ERLs for Light Sources

George R. Neil, Associate Director

Jefferson Lab

PAC 2011

March 29, 2011

New York

DOE BES Science Grand Challenges

Directing Matter and Energy; 5 Challenges for Science & the Imagination

1. How do we control materials processes at the level of the electrons?
   Pump-probe time dependent dynamics

2. How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties?
   PLD, photo-chemistry, XRS

3. How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties?
   Pump-probe time dependent dynamics, XRS

4. How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?
   Pump-probe time dependent dynamics, XRS

5. How do we characterize and control matter away -- especially very far away -- from equilibrium?
   Non-linear dynamics, ultra-bright sources

Report - Graham Fleming and Mark Ratner (Chairs).

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light from next generation light sources

Third generation x-ray sources

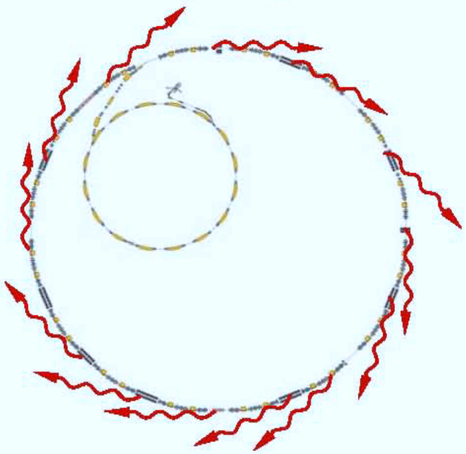
Fourth generation x-ray sources

Storage ring

$\varepsilon \sim E^2/R$

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

bunch charge 1nC



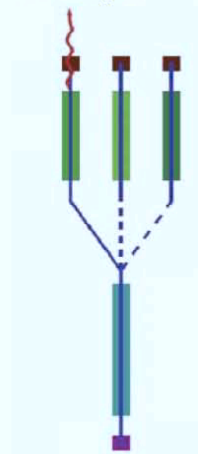
- Many experiments
- Ready tunability
- High flux
- ps pulses

LINAC source (=> FEL)

$\varepsilon \sim 1/E$

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

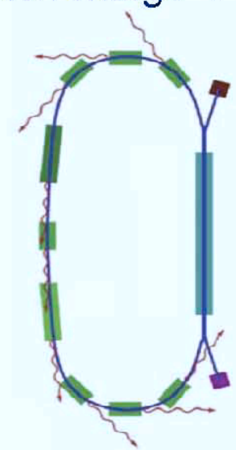
bunch charge ≤ 1 nC



- 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

Implications

Currents over ~ 1mA the cost of RF power favors recovering beam power in an ERL rather than dumping beam

Please note that:

a) 4th Generation Sources do not displace need for 3rd Generation

b) ERL operation does not preclude FEL operation

C) ERLs without FELs suffer a large decrease in light produced per bunch due to lack of longitudinal bunching

D) mitigated by: Operate at lower charge but very high repetition rate: minimizes space-charge-driven emittance growth to achieve ultimate emittance, short pulse length

Applications need high repetition rate

		Photon Attributes:						
Research Opportunities	Research Area	Coherence	Brilliance (average)	Spatial resolution (<1nm)	Time resolution (< 1 ps)	Peak Brilliance	Energy Resolution	Polarization (circular, linear)
Nano materials for energy	Nanoparticle spectroscopy for solar cells	Nano XPS			Charge carrier dynamics spectroscopy			
Nano materials for energy	Charge transfer dynamics in photosynthesis				Scattering and spectroscopy to identify and control individual steps			
Nano materials for energy	Battery stress and degradation	functional imaging and spectroscopy						
Information Technology	Magnetic quantum dot materials			Imaging in magnetic domains				
Information Technology	Understanding and development of novel supconductors		spatially resolved electronic characterization Nano-ARPES, RIXS					x
Environmental Sciences	Chemistry at the surface of mineral particles	imaging structure and function of mineral particles in a wet environment						
Catalysis and chemistry			monitor catalysis with atomic resolution under process conditions		movies of a chemical reaction, fs spectroscopy and scattering			
Life Sciences				flash imaging of function at the cellular level				
Life Sciences		3-D mapping of chromosomes						x
Health and medical Physics		Imaging and spectroscopy of enzyme chemistry					x	
Nano-materials			EXAFS of Clusters			spectroscopic characterization and imaging of individual clusters		
Quantum Control					resolving and controlling electron dynamics			
Extreme environments					X-ray imaging of plasma processes			

From W. Eberhardt

Applications need high repetition rate

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Nano materials for energy	Charge transfer dynamics in photosynthesis				Scattering and spectroscopy to identify and control individual steps			
Nano materials for energy	Battery stress and degradation	functional imaging and spectroscopy						
Information Technology	Magnetic quantum dot materials			Imaging in magnetic domains				
Information Technology	Understanding and development of novel supconductors		spatially resolved electronic characterization Nano-ARPES, RIXS					x
Environmental Sciences	Chemistry at the surface of mineral particles	imaging structure and function of mineral particles in a wet environment						
Catalysis and chemistry			monitor catalysis with atomic resolution under process conditions		movies of a chemical reaction, fs spectroscopy and scattering			
Life Sciences				flash imaging of function at the cellular level				
Life Sciences		3-D mapping of chromosomes						x
Health and medical Physics		Imaging and spectroscopy of enzyme chemistry					x	
Nano-materials			EXAFS of Clusters			spectroscopic characterization and imaging of individual clusters		
Quantum Control					resolving and controlling electron dynamics			
Extreme environments					X-ray imaging of plasma processes			

ERL

FEL

From W. Eberhardt

ERL Advantages

Flexible bunch structure + very short pulses possible

Ability to independently optimize electron optics for each insertion device (or vary with time) although multiple in-line insertion devices make changes complex to manage

Small energy spreads – more photons in narrow band

Nearly equal and small transverse emittances for nearly round beams – higher usable brightness, transverse coherence

CW operation is more stable than a pulsed linac

{*but not as stable or reliable as a ring – must work to stabilize source + educate users!* }

Major R&D Efforts Around the World

- Injector, injector, injector! No existing injector delivers required CW brightness. Many groups are working on this: LBNL, Cornell, Wisconsin, JLab, KEK, Daresbury, BNL, PKU…
- Brightness preservation: Solutions to coherent synchrotron radiation (CSR) emittance degradation, longitudinal space charge (LSC) in pulse compression
- Halo control essential for CW – non-Gaussian tails!!! $< 1\mu A$ local loss allowed
- High order mode & beam breakup control in cavities
- Wakefield and propagating mode damping

High HOM power lost at srf temps?

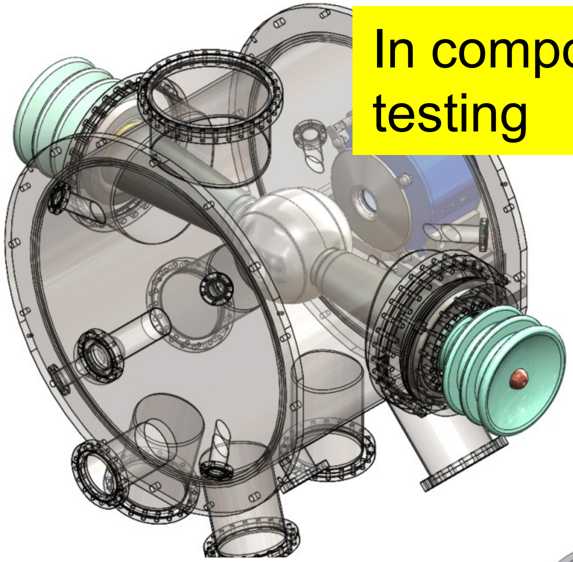
- Handling sizeable (~ 20 kW! @ 100 mA) THz radiation in bends
- Resistive wall heating in undulators 100W/m at 4mA on JLab IR FEL
- Reducing srf dynamic load to lower refrigerator costs; probably more important than increasing gradient

ERL R&D

The injector is a crucial technology– but none working yet at desired brightness

JLab Inverted DC Gun

In component testing

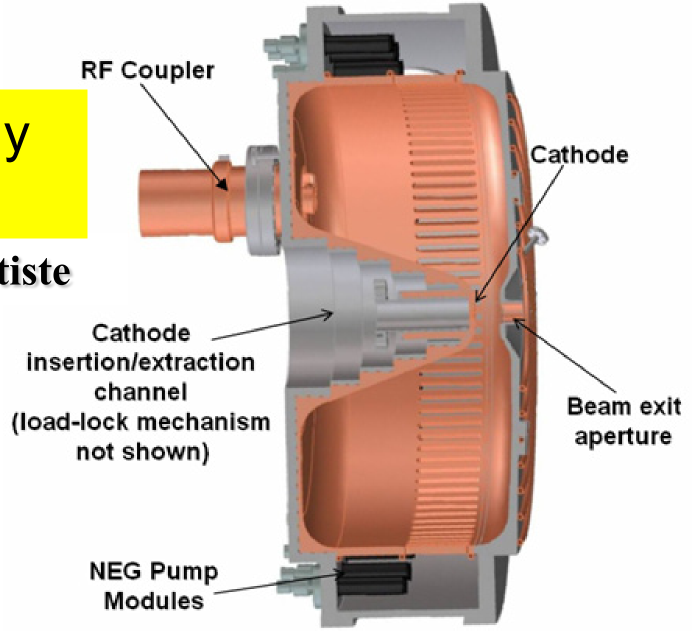


C. Hernandez-Garcia

LBNL Low Frequency RF Gun

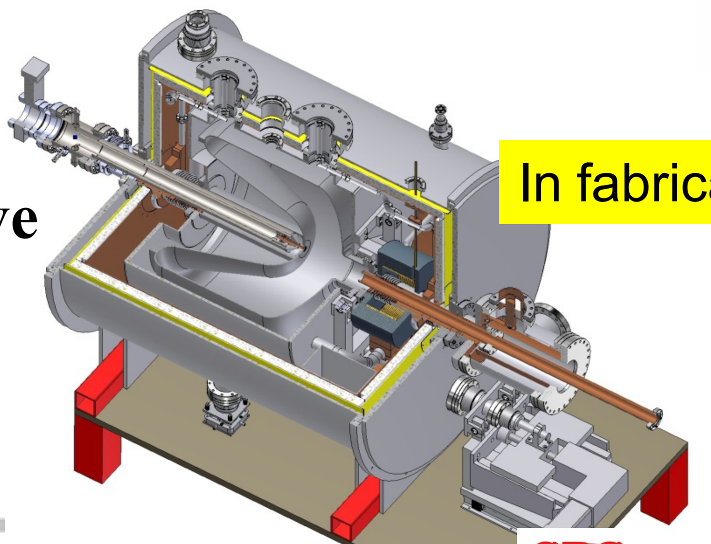
In assembly with RF

K. Baptiste



WiFEL/Niowave SRF Gun

In fabrication



J. Bisognano

INITIAL BEAM RESULTS FROM THE CORNELL HIGH-CURRENT ERL INJECTOR PROTOTYPE

I. Bazarov, S. Belomestnykh, E. Chojnacki, J. Dobbins, B. Dunham, R. Ehrlich, M. Forster, C. Gulliford, G Hoffstaetter, H. Li, Y. Li, M. Liepe, X. Liu, F. Loehl, D. Ouzounov, H. Padamsee, D. Rice, V. Shemelin, E. Smith, K. Smolenski, M. Tigner, V. Veshcherevich, CLASSE, Cornell University, Ithaca, NY 14853, U.S.A.
H. Sayed, TJNAF, Newport News, VA 23606, U.S.A

Cornell

Encouraging results with good emittance and 4 mA current

Further work underway to increase gun voltage using KEK-style insulator

Achieved desired brightness at 70 pC

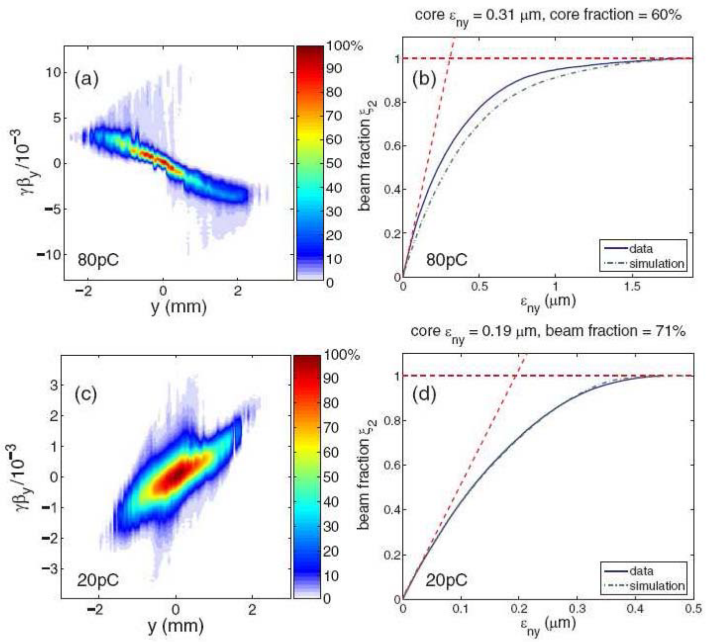


Figure 4: Measured (a), (c) transverse phase space after the gun and the corresponding emittance versus beam fraction curve (b), (d).

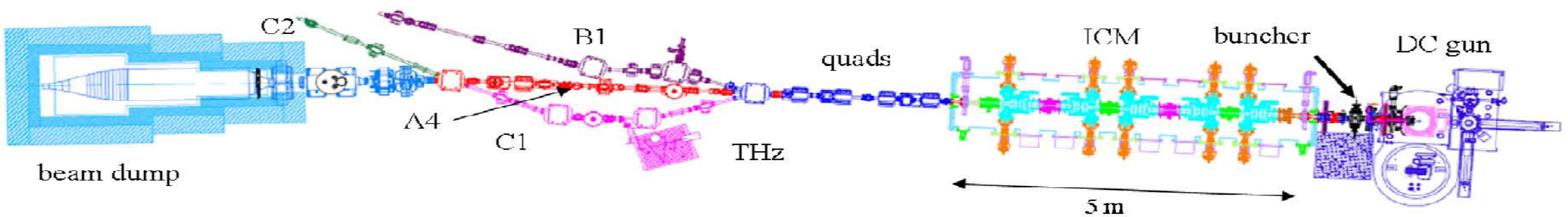


Figure 2: The layout of Cornell prototype ERL injector. Beam direction is to the left.

HIGH-VOLTAGE TEST OF A 500-KV PHOTOCATHODE DC GUN FOR THE ERL LIGHT SOURCES IN JAPAN

R. Nagai[#], R. Hajima, N. Nishimori, JAEA, Tokai, Naka, Ibaraki 319-1195, Japan
T. Muto, M. Yamamoto, Y. Honda, T. Miyajima, KEK, Oho, Tsukuba, Ibaraki 305-0801, Japa
M. Kuriki, H. Iijima, Hiroshima Univ., Higashi-Hiroshima, Hiroshima 739-8530, Japan
M. Kuwahara, S. Okumi, T. Nakanishi, Nagoya Univ., Nagoya, Aichi 464-8601, Japan

JAEA

Major advance in high voltage operation!

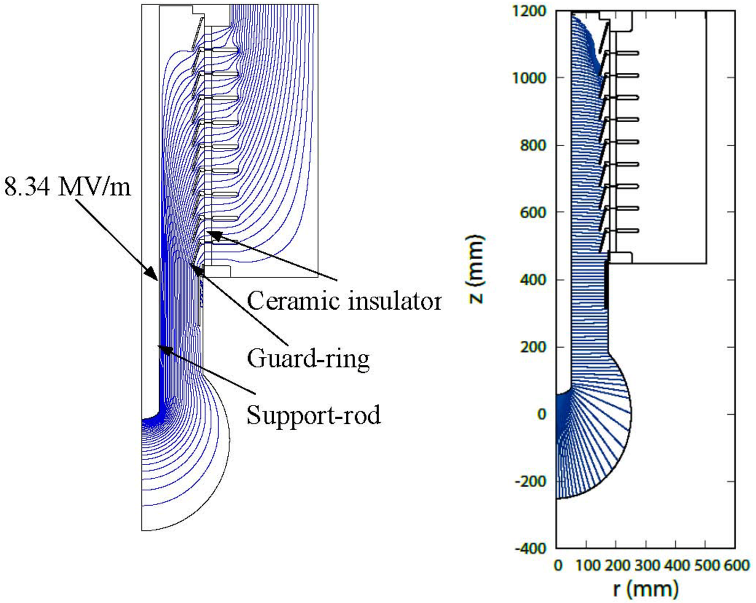


Figure 2: Field distribution (left) and emitted electron trajectories (right) of the gun.

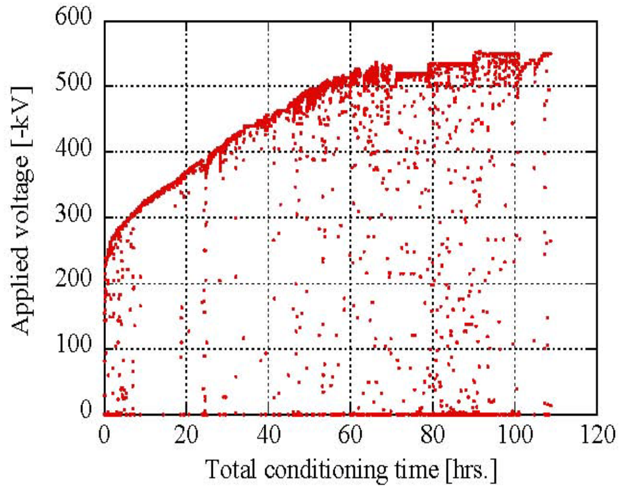
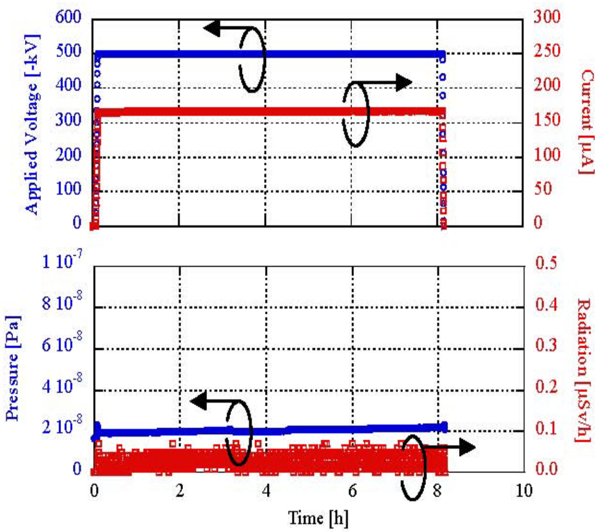
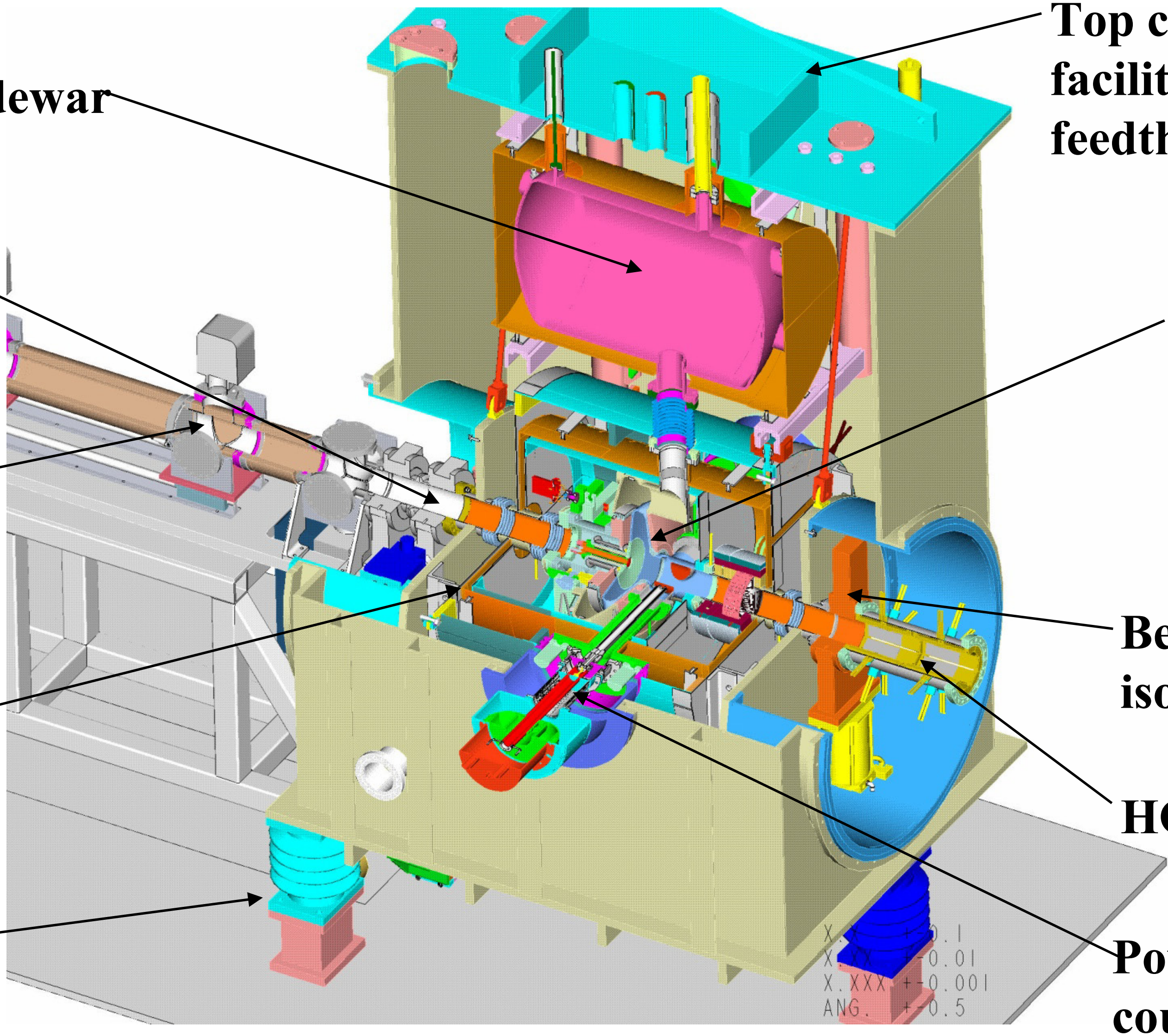


Figure 3: Applied voltage vs total time in the high-voltage conditioning.



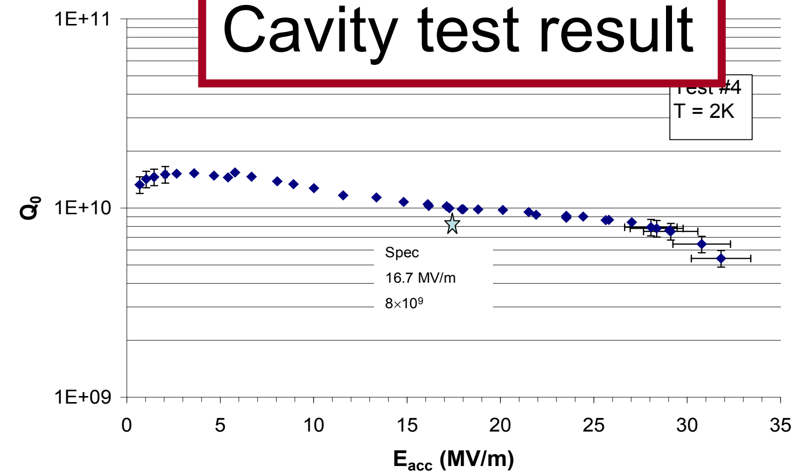
BNL High-current SRF electron-gun

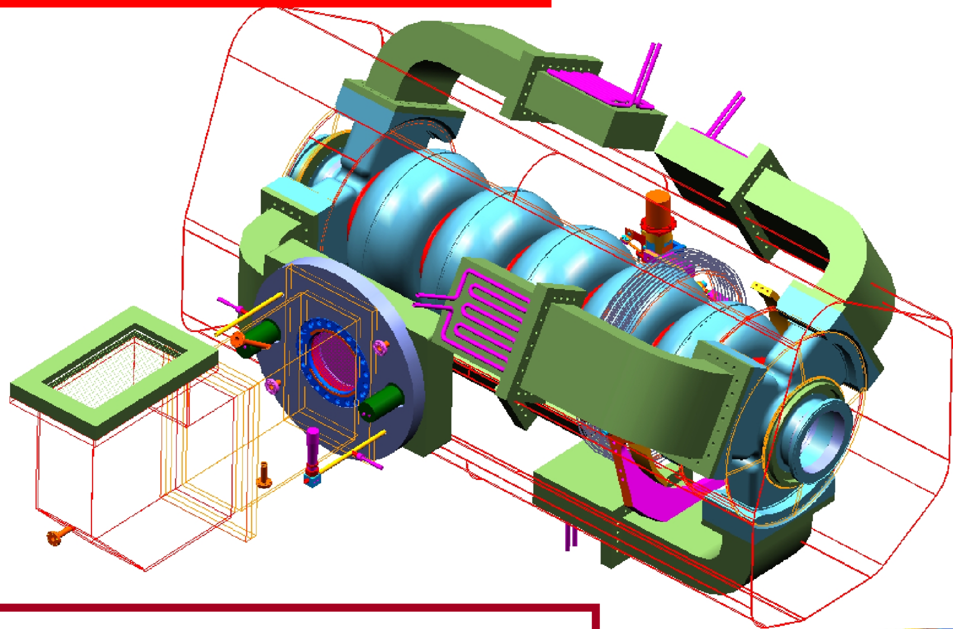


JLab Ampere-class Cavity

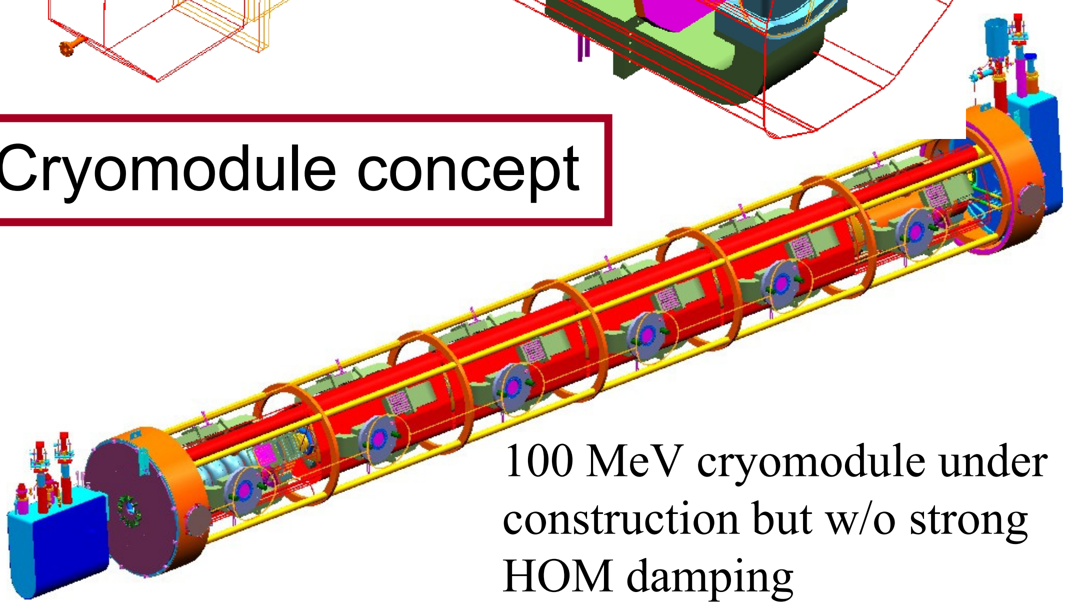
Courtesy: R. Rimmer

Cavity test result





Cryomodule concept

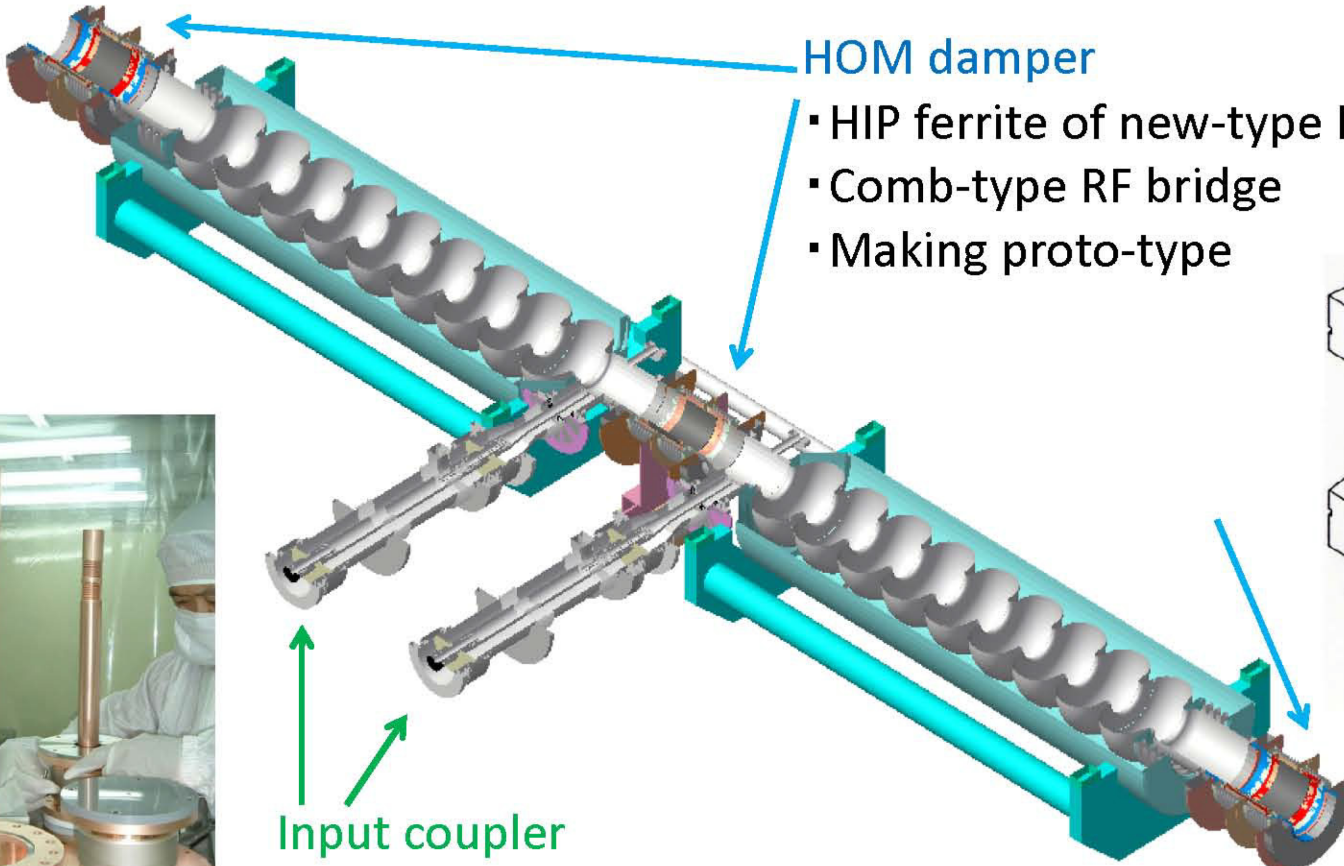


100 MeV cryomodule under construction but w/o strong HOM damping

1500 MHz Cu prototype

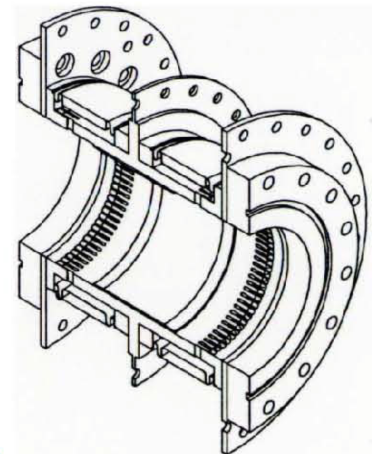
KEK

Cryomodule development



HOM damper

- HIP ferrite of new-type IB004
- Comb-type RF bridge
- Making proto-type



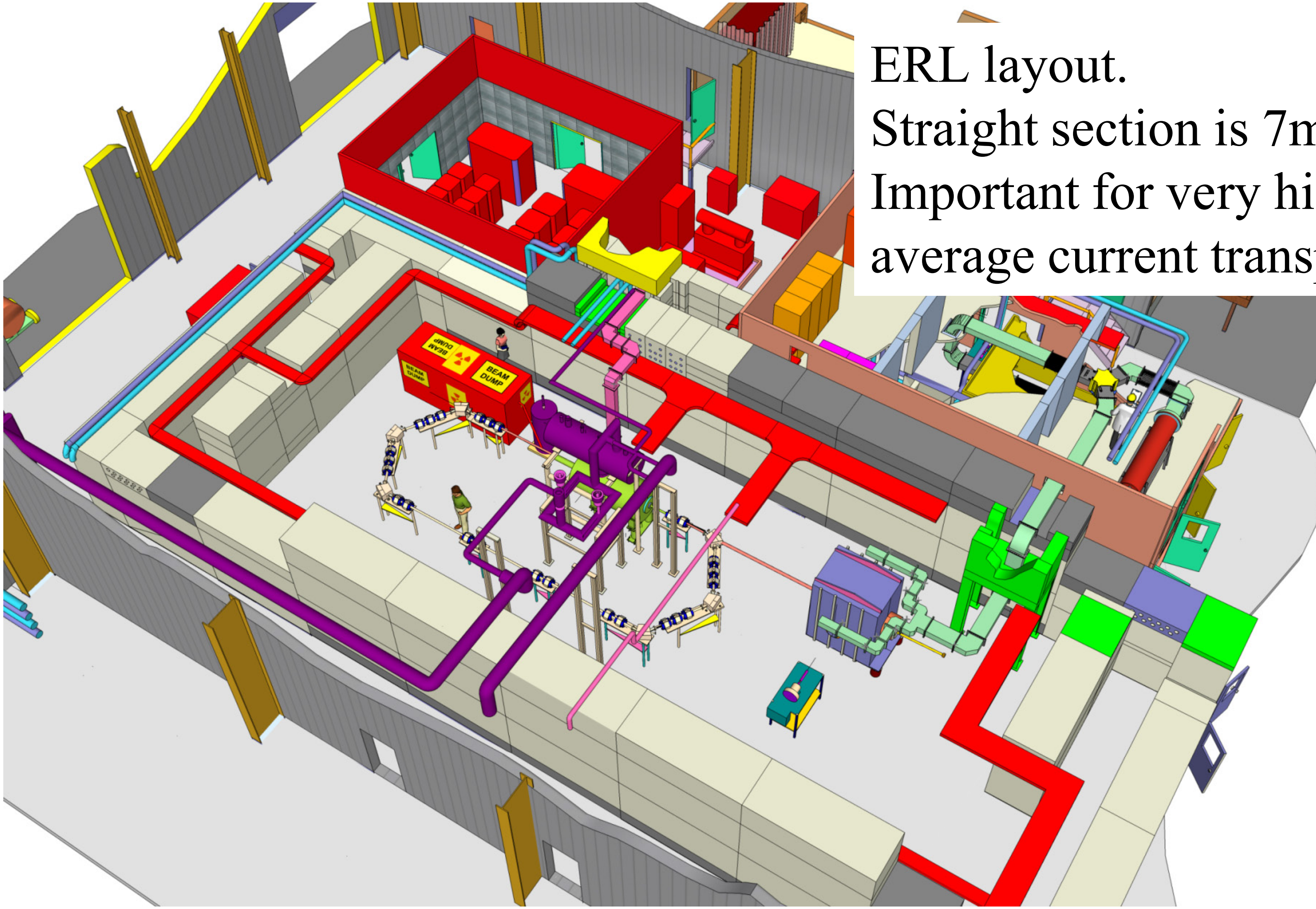
Input coupler

- Cold and warm window
- HA997 ceramic is used
- High power tests are in progress

Based on Cornell design modifications of DESY cavity at 1.3 GHz

ERL Facilities

BNL 0.5 Amp electron cooling ERL
(not a light source but relevant technologies)



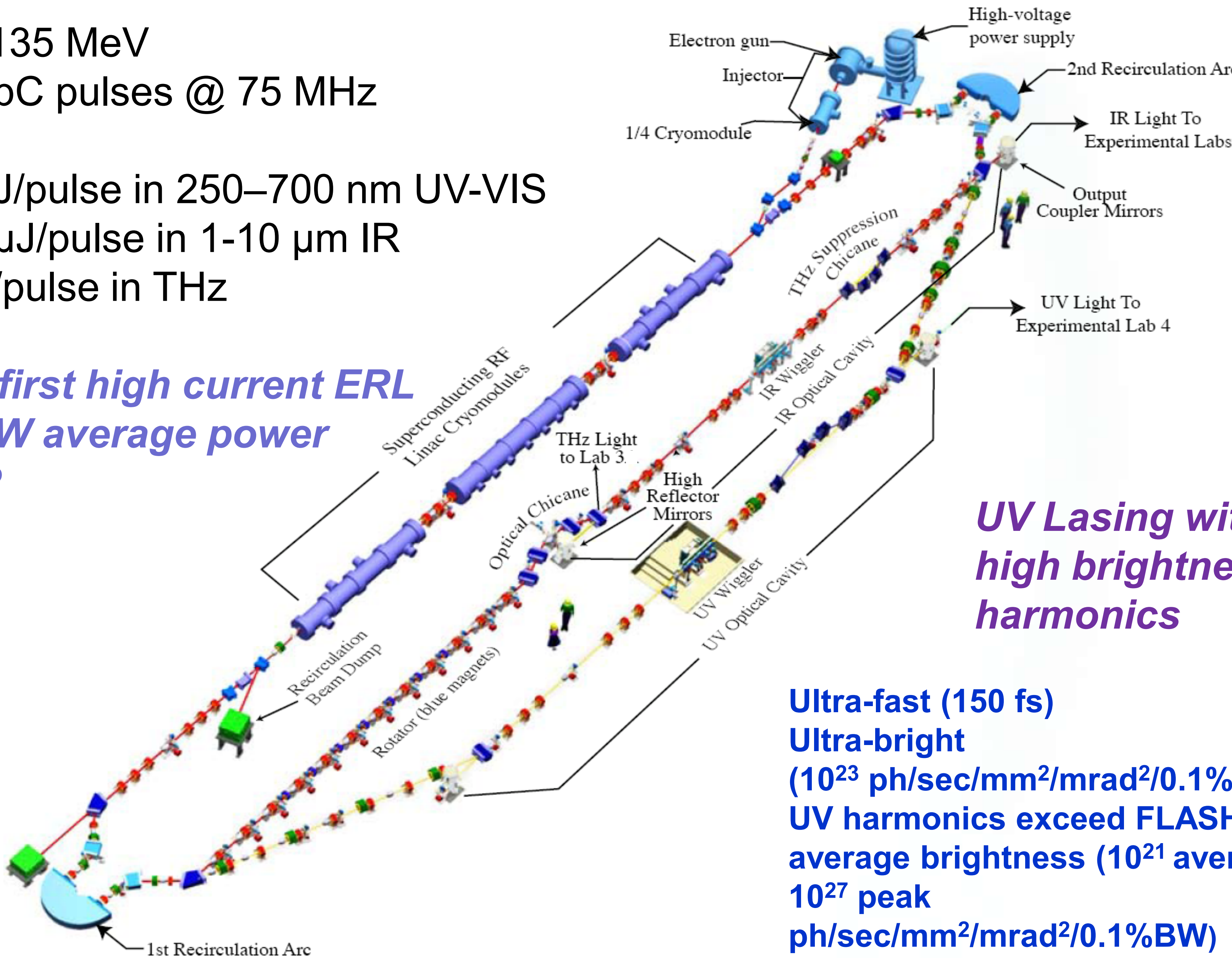
ERL layout.
Straight section is 7m long
Important for very high average current transport

JLab IR/UV ERL Light Source

E = 135 MeV
135 pC pulses @ 75 MHz

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

The first high current ERL
14 kW average power
In IR



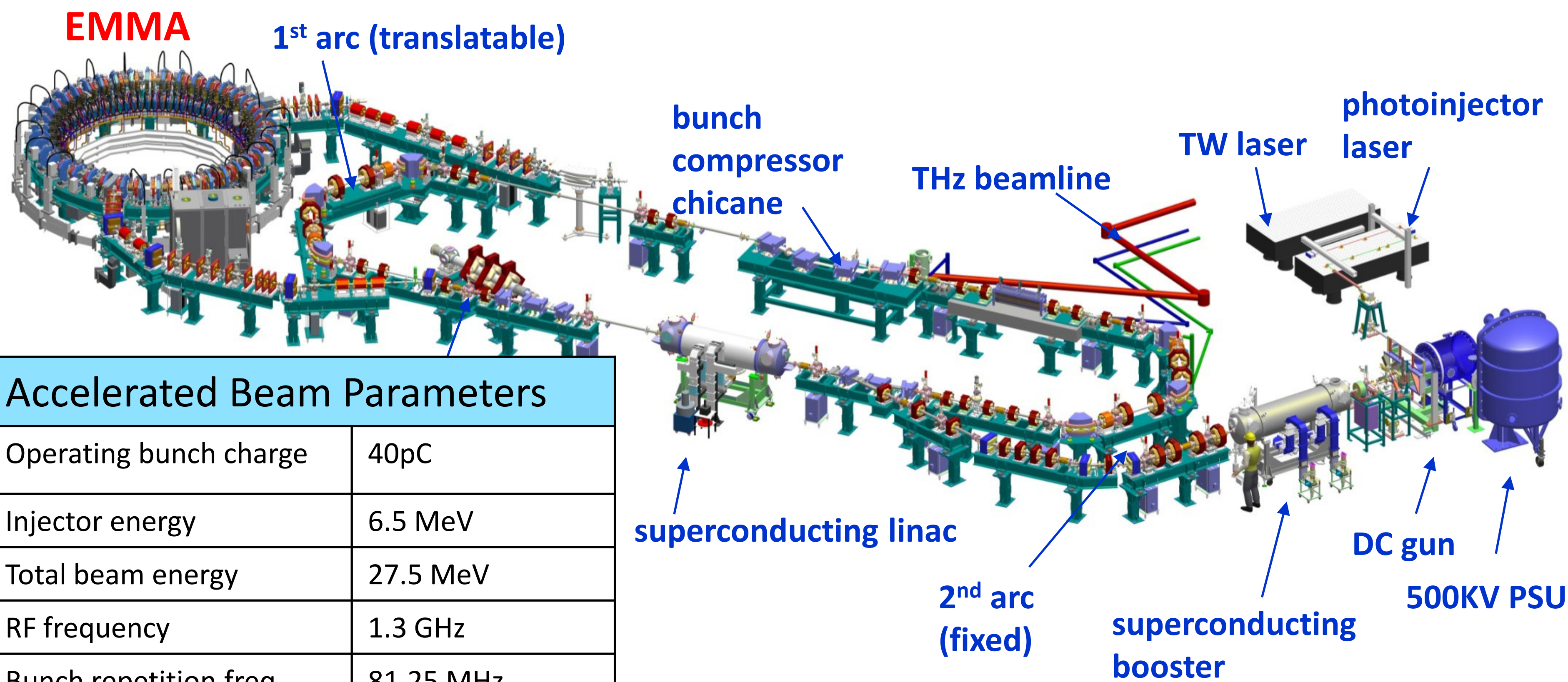
UV Lasing with high brightness harmonics

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)

ALICE Facility @ Daresbury Laboratory

Accelerators and **L**asers **I**n **C**ombined **E**xperiments

superconducting ERL-prototype operating in ER mode since 2008



Accelerated Beam Parameters	
Operating bunch charge	40pC
Injector energy	6.5 MeV
Total beam energy	27.5 MeV
RF frequency	1.3 GHz
Bunch repetition freq.	81.25 MHz
Maximum train length	100 ms
Train repetition freq.	1-10Hz
Transverse emittance	10-20 mm mrad
Compressed bunch length	<2 ps

Courtesy S. Smith

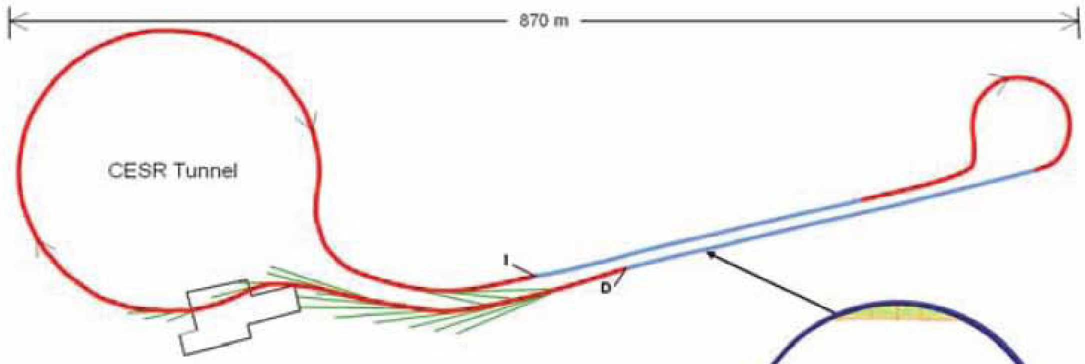
Science & Technology Facilities Council

Alice

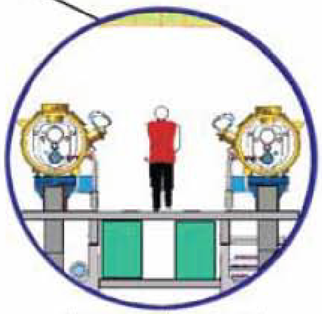
Energy Recovery Linac (ERL) Background

CLASSE
CHESS & LEPP

Sol M. Gruner*
Cornell High Energy Synchrotron Source & Physics Department
Cornell University, Ithaca, New York 14853-2501
smg26@cornell.edu



Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green lines show 18 possible beamline locations. Electrons travel around the CESR magnets clockwise and re-enter the linac out of phase. Their energy is extracted and the spent electrons are then sent to the dump (D).



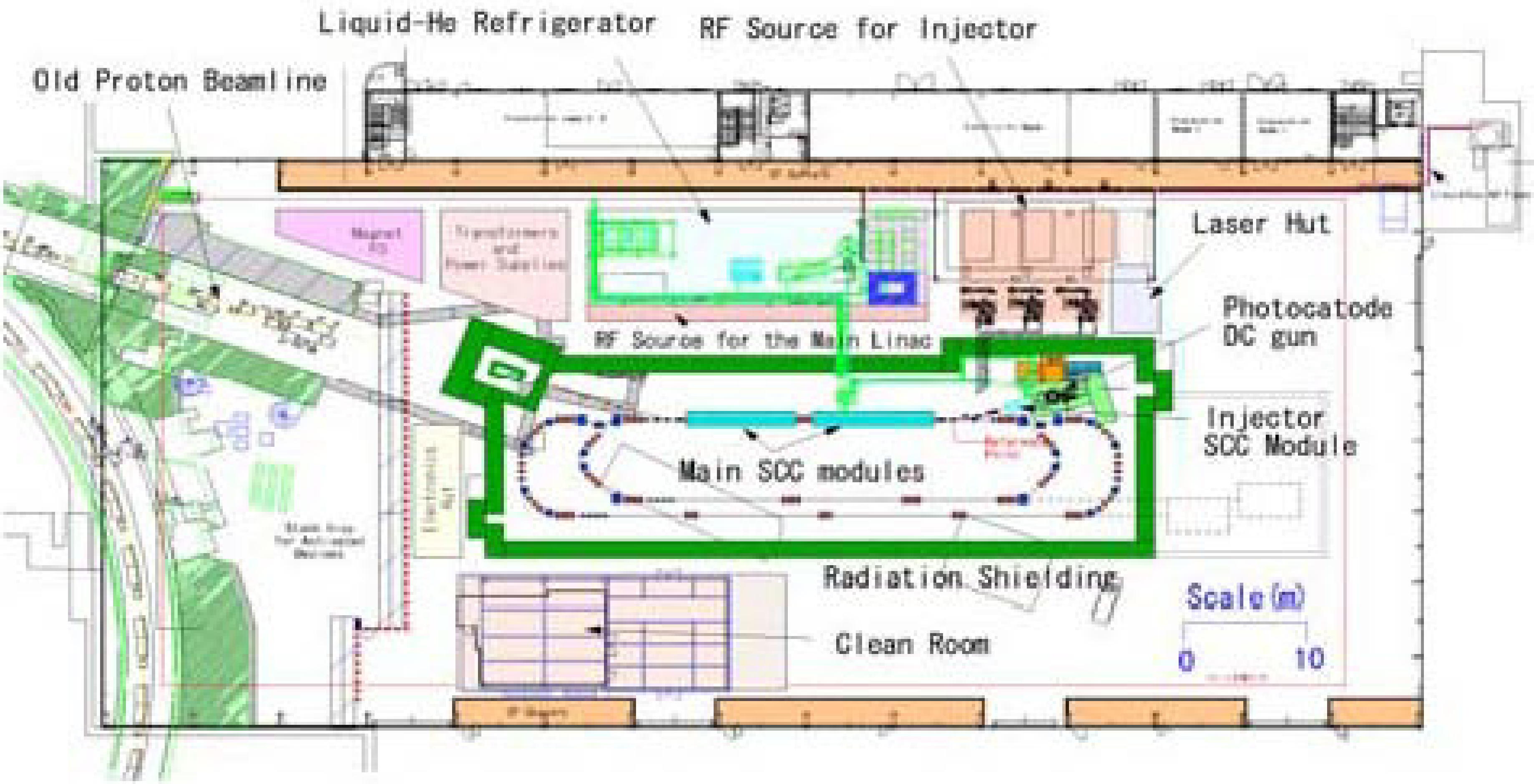
Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.

***for the CLASSE development team**

www.chess.cornell.edu

DEVELOPMENT OF A PROTOTYPE MODULE FOR THE ERL SUPERCONDUCTING MAIN LINAC AT KEK

T. Furuya, K. Hara, K. Hosoyama, Y. Kojima, H. Nakai, K. Nakanishi, H. Sakai, K. Umemori,
KEK, Tsukuba, Ibaraki 305-0801, Japan,
M. Sawamura, JAEA, Tokai, Naka, Ibaraki 319-1195, Japan,
K. Shinoe, ISSP, University of Tokyo, Kashiwa, Chiba 277-8581, Japan



BERLinPro - A PROTOTYPE ERL FOR FUTURE SYNCHROTRON LIGHT SOURCES

M. Abo-Bakr, W. Anders, T. Kamps, J. Knobloch, B. Kuske, O. Kugeler, A. Matveenko, A. Meseck, A. Neumann, T. Quast
Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Berlin, Germany

Cornell design booster

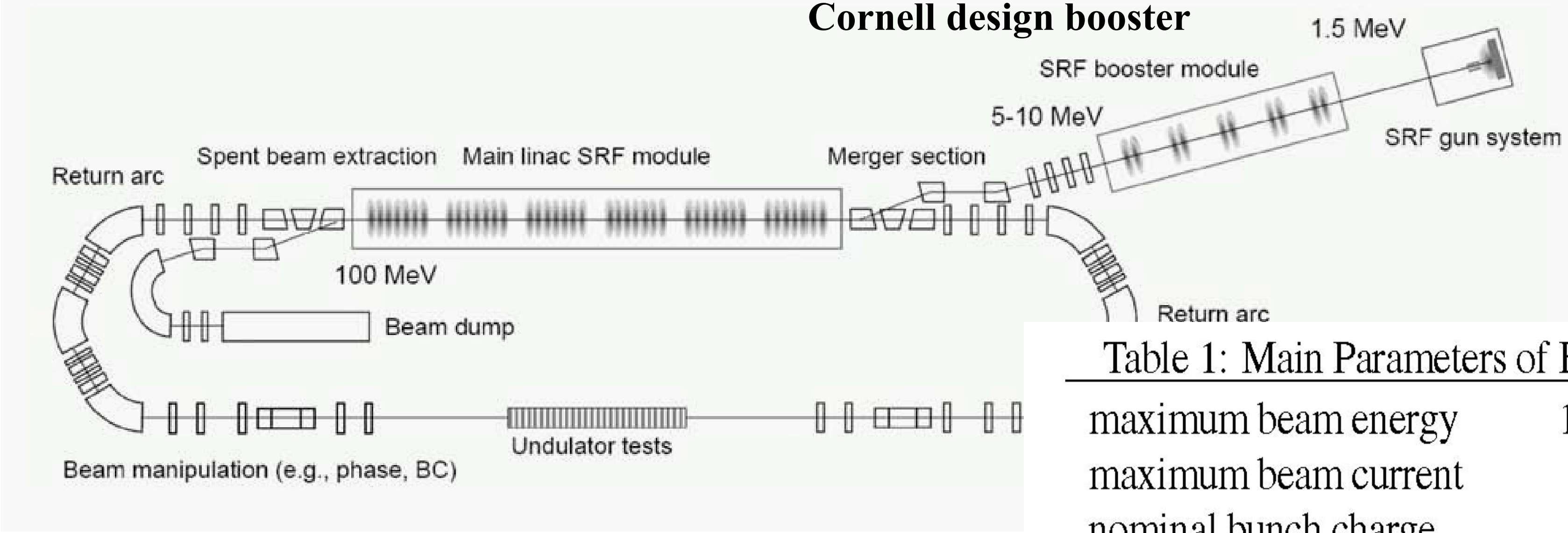
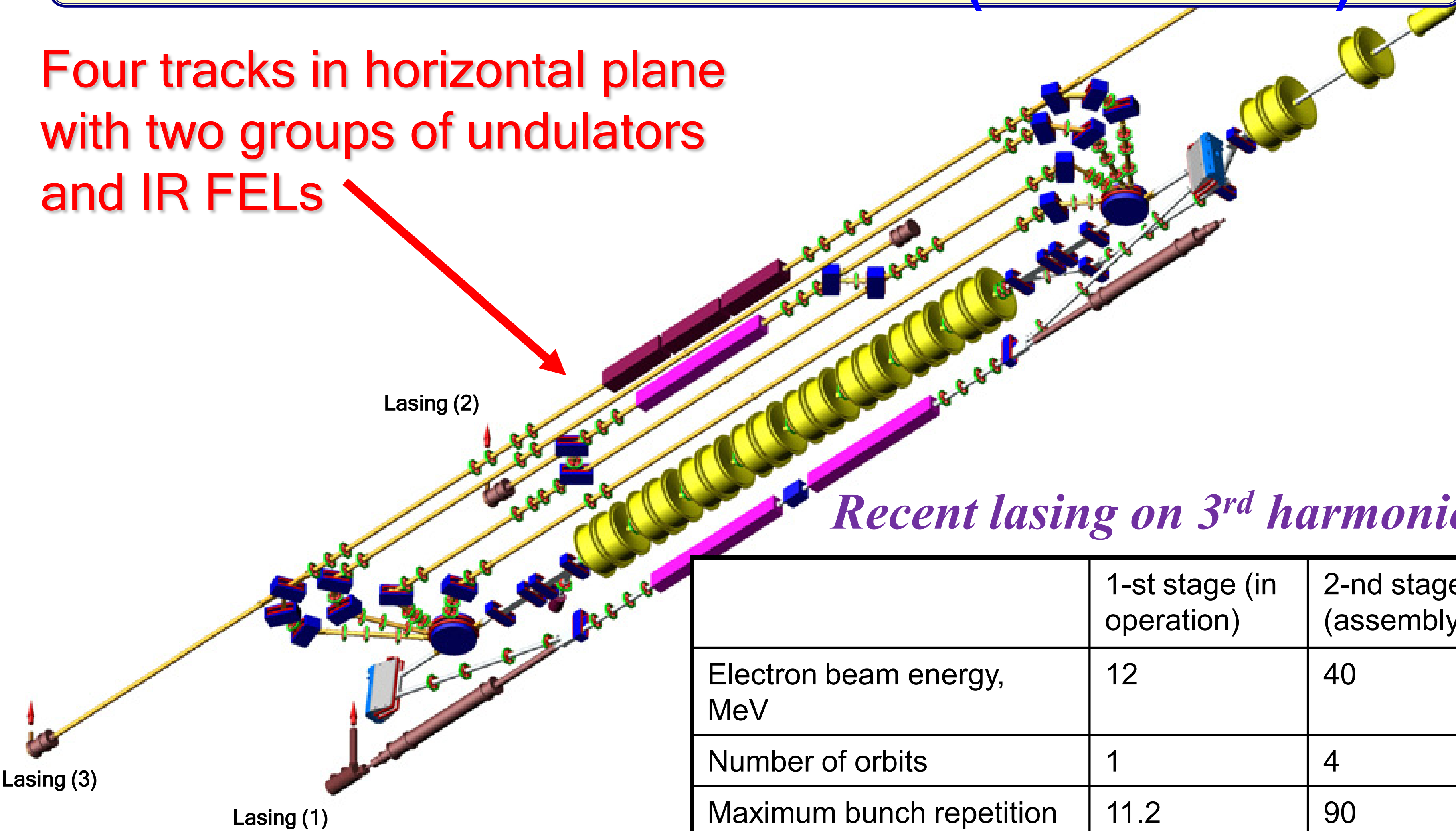


Table 1: Main Parameters of BERLinPro

maximum beam energy	100 MeV
maximum beam current	100 mA
nominal bunch charge	77 pC
maximum repetition rate	1.3 GHz
normalized emittance	< 1 mm mrad
cryogenic load at 1.8 K	240 W

Full scale Novosibirsk FEL (bottom view)



Recent lasing on 3rd harmonic!

	1-st stage (in operation)	2-nd stage (assembly)
Electron beam energy, MeV	12	40
Number of orbits	1	4
Maximum bunch repetition frequency, MHz	11.2	90
Beam average current, mA	20	150
RF frequency, MHz	180	180
Year of commissioning	2002	2007

CW Linac X-FELS

- Higher energies => longer linacs => higher cost
- More FELs/linac is better
  - Multiplicity by way of RF separation (a la CEBAF)?

- **Recirculation** may make systems more affordable
  - Cuts required srf length
  - Cuts conventional facility (tunnel)
  - Cuts cryogenic plant
  - Cuts operating cost
  - Perhaps adds synchrotron ports
  - *but adds transport lattice and perhaps tunnel….*

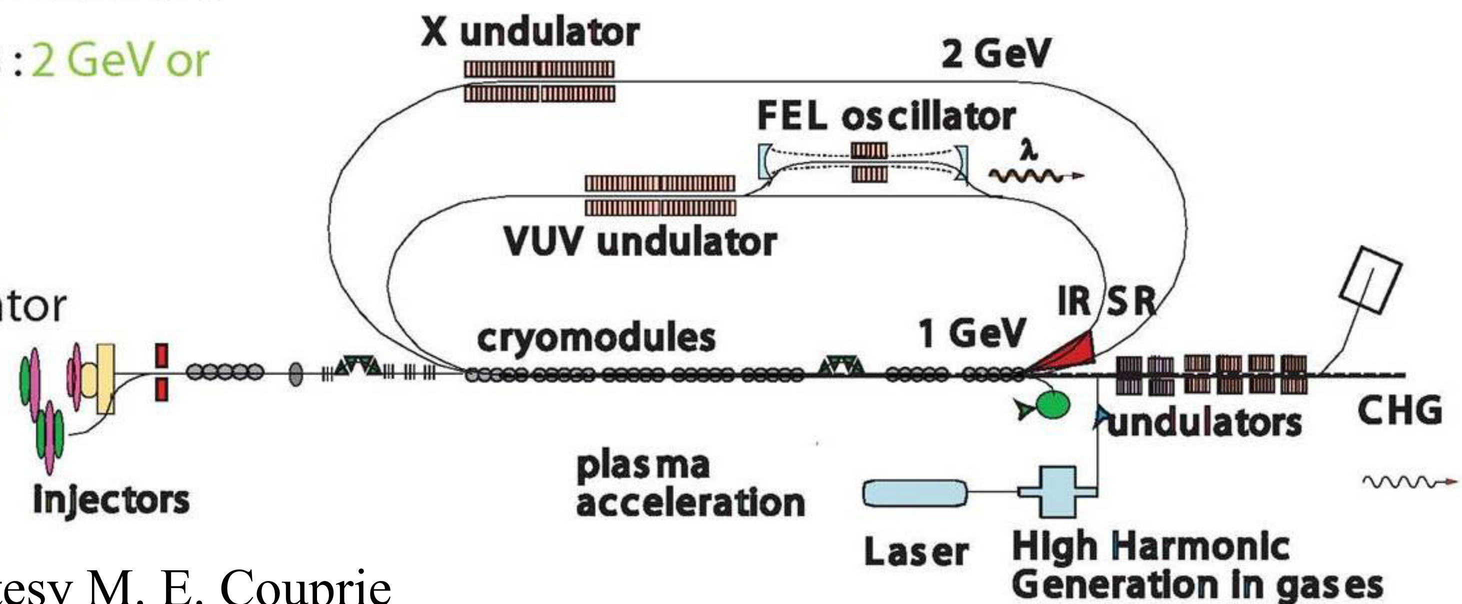
CW Linac X-FELS

- **Recirculation** may make systems more affordable
- Key issue: can you still achieve ultimate beam brightness? Will require extensive study and creative design to ensure beam quality preserved, optimum cost/benefit achieved.

Solution of recirculation physics issues of high brightness beams may have even more important impact on field than ERL!

ARC-EN-CIEL phase 3 :

Additionnal loops : 2 GeV or increased current
HGHG sources
UV FEL oscillator
VUV and X undulator

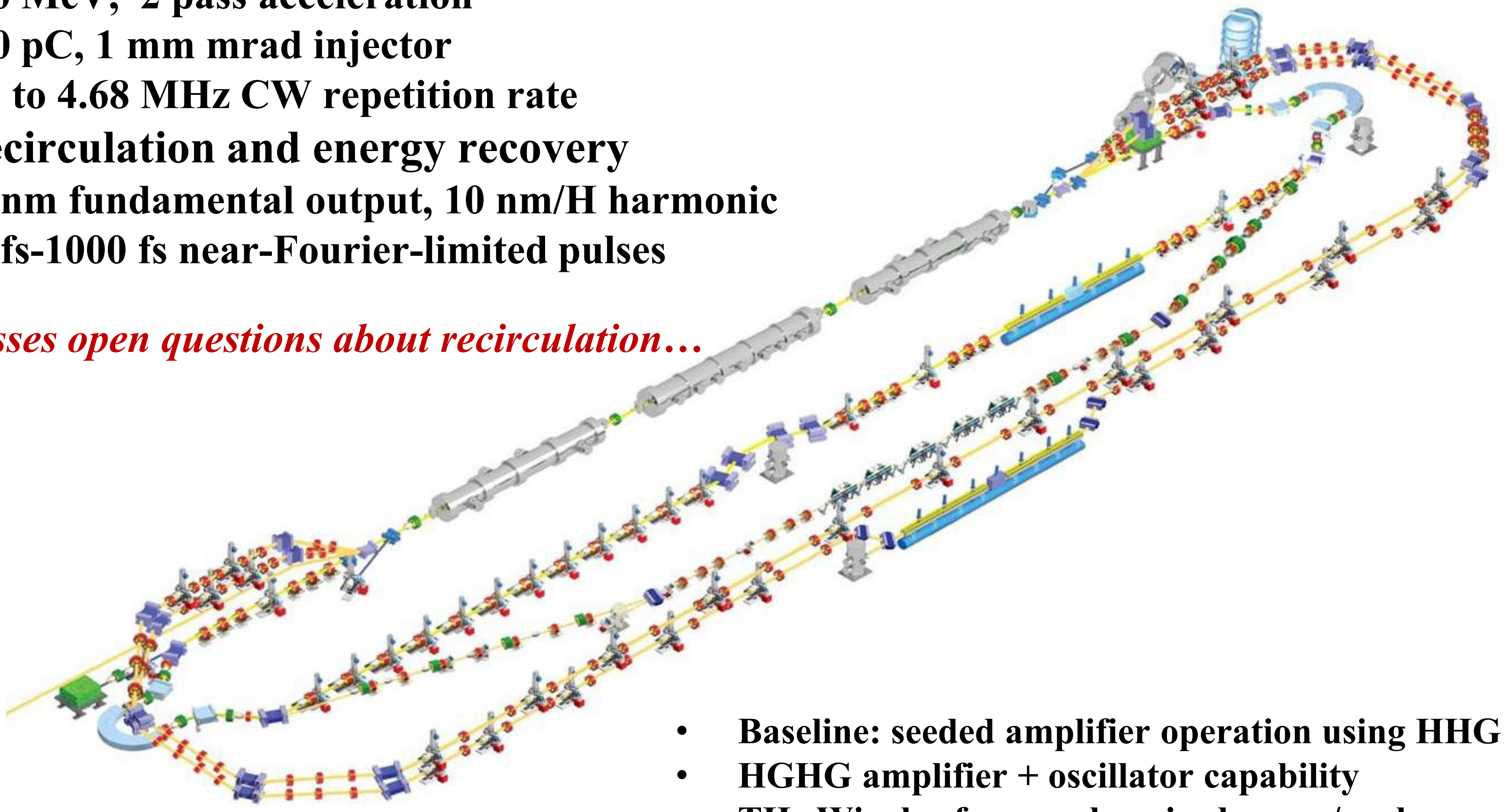


ARC-en-Ciel Courtesy M. E. Couprie

JLAMP FEL proposal for unparalleled average brightness of 10-100 eV photons

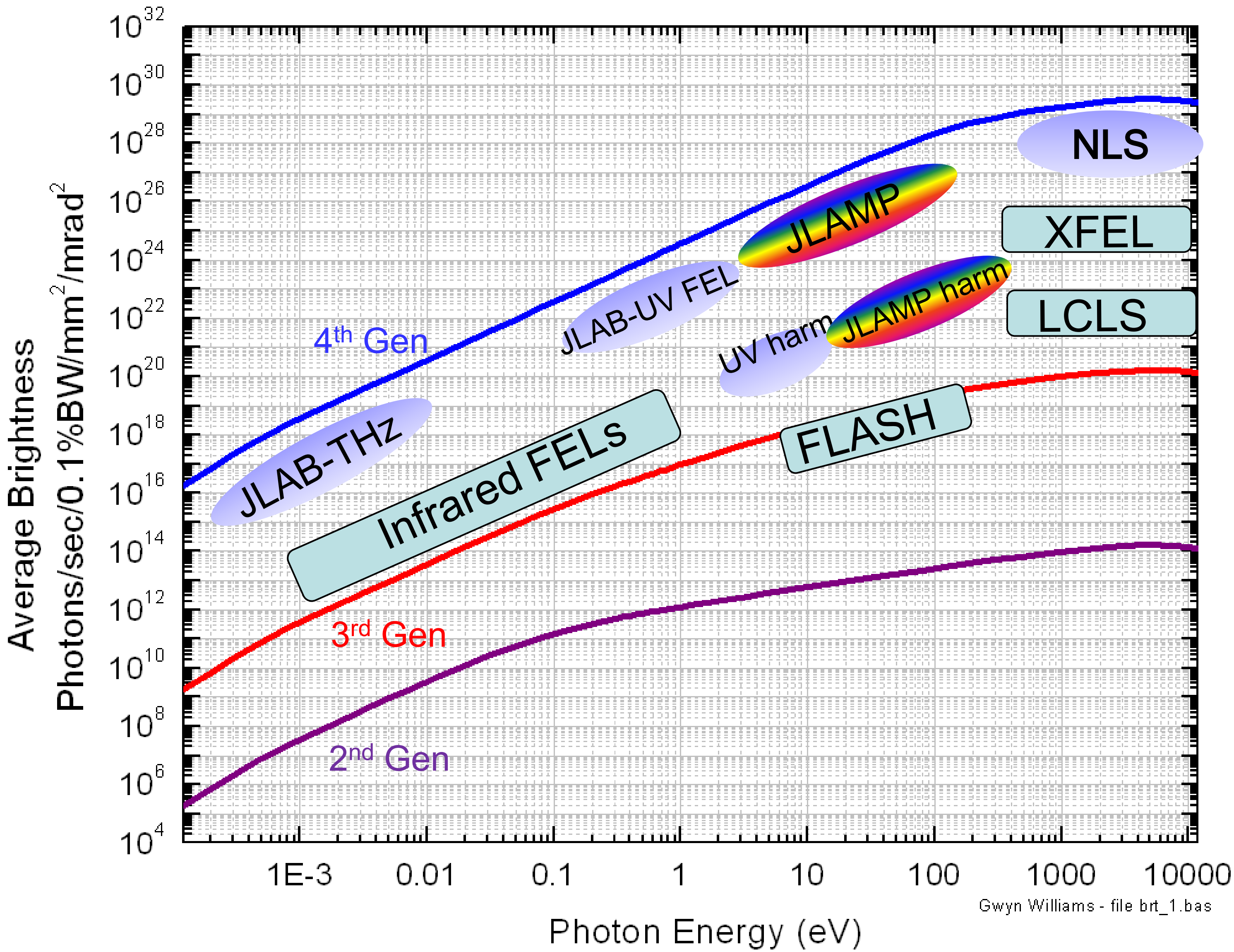
- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 nm fundamental output, 10 nm/H harmonic
- 50 fs-1000 fs near-Fourier-limited pulses

Addresses open questions about recirculation…



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

CW operation gives high average brightness in both fundamental and harmonics

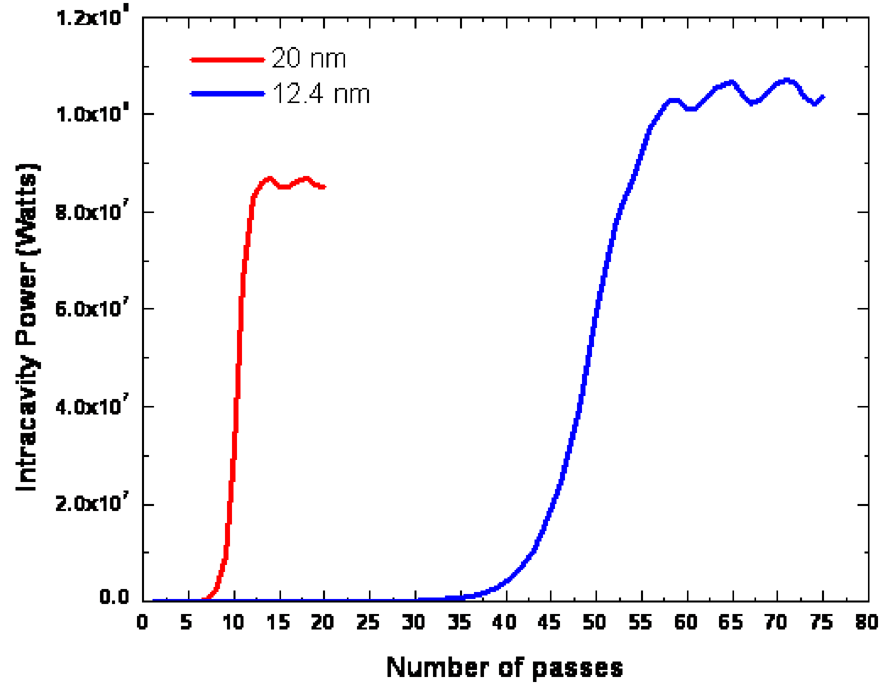


New: Soft X-ray Oscillator Proposal
- *existing technology with modest optical tolerances*

Different than K-J. Kim hard X-ray oscillator (ANL-AAI-PUB-2008-004)

Near-term, low-risk, soft X-ray oscillator possible using conventional mirrors with high gain undulator . Gain is high so reflectivity, mirror figure, and alignment are all insensitive in regenerated oscillation

Wiggler period (cm)	2.5
Number of periods	240
Wiggler gap (cm)	7
Emittance (microns)	2
Energy spread (%)	0.15
Peak current (kA)	1.44
Cavity length (m)	32.04196
Mirror radii (cm)	1.27
High reflector mirror radius of curvature (m)	flat
Output coupler mirror radius of curvature (m)	23.5
Hole radius (cm)	0.03
Mirror reflectivity (%)	70



Genesis/OPC modeling courtesy M. Shinn
- submitted to J. Modern Optics , Benson et al.

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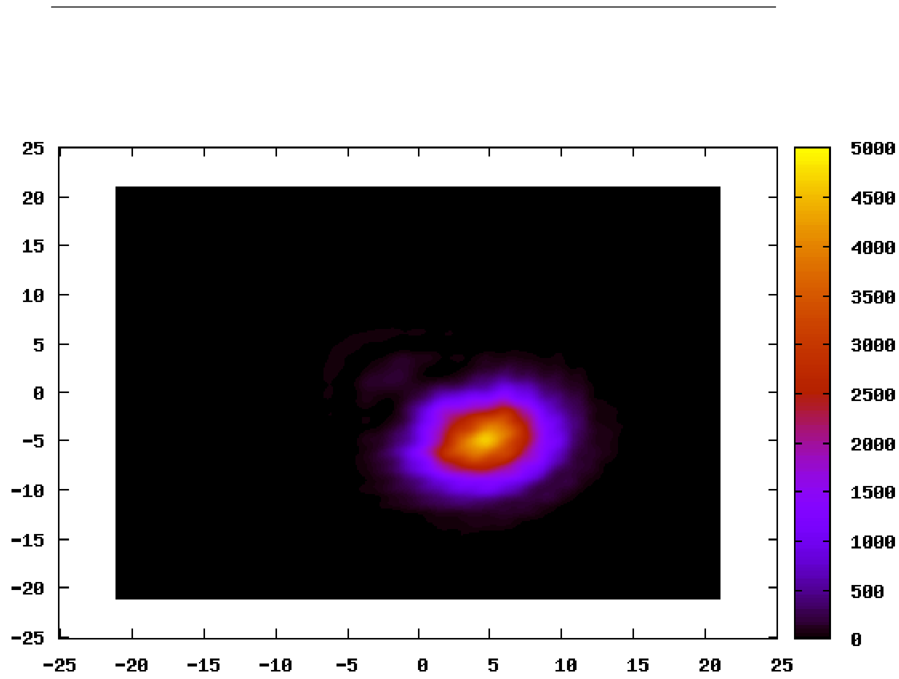

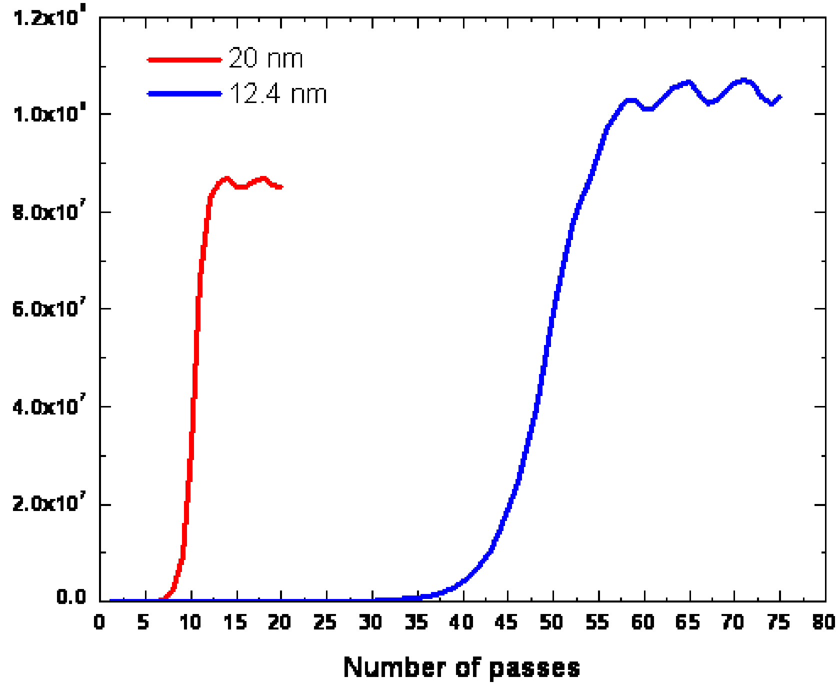

Genesis/OPC modeling courtesy M. Shinn
- submitted to J. Modern Optics , Benson et al.

Summary

- ERLs offer many advantages over existing X-ray sources
  - CW beams of very high brightness
  - Flexible format very short pulses
  - Small emittance and round beams
  - Capability for synchrotron emission or FEL operation or both
- but have some as yet unresolved issues
  - CW injectors at ultimate brightness
  - Transport challenges in maintaining brightness and handling beam
  - Cost and practicality challenges due to lack of multi-particle (longitudinal) coherence
- Can recirculating linacs help address cost barrier to CW X-FELs?
- Can soft X-ray oscillator blast through presently achievable brightness or even seed harder X-ray amplifiers???

Acknowledgements

Special thanks to

- G. Williams, D. Douglas, C. Hernandez-Garcia, S. Benson, Michelle Shinn, Bob Legg, and the JLab FEL Team
- Ilan Ben-Zvi and colleagues
- S. Gruner, G. Hoffstaetter and colleagues
- J. Bisognano and colleagues
- J. Knobloch and colleagues
- K. Baptiste and colleagues
- W. Eberhardt
- P. Dehmer
- S. Smith and colleagues
- K. Umemori and colleagues
- H. Hajima and colleagues
- Lu Xiangyang and colleagues
- Marie Couprie and colleagues

and probably others I've missed in this list

Thanks for the use of their slides

We invite you to
5th Int. ICFA ERL Workshop
ERL2011, October 16-21, 2011
Tsukuba, Japan
http://erl2011.kek.jp
We hope our Japanese colleagues continue to recover from the devastating natural disaster

We also invite you to
3rd Int. ICFA Workshop on
Future Light Sources
FLS2012, March 5-9, 2012.
Jefferson Lab, Newport News ,VA
http://conferences.jlab.org/FLS2012/