The Energy Recovery Linac (ERL) as a Driver for X-ray Producing Insertion Devices

I. Bazarov*, S. Belomestnykh*, D. Bilderback*, K. Finkelstein*, E. Fontes*, S. Gray*, S. Gruner*, R. Helmke*, G. Krafft†, L. Merminga†, H. Padamsee*, Q. Shen*, C. Sinclair†, R. Talman*, M. Tigner*

* CORNELL UNIVERSITY

CHESS / LNS

† Jefferson Lab

Supported by NSF Coop. Agrmts PHY 9809799, DMR-9713424

Supported by US DOE No. DE-AC05-4ER40150

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Critical electron beam parameters

6D Phase Space Area:

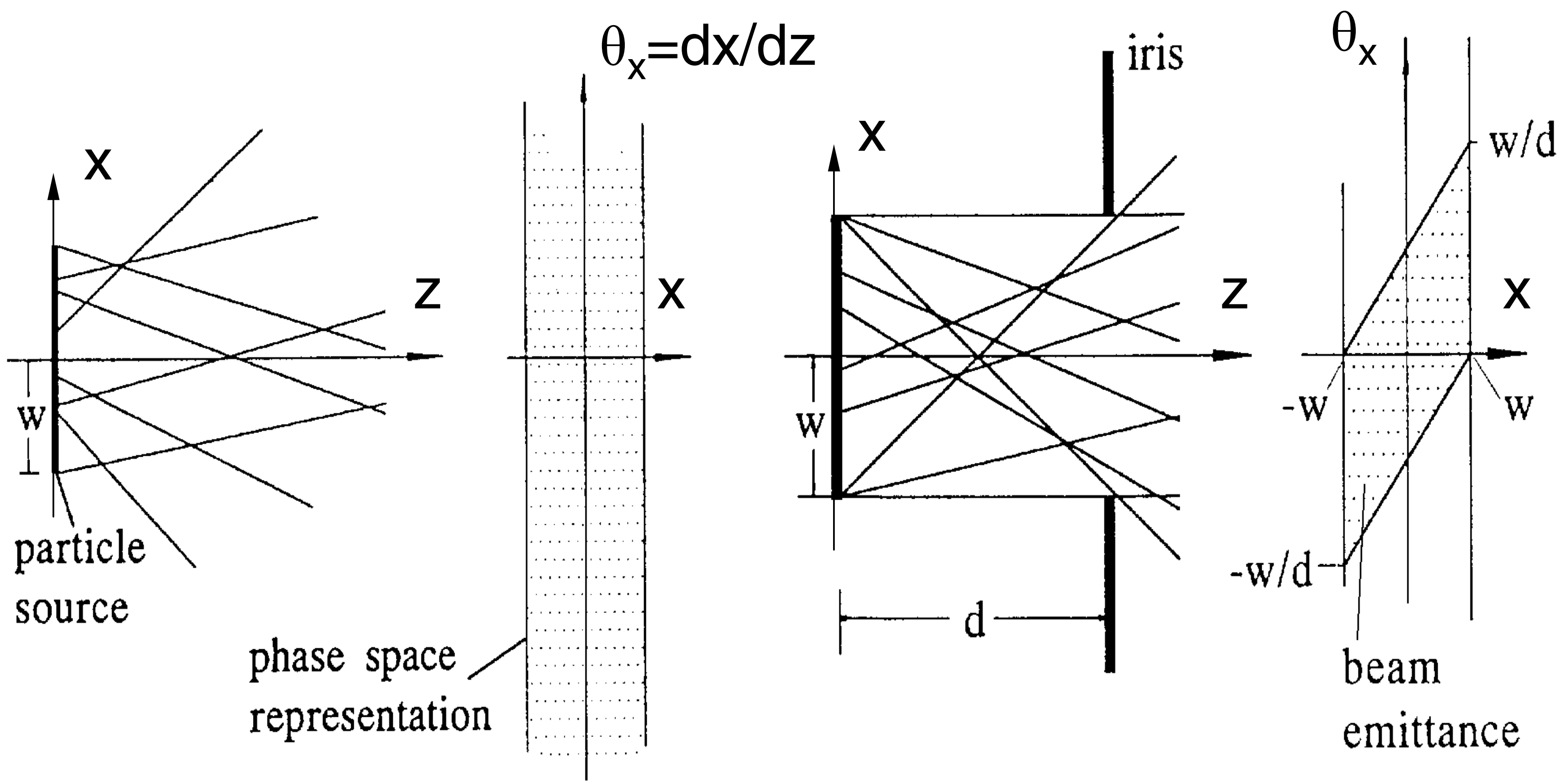
- Horizontal Emittance {x, x'}
- Vertical Emittance {y, y'}
- Energy Spread & Bunch length {ΔE, t}

Number of Electrons / Bunch, Bunch Rep Rate: I_{peak}, $I_{average}$

What exactly is emittance?

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x\theta_x \rangle^2}$$

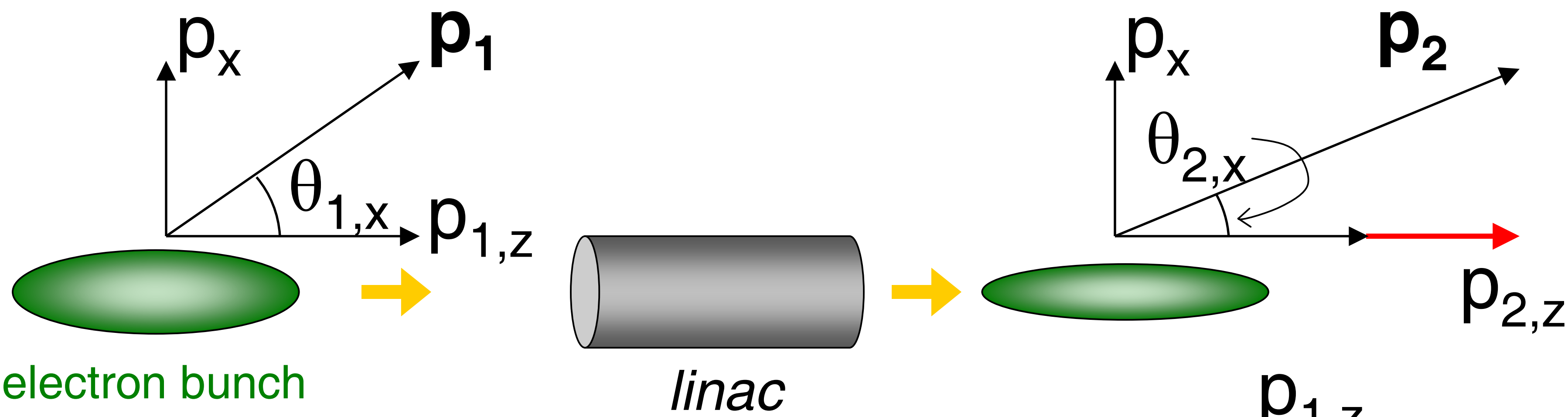
emittance [mm mrad] ~ source size · divergence



Liouville's Theorem: phase space volume is "incompressible fluid"

Adiabatic Damping

(Linear Accelerator Case)



ε_1

$$\varepsilon_2 = \varepsilon_1 \frac{p_{1,z}}{p_{2,z}}$$

geometric $\{x, \theta_x\}$

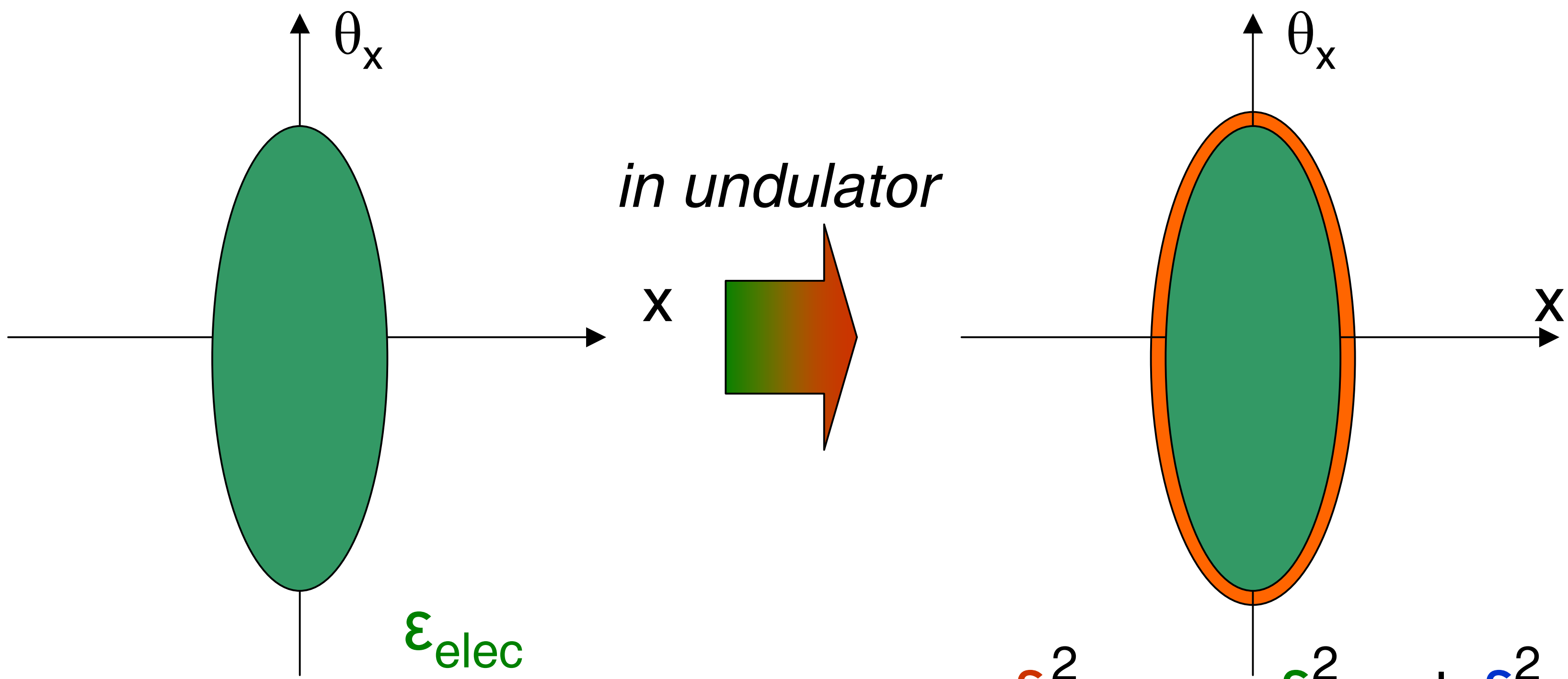
$$\varepsilon = \frac{\varepsilon_n}{\beta\gamma}$$

normalized $\{x, \frac{p_x}{mc^2}\}$

ε_n is invariant since

$\{x;\ p_x = mc^2\beta\gamma\cdot\theta_x\}$ form canonically conjugate variables

Why electron emittance matters?



$$\varepsilon^2_{x\text{-rays}} \sim \varepsilon^2_{elec} + \varepsilon^2_{ph}$$

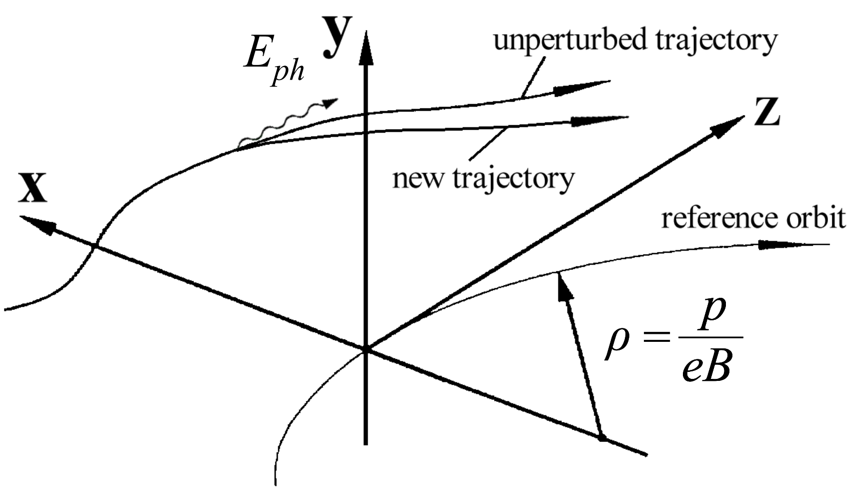
electron phase space x-rays phase space

$\varepsilon_{ph} = \lambda / 4\pi$ Diffraction Limit (Heisenberg uncertainty principle)

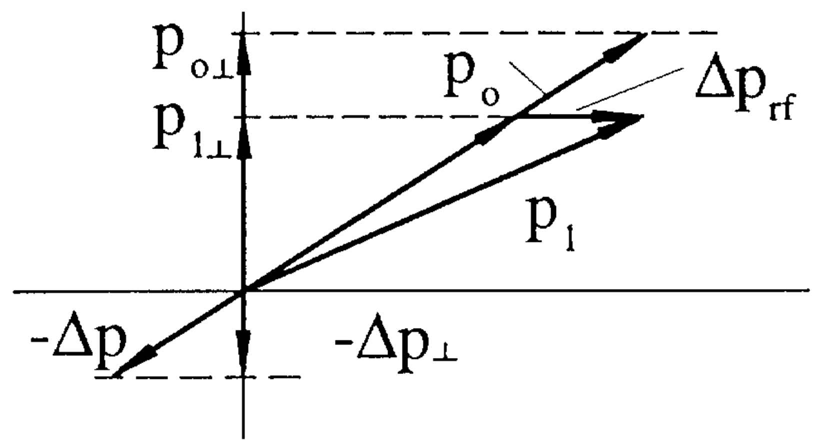
Storage Ring Case

Equilibrium

Quantum Excitation **vs.** Radiative Damping



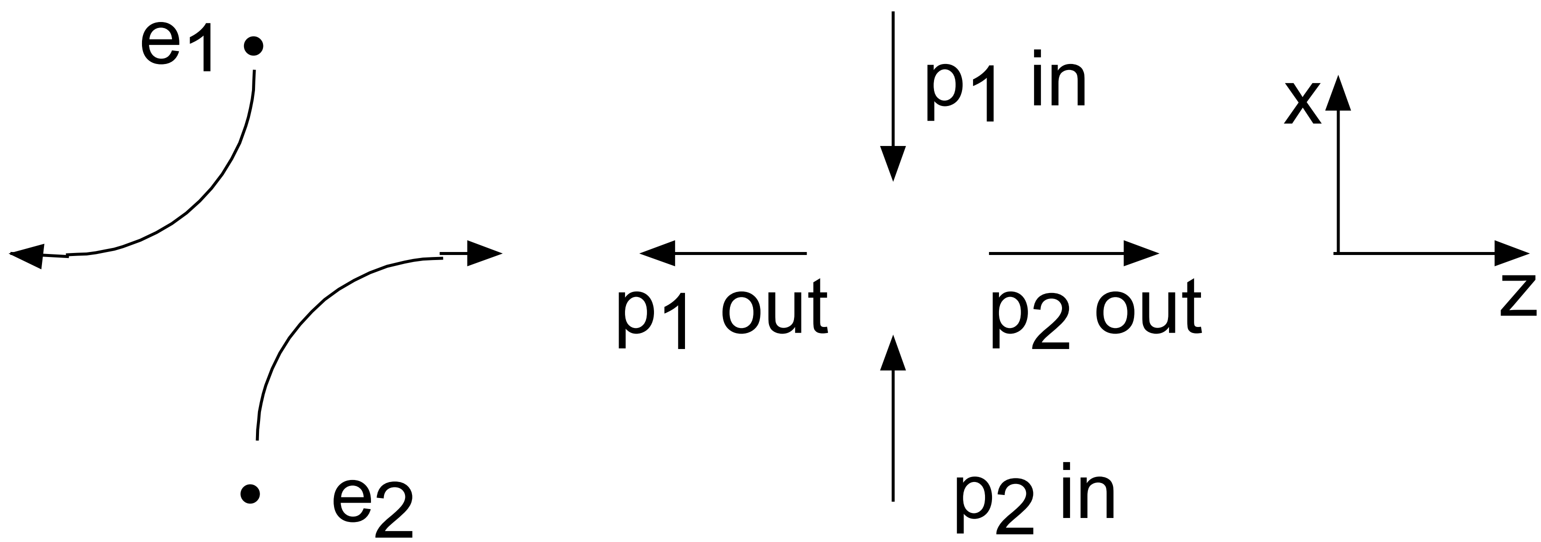
$$\frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2$$



Emittance (hor.), Energy Spread, Bunch Length

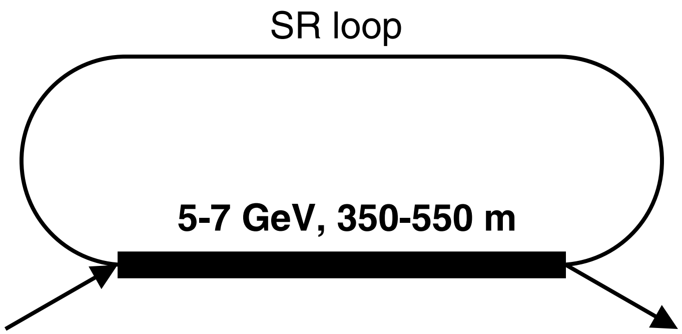
Storage Ring Case (cont.)

Touschek Effect



Beam Lifetime vs. Space Charge Density

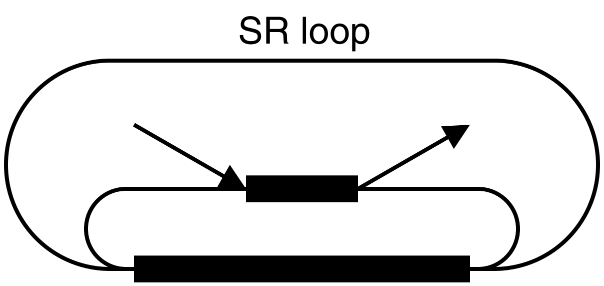
ERL X-ray SR Source Topology



Single linac scenario

Pros: only one loop

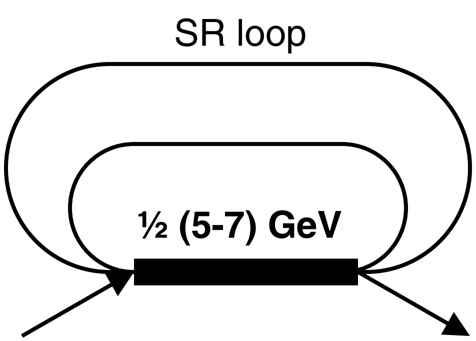
Cons: energy ratio of ~10^2–10^3



Split linac scenario

Pros: energy ratio of ~10–10^2; more flexibility for longitudinal phase space manipulations

Cons: two loops



Multipass scenario

Pros: srf structure is only half (or 1/N) the size

Cons: higher current (×N) in the linac; unstable @ ~10s mA

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ERL Sample Parameter List

Parameter	**Value**	**Unit**
Beam Energy	5-7	GeV
Average Current	100 / 10	mA
Fundamental frequency	1.3	GHz
Charge per bunch	77 / 8	pC
Injection Energy	10	MeV
Normalized emittance	2 / 0.2*	μm
Energy spread	0.02-0.3*	%
Bunch length in IDs	0.1-2*	ps
Total radiated power	400	kW

* rms values

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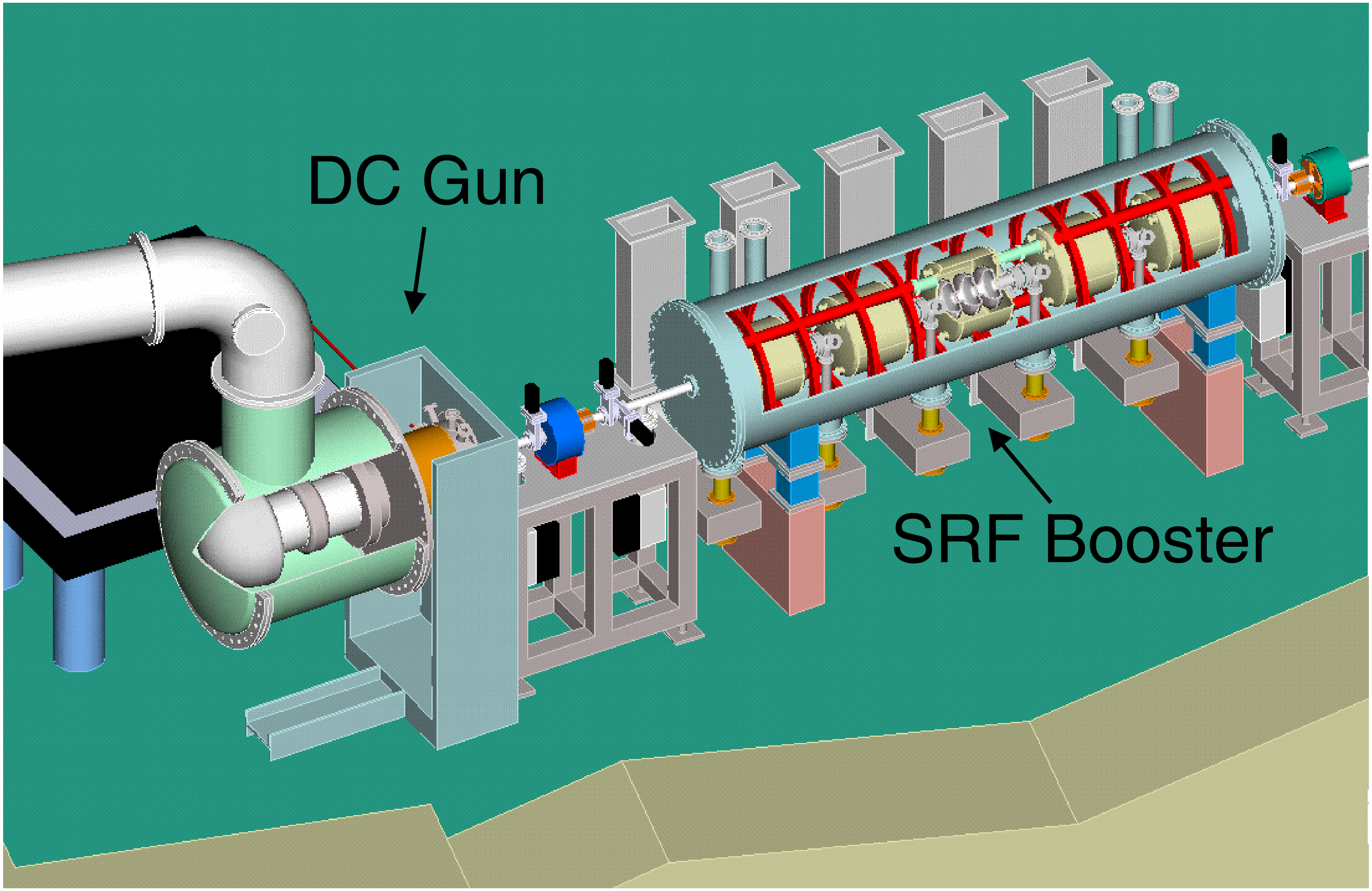
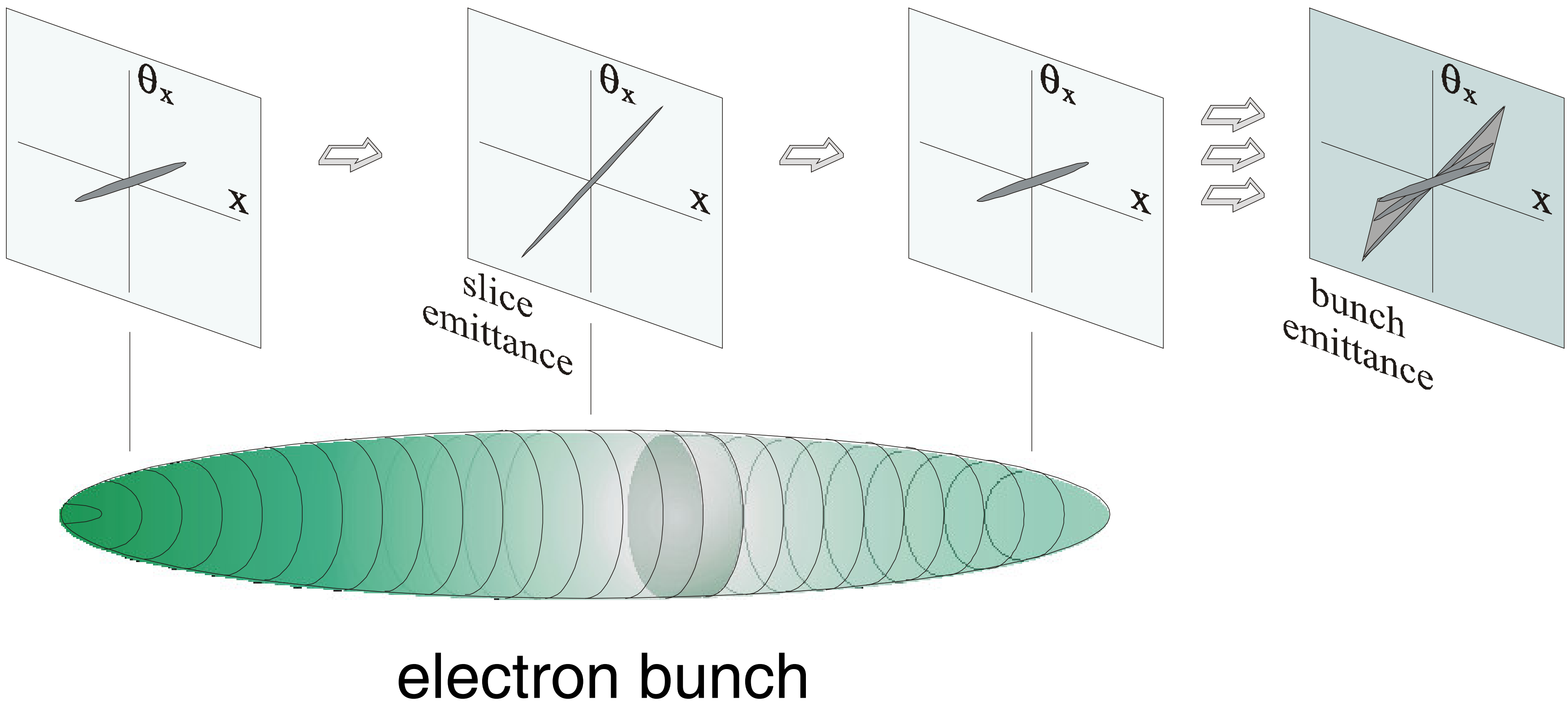
Quick Run Through the Main ERL Components …

- Electron Source
- Superconducting Linac
- Transport Loop
- Undulators
- Used Beam Dump

Electron Source



Space Charge Emittance Compensation in the Injector

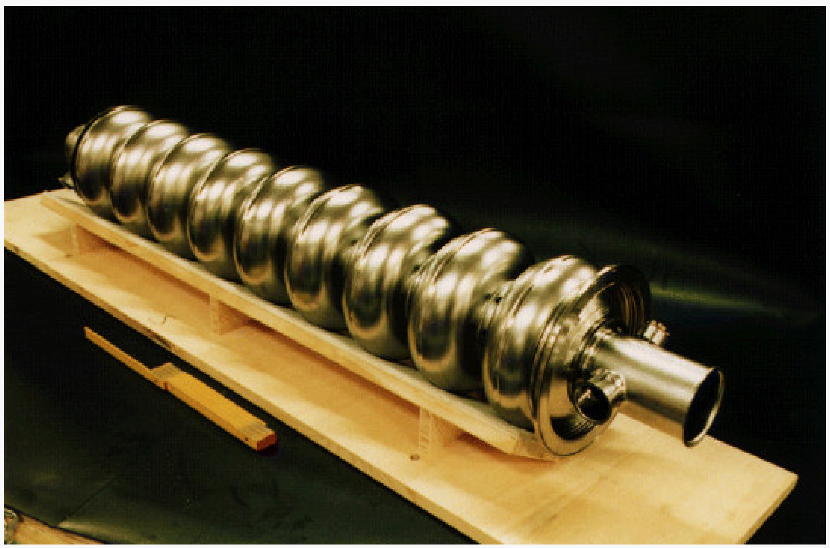


Goal: To approach thermal emittance of the Gun

Superconducting Linac

Superconducting RF cavities

($Q_0 \sim 10^{10}$ @ 20 MV/m)



TTF 9-cell 1.3 GHz niobium cavity

_+_

Cryogenic system

_+_

Klystrons

_+_

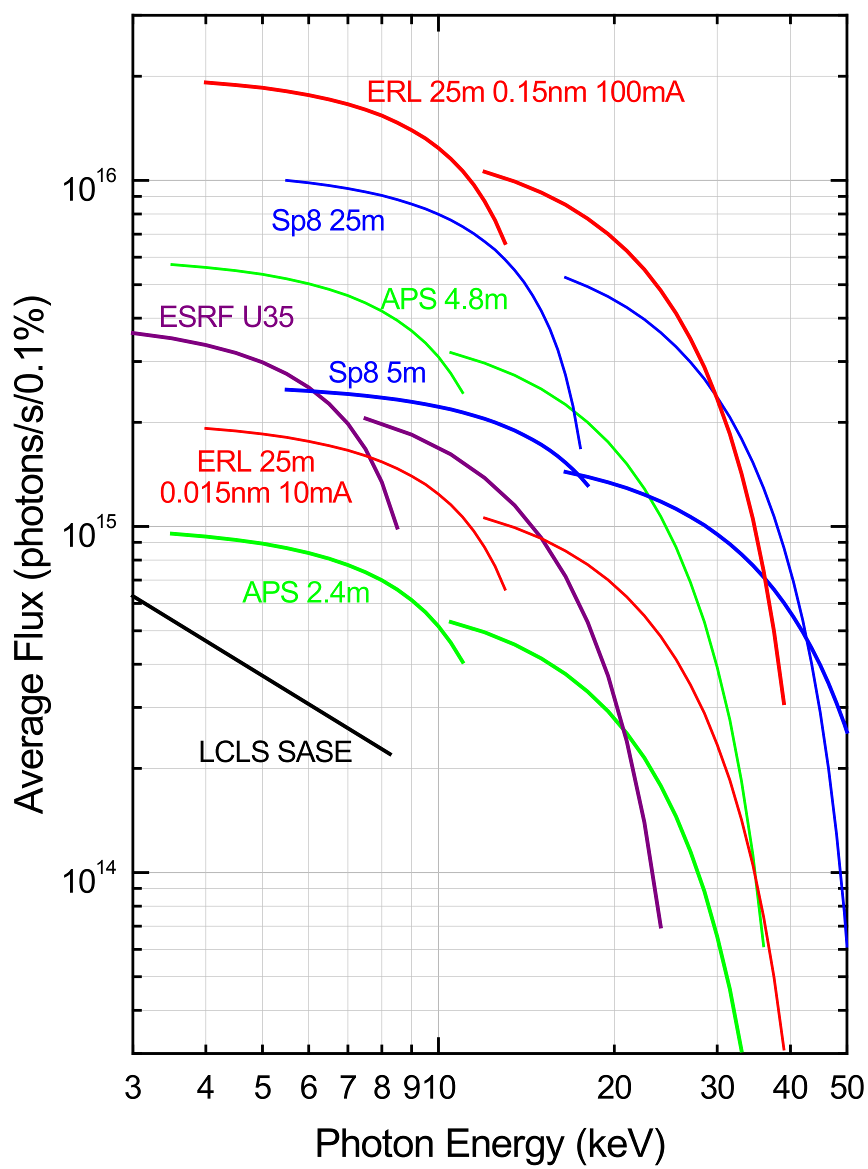
RF Control

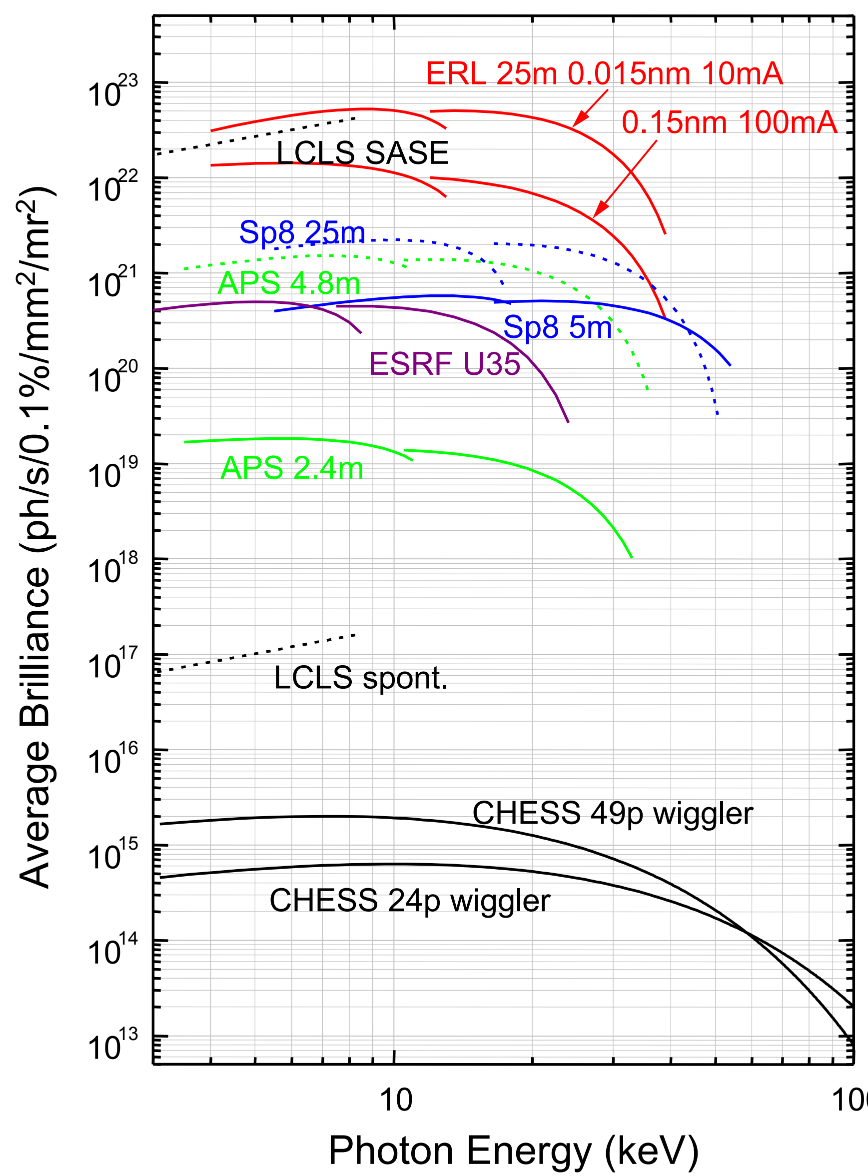
Beam Transport Loop & IDs

Transport loop is similar to that of a storage ring
+ ***flexibility to perform longitudinal gymnastics …***

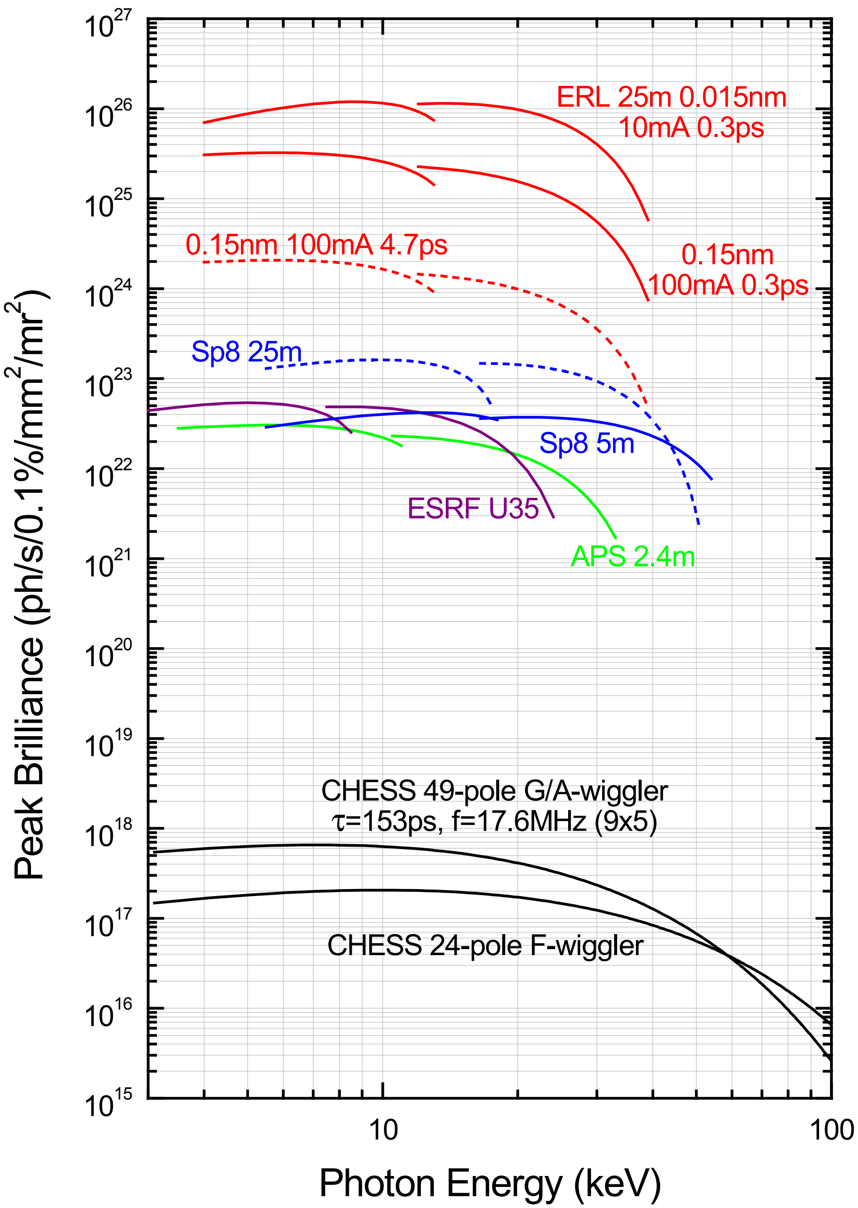
… and very loooong undulators

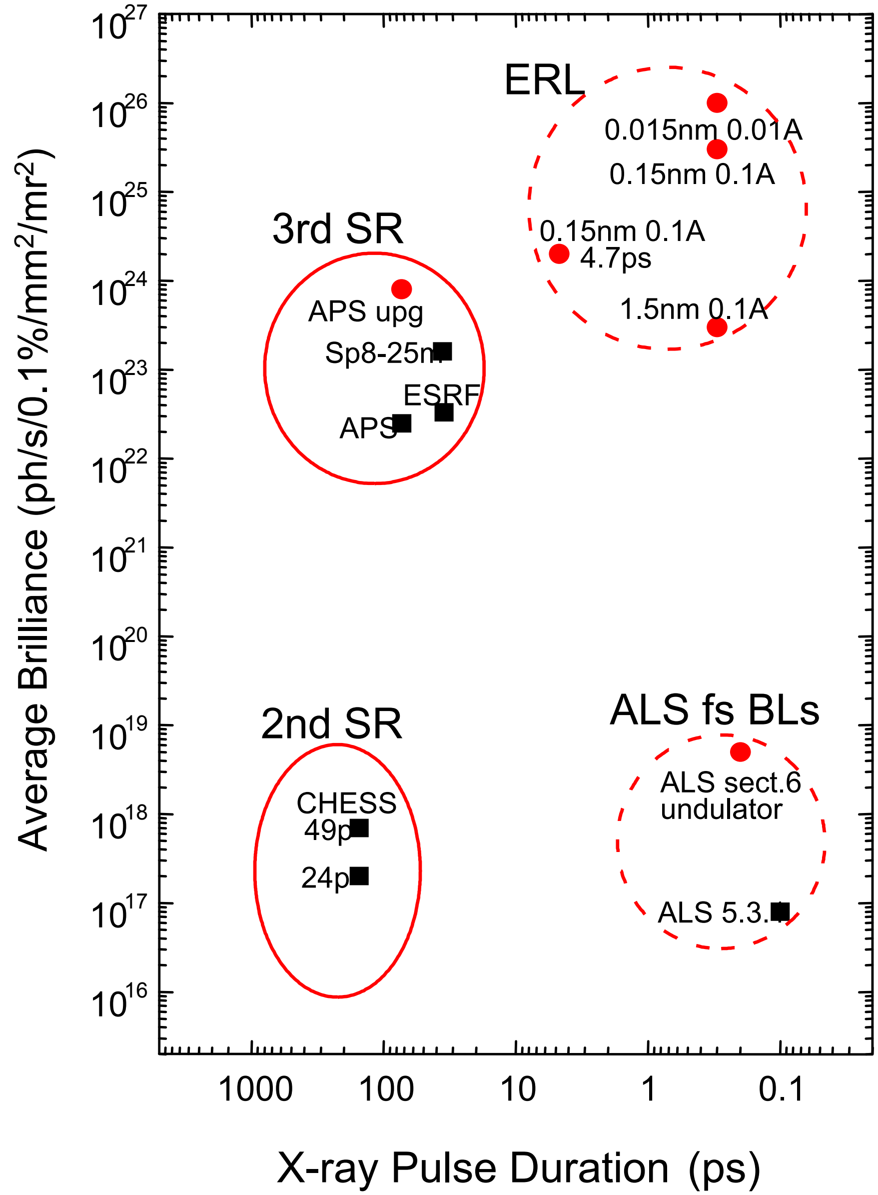
ERL X-ray Source Average Flux and Brilliance



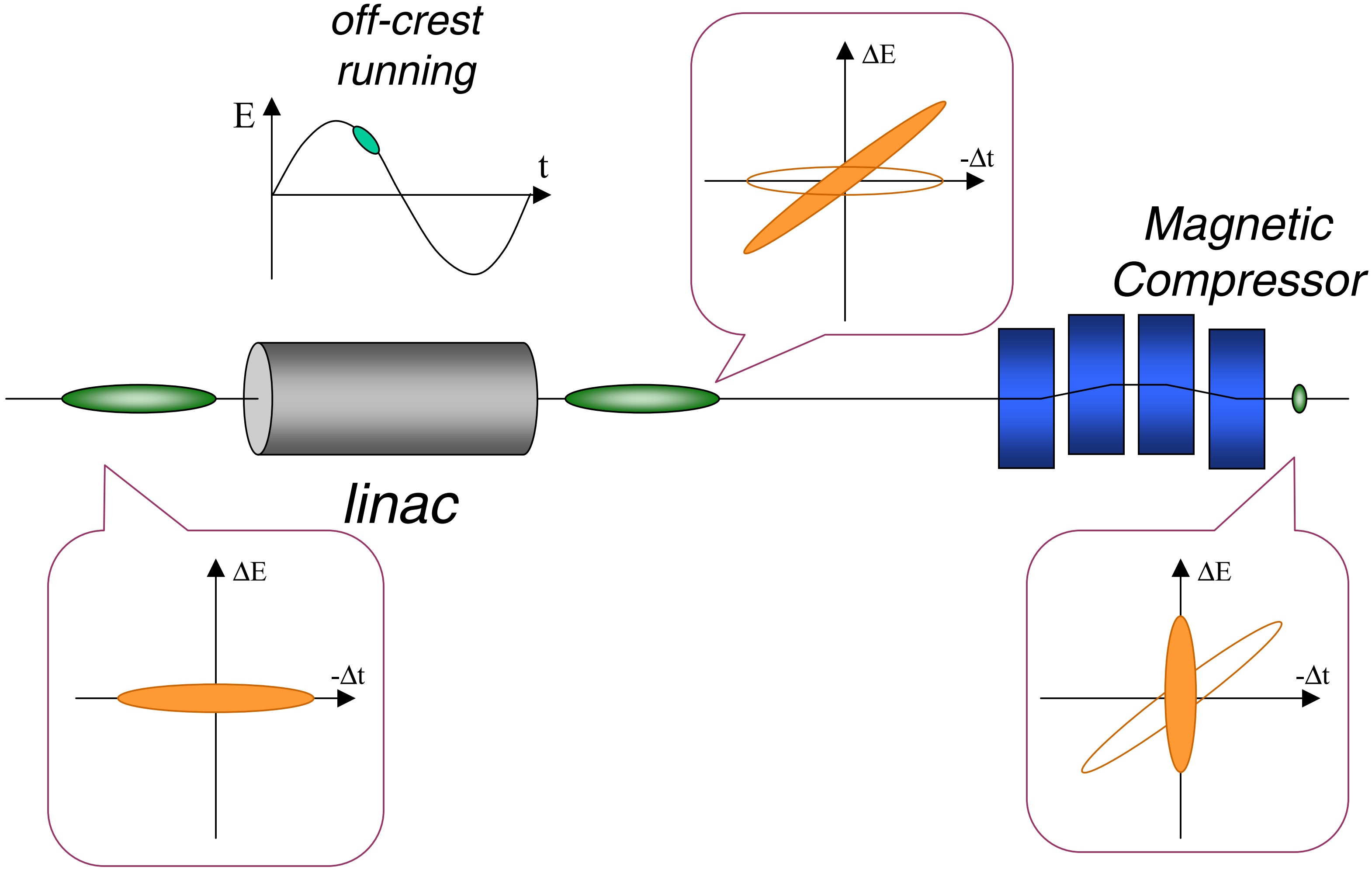


ERL Peak Brilliance and Ultra-Short Pulses





Sub-ps bunches: how to make those in ERL?



Gun *Main Linac* *Undulators*

17 ps → ***2 ps*** → ***0.1 ps***

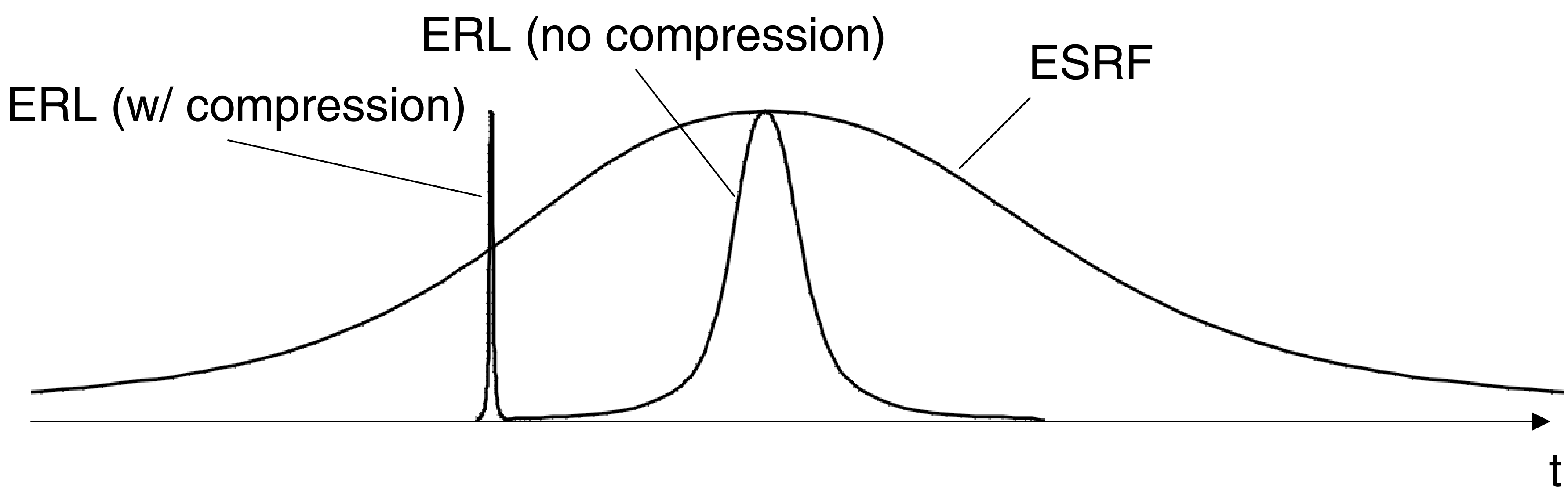
Reasons to be excited about ERL

ESRF 6 GeV @ 200 mA

ε_x = 4 nm mrad
ε_y = 0.01 nm mrad
B = 5×10^{20} ph/s/mm²/mrad²/0.1%BW
L_{ID} = 5 m

ERL 5 GeV @ 100 / 10 mA

$\varepsilon_x = \varepsilon_y$ = 0.2 / 0.02 nm mrad
B = 10^{22} ph/s/mm²/mrad²/0.1%BW
B = 3×10^{22} ph/s/mm²/mrad²/0.1%BW
L_{ID} = 25 m



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Challenges to be resolved

- Low emittance production & preservation
  - Achieving thermal emittance from gun (emittance compensation)
  - CSR, wakes (77 pC, not 1 nC!)
- Photocathode longevity at high average current (vacuum)
- Longitudinal phase space preservation in bunching (curvature correction)
- BBU in the main linac (HOMs damping)
- Beam loss ~ μA (halo)
- Highest Q_L possible (microphonics)
- Diagnostics …

Cornell involvement in ERL work

- *1965* – Original ERL concept for HEP purposes proposed by Maury Tigner
- *1999* – LNS director-to-be (Tigner) and CHESS director (Gruner) discuss ERL X-ray Source. Presented to CHESS Advisory Board in early 2000.
- *August, 2000* – ERL Machine Workshop at Cornell with JLAB contribution
- *December, 2000* – ERL Science Workshop at Cornell
- *July, 2001* – Proposal submitted to the NSF for a prototype ERL, based on studies by Cornell and JLAB scientists

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Goals of Cornell ERL Project

- Initial R&D of ERLs
- Build and Test a Phase I machine (100 mA, 100 MeV) to resolve machine issues
- Design and Build a high energy ERL (5-7 GeV) X-ray facility
- Perform R&D on utilization of ERLs and their X-ray and electron beams

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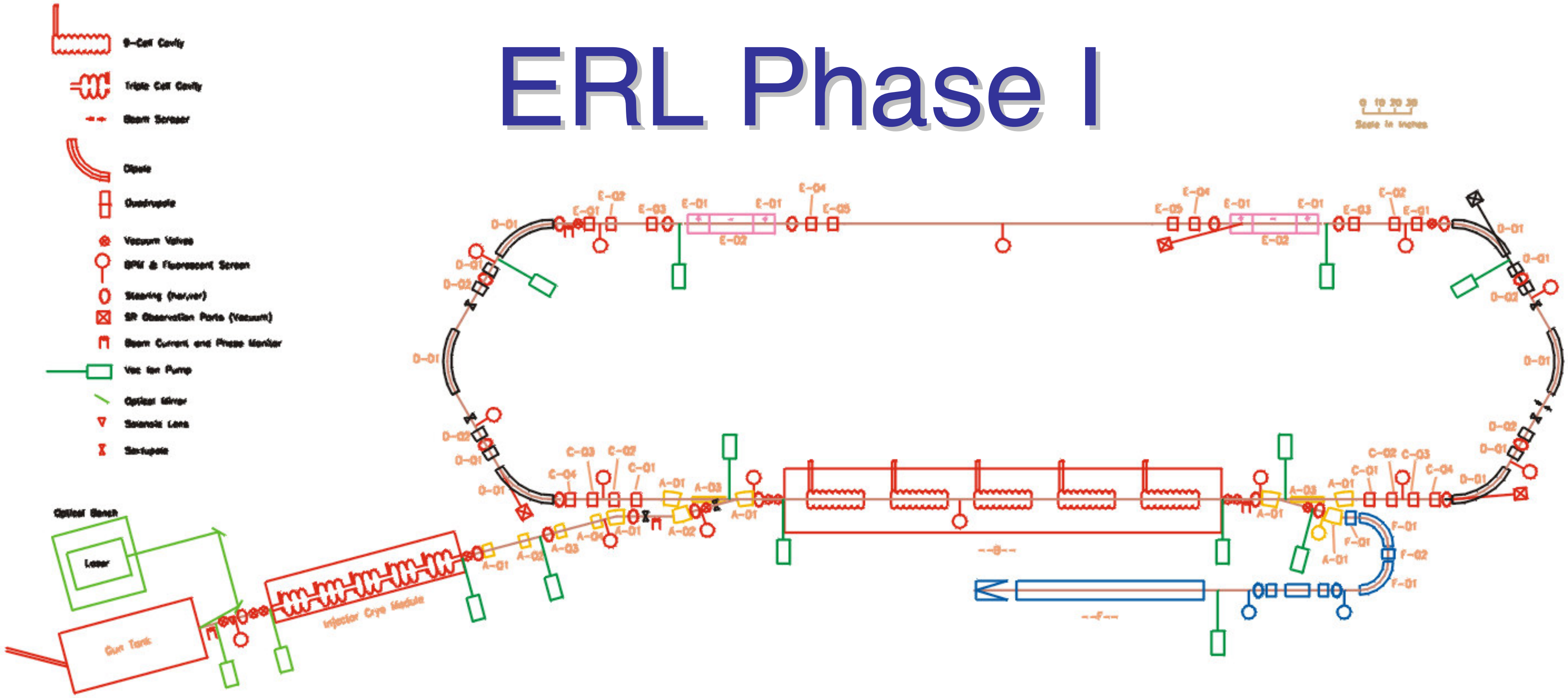
We hope to begin work in the fall!
3.5 year construction, 1.5 year measurements

ERL Phase I



Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5-8 MeV	Emittance, norm.	2* μm
Beam current	100 mA	Shortest bunch length	100* fs

* rms values