100mA, 5GeV x-ray ERL

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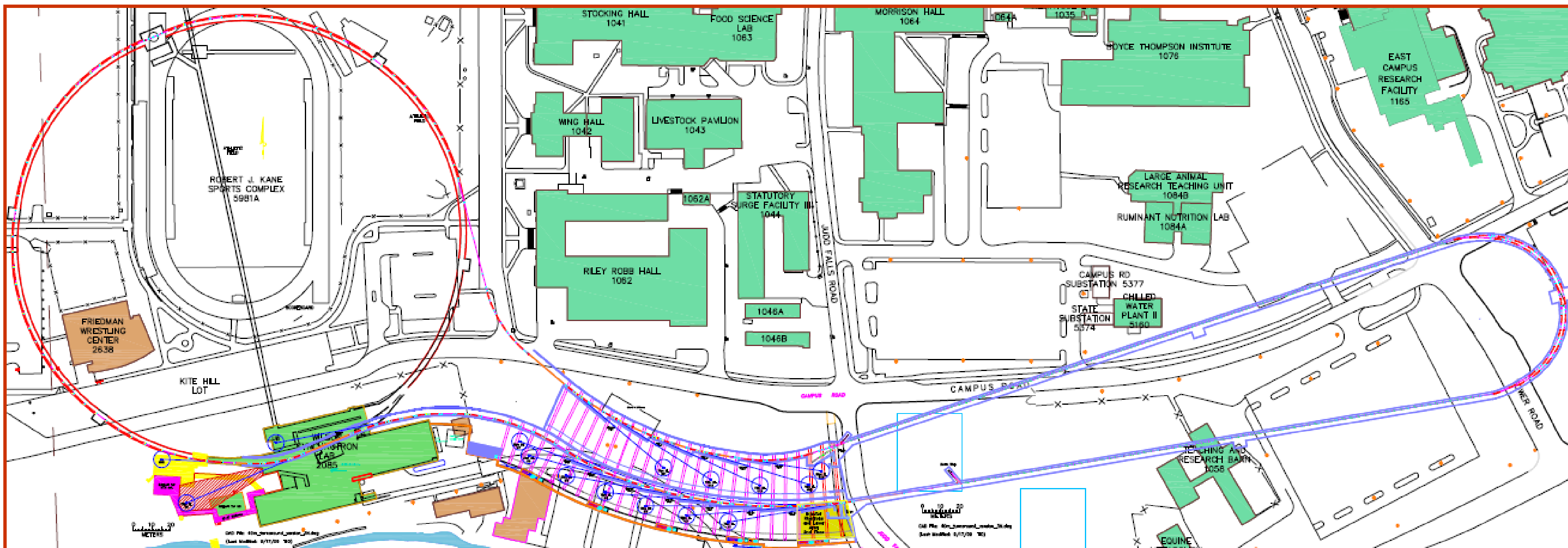
a) Advantages of ERL x-ray beams
b) Beam Challenges
c) SRF Challenges
d) Preparations at Cornell



Can X-ray beams be improved ?

- Narrower and less divergent e-beams
- More mono-energetic beams
- Shorter pulses

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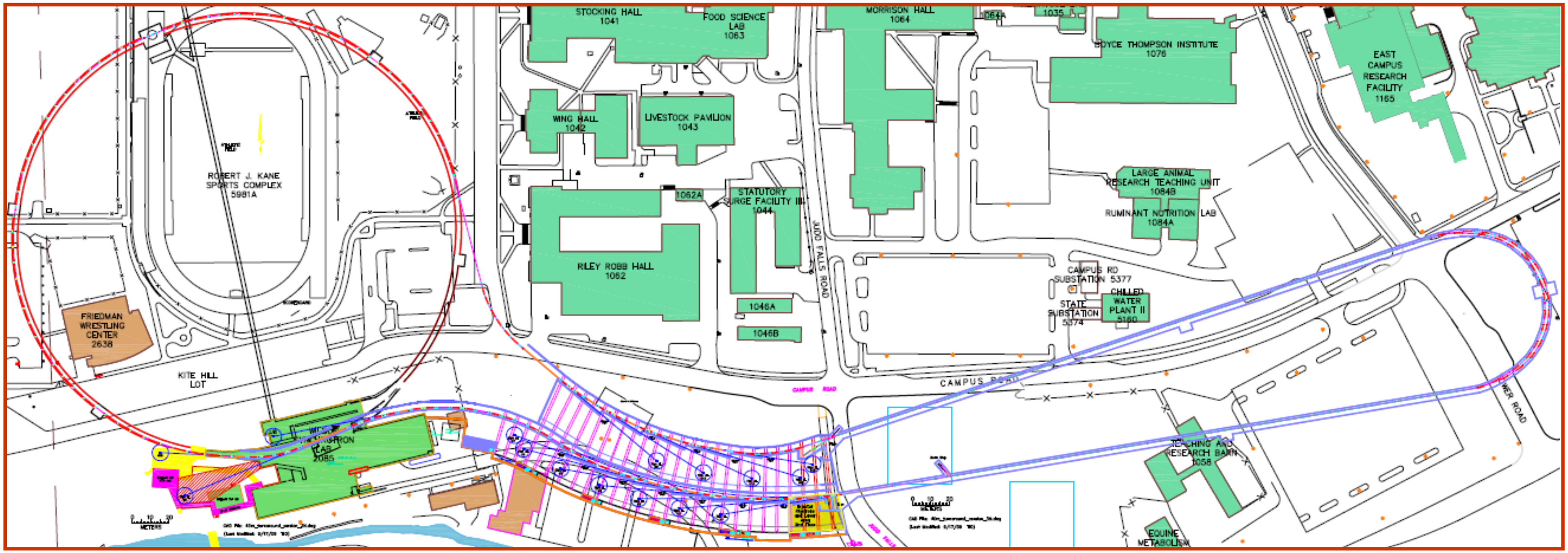
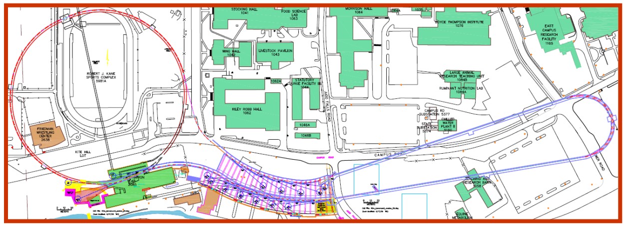
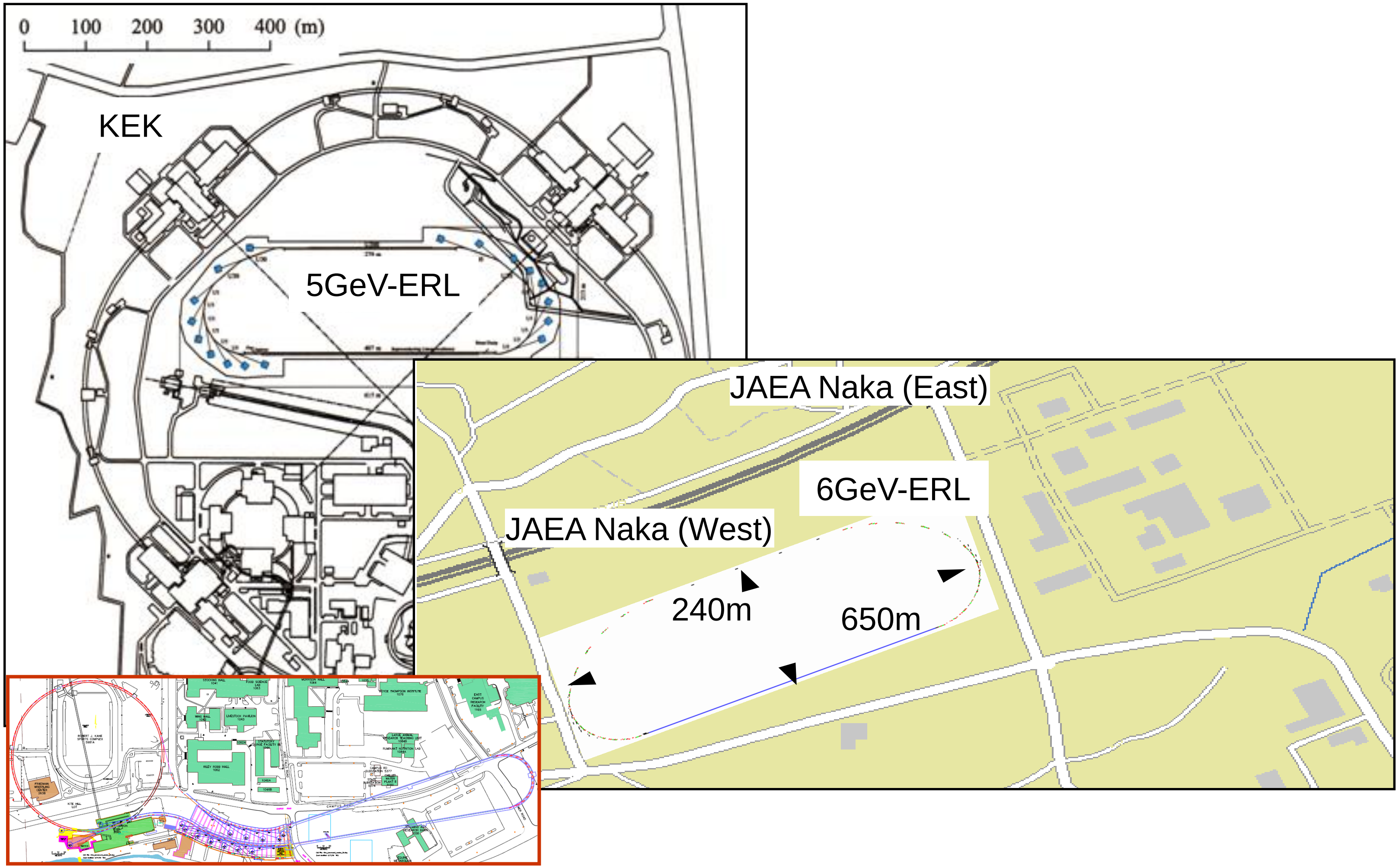
} all of the above



Cornell ERL



Cornell / KEK / JAEA ERLs



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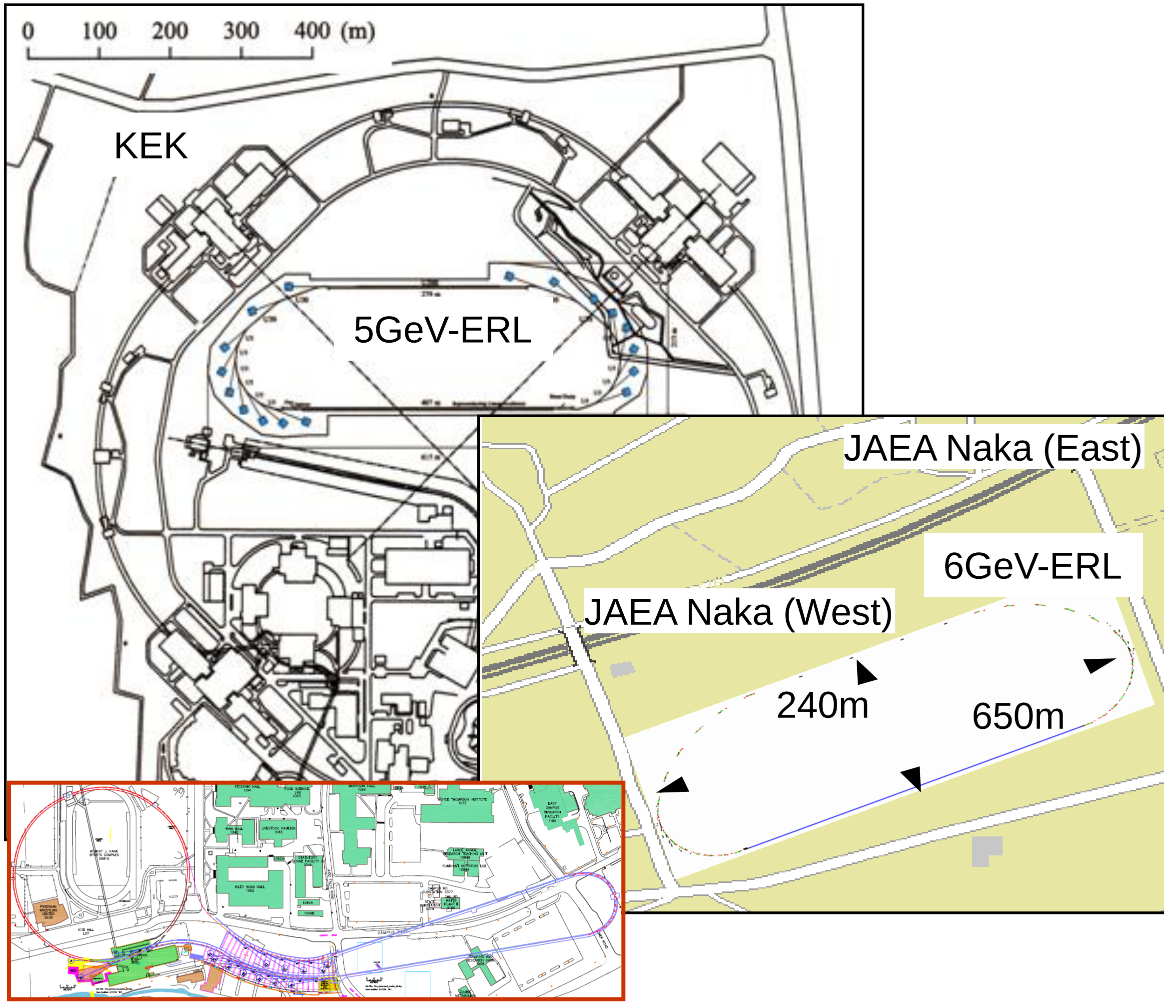
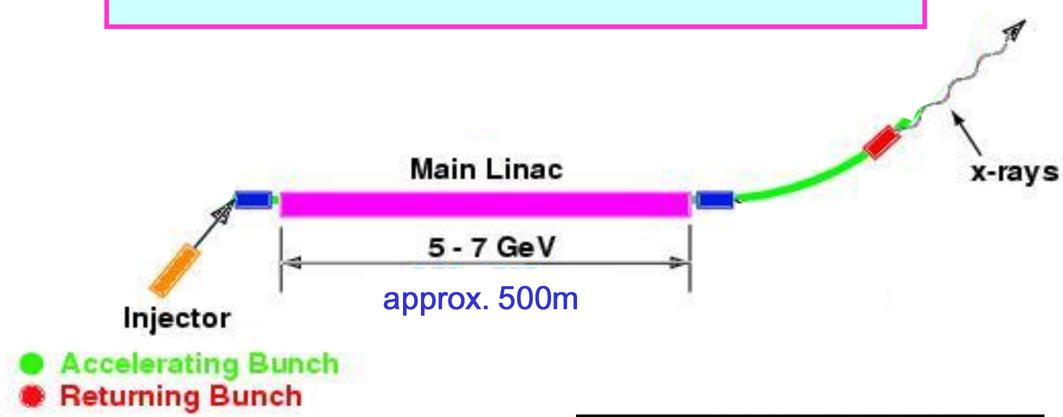
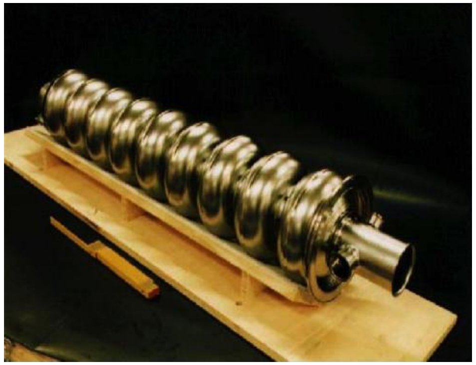


Principle of an X-ray ERL

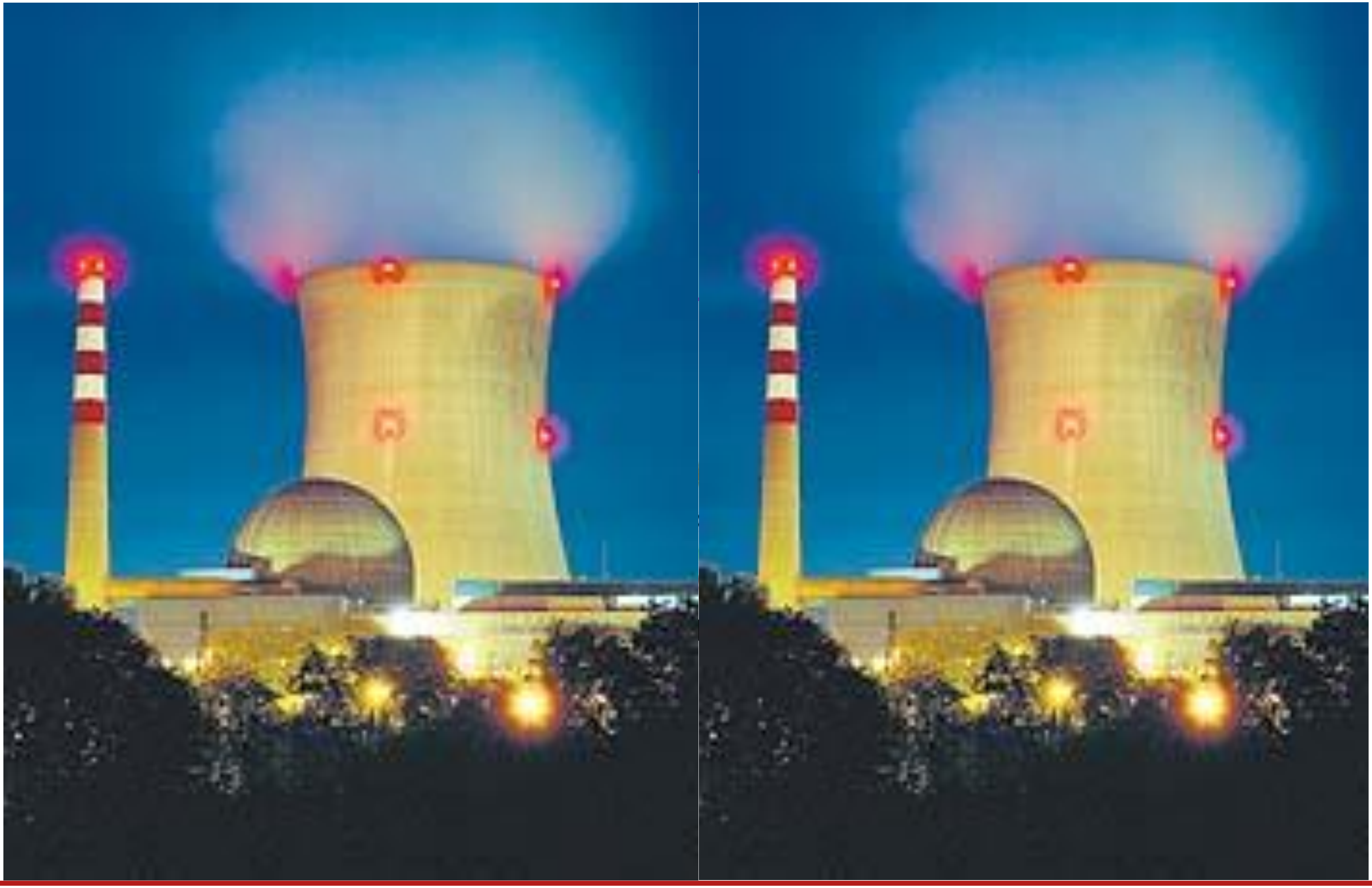
Narrow beams in rings widen up after many hundreds of turns.

5GV*100mA = 0.5GW
(good size power plant)





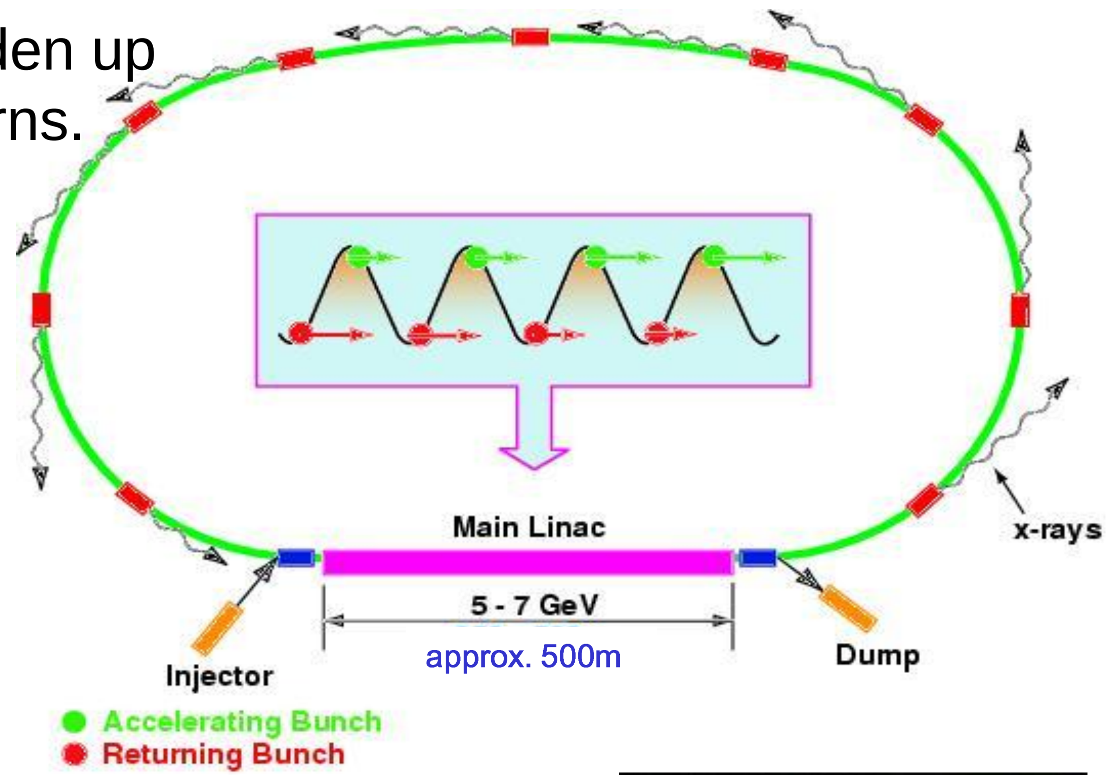
Principle of an X-ray ERL



Principle of an X-ray ERL

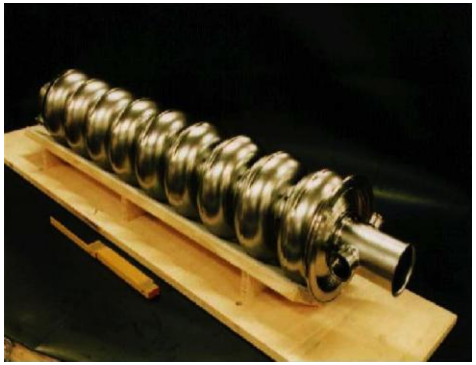
Narrow beams in rings widen up after many hundreds of turns.

Widening is limited during one turn

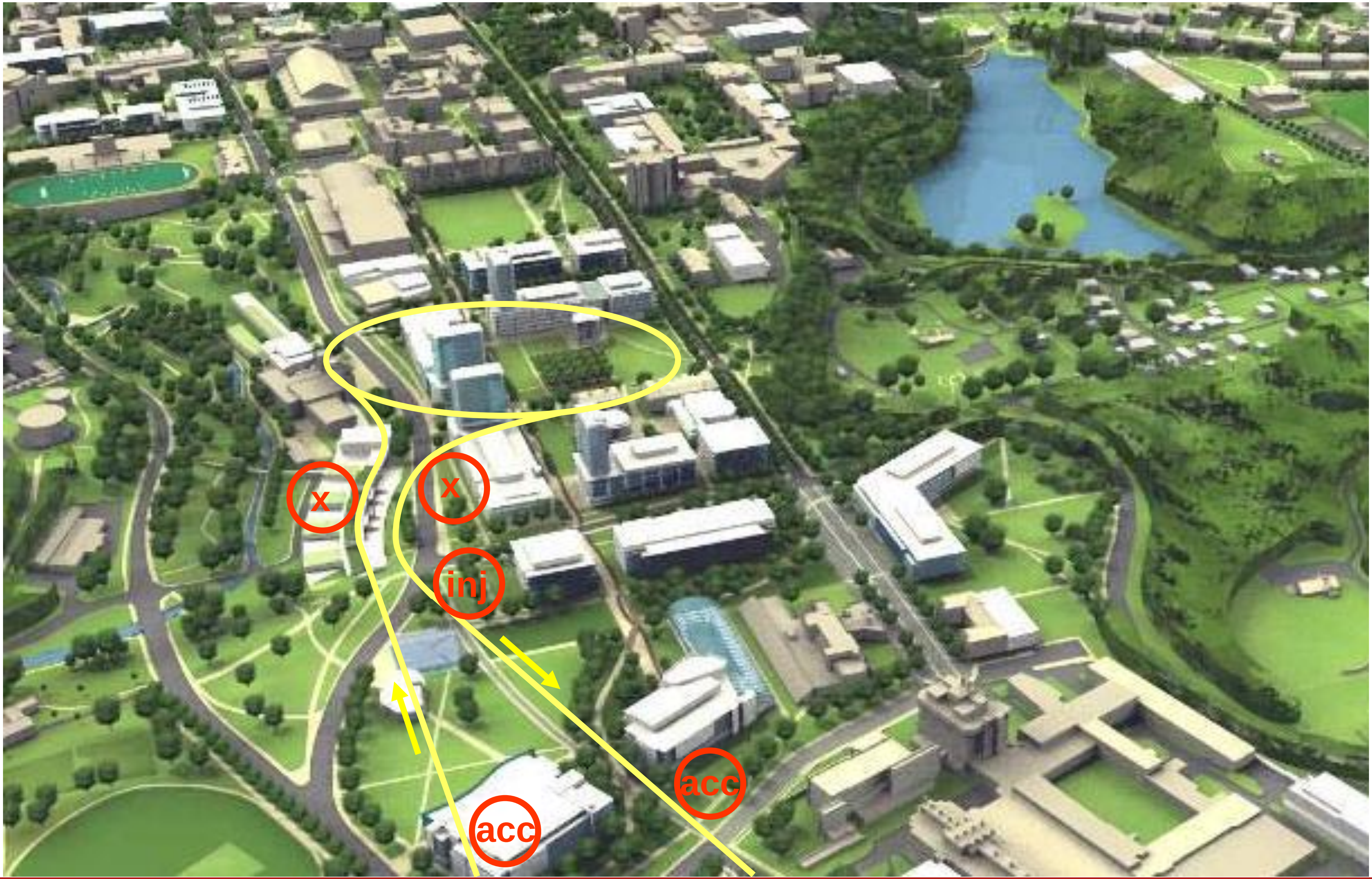


Challenges:

- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Dominated by SRF components



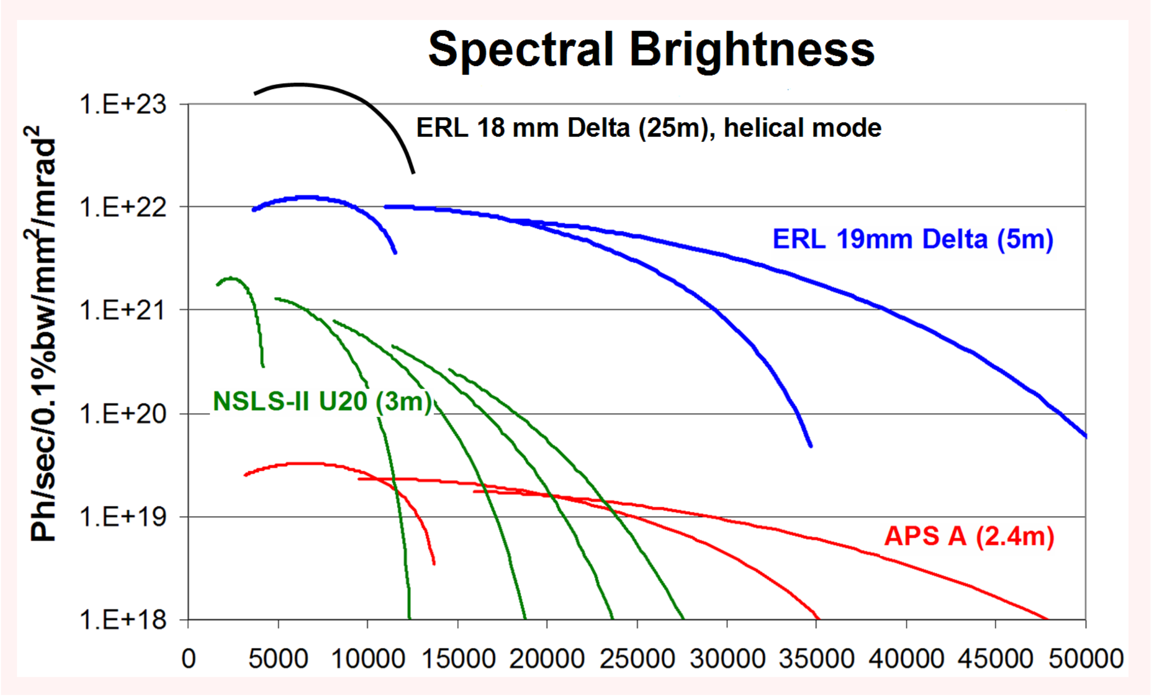
Conceptual building design



Cornell's x-ray ERL parameters

	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	2.5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.25	MW
Beam loss	< 1	< 1	< 1	<1	micro A

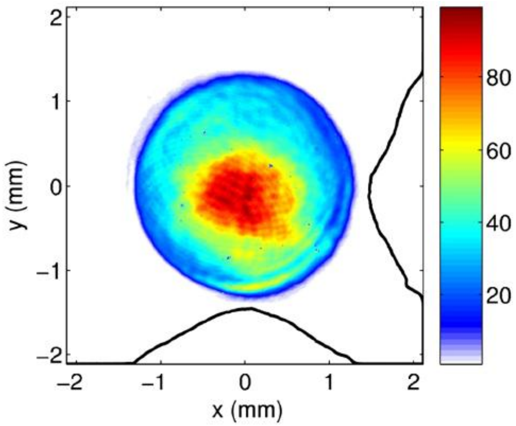
Average spectral brightness for hard x-rays

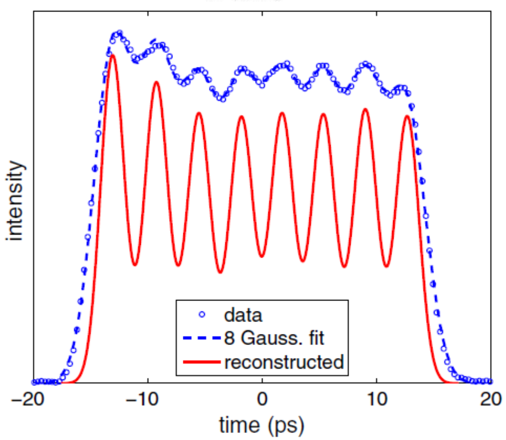


Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.

Emittances from ERL Prototyping

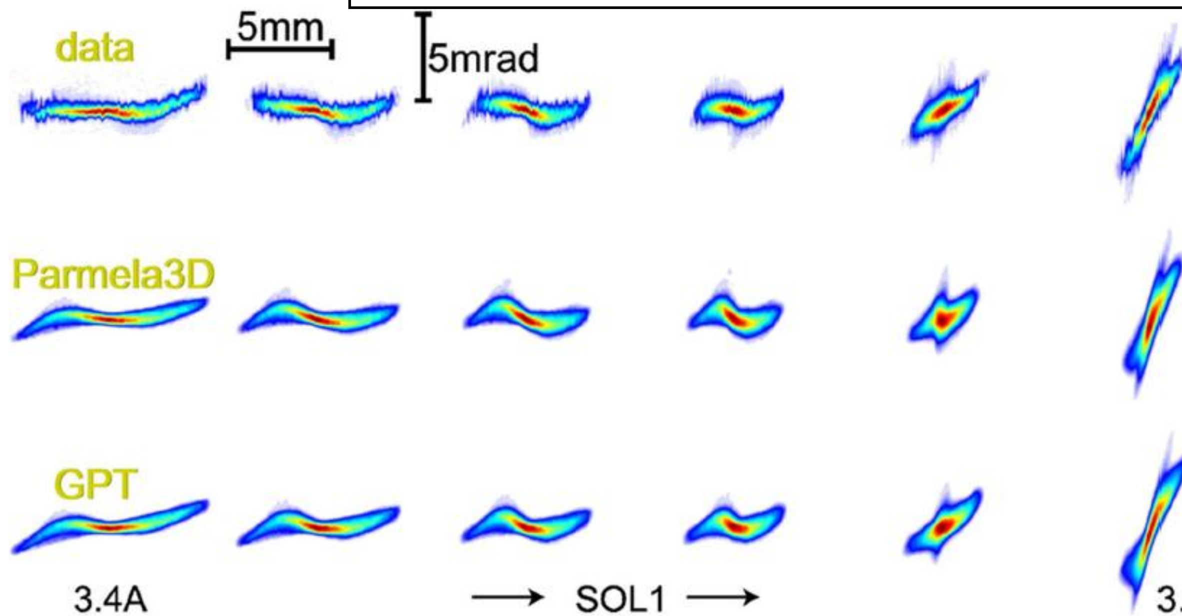
Beam properties at the cathode





Fixed slits phase space measurements

- Corrector coils for beam scanning
- 10 micron precision slits
- 1 kW beam power handling



From Phys. Rev. ST-AB 11, 100703 (2008)

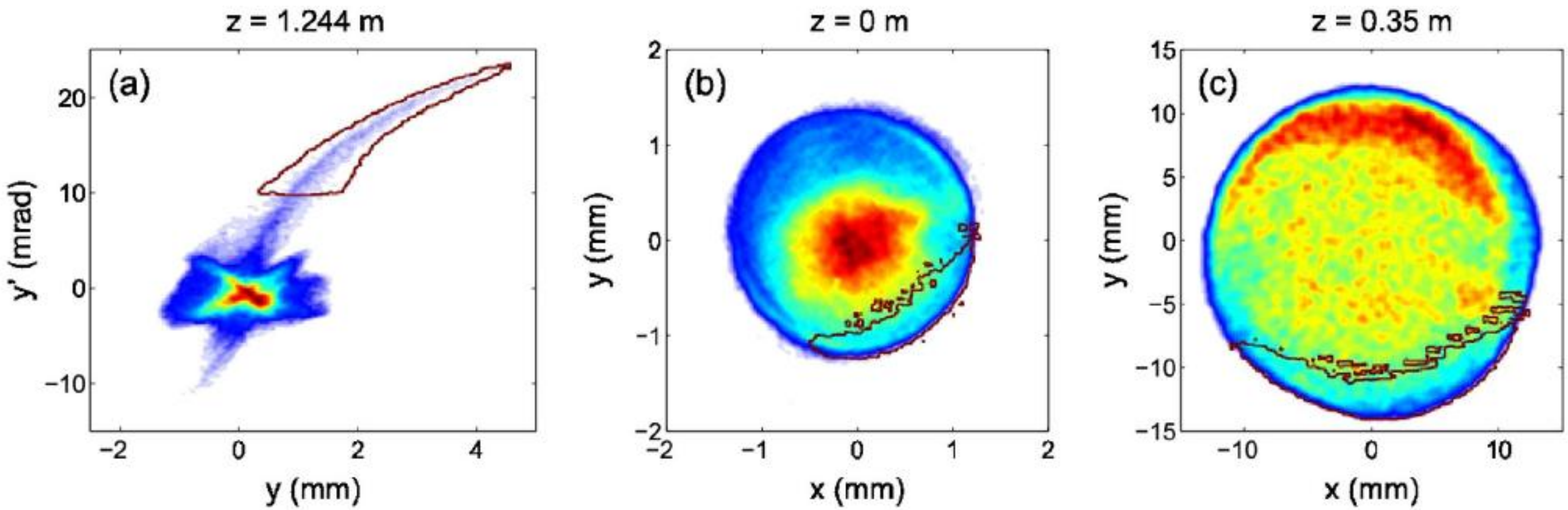
Are transported through the accelerator, measured in a fixed slit phase space measuring system, and compared with simulations.

Good agreement with theory gives confidence that the very small simulated emittances can be achieved.

Asymmetric beam distributions

Asymmetric phase space distribution leads to reduced brightness

This Brightness reduction has been traced back to asymmetric photon distributions on the cathode.



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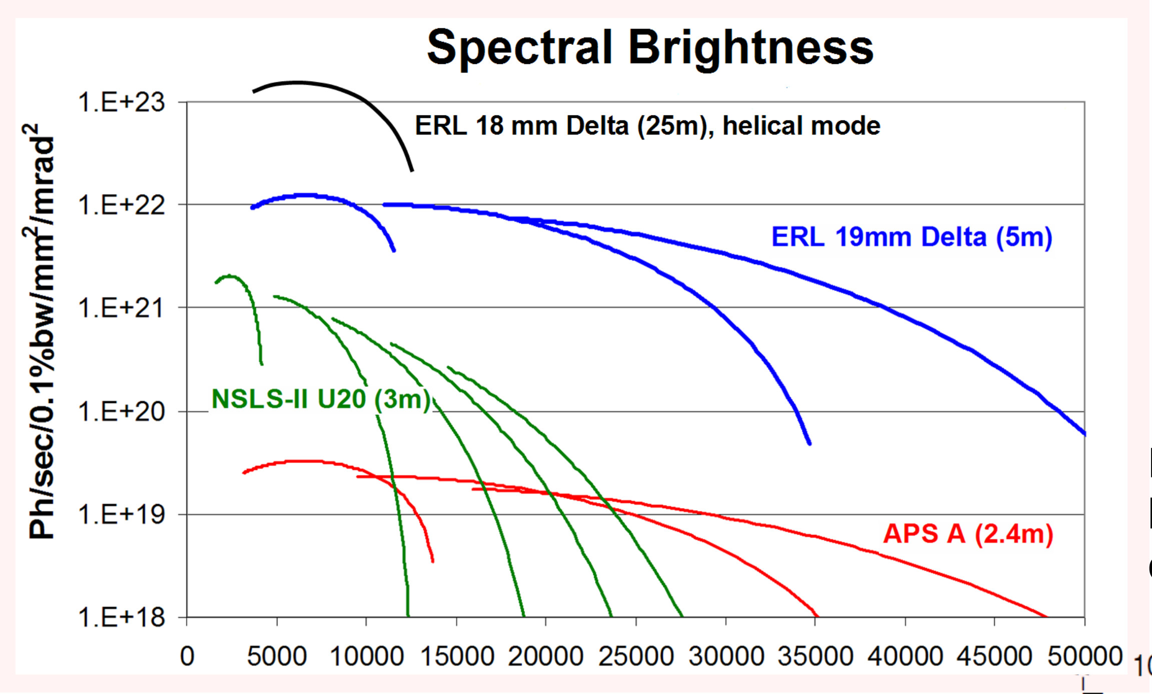
Are transported through the accelerator, measured in a fixed slit phase space measuring system, and compared with simulations.

Gun milestones:

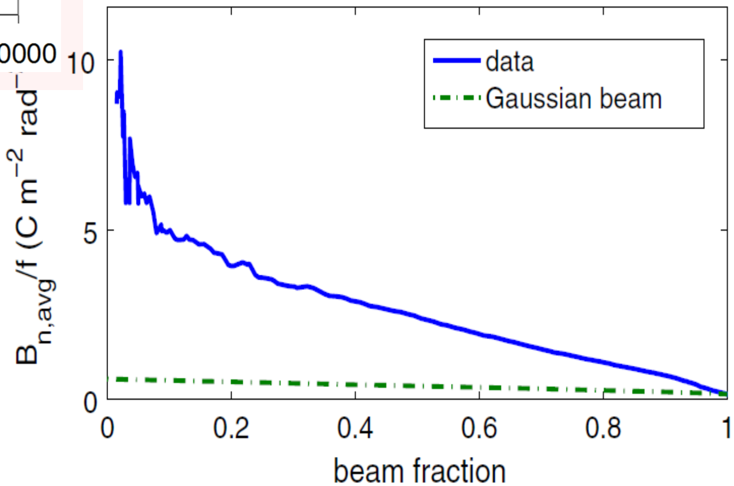
- Highest current: 25mA
- Highest voltage: 430kV
- Highest bunch charge: 80pC
- Emittance at 250keV: 1.5μm

Main advantage of a hard x-ray ELR: Average spectral brightness for hard x-rays



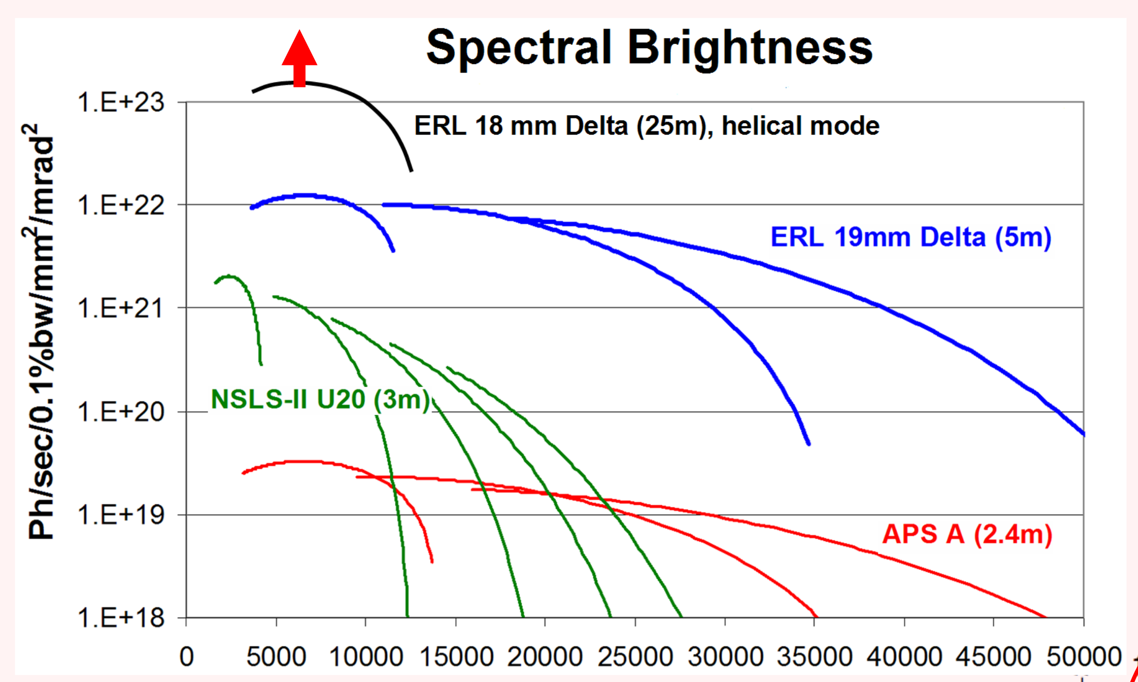
Electron beams from ERLs can have much higher brightness, especially in the core of the beam.

Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.



Measurement from phase 1a

Every challenge can show future potential in a new accelerator !



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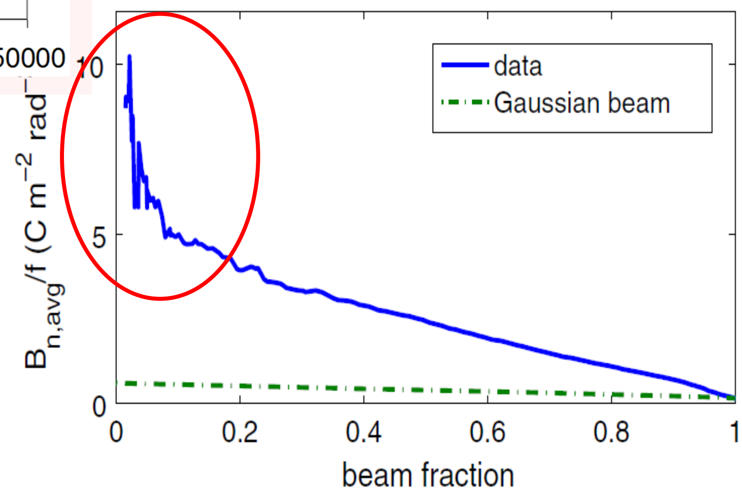

Measurement from phase 1a

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Broad applications of ERL beams: Large currents of Linac quality beams

The power in linacs is limited, but the beam quality is the highest achieved to date.

In an ERL, much larger average currents can be accelerated with linac quality beam.

An ERL is an accelerator type, and can be used for many types of light sources

1) and other accelerators, e.g. the e-RHIC nuclear physics collider
2) ERL driven FELs for IR, UV, soft and hard x-rays

   (**up to 14kW IR continuous beam achieved, UV in commissioning at JLAB, ERL-xFEL in Physical Review ST-AB (2005)**)
3) ERL driven Compton backscattering sources for hard x-ray beams (**funded at KEK**)
4) ERLs for spontaneous undulator radiation (**e.g. Cornell University**)

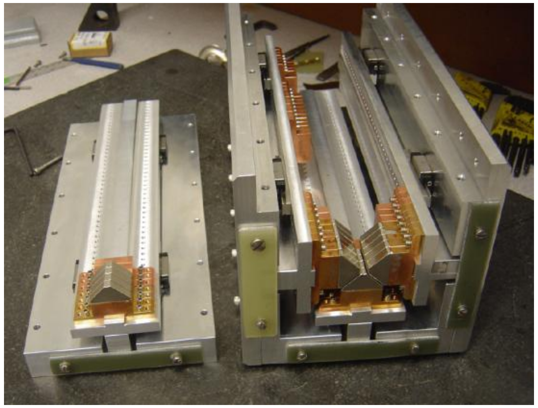
Most linac-based light sources can be operated by an ERL, but with significantly more current and output power.

A hard x-ray ERL development at Cornell has spinoffs for many accelerator projects, e.g. XFELOs with 10000 X brightness (**Phys Rev Letters (2008)**)

Broad advantages of ERLs

X-ray ERLs have unique capabilities and many advantages over rings:

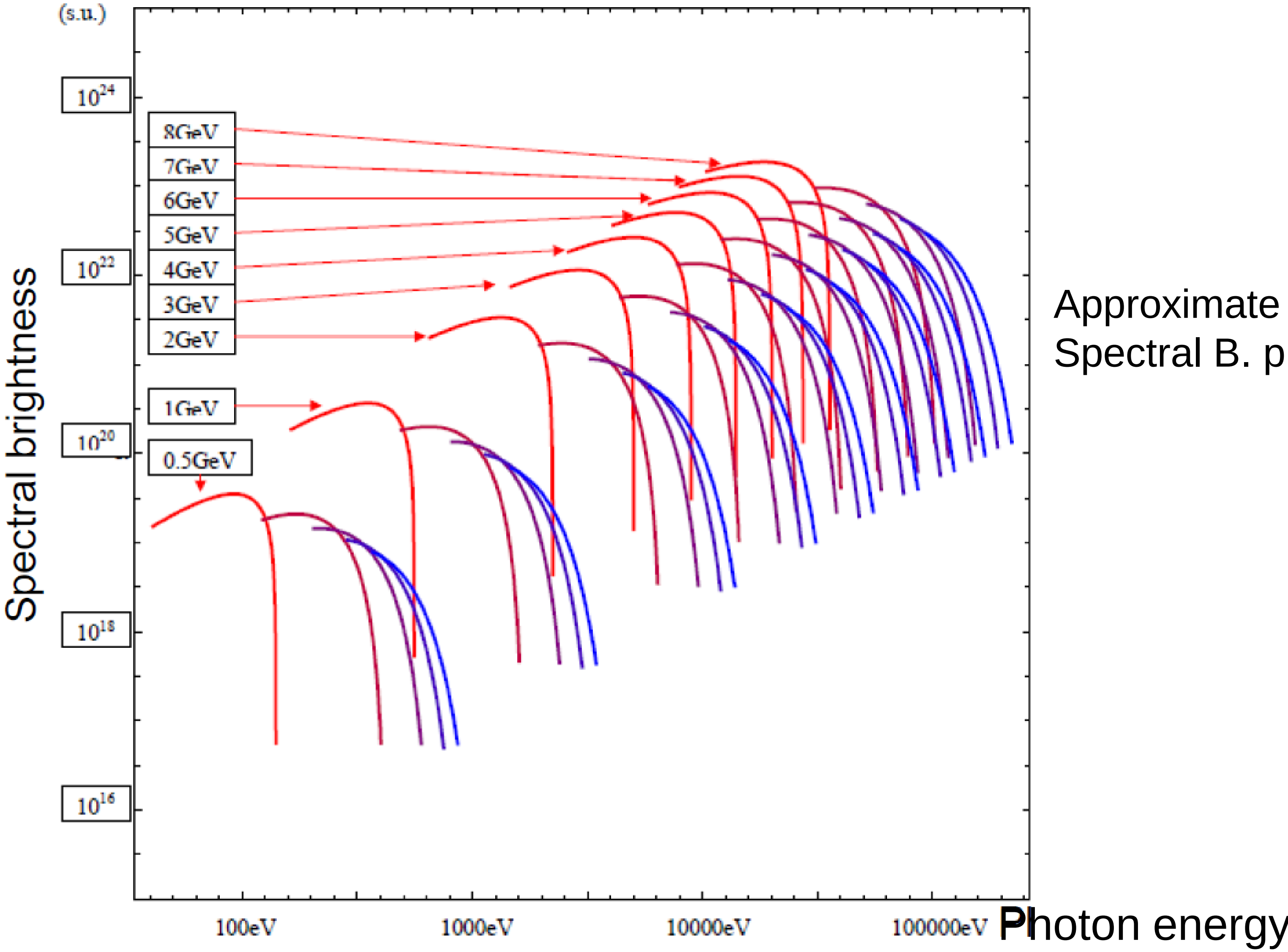
a) Large currents for Linac quality beams
b) Continuous beams with flexible bunch structure
c) Small emittances for round beams
d) Small energy spread
e) Variable Optics
f) Short bunches, synchronized and simultaneous with small emittances



The breadth of science and technology enabled is consequently very large and the ERL will be a resource for a very broad scientific community.

X-ray ERLs are at the beginning of a development sequence, whereas decades have brought x-ray rings to the end of their development.

Why 5GeV – Scaling with Energy



Approximate scaling:
Spectral B. prop. to $1/E^2$

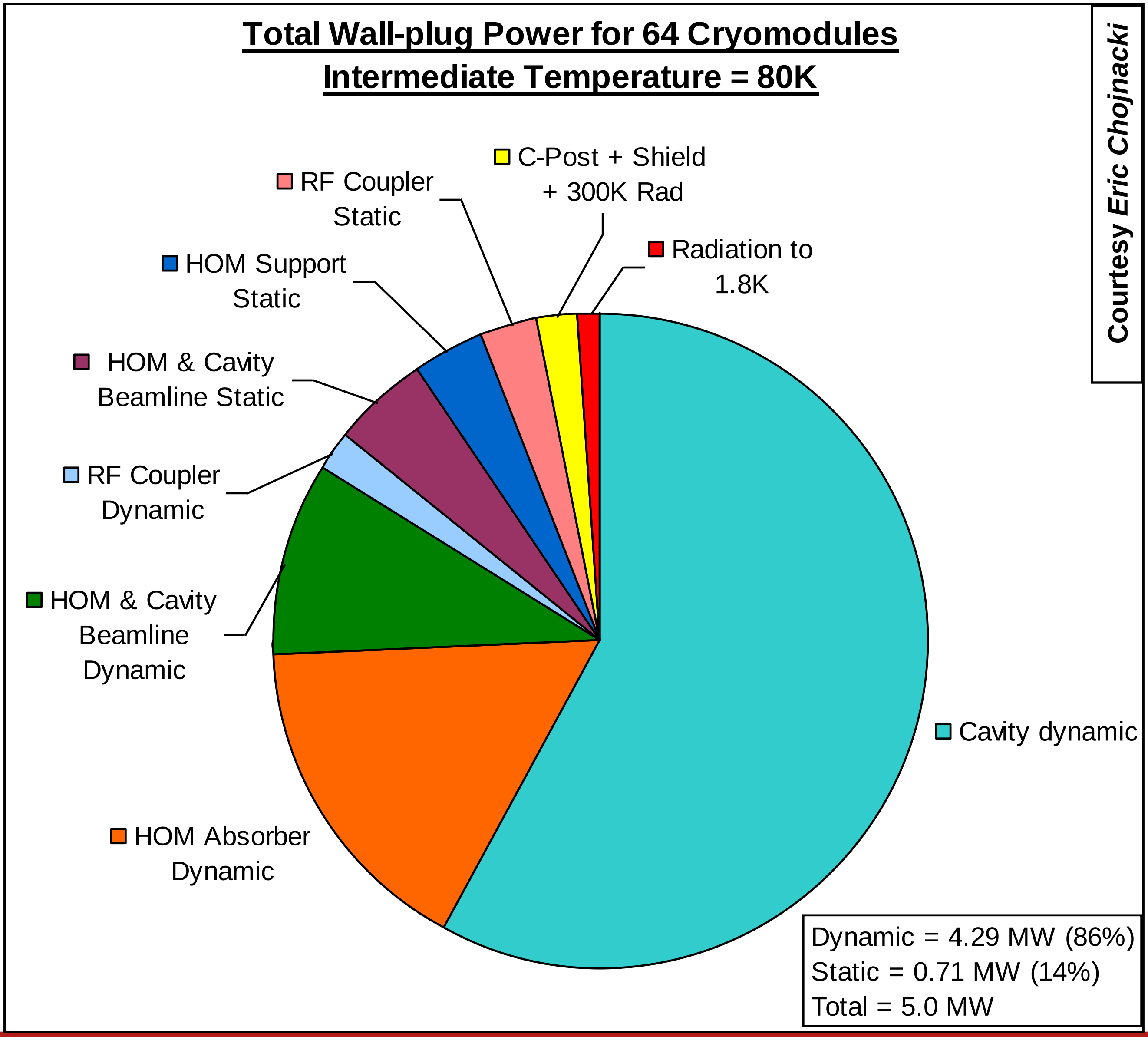
Beam challenges for x-ray ERLs

- Limit emittance growth during beam transport and acceleration
- Limit beam disturbance by ions
- Optics in the linac for very different energies (0.01 - 5GeV)
- Limit optics errors and adjust fields to radiated energy
- Limit emittance growth from incoherent synchrotron radiation (ISR)
- Coherent Synchrotron Radiation for short bunches
- Emittance growth from coupler kicks / cavity misalignments
- Limited emittance growth from ion focusing
- Fast and slow orbit stabilization
- emittance growth from intra beam scattering (IBS) and rest gas scattering
- and limit background radiation
- Limit energy spread during deceleration, e.g. by wake fields
- Limit halo development by IBS and rest gas scattering
- Damp HOMs to not loose the beam due to Beam Break Up (BBU)

SRF challenges for x-ray ERLs

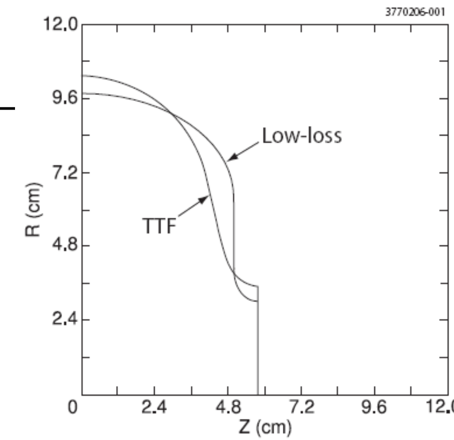
- **CW operation (or very long pulse train mode)**
  - The dynamic heat load (rf losses) dominates over the static load. (not as in ILC)
    - Design choices are dominated by lowering the dynamic load
  - RF power is another important part of the operating cost
    - Choose highest safe Qext that microphonics will allow (e.g. $2x10^7$ to 10^8)
    - Equip cavities only with the power consumption that fits their microphonics
- **High Beam current (e.g. 100 mAx2)**
  - Large HOM power (100-200 watts) per cavity
  - Need strong damping of Q's (mostly of dipole modes) for HOMs to avoid beam break-up
- **Low beam emittance for high quality light beams**
  - Low wake-fields
  - Good cavity alignment
  - Low kicks from couplers etc, esp for low energy end
  - Good amplitude and phase stability (e.g. Amplitude/phase stability 10^{-4}/0.02 deg)
- **Light source operation**
  - High reliability, low trip rate.
    - Favors moderate gradients (e.g. 15 -20 MV/m)

SRF operation cost distribution

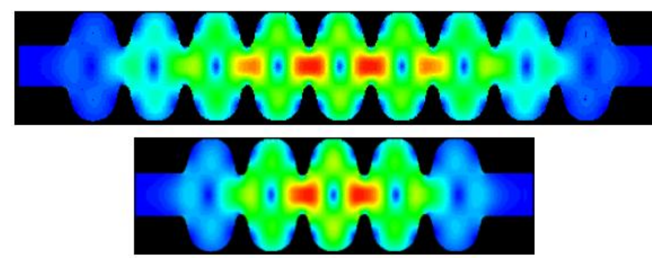


SRF operation cost distribution

- Material, treatment, frequency - for dynamic load
- Cavity – number of cells, geometry, voltage
- Input couplers - for CW power
- HOM couplers - for high broad band power
- Tuner
- Cryomodule

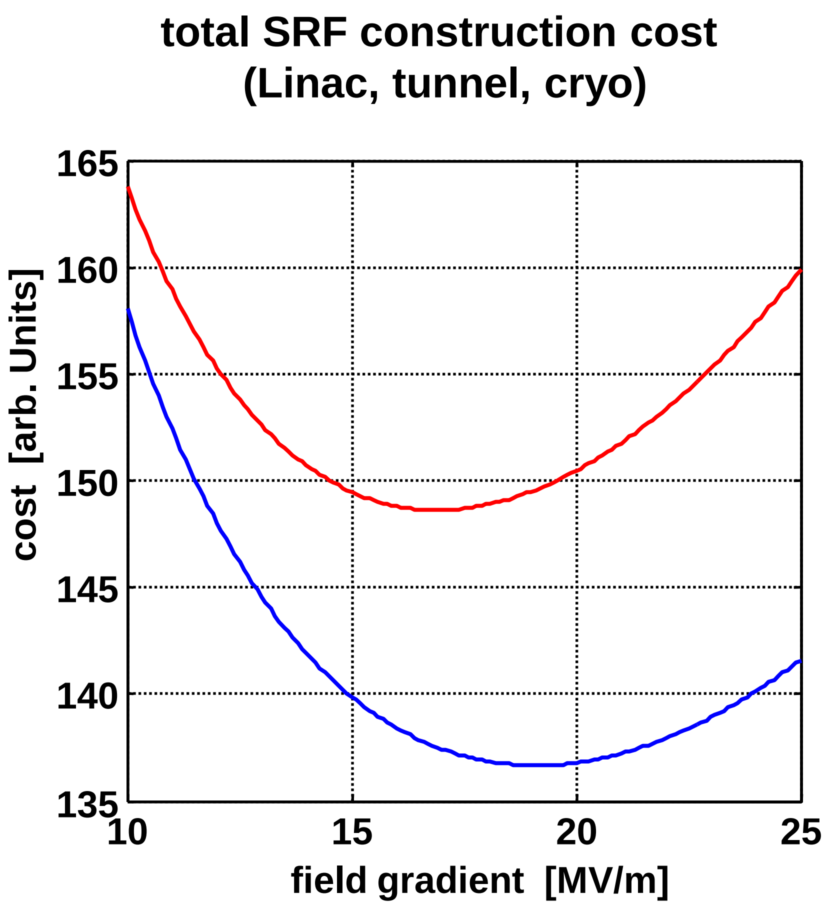


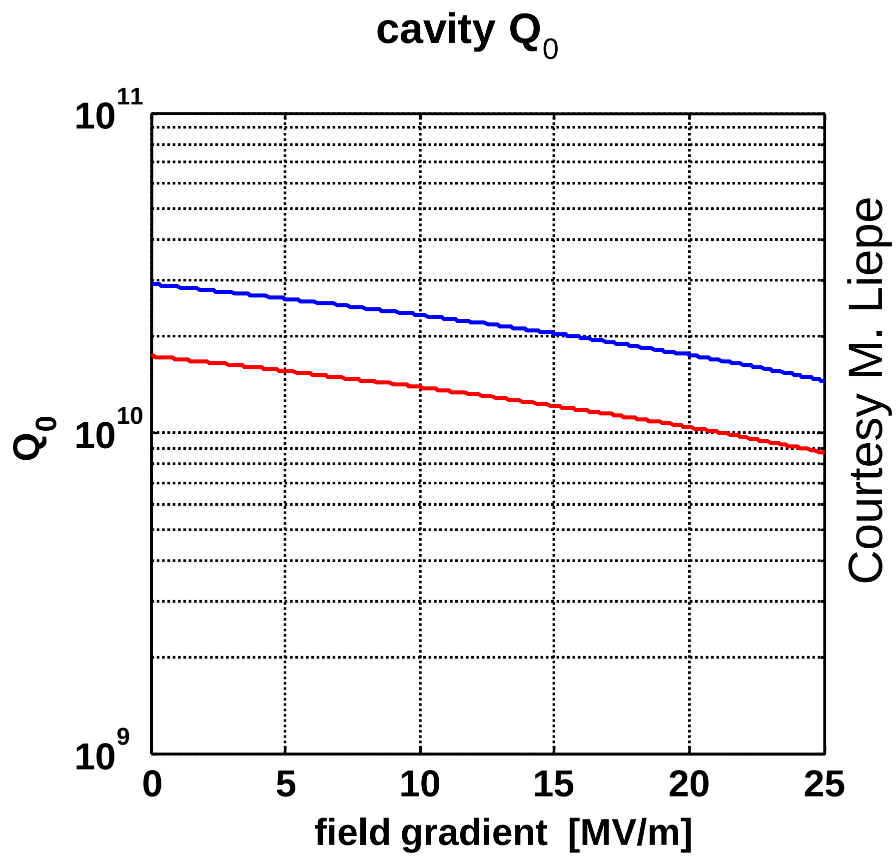
GR/Q is 12% and 13% higher for LL and RE shapes than TTF shape



Risk of trapped modes increases with number of cells.

Optimal gradients



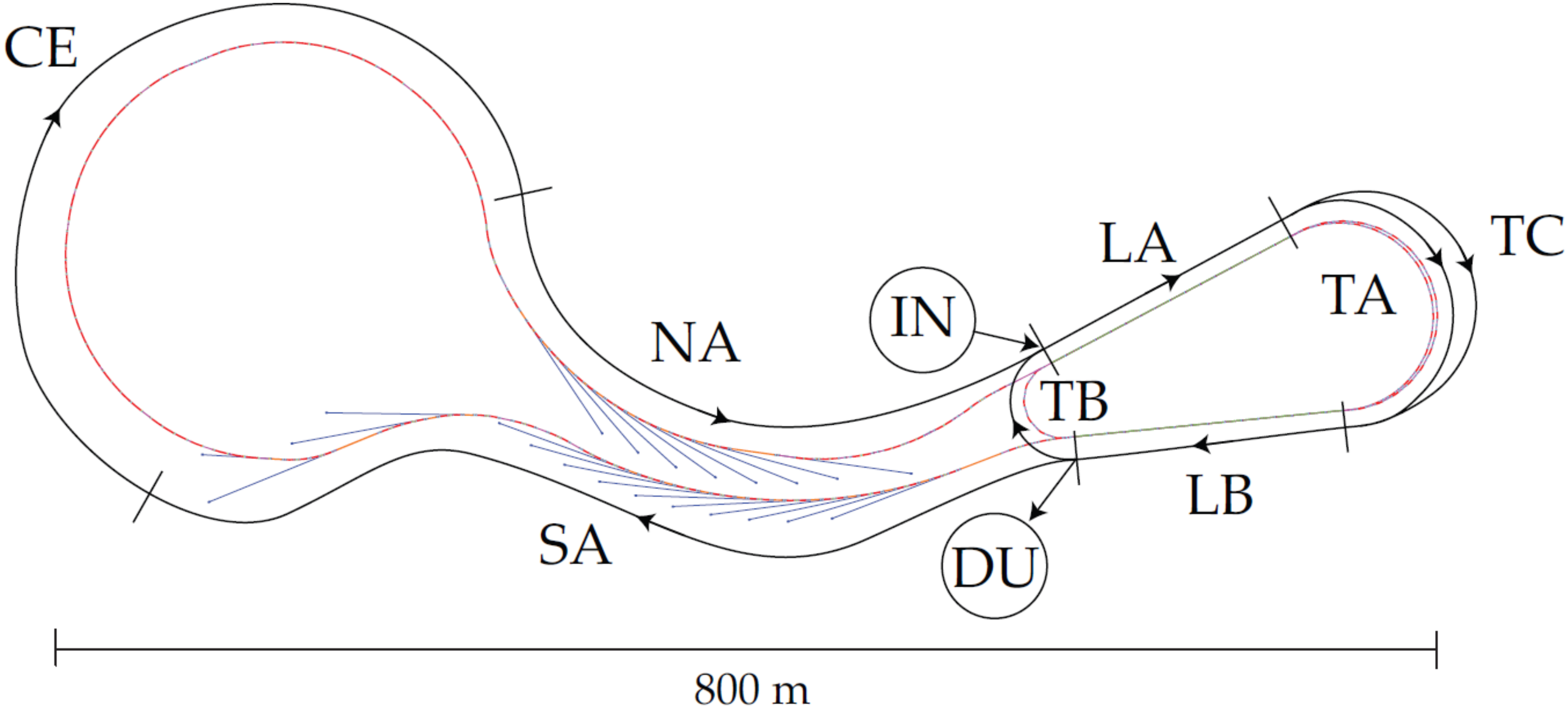


⇒Average operation at 16 MV/m

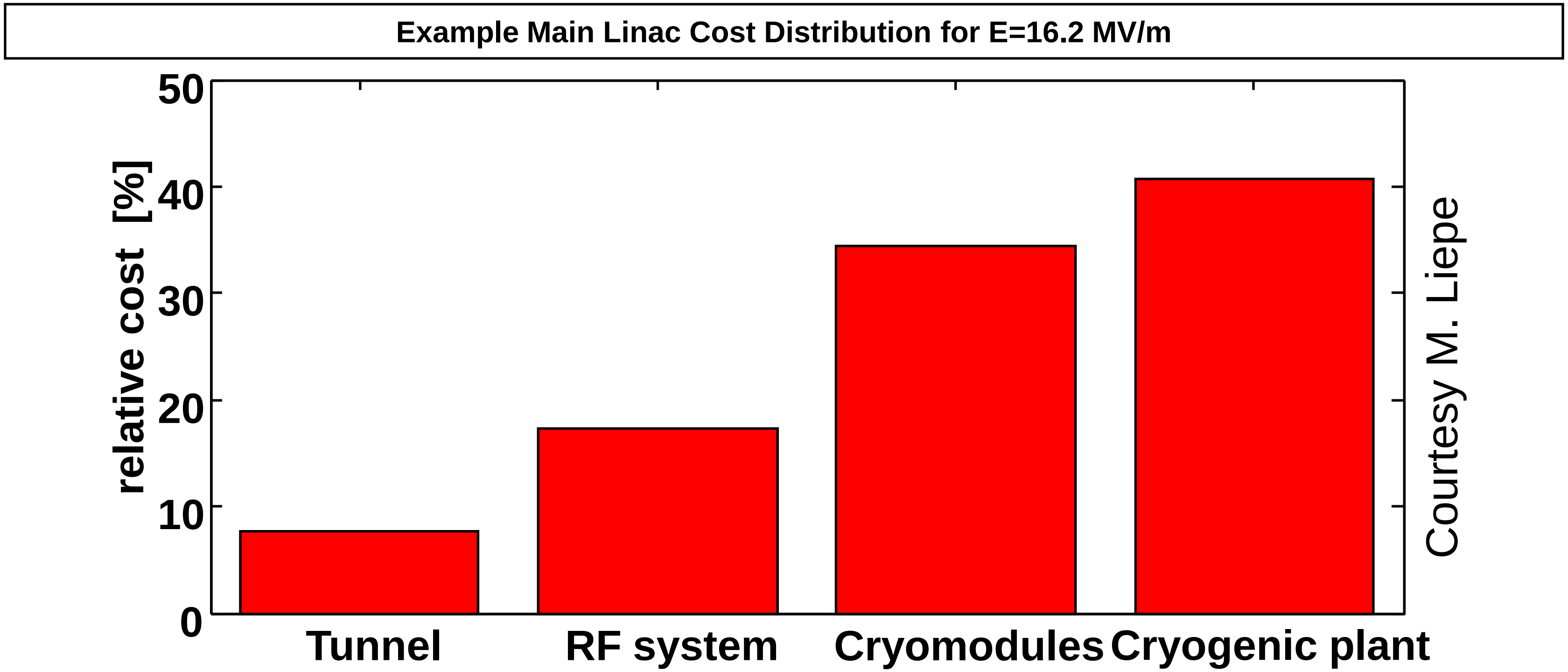
Cavities should be capable of going up to + 2 MV/m for overhead for initial performance risk and failures

Future options – Multi turn ERLs

- If the critical research subjects of HOM control and RF and beam stabilization can be mastered, extensions of the ERL principle become possible.
- E.g. multi-turn ERLs



Conclusion



- High current, multi GeV SRF linacs for ERLs are great for hard x-ray sources
- The SRF components are the cost drivers of these novel accelerators
- Driving SRF challenges are the dynamics load and therefore low loss technology.
- HOMs and their control become critical
- Microphonis and control becomes critical
- It is thus very much worth to invest in these research subjects.