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ERL for the generation of VUV and X-ray photons

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Cornell Physics Dep. / CLASSE

1) ERL principles
2) Advantages of ERL beams
    a) Large currents for Linac quality beams
    b) CW 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
3) Technology (available & required)

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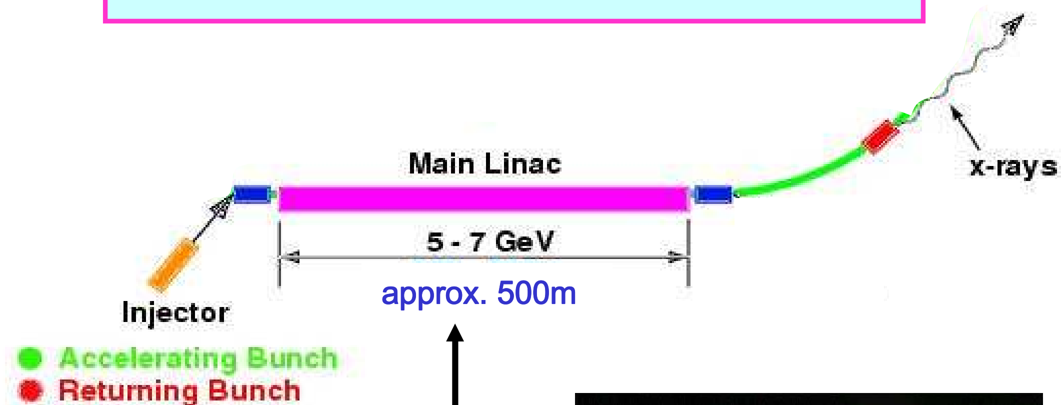
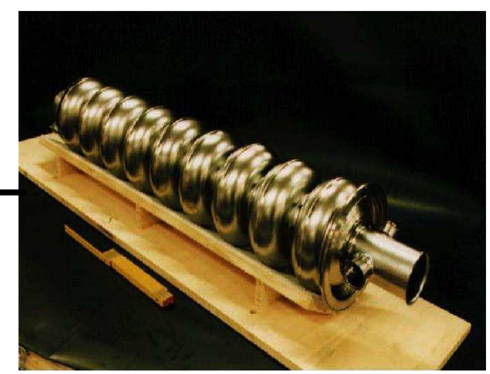
ERL principles

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

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





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ERL principles

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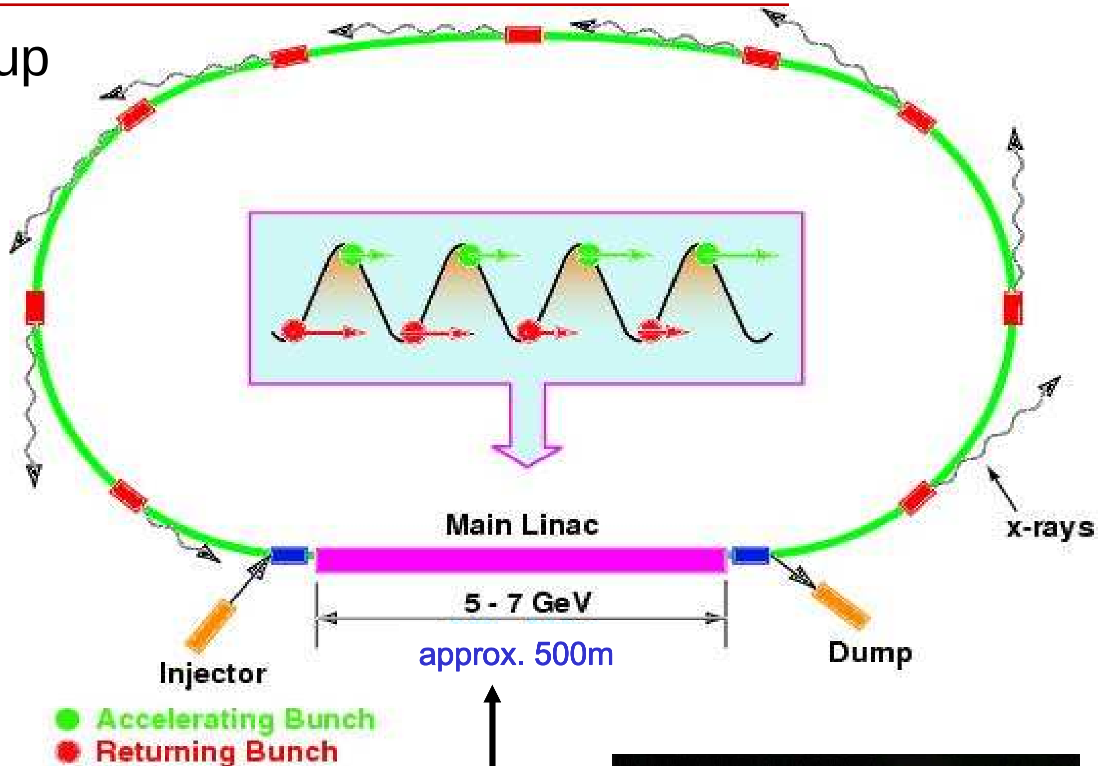
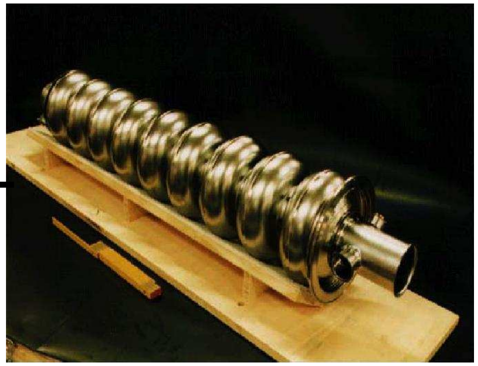
ERL principles

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

Widening is limited during one turn





Cavities have to be CW

→ superconducting RF

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Advantages of ERL beams
(a) Large currents of Linac quality beams

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The power in linacs is limited, but the beam quality can be very high

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

An ERL is an accelerator type, and can be used for many types of light sources.
(And for other accelerators, e.g. in e-RHIC)

1) ELR driven FELs for IR radiation (up to 14kW CW beam)
2) ERL driven FELs for UV radiation
3) ELR driven FELs for soft and hard x-rays
4) ERL driven Compton backscattering sources for hard x-ray beams
5) ERLs for incoherent undulator radiation

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

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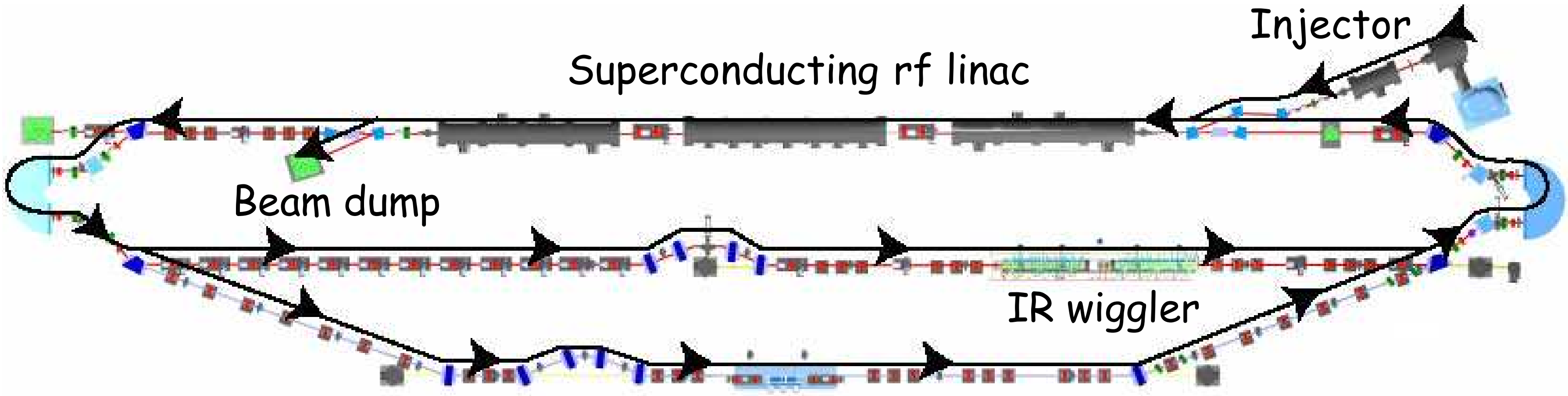
JLab 10 kW IR FEL and 1 kW UV FEL



Output Light Parameters	IR	UV
Wavelength range (microns)	0.9 - 10	0.25 - 1
Bunch length (FWHM psec)	0.2 - 2	0.2 - 2
Laser energy / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

Electron Beam Parameters	IR	UV
Energy (MeV)	80-150	150
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	>300	>250
Beam Power (kW)	1500	750
Energy Spread (%)	0.40	0.20
Normalized emittance (mm-mrad)	<10	<8
Induced energy spread (full)	12%	6%

14.2 kW average power from 8.3 mA, 75 MHz, CW electron beam

Courtesy: T. Smith and S. Benson

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ERL XFEL

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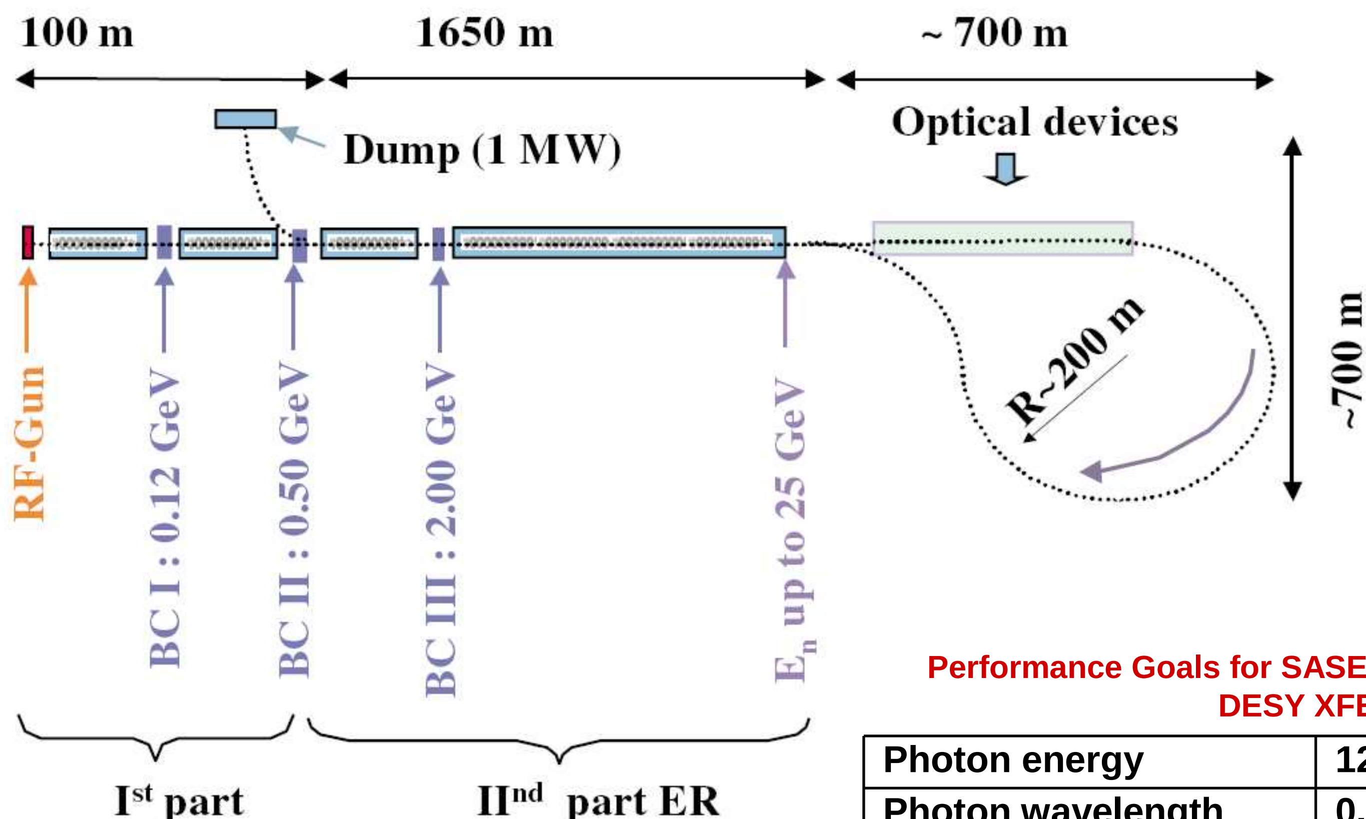

Proposed ER operation would have a rep rate of 1 MHz instead of DESY XFEL rep rate of 10 Hz, increasing **average power, brilliance and energy reach.**

Performance Goals for SASE FEL Radiation at the DESY XFEL

Photon energy	**12.4 – 0.2 keV**
Photon wavelength	**0.1 – 6.4 nm**
Peak power	**24 – 135 GW**
Average power	**66 – 800 W**
# photons/ pulse	**1 – 430 x 10^{12}**
Peak brilliance	**5.4 – 0.6 x 10^{33} ****
Average brilliance	**1.6 – 0.3 x 10^{25} ****
**** in units of photons / (s mrad^2 mm^2 0.1% b.w.)**	

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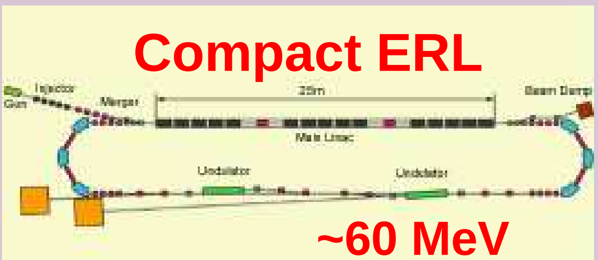
KEK ERL Plans

Development of key components

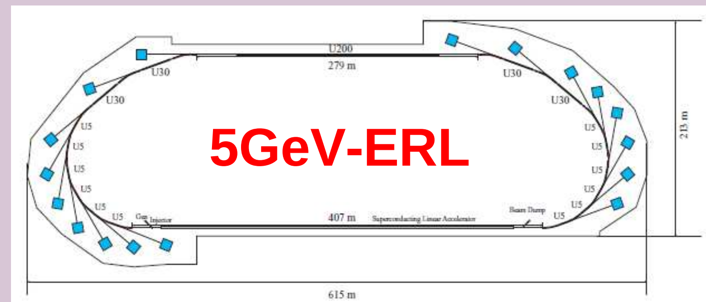


~2013

Coherent SR at THz region

Hard X-ray (-10keV) by laser inversed Compton scattering

Future light source



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Spread of the advanced compact X-ray imaging sources to hospitals

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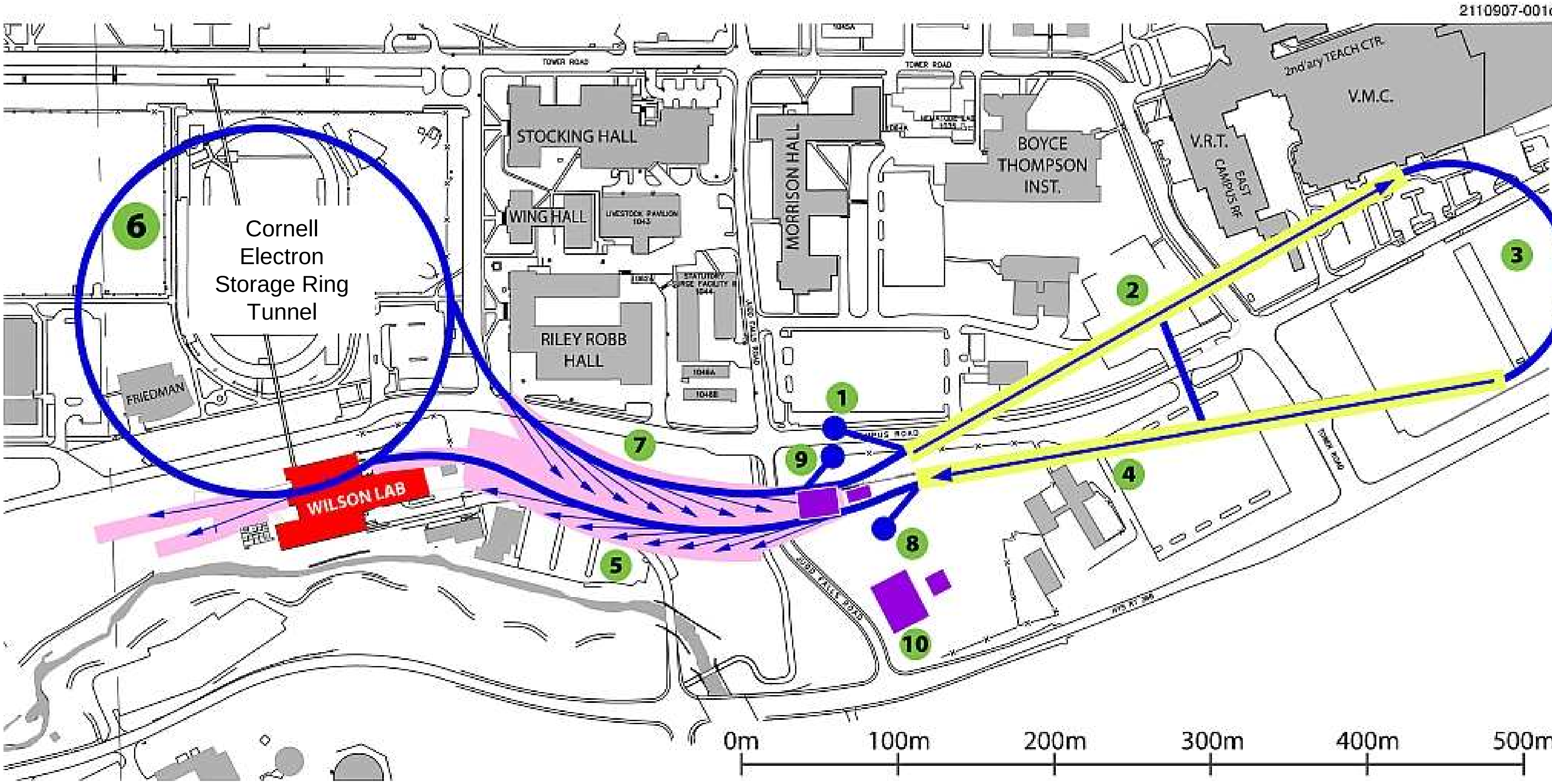
Cornell x-ray ERL



The ERL is an extension of the CESR ring

(1) Injection, (2-4) acceleration, (5-7) x-rays, (2-4) deceleration, (8) beam dump.

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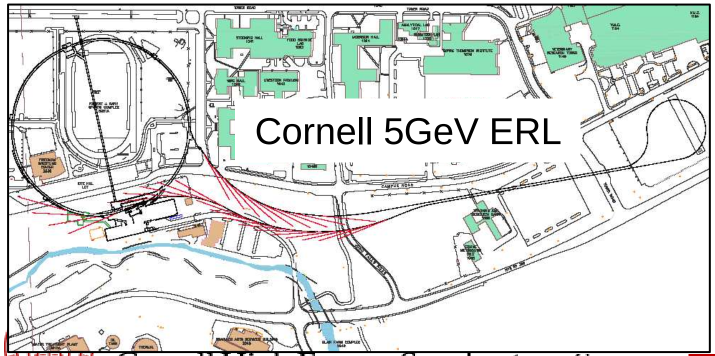
Cornell x-ray ERL



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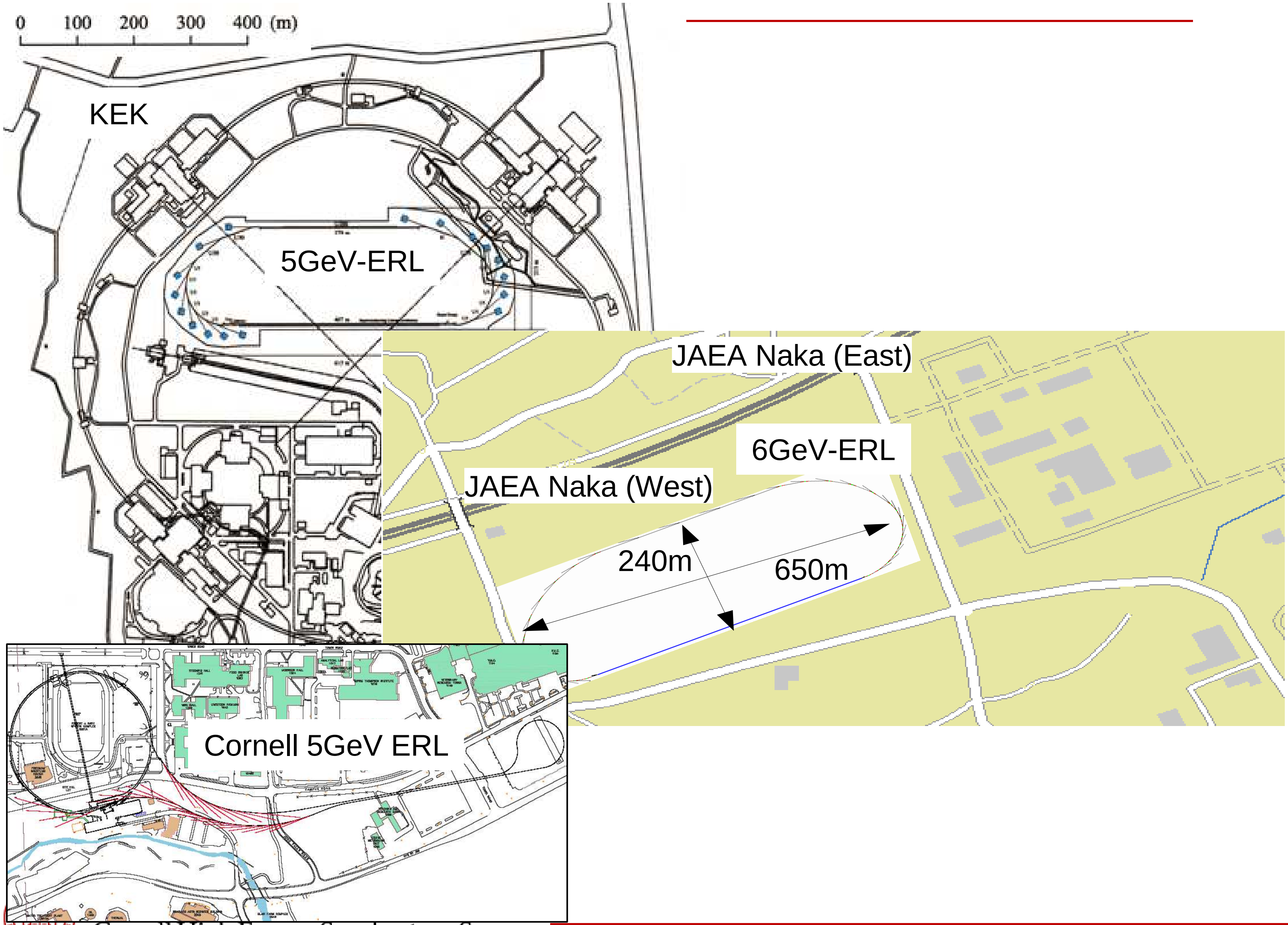
Cornell / KEK / JAEA ERL



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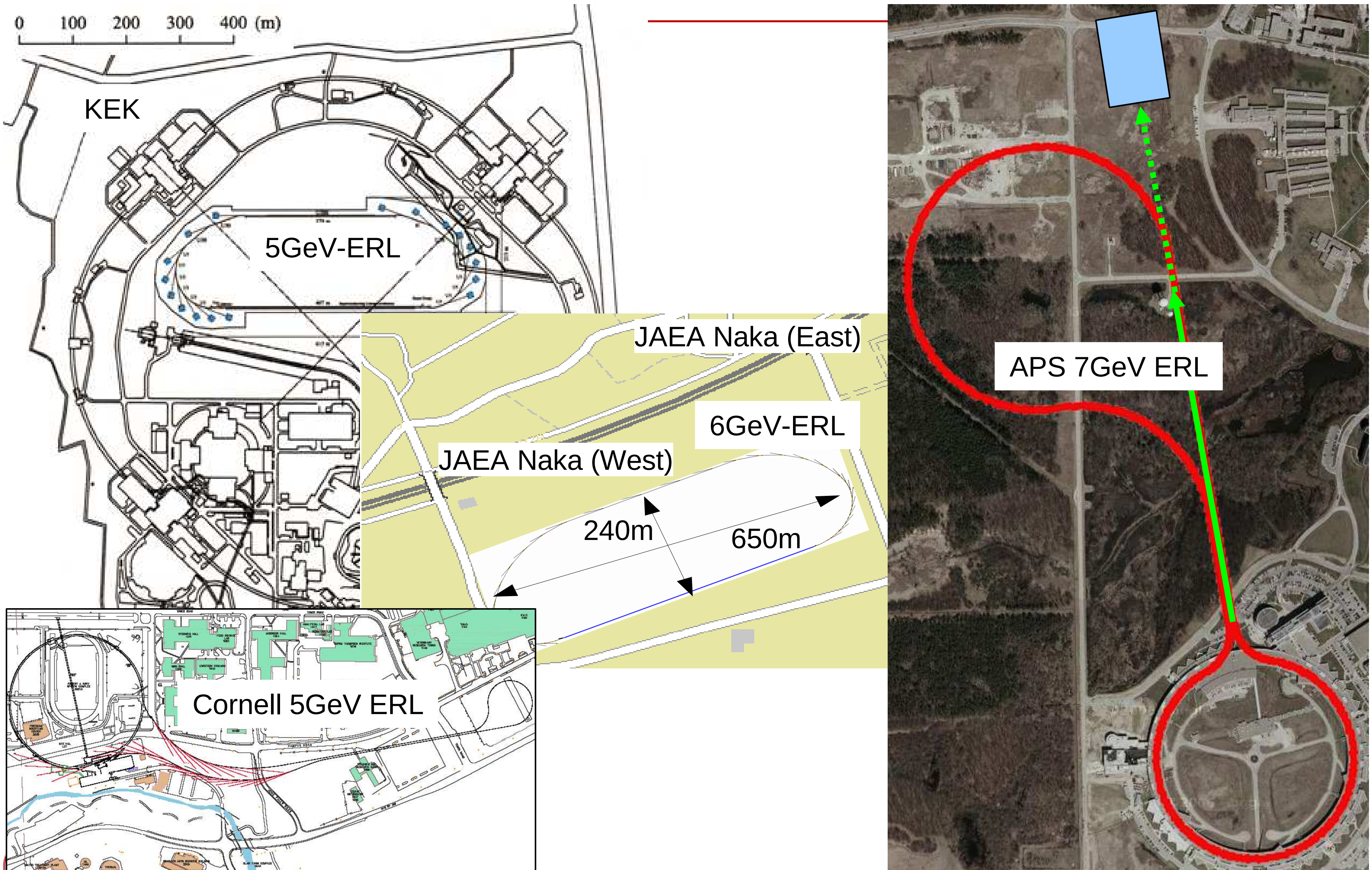
Cornell / KEK / JAEA / APS ERLs



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Advantages of ERL beams
(b) CW beams with flexible bunch structure

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1) High rep rate (up to 1.3GHz), small bunch charge
   a) Advantages for PEEM and other electron emitting methods, reduces charging
   b) Reduce sample damage for small samples
   c) Advantages for coincidence measurements, avoiding falls positives

2) Variable time structure for timing experiments

Parameter	ERL Possibilities	Jlab FEL Demonstrated
σ_t^*	10 fsec – 10 psec	< 330 fsec
Repetition Rate	1 MHz – 1.3 GHz	2 – 75 MHz
Macropulse Duration	1 microsecond - CW	1 microsecond – CW
Macropulse Frequency	1 Hz-10 kHz	0.5 Hz – 60 Hz

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FLASH performance example for pulsed beams
→ CW operation stabilizes performance

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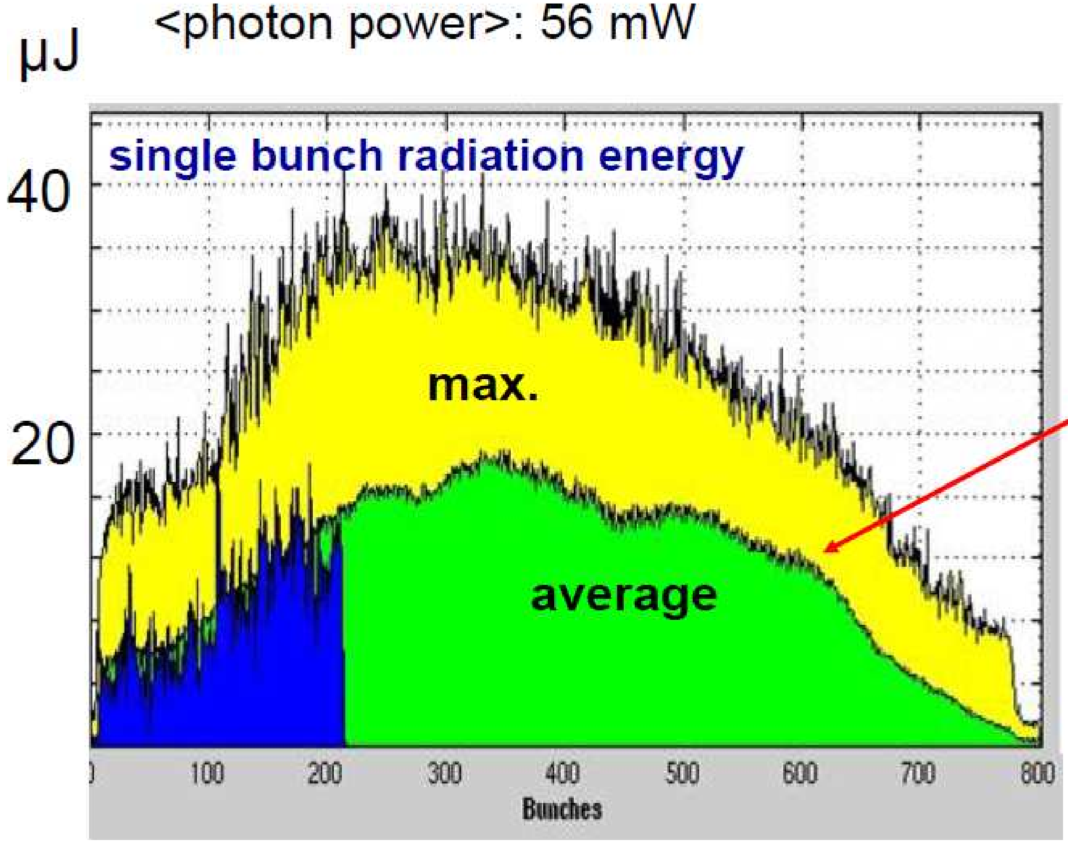
800 bunches

685 MeV (13.4 nm)

<electron beam power> : 2.7 kW

<photon power>: 56 mW



Systematic variation of SASE intensity over macro pulse!

Courtesy Florian Loehl (DESY)

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Advantages of ERL beams
(c) Small emittances for round beams

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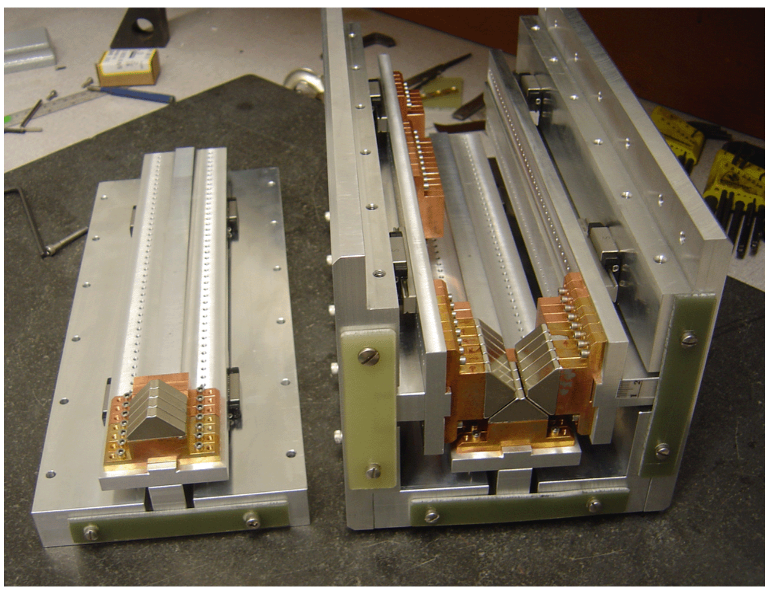
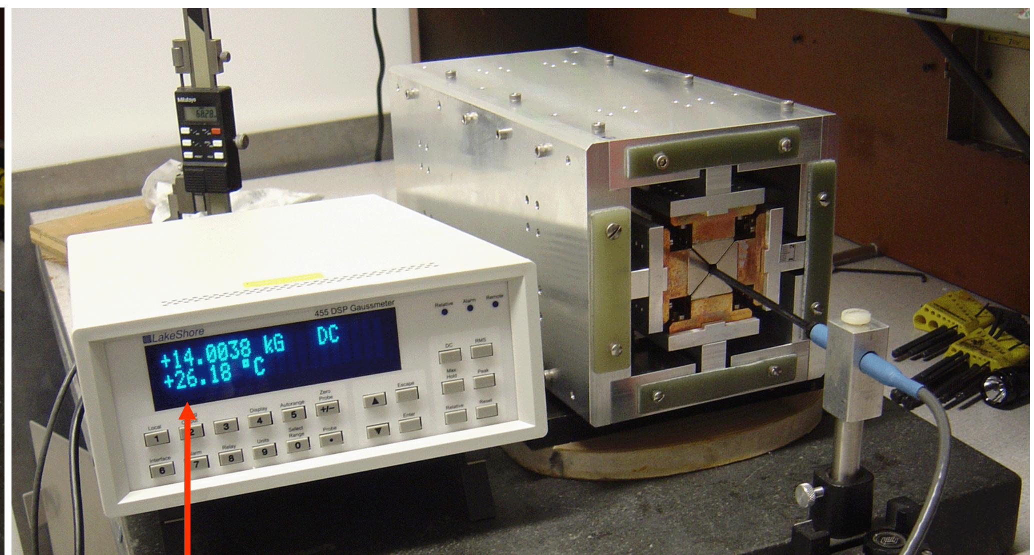
1) Small electron emittances
   a) High spectral brightness, diffraction limited beams
   b) Narrow x-ray beams and small focuses (nanobeams)
   c) Narrow electron beams at all times (no injection orbits)
2) Round beams
   a) Undulators can have small round chambers
   b) Experiments can be oriented in any directions, e.g. horizontal spectrometers
   c) Polarization changes become independent of beam dimensions





1.4T peak field in planar mode

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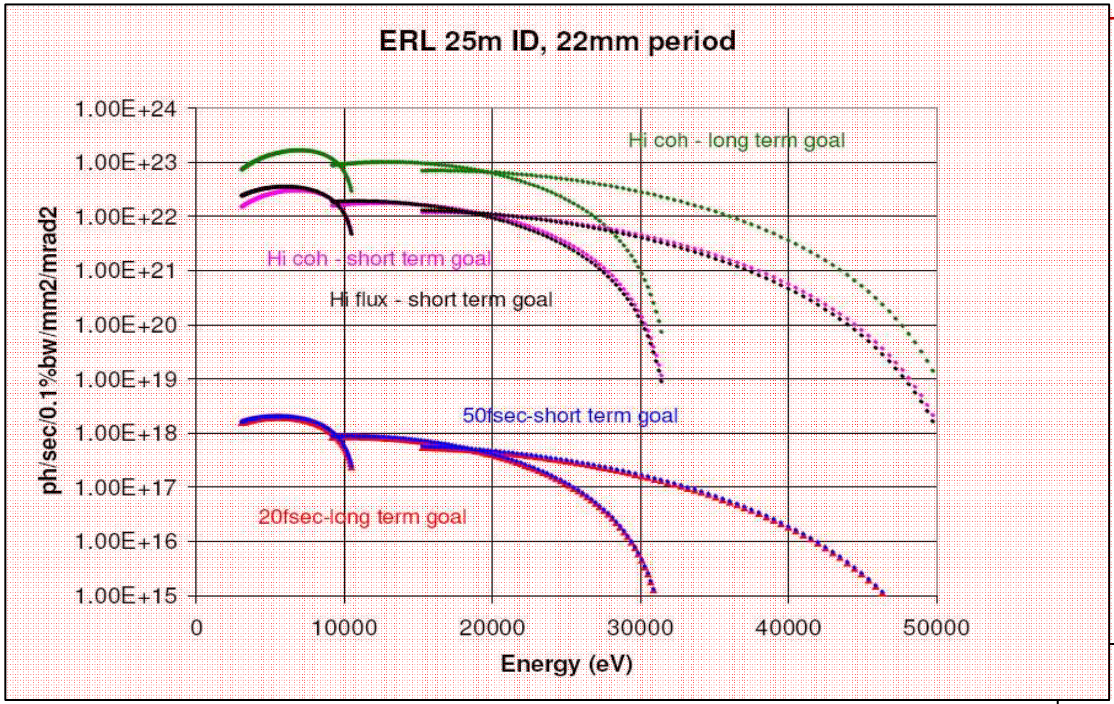
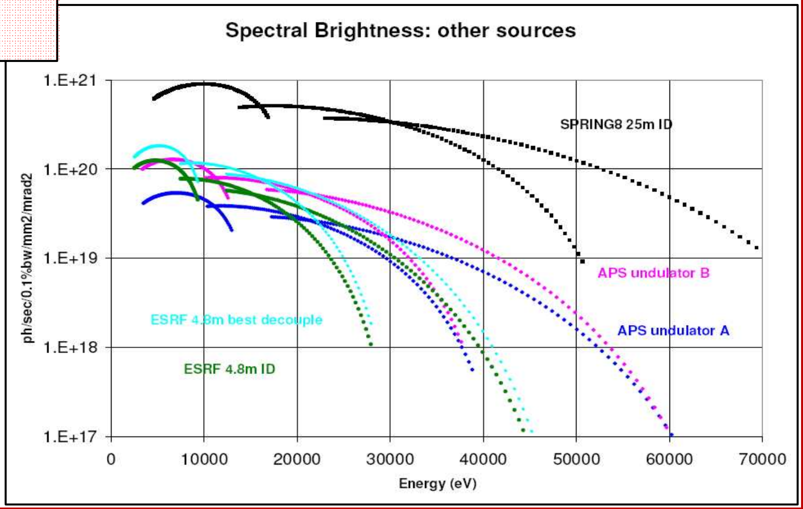
Average spectral brightness for hard x-rays



Cornell ERL

Ring based sources



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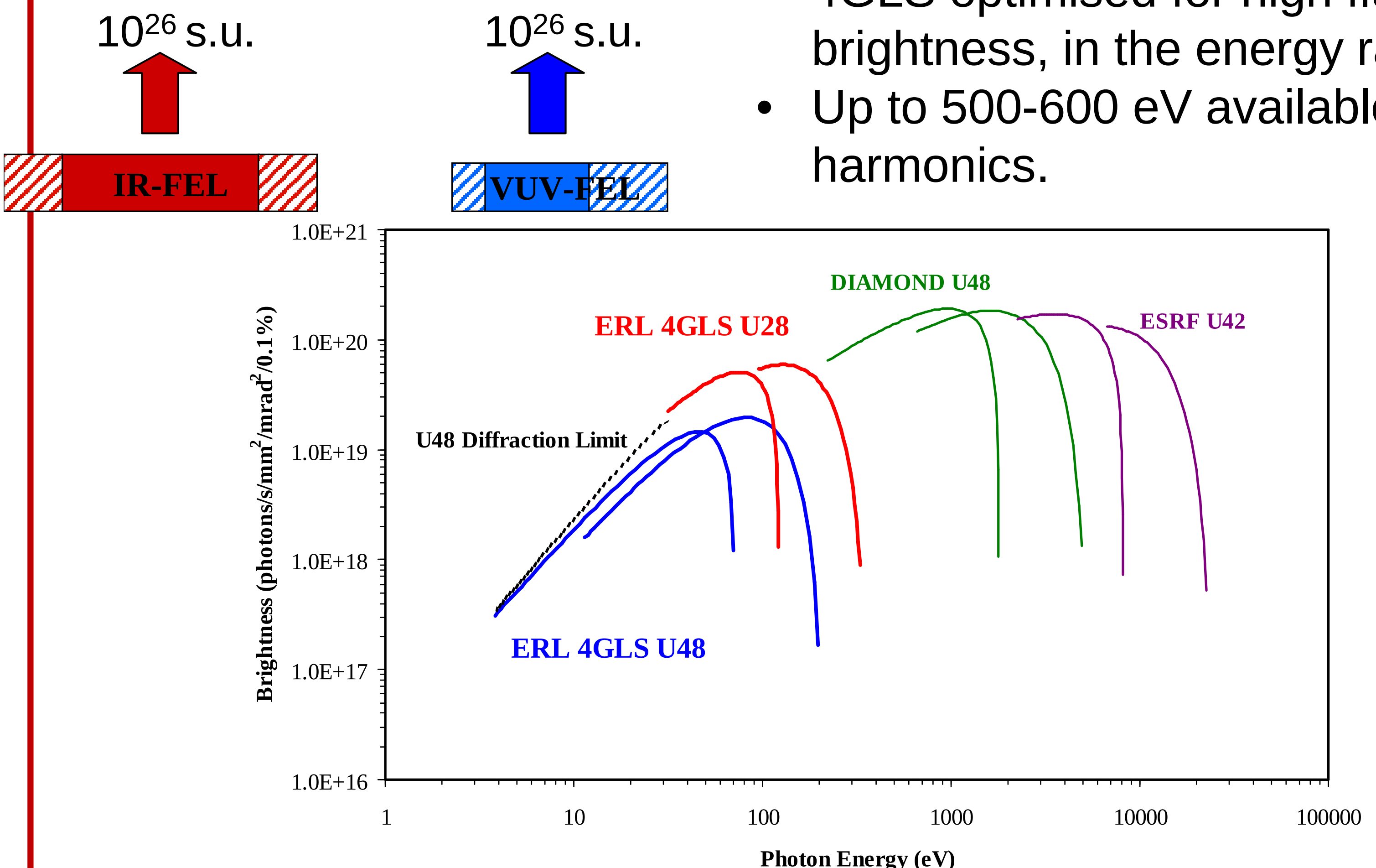
ERL UV undulator sources

- 4GLS optimised for high flux and brightness, in the energy range 4-200 eV.
- Up to 500-600 eV available in the higher harmonics.



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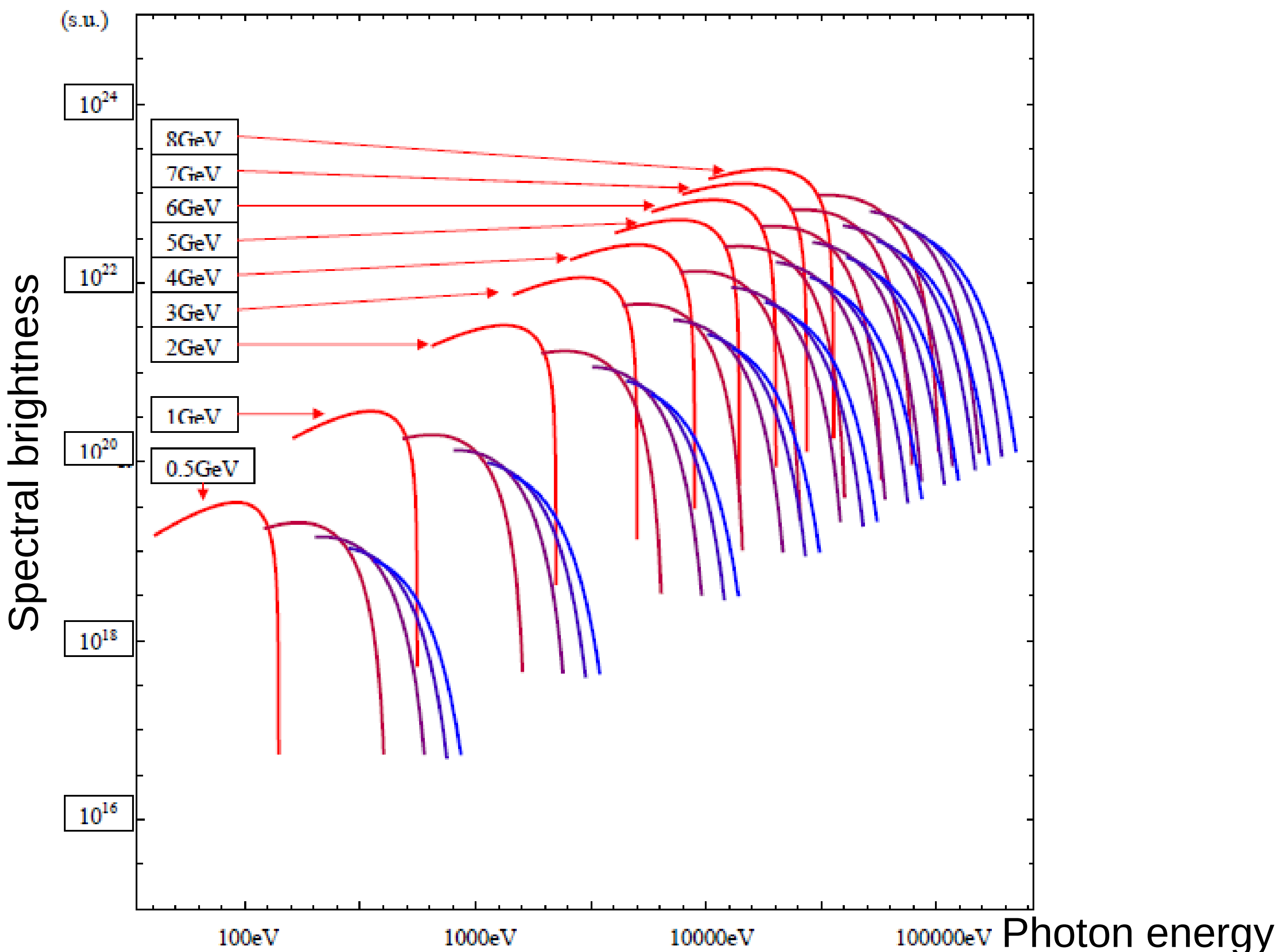
ERL for different energies



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Scaling with Energy

1) At lower electron energy, research focuses on lower x-ray energies.
2) At lower x-ray energies, the diffraction limit is easier to reach.
3) At lower energies, rings tend to reach smaller emittances.

Conclusion: the advantage in spectral brightness of ERLs over storage rings diminishes for lower energies.

Example: for a 1GeV ERL compared to a ring scaled from the ALS, the ERL has a spectral brightness that is larger by only a little more than a factor of 10.

Advantages:

a) round beams

b) very flexible source point parameters

c) short pulse length

d) lower background power for x-ray optics and front end

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Advantages of ERL beams
(d) Small energy spread (order 10^{-4})

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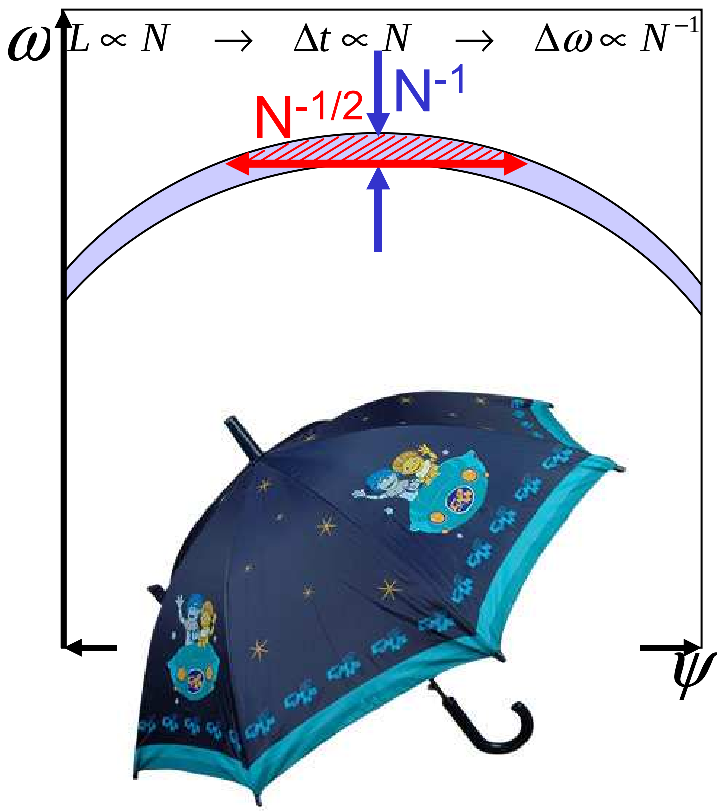
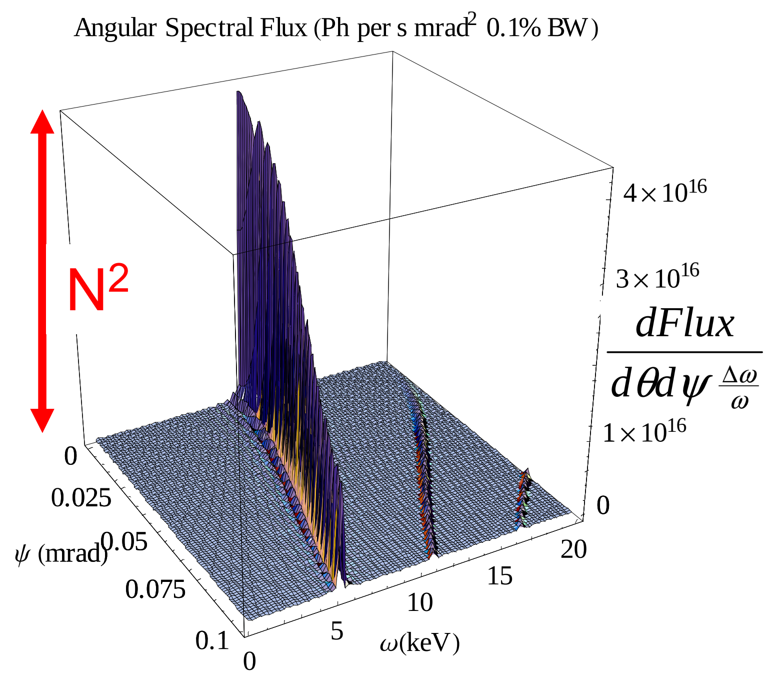
1) Many undulator poles (N)
2) Narrow central cone and thus high ratio of spectral brightness to power
3) Larger fraction of usable photons





$F_{total} \propto N$

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Advantages of ERL beams
(e) Variable optics

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1) Beam size can be changed vs. divergence

2) Matching of beam divergence to Darwin width of monochromators

3) Optimization of illuminated area

4) Defocus by changing quadrupole settings, without moving components, e.g. for scan probe experiments

5) Space for long insertion devices

6) Space for many insertion devices

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Advantages of ERL beams
(f) Short pulses, synchronized and simultaneous with small emittances

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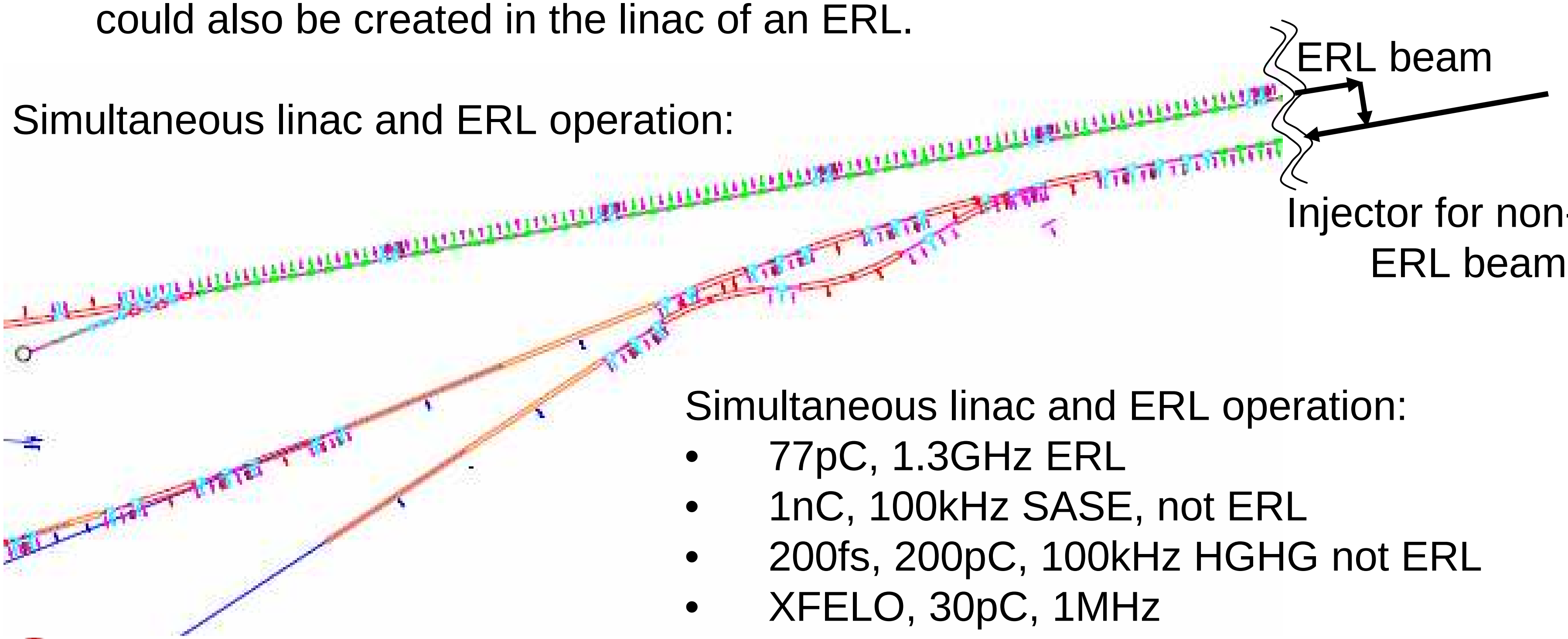
ERL driven FELs are possible, because beams can be sufficiently short

Standard bunch length in ERLs: 50fs to 2ps for high currents 1.3GHz (ERL mode)

Because ERLs have linacs, the shorter bunch lengths that other linacs propose could also be created in the linac of an ERL.

Simultaneous linac and ERL operation:



Simultaneous linac and ERL operation:
- 77pC, 1.3GHz ERL
- 1nC, 100kHz SASE, not ERL
- 200fs, 200pC, 100kHz HGHG not ERL
- XFELO, 30pC, 1MHz

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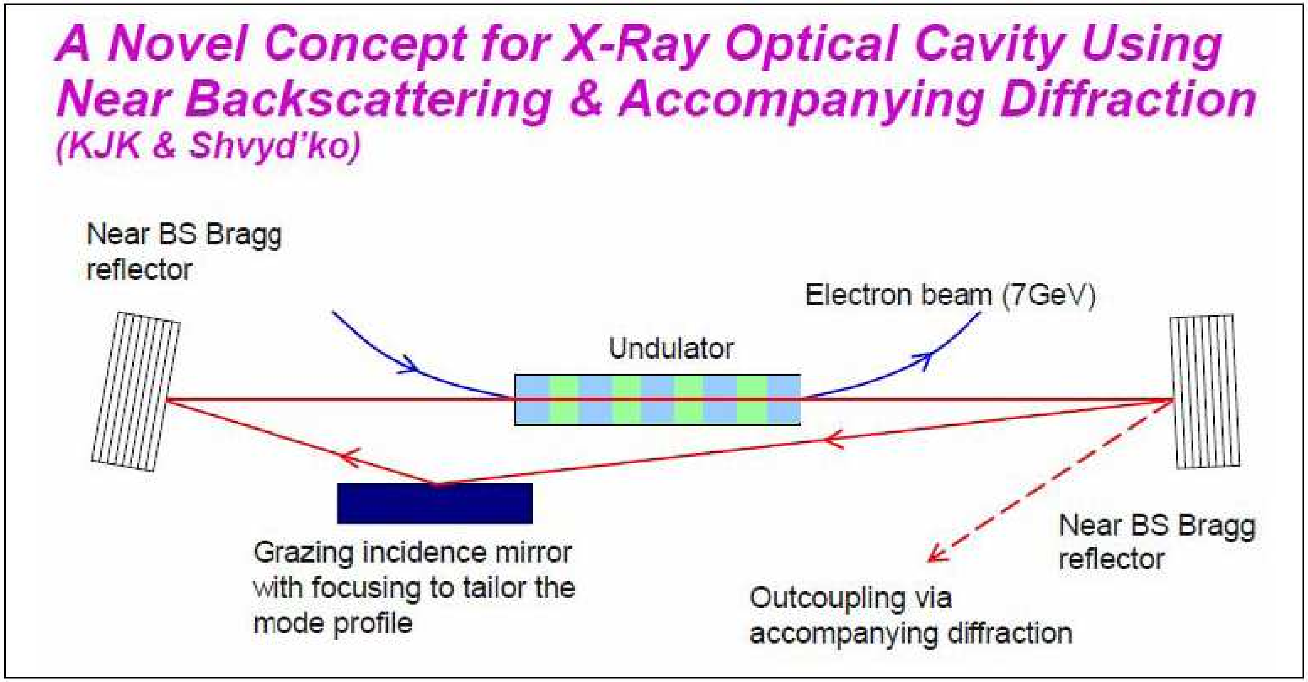
Example of ERL extention: XFELO motivated by ERL Beam

K-J. Kim



Courtesy Kwang-Je Kim

- Cornell-ERL parameters scaled to 7-GeV (19-60pC, 2ps, ε=6pm, ΔE/E=0.02%) ⟶ $\varepsilon < \lambda / 4\pi$ for 1Å
- FEL single-pass gain ~ 50% for 60pC, Lu=23m case.
- Energy spread of 0.05% (after FEL lasing) is acceptable for ERL operation.

Average spectral brightness: 10^{27} s.u. between a few keV and a few 10keV.

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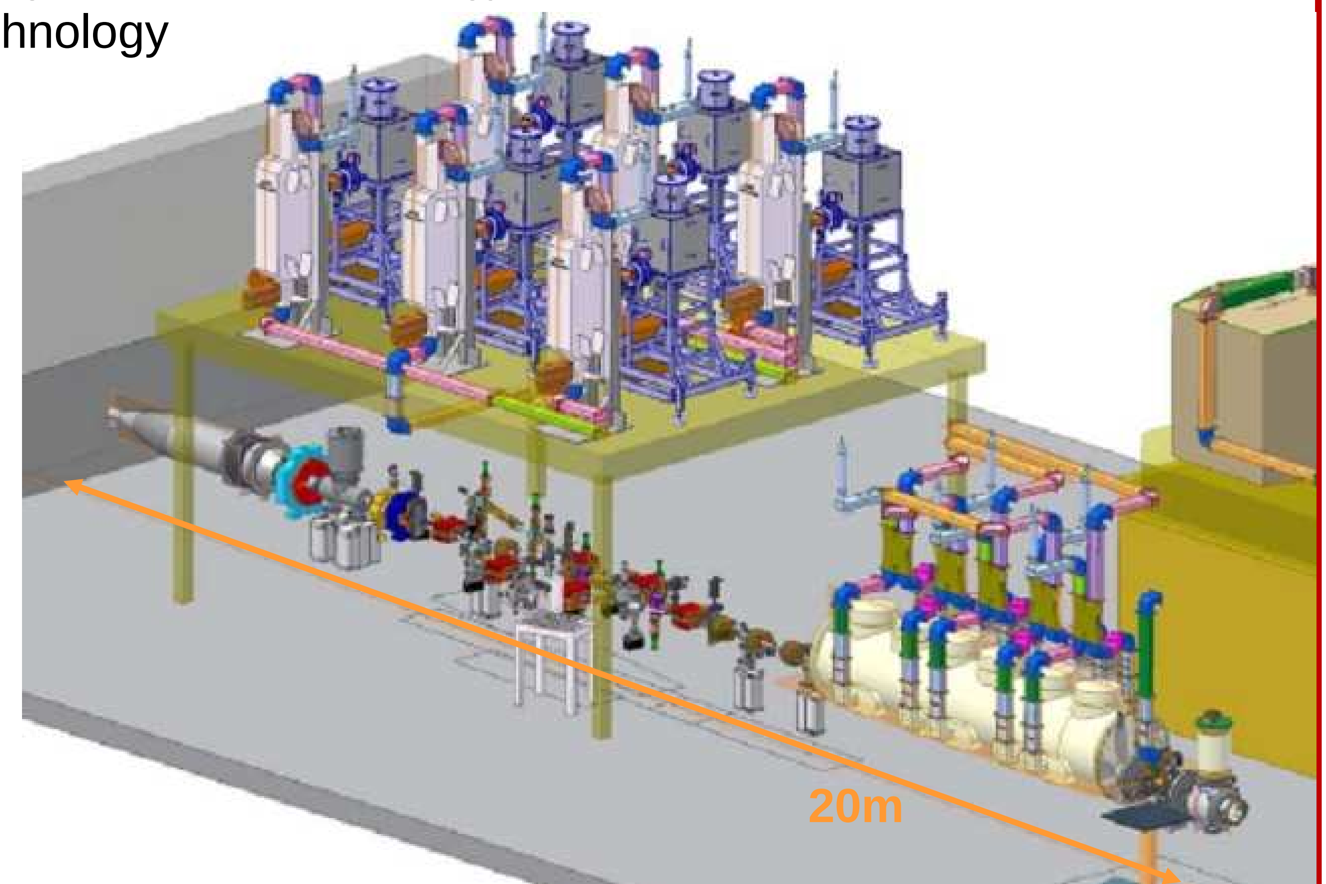
Technology (available & required)

1) Laser technology
2) High power CW Gun technology
3) High power CW superconducting RF injector technology
4) CW superconducting ERL linac technology
5) X-ray beamline technology



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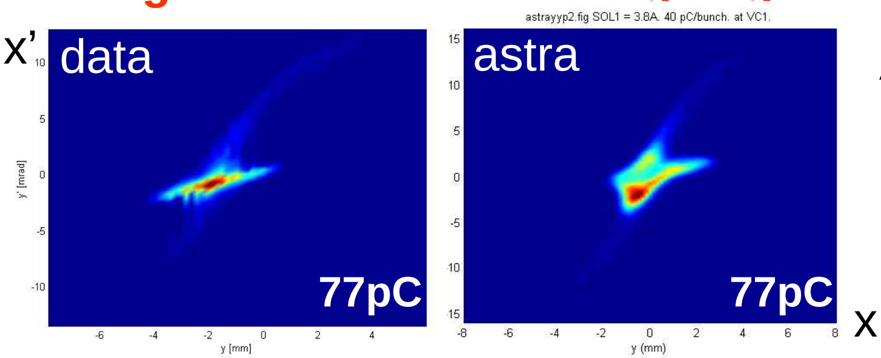
Technology (available & required)

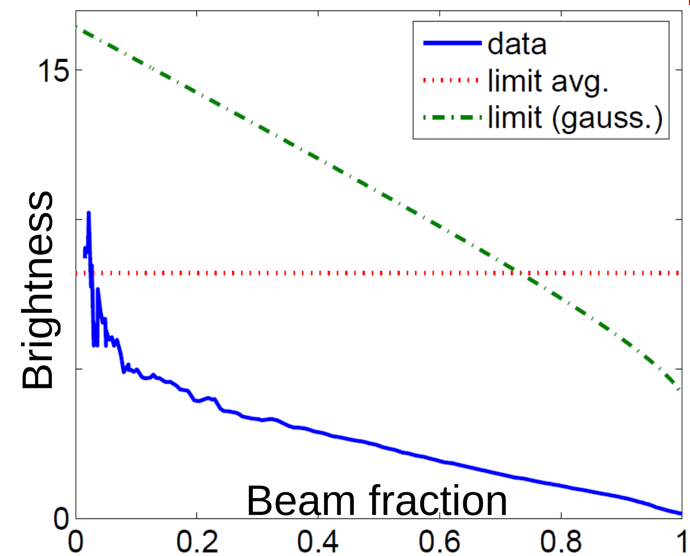
1) All ERL injector technology is setup
2) High current superconducting RF injector is commissioned
3) Gun operates up to 420keV, beam experiments at 250keV

Progress in understanding of guns:



A) Even with 250keV, **emittances have already been reached** proposed for the 750keV gun! With very good **experiment / theory agreement** !

B) The measurements show that theoretical brightness limits are reached in the core of the bunch because the tails shield space-charge forces.



Promise for even larger core brightnesses !

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The next international ERL workshop is in Cornell 2009