USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

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Cornell ERL Project

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ERL example (Cornell ERL project)

1. Introduction to ERLs (Review)
2. Vision of a Full Scale X-ray Producing ERL Facility at Cornell (Phase II)
3. Need for the ERL Prototype (Phase I)
4. Zooming-In on ERL Prototype
    1. Injector
    2. Transport Lines
    3. RF system
5. Experimental Program for ERL Prototype
6. Home Assignments
7. Further Reading on Cornell ERL

Let's review why ERL is such a great idea for a light source

We already know that for X-ray production the critical electron beam parameters are:

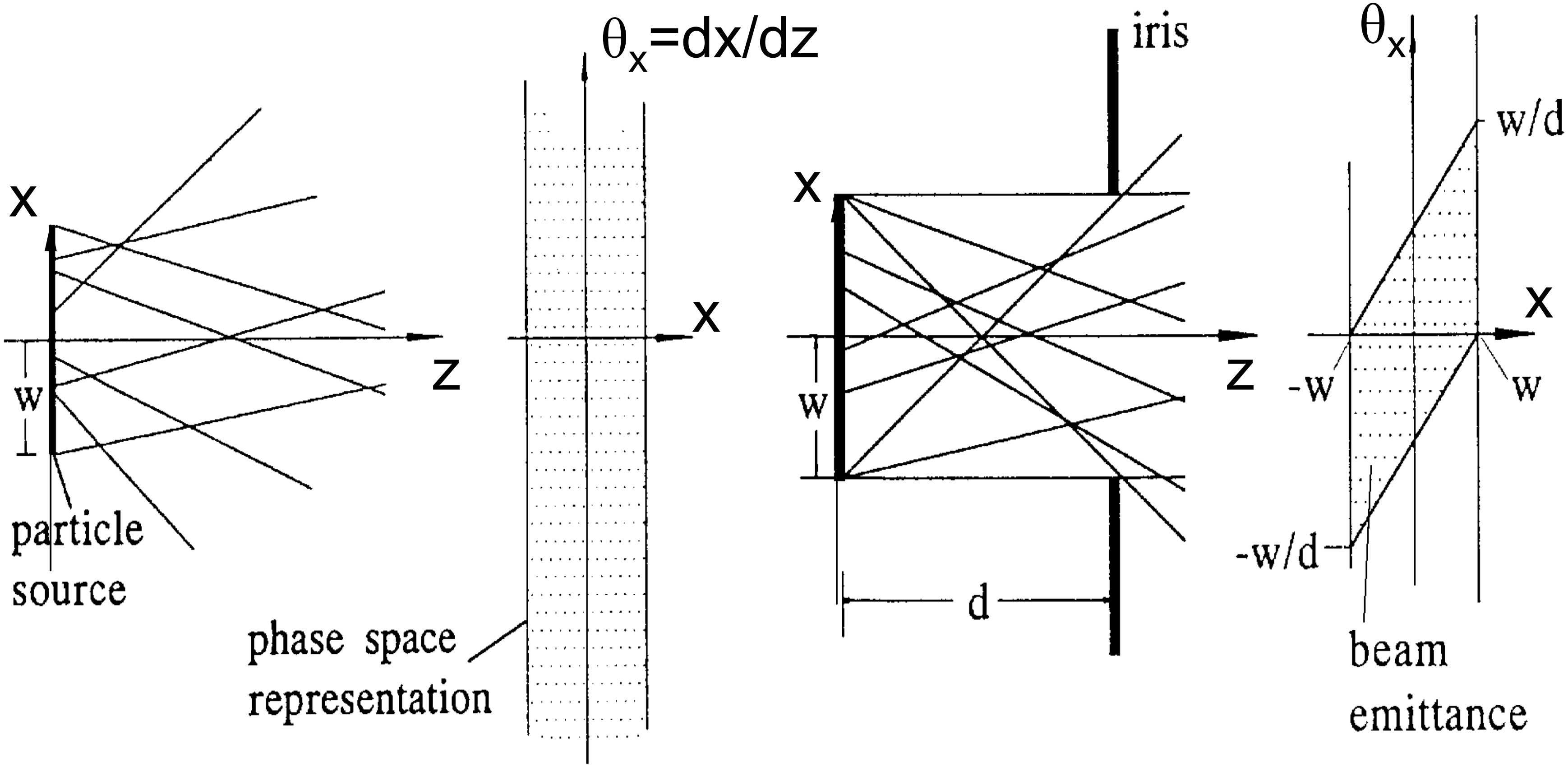
6D Phase Space Area:

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

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

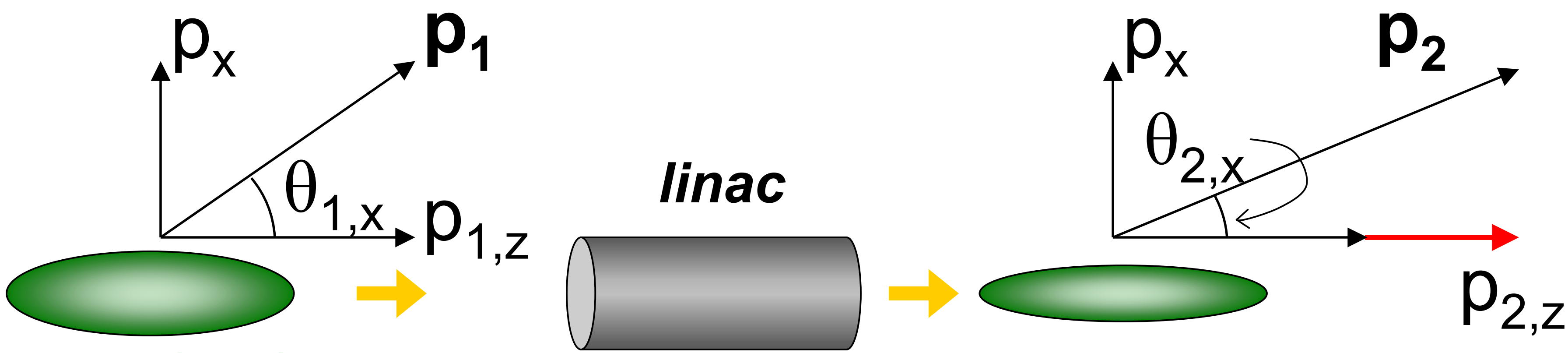
Introduction (contd.): what exactly is emittance?

R.M.S. definition:
$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x\theta_x \rangle^2}$$



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

Introduction (contd.): adiabatic damping



electron bunch

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

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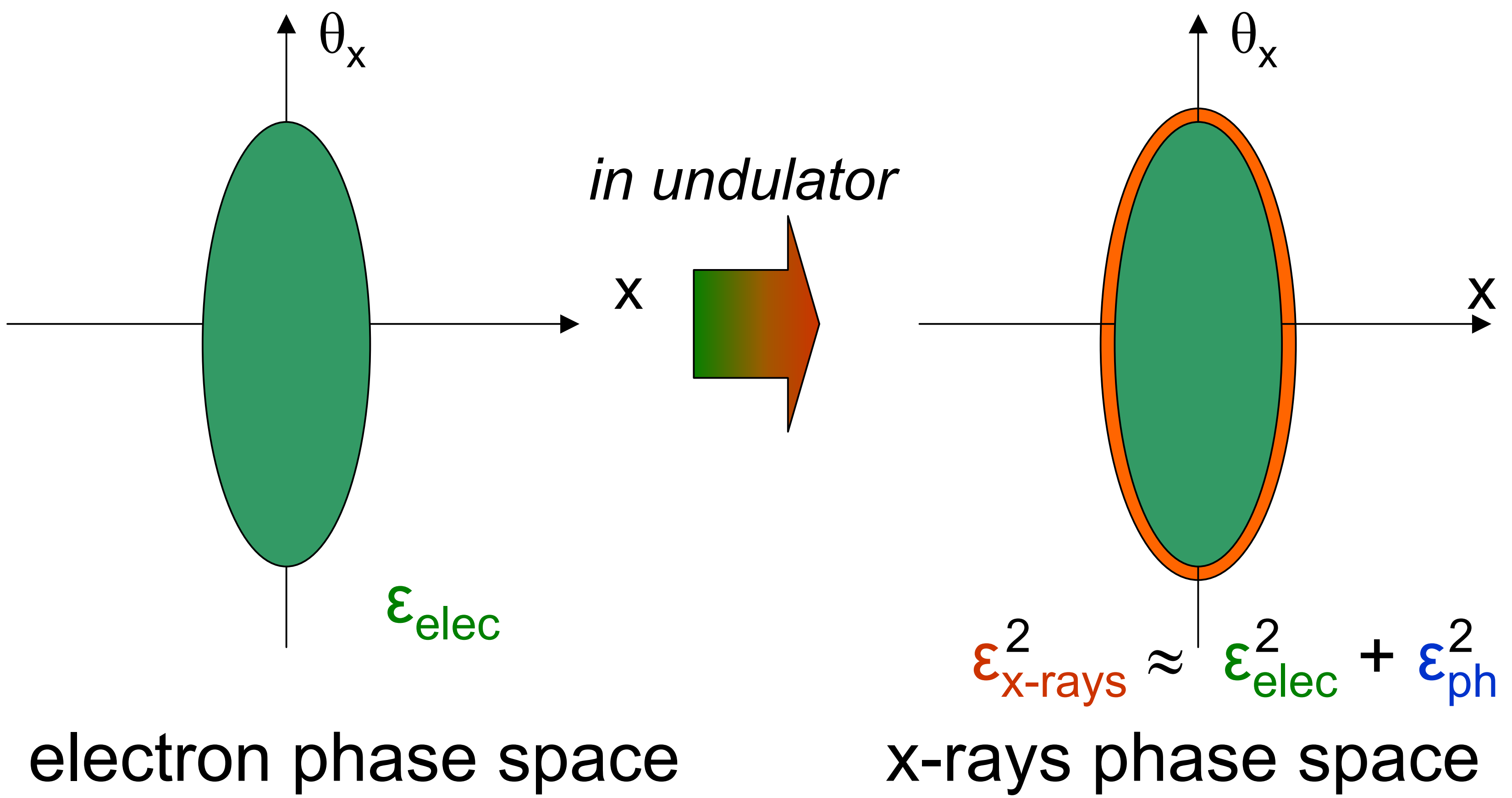
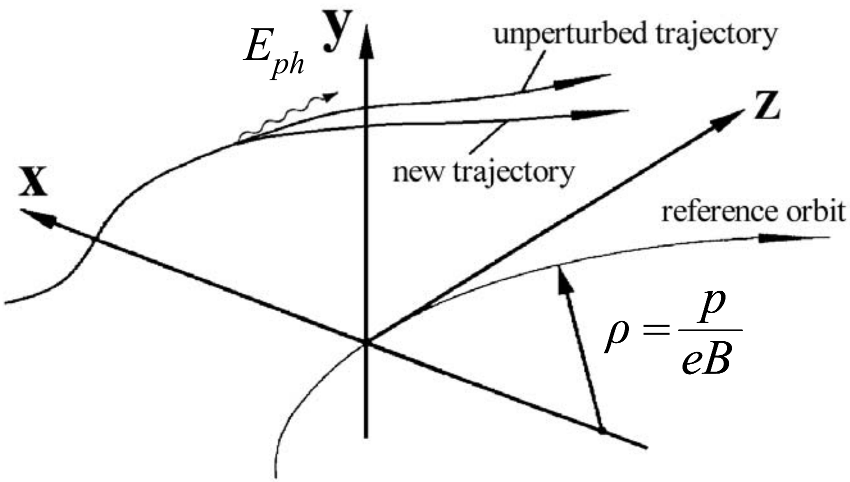
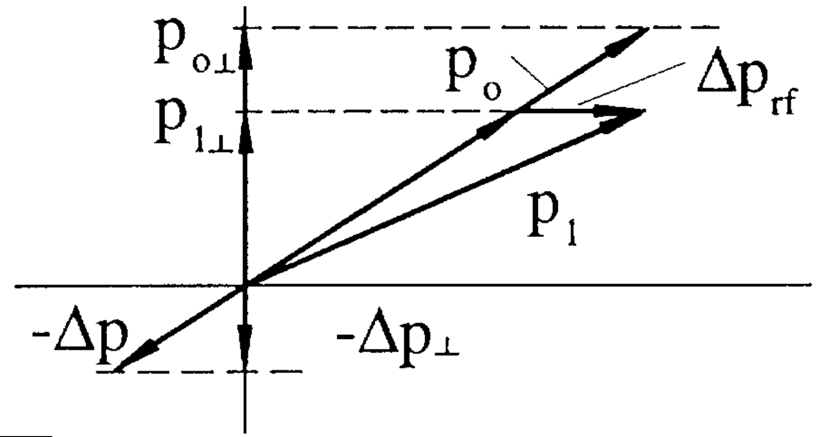


$\varepsilon_{ph} = \lambda / 4\pi$ Diffraction Limit (Heisenberg uncertainty principle)

Equilibrium

Quantum Excitation **vs.** Radiative Damping

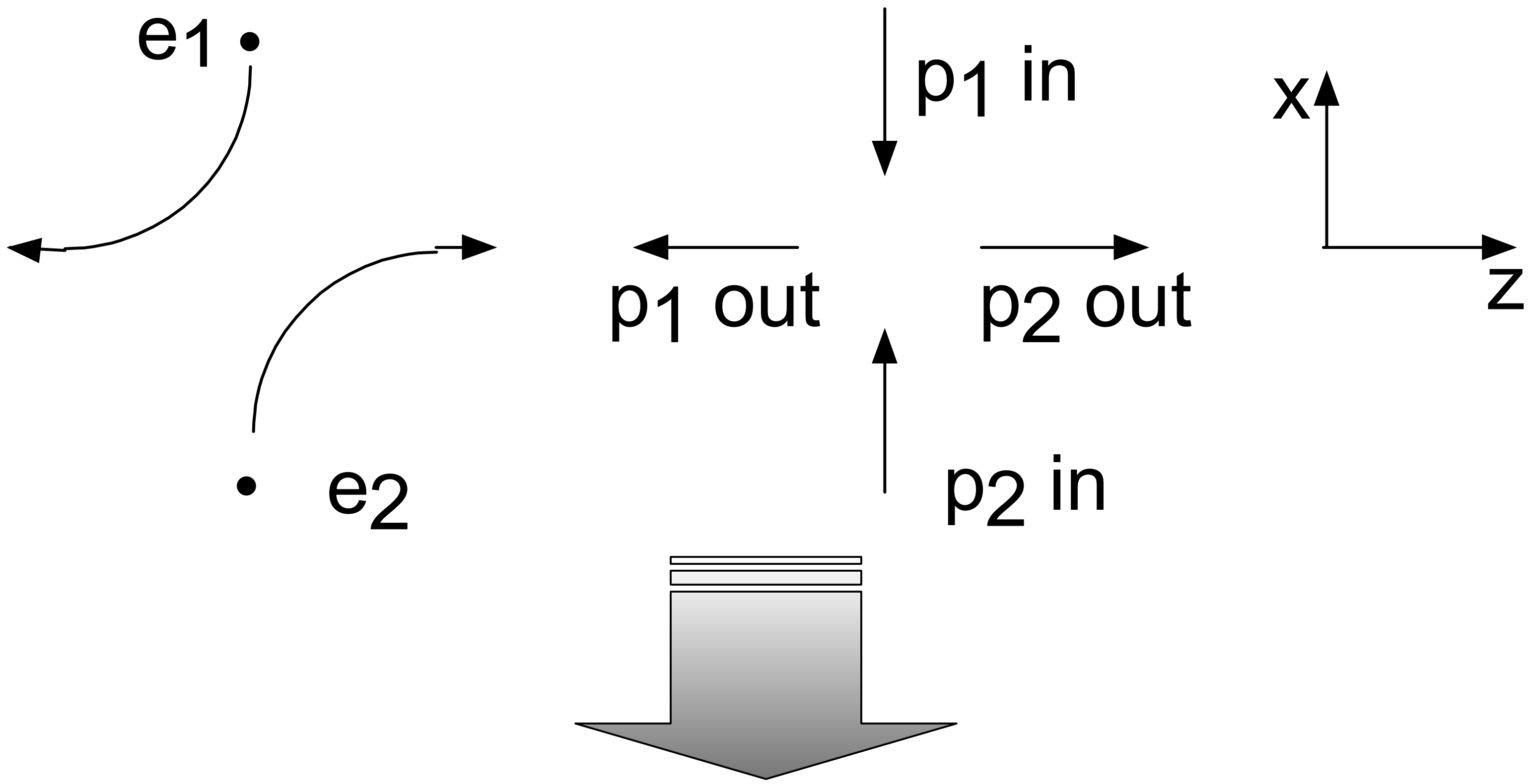




$$\frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2$$

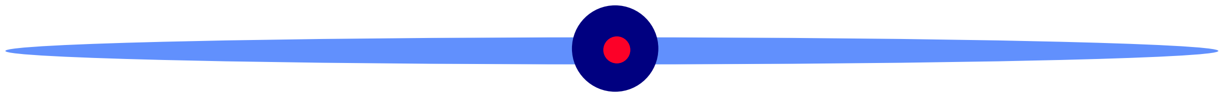
Emittance (hor.), Energy Spread, Bunch Length

Touschek Effect



Beam Lifetime vs. Space Charge Density

Introduction (contd.): why ERL?

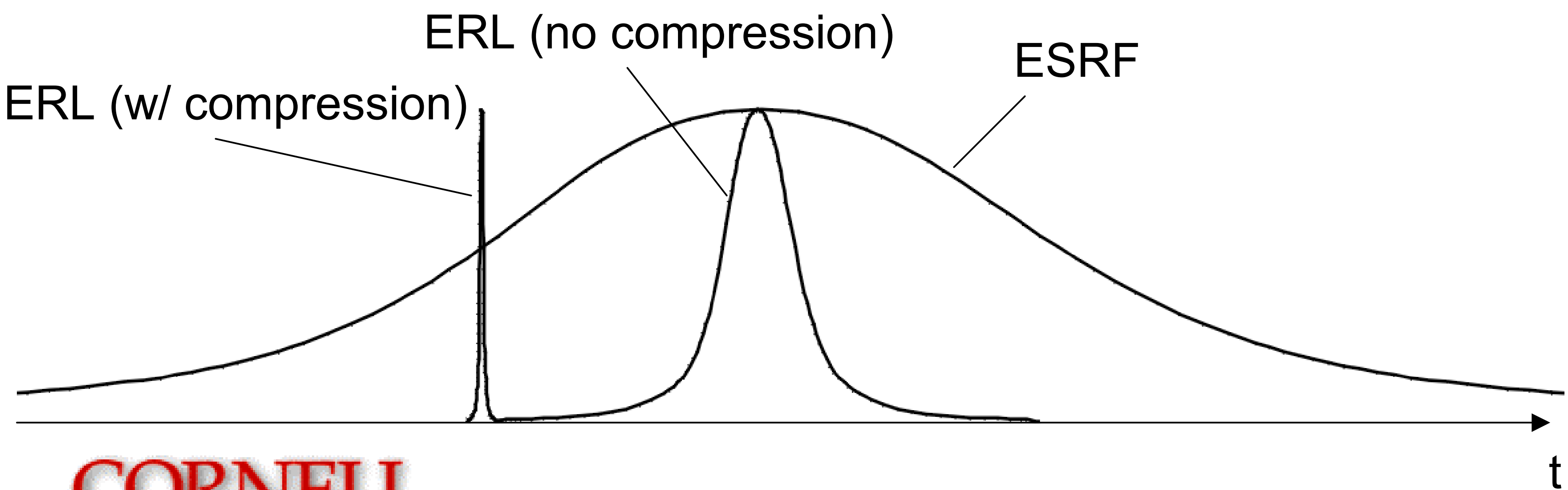


ESRF 6 GeV @ 200 mA

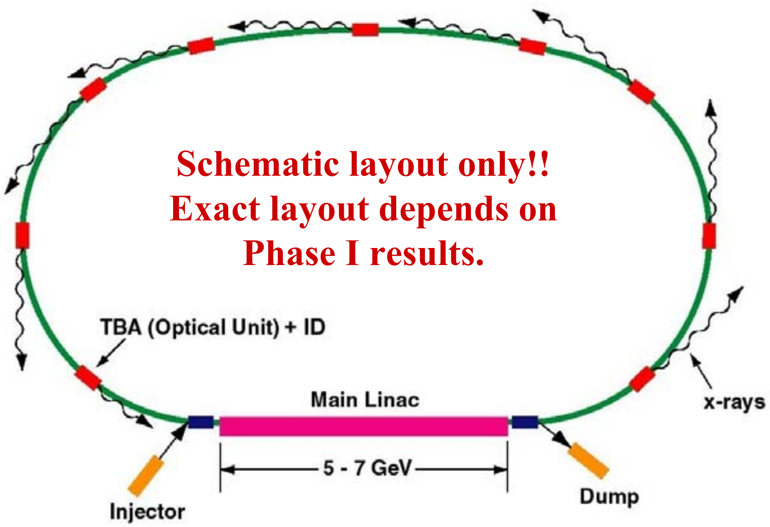
ε_x = 4 nm mrad
ε_y = 0.02 nm mrad
B ~ 10^{20} ph/s/mm²/mrad²/0.1%BW
L_{ID} = 5 m

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
L_{ID} = 25 m



Vision of ERL Facility at Cornell (Phase II)



Machine design		
	Energy E_G (GeV)	5.3
	Current I (mA)	100
	Charge q (nC/bunch)	0.077
	ε_x (nm-rad)	0.15
	ε_y (nm-rad)	0.15
	Bunch fwhm τ (ps)	0.3 – 5
	# of bunches f (Hz)	$1.3 \cdot 10^9$

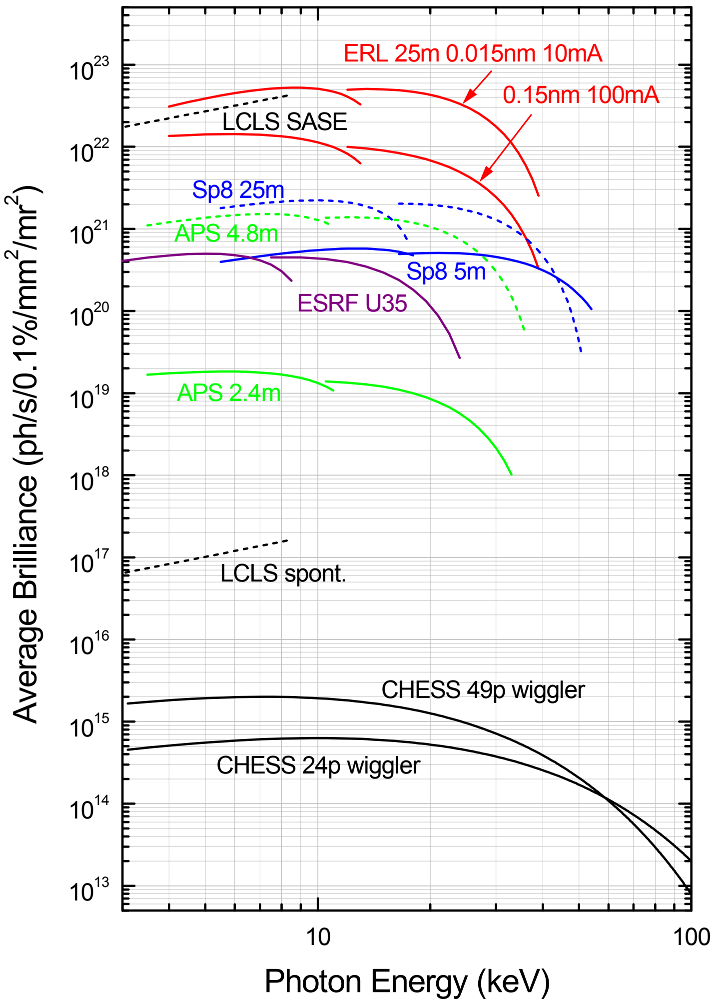


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Table 1: Comparison of the Cornell ERL source with other existing and proposed synchrotron light sources.

Assuming high duty-cycle operations		ERL hi-flux	ERL hi-coh.	APS und. A	APS upgrade	ESRF U35	Spring8 5m	Spring8 25m	LCLS spont.	LCLS SASE	TESLA spont.	TESLA SASE
Machine design	Energy E_G (GeV)	5.3	5.3	7	7	6	8	8	15	15	25	25
	Current I (mA)	100	10	100	300	200	100	100	$72\cdot10^{-6}$	$72\cdot10^{-6}$	0.063	0.063
	Charge q (nC/bunch)	0.077	0.008	14	14	0.85	0.29	0.29	1	1	1	1
	ε_x (nm-rad)	0.15	0.015	8	3.5	4	6	6	0.05	0.05	0.02	0.02
	ε_y (nm-rad)	0.15	0.015	0.08	0.0035	0.01	0.003	0.003	0.05	0.05	0.02	0.02
	Bunch fwhm τ (ps)	0.3	0.3	73	73	35	36	36	0.23	0.23	0.188	0.090
	# of bunches f (Hz)	$1.3\cdot10^{9}$	$1.3\cdot10^{9}$	$7.3\cdot10^{6}$	$22\cdot10^{6}$	$2.3\cdot10^{8}$	$3.4\cdot10^{8}$	$3.4\cdot10^{8}$	120	120	56575	56575
Insertion device	Undulator L (m)	25	25	2.4	4.8	5	4.5	25	100	100	30	87
	Period λ_u (cm)	1.7	1.7	3.3	3.3	3.5	2.4	3.2	3	3	3.81	5
	# of period N_u	1470	1470	72	145	142	187	781	3300	3300	787	1740
	Horizontal β_x (m)	12.5	4.0	15.9	4.0	35	24	24	18	18	14.7	33.3
	Vertical β_y (m)	12.5	4.0	5.3	4.0	2.5	3.9	15	18	18	14.7	33.3
	Und. K (@ E_1)	1.38	1.38	1.24	1.24	0.67	2.08	1.66	3.9	3.9	2.28	4.14
	1^{st} harmonic E_1 (keV)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.26	8.26	10	12.4
Beamline & optics	H. div. fwhm (μrad)	9.1	6.2	54.3	70.2	26.8	38.4	37.4	4.9	1	6.7	1.76
	V. div. fwhm (μrad)	9.1	6.2	16.2	9.7	10.4	10.0	4.3	4.9	1	6.7	1.76
	H. source fwhm (μm)	103	24.5	839	277	879	892	890	82	78	60	60
	V. source fwhm (μm)	103	24.5	48.6	11.4	13.9	10.6	22.8	82	78	60	60
	Power P_0 (kW)	33.9	3.4	1.2	7.2	1	15.7	31.2	0.0027	0.003	0.070	1.6

Beamline & optics	H. div. fwhm (μrad)	9.1	6.2	34.3	70.2	26.8	38.4	37.4	4.9	1	6.7	1.76
	V. div. fwhm (μrad)	9.1	6.2	16.2	9.7	10.4	10.0	4.3	4.9	1	6.7	1.76
	H. source fwhm (μm)	103	24.5	839	277	879	892	890	82	78	60	60
	V. source fwhm (μm)	103	24.5	48.6	11.4	13.9	10.6	22.8	82	78	60	60
	Power P_0 (kW)	33.9	3.4	1.2	7.2	1	15.7	31.2	0.0027	0.003	0.070	1.6
	dP/dA @20m (W/mm^2)	2600	260	180	1080	194	1830	4568	0.45	63	336	$2{\cdot}10^5$
DC experiments	Ave. flux F_n (p/s/0.1%)	$1.5{\cdot}10^{16}$	$1.5{\cdot}10^{15}$	$7.0{\cdot}10^{14}$	$4.2{\cdot}10^{15}$	$1.3{\cdot}10^{15}$	$2.4{\cdot}10^{15}$	$9.0{\cdot}10^{15}$	$3.3{\cdot}10^{10}$	$2.4{\cdot}10^{14}$	$6.4{\cdot}10^{12}$	$4{\cdot}10^{17}$
	Ave. brilliance B (p/s/0.1%/mm^2/mr^2)	$1.3{\cdot}10^{22}$	$5.2{\cdot}10^{22}$	$1.5{\cdot}10^{19}$	$1.5{\cdot}10^{21}$	$3.1{\cdot}10^{20}$	$5.0{\cdot}10^{20}$	$2.2{\cdot}10^{21}$	$1.6{\cdot}10^{17}$	$4.2{\cdot}10^{22}$	$3.6{\cdot}10^{19}$	$8{\cdot}10^{25}$
	Coh flux F_c (p/s/0.1%)	$8.1{\cdot}10^{13}$	$3.1{\cdot}10^{14}$	$0.9{\cdot}10^{11}$	$9.0{\cdot}10^{12}$	$1.8{\cdot}10^{12}$	$3.0{\cdot}10^{12}$	$1.3{\cdot}10^{13}$	$9.0{\cdot}10^{8}$	$2.4{\cdot}10^{14}$	$1.4{\cdot}10^{11}$	$4{\cdot}10^{17}$
	Coh. fraction p_c (%)	0.52	20	0.013	0.22	0.14	0.13	0.14	2.7	100	2.1	100
Pulsed expts.	Photons / bunch	$1.2{\cdot}10^{7}$	$1.2{\cdot}10^{6}$	$9.6{\cdot}10^{7}$	$1.9{\cdot}10^{8}$	$5.7{\cdot}10^{6}$	$7.1{\cdot}10^{6}$	$2.7{\cdot}10^{7}$	$2.8{\cdot}10^{8}$	$2{\cdot}10^{12}$	$1.1{\cdot}10^{8}$	$7{\cdot}10^{12}$
	Peak brilliance (p/s/0.1%/mm^2/mr^2)	$3.0{\cdot}10^{25}$	$1.2{\cdot}10^{26}$	$2.5{\cdot}10^{22}$	$8.3{\cdot}10^{23}$	$3.3{\cdot}10^{22}$	$3.6{\cdot}10^{22}$	$1.6{\cdot}10^{23}$	$4.8{\cdot}10^{27}$	$1.2{\cdot}10^{33}$	$3.4{\cdot}10^{27}$	$7{\cdot}10^{33}$
	Peak flux (p/s/0.1%)	$3.9{\cdot}10^{19}$	$3.9{\cdot}10^{18}$	$1.3{\cdot}10^{18}$	$2.6{\cdot}10^{18}$	$1.6{\cdot}10^{17}$	$1.9{\cdot}10^{17}$	$7.4{\cdot}10^{17}$	$1.2{\cdot}10^{21}$	$7.2{\cdot}10^{24}$	$6.0{\cdot}10^{20}$	$3{\cdot}10^{25}$
	Pk coh. flux (p/s/0.1%)	$2.1{\cdot}10^{17}$	$7.9{\cdot}10^{17}$	$1.7{\cdot}10^{14}$	$5.6{\cdot}10^{15}$	$2.2{\cdot}10^{14}$	$2.5{\cdot}10^{14}$	$1.1{\cdot}10^{15}$	$2.7{\cdot}10^{19}$	$7.2{\cdot}10^{24}$	$1.4{\cdot}10^{19}$	$3{\cdot}10^{25}$
	Peak degen. par. δ_D	95	368	0.078	2.6	0.103	0.113	0.49	$1.3{\cdot}10^{4}$	$3.3{\cdot}10^{9}$	$4.7{\cdot}10^{3}$	$8{\cdot}10^{9}$
Nonlinear expts.	Ave. coh. power (W)	0.10	0.40	$1.2{\cdot}10^{-4}$	0.011	0.0023	0.0038	0.017	$1.2{\cdot}10^{-6}$	0.32	$2.2{\cdot}10^{-4}$	794
	Peak coh. power (W)	269	1011	0.22	7.2	0.28	0.32	1.4	$3.8{\cdot}10^{4}$	$9{\cdot}10^{9}$	$2.2{\cdot}10^{4}$	$60{\cdot}10^{9}$
	A coh dP/dA (W/mm^2)	12.0	848	0.0029	3.5	0.19	0.40	0.84	$2.3{\cdot}10^{-4}$	0.0077	0.078	$2.8{\cdot}10^{5}$
	P coh dP/dA (W/mm^2)	$3.2{\cdot}10^{4}$	$2.2{\cdot}10^{6}$	5.4	2280	22.9	33.8	69.0	$7.2{\cdot}10^{6}$	$1.9{\cdot}10^{12}$	$7.8{\cdot}10^{6}$	$2.1{\cdot}10^{13}$
	Ave. E-field (V/m)	$1.0{\cdot}10^{5}$	$8.0{\cdot}10^{5}$	1479	$5.1{\cdot}10^{4}$	$1.2{\cdot}10^{4}$	$1.7{\cdot}10^{4}$	$2.5{\cdot}10^{4}$	416	2410	7670	$1.5{\cdot}10^{7}$
	Peak E-field (V/m)	$4.9{\cdot}10^{6}$	$4.1{\cdot}10^{7}$	$6.4{\cdot}10^{4}$	$1.3{\cdot}10^{6}$	$1.3{\cdot}10^{5}$	$1.6{\cdot}10^{5}$	$2.3{\cdot}10^{5}$	$7.4{\cdot}10^{7}$	$3.8{\cdot}10^{10}$	$7.7{\cdot}10^{7}$	$1.3{\cdot}10^{11}$

Need for the ERL prototype

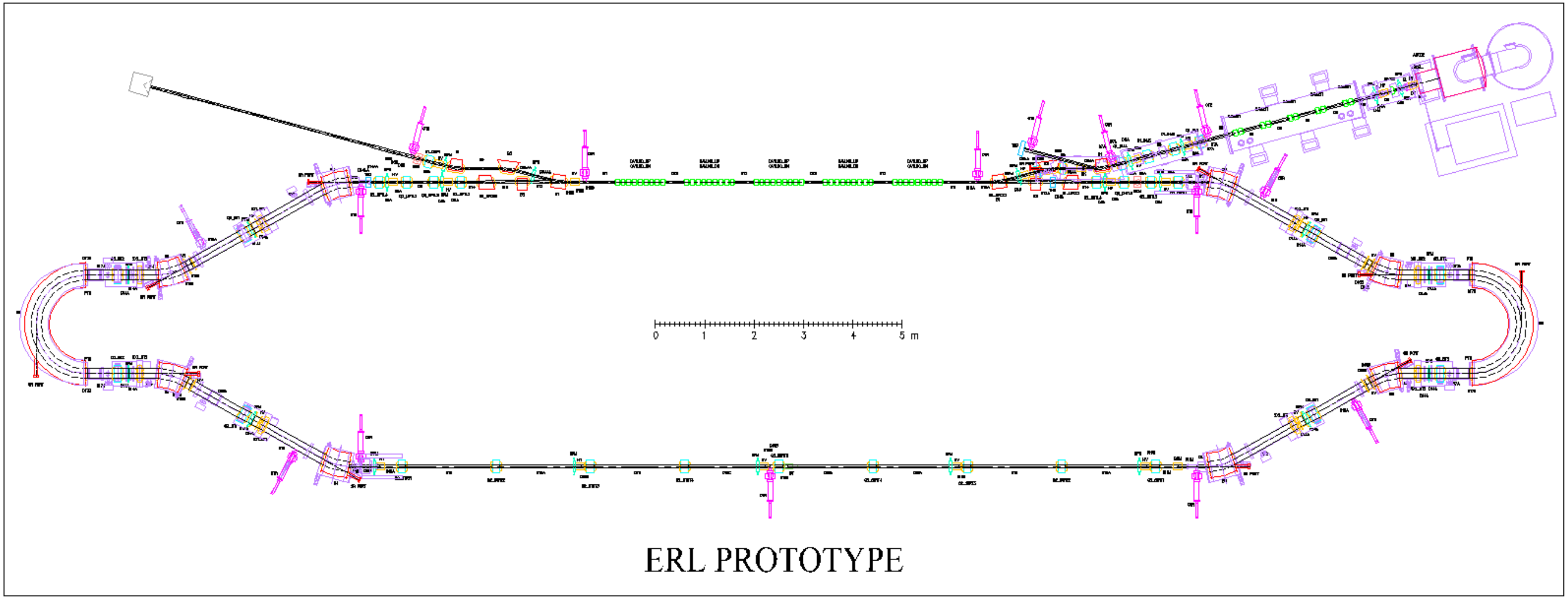
Jefferson Lab

Issues include:

- **CW injector: produce $i_{avg} \geq 100$ mA, $q_{bunch} \sim 80$ pC @ 1300 MHz, $\varepsilon_n \sim 1$ mm mr, low halo with very good photo-cathode longevity.**
- **Maintain high Q and E_{acc} in high current beam conditions.**
- **Extract HOM's with very high efficiency ($P_{HOM} \sim 10$x previous).**
- **Control BBU by improved HOM damping, parameterize $i_{thr.}$**
- **How to operate with hi Q_L (control microphonics & Lorentz detuning).**
- **Produce + meas. $\sigma_t \sim 100$ fs with $q_{bunch} \sim 0.3$–0.4 nC ($i_{avg} < 100$ mA), understand / control CSR, understand limits on simultaneous brilliance and short pulses.**
- **Check, improve beam codes. Investigate multipass schemes.**

Our conclusion: An ERL Prototype is needed to resolve outstanding technology and accelerator physics issues before a large ERL is built

Cornell ERL Prototype



Energy	100 MeV
Max Avg. Current	100 mA
Charge / bunch	1 – 400 pC
Emittance (norm.)	≤ 2 mm mr@77 pC
Injection Energy	5 – 15 MeV
E_{acc} @ Q_0	20 MeV/m @ 10^{10}
Bunch Length	2 – 0.1 ps

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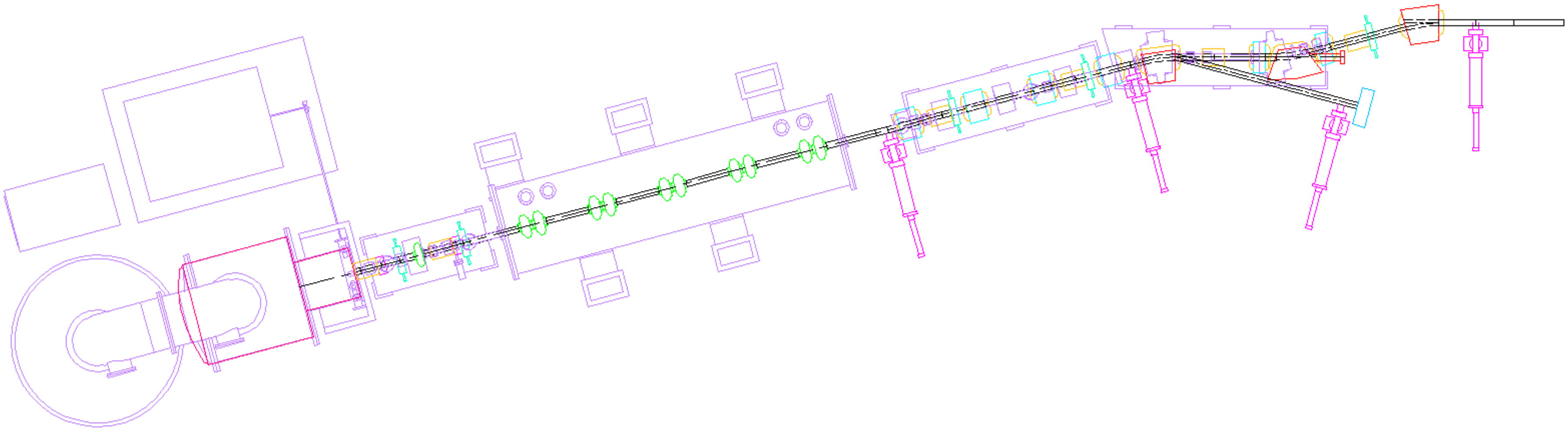
Cornell ERL Phase I: Injector



Injector Parameters:

Beam Energy Range	5 – 15[a] MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance, rms (norm.)	≤ 1.5[b] μm
Bunch Length, rms	2.1 ps
Energy Spread, rms	0.2 %

[a] at reduced average current
[b] corresponds to 77 pC/bunch

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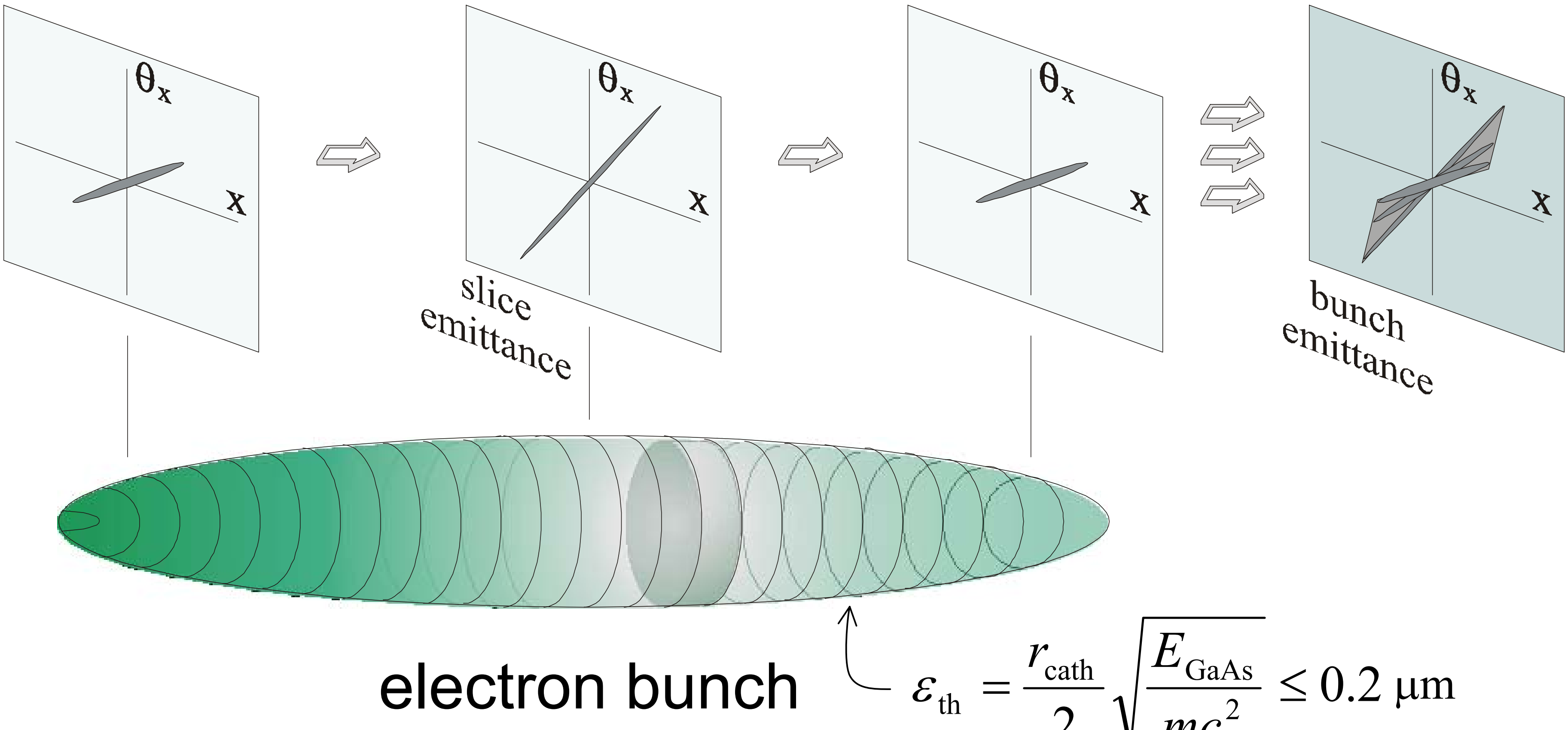
Emittance growth in the Injector



$$\varepsilon_{th} = \frac{r_{cath}}{2}\sqrt{\frac{E_{GaAs}}{mc^2}} \leq 0.2\ \mu\text{m}$$

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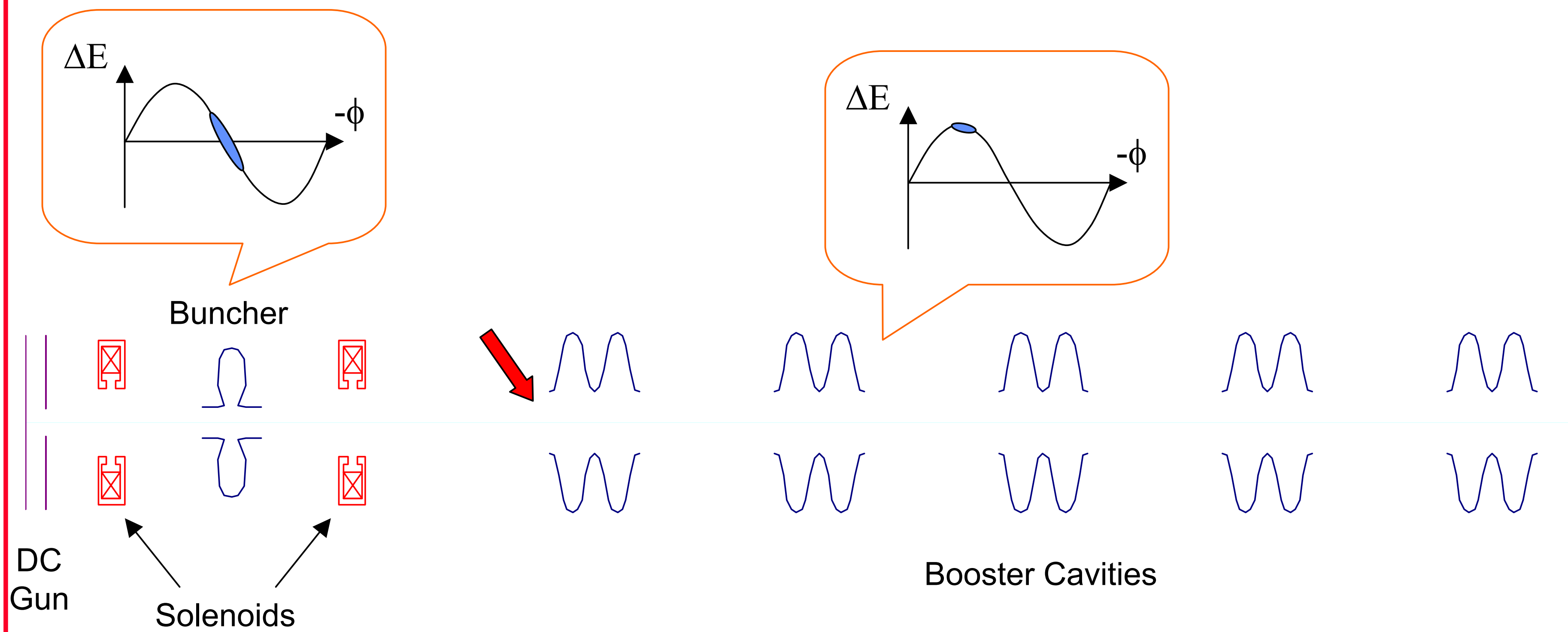
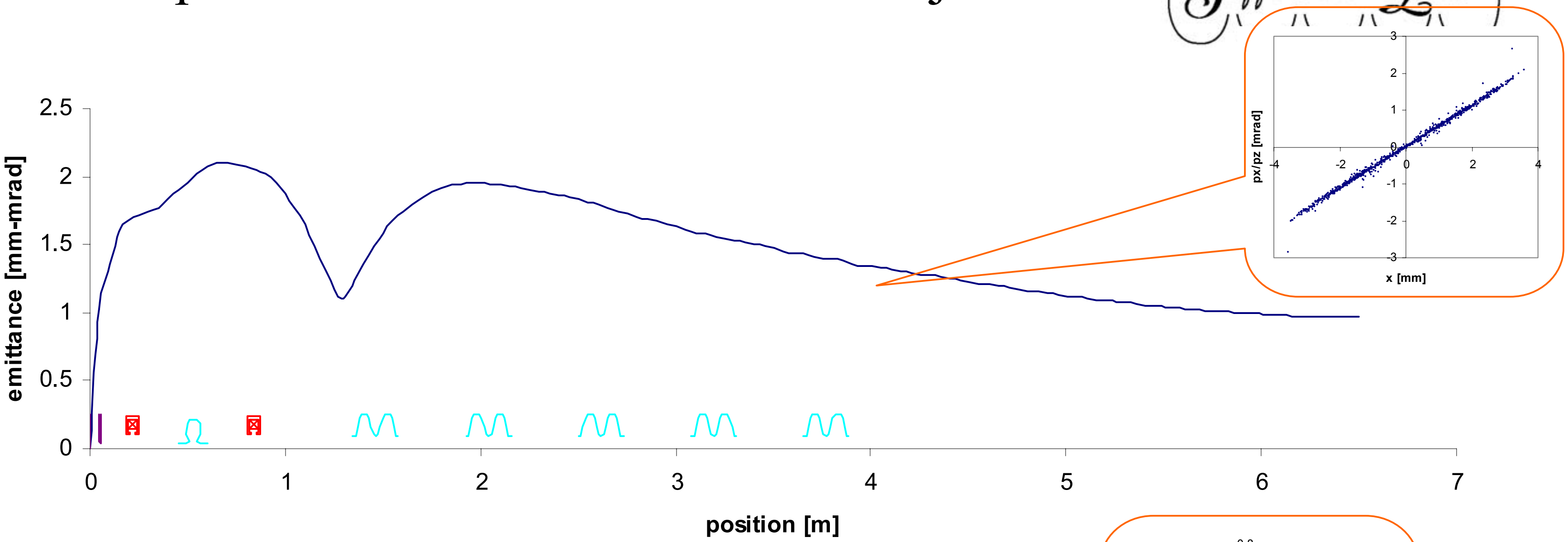
Emittance "Compensation"

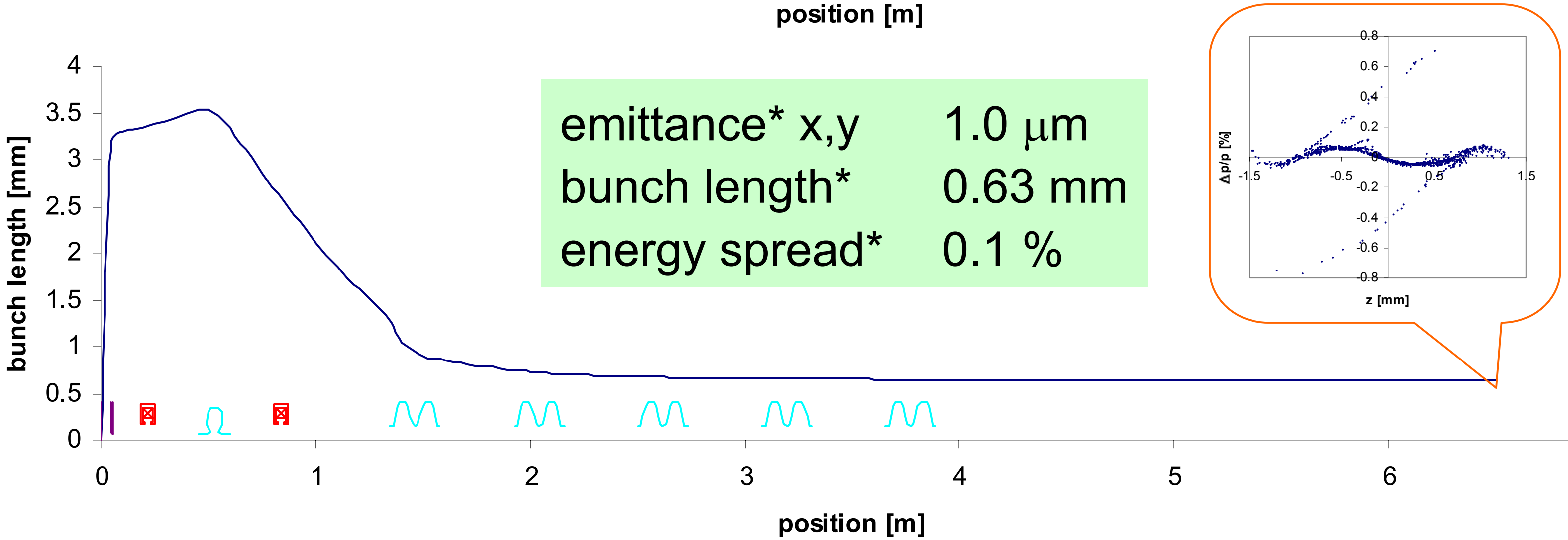


"Invariant Envelope" Flow:

$$\sigma_r = \frac{2}{\gamma'}\sqrt{\frac{I_{\text{peak}}}{3 I_{\text{Alfen}}\gamma}}$$

Example of Simulations for 5.5 MeV Injector





emittance* x,y	1.0 μm
bunch length*	0.63 mm
energy spread*	0.1 %

*rms value

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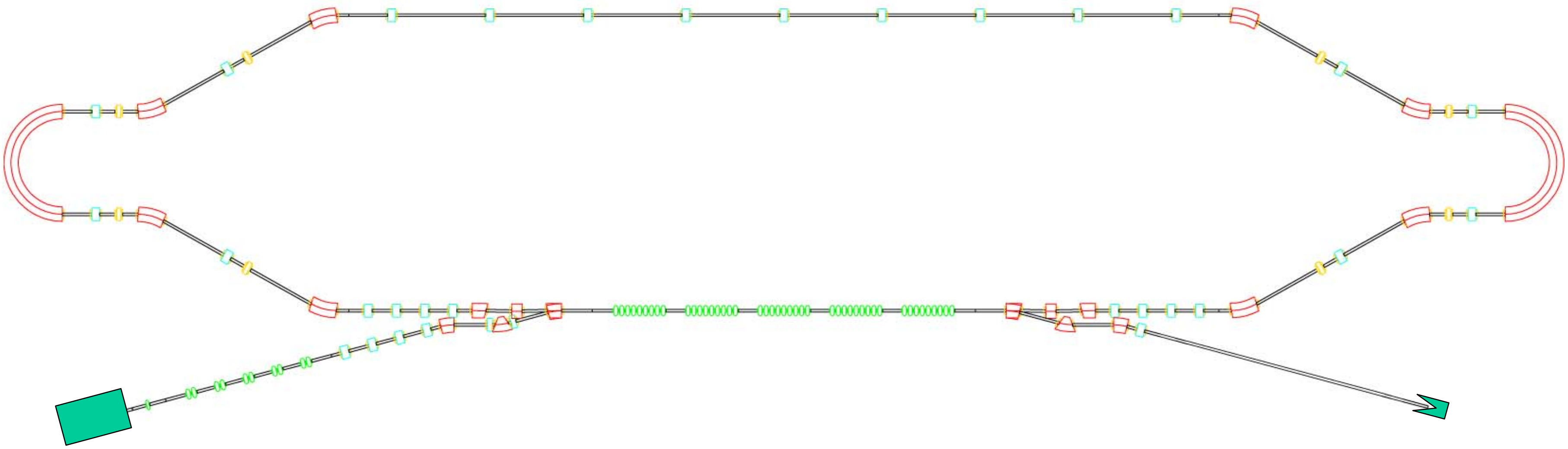
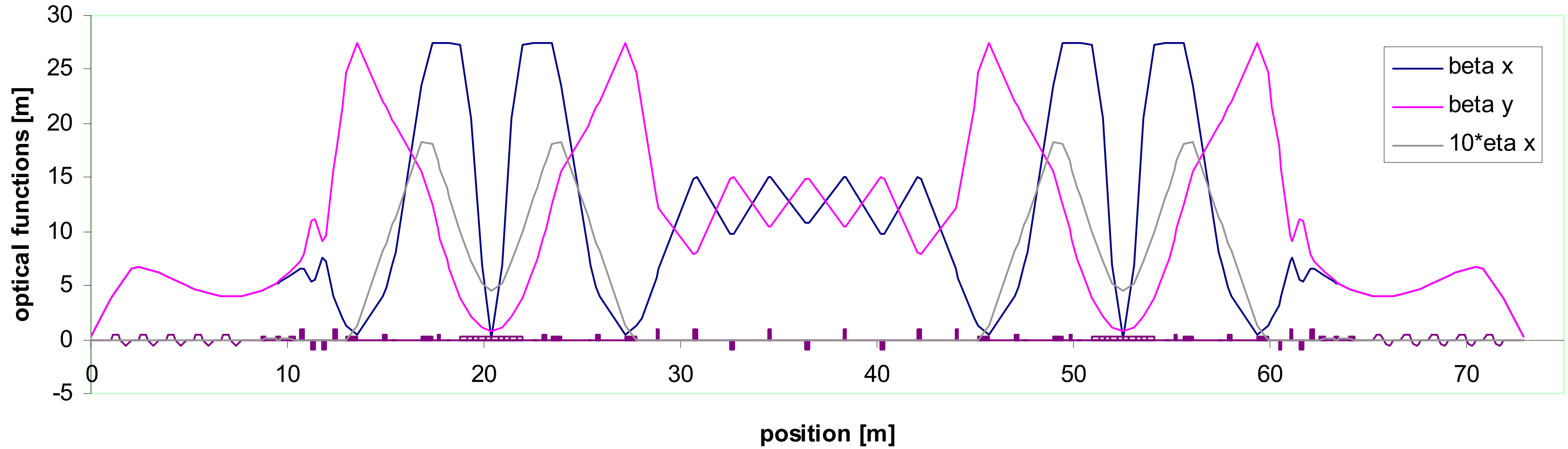
Optics requirements for prototype

- Low Chromatic and Geometric Aberrations
- Adjustable Momentum Compaction (R_{56})
- Second-Order Momentum Compaction (T_{566})
- Betatron Phase Advance Flexibility to study BBU and CSR Emittance Compensation

Prototype Optics





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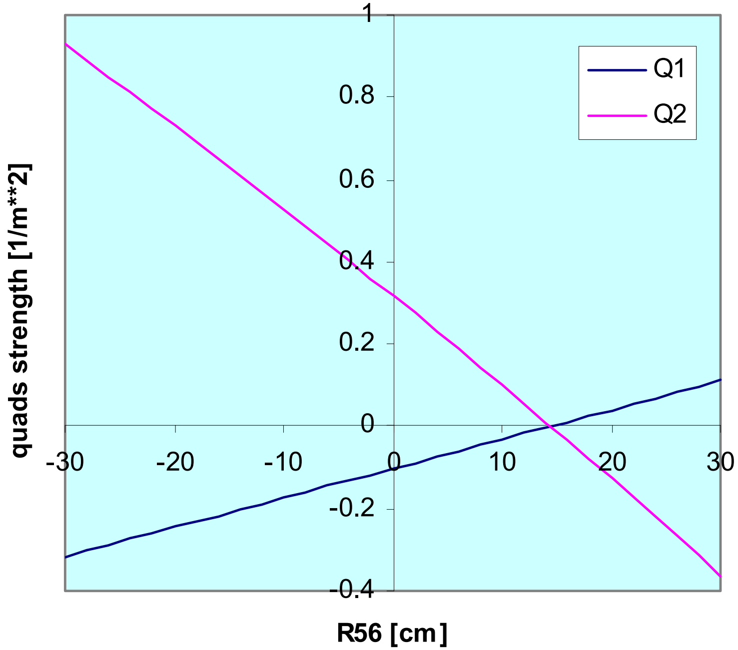
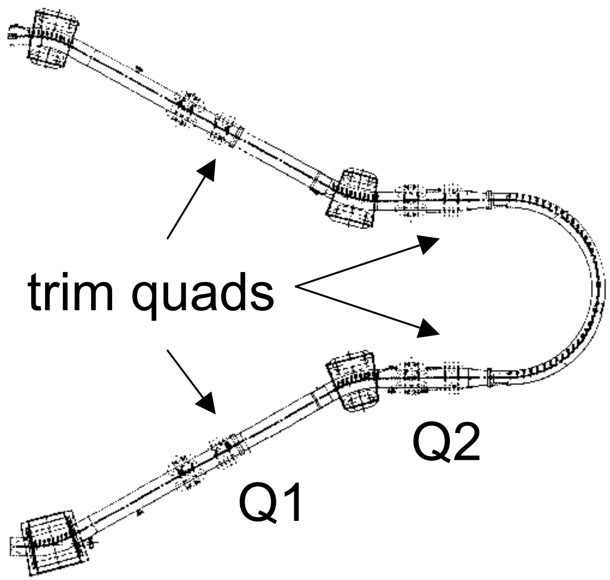
Adjustable R_{56}



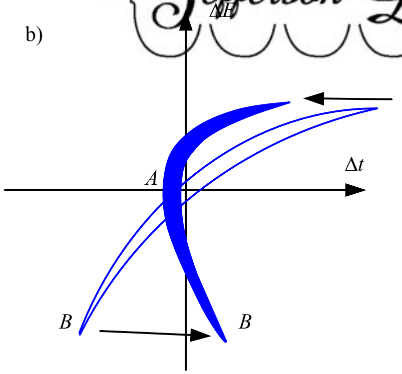


$$R_{56} = \int_1^2 \frac{\eta_x}{\rho} ds$$

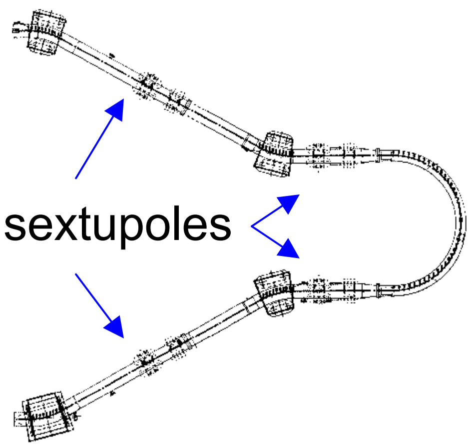
Sextupole "Linearizer"

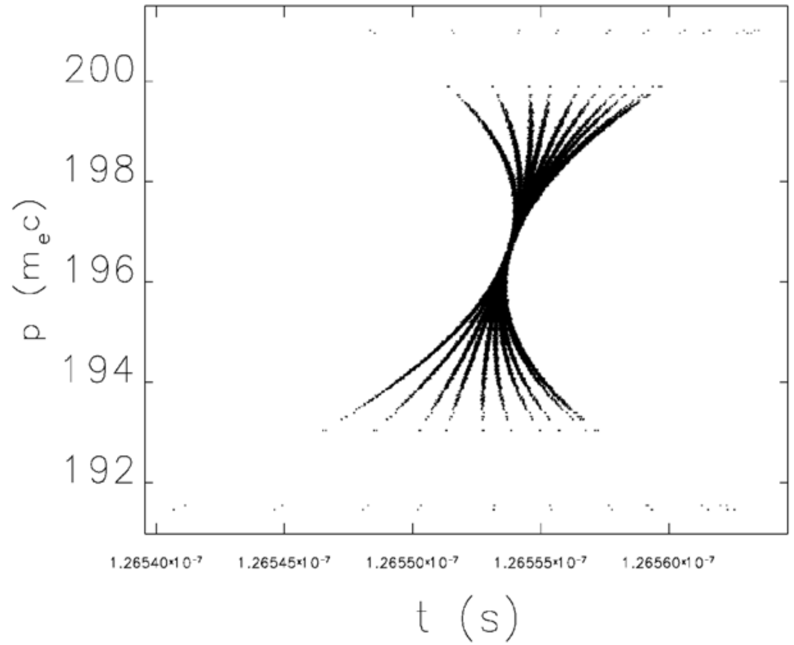
RF waveform
CSR
wakes
higher order optics effects

longitudinal phase space curvature



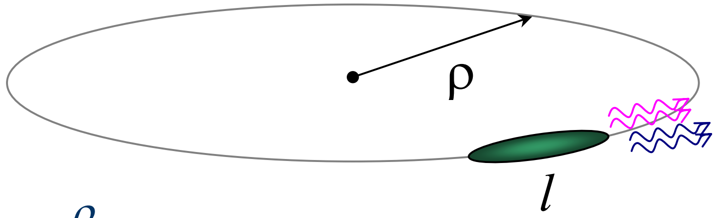
"Curvature" can be fixed with Sextupoles





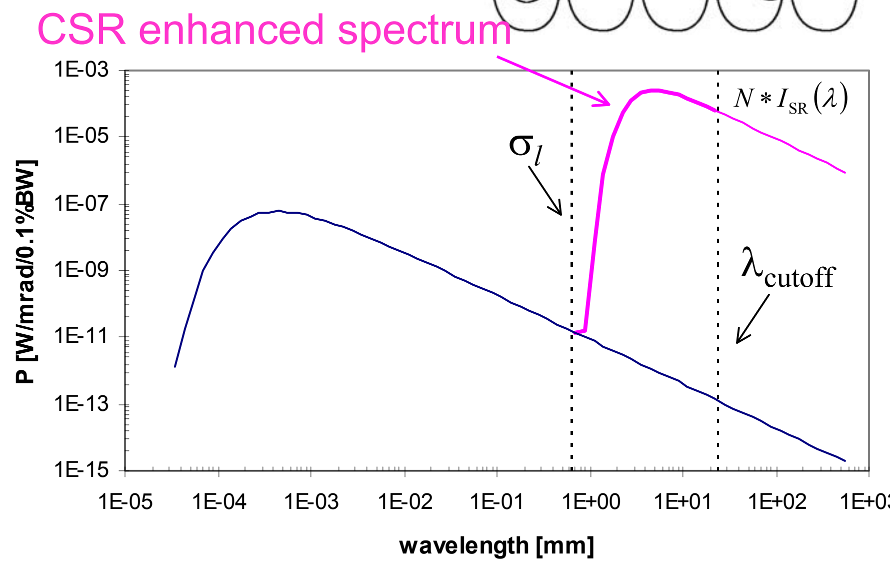
changing sextupoles strength in the Arc…

Coherent Synchrotron Radiation

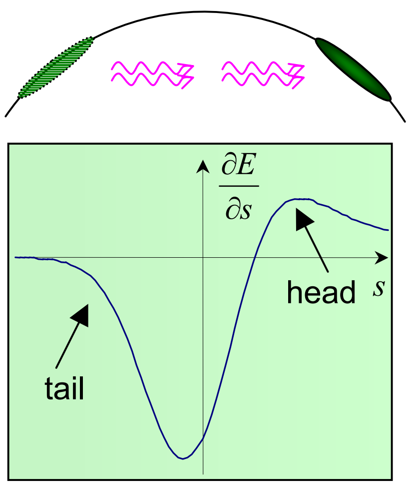


$$\lambda_{SR} \propto \frac{\rho}{\gamma^3} \qquad \lambda_{CSR} \ge l$$

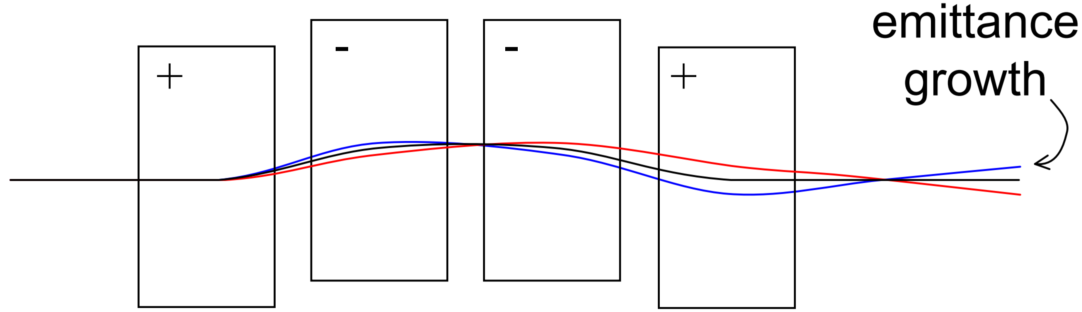
$$P_{SR} \propto N\frac{\gamma^4}{\rho^2} \qquad P_{CSR} \propto N^2 \frac{1}{\rho^{2/3} l^{4/3}}$$



Longitudinal Effect



Transverse Effect



Dispersion ≠ 0

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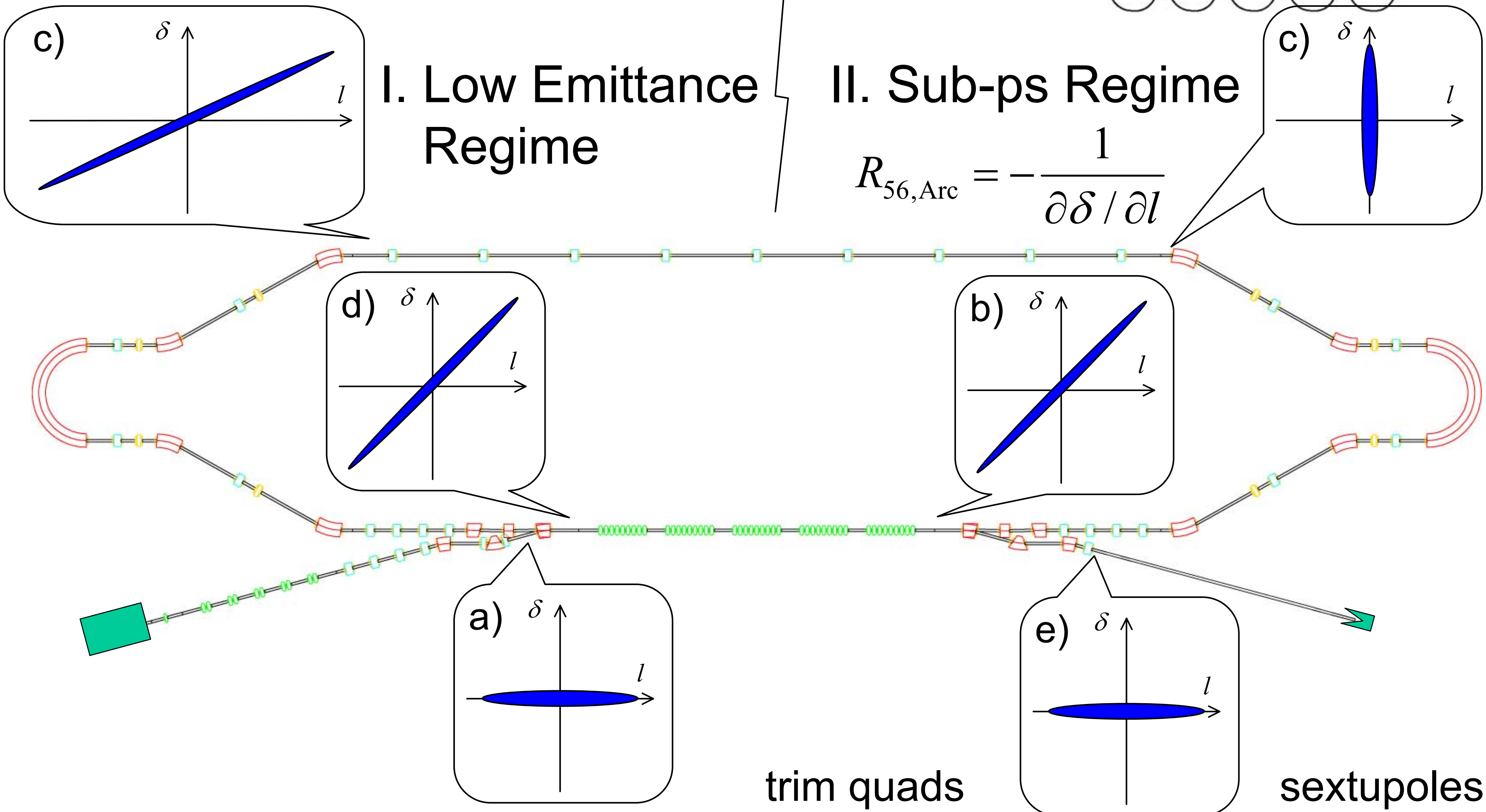
Longitudinal phase space manipulations

I. Low Emittance Regime

II. Sub-ps Regime

$$R_{56,\mathrm{Arc}} = -\frac{1}{\partial\delta/\partial l}$$



Rule of Thumb: Match $\left.\frac{\partial\delta}{\partial l}\right|_{d)} \rightarrow \left.\frac{\partial\delta}{\partial l}\right|_{b)} (R_{56})$, $\left.\frac{\partial^2\delta}{\partial l^2}\right|_{d)} \rightarrow \left.\frac{\partial^2\delta}{\partial l^2}\right|_{b)} (T_{566})$

Monopole Higher-Order-Mode Single Bunch Power Excitation per 9-Cell Cavity

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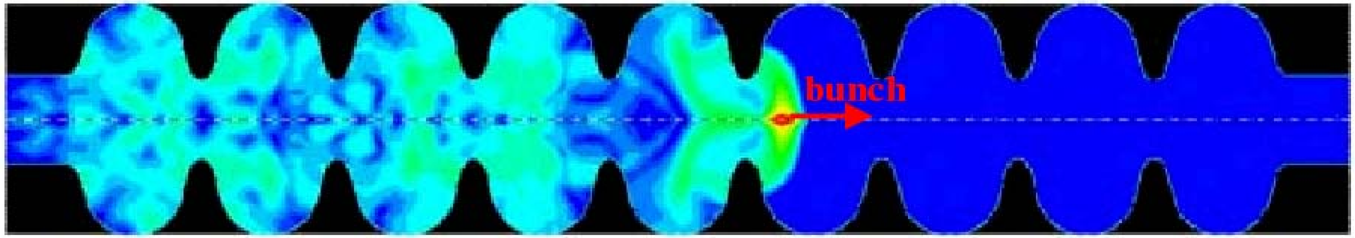
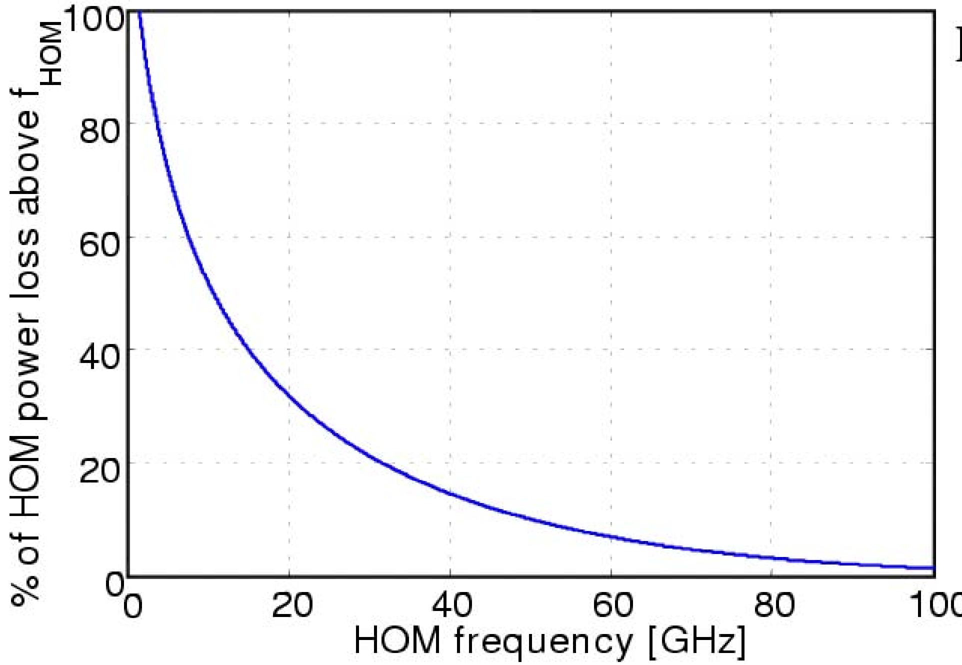


σ_{bunch} = 0.6 mm $\quad$ q_{bunch} = 77 pC



P_{total}	= 160 W
P(f<3.5 GHz)	= 30 W
P(f>3.5 GHz)	= 130 W
P(f>5 GHz)	= 115 W
P(f>10 GHz)	= 83 W
P(f>20 GHz)	= 51 W
P(f>40 GHz)	= 23 W
P(f>80 GHz)	= 5 W

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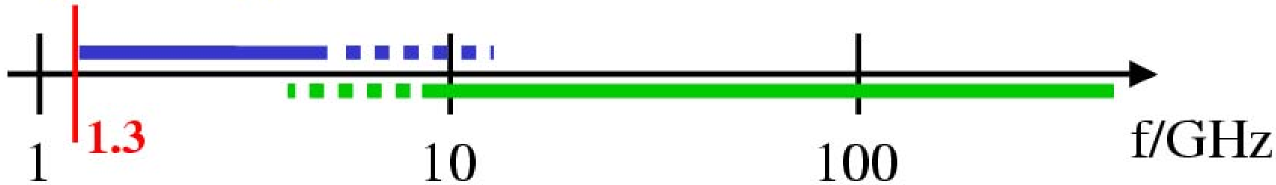
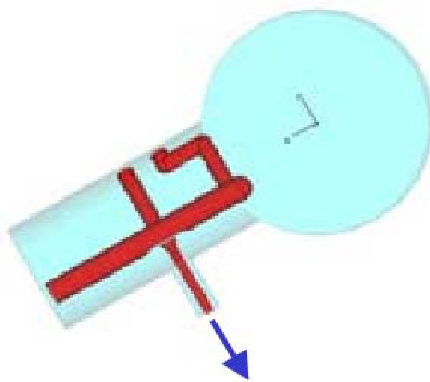
Trapped and Propagating Modes: Power Extraction

trapped and quasi trapped modes

propagating modes

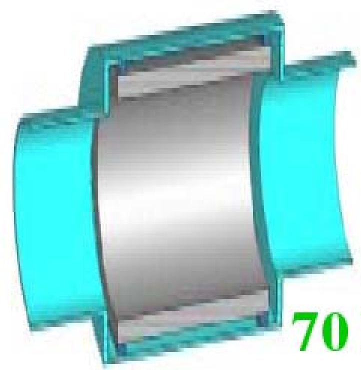


4*HOM couplers



to room temperature load

HOM beam-pipe absorber



absorber between cavities at temperature level with good cryogenic-efficiency

~ 30 W per cavity

~ 130 W per cavity

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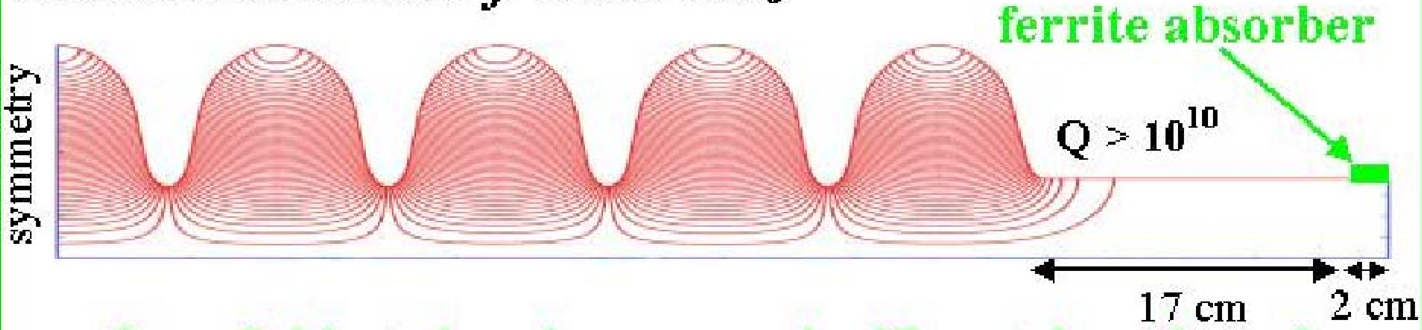
TESLA 9-Cell Cavity with HOM-Absorber

Fundamental mode: f=1.300 GHz

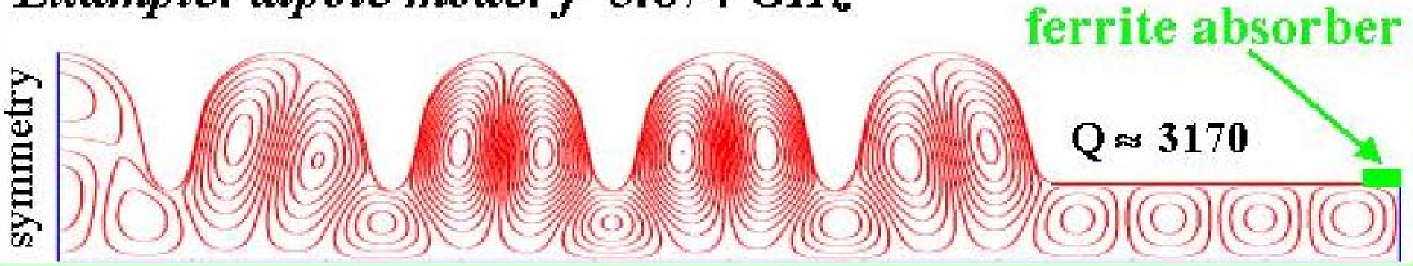


•Low field at absorber ⇒ no significant damping of fundamental mode,

but:

• Propagating modes have higher fields at the absorber ⇒ damping and power extraction!

Example: dipole mode: f=3.874 GHz



Conclusion: HOM Damping for the ERL

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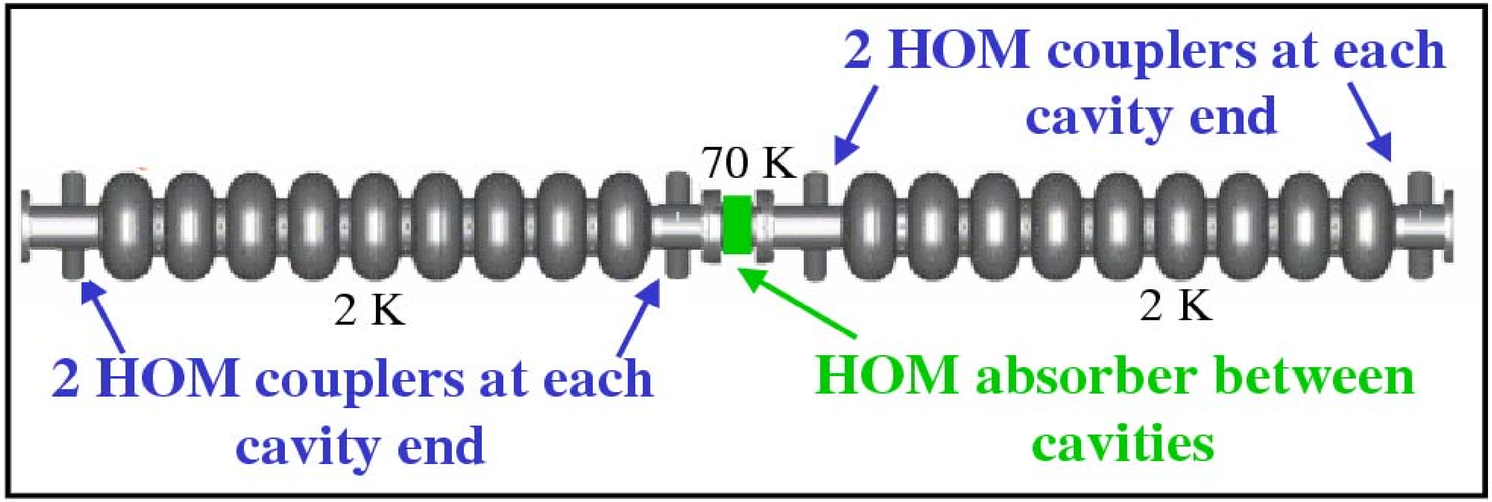
- **HOM damping scheme for the ERL:**



- **This damping scheme fulfills the requirements on:**
  - **HOM power extraction**
  - **Monopole HOM damping**
  - **Transverse HOM damping**

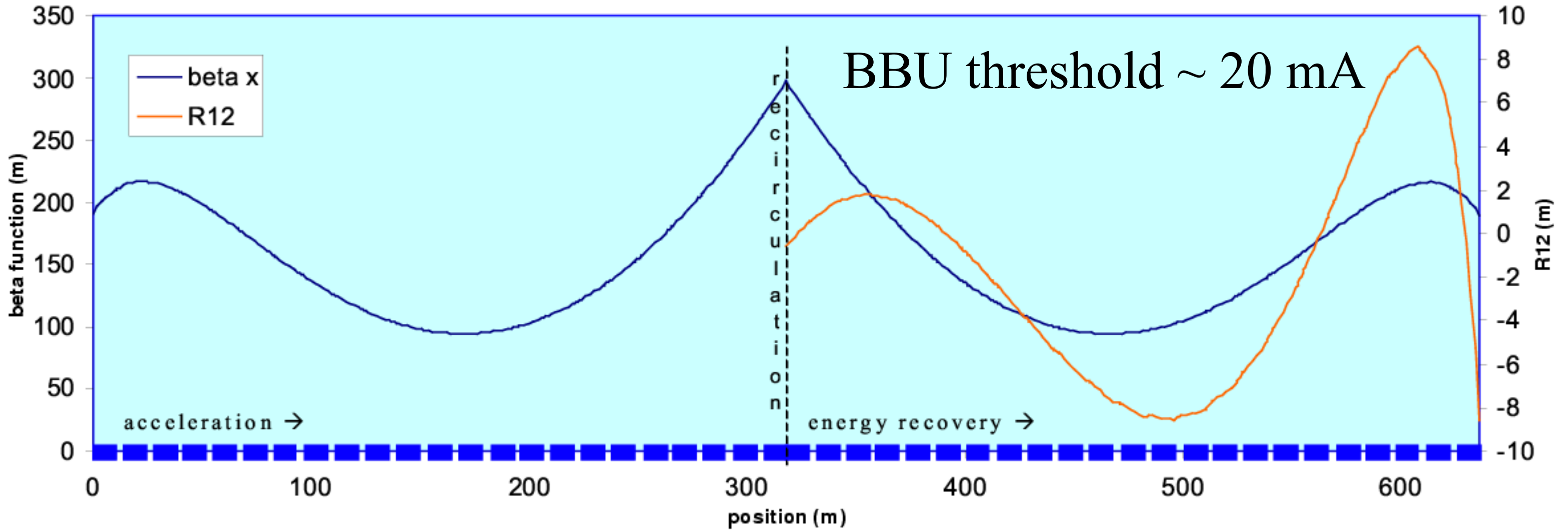
Transverse Beam-Break Up

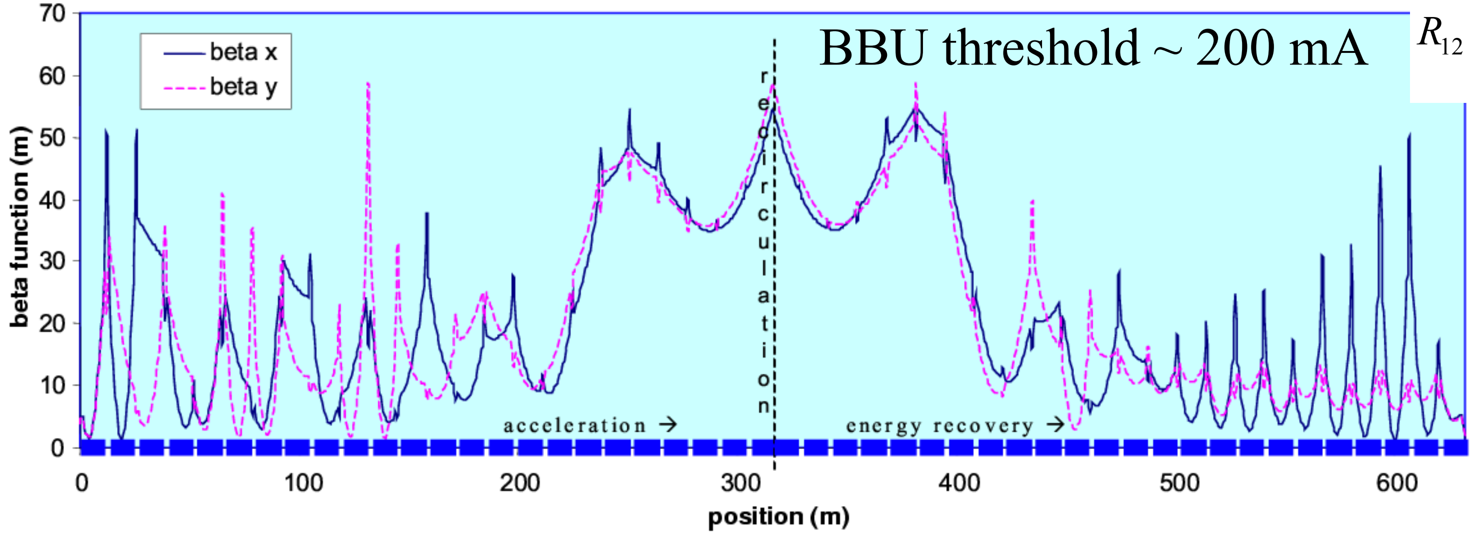
BBU threshold for a single loop, single HOM:

$$I_{\text{th}} = -\frac{2E_r}{eR_{12}(R/Q)_m Q_m k_m \sin(\omega_m t_r)}$$

1. Favors higher injection energy
2. Periodic matrix element $R_{12} = \beta \sin \mu$, i.e. recirculating phase advance ought to be $n\pi$.
3. Adequate HOM damping required (frequency spread of the same HOMs is analogous to better damping)
4. Some optimal recirculating path length exists

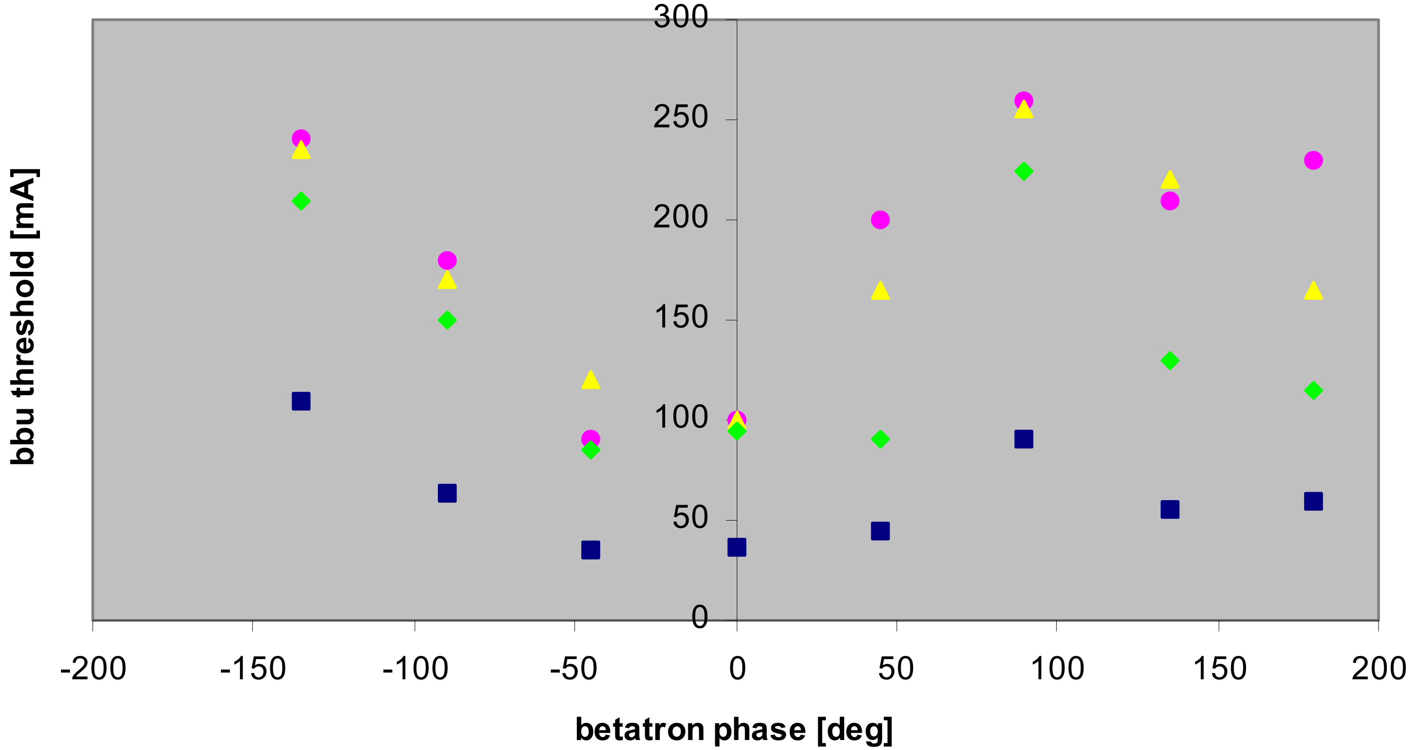
Linac Optics for BBU suppression





$$R_{12} = \gamma_i \sqrt{\frac{\beta_i \beta_f}{\gamma_i \gamma_f}} \sin \Delta\psi$$

Prototype will help benchmark the code



BBU threshold vs. betatron phase advance of the arc. Squares – no frequency randomization; circles, diamonds, triangles – HOM frequencies are random in the range [f_{HOM} , f_{HOM} + 1] MHz.

Other BBU related issues

1. Instability buildup time is relatively slow, i.e. suppression with active feedback appears to be possible

2. Such active feedback approach will be tested with the prototype

3. If systems with much higher instability threshold are developed, multi-turn ERL becomes attractive as a more economical option

List of experiments with ERL prototype

- Low emittance mode in back leg checked
- Highly compressed bunches in back leg checked
- Measured injector beam properties, checked performance of emittance compensation and checked merger CSR
- BBU stability studies completed
- CSR parameter studies utilizing bends
- Beam Loss studies completed
- HOM cooling studies completed
- Surface roughness and resistive wakes measured in experiments on the back leg
- Completed cavity HOM measurements with beam

Home Problems

1) Chicanes can be used in ERLs to achieve two different goals: bunch compression and path length adjustment. Let ρ be radius of trajectory in the dipoles, L dipole length, α bending angle in dipoles, λ spacing between the first and the second, the third and the fourth dipoles, d distance between the second and the third magnets. Chicane is an achromat due to its symmetry. Find expressions for **a**) dispersion function in the middle of chicane and **b**) momentum compaction ($R_{56} = \partial l/\partial\delta$, here l and δ are the path length difference between a trajectory and the reference particle trajectory and the relative momentum difference respectively. **c**) Design a chicane for path length adjustment corresponding to +/– 10º RF phase (frequency 1.3 GHz) at 5 GeV beam energy. What is the corresponding range of magnetic field and R_{56} for such chicane.

2) Longitudinal phase space (δ, l) can often be represented as $\delta(l) = \delta_0 + \left.\frac{\partial\delta}{\partial l}\right|_{l=0} l + \frac{1}{2!}\left.\frac{\partial^2\delta}{\partial l^2}\right|_{l=0} l^2$ where δ_0 is uncorrelated energy spread, the first partial derivative represents δ- l linear correlation coefficient, while the second derivative represents quadratic correlation or "curvature". Retaining only these two most significant terms, calculate energy spread and longitudinal emittance after 100 MeV linac for on-crest, 10º and 20º RF phase, assuming that initially bunch had no δ - l correlation, 10 MeV beam energy, 20 keV uncorrelated energy spread, and the bunch length of 1º RF (both rms values). What is the shortest bunch length achievable after compression for 10º and 20º RF phase? What is the corresponding R_{56} required in each case?

Home Problems

3) RF guns have demonstrated good performance over the years for low duty factor operation. ERL needs a high current CW source. For normal conducting (copper) RF structures CW operation poses a challenge of removing excessive heat due to wall losses. Estimate the highest accelerating gradient for a half-cell RF gun at 1.3 GHz assuming heat removal capacity of 0.5 kW/cm^2 and heat removal area of 400 cm^2. A typical value of geometric shunt impedance $R/Q = 200\ \Omega$ / cell, and copper structure at that frequency has intrinsic $Q_0 = 2 \times 10^4$. If one uses superconducting half-cell instead (e.g. $Q_0 \sim 10^9$), what would be the required refrigeration power to run at the gradient of 20 MV/m? (Tip: to remove 1 W of wall losses in cryogenic environment @ 4 °K requires ~ 400 W of refrigeration power).

4) Design a beam dump for ERL (hint: follow the Cornell ERL prototype sketch). Use the parameters of the ERL prototype. Distance from quadrupole to collector is 8 m. Assume collecting angle is tilted 6°. What is quadrupole field strength and the beam spot size near the collector? What is the required water flow to cool the collector (use water temperature difference of 20 °C)?

5) Consider ERL prototype with injection kinetic energy of 5 MeV. At this energy the bunch moves with the speed $\beta = 0.9957$. SRF structure in the linac is optimized for $\beta = 1$. **a**) Calculate phase mismatch in 100 MeV linac for injected and energy recovered beams assuming 5 m long linac. **b**) If linac consists of 5 cavities (1 m each) with independent phasing, what is the phase mismatch in the first / last cavities?

Further Reading on Cornell ERL

Two web-sites are available

1) Information about Cornell ERL, X-ray science applications, other related projects worldwide
   http://erl.chess.cornell.edu/

2) ERL technical memorandum series
   http://www.lepp.cornell.edu/public/ERL/

USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

G. A. Krafft and I.V. Bazarov
Jefferson Lab and Cornell University

ERL Examples

CHESS / LEPP

ERL examples

Other Proposals and Pre-proposals (not in any particular order)

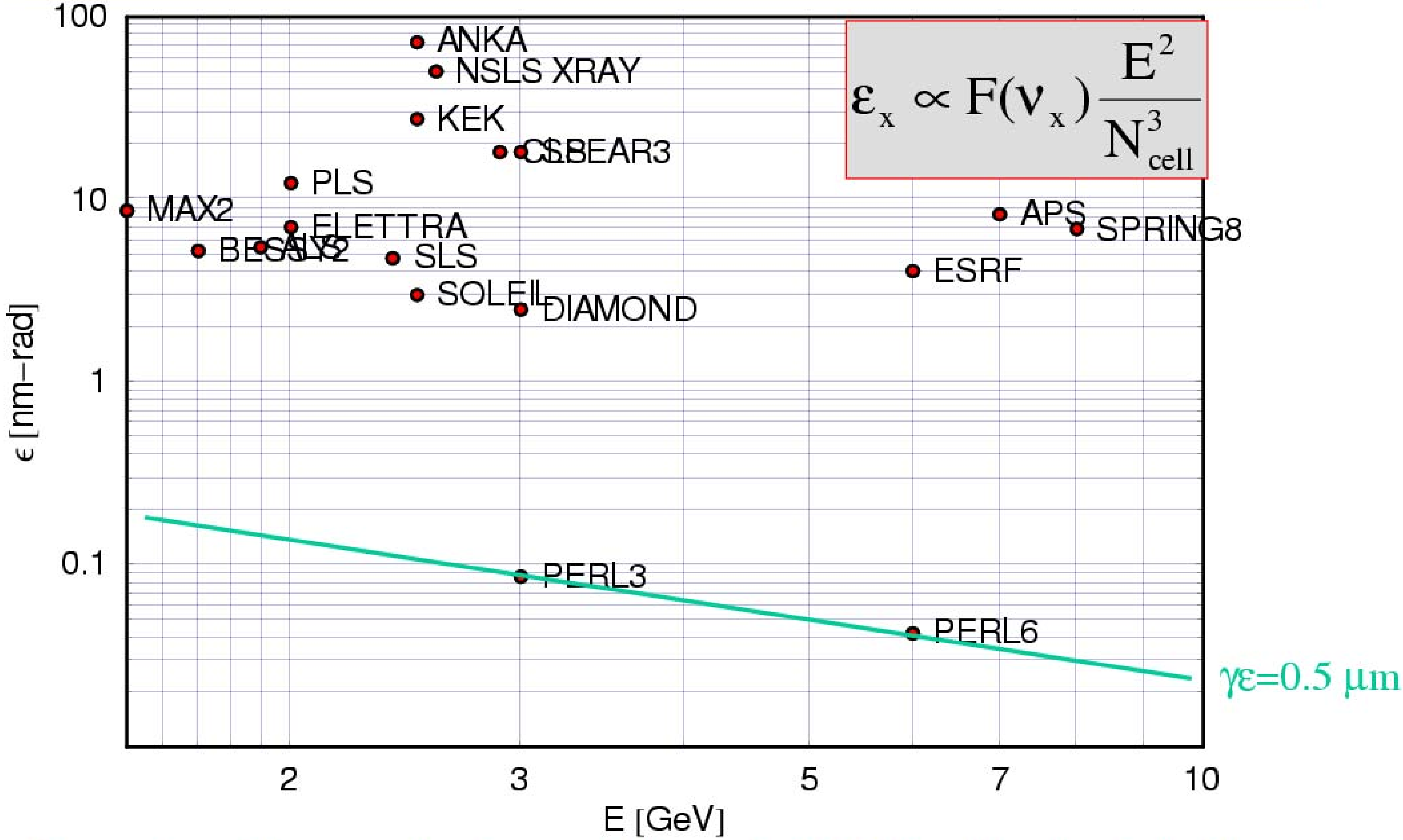
- BNL Project
- Daresbury Laboratory, 4GLS Light Source (IR, VUV, XUV)
- BINP MARS
- University of Erlangen, Synchrotron-ERL
- JAERI ERL IR-FEL

Potential Performance of a PERL Light Source at the NSLS

- Energy ~ 3-7 GeV
- Average current ~ 200 ma
- Sub-picosecond pulses ~100 fs
- Brightness ~ 10^{21-22} ph/sec/mm^2/mrad^2/0.1% BW
- Diffraction limited source:
  - λ~10 Å in BOTH planes, $\varepsilon_x\varepsilon_y$~ (1Å)^2 at 3-GeV.
  - λ~ 5Å in BOTH planes, $\varepsilon_x\varepsilon_y$~ (0.5Å)^2 at 6-GeV.
- Round beams and variable $\varepsilon_x/\varepsilon_y$ emittance ratio, (at a constant product $\varepsilon_x\varepsilon_y$)
- Virtual 'top-off' yielding a constant heat load on chambers, optics - high long-term stability
- Electro-optical control of the pulse-format

Presented by J. Murphy at SRI 2001 ERL workshop

Hor. Emittance of Rings vs. PERL



$$\varepsilon_x \propto F(\nu_x)\frac{E^2}{N_{cell}^3}$$

A reduction of ε by at least 10^2 is desirable!

Presented by J. Murphy at SRI 2001 ERL workshop

Average Brightness

$$B \propto \frac{I\,L_u}{\varepsilon_x \varepsilon_y}$$

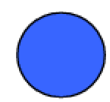
PERL: $\varepsilon_x \varepsilon_y = \varepsilon_0^2$

Ring: $\varepsilon_x \varepsilon_y = \frac{r\varepsilon_0}{(1+\chi)} \frac{r\varepsilon_0 \chi}{(1+\chi)}$

Flat Beam: χ << 1, r =10²

$$B_{PERL} \approx B_{RING} \times \begin{cases} 10, & \chi = 10^{-3} \\ 10^2 & \chi = 10^{-2} \end{cases}$$

Round Beam: χ = 1, r =10²



$$B_{PERL} \approx 2500 \times B_{RING}$$

PERL can provide a brightness increase of 10-10³!

Presented by J. Murphy at SRI 2001 ERL workshop

Electron Bunch Length & Peak Current

Machine	E [GeV]	σ_L [ps]	I_{pk}[A]
ALS	1.5	14	
SLS	2.4	13	
SOLEIL	2.5	12	
NSLS XRAY	2.8	158	90
DIAMOND	3	10	
ESRF	6	21-61	295
APS	7	17-54	
PERL	3-7	0.1-0.4	600

A reduction of σ_L by at least 10^2 is desirable!

Presented by J. Murphy at SRI 2001 ERL workshop

S. Pjerov & X.J. Wang

L-Band Gun + 25 MeV Pre-Accelerator

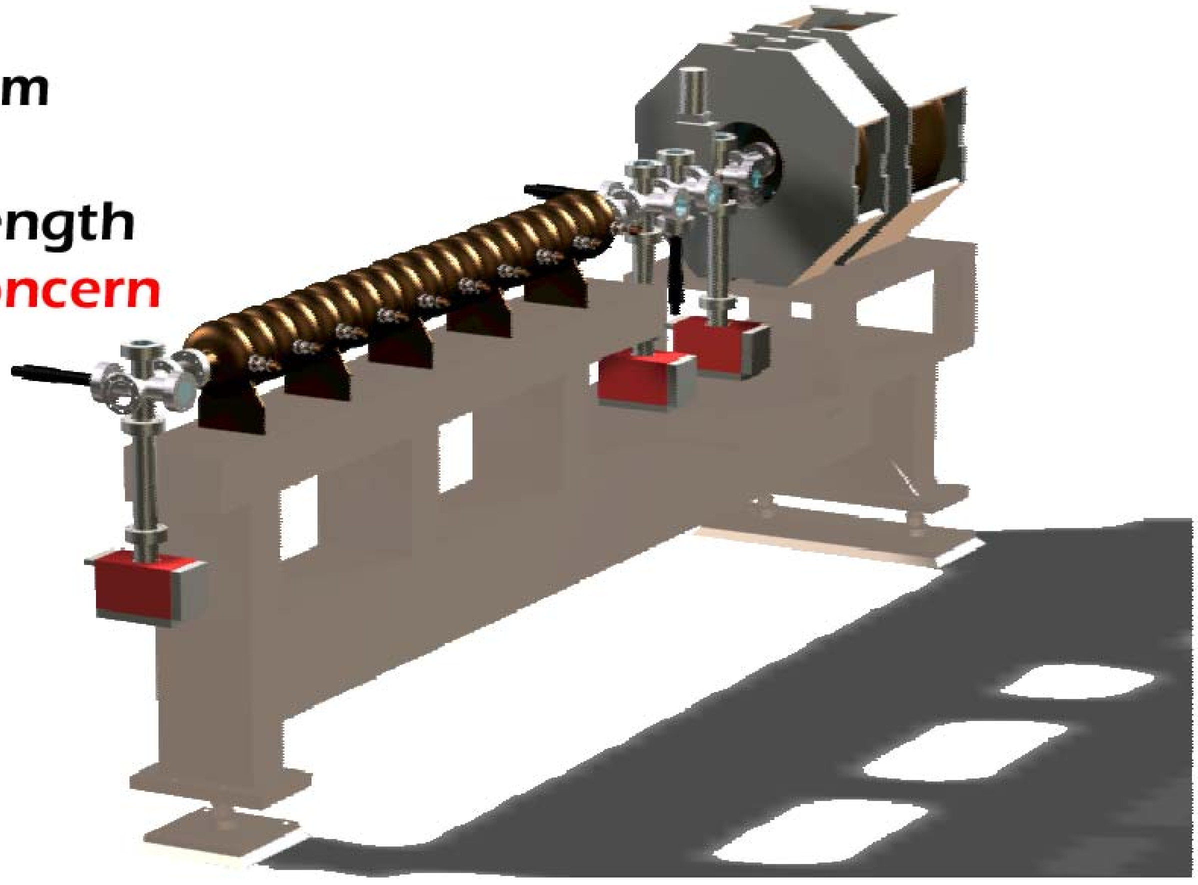
<u>E = 2 MeV</u>

$\gamma\varepsilon$ ~ 0.5-1 μm

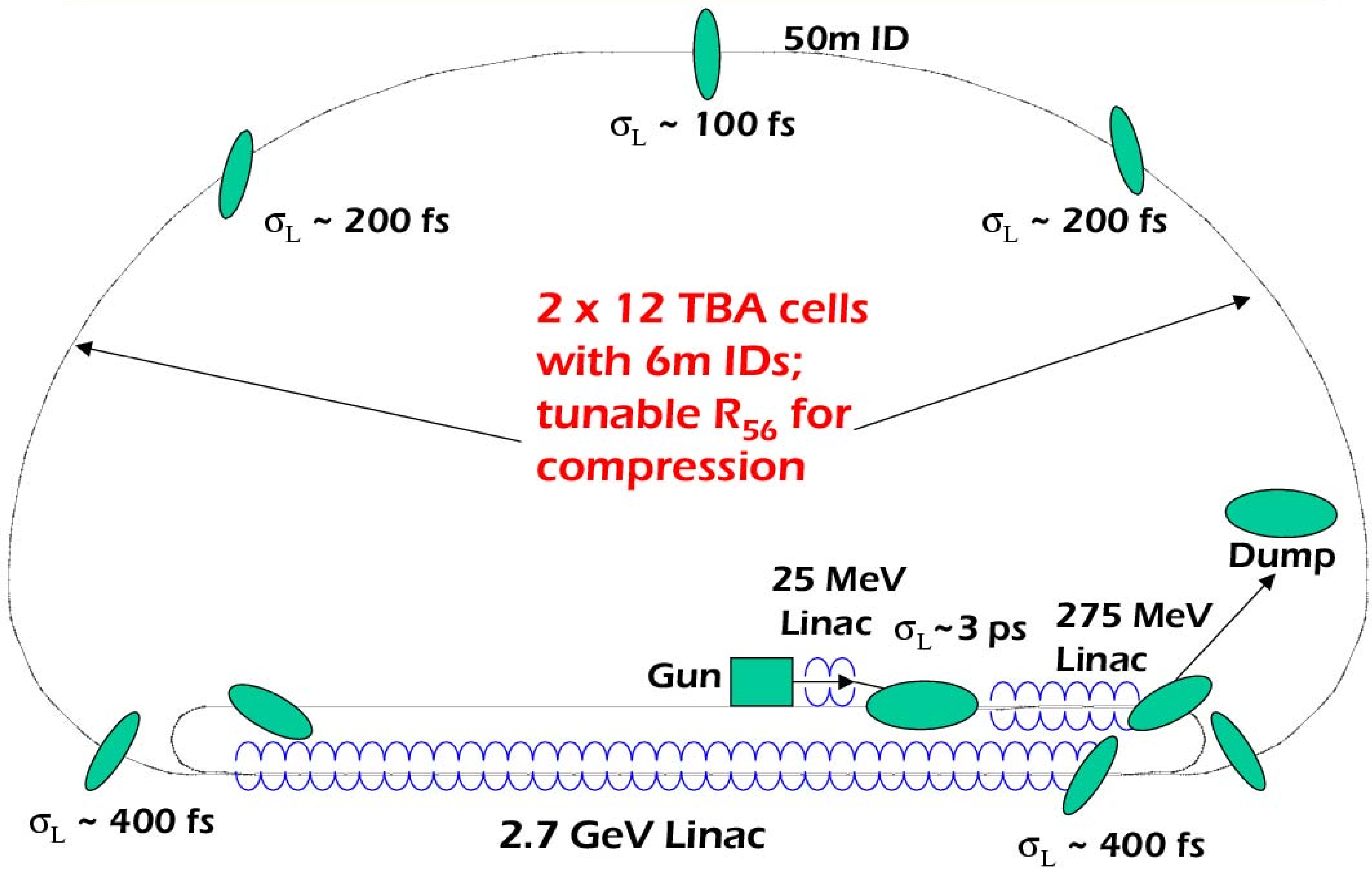
K_2CsSb

3 ps RMS length

heat is a concern



Strawman Layout for a 3 GeV PERL

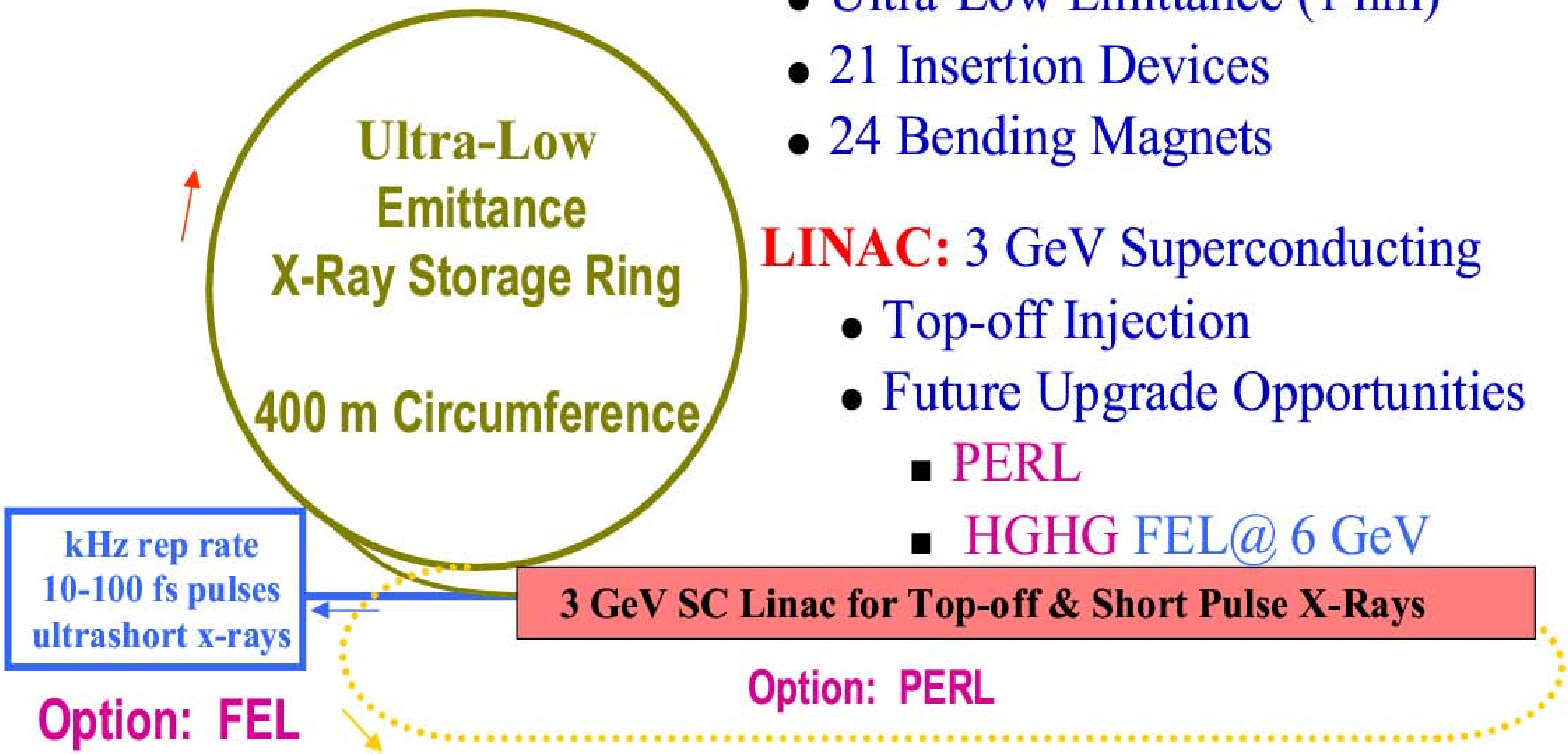


Presented by J. Murphy at SRI 2001 ERL workshop

NSLS Upgrade: Ultra-bright X-ray Source

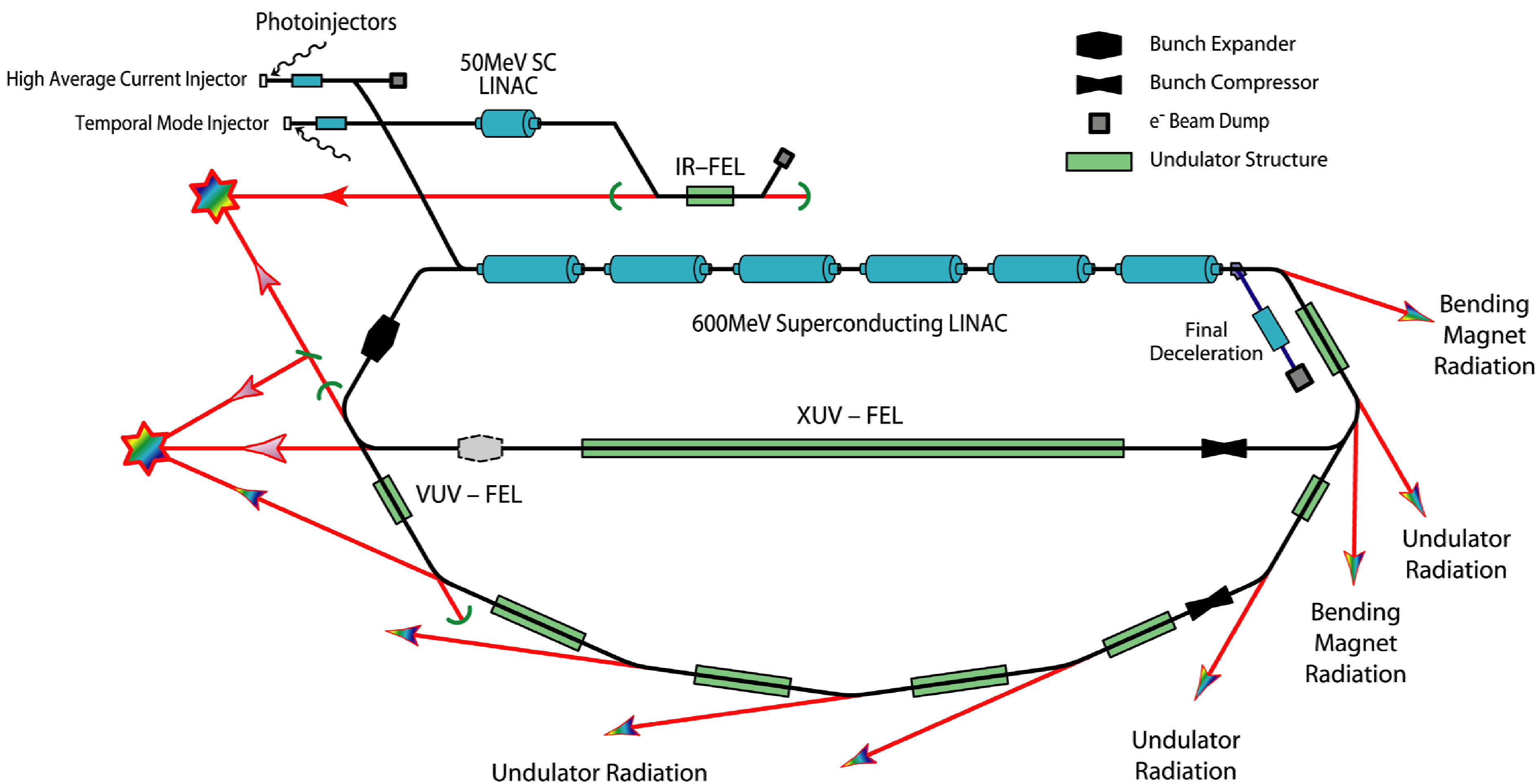
Ring: 24 Cell, Triple Bend Achromat
- Ultra-Low Emittance (1 nm)
- 21 Insertion Devices
- 24 Bending Magnets

LINAC: 3 GeV Superconducting
- Top-off Injection
- Future Upgrade Opportunities
  - PERL
  - HGHG FEL@ 6 GeV



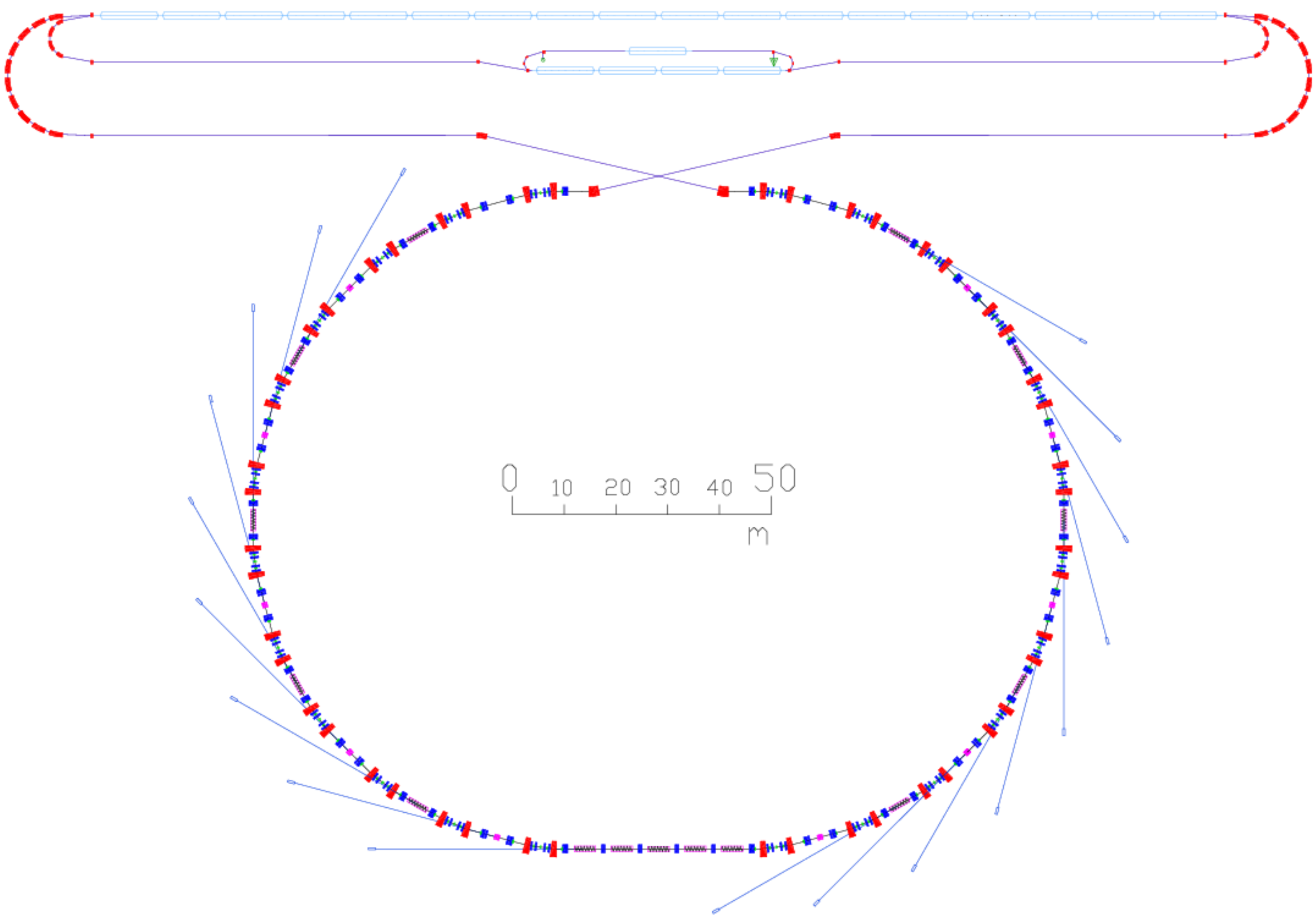
BROOKHAVEN
NATIONAL LABORATORY

Daresbury Project 4GLS FEL (IR, VUV, XUV)



http://www.4gls.ac.uk/

Erlangen Univesity, ERLSYN



Phase I. 3.5 GeV storage ring

Phase II. ERL using same beamlines (shown)

http://www.erlsyn.uni-erlangen.de/

Presented by G. Kulipanov
at SRI 2001 ERL workshop

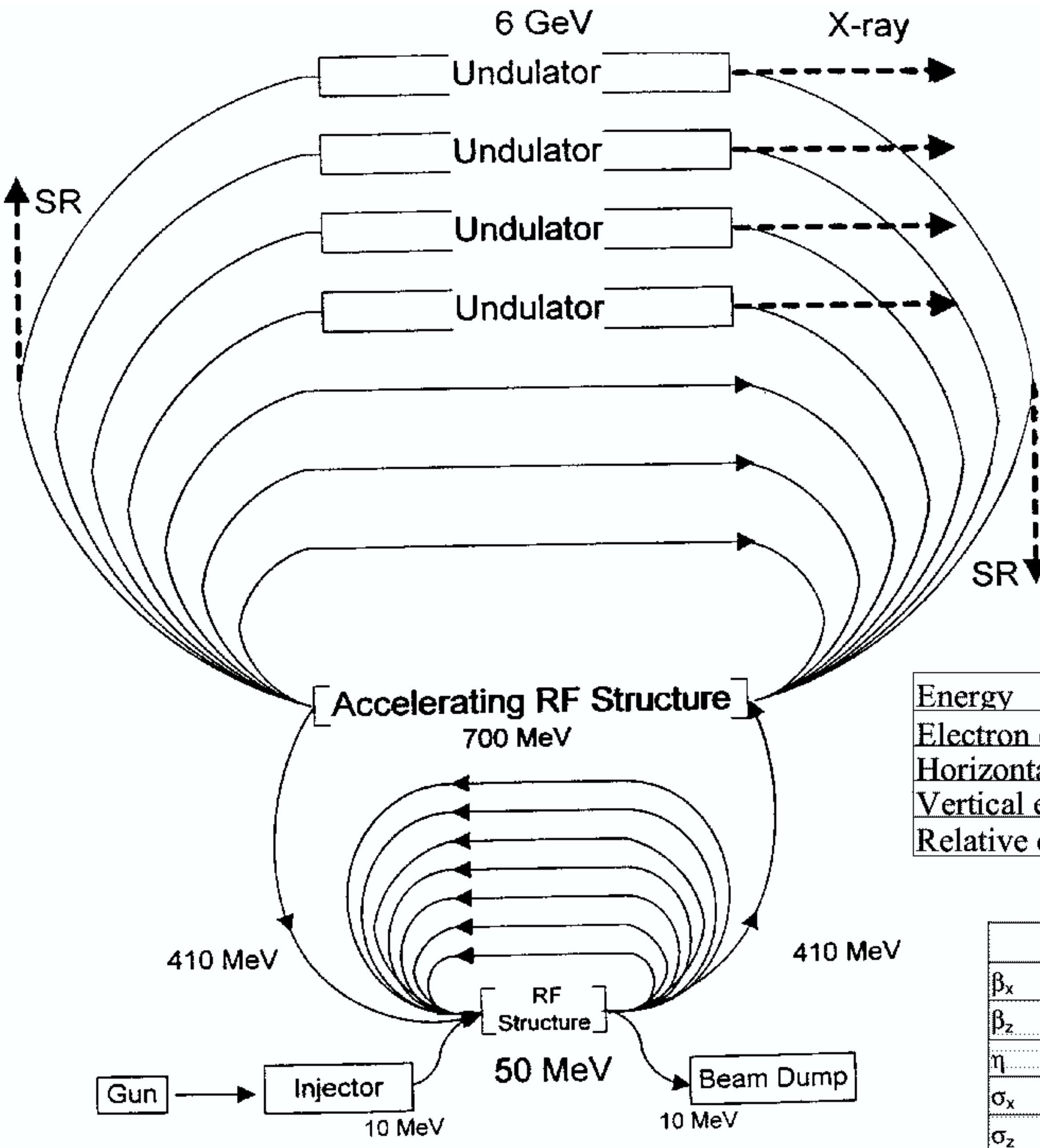


Fig. 1: Scheme of MARS.

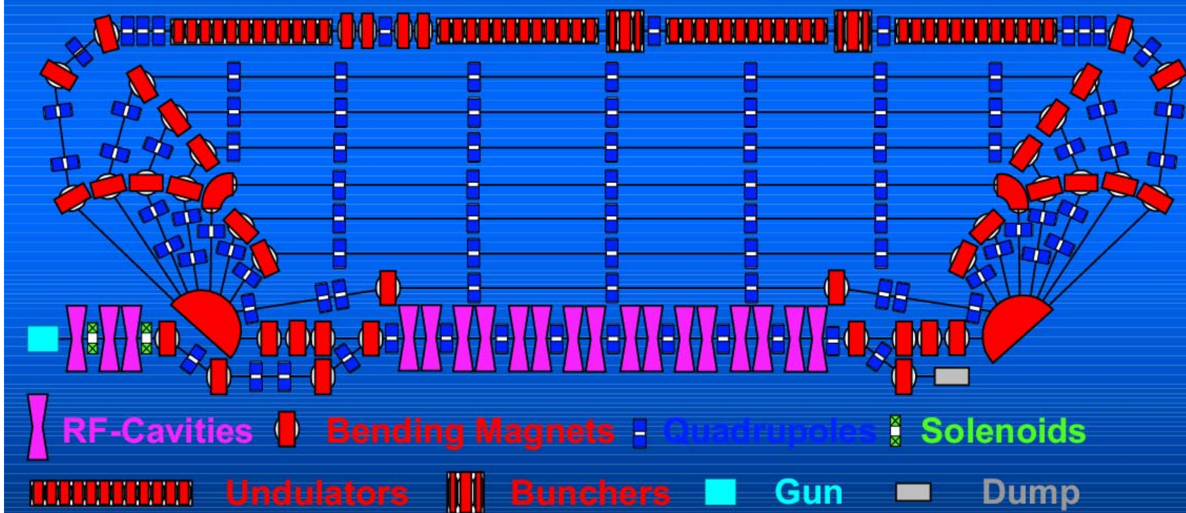
Table 6: Accelerator parameters.

Energy	GeV	6
Electron current	mA	1
Horizontal emittance	nm-rad	5.3×10^{-3}
Vertical emittance	nm-rad	4×10^{-3}
Relative energy spread		2.4×10^{-5}

Table 5: MARS sourse parameters.

		Undulator	Bend. magnet
β_x	m	75	1.5
β_z	m	75	12
η	m	0	0.05
σ_x	μm	18	2.8
σ_z	μm	11	6.9
σ'_x	μrad	0.9	1.9
σ'_z	μrad	0.8	0.6

Schematic Drawing of the FEL Driven by an Accelerator-Recuperator



IR-FEL being built at BINP, Novosibirsk

IR-FEL: Basic Parameters

♦ Wavelength of emitted radiation, μm	2...10
♦ Pulse duration, ps	10...100
♦ Pulse energy, J	up to $5{\cdot}10^{-3}$
♦ Repetition rate, MHz	2.25...22.5
♦ Average power, kW	up to 100
♦ Relative bandwidth of emission spectrum	$3{\cdot}10^{-5}...10^{-3}$

RF Accelerator-Recuperator: Basic Parameters

Machine itself:

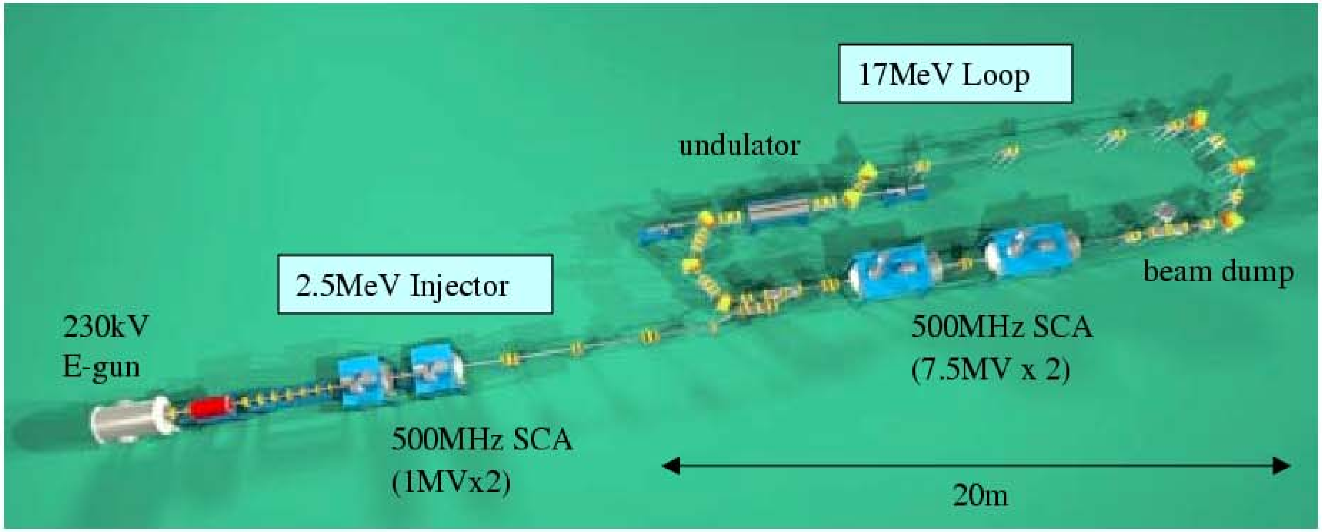
♦ RF accelerating frequency, MHz	181
♦ Number of RF-cavities	16
♦ Amplitude of accelerating voltage per cavity, MV	up to 0.8
♦ Total RF-power, MW	up to 1.2
♦ Injection and extraction energy (full), MeV	2

RF Accelerator-Recuperator: Basic Parameters

Accelerated beam:

♦ Bunch repetition rate, MHz	up to 22.5
♦ Average electron current, mA	up to 50
♦ Electron energy, MeV	up to 100
♦ Electron energy spread (relative)	10^{-3}
♦ Bunch duration, ps	10...20
♦ Peak current, A	100...200

JAERI Energy-Recovery Linac for 10kW FEL



- Natural extension of the original configuration.
- 8 times larger e-beam power.
- Fitting to the concrete boundary.

Energy = 17MeV

FEL : λ = ~22μm

Bunch charge =500pC

Bunch length = ~15ps (FWHM)

Bunch rep. = 10.4MHz – 83.3MHz *in a macropulse*

Average current = 5.2mA – 40mA

after injector-upgrade

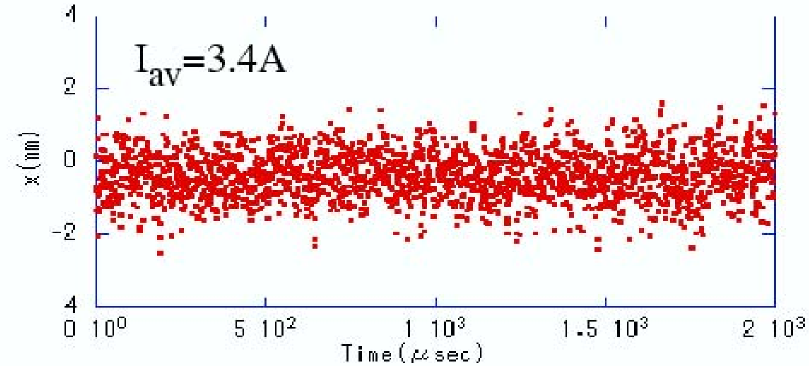
Analysis of HOM instability

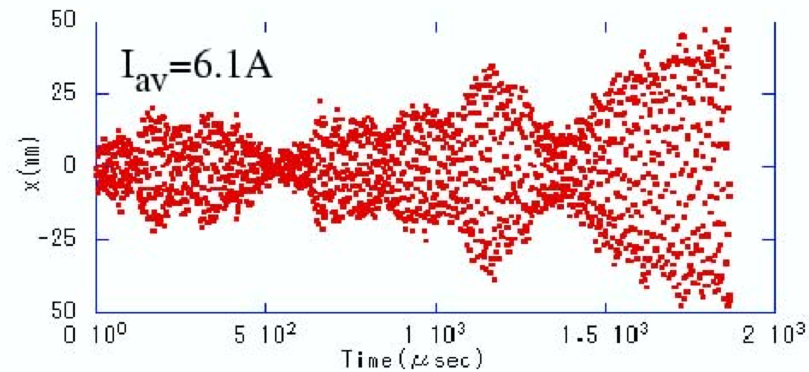
Using measured HOM parameters, designed optics, and a numerical code similar to TDBBU.

↓

I_{AV}=40mA is far below the instability threshold.

HOM instability is not a critical phenomenon for JAERI-ERL.





Beam energy compression at the return path

Energy compression for ΔE/E=8% beam

ΔE=1.33MeV@undulator, 17MeV

↓

ΔE=0.46MeV@dump, 2.8MeV