Status of the Energy Recovery Linac (ERL) project at Cornell University

CHESS & LEPP

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

***for the ERL/LEPP/CHESS development team**

www.chess.cornell.edu

- ERL Overview
- ERL prototyping status
- Full-scale ERL facility status

What is needed to do experiments that cannot be done with the best existing sources?

1. Higher spectral brightness.
2. Faster x-ray pulses.
3. Smaller x-ray source sizes for nanobeams.

SR properties follow from bunch emittances & bunch length

CHESS & LEPP

Flux ~ I (current)

Brilliance ~ $I/\bar{\varepsilon}_x\bar{\varepsilon}_y$ (ε is emittance)

Peak Brilliance ~ $I/\bar{\varepsilon}_x\bar{\varepsilon}_y\tau$ (τ is bunch length)

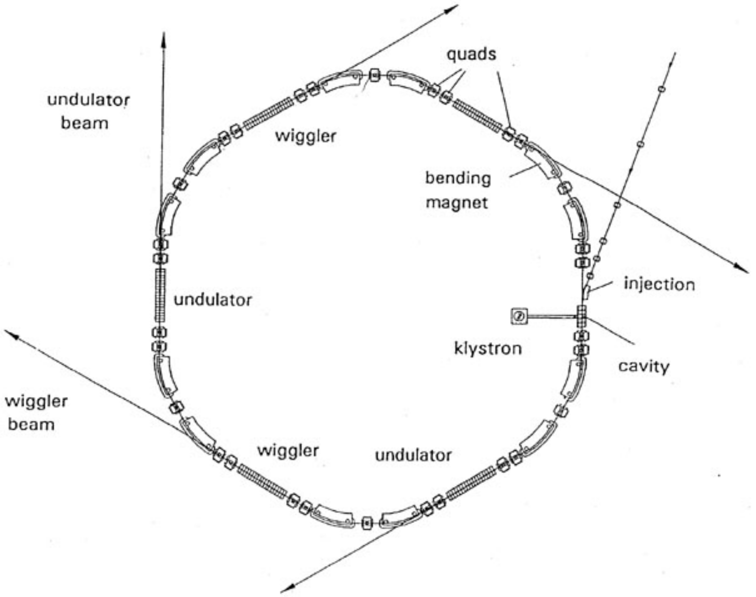
Coherent Flux ~ $I/\bar{\varepsilon}_x\bar{\varepsilon}_y$

Photon Degeneracy ~ $I/\bar{\varepsilon}_x\bar{\varepsilon}_y\tau$

Thus, I, ε_x, ε_y, τ are fundamental.

Storage Rings Limit Experiments

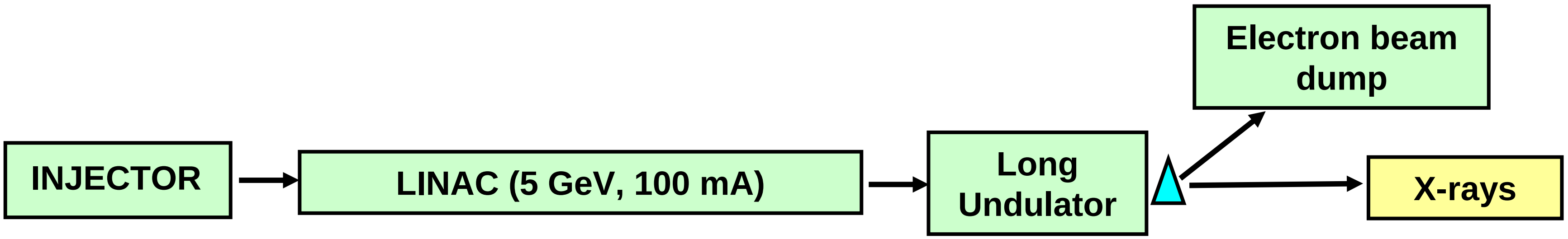
- **All existing hard x-ray SR facilities use storage rings to produce x-rays.**



- **Storage rings technology is well-developed.**

- **An unavoidable consequence of storage is that the electron bunches are degraded, limiting the brilliance, coherence, pulse length, size, and time structure of the x-ray beams.**

LINACS present an alternative



INJECTOR → LINAC (5 GeV, 100 mA) → Long Undulator → Electron beam dump / X-rays

Advantages:

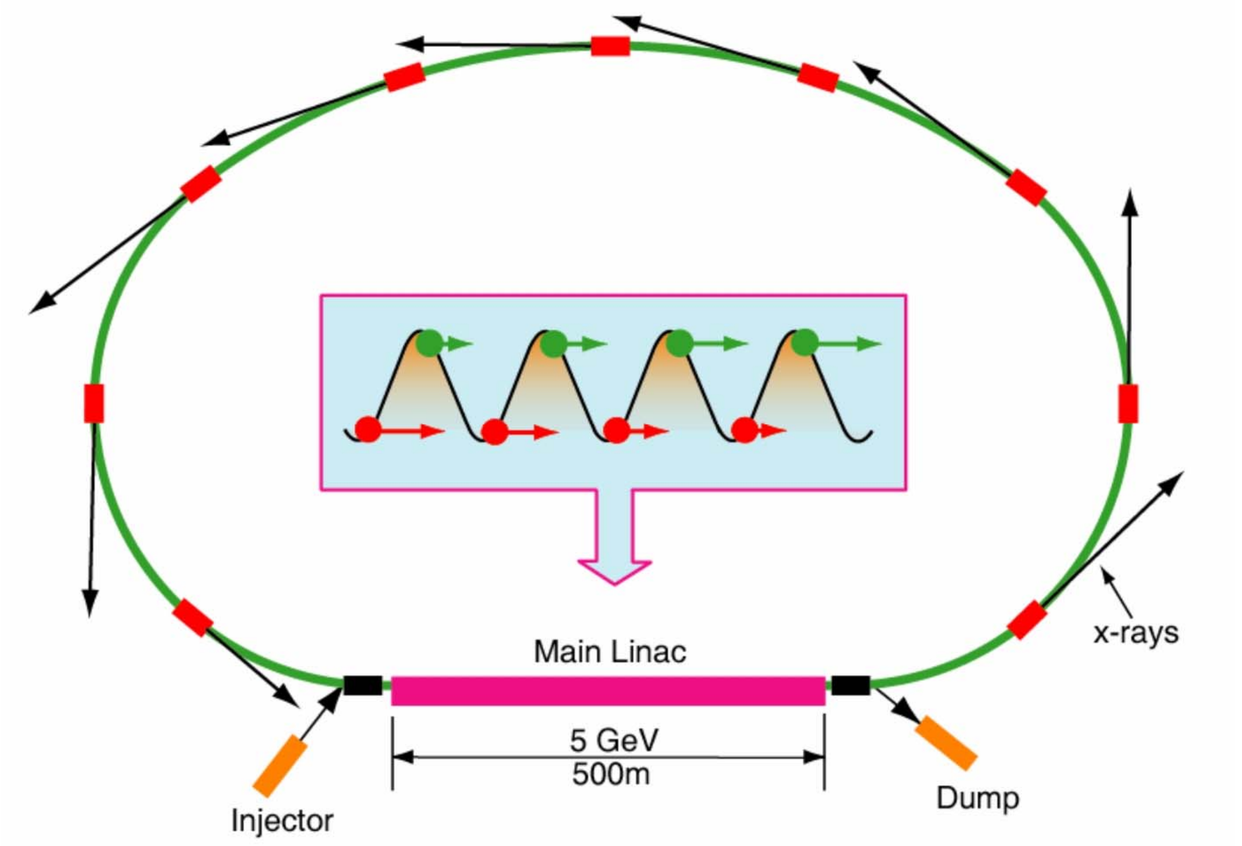
- Injector determines emittances, pulse length, current.
- Complete flexibility of pulse timing & structure.
- Small source size ideal for nanoprobes
- No fill decay.

Disadvantage: You'd go broke!!

(5 GeV) x (100 mA) = 500 MW!!

Energy Recovery Linac

CHESS & LEPP



- ● Accelerating bunch
- ● Returning bunch

A superconducting linac is required for high energy recovery efficiency

Goals of Cornell ERL Project (In Collaboration with other ERL partners)

CHESS & LEPP

- ERL Study (w/ Jlab) (Completed in 2001)
- Phase I: Build, test injector, linac modules; resolve machine issues. Engineering studies for Phase II (in process; $30M NSF & NY State in 2005/2006)
- Preconstruction R&D (to ~2011)
- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. Phase II (~2011-2015)
- Perform experiments, R&D on ERLs, in context of a user facility. (> 2015)

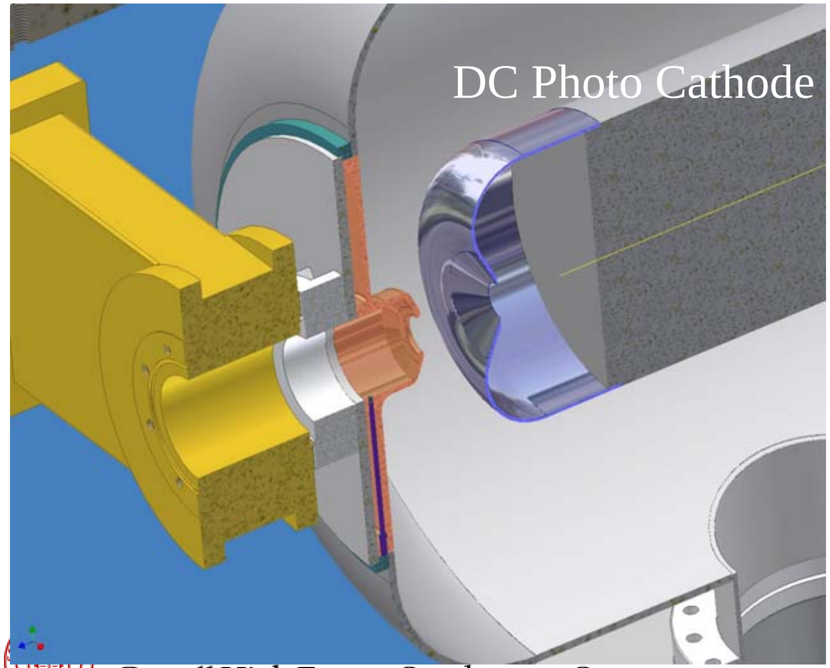
ERL Machine Challenges

- Production of very small emittance beam
- Emittance preservation in beam transport sections and linacs
- Achieve sufficient beam stability for 100 mA beam current
- Beam diagnostics for small emittance, short bunch beams
- Control beam loss
- High gradient, high Q cavity operation with excellent field stability

The nature of these challenges range from basic science to engineering.

Ongoing Activities

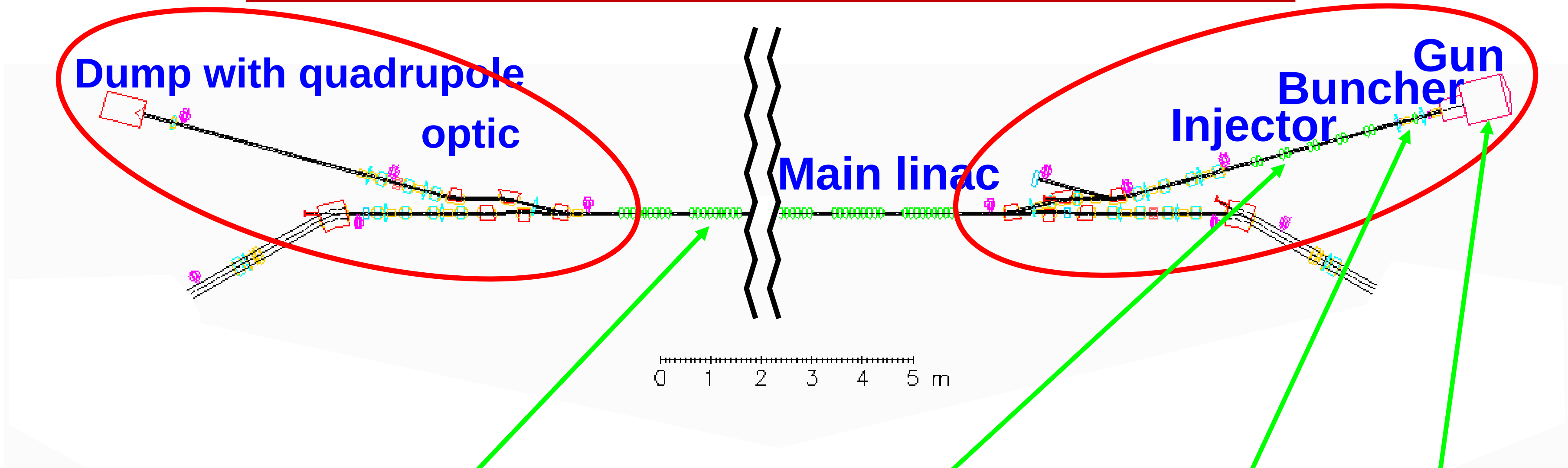
1) DC electron source
   - Gun development
   - HV power supply
   - Photocathode development
   - ERL injector lab
   - Laser system development

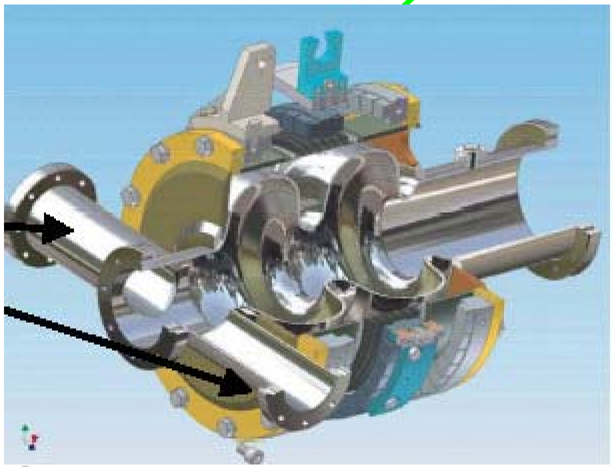


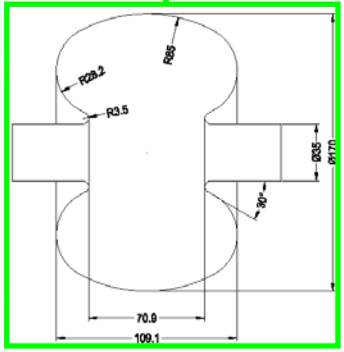
2) Superconducting RF
   - RF control
     (tests at CESR/JLAB)
   - HOM absorbers
   - Injector klystron
   - Input coupler (with MEPI)
   - Injector cavity / Cryomodule
3) Beam dynamics
   - Injector optimization with space charge
   - Beam break up instability (BBU)
   - Optics design
4) Accelerator design
   - Optics
   - Beam dynamics
   - Beam stability
5) X-ray beamline design
   - X-ray optics
   - Undulator design

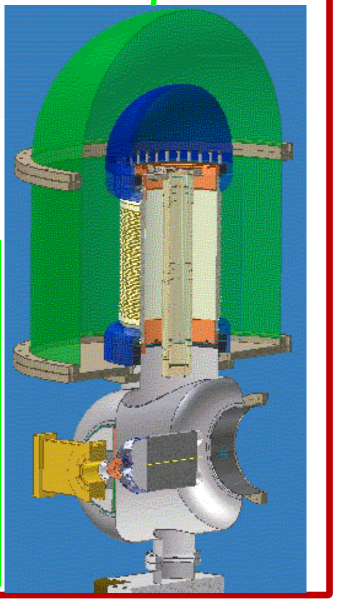
ERL Phase I

CHESS & LEPP

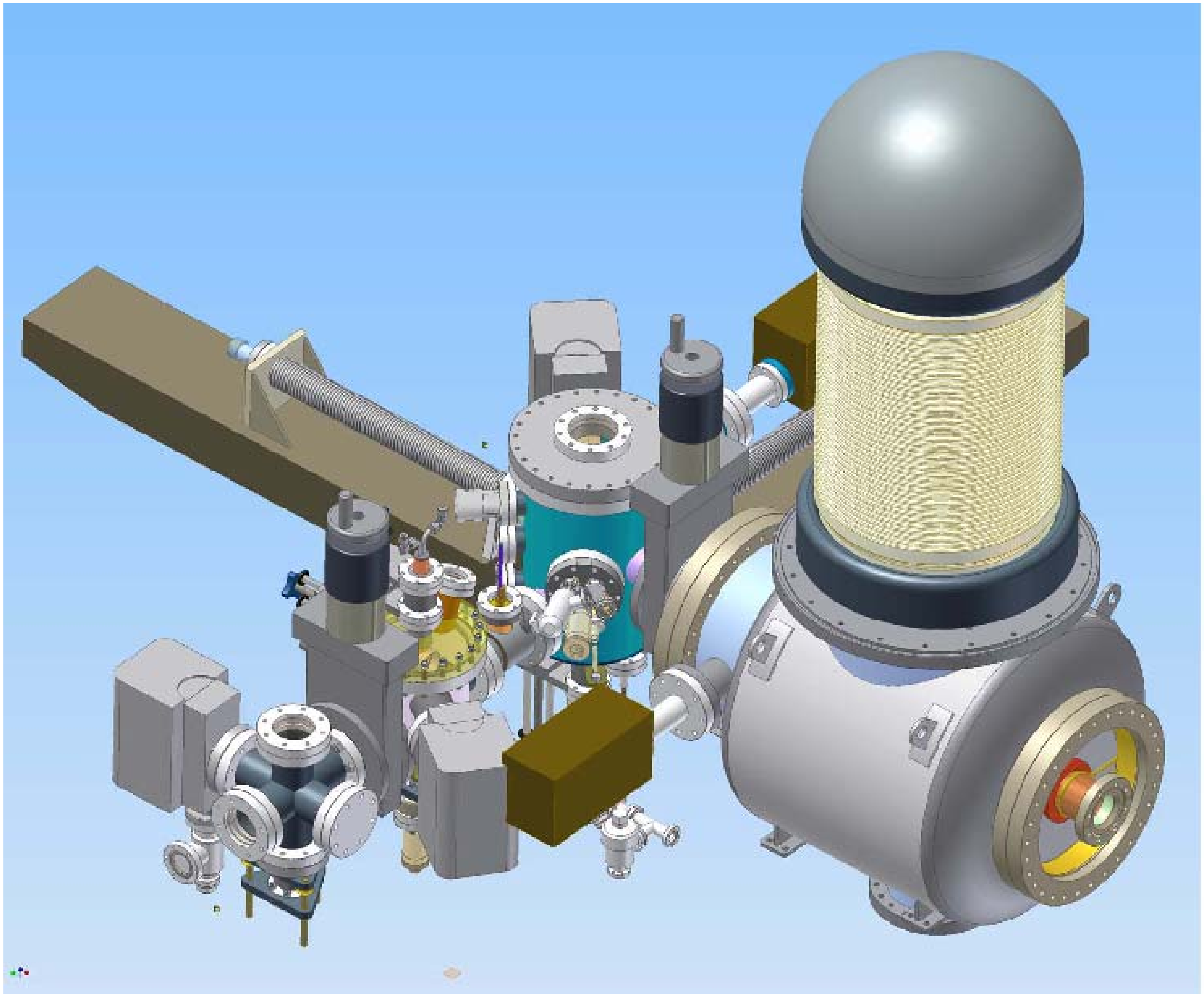


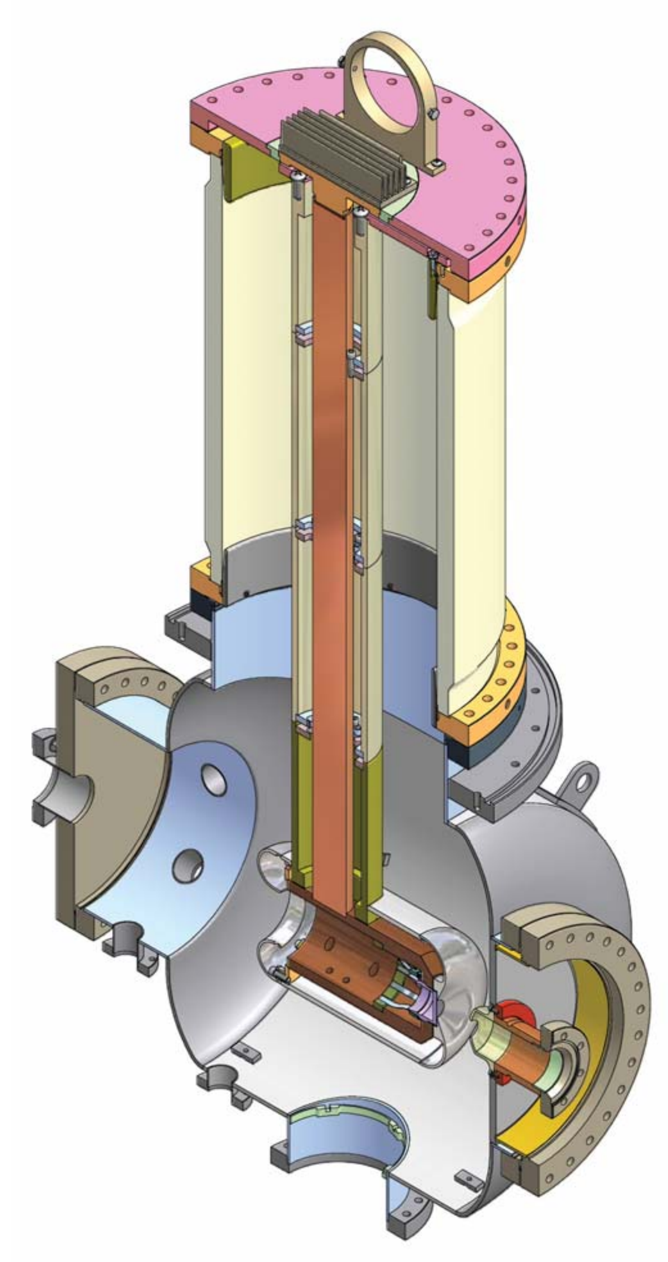






Photoemission Electron Gun Design





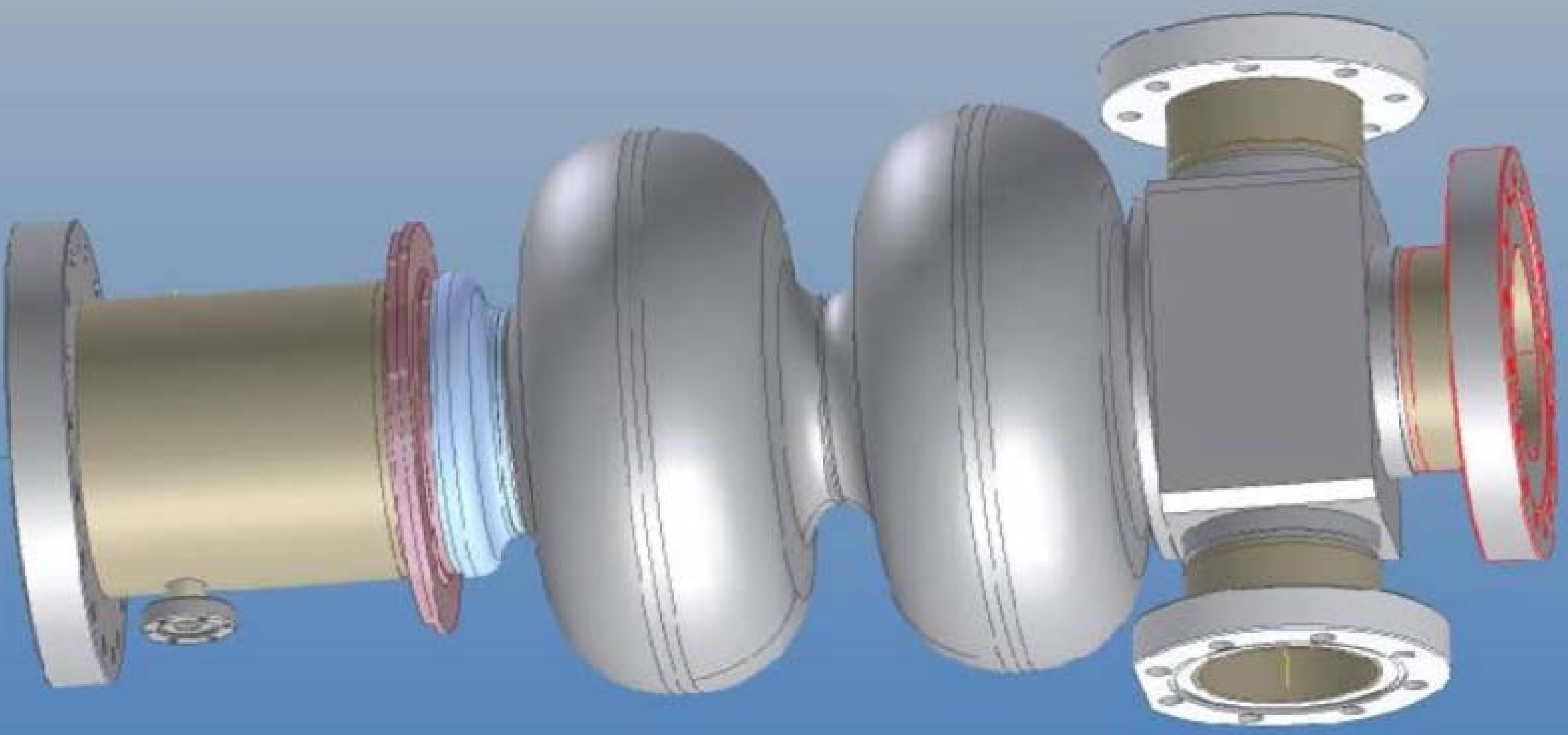
The ERL Gun design incorporates novel features, such as cooling of the photocathode, a beryllium anode, and over 20 m^3/s pumping speed for hydrogen

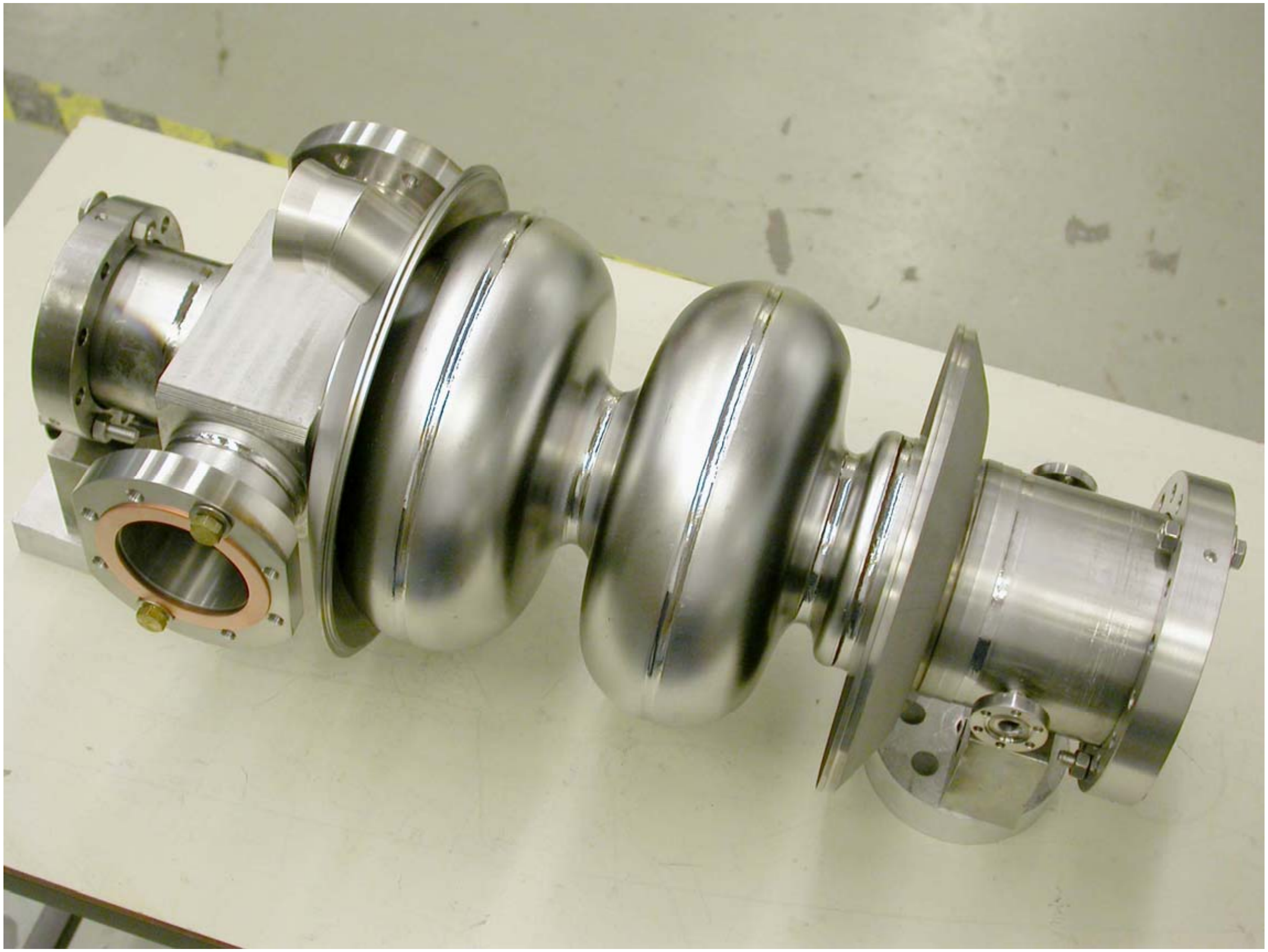
Cathode electrode structure during assembly

Installing the SF_6 tank over the large ceramic insulator of the electron gun

Initial assembly of test beam line in Wilson Lab

Two-cell ERL Injector Cavity Subassembly Engineering Design

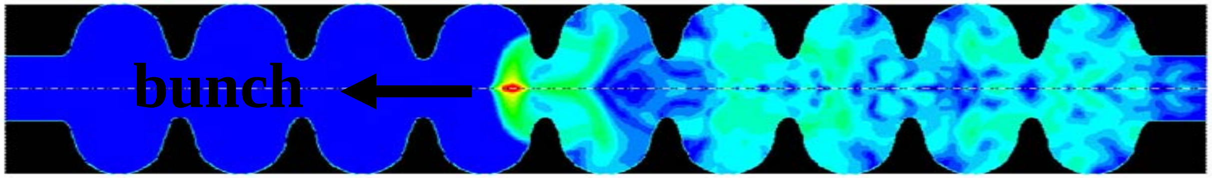




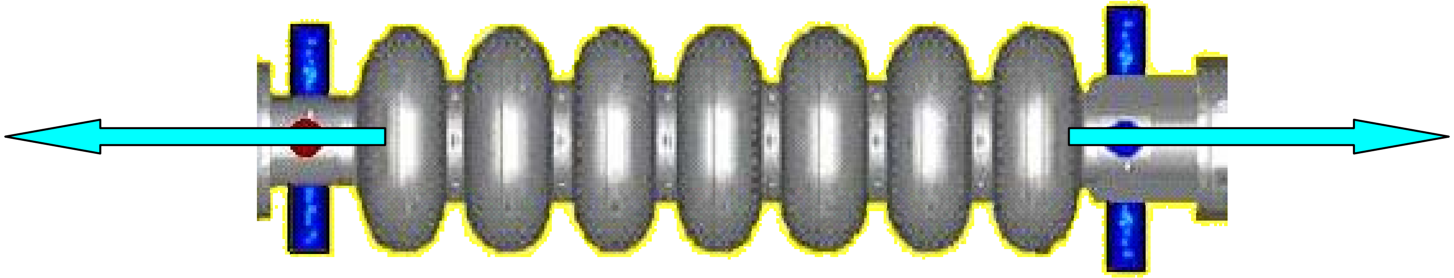
The first two-cell niobium cavity for the ERL injector

Higher-Order Mode Power

CHESS & LEPP



Bunch excites EM cavity eigenmodes (Higher-Order Modes)

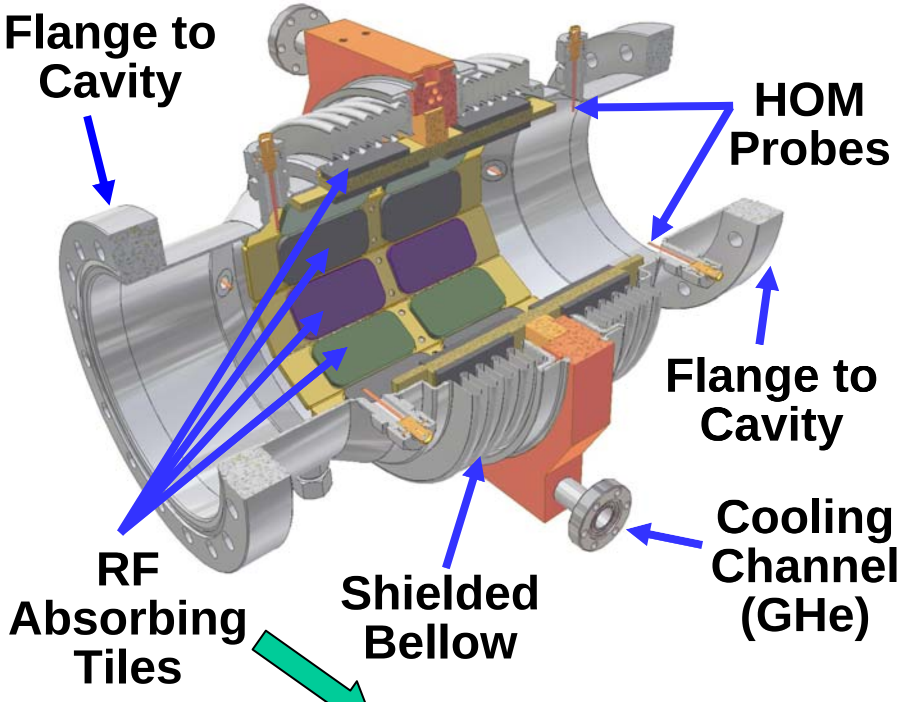


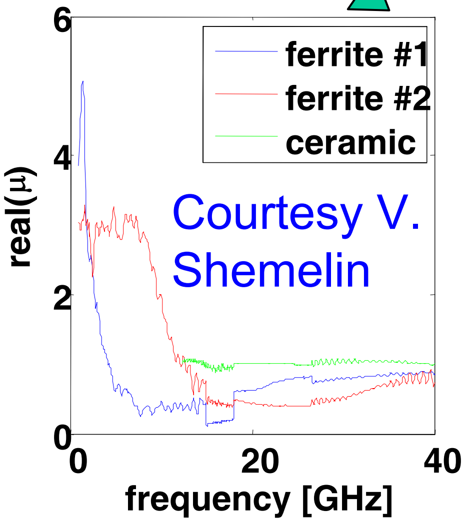
140 W HOM power,

f = 1.4 to > 100 GHz

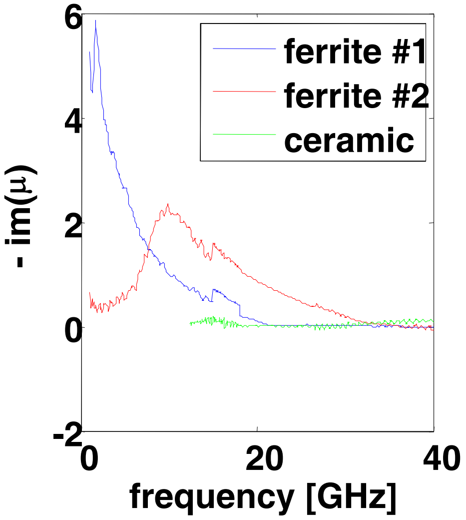
Cornell ERL HOM Absorber

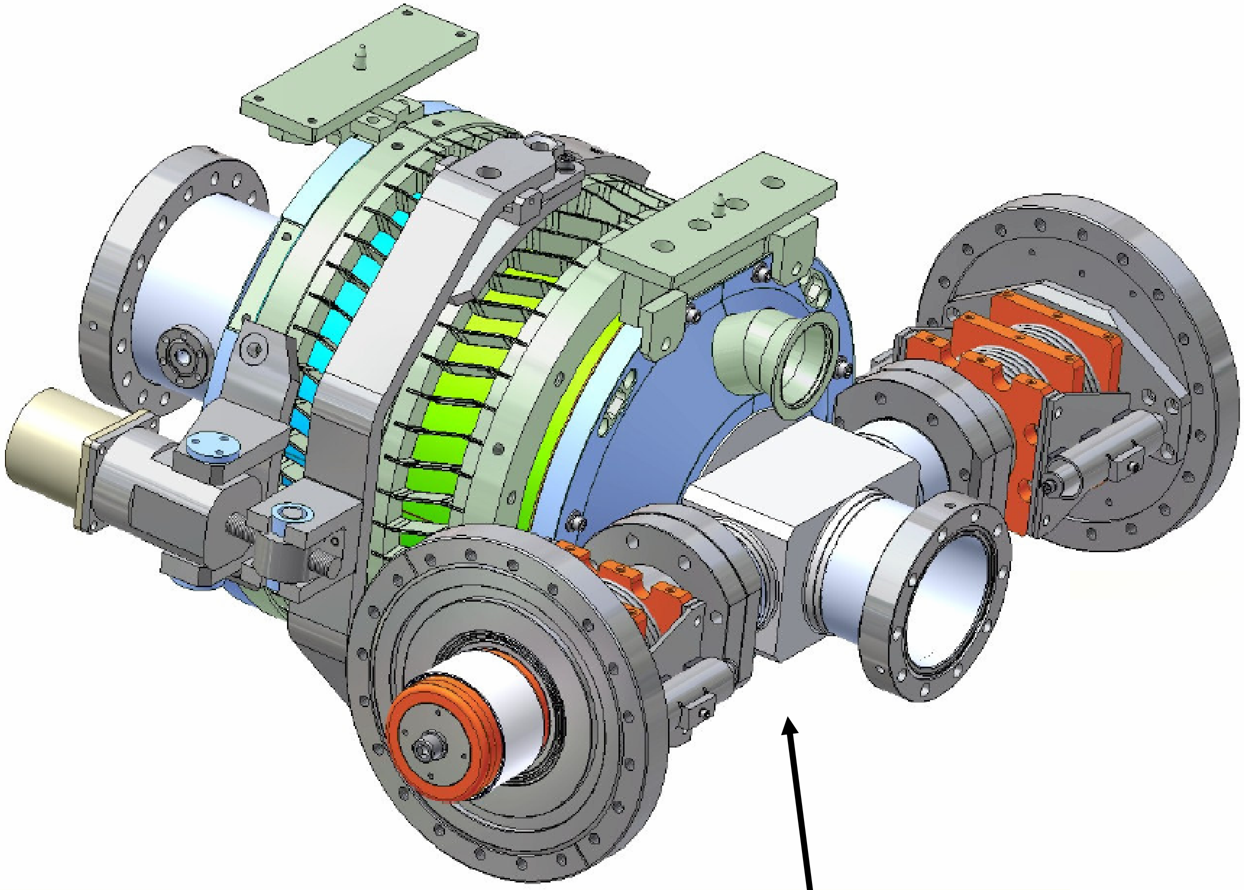
- Extensive research program to find absorber materials which
  - are effective at 80 K
  - And absorb over the required wide frequency range
- Three materials selected to cover full frequency range
- Simulated damping for 100s of modes ⇨ all modes are sufficiently damped
- The injector cryomodule will be the first high current, short bunch s.c. cavity module.





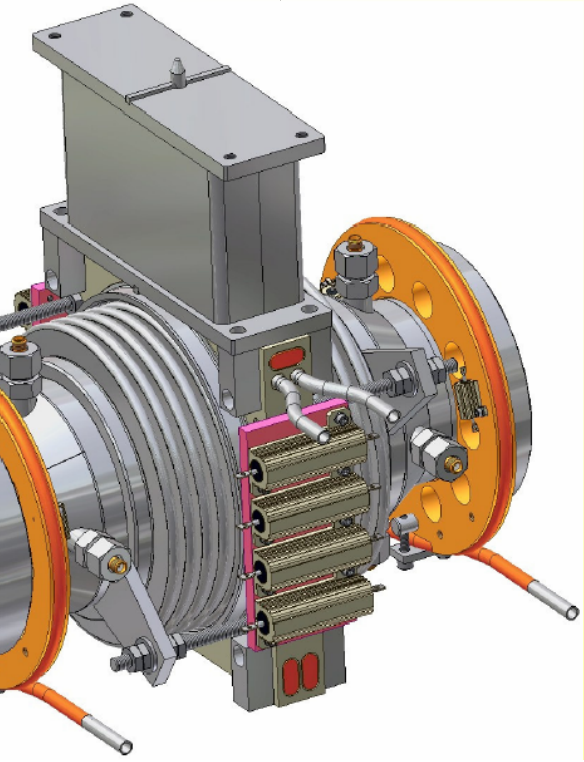
Courtesy V. Shemelin



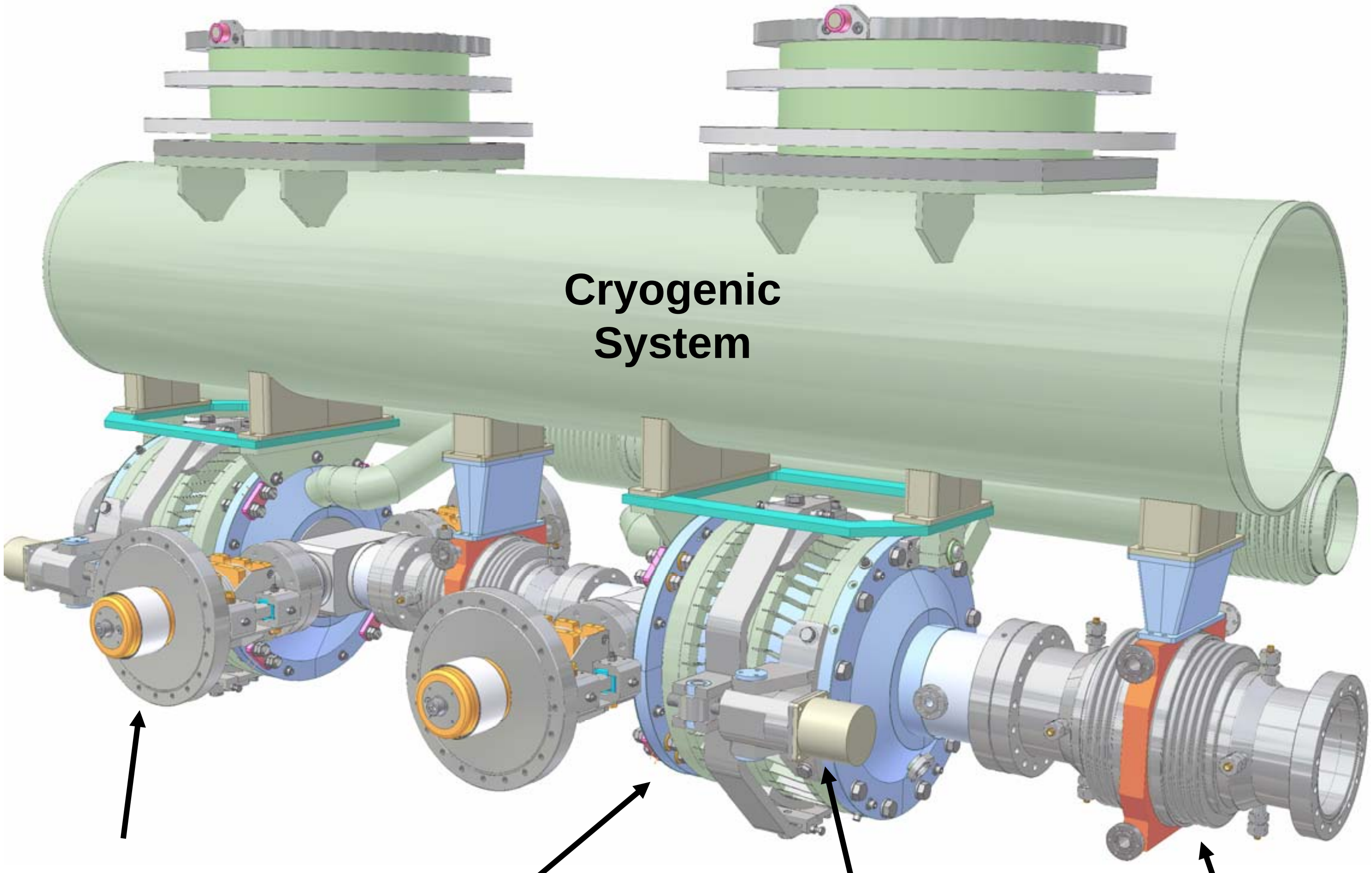


The cavity with its tuners and power couplers attached (above)

The HOM load (below)



New cryomodule design concept



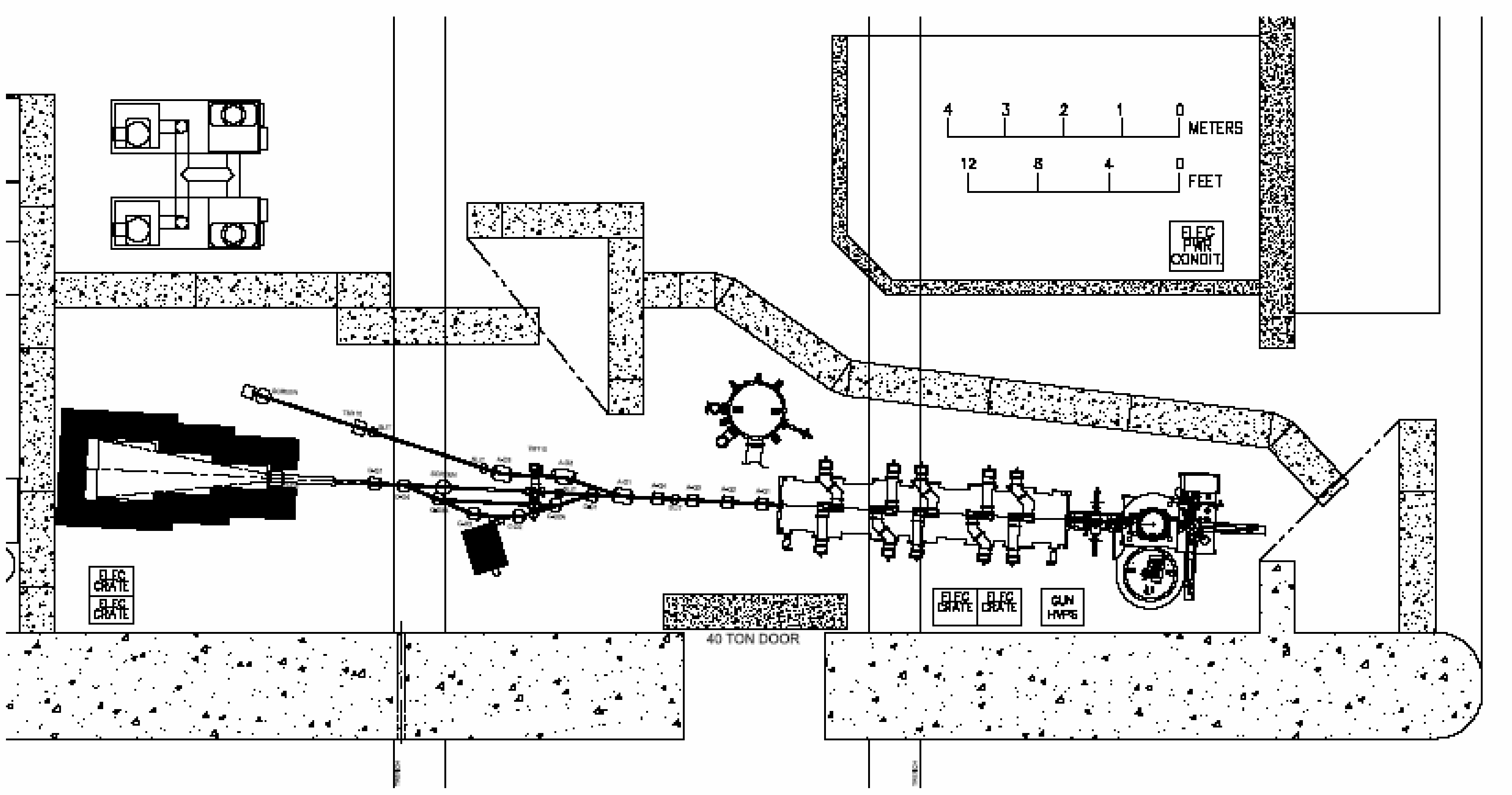
Cryogenic System

Input Coupler

RF Cavity in He Vessel

Frequency Tuner

HOM Absorber



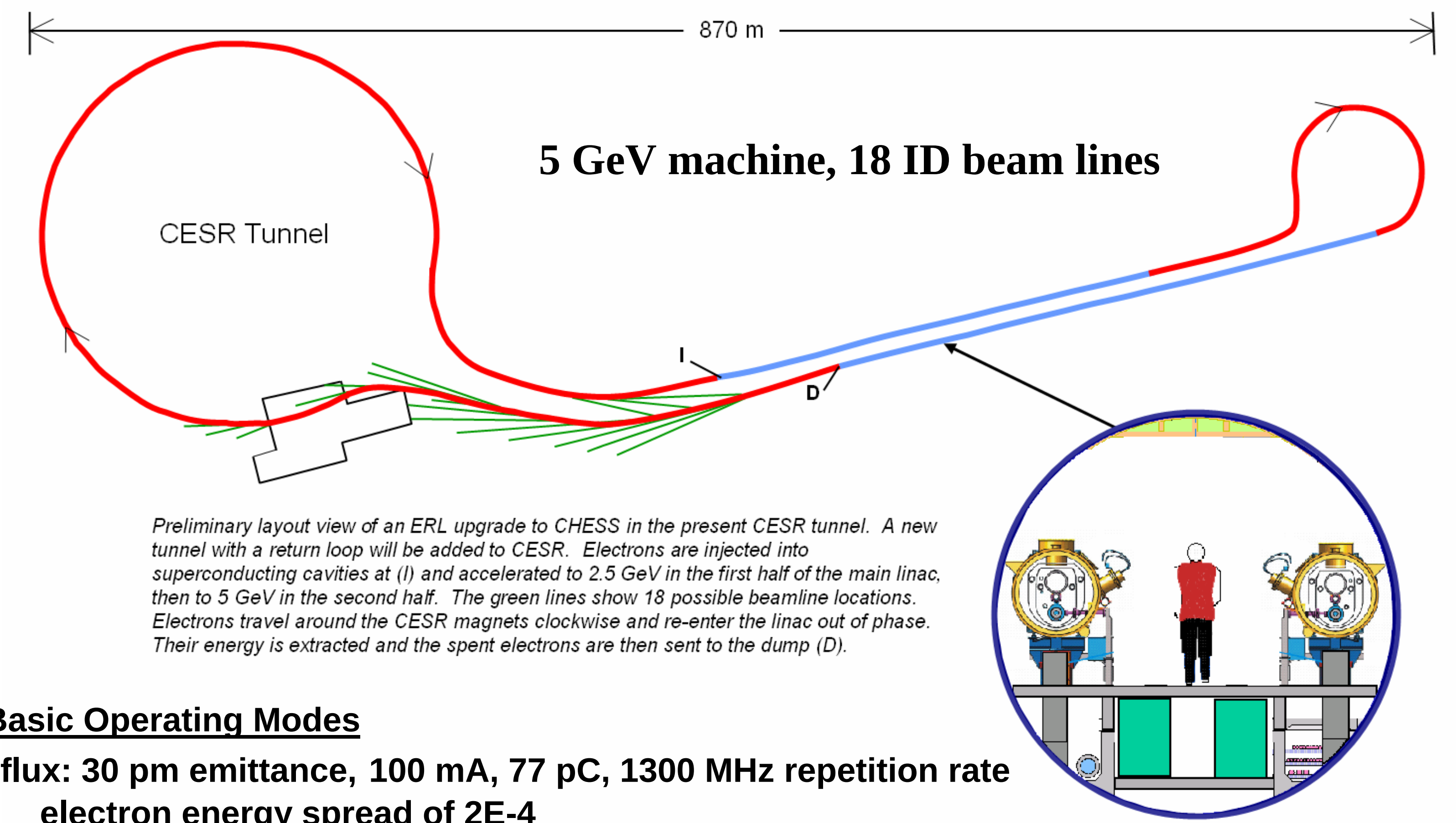
Layout of full ERL injector in Wilson Lab L0

Cornell Phase II ERL Layout

(current version, layout still under development)

CHESS & LEPP

5 GeV machine, 18 ID beam lines



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.

3 Basic Operating Modes

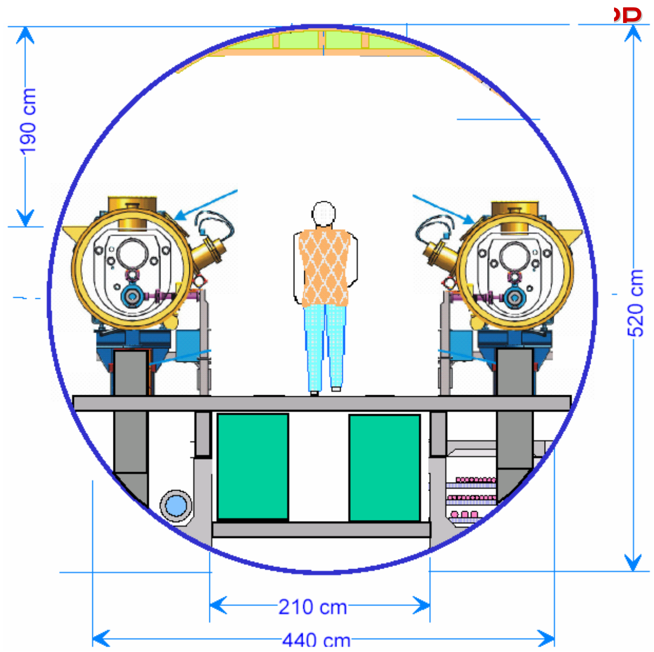
Hi-flux: 30 pm emittance, 100 mA, 77 pC, 1300 MHz repetition rate electron energy spread of 2E-4

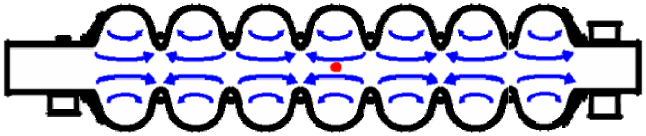
Hi-coherence: 8 pm, 25 mA, 19 pC, (5 pm, 100 mA long-term goal)

Ultra-fast: 500 pm, 1 mA, 1 nC, 1 MHz repetition rate (10 nC, 20 fs long-term goal)

ERL 5 GeV Main Linac

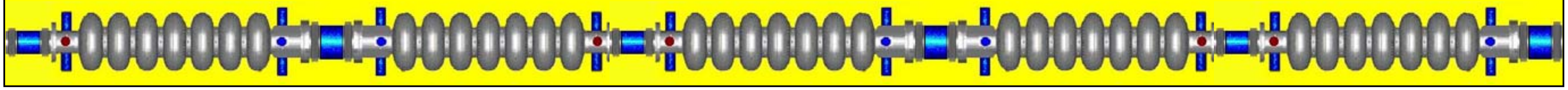
- 5 GeV superconducting linac
- 390 7-cell 1.3 GHz SRF cavities at 1.8K
- 390 power sources with feedback control
- 16 MV/m accelerating field gradient
- 100 mA beam current





≈ 1 m

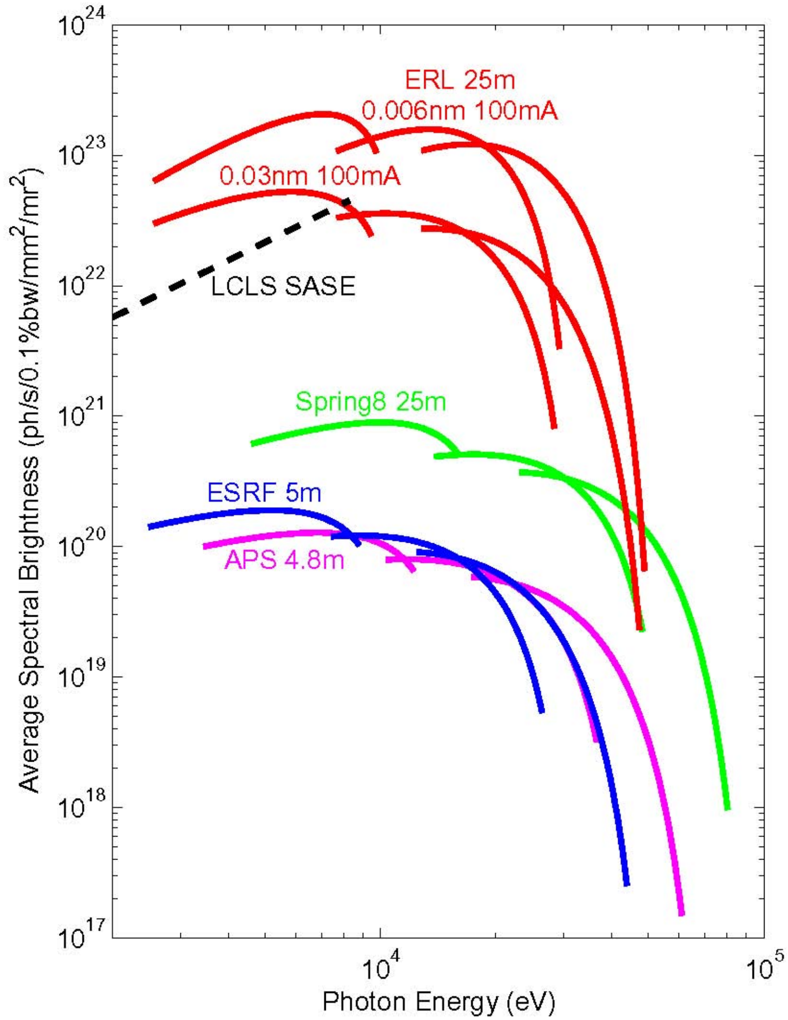
5 GeV = 625 m linac = 39 cryomodules = 390 cavities = 2730 cells



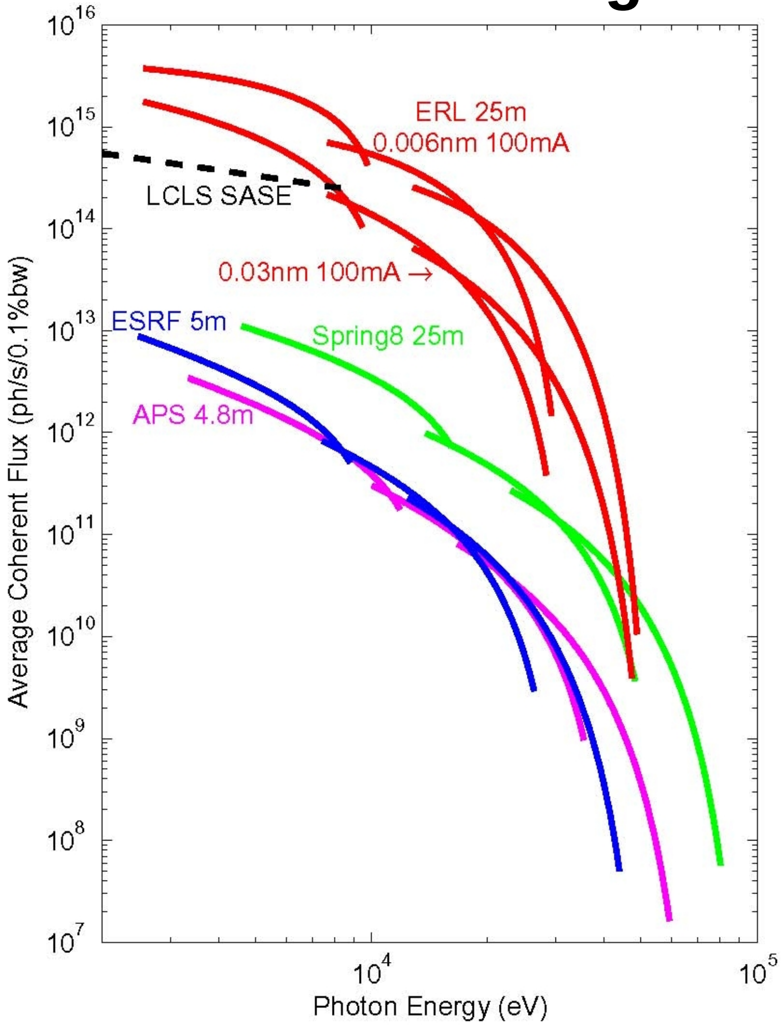
ERL will excel in Spectral Brightness, Source Size and Pulse Duration

CHESS & LEPP

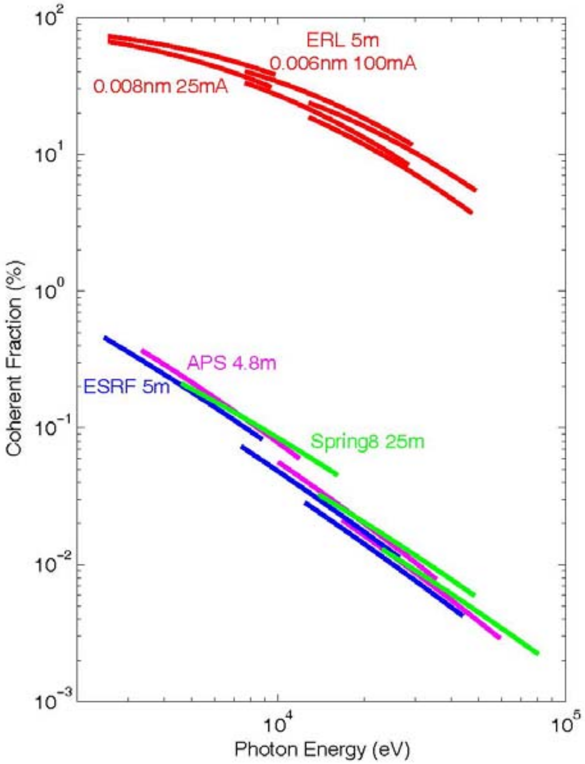
- **ERL hi-brightness mode for coherence applications**
- **A few micron diameter electron source size – good for intense, possibly one nm diameter, hard x-ray beams.**
- **Bunch compression allows pulses < 50fs.**

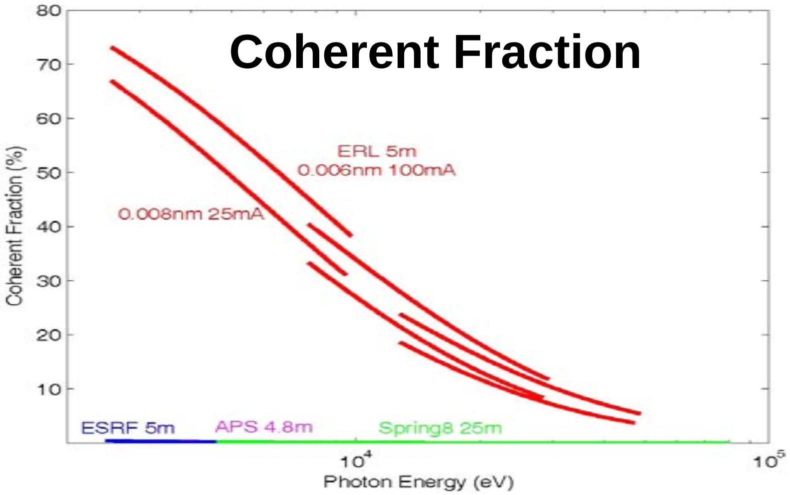


ERL has High Transverse Coherence



Avg. Coherent Flux




Coherent Fraction

X-ray Technical Challenges

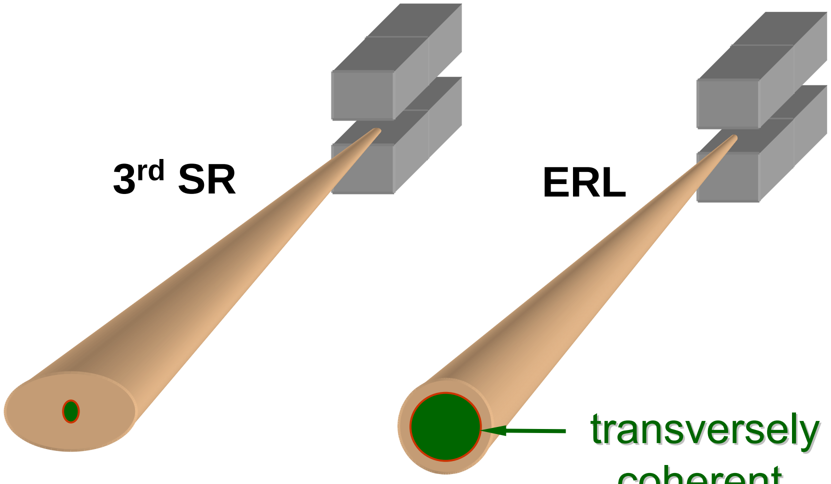
- Short period, short gap, long undulators w/ phased segments.
- X-ray windows that preserve coherence.
- X-ray BPMs that work on a submicron scale.
- Monochromators that don’t distort under a high-heat load.
- X-ray optics to make nm diameter hard x-ray beams.
- Mirrors with extraordinarily small slope error & roughness.
- X-ray area detectors with nsec readout time.

In some cases, 3rd generation quality instrumentation is sufficient.

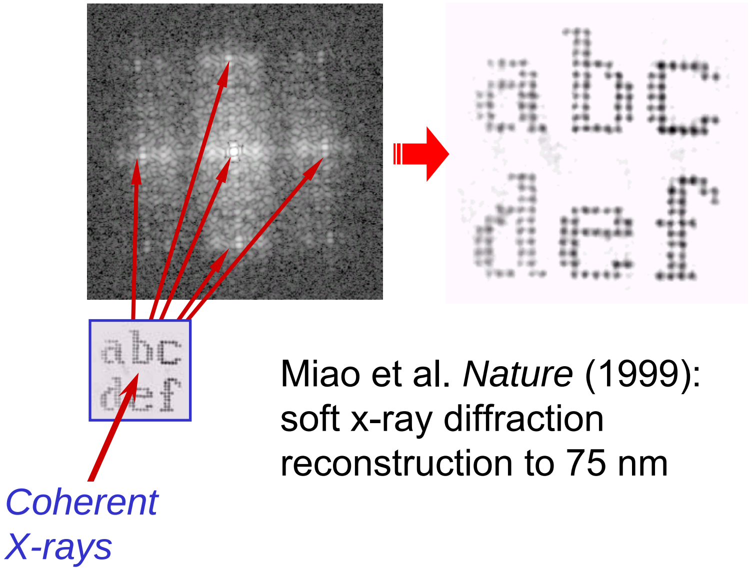
In other cases, important specs have to be improved to fully use an ERL quality beam.

Molecular Imaging

- Molecular imaging requires much higher lateral resolution => limit on optics
- To go beyond the limit, lens less diffraction imaging using a transversely coherent beam is an attractive alternative
- Coherent diffraction imaging is similar to crystallography, but for noncrystalline materials



- Present Status: using a pin-hole to select a coherent x-ray beam
- Future ERL sources would change this dramatically:
  - ➔ nearly fully coherent x-ray beams
  - ➔ Several hundred to a thousand-fold increase in coherent flux
- Open up structural science to noncrystalline materials

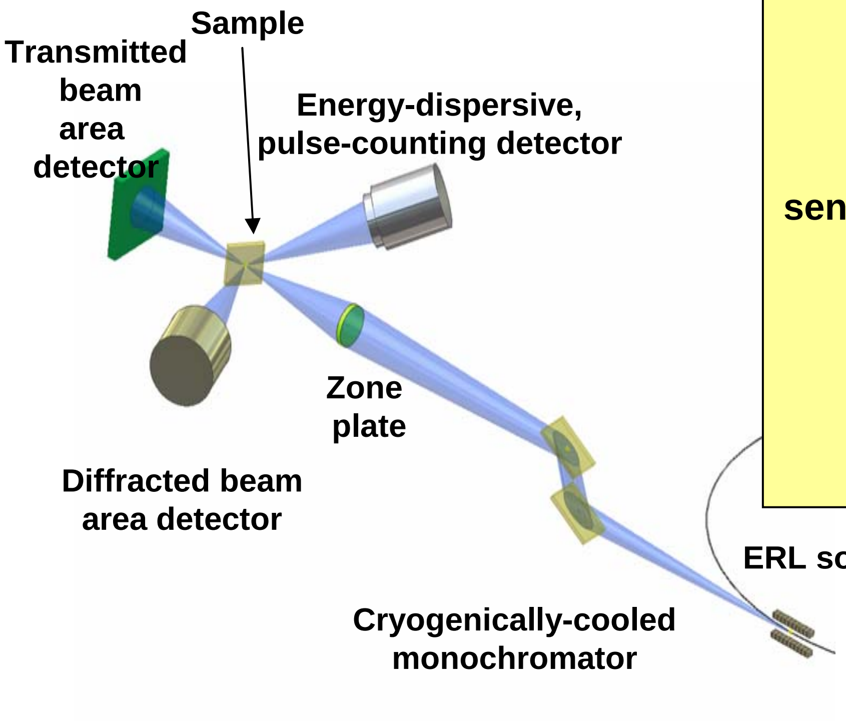


Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

ERL Provides Unprecedented Nanobeams for X-ray Experiments

Storage ring nanobeam flux limited by source size, shape, and divergence.

- Intense 1-10 nm probe size (rms), 1-10 keV beam allows study of nanostructures and molecules
- Quantitative atomic-scale structure, strain, orientation imaging
- Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)
- Sensitive to chemical state via XAFS at at ultra-low concentrations
- Ability to penetrate thick layers, nasty gas environments, etc. (as opposed to EM)



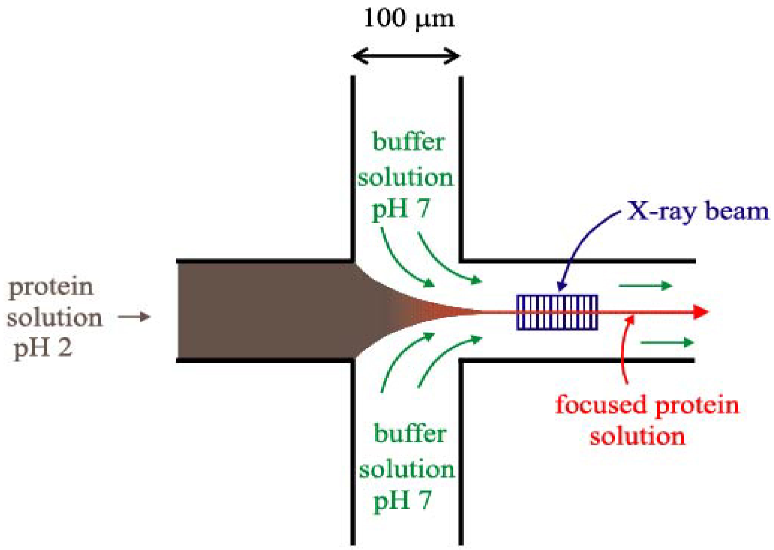
ERL source with electron beam size of 2 microns rms for 1 m long undulator and 0.5 m beta function demagnify by 2000x to make 1 nm beam size, etc.

Biological and Polymer Science:

Structural dynamics of macromolecular solutions

CHESS & LEPP

- Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.
- Microfabricated laminar flow cells access microsecond equilibration mixing times.
- Data acquisition entirely limited by source brilliance. The ERL will extend time scales from present milliseconds to microseconds.



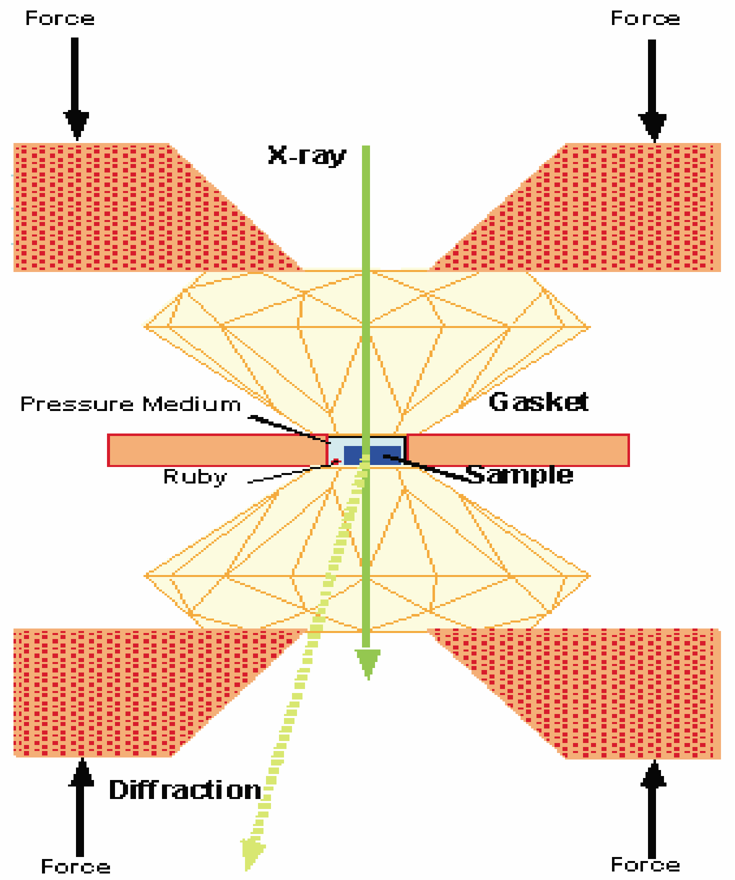
Lois Pollack

High Pressure: Materials, Engineering, Geological and Space Sciences.

J. B. Parise, H.- K. Mao, and R. Hemley at ERL Workshop (2000)

CHESS & LEPP

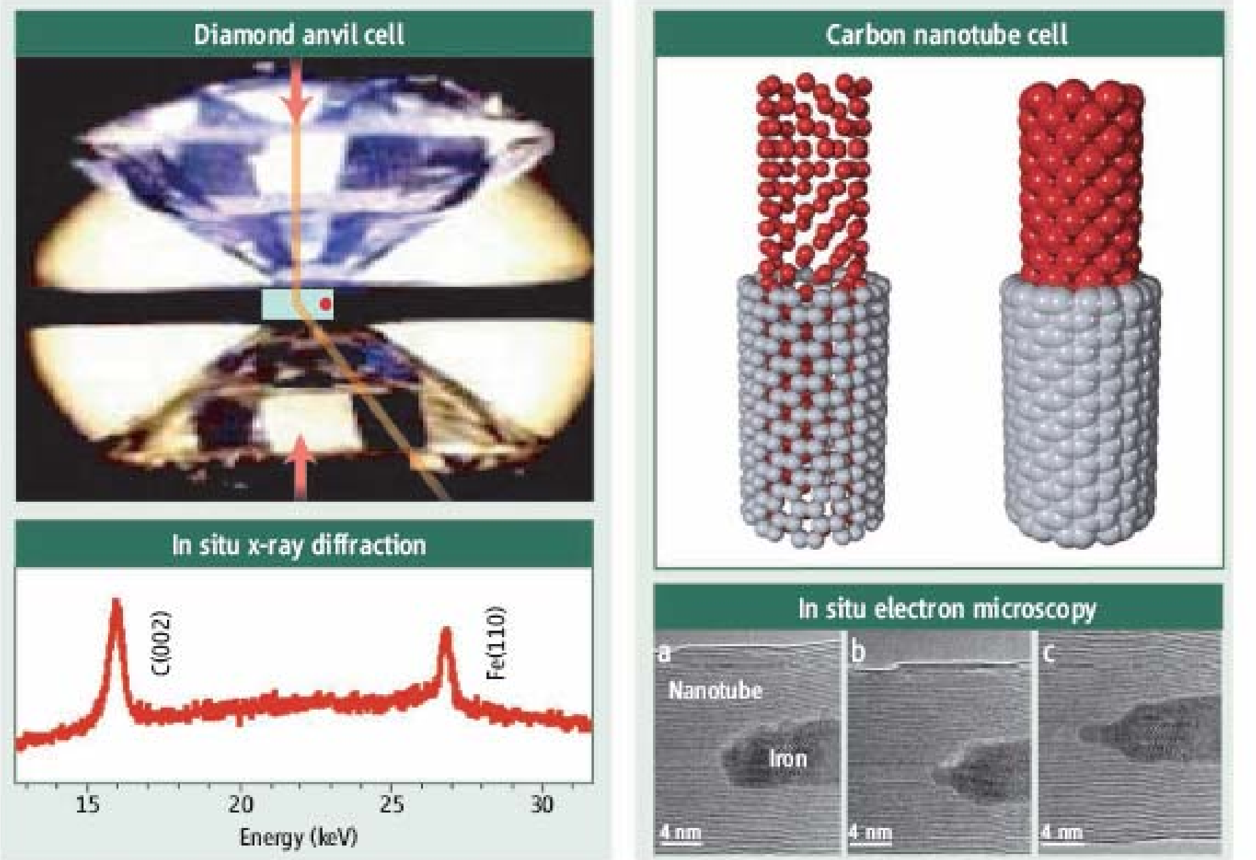
- HP experiments are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Higher P ⇒ smaller samples.
- No ideal pressurization medium ⇒ need to scan sample.
- Peak-to-background critical.
- ERL will greatly extend pressures and samples that can be studied.



Parise, Hemley & Mao

High Pressure in Carbon Nanotubes

CHESS & LEPP



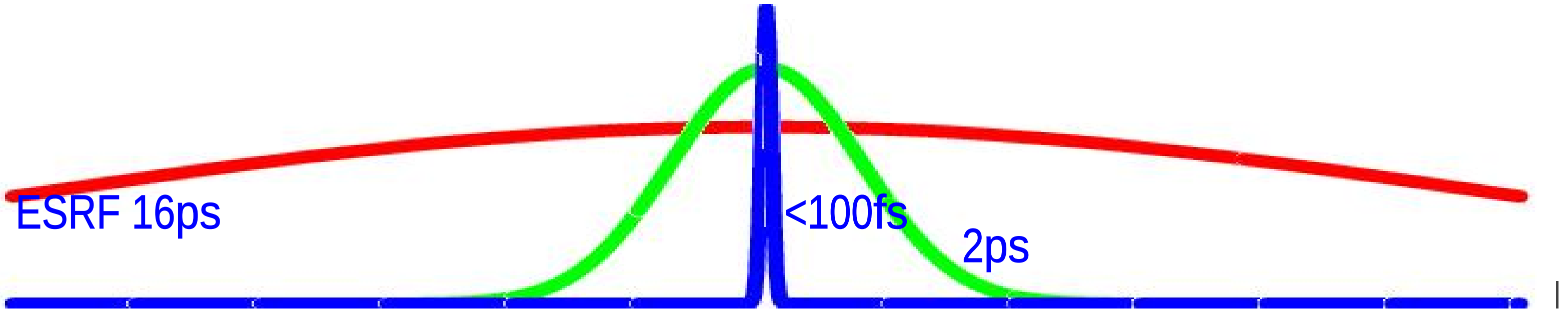
A matter of scale. (**Left**) A transparent diamond anvil cell allows in situ spectroscopic measurements of bulk samples. The red arrow represents an x-ray beam that is diffracted by the sample. (**Right**) A carbon nanotube self-compression cell enables in situ atomic-resolution snapshots at zero (a), intermediate (b), and high (~40 GPa) (c) pressure.

Wang &Zhao, *Science*, **312** (2006) 1149; Sun et al., *Science*, **312** (2006) 1199.

ERL can produce very short bunches

CHESS & LEPP

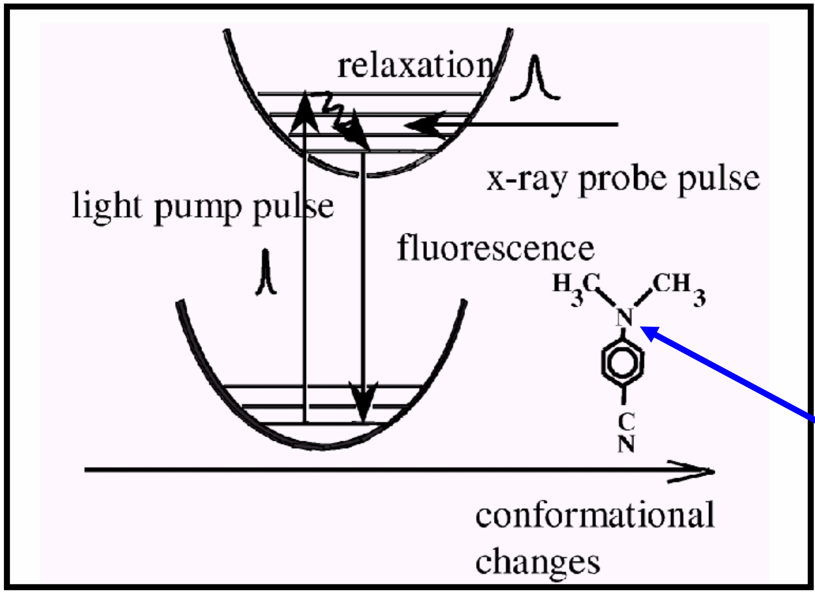
- The bunch length can be made much smaller than in a ring.
- Bunch charge can be increased at the cost of brightness.
- Rep rate is also very flexible.

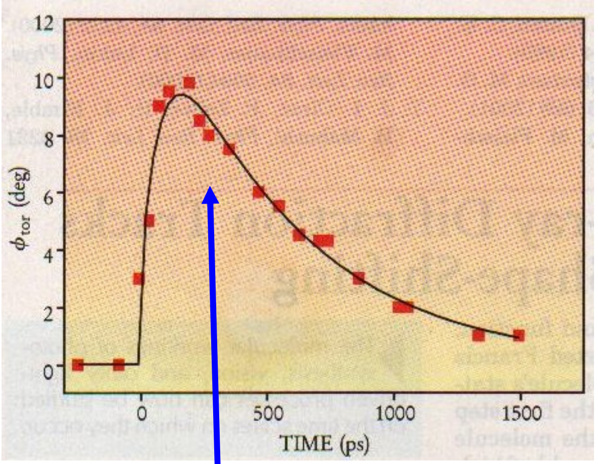


ERL Enables Following Structure of Ultrafast Chemical Reactions

Scientific challenge is to understand the structural evolution of the "transition state(s)" intermediate between reactant and product species.

S. Techert, F. Schotte, and M. Wulff, Phys. Rev. Lett. **86**, 2030-2033 (2001).

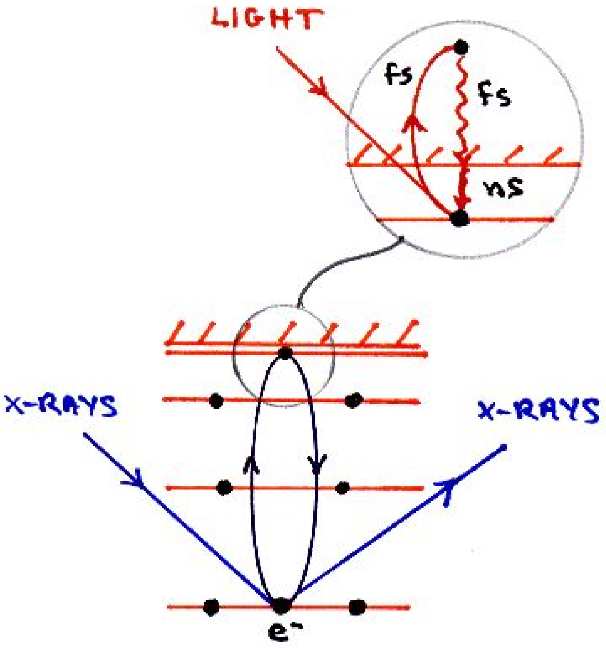


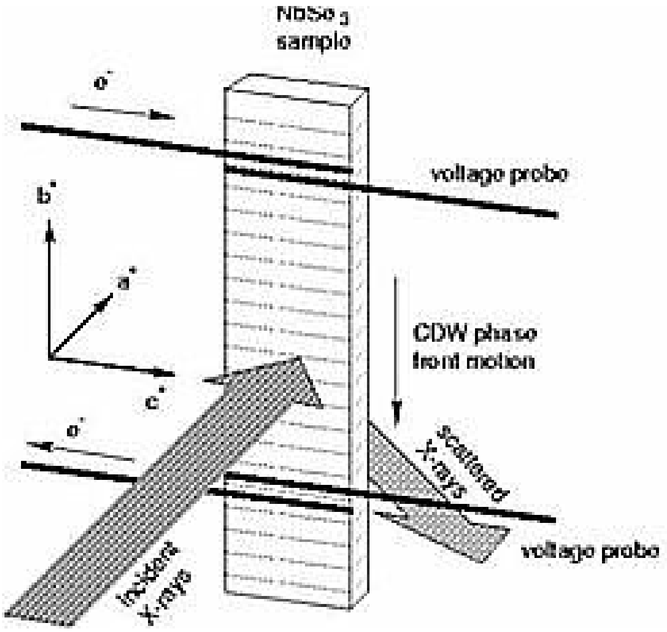


ESRF expt. showed 10° of bond rotation over 100's of picoseconds

ERL can follow reactions on the <100 femtosecond time scale.

Ultra-fast Dynamics of Charge Density Waves





Mode-locked Ti:Al_2O_3 Laser, MHz repetition rate, 50-70 fs pulse width

λ≈800 nm (1.58 eV), 100 µm spot, 0.1 – 1 µJ/cm^2

Joel Brock, Applied Physics, Cornell Univ.

REASONS TO DEVELOP ERLs

CHESS & LEPP

1. **A large user community already exists**. ERLs does everything now possible at the most advanced 3rd gen SR sources, thus meeting growth in demand for SR.
2. **ERLs enable SR experiments not now possible.** Follows from high ERL brilliance, coherence, short pulses and flexible bunch structure. Will lead to new science.
3. **ERLs are a promising technology with limits yet to be determined.** Injector improvements will provide low cost upgrades for ERLs. ERL retrofits to storage rings may provide cost-effective upgrades of enhancing existing rings. ERL XFELs are possible.

Conclusions

CHESS & LEPP

- ERL will lead to new, very exciting scientific capabilities.
- Most supporting hardware will need upgrading (optics, windows, detectors, etc.) to match the ERL challenges.
- Excellent progress is being made in both machine and beamline areas.

END