The Energy Recovery Linac Project - A Next Generation Source of Synchrotron Radiation X-rays

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LEPP/CHESS

Synchrotron Radiation X-ray Sources

- First Generation – X-rays from the bending magnets of circular accelerators built for nuclear and high energy physics research
- Second Generation – X-rays from the bending magnets of accelerators purpose built for X-ray production
- Third Generation – X-rays from insertion devices (wigglers and undulators) in accelerators purpose built to include them
- ~ 70 rings operating or in construction worldwide

History at Cornell

- Cornell has a long history in developing electron accelerators, and in the use of synchrotron radiation X-rays
- 300 MeV, 1.4 GeV, 2.2 GeV, and 10 GeV synchrotrons, and an 8 GeV storage ring
- First measurement of the synchrotron radiation spectrum – Tomboulian and Hartman on the 300 MeV machine
- CHESS facility for hard X-rays at the 8 GeV storage ring (2^{nd} generation)

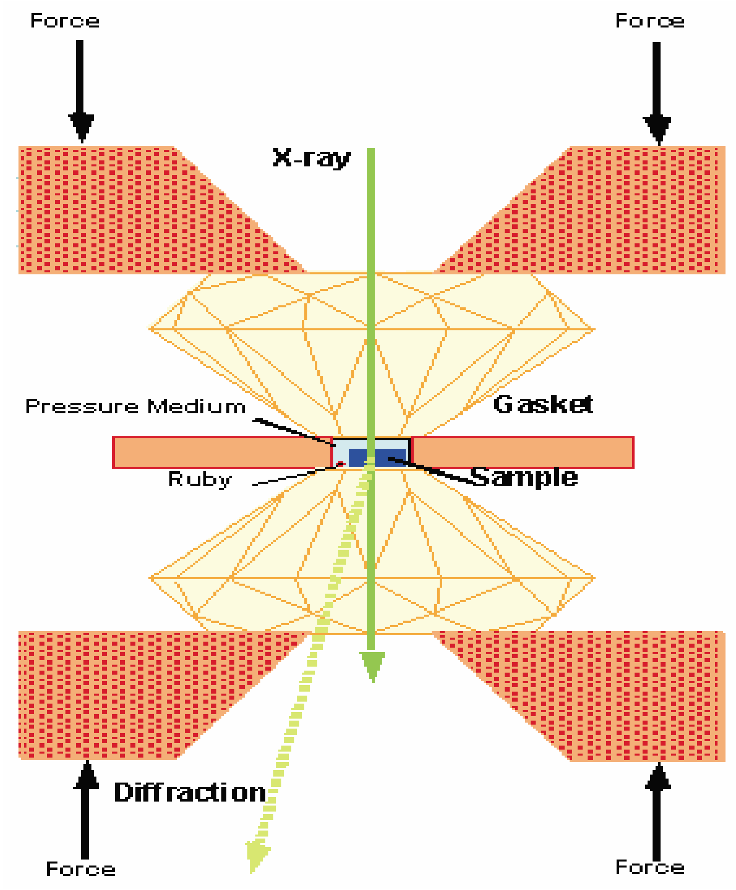
The Motivation for an ERL Light Source – X-ray Experimenter's Needs

- <u>Higher brilliance</u> – allows studies with smaller samples
- <u>Higher coherent flux</u> – allows one to capitalize on interference effects
- <u>Shorter duration pulses</u> – allows one to conduct pump-probe experiments

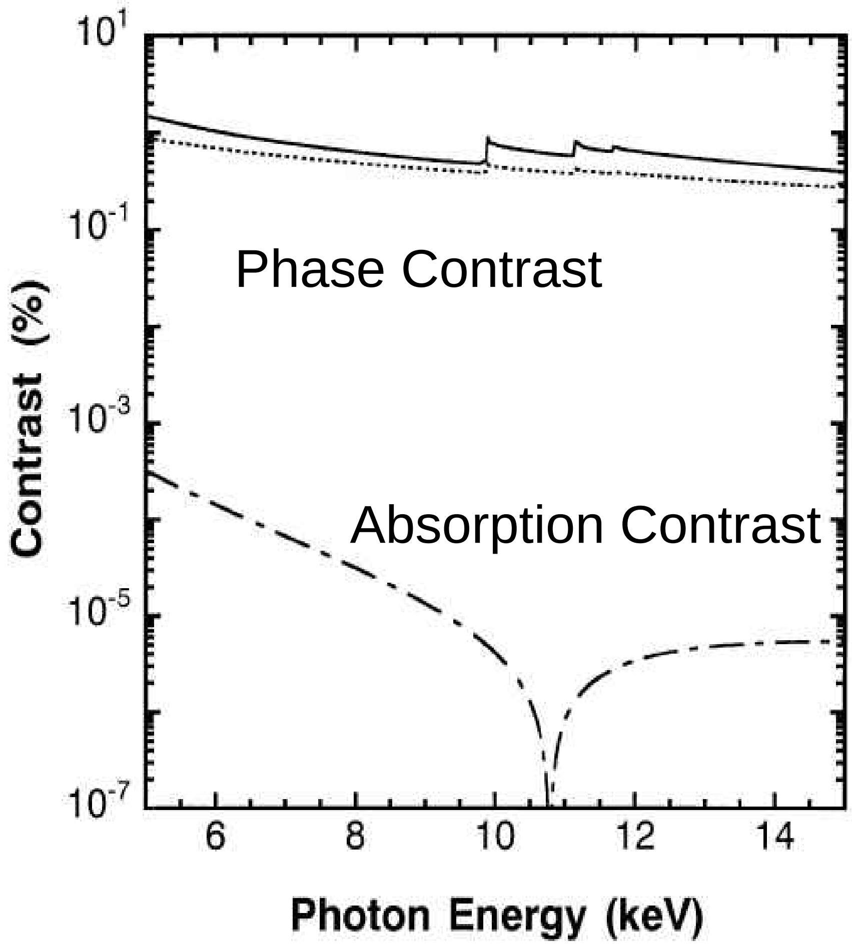
These needs translate into a requirement for high average current electron beams with much smaller emittances and much shorter bunch lengths

High Pressure: Materials, Engineering, Geological and Space Sciences

- High Pressure experiments are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Higher P $\Rightarrow$ smaller samples.
- The high brightness of ERL x-ray beams will greatly extend the pressures and samples that can be studied.



Phase vs. Absorption Contrast

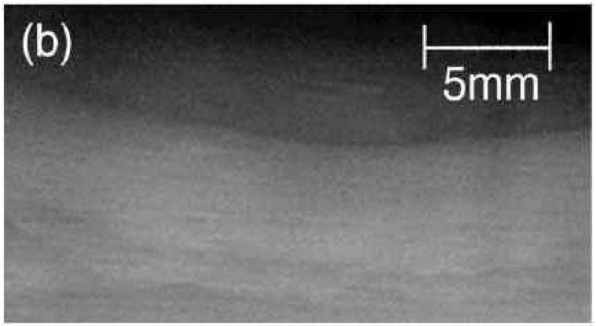


Kagoshima et al. (2001)

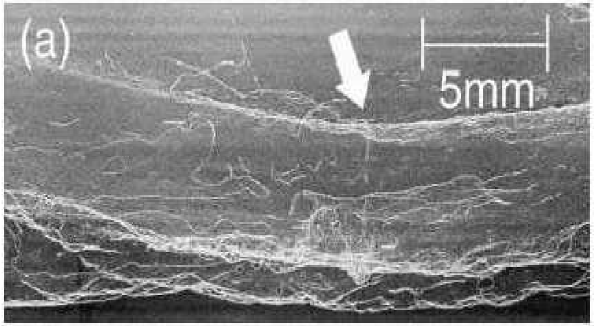
Protein $C_{94}H_{139}N_{24}O_{31}S$ in water

Phase contrast is 10^4 higher than absorption contrast for protein in water at 8 keV

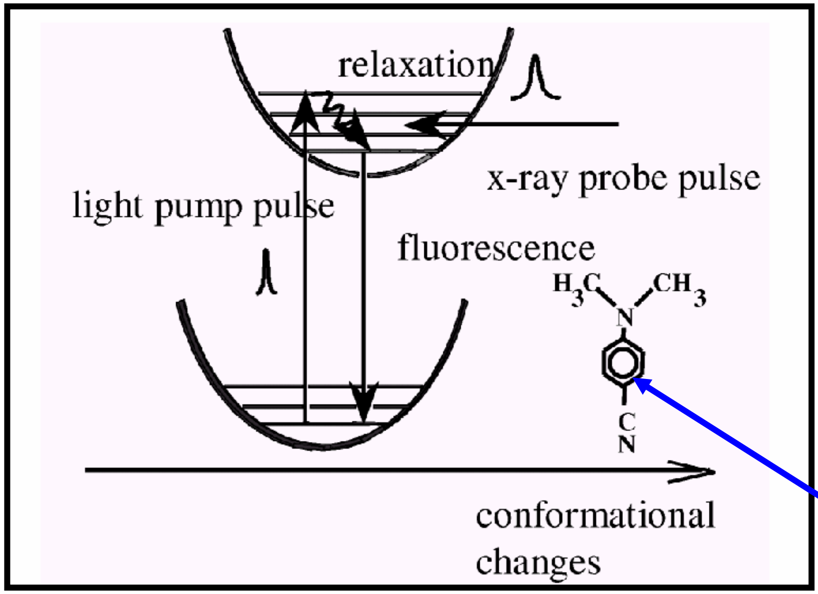
Absorption contrast ~ λ^3

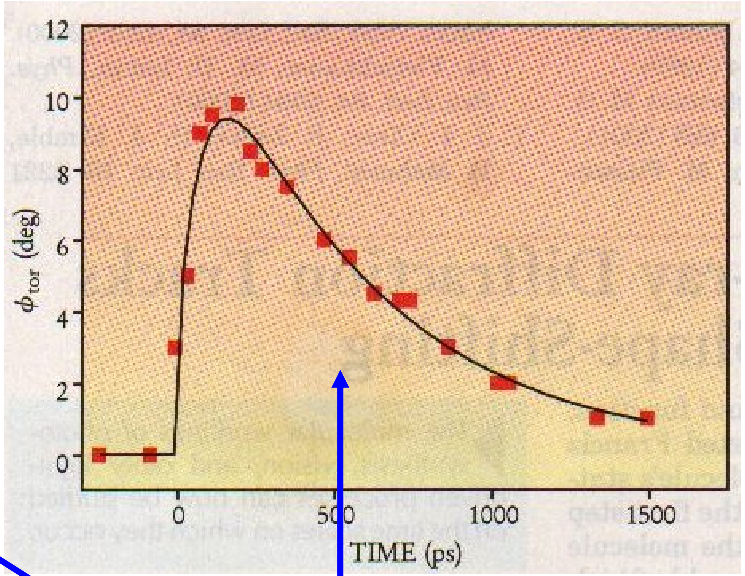


Phase contrast ~ λ



ERL Enables Following the Structure of Ultrafast Chemical Reactions

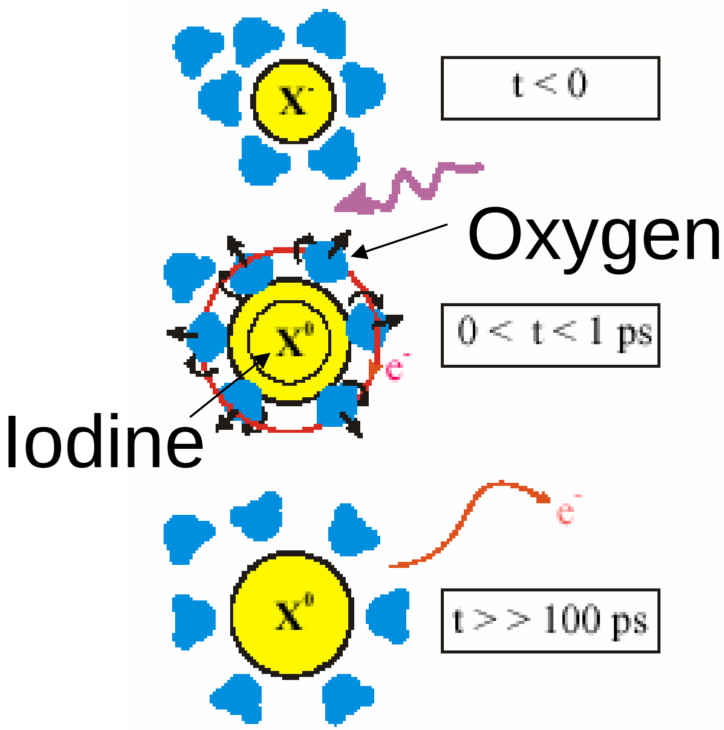


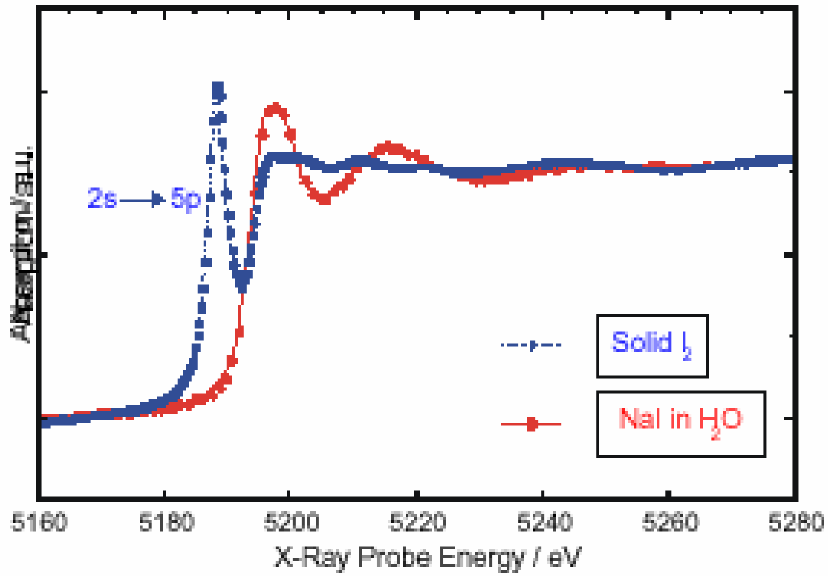


ESRF expt. showed 10° of bond rotation over 100's of picoseconds

An ERL will allow following reactions on the 100's of femtosecond time scale.

Hydration dynamics is not well understood





Schematic illustration of Photo-neutralization of I- in liquid phase. EXAFS of 2s $\rightarrow$ 5p. Change in spectra arises from changed I-O distances. (From Schoenlein & Falcone).

An ERL will allow examination of intermediate states and the development of structural models of what really happens during hydration!

X-ray beam characteristics depend on electron beam properties

- Flux ~ I (average current)
- Brilliance ~ $I/\varepsilon_x\varepsilon_y$ (ε_x and ε_y are emittances)
- Peak Brilliance ~ $I/\varepsilon_x\varepsilon_y\tau$ (τ is bunch length)
- Coherent Flux ~ $I/\varepsilon_x\varepsilon_y$
- Photon Degeneracy ~ $I/\varepsilon_x\varepsilon_y\tau$

I, ε_x, ε_y, and τ are the electron beam properties that determine the key X-ray beam qualities.

Storage Ring Beam Quality

In a storage ring, the emittances and bunch length are determined by equilibrium phenomena which set in over a few thousand turns – i.e. within a fraction of a second.

The very best X-ray beams available are limited by the realities of the storage ring. Storage ring technology is very close to the limits of the possible in terms of emittance and bunch length.

State-of-the-art Storage Rings

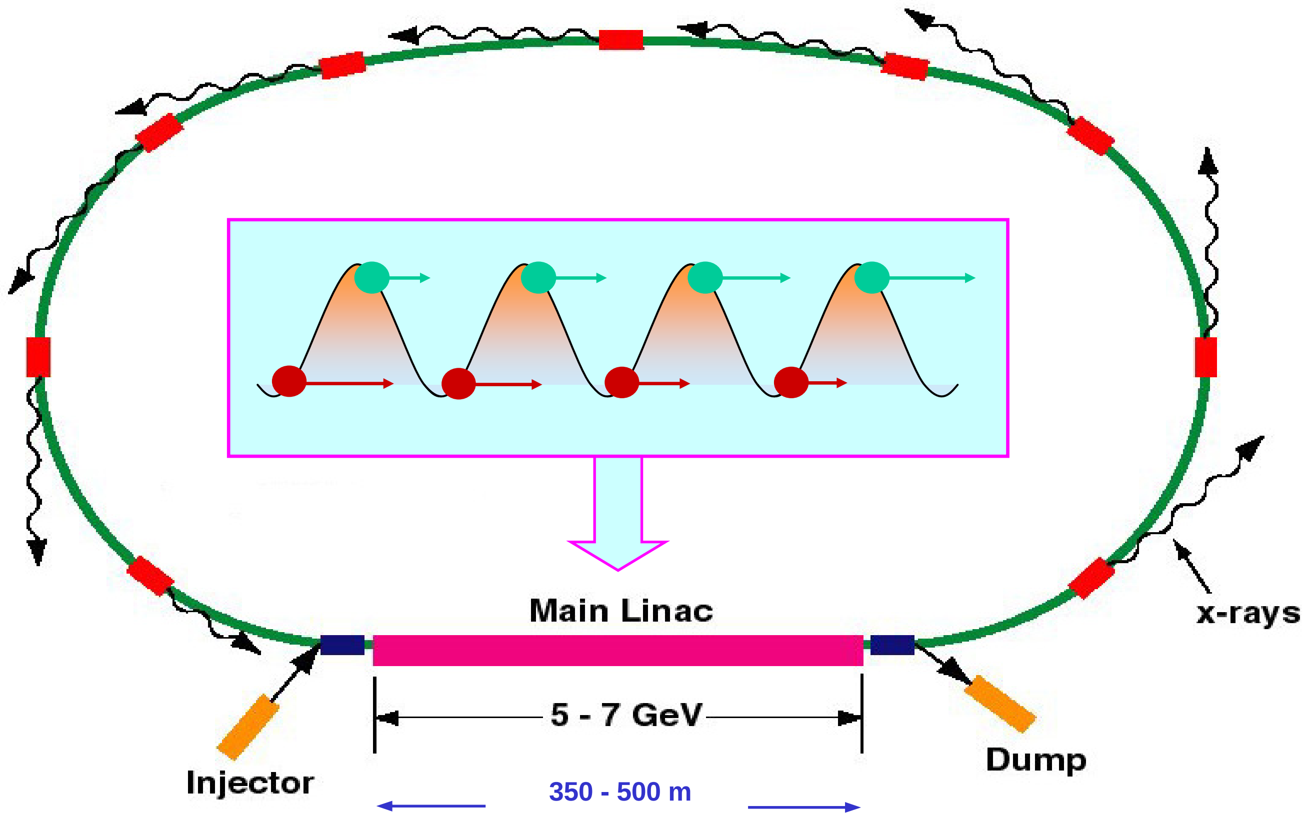
- Maximum beam energy – 6 to 8 GeV
- Circulating current – ~ 500 mA
- Circulating electron beam power – few GW
- Electron beam lifetime – few hours
- Total power radiated as X-rays – few MW
- Total number of X-ray beam lines – 50 – 60
- Total construction cost - ~ $1B
- "Big Three" machines – ESRF (6 GeV, Europe), APS (7 GeV, US), Spring-8 (8 GeV, Japan)

The ERL Idea

We can generate beams with the smaller emittances and shorter duration pulses we want, with a suitable electron source delivering beam to a linear accelerator, but providing the beam power would be prohibitively expensive

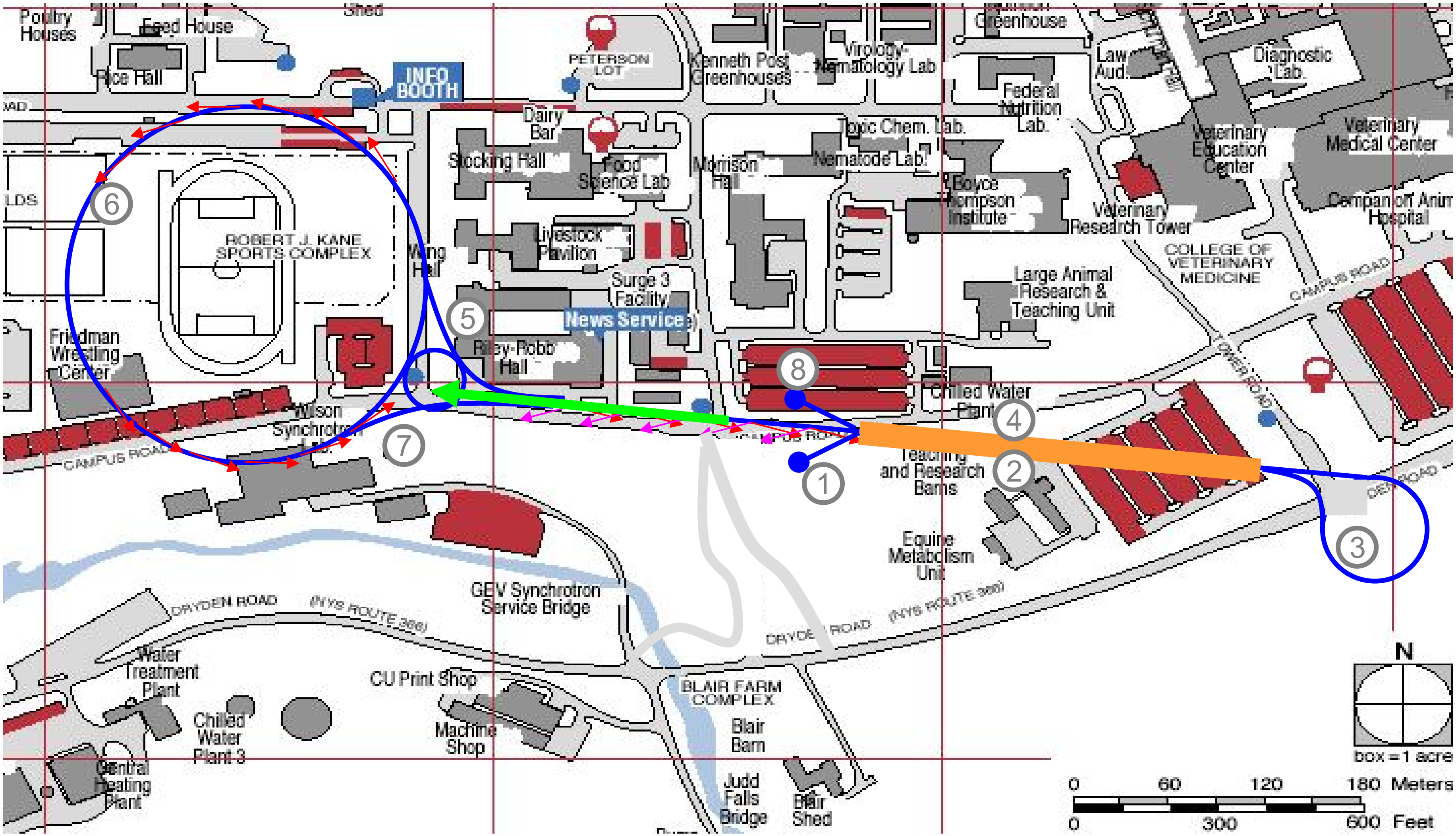
So, after the beam has been used to generate X-rays – run it back through the linear accelerator a second time, 180 degrees out of RF phase,. This way, the beam returns its energy to the microwave fields of the accelerator.

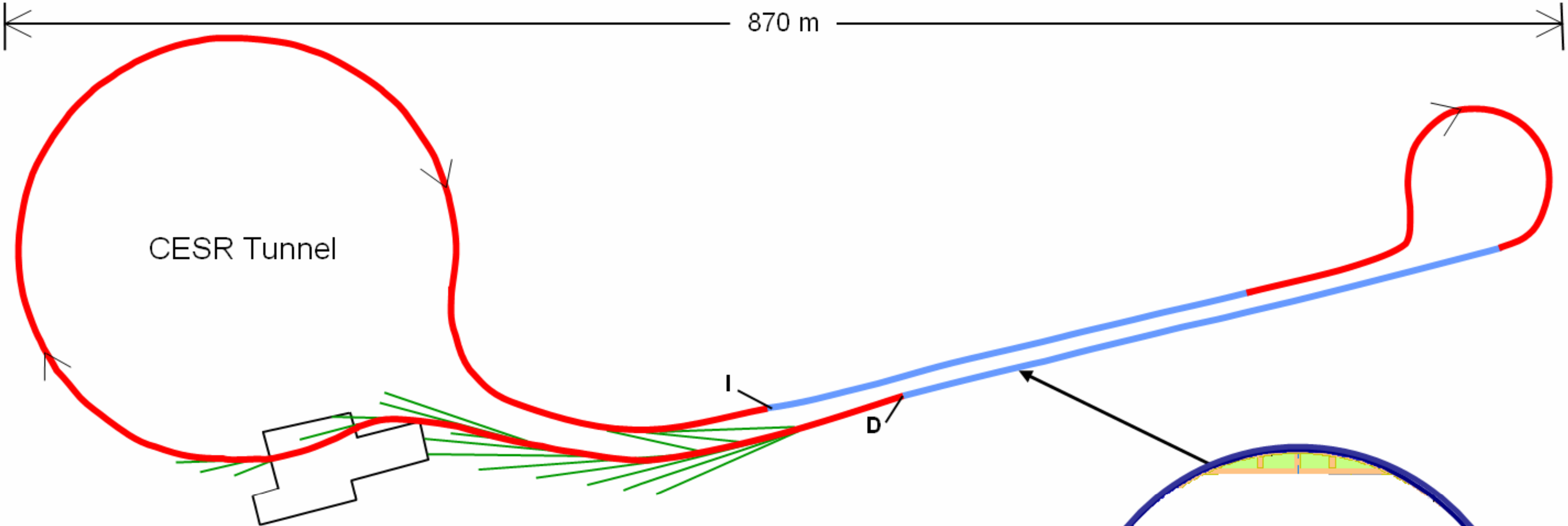
Energy Recovery Linac



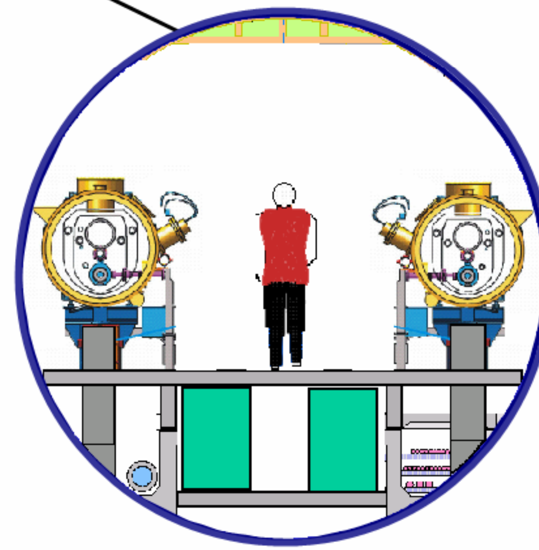
- Accelerating Bunch
- Decelerating Bunch

A possible ERL upgrade to CESR



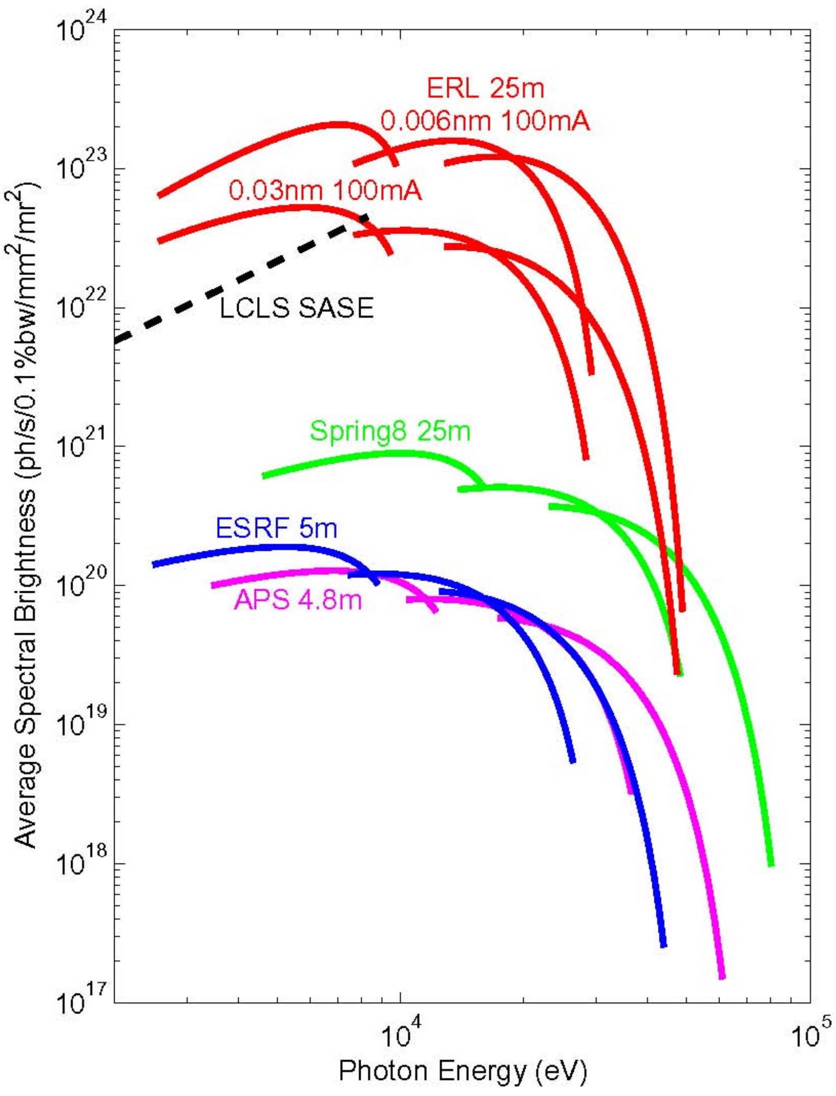


Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green 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).



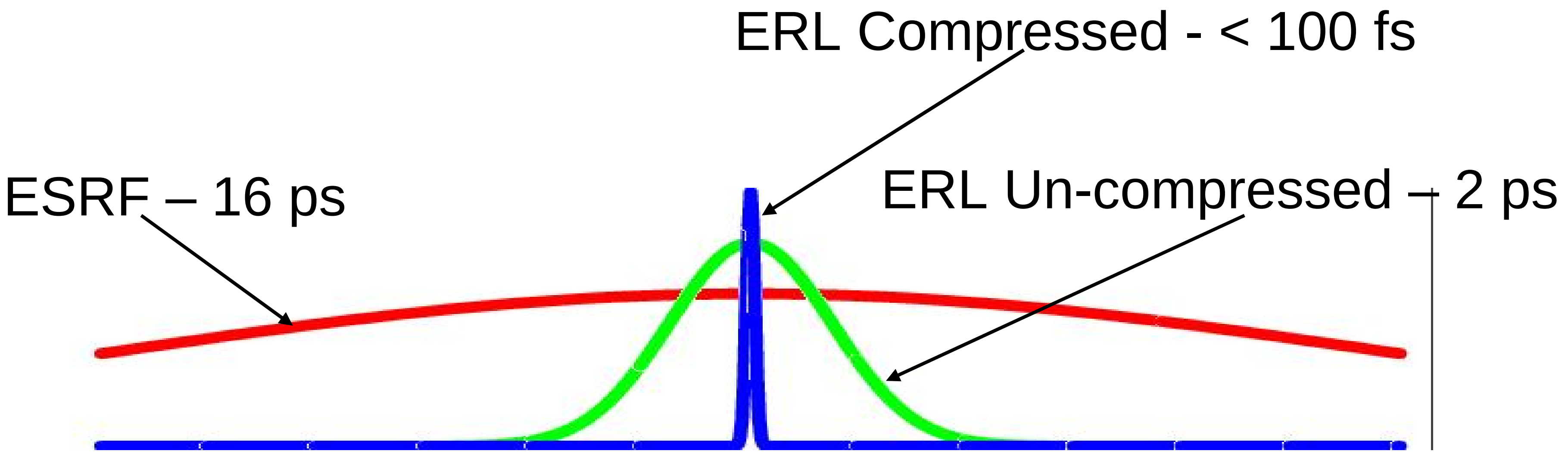
Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.

ERL has high spectral brightness

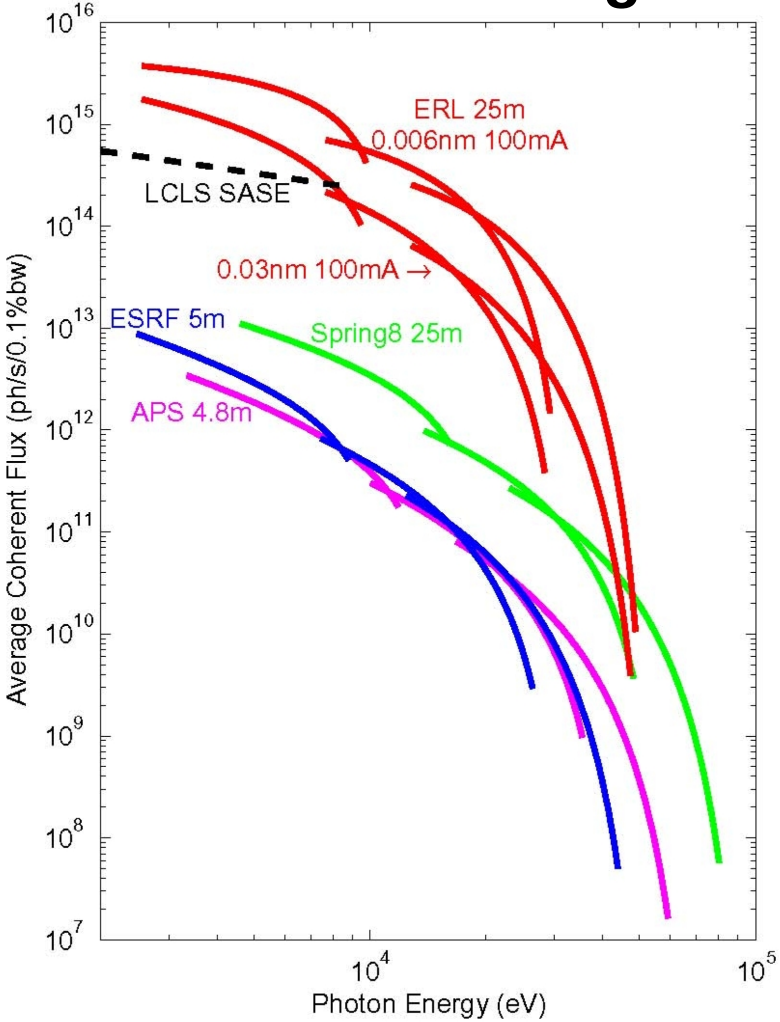


ERL can produce very short pulses

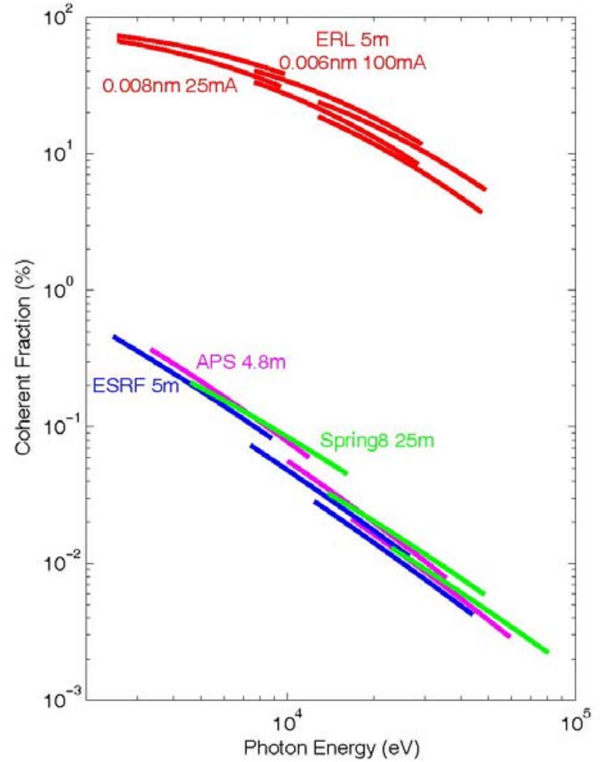
- Bunch charge can be made large at the cost of beam brightness
- Bunch repetition rate is flexible, and can be quite high – e.g. 1 MHz

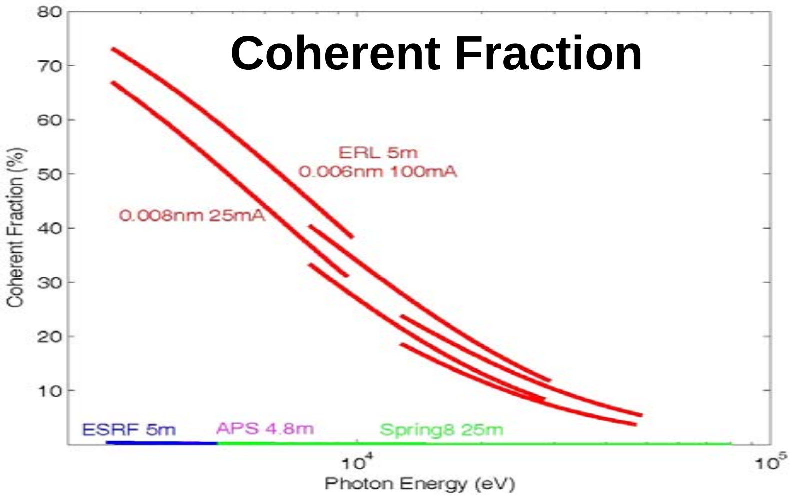


ERL has High Transverse Coherence



Avg. Coherent Flux





Coherent Fraction

Comparison – APS and ERL

Parameter	APS 3rd generation storage ring	Energy recovery linac	Gain with ERL
Electron source size in microns (rms)	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
Micro x-ray beam size	100 nm to 1 micron	1 nm	100 to 1000
Coherent flux x-rays/sec/0.1% bw	3×10^{11}	9×10^{15}	3000
Pulse duration (rms)	32 ps	<100 fs	> 320 times shorter

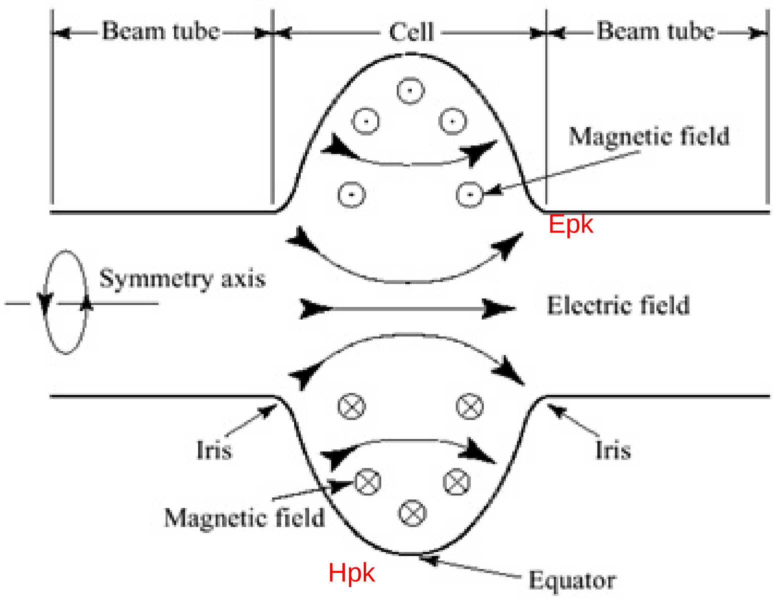
What developments make the ERL idea feasible?

- Development of high accelerating gradient superconducting microwave accelerator cavities
- Demonstration of energy recovery in a moderate energy, moderate current accelerator (the Jefferson Lab FEL)
- Development of high brightness electron sources based on photoemission

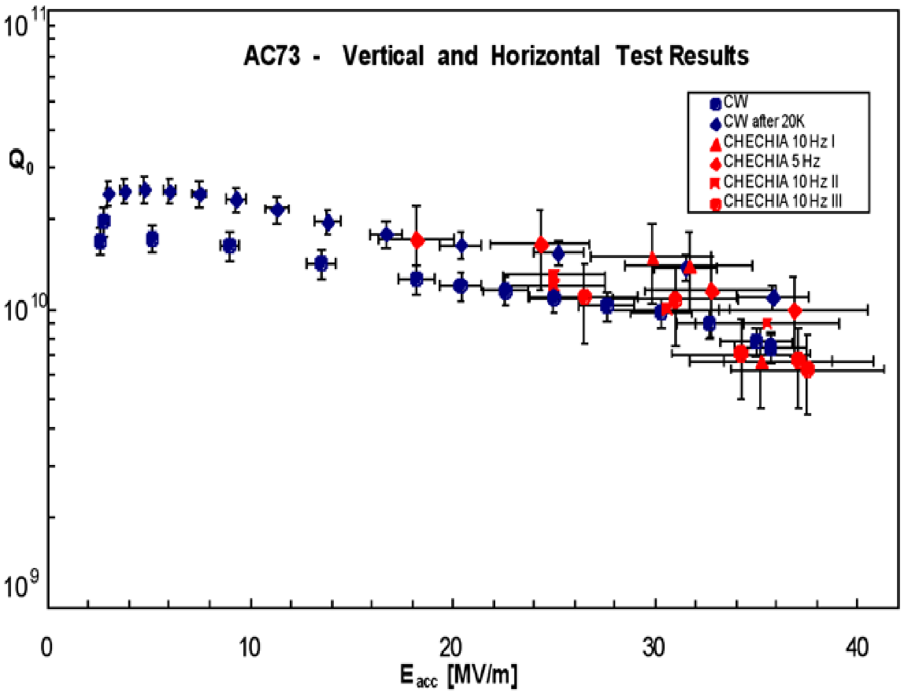
Superconducting Accelerator Cavity Developments

- Cavity cell shape that inhibits multipactor
- High purity niobium for thermal stability
- Manufacturing and processing methods that allow high accelerating gradients and very high Q_o to be reliably obtained
- Development of efficient refrigerators to reach 2 K operating temperatures

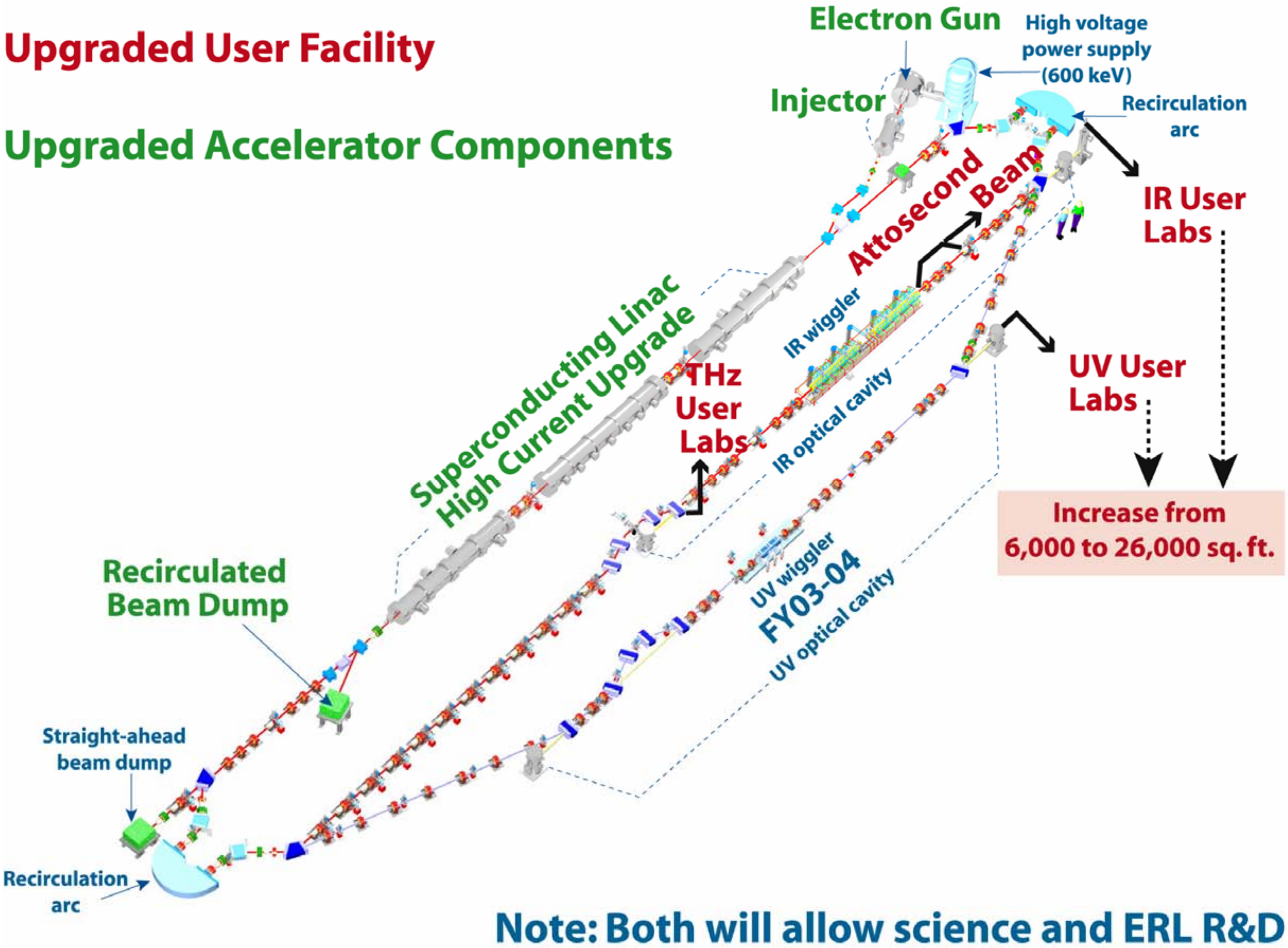
Cornell has played a leading role in these advances for many years



Beam tube
Cell
Beam tube
Magnetic field
Epk
Symmetry axis
Electric field
Iris
Iris
Magnetic field
Hpk
Equator



AC73 - Vertical and Horizontal Test Results
CW
CW after 20K
CHECHIA 10 Hz I
CHECHIA 5 Hz
CHECHIA 10 Hz II
CHECHIA 10 Hz III
Q_0
10^{11}
10^{10}
10^{9}
0
10
20
30
40
E_{acc} [MV/m]



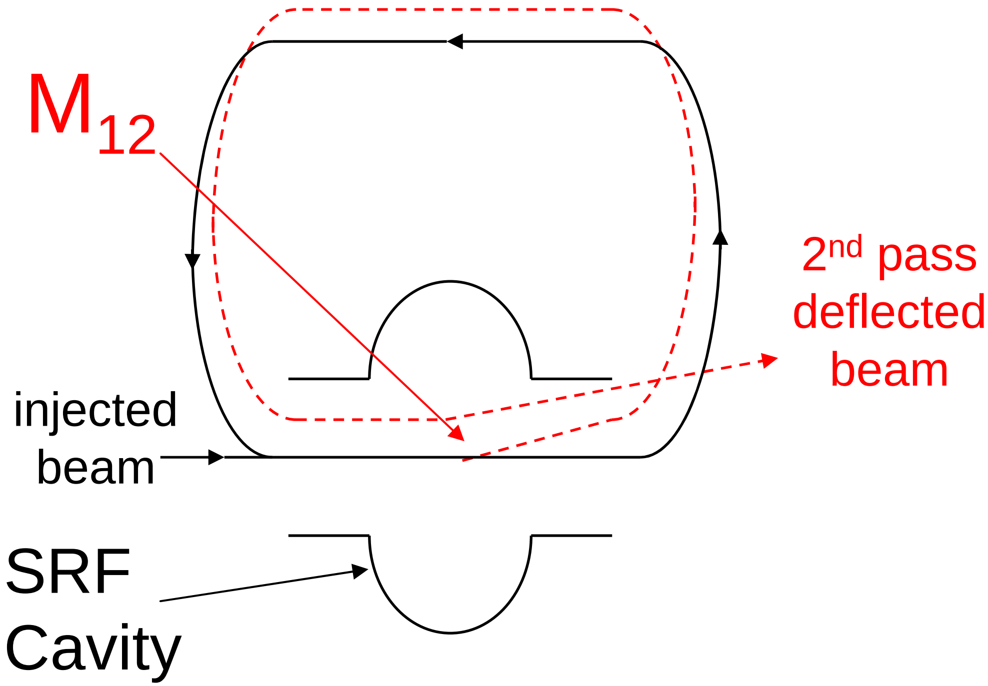
Upgraded User Facility
Upgraded Accelerator Components
Electron Gun
High voltage power supply (600 keV)
Injector
Recirculation arc
IR User Labs
Attosecond Beam
Superconducting Linac High Current Upgrade
IR wiggler
THz User Labs
IR optical cavity
UV User Labs
Increase from 6,000 to 26,000 sq. ft.
Recirculated Beam Dump
UV wiggler FY03-04
UV optical cavity
Straight-ahead beam dump
Recirculation arc
Note: Both will allow science and ERL R&D

JLab FEL Results

- Beam recirculated, with energy recovery, up to 9.1 mA at ~ 88 MeV (800 kW)
- Achieved over 1 MW of circulating electron beam power at higher energy
- Beam breakup limits the maximum circulating electron beam current

Beam Breakup

- Results from interaction of the beam with higher-order modes (HOMs) in SRF cavity
- This is a key issue for ERLs – we need beam stability with a high current passing through hundreds of superconducting cavities



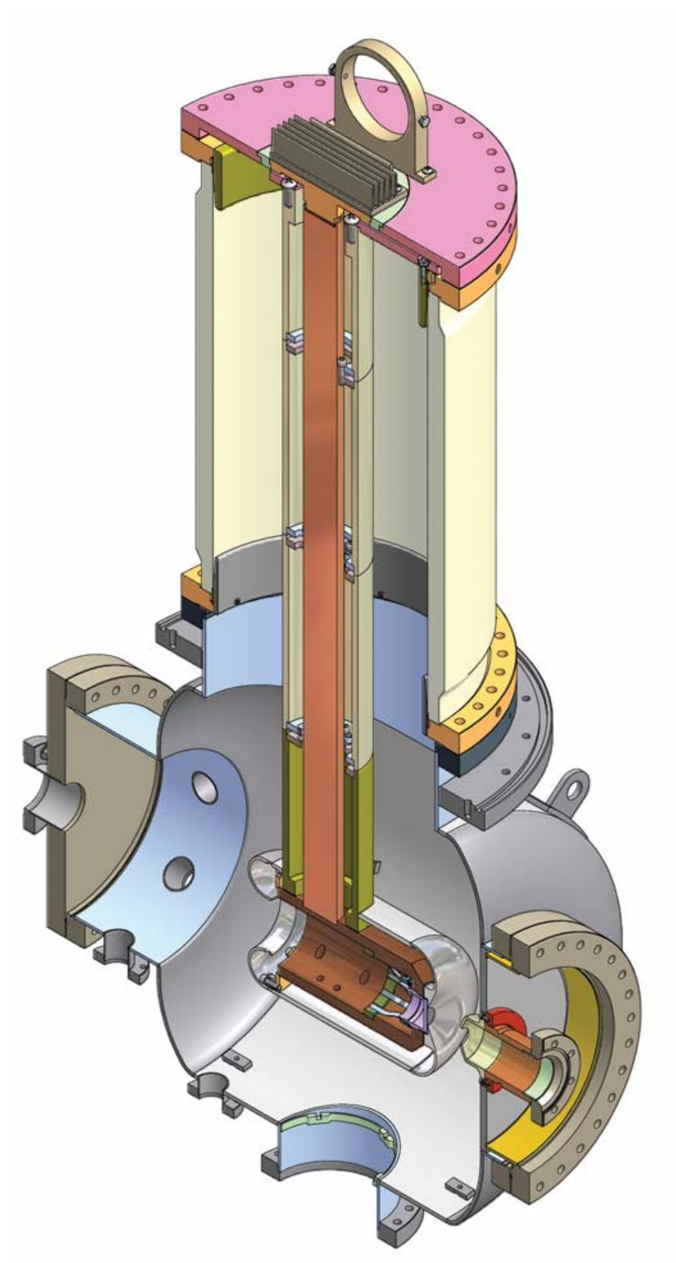
M_{12} is the electron optics transport matrix element around the electron beam path

Cornell ERL Program

- Phase I – demonstrate a high average current, high brightness electron injector for an ERL
- Phase II – construct a high energy (~ 5 GeV) ERL as a synchrotron light source at Cornell
- We have a four year, $18 M grant from NSF for the Phase I injector development
- We have a four year,$12 M NY State grant to begin site work and project planning (NSF doesn't pay for this)
- We are actively working on the Phase II proposal

ERL Injector Elements

- 750 kV photoemission electron gun
- Normal conducting buncher cavity
- 5-15 MeV superconducting RF accelerator – five 2-cell cavities
- Precision-controlled high power RF sources
- High precision electron beam diagnostics
- High power beam dump



The ERL Gun design incorporates novel features, such as cooling of the photocathode, a beryllium anode, and over 20 m^3/s pumping speed for hydrogen

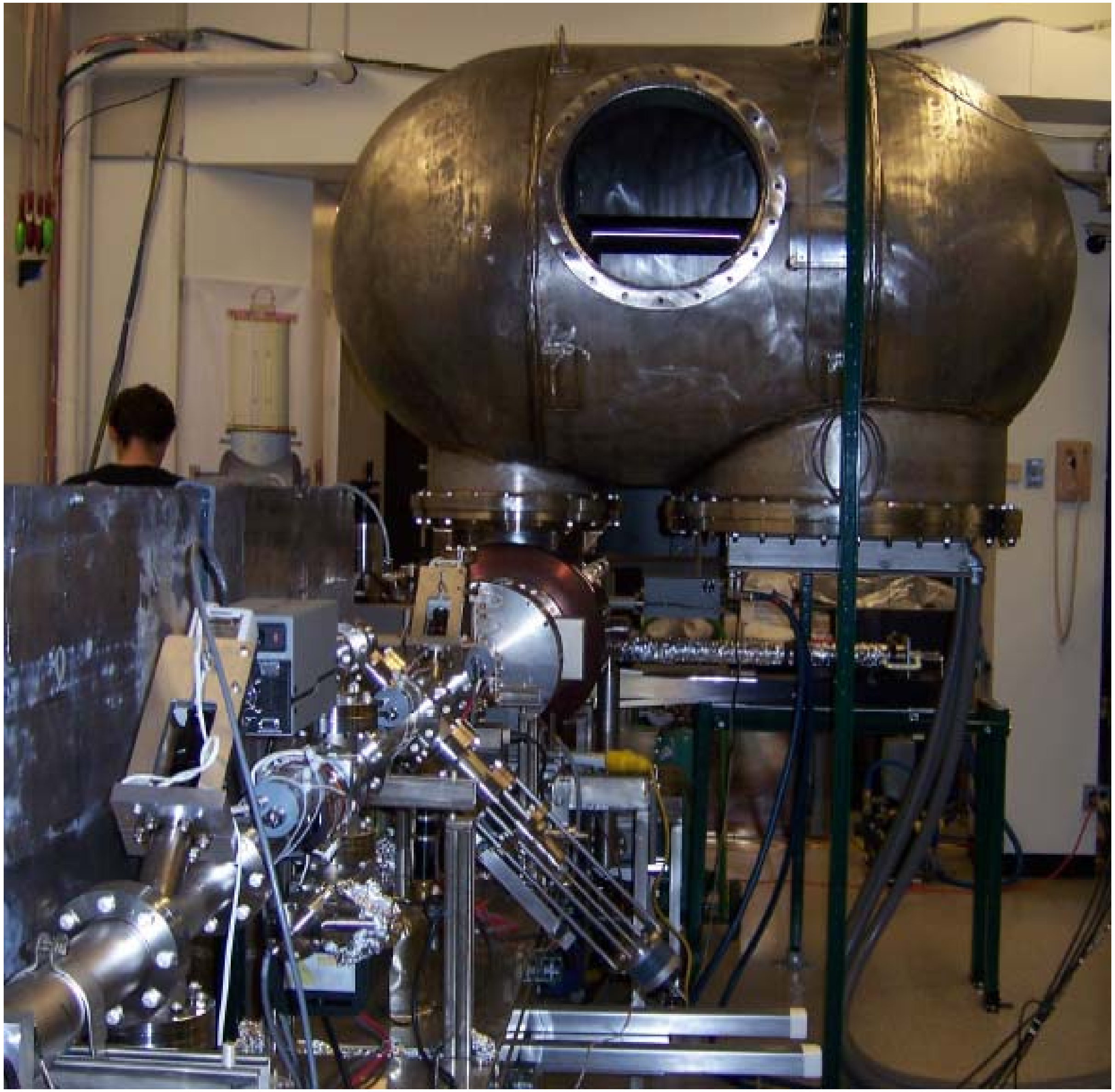
Photoemission Cathodes

- Can deliver high current density (10s to 100s of A/cm^2)
- Can be modulated to very high frequencies (10s of GHz) – either spatially or temporally
- Negative Electron Affinity (NEA) photocathodes emit from a thermalized electron population, giving the possibility of a very low emittance
- Can operate at low temperature for improved brightness

Photocathode Drawbacks

- Operation in exceptionally good vacuum (below 10^{-11} mbar) is required for a high quantum efficiency cathode with good operational life
- Very high cathode field strengths are required to deliver a large charge from a small area in a short duration pulse
- The required laser systems are complex and costly
- Best performance is obtained for non-Gaussian shaped optical pulses

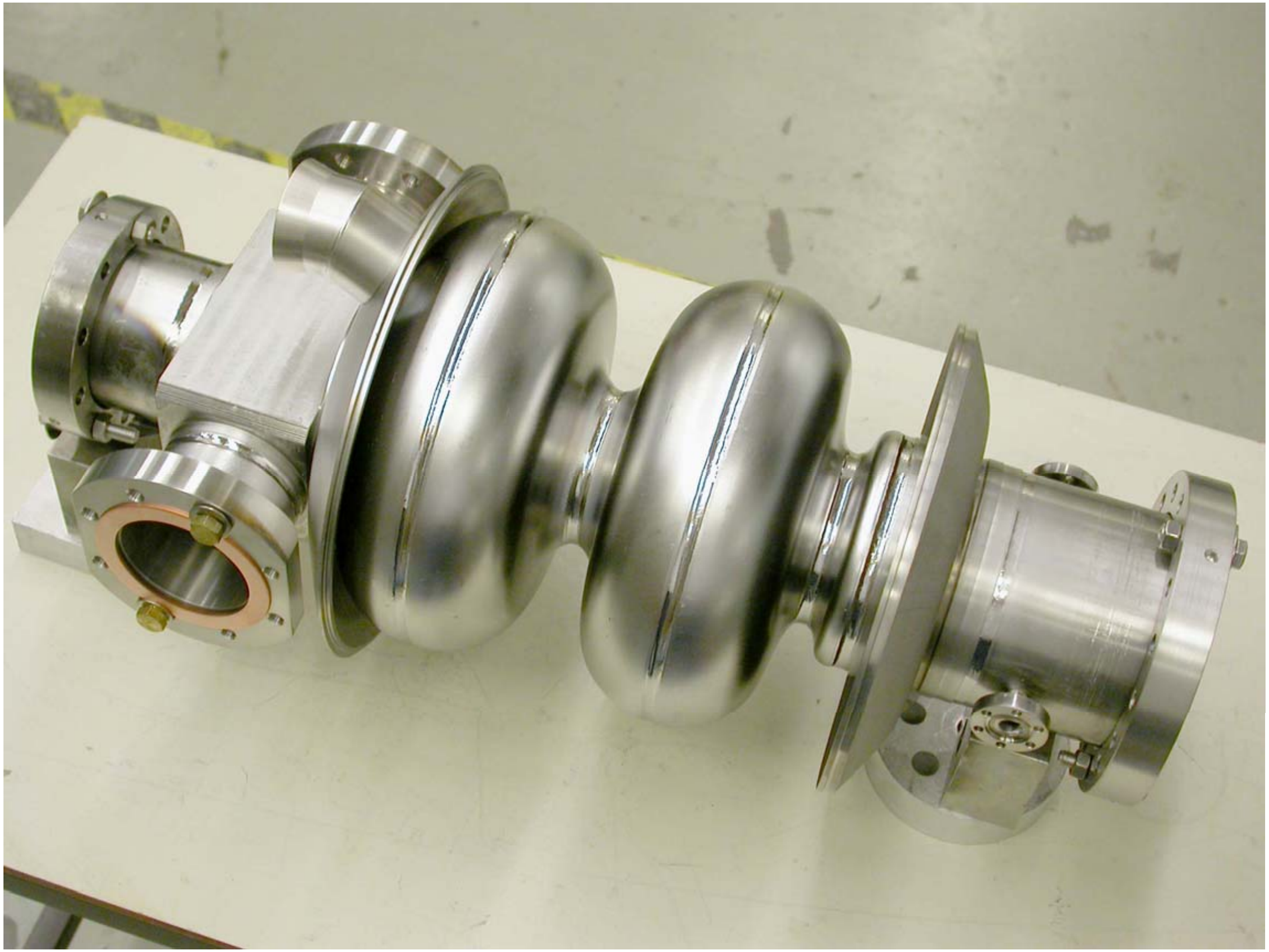
ERL Gun test setup in Wilson Lab



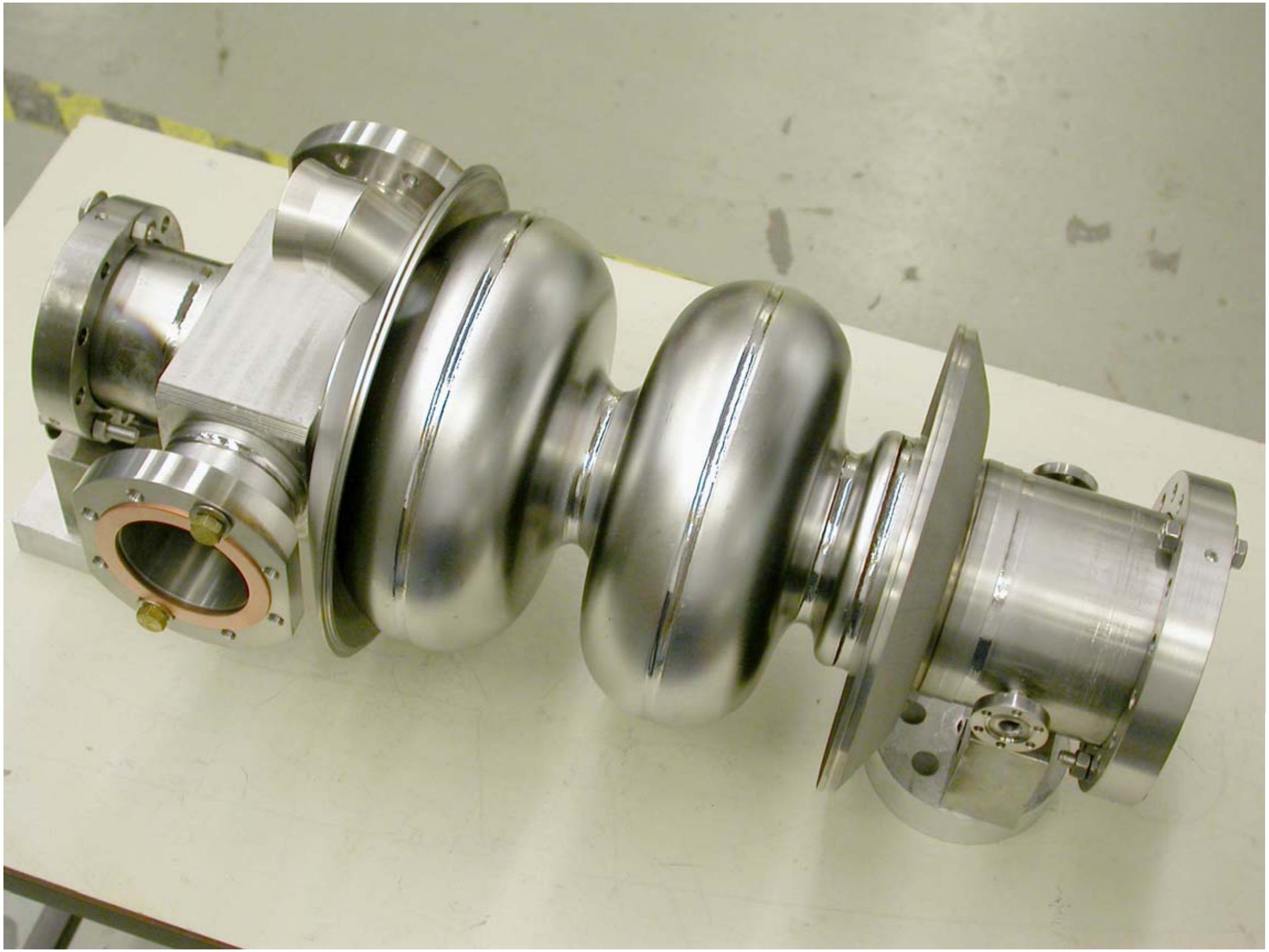
Injector Cryomodule

- Five two-cell SRF accelerating cavities
- HOMs propagate out of SRF cavity to HOM load
- Two RF power couplers, with variable coupling, for each cavity
- Cold HOM loads on both sides of each cavity, absorb to > 40 GHz

This is the first SRF cryomodule designed to accelerate a high average current, high brightness electron beam

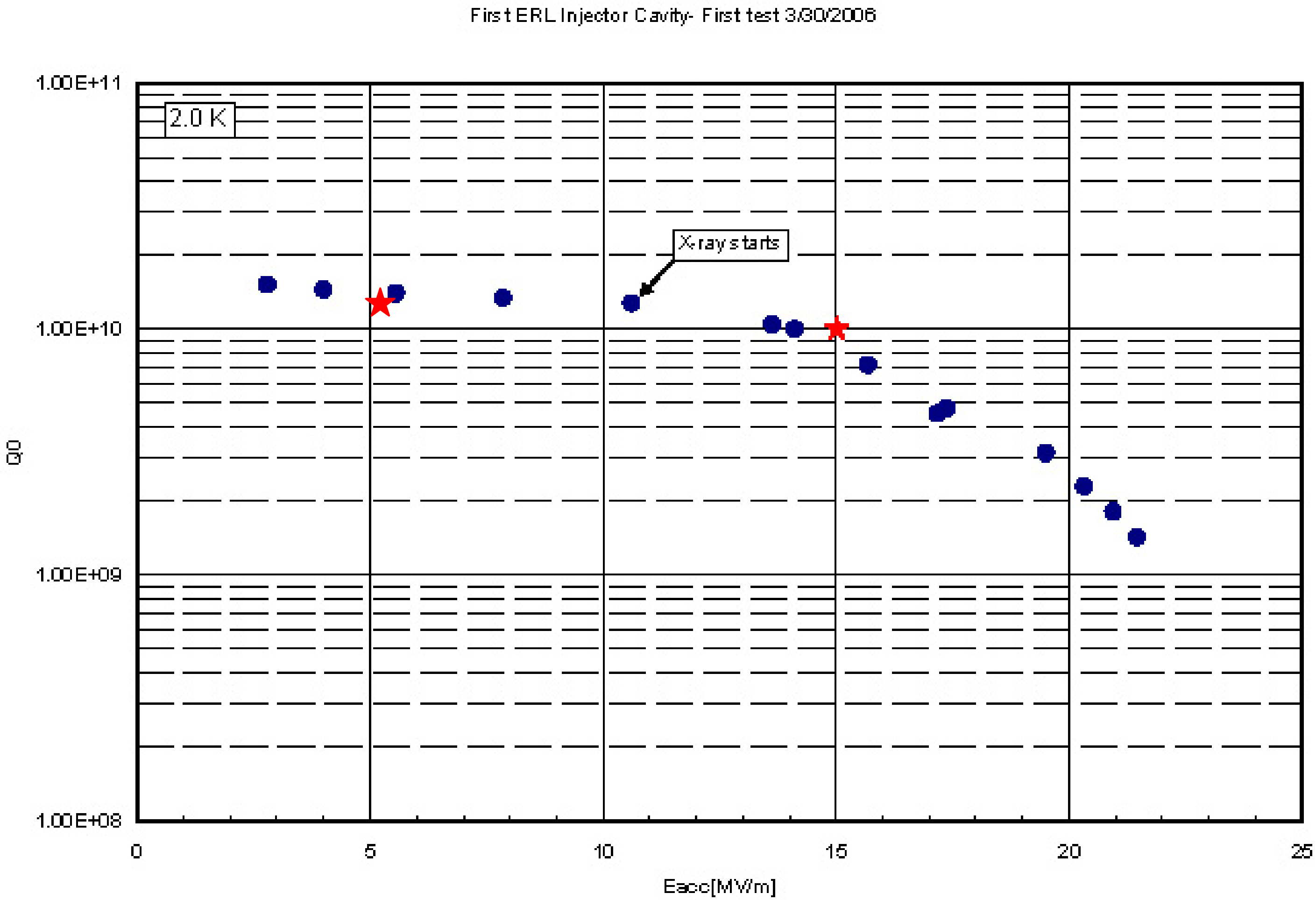


The first two-cell niobium cavity for the ERL injector

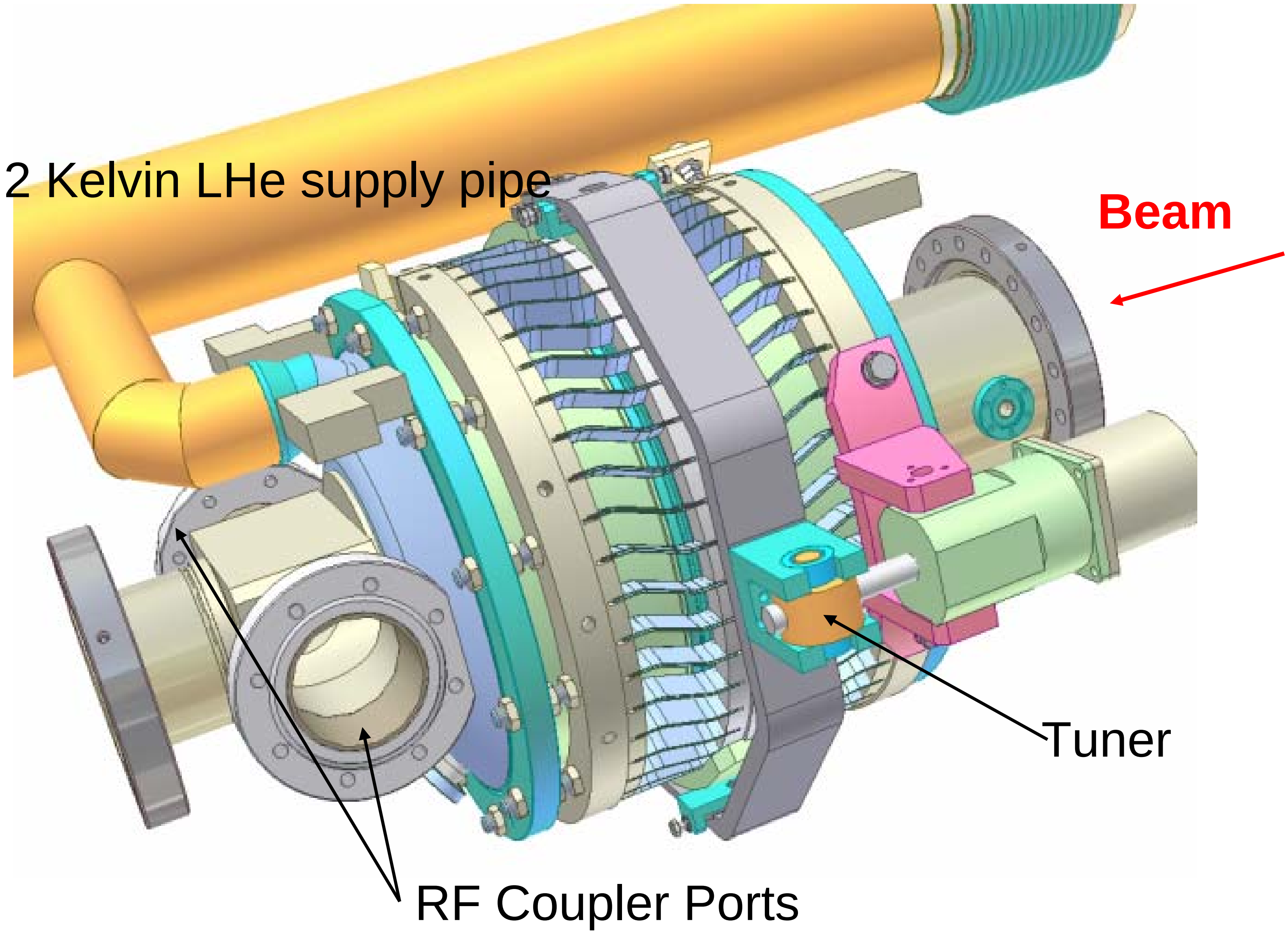


The first two-cell niobium cavity for the ERL injector

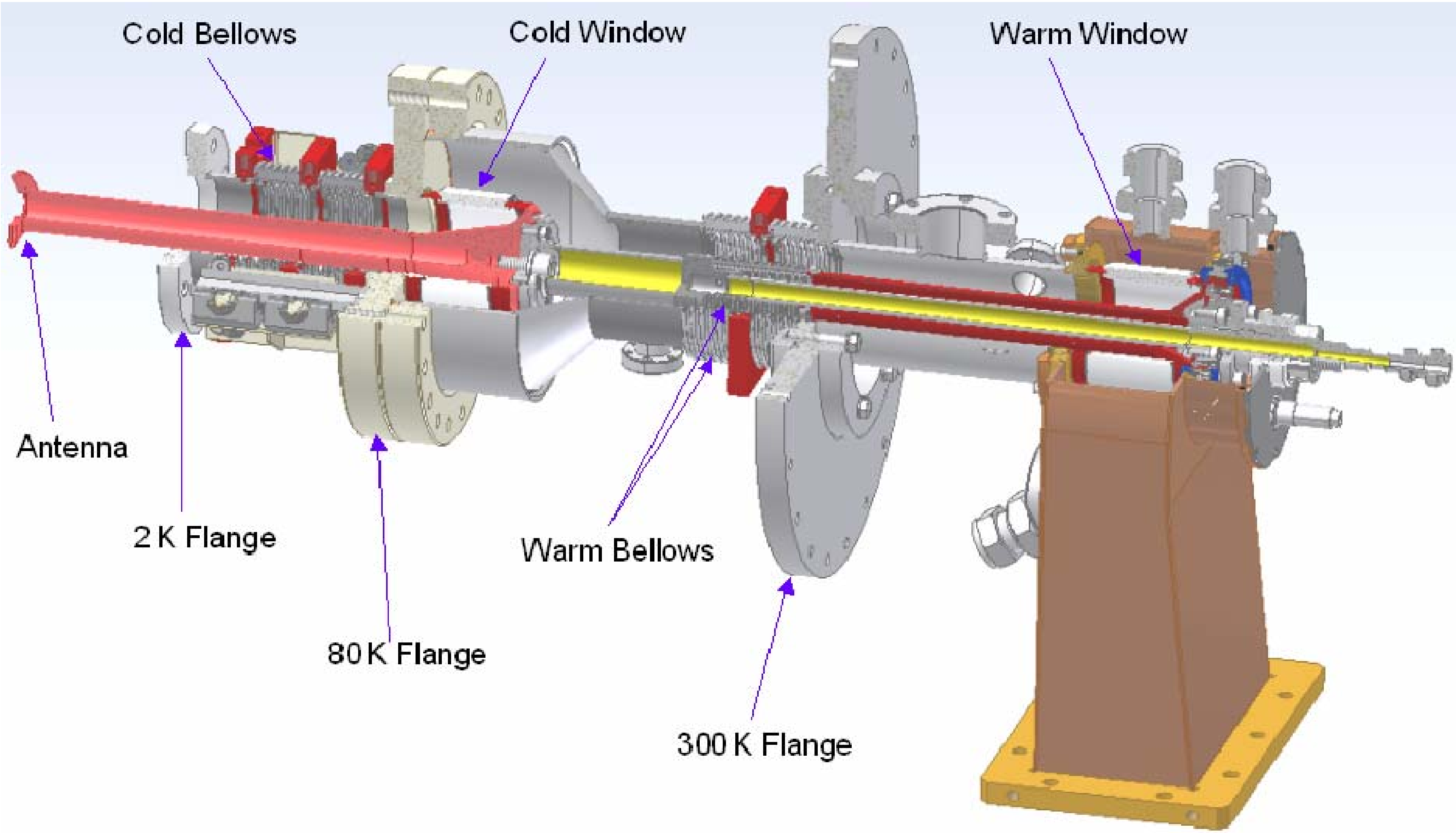
The cavity assembled for its first vertical test, and the test results

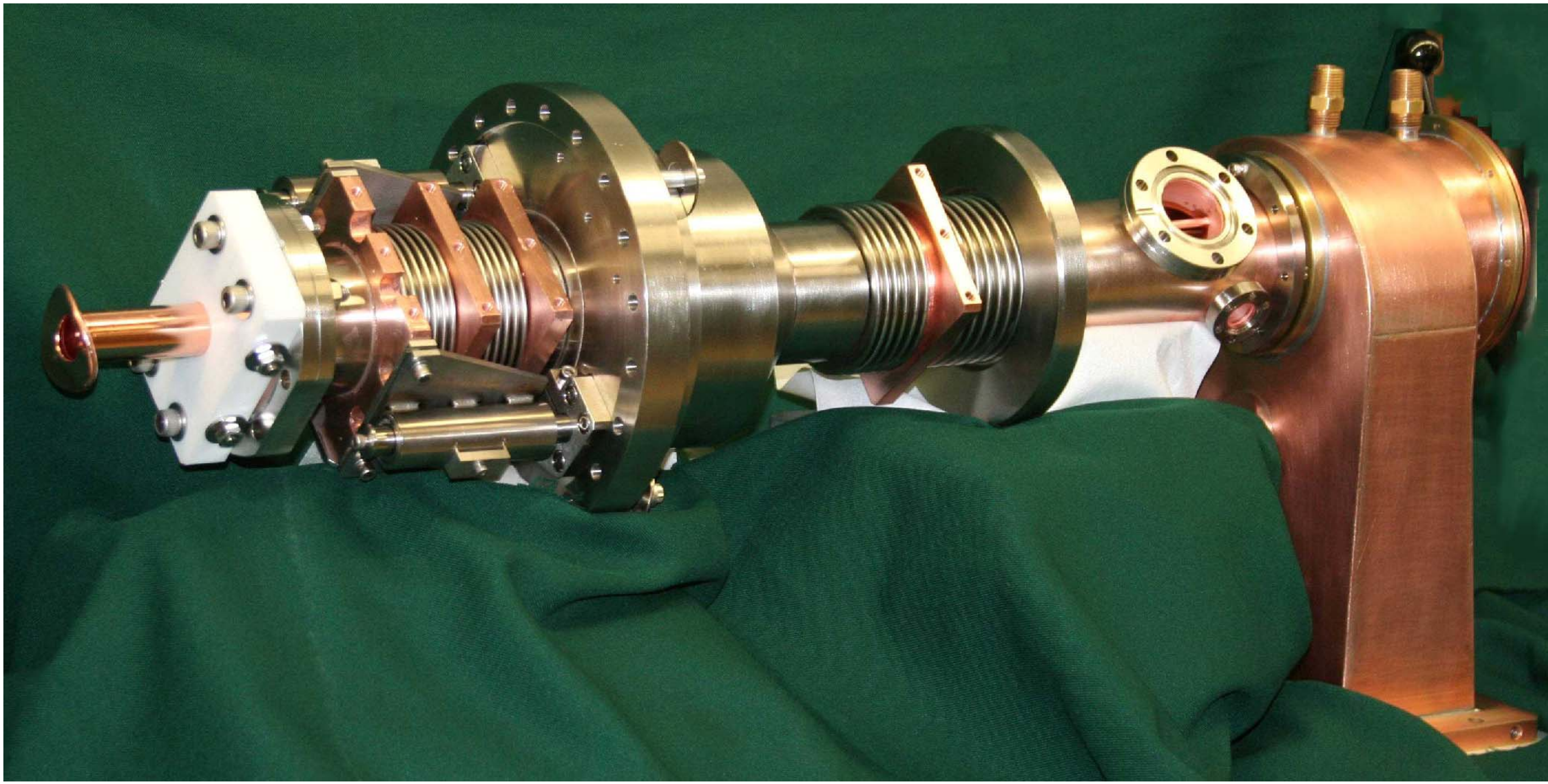


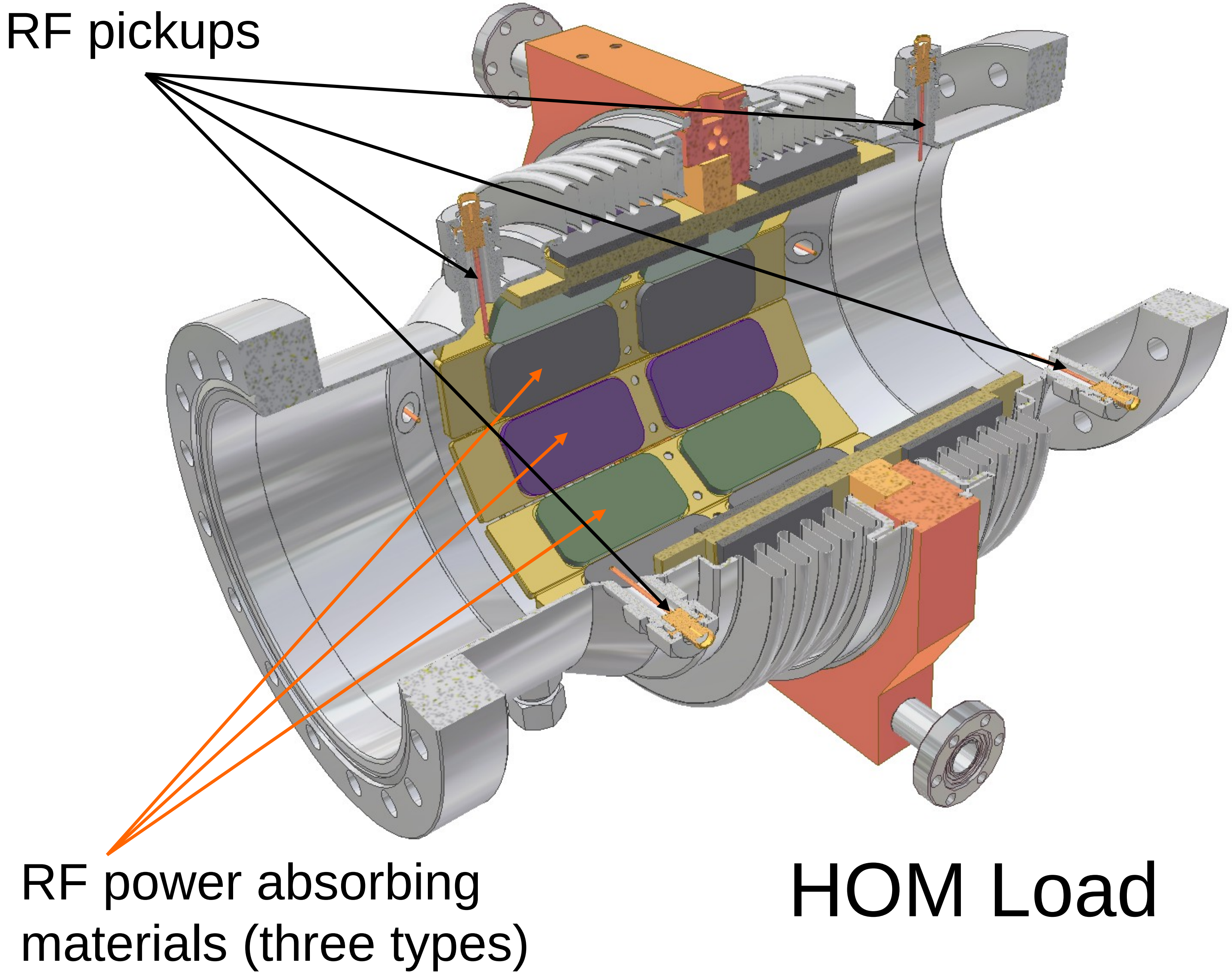
Cavity in helium vessel, tuner attached



ERL Injector Cavity Coupler

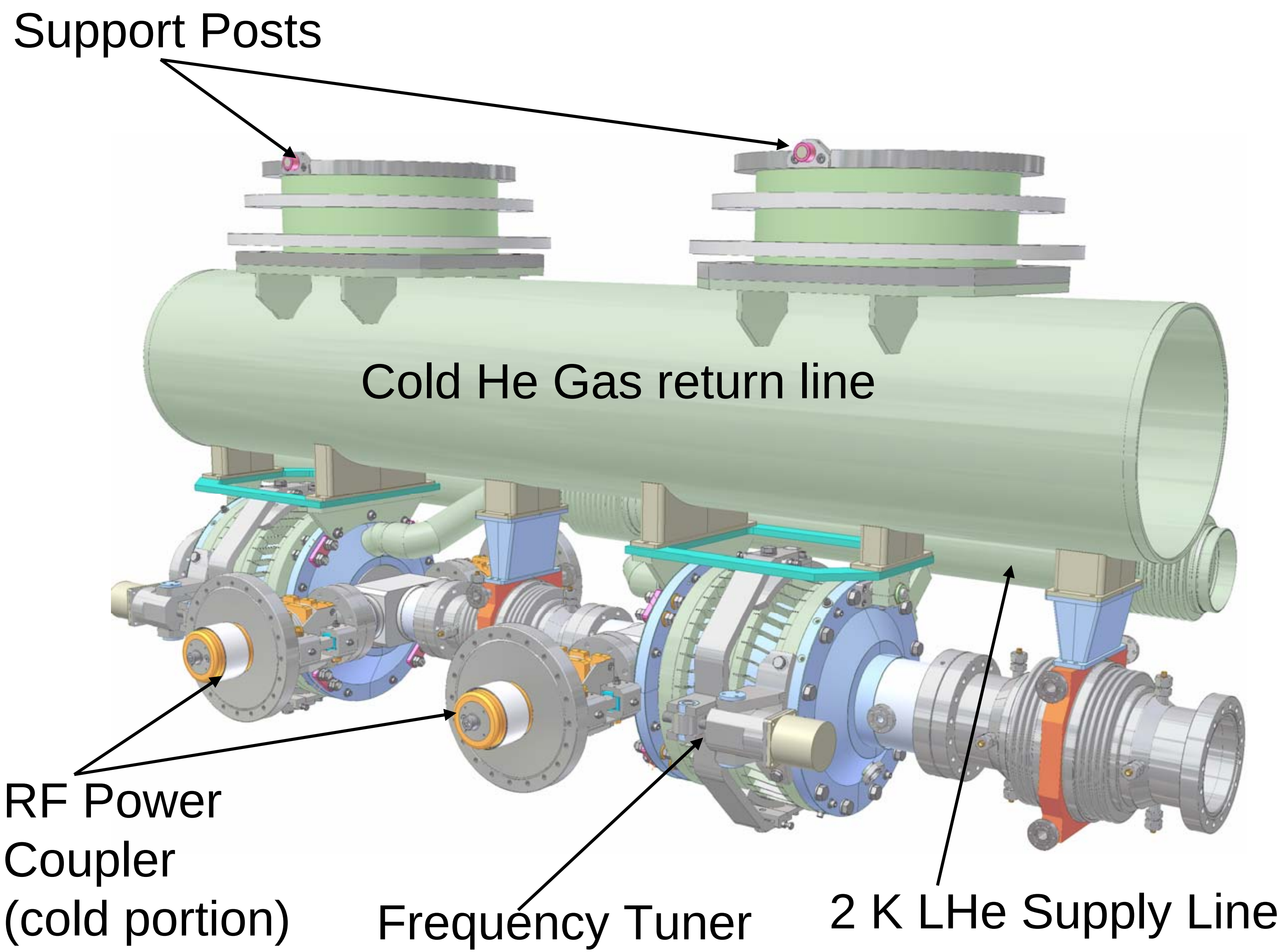




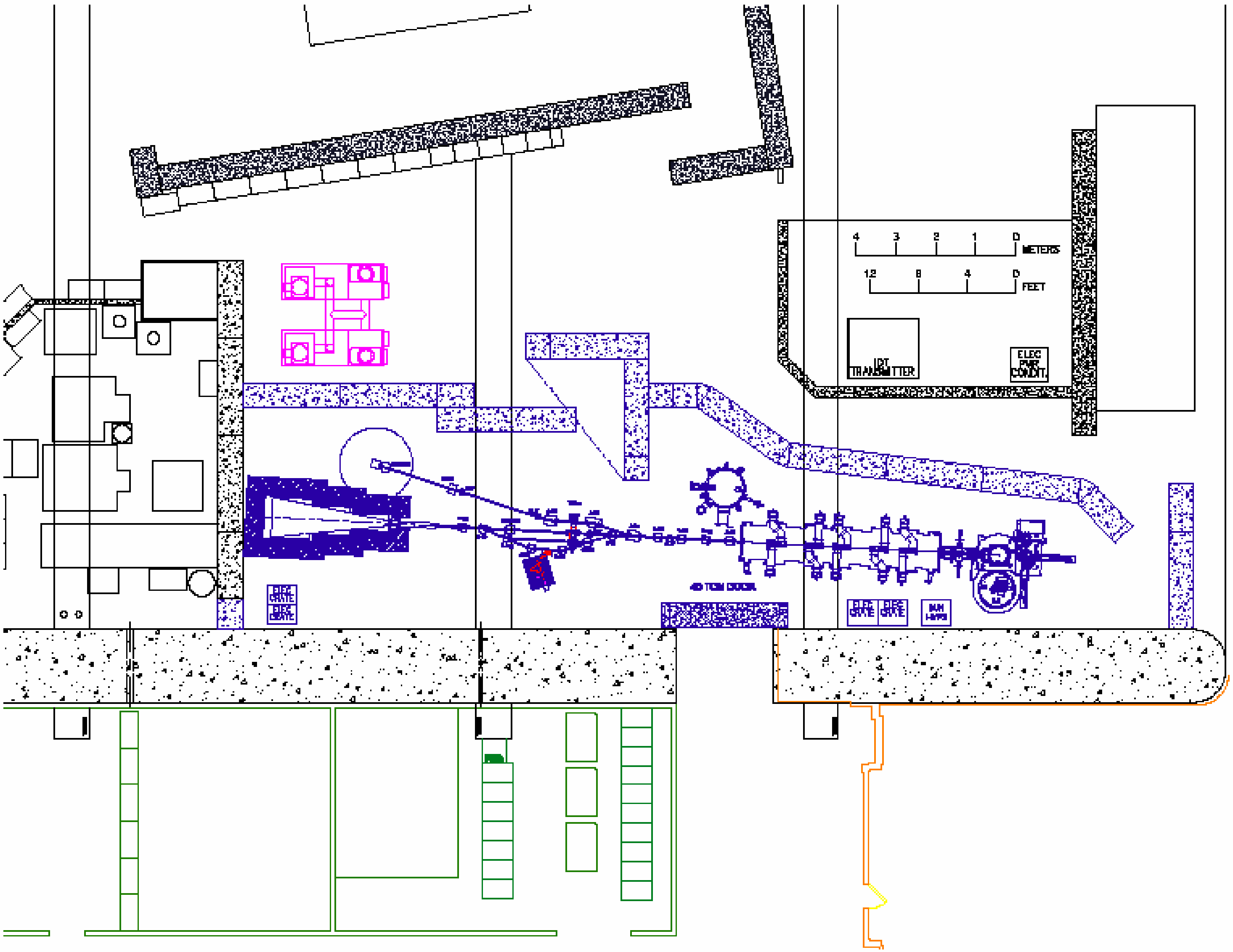


HOM Load

Injector Cryomodule Design



ERL Injector Layout in L0 area of Wilson Lab



Summary

- High energy ERLs promise to deliver exceptional SR x-ray beams, with transformational improvements in brightness, coherence, and pulse duration
- ERLs are a natural and cost effective upgrade path for existing storage ring light sources
- At Cornell, we are funded to build an injector to deliver 100 mA average current with very small emittances

- Important experiments are underway on some of the key issues
  - BBU (JLab-Cornell collaboration at the FEL)
  - RF Control (Cornell-JLab collaboration at the FEL and the CEBAF accelerator
  - Full to injected energy ratio at the CEBAF accelerator (JLab)
- In parallel with our injector development work, we are preparing a complete proposal for a 5 GeV ERL upgrade to the CESR storage ring