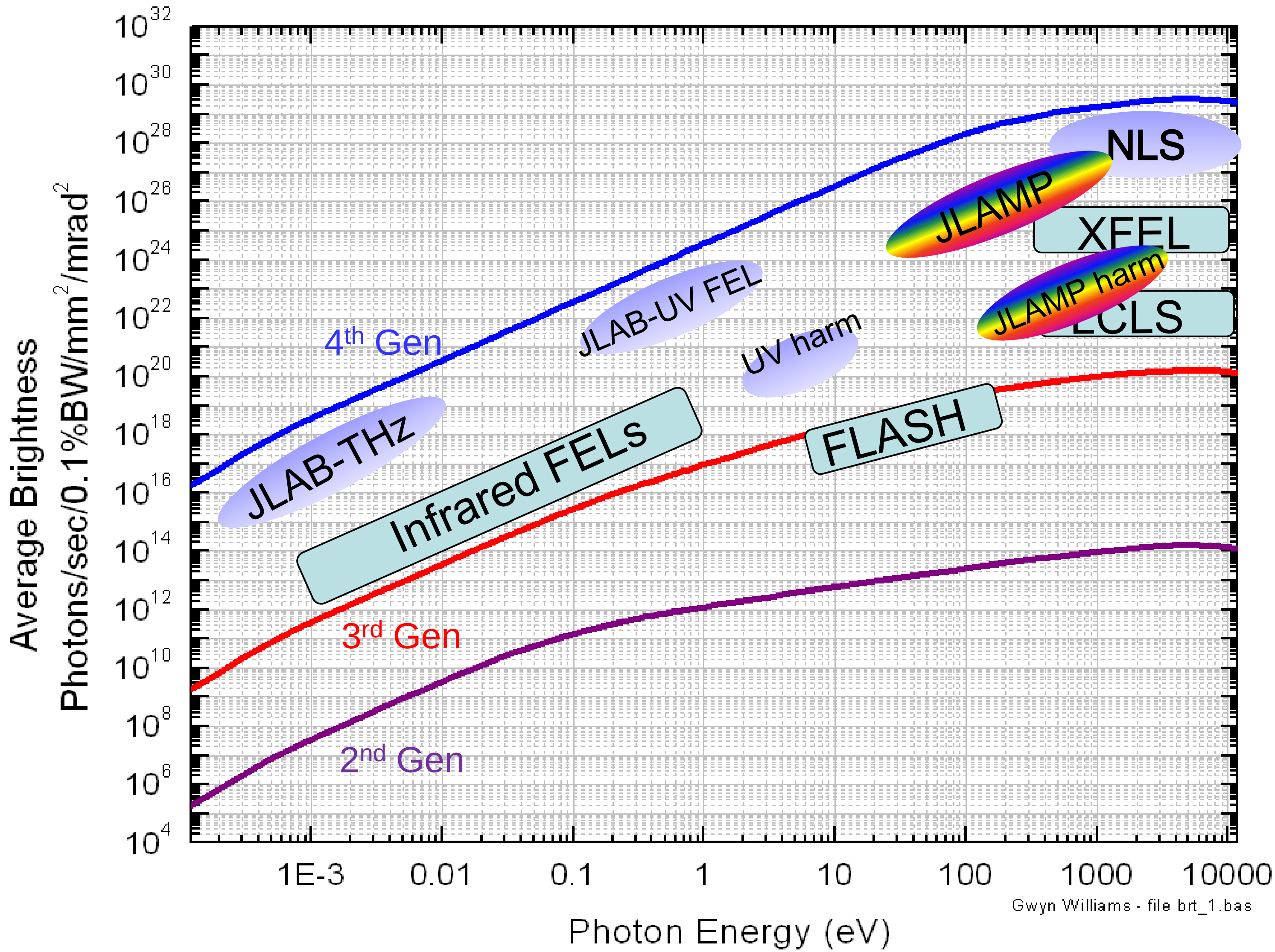
- **CW Linacs are expensive!**
  - Get 1 eV photon with energy of ~100 MeV
  - Get 100 eV with ~ 1GeV
  - Get 1000 eV with 3 GeV
  - Get 10 keV with 10 GeV
- **Linacs presently achieve < 12 MV/m real estate gradient CW**
- **3 GeV means > 300m of linear accelerator, >$200M for the linac!**
- **Undulators are also expensive > 0.4M/m x 100m = $40M per undulator x 10? = $ 400M**
- **Add in the cost of cryogenic refrigerator, conventional facilities, etc. and the total for 1 Angstrom output is well above $1B**

Physics advances are also required

- **Injectors: ultimate brightness at low (100 pC) and high (1 nC) charge.**
  - Approaches: DC gun, copper RF gun, SCRF gun, . . .
  - We don't presently know how to make a high charge, high brightness CW gun.
- **Brightness preservation in transport: Solutions to**
  - Coherent synchrotron radiation (CSR)
  - Emittance degradation,
  - Longitudinal space charge (LSC) effects in pulse compression
- **Is recirculation feasible while retaining brightness? Cuts linac cost by 2x!**
- **Halo and dark current control are essential for CW operations**
- **High order mode & beam breakup control in cavities**
- **Wakefield and propagating mode damping**

JLAMP is a path to understand many of the machine design issues at a cost that is affordable.

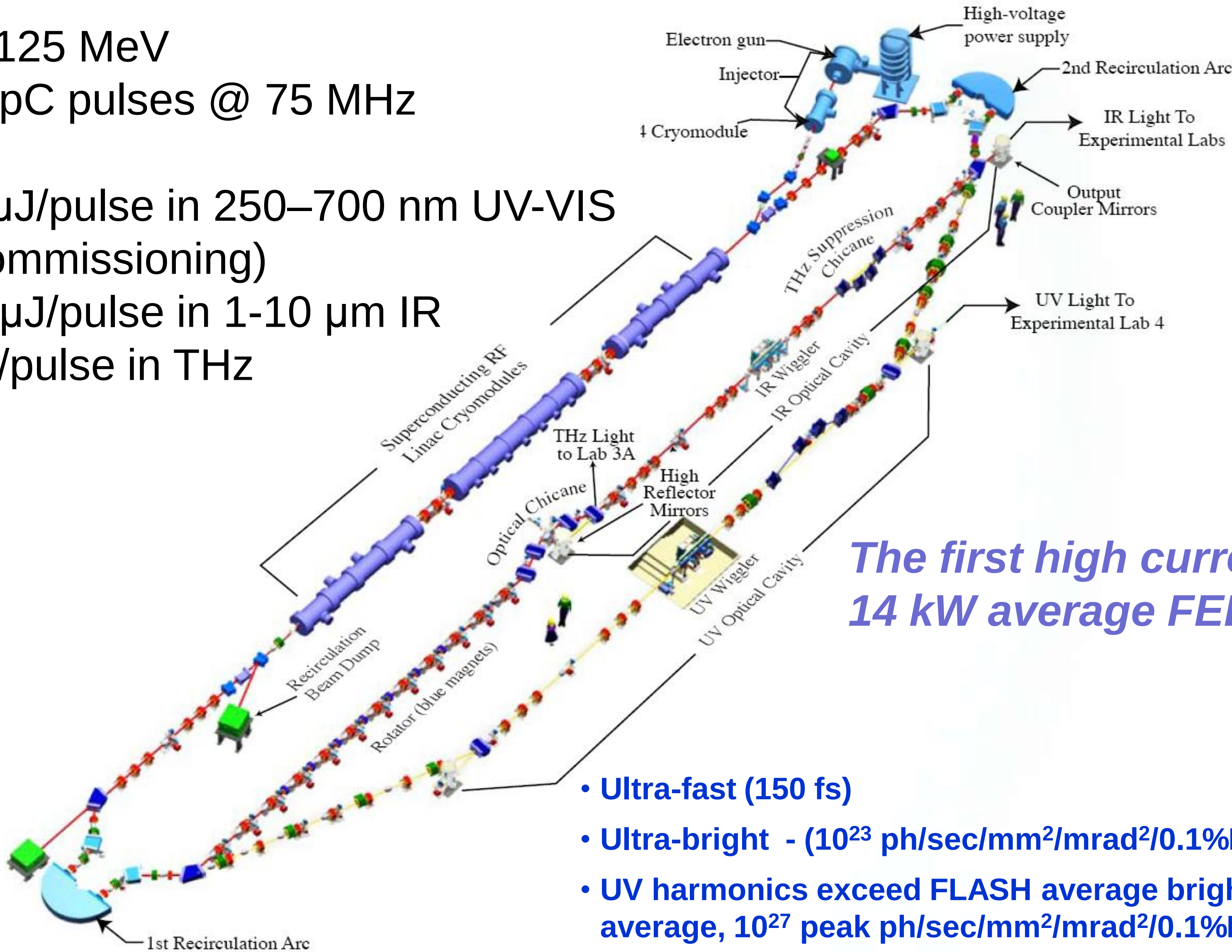
CW operation gives high average brightness in both fundamental and harmonics



Existing JLab 4th Generation IR/UV Light Source

E = 125 MeV
135 pC pulses @ 75 MHz

(20 μJ/pulse in 250–700 nm UV-VIS in commissioning)
120 μJ/pulse in 1-10 μm IR
1 μJ/pulse in THz



The first high current ERL
14 kW average FEL power

- **Ultra-fast (150 fs)**
- **Ultra-bright - (10^{23} ph/sec/mm^2/mrad^2/0.1%BW)**
- **UV harmonics exceed FLASH average brightness (10^{21} average, 10^{27} peak ph/sec/mm^2/mrad^2/0.1%BW)**

First Conceptual Design

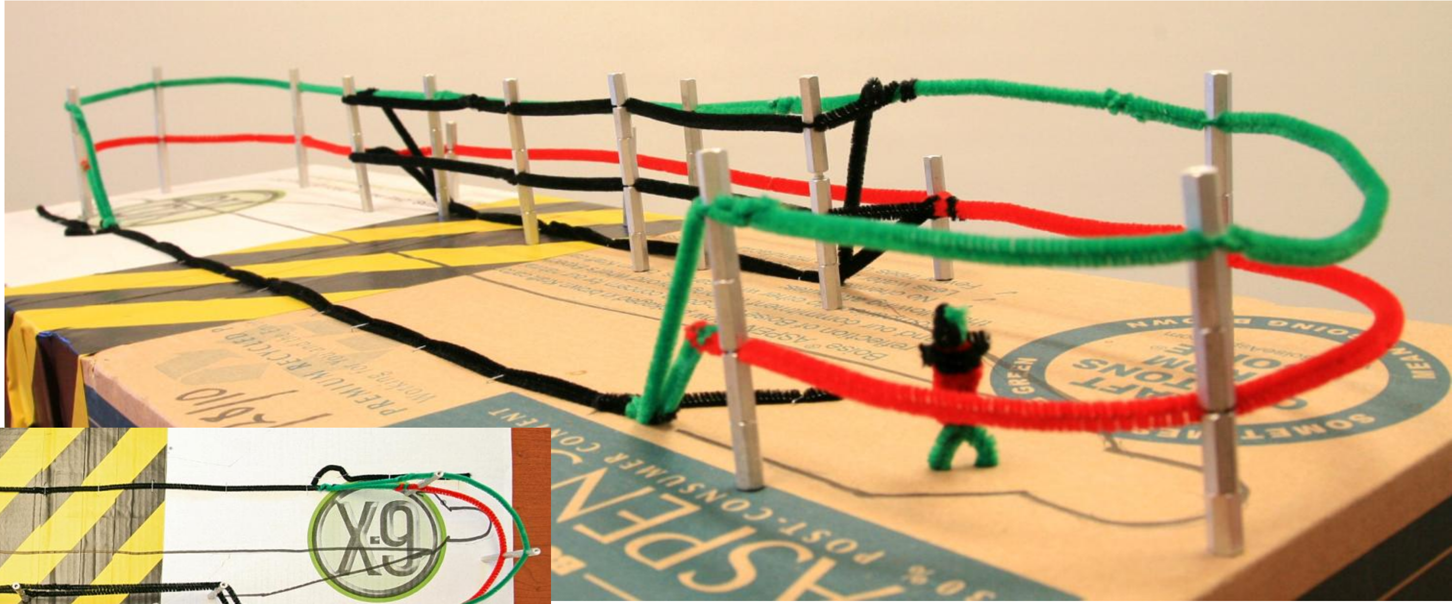
A simple model of a machine was built so that the beam physics team had a notion of what they were designing.

- Two pass machine
- Linac must remain 0.7 m beam line height
- Chicane so that Wiggler beam line is at standard Light source height of 1.4 m.
- Potential for multiple wiggler beam lines

First Conceptual Design

A simple model of a machine was built so that the beam physics team had a notion of what they were designing.

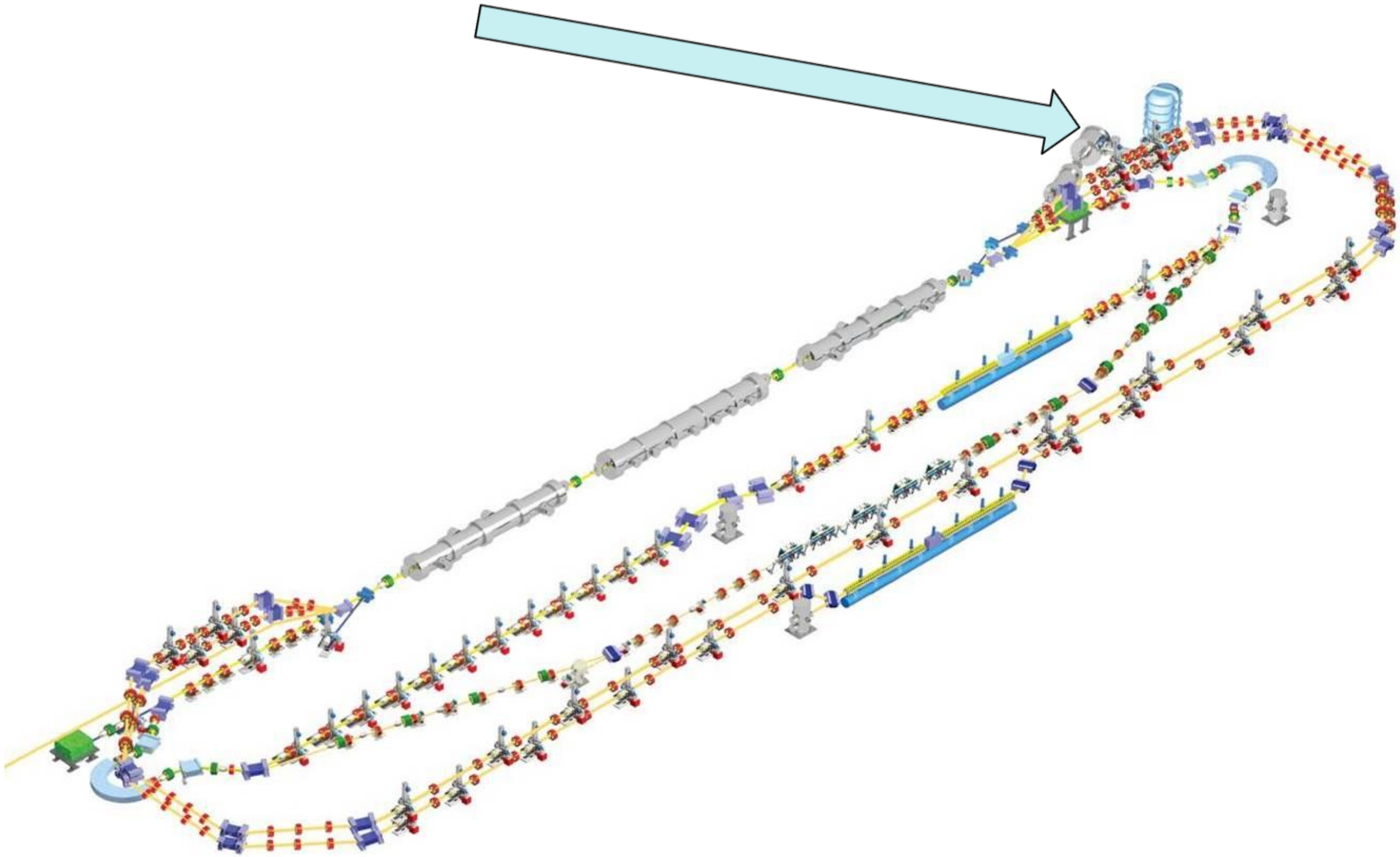
- Two pass machine
- Linac must remain at 0.7 m beam line height because of ceiling clearance for U-Tubes
- Chicane included so that Wiggler beam line is at standard light source height of 1.4 m.
- Potential for multiple wiggler beam lines



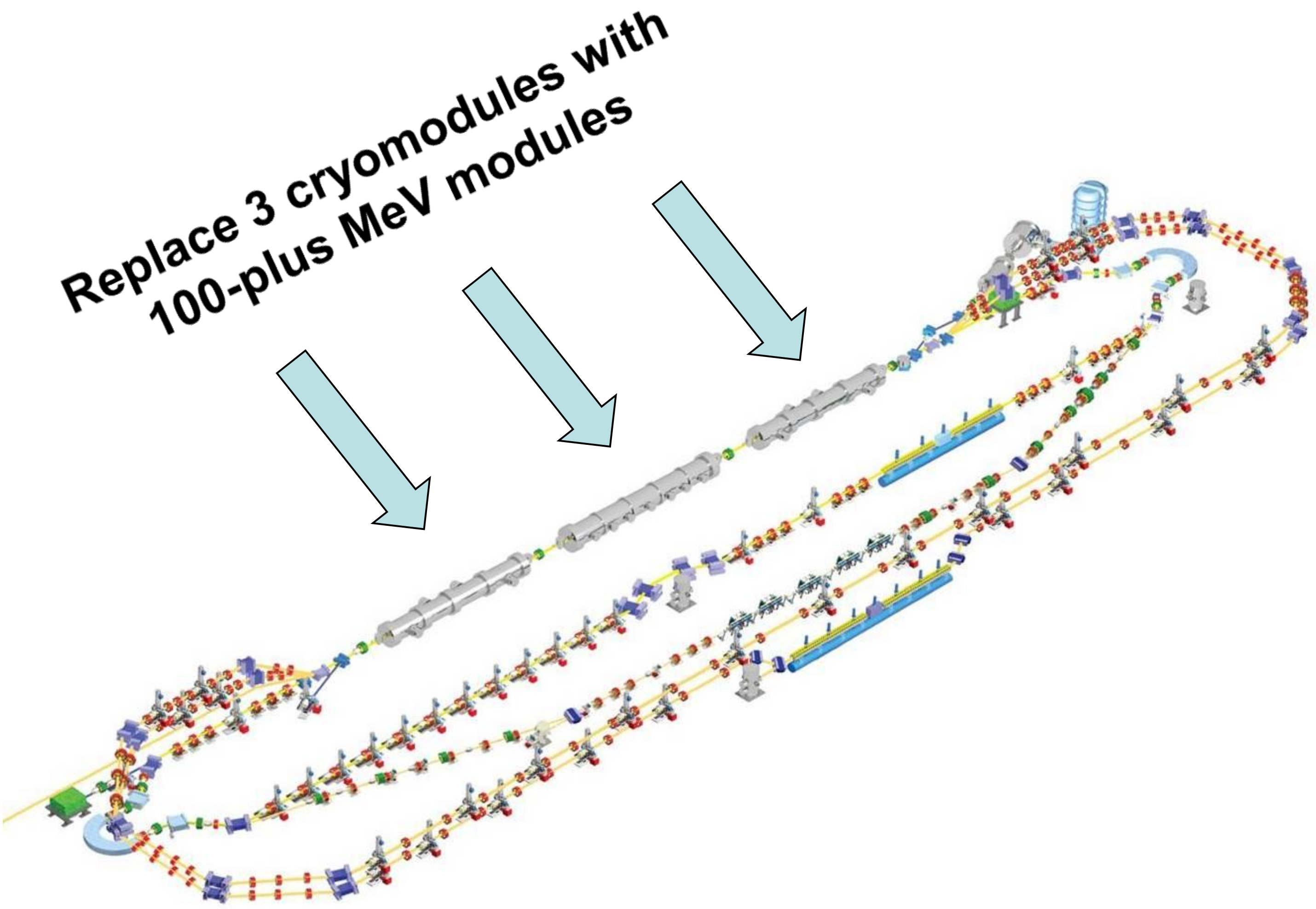
Transforming to JLAMP

Upgrade

- The injector to a high brightness DC or RF Gun and 750 MHz booster



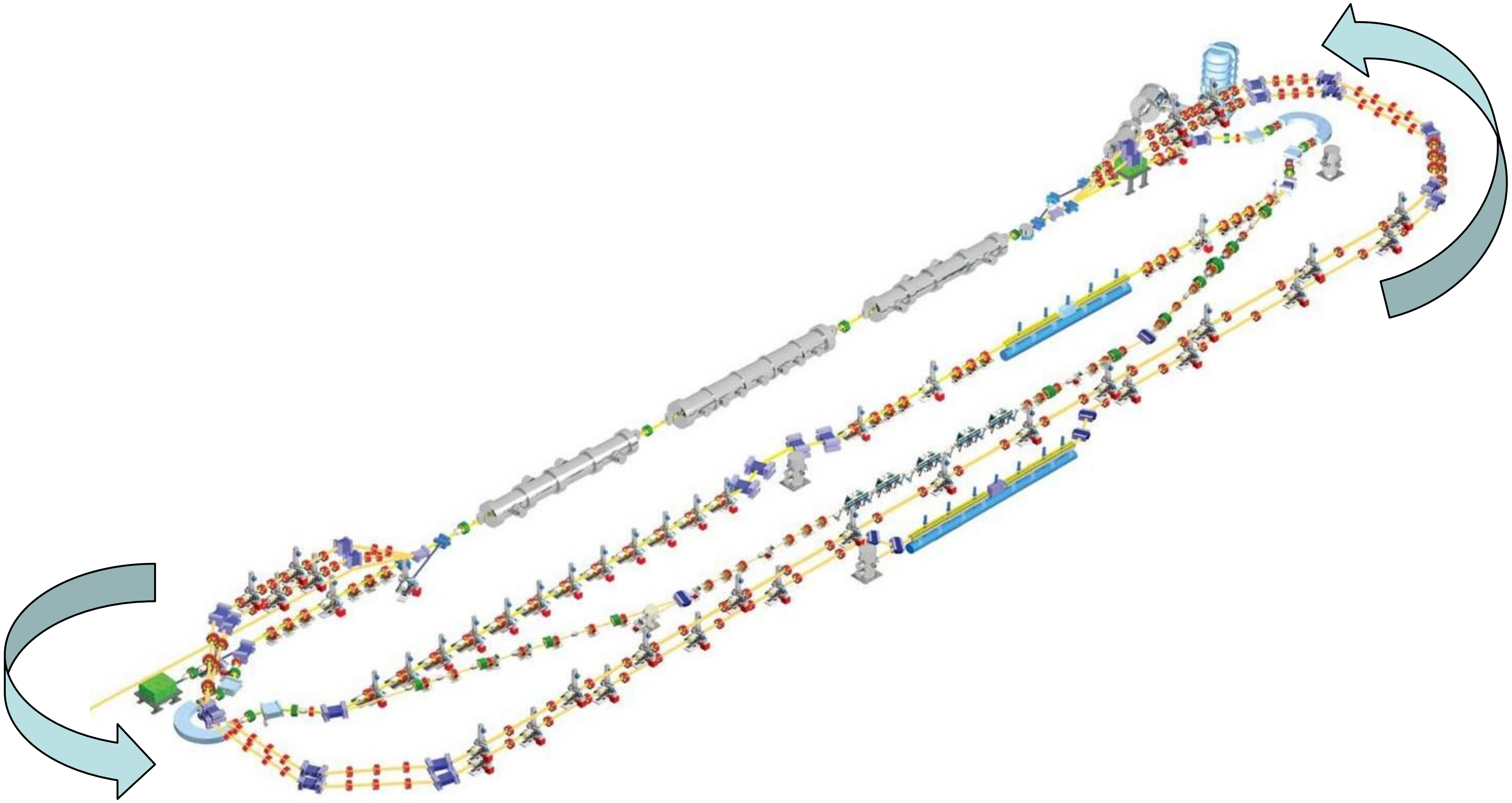
Transforming to JLAMP



Transforming to JLAMP

Add

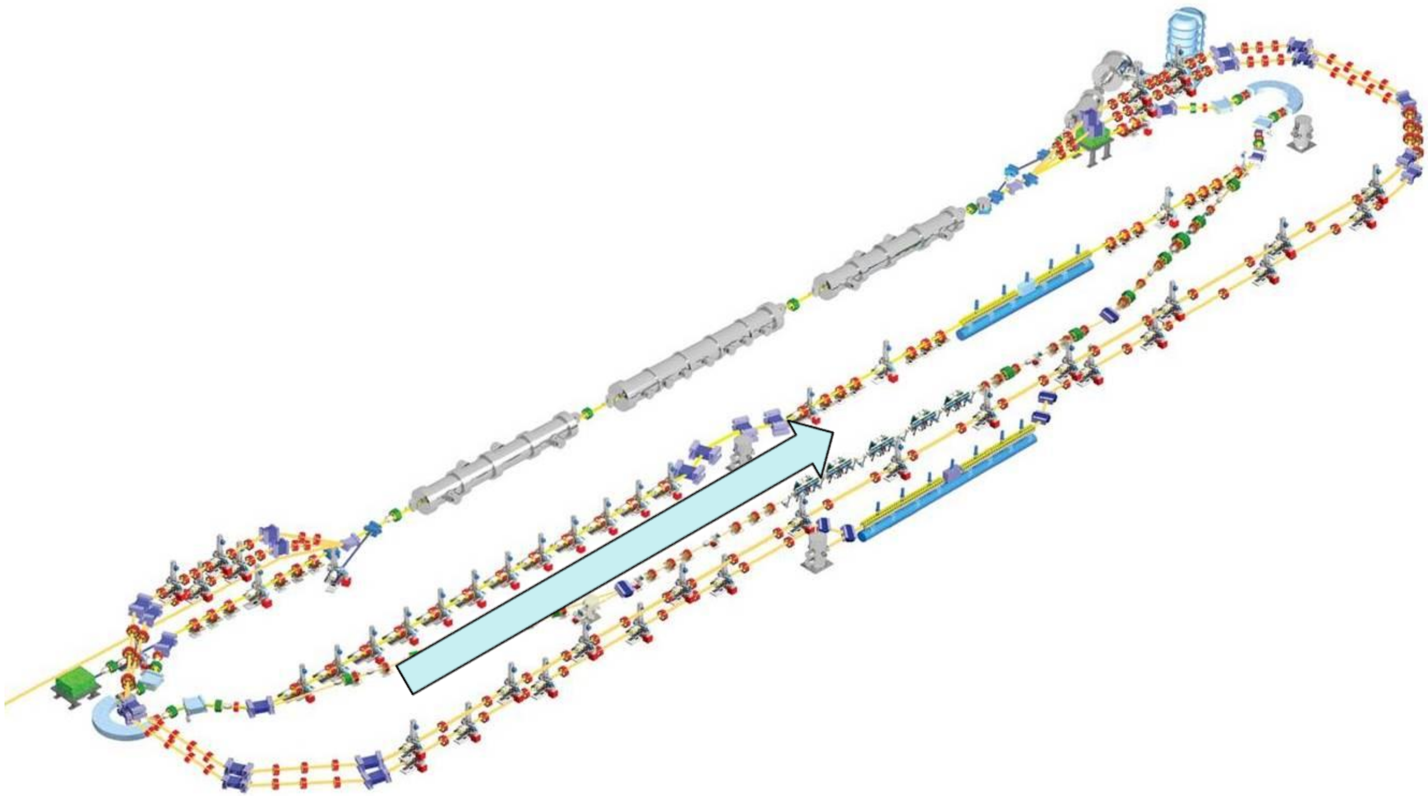
- Two more arcs



Transforming to JLAMP

Add

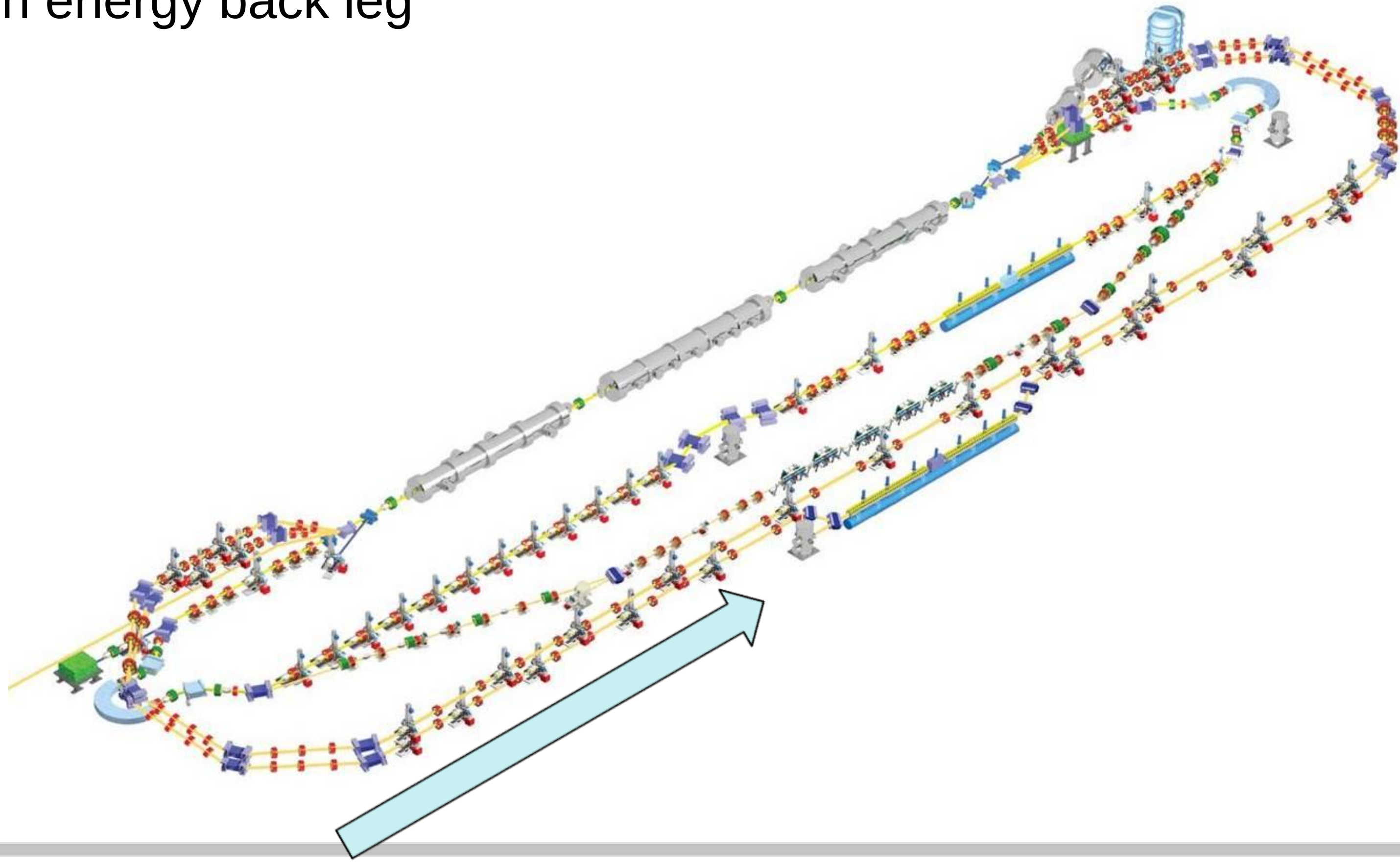
- Two more arcs
- A low energy back leg



Transforming to JLAMP

Add

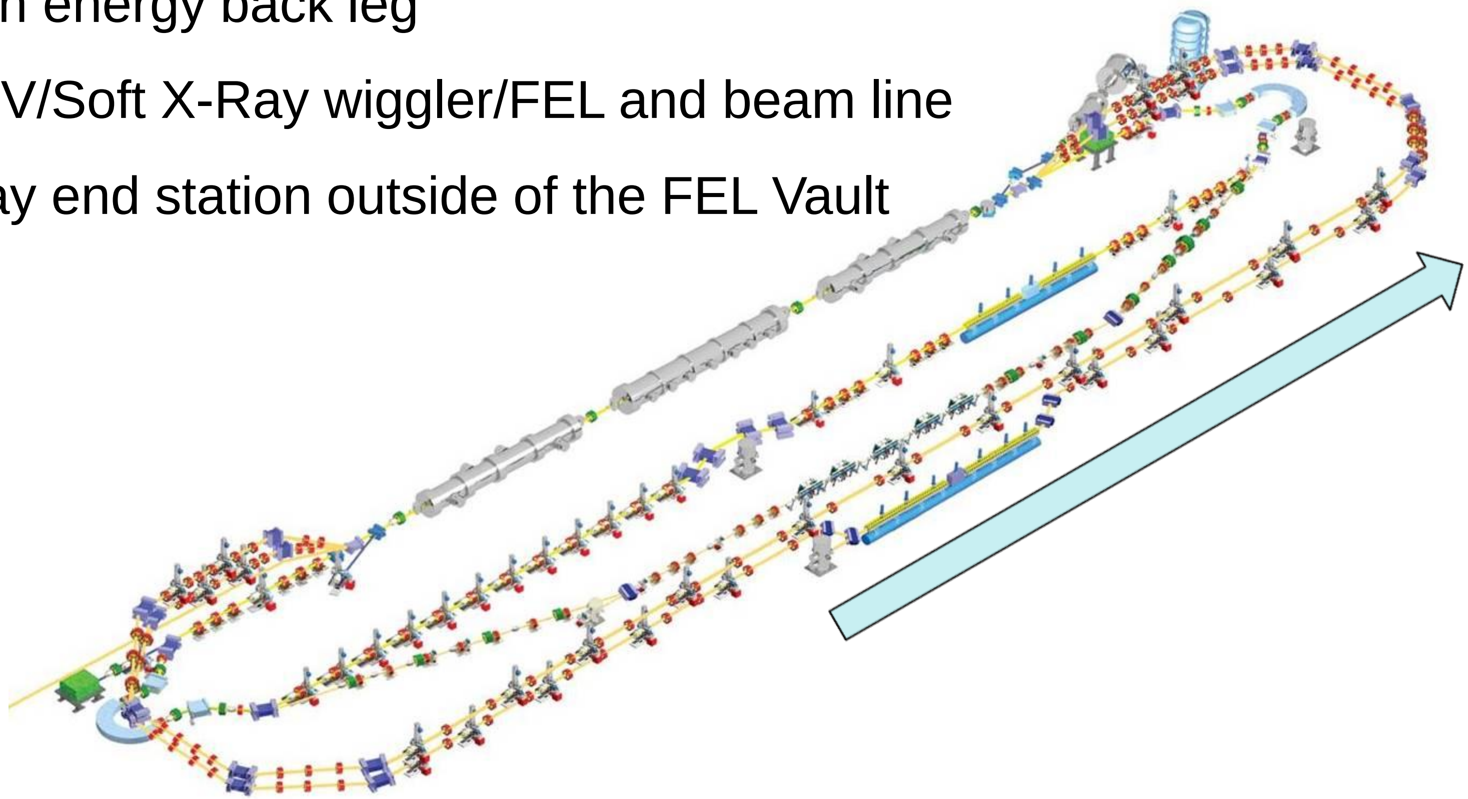
- Two more arcs
- A low energy back leg
- A high energy back leg



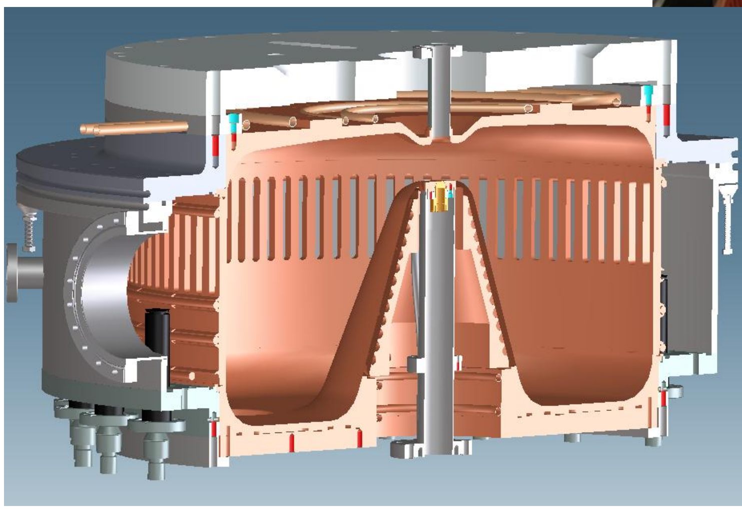
Transforming to JLAMP

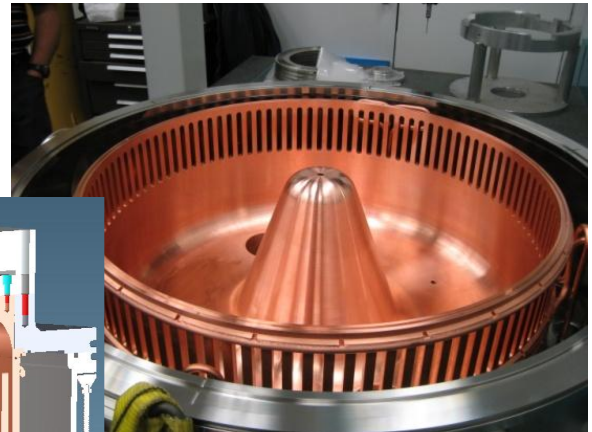
Add

- Two more arcs
- A low energy back leg
- A high energy back leg
- A VUV/Soft X-Ray wiggler/FEL and beam line
- A Xray end station outside of the FEL Vault



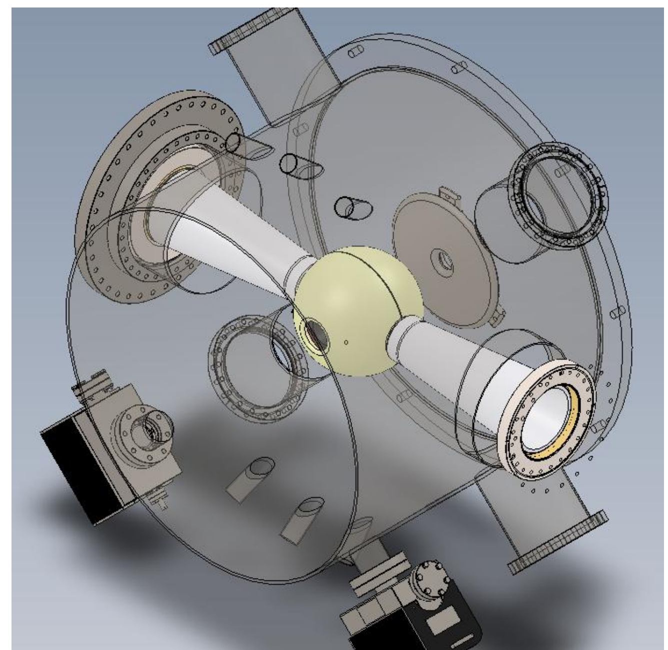
Injector Gun Technologies





Berkley NCRF gun*

- 24.1 MV/m peak surface fields
- 19.5 MV/m at the cathode
- 750 keV output beam energy
- Easy Cathode Installation.
- Operating frequency 187.1 MHz
- Dual coaxial RF feeds.

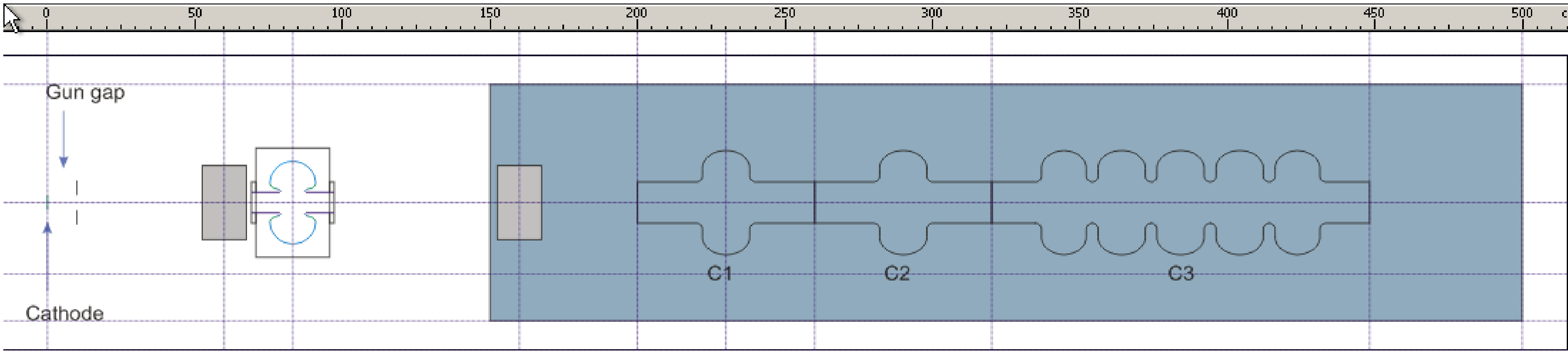


JLAB inverted insulator DC gun

- 500 keV operation
- Integral load lock
- Water cooled cathode
- Ultra high vacuum pumping
- Designed for 1 nC at >100 MHz

*Ken Baptiste, et. al. Lawrence Berkeley National Lab

Injector Layout



- **Common Booster/Merger layout for either gun.**
- **Presently considering layout with:**
  - Buncher cavity
  - Two single-cell capture cavities **β** < 1
  - One 5-cell accelerating cavity **β** = 1
  - Operating frequency of 748.5MHz

ERL Cryomodules

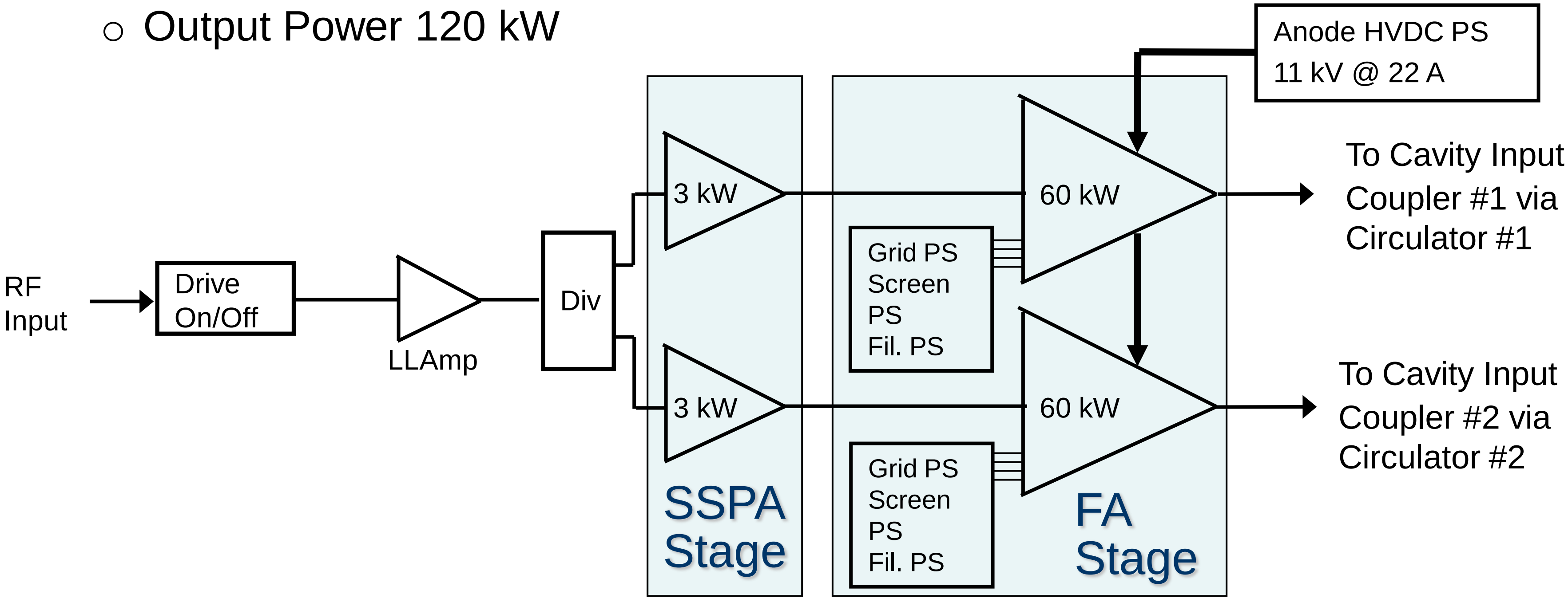
- **ERL cryomodules are based on the proven 12 GeV C100 cryomodule design**
- **Three cryomodules each with 5.6 m of active length.**
- **Design gradient 19 MV/m average with the potential to operate at higher gradients.**

RF Power Required for Different Operating Modes

	1 Pass Tune Beam	2 Pass Tune Beam	Pulsed 2 Pass ERL Oscillator	CW 2-Pass ERL Oscillator	2 Pass FEL Amplifier
Maximum Charge (pC)	200	200	200	200	200
Repetition rate (MHz)	2.34	1.17	4.68	4.68	Single or double shot to 0.10
Macro Pulse Length (μs)	100	100	100 to 1000	CW	CW
Macro Pulse Rep. Rate (Hz)	2	2	2 to 60	CW	CW
Beam Current During Pulse or CW (μA)	468	468	936	936	< 20
Linac Power / Cavity at 22 MV/m (kW)	10.6	10.6	7.2	7.2	4.4
Minimum Injector RF Power for 20 MeV (kW)	9.36	4.68	18.7	18.7	0.4

NCRF Gun RF Requirements*

- **Calculated RF power requirement 87.7 kW at 187.125 MHz**
- **Amplifier implementation**
  - Thales TH 571B based, class AB tetrode amplifier.
  - Frequency 187 ± 3 MHz
  - Output Power 120 kW



High Power Amplifier with HVDC Power Supply

Commercial Vendor Developed High Power Amplifier

- **HPA developed by ETM Electromatic For LBNL working under a DOE Contract.**
  - Order placed in June 2009
  - Production testing to be completed May 2010
  - Delivery expected May 2010
- **Approximate costs $1M for HPA and HVPS only.**

Approximately 3.3m W x 1.55m H x 1.5m D and 4,300 kg

Parameter	Expected
Frequency	187 MHz
Bandwidth (-1dB)	3 MHz
Filament Voltage	7.5 V
Anode Voltage	9.6 kV
Anode Current	9.7 A
Screen-grid Voltage	710 V
Screen-grid Current	310 mA
Control-grid Voltage	-110 V
Control-grid Current	180 mA
TH 571B RF Input	1.4 kW
RF Output	2 x 60 kW

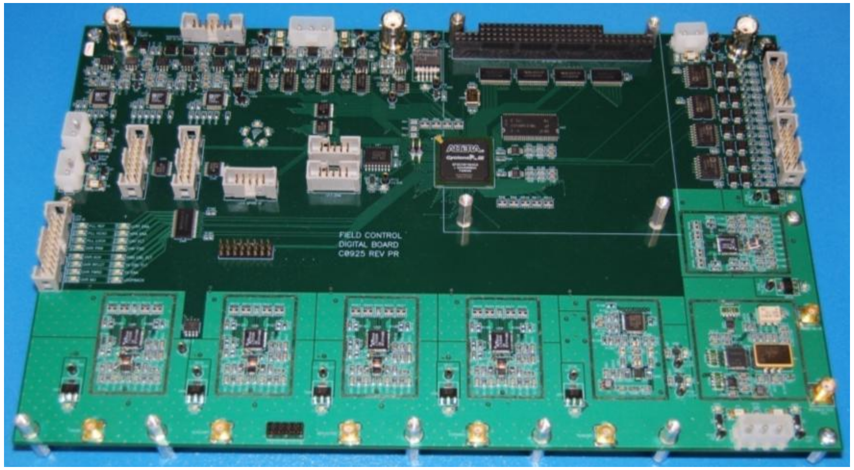
*Ken Baptiste, et. al. Lawrence Berkeley National Lab

Buncher and Injector Cryomodule HPRF requirements

- **Total injector RF power to the beam < 20 kW**
- **Frequency is 748.5 MHz**
- **The bulk of the acceleration comes from the 5-cell cavity:**
- **Margin added for**
  - Microphonics
  - Cavity detuning effects
  - Non-ideal loaded-Q
- **Currently the predicted RF Power needs are:**
  - 5-cell cavity approximately 25 kW
  - 1-cell cavities less than 10 kW
  - Buncher cavity less than 5 kW
- **The Current plan is to use off the shelf IOT technology for the system.**
- **DC power compatible with pulsed cavity and beam operations is critical.**

Low Level RF

- **LLRF system based on 12 GeV upgrade system.**
  - Common digital board, interface and packaging
  - 100 units currently in production
  - Will require the development of two new RF front end daughter cards one for 748.5 MHz and one for 187.125 Mhz.



- **Drive/Seed laser will use the same control electronics.**
  - Will be designed such that the standard LLRF module will control drive and seed laser phase and frequency.
  - Will require development of tuning algorithms as well as a method to synchronize other electro optical devices to the drive laser micro pulse repetition frequency.
  - Seed Laser will make use of beam based phase feedback system for tracking beam phase drifts.

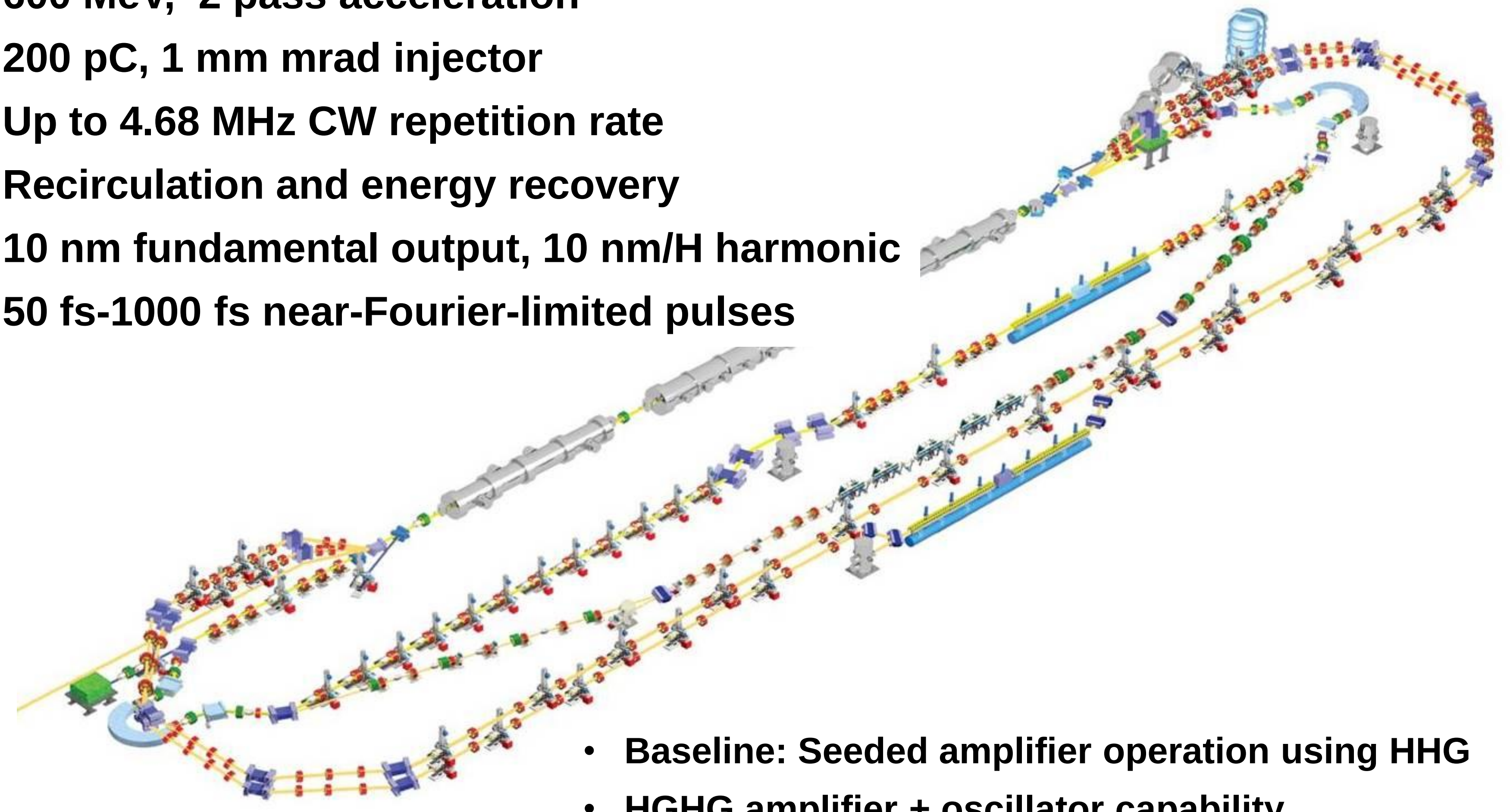
- **Fiber optic based timing system required for triggering of end station experiments, and desirable for the injector and linac synchronization.**

Linac RF Requirements

- **Linac RF to be copies of the CEBAF 12 GeV systems.**
  - Will make use of existing infrastructure and personnel.
  - Will make use of existing spare parts, test fixtures, etc.
  - Substantially reduced NRE.
  - If the timing works we can purchase components as options on existing contracts.
- **Klystron based system.**
  - 13 kW saturated power.
  - 24 klystrons plus spares to be purchased.
  - Current vendor costs is approximately $45k per klystron.
- **DC Power to be copies of 12 GeV hardware**
  - 16 kV
  - 14 Amps per zone
  - Interlocks, HPA and controls are CEBAF designs used for the 12 GeV project.
  - Current vendor costs approximately $115k per 8-klystron zone.
- **Requires new circulators, loads, and some waveguide hardware**
- **Controls, packaging and system integration are an in-house effort.**

JLAMP FEL designed for unparalleled 10-100 eV average brightness

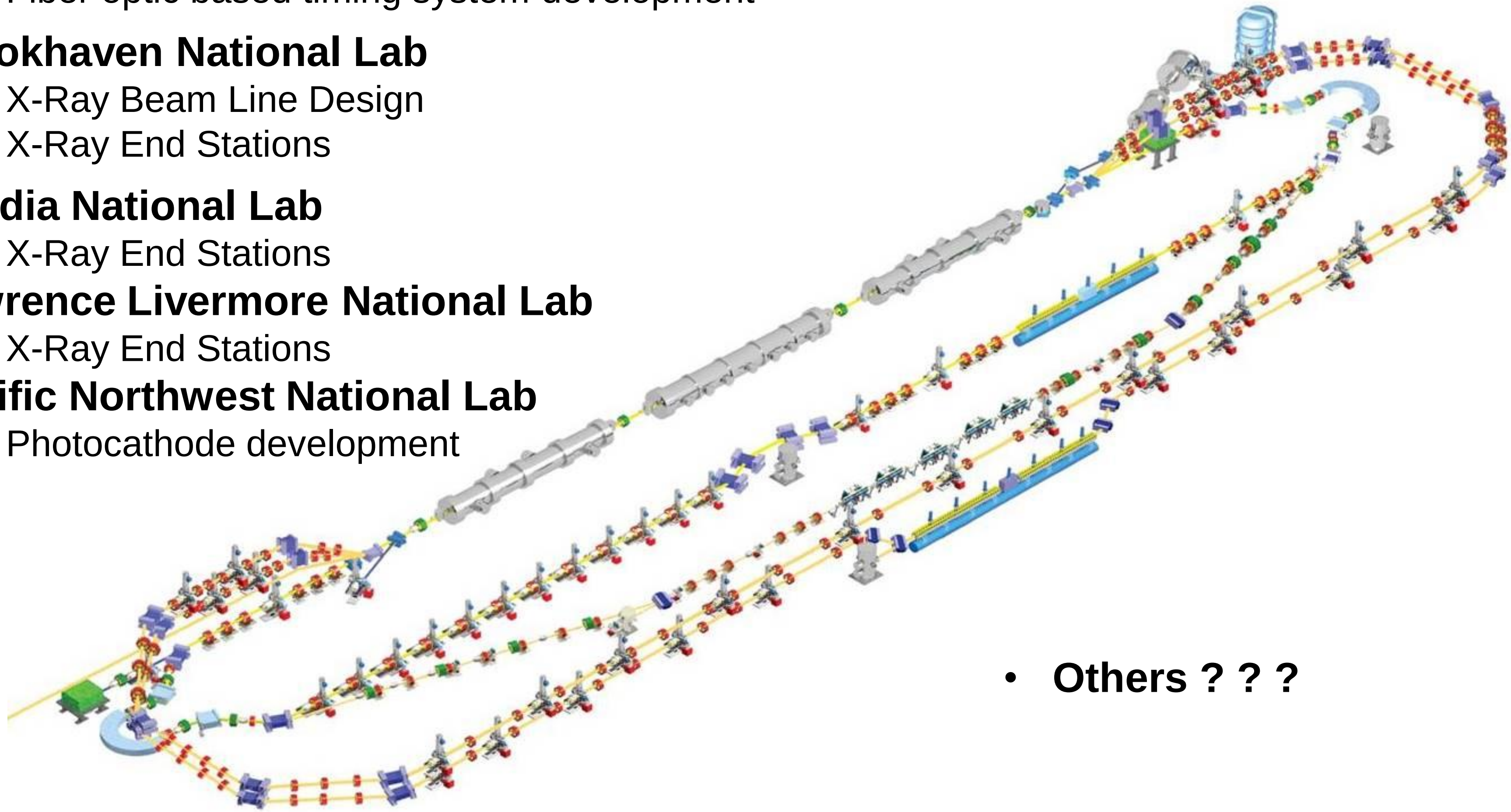
- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 nm fundamental output, 10 nm/H harmonic
- 50 fs-1000 fs near-Fourier-limited pulses



- Baseline: Seeded amplifier operation using HHG
- HGHG amplifier + oscillator capability
- THz wiggler for synchronized pump/probe

JLAMP FEL Will be a Multi-Lab Cooperative Effort

- **Lawrence Berkeley National Lab**
  - NCRF Gun and VHF amplifier
  - Injector design studies
  - Fiber optic based timing system development
- **Brookhaven National Lab**
  - X-Ray Beam Line Design
  - X-Ray End Stations
- **Sandia National Lab**
  - X-Ray End Stations
- **Lawrence Livermore National Lab**
  - X-Ray End Stations
- **Pacific Northwest National Lab**
  - Photocathode development



- **Others ? ? ?**

JLAMP – 4^{th} Generation VUV/Soft X-Ray Light Source

Operates from 7 eV table-top laser energy to 500 eV with harmonics

3 to 6 orders of magnitude brighter than FLASH

Scientific case focused on DOE-BES Grand Challenges from world-class committee

- Materials science
- AMO (Atomic, Molecular, Optical Science)
- Imaging

Secondary goals address BES R&D priorities (injector, srf, collective effects, seed lasers) for next generation hard X-ray photon facility

< $100M and fast schedule since it builds on existing FEL infrastructure

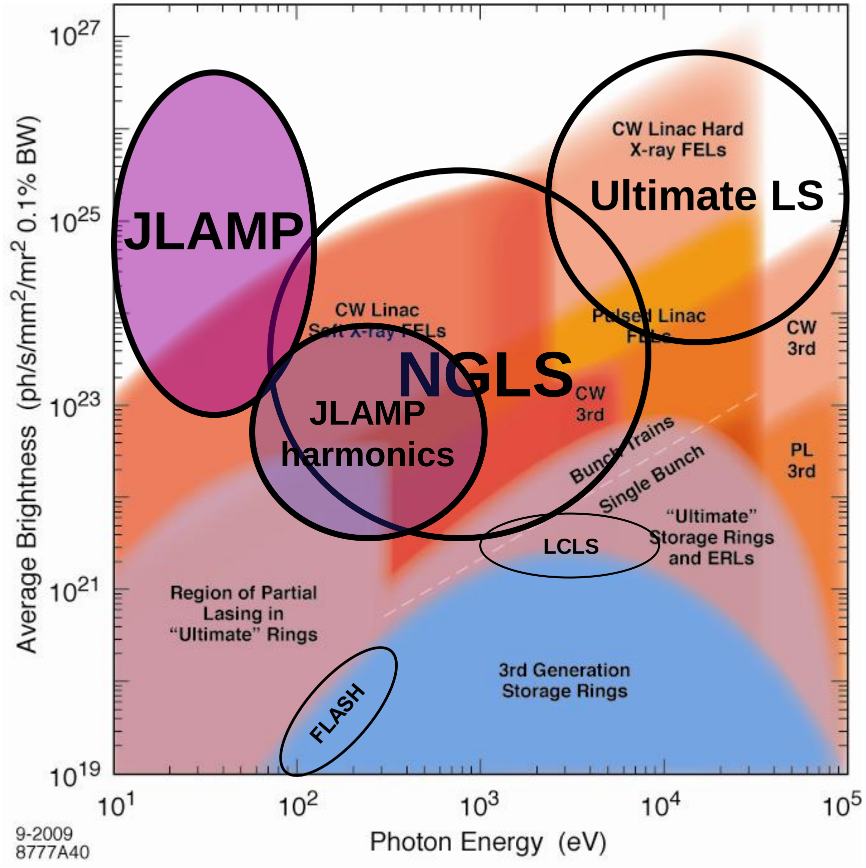
Collaborative effort with support and funding from ? ? ?

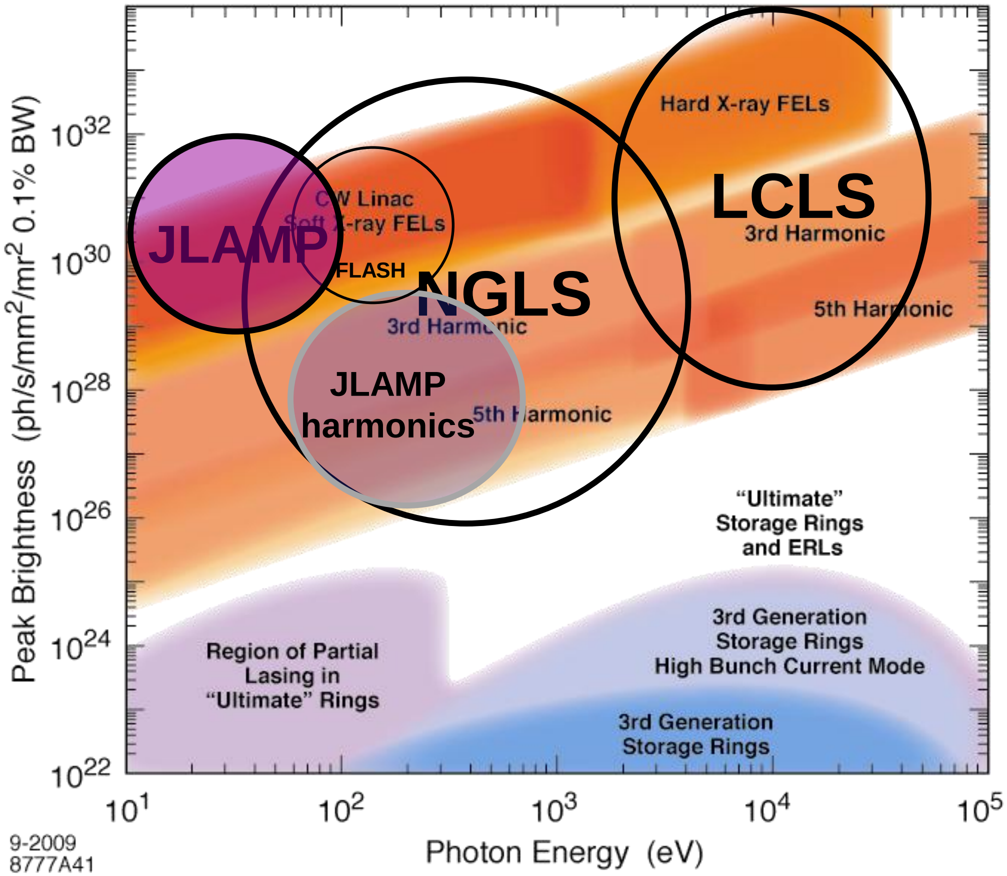
The Jefferson Lab FEL Team

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the DOE Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

Backups

JLAMP in the Light Source Landscape





JLAMP delivers important parameter space un-addressed in hard X-ray proposals, with chemical selectivity to measure atomic structure at the nano-scale, measurement of dynamics on the attosecond timescale of electron motion, and imaging

User Topic Summary

Condensed matter physics

- Ultrafast photoemission spectroscopy of coherently controlled complex materials
- Femtosecond Pump/Probe ARPES in artificial nanosystems
- Electronic states in strongly correlated systems using soft X-ray scattering

Chemical physics and Atomic, Molecular, Optical physics

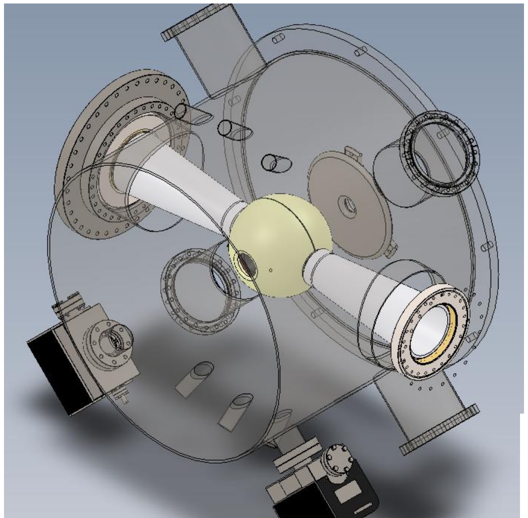
- Matter at small dimensions
  - Atomic and electronic structure of size-selected clusters
  - Chemical reactivity of size-selected neutral clusters and nanoparticles
  - Time-resolved nanoscale "surface" dynamics
- Molecular movies
  - Electronic dynamics using time-resolved ESCA
  - Time-resolved photoelectron diffraction in gas-phase molecules
- Ultrasensitive trace analysis of noble gas isotopes

Imaging biological and soft condensed matter

- High resolution structural determinations of non-periodic materials and dynamic studies of soft matter

Many approaches for a CW High Brightness Gun – but none working yet

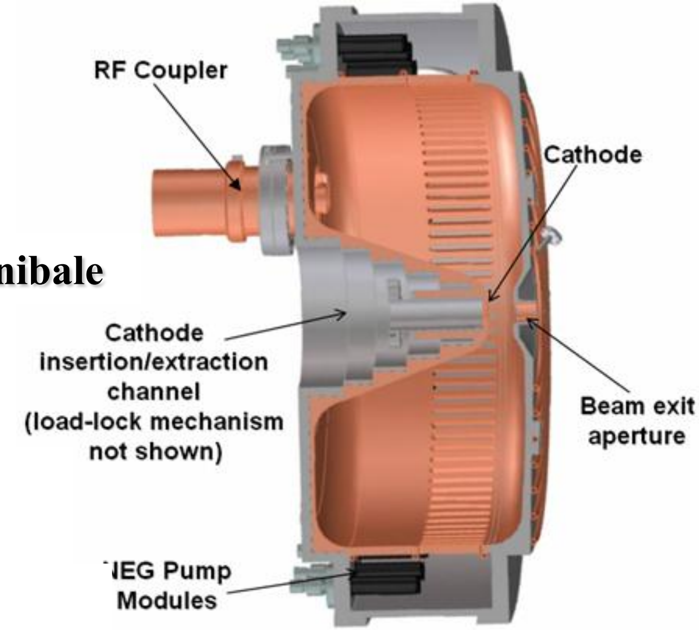
JLab Advanced DC Gun



C. Hernandez-Garcia

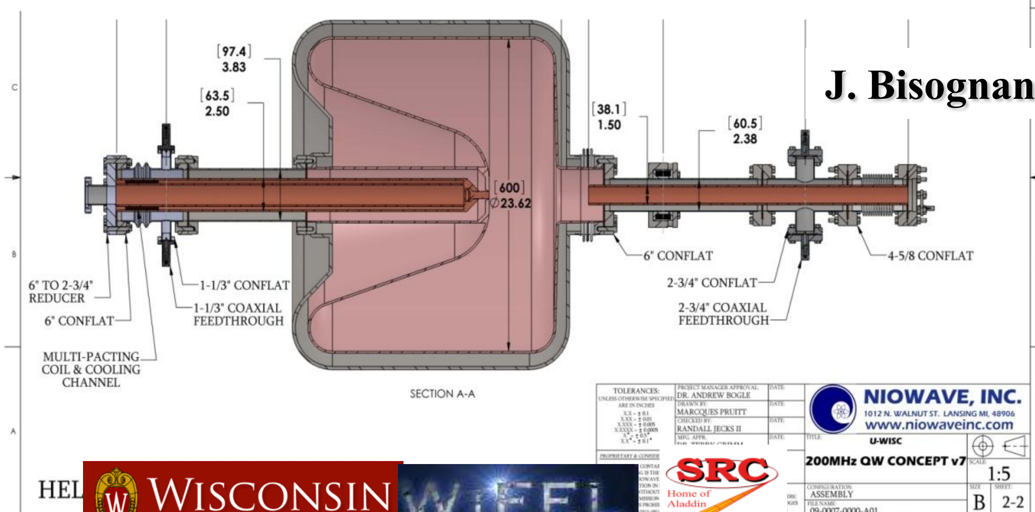
LBNL Low Frequency RF Gun

F. Sannibale



WiFEL/Niowave SRF Gun

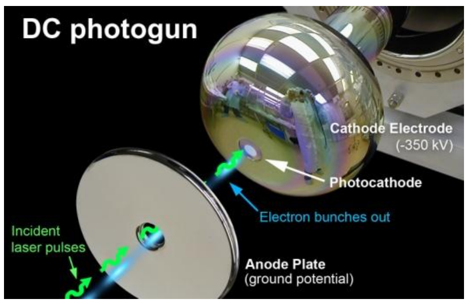
J. Bisognano



HV DC Photoemission Guns for 4th Generation Light Sources

Carlos Hernandez-Garcia, Jefferson Lab

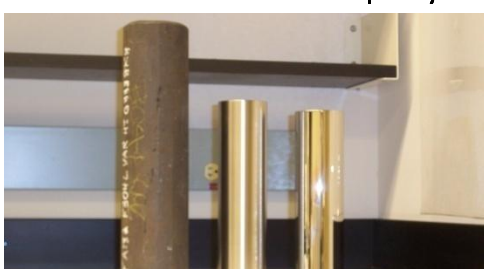
- **The 4GLS accelerators need unprecedented average brightness electron beam (sub-micron emittance like the LCLS injector *AND* >10 mA CW beam like the Jefferson Lab FEL injector)**
- **Such an electron beam has not been demonstrated and represents a major technical challenge**
- **We need support for R&D on fundamental cathode physics (electron emission) and on electron beam dynamics near the cathode surface**



Electron pulses are generated when the GaAs photocathode is illuminated with laser pulses operating at a sub-harmonic of the accelerator frequency

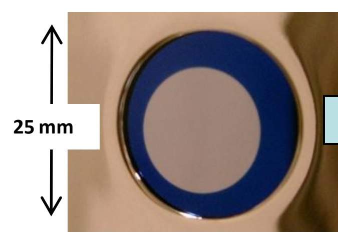
The FEL gun has delivered a record 7000 Coulombs and over 900 hours of CW beam time between 2004 and 2007. At 10 mA and 350kV DC is the most powerful photoemission gun to ever power an FEL.

The JLab FEL team is developing the next generation of High Voltage DC electron guns designed to meet the beam requirements for high repetition rate VUV and soft X-ray accelerator based light sources

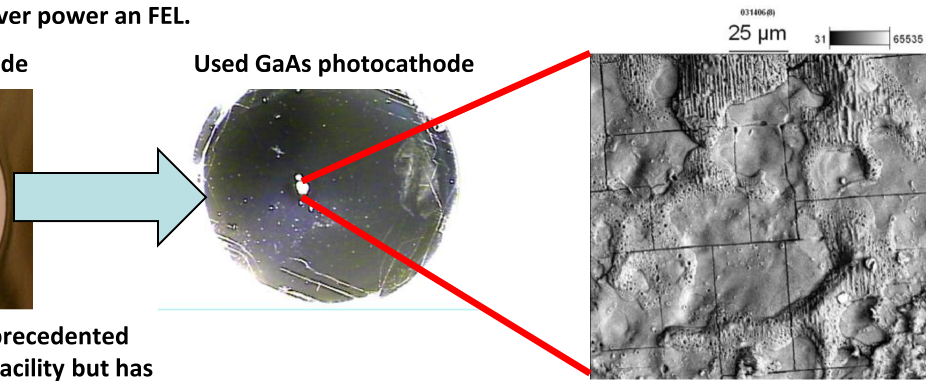


Field emission from electrodes represents one of the technical challenges of ultra-high brightness and high current photoguns

Fresh GaAs photocathode



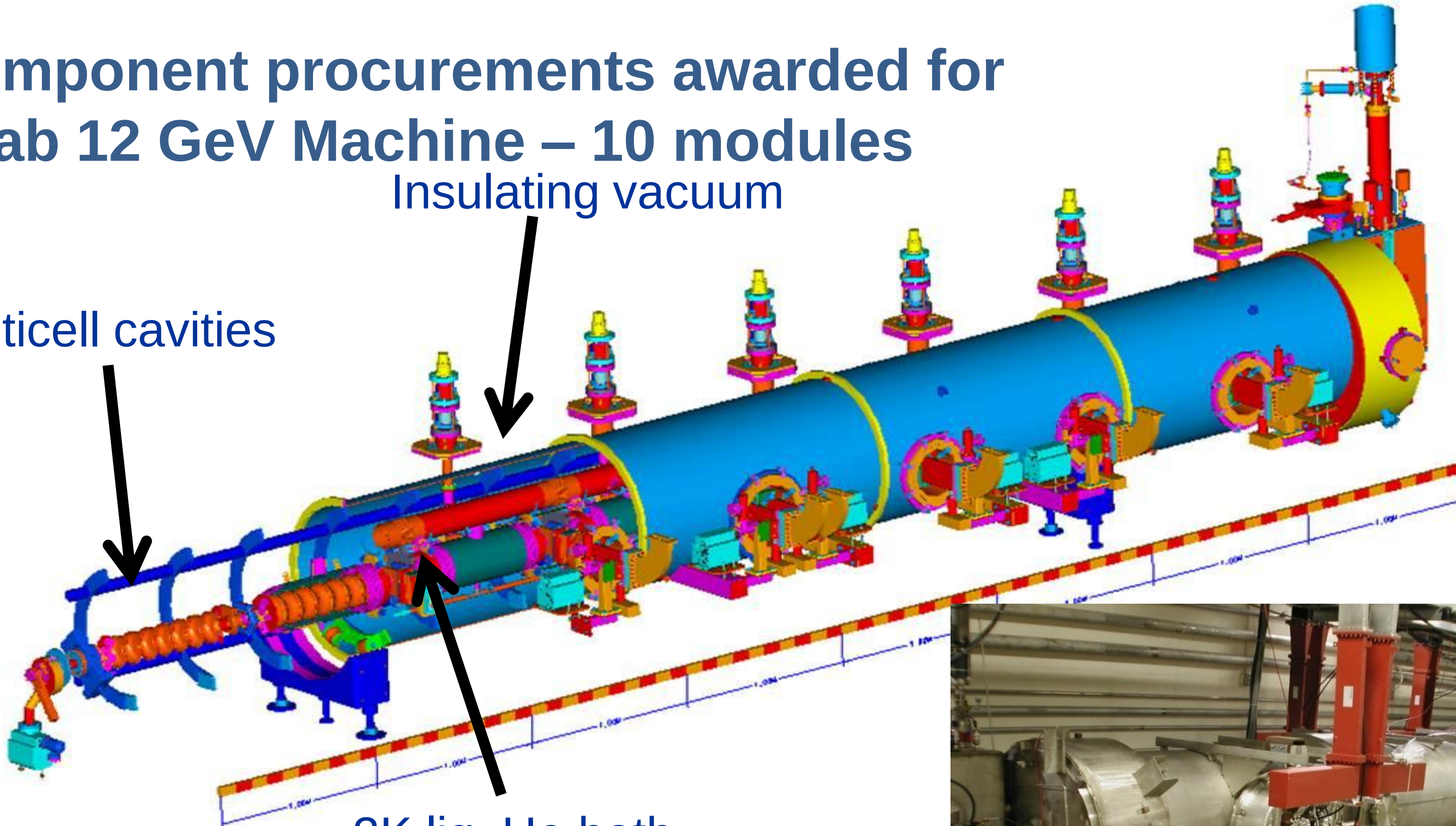
Used GaAs photocathode



Photocathode robustness at unprecedented average current is key for an user facility but has not been demonstrated yet

100 MeV High Gradient Module

Component procurements awarded for JLab 12 GeV Machine – 10 modules



Original CEBAF module