Energy Recovery Linac (ERL) Background

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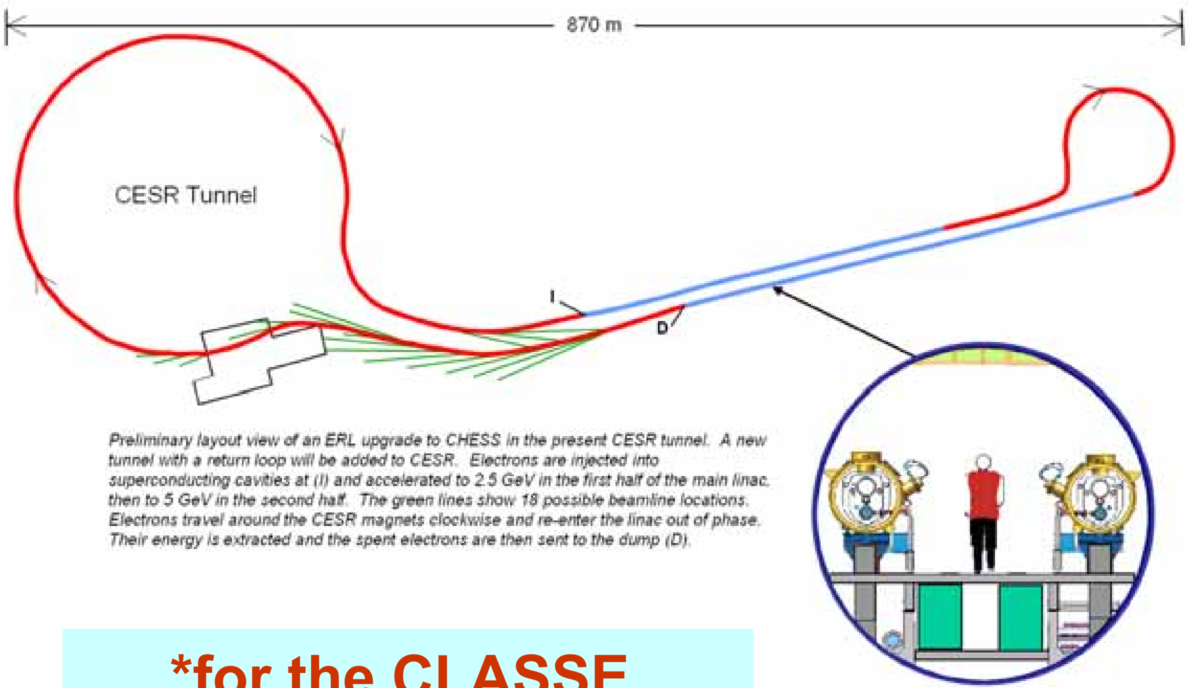
Sol M. Gruner*
Cornell High Energy Synchrotron Source & Physics Department
Cornell University, Ithaca, New York 14853-2501
smg26@cornell.edu



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

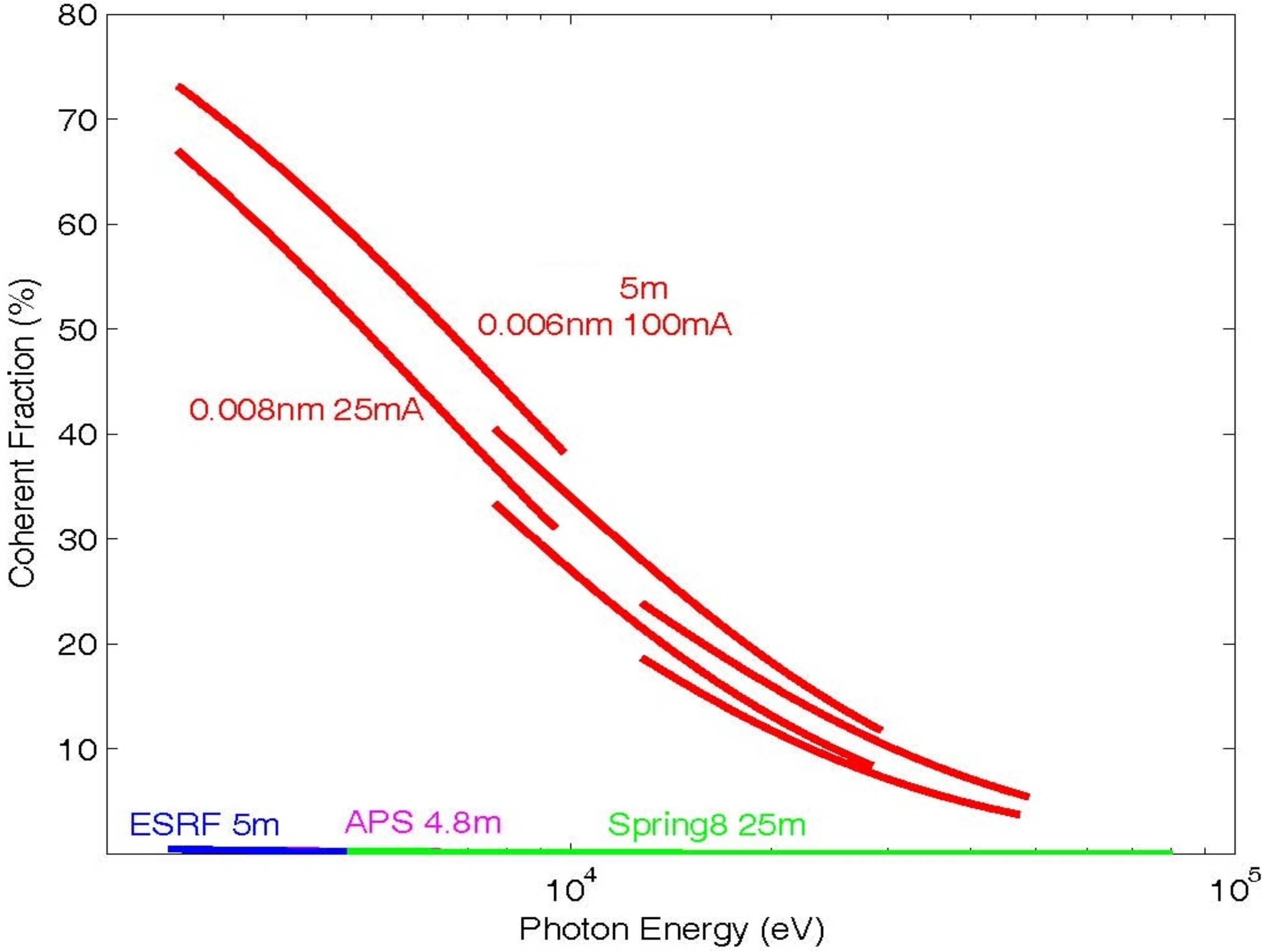
Purpose: Why Build an ERL?

Growth in Synchrotron Radiation (SR) demand is both in availability and capability

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

1. **Higher coherent flux.**
2. **Faster x-ray pulses.**
3. **Smaller x-ray source size for nanobeams.**

Existing Storage Rings are Incoherent Sources



Lensless Imaging Revolution

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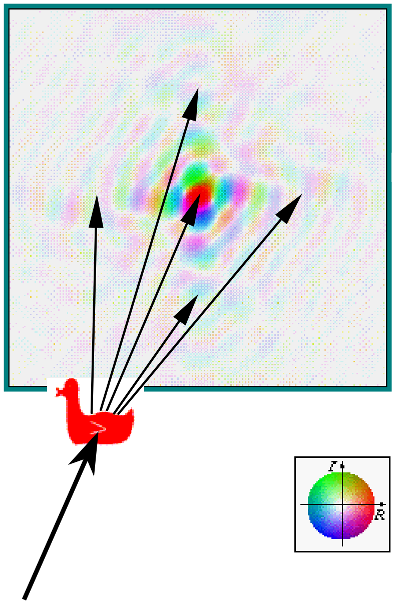
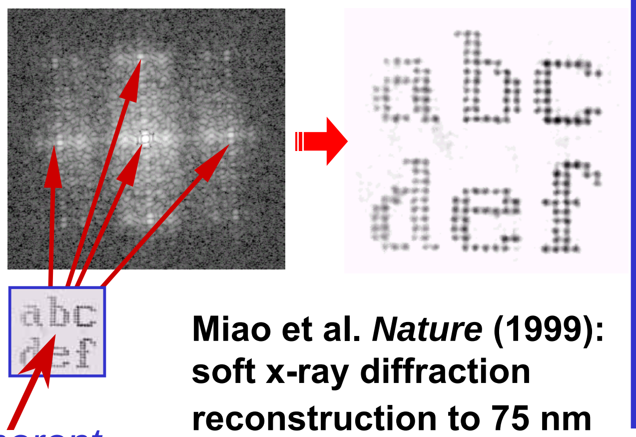


Coherent X-rays

- Analogous to crystallography, but also works for **noncrystalline** materials
- Coherent diffraction from noncrystalline specimen: => continuous Fourier transform
- Spatial resolution: essentially no limit. (only limited by $\Delta\lambda/\lambda$ and weak signals at large angles)
- Coherence required for illumination of sample
- Present limitations: Lack of intense, coherent microbeams. ERL would change this dramatically.

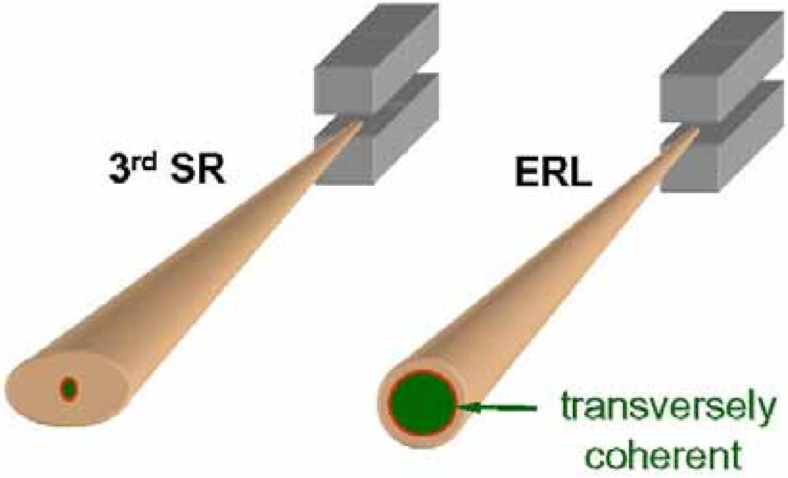


Coherent X-rays

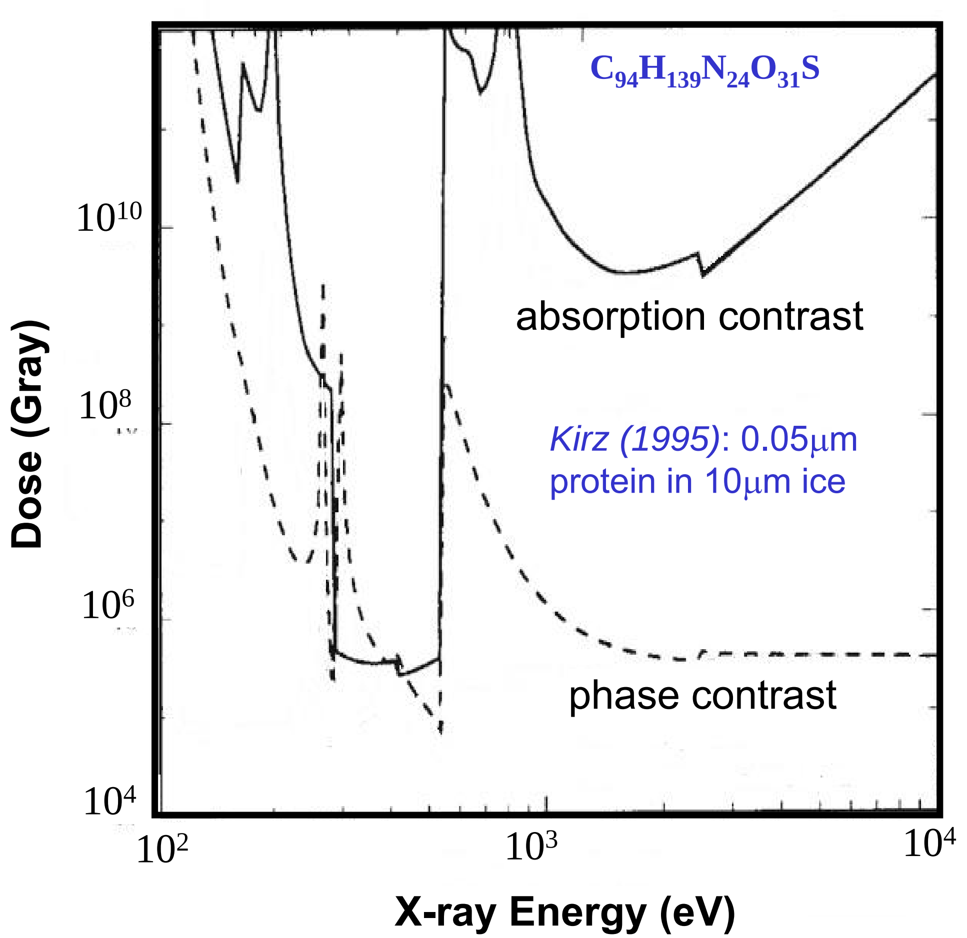
Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

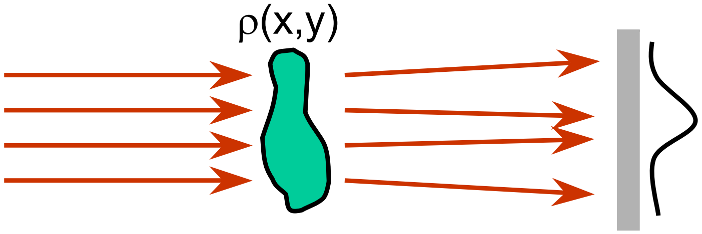
Lensless Imaging Revolution

- Present Status: pin-hole selects coherent x-ray beam. Discards most of the flux.
- Future ERL sources would change this dramatically:
  ➔ almost fully coherent x-ray beams
  ➔ Great increase in coherent flux
- Opens structural science to noncrystalline materials



Why is Coherence Essential?



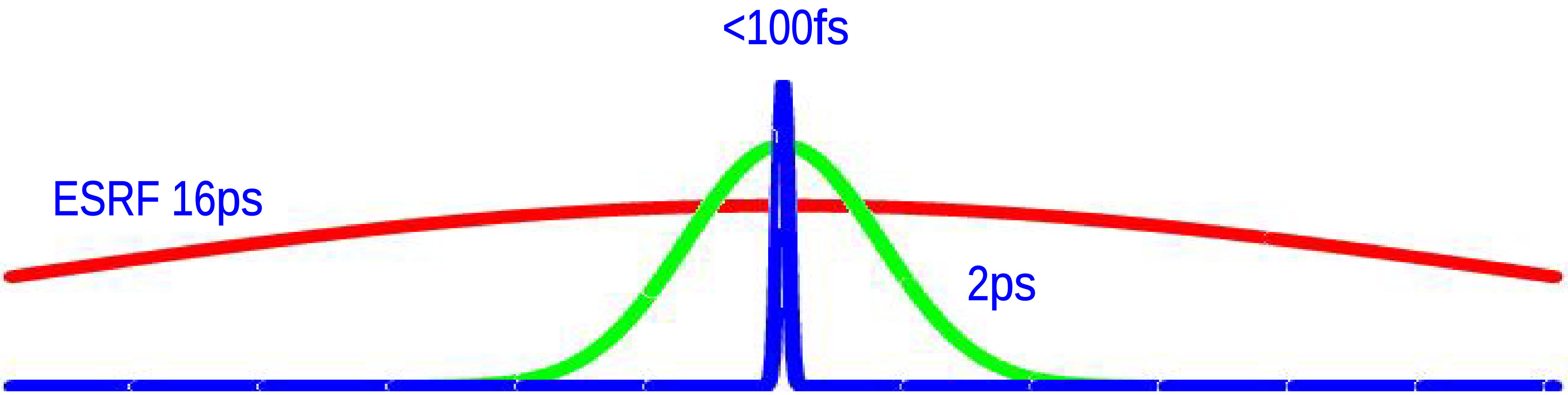


Refraction index: $n = 1 - \delta - i\beta$

- Phase contrast is 10^4 - 10^6 higher than absorption contrast for protein in water at hard x-rays energies
- Required dose is reduced with phase contrast

In general, phase contrast requires more coherent x-ray beams

Many Phenomena Occur Faster than 10^{-11} Seconds



Ultrafast Structure Studies

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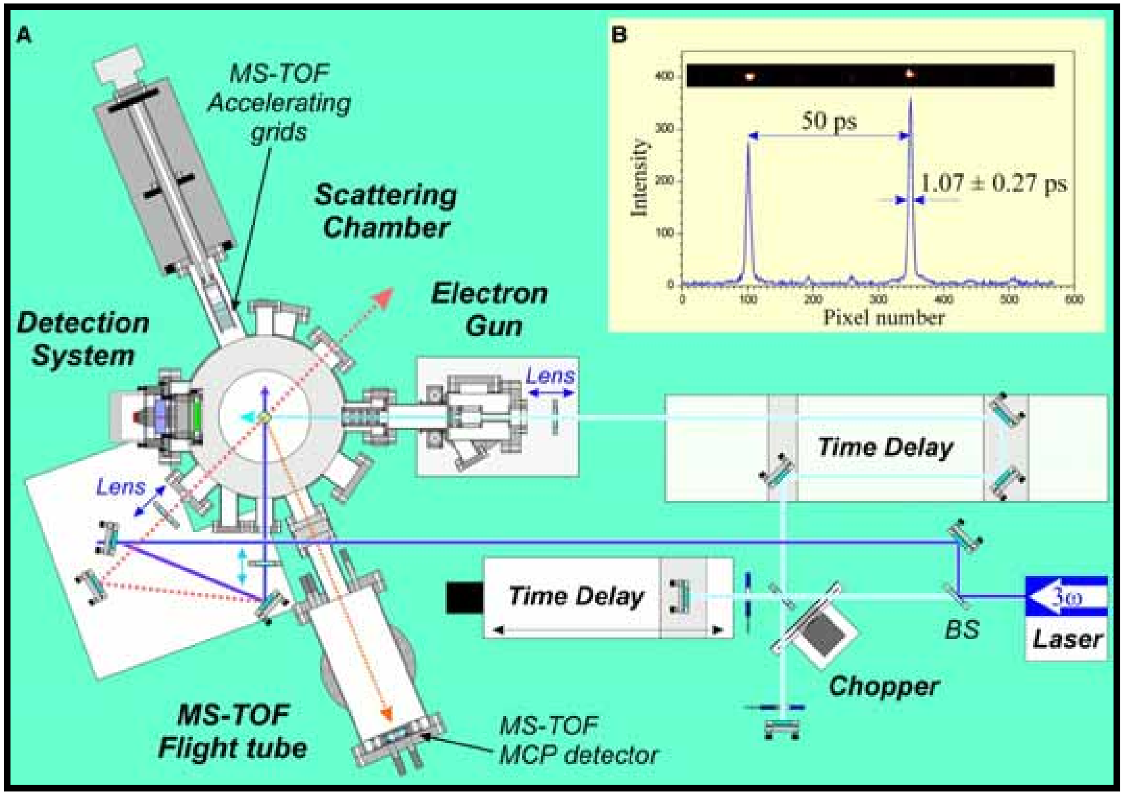

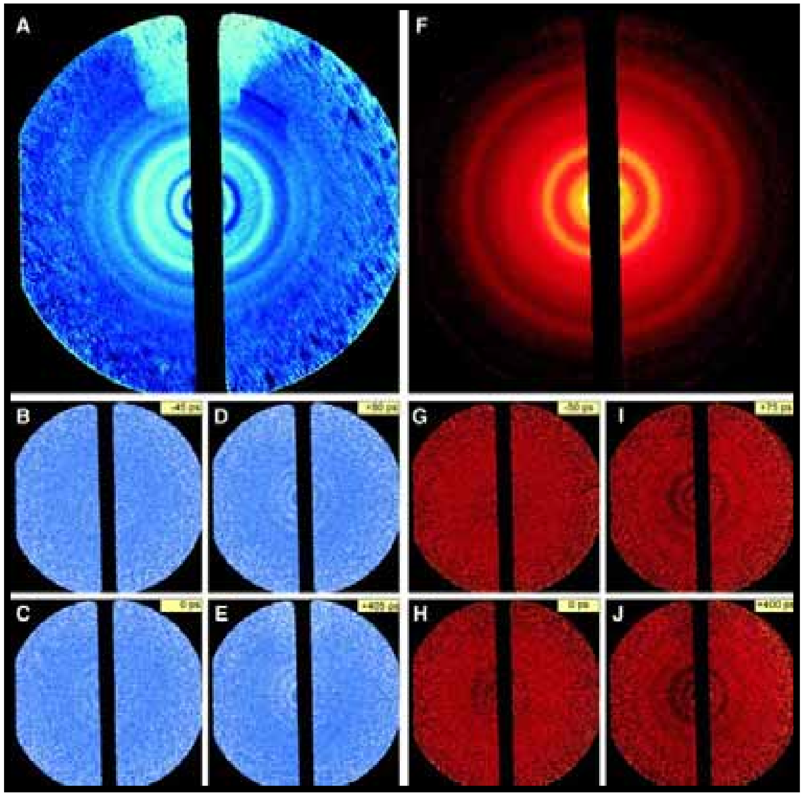

Caltech's Ultrafast Electron Diffraction (UED) apparatus.

UED images of $C_2F_4I_2$ (blue) and 1,3-cyclohexadiene (red).

H. Ihee, V.A. Lobastov, U.M. Gomez, B.M. Goodson, R. Srinivasan, C.-Y. Ruan, and A. Zewail, Science **291**, 458-462 (2001).

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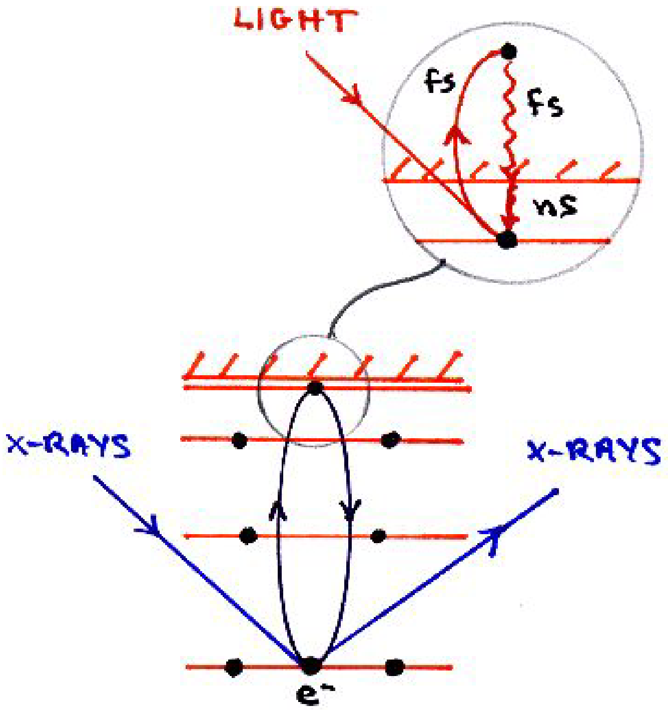
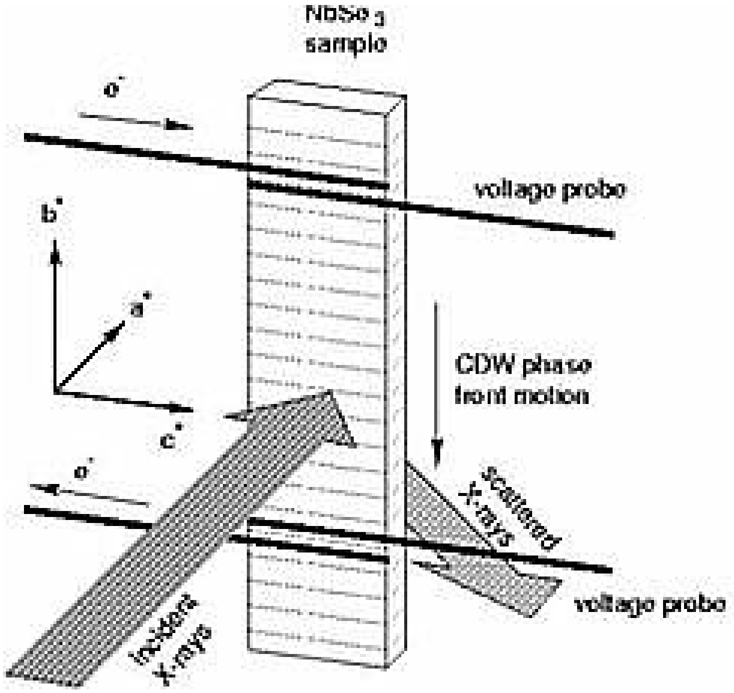
Ultra-fast Dynamics of Charge Density Waves





Mode-locked Ti:Al$_2$O$_3$ Laser, 78 MHz repetition rate, 50-70 fs pulse width

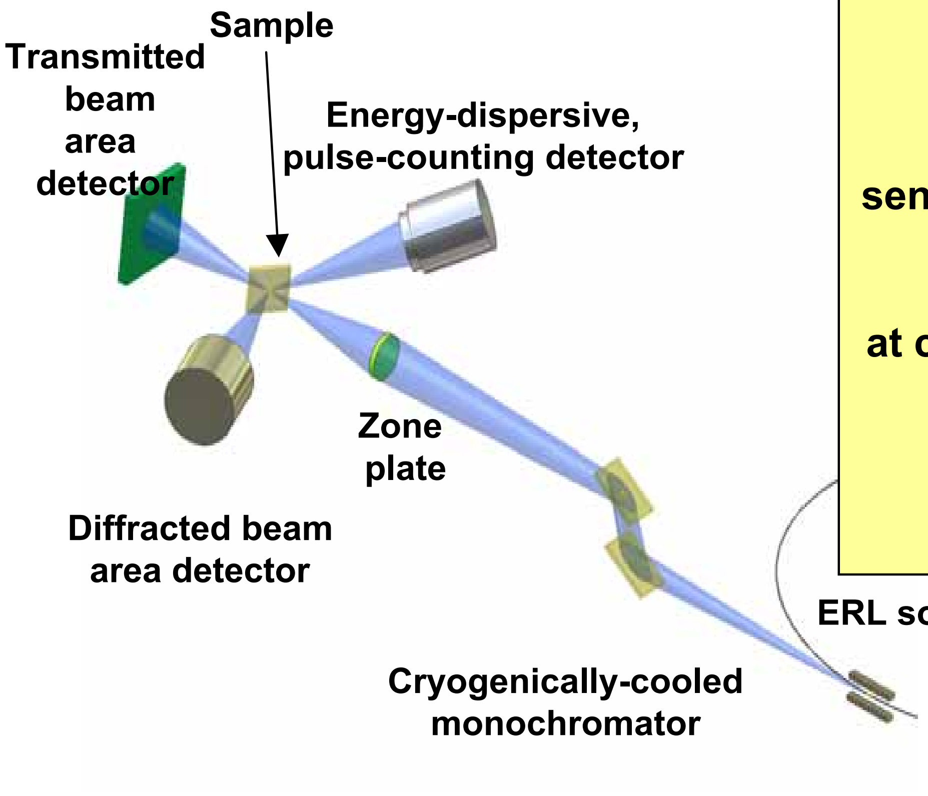
λ≈800 nm (1.58 eV), 100 µm spot, 0.1 – 1 µJ/cm^2

Joel Brock, Applied Physics, Cornell Univ.

Cornell University
Cornell High Energy Synchrotron Source

ERL Provides Unprecedented Nanobeams

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



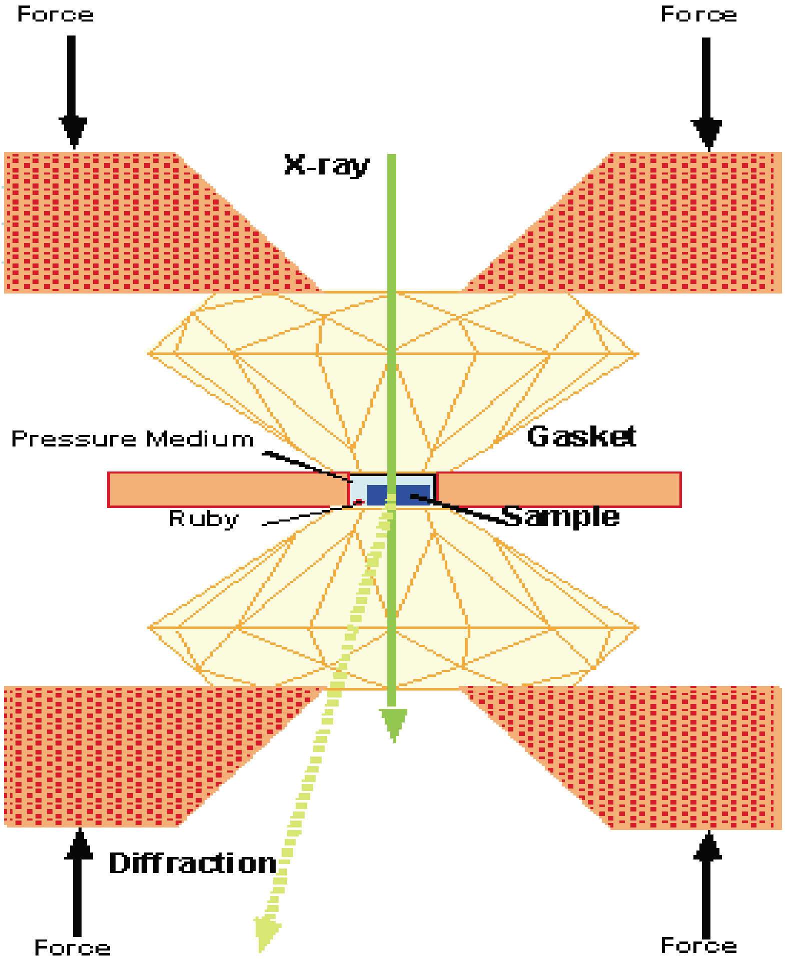
- **Intense 1-10 nm probe size (rms), 1-10 keV beam allows study of nanostructures and molecules**
- **Quantitative atomic-scale structure, strain, orientation imaging**
- **Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)**
- **Sensitive to chemical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

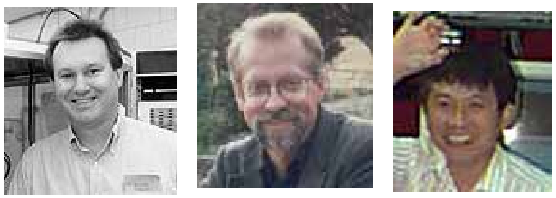
ERL source with electron beam size of 2 microns rms for 1 m long undulator and 0.5 m beta function demagnify by 2000x to make 1 nm beam size, etc.

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

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

- 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 Science Areas

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- **Nature of dense hydrogen -** *From cryogenic to brown dwarf conditions*
- **Composition, elasticity, and thermal state of Earth's core -** *Complex alloys to core P- T*
- **Structures of complex hydrous phases -** *Clathrates, molecular compounds, hydrous silicates*
- **Supercritical fluids and liquids -** *Structure and dynamics and effect on chemical reactions*
- **Structure & dynamics of silicate melts & glasses -** *Implications for glass technology & volcanism*
- **Planetary ices -** *Structure, strength, and dynamics of ices under P, T, and stress*
- **Real- time in situ monitoring of transformations in 'real rocks" -** *Modeling subduction to high P- T conditions*
- **Strength and rheology of materials, including Earth materials -** *Relationship to brittle and ductile failure*
- **Influence of pressure and stress on magnetic properties -** *From low to high temperatures*
- **Dynamics of protein folding and unfolding -** *Implications for food technology and life at extreme conditions*
- **Structure and dynamics of nanomaterials under pressure -** *Nanotubes, fullerenes, and their derivatives*
- **General phase transition studies -** *Mechanisms and identification with unprecedented resolution*
- **Stockpile stewardship issues -** *Light element studies for code verification*

From, John Parise, SUNY Stonybrook, at ERL Science Workshop

High Pressure in Carbon Nanotubes

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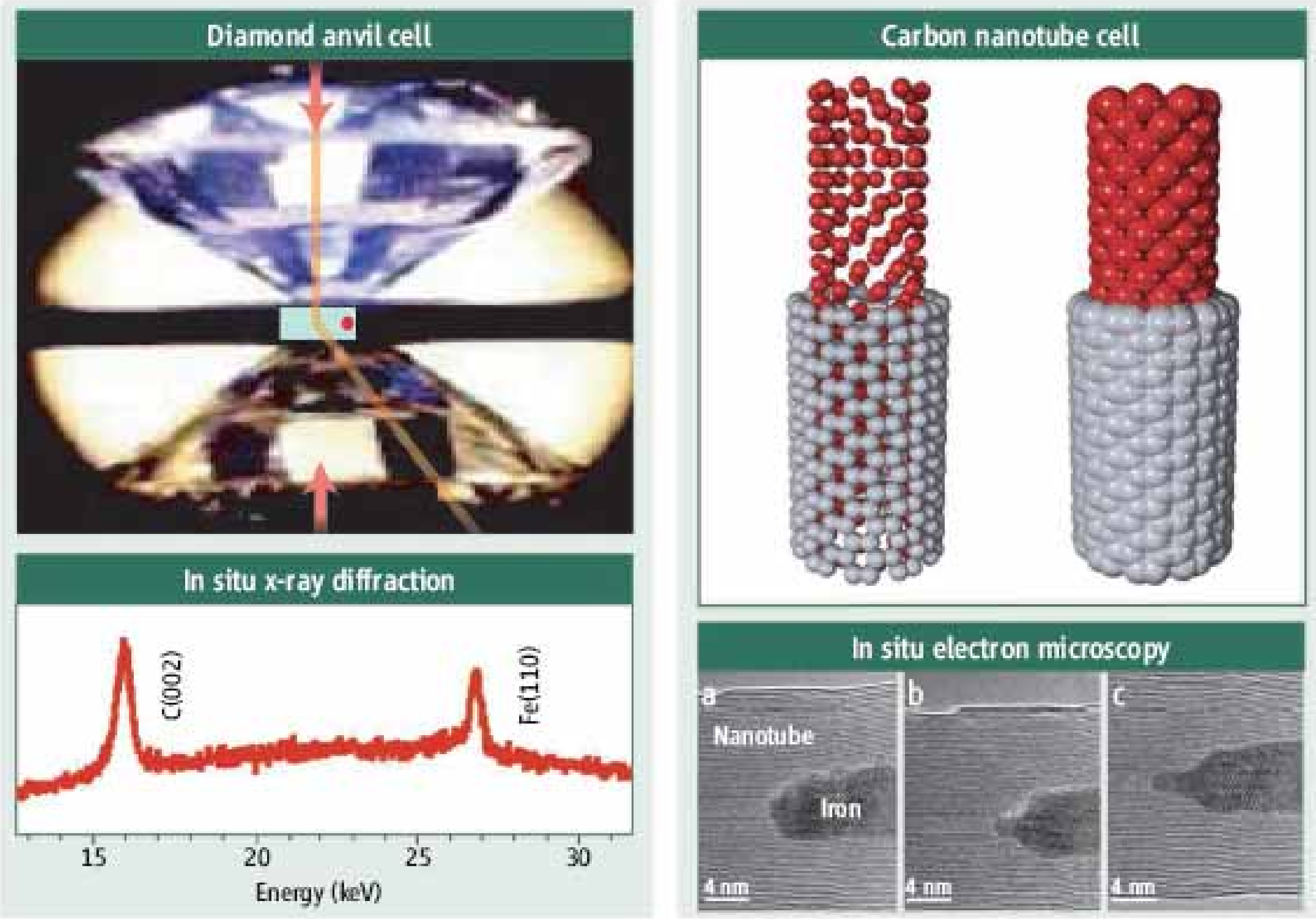

A matter of scale. (Left) A transparent diamond anvil cell allows in situ spectroscopic measurements of bulk samples. The red arrow represents an x-ray beam that is diffracted by the sample. **(Right)** A carbon nanotube self-compression cell enables in situ atomic-resolution snapshots at zero (a), intermediate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

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

Biological and Polymer Science:

Structural dynamics of macromolecular solutions

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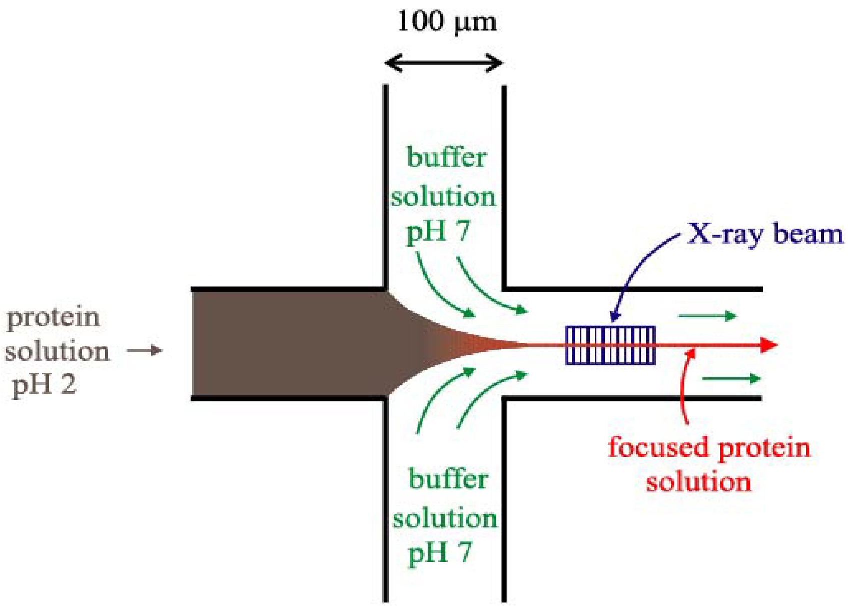
- Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.
- Microfabricated laminar flow cells access microsecond equilibration mixing times.
- Data acquisition entirely limited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



Thanks to Lois Pollack

Cornell Univ.

REASONS TO DEVELOP ERL TECHNOLOGY

1. ERLs can do everything possible at most advanced 3rd gen SR sources, thus meeting growth in demand for SR. As opposed to XFELs, a huge ERL user community already exists.
2. ERLs additionally enable SR experiments not now possible due to high ERL brilliance, coherence, short pulses and flexible bunch structure. These include new regimes of
   - Microbeam diffraction and fluorescence
   - High pressure diffraction and spectroscopy
   - Femtosecond x-ray studies of solids, molecules and proteins
   - Coherent imaging and microscopy
   - Photon correlation spectroscopy
   - Nuclear resonant scattering
   - Inelastic x-ray scattering
   - Normal diffraction, x-ray metrology, and x-ray interferometry
   - Polarized x-ray beam studies, resonant scattering and circular magnetic dichroism studies
3. The inherent limits of ERLs are not yet known. Expect improvements, providing an attractive upgrade pathway.

Question: Why Not Use and XFEL?

XFELs are coherent and the pulses are fast.

Answer: The community is starting to realizing that some experiments are best done with an XFEL and some are best done with a continuous duty source, such as an ERL.

- **ERLs deliver photons in lots of small buckets.**
- **XFELs deliver photons in a few big buckets.**

When delivered faster than thermal equilibration…

0.1 eV/atom

Threshold for permanent structural damage

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↓

1 eV/atom

Most materials melt

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When delivered faster than thermal equilibration…

0.1 eV/atom

Threshold for permanent structural damage

↓

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Most materials melt

↓

10 eV/atom

Ablation occurs

- **ERLs deliver photons in lots of small buckets.**
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When delivered faster than thermal equilibration…

0.1 eV/atom

Threshold for permanent structural damage

↓

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Most materials melt

↓

10 eV/atom

Ablation occurs

Assuming “average” element is carbon (85 barn /atom cross-section), LCLS will give 1eV/atom for beams 10-30 μm diameter.

Even more severe for higher Z or for European XFEL

- Assume carbon-based material. At 8 keV, absorption length is ~1mm.
- Single LCLS pulse is about 1 mJ.
- Assume 1μm dia beam. Most of the energy of a single pulse is deposited in volume 1mm x $(1\mu m)^2 = 10^{-15}$ m^3.
- Specific heat of matter ~2×10^6 J/K-m^3.
- ΔT/bunch ~ $(10^{-3}\ J)/((10^{-15}\ m^3) \times (2\times10^6\ J/K\text{-}m^3)) = 5\times10^5\ K$!

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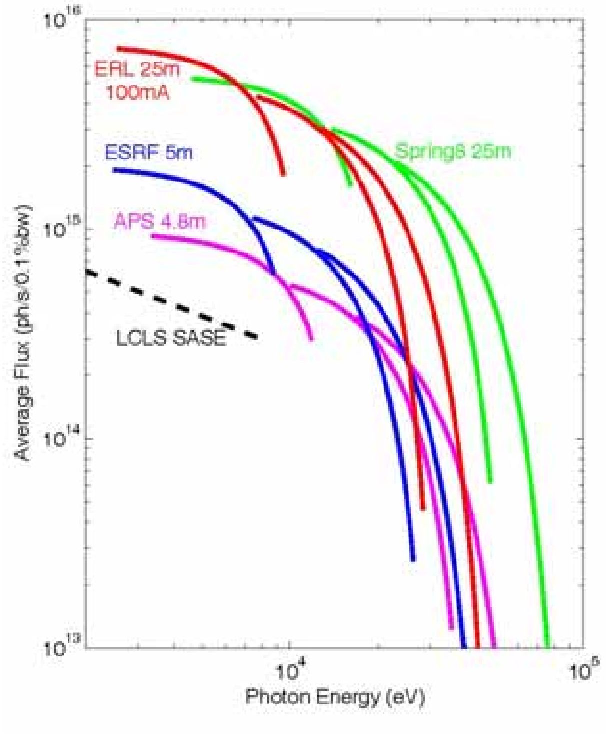
Conclude: XFELs well-suited for experiments that allow a new specimen for every pulse or can use beams 10s of μm in diameter.



ERL pulses carry ~10^{6} less energy/bunch. Heating is still be an issue, but over longer time scales.

XFEL and ERL are Complementary Sources. Science needs them both.

Bottom line:

- Some experiments are well suited for XFELs and not for ERLs.
- Some are well suited for ERLs and not XFELs.

Our interests are in the latter.

Areas of Opportunity

1	nanoprobe	Spot ≤ 1nm
2	timing experiments	τ~ 1 ps & ~100 fs flexible pulse structure
3	hard x-ray coherent scattering (XPCS)	Nearly diffraction limited at 10KeV
4	soft x-ray coherent scattering	
5	high energy scattering	E >> 10 KeV
6	coherent imaging	

Operating Mode Targets

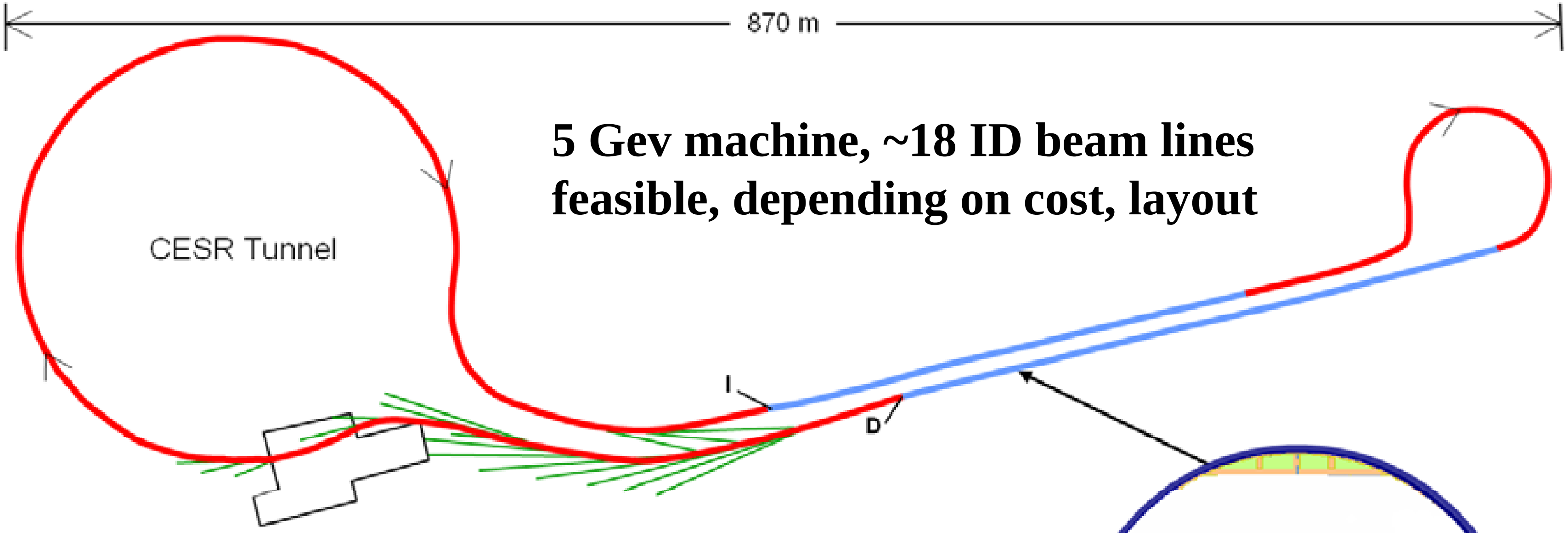
	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	2.5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm-mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	100	50	fs
Relative energy spread	$2x10^{-4}$	$2x10^{-4}$	$1x10^{-3}$	$3x10^{-3}$	
Beam power	500	125	500	0.25	MW
Beam loss	< 1	< 1	< 1	<1	µA

Status of Cornell ERL Project

- 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)
- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. This is ERL@CESR Phase II
- Use ERL@CESR to perform experiments, R&D on ERLs, in context of a user facility.

Cornell Phase II ERL Layout

5 Gev machine, ~18 ID beam lines feasible, depending on cost, layout



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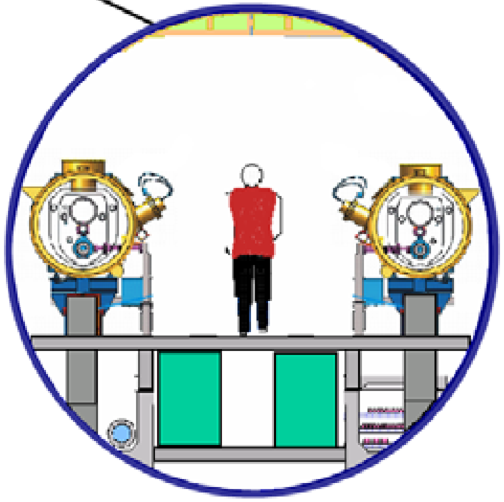
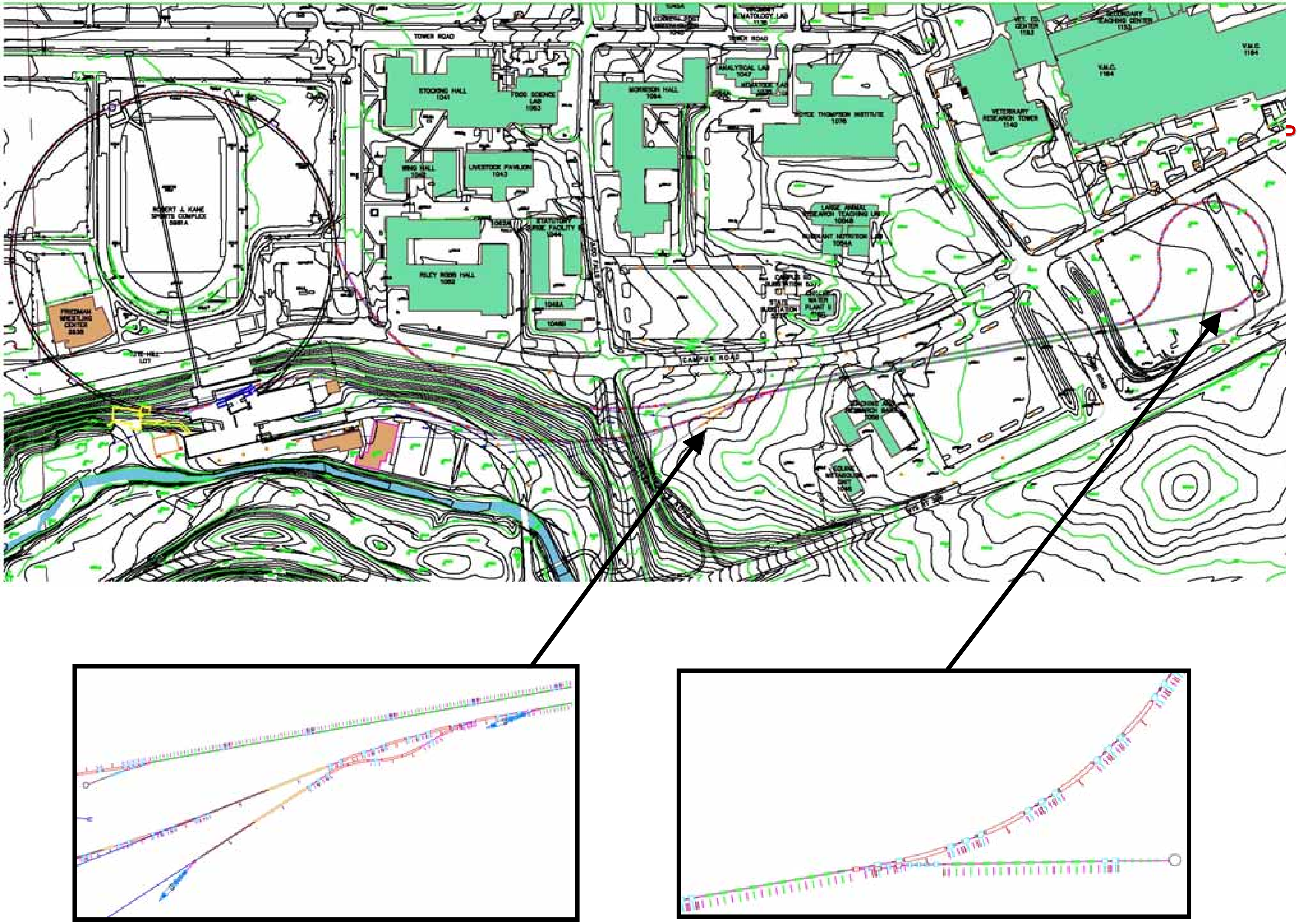


Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.



Cornell University
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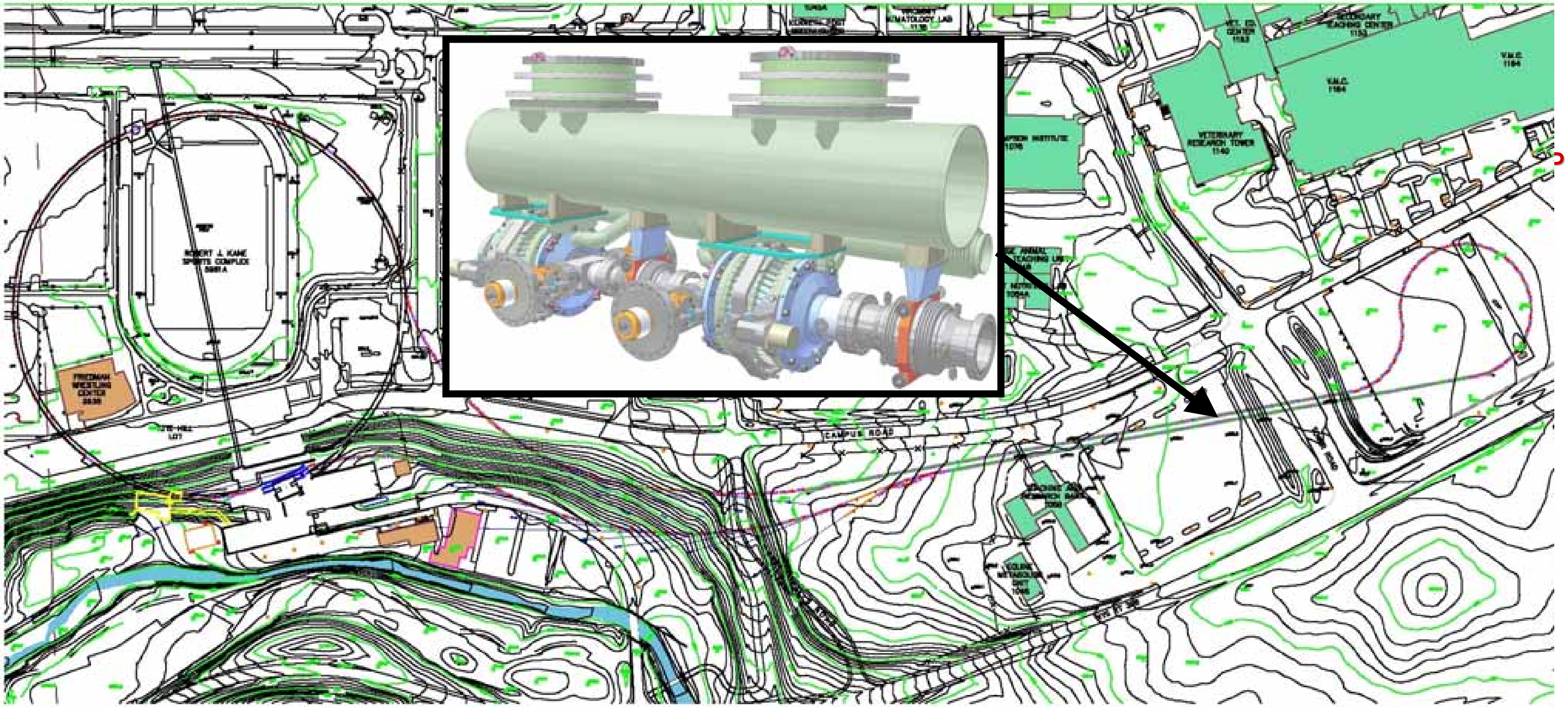
• Georg Hoffstaetter, Chris Mayes	Layout & Machine Optics
• Georg Hoffstaetter, Mike Billing Sasha Temnyk, Changsheng Song	Accel. Physics Considerations
• Ray Helmke	Control Systems



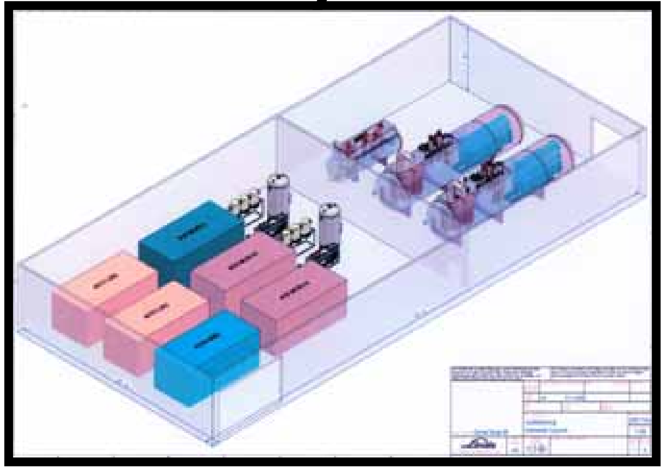
LINAC

Hasan Padamsee

Matthias Liepe

Eric Chojnacki

Sergey Belomestnykh



Richard Ehrlich

Cryoplant

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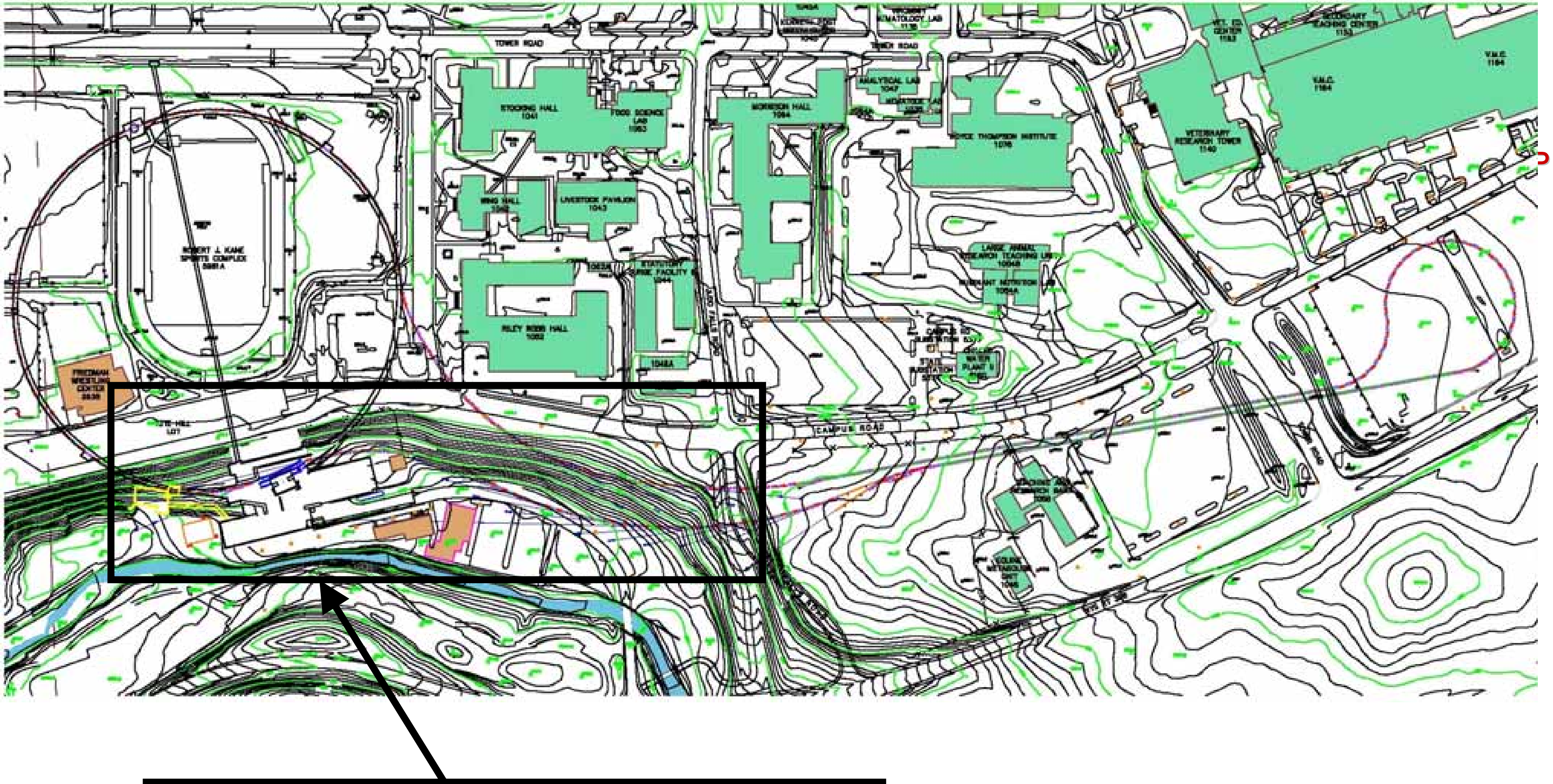
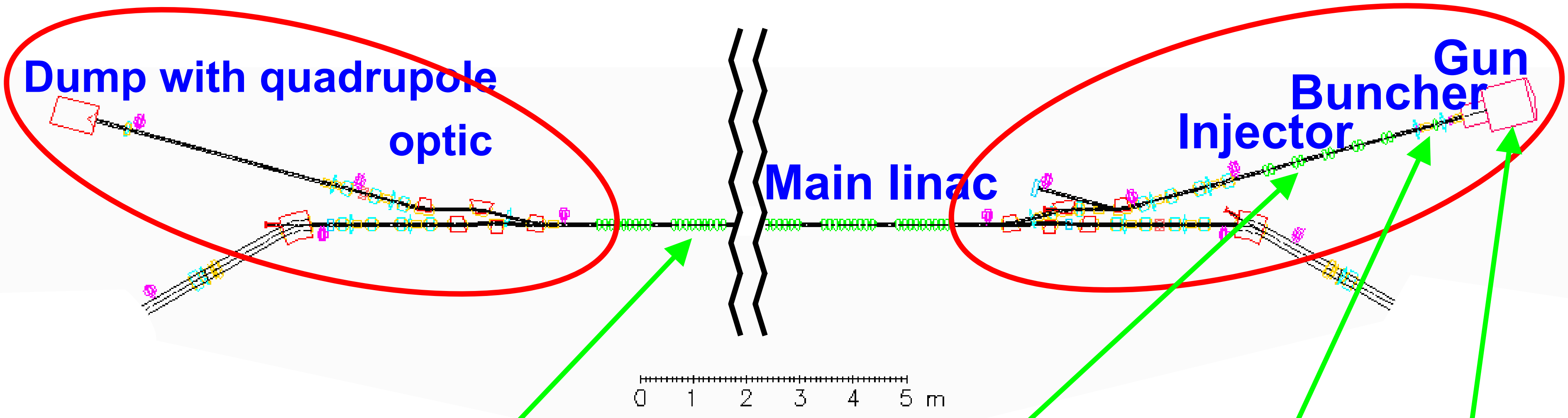


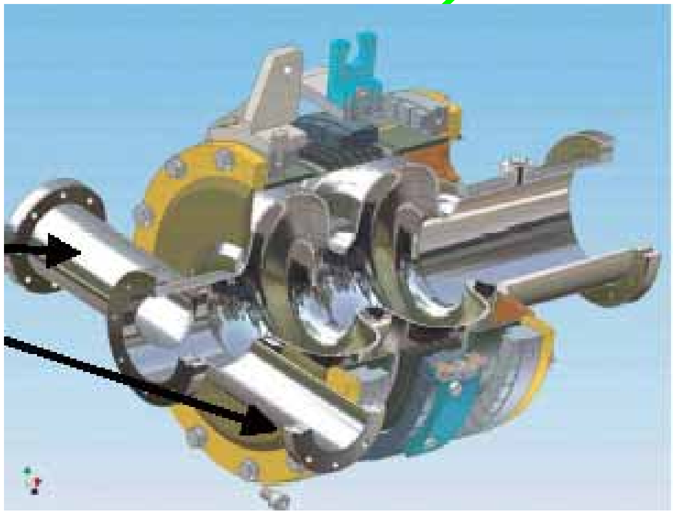
Don Bilderback

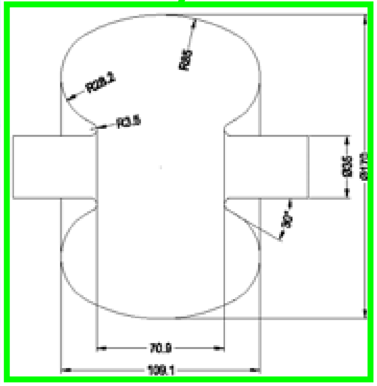
Conventional Facilities

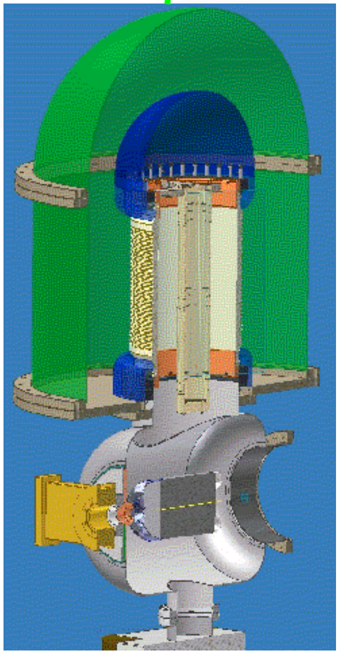
Bruce Dunham, Ivan Bazarov, Eric Chojnacki

ERL Phase 1a Injector in L0









Areas Not Covered

- Insertion devices
- Machine protection system
- Detailed radiation protection system
- Environmental issues
- Dump
- X-ray beamline issues (optics, stabilization, detectors, experimental hutches, etc.)
- Etc.

END