ERL-based X-ray source: promises and challenges

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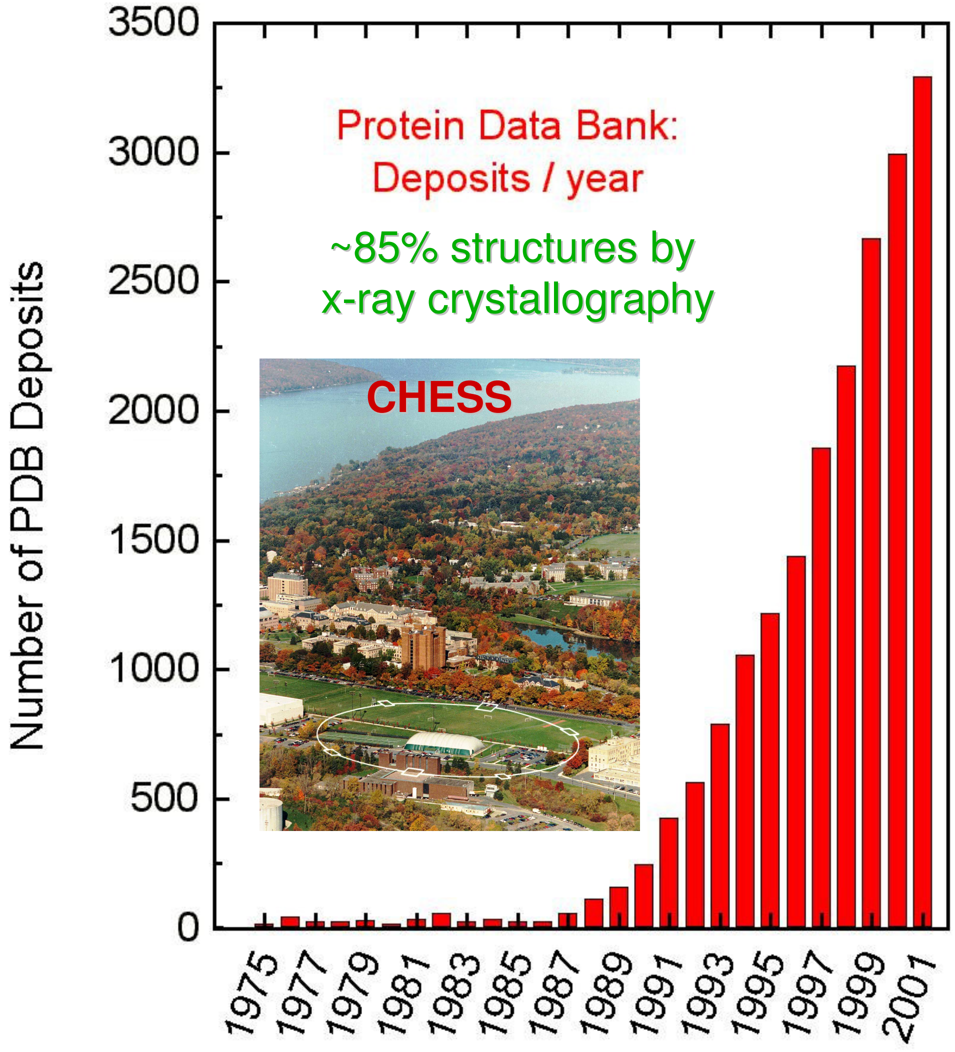
Outline

- Justification for an ERL X-ray source
    - cf. rings
    - cf. XFELs
- Main challenges
    - Injector performance
    - Beam-cavity interaction
    - Recirculating arc lattice & dynamics
- Summary & Outlook

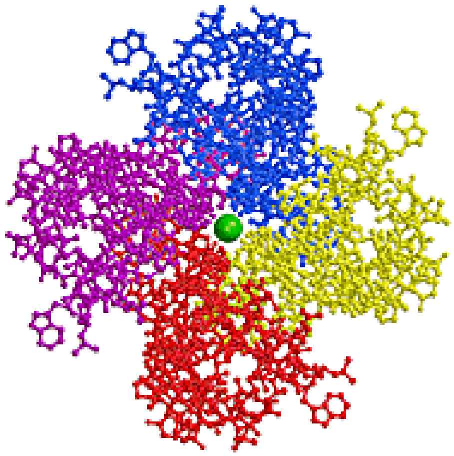
Demand for more X-rays



Protein Data Bank:
Deposits / year

~85% structures by
x-ray crystallography

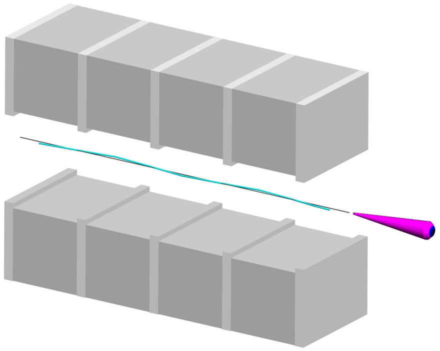
Ion channel protein



2003 Nobel Prize
in Chemistry:

Roderick MacKinnon
(Rockefeller Univ.)
1st K^+ channel structure
by x-ray crystallography
based on CHESS data (1998)

X-ray characteristics needed



- for properly tuned undulator: X-ray phase space is a replica from electron bunch + convolution with the diffraction limit

- ideally, one wants the phase space to be diffraction limited (i.e. full transverse coherence), e.g. $\varepsilon_{\perp,\mathrm{rms}} = \lambda/4\pi$, or 0.1 Å for 8 keV X-rays (Cu K_α), or **0.1 μm** normalized at 5 GeV

Flux	ph/s/0.1%bw
Brightness	ph/s/mrad^2/0.1%bw
Brilliance	**ph/s/mm^2/mrad^2/0.1%bw**

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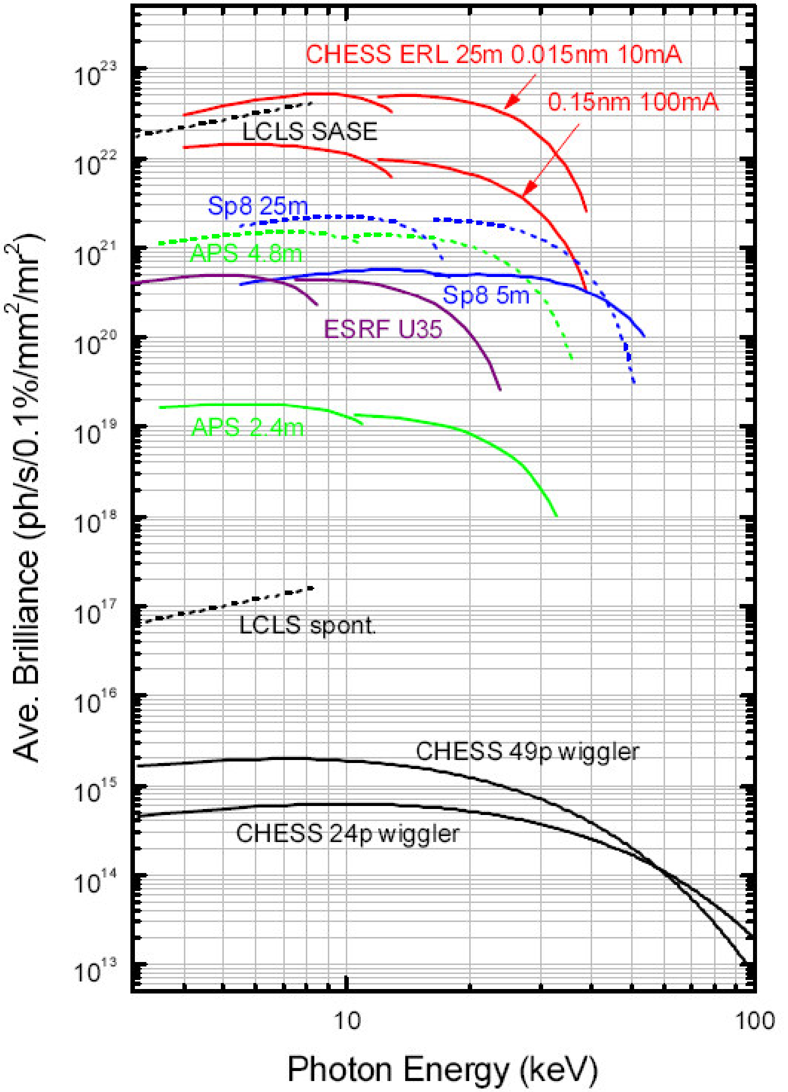
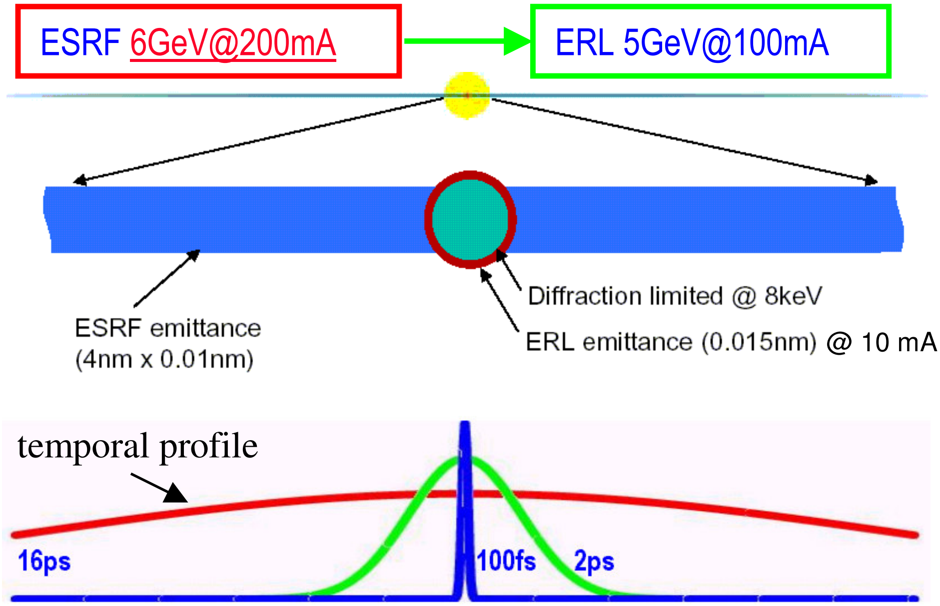
ERL vs. rings: 'fireworks' curves





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ERL vs. XFELs

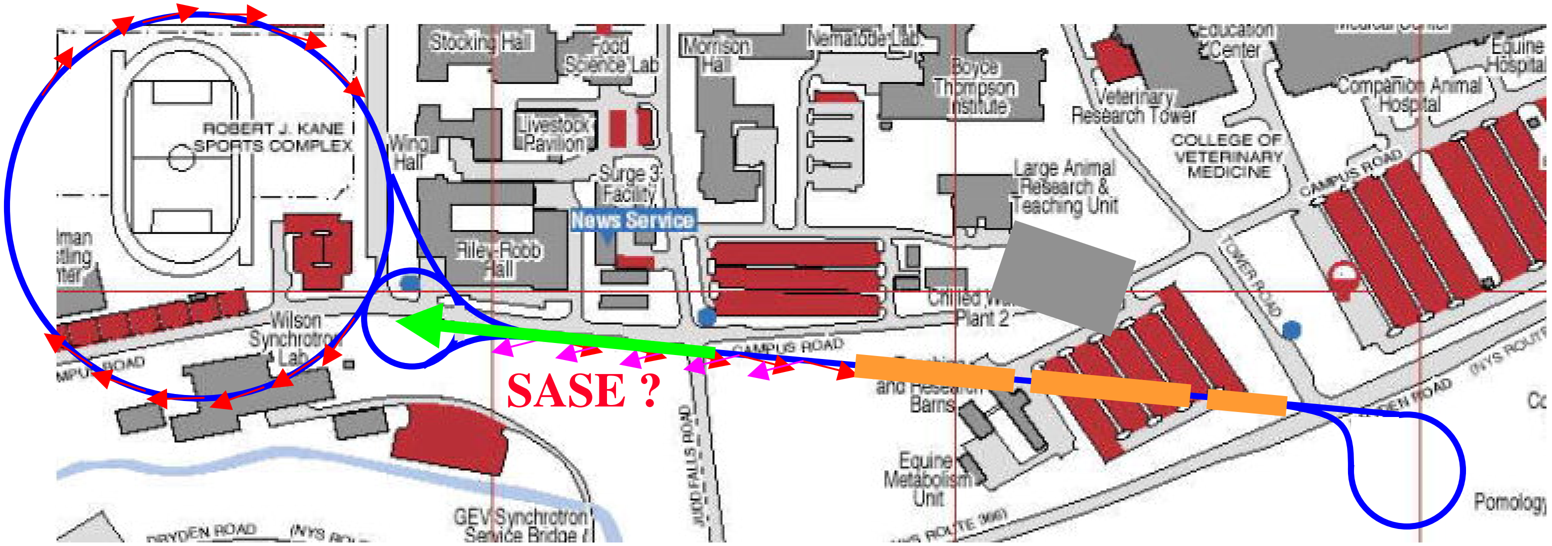
- Number of “coherent” photons *per electron* from an undulator with N_p periods is approximately $\alpha = 1/137$ (in $1/N_p$ bandwidth)
- XFEL produces $\times \rho N_e$ more “coherent” photons *per electron*, so a 10 μA XFEL will have similar average brilliance as 0.1 A ERL
- Why build an ERL?

ERL vs. XFELs (contd.)

- Fast non-thermal damage in XFELs will limit most of its experiments to a single shot ultrafast applications
- Virtually none of the existing X-ray experiments are of that sort
- E.g. LCLS pulse is damaging *low* Z material if focused to better than 10-30 µm, and worse for *high* Z elements (cf. X-ray microbeams used at the existing synchrotron sources are ≤ 100 nm)
- Bottom line: XFELs will *not* replace CW sources, but will complement them

Detour

- is it possible to design a future light source that will have both ERL and XFEL light production schemes (separately) in the hard X-ray region?
- such a machine will cover all basic needs / wishes of an X-ray experimentalist
- quick and dirty estimates show that a 5-7 GeV linac can in principle lase at few Angstrom wavelength



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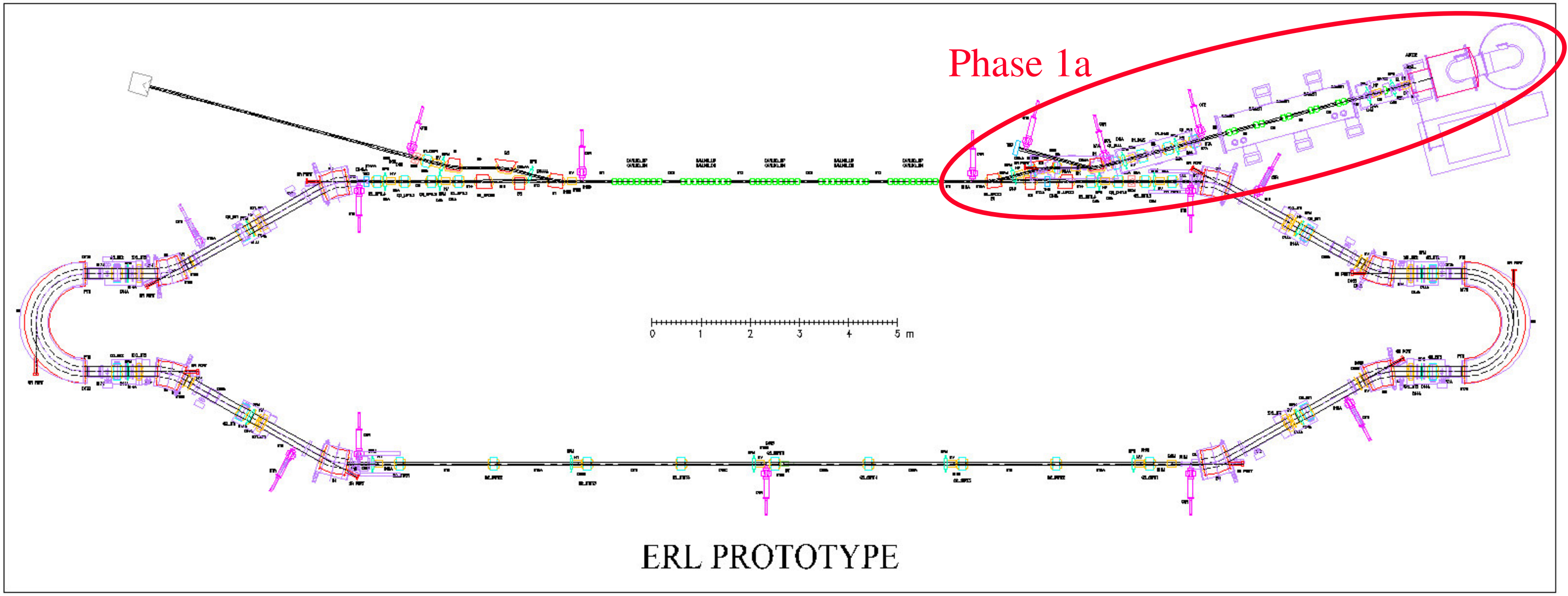
ERL Phase 1a+1b



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

Injector specs that justify ERL

- Most often used figure of merit for synchrotron light-sources

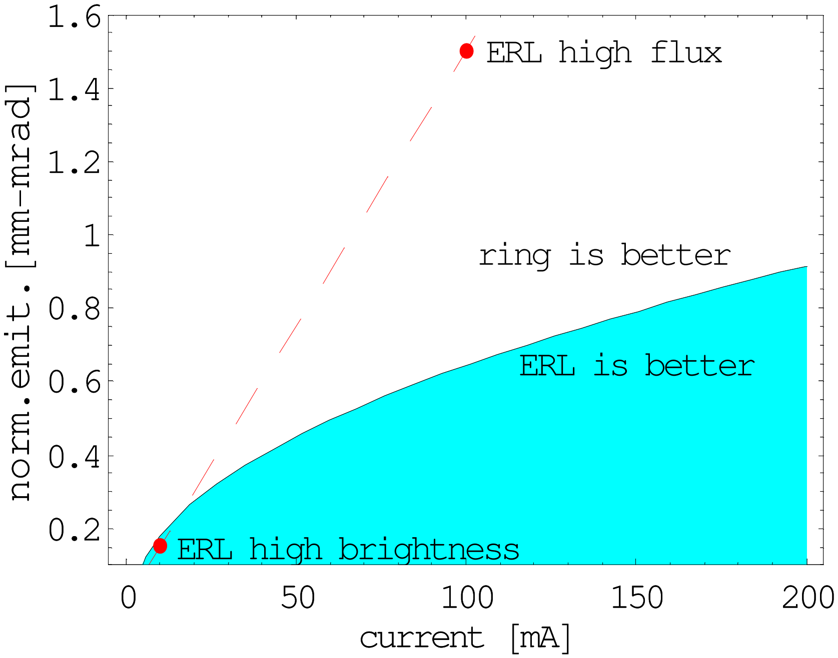
$$B \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

- Storage rings already operate at diffraction limit in vertical plane (for ~ 10 keV photons that corresponds to 0.1 Å-rad rms), also future rings will be designed with yet smaller horizontal emittance

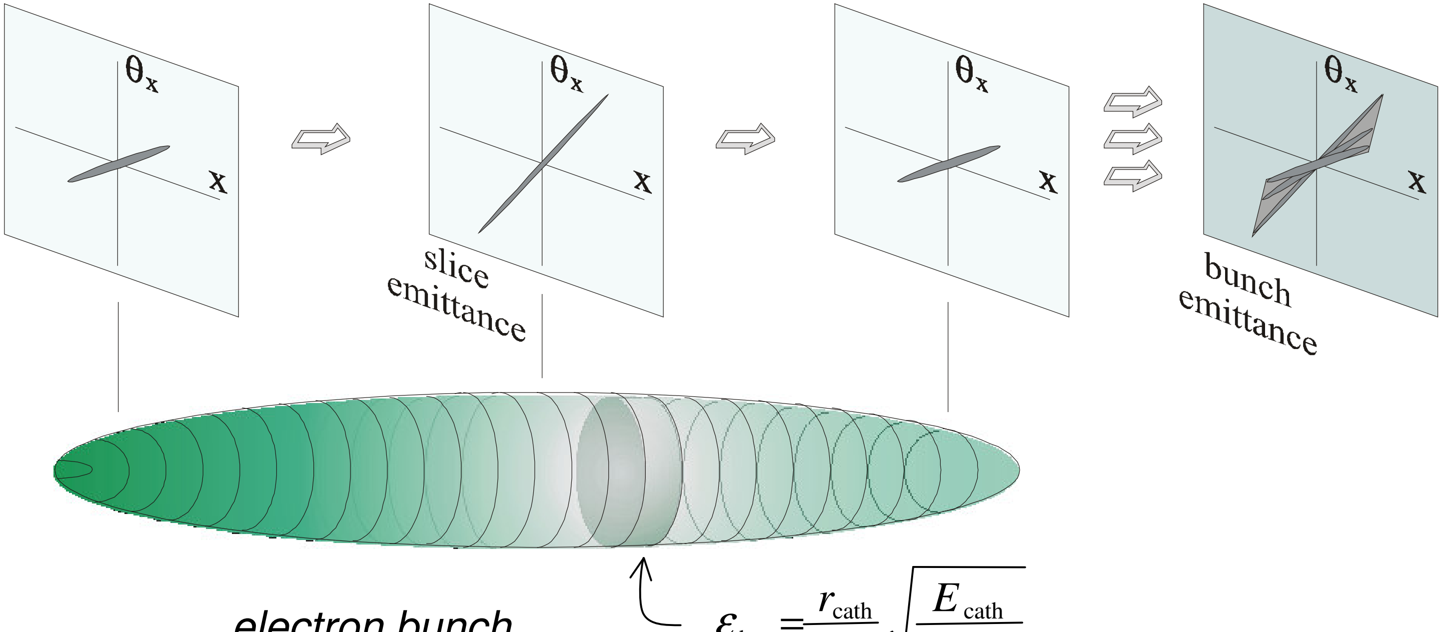
- e.g. NSLS planned new ring

$$B \propto \frac{500\,\text{mA}}{15 \times 0.1\,(\text{Å-rad})^2} \quad \Rightarrow$$

5.11 GeV ERL



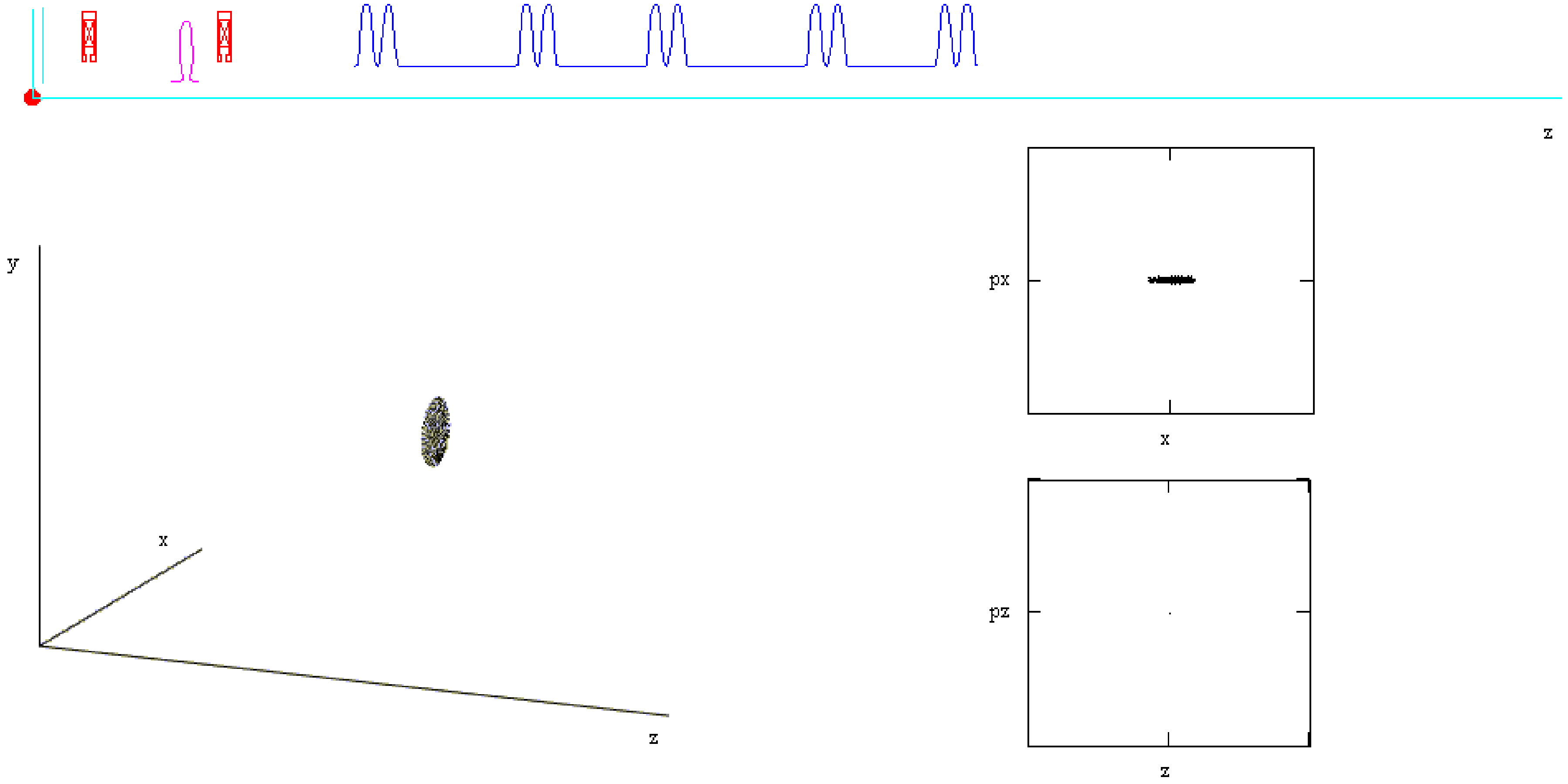
Space charge in the injector



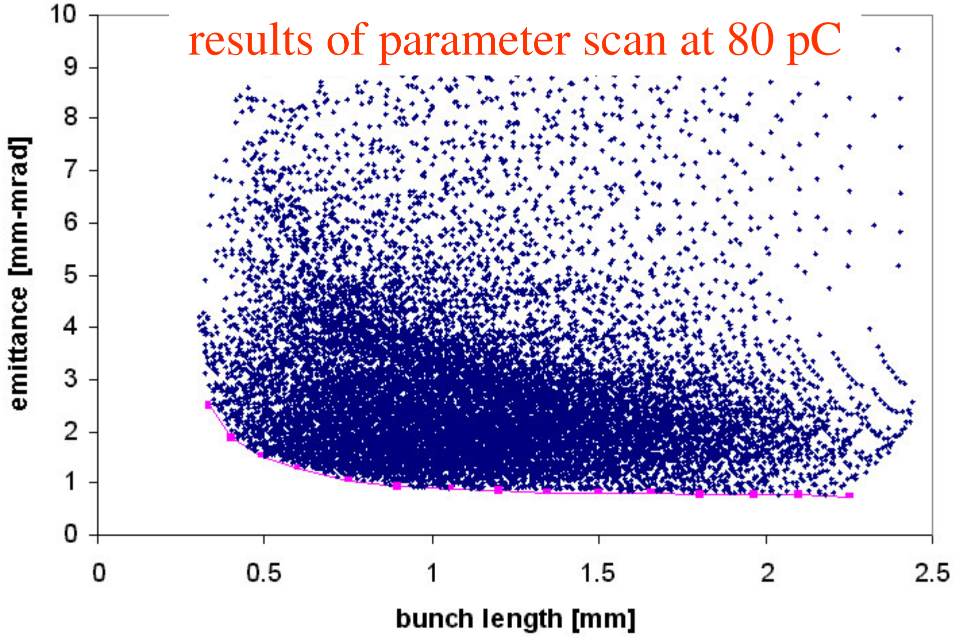
$$\varepsilon_{\text{th}} = \frac{r_{\text{cath}}}{2}\sqrt{\frac{E_{\text{cath}}}{mc^2}}$$

- if beam matched to Brillouin eq. flow condition → s.c. vs. external focusing leads to reversible emittance oscillations → ‘freeze out’ the s.c. by acceleration when minimum occurs (e.g. Phys. Rev. E, **55**, 7565)
- one can use sliced-beer-can model code HOMDYN to find appr. working points
- ultimately, a complete simulation with ***realistic*** profiles (esp. long.) is required

Bunch dynamics in the injector (77 pC)



‘feynman’ at work on ERL injector



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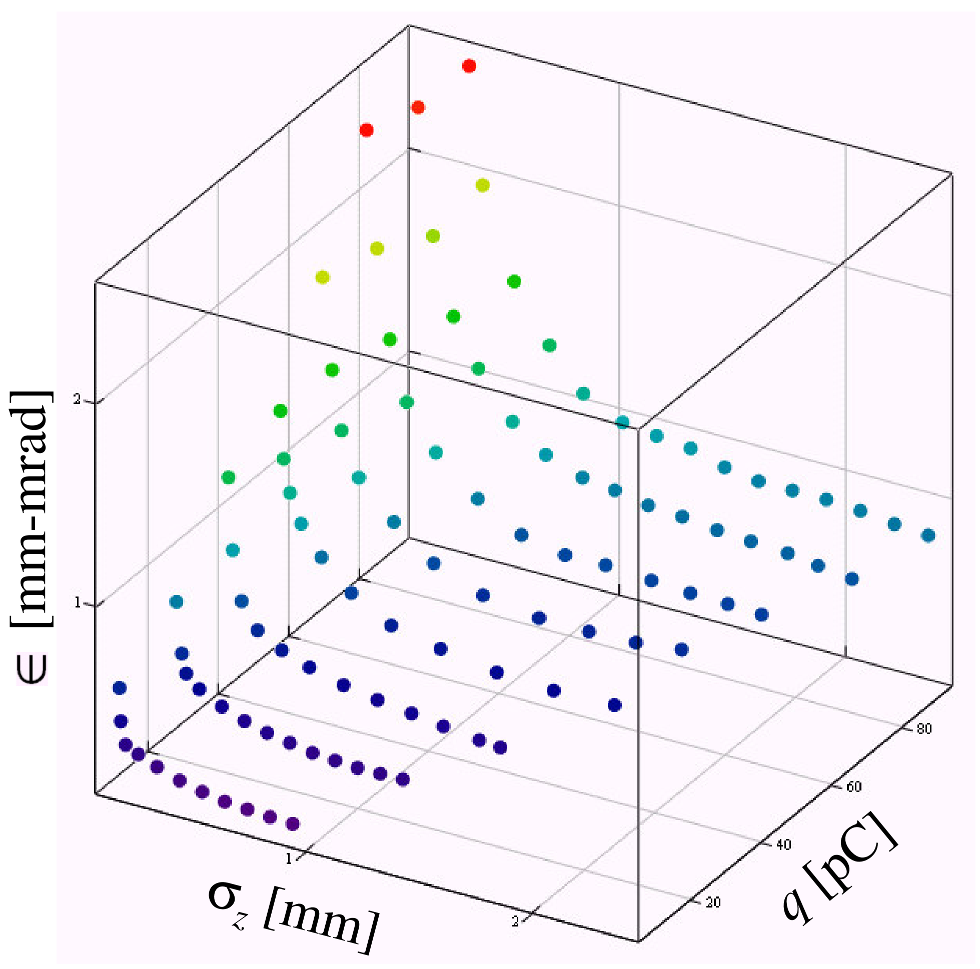
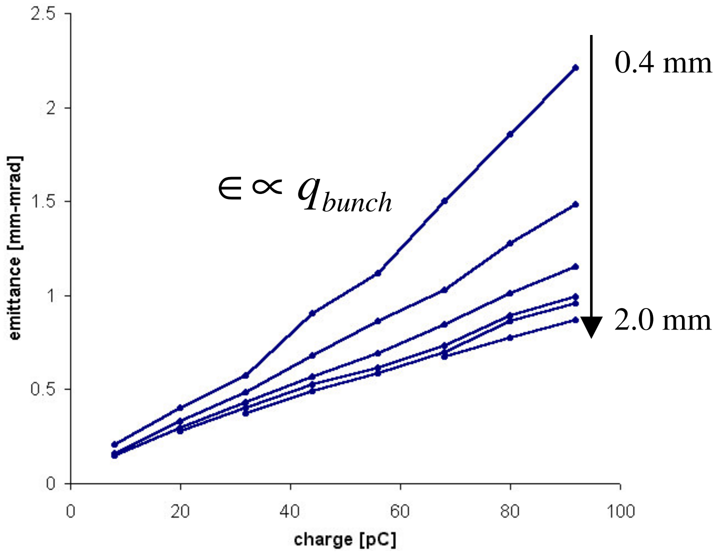
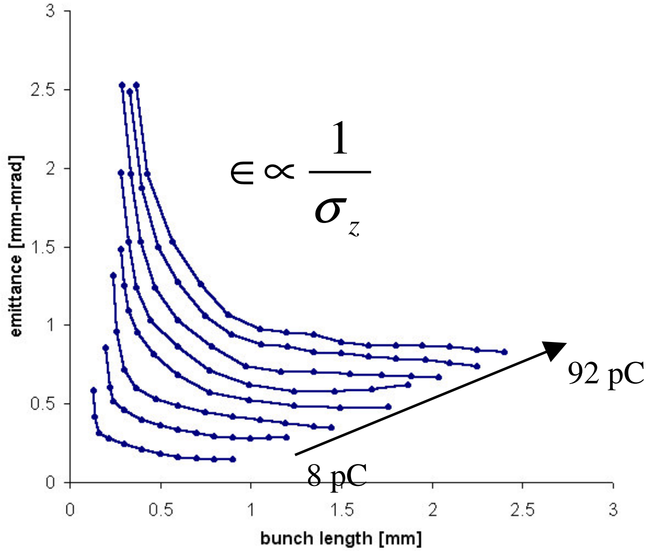
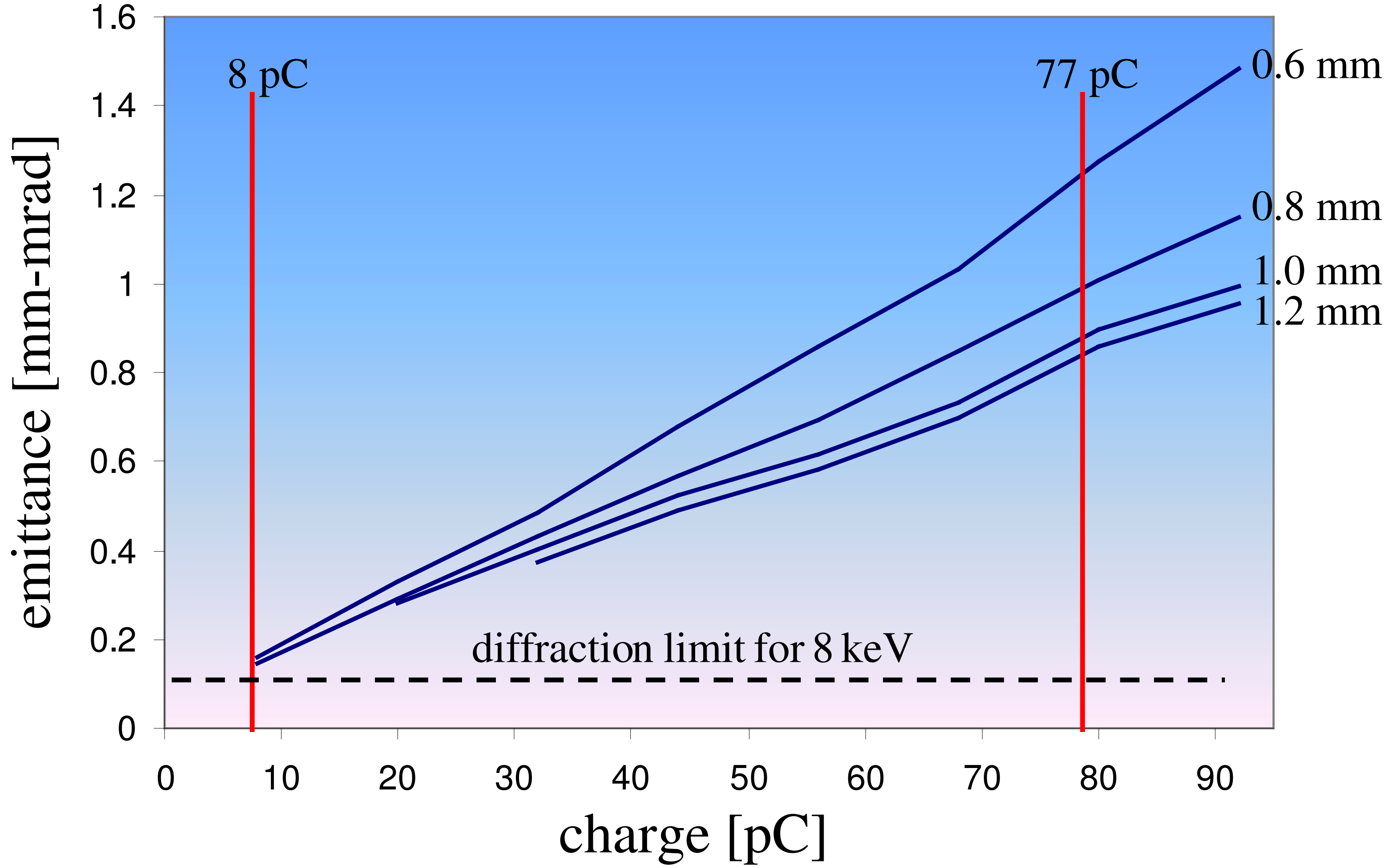
Emit. scaling vs. charge, vs. bunch length







Scaling with charge (6 MeV inj. energy)



Some more optimization results

- Optimization for emittances in case of realistic transverse, longitudinal gaussian 'laser' profile:
  - 0.086 mm-mrad for 8 pC/bunch
  - 0.58* mm-mrad for 80 pC/bunch
  - 5.3 mm-mrad for 0.8 nC/bunch

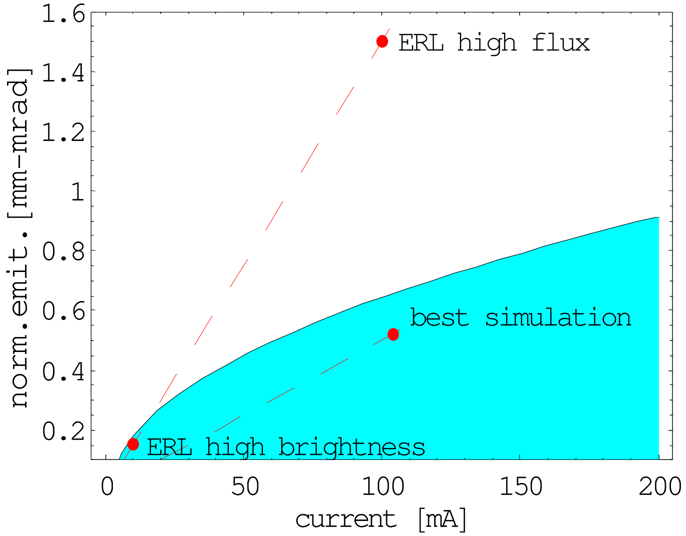
  } final bunch length < 0.9 mm

- Simulations suggest that thermal emittance is not important for high charge / bunch (~ nC), but is important for low charge bunch (~ pC)
- Better results if longitudinal laser profile shaping can be employed
- Note: results are starting to look similar to those of RF guns

***Goal**: to have a paper design that delivers ~ 0.1 mm-mrad at 80 pC*

***0.52 mm-mrad achieved for**

DF beta = 15 transverse
Gaussian longitudinal
35 meV thermal



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Not the whole story…

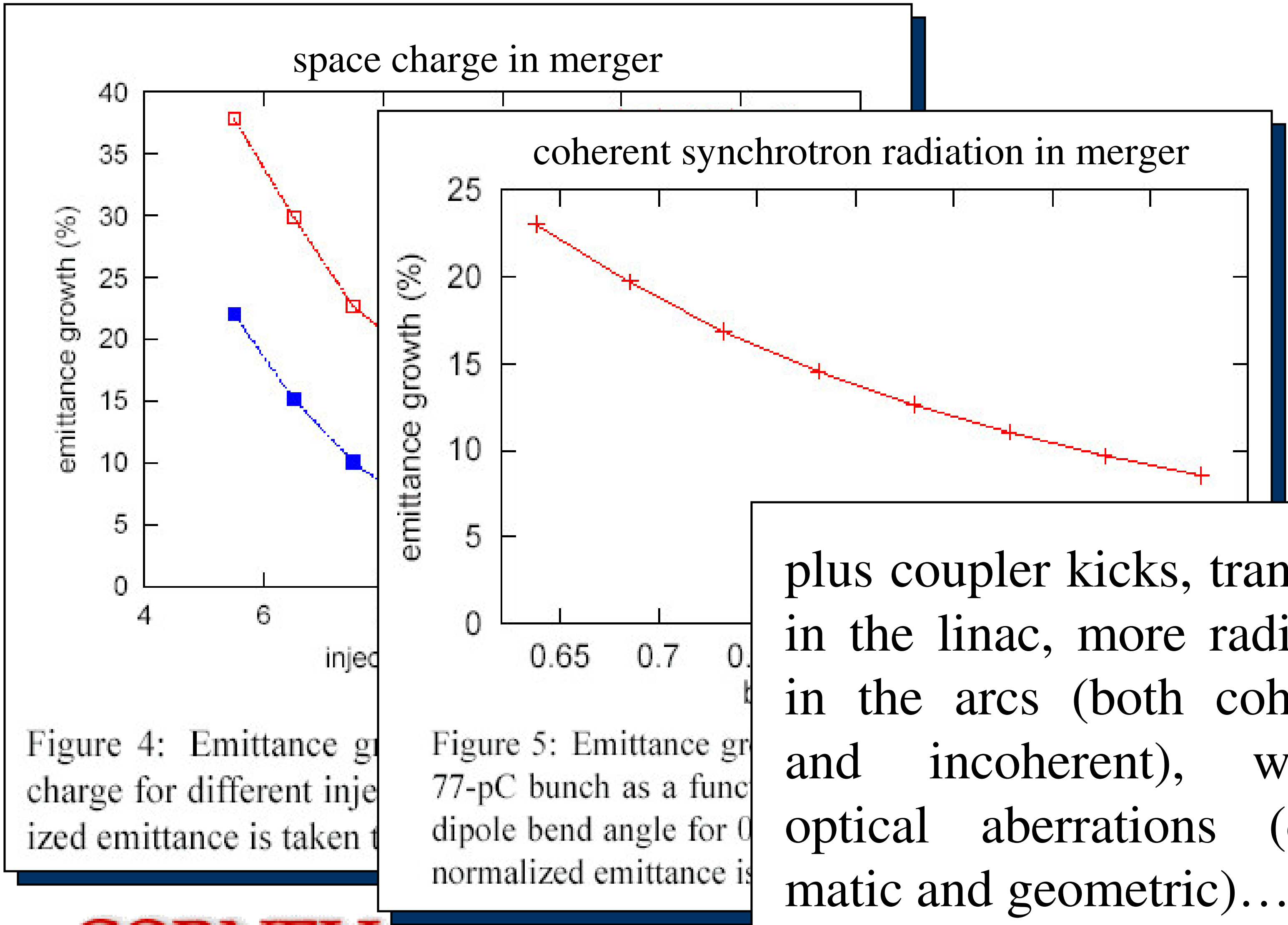

Figure 4: Emittance g
charge for different inje
ized emittance is taken t

Figure 5: Emittance gr
77-pC bunch as a func
dipole bend angle for 0
normalized emittance is

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

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HOM-beam interactions

Two basic concerns:

- Multipass beam breakup (dipoles)
- Resonant excitation of a higher order mode (monopoles)

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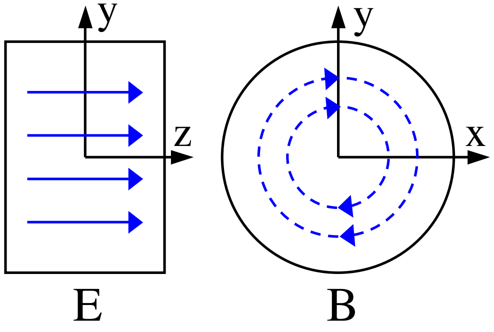
monopole ($m = 0$)

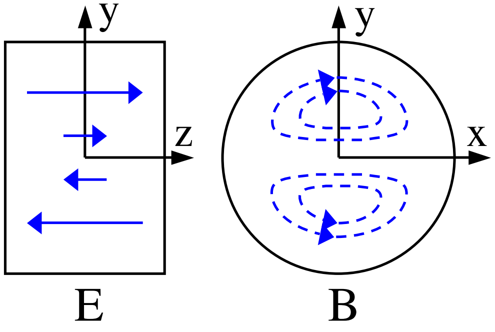
TM_{01}-like



high energy losses, no kick

dipole ($m = 1$)

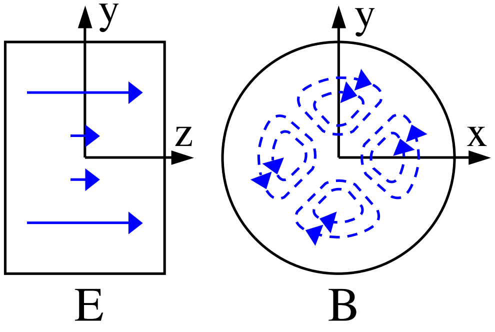
TM_{11}-like



kick and losses when beam is not centered

quadrupole ($m = 2$)

TM_{21}-like



kick, coupling and losses when beam is not centered

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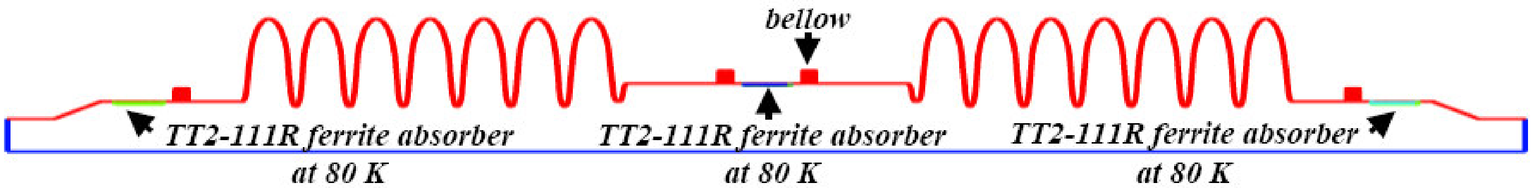
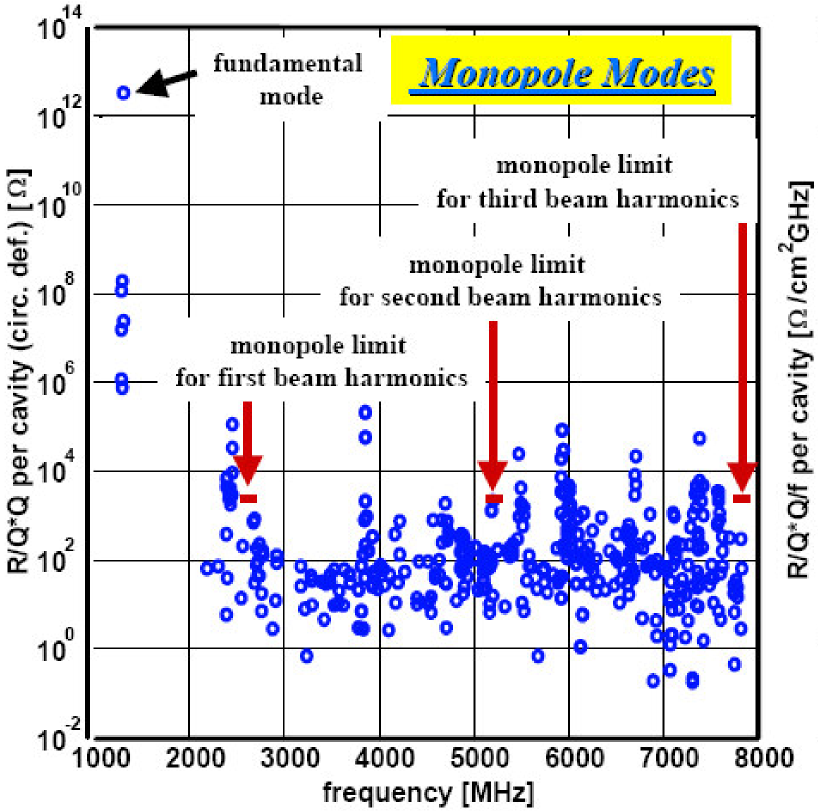
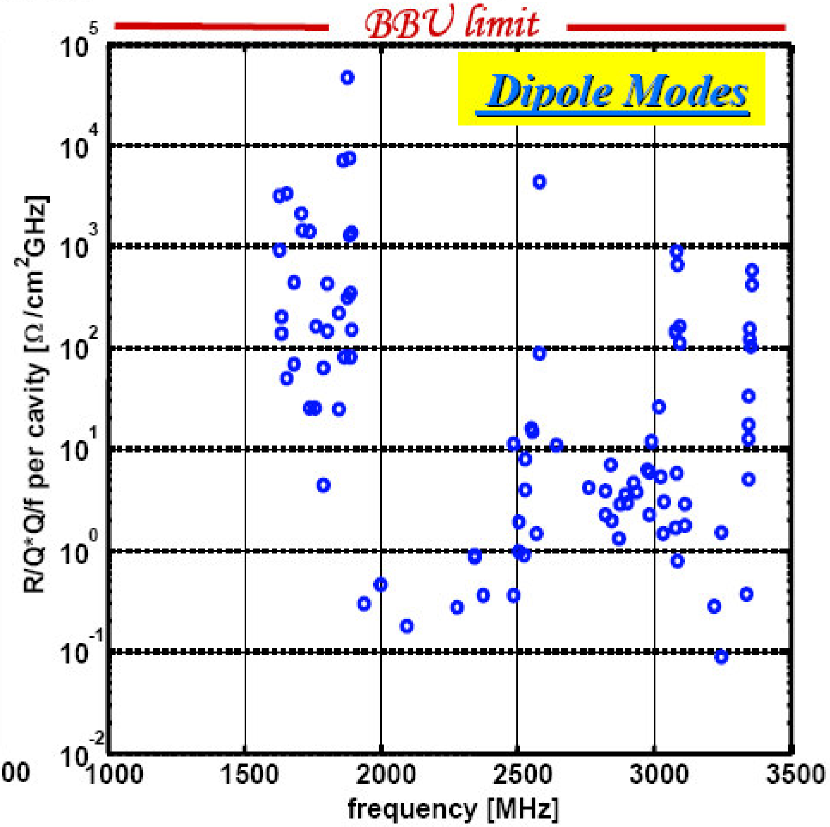
Main linac cavity HOMs: monopoles and dipoles







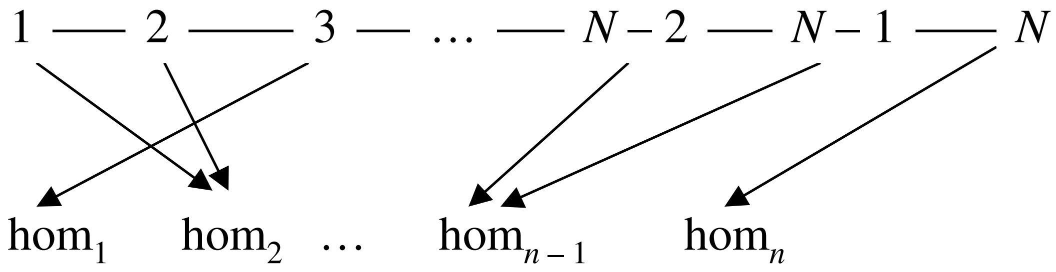
CLANS sims by M. Liepe

New cavity-beam interaction code: Algorithm

Unfold beam line into a consecutive list of cavities (pointers) in the same order a bunch sees them (most repeat *n_pass* times) in its lifetime (from injection to dump);

Link pointers to actual HOMs (i.e. cavities);

consecutive list of cavities a bunch sees in its lifetime (total number N):



$1 — 2 —— 3 — \dots — N-2 — N-1 —— N$

actual HOMs or cavities ($n \leq N$):

$\text{hom}_1 \quad \text{hom}_2 \quad \dots \quad \text{hom}_{n-1} \quad \text{hom}_n$

Start filling beam line with bunch train;

Determine which pointer sees a bunch next;

Update wake-field in HOM which the pointer points to;

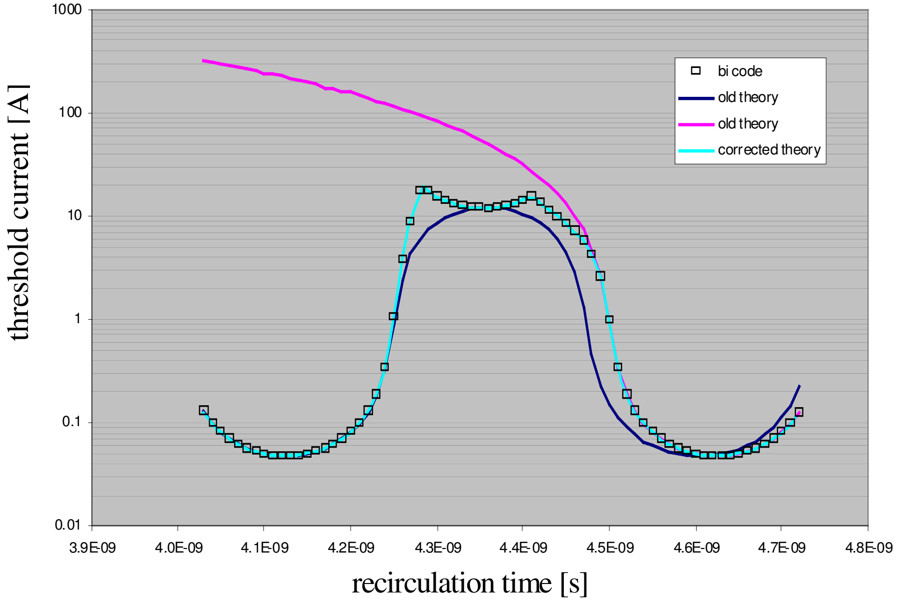
Push the bunch to next pointer, store its coordinates until they are needed by any bunch that will reach this point next;

`bi` – ‘beam instability’ code (contd.)

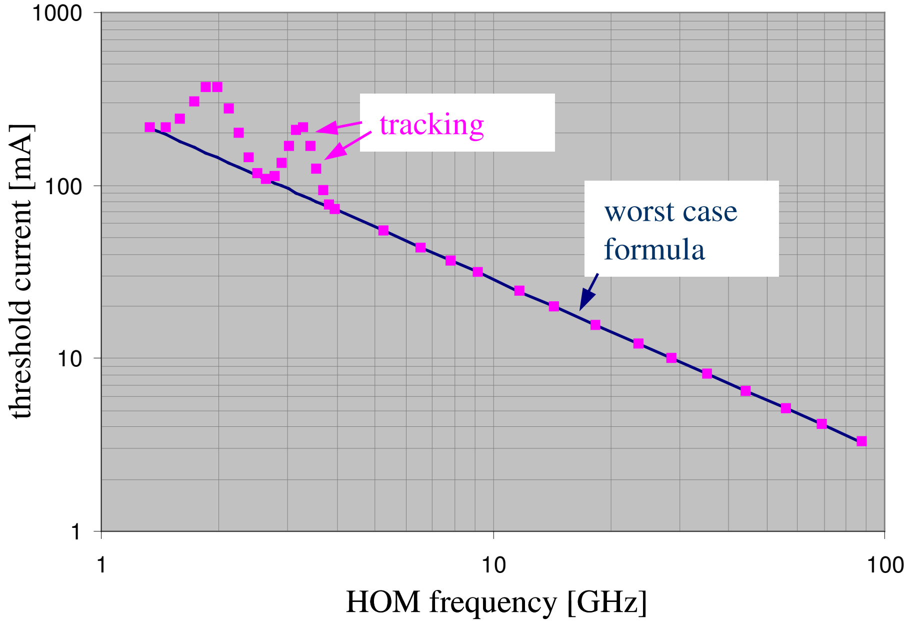
Features:

- allows any ERL topology
- arbitrary bunch pattern (can setup a cloud to study singe bunch effects)
- transverse / longitudinal BBU
- fast, http://lepp.cornell.edu/~ib38/bbucode/

transverse bbu

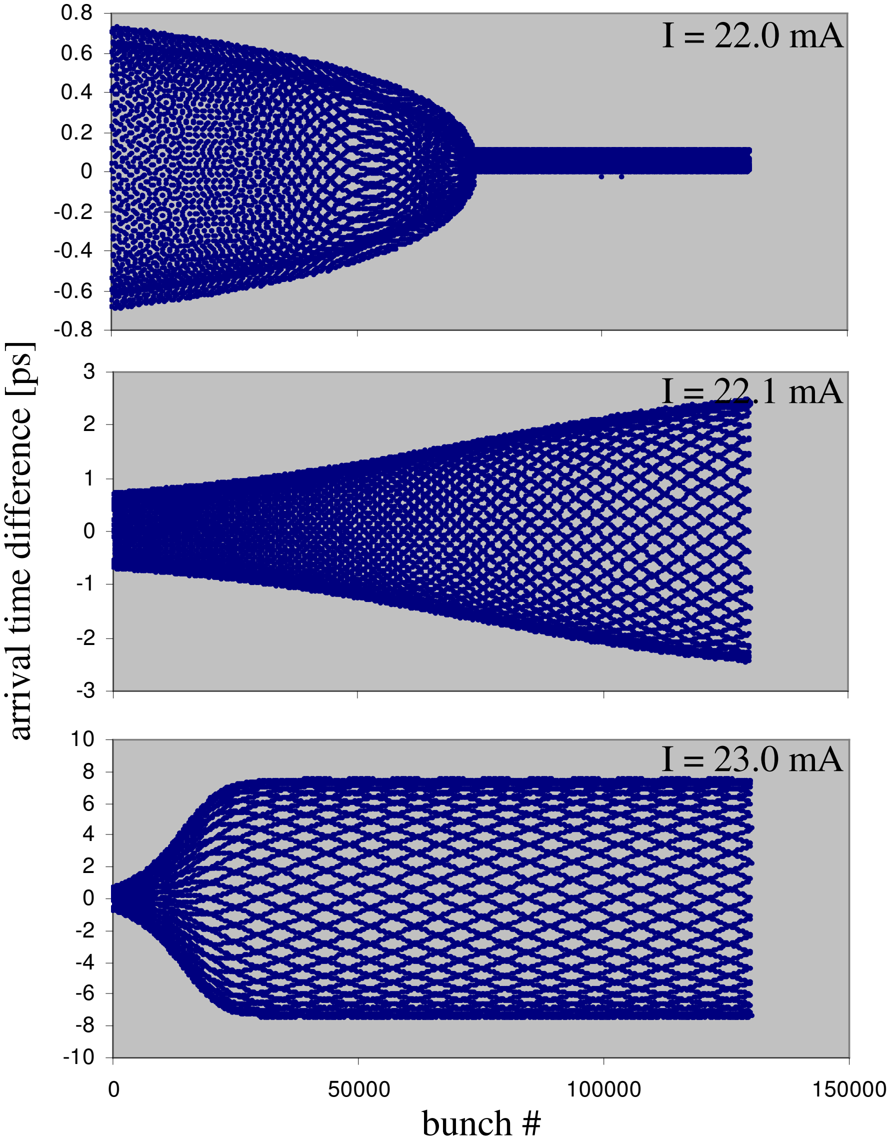


longitudinal bbu



Some features of the longitudinal instability

- similar to transverse BBU in its scaling: $\propto [(R/Q)Q\omega]^{-1}$, $\propto E$
- "bad" frequencies $(n + ¼)\omega_0$, n is an integer
- does not grow exponentially, but saturates
- **Not an issue in ERL** (time of flight of the lattice is nearly zero)



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Observations about BBU (dipole, single HOM)

$$\boxed{t_r \frac{\omega_\lambda}{2Q_\lambda} \ll 1}$$

$$\epsilon = \frac{\omega_\lambda}{2Q_\lambda} t_b, \ \epsilon \ll 1$$

$$T_{12} \sin \omega_\lambda t_r > 0$$

$$I_0 = \frac{2}{\mathcal{K}|T_{12}|} \sqrt{\epsilon^2 + \frac{1}{n_r^2} \mathrm{Mod}(\omega_\lambda t_r, \pi)^2}$$

I_0 is *independent* of Q_λ for *some* ω_λ

$$\boxed{t_r \frac{\omega_\lambda}{2Q_\lambda} \gg 1}$$

$$I_0 = \frac{2}{\mathcal{K}|T_{12}|} \sqrt{\epsilon^2 + \frac{1}{n_r^2} \mathrm{Mod}(\omega_\lambda t_r \pm \frac{\pi}{2}, 2\pi)^2}$$

$I_0 \approx 2\epsilon / \mathcal{K}|T_{12}|$, is *independent* of t_r

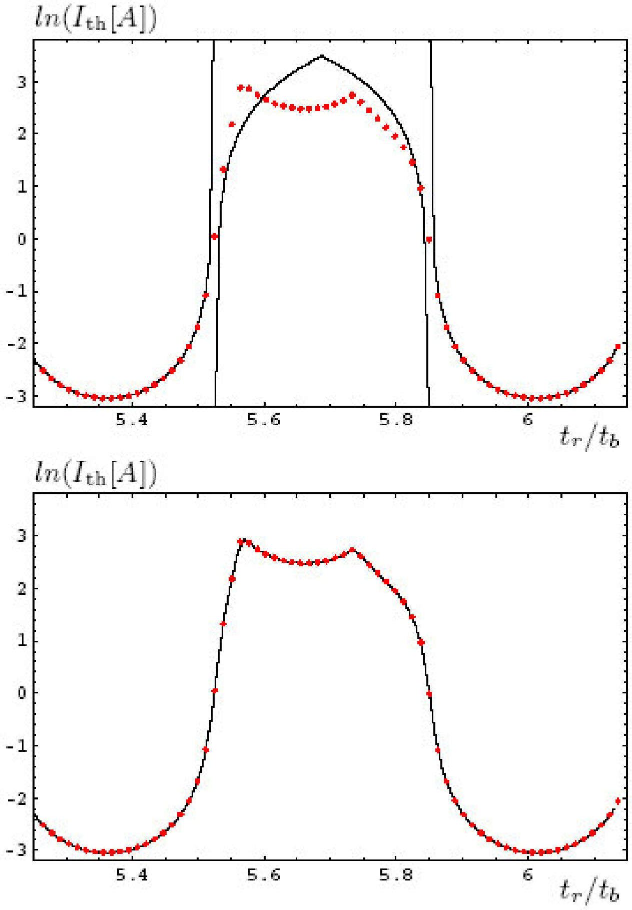

FIG. 3: Threshold current obtained by tracking (red dots) and approximate analytical solution (top) and by a numerical solution (bottom) of the dispersion relation Eq. (16). Parameters: $n_r - \delta \in [6.135, 7.234]$, $(R/Q)_\lambda = 100\,\Omega$, $Q_\lambda = 10^4$, $T_{12} = -10^{-6}\,\mathrm{eV/c}$, $\omega_\lambda t_b = 9.67$.

Observations about BBU (two HOMs)

Two modes are decoupled if their frequencies are >> $\frac{\omega_\lambda}{2Q_\lambda}$ away

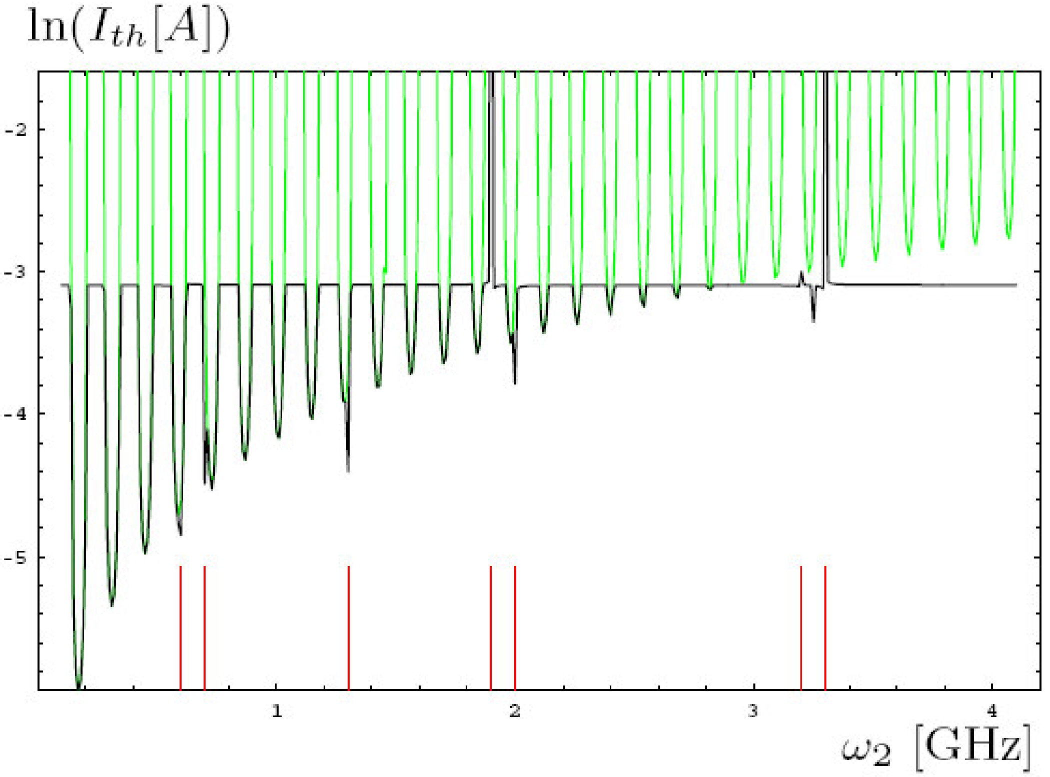

FIG. 4: Dark black curve: the threshold current $\ln(I_{th}[\mathrm{A}])$ for one HOM at $\omega_1/2\pi = 2\,\mathrm{GHz}$ as a function of a second HOM with frequency ω_2. Light green curve: threshold current when only the second HOM is present. Light red lines: frequencies for which $\cos\omega_2 t_b \approx \cos\omega_1 t_b$ where the threshold current is not simply the minimum of the threshold currents produced by the individual HOMs.

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Observations about BBU (many HOMs)

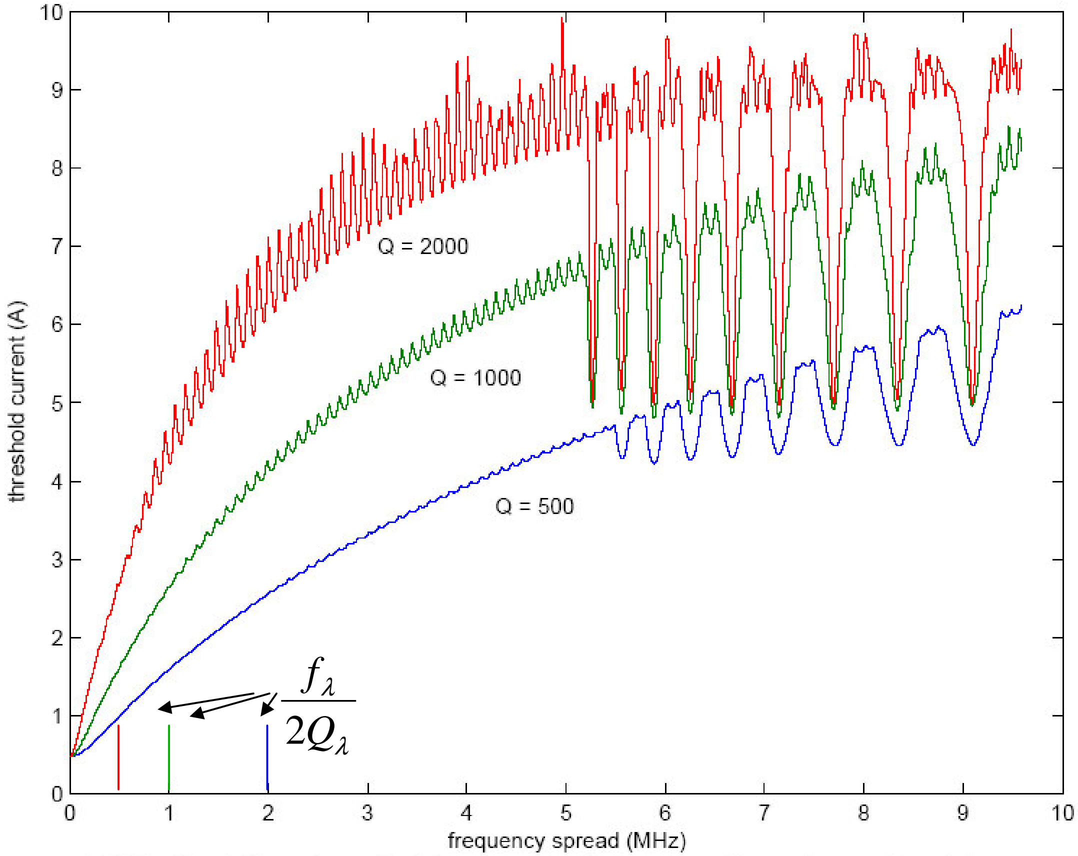
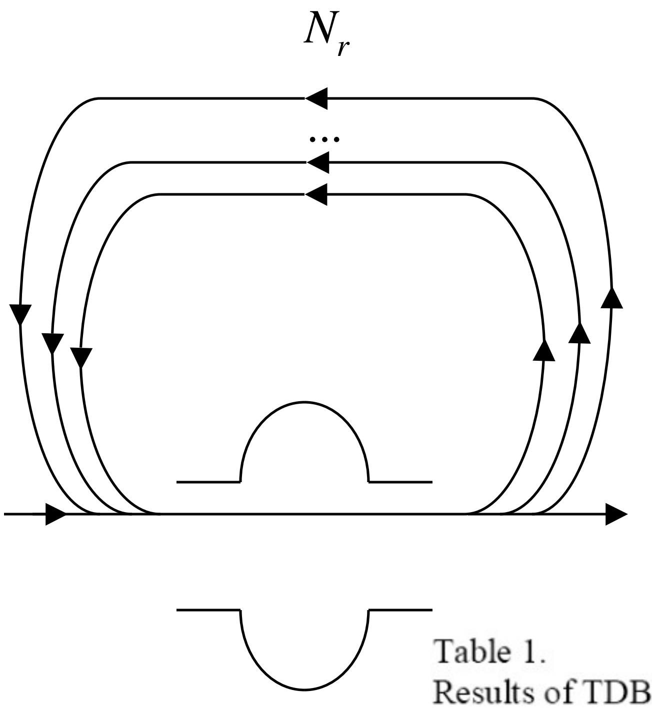


FIG. 5: The threshold current I_{th} as a function of uniform equidistant frequency spread for 20 HOMs in a single cavity. Abscissa displays frequency difference between the two HOMs adjacent in frequency. Parameters: $\bar{\omega}_\lambda/2\pi = 2\,\text{GHz}$, $(R/Q)_\lambda Q_\lambda = 5000\,\Omega$, $T_{12} = -10^{-6}\,\text{eV/c}$, $t_r = 1.000125 \cdot 10^{-6}\,\text{s}$, $\omega_0/2\pi = 1.3\,\text{GHz}$. Threshold is determined by tracking with accuracy 0.1%.

Observations about BBU

Multiple Recirculation Turns



$$I_{th}^{N_r} = -\frac{2c^2}{e(\frac{R}{Q})_\lambda Q_\lambda \omega_\lambda} \frac{1}{\sum\limits_{I>J} \sin(\omega[t^I - t^J])T^{IJ}}$$

worse by a factor of

$$\sum_{I>J} |T^{IJ}|/|T_{12}| \approx N_r(2N_r - 1)$$

than a single pass ERL

Table 1.
Results of TDBBU runs for 1-pass and 2-pass 5 GeV ERL. March, 2002
new 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)
1699	88.40	5.00E+04	4.42E+06	160	20
1873	56.39	7.00E+04	3.95E+06	190	25
2575	51.50	5.00E+04	2.57E+06	115	15
1725	118.64	2.00E+04	2.37E+06	135	15
1864	42.84	5.00E+04	2.14E+06	> 200	40
1880	11.08	1.00E+05	1.11E+06	> 200	90

. . .

Dave’s concern (one HOM, one recirc.)

$$\Delta p_x(t) \equiv \frac{e}{c}\Delta V(t) = \frac{e}{c} W(t-t')x(t')I_0(t')dt' \qquad (1)$$

but now one has bunches with current fraction dI, $\int dI = I_0$ having uncorrelated energy spread (FEL) δ_{dI}

$$x_{dI}(t+t_r) = T_{12}(\delta_{dI})p_x(t) = T_{12}(\delta_{dI})\frac{e}{c}V(t)$$

substituting into (1) and integrating with respect to *dI*, *dt* yields

$$V(t) = \int_{-\infty}^{t} dt' \underbrace{\int_{I_0} dI(t')T_{12}(\delta_{dI})}_{= I_0(t')\frac{1}{I_0}\int T_{12}(\delta_{dI})dI \equiv I_0(t')\langle T_{12}\rangle} \frac{e}{c} \overbrace{V(t'-t_r)W(t'-t)}^{dI \text{ independent}}$$

Proceeding with the derivation as before, but now with $\langle T_{12}\rangle = \frac{1}{I_0}\int T_{12}(\delta_{dI})dI$

Note: the situation is quite different if e.g. the energy spread is position *x* correlated

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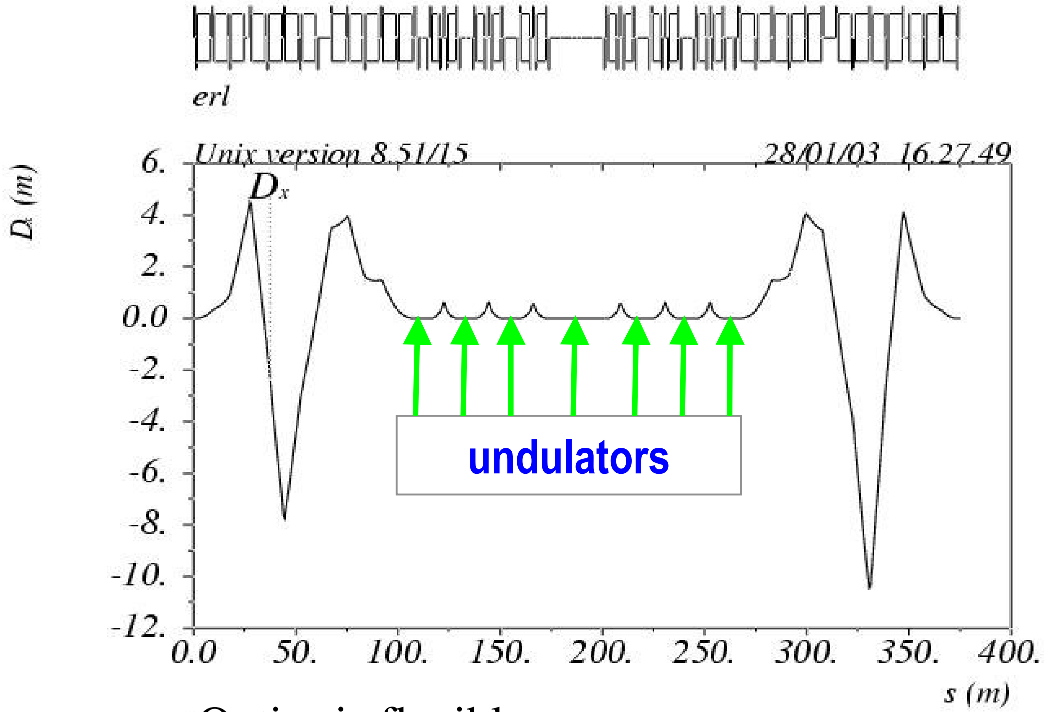
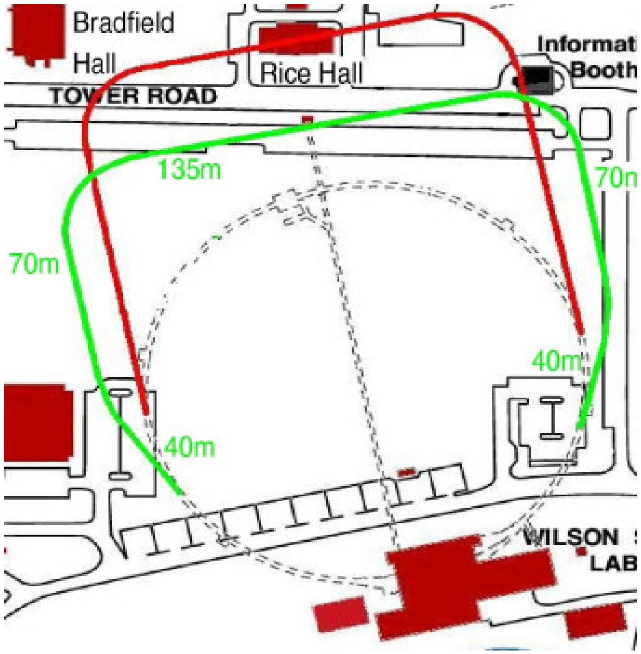
Arc optics design exercise

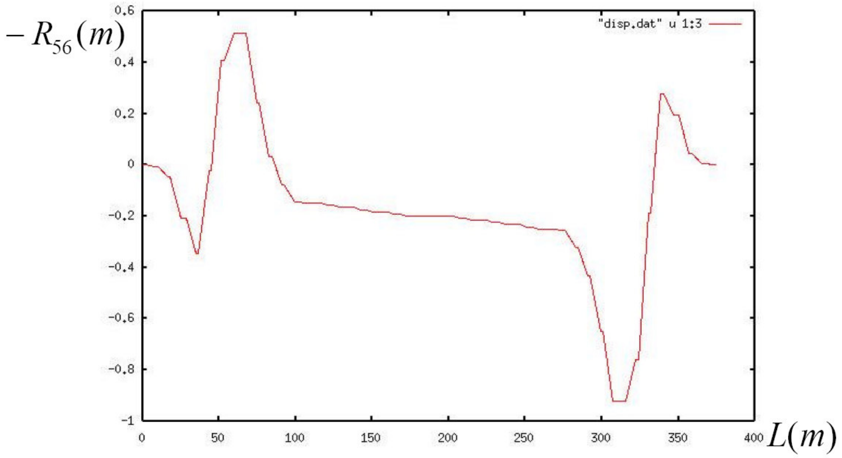


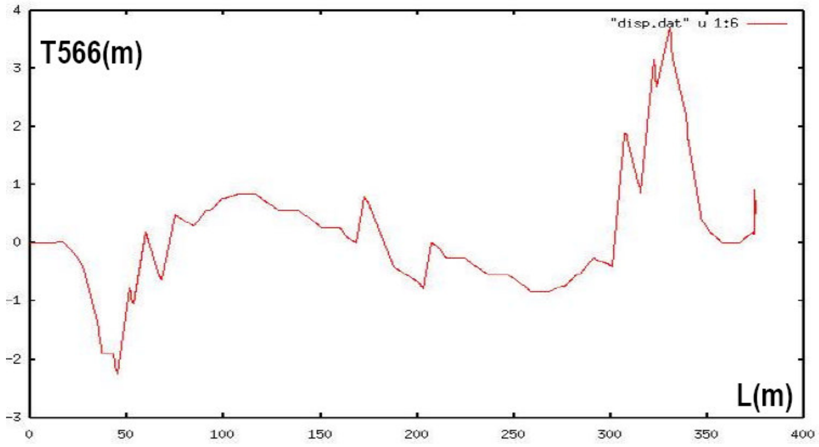


- Optics is flexible
- Lumps with large (negative) dispersion (or reverse bends) are handy
- Control of time-of-flight terms R_{56} and T_{566} is critical for successful energy recovery when doing bunch compression (i.e. running off-crest)
- Eliminating second-order dispersion T_{166} (and to a lesser degree T_{266}) is sufficient for clean transport in terms of aberrations

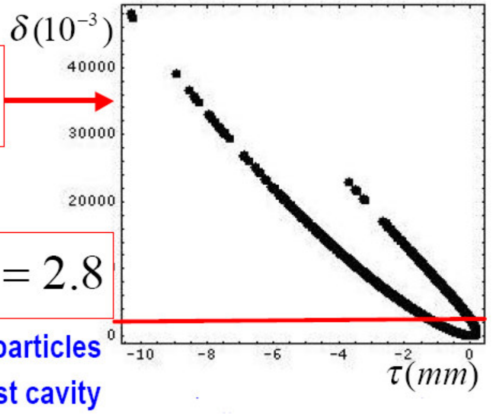
First, second order time of flight (R_{56}, T_{566})

- Isochronous (approximately) lattice to second order is critical for off-crest running





15° off-crest, **without** T_{566} correction

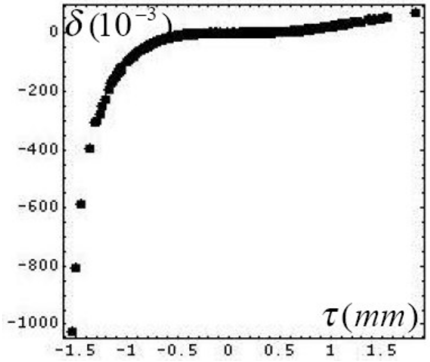


After ERL (10MeV)

$\langle\delta\rangle = 2.8$

The low energy particles are lost in the last cavity

after ERL **with** T_{566} correction



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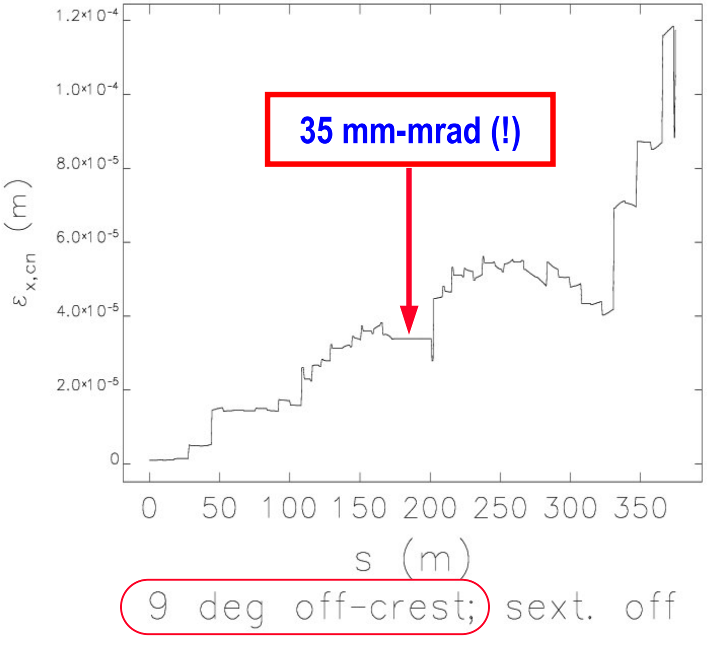
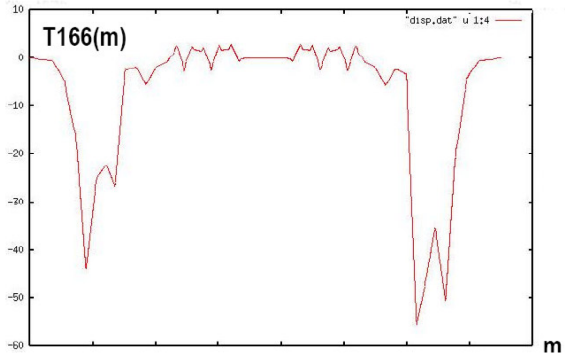
Second order dispersion (T_{166})

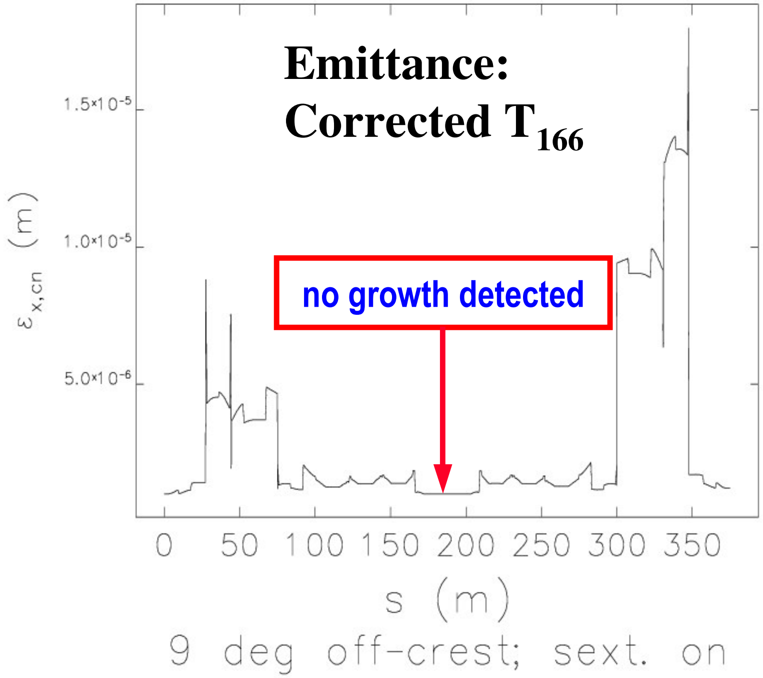
- Eliminating second-order dispersion T_{166} (and to a lesser degree T_{266}) is sufficient for clean transport in terms of aberrations

Emittance: Uncorrected T_{166}



35 mm-mrad (!)





Emittance: Corrected T_{166}

no growth detected

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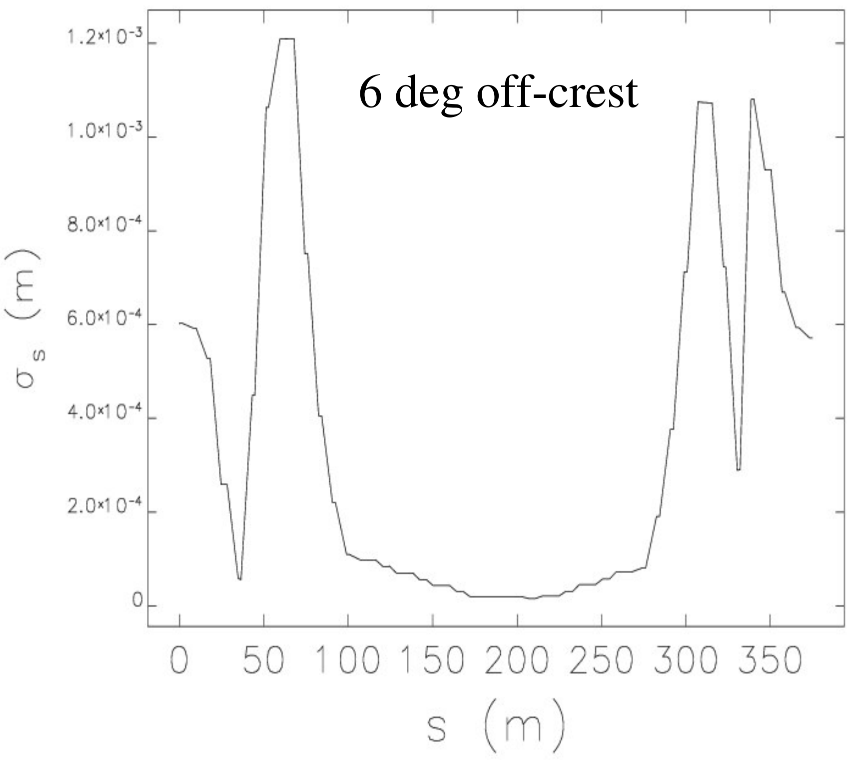
CSR effect

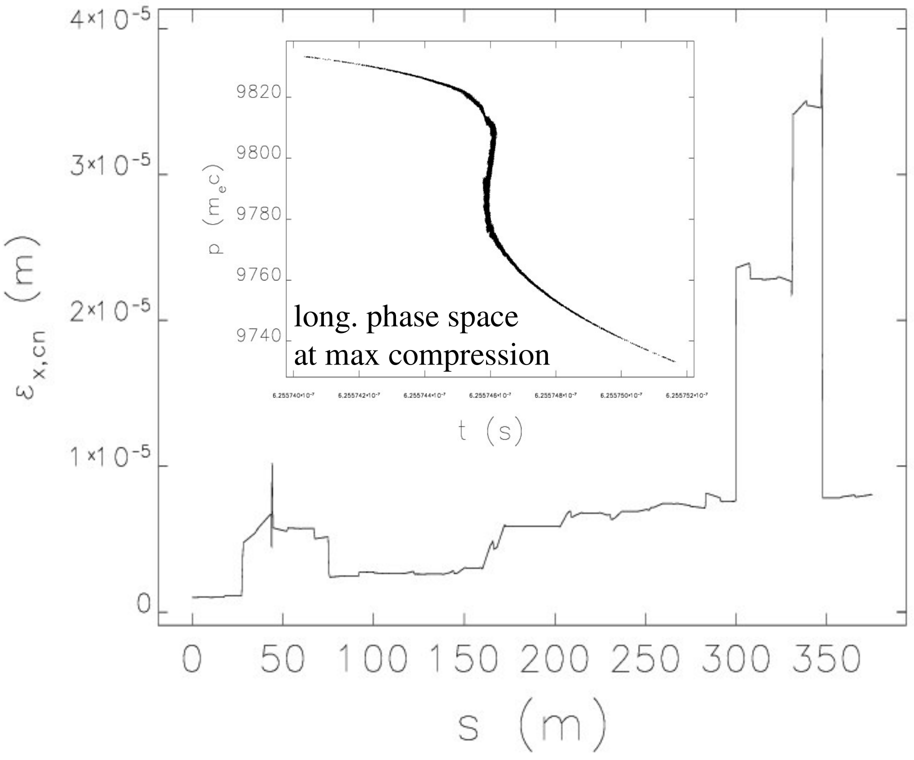
- When not compressing (on crest), CSR is largely not a player
- When slightly under-compressing, CSR emittance growth is moderate



Bunch length

6 deg off-crest

bunch length in 25 m wiggler is 19 um



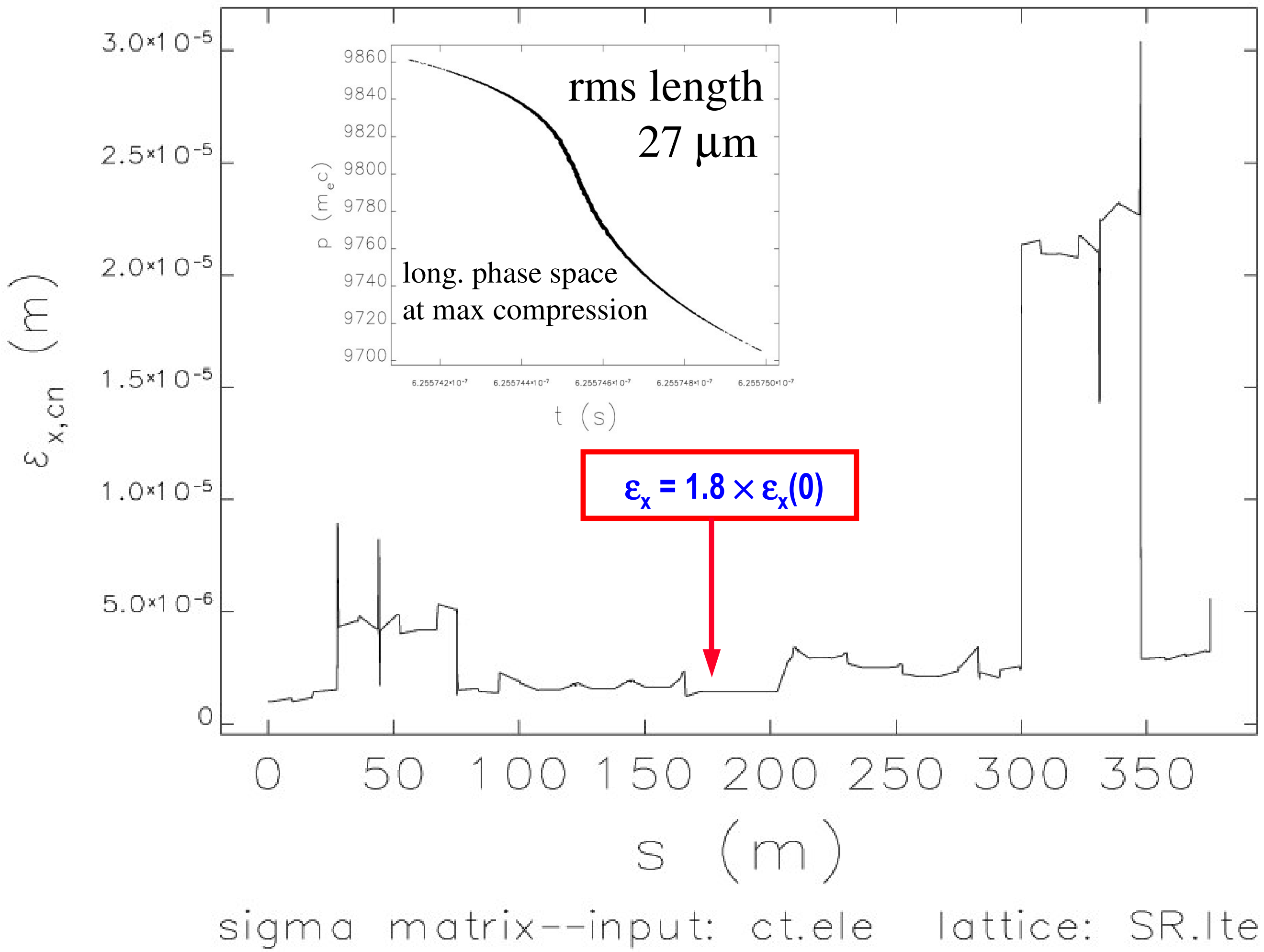
Emittance: over-compressed

long. phase space
at max compression

emittance in 25 m wiggler is 5.85 um

CSR when under-compressed

Emittance: under-compressed



rms length 27 µm

long. phase space at max compression

$\varepsilon_x = 1.8 \times \varepsilon_x(0)$

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Manipulations with longitudinal phase space

- RF phase + time-of-flight terms provide great flexibility for longitudinal phase space manipulations, e.g.
    - lattice linearizer (off-crest running + T_{566})
    - energy compressor (two part of linac + R_{56}, T_{566}), etc.
- Easily implemented with only modest number of sextupoles
- Likely to have a dedicated mode for compressed bunches at somewhat lower rep. rate for timing experiments
- On-crest operation without bunch compression is preferred to maximize brilliance from long undulators (both emittance and energy spread)
- RF stability being a major issue

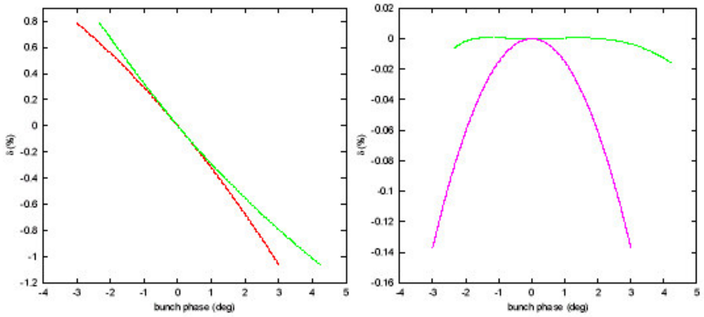

Figure 3. Energy spread compression using split linac configuration. On the left: longitudinal phase-space after the first section (solid line) and after properly chosen T_{566} (dashed line). On the right: the phase-space after linear and quadratic correlations have been removed after the second linac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

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Summary

- Successful IRFEL Demo at JLAB spurred considerable interest worldwide to pursue ERL-type devices for various purposes
- Cornell ERL light source, by competing with mature storage ring technology, sets very high demands on several key technologies pertaining to ERL, with the goal of building an ‘ultimate’ (in terms of performance) ERL
- A list of R&D issues to enable high energy, high current ERL appears to be well defined
- The road towards funding the prototype at Cornell has been long and thorny
- We are not there yet…

Thank you for
your attention