Cornell University

CHESS & LEPP

Toward an Energy Recovery Linac x-ray source at Cornell University

Georg Hoffstaetter
Cornell Physics Dept. / LEPP

- The ERL principle
- Studies for an x-ray ERL at Cornell University
- Limits of ERLs

CESR @ Cornell

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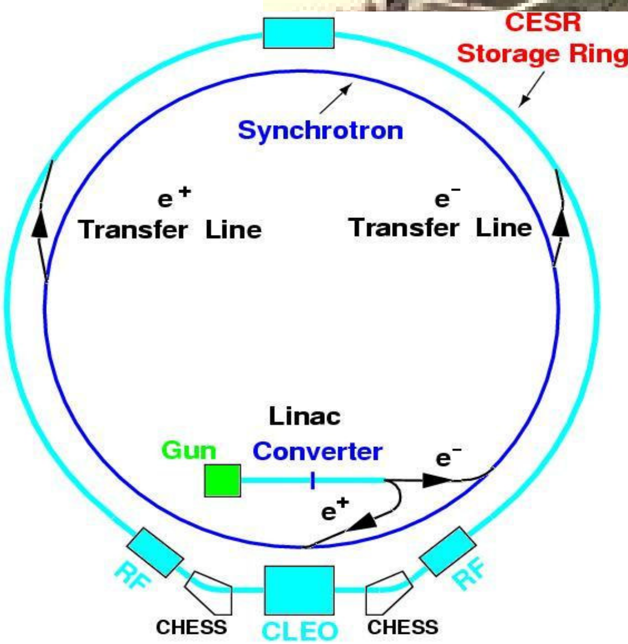

A goldmine at Cornell

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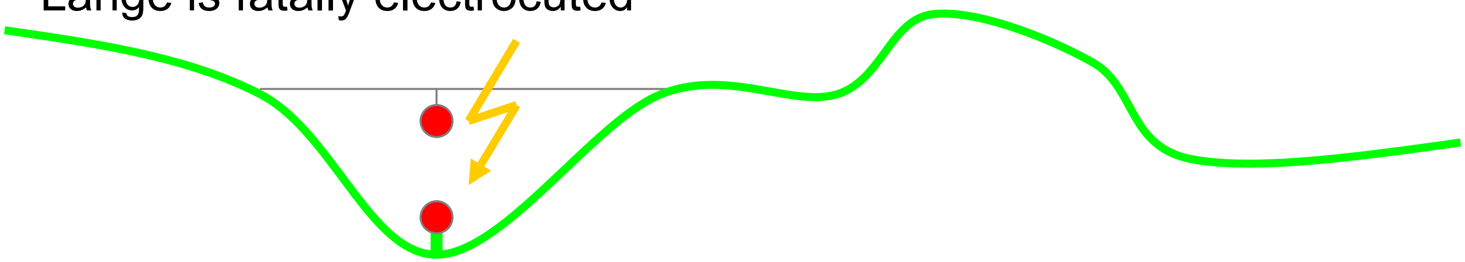
In ...

Tunnel digging
(as of 1966)

... out

Accelerator Physics @ Cornell

- 1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted



- 1934: Livingston builds the **first Cyclotron away from Berkely** (2MeV protons) at Cornell (in room B54)
- 1949: Wilson et al. at Cornell are **first to store beam in a synchtotron** (later 300MeV, magnet of 80 Tons)
- 1954: Wilson et al. build **first synchrotron with strong focusing** for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1965: **First paper on Linear colliders and ERLs**
- 1979: 5GeV electron positron collider CESR (designed for 8GeV)
- Currently:
  - CESR operation and optimization for the CLEO experiment
  - CESR operation and optimization for CHESS
  - ERL prototyping facility (ERL e-source and injector linac)
  - ERL and CESR upgrade to an ERL
  - ILC design, simulations, damping ring studies with CESR

Synchrotron Radiation @ Cornell

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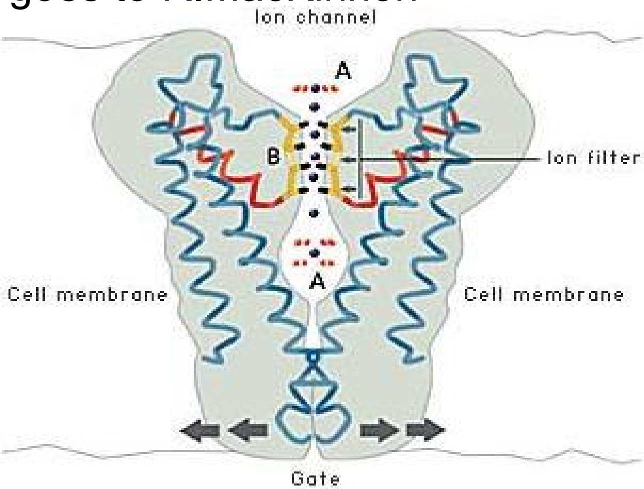
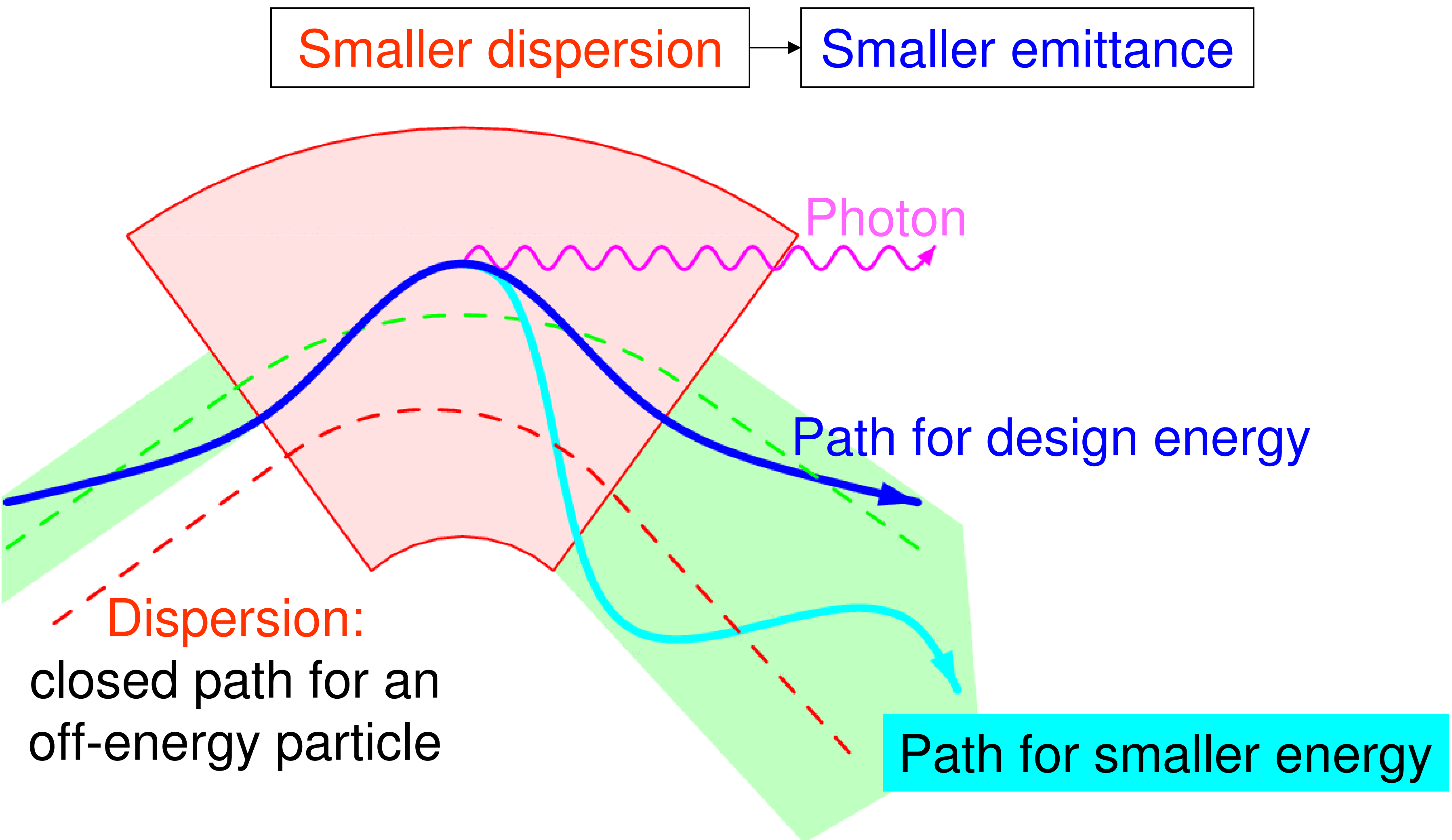
- 1947: **1st** detection of synchrotron light at General Electrics. Soon advised by D.H.Tomboulian (Cornell University)
- 1952: **1st** accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1953: **1st** measurement of the synchrotron radiation spectrum by Paul Hartman with the Cornell 300MeV synchrotron.
- Worlds **1st** synchrotron radiation beam line (Cornell 230MeV synch.)
- 1961: **1st** measurement of radiation polarization by Peter Joos with the Cornell 1.1GeV synchrotron.
- 1978: X-Ray facility CHESS is being build at CESR
- 2003: **1st** Nobel prize with CESR data goes to R.MacKinnon

Dale Corson
Cornell's 8th president



Roderick MacKinnon

Emittance Excitation



Beam Size in a Linear Accelerator

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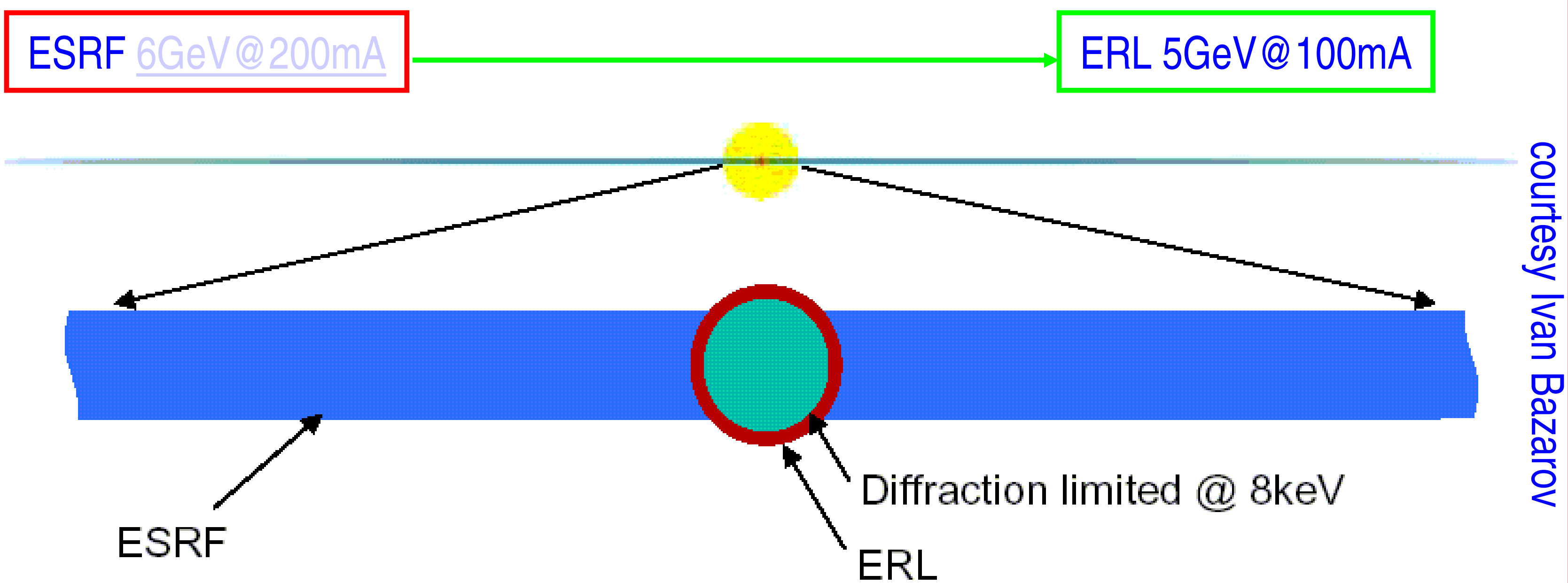
The beam properties are to a very large extend determined by the injector system:

- **The horizontal beam size can be made much smaller than in a ring**
- **While the smallest beams that are possible in rings have almost been reached, a linear accelerator can take advantage of any future improvement in the electron source or injector system.**



Microprobe

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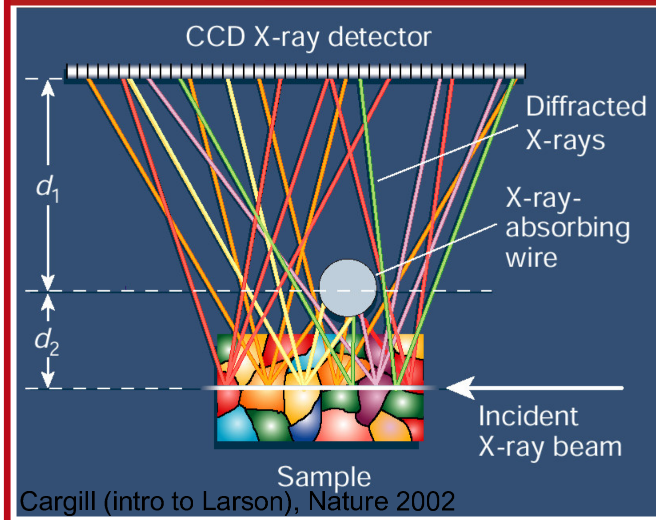
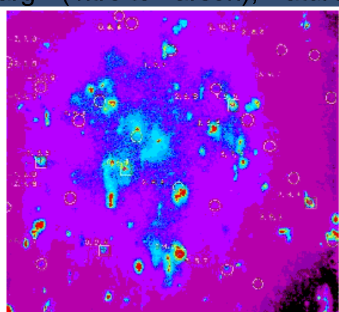


Cargill (intro to Larson), Nature 2002

Differential-Aperture X-ray Microscopy (DAXM)

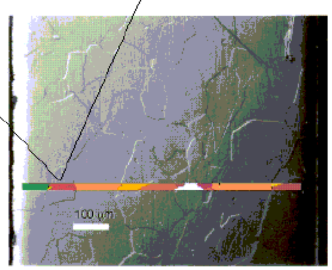
- Smaller beams lead to better spatial resolution (currently sub µm)

ERL: 100-1000 times smaller area



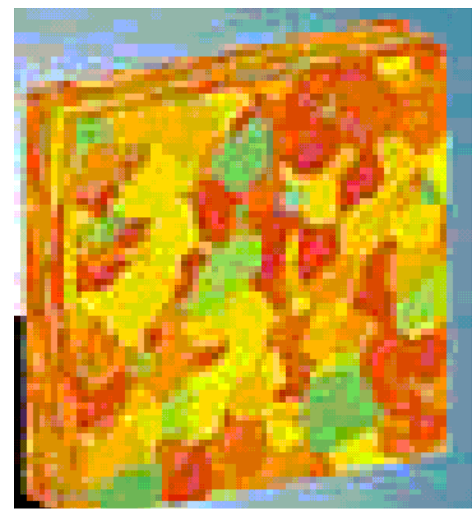
Orientation of crystals and

Stress and strain in crystals



Ben Larson (2000), ERL science workshop, Cornelll

3-D Studies of Structure



Smaller Beams and more Coherence

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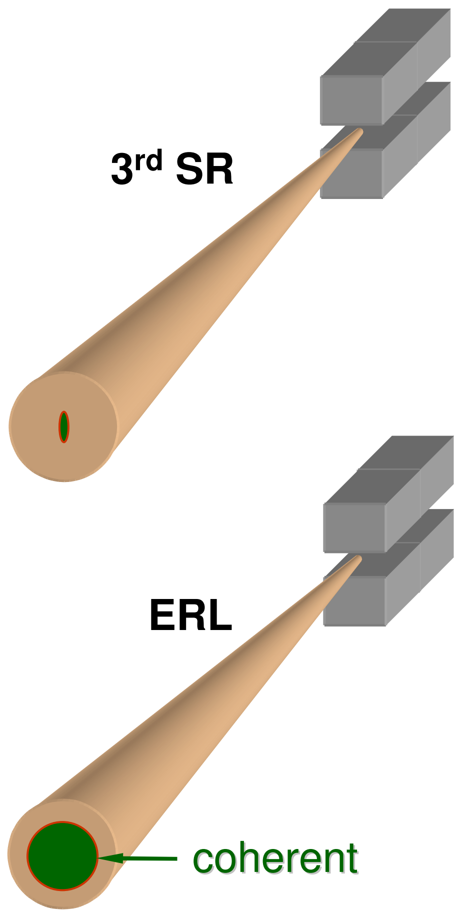
- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.



Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays

Real-time insect breathing

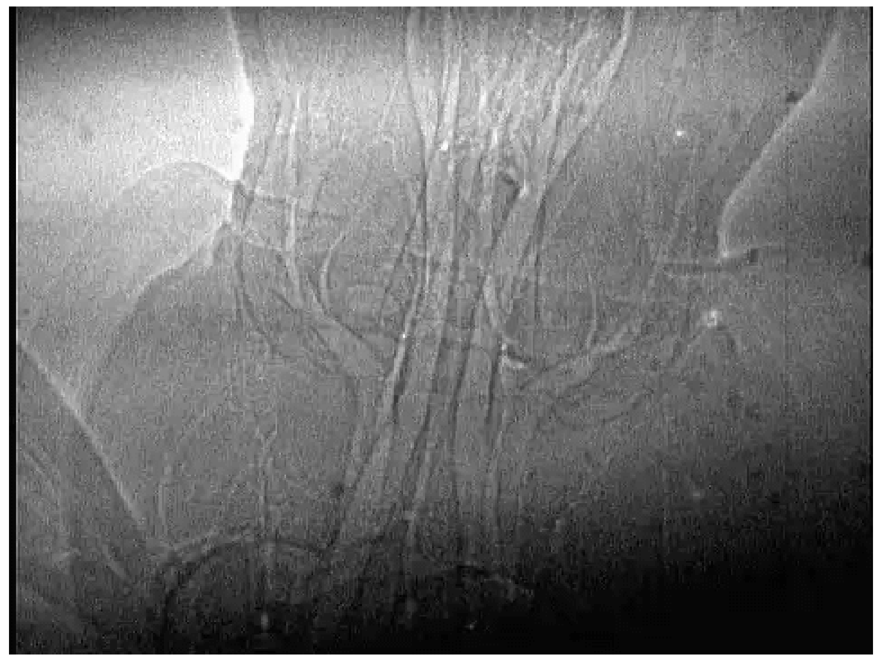
CHESS & LEPP

Tracheal Respiration in Insects Visualized with Synchrotron X-ray Imaging

Mark W. Westneat,*[1] Oliver Betz,[1,2] Richard W. Blob,[1,3]
Kamel Fezzaa,[4] W. James Cooper,[1,5] Wah-Keat Lee[4]
Field museum of Chicago & APS, Argonne National Lab.

Science (2003) 299, 598-599.

- Animal functions
- Biomechanics
- Internal movements
- New findings



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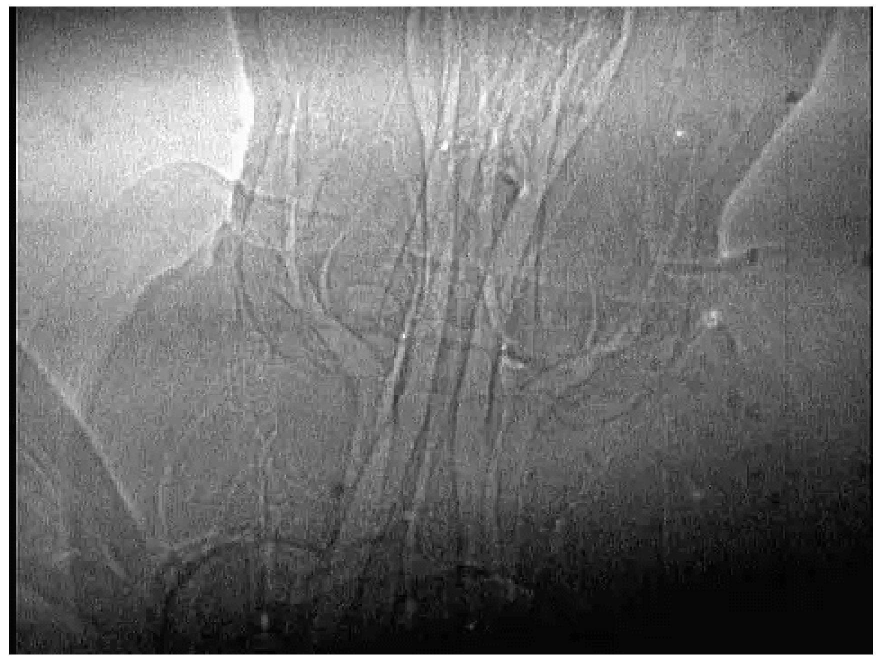

- ERL would extend these studies to much higher lateral resolution (sub μm) and faster time scales

Bunch length in a Linac

CHESS & LEPP

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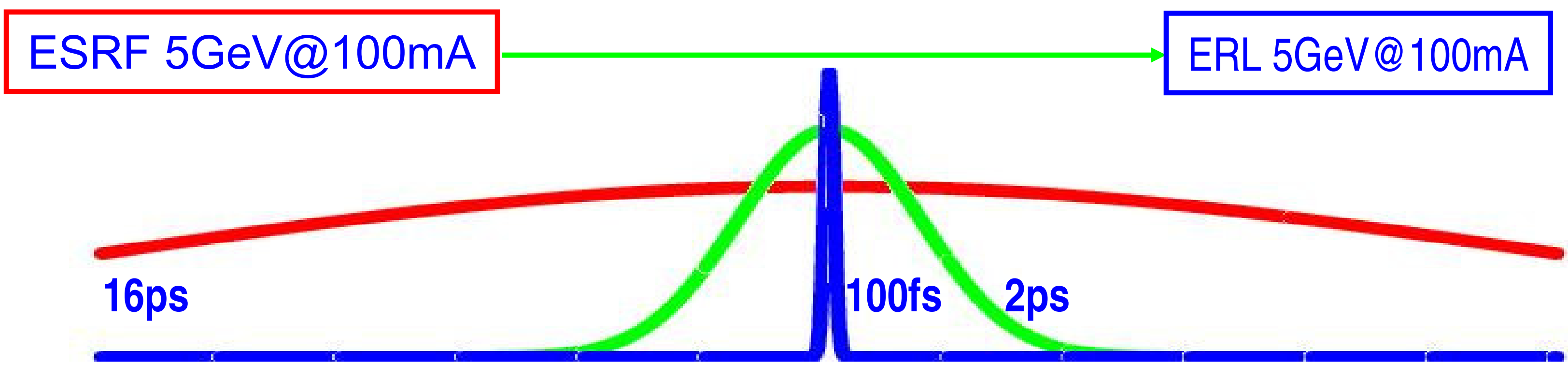
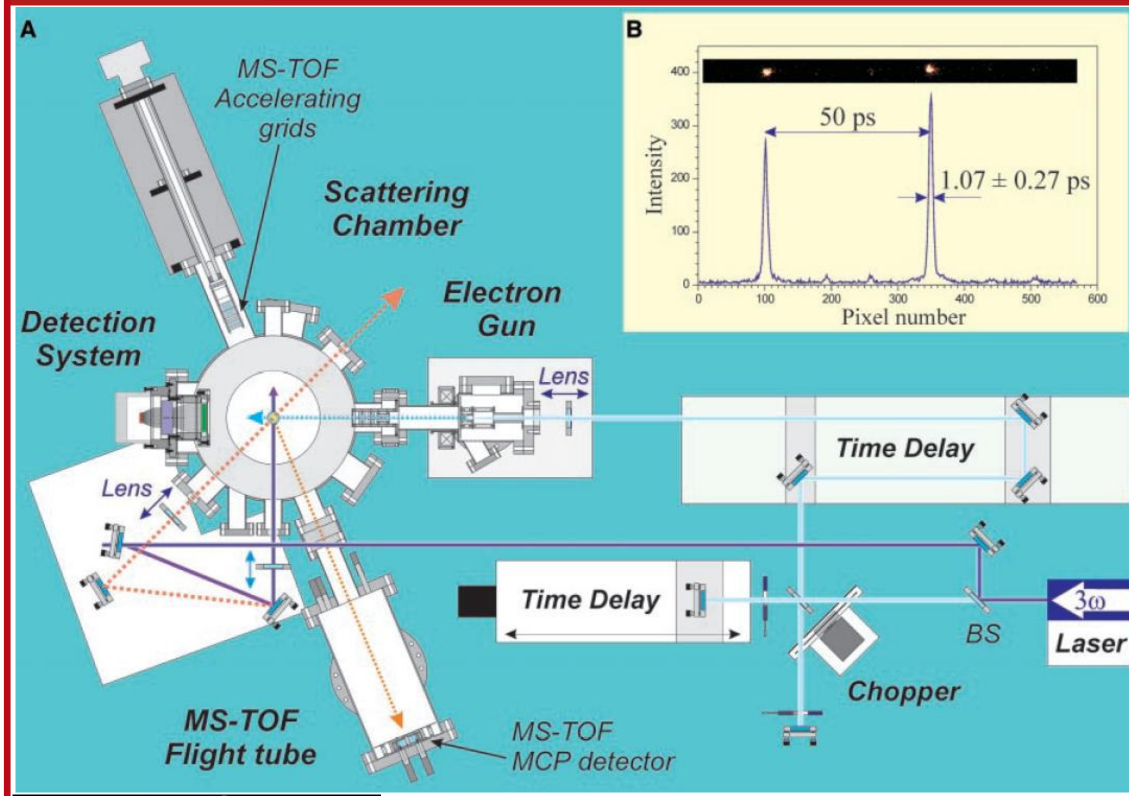
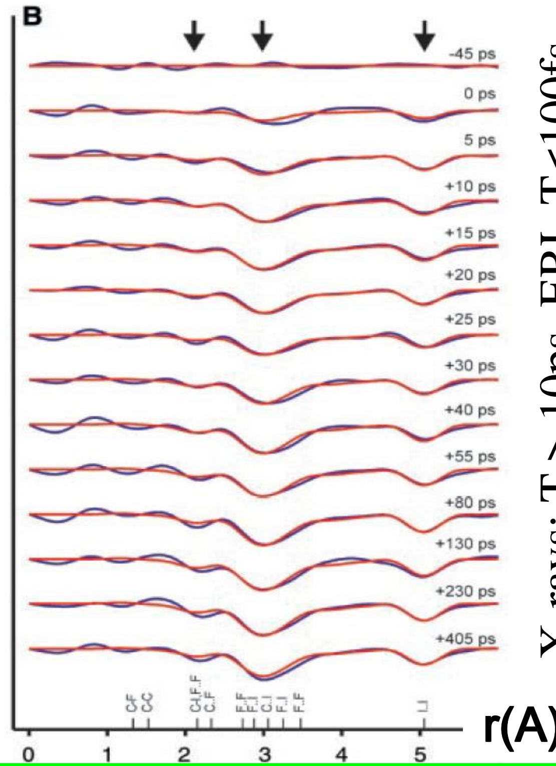
- While the shortest bunches possible in rings have almost bean reached, a linear accelerator can take advantage of any future improvement in the source source or injector system.



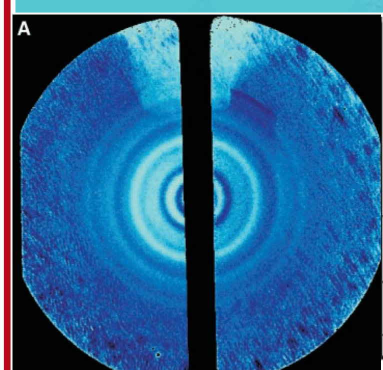
Ultra-fast Electron Diffraction

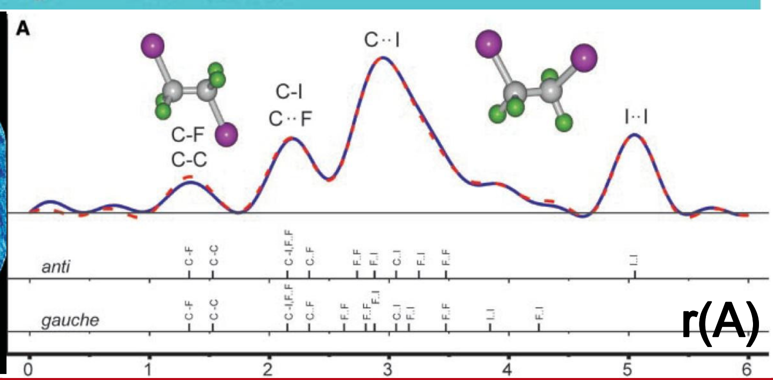
CHESS & LEPP

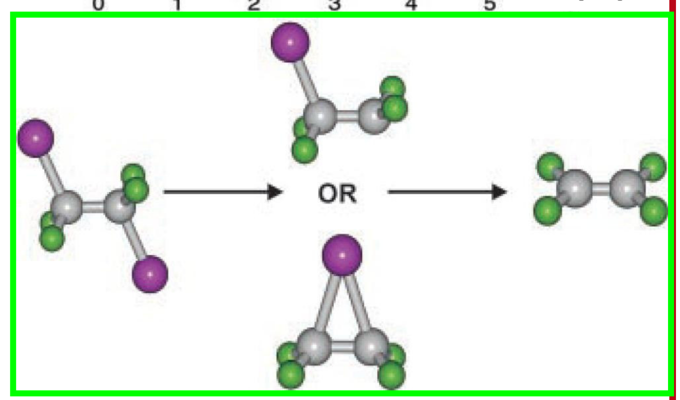




X-rays: T > 10ps, ERL T<100fs







Pro and Con for an x-ray Linac

As compared to a ring, the beam properties are largely determined by the injector system:

- **The bunch length can be made much smaller than in a ring**
- **Smaller emittances**
- **Higher coherence fraction**

ESRF 6GeV@200mA → ERL 5GeV@100mA

Current of 100mA and energy of 5GeV leads to a beam power of 0.5GW !!!

The energy of the spent beam has to be recaptured for the new beam.

Pro and Con for an x-ray Linac

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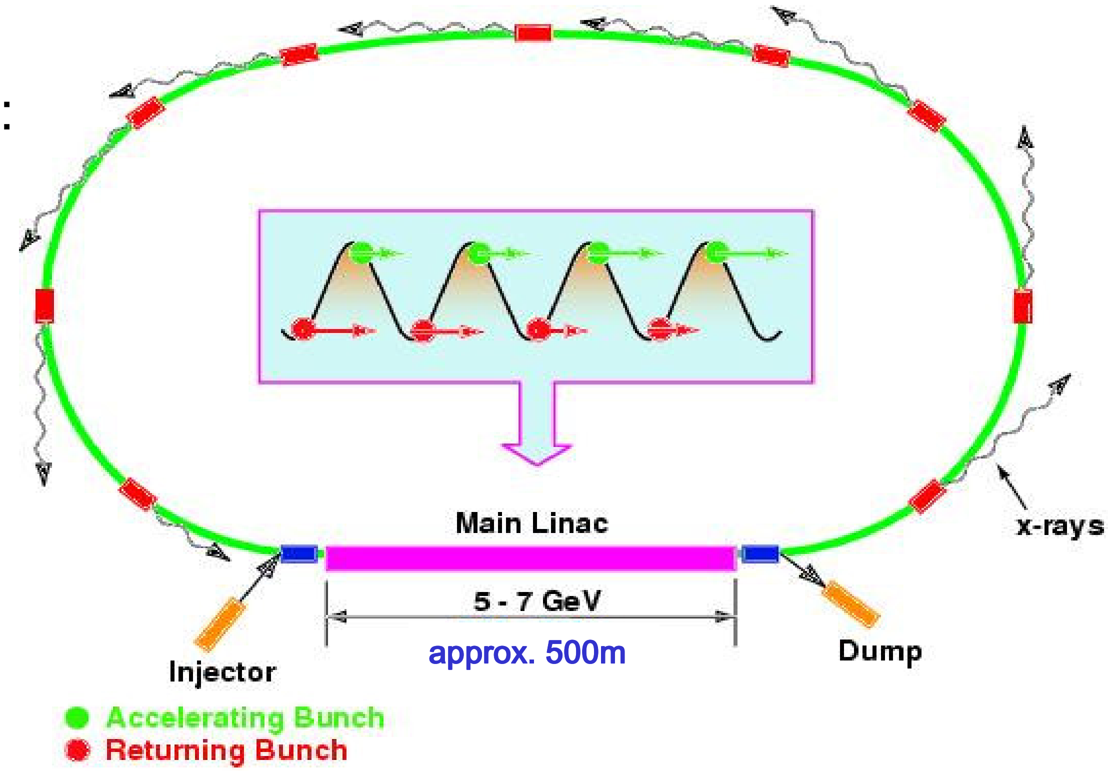
ERLs

X-ray analysis with highest resolution in space and time:

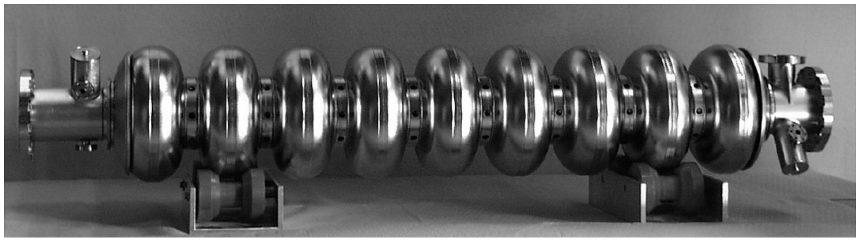


Challenges:

- Invented in 1965
- Needs superconducting RF, otherwise high Voltage CW cavities melt
- High Voltage SRF only had a boost end of ’90s due to the linear collider

Accelerator Physics @ CESR

CHESS & LEPP



$Q = 10^{10}$

$E = 20 MV/m$

A bell with this Q would ring for a year.

- Very low wall losses.
- Therefore continuous operation is possible.
- Energy recovery becomes possible.

Normal conducting cavities

- Significant wall losses.
- Cannot operate continuously with appreciable fields.
- Energy recovery was therefore not possible.

An existing ERL

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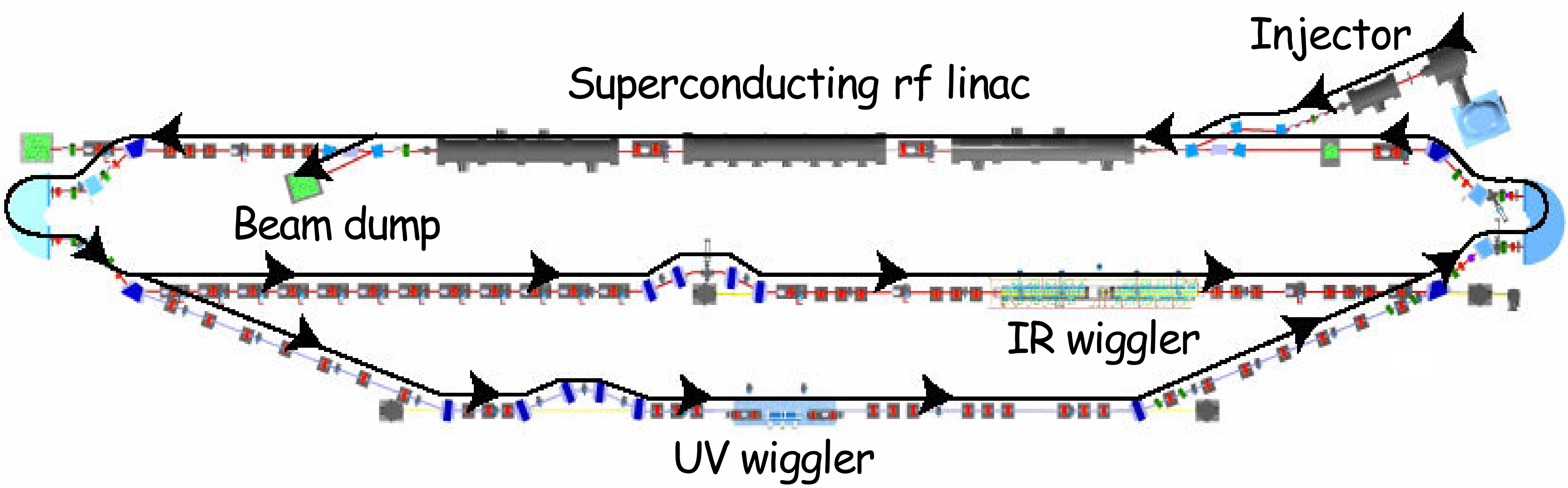
Promise: High average laser power (~ 100 kW)
High overall system efficiency
Reduced beam dump activation

Reality: JLab 10kW IR FEL and 1 kW UV FEL
JAERI 2.3kW IR FEL
Novosibirsk NRF 180MHz recuperator



courtesy Lia Merminga

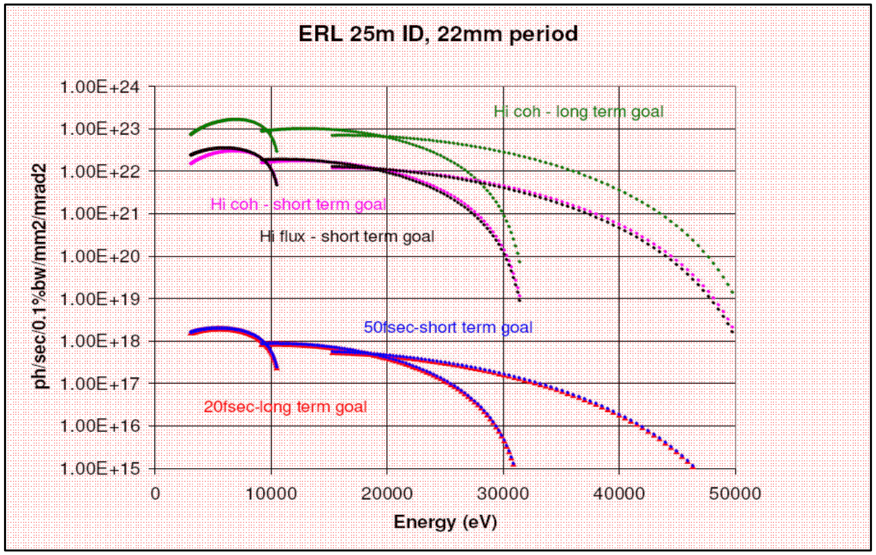
Cornell ERL Goals

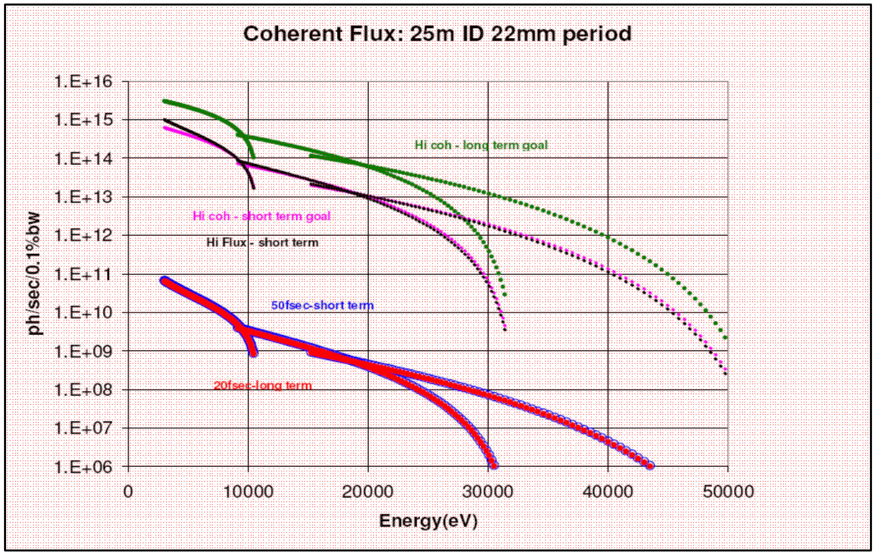
CHESS & LEPP

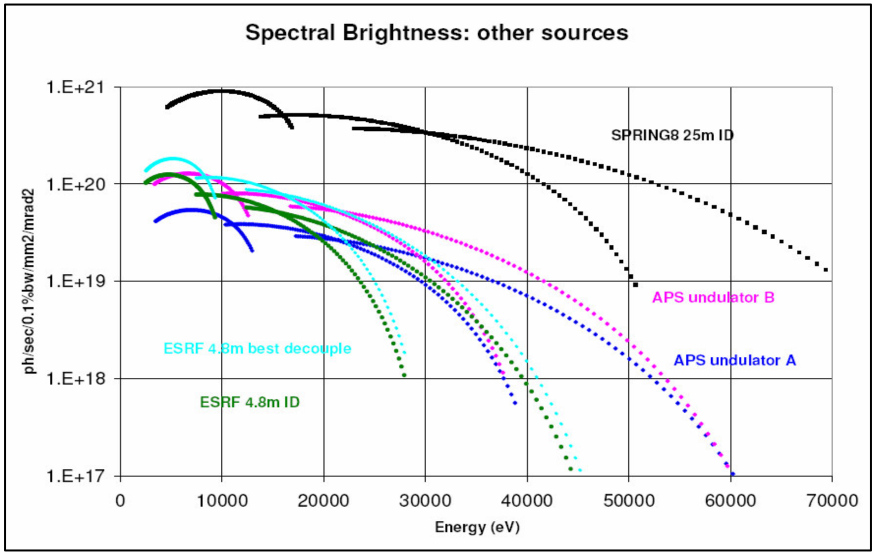
	Short-Term Goals			Long-Term Goals		
Modes:	**(A) Flux**	**(B) High-Coherence**	**(C) Short-Pulse**	**(D) Ultra High-Coherence**	**(E) Ultra Short-Pulse**	**Units**
Energy	5	5	5	5	5	GeV
Current	100	25	1	100	1	mA
Bunch charge	77	19	1000	77	10000	pC
Repetition rate	1300	1300	1	1300	0.1	MHz
Norm. emittance	0.3	0.08	5.0	0.06	5.0	mm mrad
Geom. emittance	31	8.2	511	5.1	511	pm
Rms bunch length	2000	2000	50	2000	20	fs
Relative energy spread	2 10-4	2 10-4	3 10-3	2 10-4	3 10-3	
Beam power	500	125	5	500	5	MW
Beam loss	< 1	< 1	< 1	< 1	< 1	micro A

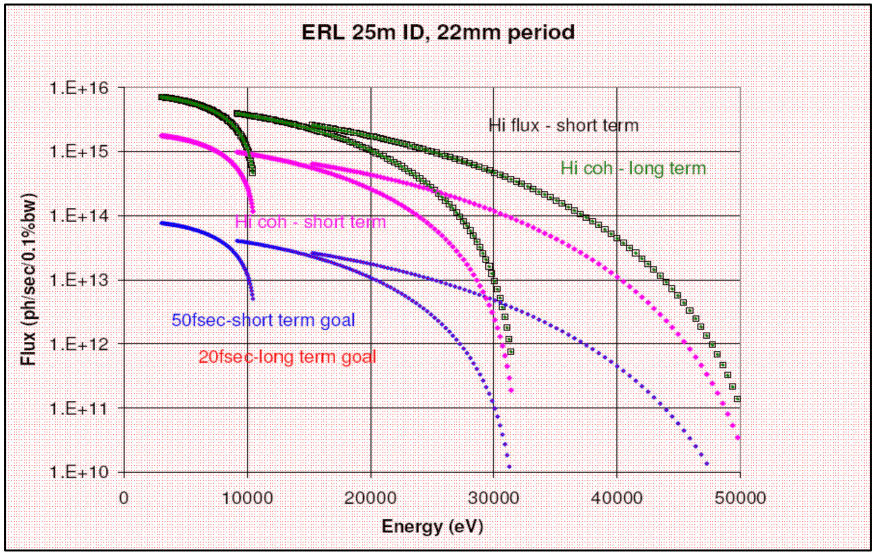
Flux and Brilliance

CHESS & LEPP



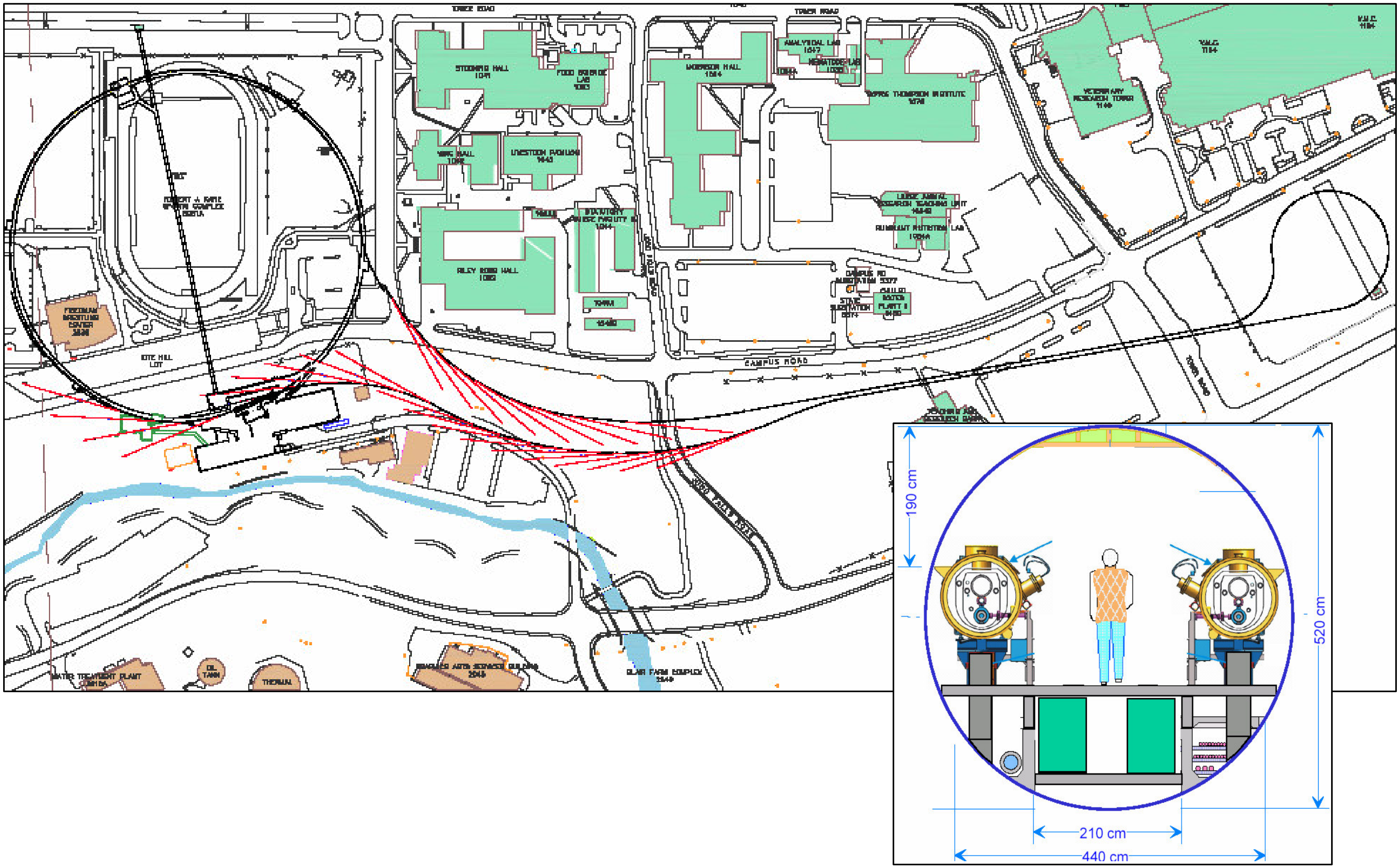






Accelerator Physics @ CESR

CHESS & LEPP



Advantages of ERL@CESR

- Operation of CESR and ERL test simultaneously.
- Use all of the CESR tunnel.
- Lots of space for undulators.
- Space for future upgrades, like an FEL.
- No basements of existing buildings to worry about.
- Only one tunnel for two linacs.
- Less competition, since other sights cannot offer upgrades.
- Example character for other existing light sources.

Superconducting RF infrastructure

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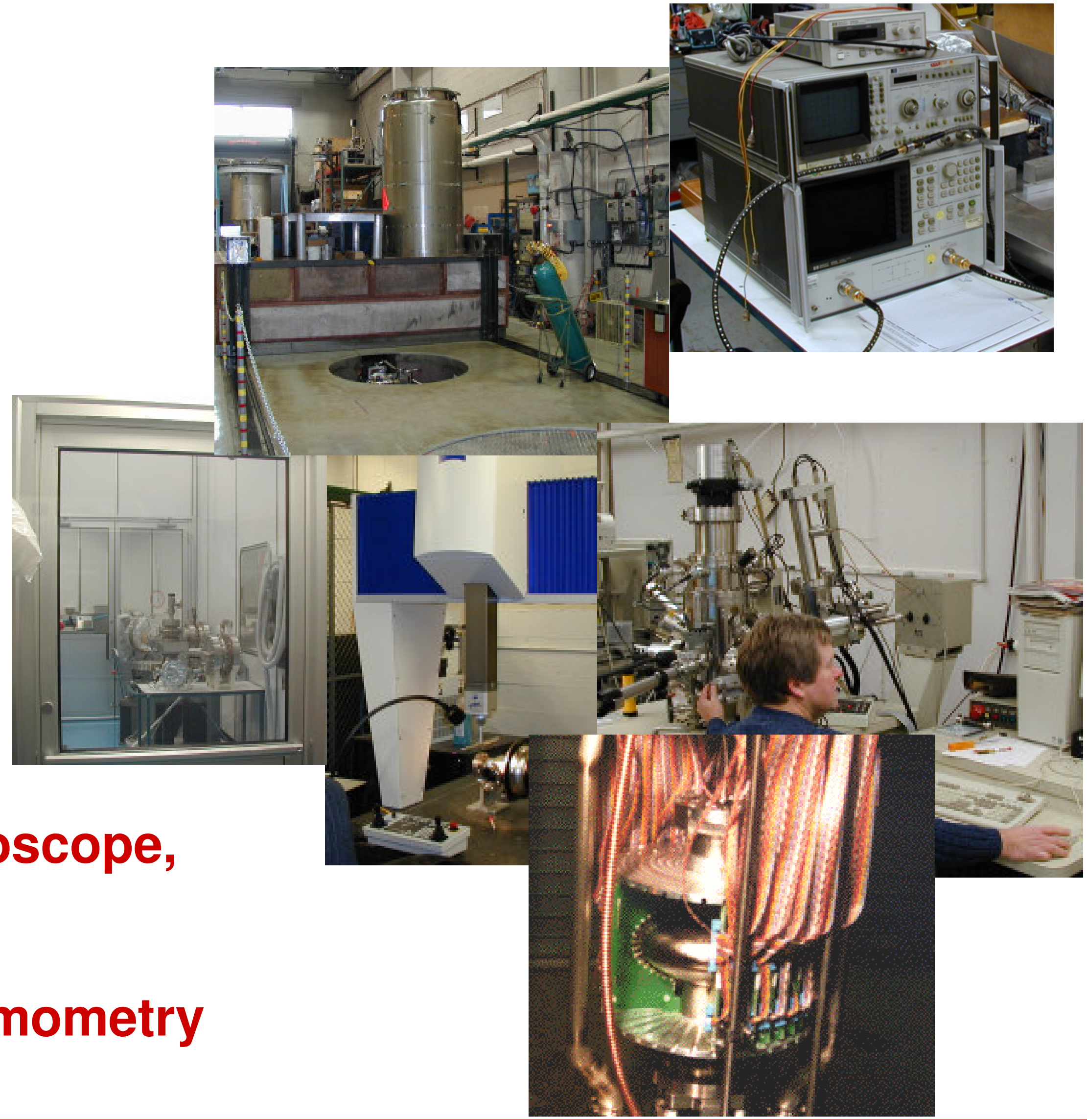
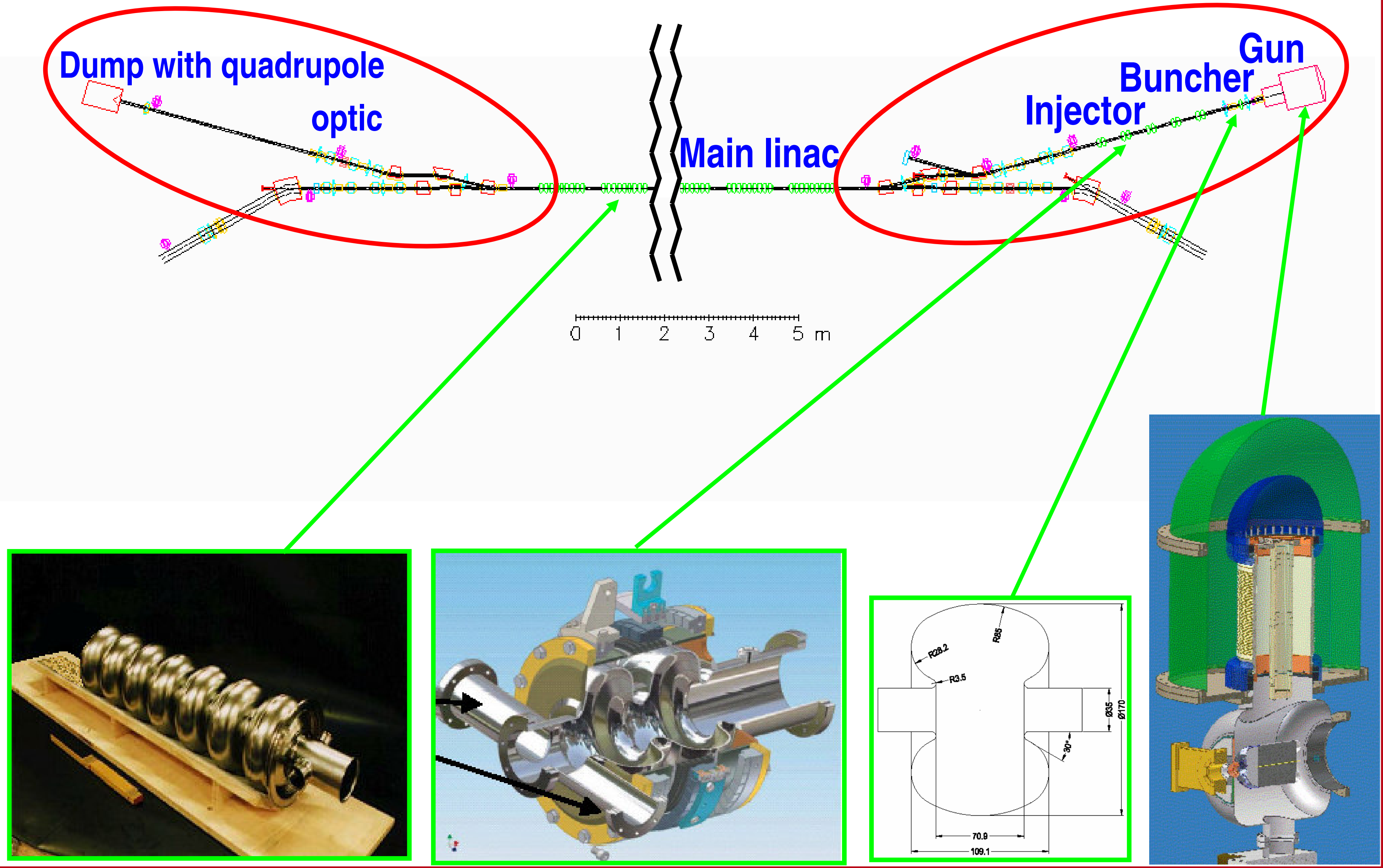
- RF measurement lab
- Shielded test pits, cryogenics
- Clean room
- Chemical handling
- Precision coordinate measurement
- Scanning electron microscope, Auger analysis
- Advanced μ-Kelvin thermometry



Ongoing ERL prototyping

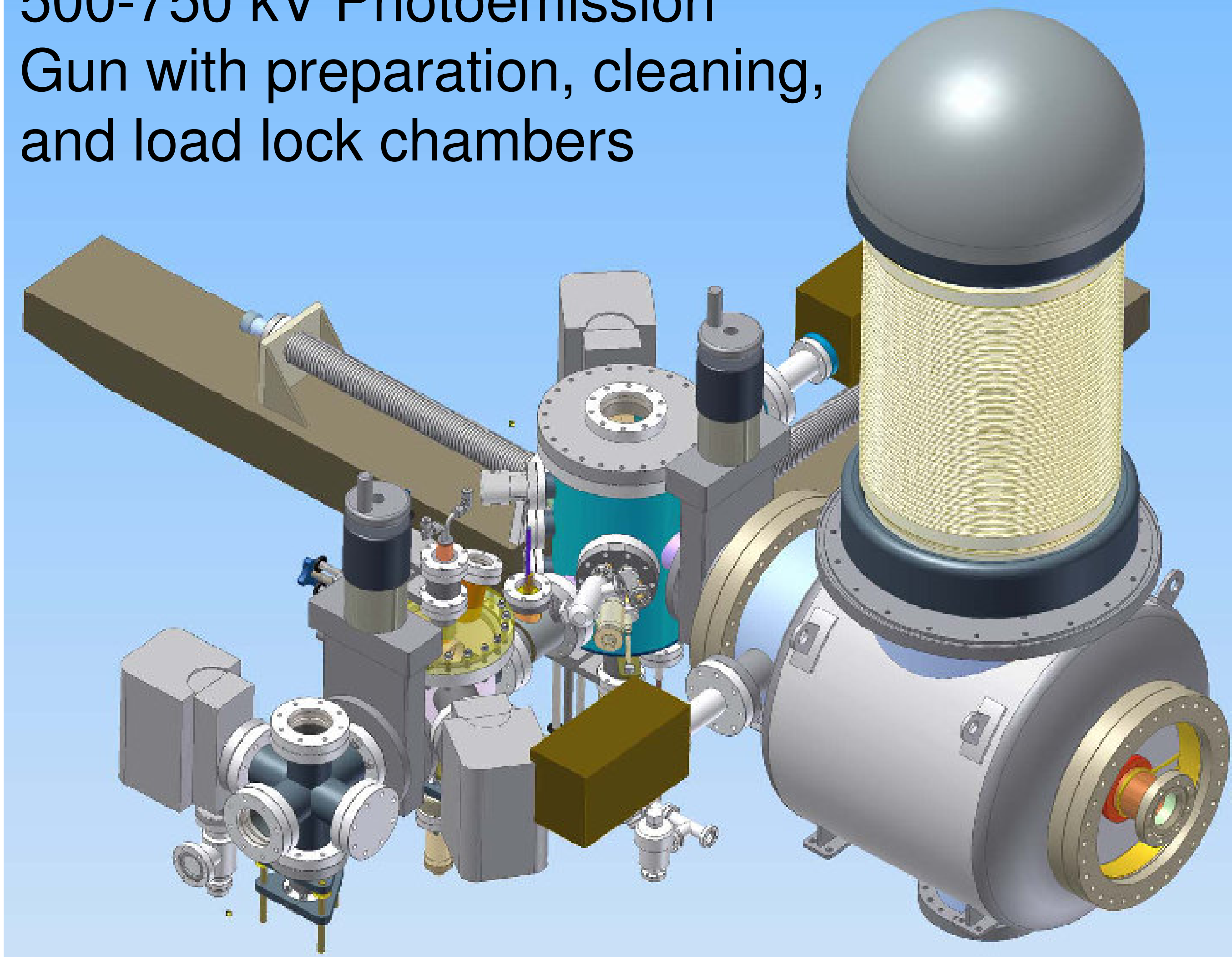
CHESS & LEPP



Bright Electron Source and ERL

CHESS & LEPP

500-750 kV Photoemission Gun with preparation, cleaning, and load lock chambers

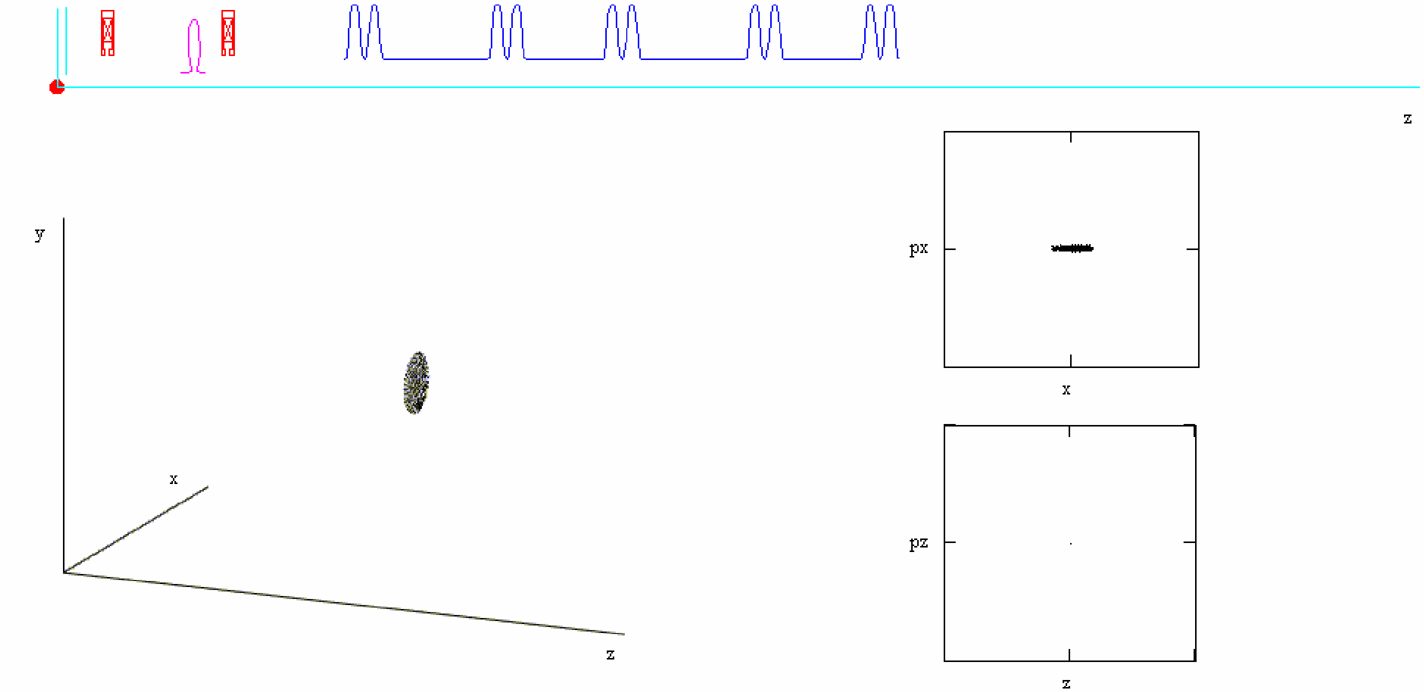


Emittances: down to 0.1mm mrad

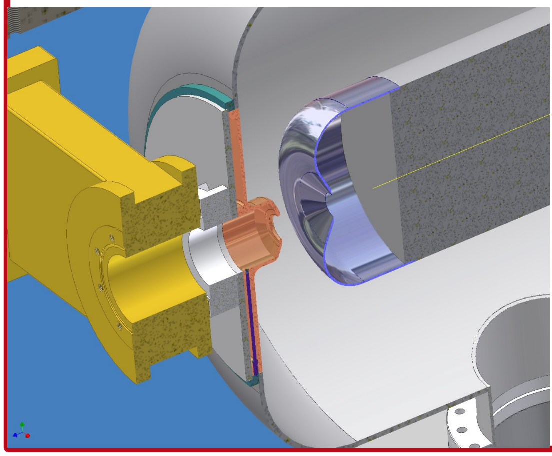
Current: up to 100mA

DC, 1.3GHz

Source development



courtesy Ivan Bazarov



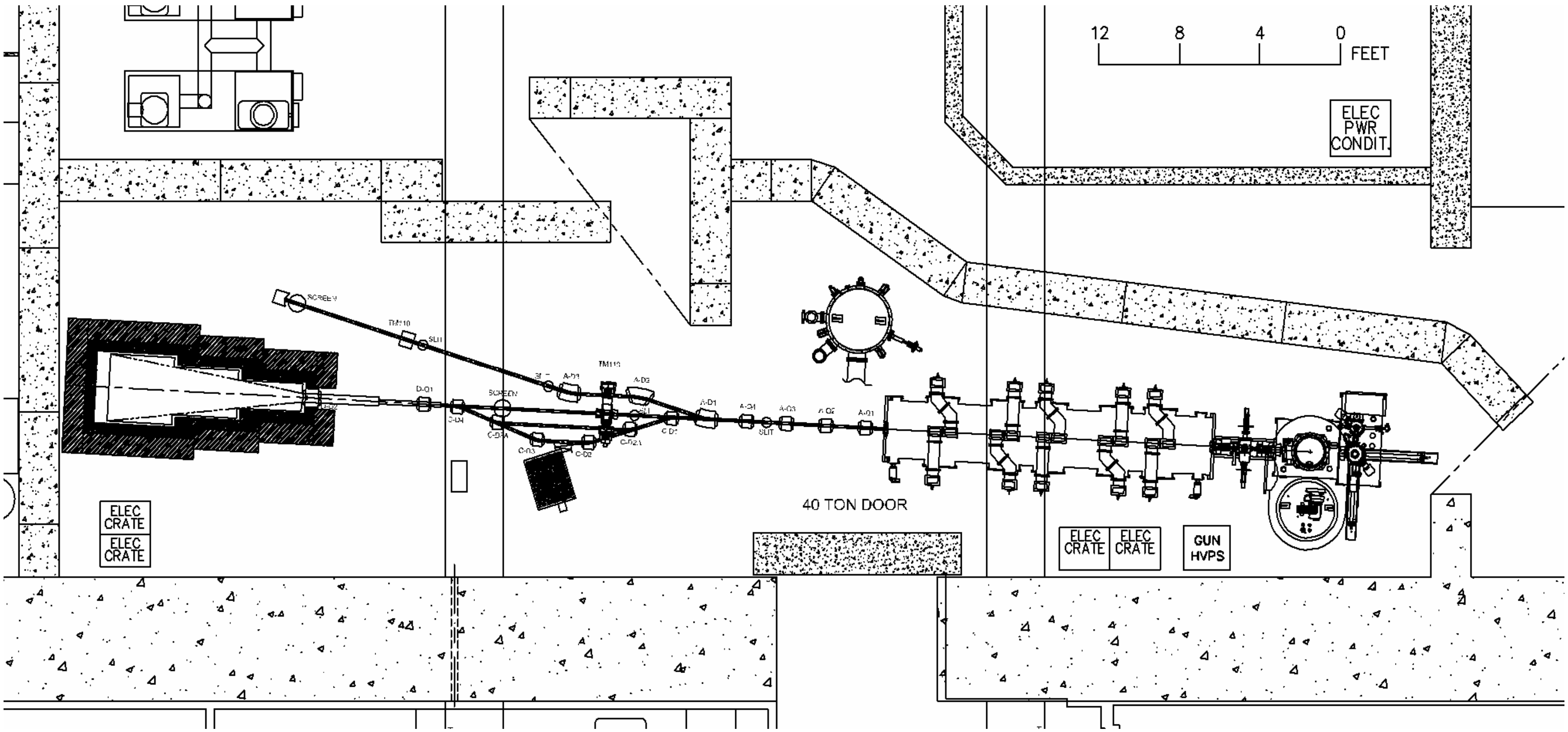
DC source for high current & low emittances

- Simulations show 10 times smaller emittances than previously thought possible, and 50 times smaller than standard.
- Gun development, coating for low field emission
- Photocathode development, neg. el. affinity GaAs, cooled
- Laser beam shaping

ERL prototyping layout

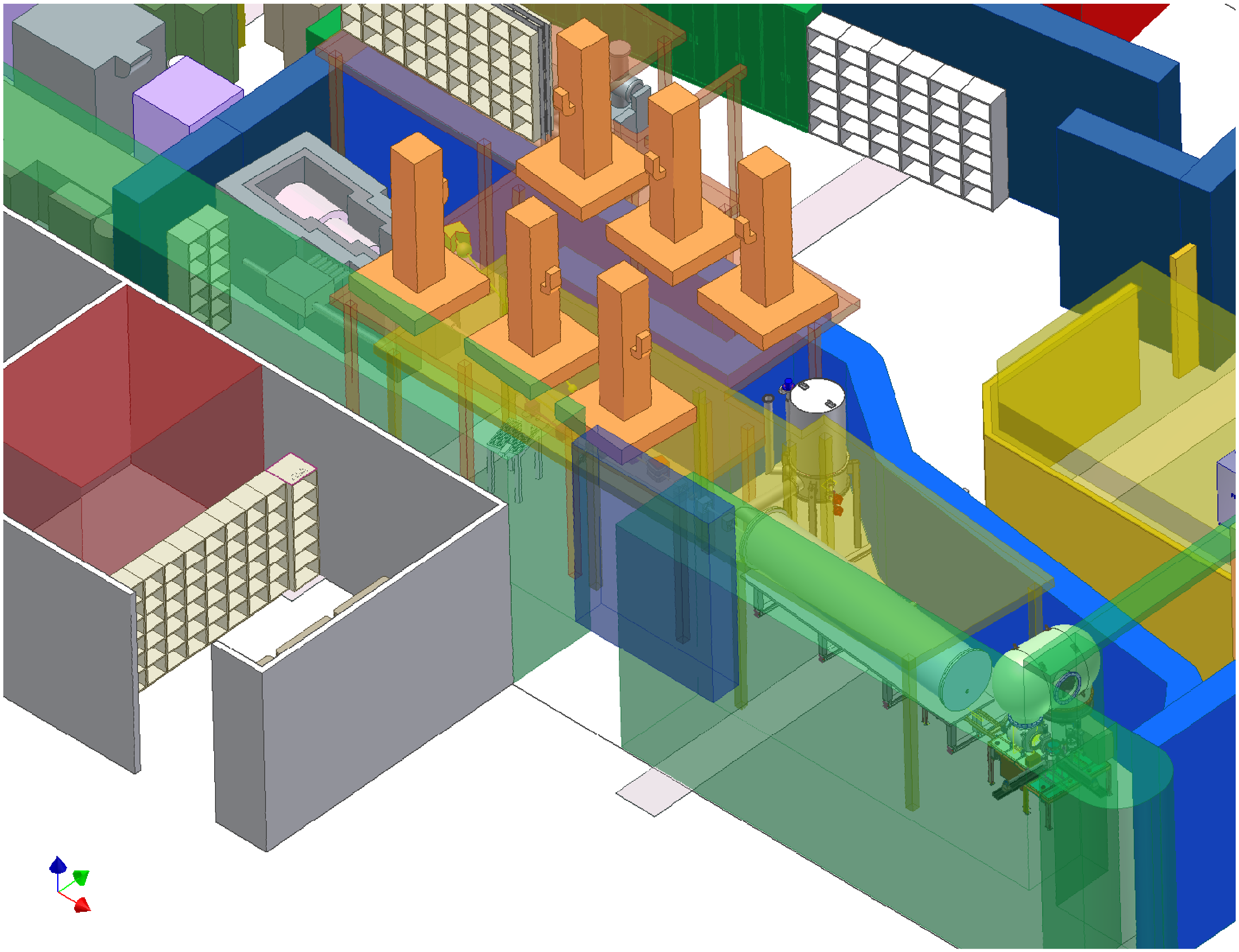
CHESS & LEPP

Max current	100 mA
Energy range	5 – 15 MeV
Installed RF power	0.5 MW + 75 kW HV PS
Emittance goal	0.1 – 1 mm-mrad
Typical bunch length	2-3 ps rms (shortest 0.2 ps)



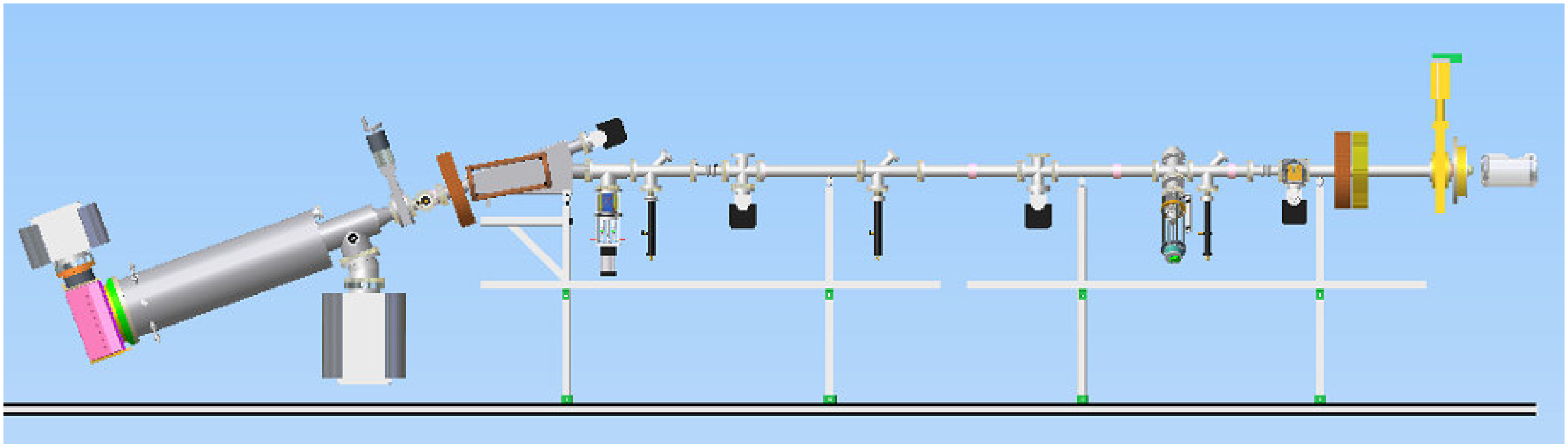
ERL prototyping layout

CHESS & LEPP



First stage gun test stand

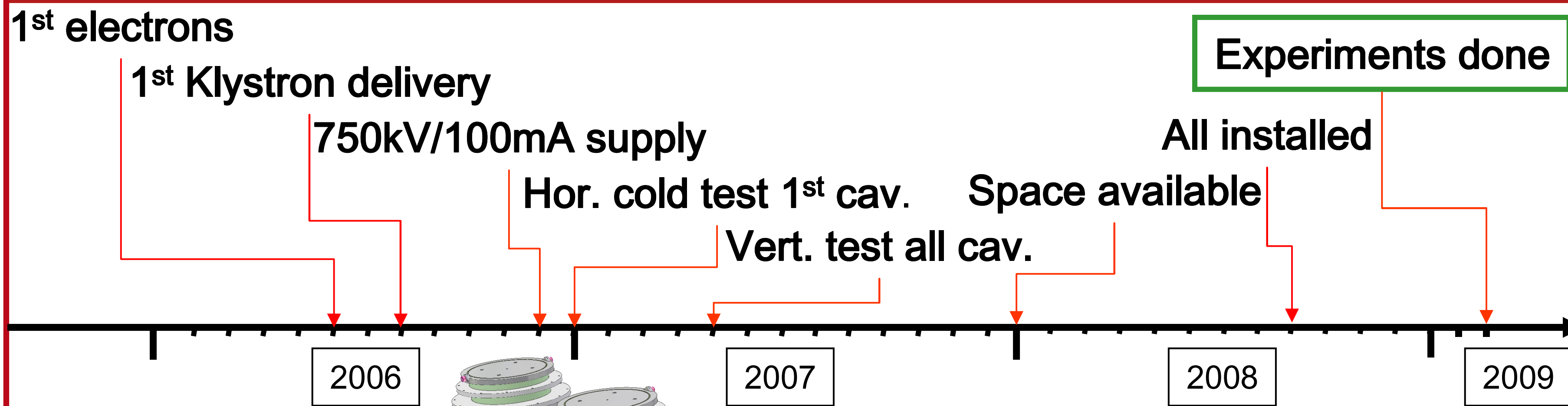
CHESS & LEPP

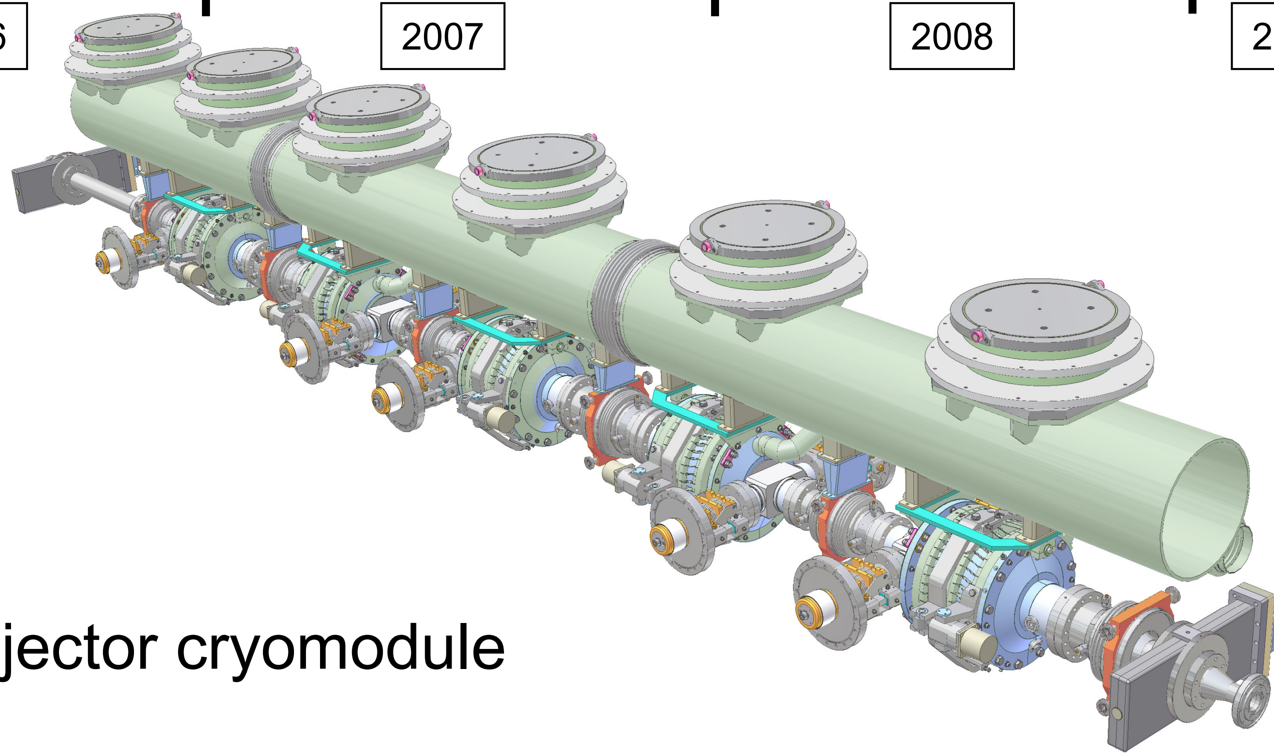


- Initial power supply from the vendor for 300 kV
- 100 mA DC beam tests:
- cathode (GaAs, GaAsP, K_2CsSb) lifetime / ion backbombardment
- thermal emittance characterization vs. wavelength

ERL prototyping milestones

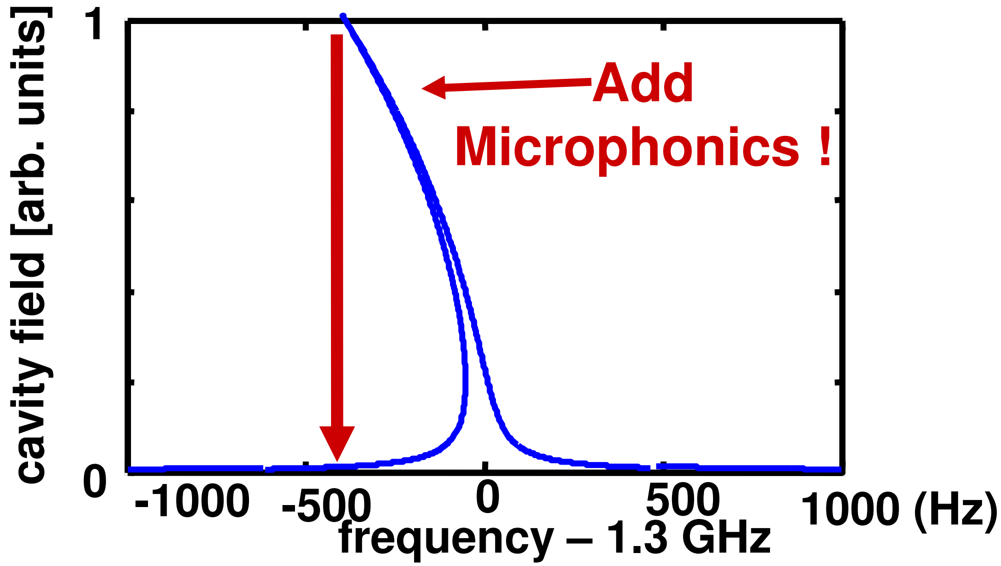
CHESS & LEPP

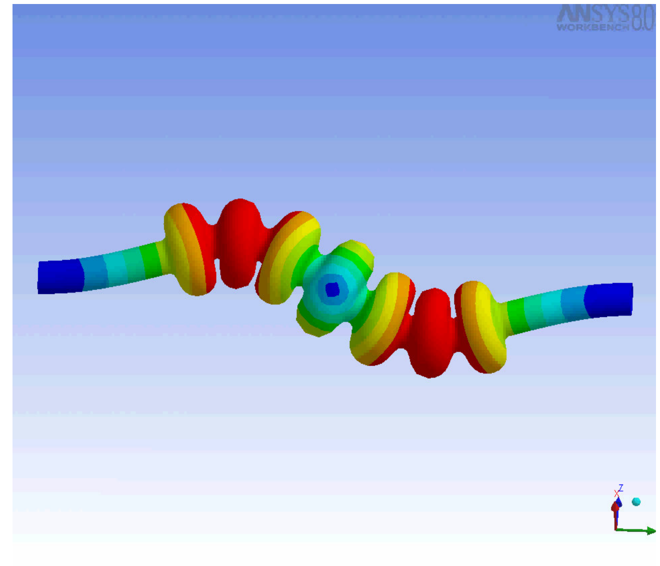


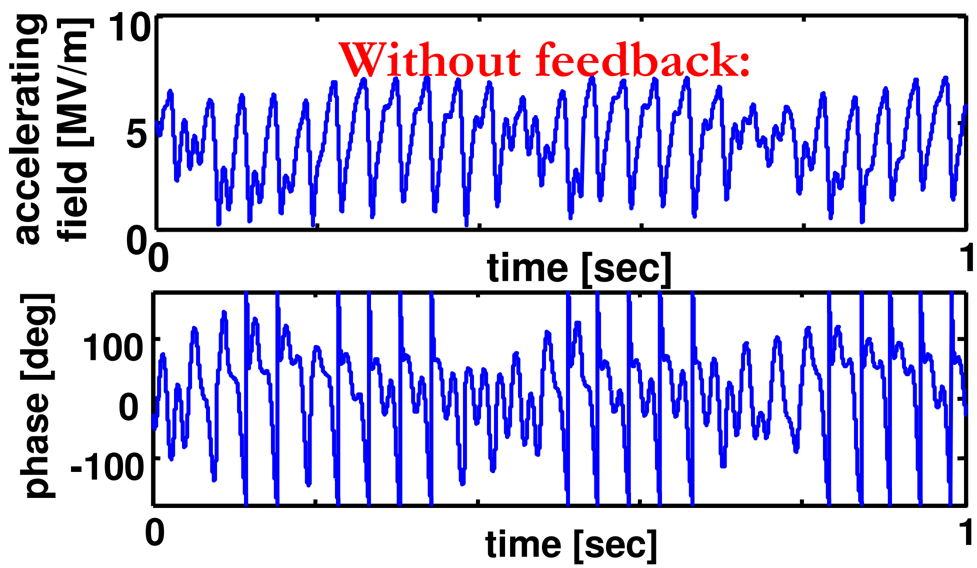


Injector cryomodule

High loaded Q cavity control



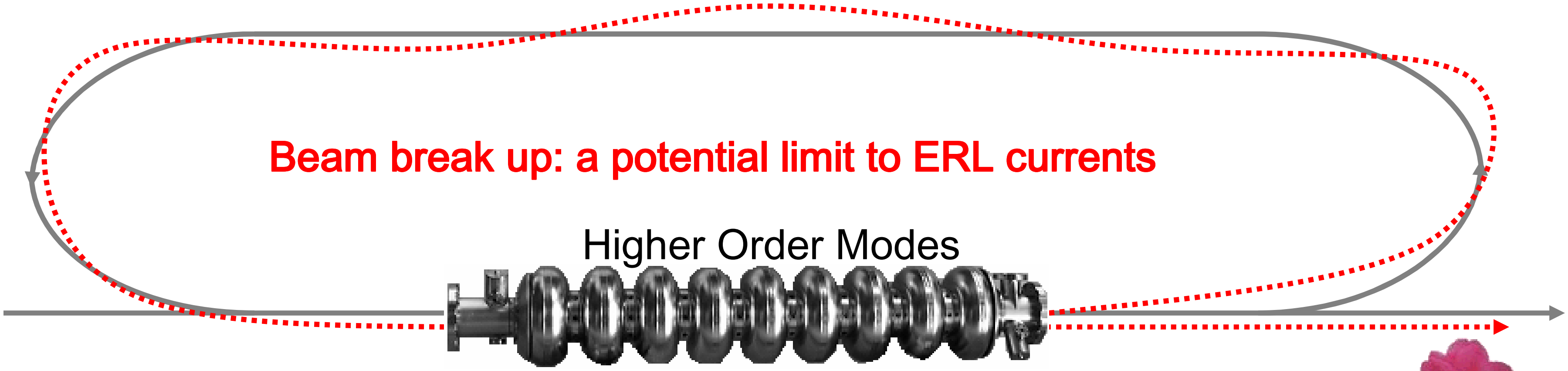




- Run cavity at highest possible loaded Q for Energy recovery linac mode, i.e. without beam loading
- But: The higher the loaded Q, the maller the cavity bandwidth!

BBU: Collective Instabilities

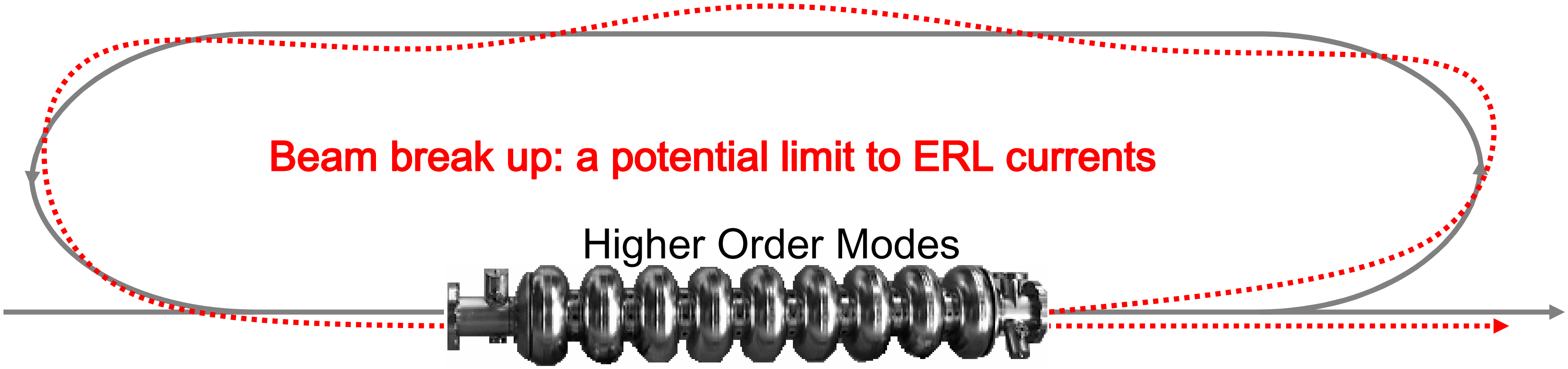
CHESS & LEPP



$$V_x(t) = T_{12}\,\tfrac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

- Similar instabilities would occur in the Linear Collider

BBU: Collective Instabilities



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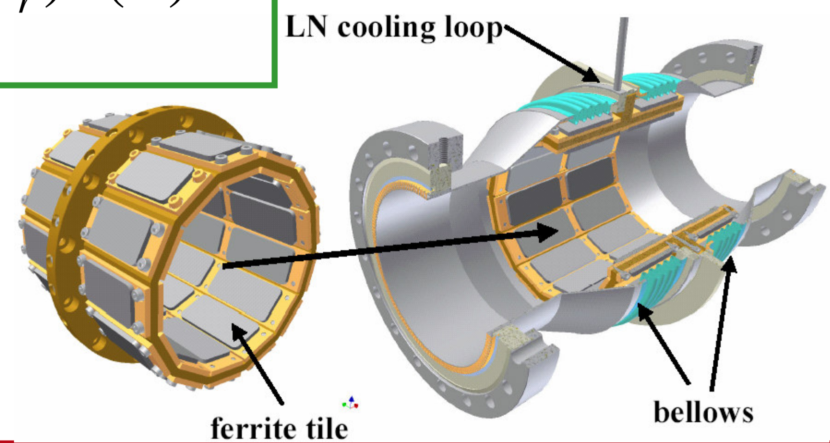
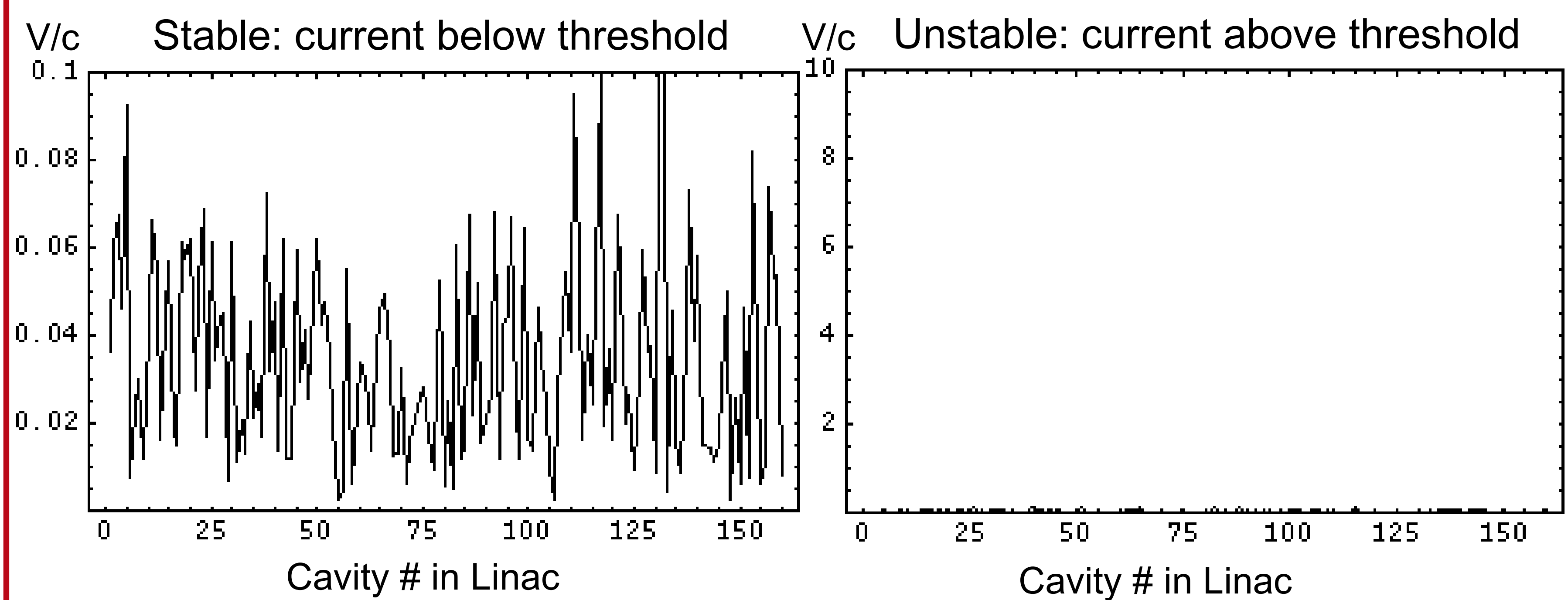


HOM with BBU: Starting from Noise



Ion accumulation in the beam potential

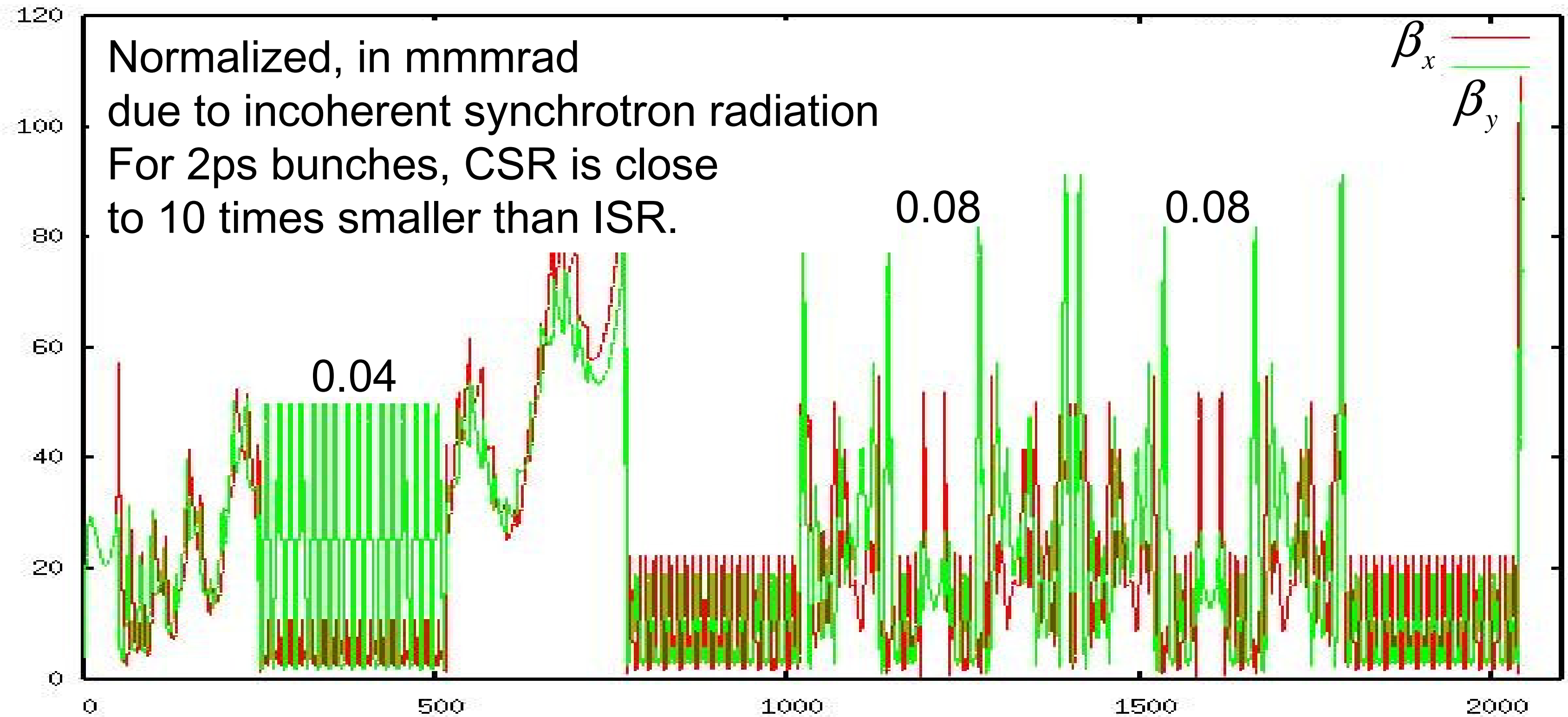
Ion are quickly produced due to high beam density

Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

- Ion accumulate in the beam potential. Since the beam is very narrow, ions produce an extremely steep potential – they have to be eliminated.
- Conventional ion clearing techniques can most likely not be used:
  1) Long clearing gaps have transient RF effects in the ERL.
  2) Short clearing gaps have transient effects in injector and gun.
- DC fields of about 150kV/m have to be applied to appropriate places of the along the accelerator, without disturbing the electron beam.

Emittance growth along the X-ray ERL

CHESS & LEPP



A mini-workshop on ultra low emittance light-sources in July addressed this issue.

Other analyzed sources of emittance growth:

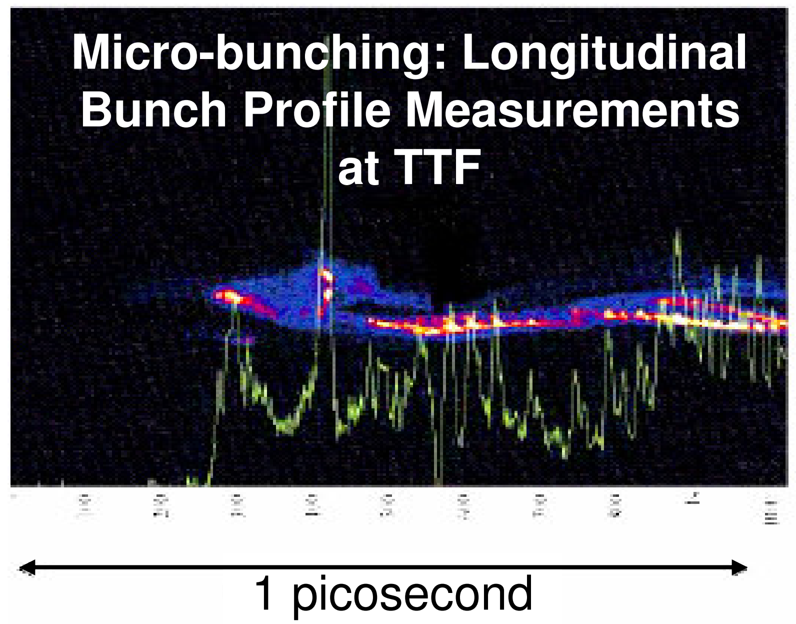
Coupler kick → 7 % of 10^{-6}m emittance
→ 30 % of 10^{-7}m emittance

Bright Electron Source and ERL

CHESS & LEPP

Aspects of x-ray ERL that are of general relevance for future accelerators

- Bright electron beams, gun developments for ILC and beyond.
- Component and technology development
- Space charge dominated beams
- Coherent Synchrotron Radiation
- Bunch compression



First quantitative CSR/bunch length measurements (A.Sievers et al. at Cornell)

- **Ongoing measurement developments**

Coherent Synchrotron Radiation

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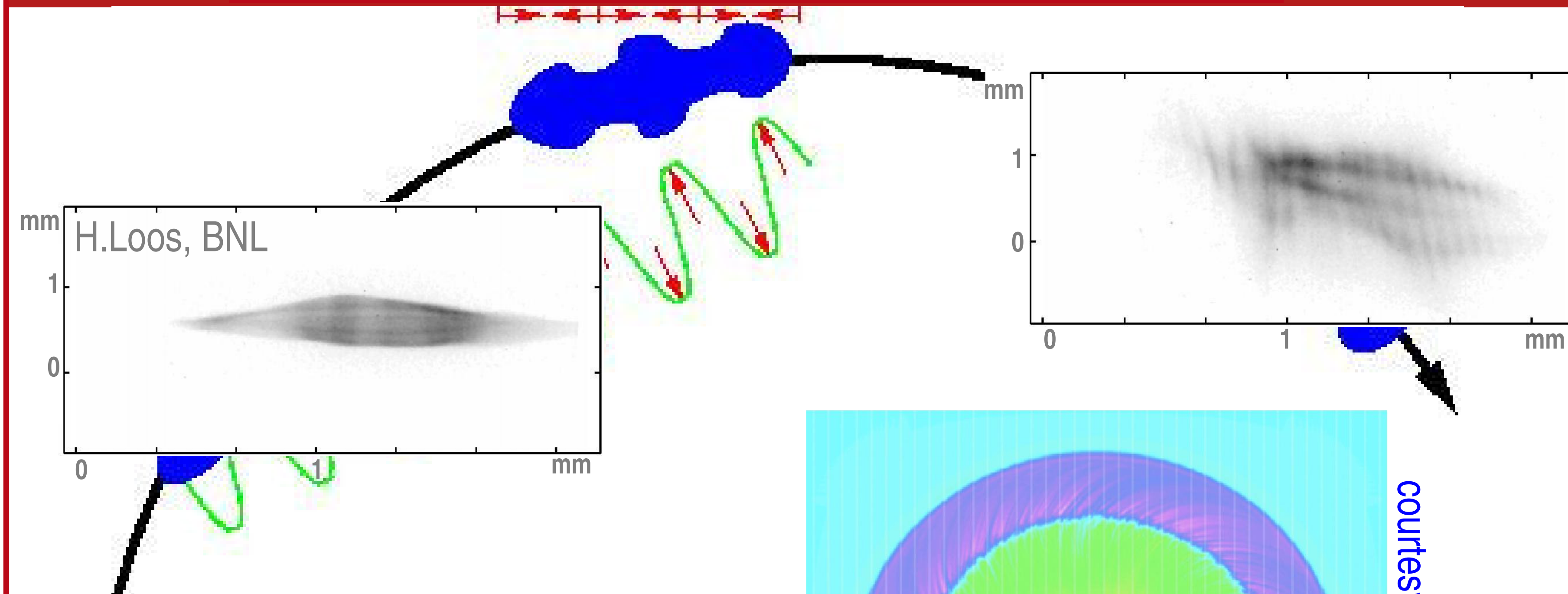
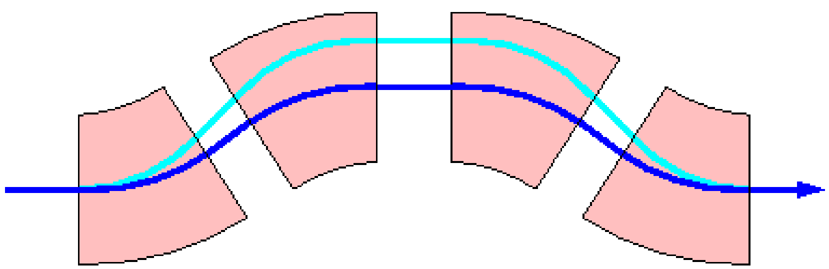
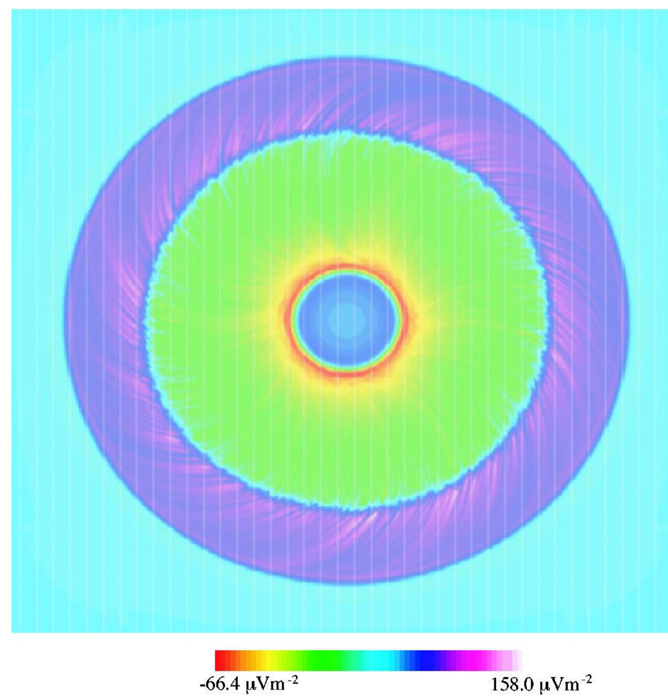




Bunch compressor in an ERL



courtesy Bjoern Schmekel

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R&D toward an X-ray ERL

- Full average current injector with the specified emittance and bunch length
- Emittance preservation during acceleration and beam transport:
  - Nonlinear optics (**code validation at CEBAF**), coherent synchrotron radiation (**JLAB,TTF**), space charge
- Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (**TTF**)
- Dependence of emittance on bunch charge
- Stable RF control of injector cryomodule at high beam power
- Stable RF control of main linac cavities at high external Q, high current, and no net beam loading (**JLAB to 10mA**)
- Understanding of how high the main linac external Q can be pushed (**JLAB**)
- Study of microphonic control using piezo tuners (**JLAB, SNS, NSCL, TTF**)
- Recirculating beam stability as a function of beam current with real HOMs, and benchmarking the Cornell BBU code (**JLAB**)
- Feedback stabilization of beam orbit at the level necessary to utilize a high brightness ERL
- Photocathode operational lifetime supporting effective ERL operation
- Performance of high power RF couplers for injector cryomodule
- Demonstration of non-intercepting beam size and bunch length diagnostics with high average current at injector energy and at high energy (**TTF**)
- HOM extraction and damping per design in injector and main linac (**code validation from Prototype**)
- Performance of HOM load materials to very high frequency
- Performance of full power beam dump
- Detailed comparison of modeled and measured injector performance
- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (**JLAB**)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (**JLAB**, **NAA**)
- Precision path length measurement and stabilization (**Prototype**, **JLAB**)

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R&D toward an X-ray ERL

1. Recirculating beam stability (**JLAB – under way**)
2. Diagnostics with high average current at injector energy and at high energy (**TTF – under way**)

   Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (**TTF – under way**)

4. Stable RF control of main linac cavities at high external Q, high current, and no net beam loading

   (**JLAB to 10mA – under way**)

   Understanding of how high the main linac external Q can be pushed (**JLAB – under way**)

   Study of microphonic control using piezo tuners (**JLAB, SNS, NSCL, TTF**)

- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (**JLAB**)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (**JLAB**)
- Precision path length measurement and stabilization (**Prototype**, **JLAB**)

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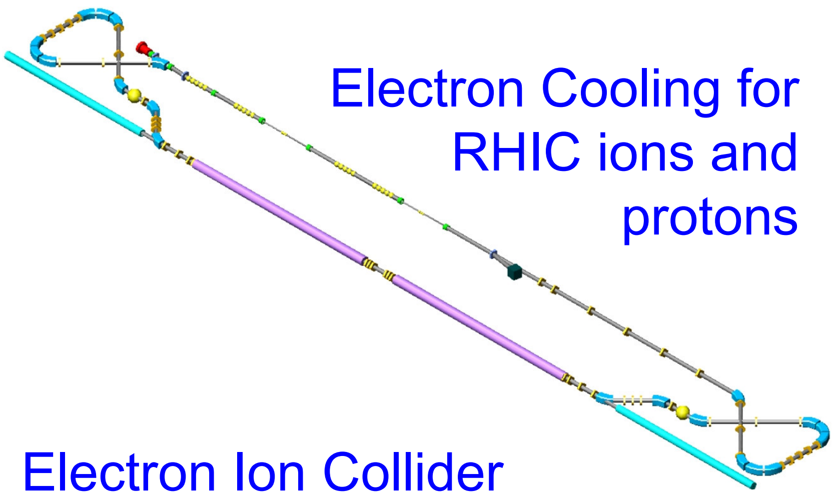
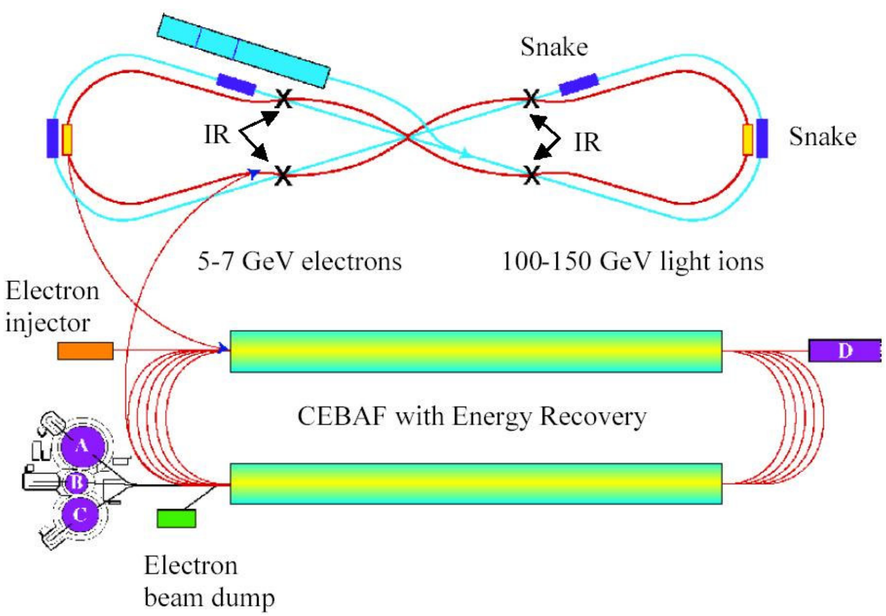
Non Light Source ERLs

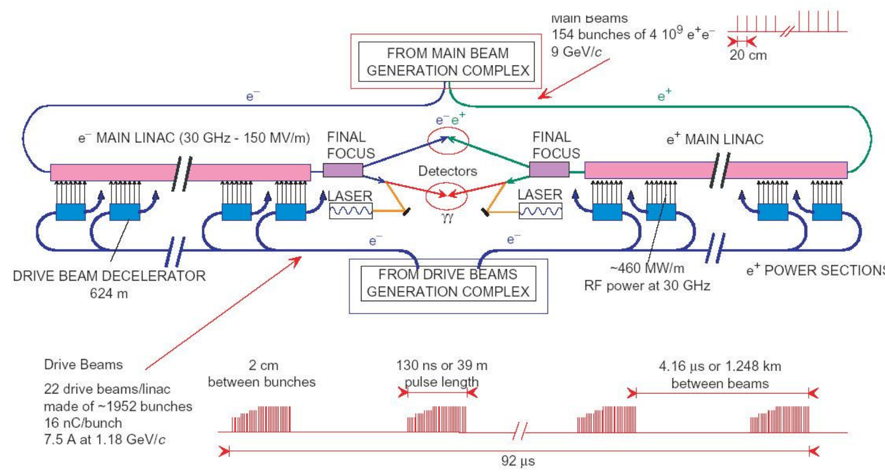
Electron Cooling for RHIC ions and protons



Electron Ion Collider



CLIC-like drive beam ERL



A low emittance RF source
Could save the electron
damping ring in a LC

Accelerator Physics @ CESR

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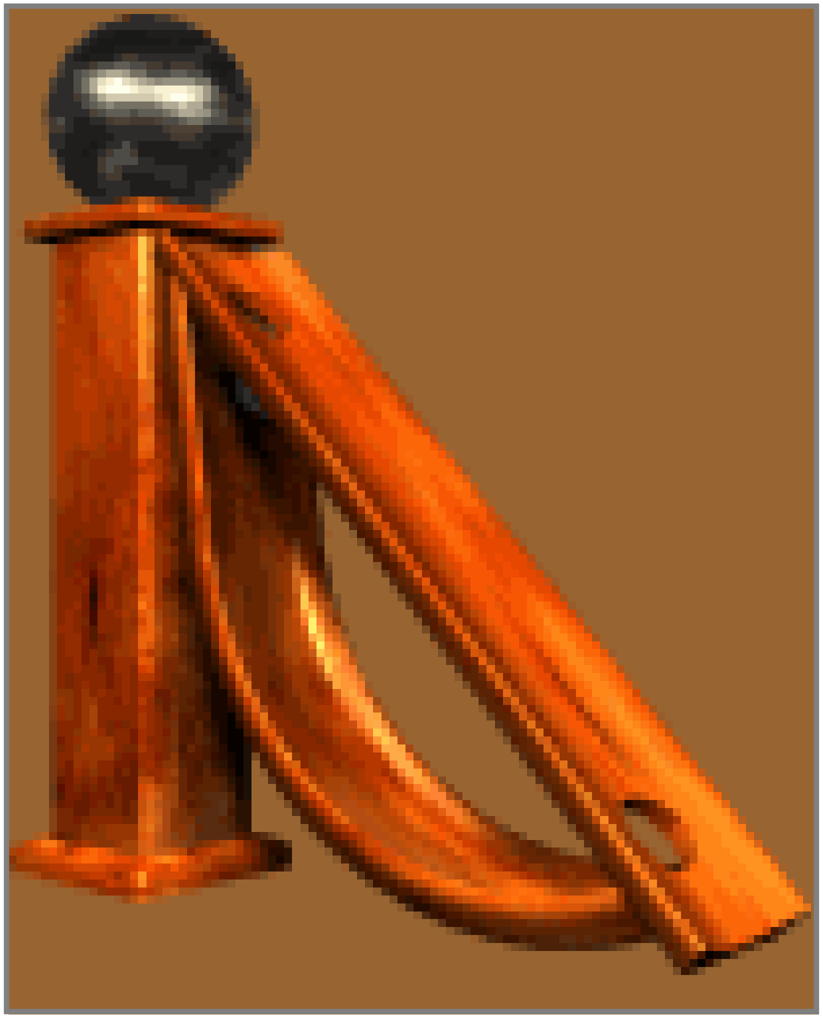

Accelerator Physics @ CESR

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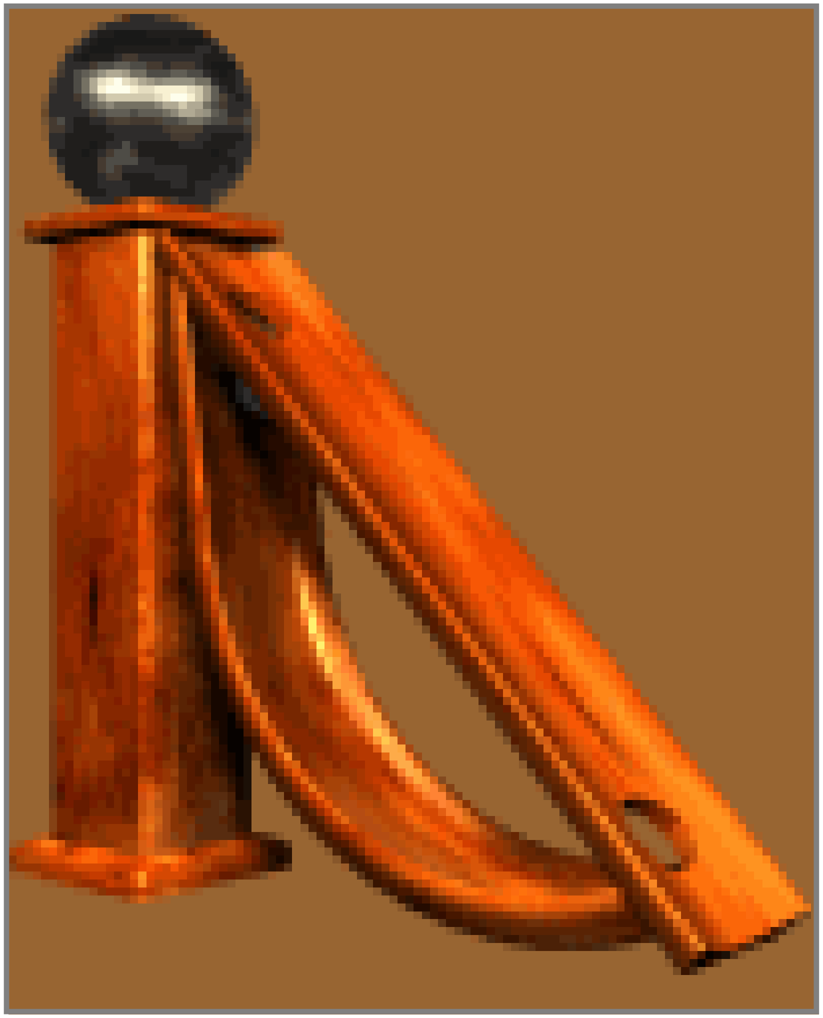

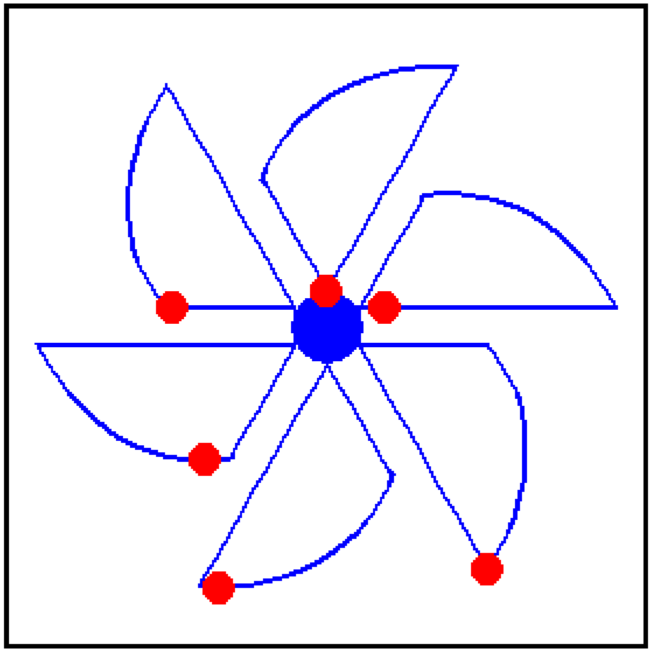

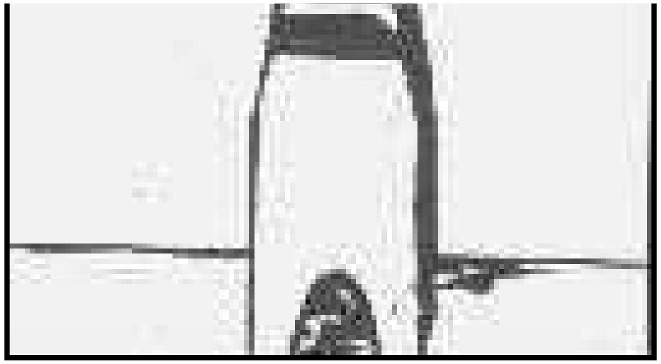

Accelerator Physics @ CESR

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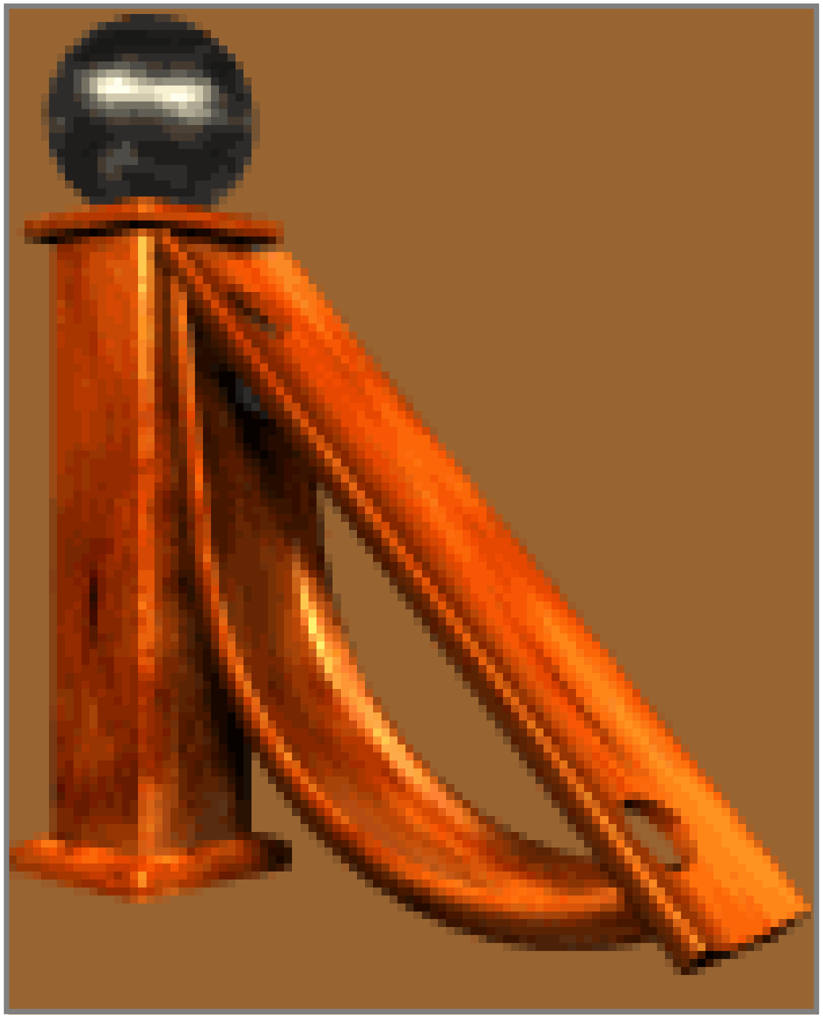

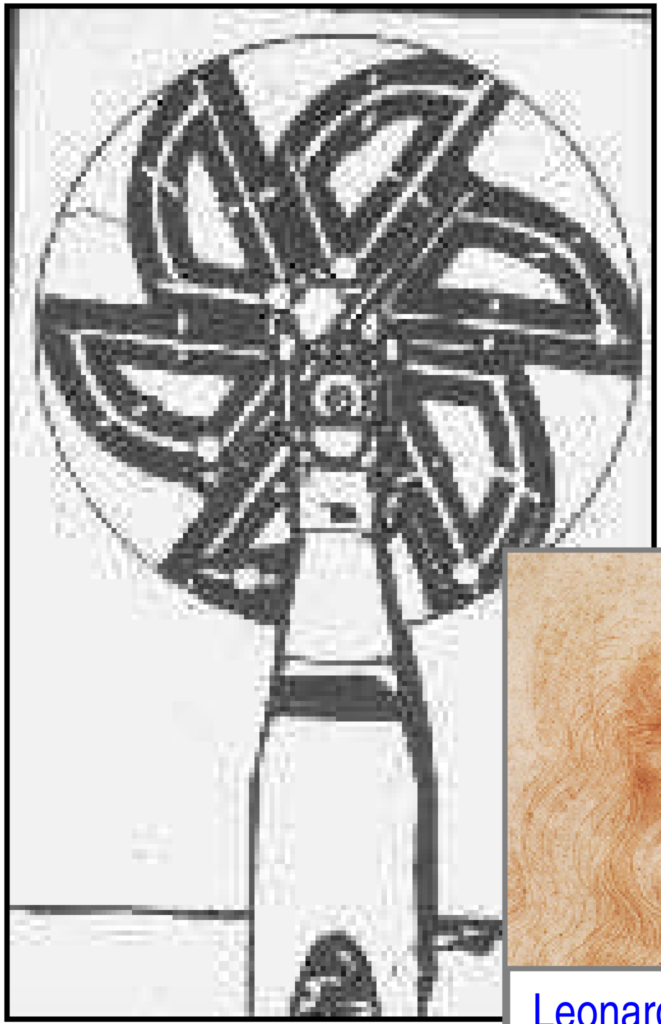

Leonardo da Vinci
(1452-1519)

Optimistic Outlook

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- The ERL parameters are **dramatically** better than present 3rd generation storage rings
- The use of ERL microbeams, coherence, and ultra-fast timing will lead to new unique experiments that can be expected to transform the way future x-ray science experiments are conducted
- Most critical parameters to achieve in an ERL are therefore, narrow beams, small emittances, short bunches, at large currents.

Parameter	APS ring	ERL*	Gain factor
Rms source size(µm)	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
x-ray beamsize	100nm - 1µm	1 nm	100 to 1000
Coherent flux x-rays/s/0.1% bw	3×10^{11}	9×10^{14}	3,000
Rms duration	32 ps	0.1 ps	over 300

Diagnostics for Prototyping

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- slit & TM110 for slice emittance measurements
- flying wire
- CSR spectrum measurements for bunch profile autocorrelation