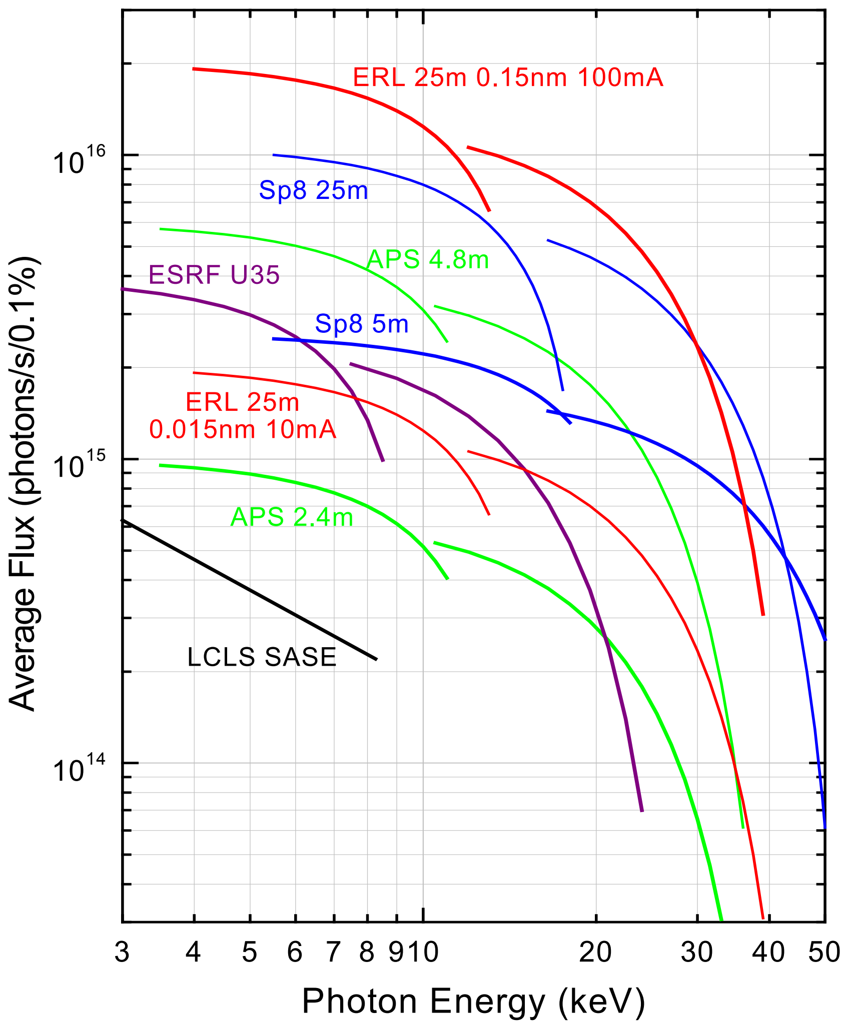
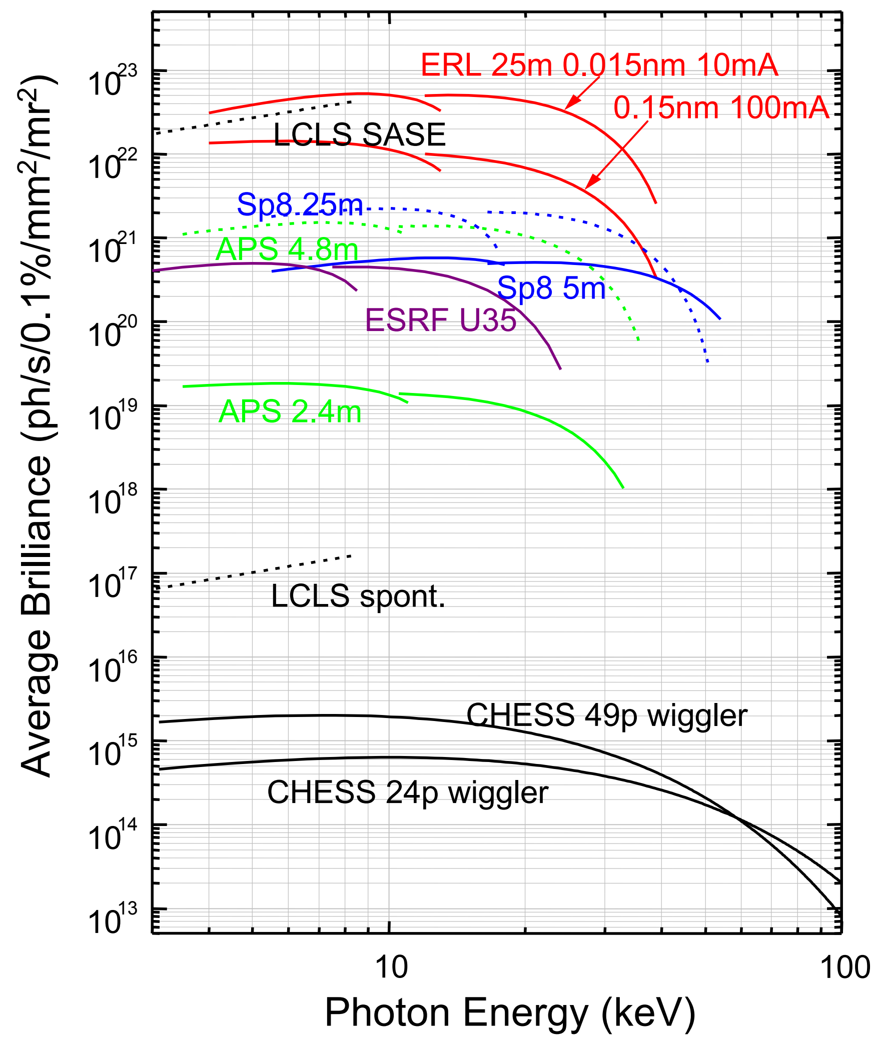
Considering an ERL x-ray source based on double acceleration

Considering an ERL x-ray source

Outline

- Power crisis for ERL
- Optimizing for flux, brightness, brilliance
- Injector performance
- Layout of ERL x-ray source





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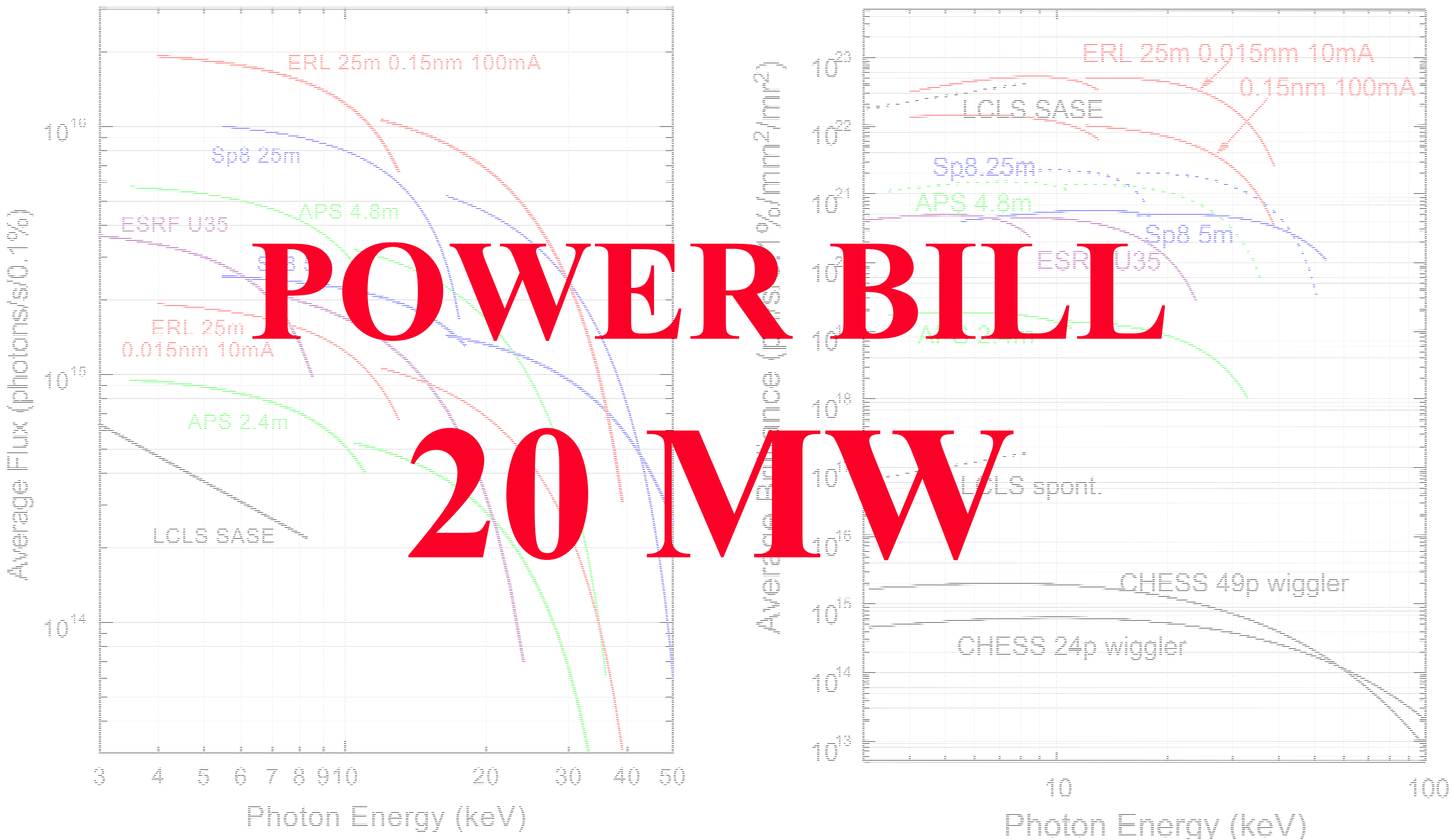

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Estimates of ERL power

Refrigeration	………	8.6 MW
Main linac rf power	………	7.5 MW
Injector rf power	………	2 MW
Magnet power supplies	………	< 1 MW
	Total:	19 MW

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Note: this is not a pessimistic number

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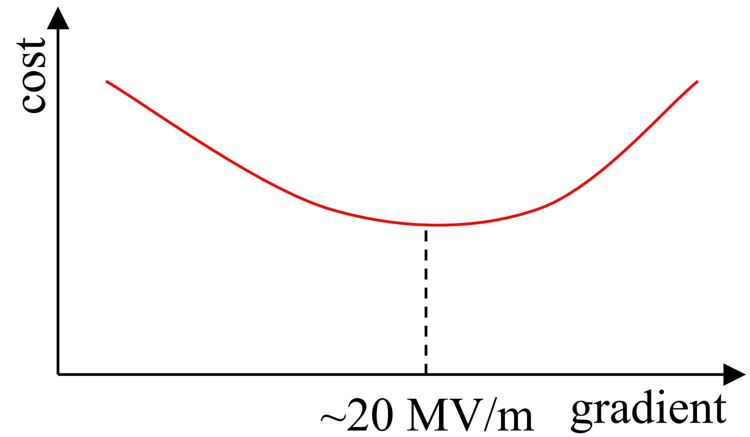
Big ticket item: 5 GeV linac

Reduce the power by

a) lowering the gradient (works if cavities are cheap)



b) going multipass

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  - ✓ linac cost
  - ✓ power (~ 9 MW)

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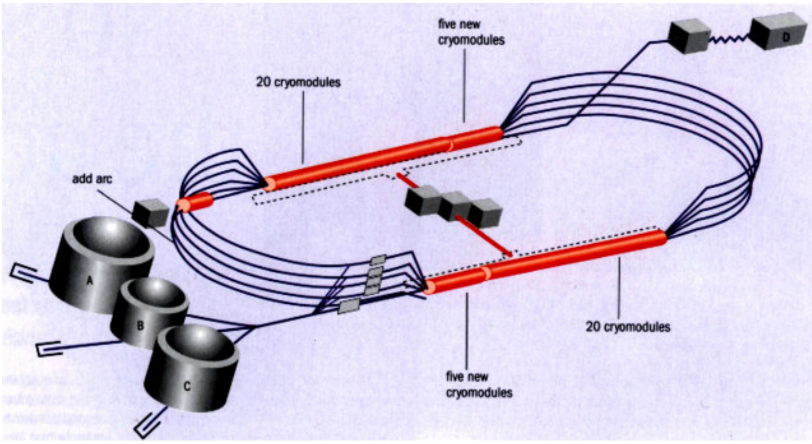
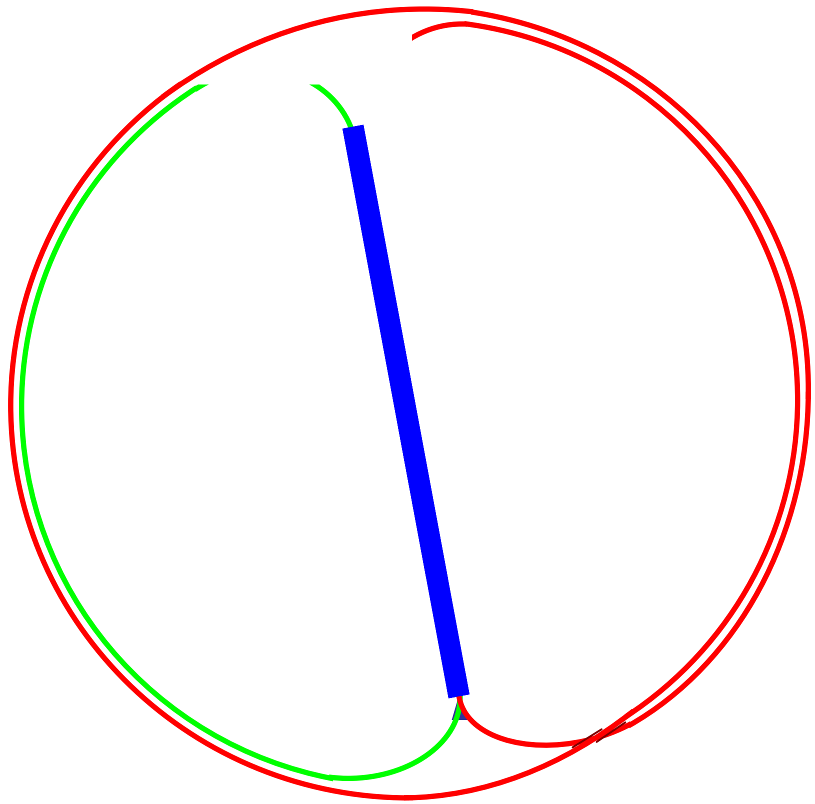
- Beam current in linac would be 400 mA (difficult even for storage rings), e.g. beam induced losses would go up by a factor of 4

Multipass configuration





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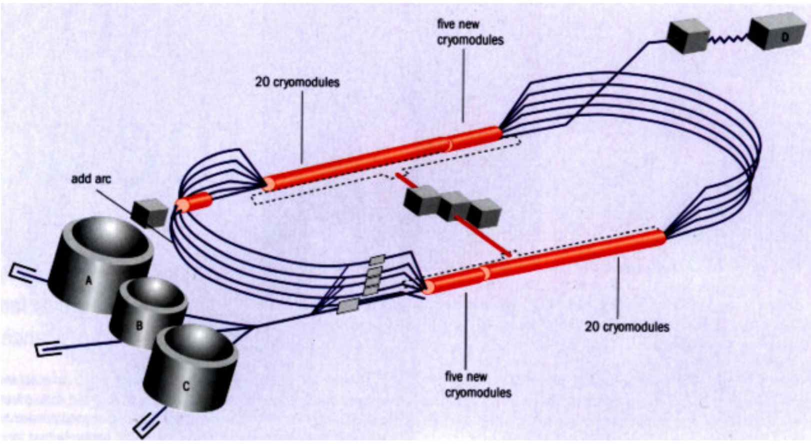
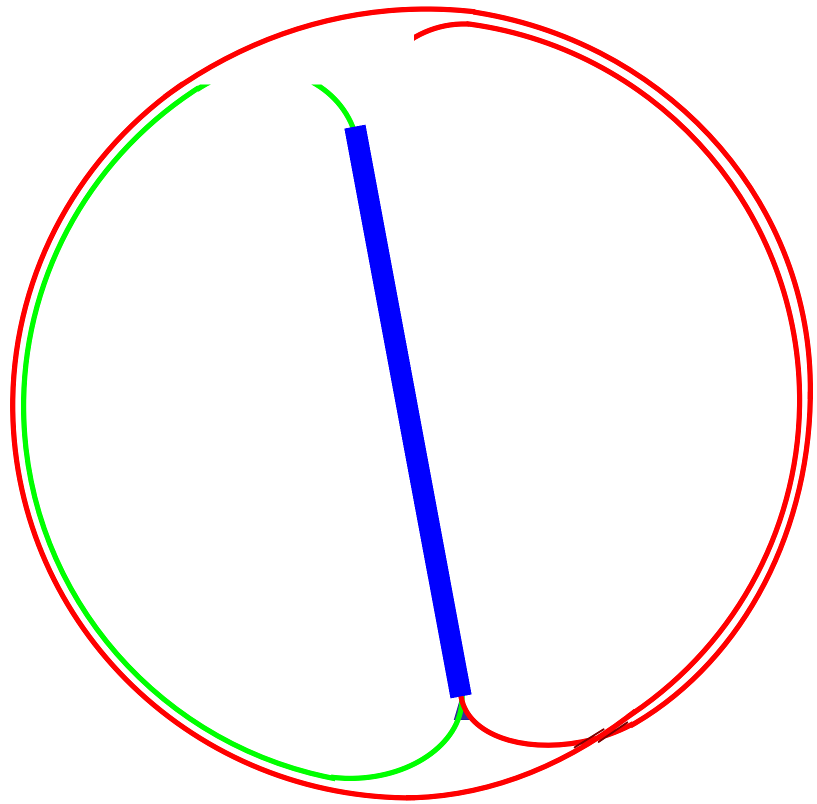


200 μA only. Each energy has its own arc.



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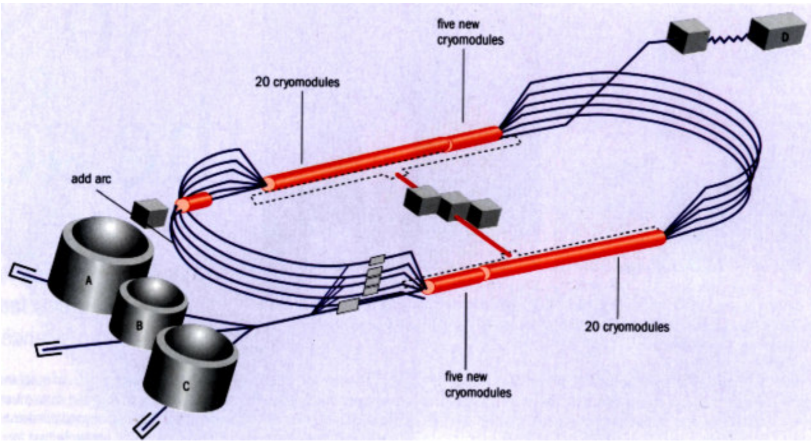

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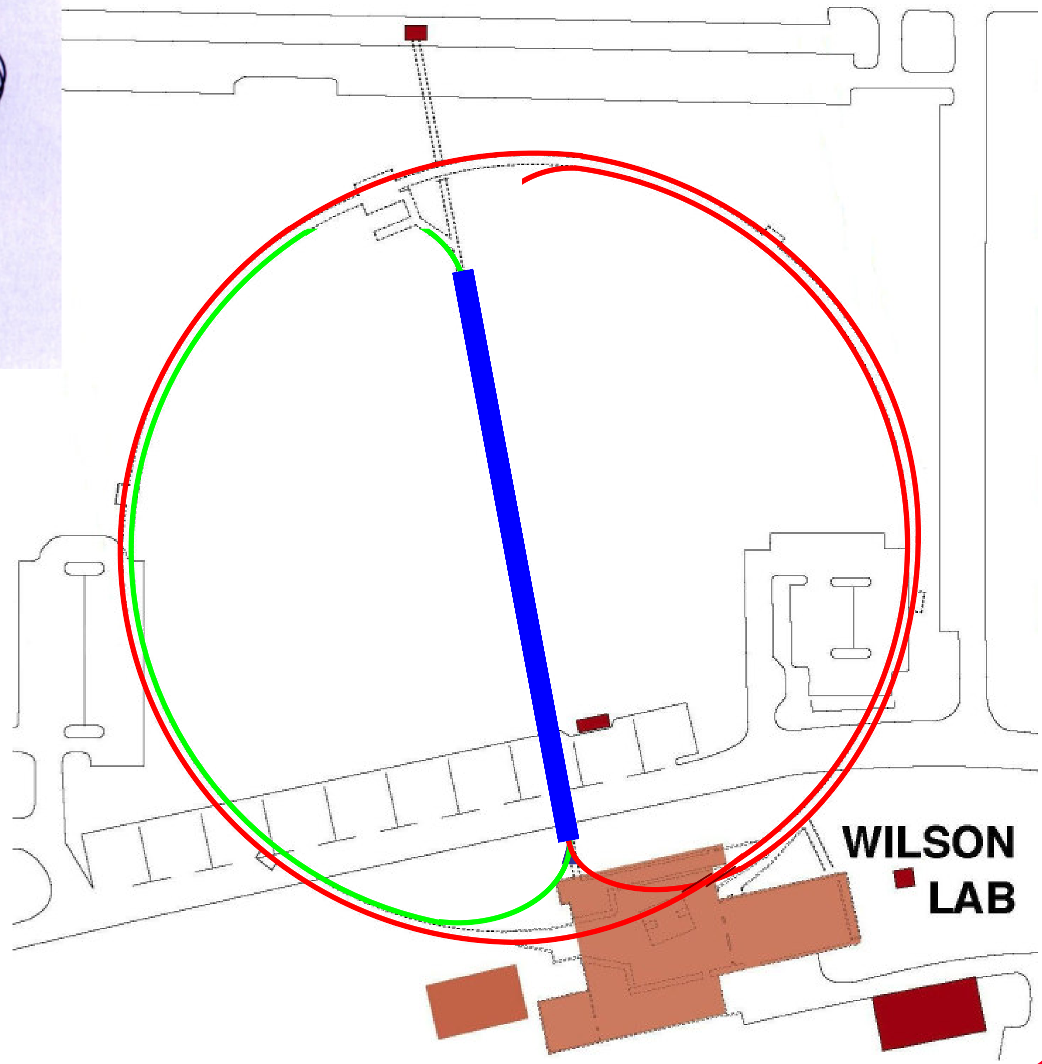

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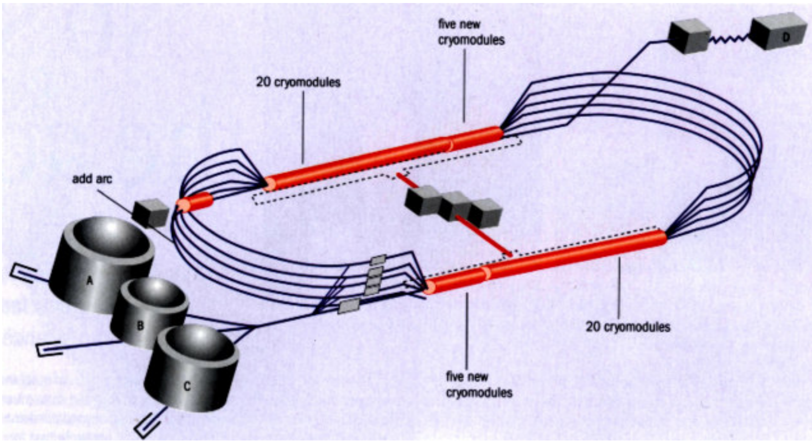

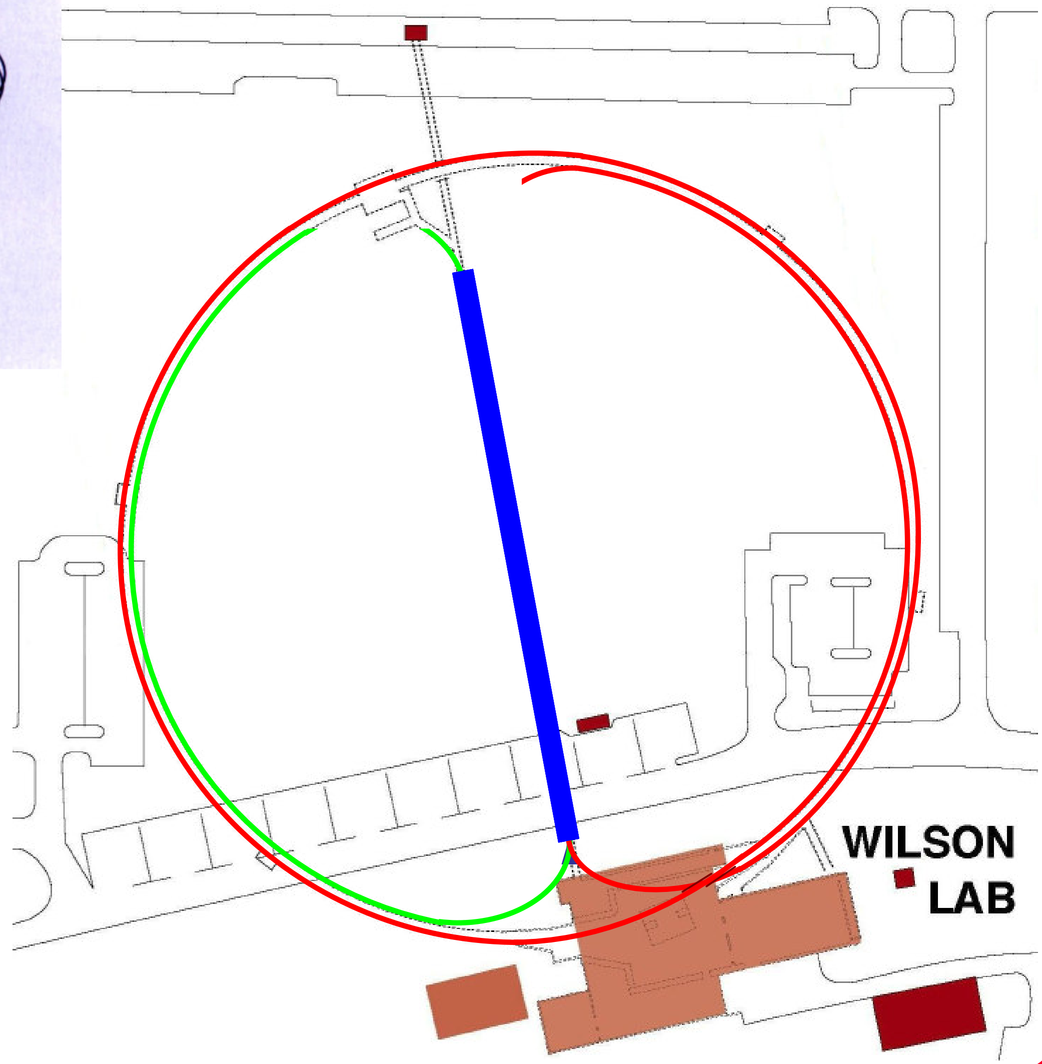

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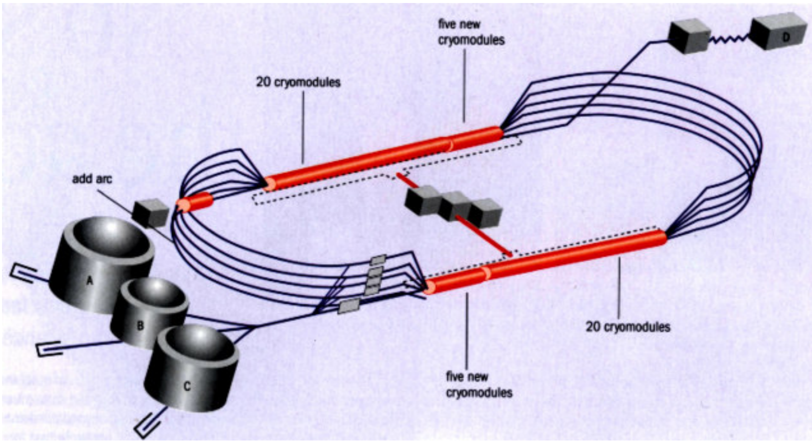

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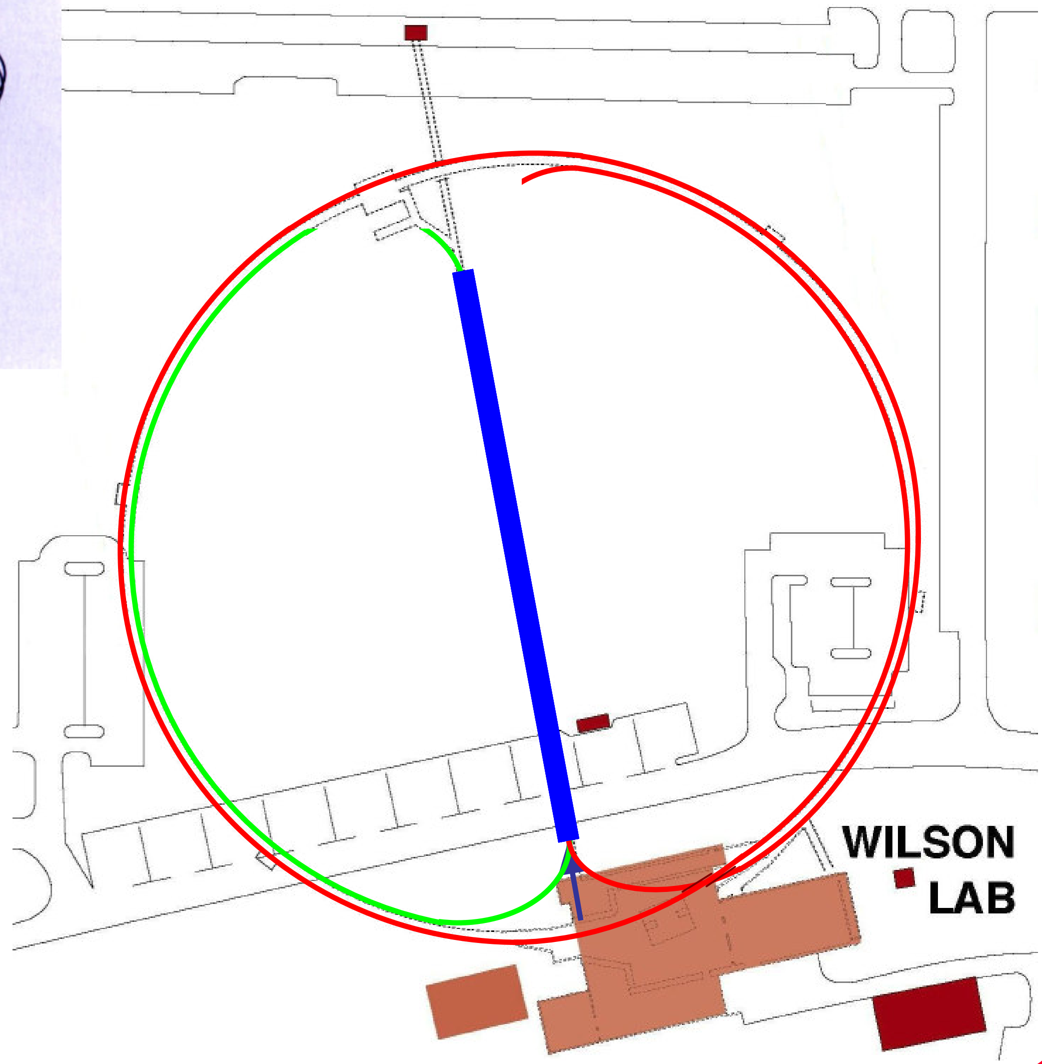

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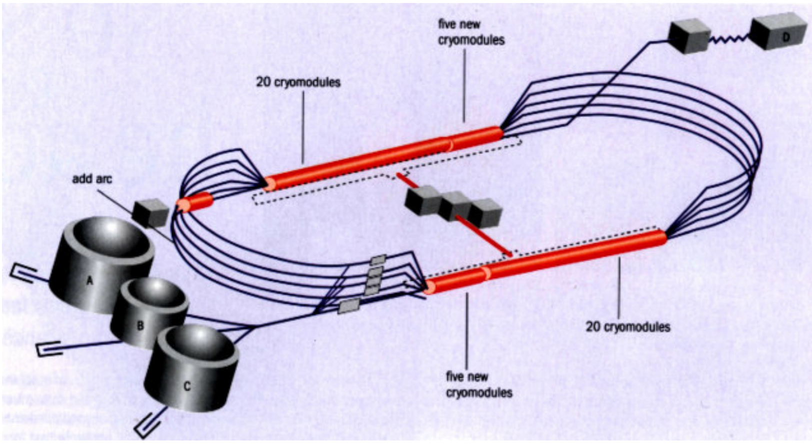

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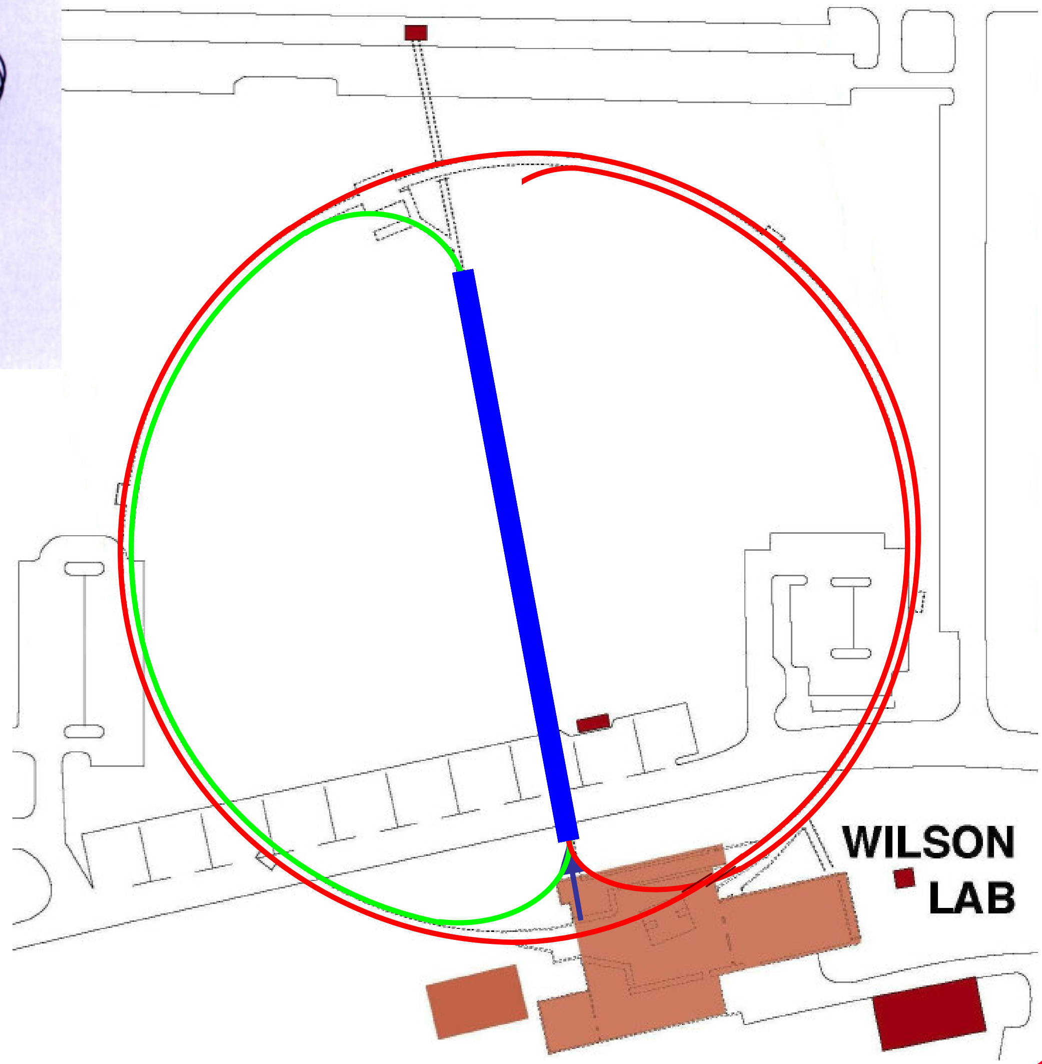

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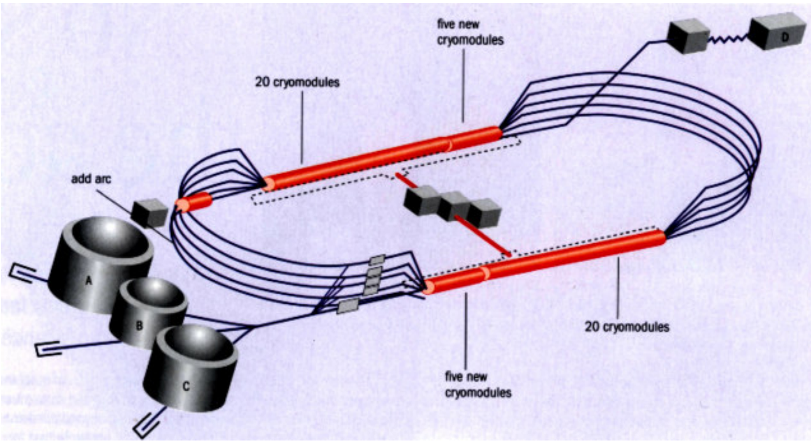

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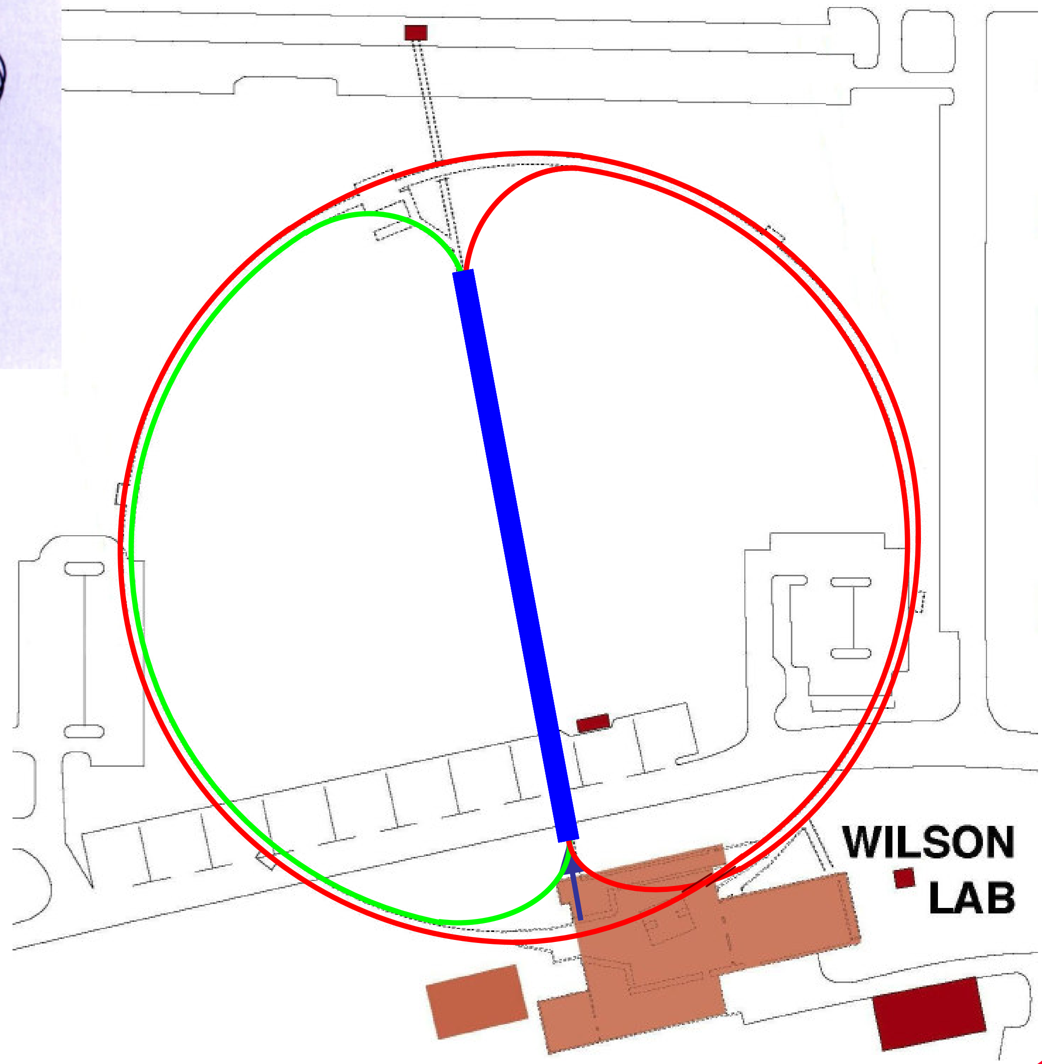

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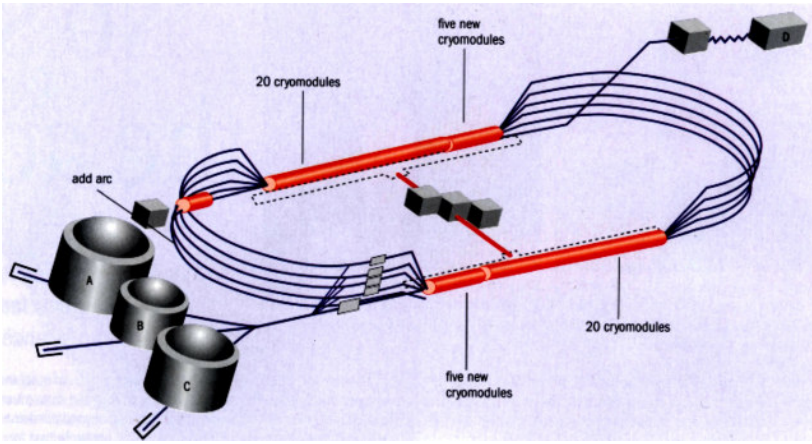

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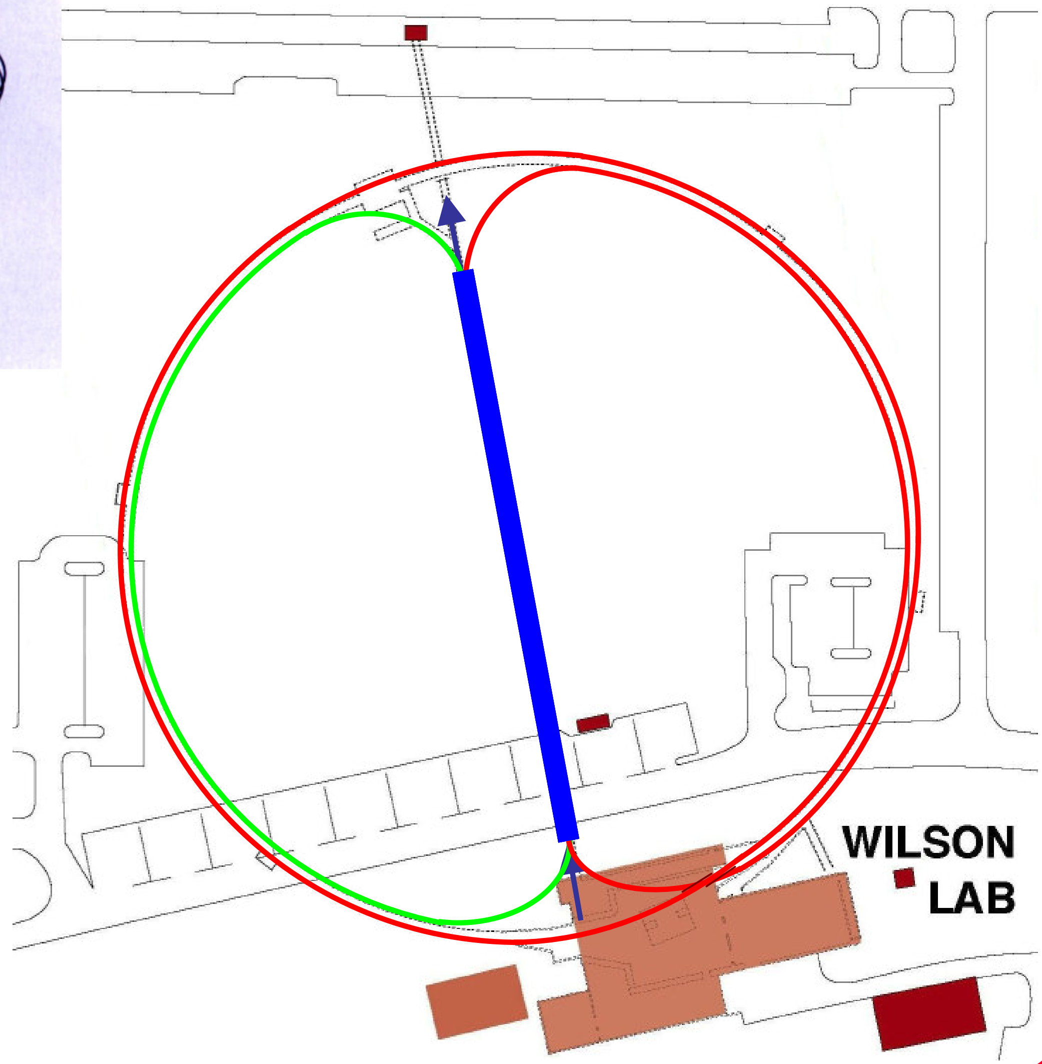

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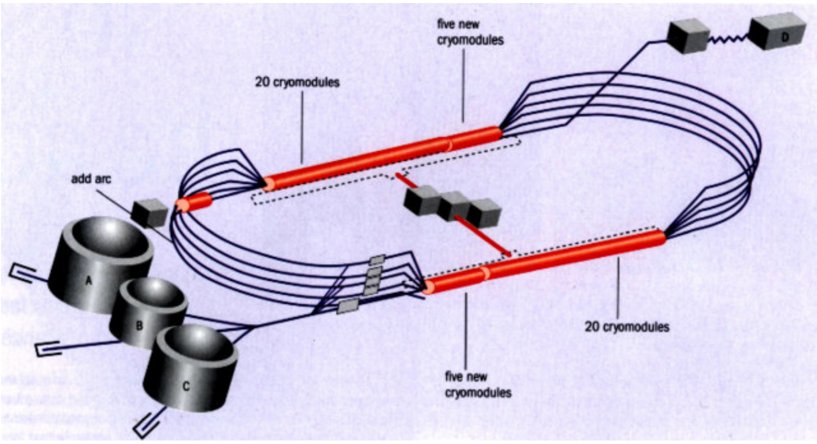

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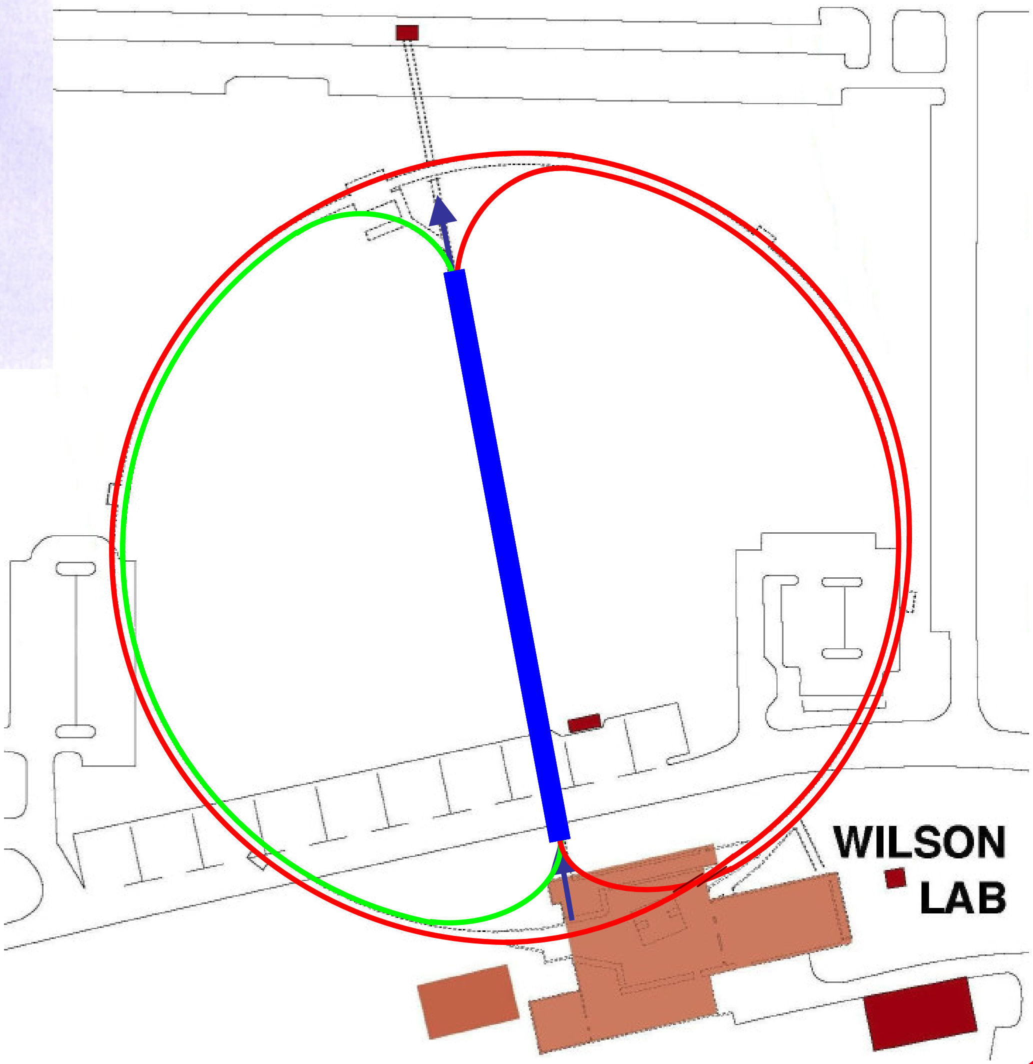
With 400 mA in linac, such machine is more vulnerable to **BBU**



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Multipass beam breakup

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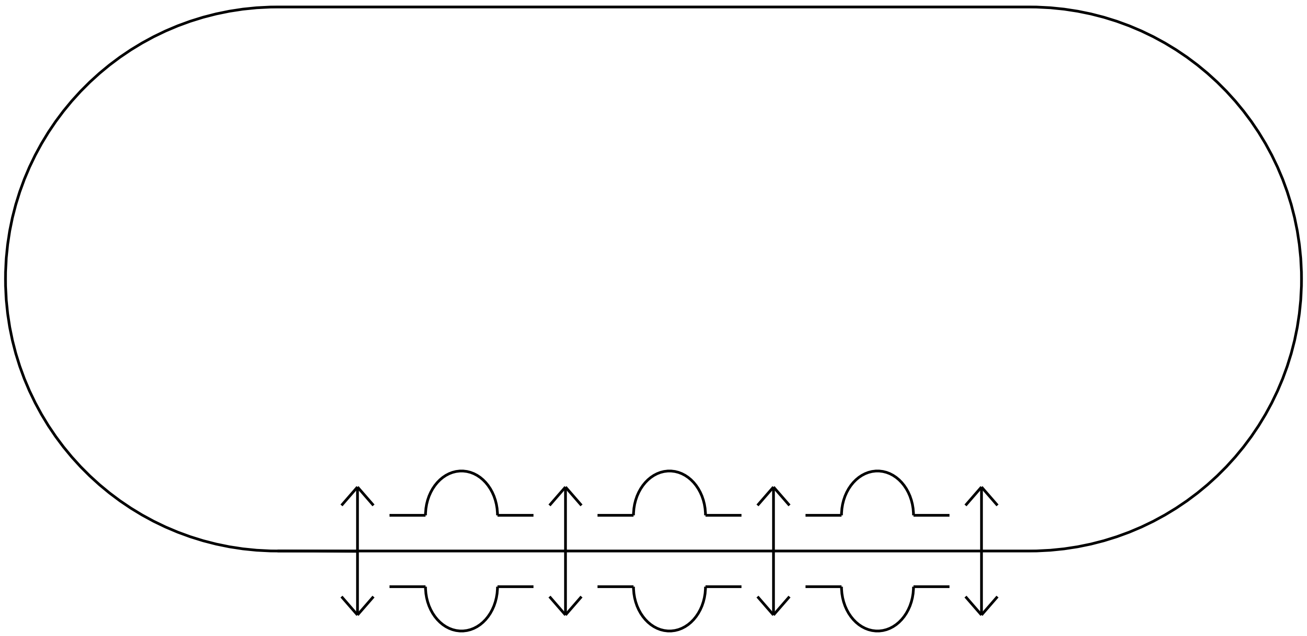

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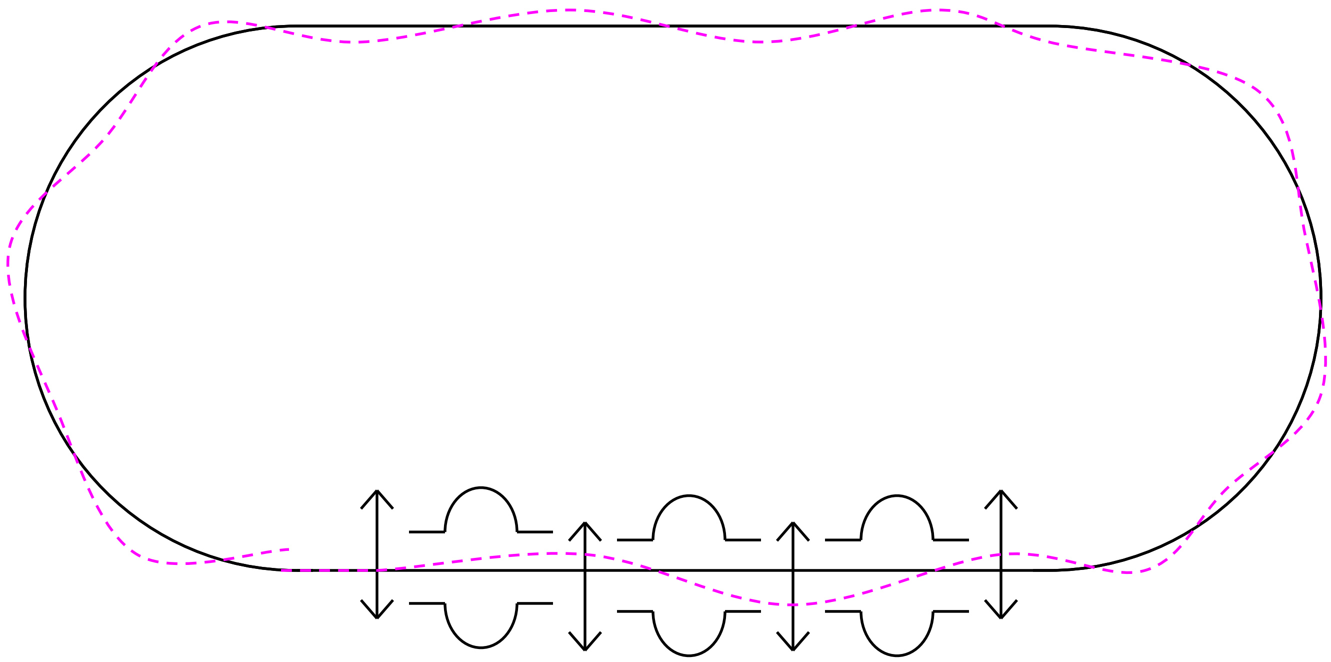

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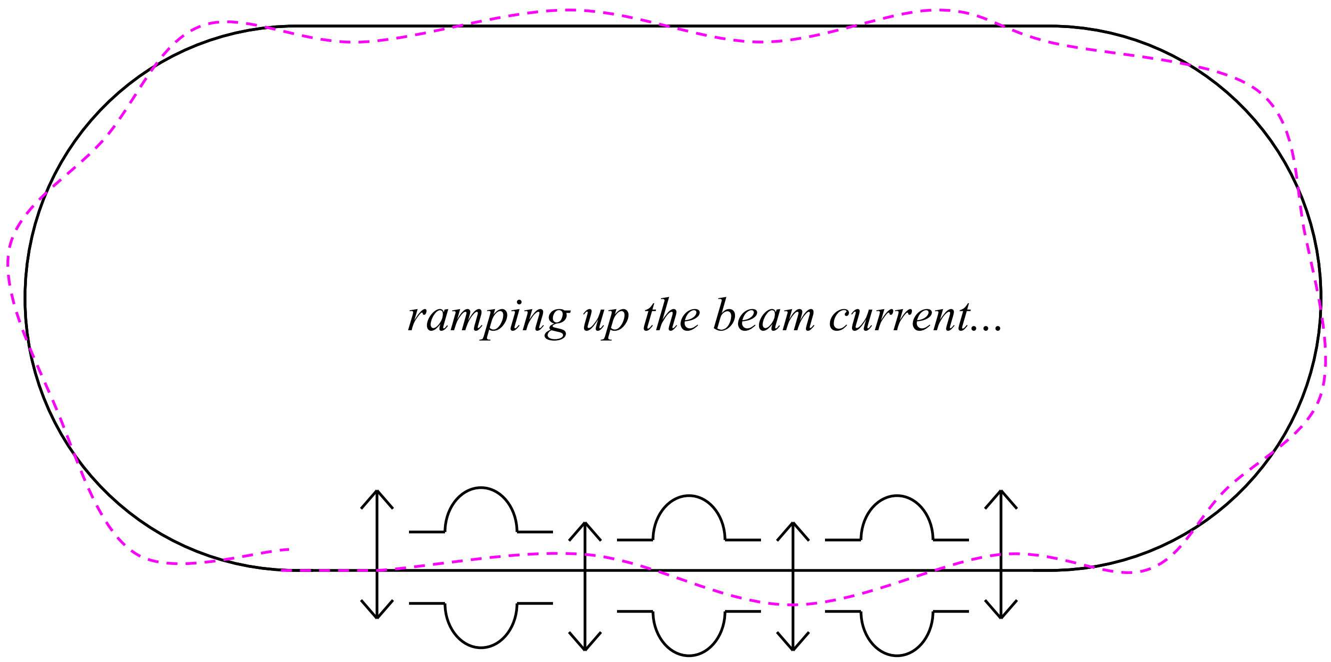

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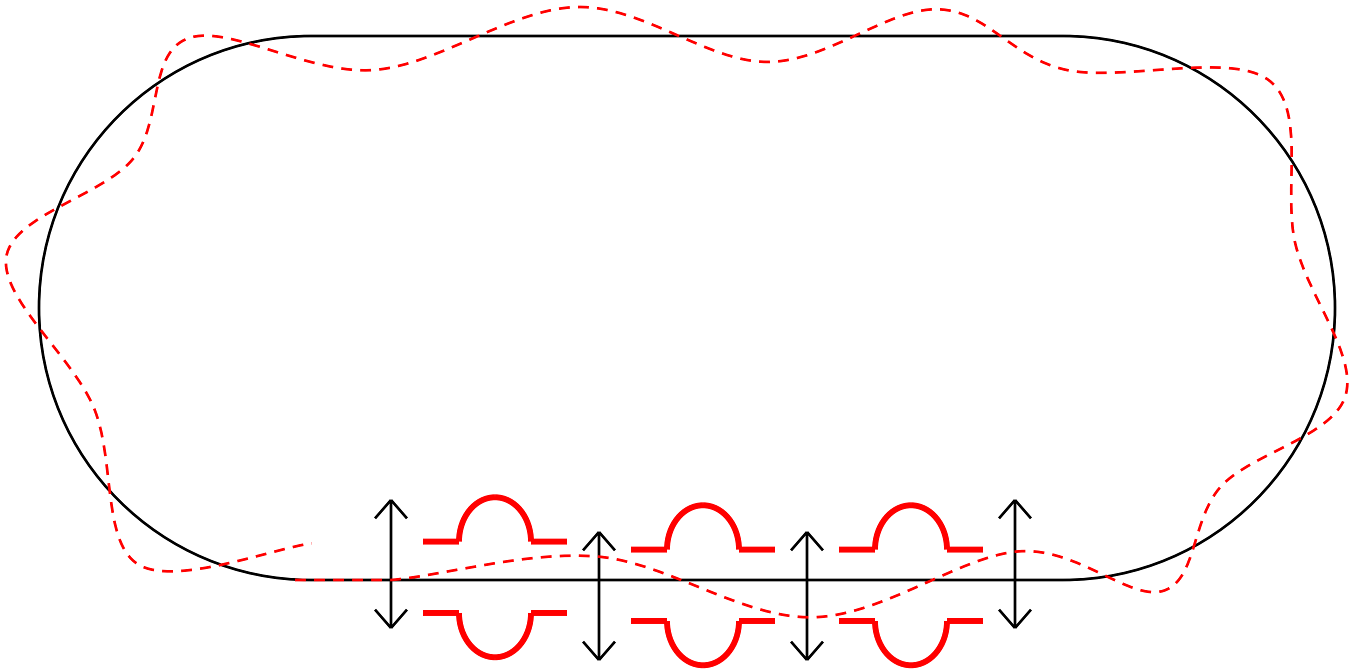

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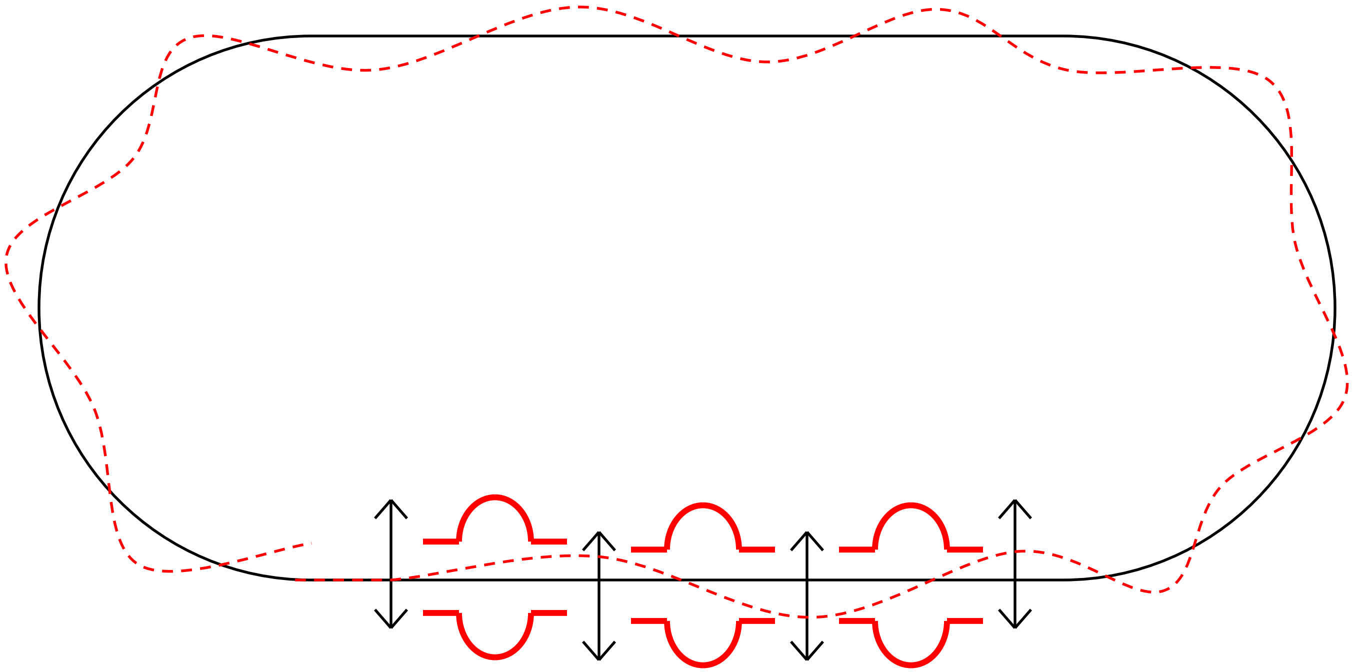

- higher order mode damping
- recirculating optics
- injection energy

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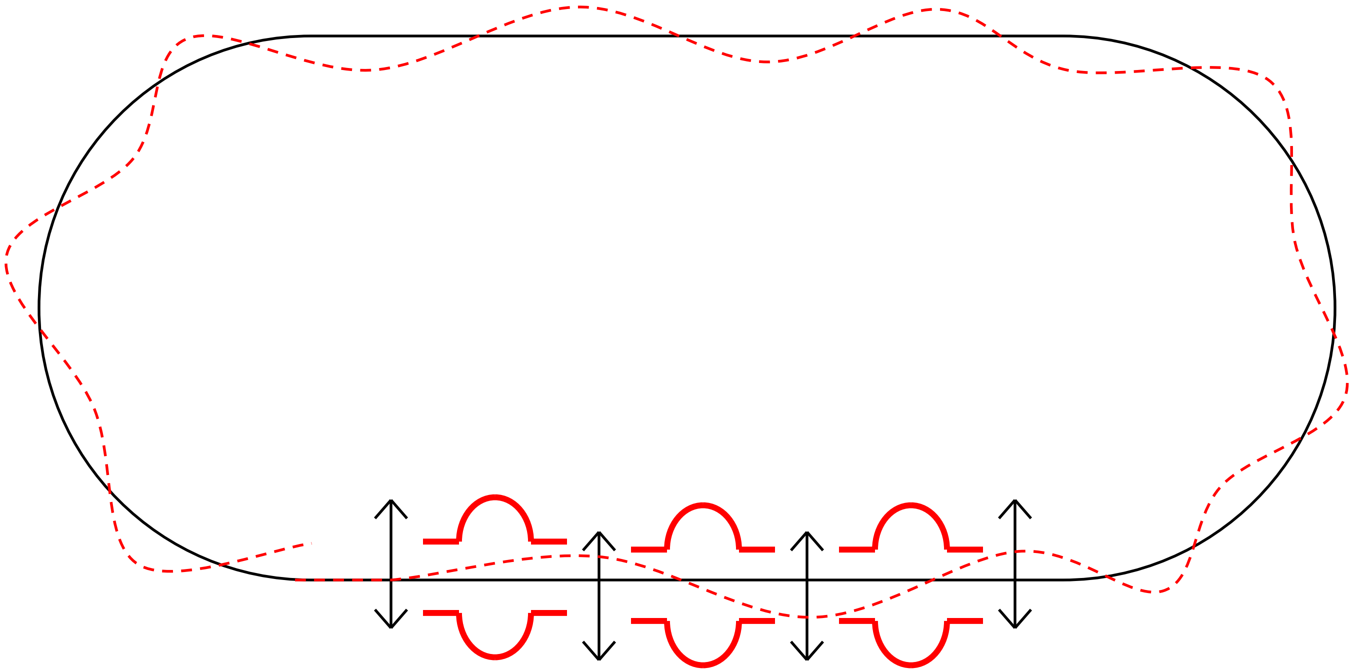

threshold current ←
- higher order mode damping
- recirculating optics
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BBU in two-pass ERL: gruesome look

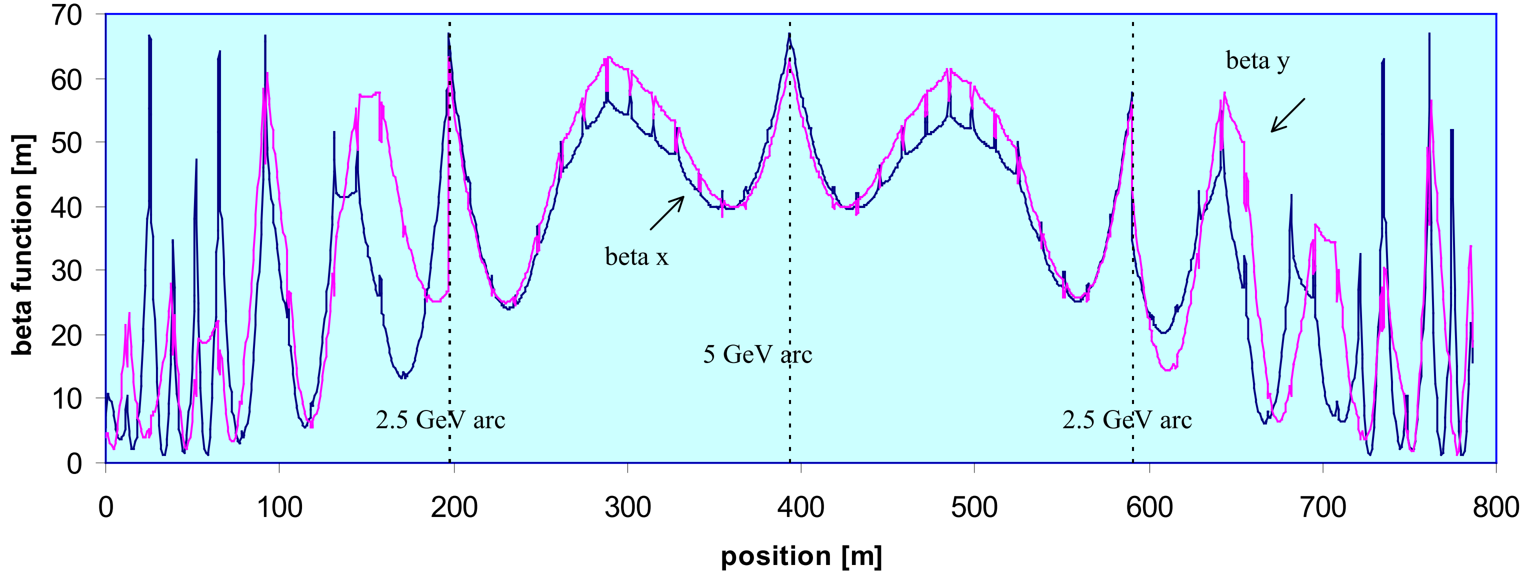

Table 1.
Results of TDBBU runs for 1-pass and 2-pass 5 GeV ERL.
HOM table (TESLA TDR 03/2001)

f (MHz)	R/Q (Ohm)	Q	(R/Q)*Q	1-pass 5 GeV ERL BBU (mA)	2-pass 5 GeV ERL BBU (mA)	Q*	Improved by a factor of
1699	88.40	5.00E+04	4.42E+06	160	20	8.00E+02	62.5
1873	56.39	7.00E+04	3.95E+06	190	25	1.30E+03	53.8
2575	51.50	5.00E+04	2.57E+06	115	15	9.00E+02	55.6
1725	118.64	2.00E+04	2.37E+06	135	15	5.00E+02	40.0
1864	42.84	5.00E+04	2.14E+06	> 200	40	2.00E+03	25.0
1880	11.08	1.00E+05	1.11E+06	> 200	90	8.00E+04	1.3
…	…	…	…	> 200	> 100		

* BBU th >=100 mA

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Cons: lower flux per meter of insertion device

Maxim time

Never trade flux for brilliance

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Never say “never”

Flux: how many bulbs does it take?

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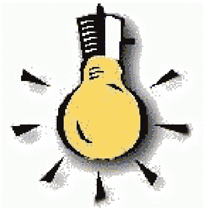
FLUX



BRILLIANCE

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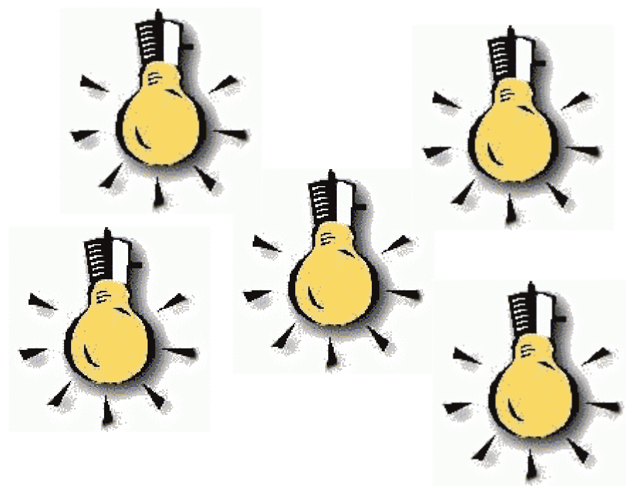
Flux: how many bulbs does it take?

N×FLUX



N

BRILLIANCE

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Naïve scaling for ERL x-ray source

If source is completely dominated by e^--beam

Flux	ph/s/0.1%bw	$\propto I$
Brightness	ph/s/mrad²/0.1%bw	$\propto I/\in$
Brilliance	ph/s/mm²/mrad²/0.1%bw	$\propto I/\in^2$

$$assuming \;\; \in \propto q$$

$$F \propto I \qquad dF/d\Omega \propto \text{const} \qquad B \propto 1/I$$

If near the diffraction limit, it's current that matters

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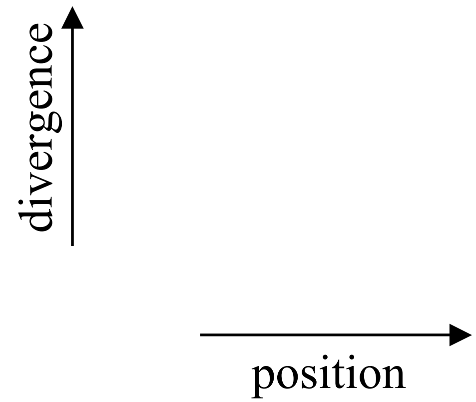
Beam matching & energy spread effect

$$\frac{dF_n}{d\Omega} = \frac{F_n}{2\pi\sqrt{\sigma'^2_{cen}+\sigma^2_{x'}}\sqrt{\sigma'^2_{cen}+\sigma^2_{y'}}}$$

optimizing brilliance



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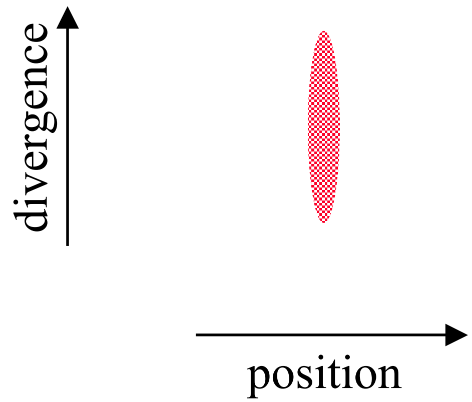

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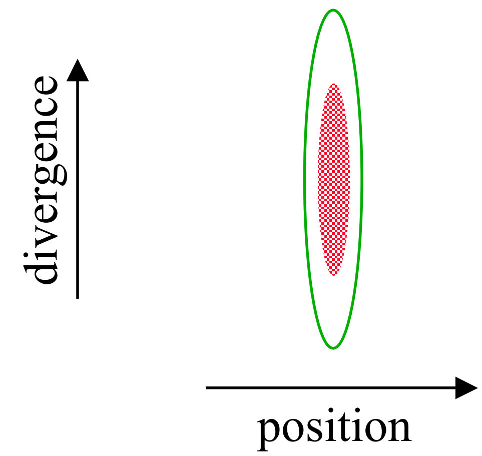

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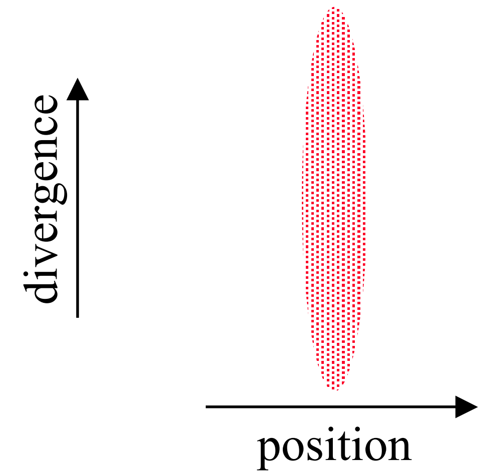

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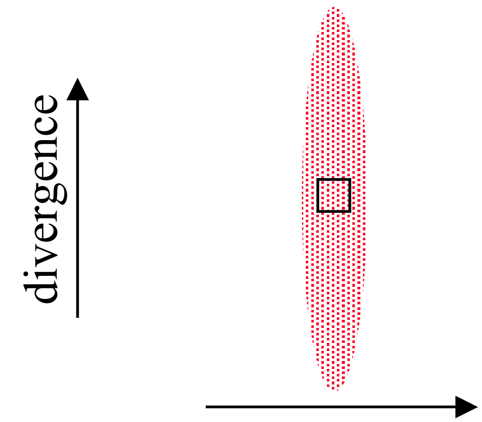

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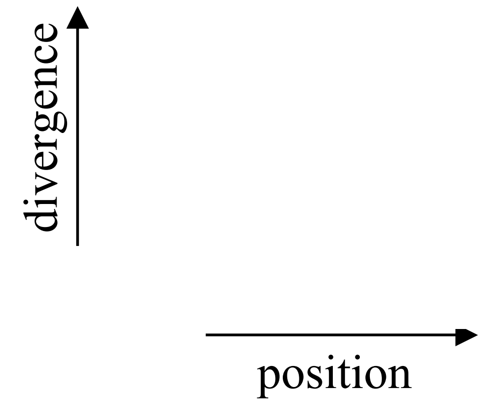

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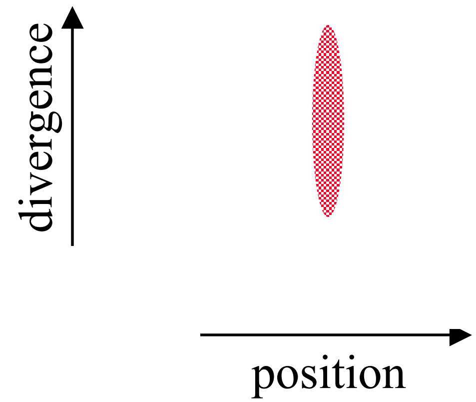

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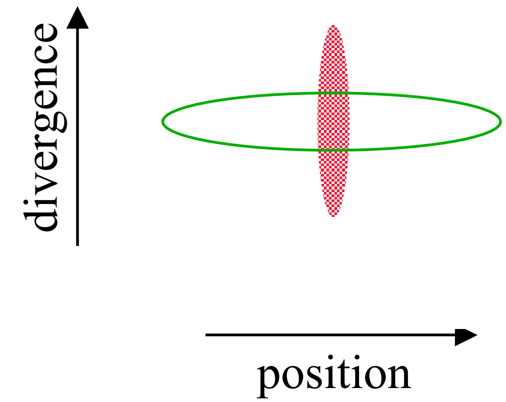

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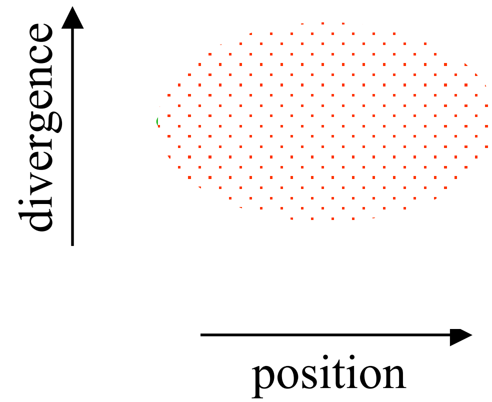

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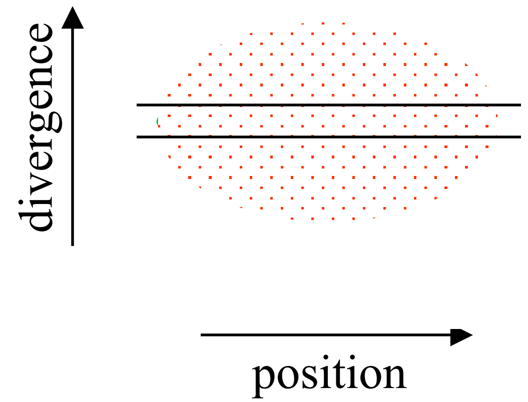

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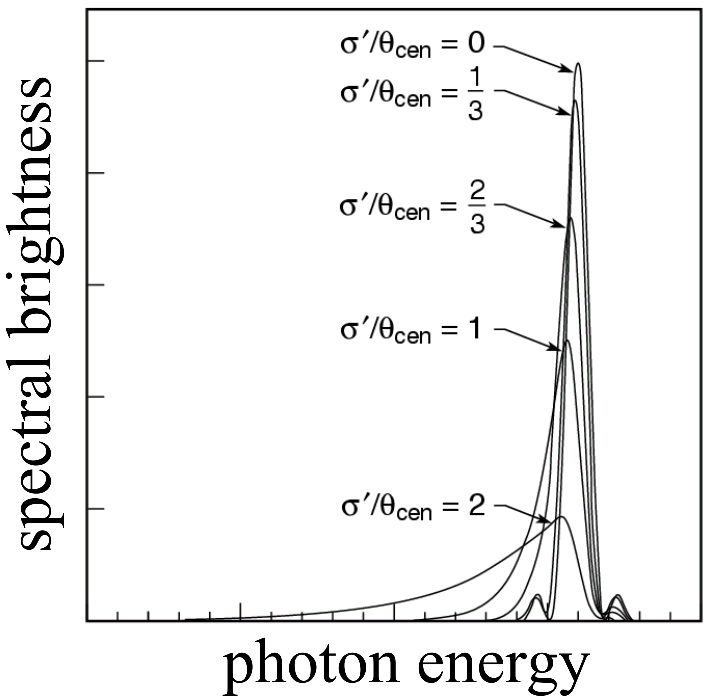

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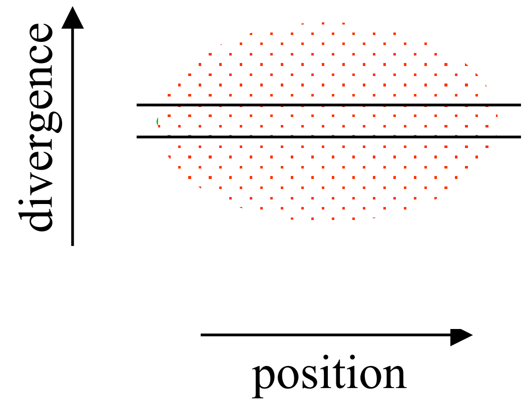

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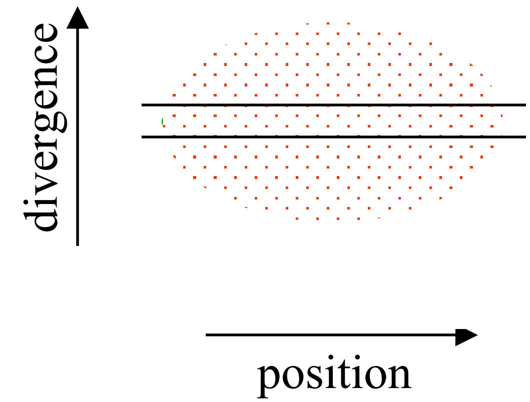

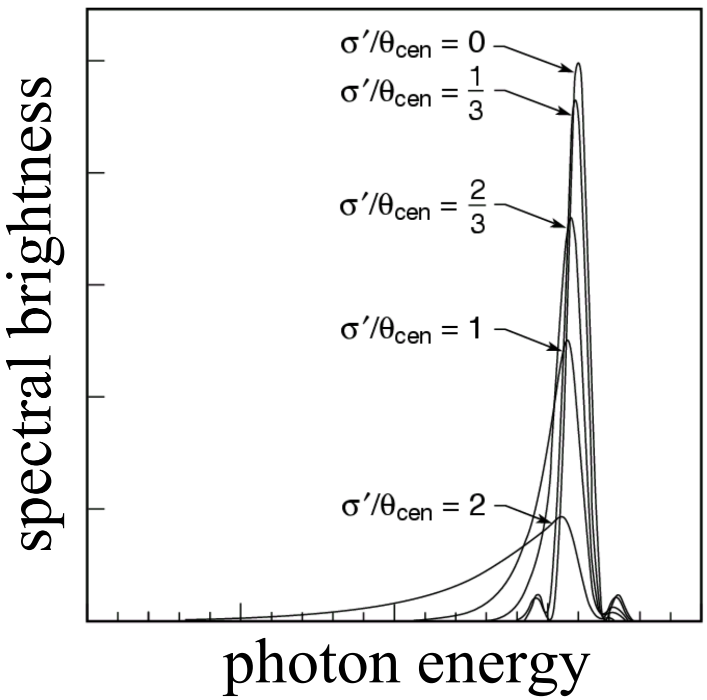

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \tfrac{1}{2}K^2 + \gamma^2\theta^2\right)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_u}{2}\theta^2 \quad \Rightarrow \quad \left.\frac{\Delta\lambda}{\lambda}\right|_{FWHM} \approx \frac{1}{N}\frac{\sigma'^2_T}{\sigma'^2_{cen}}$$

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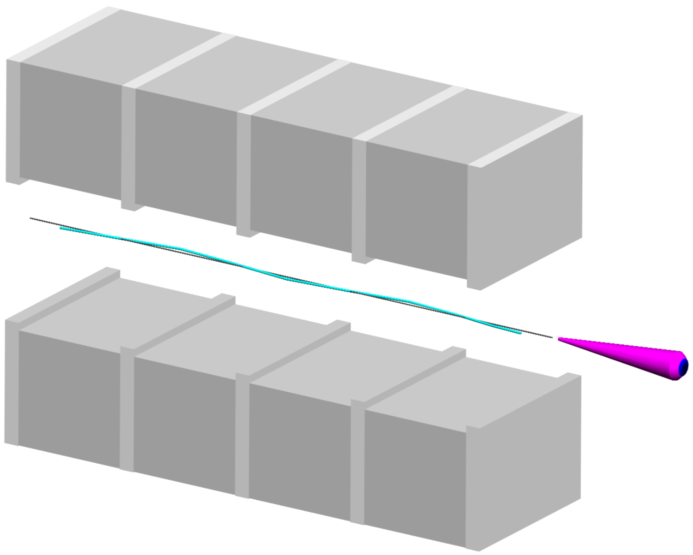
Intuitive picture of undulator radiation



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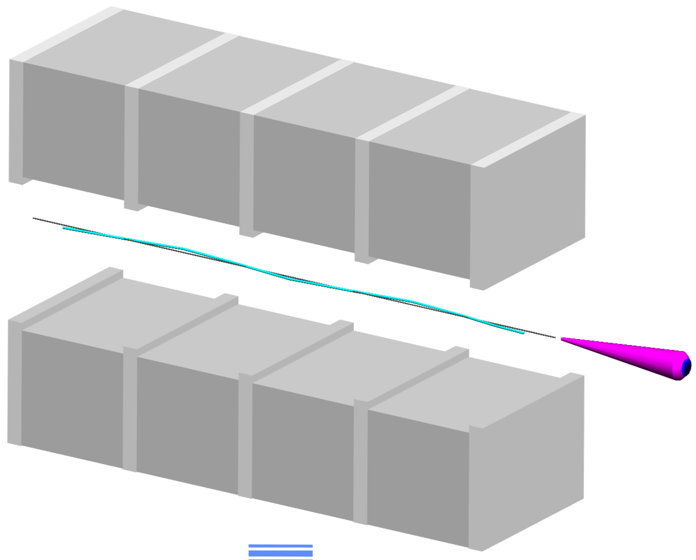
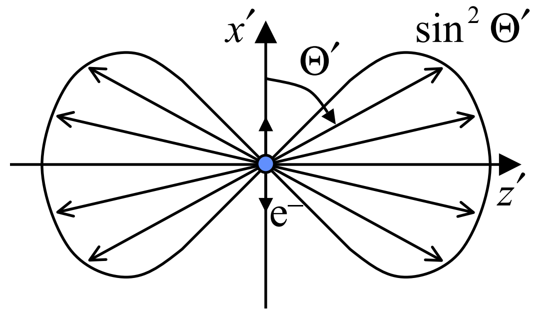
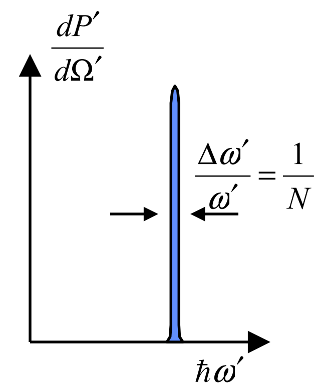


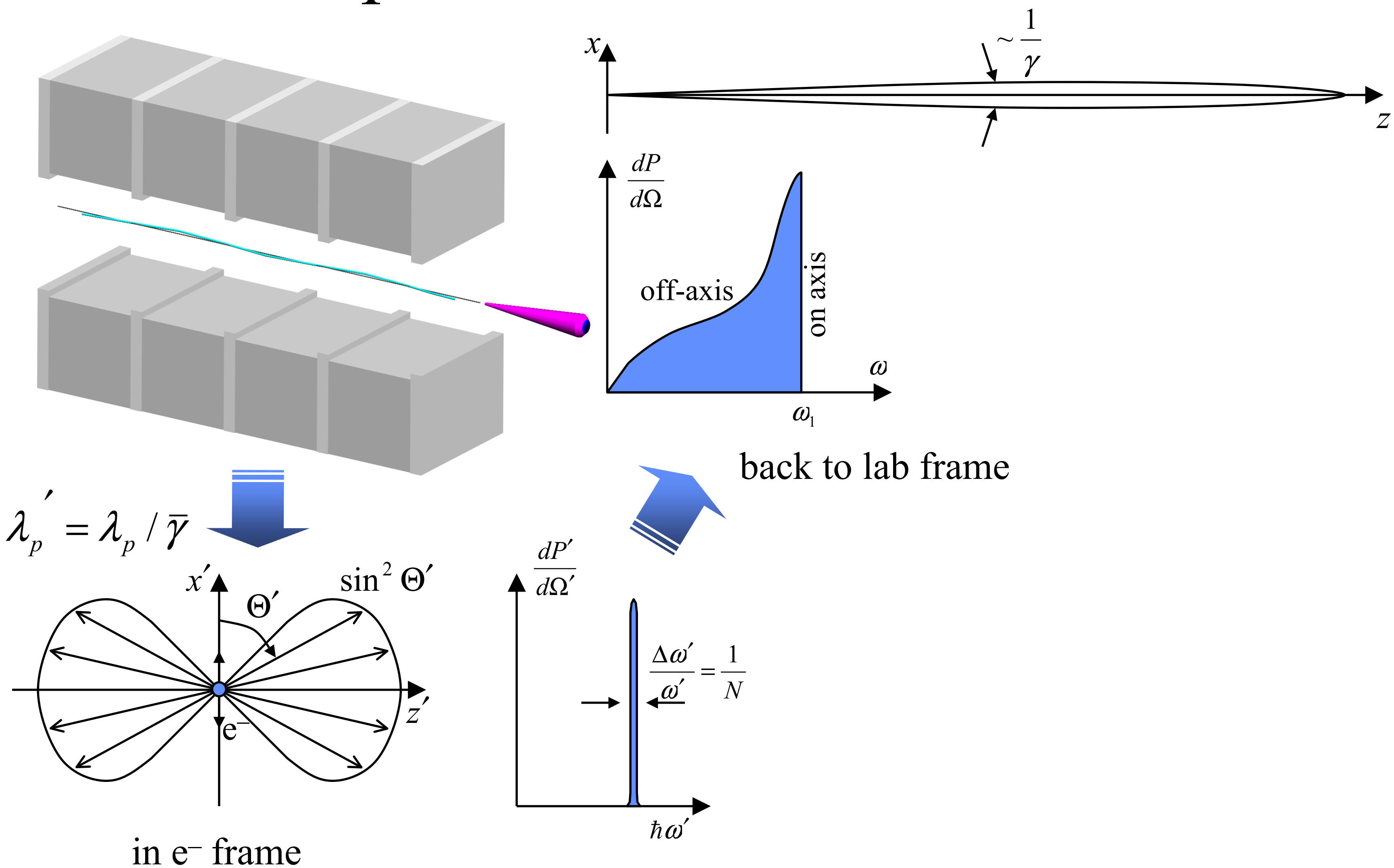
$$\lambda_p' = \lambda_p / \bar{\gamma}$$





in e⁻ frame

Intuitive picture of undulator radiation



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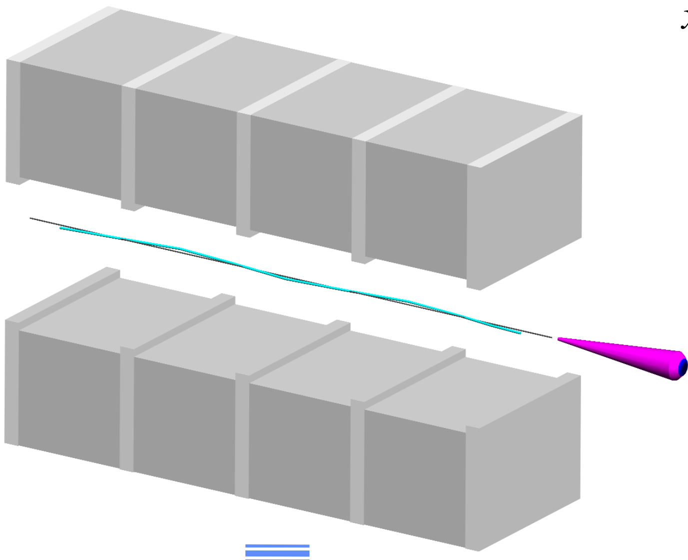
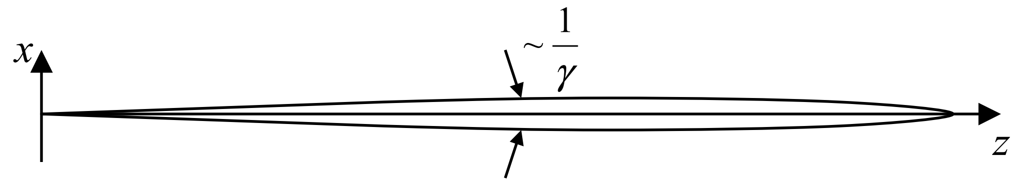
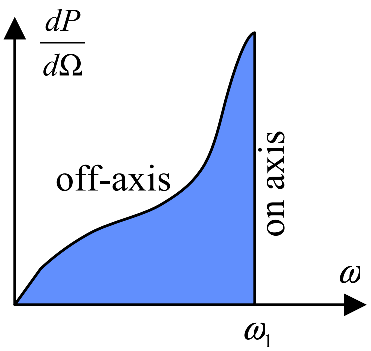
Intuitive picture of undulator radiation

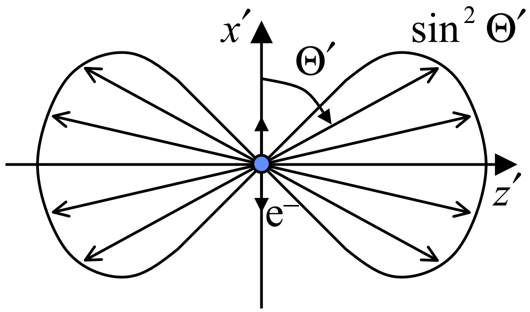




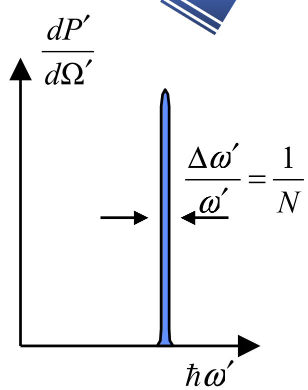


back to lab frame

$$\lambda_p' = \lambda_p / \bar{\gamma}$$



in e^- frame



$$\lambda_n = \frac{\lambda_p}{2\gamma^2 n}\left(1 + \tfrac{1}{2}K^2 + \gamma^2\theta^2\right)$$

$$\frac{\Delta\lambda}{\lambda_n} \sim \frac{1}{nN_p}$$ (for fixed θ only!)

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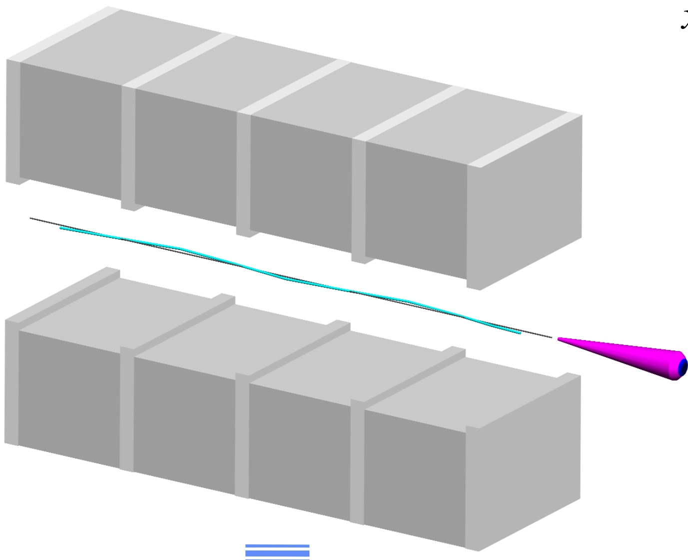
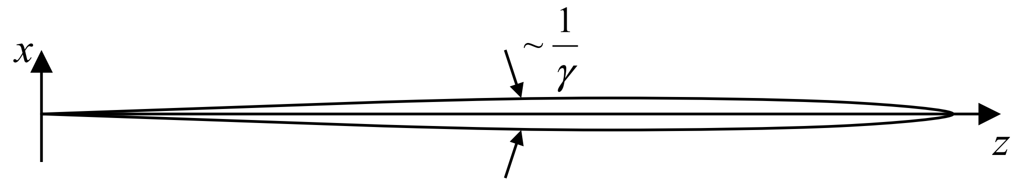
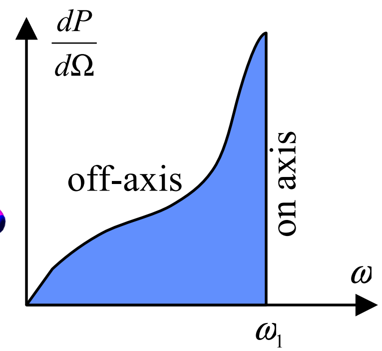
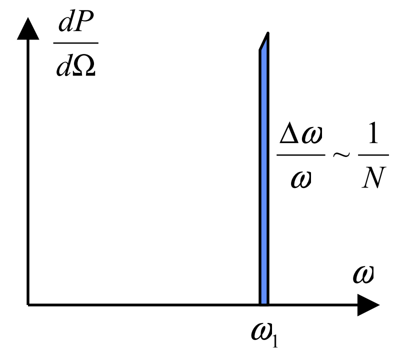
Intuitive picture of undulator radiation





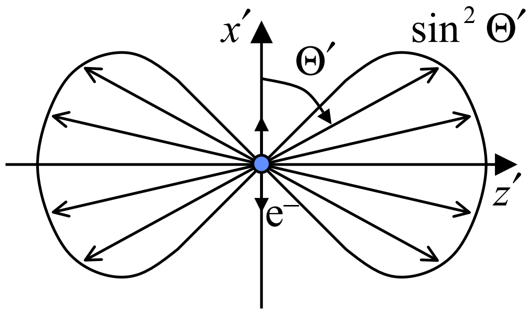


back to lab frame

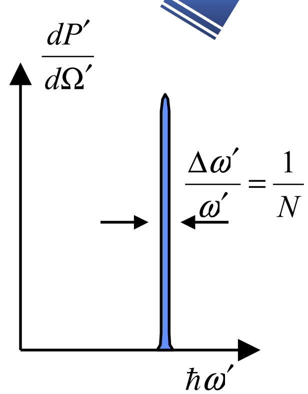


after pin-hole aperture

$\lambda_p' = \lambda_p / \bar{\gamma}$



in e⁻ frame

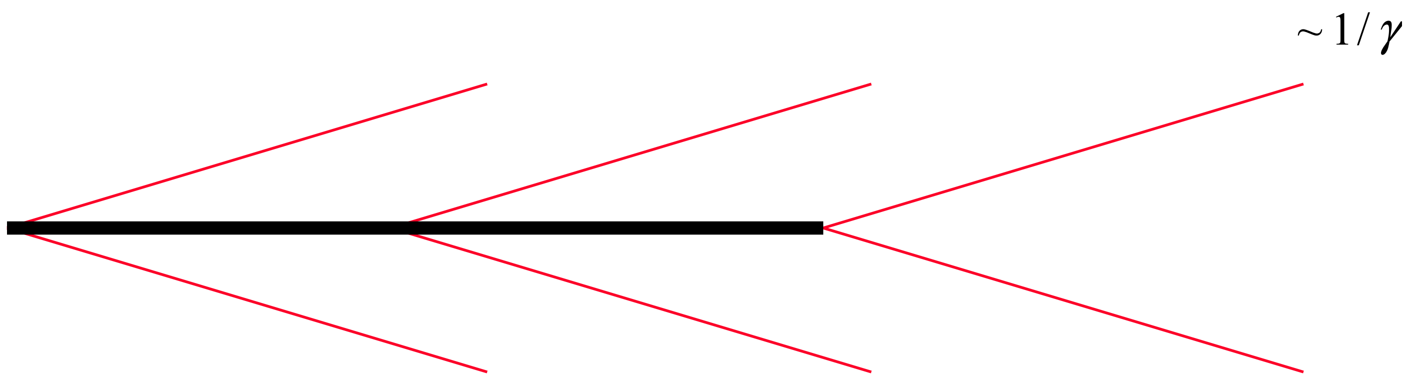


$$\lambda_n = \frac{\lambda_p}{2\gamma^2 n}\left(1 + \tfrac{1}{2}K^2 + \gamma^2\theta^2\right)$$

$$\frac{\Delta\lambda}{\lambda_n} \sim \frac{1}{nN_p}$$

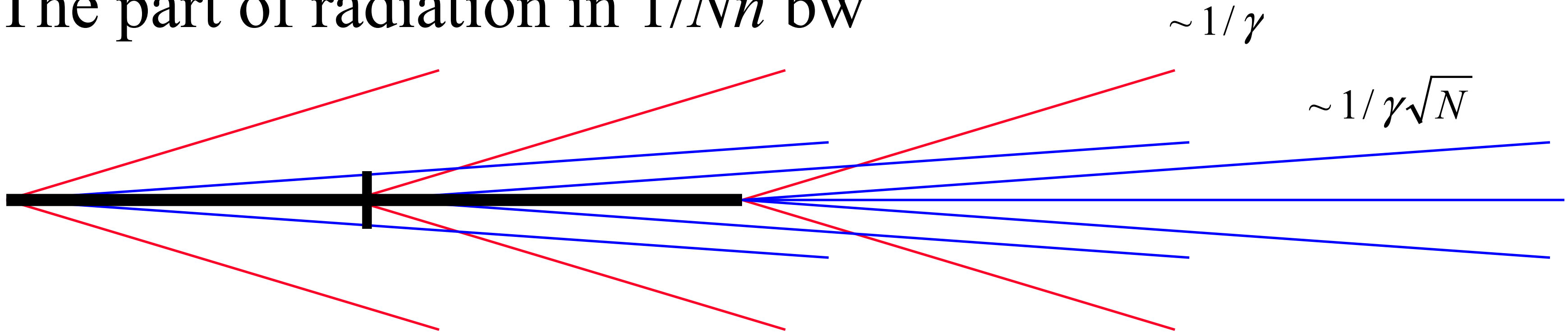
(for fixed θ only!)

Central cone concept



Central cone concept

The part of radiation in 1/*Nn* bw



$$\sigma'^2_{cen} = \frac{\lambda}{2L}$$

$$\sigma^2_{cen} = \frac{2\lambda L}{(4\pi)^2}$$

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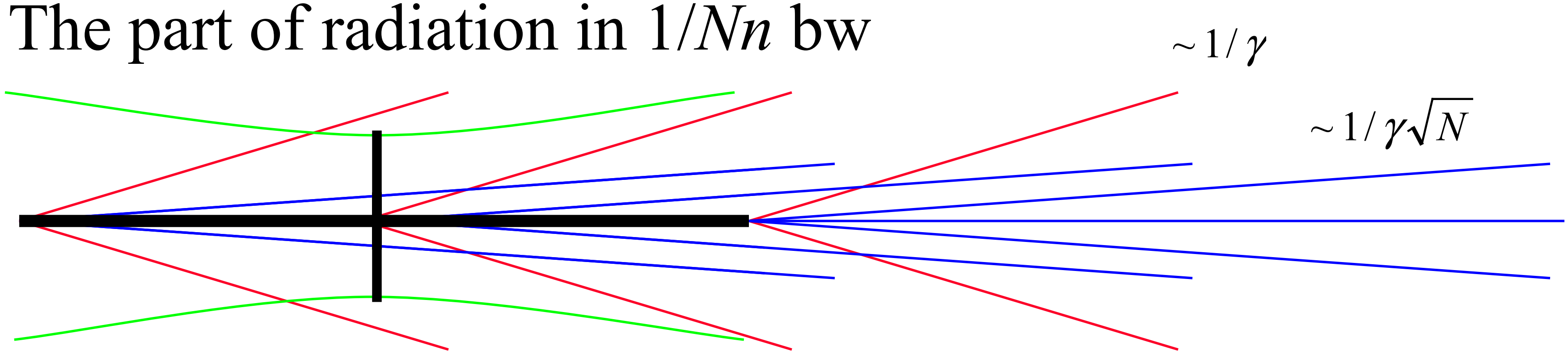
Central cone concept

The part of radiation in $1/Nn$ bw



$$\sigma'^2_{cen} = \frac{\lambda}{2L}$$

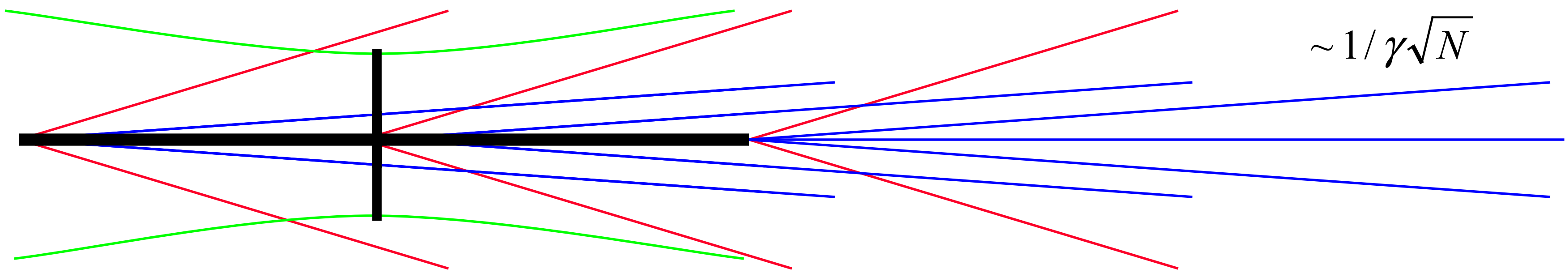
$$\sigma^2_{cen} = \frac{2\lambda L}{(4\pi)^2}$$

$$\sigma'^2_T = \sigma'^2_{cen} + \frac{\in}{\beta}$$

$$\sigma^2_T = \sigma^2_{cen} + \in \beta$$

Central cone concept

The part of radiation in $1/Nn$ bw



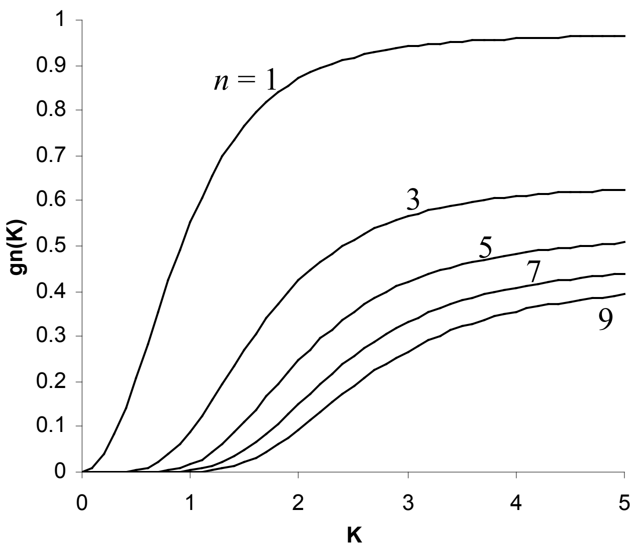
$$\sigma'^2_{cen} = \frac{\lambda}{2L}$$

$$\sigma^2_{cen} = \frac{2\lambda L}{(4\pi)^2}$$

$$\sigma'^2_T = \sigma'^2_{cen} + \frac{\in}{\beta}$$

$$\sigma^2_T = \sigma^2_{cen} + \in \beta$$

$$F_n = \pi\alpha N \frac{I}{e} g_n(K)$$



Function $g_n(K) = \frac{nK^2[JJ]}{(1+\frac{1}{2}K^2)}$

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Flux (central cone) through aperture

For aperture σ_a at distance D, $\sigma'_a = \sigma_a / D$

$$F_n \frac{1}{1+\frac{1}{\sigma'^2_a}\left(\sigma'^2_T+\frac{\sigma^2_T}{D^2}\right)} \frac{1}{\sqrt{1+\left(\frac{N}{N_\delta}\right)^2 \frac{\sigma'^2_{cen}}{\sigma'^2_{x-ray}}}}$$

electron beam energy spread

$$N_\delta \approx \frac{1}{5\sigma_\delta}$$

Optimum $\beta \approx D$

here x-ray divergence after pinhole $\sigma^2_{x-ray} = \frac{\sigma'^2_T}{1+\sigma'^2_T/(\sigma'^2_a+\frac{\sigma^2_T}{D^2})} \approx \sigma'^2_T$

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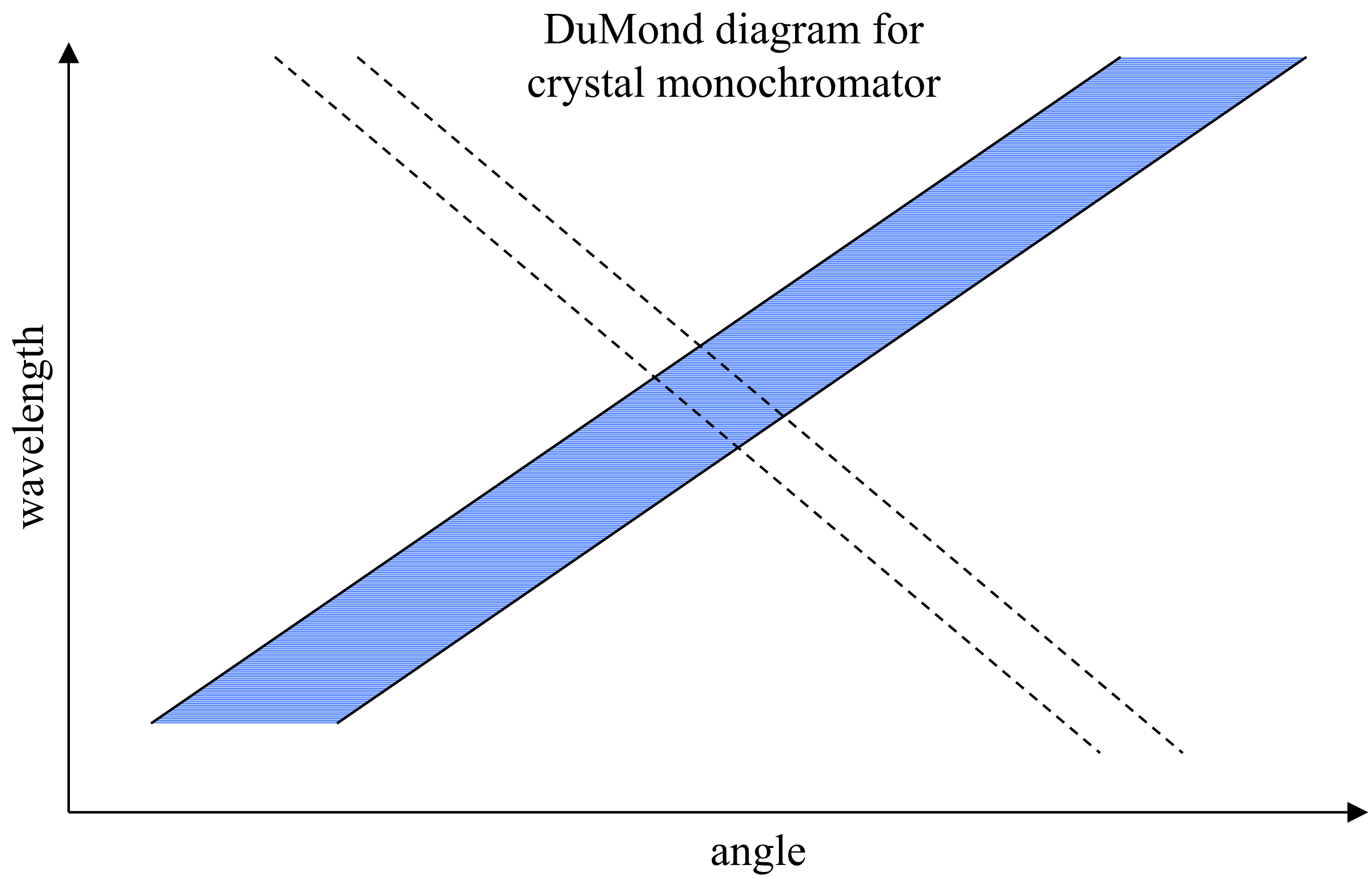
Brightness through aperture

For aperture σ_a at distance D, $\sigma'_a = \sigma_a / D$

$$\frac{F_n}{2\pi\sigma'^2_T} \frac{1}{1+\frac{\sigma_T^2}{\sigma_a^2}} \frac{1}{\sqrt{1+\left(\frac{N}{N_\delta}\right)^2 \frac{\sigma'^2_{cen}}{\sigma'^2_{x-ray}}}}$$

Optimum β depends on the pinhole, usually large

Real figure of merit for many beamlines



to maximize monochromator throughput one needs 1D brightness (flat beam ok)

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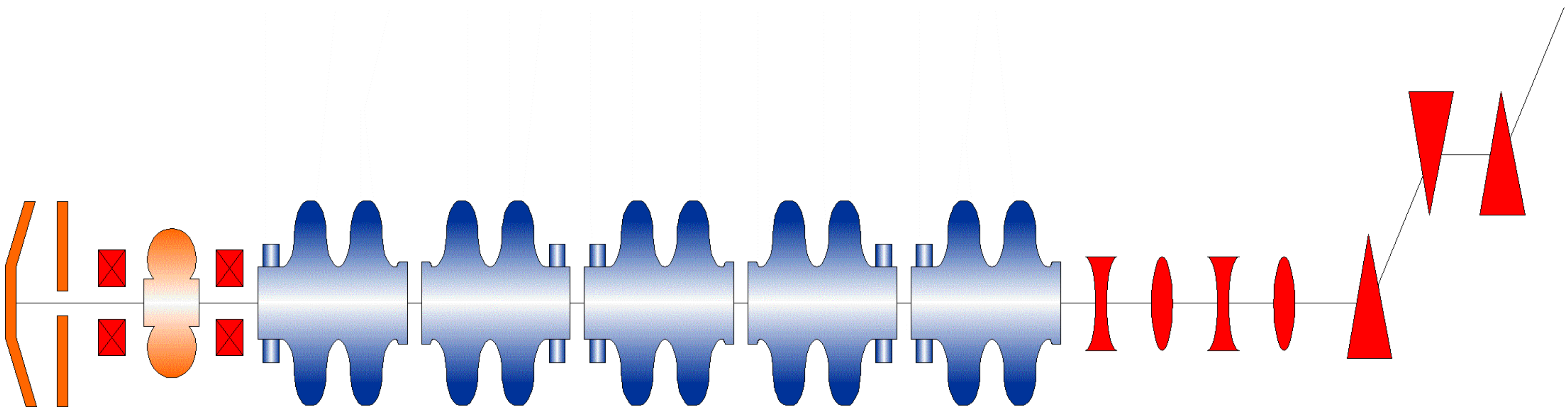
Optimized brilliance

$$\frac{F_n}{(\lambda/2)^2}\frac{1}{\left(1+\frac{\in}{\lambda/4\pi}\right)^2}\frac{1}{\sqrt{1+\left(\frac{N}{N_\delta}\right)^2\frac{\sigma'^2_{cen}}{\sigma'^2_{x-ray}}}}$$

For optimum $\beta \approx \frac{L}{2\pi}$

Phase 1a ERL injector schematic



Defocusing for uniform cylinder: $K_{s.c.} = -\frac{1}{2\in_{x,n}\beta_x(\beta\gamma)^2}\frac{I}{I_A}, \quad f_{s.c.} = \lim_{\Delta z \to 0}\frac{1}{K_{s.c.}\Delta z}$

One might expect this scaling: $\in \propto \frac{q_{bunch}}{\sigma_z}$

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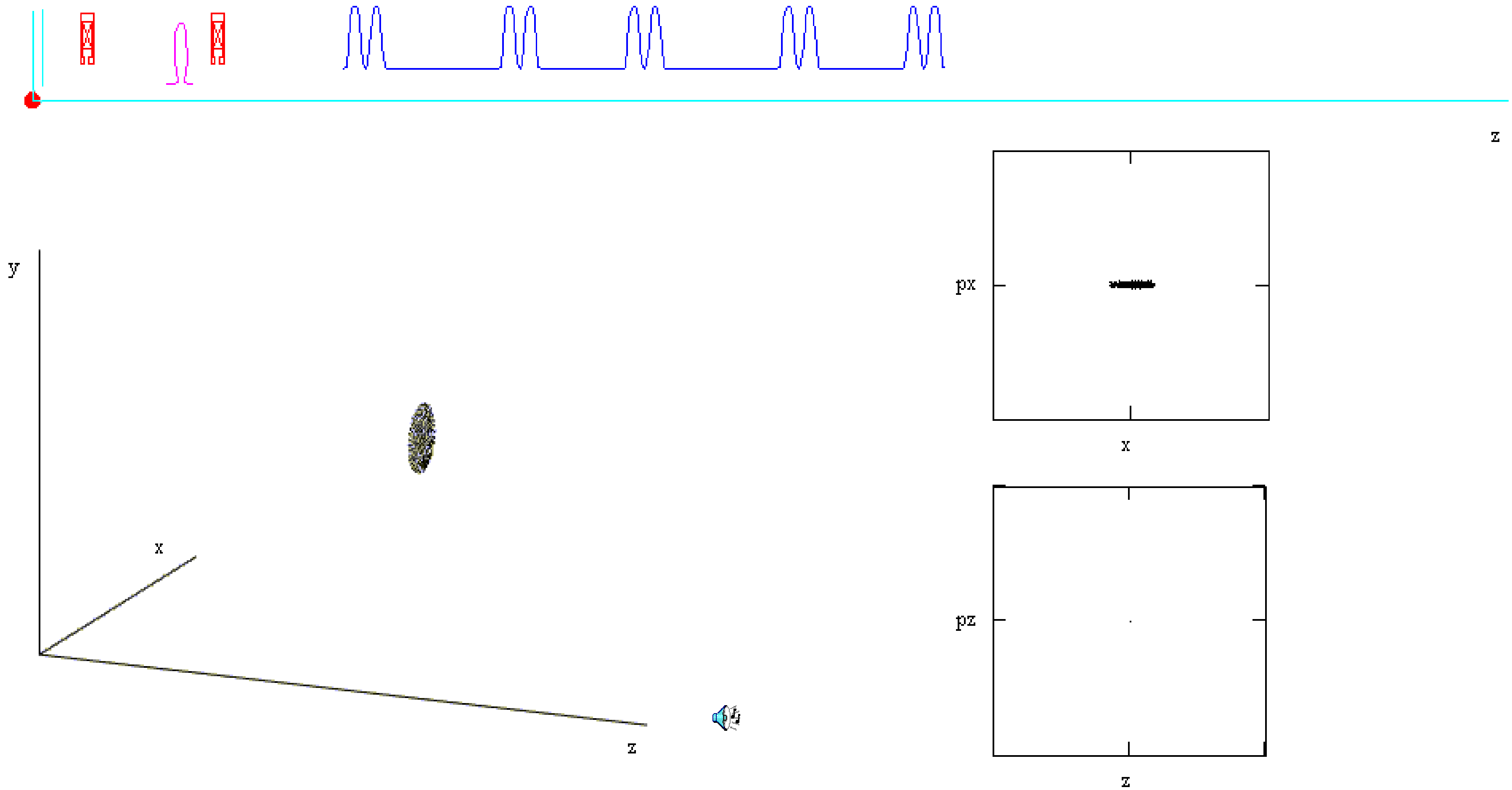
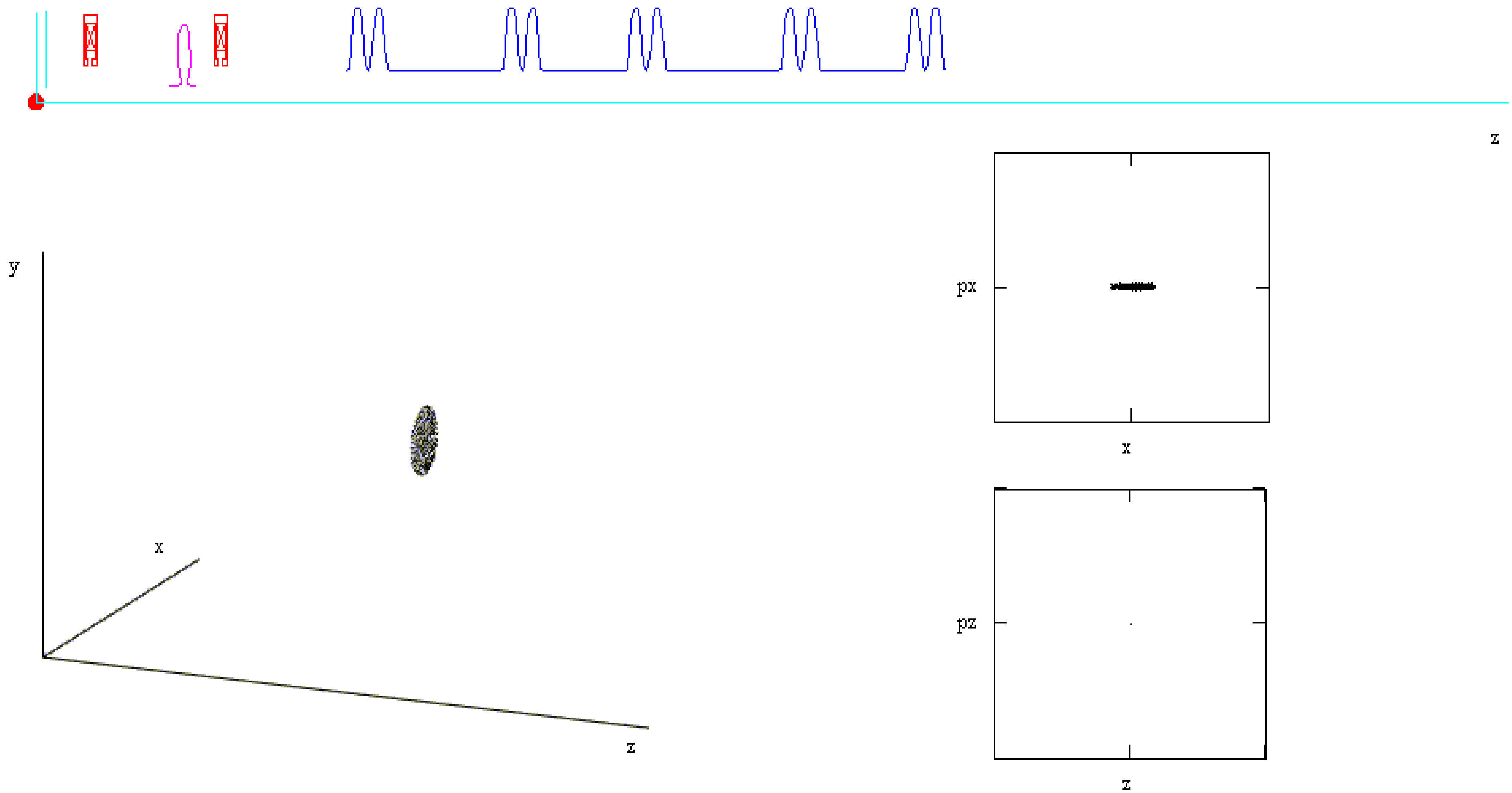
Bunch dynamics in the injector (77 pC)



Bunch dynamics at the DC gun (77 pC)



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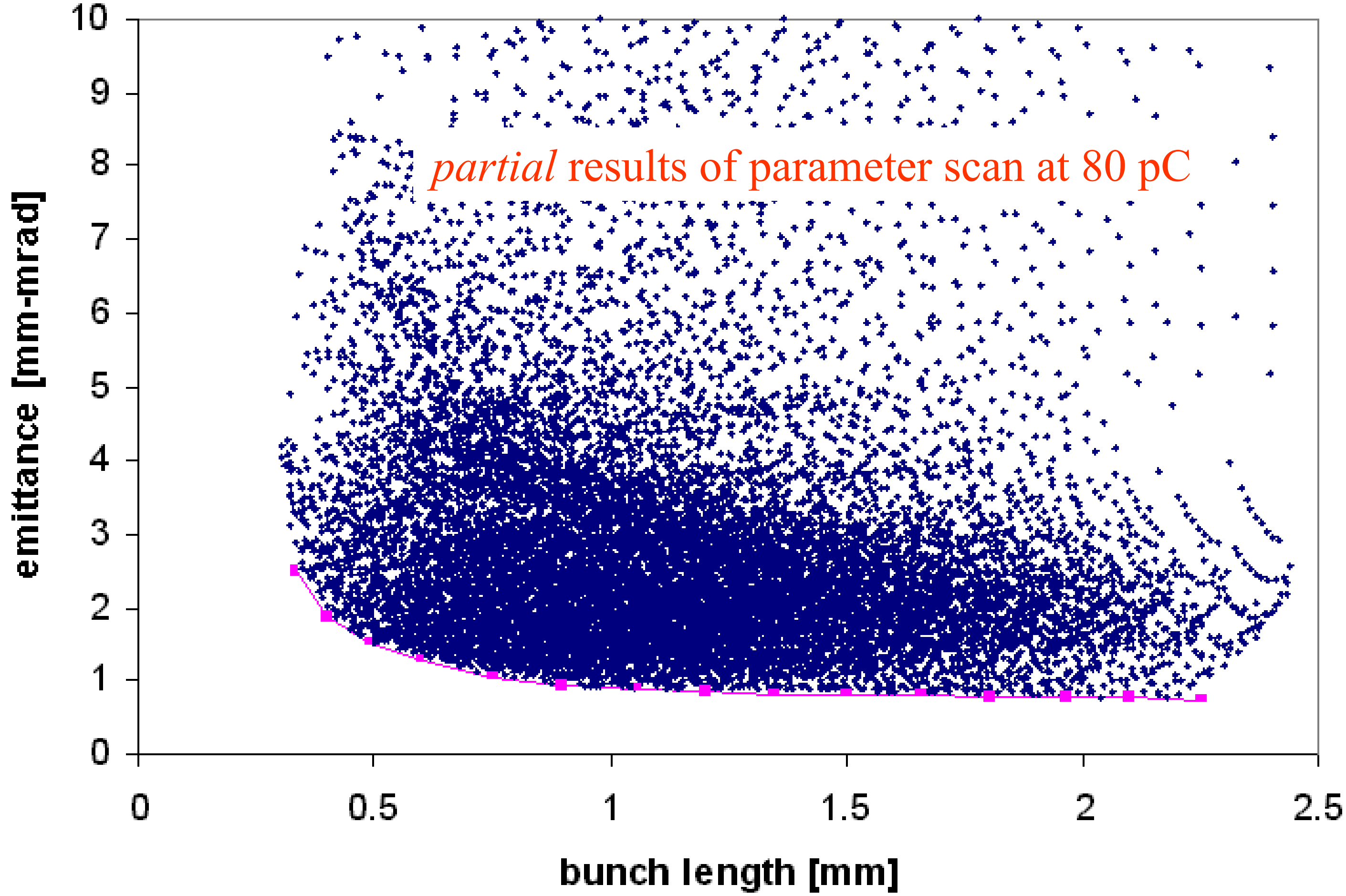
‘feynman’ at work on ERL injector



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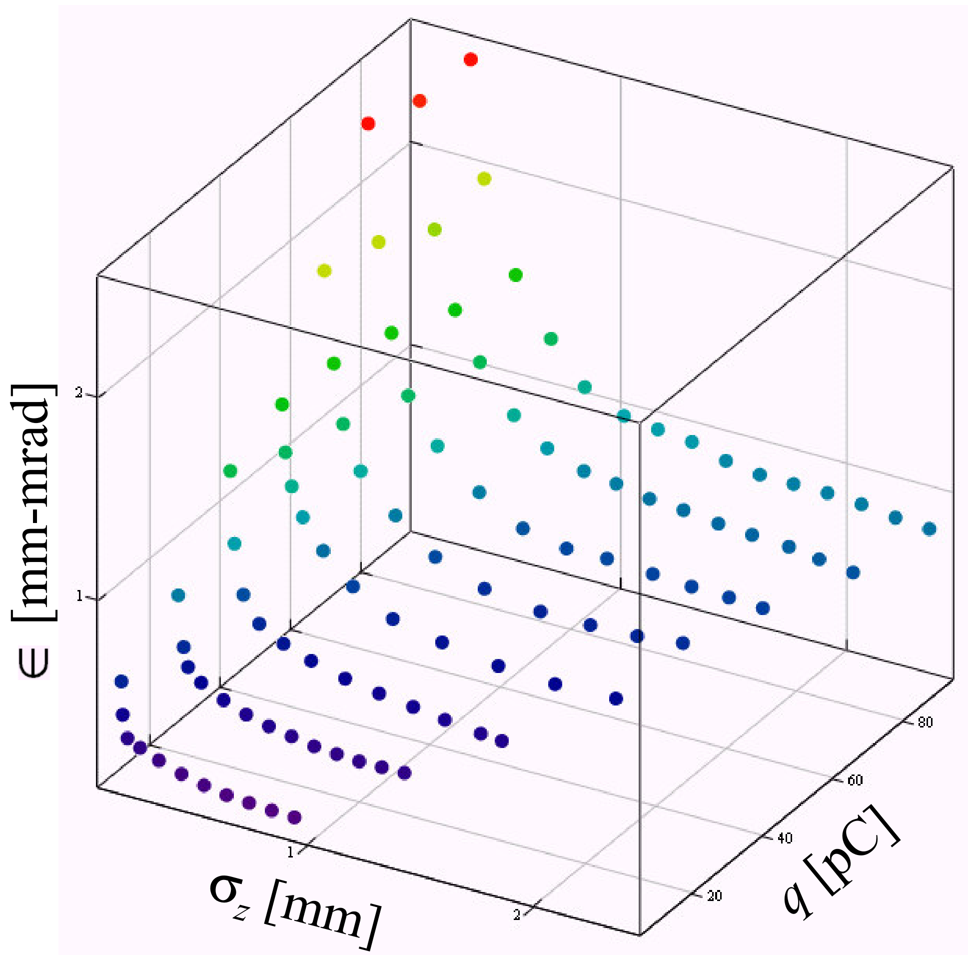
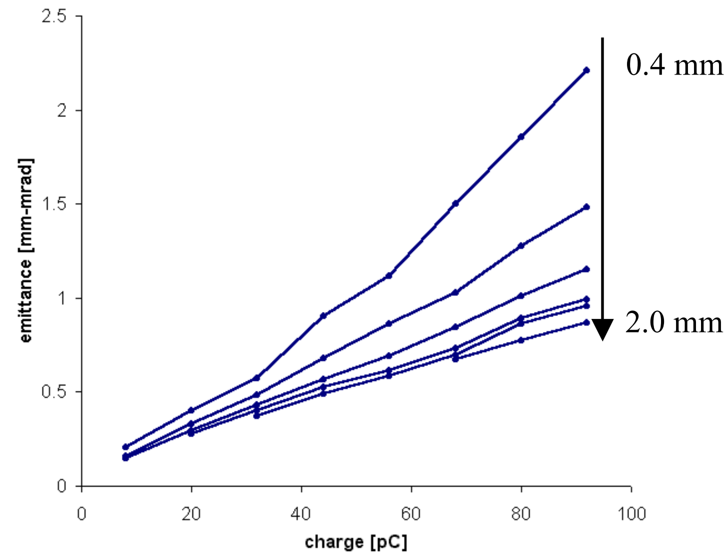
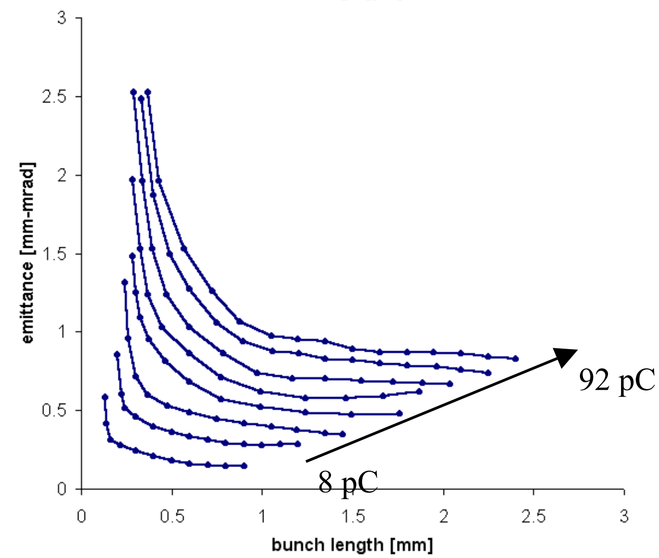
Emit. scaling vs. charge, vs. bunch length







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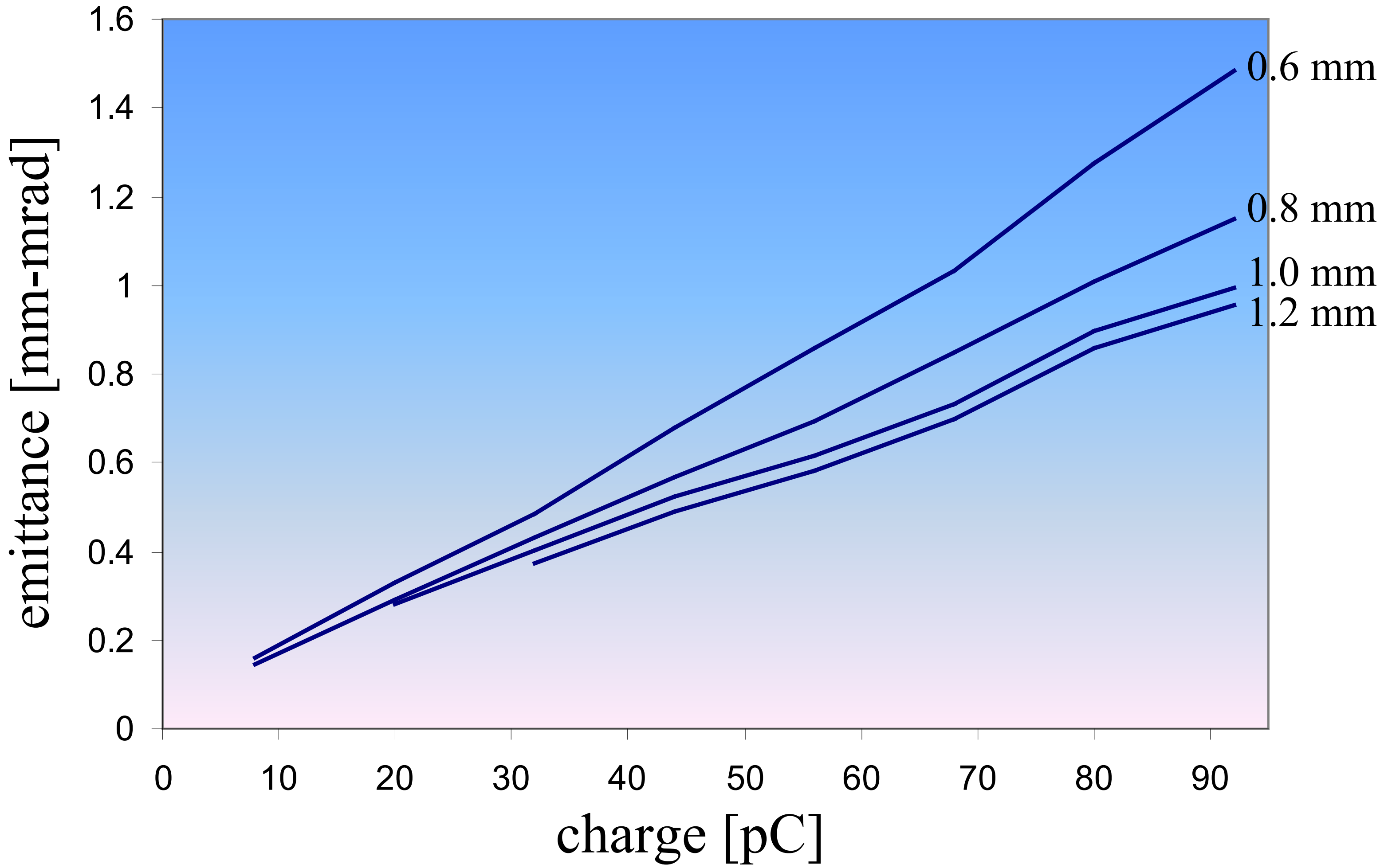
Scaling with charge



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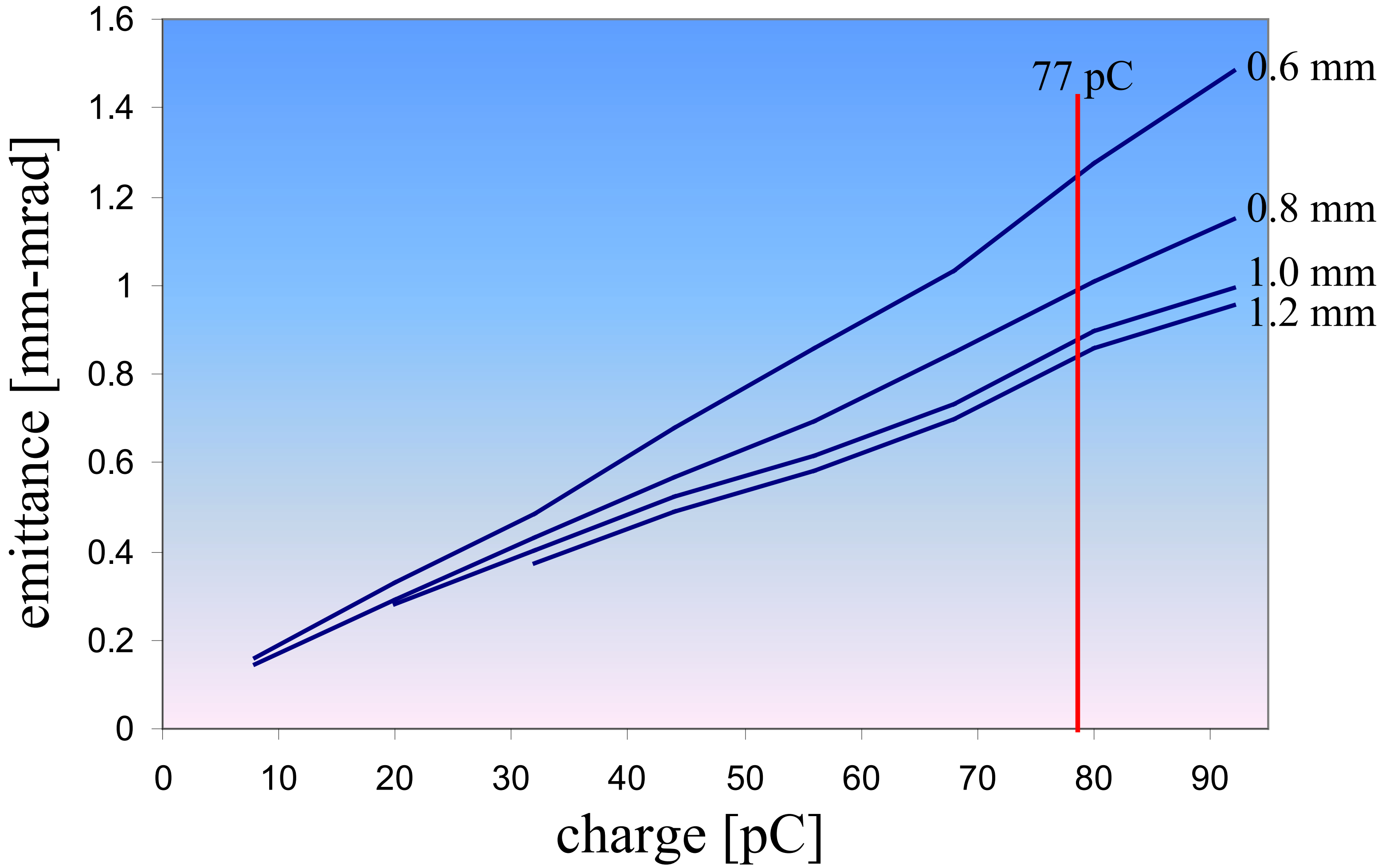
Scaling with charge



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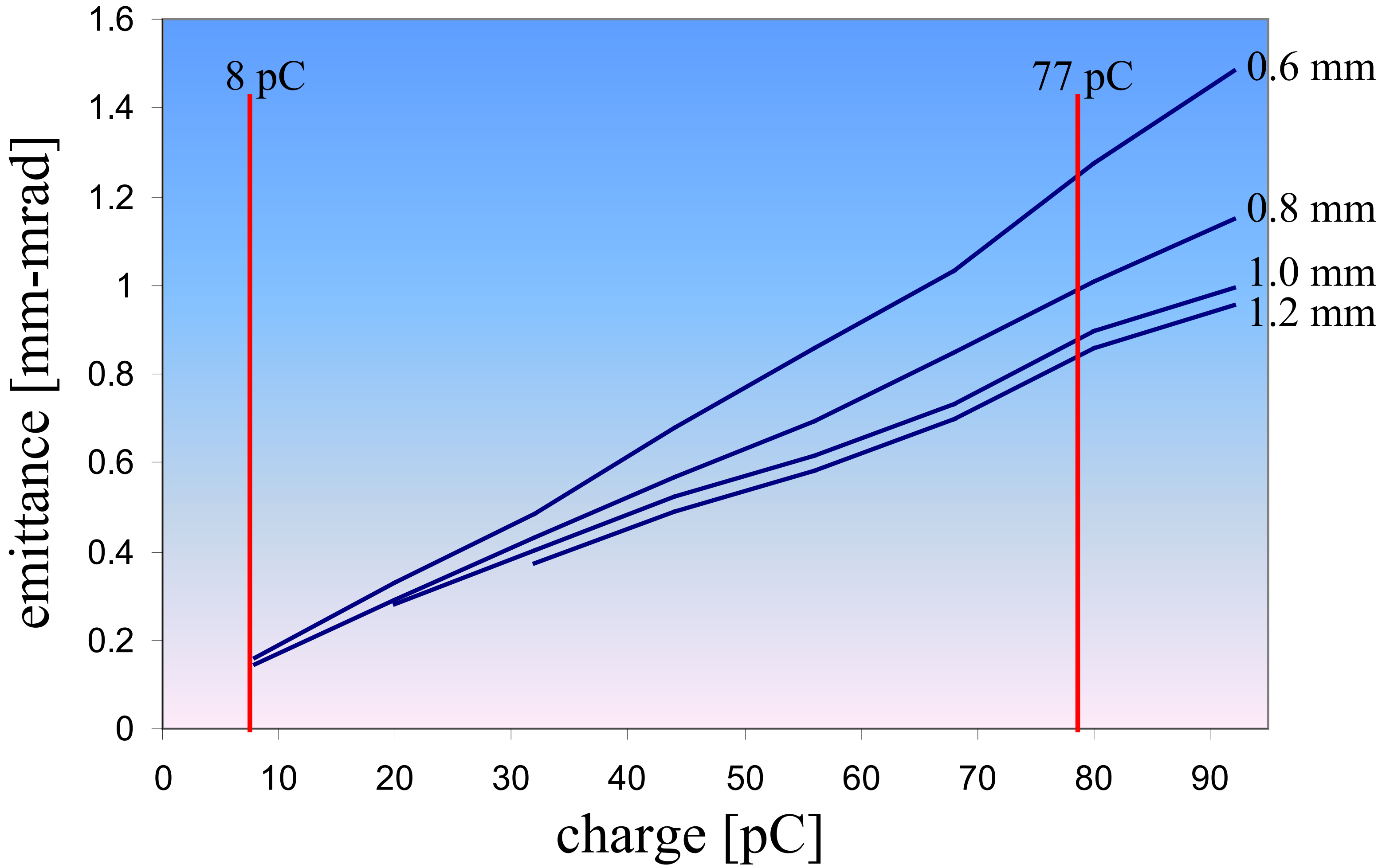

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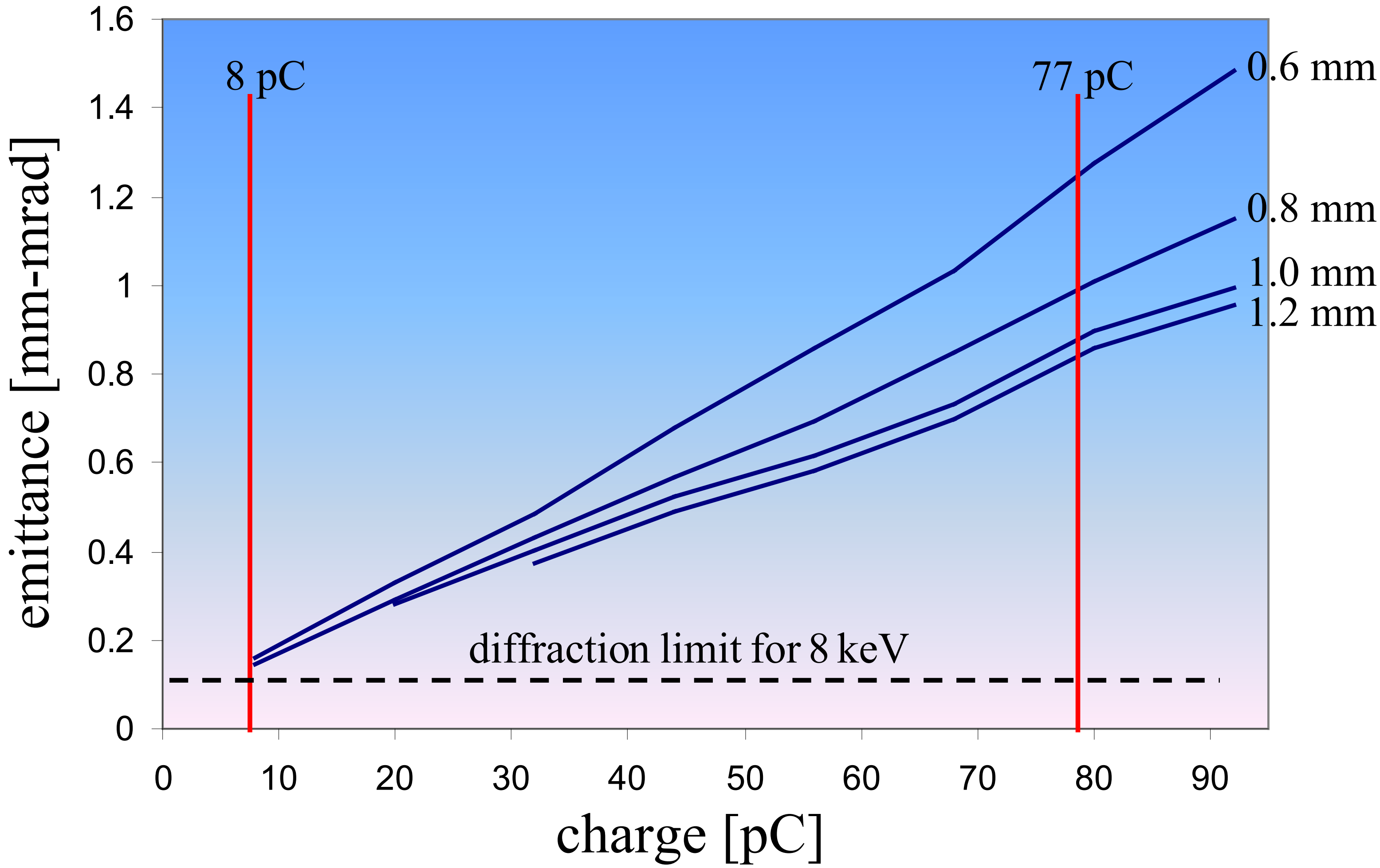

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Not the whole story…

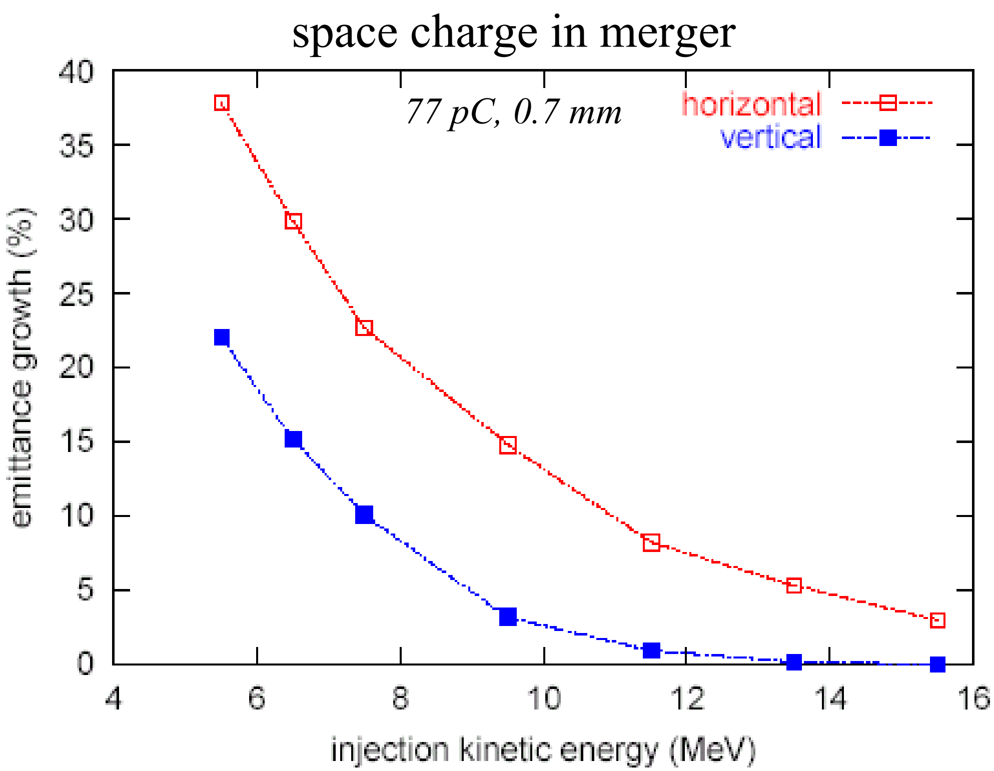

Figure 4: Emittance growth in the merger due to space charge for different injection energies. Initial rms normalized emittance is taken to be 1 mm-mrad.

Not the whole story…

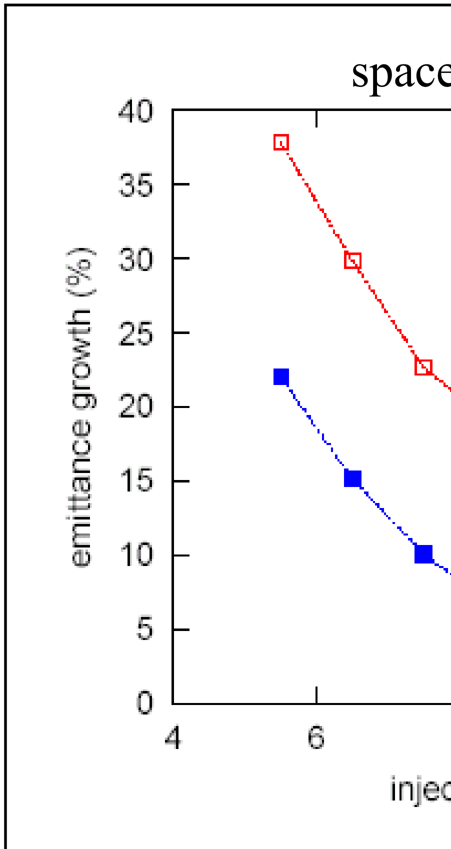

Figure 4: Emittance gr
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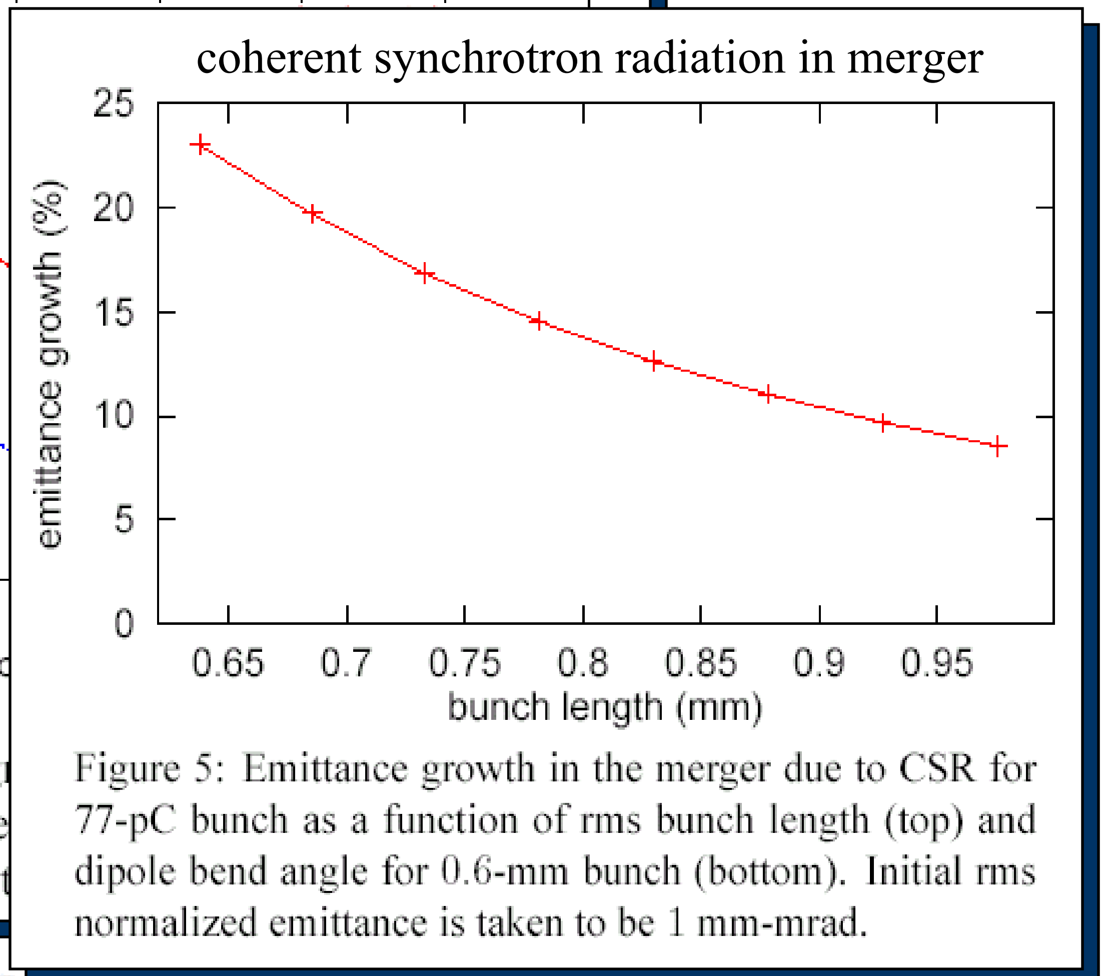
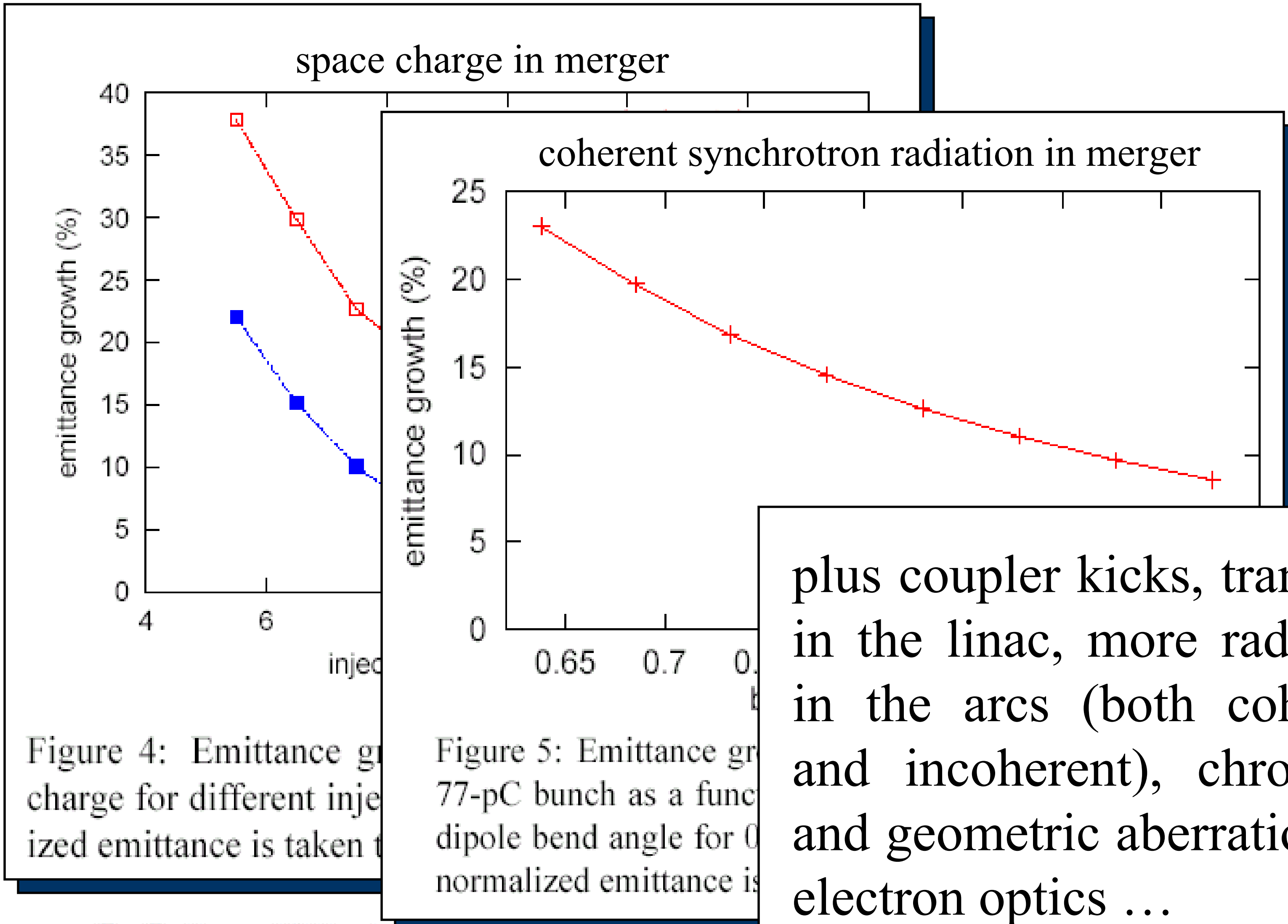


Figure 5: Emittance growth in the merger due to CSR for 77-pC bunch as a function of rms bunch length (top) and dipole bend angle for 0.6-mm bunch (bottom). Initial rms normalized emittance is taken to be 1 mm-mrad.

Not the whole story…



plus coupler kicks, transport in the linac, more radiation in the arcs (both coherent and incoherent), chromatic and geometric aberrations in electron optics …

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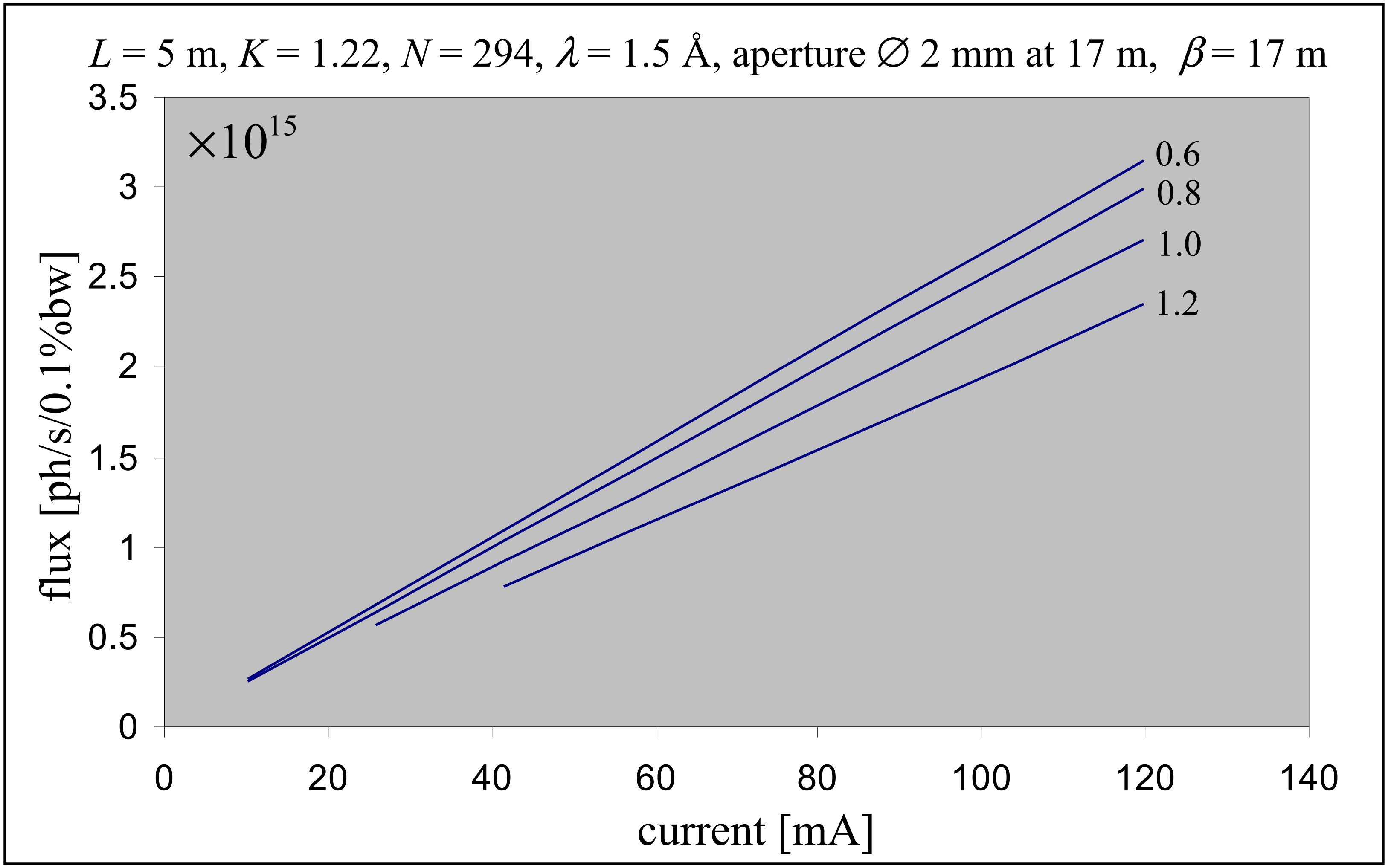
Flux scaling



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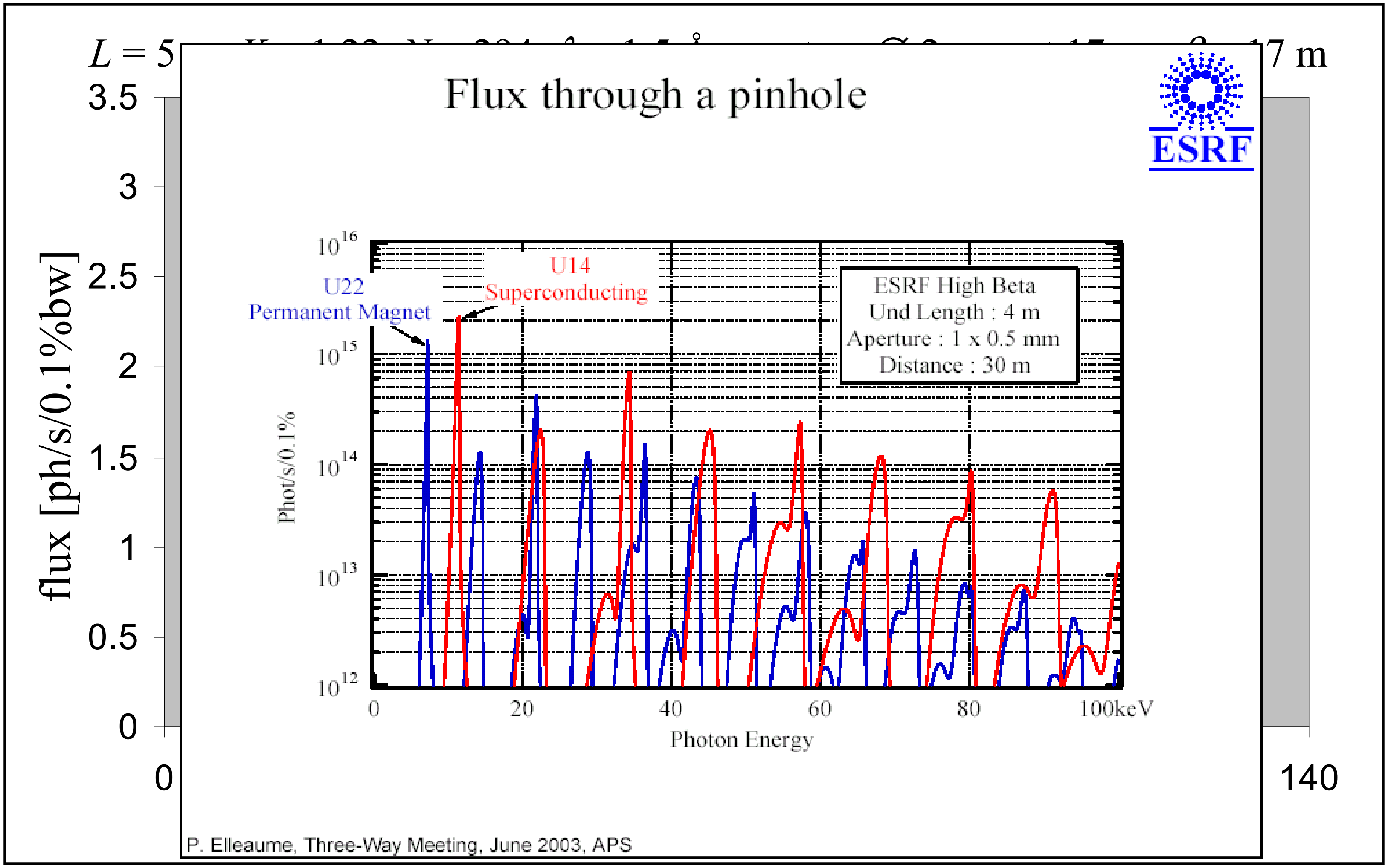

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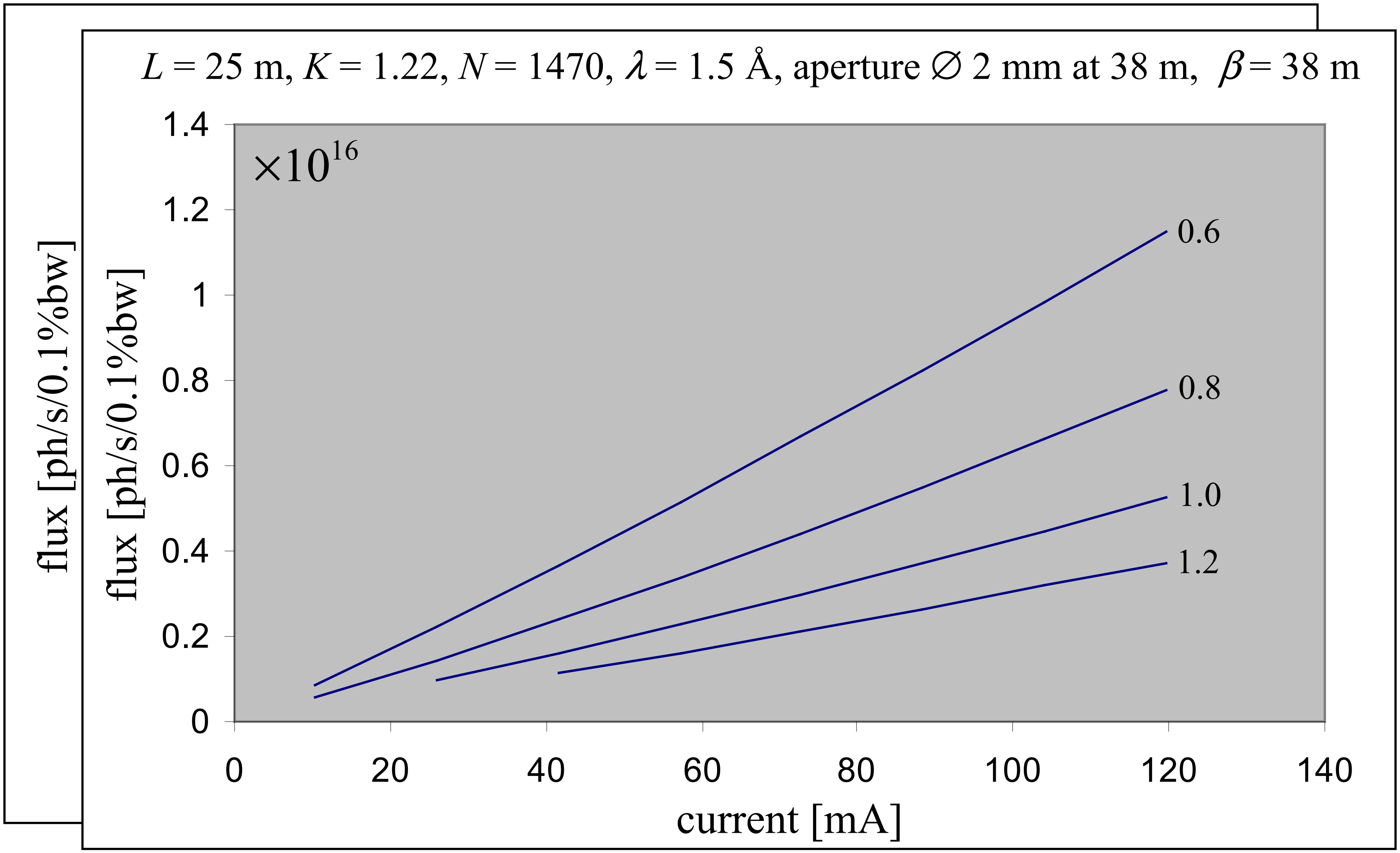
Flux scaling



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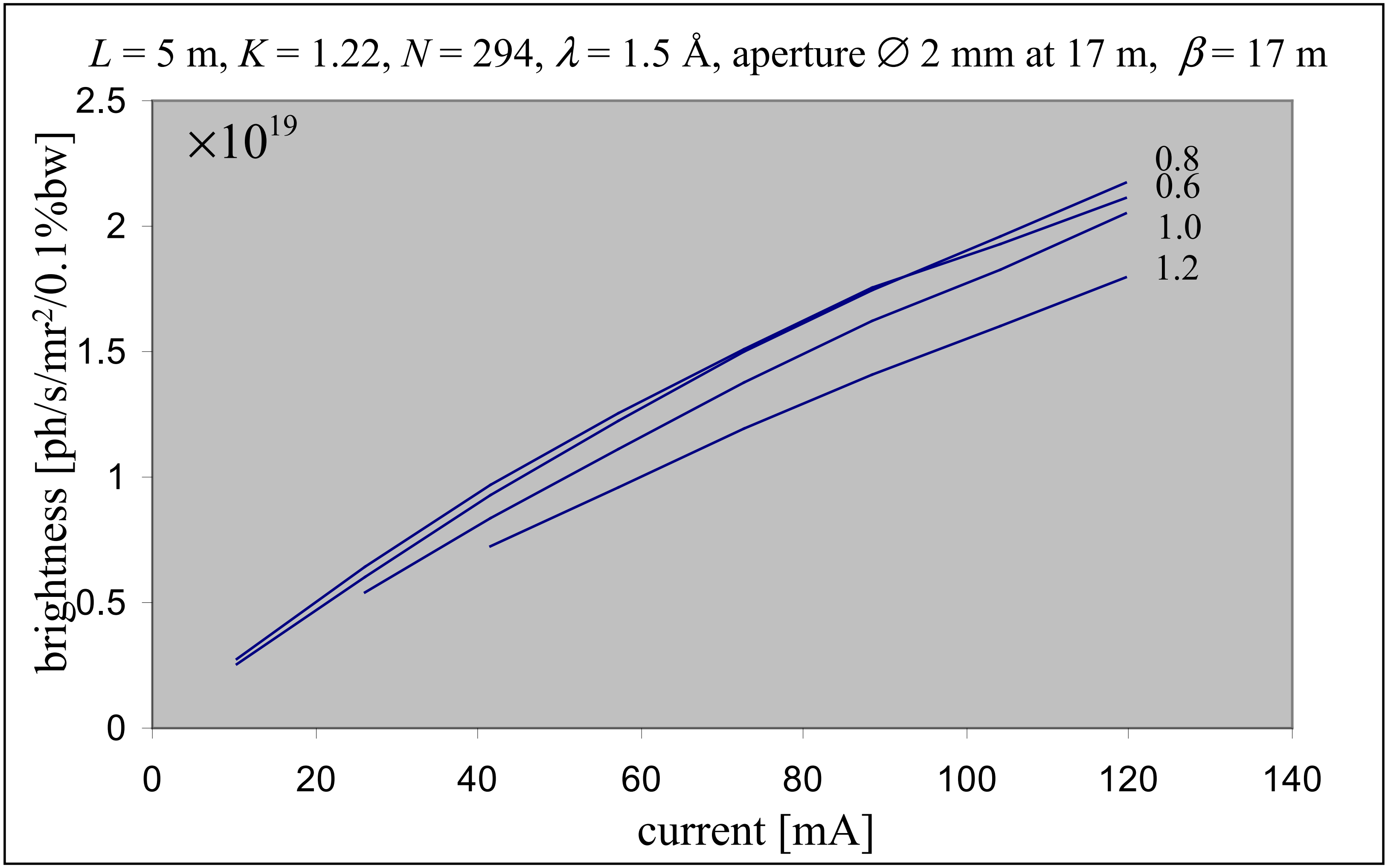
Brightness scaling



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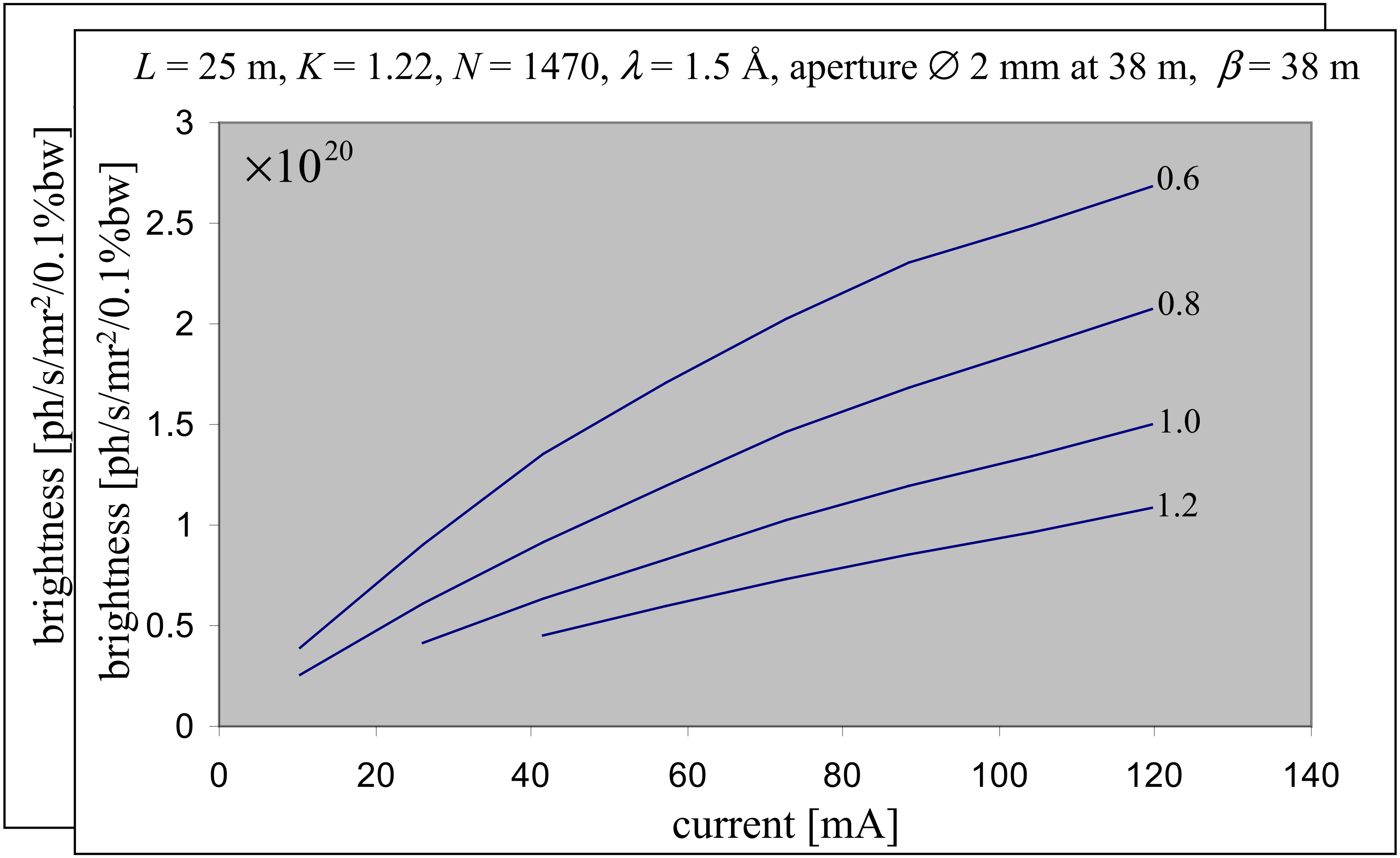
Brightness scaling



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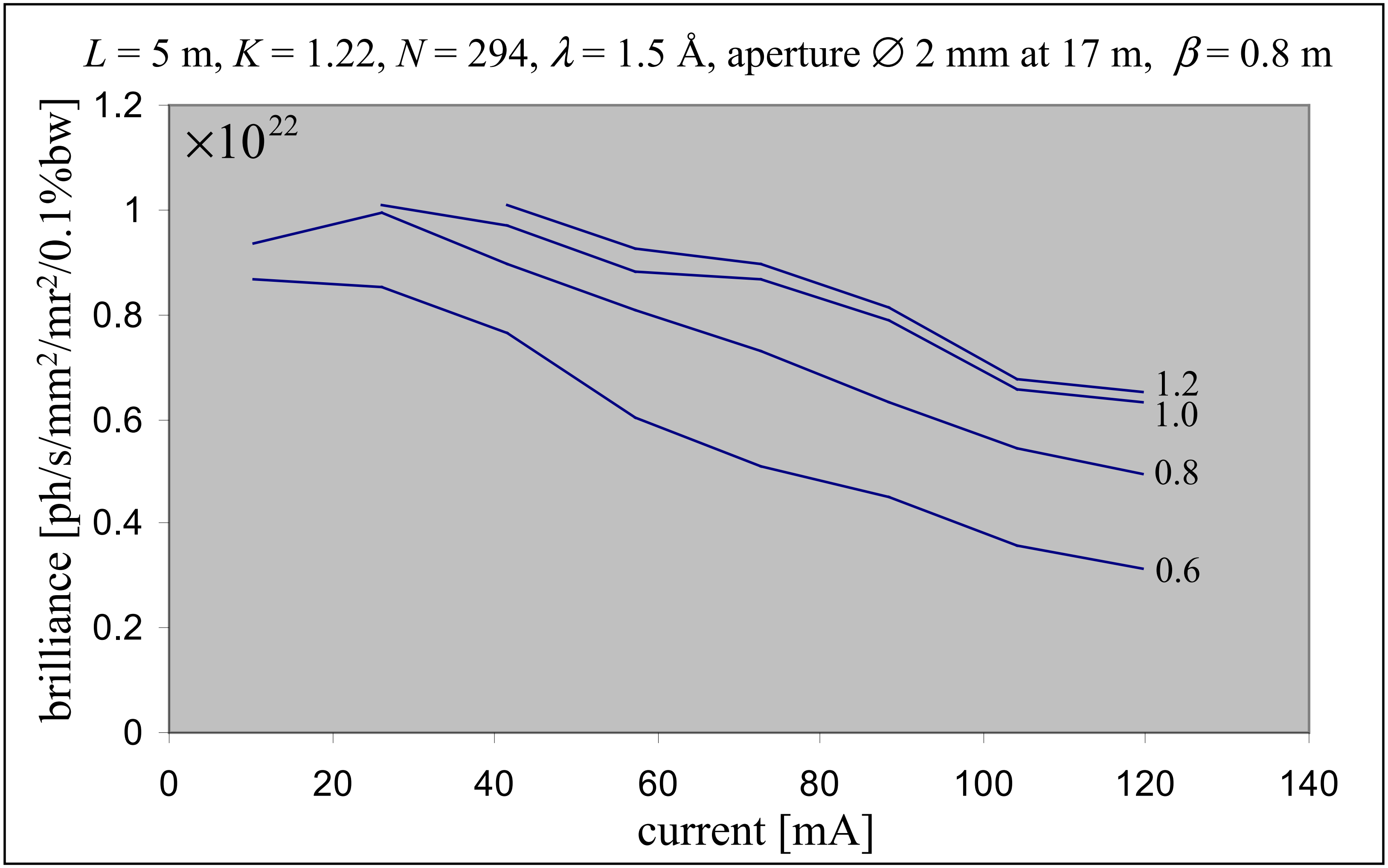
Brilliance scaling



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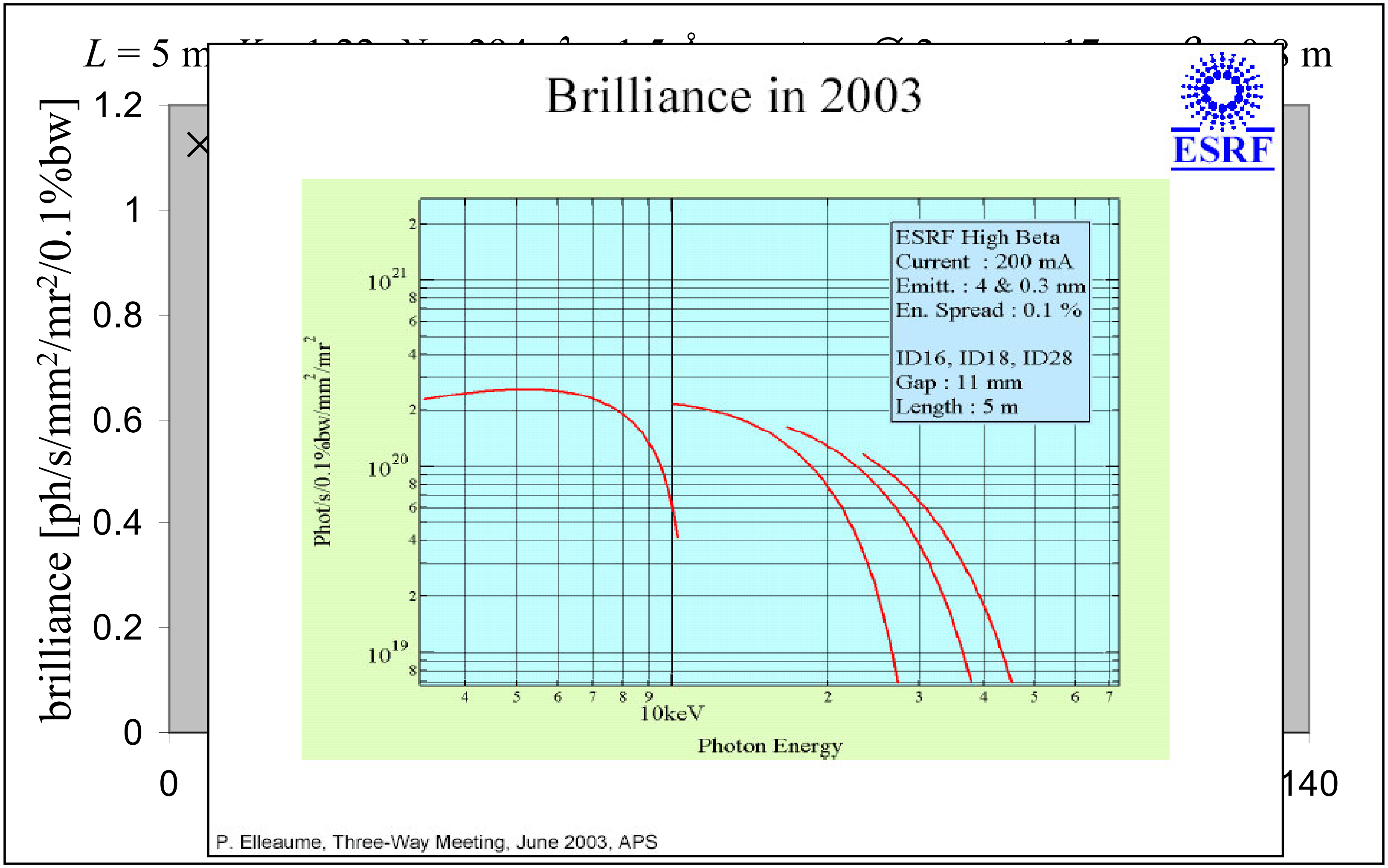
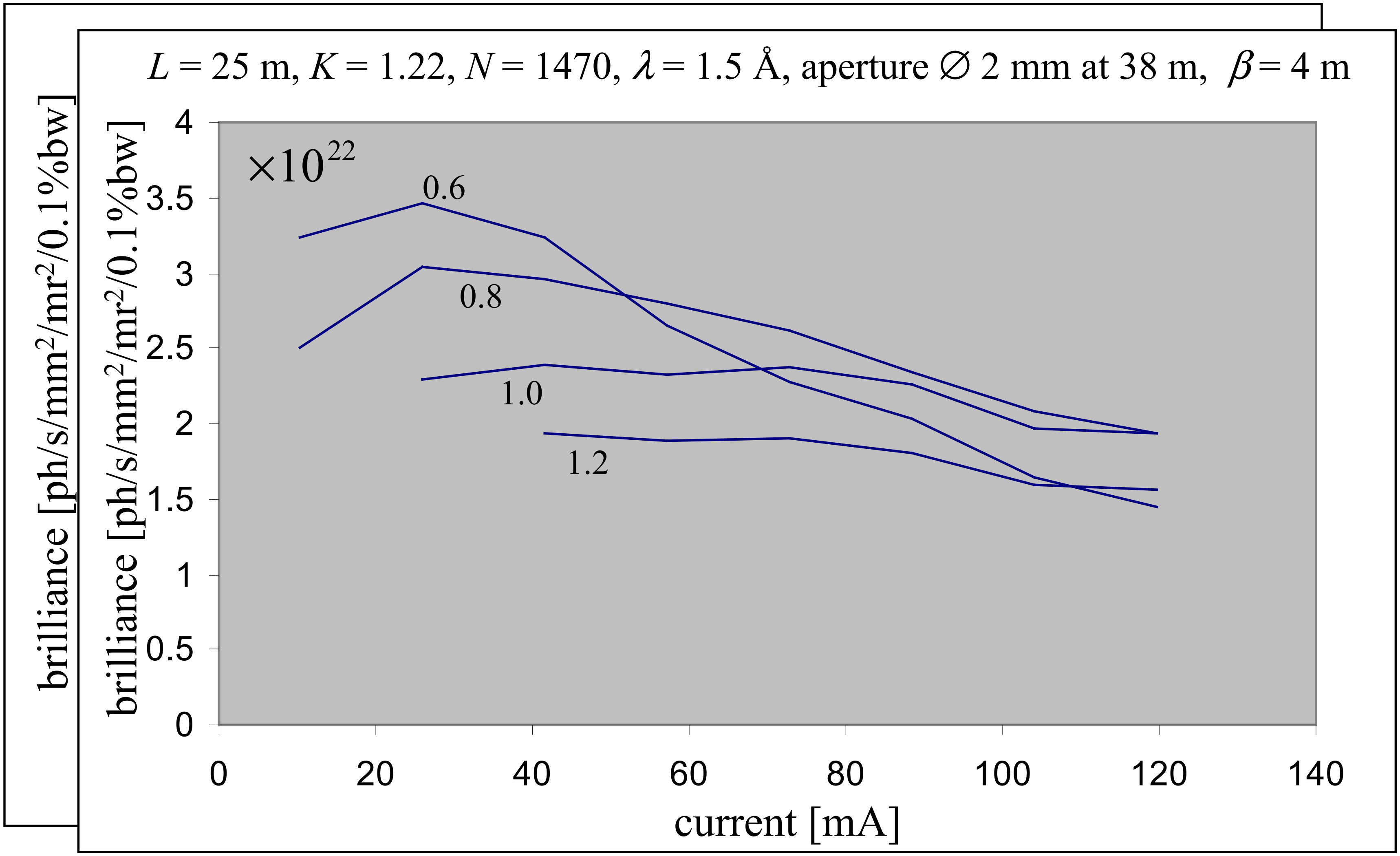
Brilliance scaling



Brilliance scaling



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Need small energy spread

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- compress the bunch length (either in the injector or early on in the main linac)

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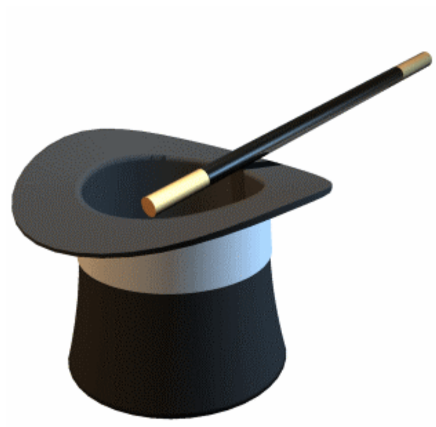

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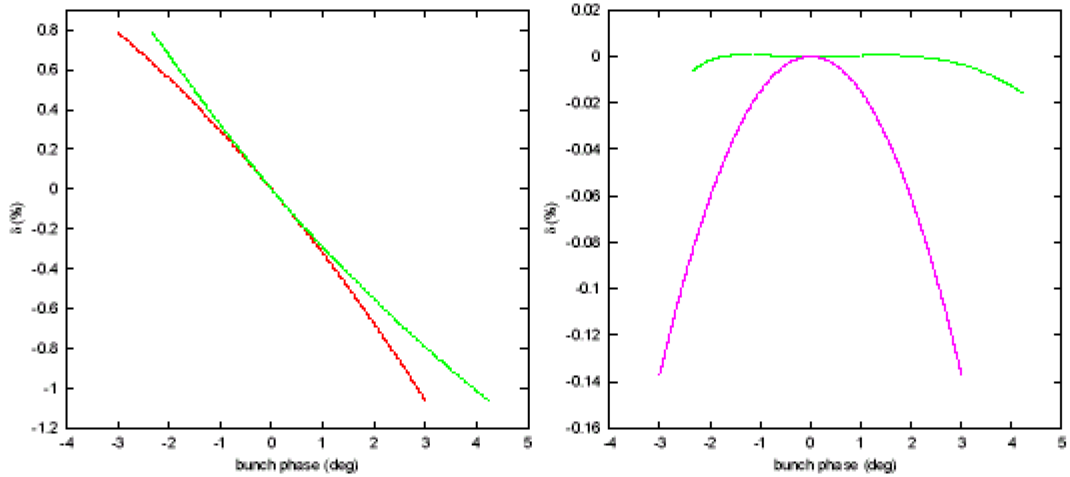
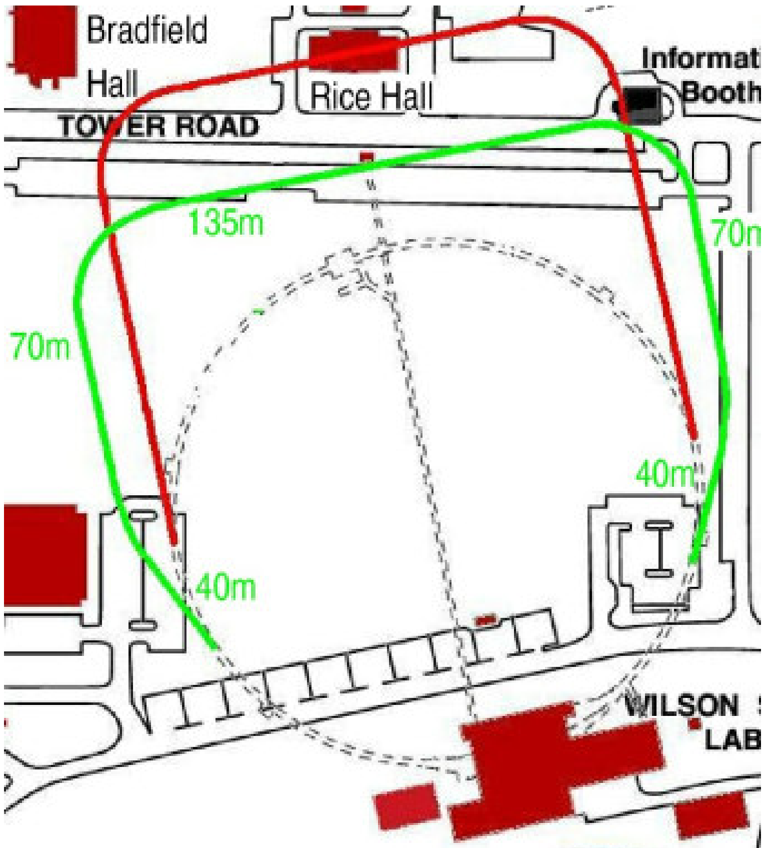
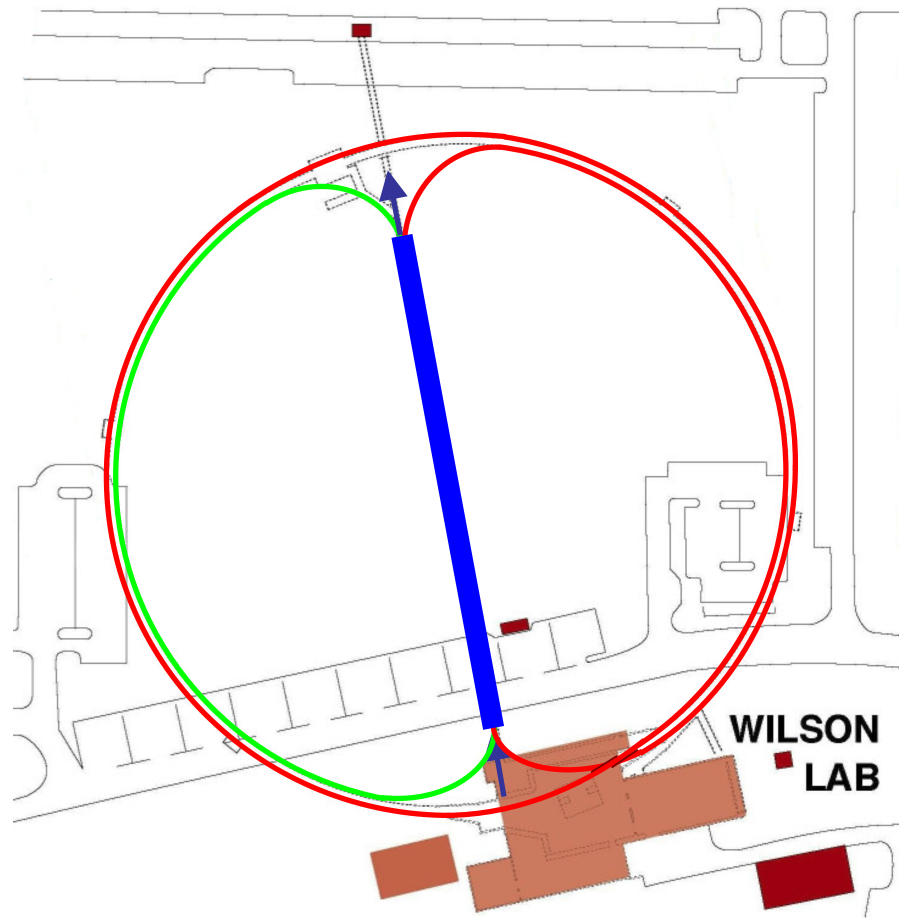


Figure 3. Energy spread compression using split linac configuration. On the left: longitudinal phase-space after the first section (solid line) and after properly chosen T_{566} (dashed line). On the right: the phase-space after linear and quadratic correlations have been removed after the second linac section. Phase-space distribution for on-crest operation is shown for comparison (dotted line).

Laying out ERL x-ray source





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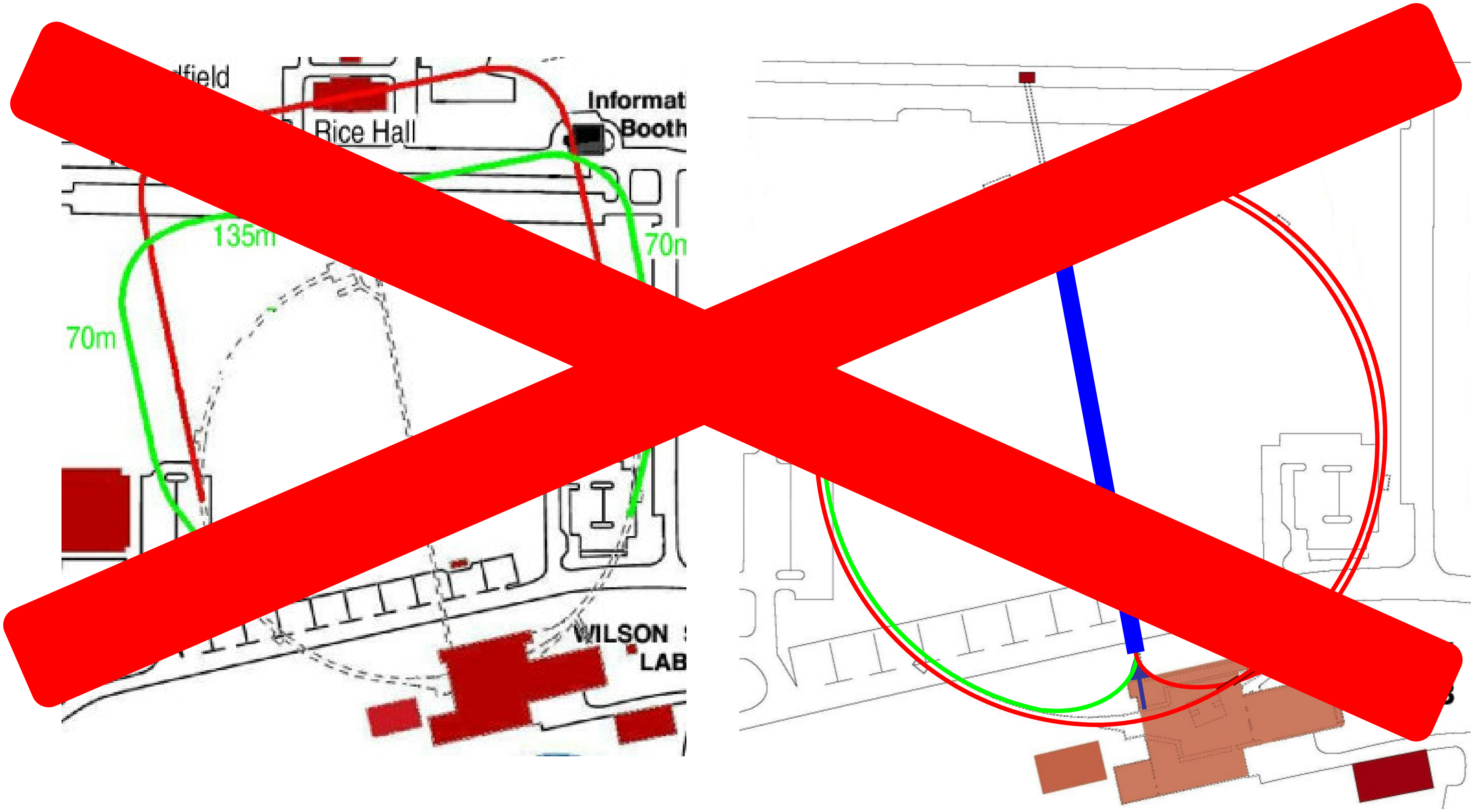
Laying out ERL x-ray source



Laying out ERL x-ray source

We're starting from the wrong end!

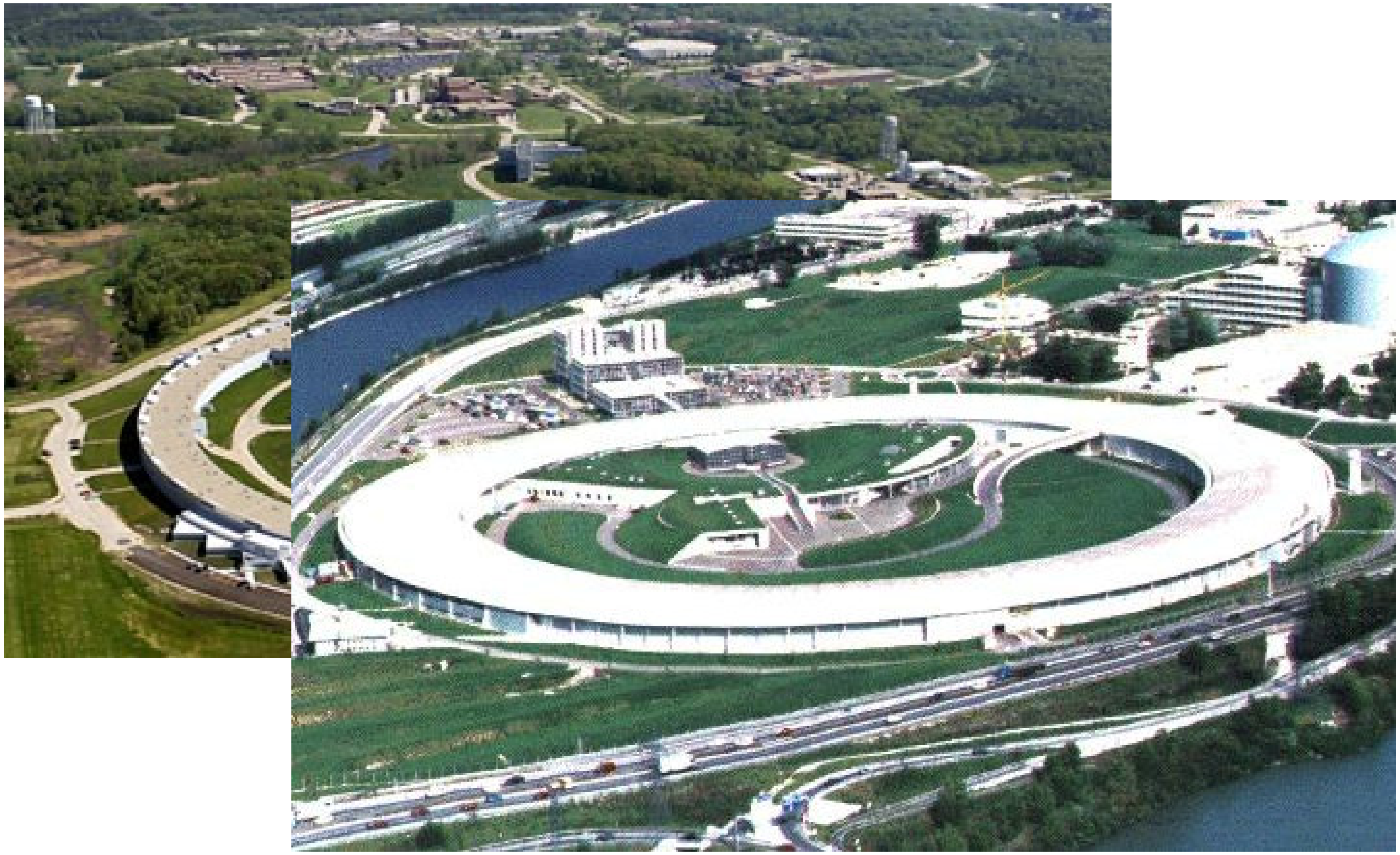
Should layout x-ray laboritories, beamlines, undulators first.

Accelerator folks will produce the rest of it.

Observation

Observation

Observation



Observation

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Observation

All ground level

To do list

X-ray folks

- (re)calculate photon budget & design beamlines' frontend (30 – 70 m) with specific applications / science case in mind, layout lab-space, undulators (≥ 12, i.e. should <u>not</u> be less than CHESS beamlines)

Accelerator folks

- continue to resolve outstanding issues, proceed with detailed proposal for accelerator after the input from CHESS