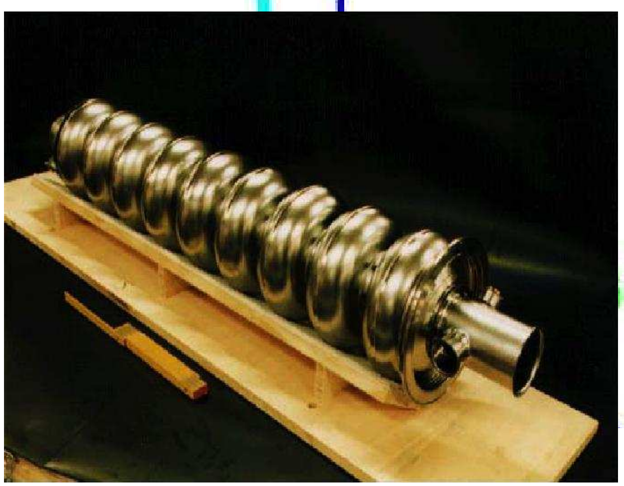
01/05/2004

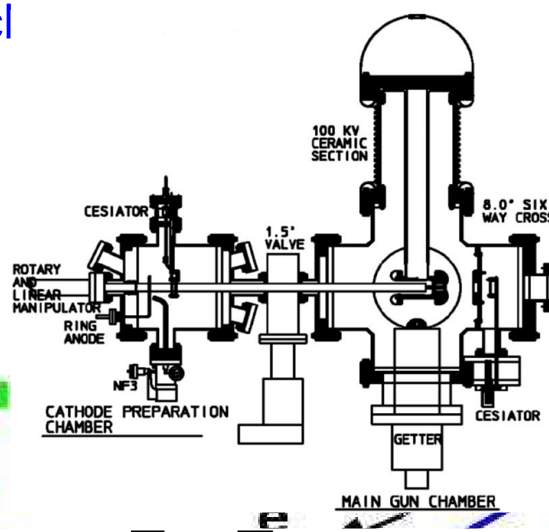
The Cornell ERL Project

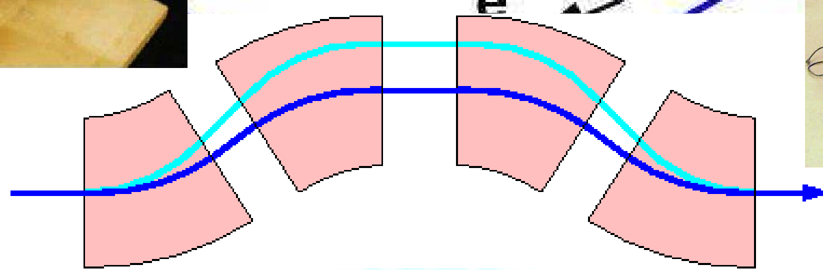
Georg Hoffstaetter (LEPP)

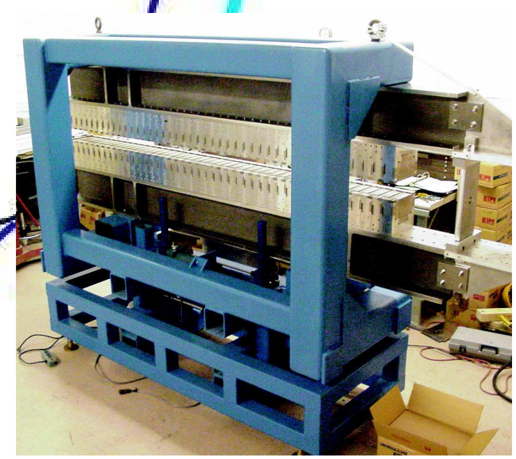
for the ERL endeavor

B.Barstow, I.V.Bazarov, S.Belomestnykh, D.Bilderback, J.Brock, K.Finkelstein, S.Gruner, G.H.Hoffstaetter, Alex Kazimirov, M.Liepe, Y.Lin, H.Padamsee, D.Sagan, V.Shemelin, Qun Shen, C.Sinclair, R.Talman, M.Tigner, V.Veshcherevicl









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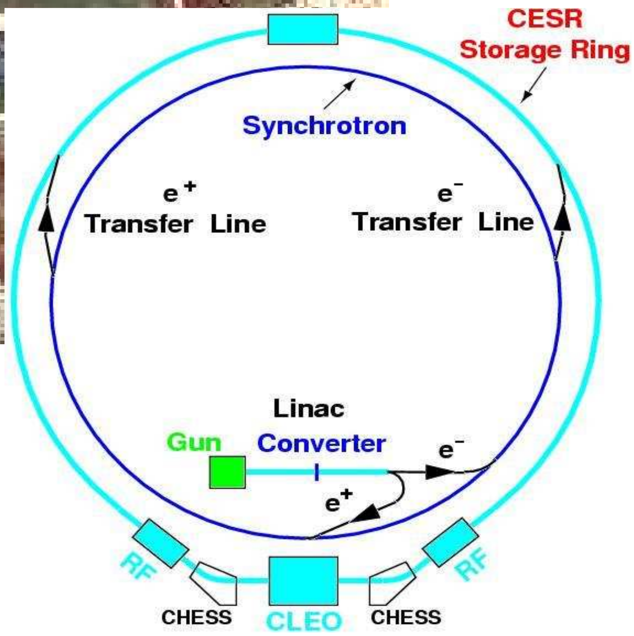
Could an ERL use the CESR tunnel



- An extension of the tunnel could easily conflict with buildings
- But the tunnel sealing is at about 836 ft ASL whereas
- The base of the deepest relevant building's foundation is at 862ft ASL, yielding about 10m of space.

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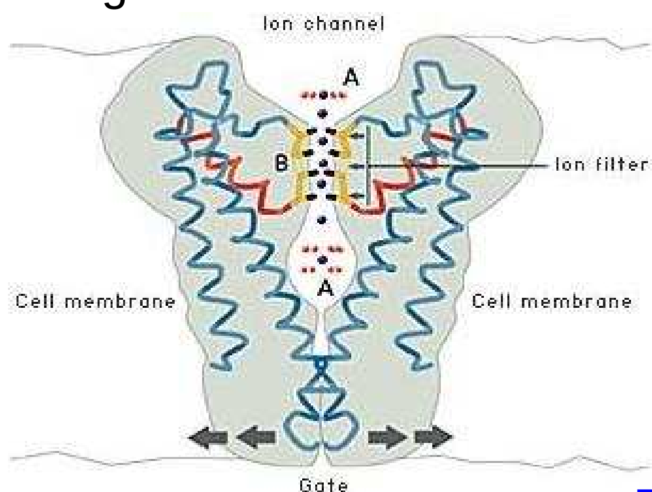
Synchrotron Radiation @ Cornell

- 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

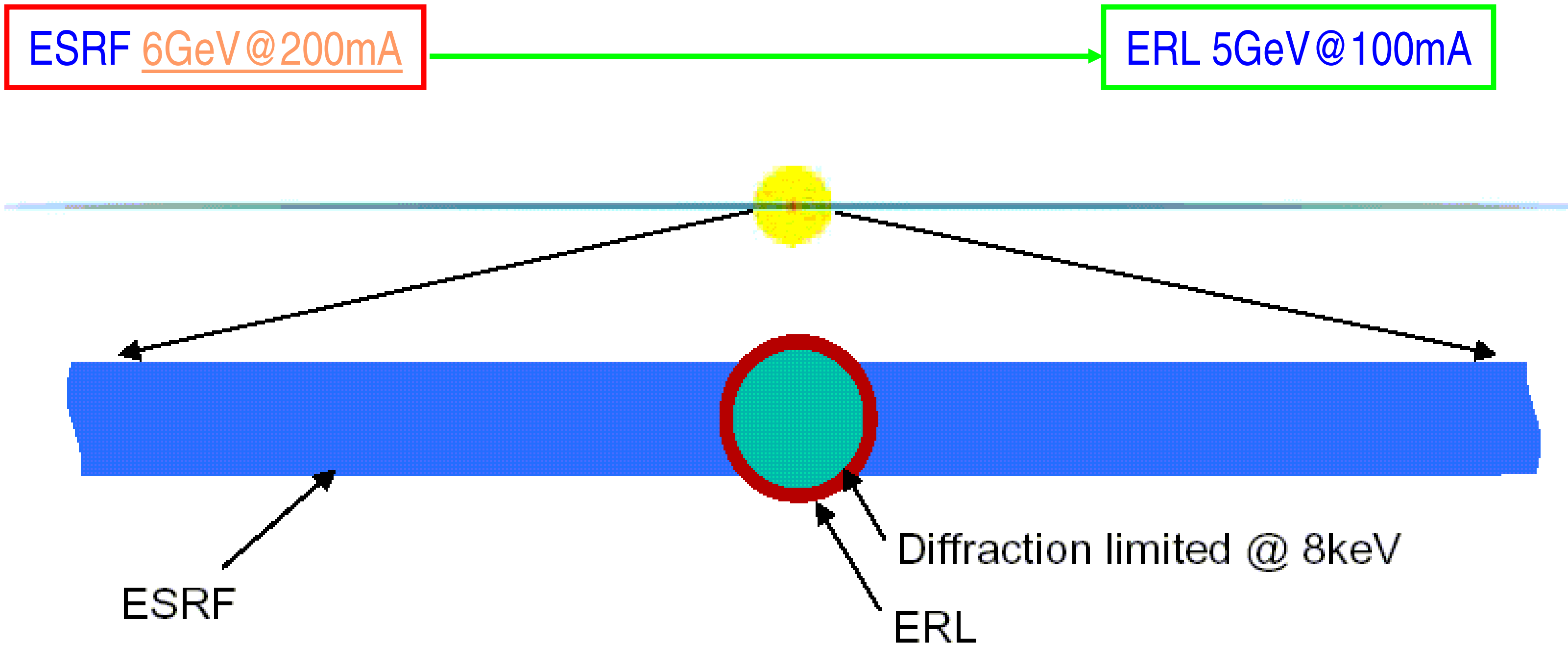


Roderick MacKinnon

Beam size in a linear accelerator

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.**



courtesy Ivan Bazarov

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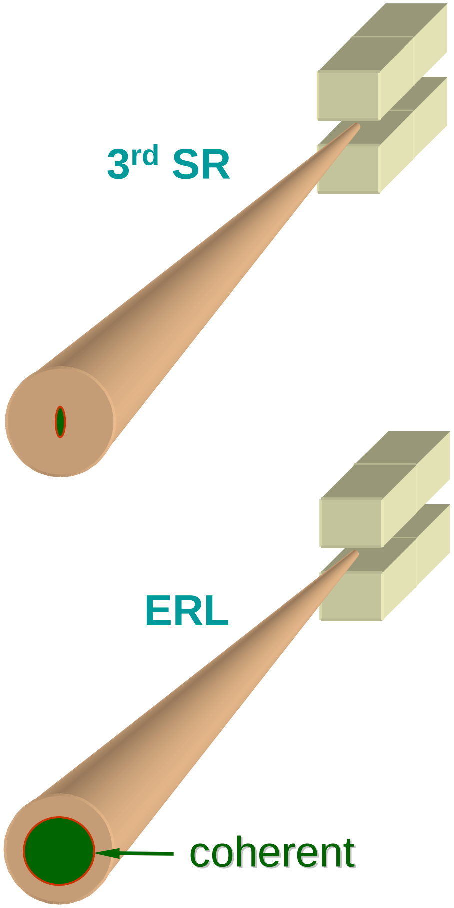
Smaller Beam z   more Coherence

Recall: Physics Colloquium by Qun Shen last Monday

- 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

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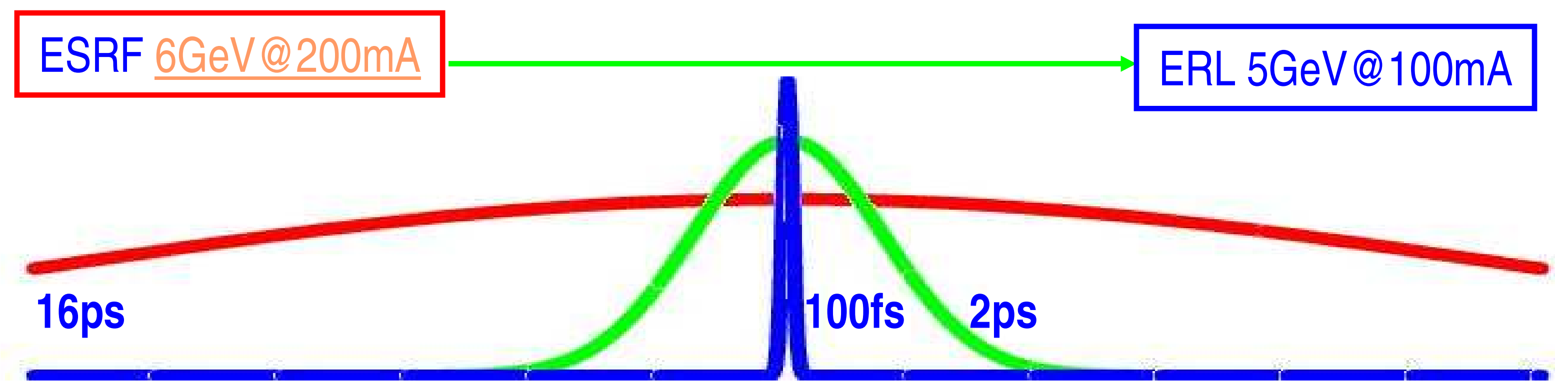
Bunch length in a linac

- The bunch length can be made much smaller than in a ring

- 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.



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'Fireworks' curves

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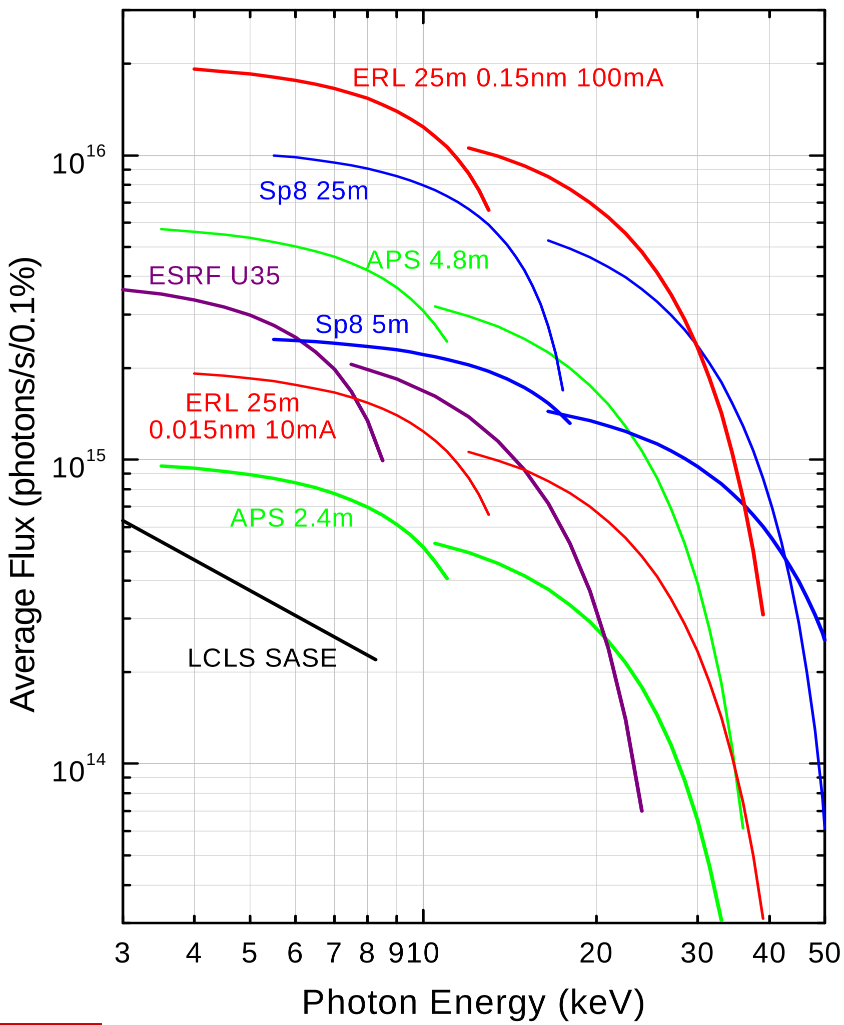

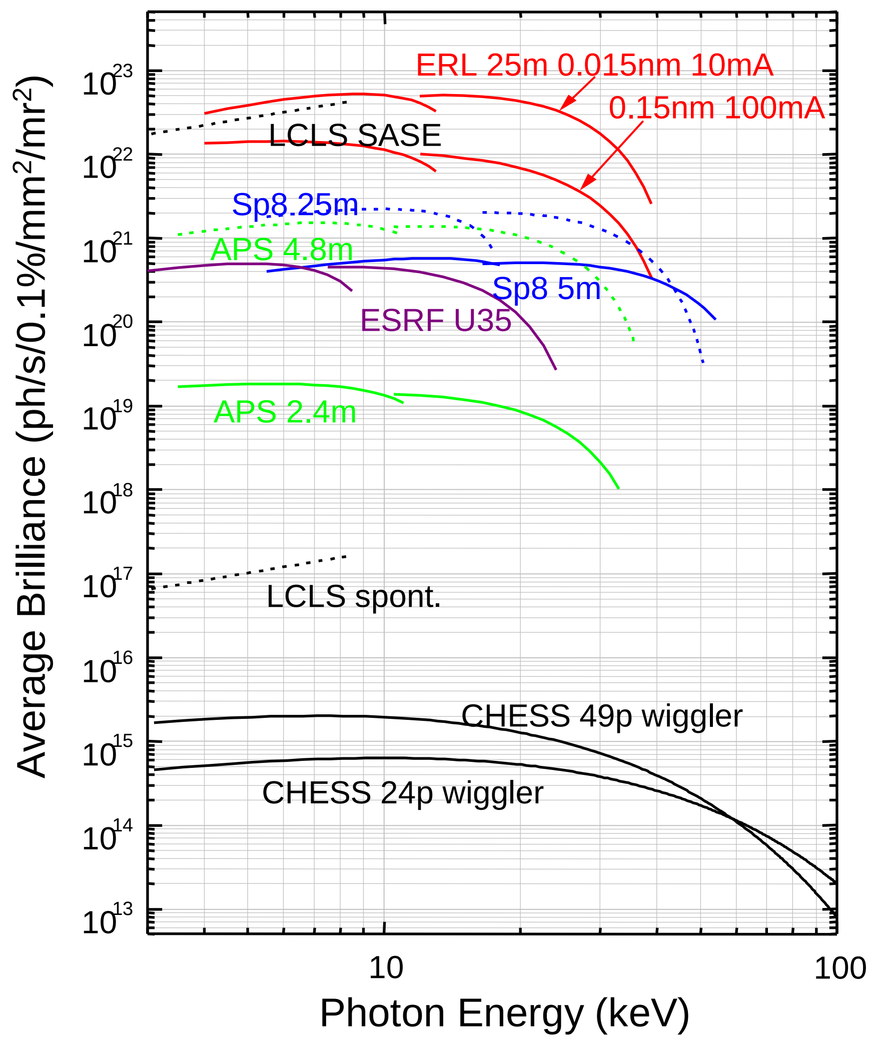

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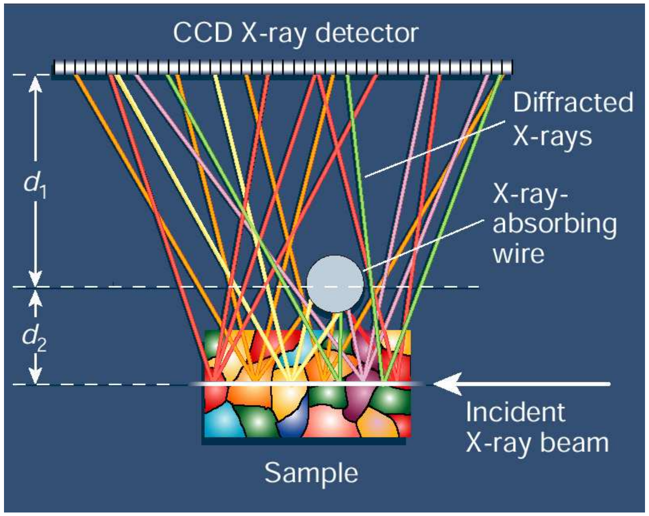
Microprobe

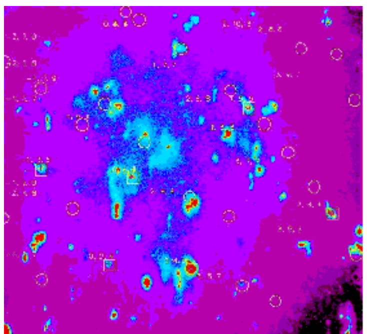
Cargill (intro to Larson), Nature 2002



Differential-Aperture X-ray Microscopy (DAXM)

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

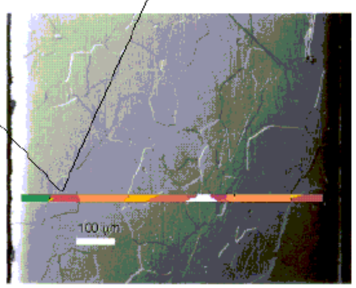
ERL: 100-1000 times smaller area



Orientation of crystals and

Stress and strain in crystals

3-D Studies of Structure



Ben Larson (2000), ERL science workshop, Cornelll

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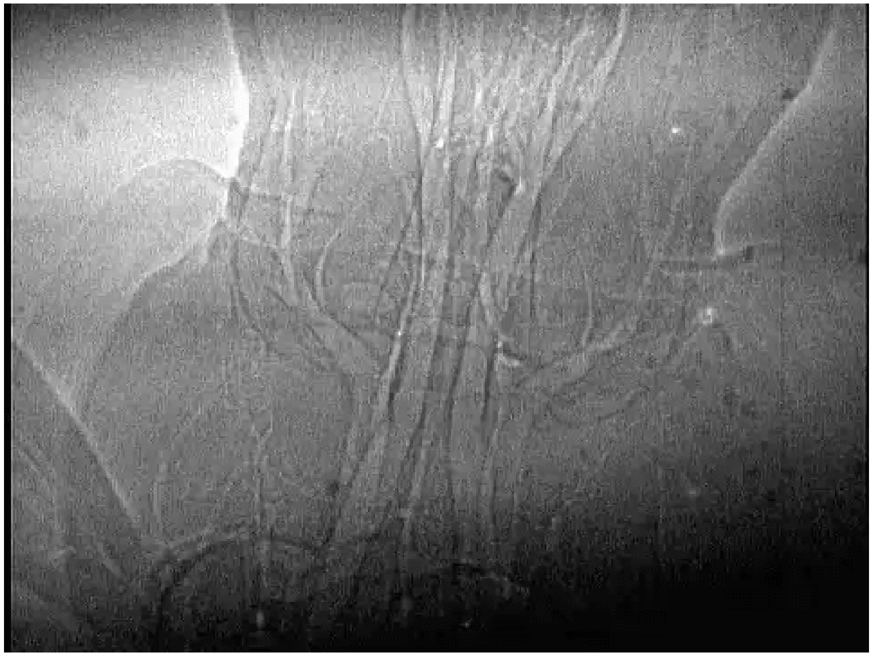
Real-Time: Insect Breathing

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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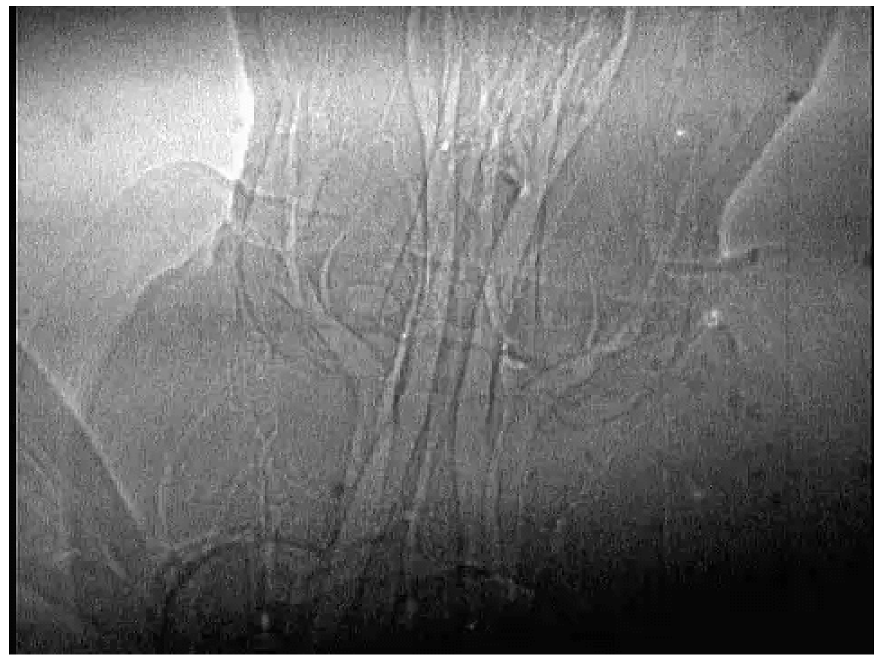
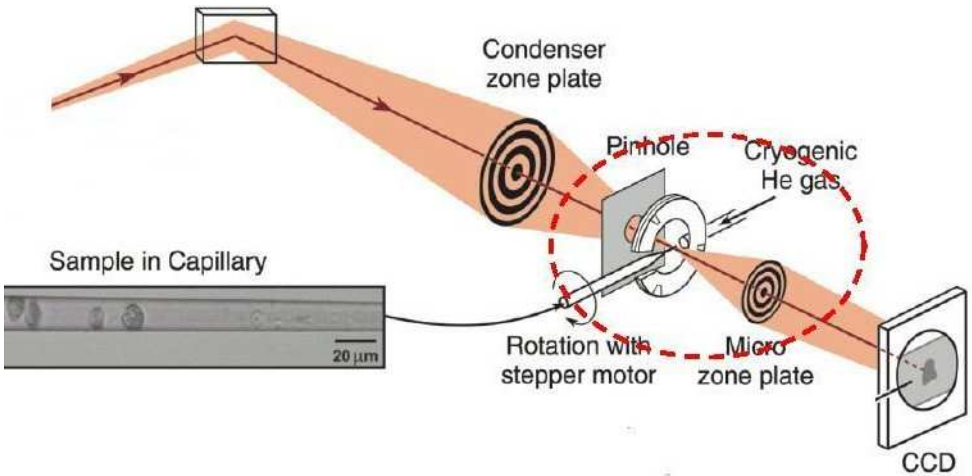


- ERL would extend these studies to much higher lateral resolution (sub μm) and faster time scales

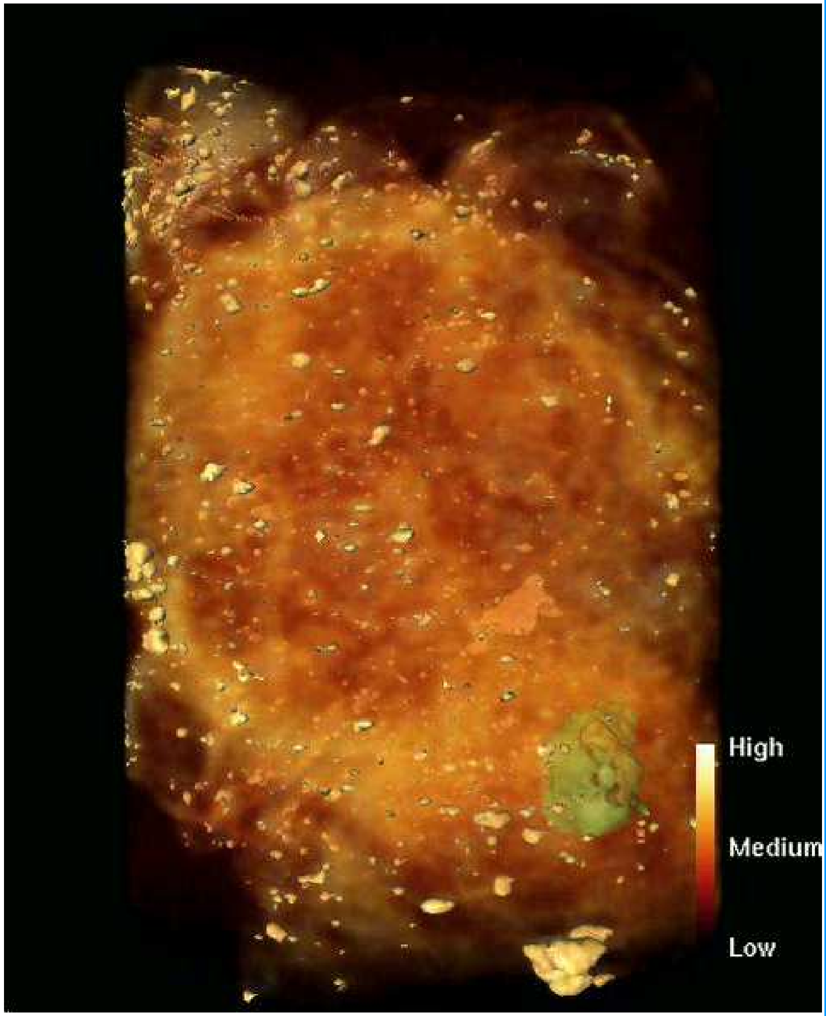
3D Tomograph of Cells



ERL: 100-1000 more brightness

Drosophila embryonic cell
(G. Schneider, LBNL)

Green = nucleolus
Gold = sex-determining protein



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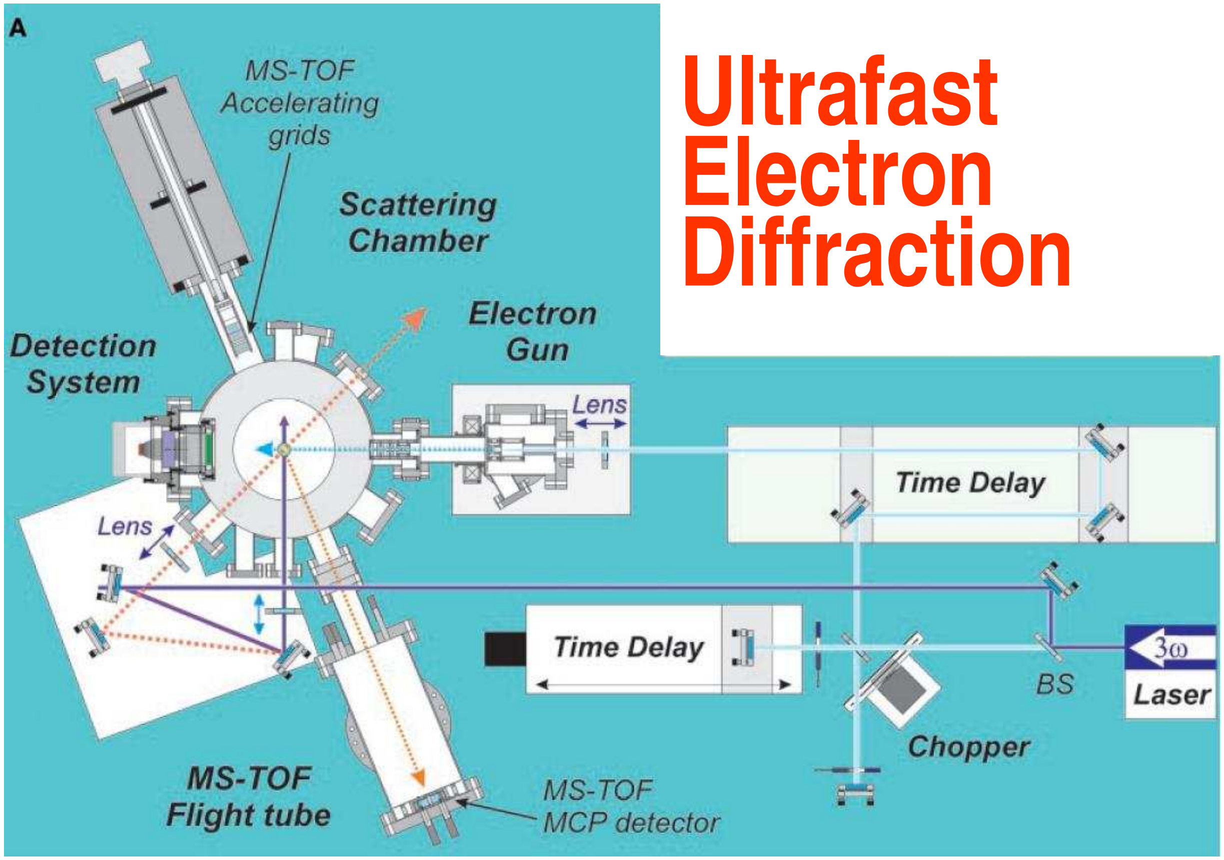
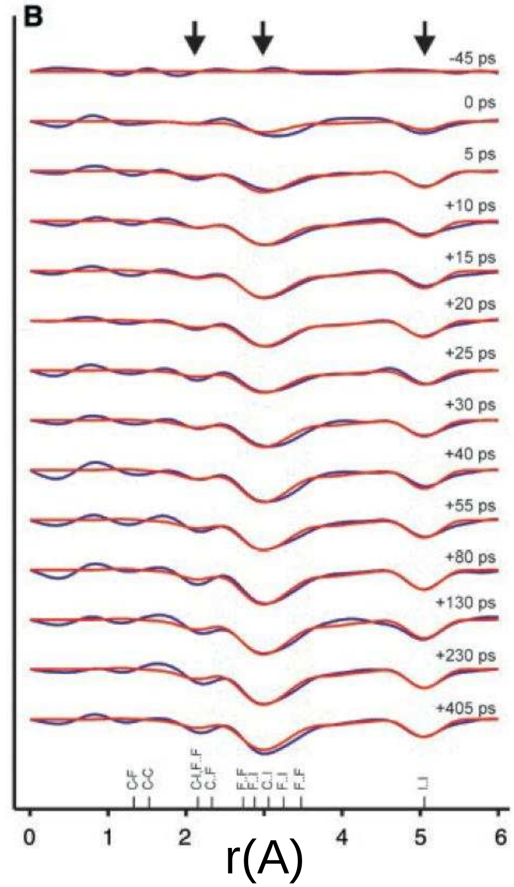
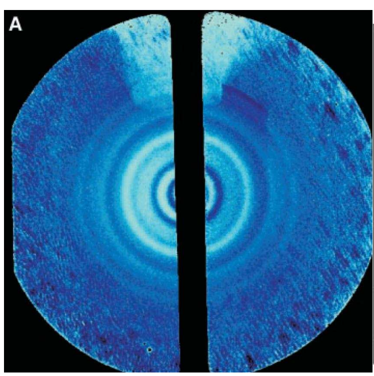
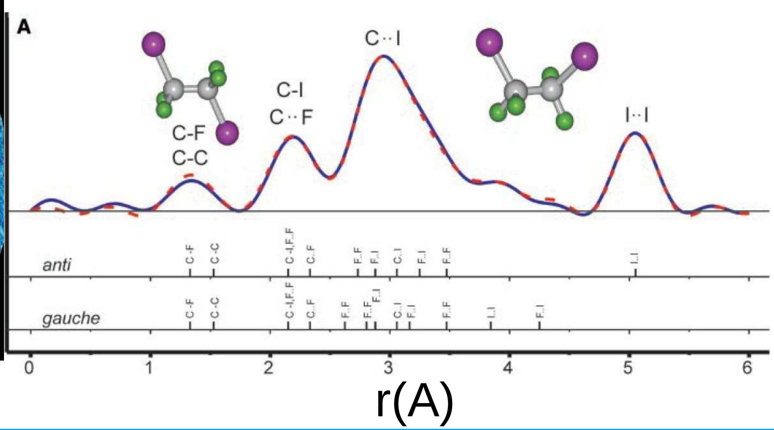
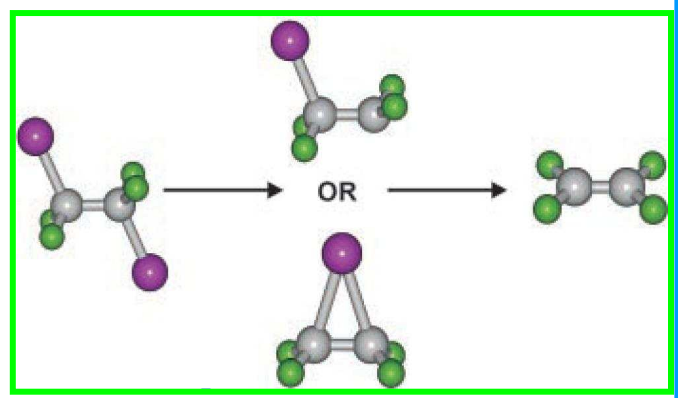
Ultrafast Electron Diffraction











Pro and Con for a Linac

The beam properties are to a very large extend 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.

Previous Energy Recovery Linacs

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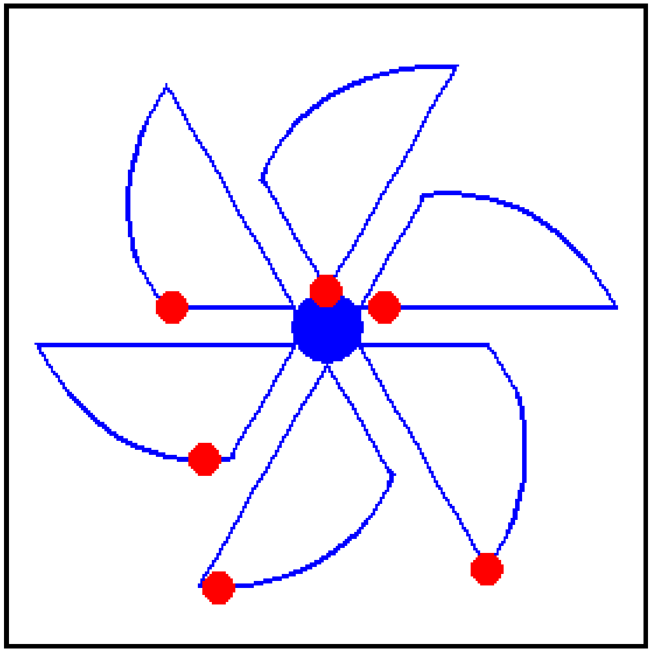
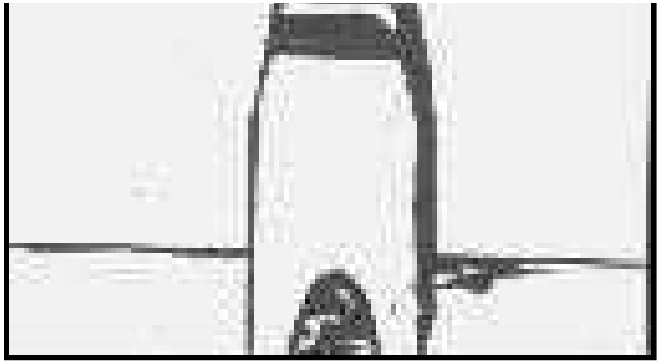
Previous Energy Recovery Linacs





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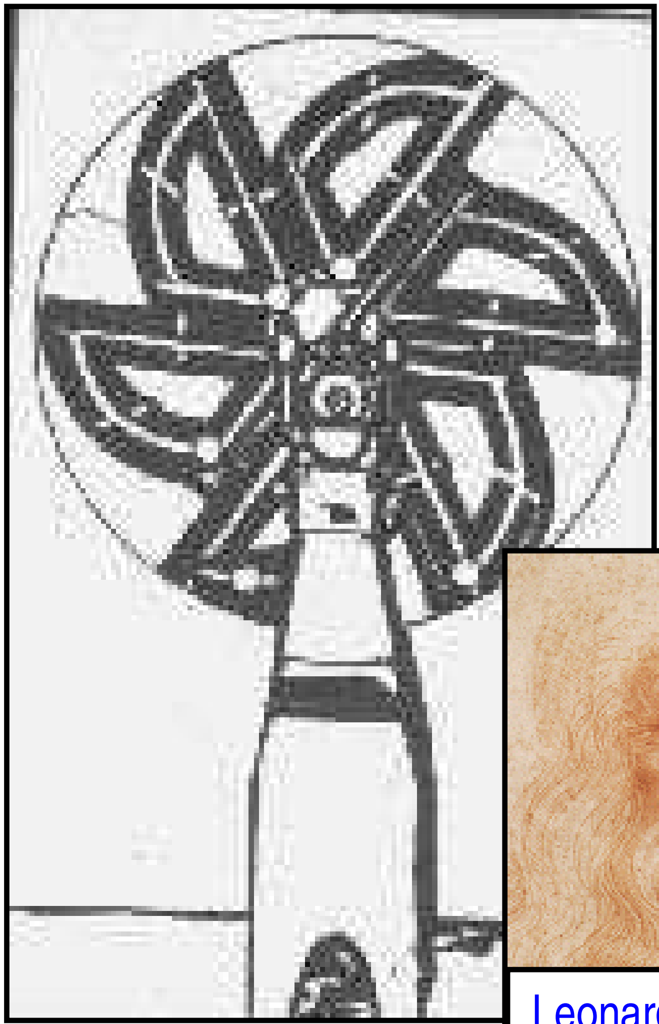
Previous Energy Recovery Linacs



Leonardo da Vinci
(1452-1519)

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"Now, why should that not work?"

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The Cornell ERL

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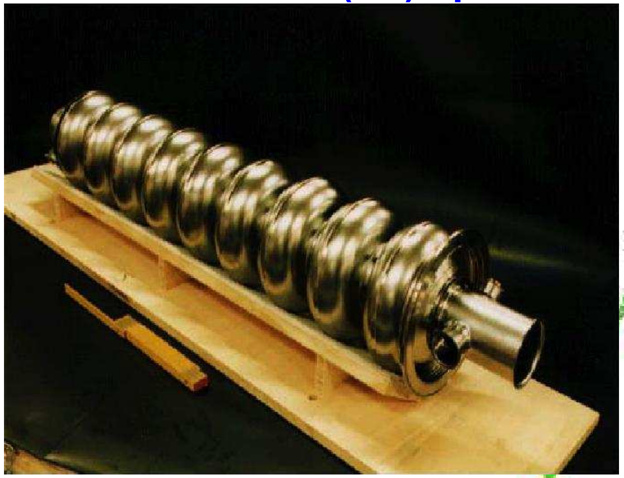
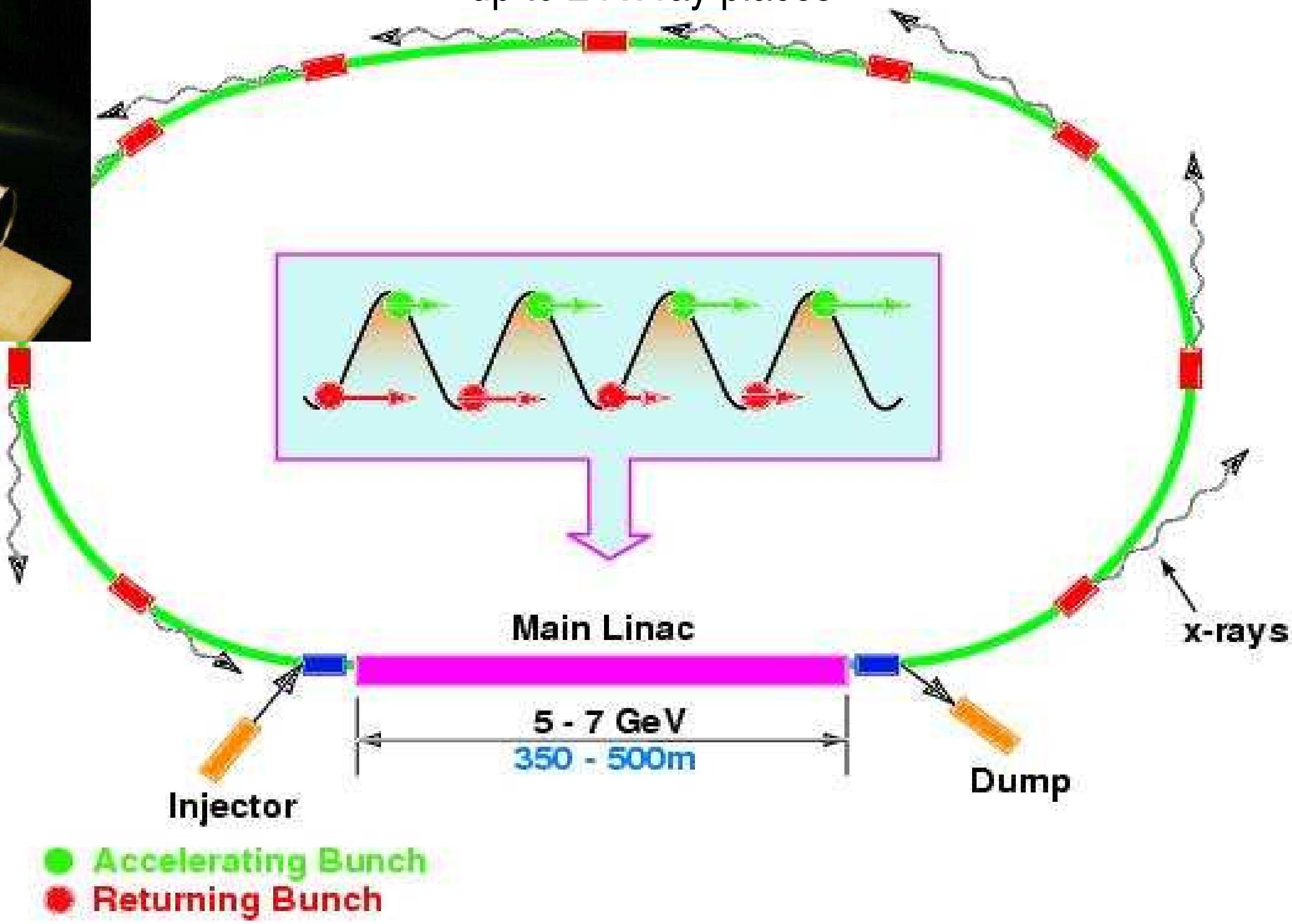
Superconducting cavities with continuous wave (cw) operation:





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Superconducting cavities

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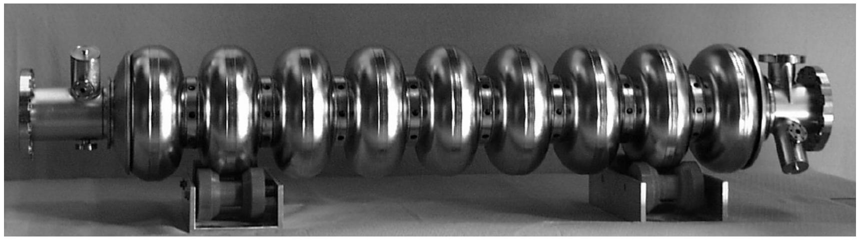

$Q = 10^{10}$

$E = 20MV/m$

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.

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ERLs in the World

After the success of high gradient super-conducting RF, several laboratories have worked on ERLs:

Upgrades of: TJNAF, JAERI

Light production: Brookhaven, Cornell, Daresbury, KEK, Novosibirsk

Electron Ion colliders: TJNAF

High energy electron cooling for RHIC: Brookhaven

Neither an electron source, nor an injector system, nor an ERL has ever been built for the required large beam powers and small transverse and longitudinal emittances.

- **A prototype at Cornell should verify the functionality**

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Limits to ERLs

Limits to Energy :

- Ø Length of Linac and power for its cooling to 2K

Limits to Current :

- Ø Beam Break Up (BBU) instability

for narrow beams :

- Ø Coulomb expulsion of bunched particles (Space Charge)
- Ø Radiation back reaction on a bunch (CSR)

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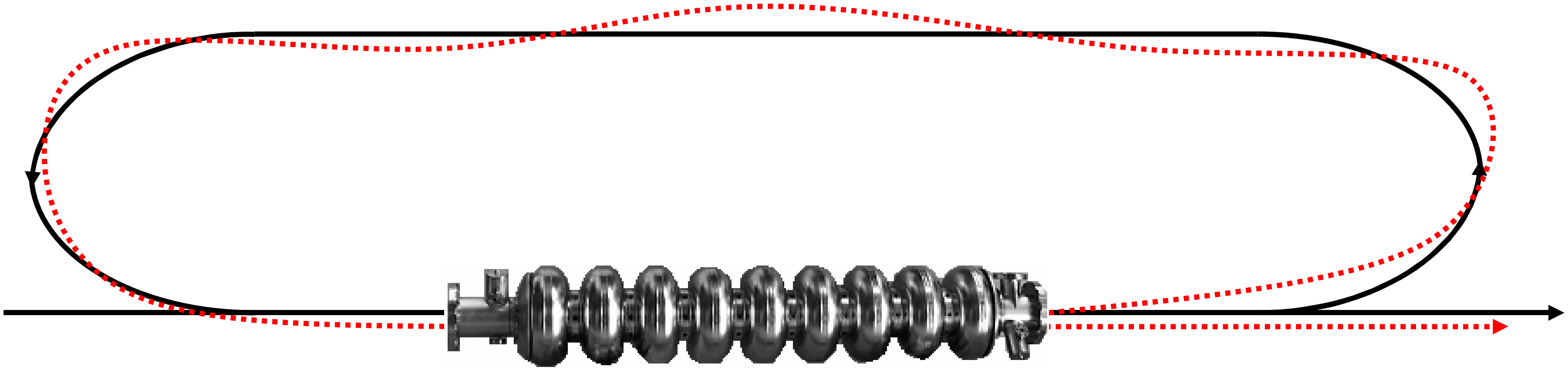
Instability with a single cavity and single Higher order mode



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

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

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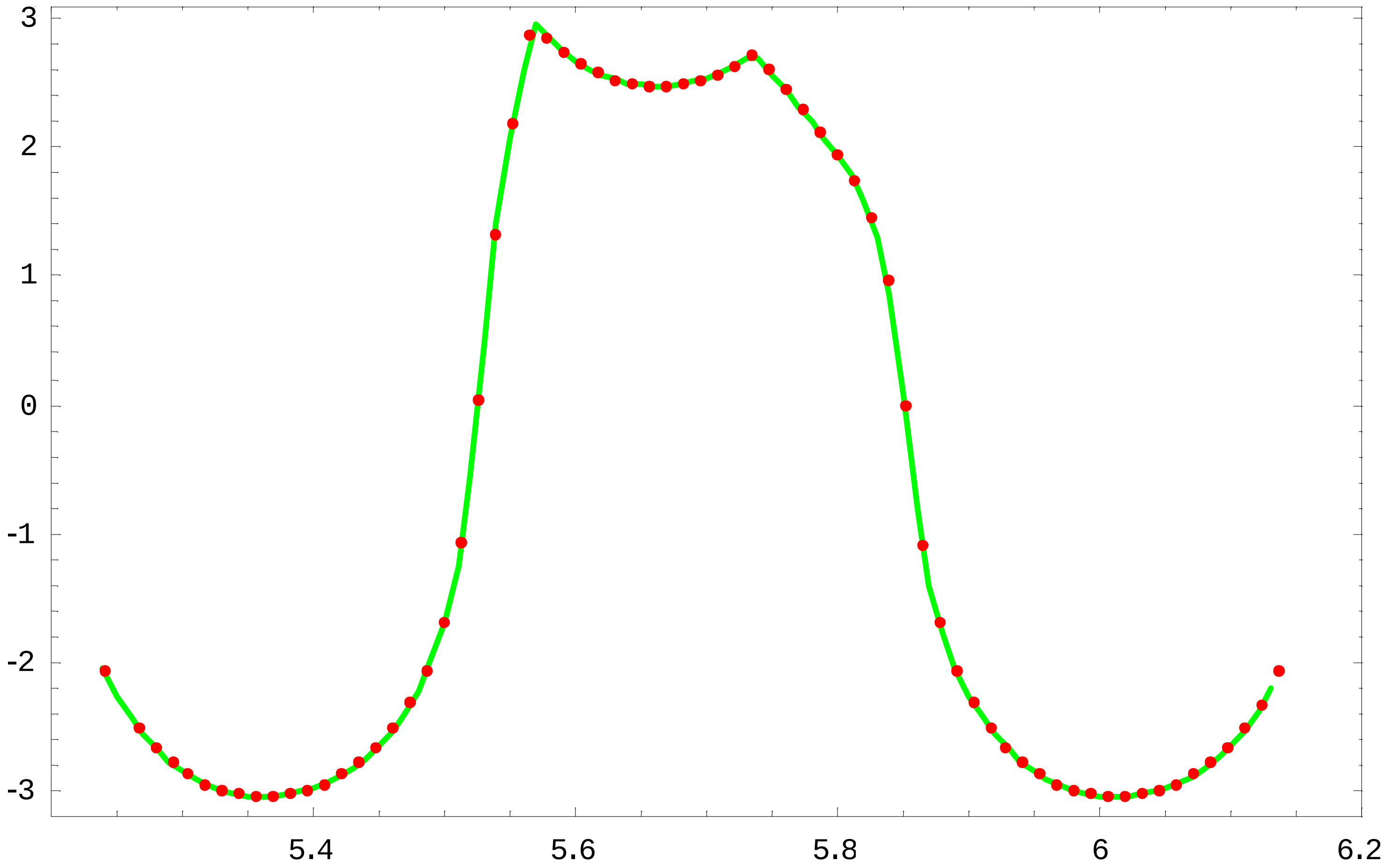
Comparison with Tracking



This agreement shows both, the quality of tracking and that of the theory.

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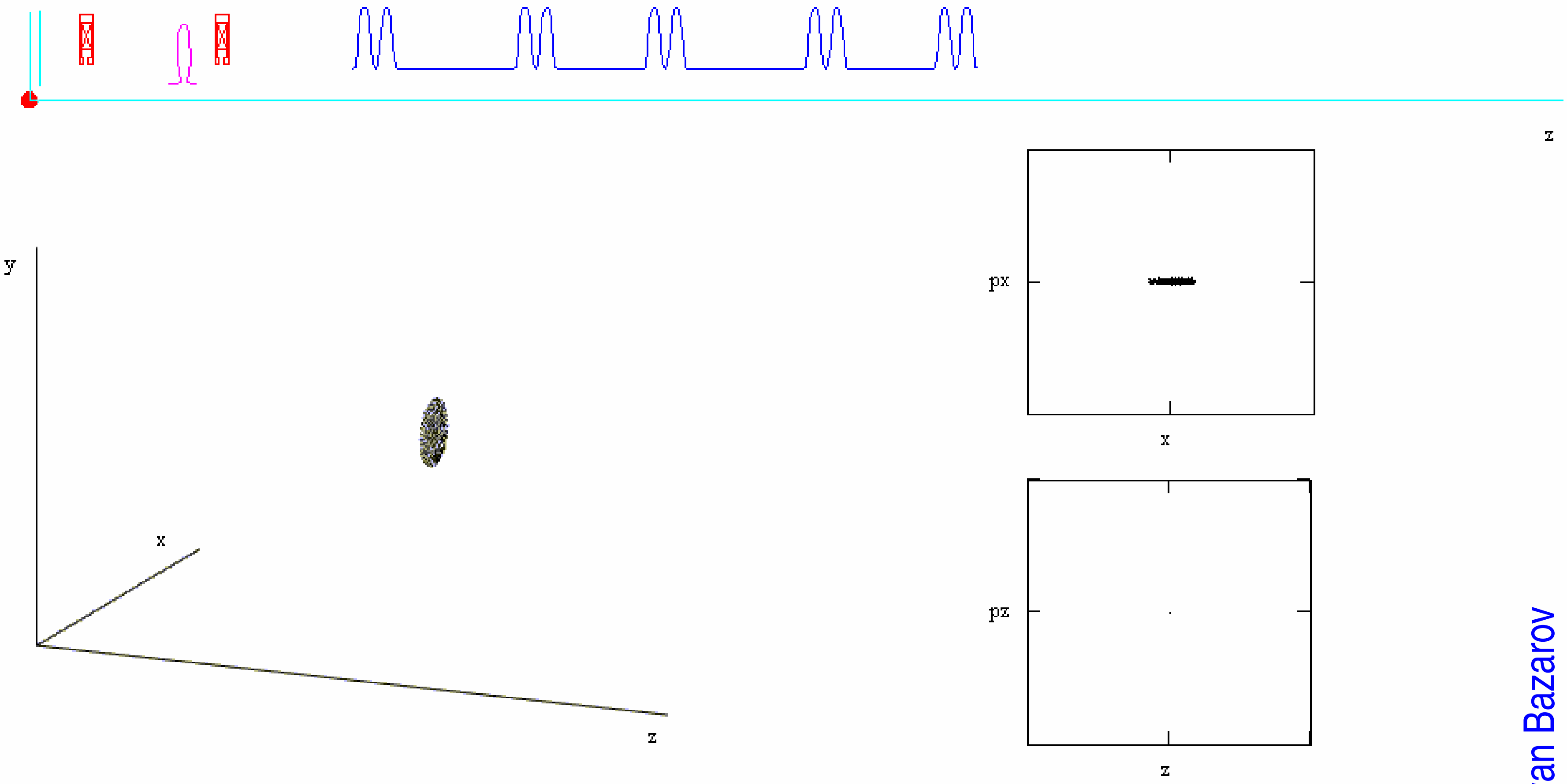
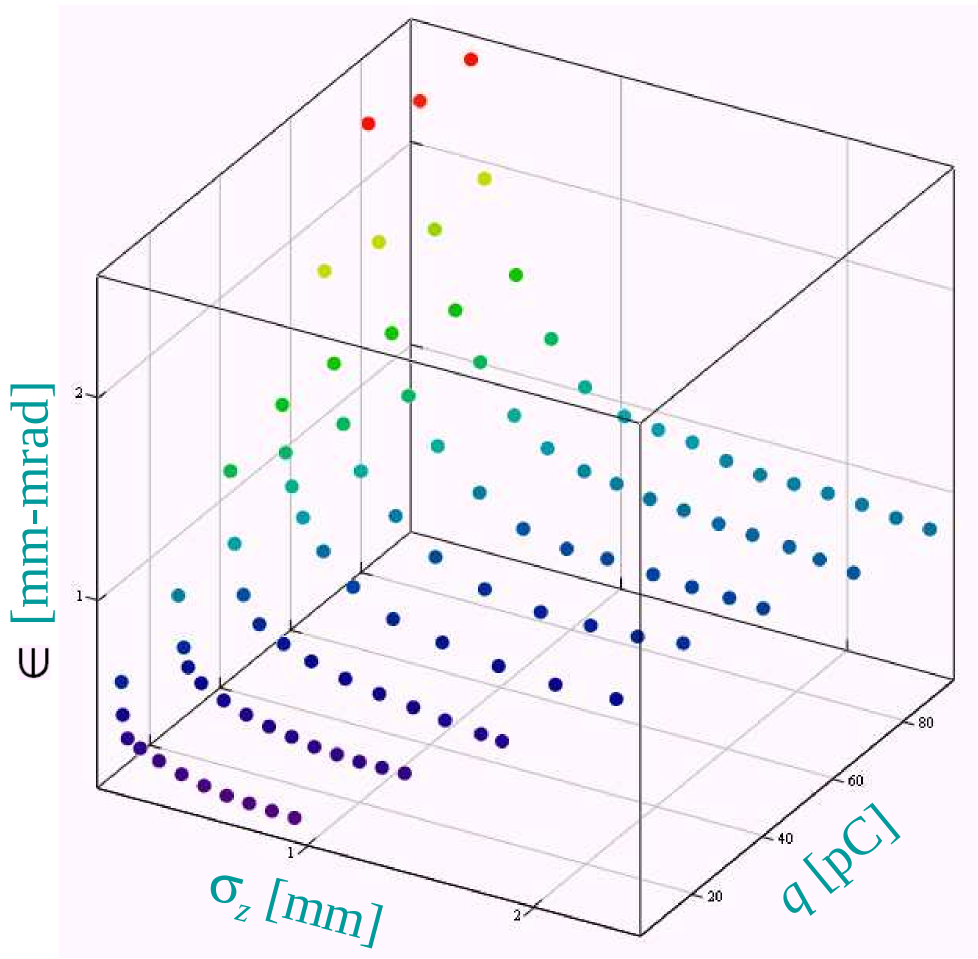
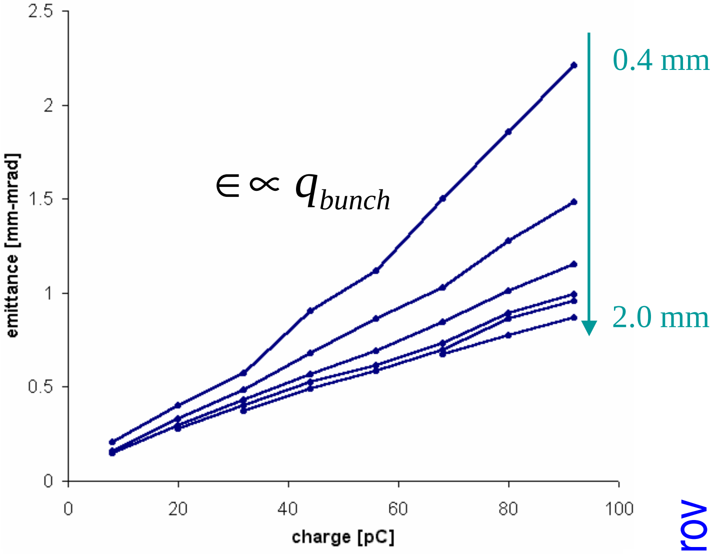
Gun simulations

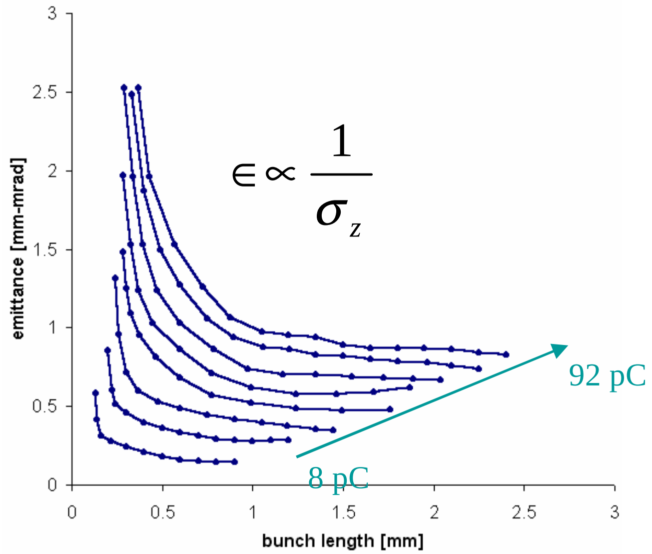


Curtsey Ivan Bazarov

Emit. scaling vs. charge, vs. bunch length







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Optimization results

- Optimization for emittances in case of transverse uniform, longitudinal gaussian 'laser' profile:
  - 0.086 mm-mrad for 8 pC/bunch
  - 0.58 mm-mrad for 80 pC/bunch
  - 5.3 mm-mrad for 0.8 nC/bunch

  } final bunch length < 0.9 mm
- Simulations suggest that thermal emittance is not important for high charge / bunch (~ nC), but is important for low charge bunch (~ pC)
- Better results if longitudinal laser profile shaping can be employed
- Note: results are similar to those of RF guns

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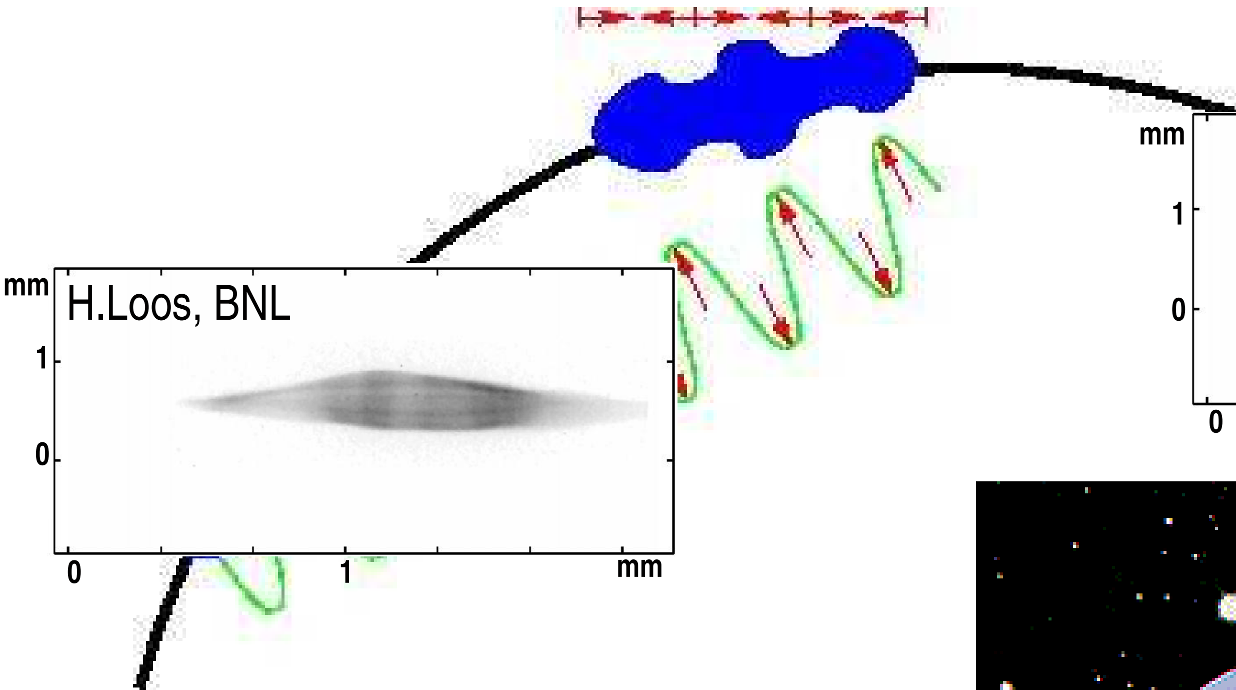
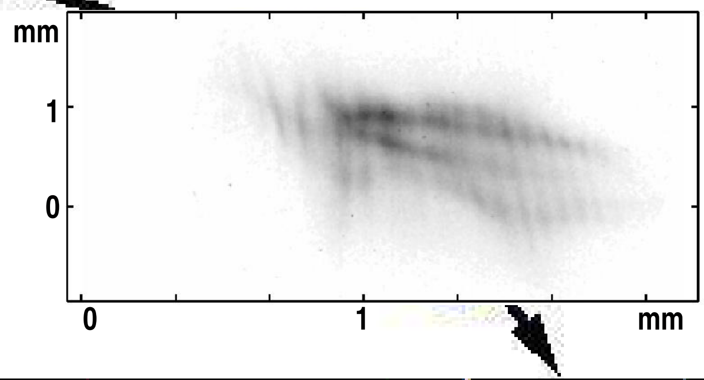
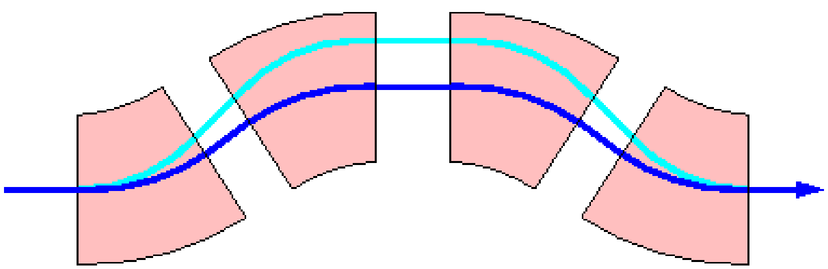
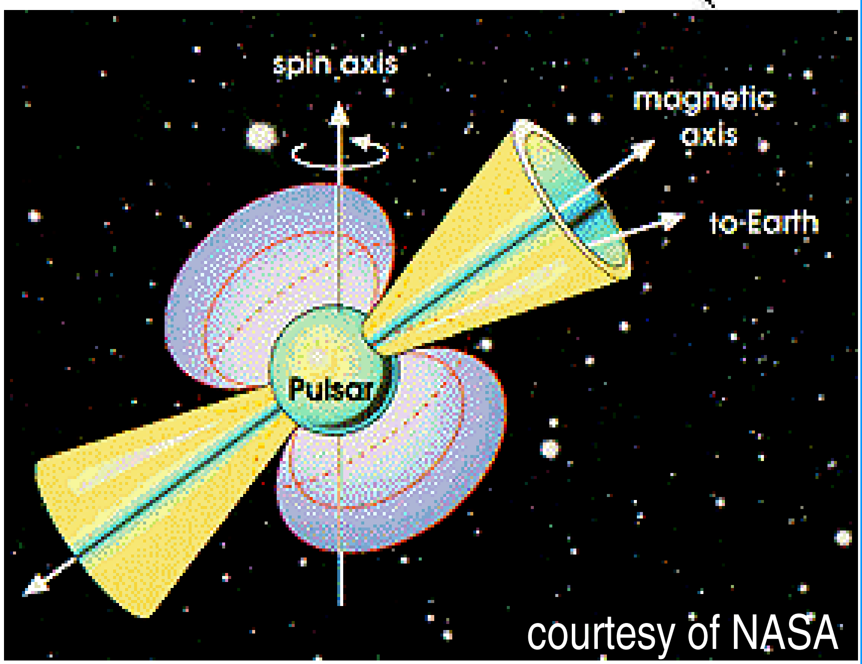
Coherent Synchrotron Radiation







Bunch compressor in an ERL



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Emittance Growth in the Merger

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space charge in merger

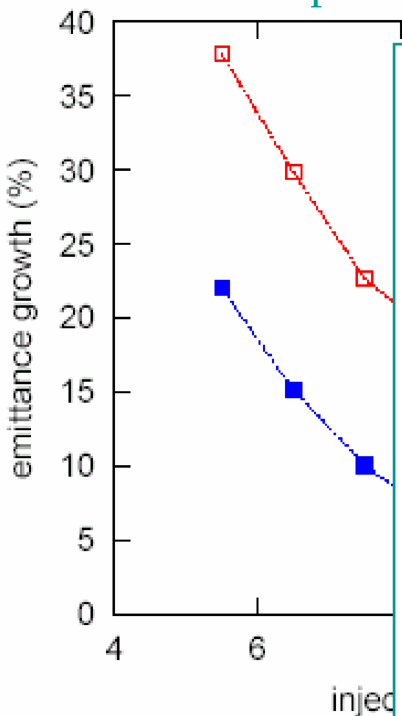

Figure 4: Emittance gr
charge for different inje
ized emittance is taken t

coherent synchrotron radiation in merger

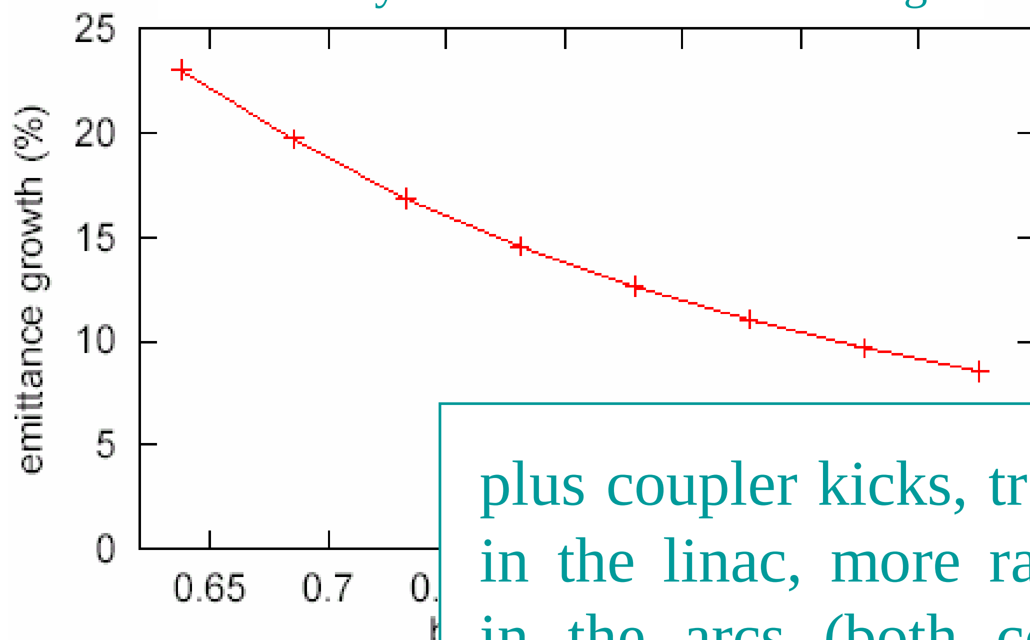

Figure 5: Emittance gr
77-pC bunch as a func
dipole bend angle for 0
normalized emittance is

plus coupler kicks, transport in the linac, more radiation in the arcs (both coherent and incoherent), wakes, optical aberrations (chromatic and geometric)…

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ERL Prototype Ia+Ib

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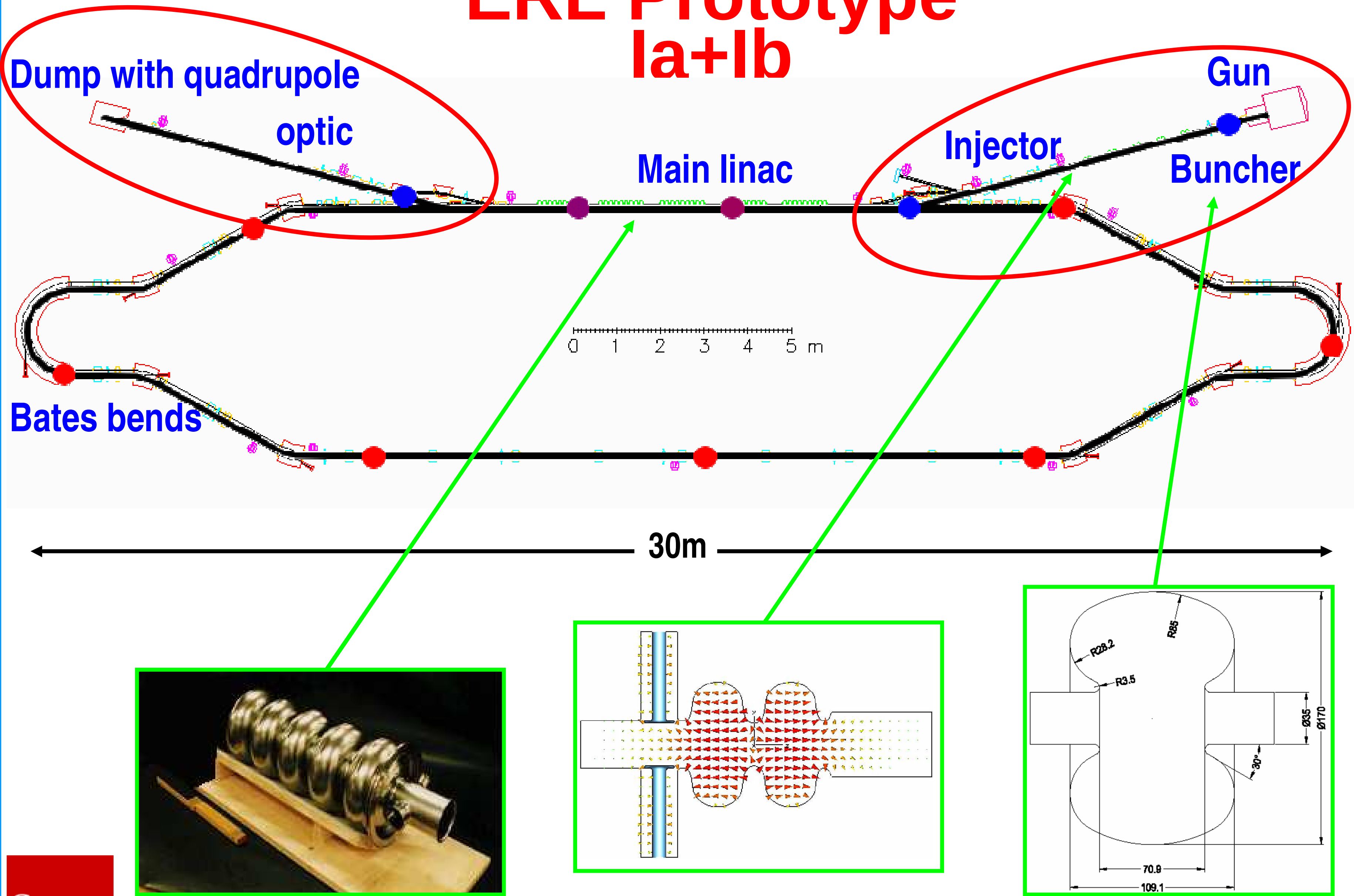

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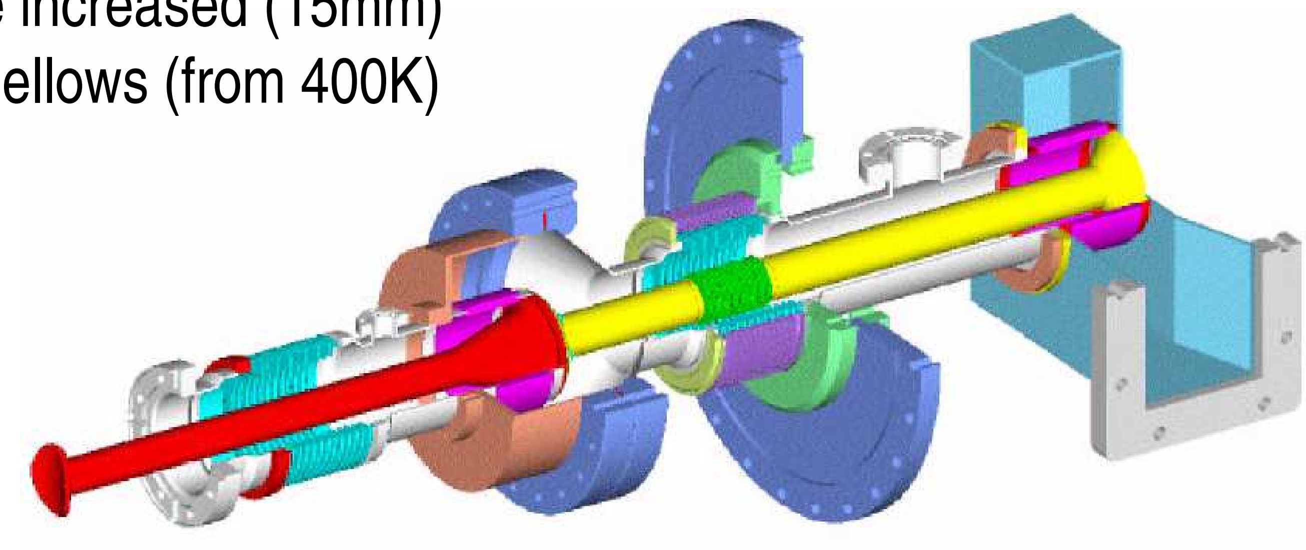
Injector coupler

- Coupling: 50 kW, but only 4% emittance growth due to coupler-focusing
- Flexibility: Energy gain = 1 to 3 MV, $Q_{ext} = 4.6 \cdot 10^4$ to $4.1 \cdot 10^5$
- Close to the TTF III coupler but:

  62mm (from 40) coax line
  multicasting free
  larger antenna
  travel range increased (15mm)
  air-cooled bellows (from 400K)



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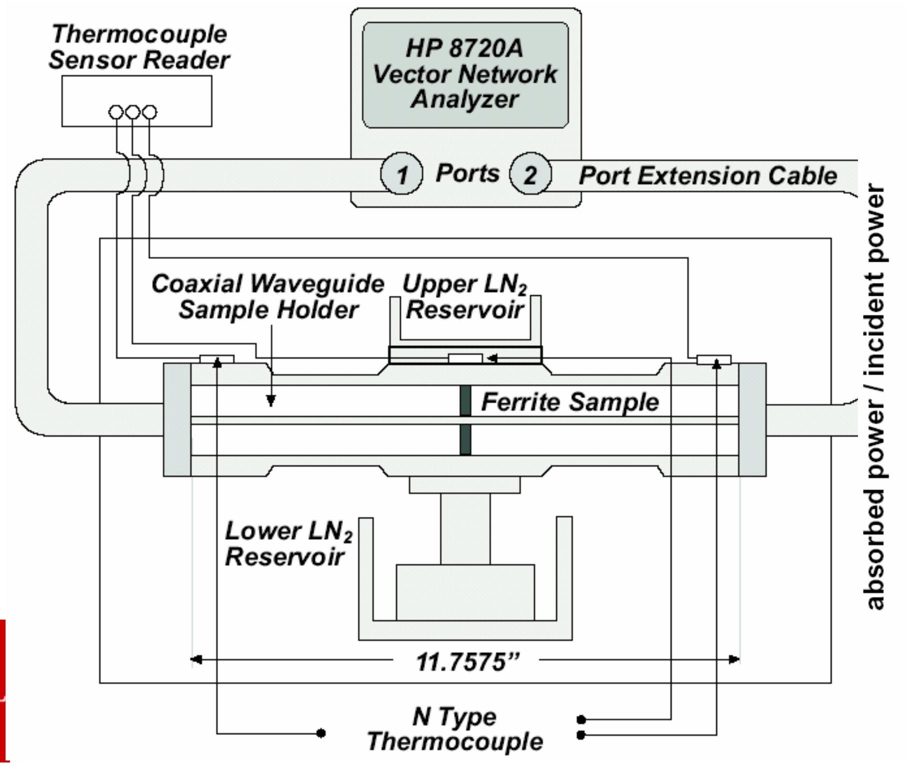
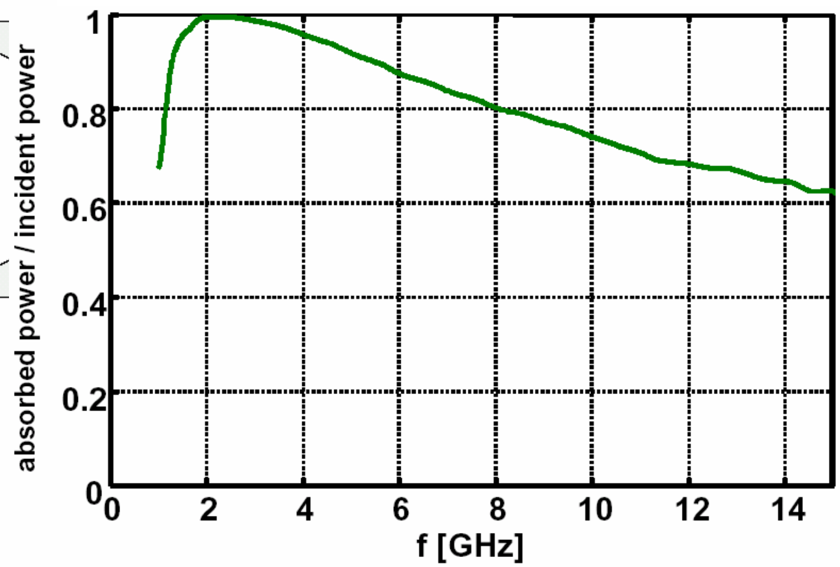
HOM dampers

- 2 X 2 HOM output coupler per cavity for frequencies up to about 3GHz
- One beam pipe ferrite HOM dampers for > about 3GHz
- Up to which frequency do beam pipe HOM dampers work ?
- Up to 15 GHz OK, studies for 40 GHz arranged with FNAL





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HOM Damping in the ERL Main Linac

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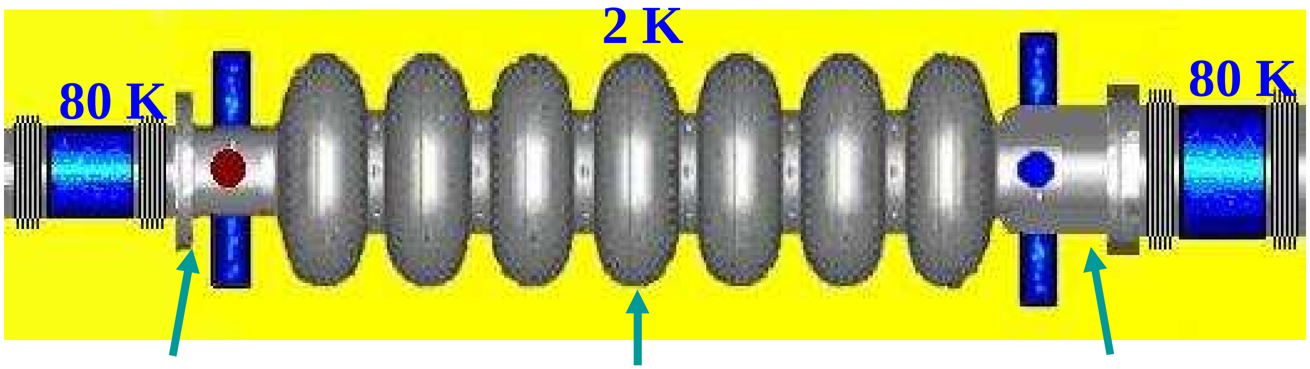

- In average 140 W losses per cavity from beam-excited monopole modes.
- Opposite HOM couplers to reduce transverse kicks.
- Enlarged beam tube on one side to propagate all TM monopole modes and most dipole modes.
- 6 HOM loop coupler per cavity to reduce power per coupler and to damp quadrupole modes reliable.
- Ferrite broadband absorbers at 80 K between cavities to damp propagating modes.

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Parameters

Parameter		Prototype	Light source
Energy	(GeV)	0.1	5
Current	(mA)	100	100
Inj. energy	(MeV)	5–15	5–15
Rep. Rate	(GHz)	1.3	1.3
Acc. gradient	(MV/m)	20	20
Q of cavities	(10^{10})	1	1
external Q	(10^7)	2.6	2.6
Charge/Bunch	(pC)	77	77
nominal σ_E	(10^{-3})	0.2	0.2
nominal σ_τ	(ps)	2	2
nominal ϵ_N	(μm)	2	2
short pulse σ_τ	(ps)	< 0.1	< 0.1
microbeam ϵ_N	(μm)	0.2	0.2
Main Linac Cavities		5	≈ 250
Cooling@2K	(kW)	0.2	≈ 17

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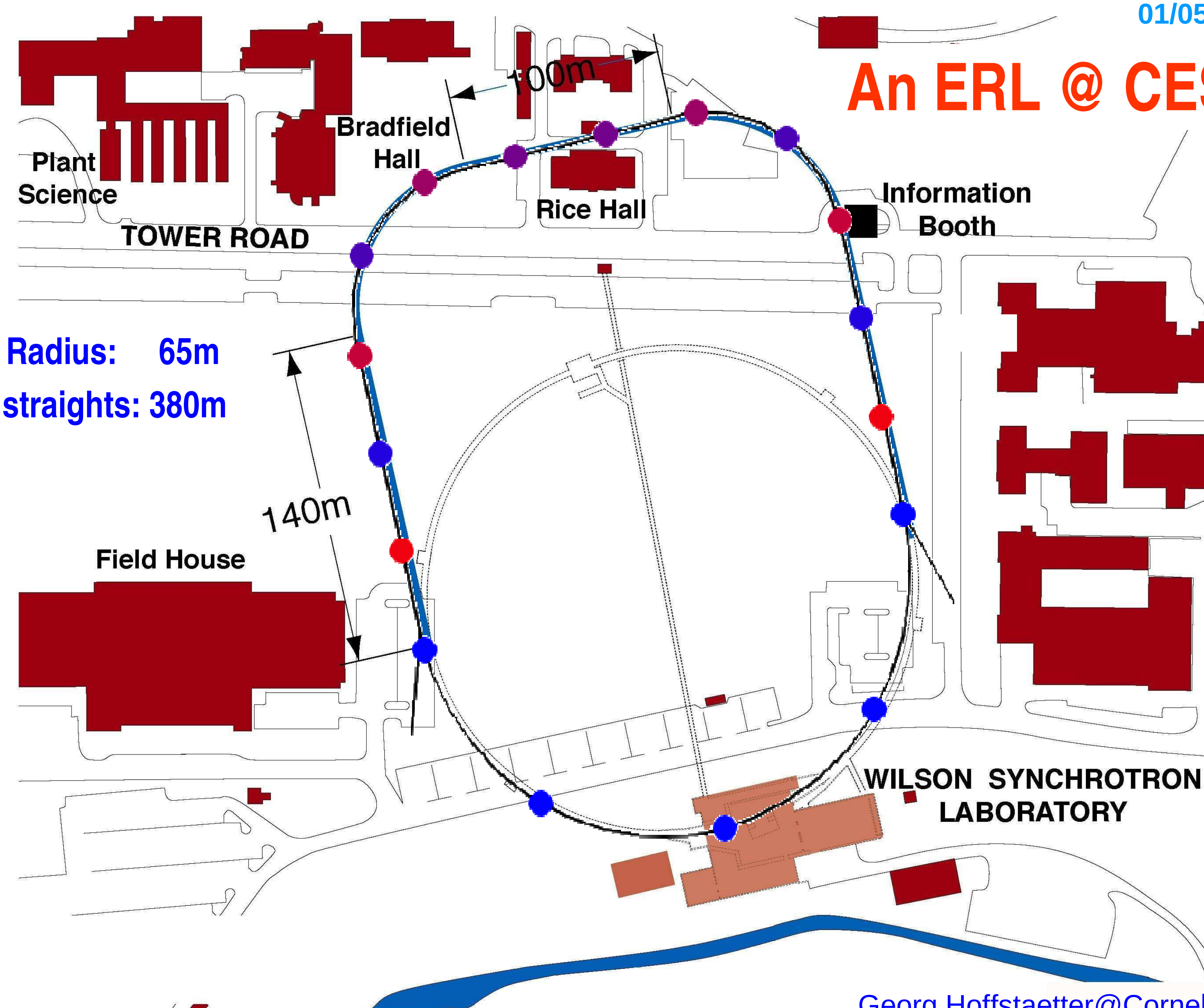
An ERL @ CESR

Bend Radius: 65m

Total straights: 380m



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Advantages over a green field design:

(Assuming the physics research of Wilson lab winds down in about 5 years)

- Savings when reusing
  - Part of the CESR tunnel
  - Part of Magnets, Power supplies, and Vacuum system
  - Part of X-ray beam lines
  - Wilson Lab building and infrastructure
- Can be viewed as a CESR upgrade by funding agencies

But: Many components and buildings could also be reused in a green field design.

Goal: Make a design that tries to reuse as much as possible of CESR. Whenever something can not be reused, show why not. This will either lead to a useful ERL design that convinces funding agencies, or it will act as a good response when funding agencies ask why CESR should be abandoned.

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Problems to be addressed

What is needed?

- How many beamlines are needed
- How many beamlines need ultra short bunches

Is an ERL@CESR geographically possible?

- How much extension does the campus allow for (foundations, etc.)
- How much energy is possible

Is the linac design possible with bends?

- Does the BBU instability allow for high enough currents
- What energy jitters are allowed in the bend sections between linacs
- How destructive is CSR in these sections
- How can the linac be shielded from X-rays by weak bends

Is the optics design possible with CESR tunnel constraints?

- Can ultra short bunches be transported
- How destructive is CSR in the CESR arcs
- How sensitive to energy jitter and field jitter is the particle motion

Is it favorable over a green field design?

- How much of CESR could be reused
- How much money does one save by reusing tunnel, beam lines, Wilson Hall, ...

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01/05/2004

Depth of buildings

Top of Wilson tunnel

Floor at 827''+ approximately 9'' tunnel hight:: 836''

Streamlines along tower road south of Bradfield and Rice Hall

Lines above 870.45'', bottom of vaults: 868''

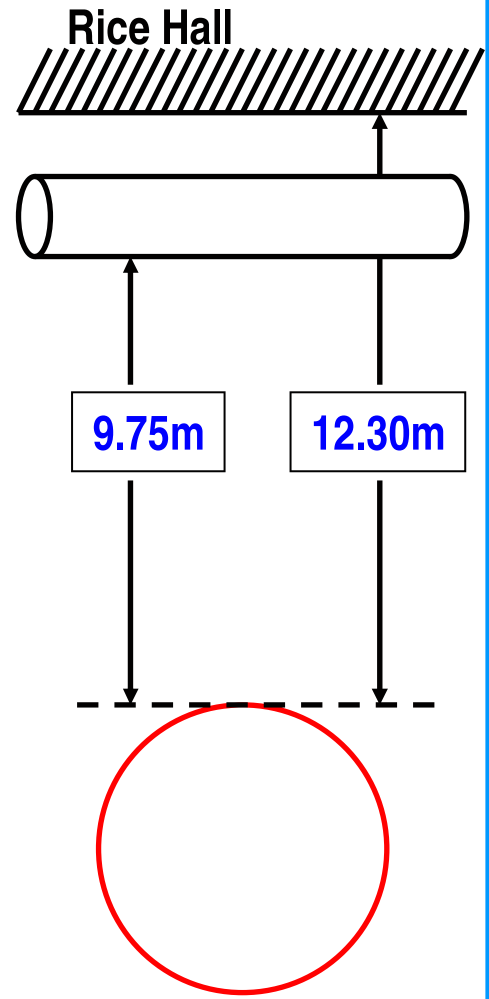
Rice Hall lowest bottom of foundation 876.25''

Bradfield Hall

pile caps 867.5'' (4'' below basement), piling depth unknown.

Plant Science building

base of piling: 862''



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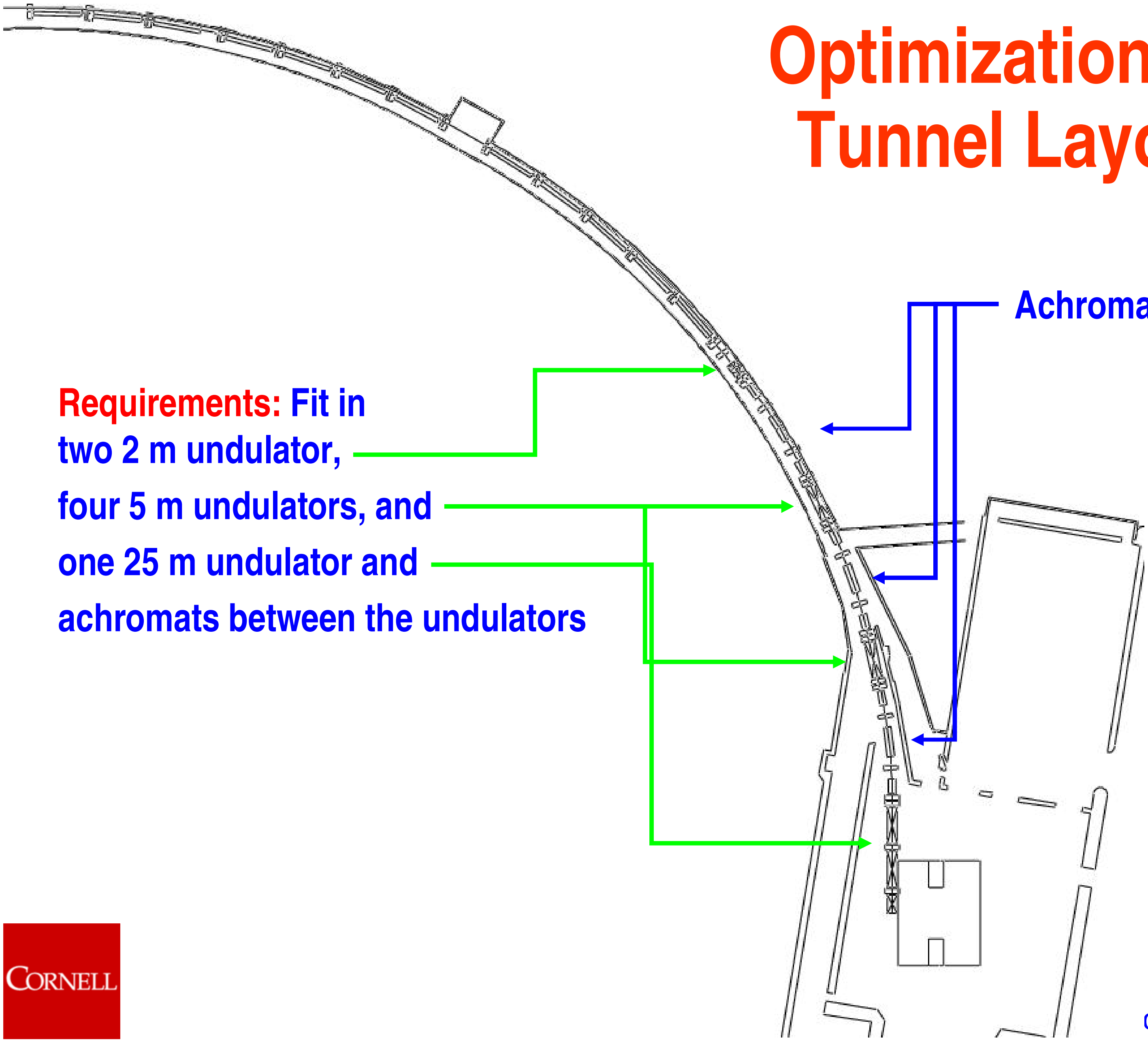
Optimization of Tunnel Layout



Requirements: Fit in
two 2 m undulator,
four 5 m undulators, and
one 25 m undulator and
achromats between the undulators

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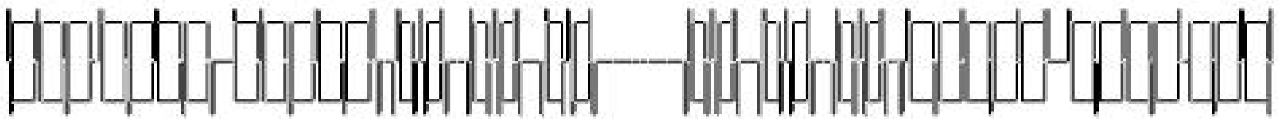
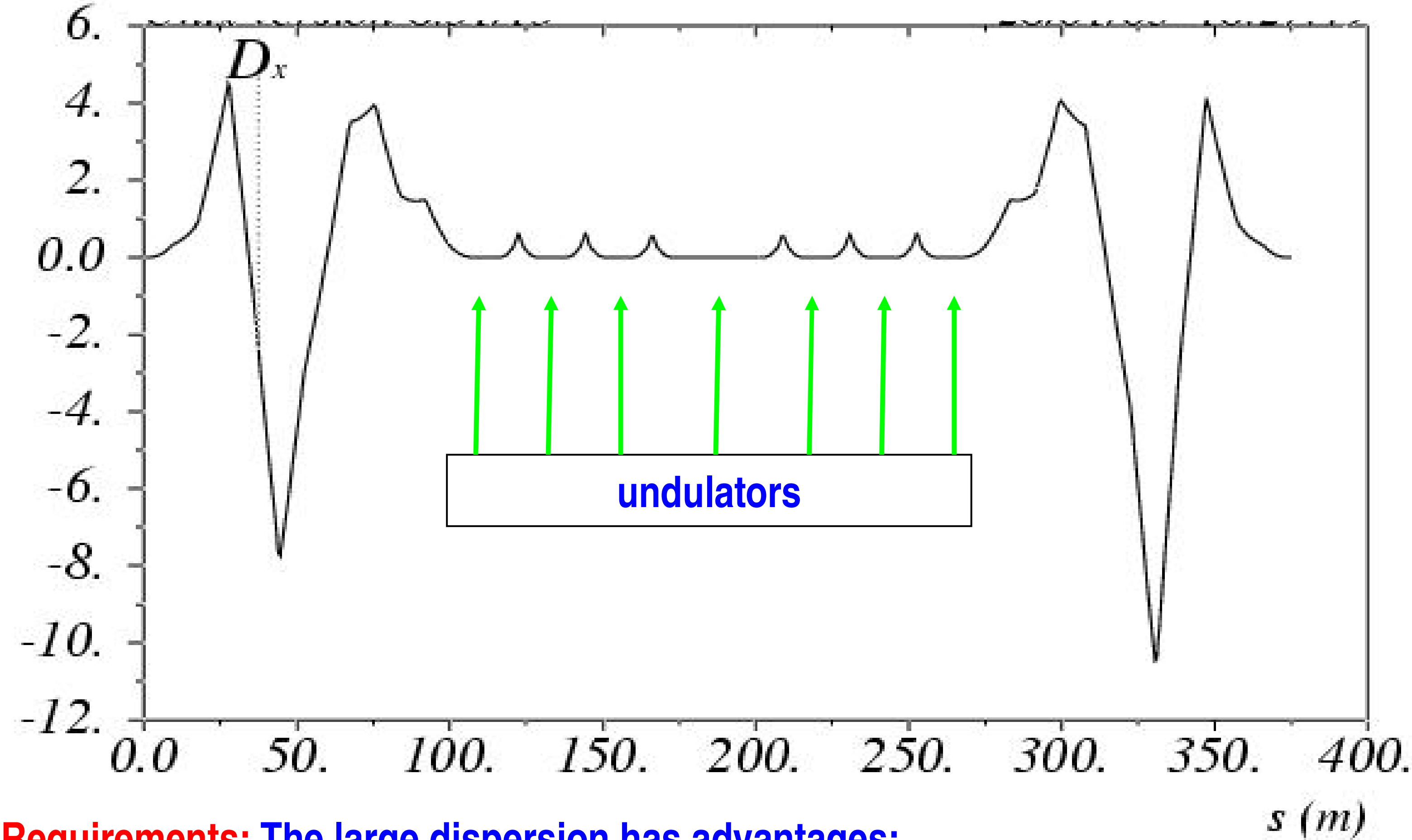


Dispersion for short bunch operation



Requirements: The large dispersion has advantages:

Can be used to manipulate R56, and with sextupoles also higher chromatic orders.

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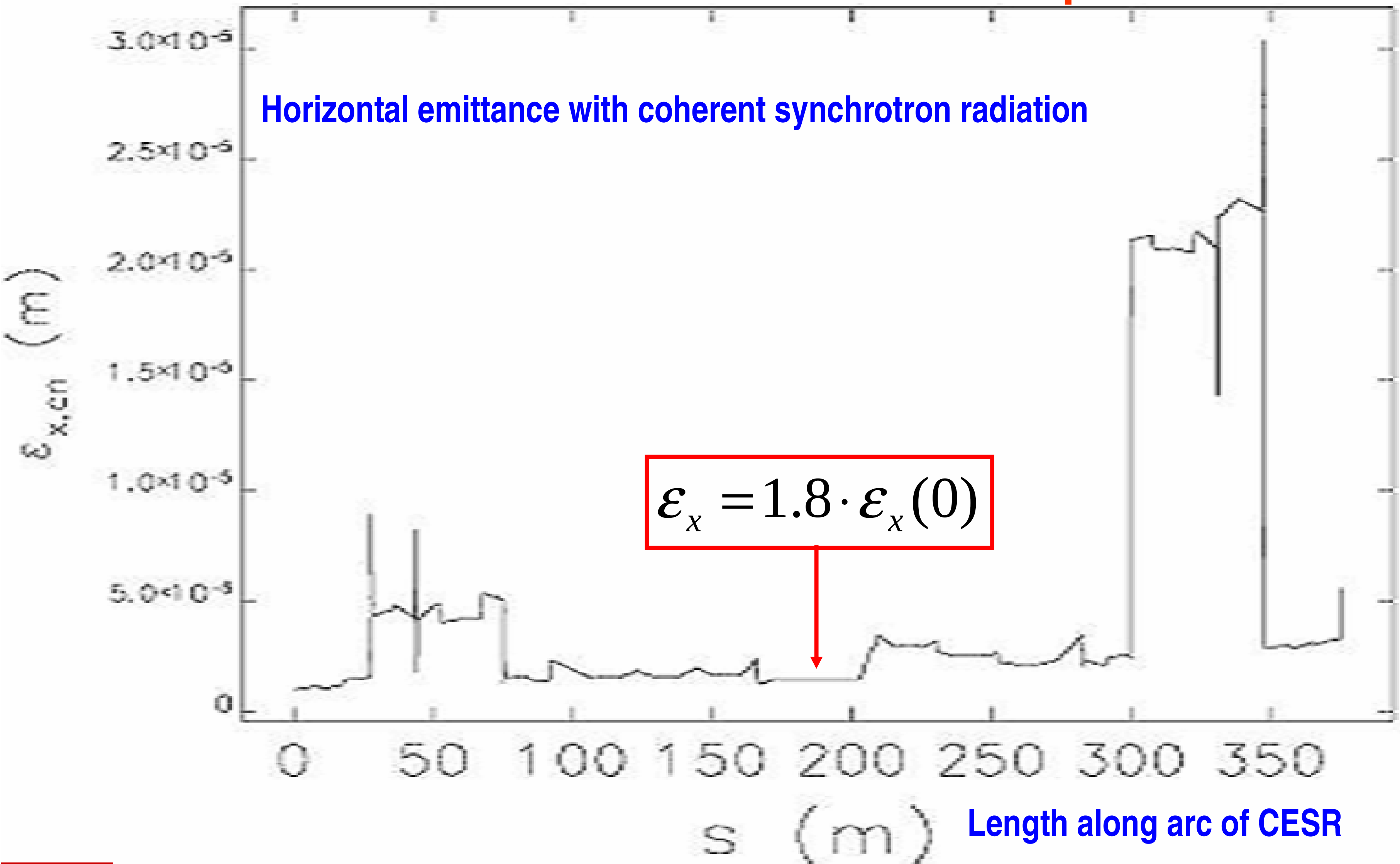
Emittance with CSR and nonlinear optics

01/05/2004



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Result: After suitable nonlinear bunch length manipulation, the emittance growth can be controled in all undulators.

01/05/2004

Conclusion

- Possibilities of extending the CESR tunnel to accommodate an ERL have been investigated.

- First and second order optics have been found for an ERL
  - which uses one half of the current CESR arc
  - which can be used to compress 2ps bunches to 100fs
  - which leads to less than a factor of 2 in transverse emittance increase due to CSR
  - Nearly all quadrupoles and sextupoles have a strength which can be achieved in CESR today
  - The BBU limit is at least as large (100 – 200mA) than in the white paper ERL design.

- A list of some of the issues which still have to be investigated has been specified

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ERL@CESR being analyzed

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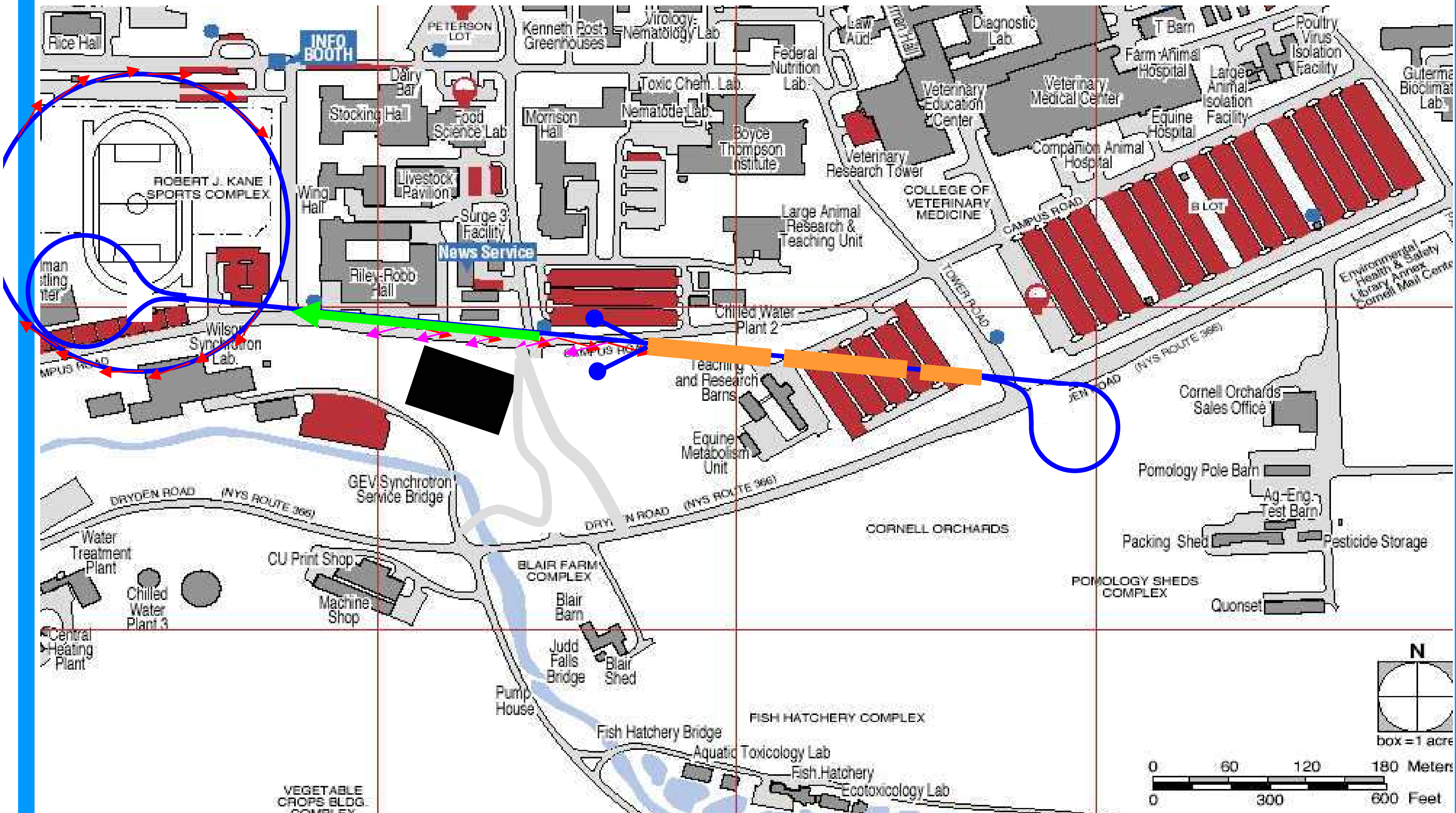

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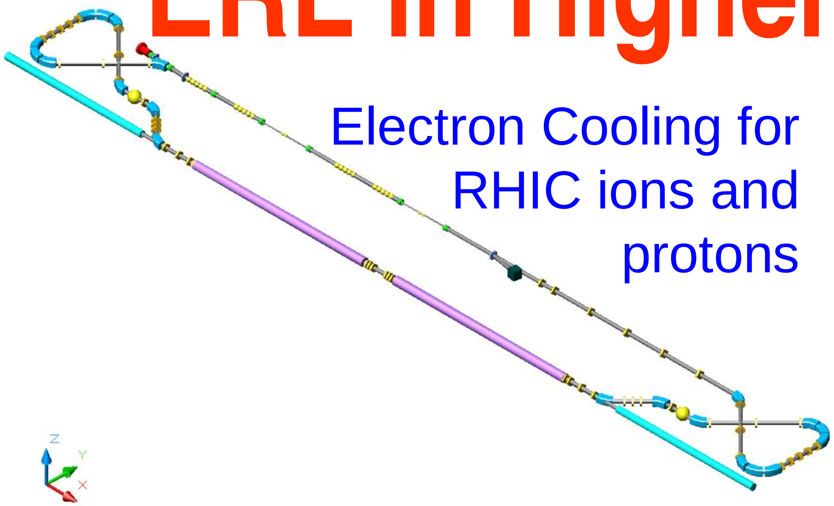
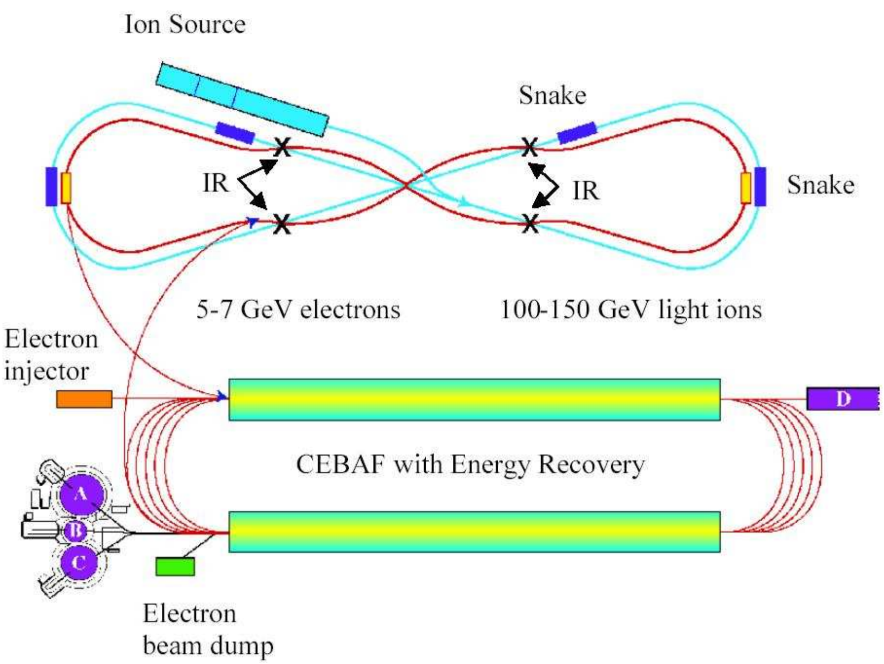
ERL in Higher Energy Physics

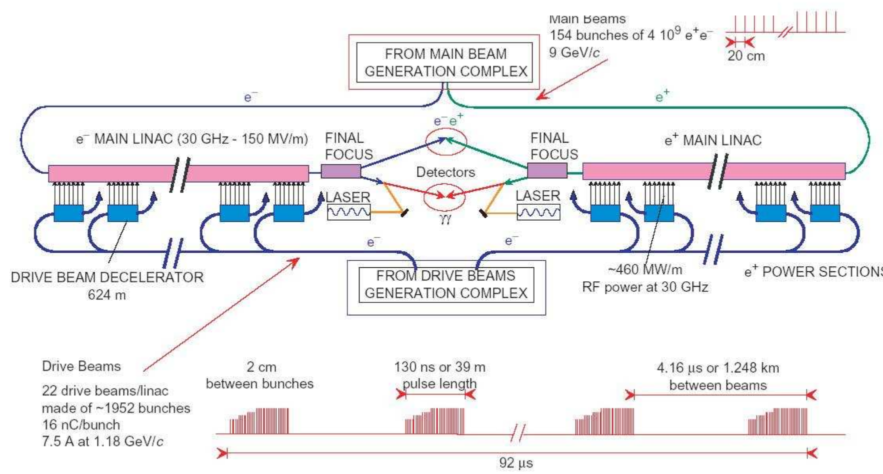


Electron Cooling for RHIC ions and protons

Electron Ion Collider



CLIC-like drive beam ERL



A low emittance RF source

Could save the electron

damping ring in a LC

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Why at Cornell ?

- Great research opportunities for internal and external x-ray science
- Great research opportunities for accelerator physics and technology
- Great experience for students to join a large project in its design, proposal and test stage
- This project urgently has to start soon
- Expertise
- History
- Space and tunnel available soon
- University support

President Lehman's question:

Should we be identifying special domains of research emphasis where Cornell is unusually well suited to make enduring and significant contributions?

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