Worldwide ERL R&D Overview

George R. Neil

Jefferson Lab

LINAC10

Tsukuba, Japan

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

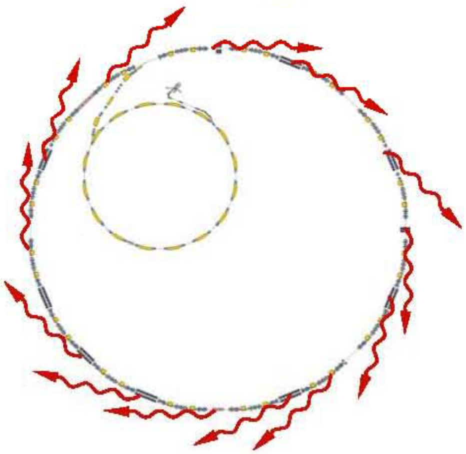
Fourth generation x-ray sources

Storage ring

$\varepsilon \sim E^2/R$

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

bunch charge 1nC



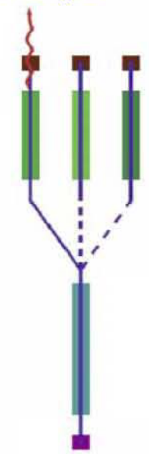
- Many experiments
- Ready tunability
- High flux
- ps pulses

LINAC source (=> FEL)

$\varepsilon \sim 1/E$

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

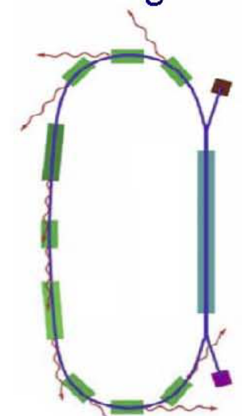
bunch charge ≤ 1 nC



- 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 display 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: operation at lower charge but very high repetition rate minimizes space charge driven emittance growth to achieve ultimate emittance

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			

ERL

FEL

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**
- **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 + educate light source users!* }**

Major R&D Efforts Around the World

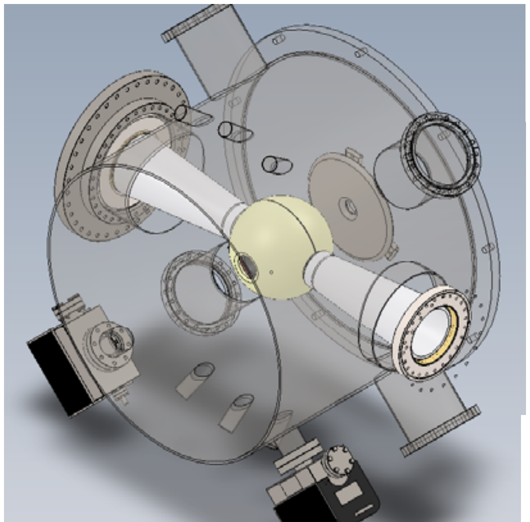
- **Injector, injector, injector! No existing injector delivers required CW brightness. Many groups are working on this: LBNL, Cornell, Wisconsin, JLab, KEK, Daresbury, BNL, PKU…**
- **Brightness preservation: Solutions to coherent synchrotron radiation (CSR) emittance degradation, longitudinal space charge (LSC) in pulse compression**
- **Halo control essential for CW – non-Gaussian tails!!!**
- **High order mode & beam breakup control in cavities**
- **Wakefield and propagating mode damping**
- **Handling sizeable (~ 20 kW! @ 100 mA) THz radiation in bends**
- **Resistive wall heating in undulators**
- **Reducing srf dynamic load to lower refrigerator costs; probably more important than increasing gradient**

Note: there are other applications for ERLs than just light sources, I will talk about those, too!

ERL R&D

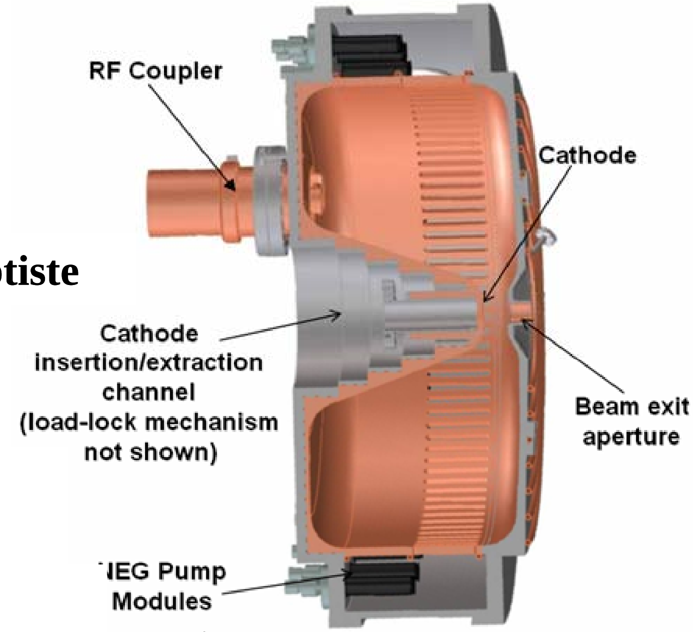
Many approaches for a CW High Brightness Gun – but none working yet

JLab Advanced DC Gun



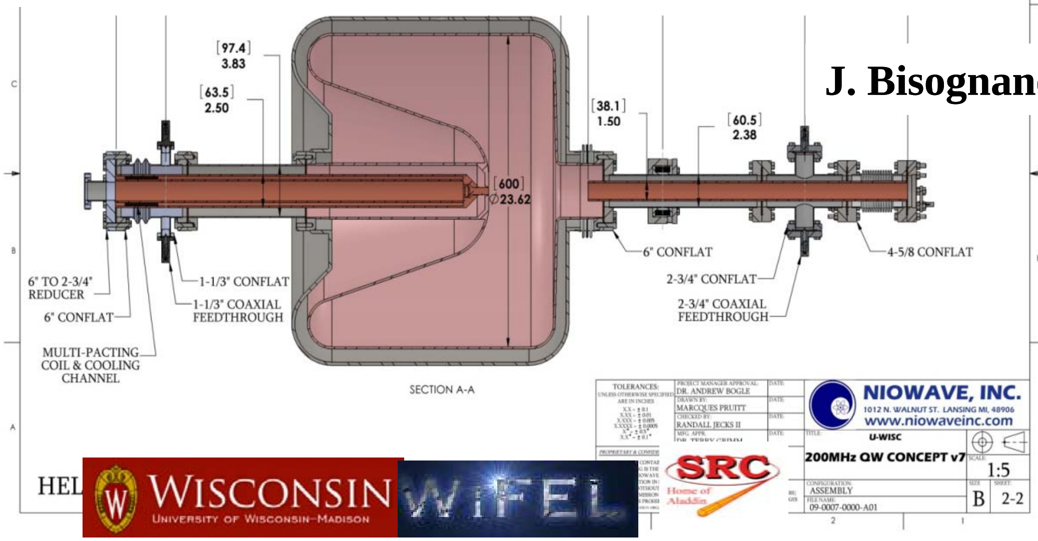
C. Hernandez-Garcia

LBNL Low Frequency RF Gun



K. Baptiste

WiFEL/Niowave SRF Gun



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

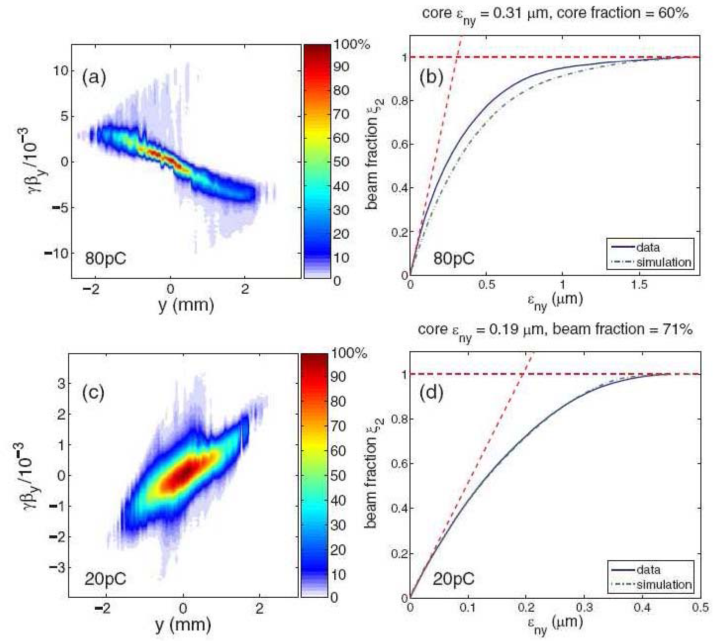


Figure 4: Measured (a), (c) transverse phase space after the gun and the corresponding emittance versus beam fraction curve (b), (d).

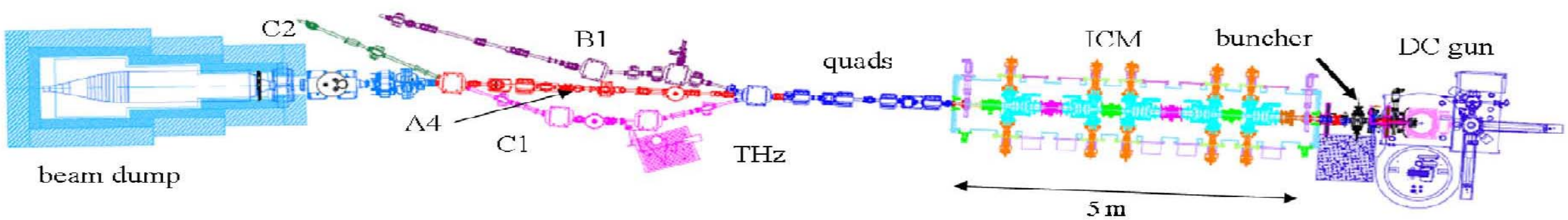


Figure 2: The layout of Cornell prototype ERL injector. Beam direction is to the left.

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

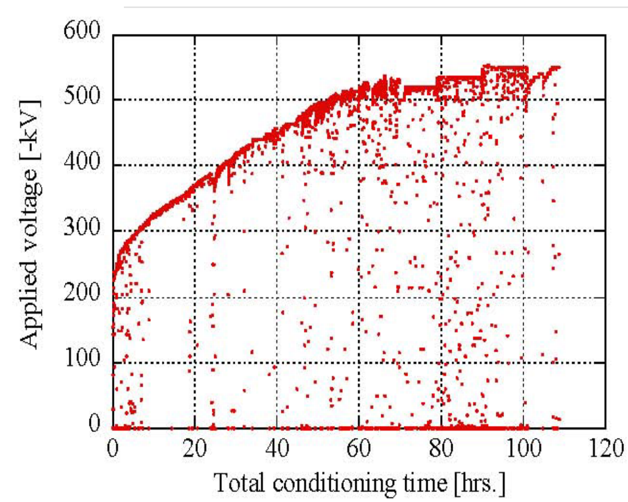


Figure 3: Applied voltage vs total time in the high-voltage conditioning.

JAEA

Major advance in high voltage operation!

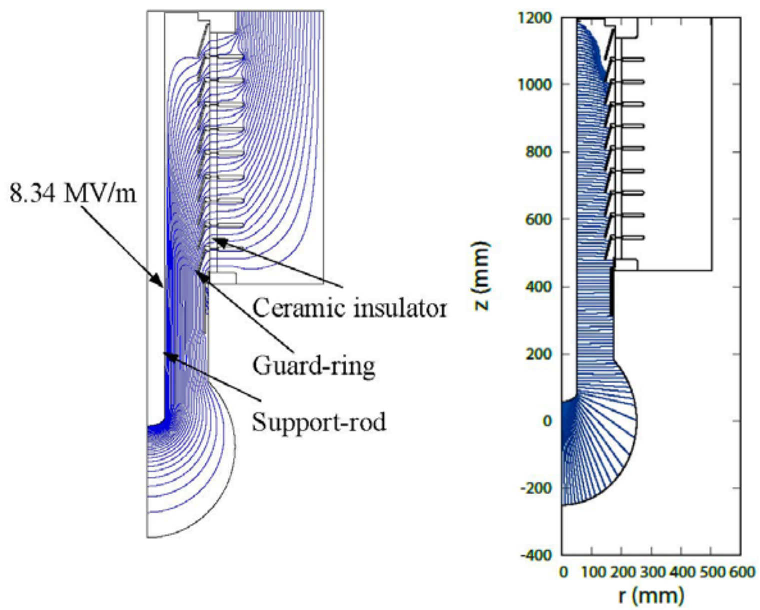
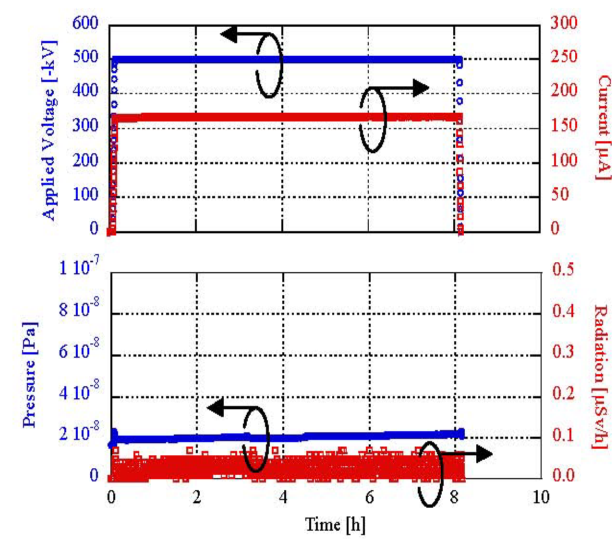
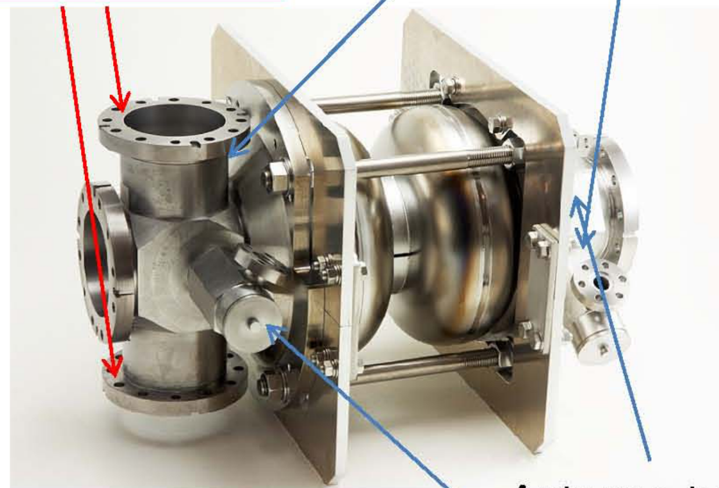


Figure 2: Field distribution (left) and emitted electron trajectories (right) of the gun.



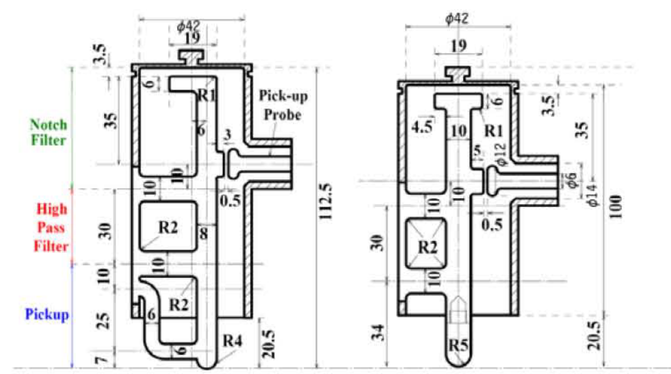
KEK 2-cell injector cavity

- Same cell shape with STF-BL cavity and slightly enlarged beampipe
- Two input port for each cavity
- Two types, loop and antenna, of HOM couplers are applied
- 4 or 5 HOM couplers per one cavity



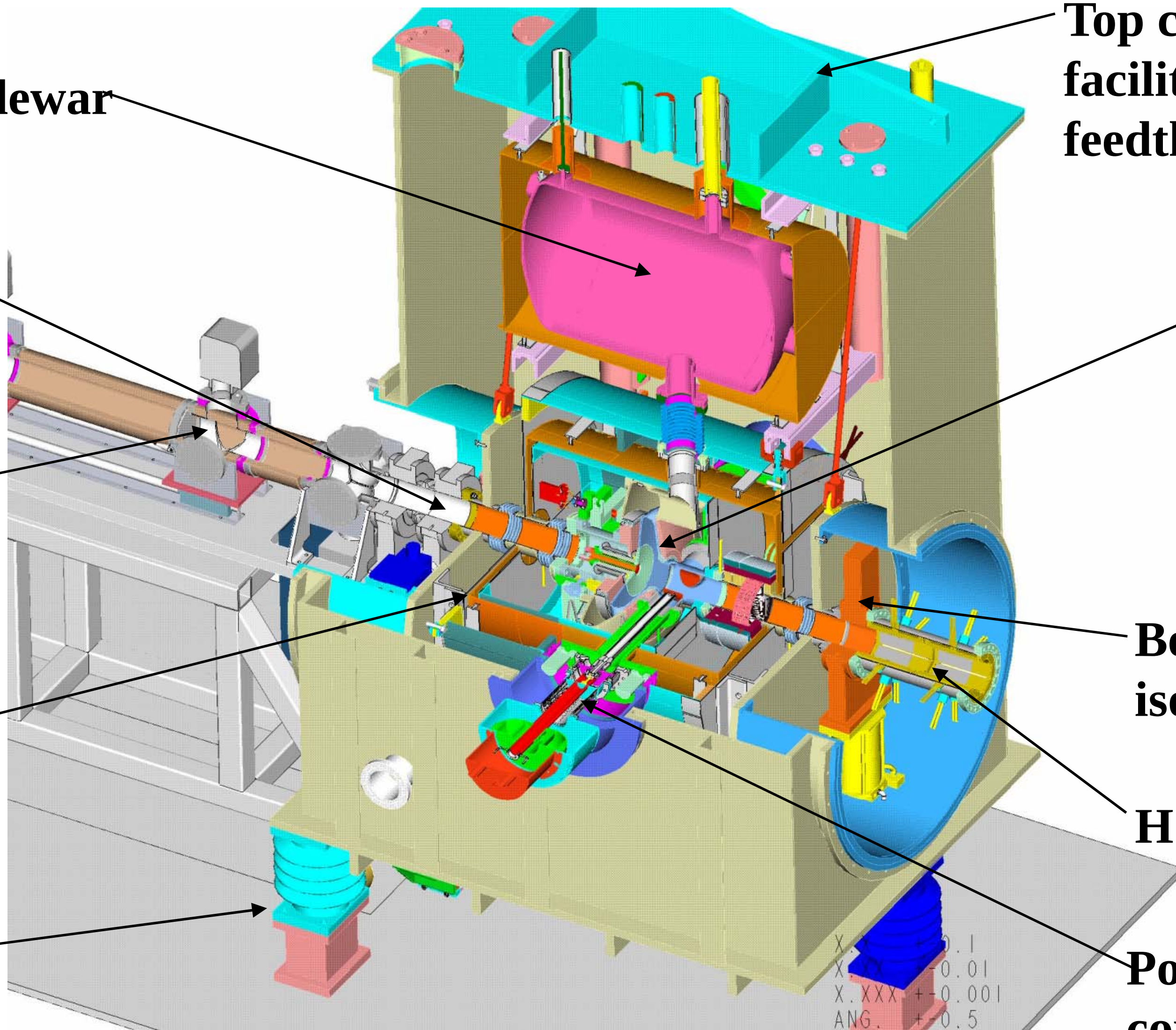
Basic cavity Parameters for Injector at KEK

Frequency	1.3	GHz
Number of Cell	2	
R/Q	205	
Operating Gradient	14.5	MV/m
Number of Input coupler	2	
Coupler power	167	kW
Coupler coupling	3.3×10^5	
Number of HOM coupler	5	
Operating Temperature	2	K

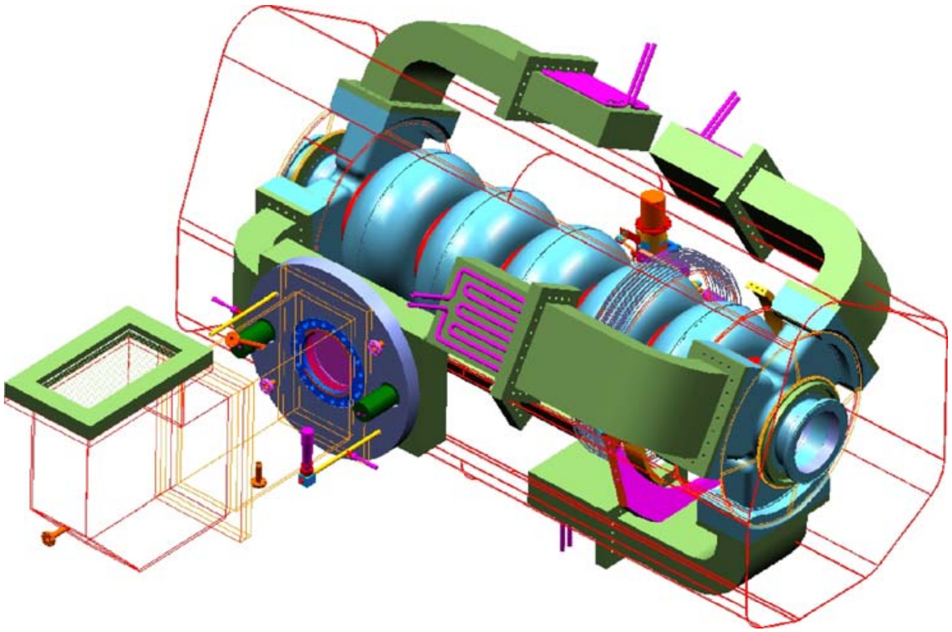


Loop-type HOM coupler　Antenna-type HOM coupler

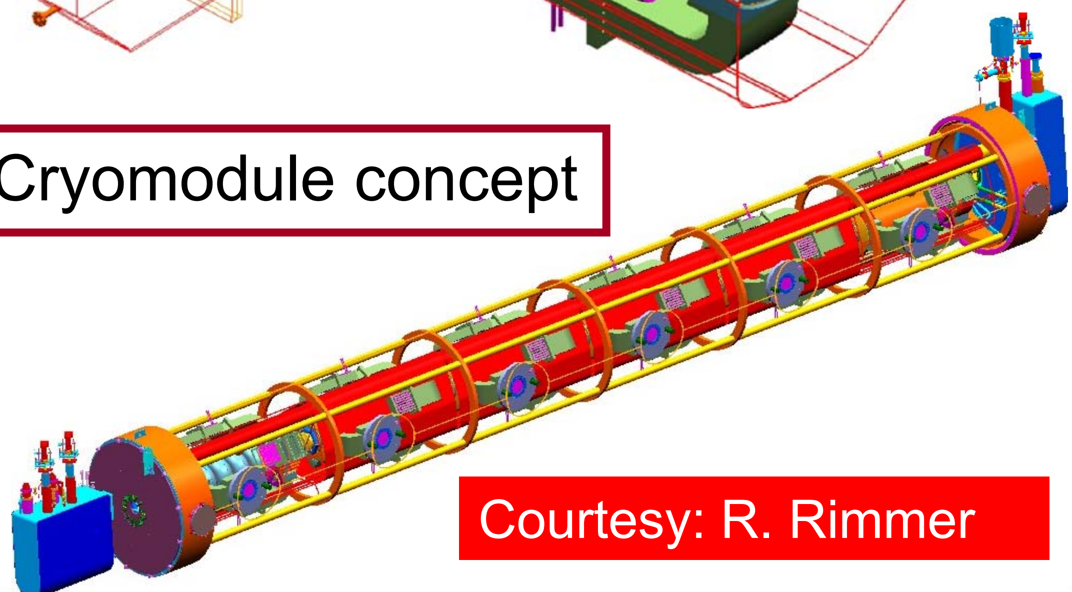
BNL High-current SRF electron-gun



JLab Ampere-class Cavity

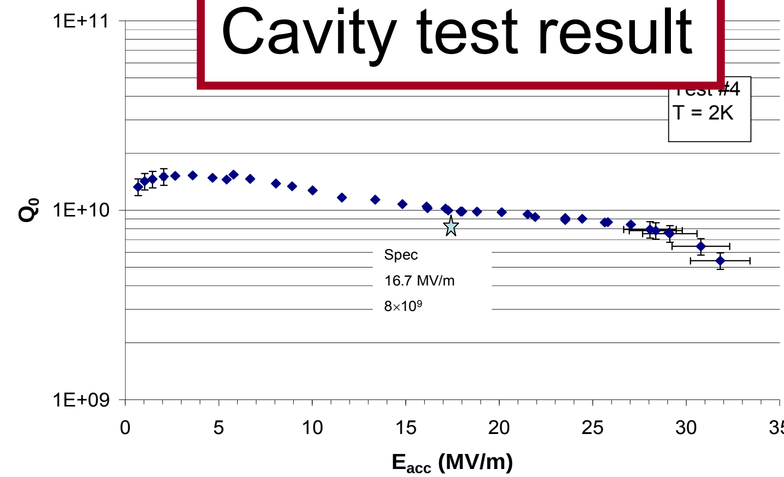


Cryomodule concept



Courtesy: R. Rimmer

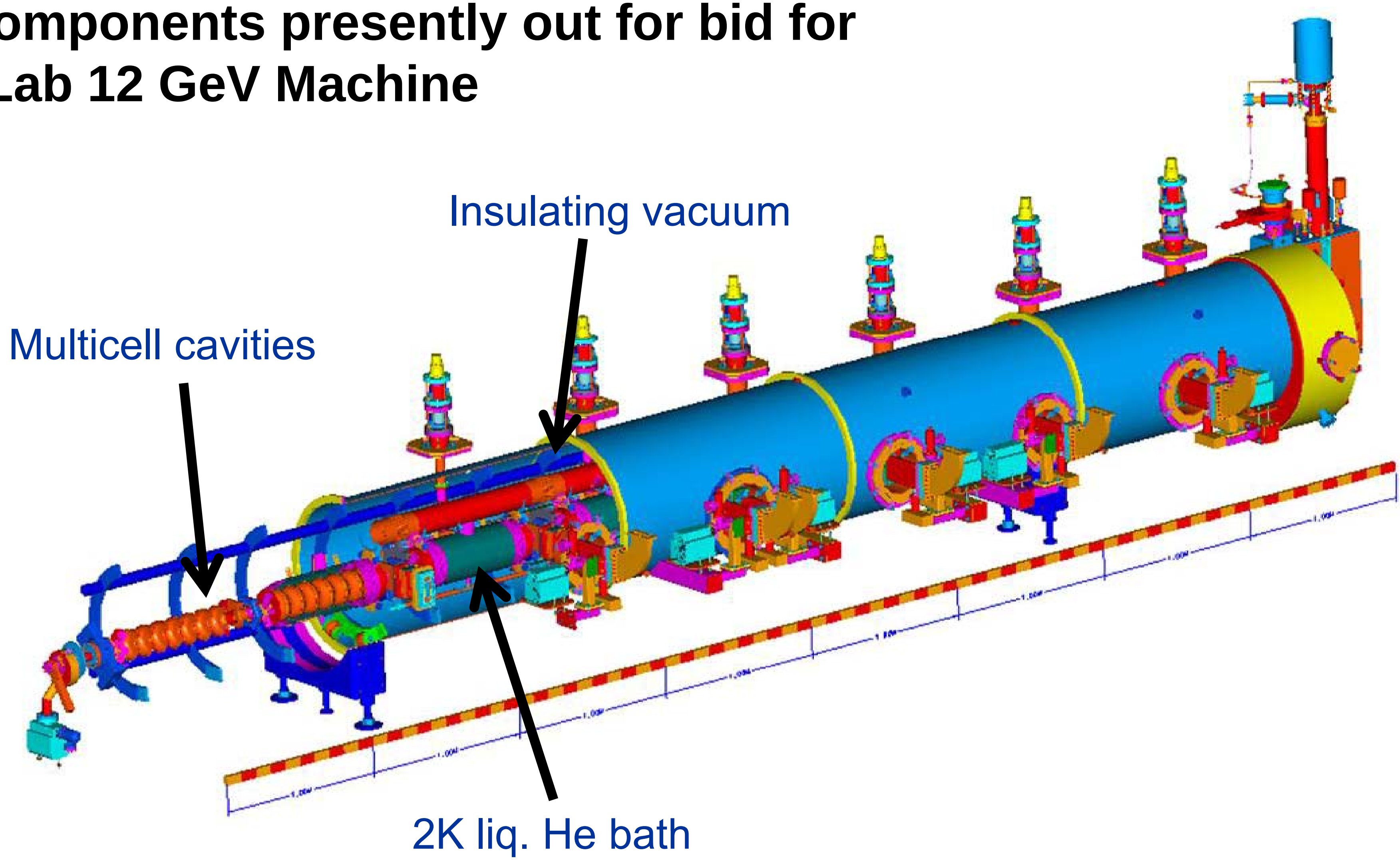
Cavity test result



1500 MHz Cu prototype

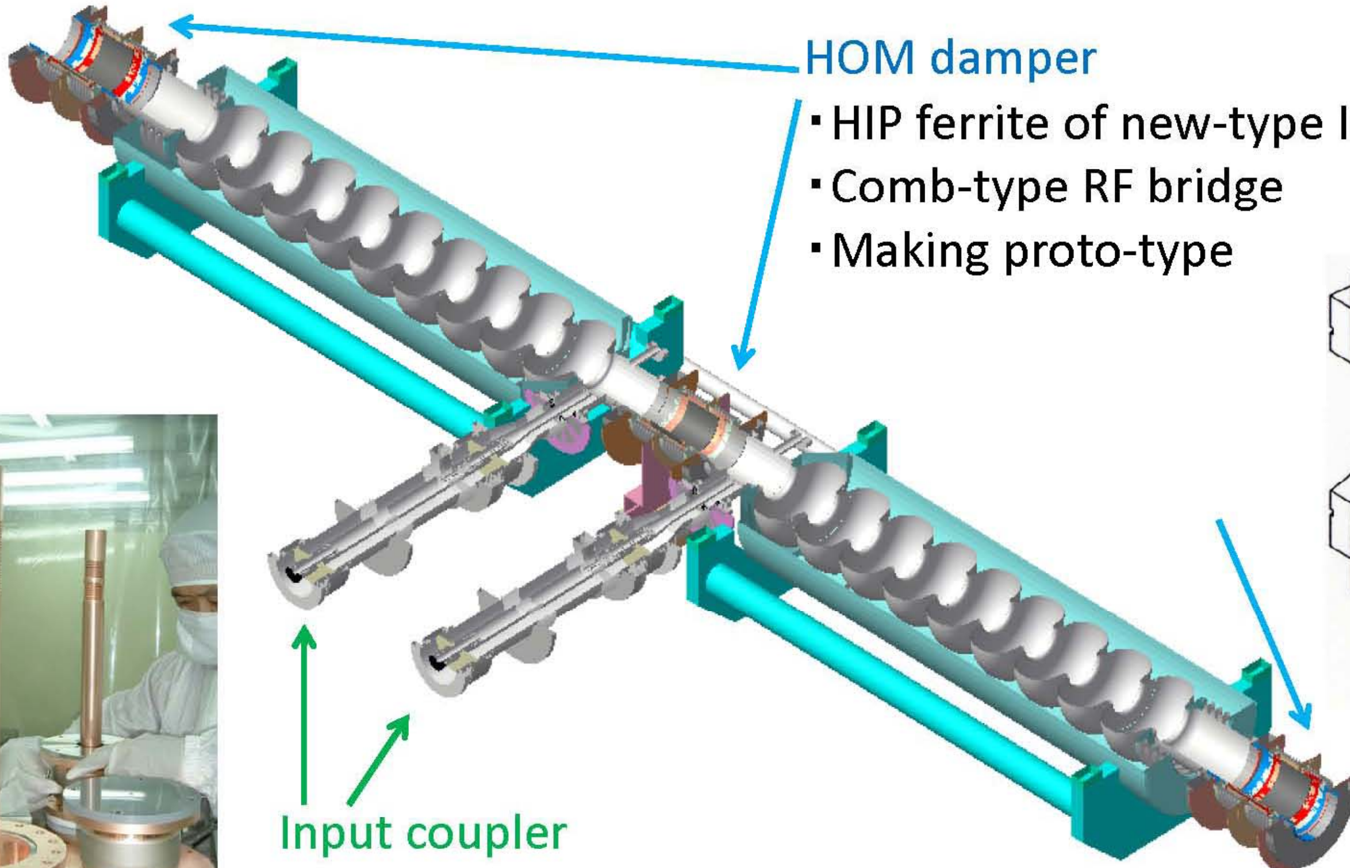
100 MeV High Gradient Module

Components presently out for bid for JLab 12 GeV Machine



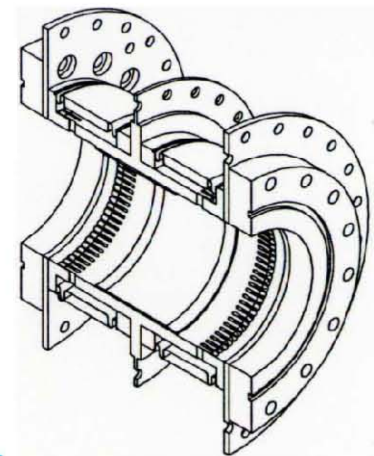
KEK

Cryomodule development



HOM damper

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

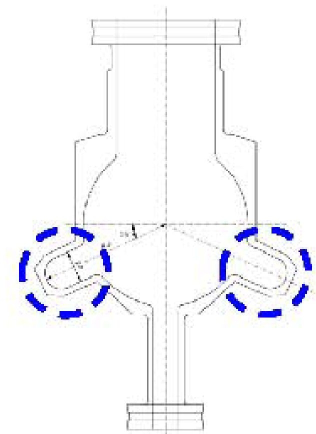


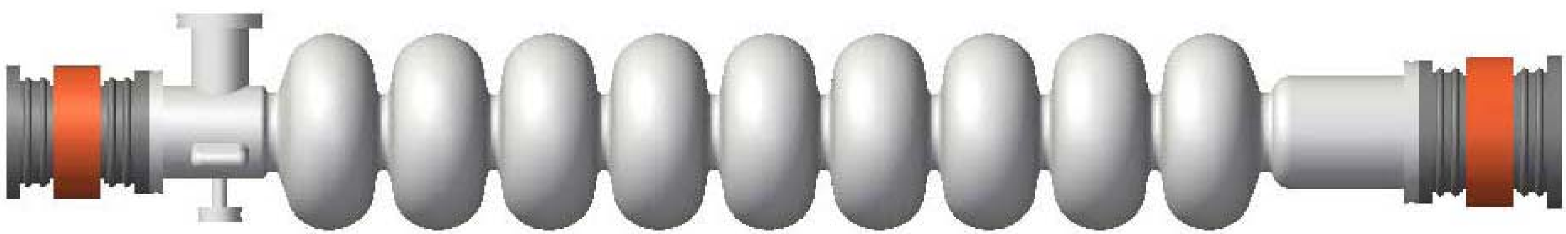
Input coupler

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

KEK-ERL model-2 Cavity

1) Cell shape is optimized to reduce HOM impedances
   - Iris diameter 80mm, elliptical shape at equator
   - Cell diameter 206.6mm
2) Eccentric-fluted beampipe
   - Suppress Quadrupole HOMs
3) Large beampipes mounted with RF absorber
   - Bempipe diameter 100mm and 120mm





Main parameters for the acceleration mode

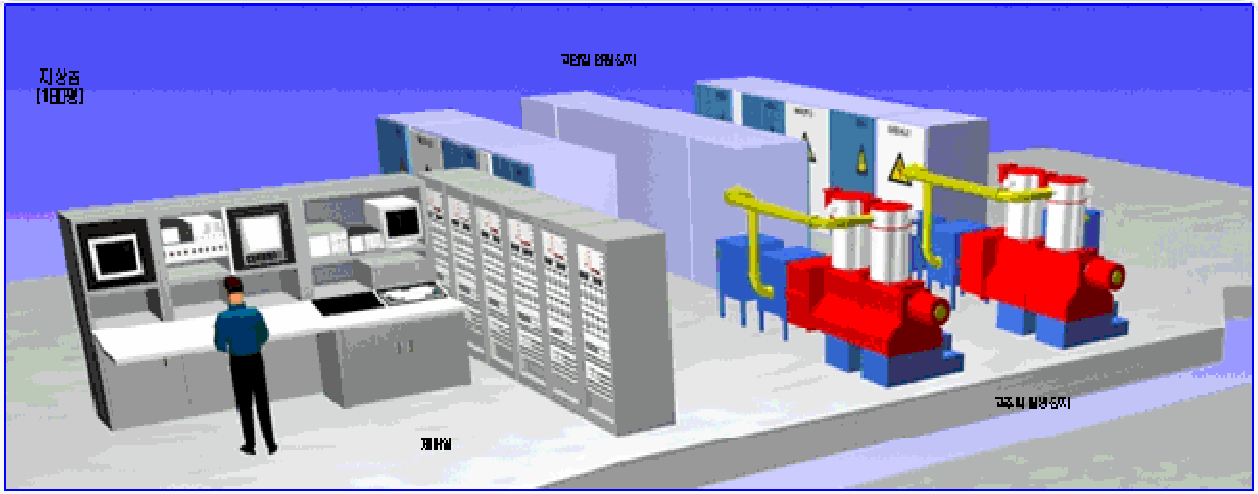
Frequency	1300 MHz	Coupling	3.8 %
Rsh/Q	897 Ω	Qo x Rs	289 Ω
Ep/Eacc	3.0	Hp/Eacc	42.5 Oe/(MV/m)

ERL Facilities

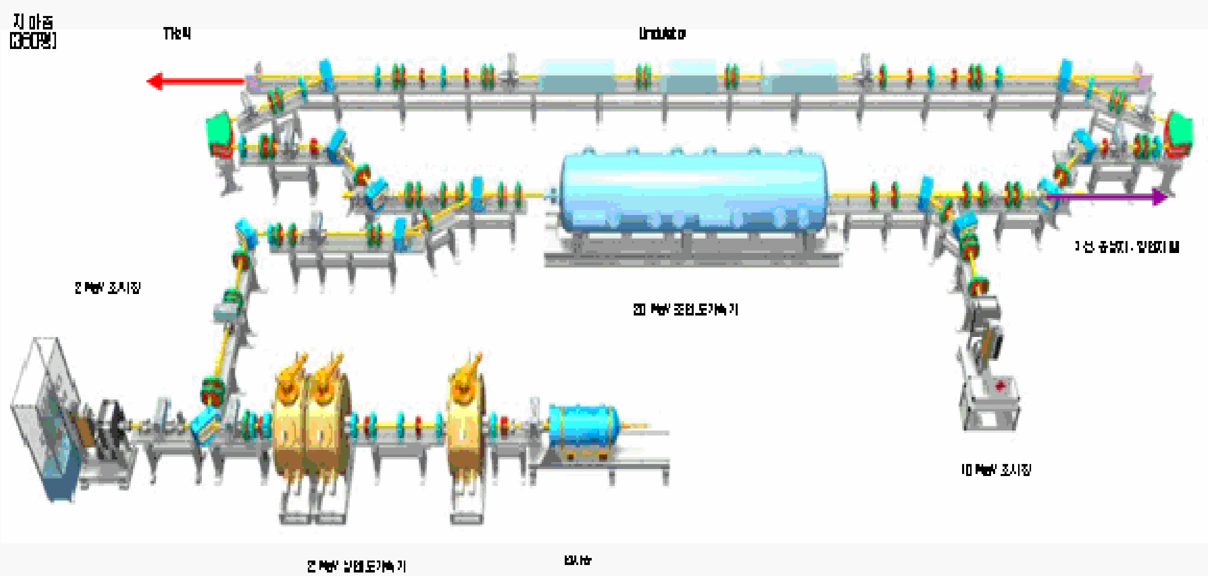
Proceedings of RuPAC 2006, Novosibirsk, Russia

AN UPGRADE OF SC LINAC AT KAERI TO ERL

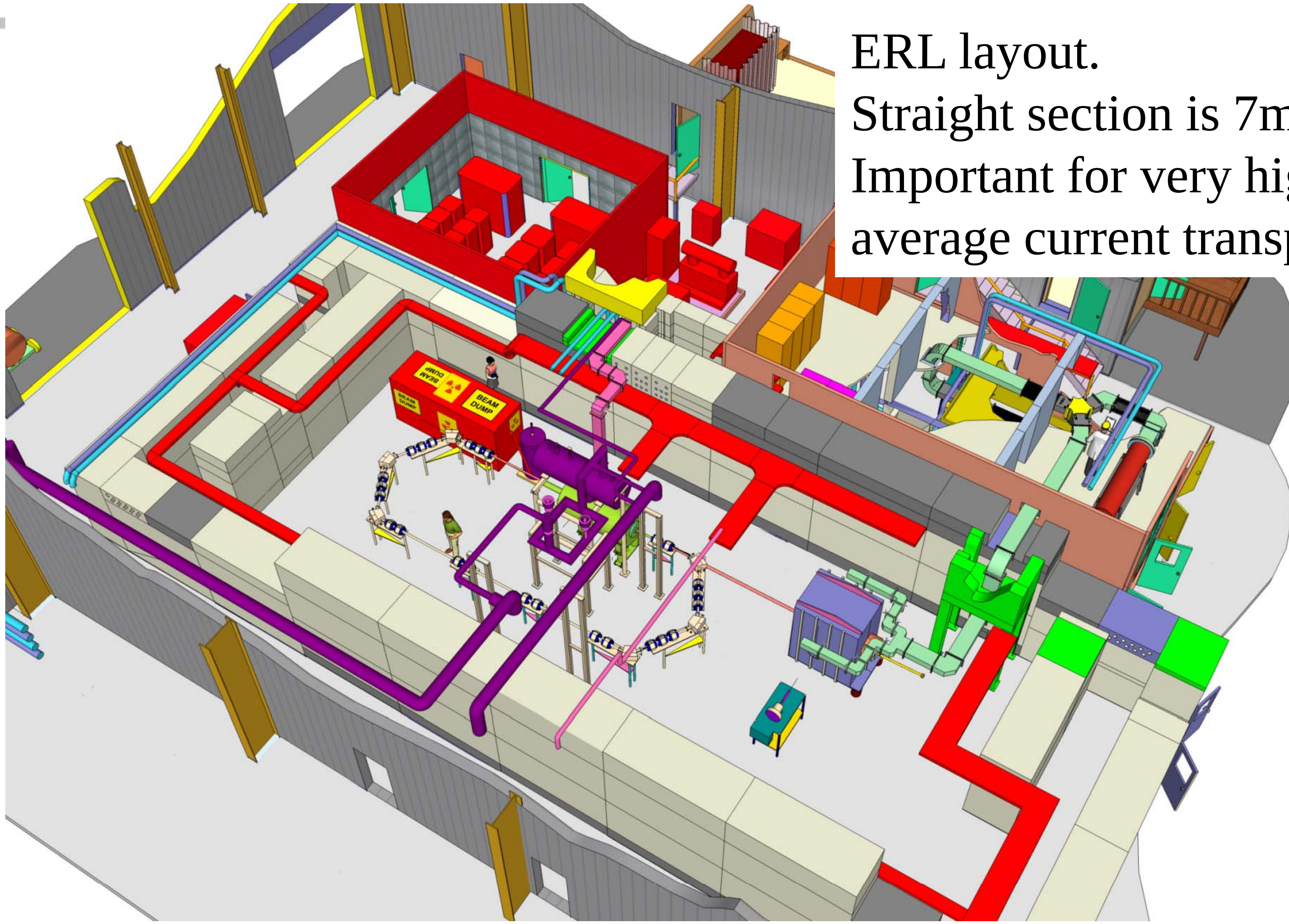
A.V.Bondarenko, S.V.Miginsky, Budker Institute of Nuclear Physics, Novosibirsk, Russia
B.C.Lee, S.H.Park, Y.U.Jeong, Y.H.Han, Korea Atomic Energy Research Institute, Daejeon, Korea



Used for
- T-wave generation
- Compton scattering X-ray production



BNL 0.5 Amp electron cooling ERL



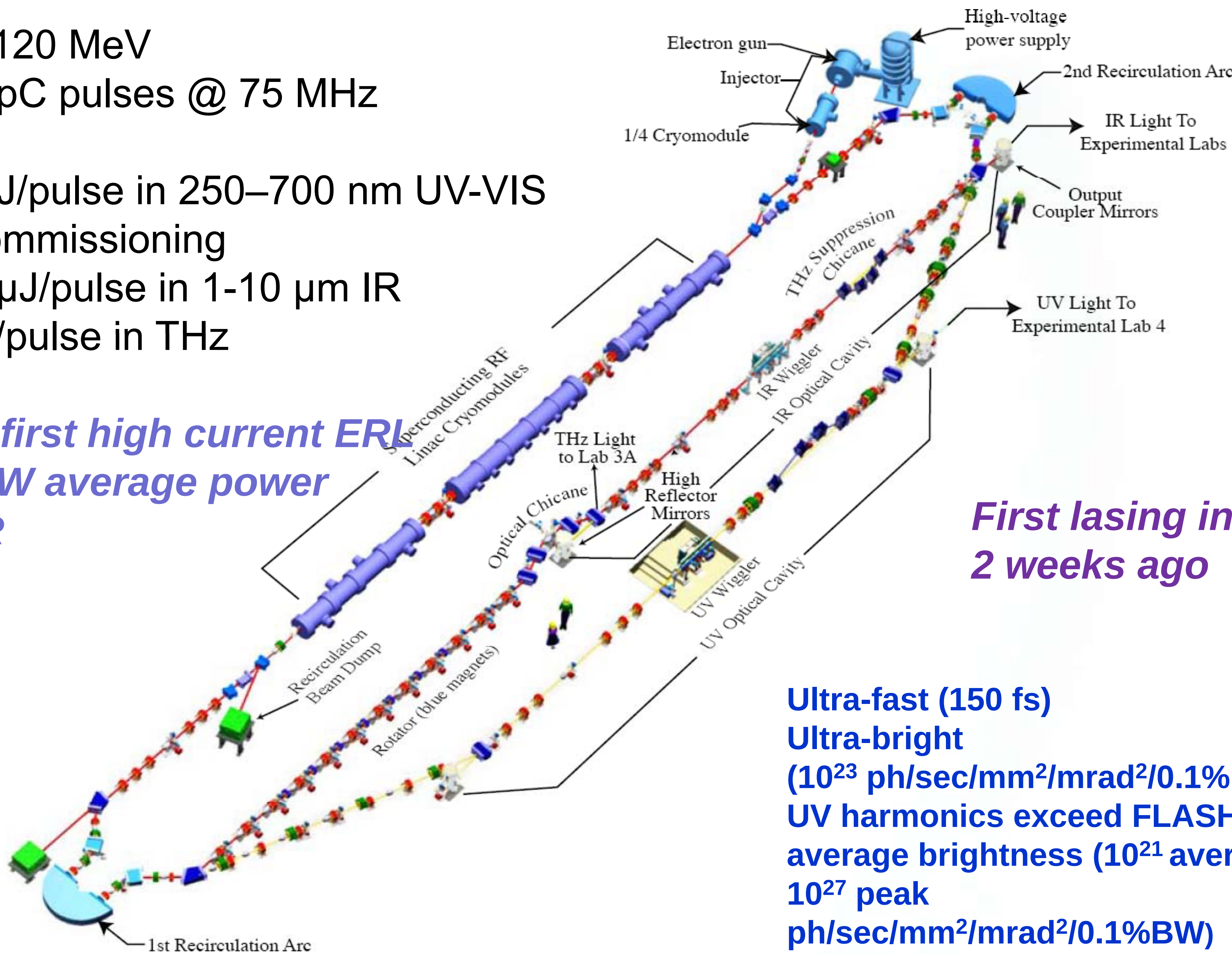
ERL layout.
Straight section is 7m long
Important for very high average current transport

JLab 4th Generation IR/UV ERL Light Source

E = 120 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 power
In IR



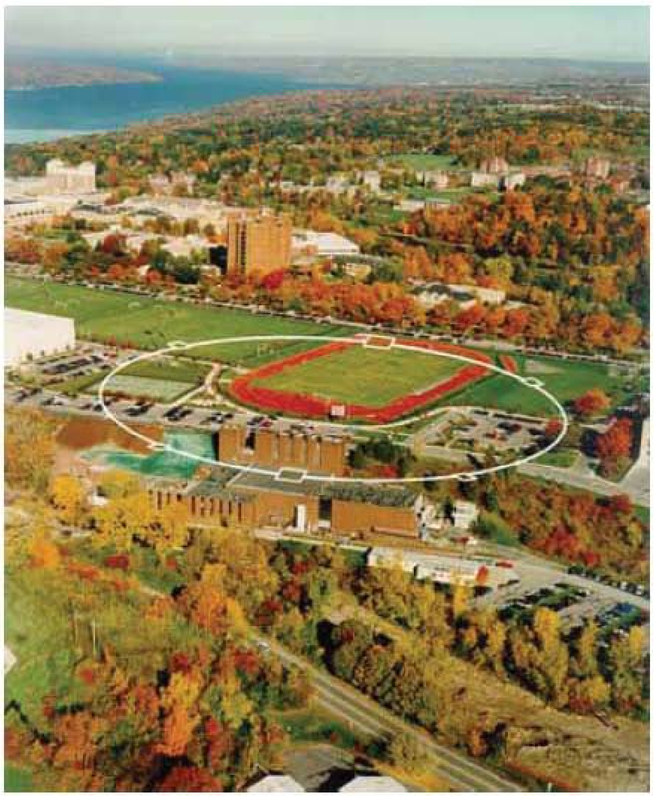
First lasing in UV
2 weeks ago

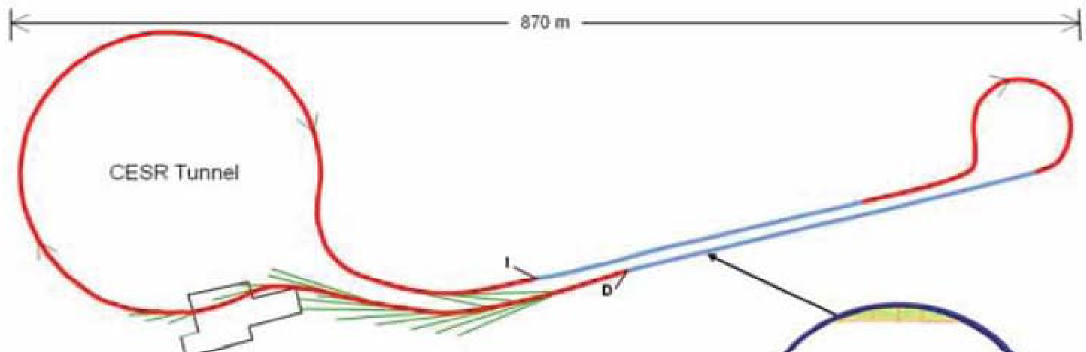
Ultra-fast (150 fs)
Ultra-bright
(10^{23} ph/sec/mm^2/mrad^2/0.1%BW)
UV harmonics exceed FLASH average brightness (10^{21} average, 10^{27} peak ph/sec/mm^2/mrad^2/0.1%BW)

Energy Recovery Linac (ERL) Background

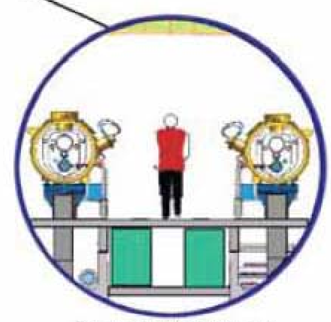
CLASSE
CHESS & LEPP

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).



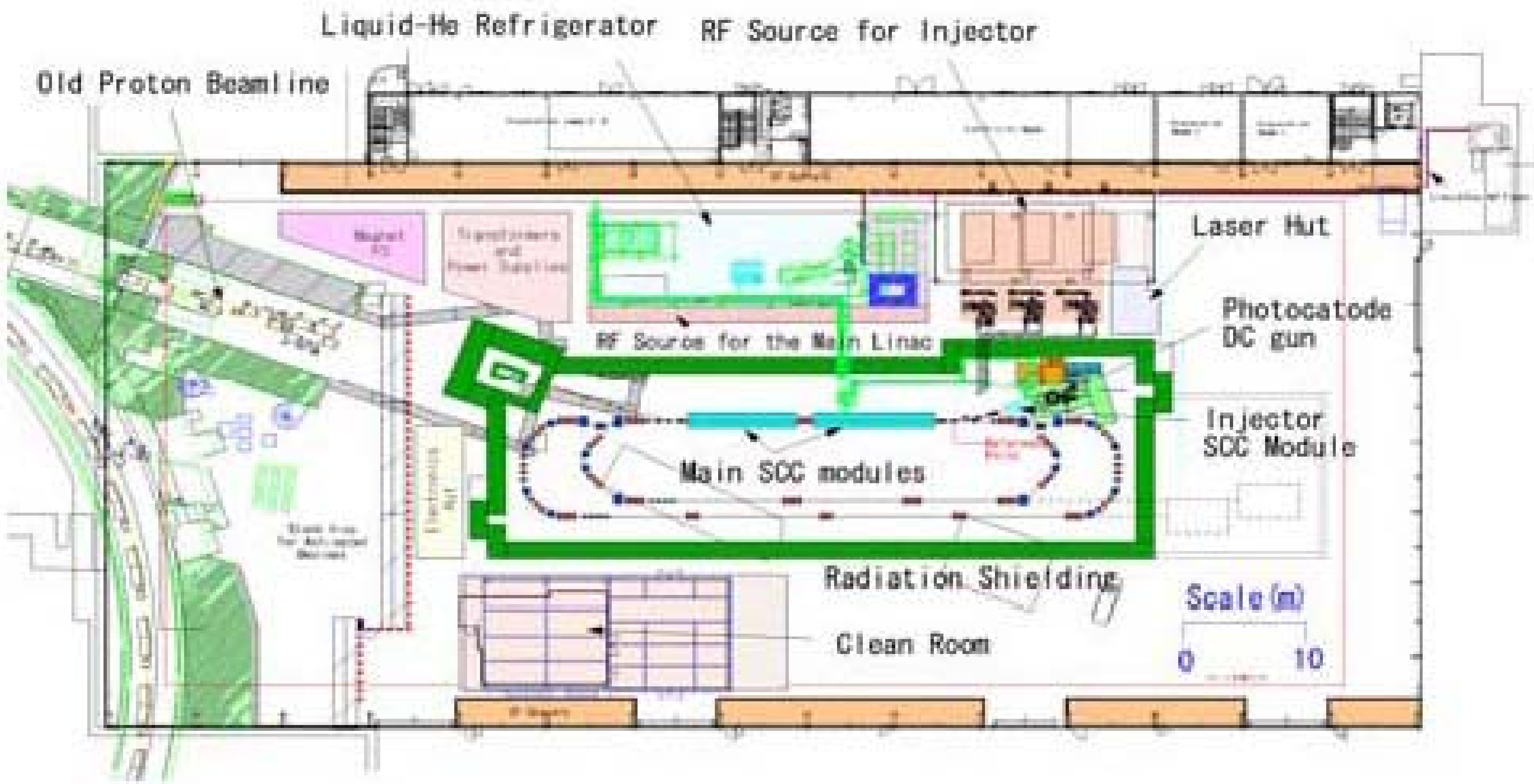
Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.

***for the CLASSE development team**

www.chess.cornell.edu

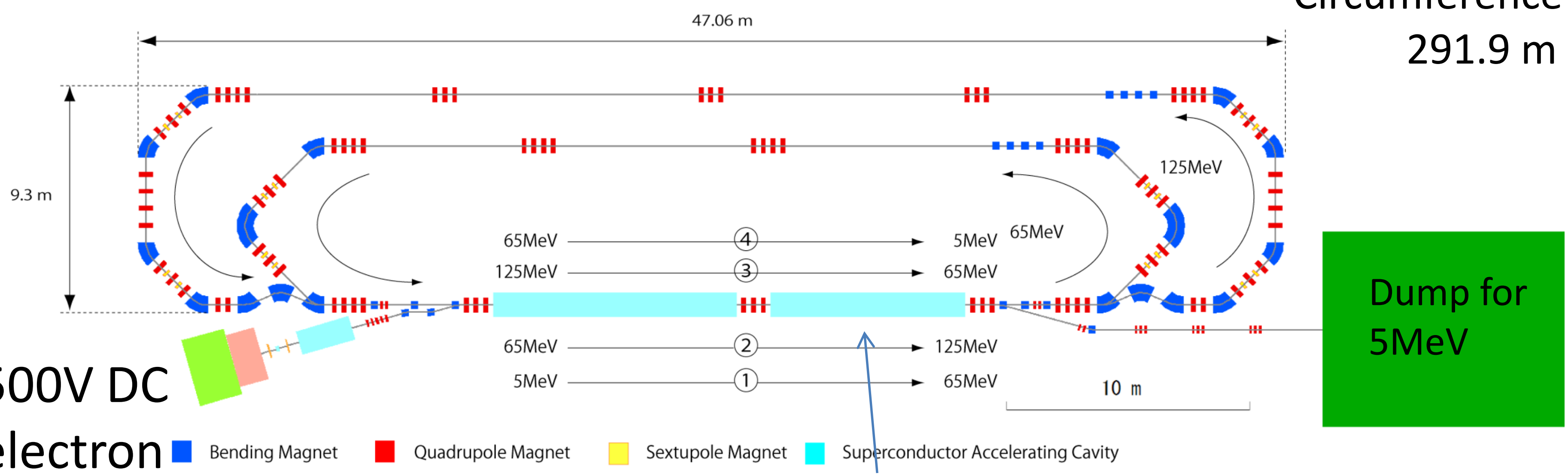
DEVELOPMENT OF A PROTOTYPE MODULE FOR THE ERL SUPERCONDUCTING MAIN LINAC AT KEK

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



Lattice design of 2-loop compact ERL (cERL)

Circumference
291.9 m



500V DC electron gun

Main superconductor cavities

- Very important research for compact, efficient design and high brightness transport of beams

High Energy Accelerator Research Organization, KEK

Miho Shimada and Yukinori Kobayashi

Source: Shimada, ERL’09

B*ERL*inPro - 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

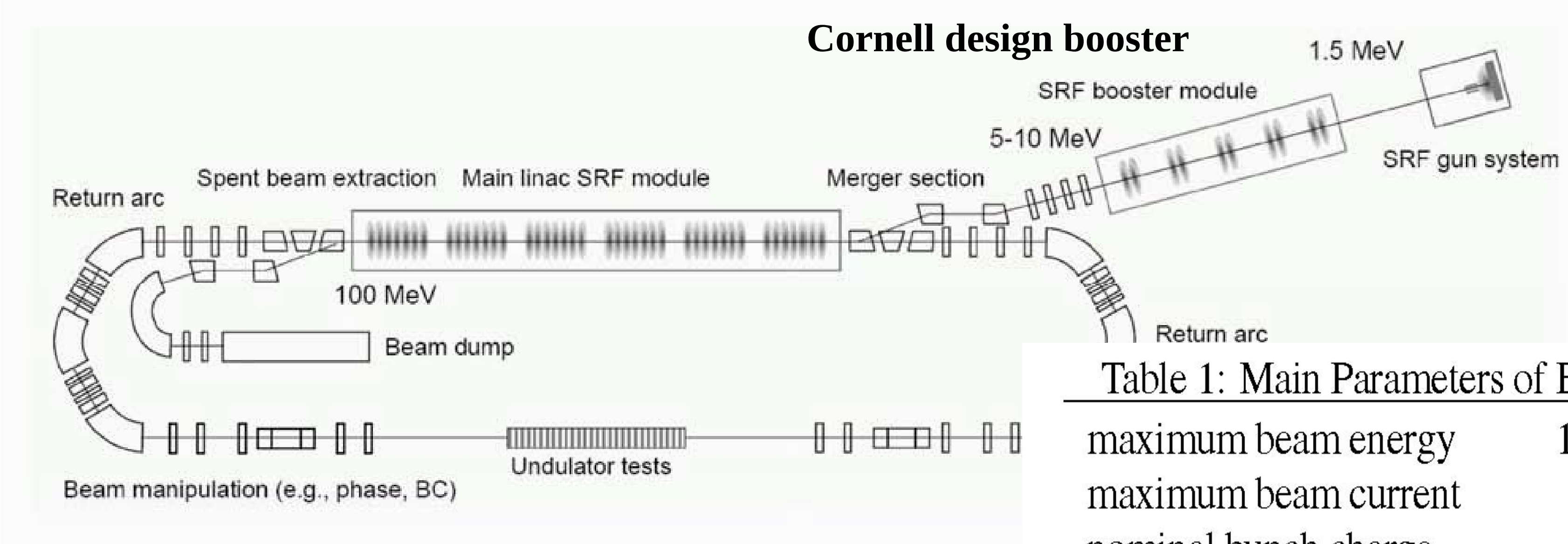
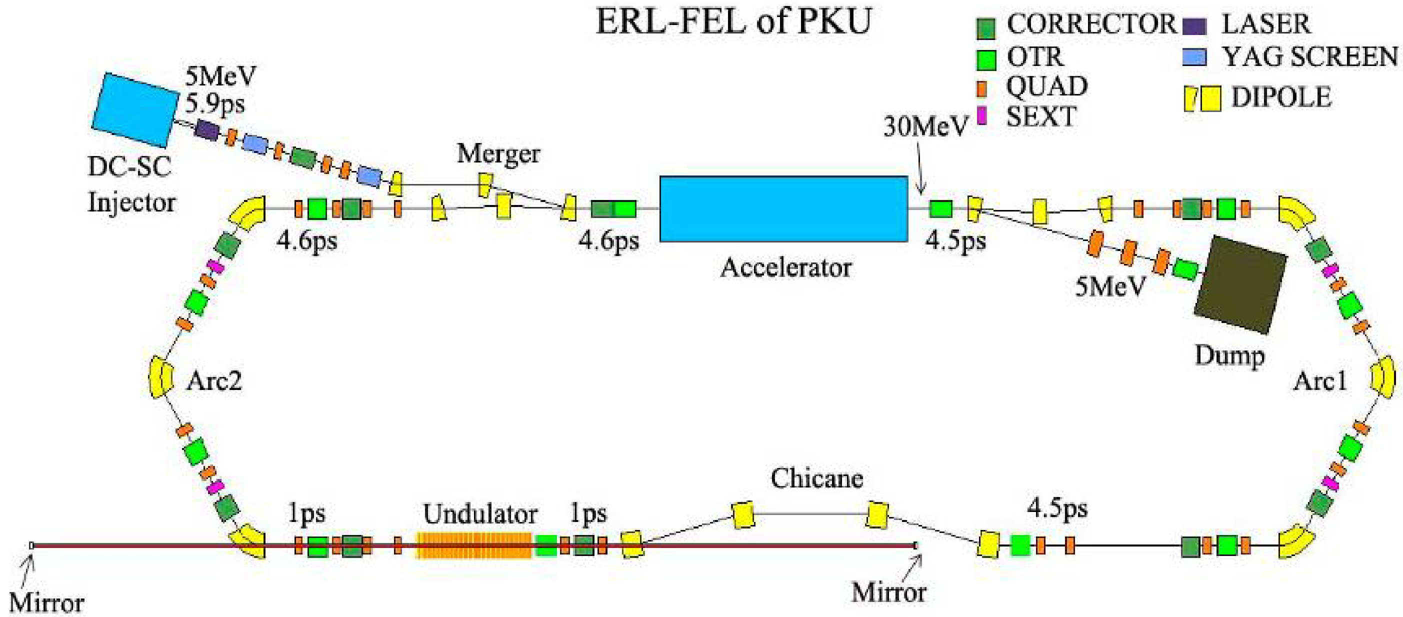
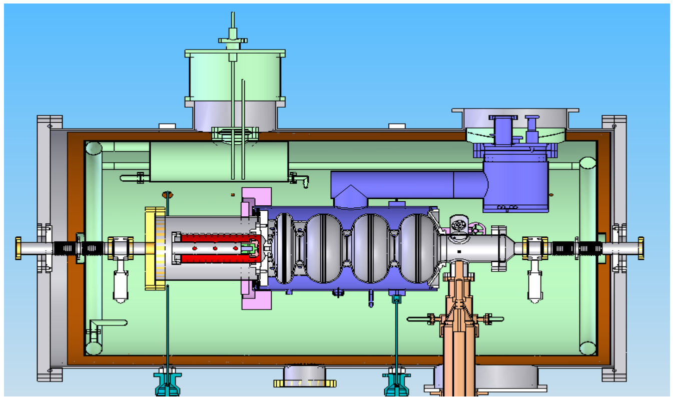


Table 1: Main Parameters of B*ERL*inPro

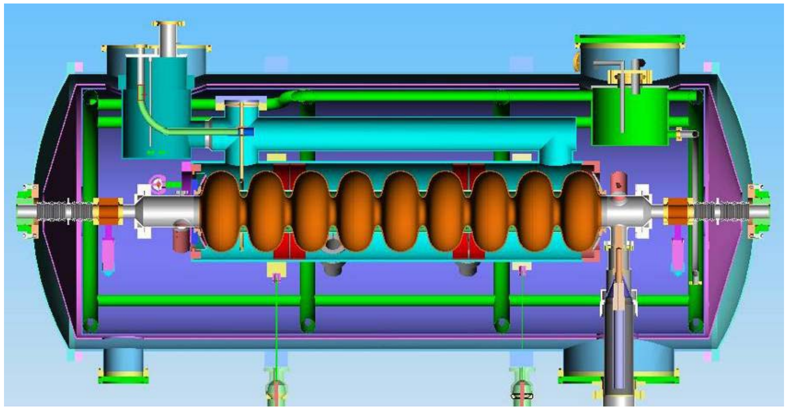
maximum beam energy	100 MeV
maximum beam current	100 mA
nominal bunch charge	77 pC
maximum repetition rate	1.3 GHz
normalized emittance	< 1 mm mrad
cryogenic load at 1.8 K	240 W

PKU ERL FEL Facility





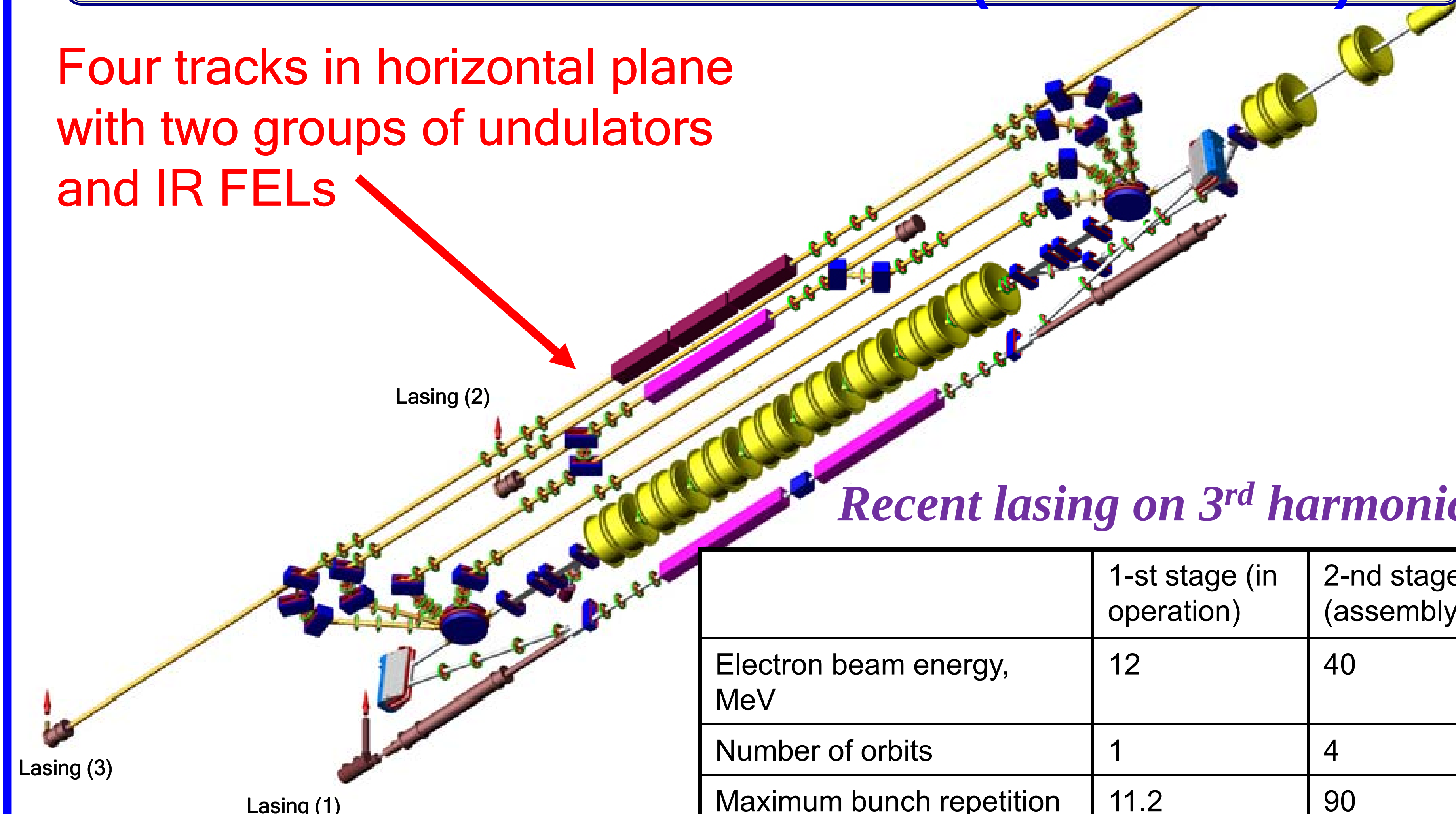
DC/SRF Hybrid Injector



Accelerator module

Full scale Novosibirsk FEL (bottom view)

Four tracks in horizontal plane with two groups of undulators and IR FELs



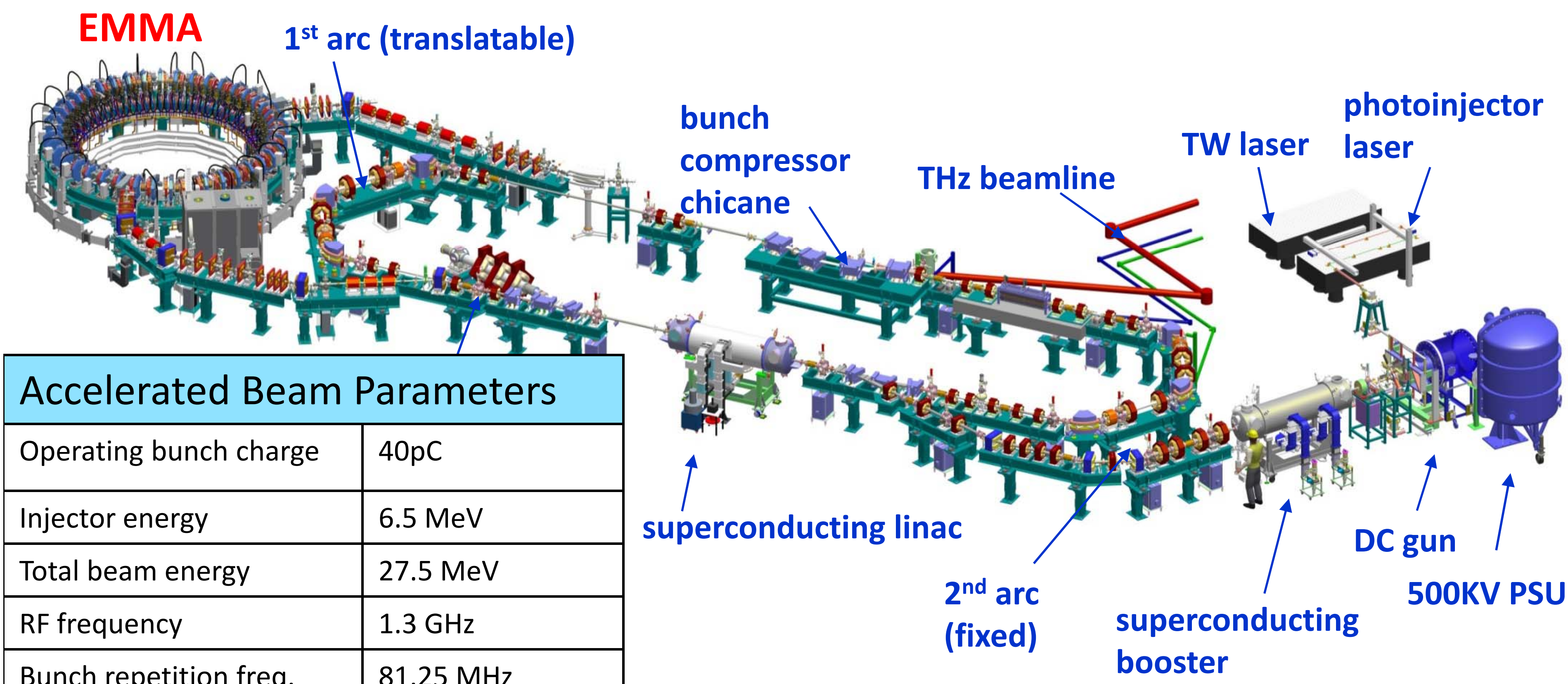
Recent lasing on 3rd harmonic!

	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

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

Science & Technology Facilities Council

Alice

ALICE Plans

- Continued commissioning of IR FEL towards lasing
  - Machine operation with increased bunch charge, RF improvements & optimisation, electro-optic bunch length diagnostics
- EMMA – first demonstration of acceleration in non-scaling FFAG
- THz dedicated beamline
  - Living cells exposures in dedicated tissue culture lab
- Microbunching experiments
  - Using THz source from converted tWatt Laser.
  - Transverse effects to be studied in compressor and return arc.
- Digital low-level RF upgrade (improved phase and amplitude stability)
- Linac cavity/cryomodule upgrade for CW ER operation
  - Collaboration with Cornell, Stanford, LBNL, FRZ Rossendorf
- Gun upgrade
  - Load-lock system for improved cathode replacement system

CW Linac X-FELS

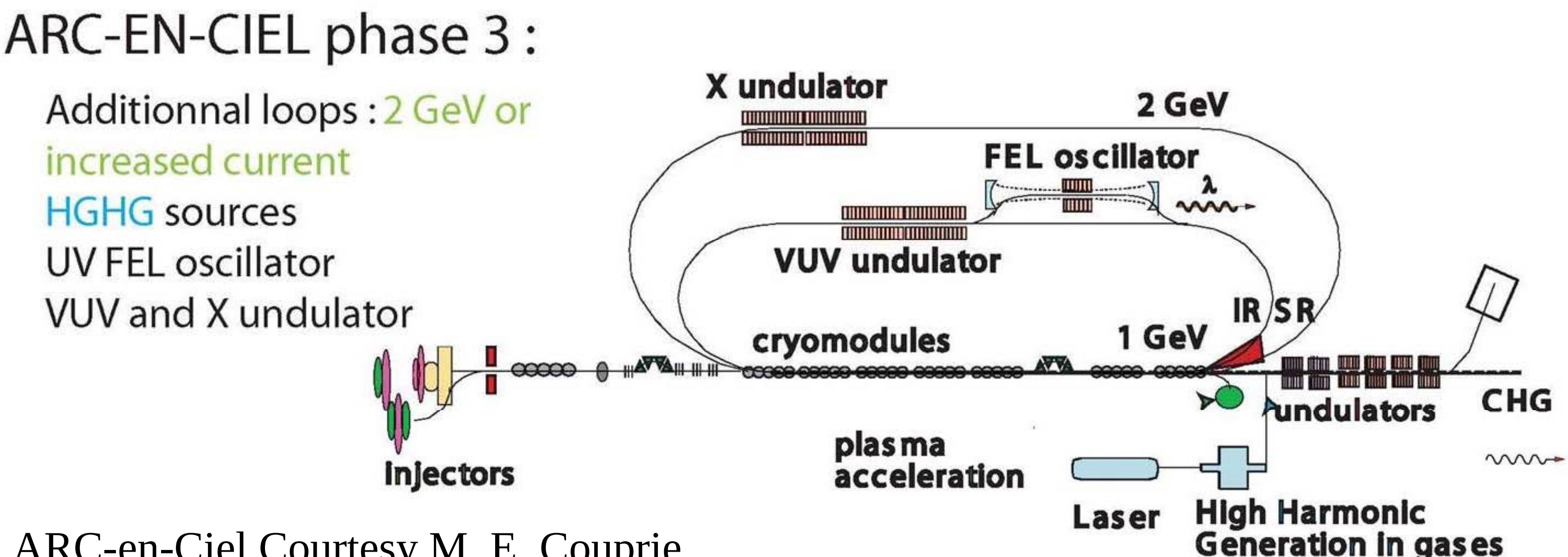
- Higher energies => longer linacs => higher cost
- More FELs/linac is better
  - Multiplicity by way of RF separation (a la CEBAF)?

- **Recirculation** may make systems more affordable
  - Cuts required srf length
  - Cuts conventional facility (tunnel)
  - Cuts cryogenic plant
  - Cut s operating cost

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!***

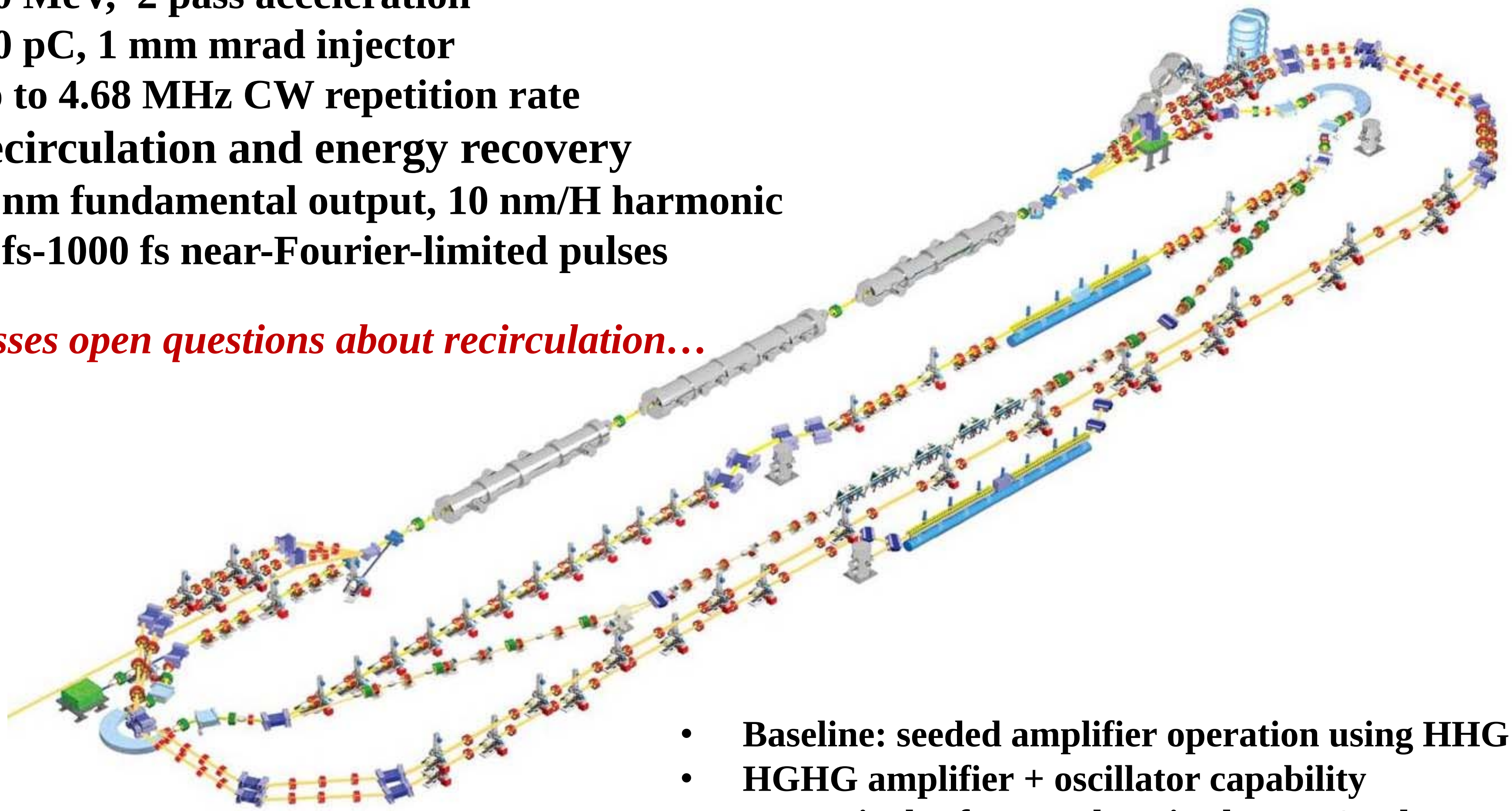


ARC-en-Ciel Courtesy M. E. Couprie

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

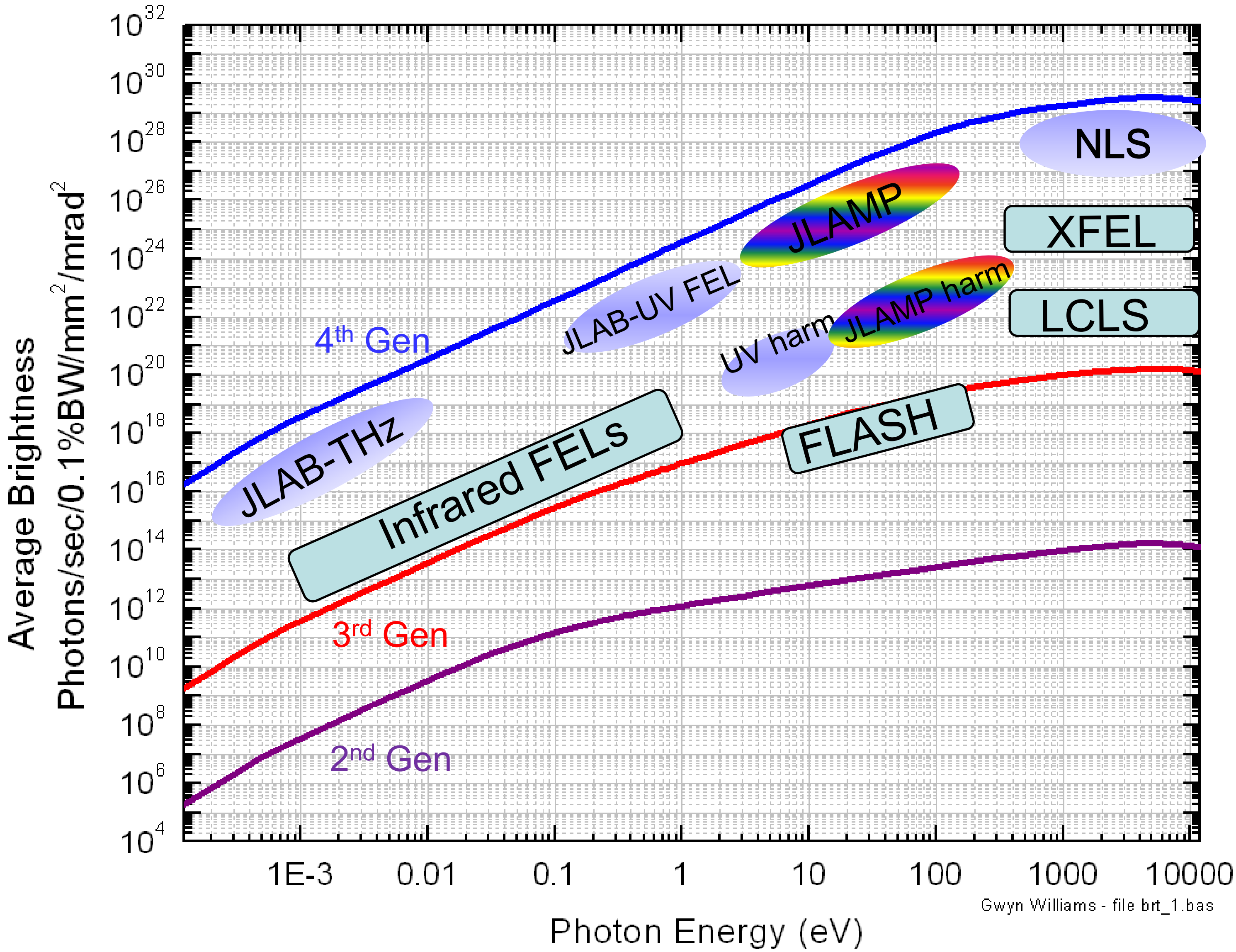
- **600 MeV, 2 pass acceleration**
- **200 pC, 1 mm mrad injector**
- **Up to 4.68 MHz CW repetition rate**
- **Recirculation and energy recovery**
- **10 nm fundamental output, 10 nm/H harmonic**
- **50 fs-1000 fs near-Fourier-limited pulses**

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



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 multiparticle (longitudinal) coherence**
- **Can recirculating linacs address cost barrier to CW X-FEL facilities???**

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