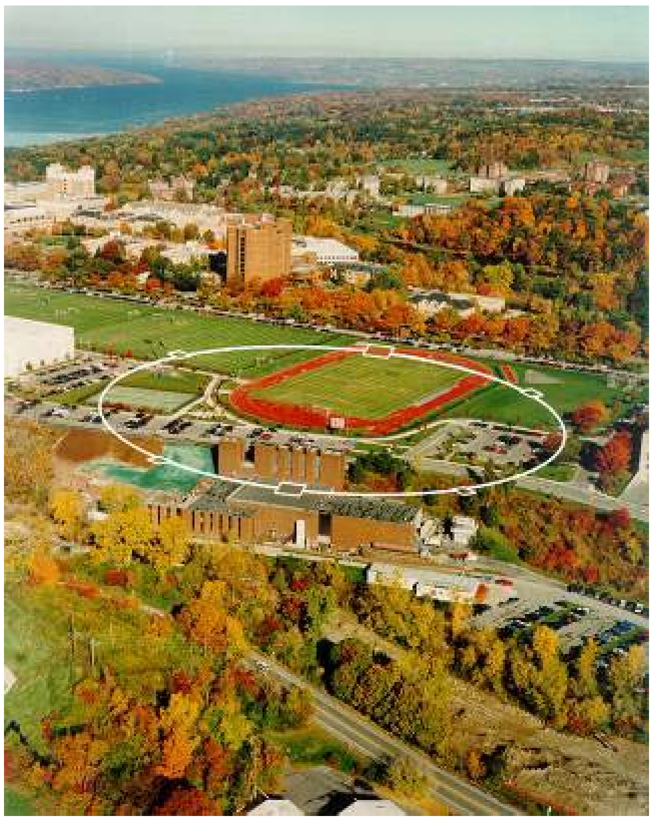
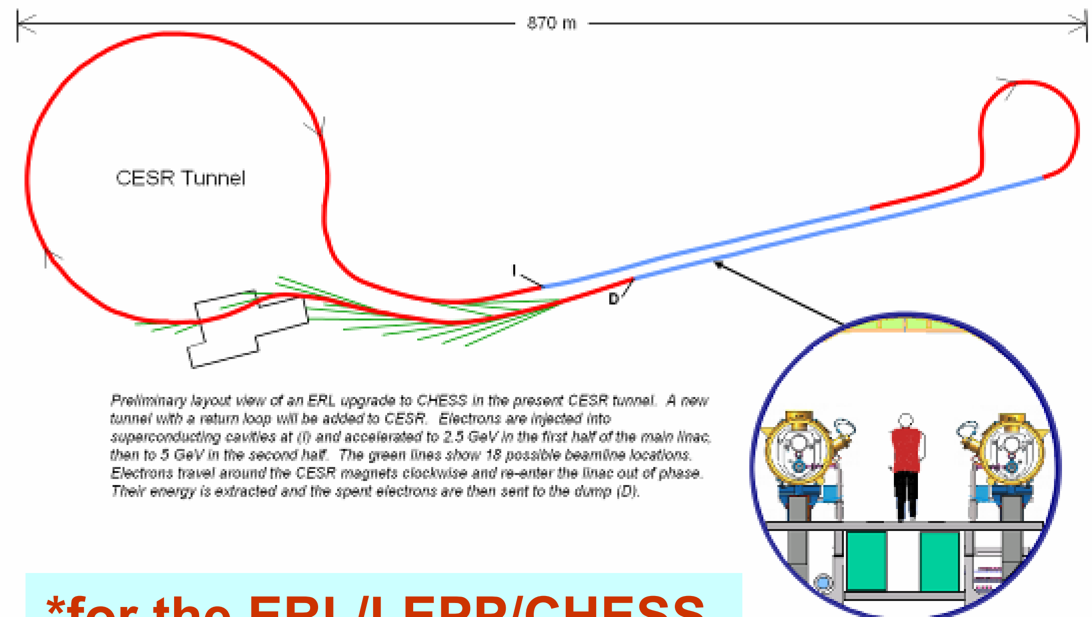
Energy Recovery Linacs (ERL)

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 ERL/LEPP/CHESS development team**

http://erl.chess.cornell.edu

Outline

- What is an ERL?
- What can it do?
- What is the present status?

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CHESS & LEPP

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What limits science at storage rings?

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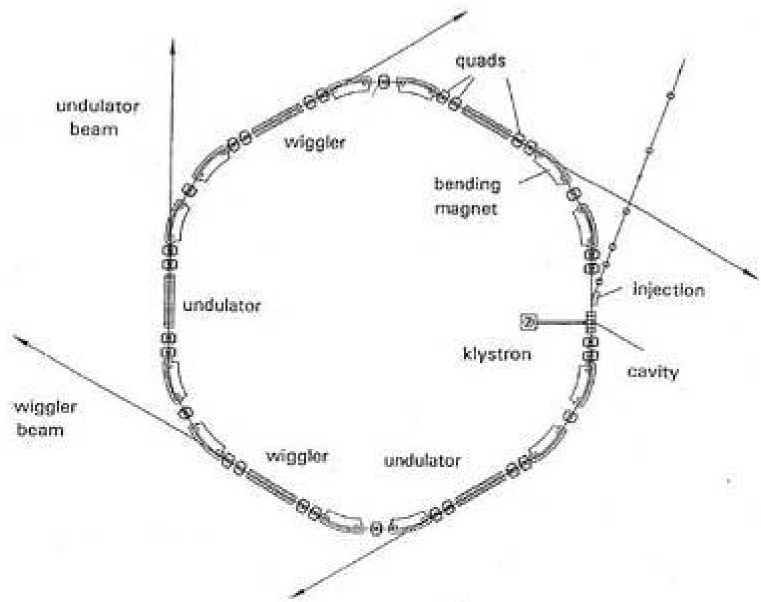
1. **Transversely coherent flux.**
2. **Time structure.**
3. **Source size to optimize nanobeams.**

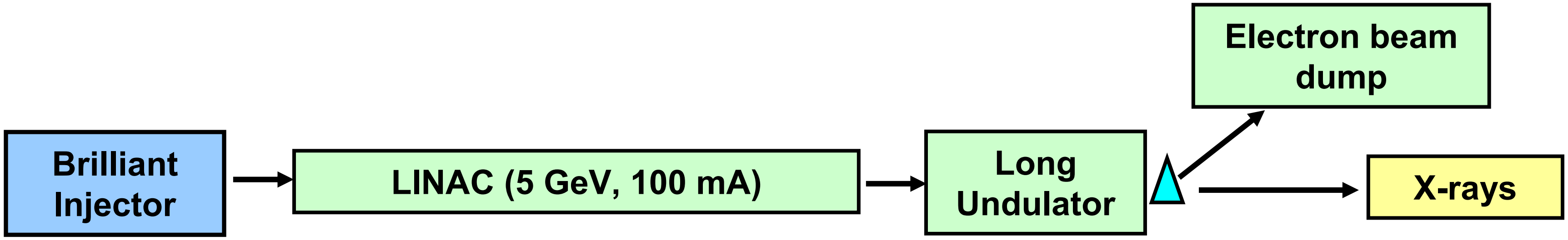
Sources that overcome these limitations will be truly transformative!

Coherent Flux ~ Current / ($Emitt_X$ x $Emitt_Y$)



Emittance dilution is a result of storage

LINACS present an alternative



Advantages:

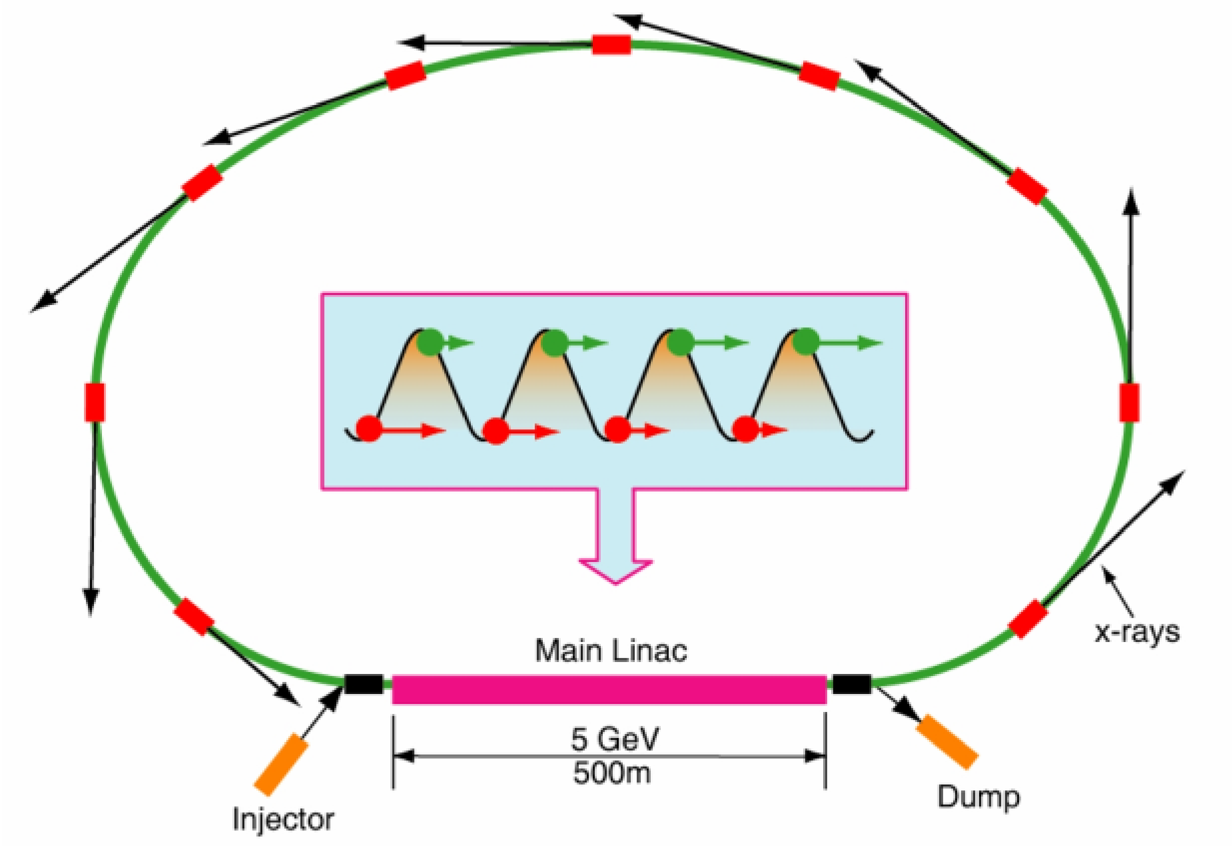
- Injector determines emittances, pulse length, current.
- Flexibility of pulse timing and pulse length.
- Small source size ideal for nanoprobes
- No fill decay.

Disadvantage: You'd go broke!!

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

Energy Recovery Linac
a radically new SR concept

CHESS & LEPP



- Accelerating bunch
- Returning bunch

A superconducting linac is required for high energy recovery efficiency

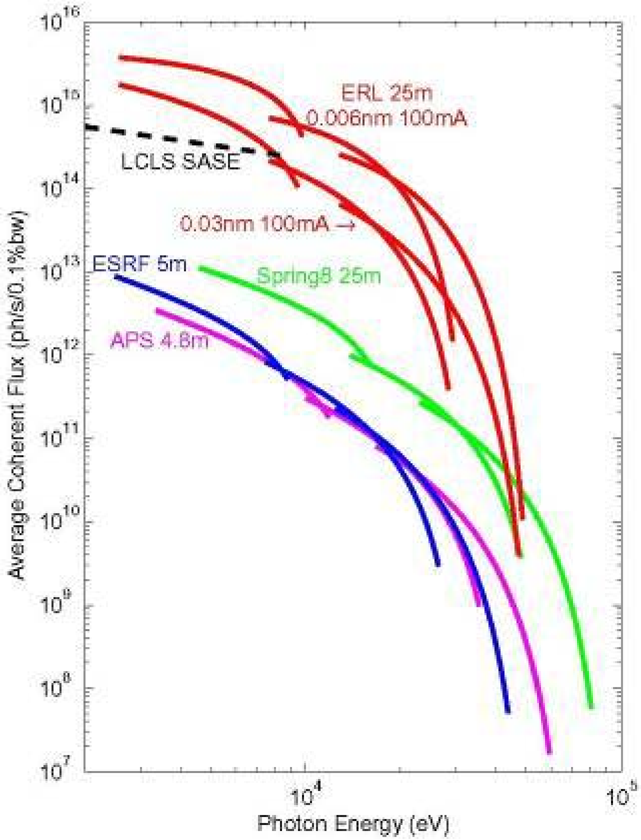
ERL will excel in Spectral Brightness, Source Size and Pulse Duration

CHESS & LEPP

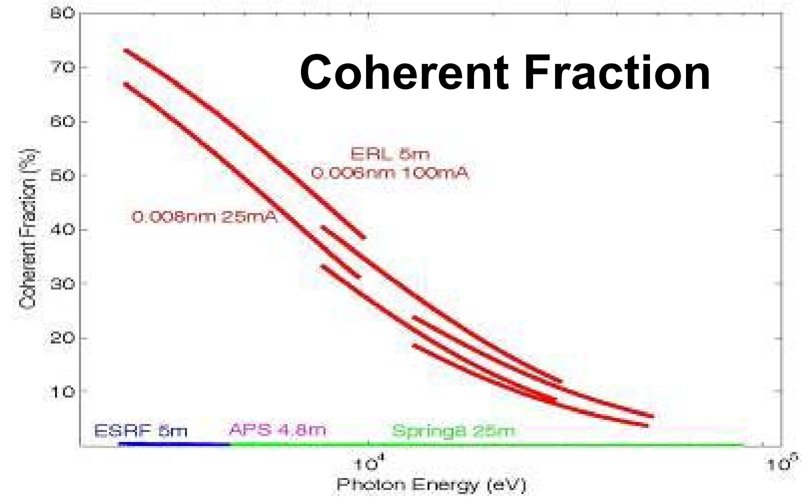
- ERL hi-brightness for coherence applications.
- Electron source size of a few microns– good for intense, nm diameter, hard x-ray beams.
- Bunch compression allows pulses < 100fs.
- Same beam characteristics in Hor. & Vert.
- Great flexibility in modes of operation.

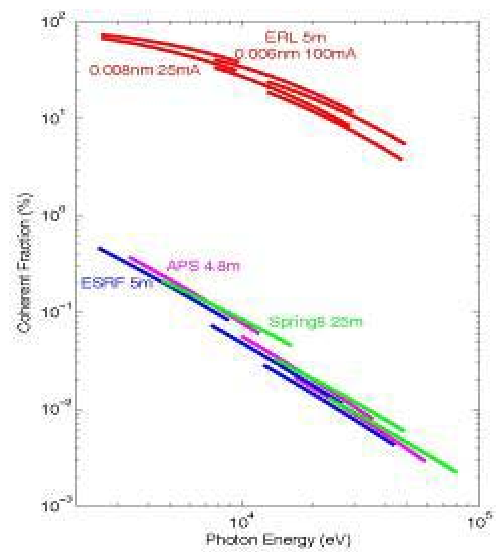
CHESS & LEPP

Transverse Coherence



Avg. Coherent Flux





ERL can produce very short bunches

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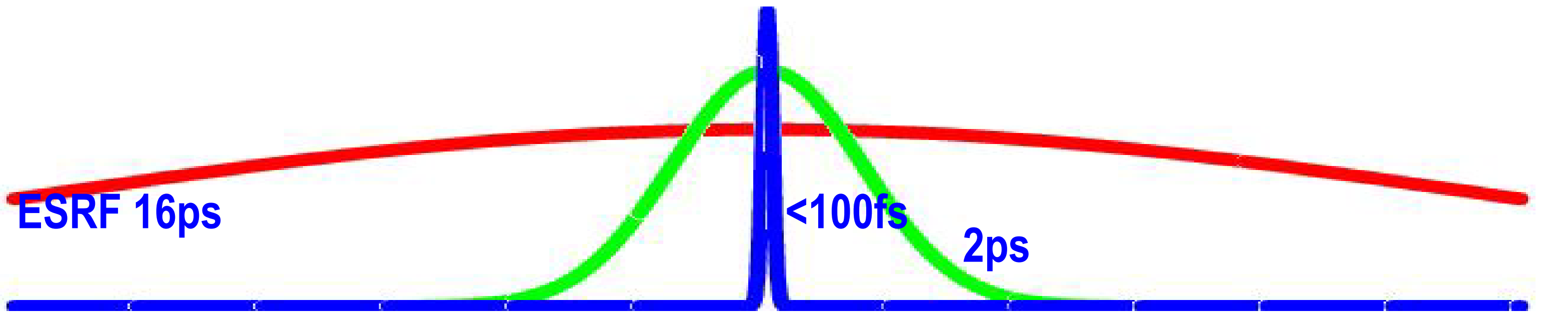
- The bunch length can be made much smaller than in a ring.
- Bunch charge (e.g., flux) can be traded against brightness.
- Rep rate is very flexible.



Outline

CHESS & LEPP

- What is an ERL?
- **What can it do?**
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ERL X-ray Science Workshops

ALL Workshops held:
2nd floor Robert Purcell Conference Center, Cornell University, Ithaca, NY 14853

Workshop 1 - June 5 & 6, 2006

"Future Frontiers in High-Pressure Science with ERL X-Ray Beams"

Organizers: Neil Ashcroft (Cornell University), Bill Bassett (Cornell University), Raymond Jeanloz (University of California at Berkeley), & Rus Hemley (Carnegie Institution)

Workshop 2 - June 14 & 15, 2006

"Scientific Potential of High Repetition-Rate, Ultra-short Pulse ERL X-Ray Source"

Organizers: Joel Brock (Cornell University), Alex Gaeta (Cornell University), & David Reis (University of Michigan)

Workshop 3 - June 16 & 17, 2006

"Almost Impossible Materials Science: Pushing the Frontier with ERL X-Ray Beams"

Organizers: Ernie Fontes (Cornell High Energy Synchrotron Source), Peter Abbamonte (University of Illinois at Urbana-Champaign), Darren Dale (Cornell High Energy Synchrotron Source), Qun Shen (Advanced Photon Source, Argonne National Laboratory), & P. James Viccaro (Advanced Photon Source, Argonne National Laboratory)

Workshop 4 - June 19 & 20, 2006

"Unique Opportunities in Soft Materials and Nanoscience with an ERL"

Organizers: Detlef Smilgies (Cornell University), & Ron Pindak (Brookhaven National Laboratory)

Workshop 5 - June 21 & 22, 2006

"Workshop on Frontier Applications of X-Ray Science in Biology with an ERL X-Ray Source"

Organizers: Richard Gillilan (Cornell University), Wah-Keat Lee (Advanced Photon Source, Argonne National Laboratory), & Lois Pollack (Cornell University)

Workshop 6 - June 23 & 24, 2006

"Workshop on New Science Opportunities with Nanometer-Sized ERL X-Ray Beams"

Organizers: Don Bilderback (Cornell University), Gene Ice (Oak Ridge National Laboratory), Kenneth Evans-Lutterodt (National Synchrotron Light Source, Brookhaven National Laboratory), Friso van der Veen (Swiss Light Source), & Wenbing Yun (Xradia)

- **SRI workshops**
- **APS workshops**
- **Coherence 2007**
- **Gordon Conference**
- **…**

What Goes on Deep in the Earth & Planets?

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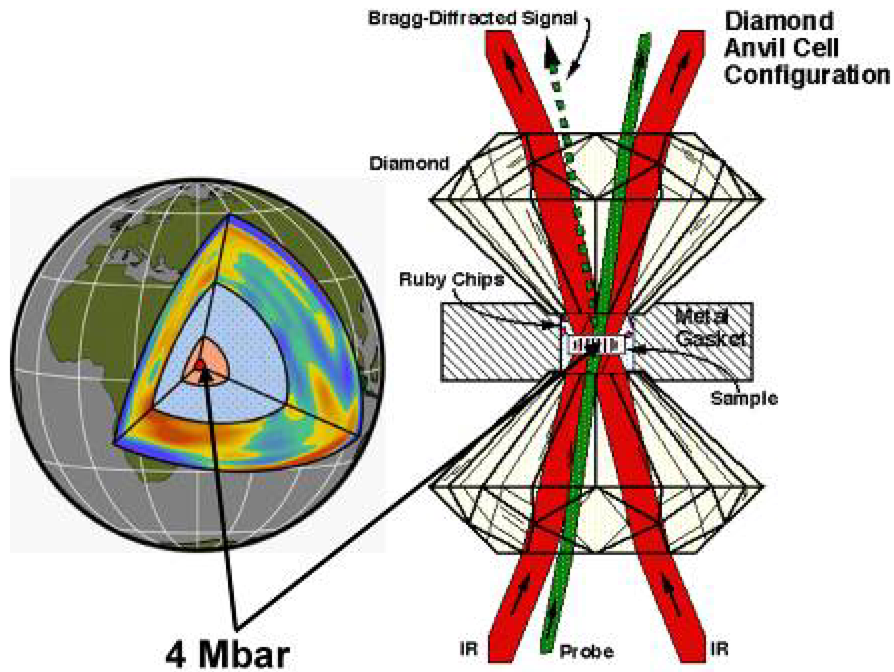
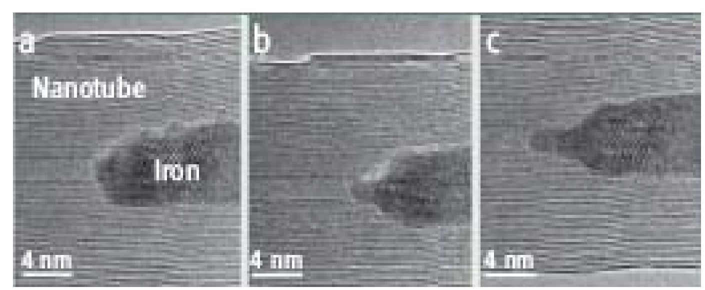
- Phys & Chem completely altered. $PV > R_H$
- Many superconductors
- Chemical dynamics drastically modified
- Impacts ore generation, earthquake dynamics, volcanism, weather



Why ERL?

- DAC expts photon starved at existing sources
- ERL nanobeams $10^3 – 10^5$ intensity
- Enables dynamical studies
- High average flux preserves DAC

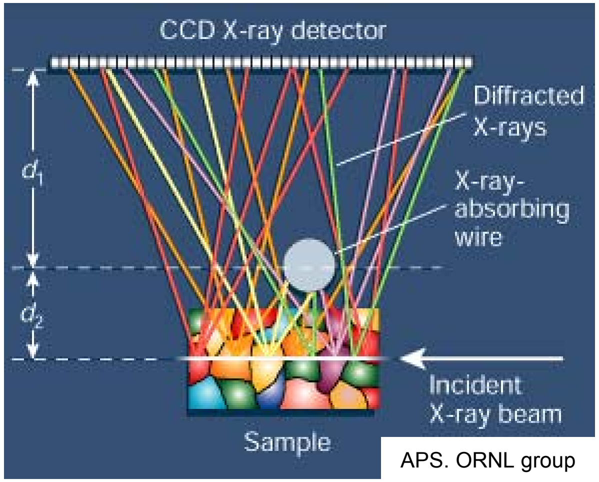


Sun et al., *Science*, 312 (2006) 1199

Can We Improve Polycrystalline Materials?

CHESS & LEPP

- **Most real materials polycrystalline**
- **Properties far from single crystal ideal**
- **Wish to probe matter on single grain length scales**
- **Nanocrystalline matter is new frontier. Revolution in lensless imaging. Requires coherence.**

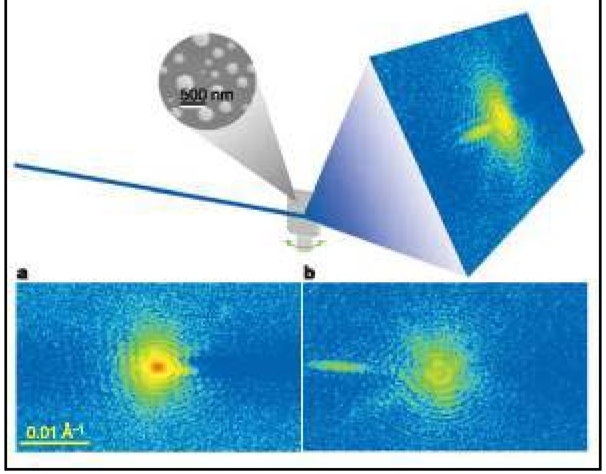


APS. ORNL group

Why ERL?

- **80x80x80 voxels takes 3 hr → few seconds**
- **150 s/frame x 50 frame ≈ 2 hr → few seconds**
- **Can study dynamics: annealing, strain, coarsening, etc.**

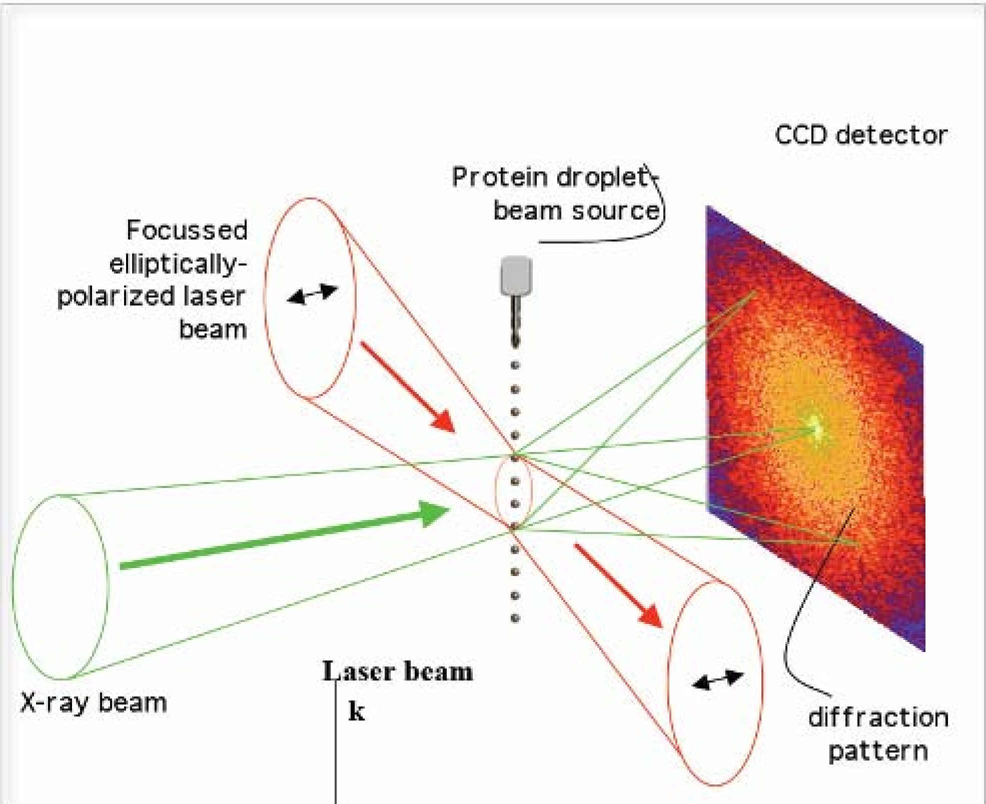
Pfeifer et al, Nature, 2006



Can We Determine Macromolecular Structure Without Crystals?

CHESS & LEPP

D. Starodub et al. (Spence U Ariz./ALS/LLNL)

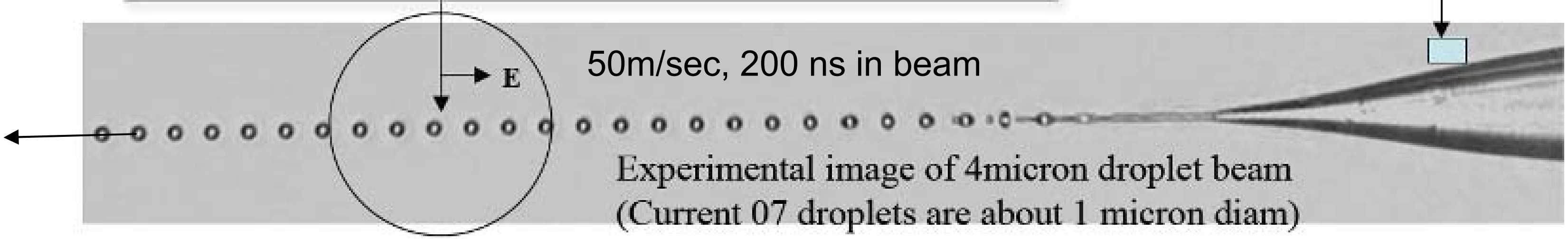


Why ERL?

GroEL–GroES protein complex,

	d= 0.7 nm	d= 1 nm
ALS	9.5×10^5 s	2.3×10^5s
APS	2.1×10^4 s	5.1×10^3 s
ERL	227 s	54 s

Calculated exposures (JSR, in print)

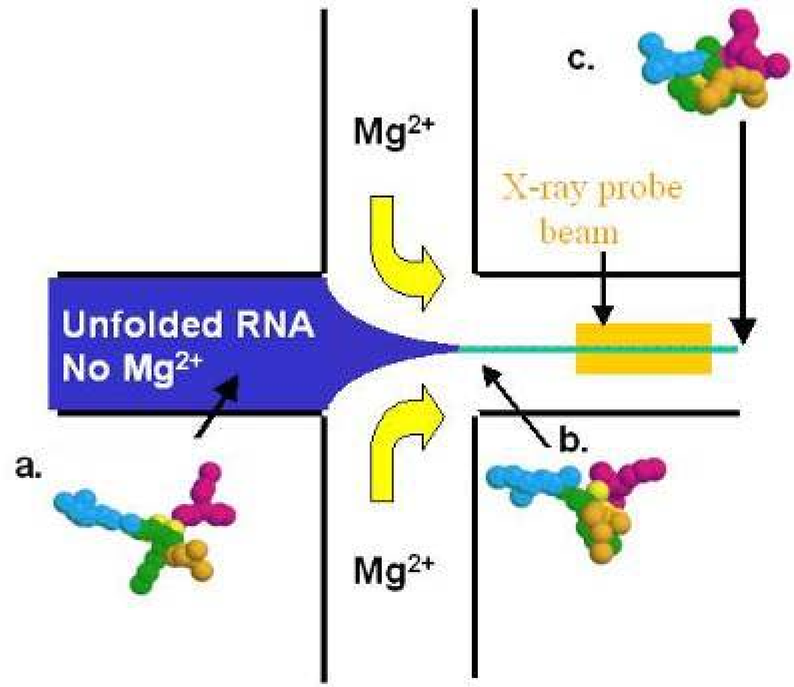


Experimental image of 4micron droplet beam
(Current 07 droplets are about 1 micron diam)

Can We Probe Dynamics of Macromolecules in Solution?

CHESS & LEPP

- Life, polymers, etc. all involve dissolved macromolecules.
- Proteins & RNA fold, multimers associate & disassociate, polymers collapse, etc.
- No good way exists to probe global structural dynamics of large molecules in solution.
- Laminar flow cells access microseconds



Why ERL?

- Existing sources limit expt to msec.
- ERL would reach to microseconds

What is the Nature of the Glass Transition?

- The glass transition is one of the most important outstanding questions in all of science (*Science* magazine, 125th anniv. Issue)
- "The deepest and most interesting unsolved problem in solid state theory is probably the nature of glass and the glass transition." Phil Anderson, *Science*, 1995.
- If we knew where every atom was in a nanoparticle of glass as it melted, we'd have an enormous handle on the glass transition. (Jim Sethna)

Why ERL?

- Lensless coherent imaging offers a way to <u>repetitively</u> determine atomic structure of aperiodic matter as it is warmed.

REASONS TO DEVELOP ERLs

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1. **A large user community already exists**. ERLs can do all experiments 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 coherence, short pulses and flexible bunch structure. Leads to transformative science.

3. **ERLs are a promising technology with limits yet to be determined.** ERL retrofits to storage rings and ERL XFELs are good possiblities.

Outline

CHESS & LEPP

- What is an ERL?
- What can it do?
- **What is the present status?**
    - ➢ **Where are we headed?**
    - ➢ Where are we now?

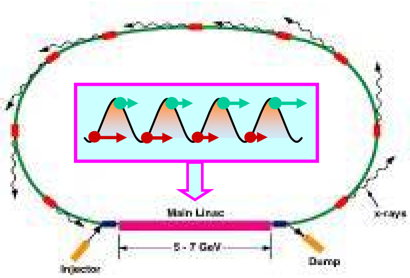
Next-Generation NSF Light Source Must Meet 3 Criteria:

1. It must be transformational.
2. It must complement DOE sources.
3. It must succeed.

Cornell's Impact on Synchrotron Science, most with NSF support

World's first SR beam line, 1952
Tomboulian & Hartman

CHESS today



ERL

1945	LNS (LEPP) started by Bethe returning from Los Alamos
1952	World's first SR beamline on 300 MeV synchrotron
1965	Tigner proposes ERL idea
1975	Cornell SC synchrotron tests
1979	Cornell Electron Storage ring (CESR) & CHESS start
1982	First storage ring SC tests
1982	Demonstration of curved crystal sagittal focusing
1984	CEBAF cavities developed & tested at CESR
1985	First mammalian virus structure
1985	Image plate developments
1986	Cryogenic monochromator crystal cooling
1987	First hard x-ray circular polarization phase plate
1988	Discovery of resonant x-ray magnetic scattering
1988	First dedicated HP Diamond Anvil Station
1988	Long-period standing waves demonstrated
1989	APS undulator A tested at CESR
1989	Development of cryoloop protein crystal freezing
1991	First CCD detectors for protein crystallography
1992	First Complete Stokes Polarimetry for X-rays
1993	First microsecond time resolved XAFS
1995	First TESLA cavity
1998	K^+ Channel structure
1999	First fully SC powered x-ray storage ring
2000	ERL study
2001	First microsecond x-ray Pixel Array Detectors
2001	Envelope phasing of macromolecules
2003	Microfabricated crystal cryomounts
2004	41 attosecond imaging of disturbances in water
2004	Pulsed laser deposition system & layer-by-layer growth studies
2004	Confocal microscope developed and applied to art works
2005	Narrow bandwidth artificial multilayers
2005	High pressure protein crystal cryocooling
2007	ERL injector development

Cornell ERL Project

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- ERL Study (w/ Jlab) (Completed in 2001)
- Phase I: R&D on injector, linac modules, machine issues. Engineering studies for Phase II (in process: $30M NSF & NY State in 2005/2006; continued R&D proposed).
- Phase II proposal in 2008.
- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. (~5 year construction)

Operate ERL as University-based NSF user facility.

Mission 1: High Research Impact & Productivity

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Some CHESS Macromolecular Covers

Mission 2: Train scientists who populate other labs

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People are our most important “product”

Schematic ERL Layout View

5 GeV

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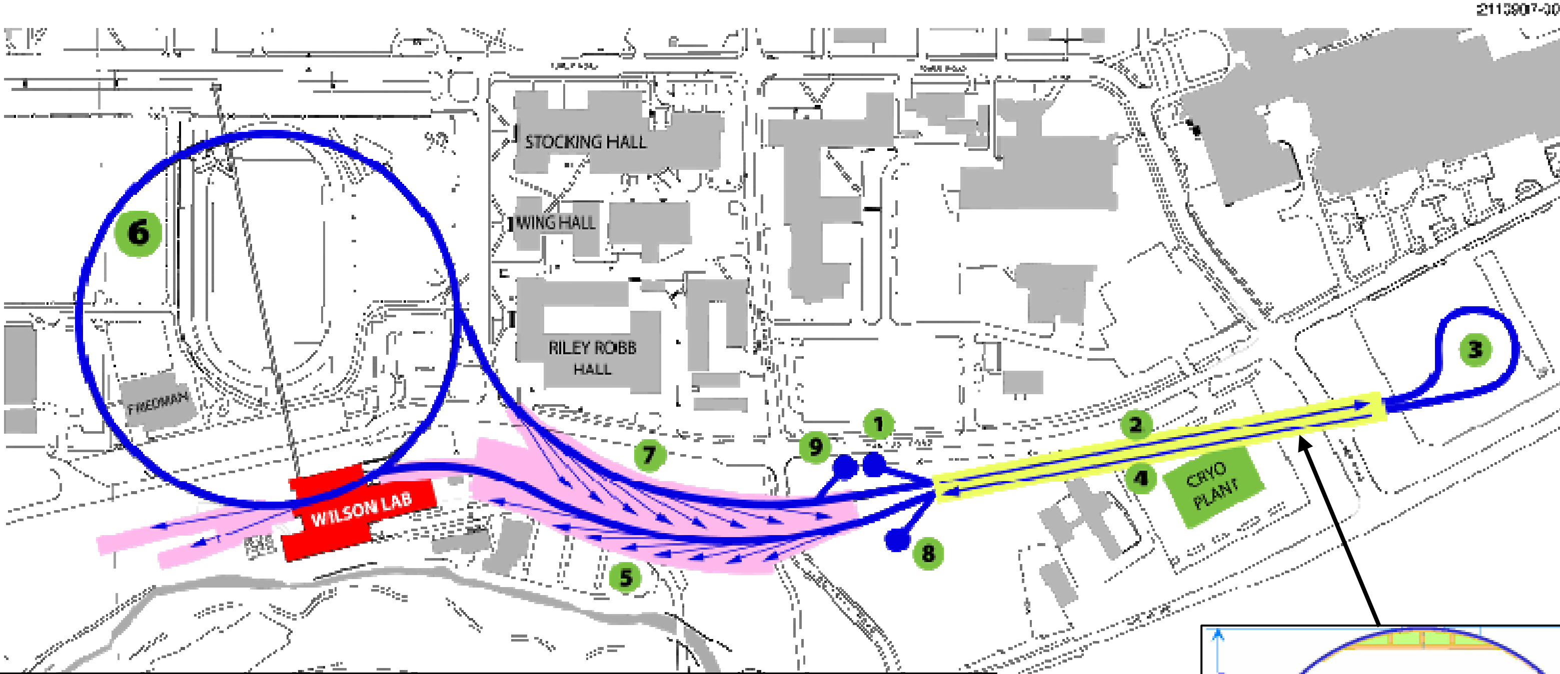
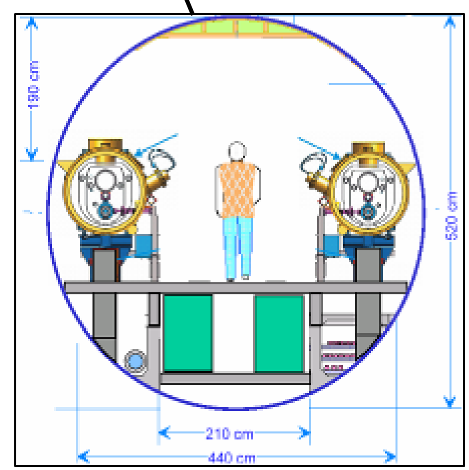




Key: 1=Main injector; 2=first 2.5 GeV linac; 3=East return loop;
4=second 2.5 GeV linac + cryoplant; 5=South undulator beamlines
6=West return loop (CESR); 7=North undulator beamlines;
8=Beam dump; 9=dump for non-energy recovered fast-pulse undulator beam line.

ERL Parameters

CHESS & LEPP

Modes	Hi-Flux	Hi-Coherence	Fast, Hi-Rep Rate	Fast, Lo-Rep Rate
Energy (GeV)	5	5	5	5
Current (mA)	100	25	TBD	0.1
Bunch charge (pC)	77	19	TBD	1000
Repetition rate (MHz)	1300	1300	1300	0.1
Geom. emittance (pm)	30	8	TBD	5000
RMS bunch length (fs)	2000	2000	<100	<100
Relative energy spread ($x10^{-3}$)	0.2	0.2	1	1
Energy recovered?	Yes	Yes	Yes	No

Beamlines will NOT look like typical 3rd generation beamlines. Optimize for experiments that take advantage of unique ERL properties. Emphasis on helical undulators, windowless beamlines with minimal or no optics, multilayers, specimen chambers with multiple simultaneous probes (e.g., EM, optical, magnetic), tailored detectors.

ERLs have many 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 diagnostic for small emittance, short bunch beams
- Control of beam loss
- High gradient, high Q cavity operation with excellent field stability, HOM loads
- Short period, short gap, but long undulators with phased segments
- X-ray windows that preserve coherence
- X-ray BPMs that work on a submicron scale
- X-ray monochromators that don't distort under a high-heat load
- X-ray optics to make a nm diameter hard x-ray beams
- X-ray mirrors with extraordinarily small slope error & roughness
- Specialized x-ray detectors optimized for most challenging applications.
- Etc.

The nature of these challenges range from basic science to engineering. Based on R&D to date, there are excellent prospects for success.

But a lot of work needs to be done!

***XFELs have a comparable list**

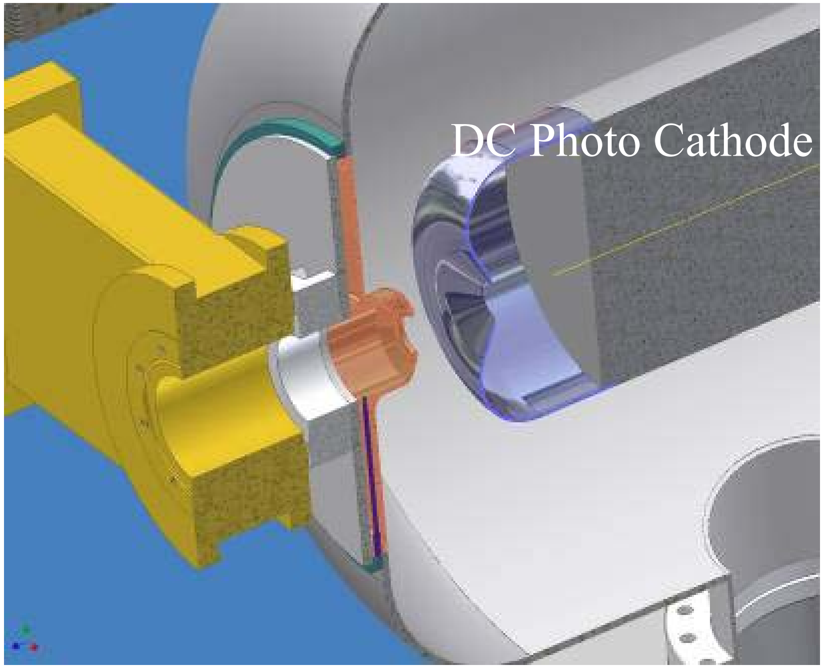
Outline

- What is an ERL?
- What can it do?
- What is the present status?
  - Where are we headed?
  - Where are we now?

Ongoing Cornell R&D Activities

CHESS & LEPP

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

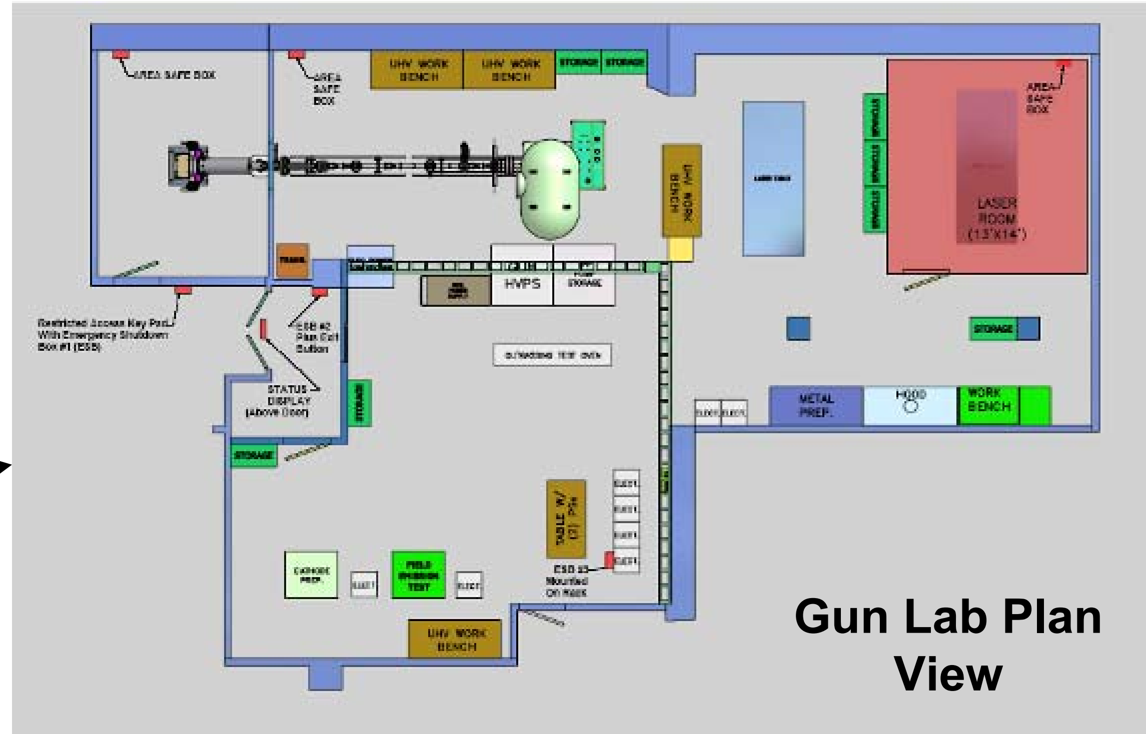
3) Beam dynamics
- Injector optimization with space charge
- Beam break up instability (BBU)
- Optics design

4) Accelerator design
- Optics
- Beam dynamics
- Beam stability

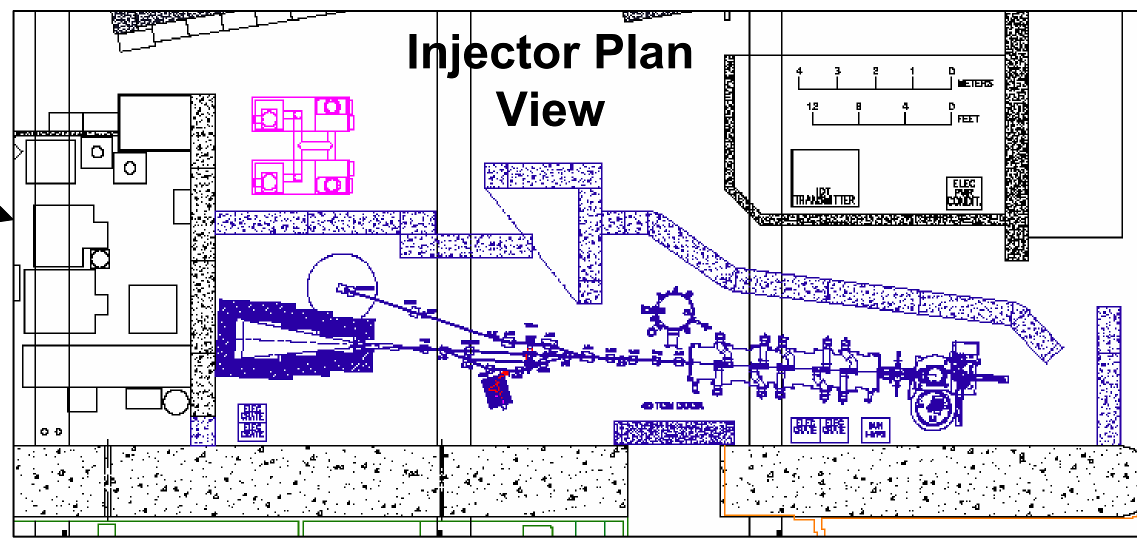
5) X-ray beamline design
- X-ray optics
- Undulator design

Injector Development: Two stages

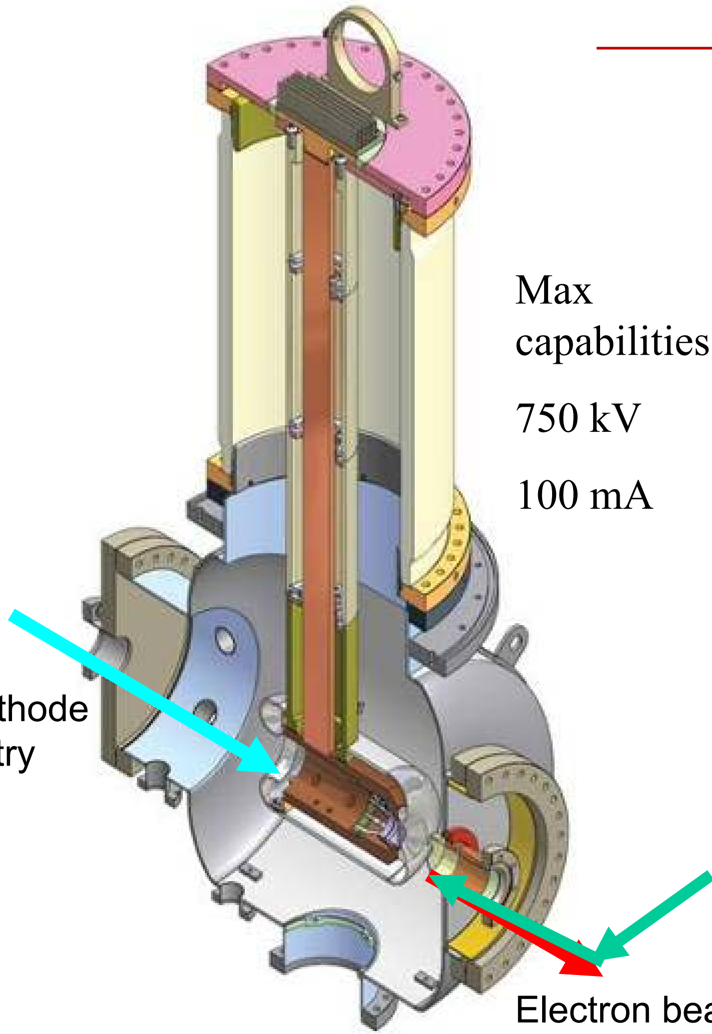
- **Now:** Operate gun and diagnostics in gun lab.



- **1st Quarter '08:** Operate full injector assembly, the heart of the ERL.



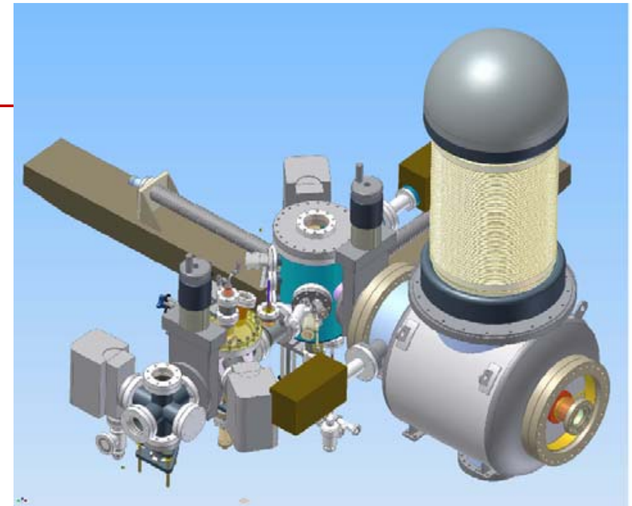
Photoemission Gun



Max capabilities:

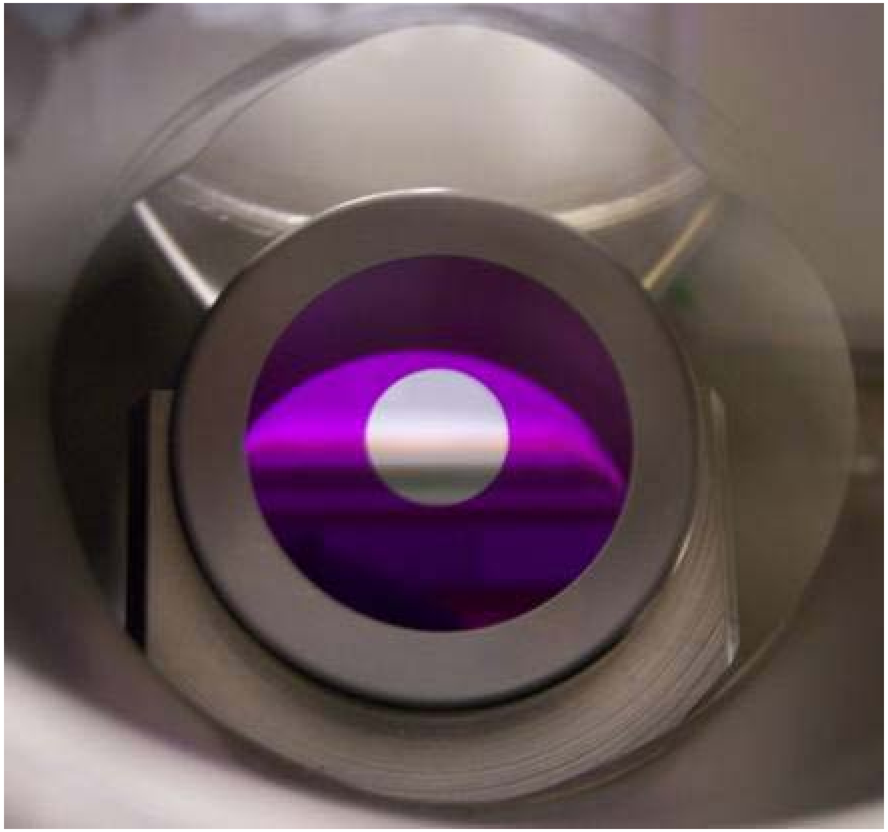
750 kV

100 mA



GaAs Photocathode

CHESS & LEPP

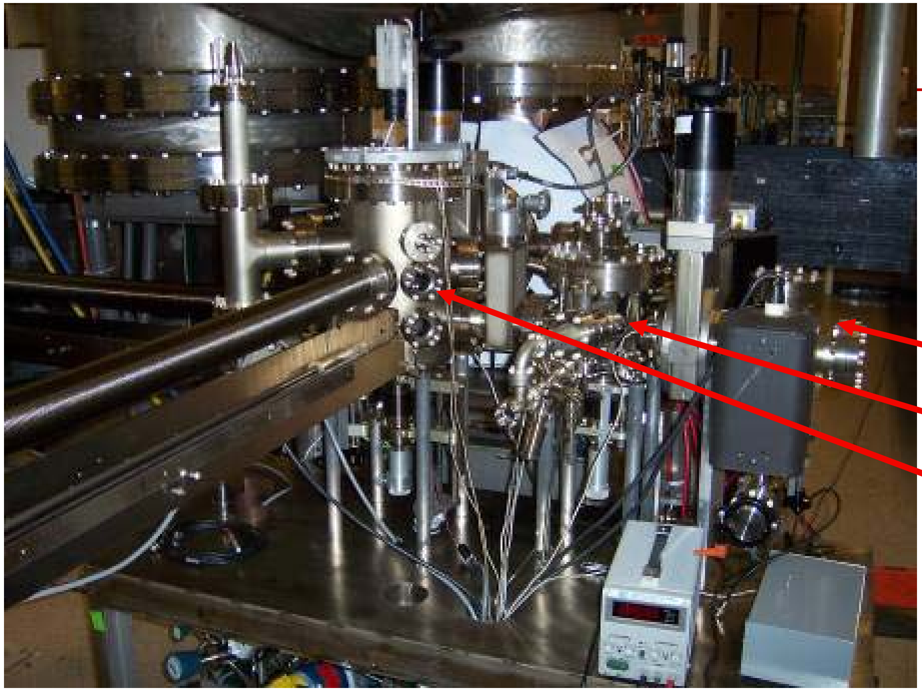


GaAs:Cs is cathode of choice

- good quantum efficiency
- low thermal emittance
- fast time response (@520 nm)
- need extreme UHV for lifetime
- minimum thermal emittance near bandgap (lower QE)
- R&D on other cathodes

Load Lock System

CHESS & LEPP



•Load lock chamber w/quick bakeout capability

•Heater chamber

•Cathode preparation and transfer chamber

Can swap a fresh cathode
into the gun in ~30 minutes

Beam Line looking toward Gun

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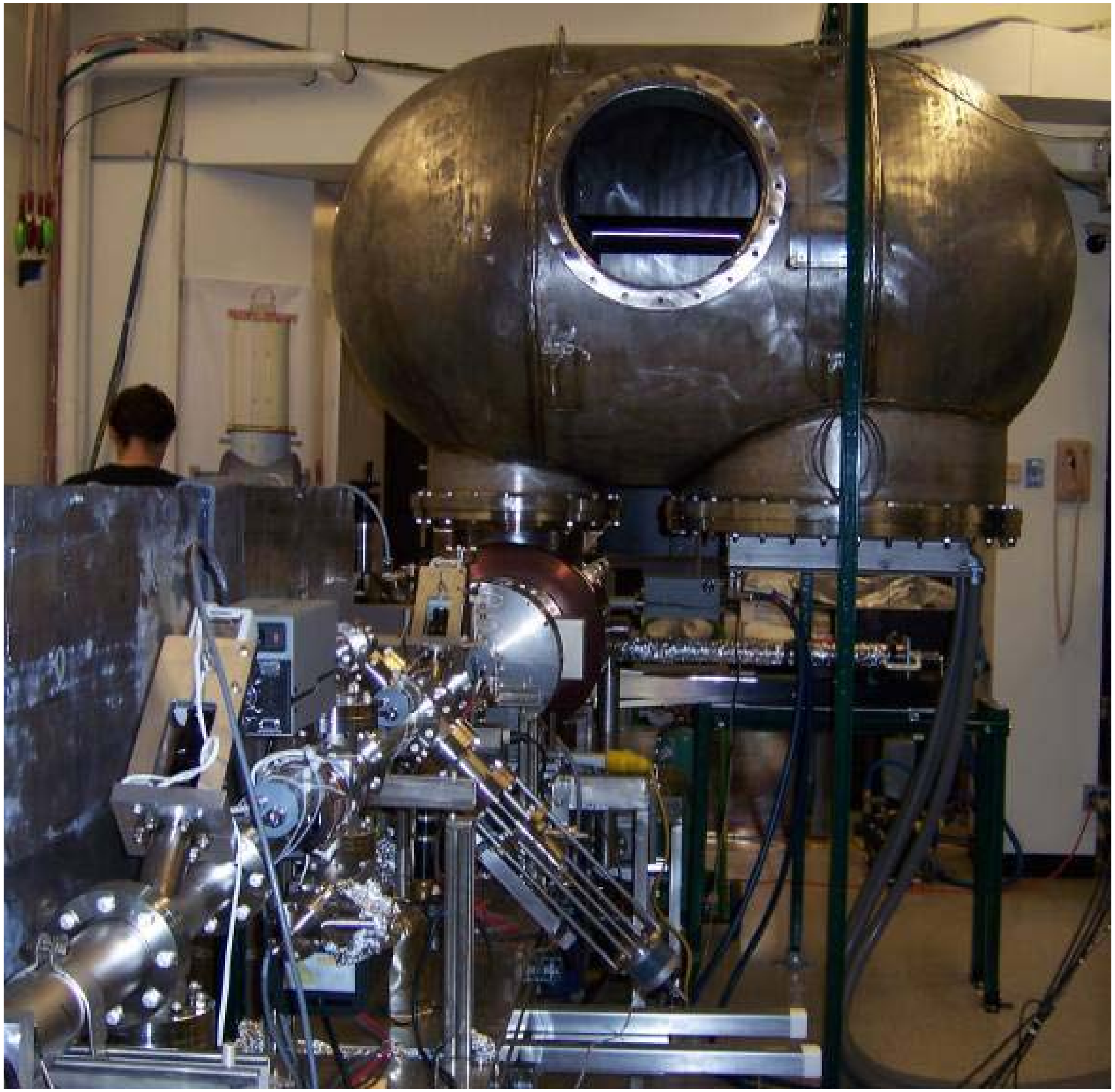

Cornell University
Cornell High Energy Synchrotron Source

Gun and Power Supply in Tank

CHESS & LEPP

750 kV, 100 mA Power Supply

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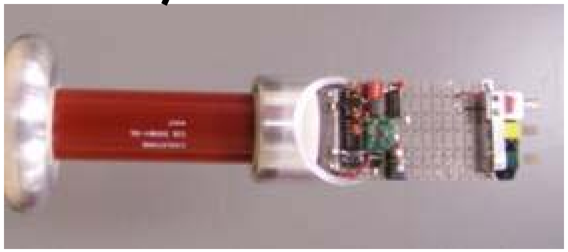
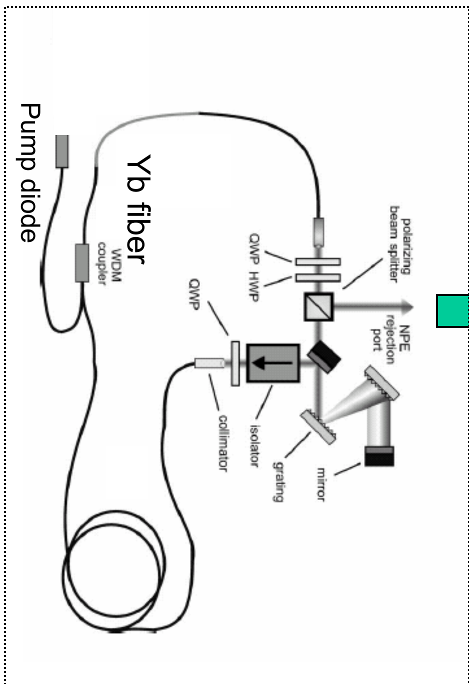


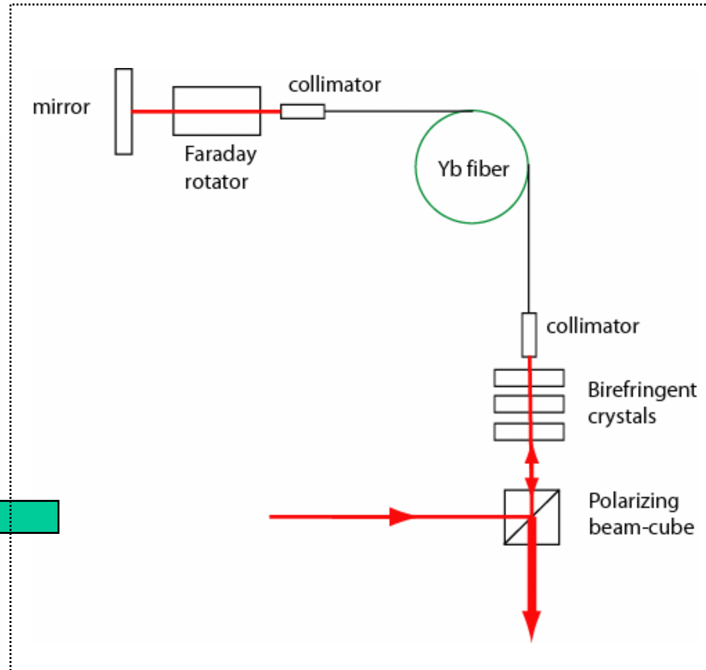
Fiber Laser Description

Oscillator



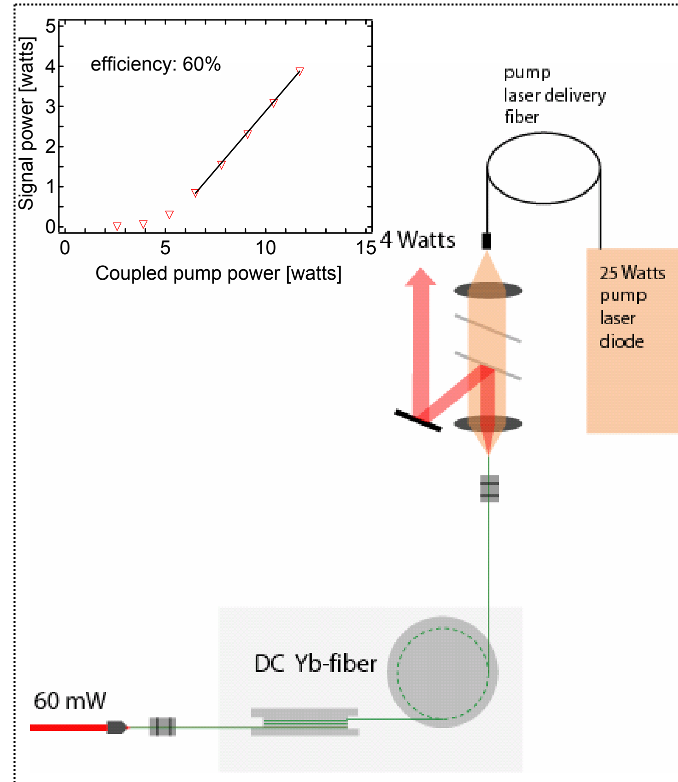
15 mW
300 pJ

Pre-Amplifier



60 mW
1.2 nJ

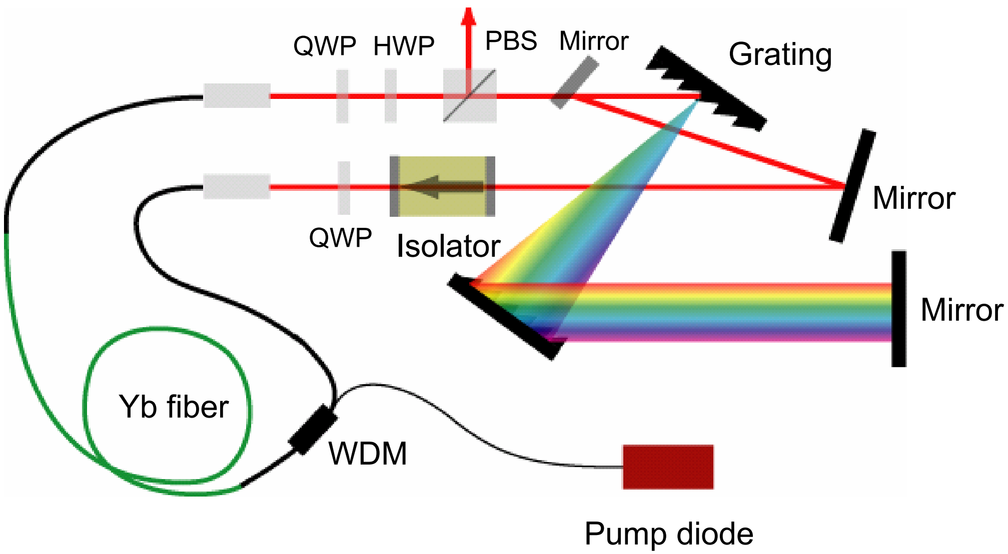
Amplifier



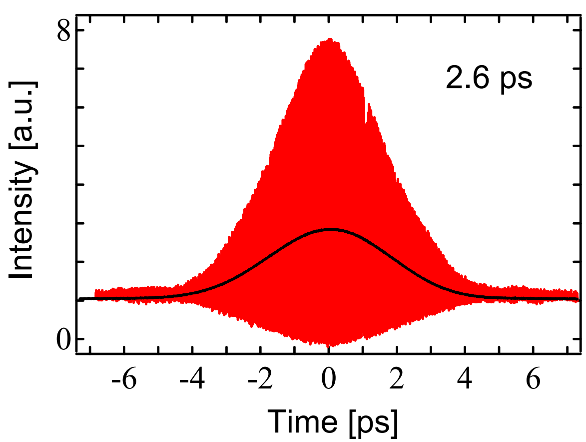
4 W
80 nJ

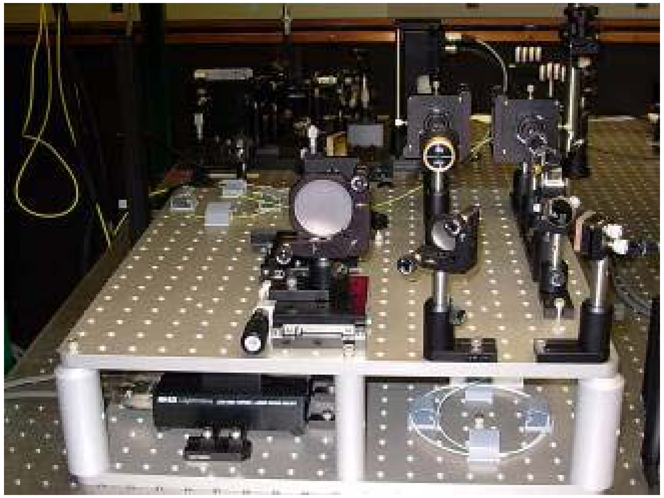
Laser Oscillator

CHESS & LEPP



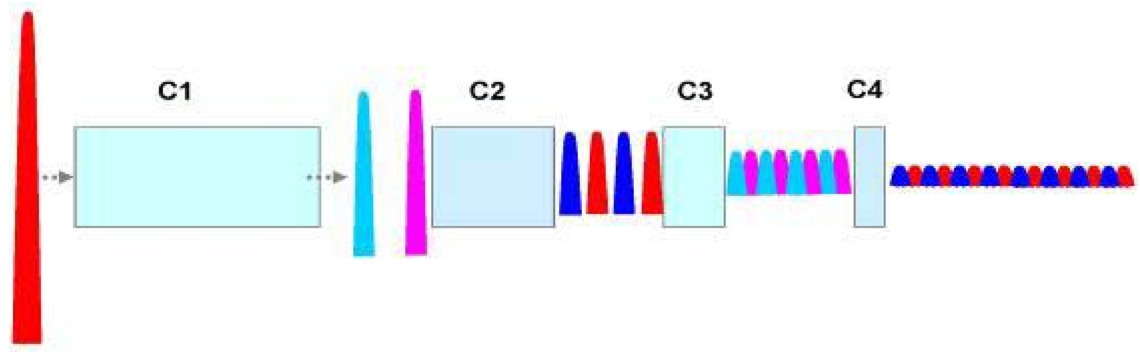
λ = 1040 nm
pulse duration ~ 2.5 ps
power ~ 15 mW





Laser Shaping

CHESS & LEPP



Use 'optical pulse-stretcher' to get 20-40 ps flat-top pulses from 2 ps laser (DPA – divided pulse amplifier)

Gauss to flat top using commercial aspheric lens

Initial Beam Tests

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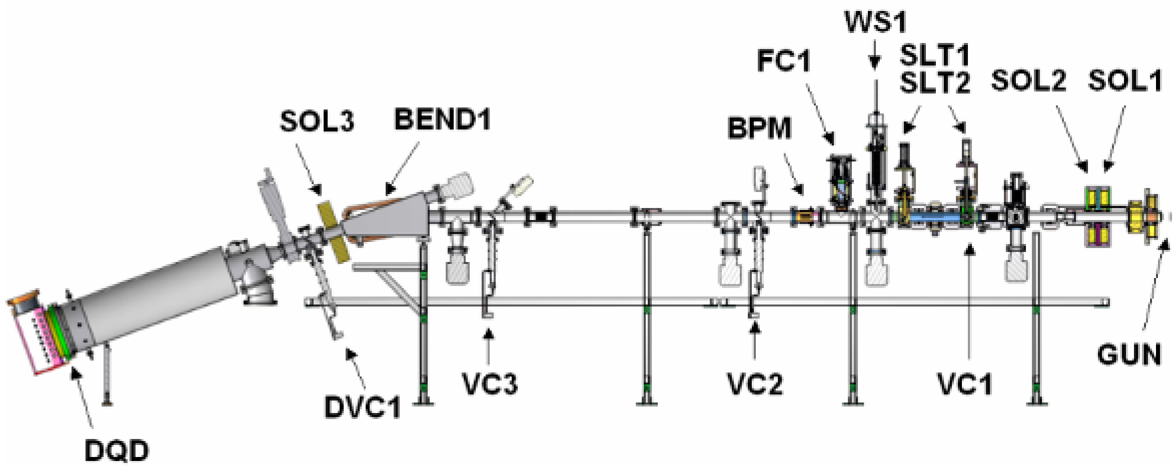
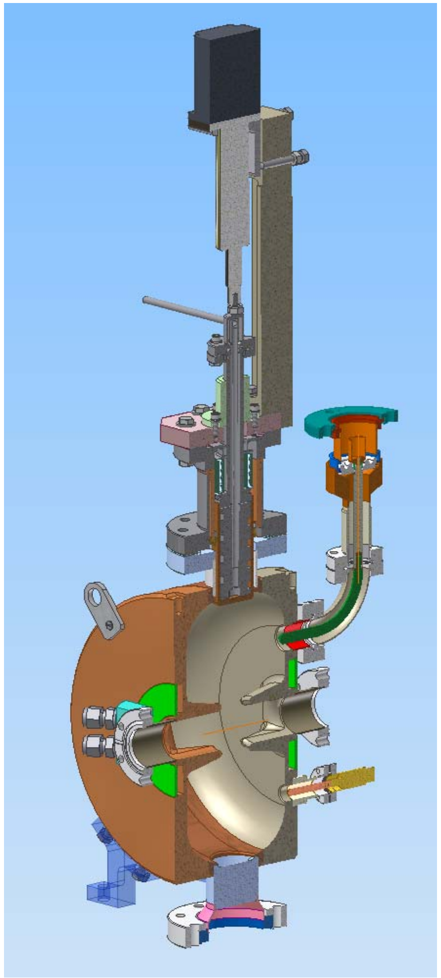
- Goal: full understanding of gun beam phase space
- Build gun & diagnostics line
- Full phase space characterization capability after the gun
- Temporal measurements with the deflecting cavity
- Lifetime studies



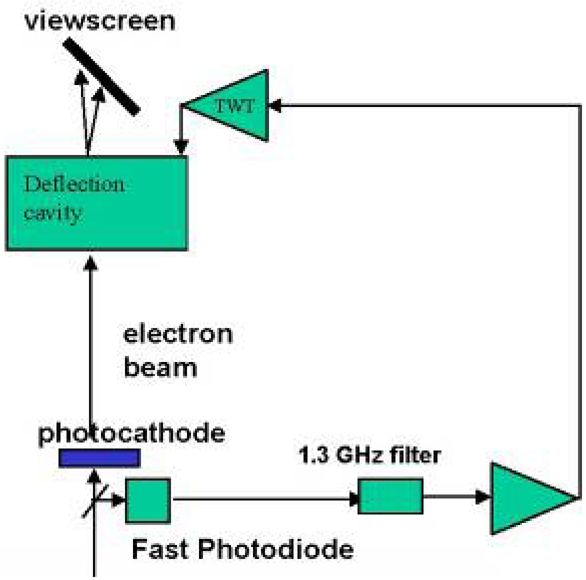
Cathode Response Time

CHESS & LEPP



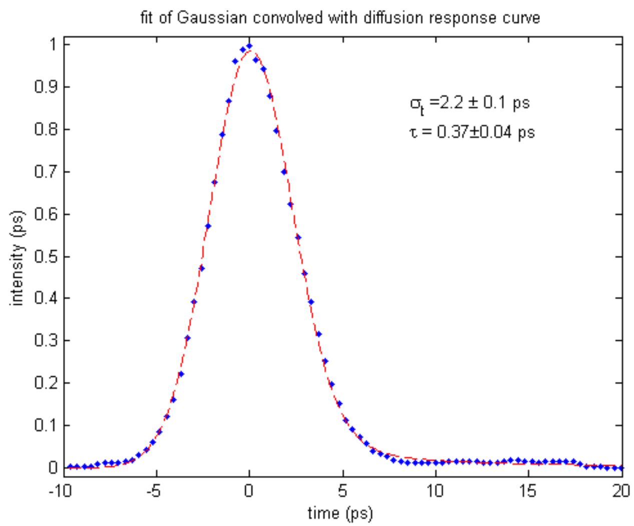
Deflecting cavity transforms bunch length into transverse spot on view screen.

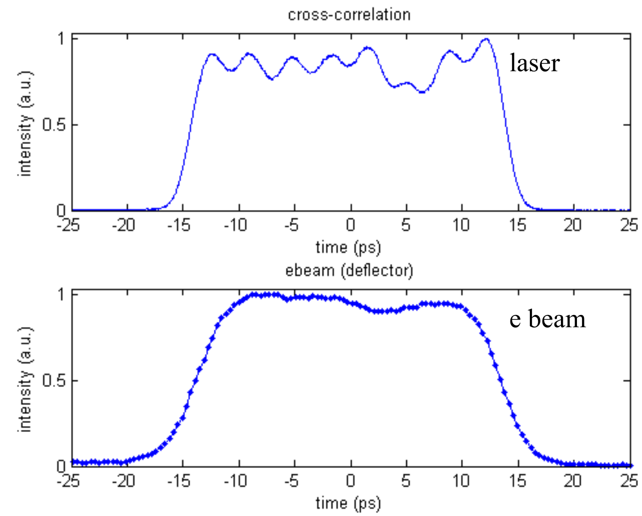
Gives direct of bunch length measurement



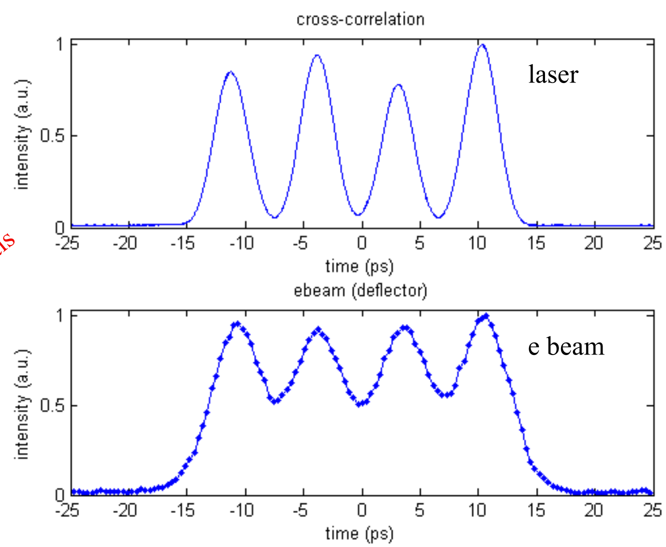
Cathode Response Data

CHESS & LEPP



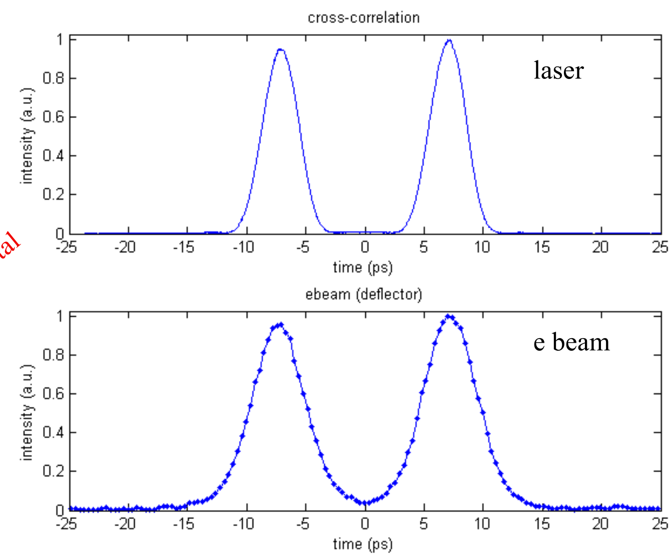


3 crystals



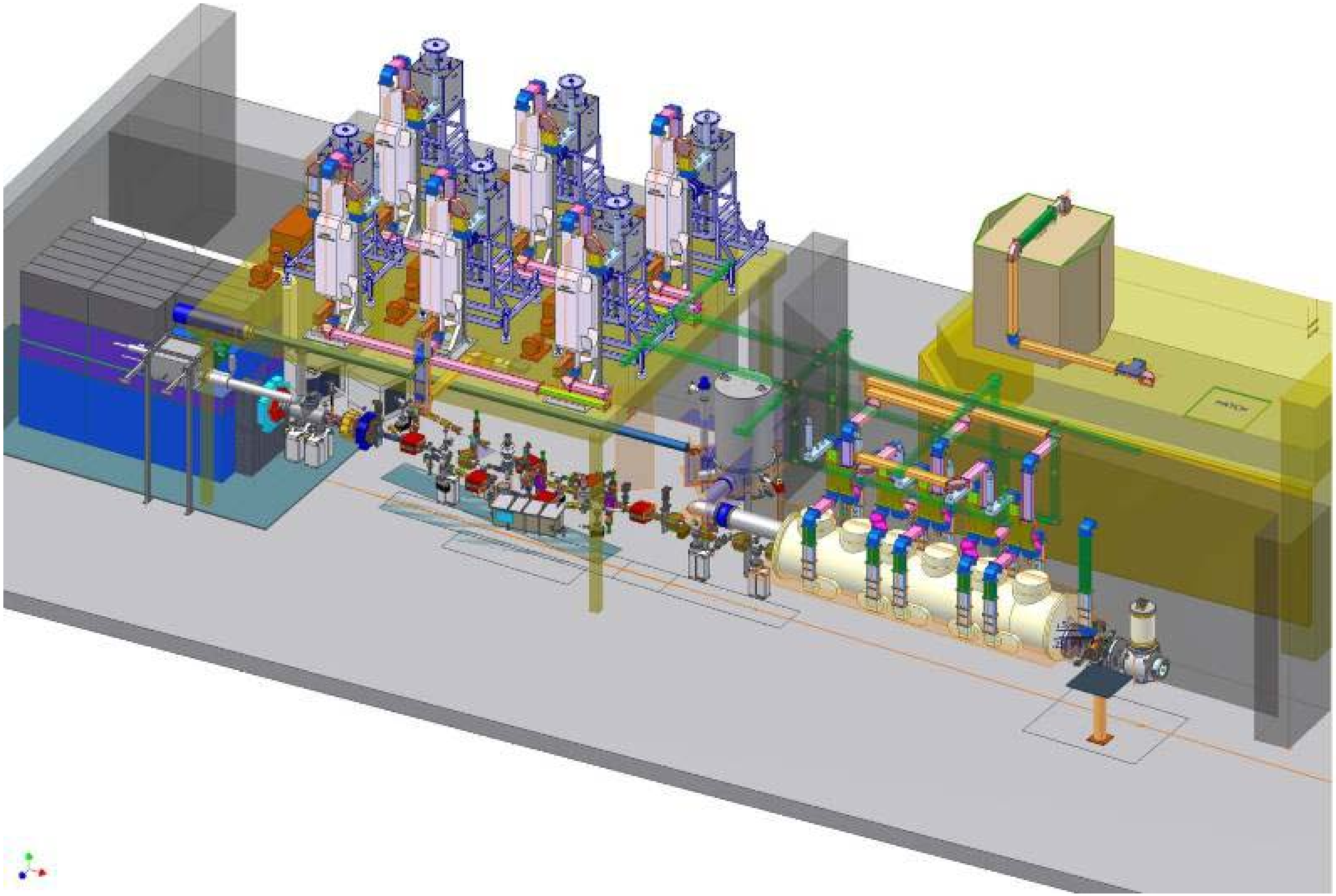
2 crystals

1 crystal



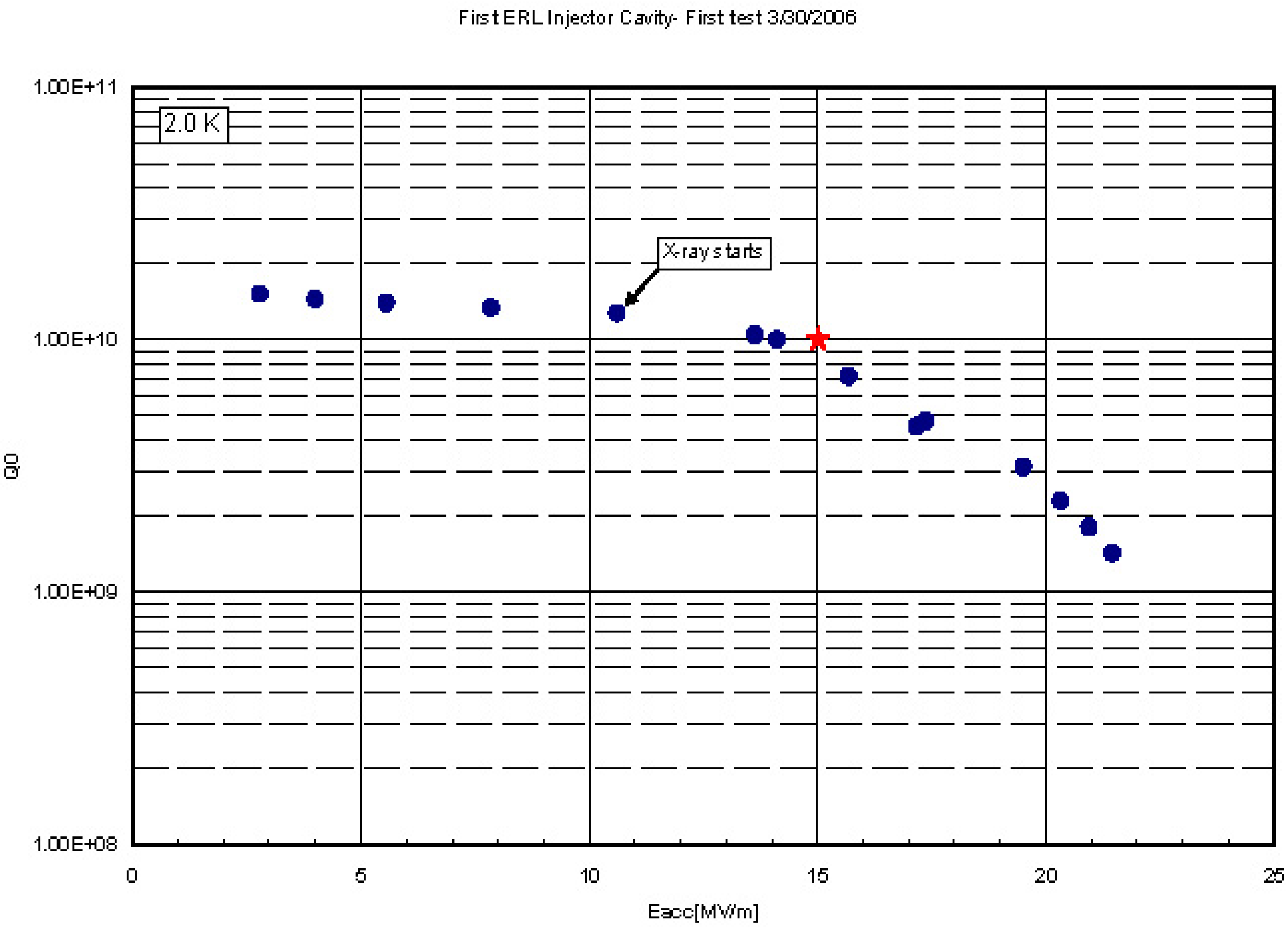
Full Injector Prototype Progress

CHESS & LEPP



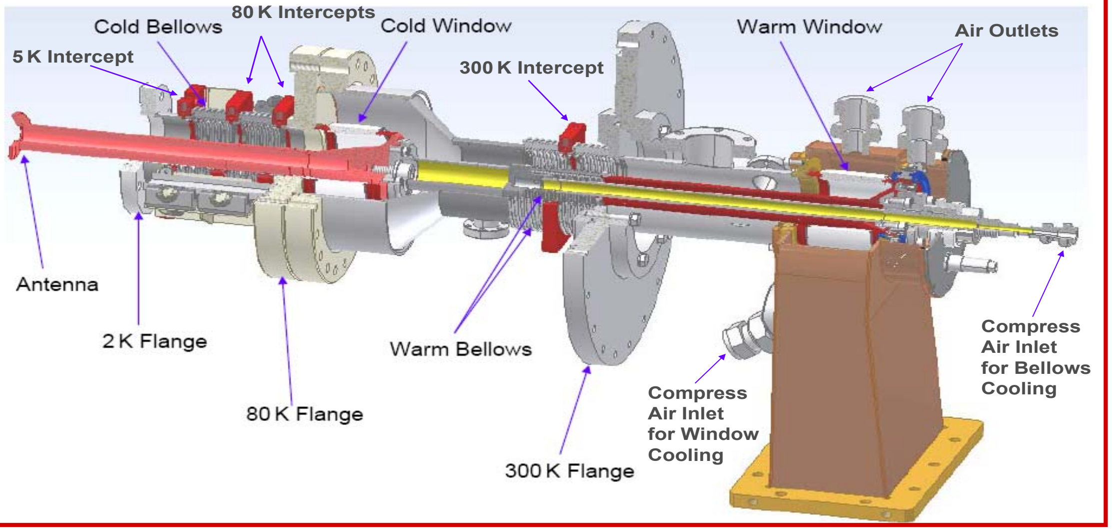
Two-cell niobium cavity for ERL injector

Vertical Cold Test

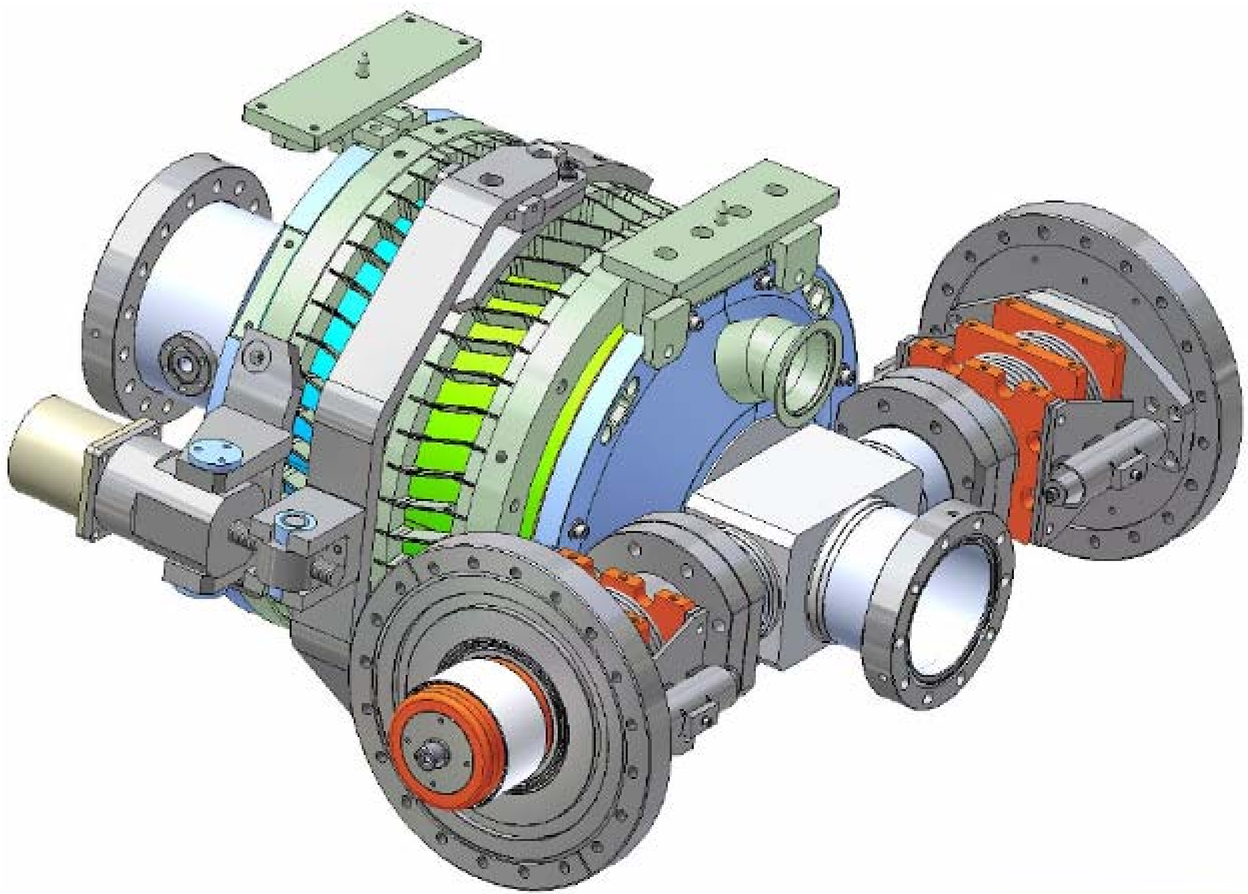


RF Input Coupler

CHESS & LEPP

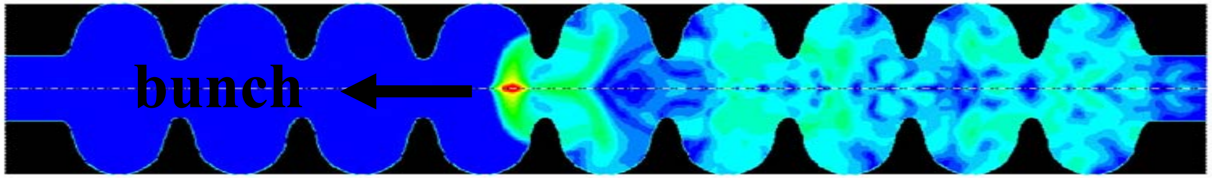


2-cell injector cavity with tuners and power couplers attached

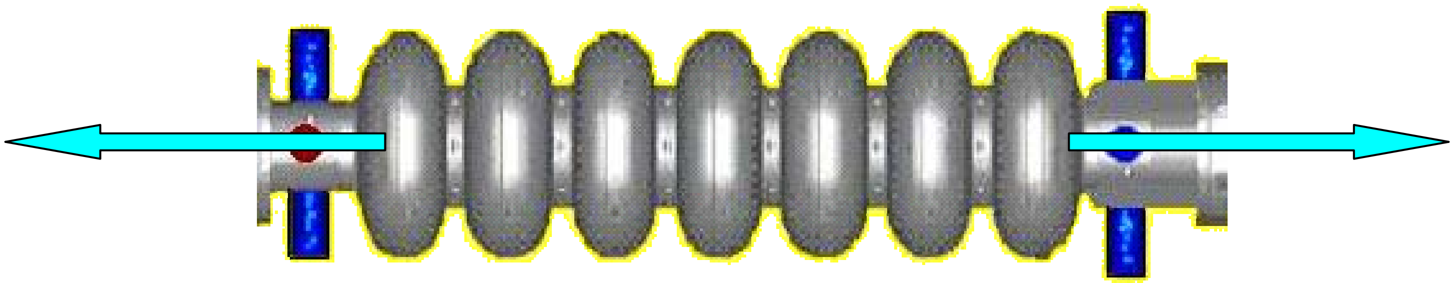


Higher-Order Mode Power

CHESS & LEPP



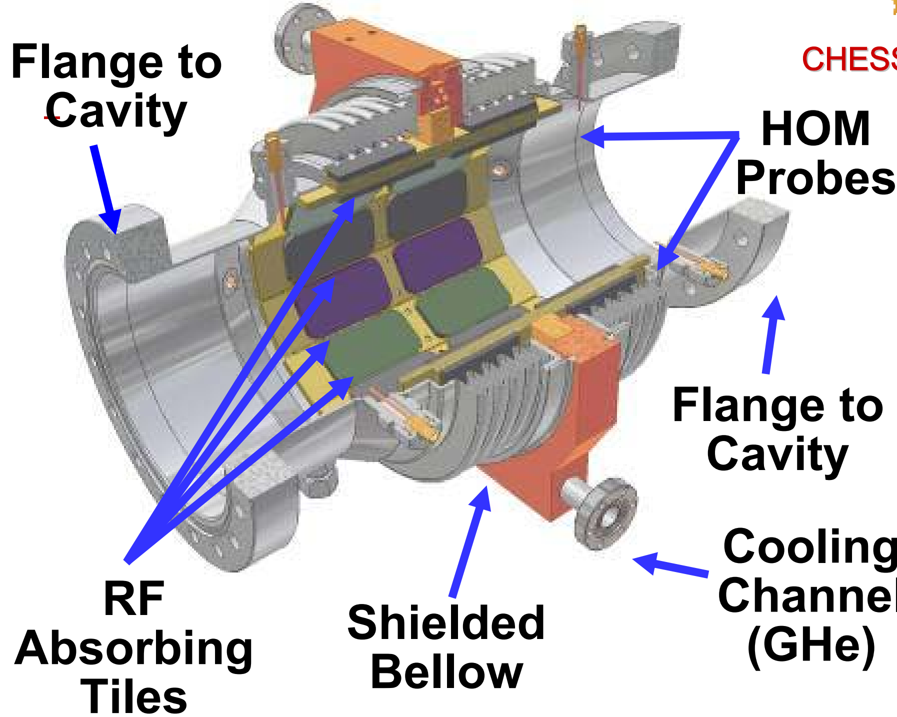
Bunch excites EM cavity eigenmodes (Higher-Order Modes)



140 W HOM power,
f = 1.4 to > 100 GHz
(7-cell main LINAC cavity shown)

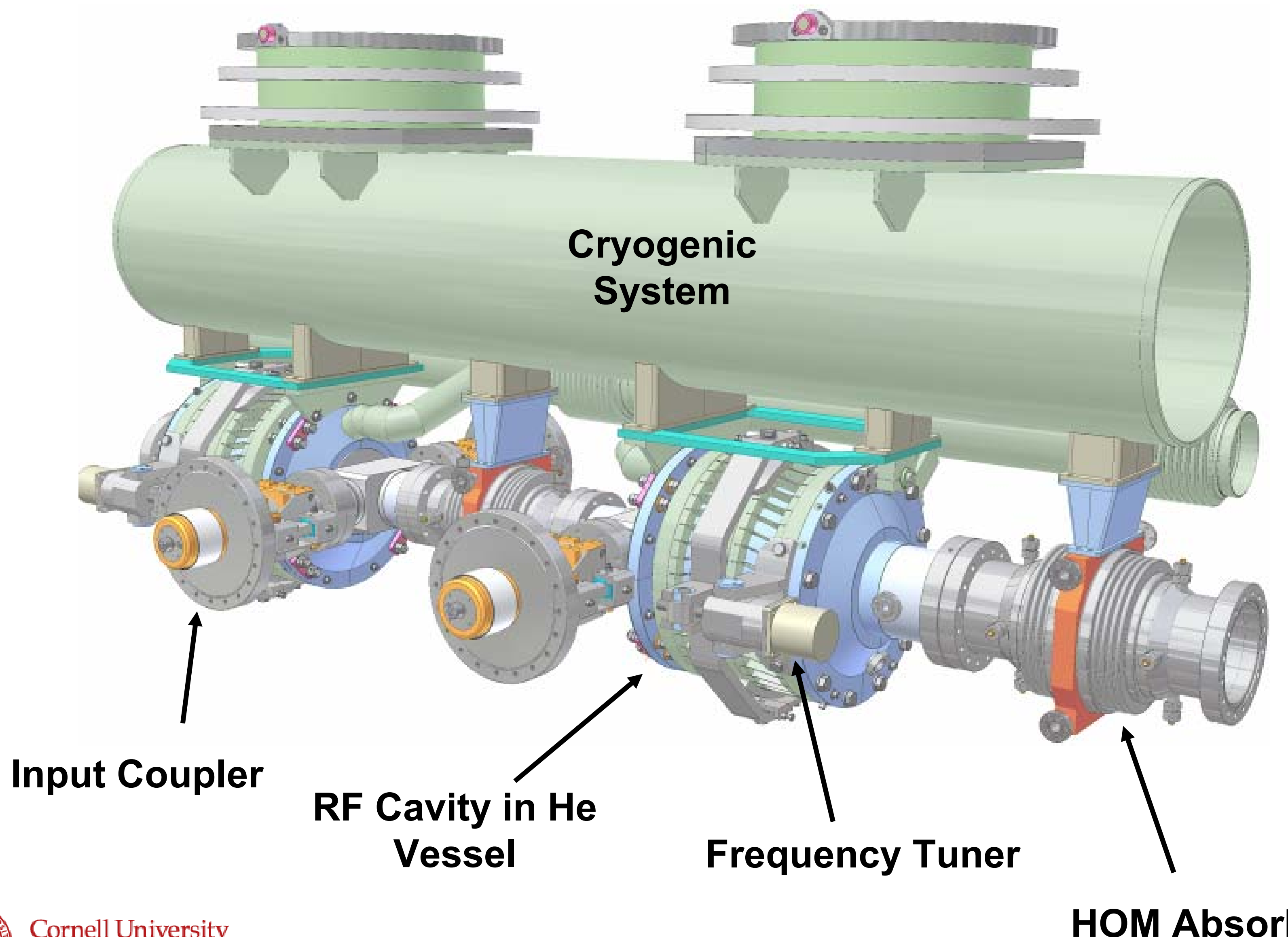
Cornell ERL HOM Absorber

- Extensive research program to find absorber materials which
  - are effective at 80 K
  - And absorb over required 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.



Cryomodule design

CHESS & LEPP

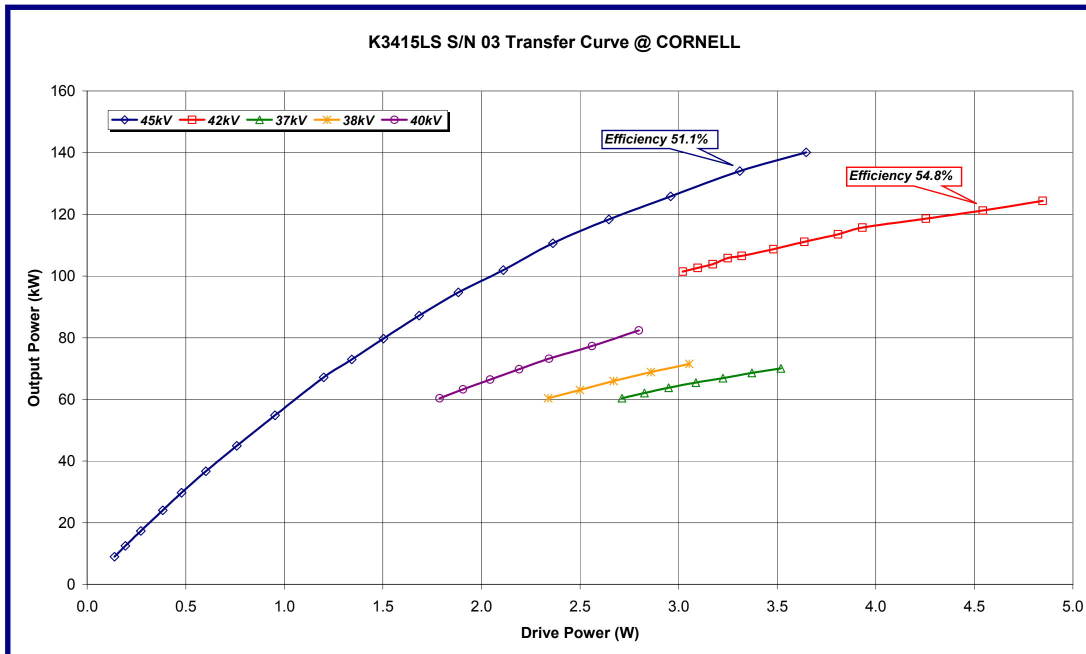


Full 5-cavity String Out of Cryostat

CHESS & LEPP

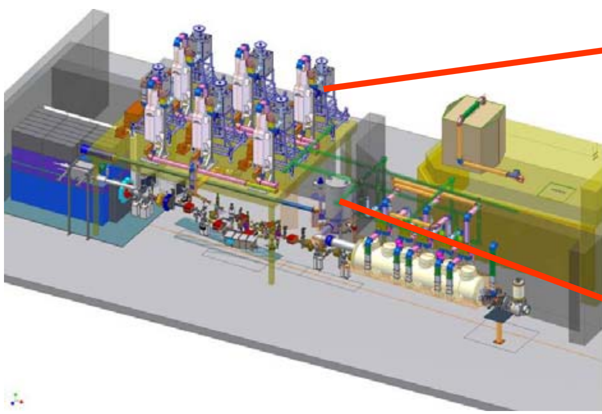
ERL injector klystron

- e2v designed high CW power klystron.
- Parameters: 7-cavity tube, max. beam voltage 45 kV, current 5.87 A, full power collector, max. output power 135 kW @ >50% efficiency, gain >45 dB, bandwidth >±2 MHz @ 1 dB and >±3 MHz @ 3 dB.
- First tube delivered and successfully tested in March, 2007.
- Transfer curves were measured for several HV settings.



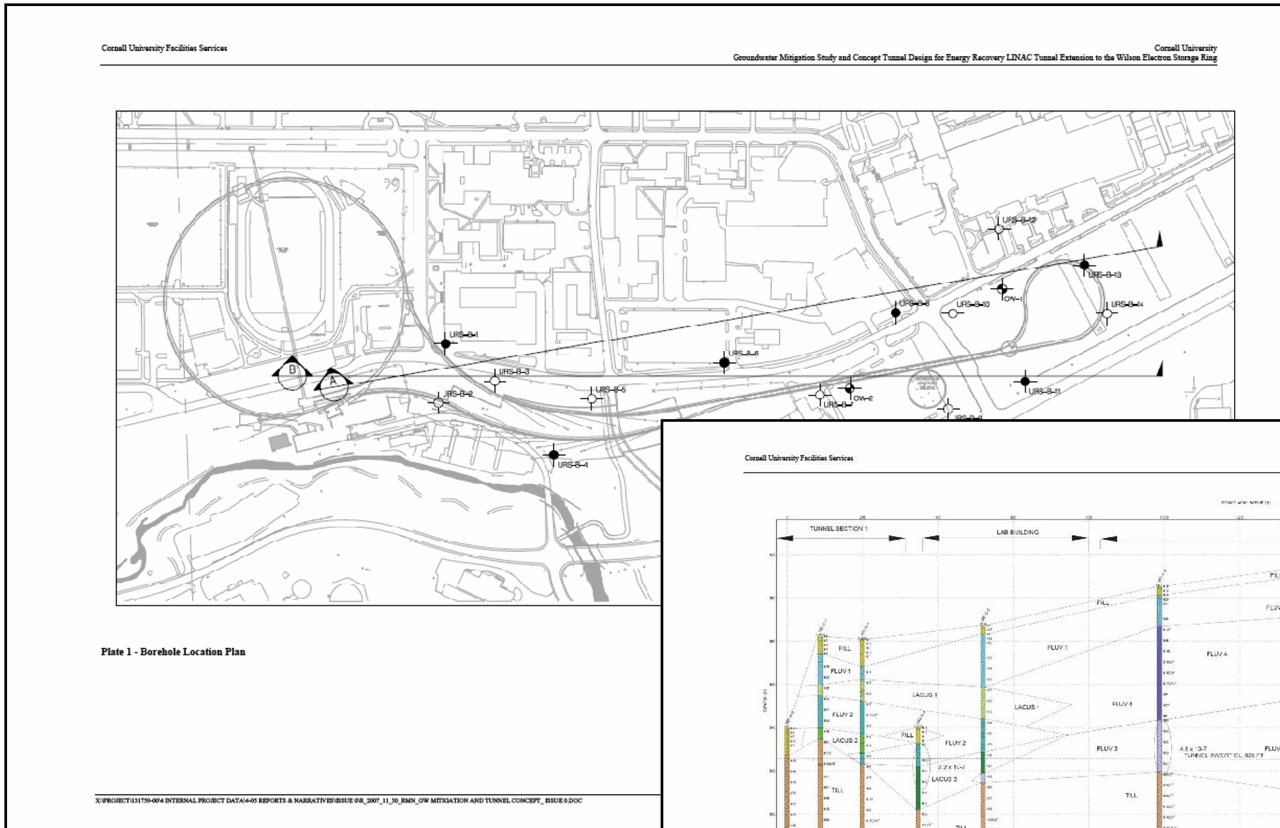
Injector Assembly 7 Jan 2008

CHESS & LEPP

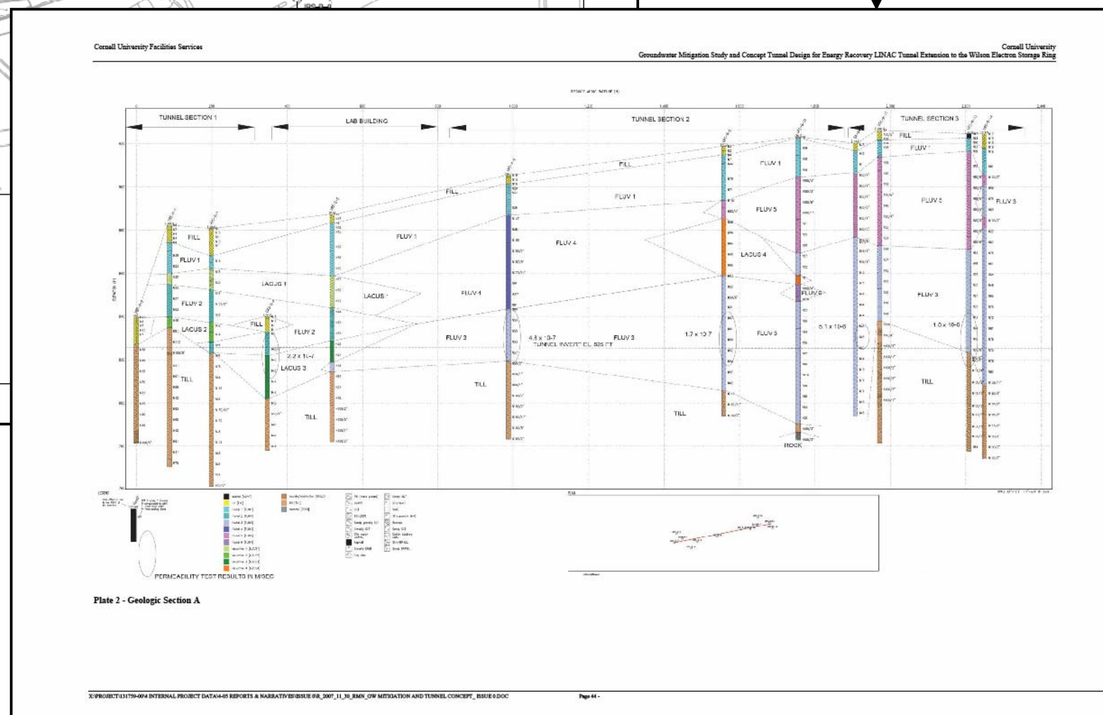


Meanwhile, NYS Supports Proposal Development

CHESS & LEPP



Site Test Borings and Hydrogeology



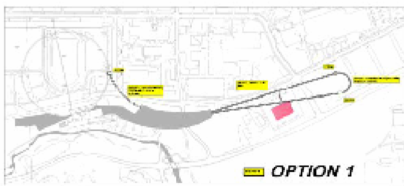
Tunnel Options

CHESS & LEPP

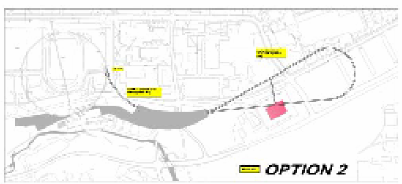
4.4 Tunnels

The original tunnel alignment selected and included in the original pricing was Option 0.

Alternative tunnel alignments have been studied which allow different (and cheaper) tunneling methods. It is noted that the engineering design for Options 1 and 2 has not been developed to the same level as Option 0 and these cost estimates are to be used to establish the potential magnitude of savings for adopting an alternative tunnel alignment.



Potential saving $2.5M



Potential saving $5.8M

4.5 Master schedule (construction/procurement) and early design work

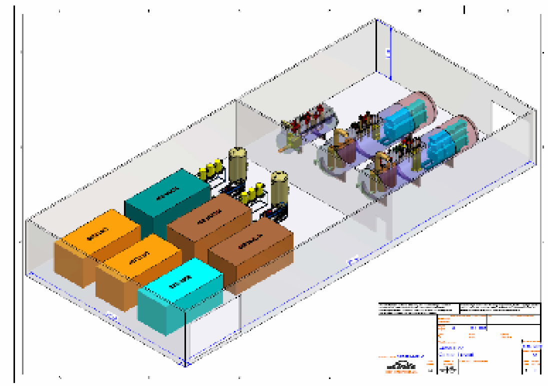
The current construction schedule of 2 years has been considered in isolation to the installation and commissioning of the LINAC, the experimental equipment housed in the laboratory and the cryogenics plant.

Discussions at the workshop indicated that a complex sequencing of activity would be required to install and commission the whole. In addition, procurement of the LINAC and cryogenics plant particularly would be complex and time consuming given the unique nature of the product and the scarcity of manufacturers available globally to be engaged.

Cryoplant Studies

B1 Cryoplant information

The workshop, together with a separate cryoplant focused meeting on November 16th, gave rise to a significant amount of information on this element of the project. The below captures some of that key information



B1.1 Design

The cryoplant process comprises a number of components which fits into a 'box' of approx. 55mx25mx7m internal height. There is some flexibility on the layout within the 'box' and there may be an ability to 'stack' certain components. Currently, there is no scope definition on which items will be provided by the cryoplant provider and which will be provided by the main project:

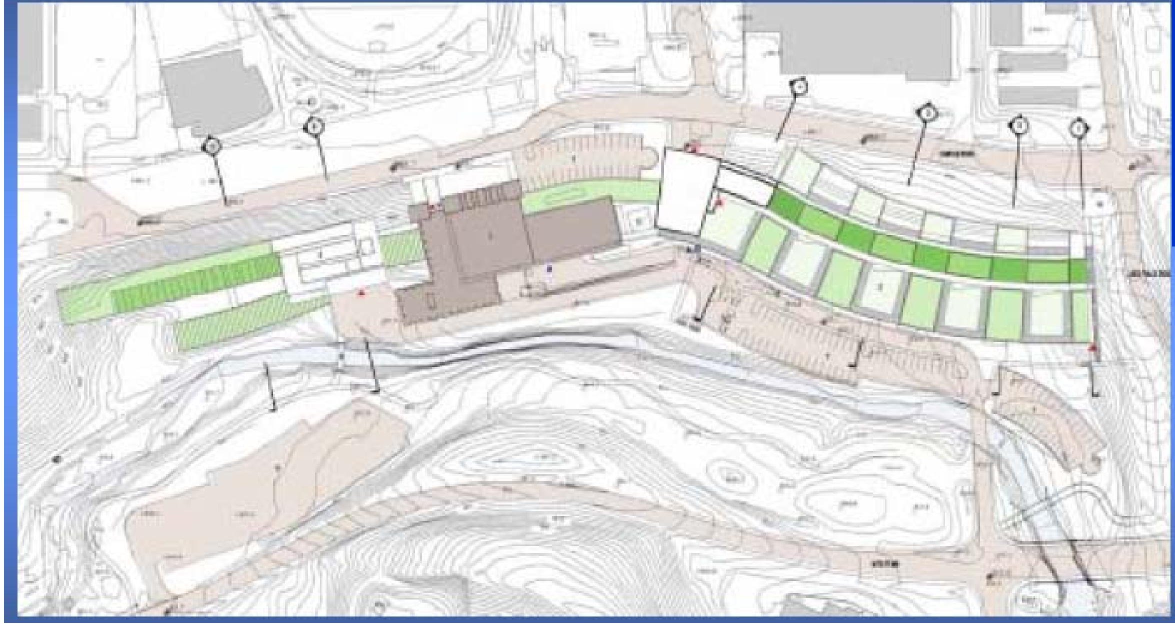
- Control room
- Storage vessels ('warm' and 'cold', 'liquid' and gaseous' - can be external)
- Compressors (heavy and cause significant vibration)
- 1 no. 4K cold box and 1 no. shield (50,000kg each)
- 1no. 1.8K cold box (30,000kg)
- Delivery lines to beam line
- Ancilliary equipment

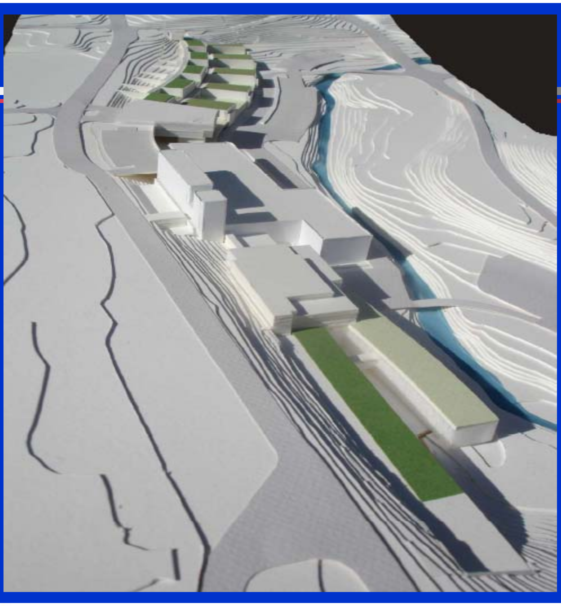
The pipe work connecting each component gets increasingly 'expensive' as the plant reduces the temperature. In some instances having the lowest temperature cold boxes close to the beam line can help mitigate this. However, the boxes need inspections,

Architectural & Environmental Site Studies

CHESS & LEPP

Site Layout





Etc.

Cornell ERL Project

- ERL Study (w/ Jlab) (Completed in 2001)
- Phase I: R&D on injector, linac modules, machine issues. Engineering studies for Phase II (in process: $30M NSF & NY State in 2005/2006; continued R&D proposed).
- Phase II proposal in 2008.
- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. (~5 year construction)

Operate ERL as University-based NSF user facility.

END