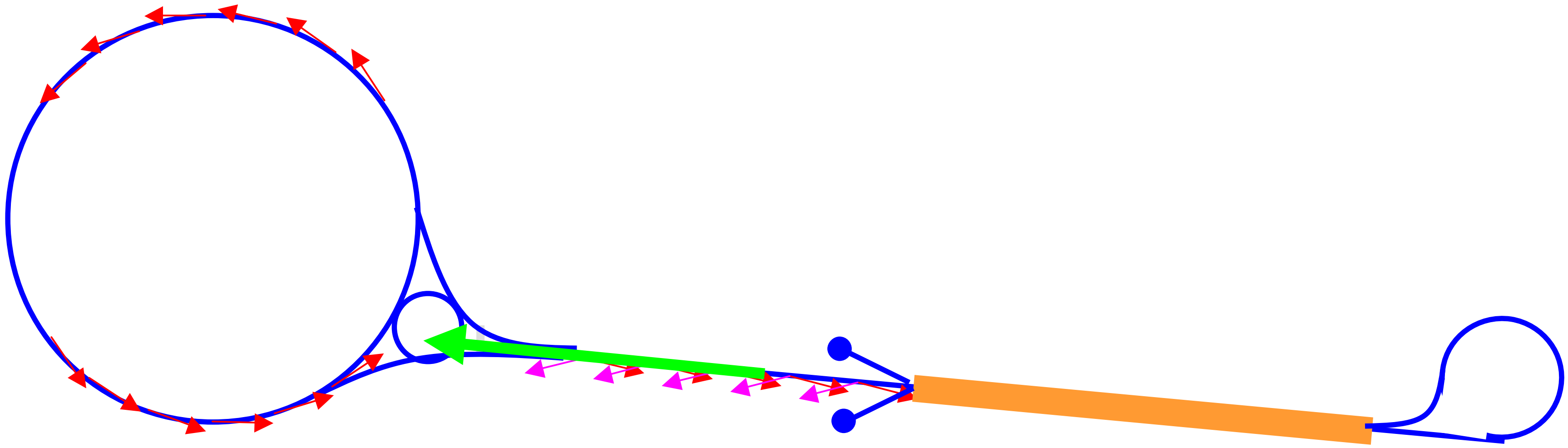
07/12/2004

The Cornell ERL Project

Georg Hoffstaetter

(for the Cornell ERL endeavor)

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



Could an ERL use the CESR tunnel

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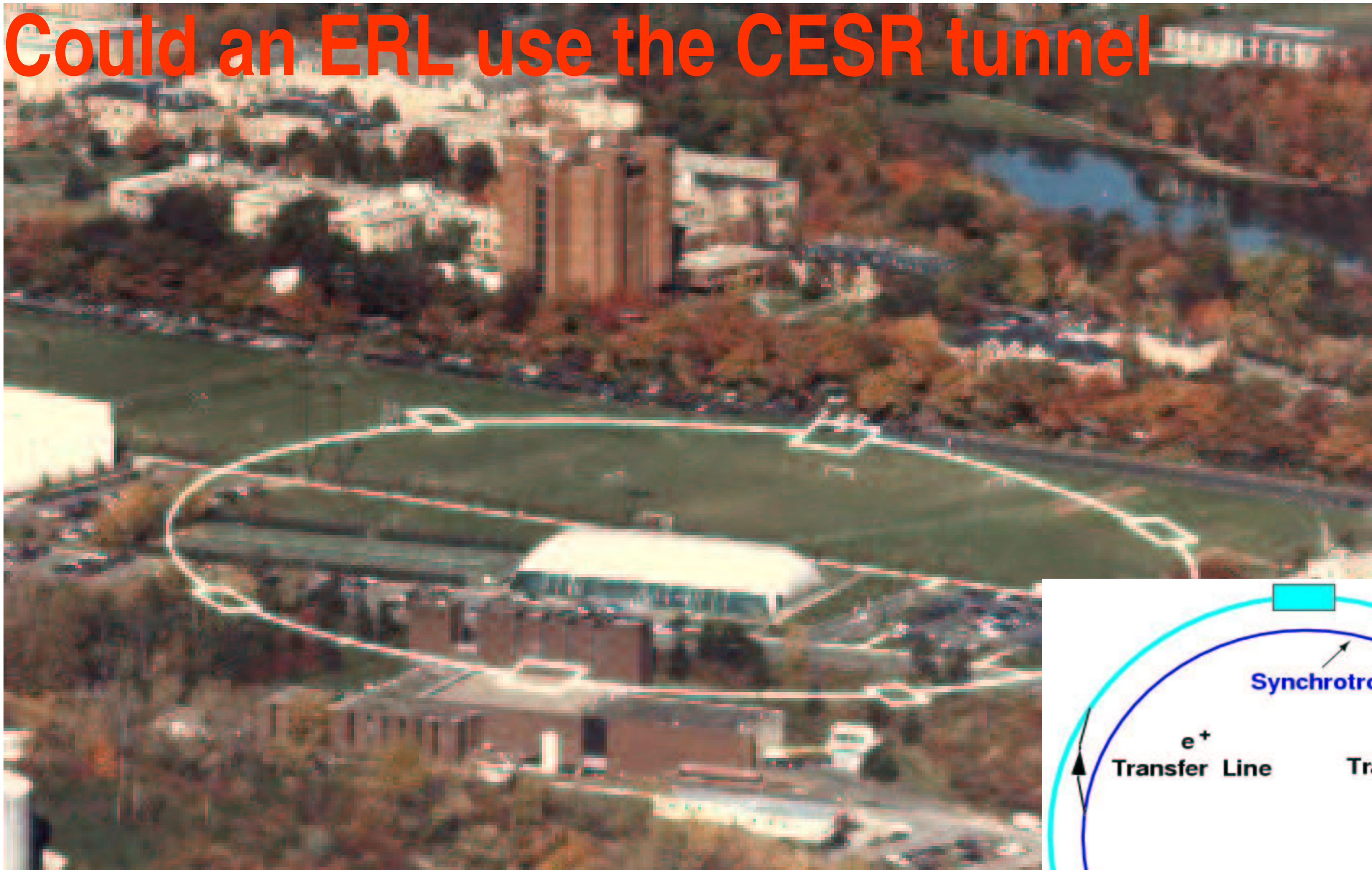

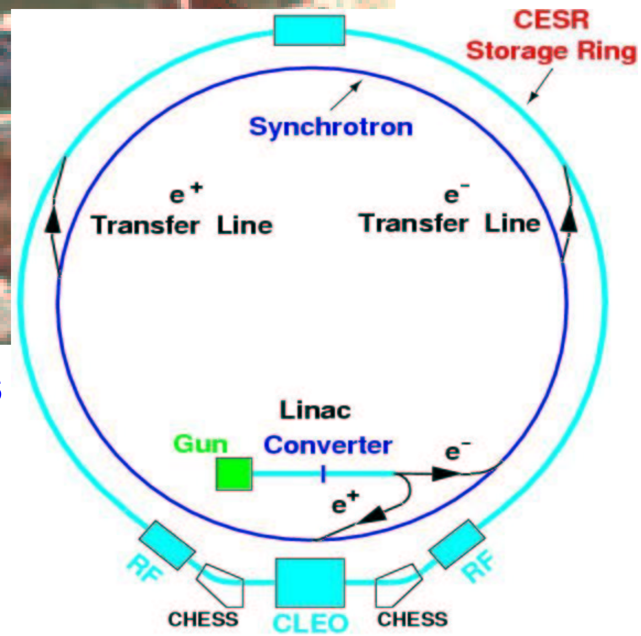

- An extension of the tunnel could easily conflict with buildings
- But the tunnel sealing is at about 836 ft ASL whereas
- The base of the deepest relevant building’s foundation is at 862ft ASL, yielding about 10m of space.

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Synchrotron Radiation @ Cornell

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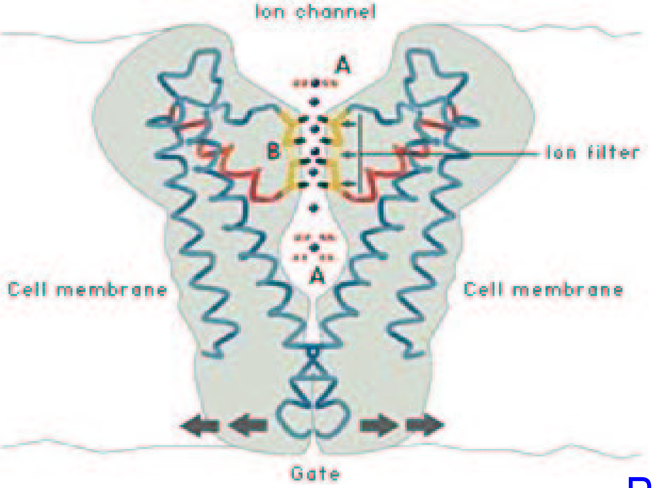
- 1947: 1st detection of synchrotron light at General Electrics. Soon advised by D.H.Tomboulian (Cornell University)
- 1952: 1st accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1953: 1st measurement of the synchrotron radiation spectrum by Paul 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

Energy Recovery & Linear Coll.

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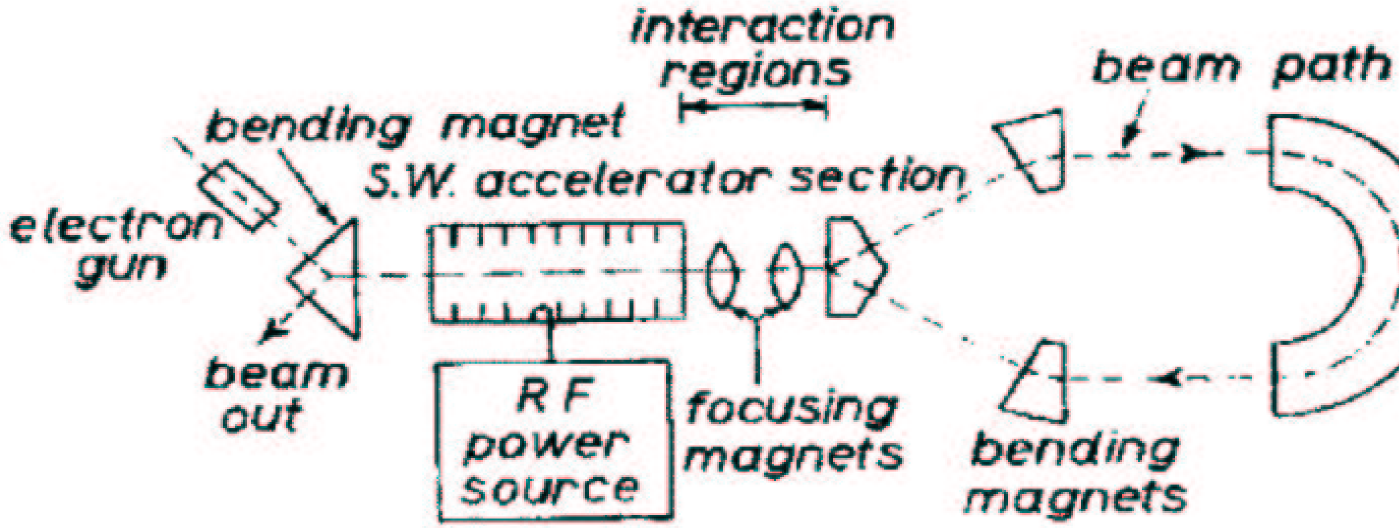
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)



Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities get too hot.
- Superconducting cavities used to have too low fields.

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Parameters

Operation mode	High Flux	Coherence	Short pulse
Current (mA)	100	10	1
Charge/b (nC)	0.08	0.008	1.0
$\epsilon_{x/y}$(nm)	0.1	0.015	1
Energy (GeV)	5.3	5.3	5.3
Rep. rate (GHz)	1.3	1.3	0.001
Av. flux $(\frac{\text{ph}}{0.1\%\ \text{s}})$	$9\ 10^{15}$	$9\ 10^{14}$	$9\ 10^{12}$
Av. brilliance $(\frac{\text{ph}}{0.1\%\ \text{s mm}^2\ \text{mrad}^2})$	$1.6\ 10^{22}$	$3.0\ 10^{22}$	$2.0\ 10^{17}$
Bunch length (ps)	2	2	0.1

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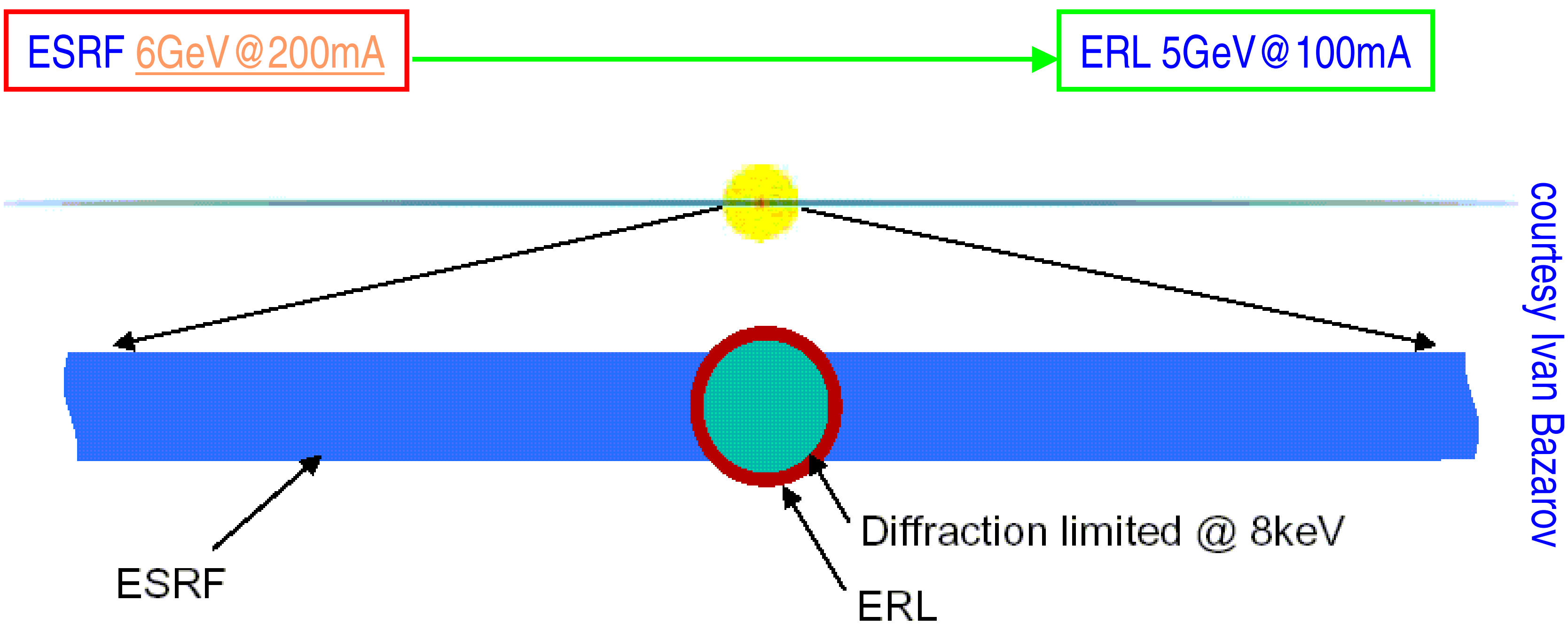
Beam size in a linear accelerator

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.**



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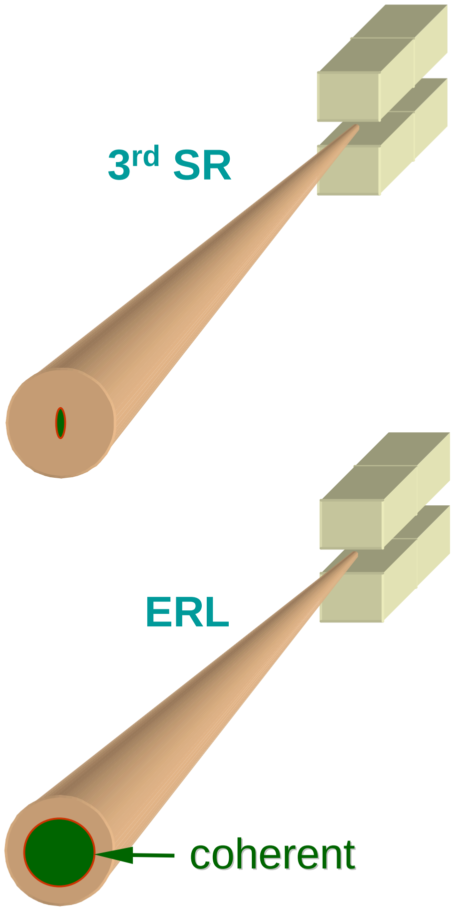
Smaller Beam → more Coherence

- 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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Flux and Brilliance

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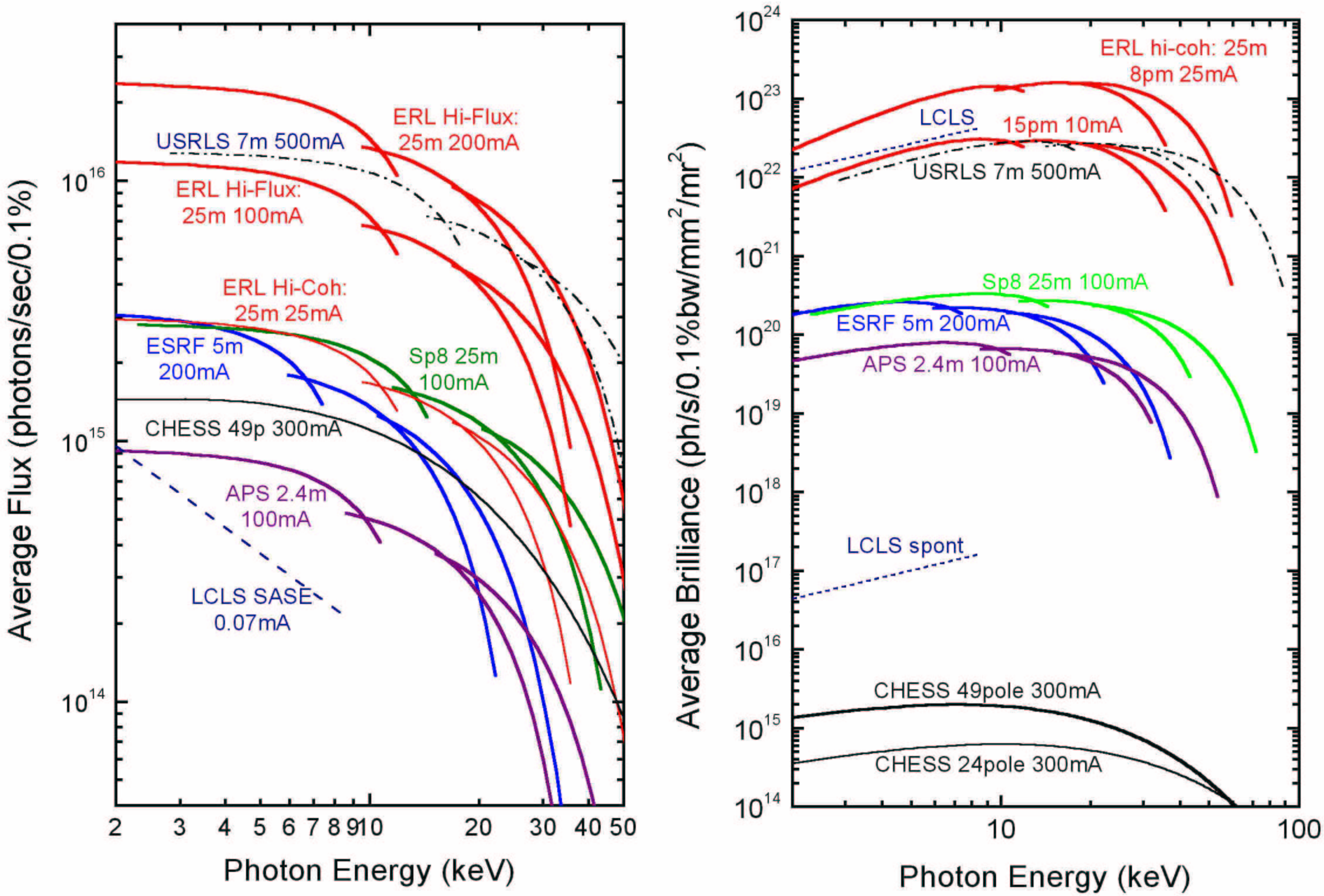
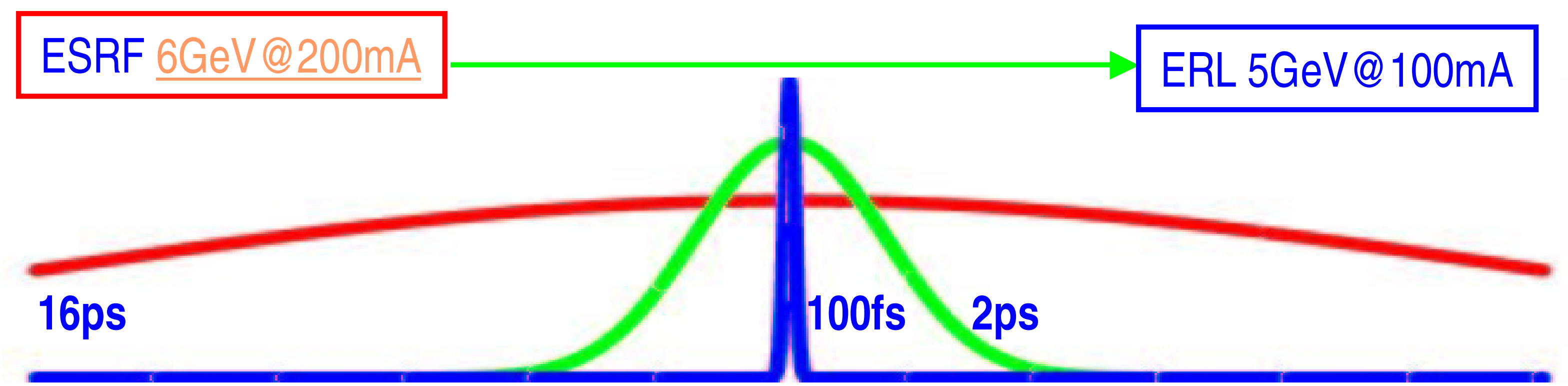


Bunch length in a linac

- 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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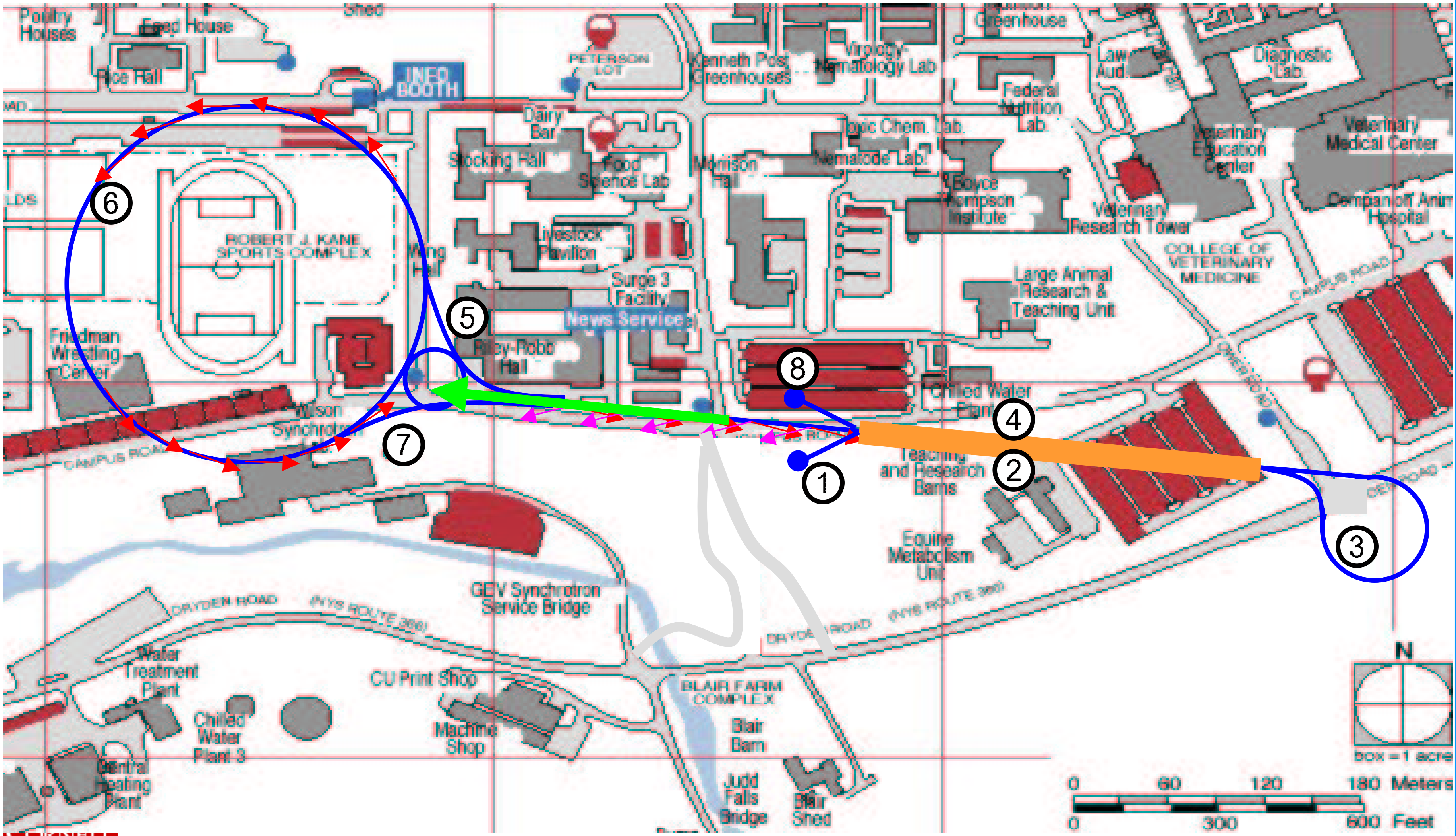
ERL@CESR being analyzed



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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: Cornell, KEK, Daresbury, 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.

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

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An existing ERL

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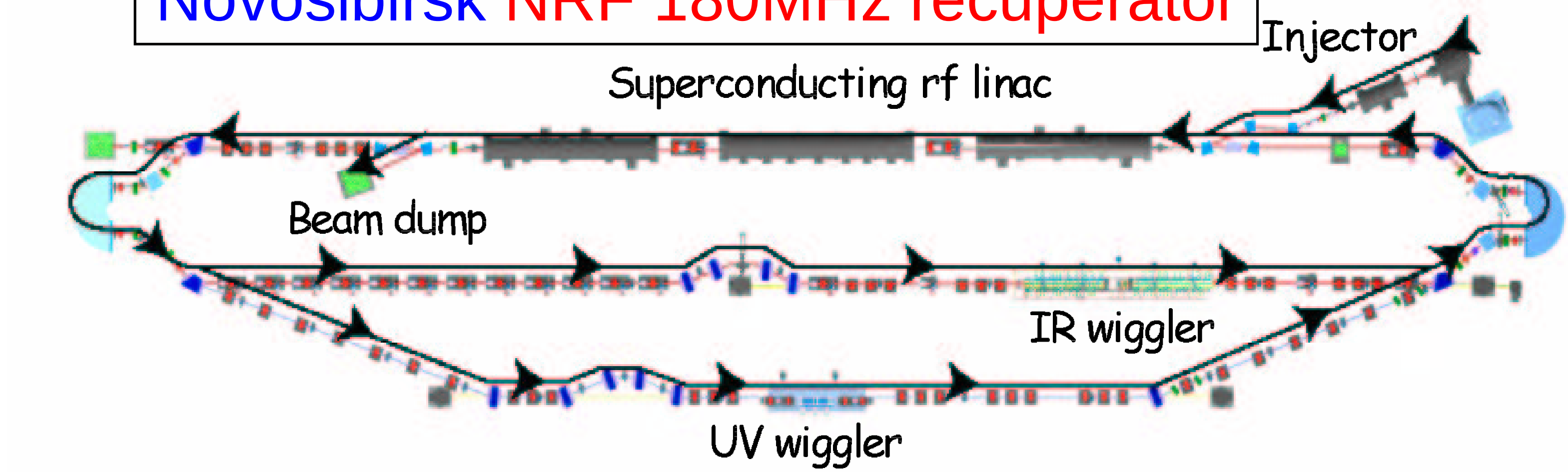
Promise:

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



Achieved: 8.5kW CW IR power (06/24/04), Energy recovered up to 5mA at 145MeV, up to 9mA at 88MeV

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How close is the JLAB-ERL to the X-ERL ?

- Beam energy of 5GeV – up by 5
- 1300MHz bunch repetition rate – up by 17
- 100 mA or higher average beam current – up by 10
- Normalized rms emittance ~1 mm-mrad at full energy – down by 10
- Bunch length < 0.1 ps – down by 4

And all these improvements simultaniously!

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Limits to ERLs

Limits to Energy :

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

Limits to Current :

- Beam Break Up (BBU) instability

For small emittances in all 3 dimensions :

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

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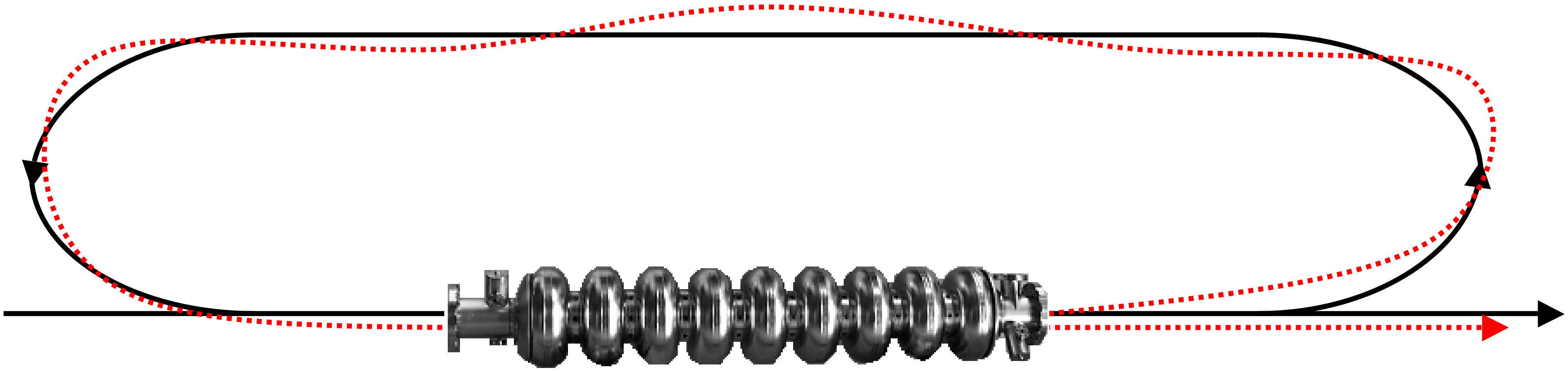
Instability with a single cavity and single Higher order mode



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

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

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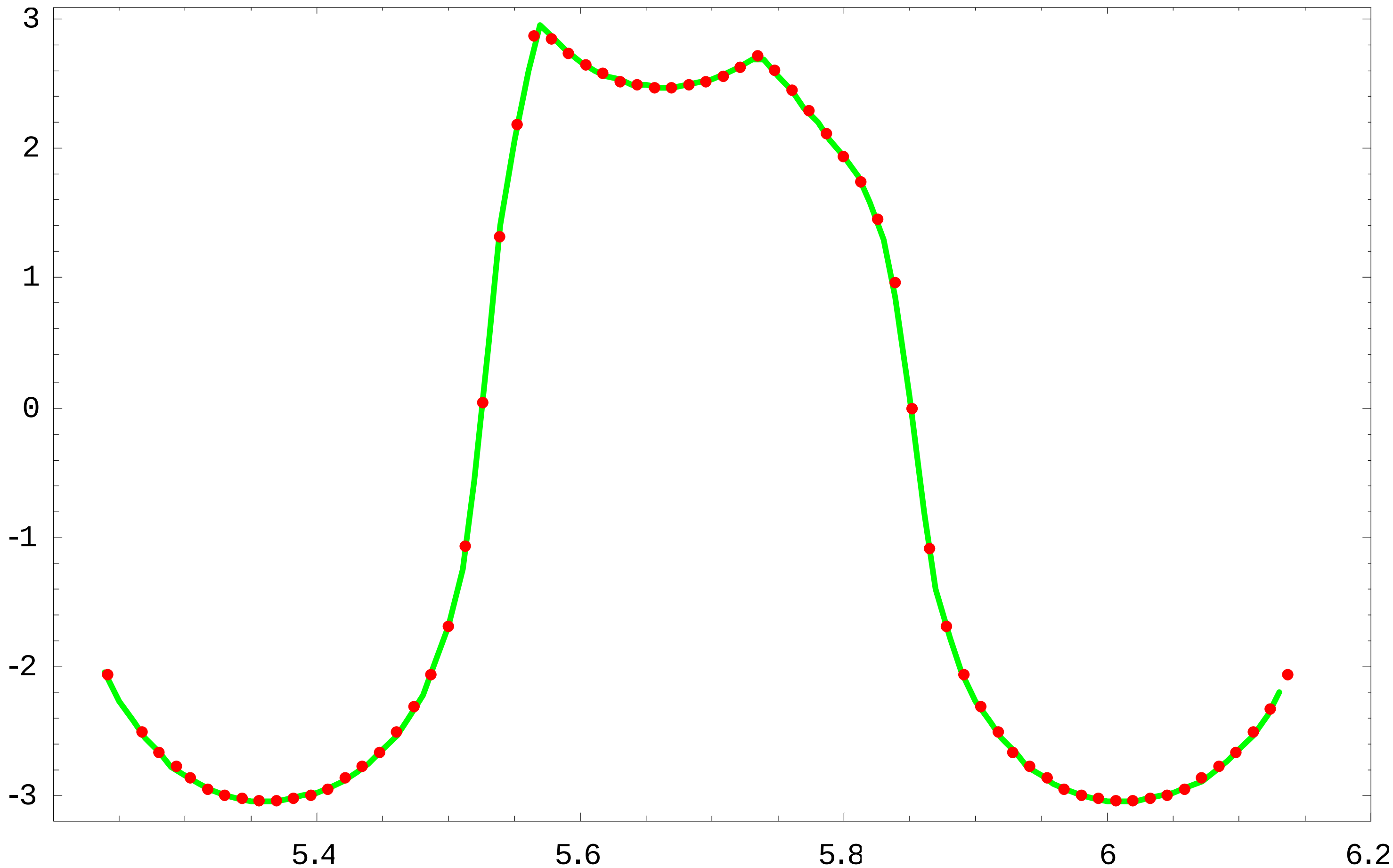
Comparison with Tracking



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

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Results on BBU

Many HOMs in one cavity :

- only the most dangerous HOM contributes to the threshold.

HOMs in different cavities :

- HOMs in different cavities cannot cancel, but they can be decoupled by optical choices.

Multi turn recirculation :

- The threshold decreases approximately quadratically with the number of turns.

Closed orbit drift instability :

- Allways has a threshold that is larger than the coherent oscillation BBU

- ERL@CESY: 400mA BBU limit for 7-cell TESLA-like cavities.

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See PRST-AB May 2004

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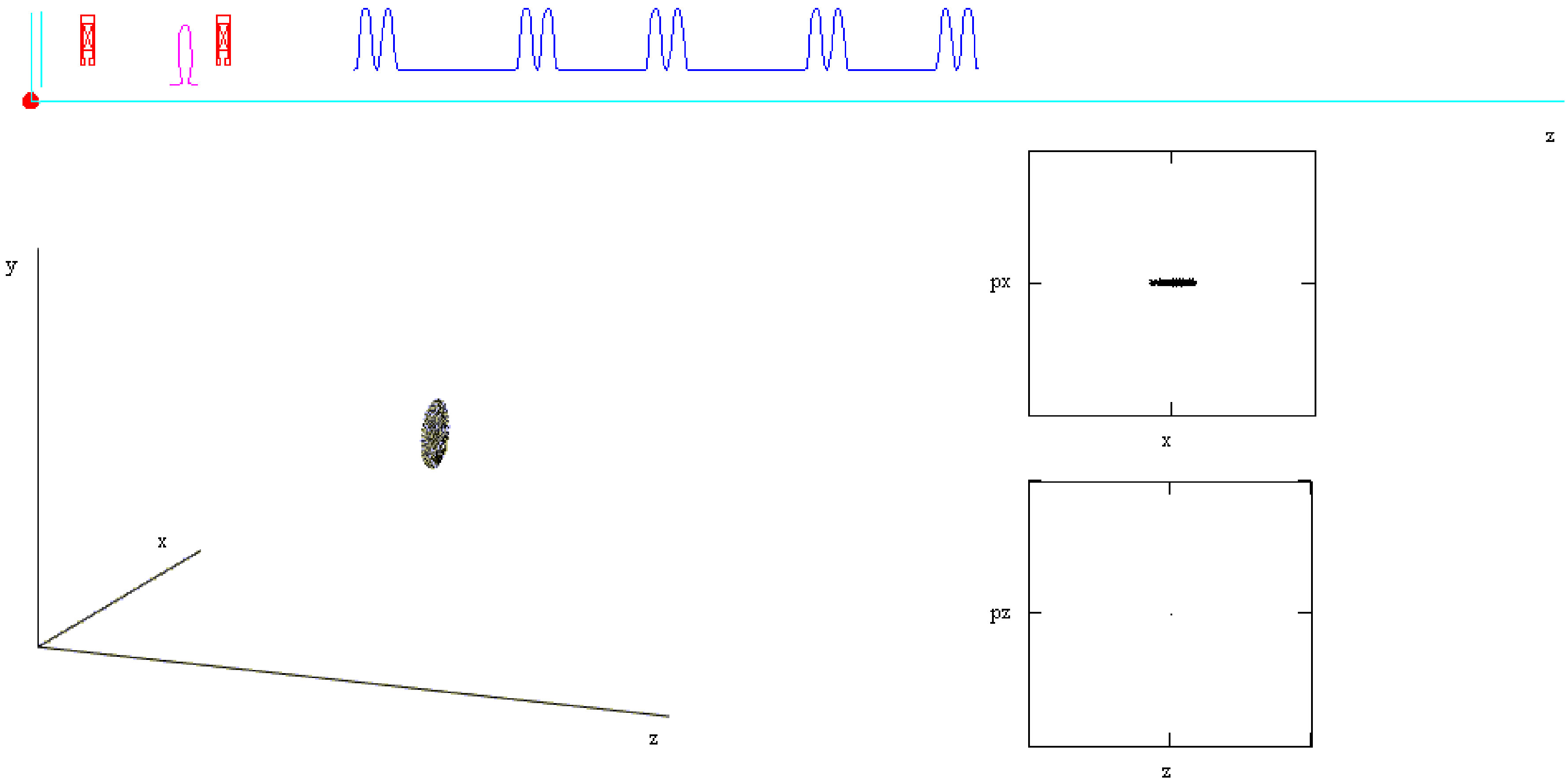
Gun simulations



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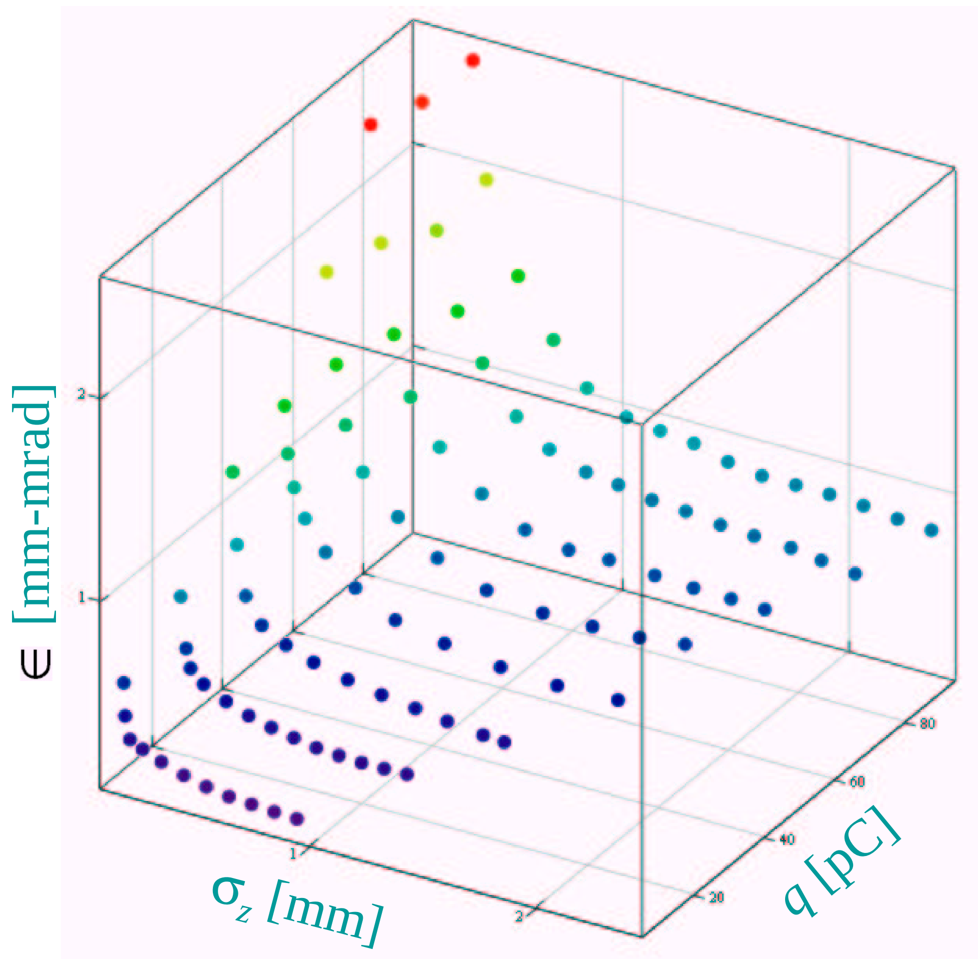
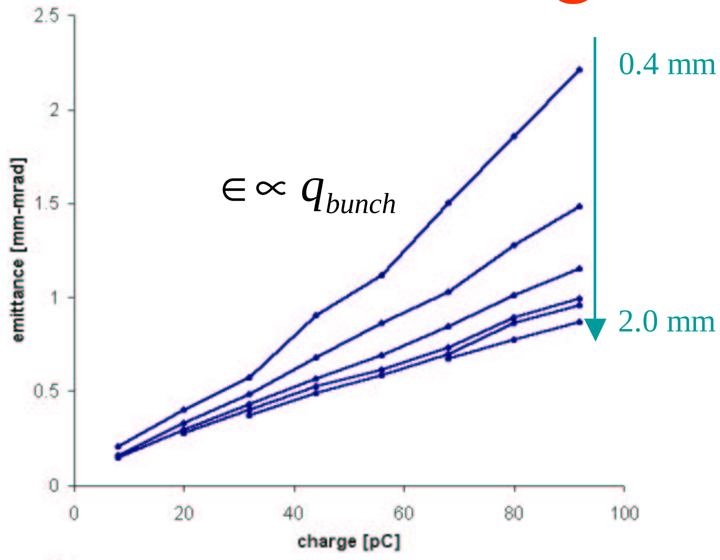
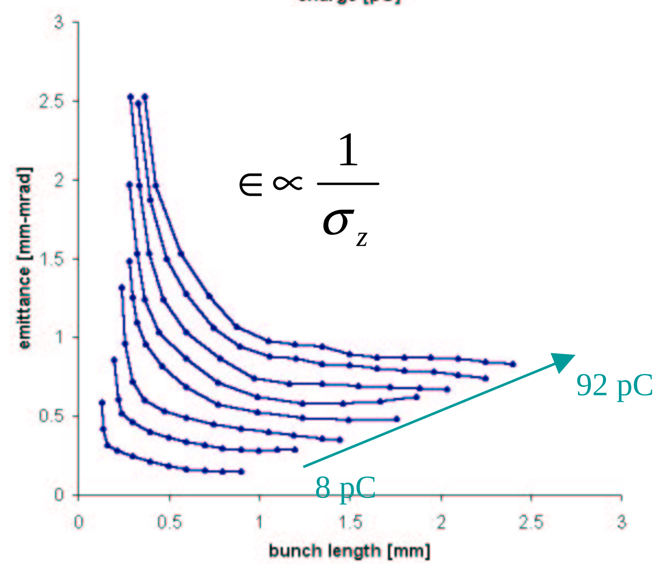
Emit. scaling vs. charge, vs. bunch length







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Optimization results

- Optimization for emittances in case of transverse uniform, longitudinal gaussian 'laser' profile:
  - 0.08 mm-mrad for 8 pC/bunch
  - 0.4 mm-mrad for 80 pC/bunch   final bunch length < 0.9 mm
  - Ongoing simulations for an ideal gun lead to even much smaller emittances
- 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
- RF Guns might be used for the 1nC working mode

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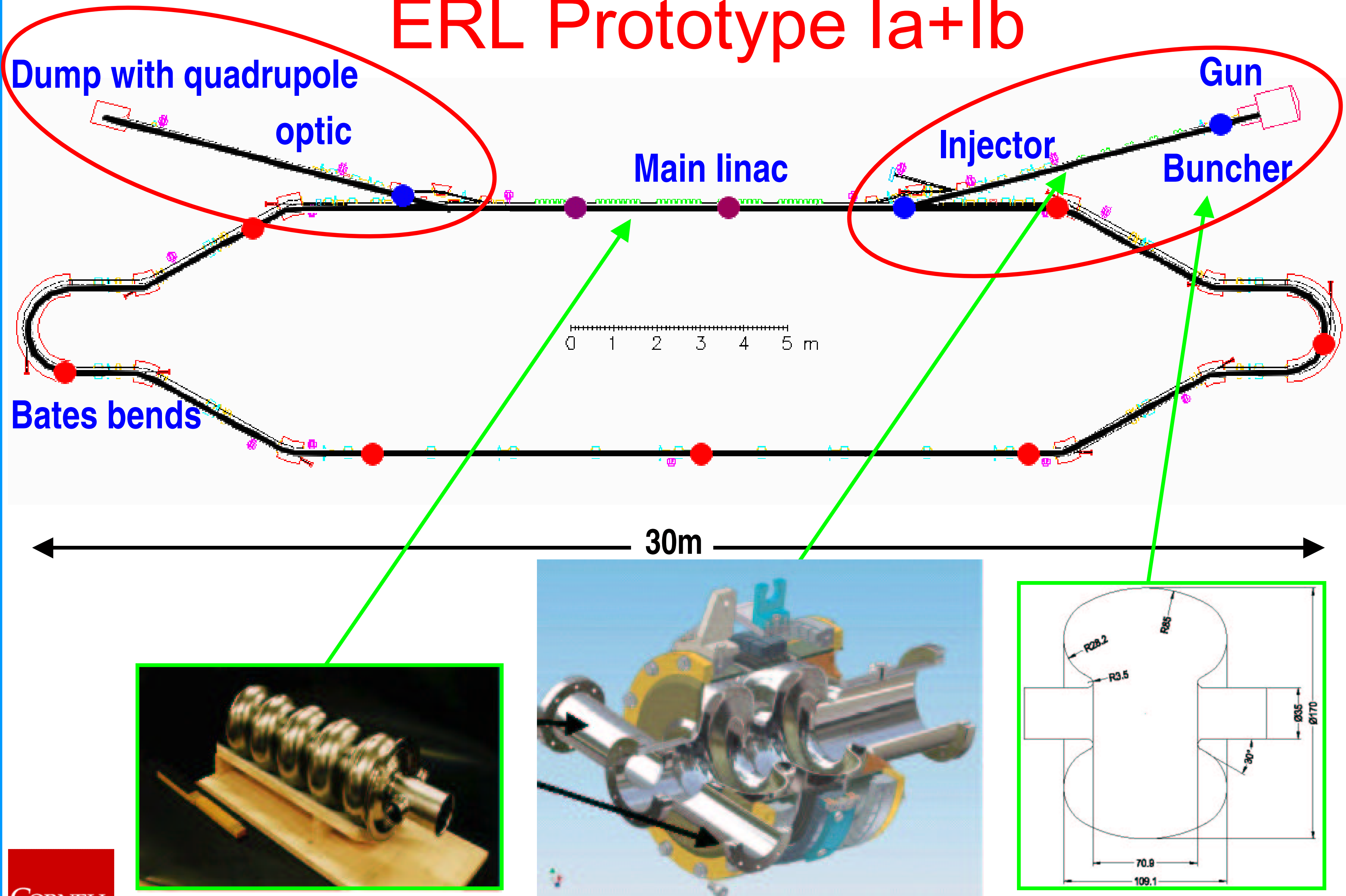
ERL Prototype Ia+Ib



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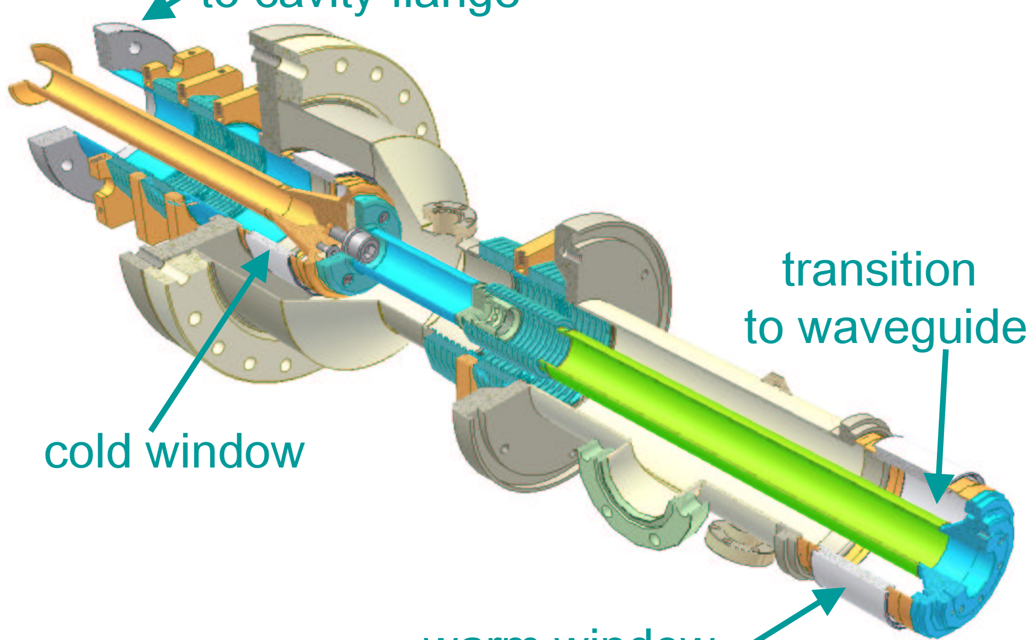
Injector coupler

- 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
multipacting free
larger antenna
travel range of 15mm
air-cooled bellows



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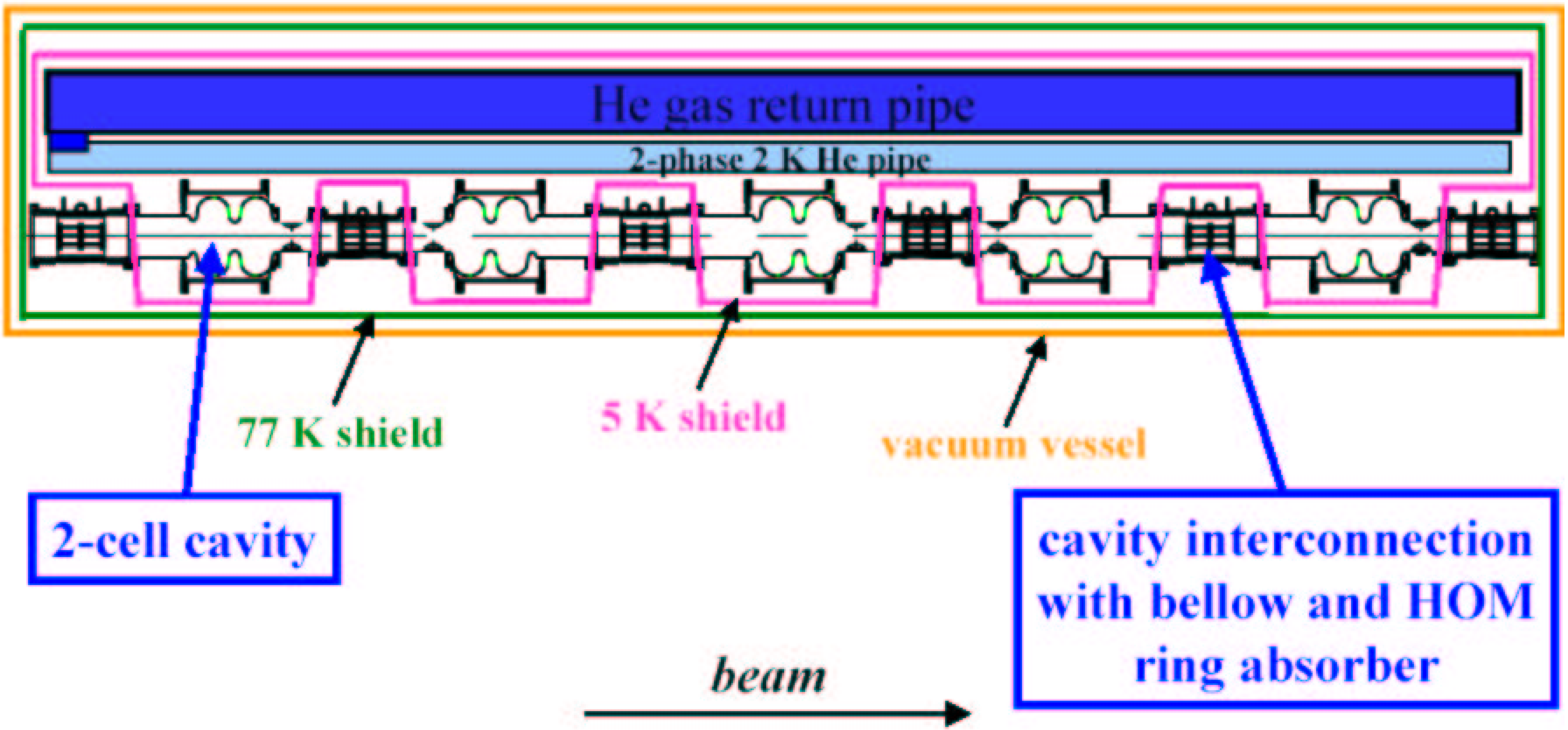
Injector cryomodule concept



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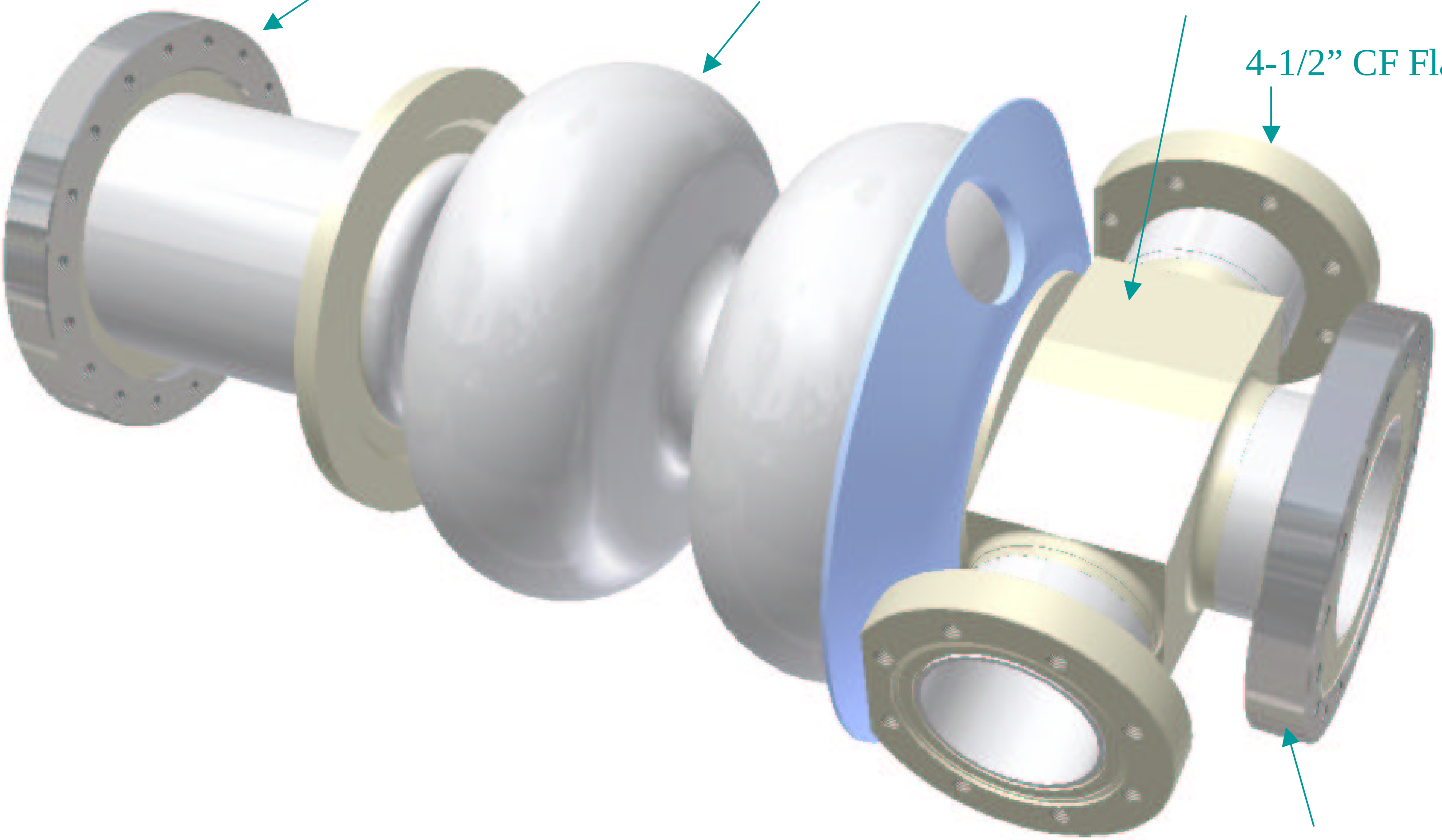

2-cell cavity

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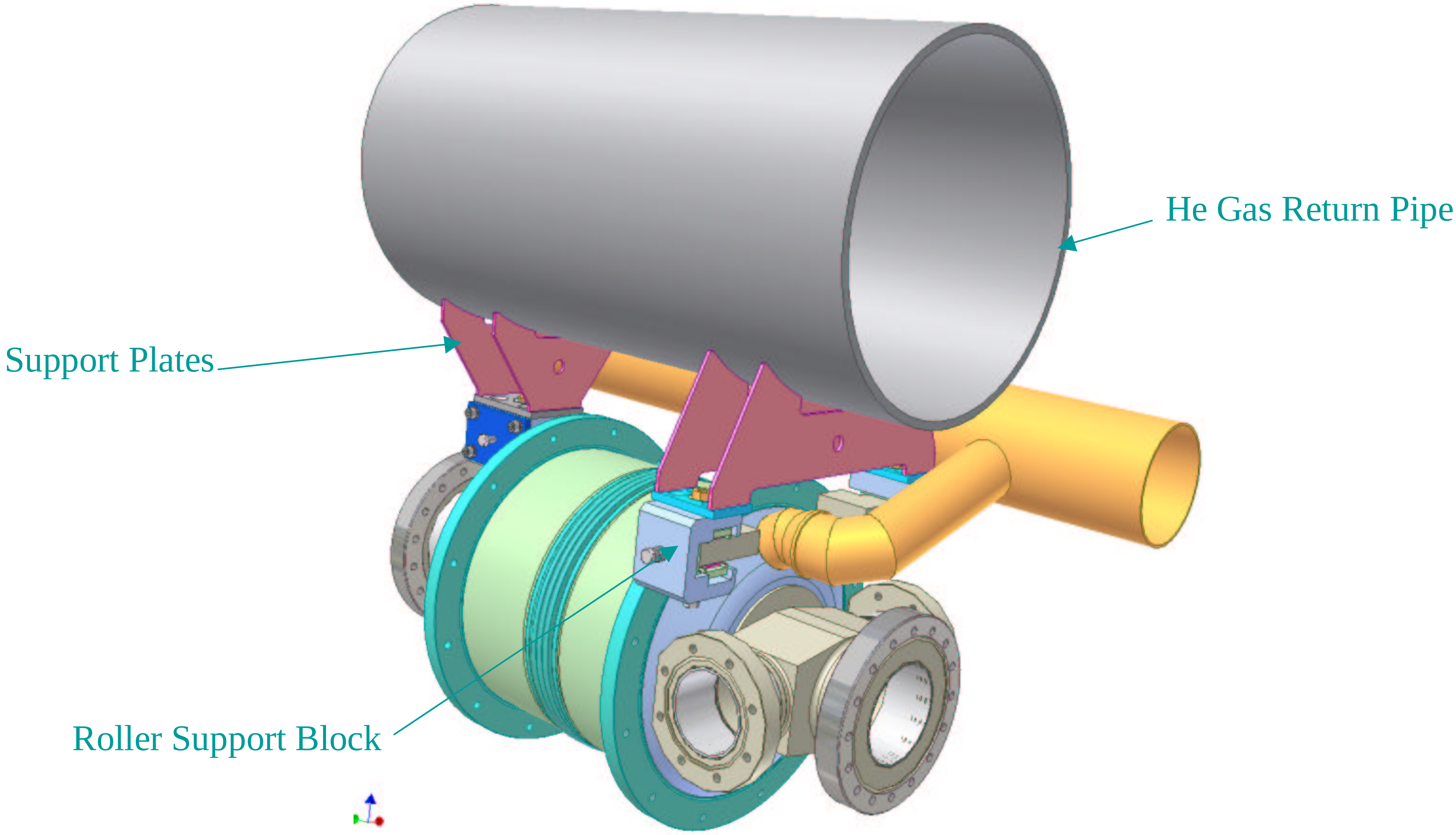

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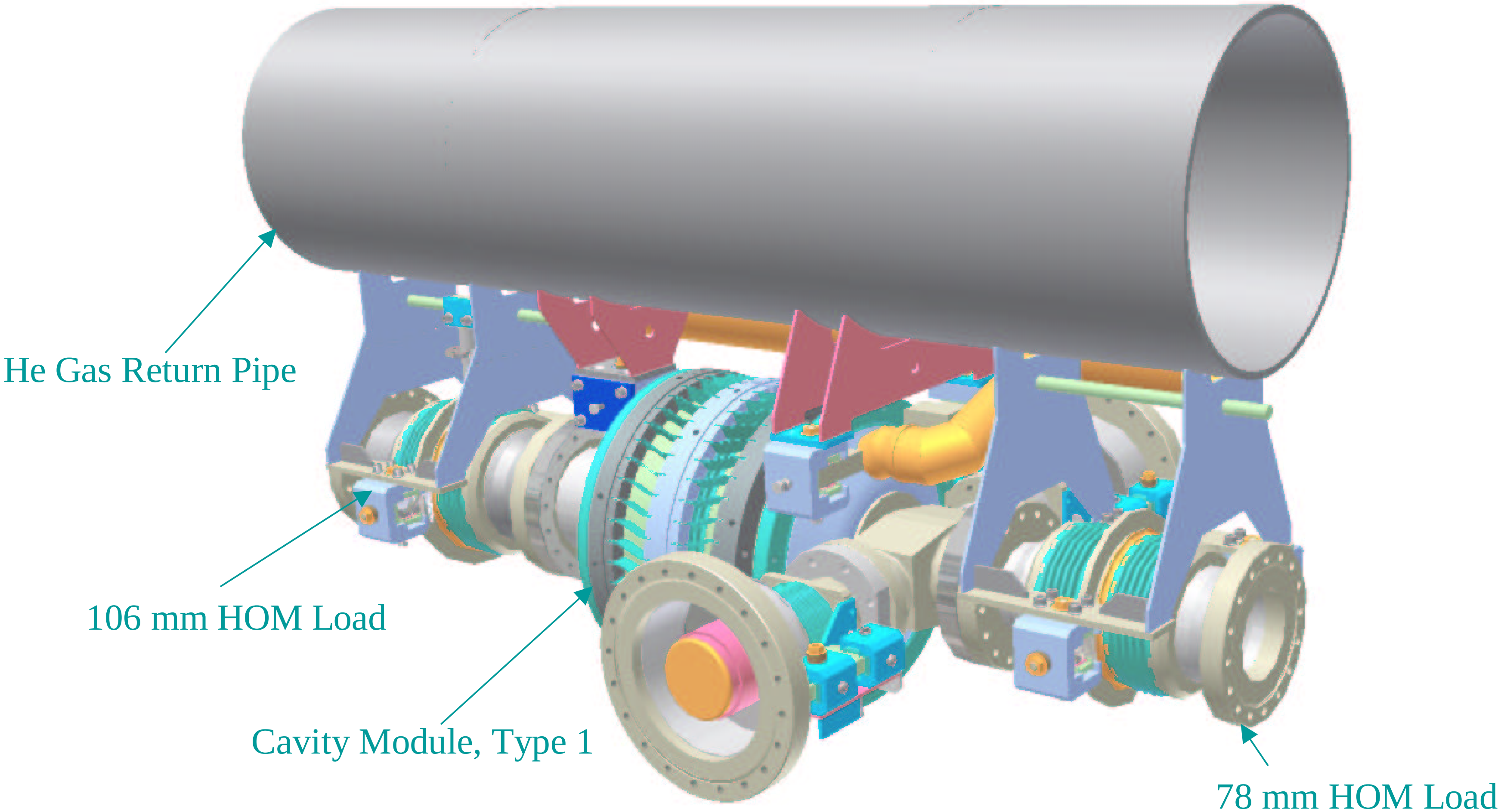

Cavity and HOM Loads Assembly

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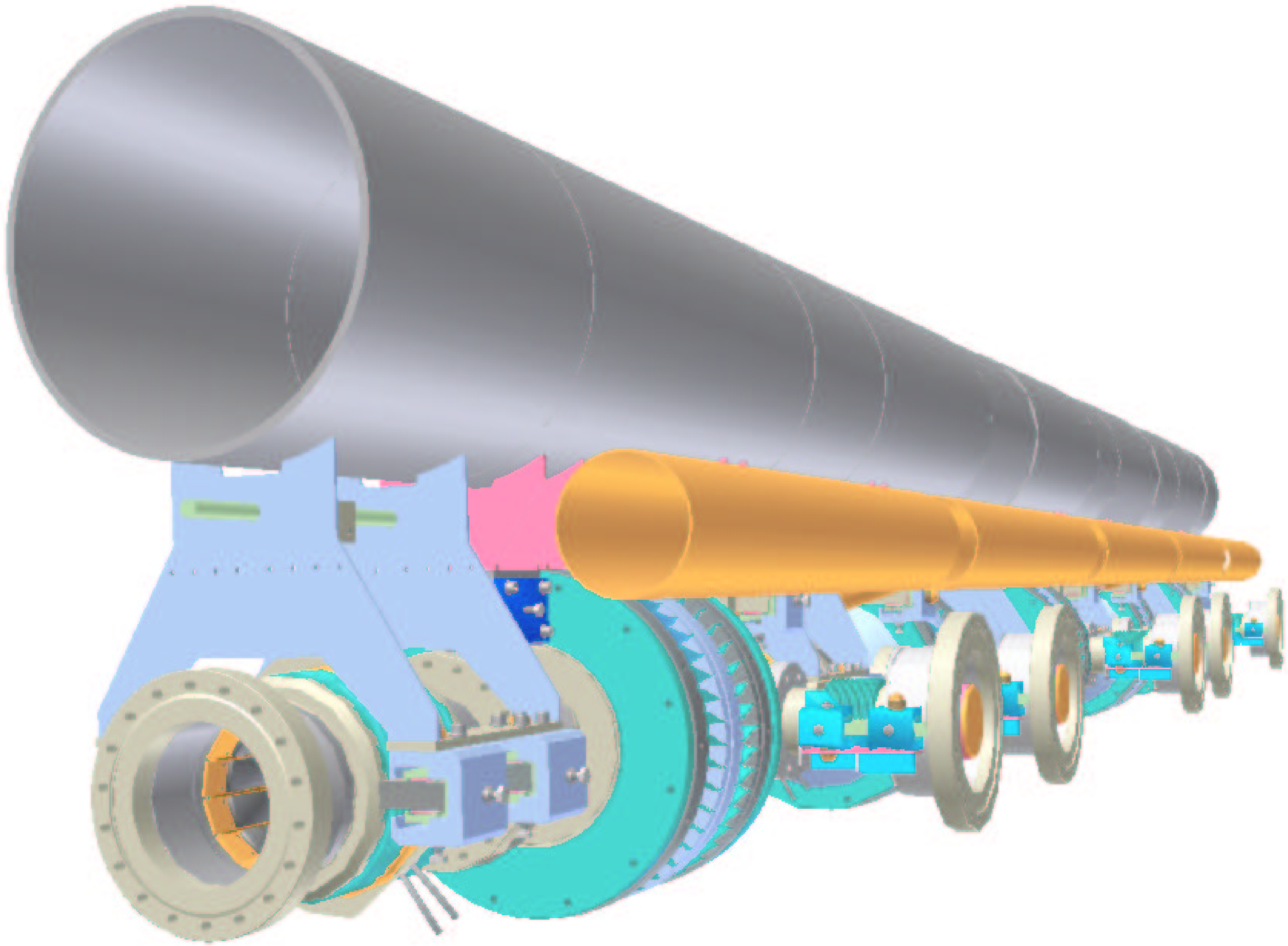

Cavity String

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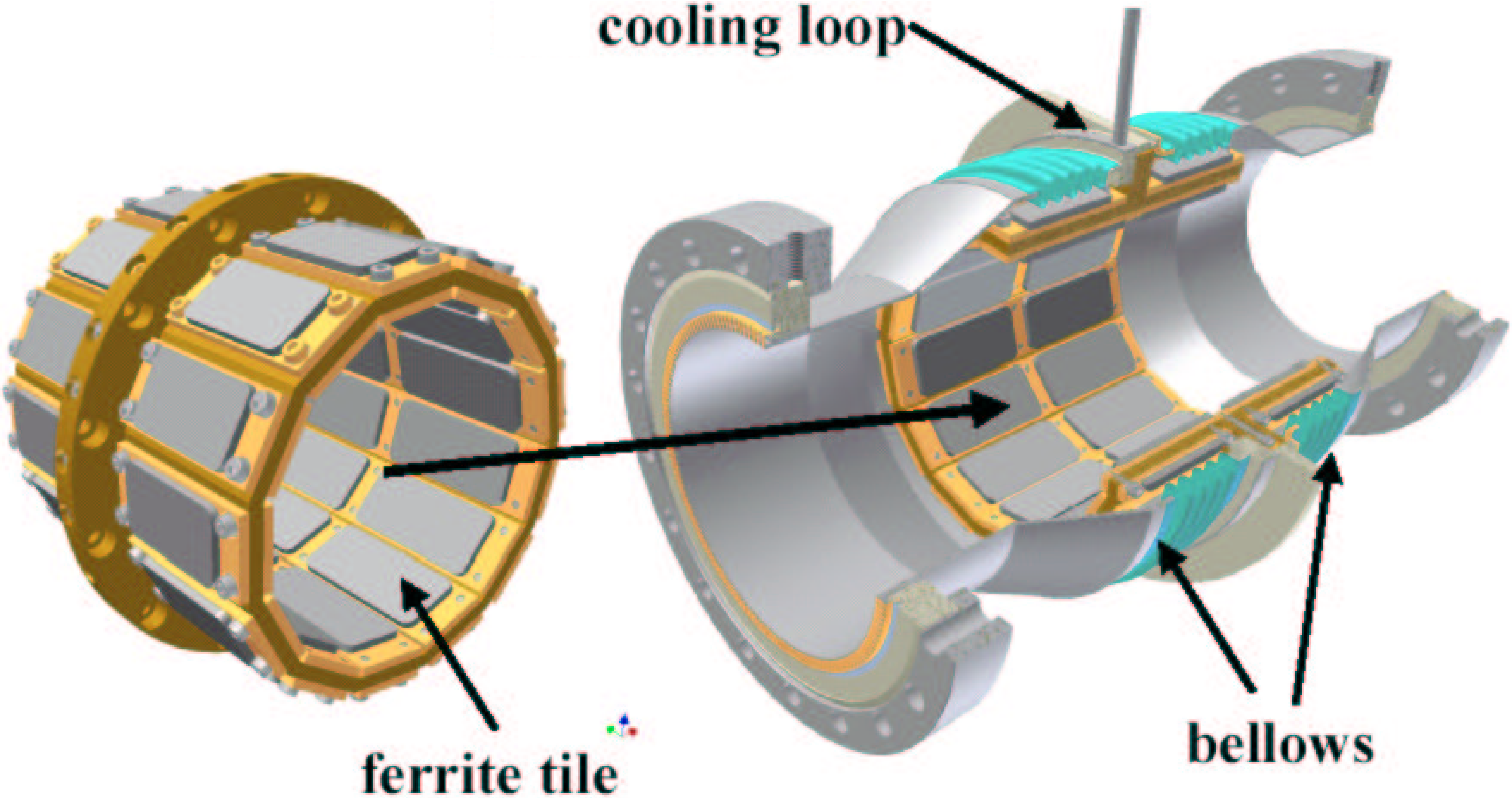
Ferrite shielded bellows



The bare bellows would lead to a loss factor of 1.2V/pC into the bellows.

The absorption is being studied up to 40GHz as a function of temperature.

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	ERL buncher cavity	ERL s.c. injector cavities	ERL s..c. main linac cavities
frequency [MHz]	1300	1300	1300
number of cavities	1	5	7
cells per cavity	1	2	7
R/Q [Ω] (circuit def.)	105	109	392
Q_0	20,000	$> 5 \cdot 10^9$	$> 10^{10}$
Q_{ext}	9,900	$4.6 \cdot 10^4$ ($4.1 \cdot 10^5$)	$2.6 \cdot 10^7$ for 25 Hz peak detuning
acc. voltage per cavity [MV]	0.12	1 (3)	≈ 16 (20 MV/m)
required klystron power per cavity [kW]	7	130	11
required relative amplitude stability (rms)	$8 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
required phase stability (rms)	0.1°	0.1°	0.06°

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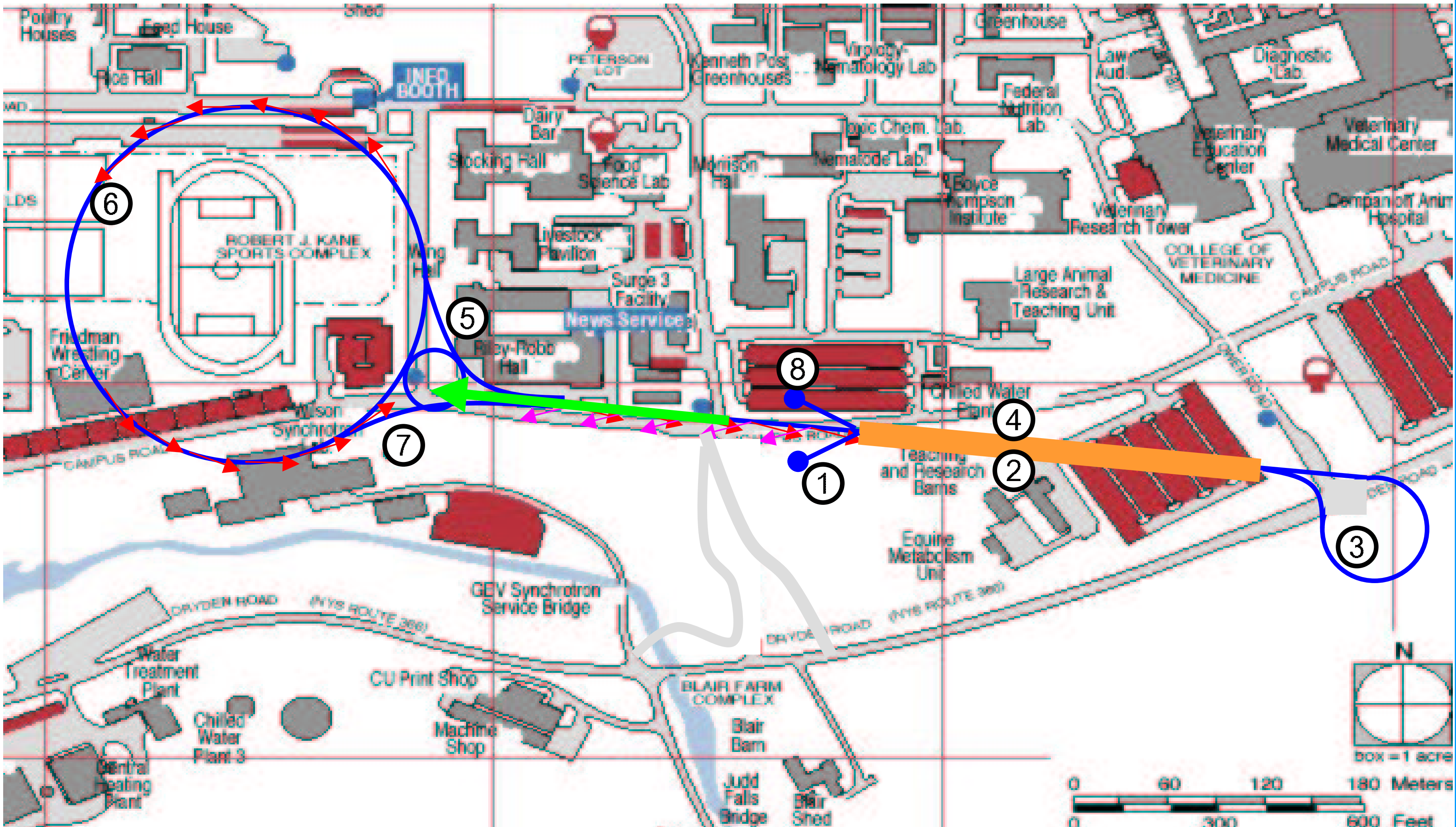
ERL@CESR being analyzed



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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.

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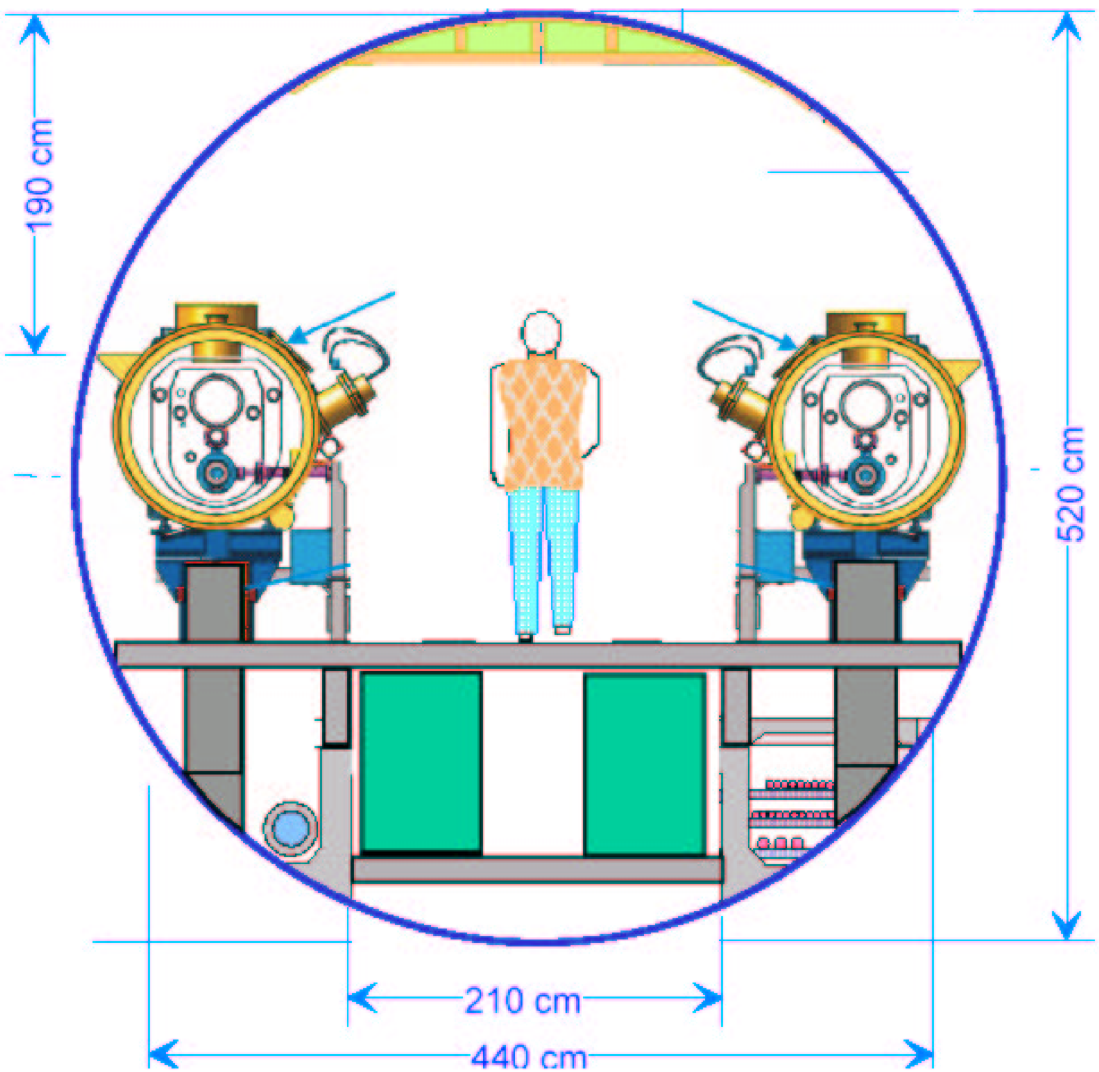
Double linac tunnel



Two modified TESLA type cryomodules, two times the 17kW IOTs, etc. in one tunnel.

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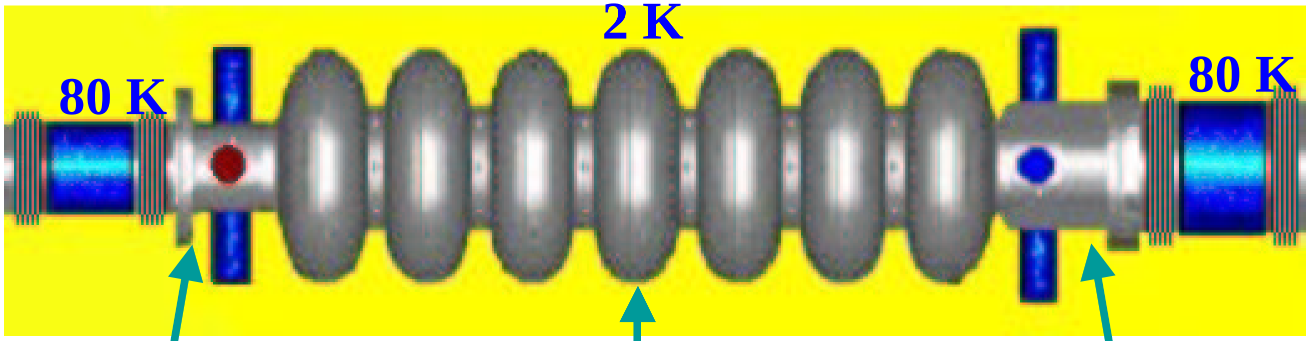
HOM Damping in the ERL Main Linac



small 78 mm beam tube

7-cell s.c. cavity, TESLA shaped center cells

large 106 mm beam tube

- 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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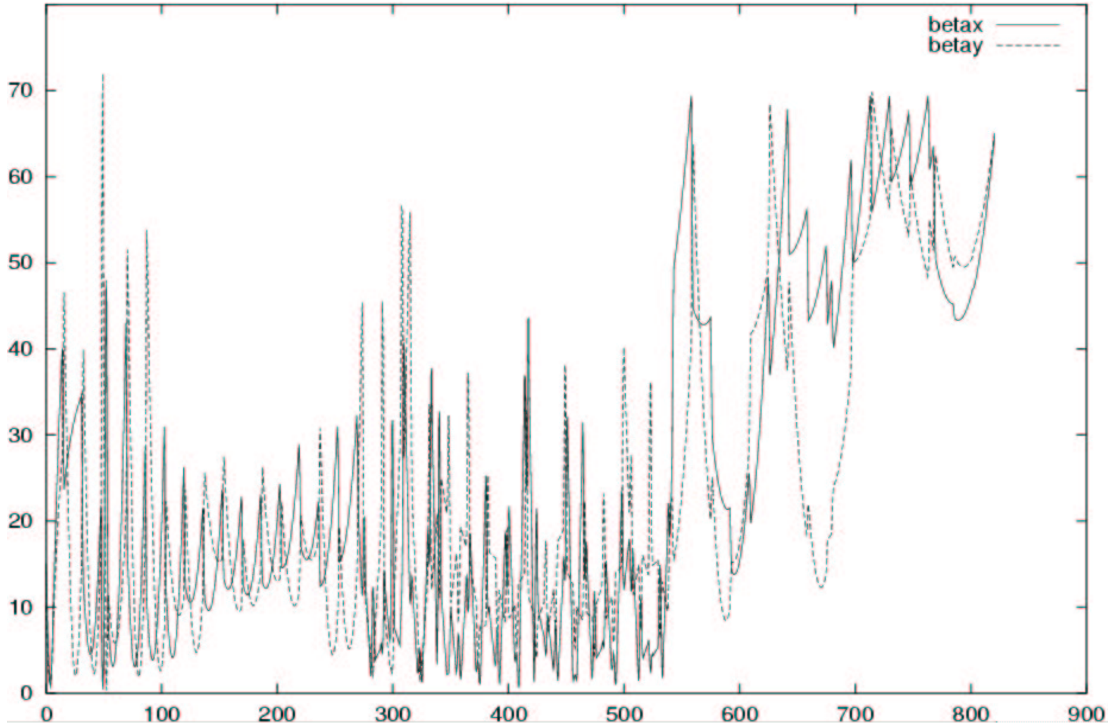
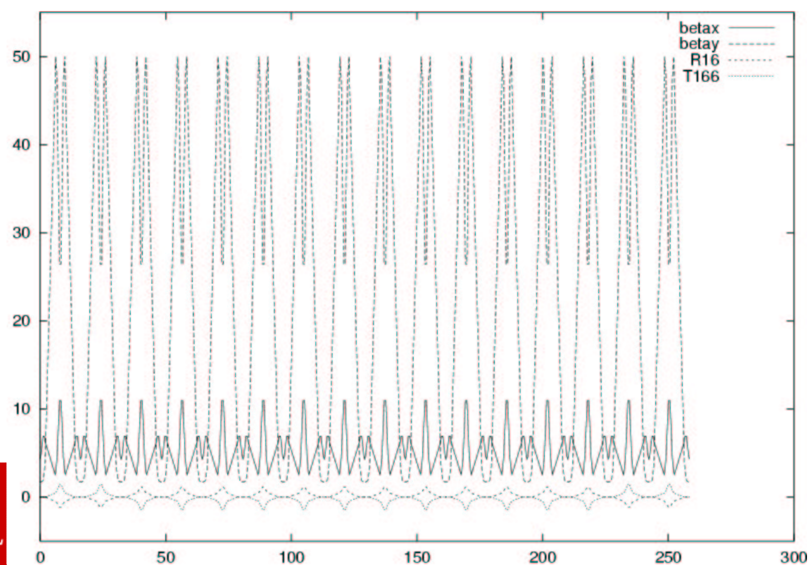


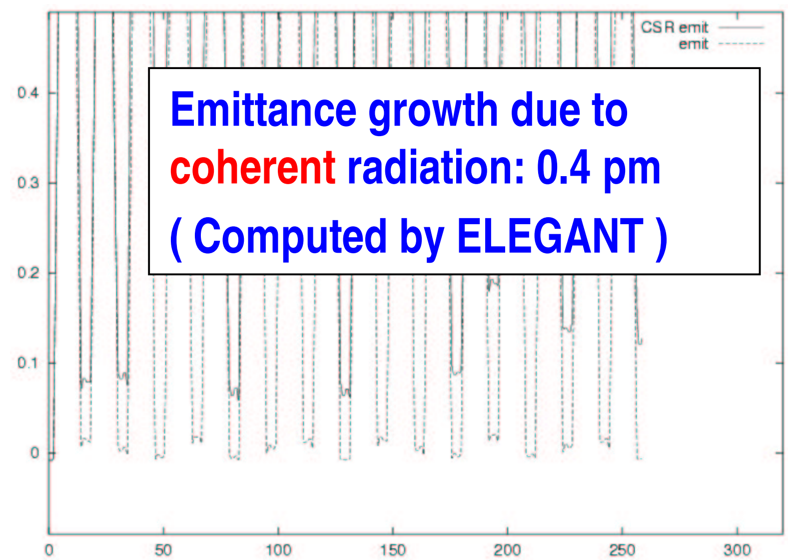
Linac optics

Optimize optics in the Linac for the accelerated and the decelerated energy.

Emittance growth due to incoherent radiation: 4 pm

Return arc optics





Emittance growth due to coherent radiation: 0.4 pm

(Computed by ELEGANT)

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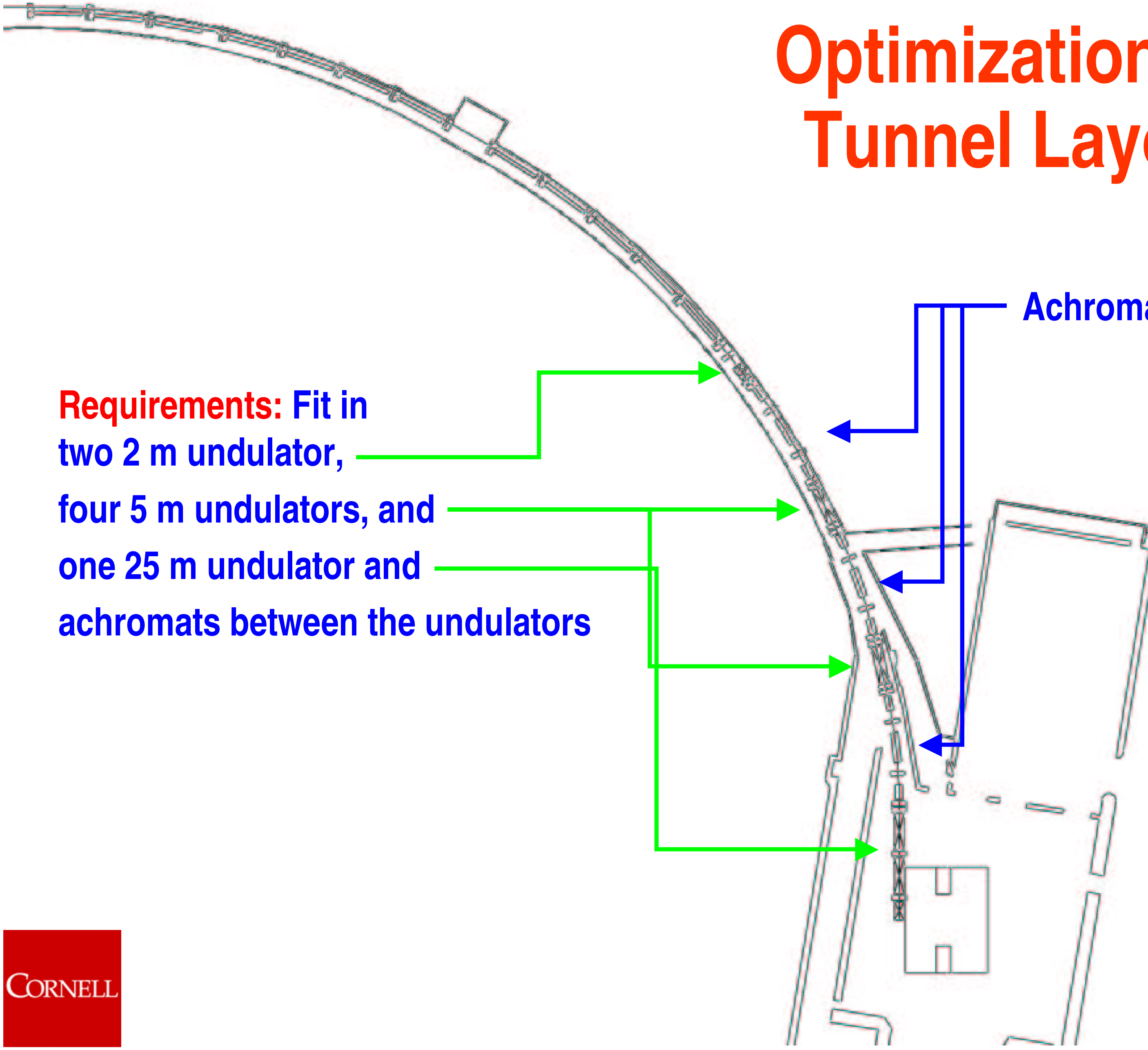
Optimization of Tunnel Layout



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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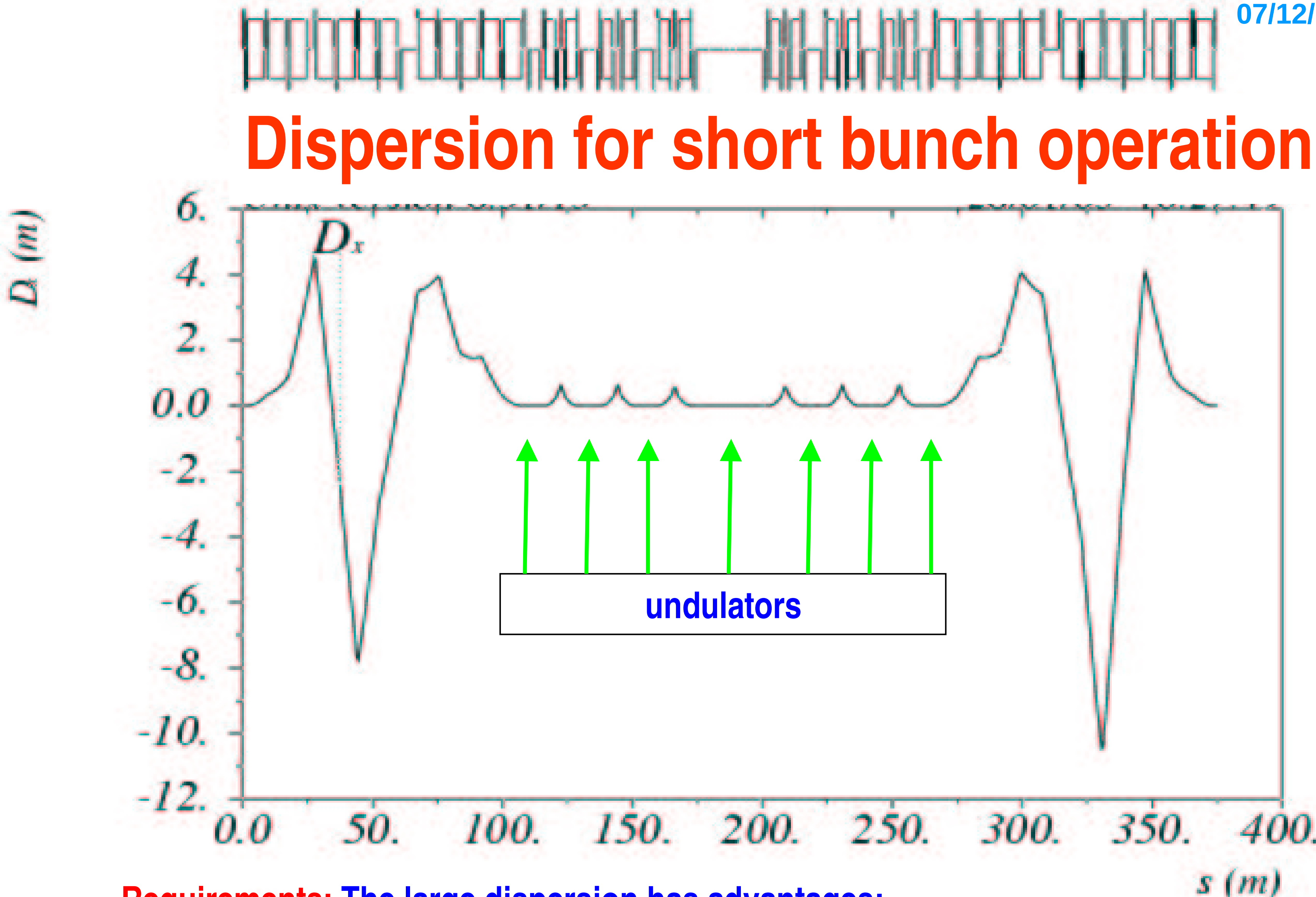
Dispersion for short bunch operation



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

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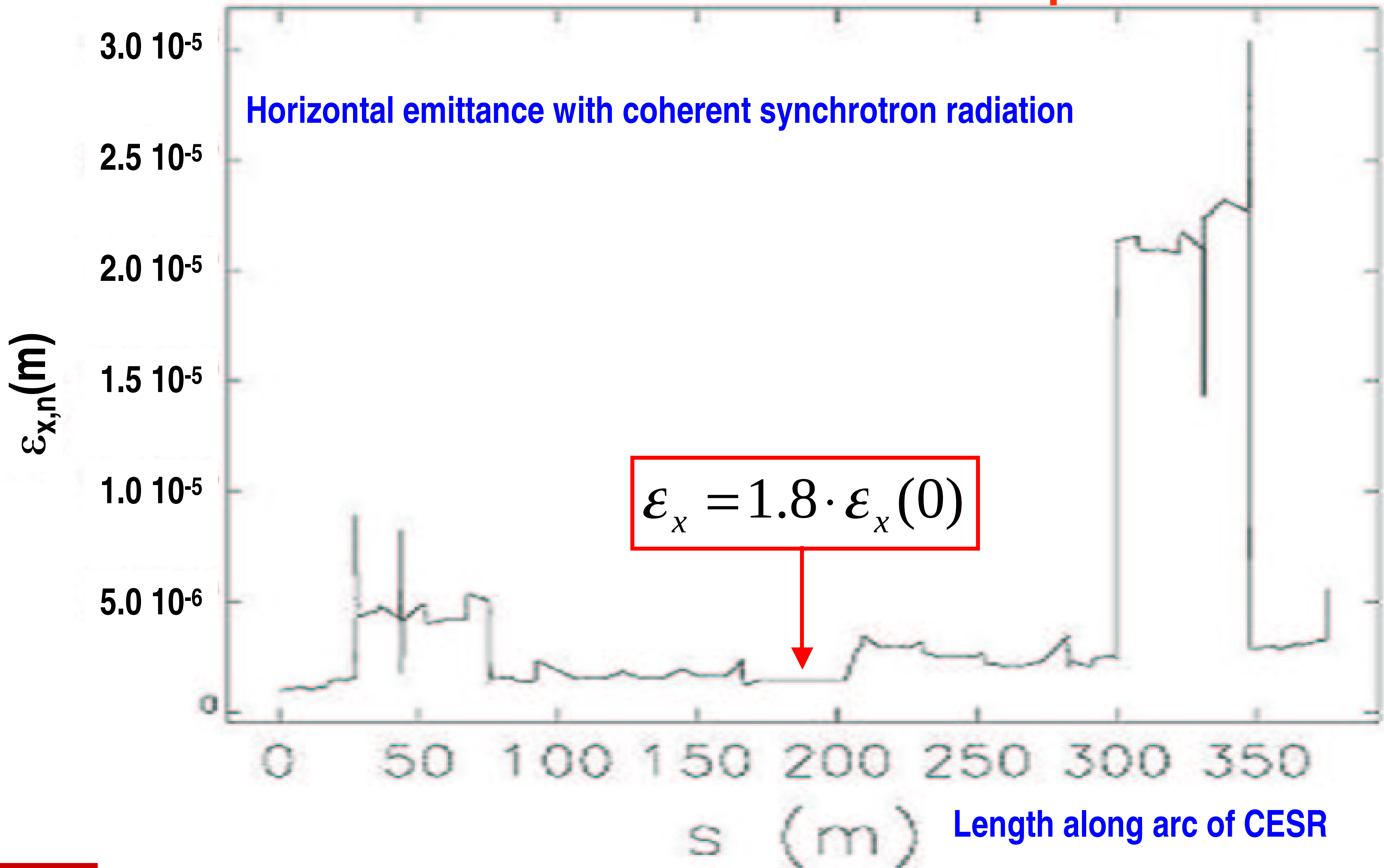

Result: After suitable nonlinear bunch length manipulation, the emittance growth can be controlled in all undulators.

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Conclusion

- First and second order optics have been found for an ERL in the CESR tunnel
  - which uses the current CESR tunnel and many of its components
  - 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 computed to be > 600mA

- This upgrade of CESR to an ERL light source would be a demonstration of an upgrade path that could then be open to many existing X-ray rings.

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Previous Energy Recovery Linacs

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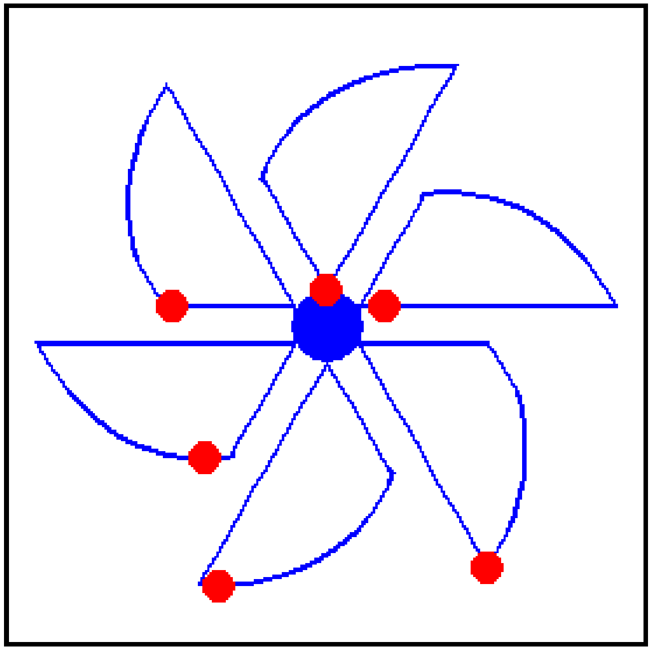
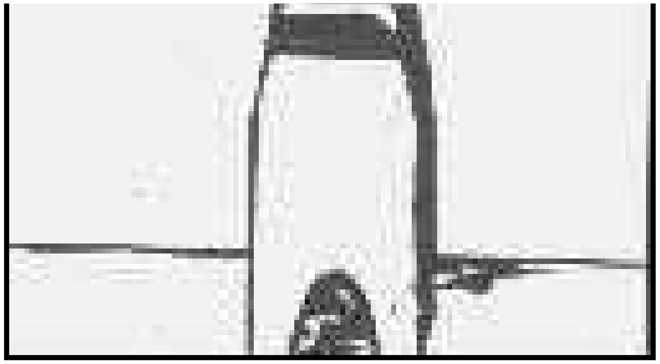
Previous Energy Recovery Linacs





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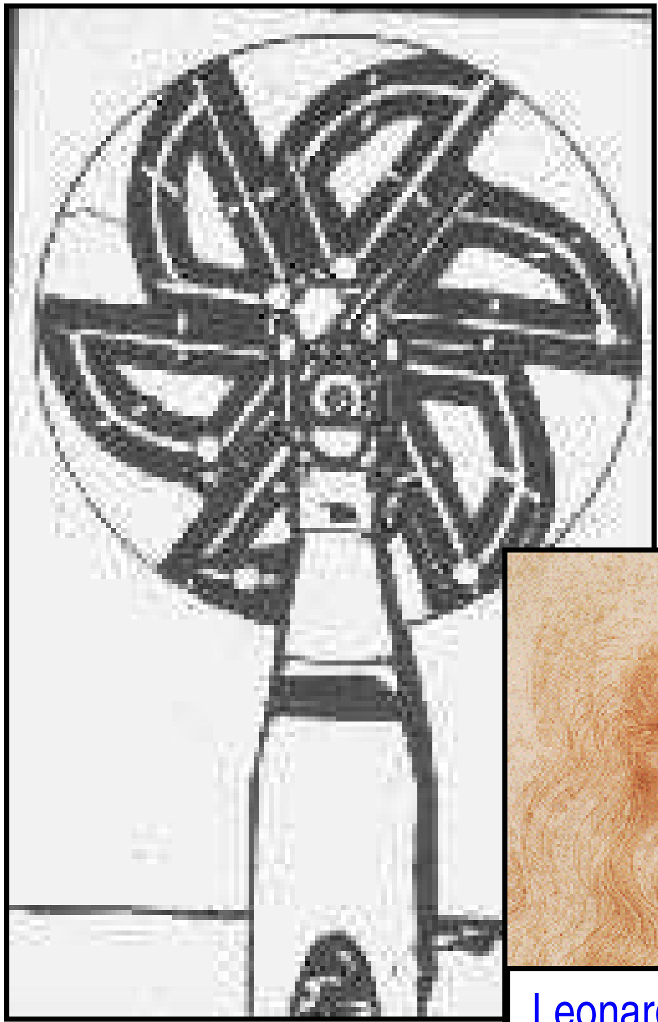
Previous Energy Recovery Linacs



Leonardo da Vinci
(1452-1519)

"Now, why should that not work?"

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