How short can you go? Limits to bunch length in storage rings

John Byrd
Lawrence Berkeley National Laboratory

Overview

- Natural bunch length in a storage ring
  - low momentum compaction
  - Harmonic cavities for bunch shortening
- Why life isn't so easy: wakes and impedances
  - Bunch shape distortion
  - Turbulent bunch lengthening
  - Ultimate limits to bunch length
- Phase space gymnastics
  - making bunches dance
  - strong longitudinal focusing

Natural bunch length

John Byrd

momentum compaction
(dL/L=dE/E)

energy spread
(α E/sqrt(ρ))

beam energy

$$s_t = \frac{a\, s_e}{2p\, f_s}\, \mu \sqrt{\frac{a\, E^3}{r\, \dot{V}_{rf}}}$$

synchrotron frequency

bend radius

slope of RF voltage
($=\omega_{rf} V_{rf}$)

E	7	1.9	3.5	3.5
α	2.3e-4	1.3e-4	1.3e-5	1.3e-4
V_{rf}(MV)	11	22	11	100
σ_τ(psec)	16	1.1	1.25	1.3

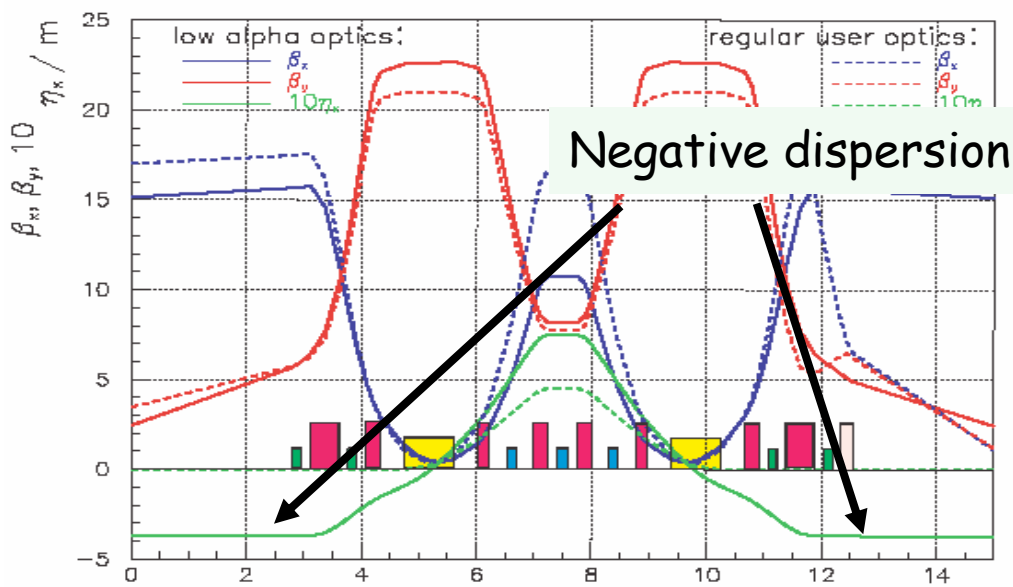
Ignore "trivial" limitations:
-melting vacuum chamber
-sparking RF cavities
-intrabeam scattering

Low α

The momentum compaction can be varied by making negative dispersion in the bends

$$a = \frac{1}{C}\int_{dipoles} \frac{h}{r} ds$$

Relatively simple in a DBA lattice



BESSY-II low α lattice

Caveats:

1) Nonlinear terms become important

$$\alpha = \alpha_1 + \alpha_2 \frac{\Delta p}{p_0} + \alpha_3 \left(\frac{\Delta p}{p_0}\right)^2 + \ldots.$$

Instabilities!!!

$$\frac{\hat{I}\,|Z_{//}/n|}{2\pi\alpha\, s_d^2 (E/e)} \check{S}\ 1$$

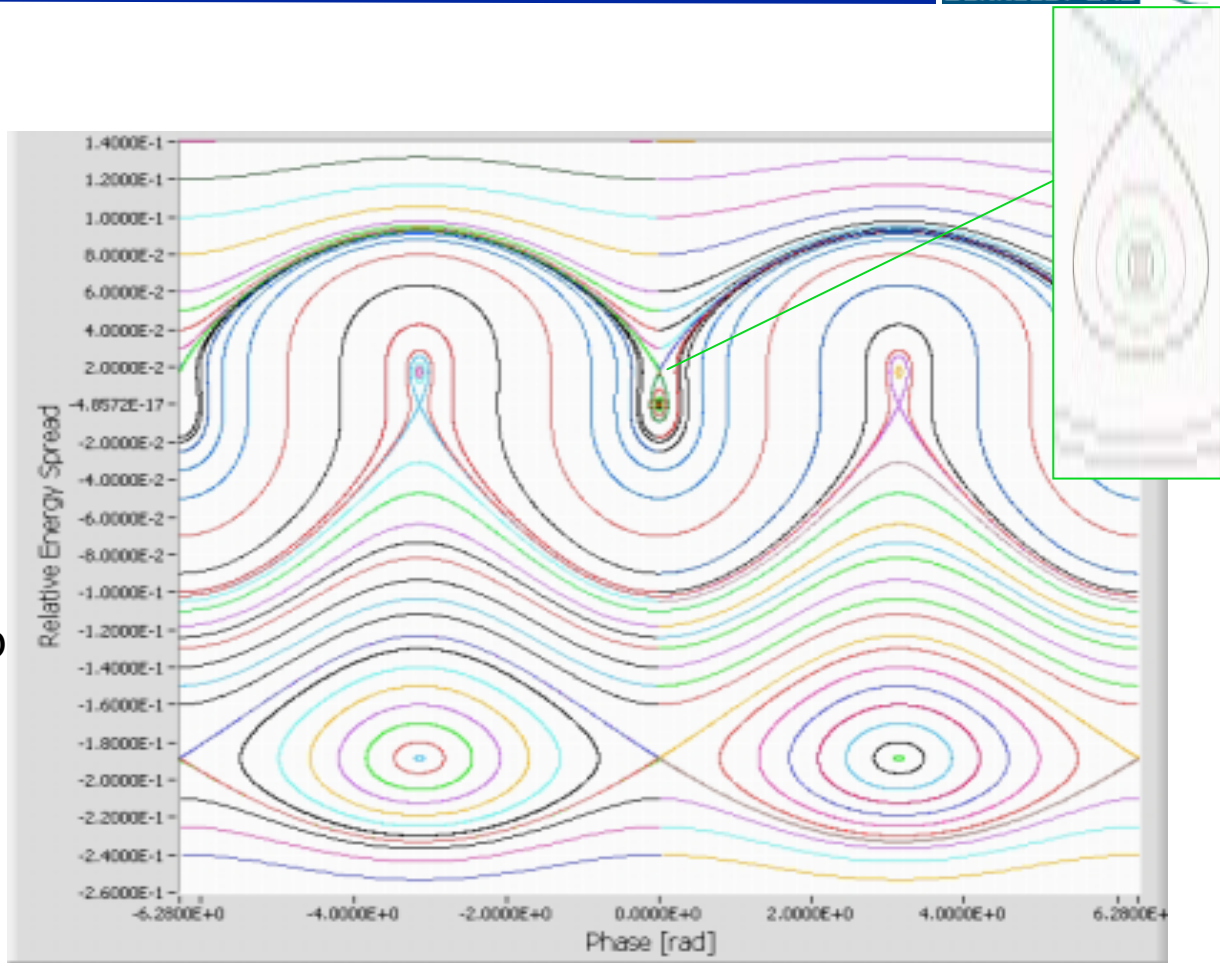
Low α: nonlinear effects

John Byrd

Higher order terms in the α can lead to weird longitudinal focussing effects such as:
-multiple bunches in a single RF bucket
-different energy beams stored simultaneously
(see J. B. Murphy and S. L. Kramer Phys. Rev. Lett. 84, 5516-5519 (2000))

A low α lattice must be able to correct these effects.

$$\alpha_1 = 3.93\,10^{-5}$$
$$\alpha_2 = -2.055\;10^{-3}$$
$$\alpha_3 = -1.20\,10^{-2}$$
$$\alpha_4, \alpha_5, ... = 0$$



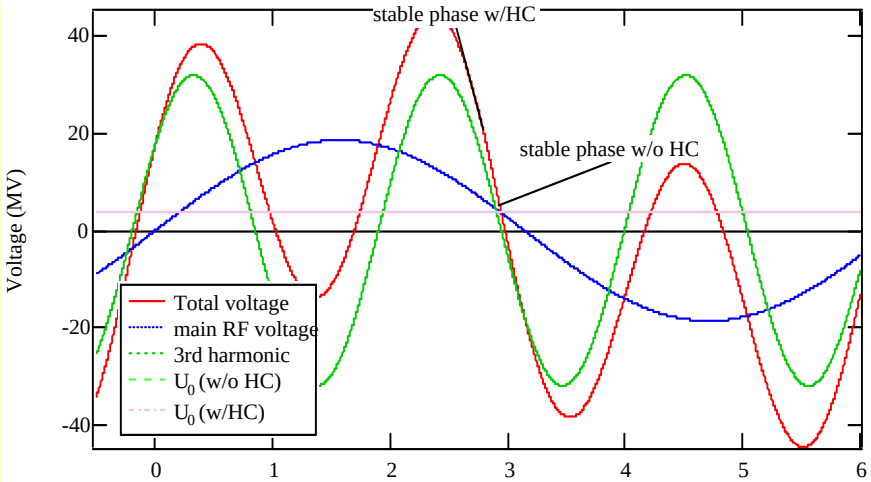
Five stable regions in a single bucket!
(None of them are very short)

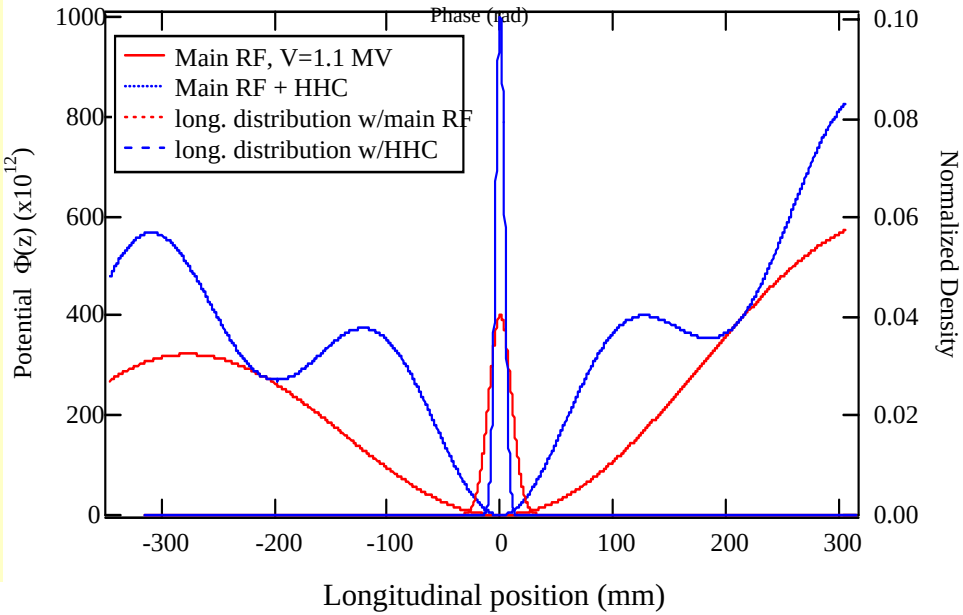
Passive SC Harmonic cavities

John Byrd

Shorten bunches with more focussing

- Increase main RF voltage
  - Increase number of cells
  - Increase number of klystrons
    - Further cost (equipment and wallplug)
  - No hardware R&D required
- Add passive harmonic cavities
  - Sqrt(n) gain per Volt effective in longitudinal focussing
  - SC passive cavity operates reactively: very little power dissipation
  - Passive operation requires no external power source (i.e. beam is the power source)
  - Significant R&D required (cryo system, cryostat, etc.)





Bunch lengthening effects

Natural bunch length $\sigma_{\tau o} \approx \sqrt{\dfrac{\alpha E^3}{\omega_{rf} V_{rf}}}$ $@\, I = 0\, mA$

Demonstrated @ (SuperAco, ESRF, ALS, UVSOR…)

@ high current **bunch length independent of α and Energy**

Slope of asymptotic curve for each ring determined by $|Z/n|_{effective}$ of the ring

Above instability threshold, peak current adjusts itself to stay constant

$$\frac{\hat{I}\left| Z_{//} / n \right|}{2\text{pa s}\,{}^{2}_{\text{d}}(E / e)} \text{ Š } 1$$

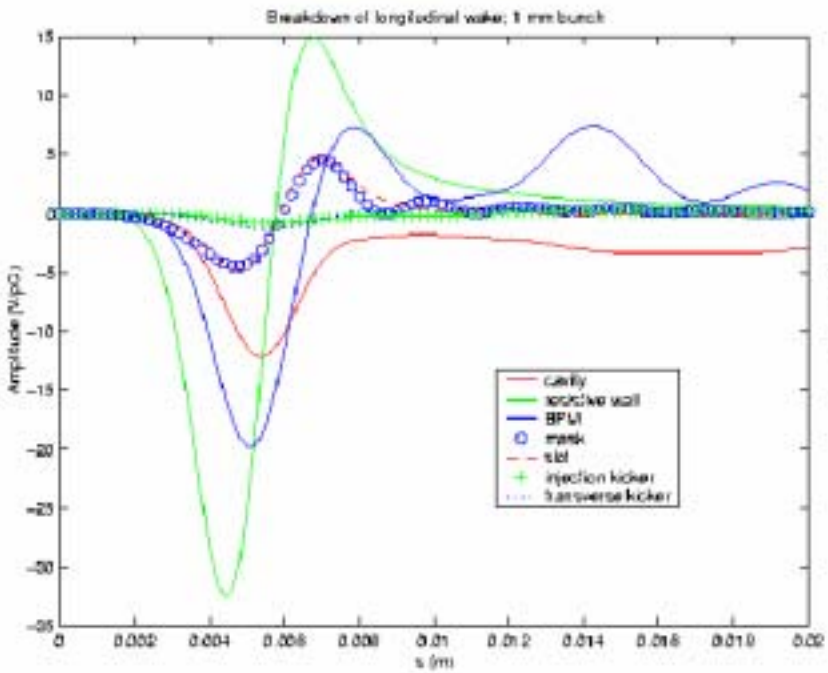
Radiation damping
α E^3

σ_τ *follows* $\left(\dfrac{\left| Z/n \right|_{eff} I}{\omega_{rf} V_{rf}} \right)^{1/3}$

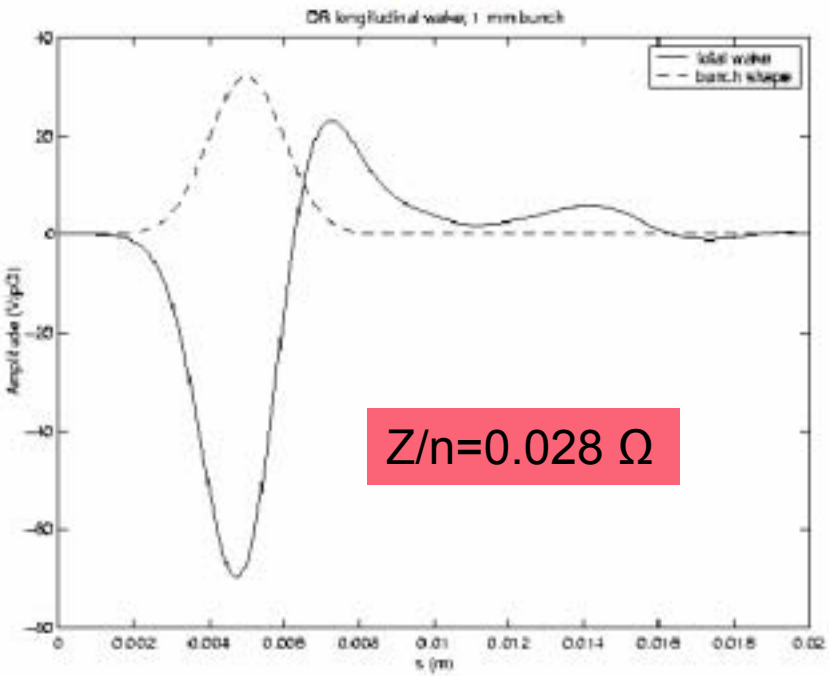
Storage ring impedance

The vacuum chamber impedance can be evaluated using EM codes for gaussian bunches. The net result is lumped together and can be characterized by an effective resistance, inductance, capacitance.

Breakdown



Total

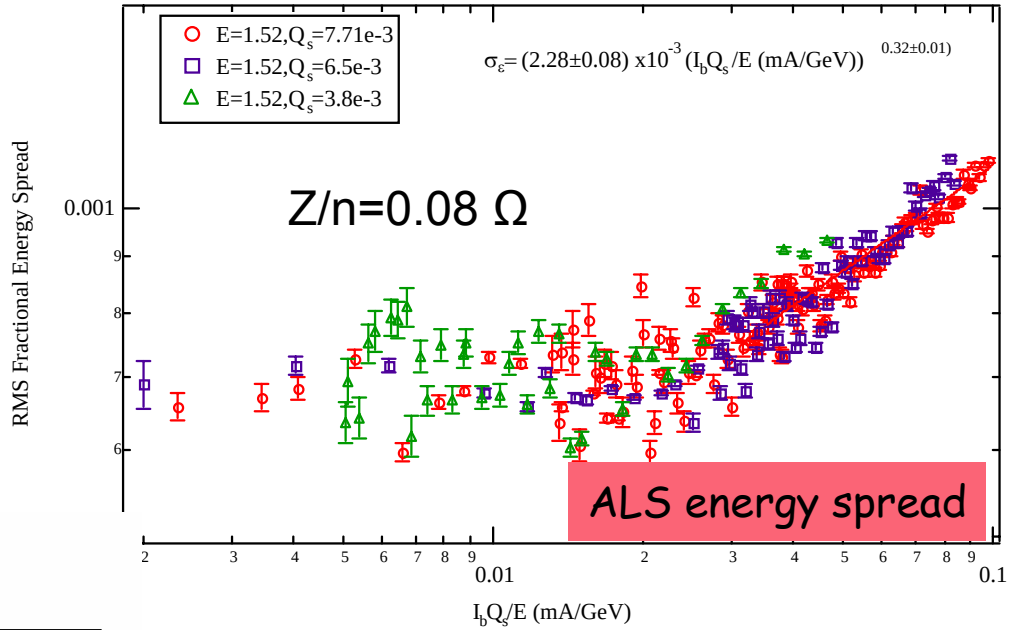


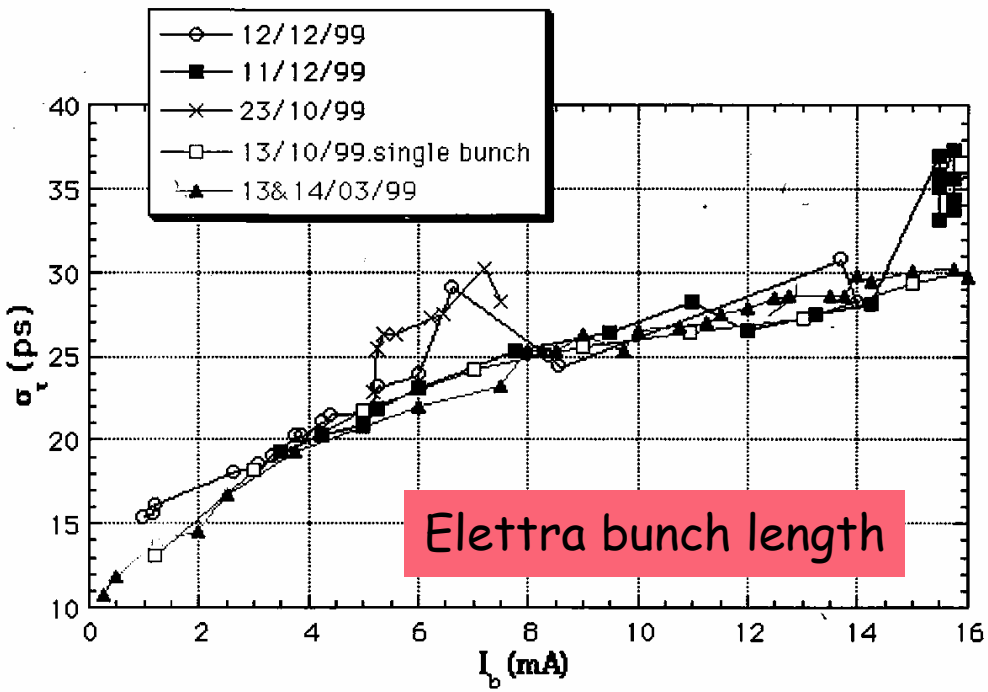
Z/n=0.028 Ω

Bane, Corlett, Ng, DR Impedance Workshop, 2000

Examples

Bunch length, energy spread vs current measurements have been made on all 3G rings.

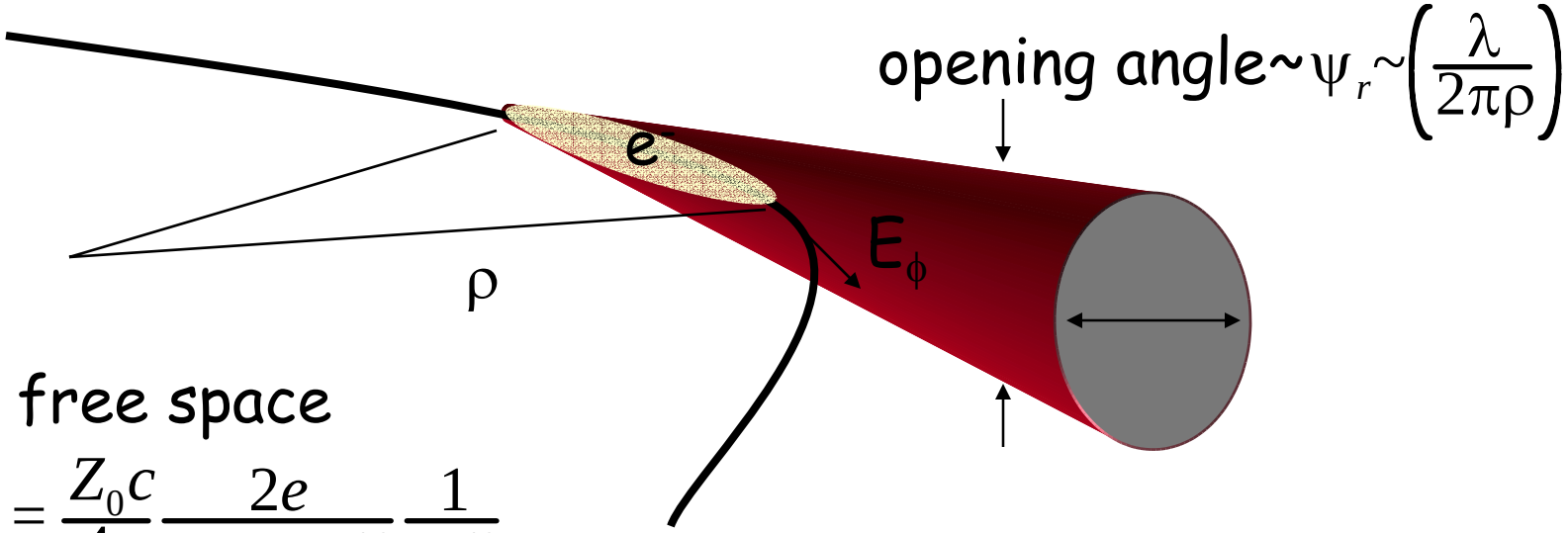




Almost all rings show a dependence on $I^{1/3}$, indicating a mainly inductive impedance with Z/n<1 Ohm.

Radiation Wake Field

John Byrd



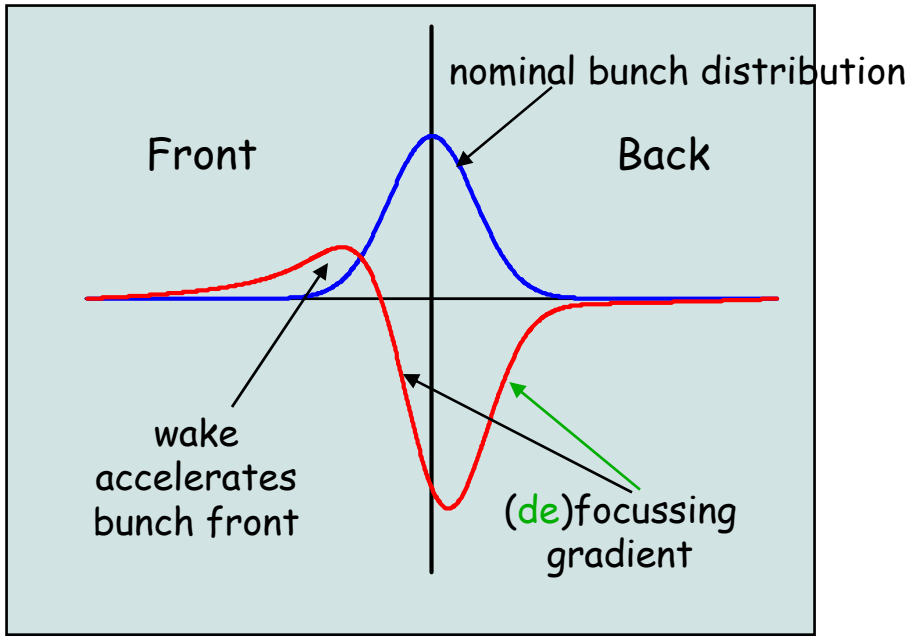
In free space

$$E_\phi = \frac{Z_0 c}{4\pi} \frac{2e}{\left(3^4 \rho^2\right)^{1/3}} \frac{1}{s^{4/3}}$$

for s>0

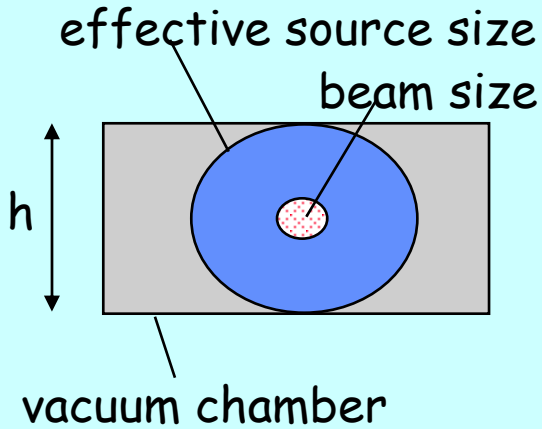
Total voltage on a bunch

$$V(s) = 2\pi\rho \int_{-\infty}^{s} ds' E_\phi(s-s') I(s')$$



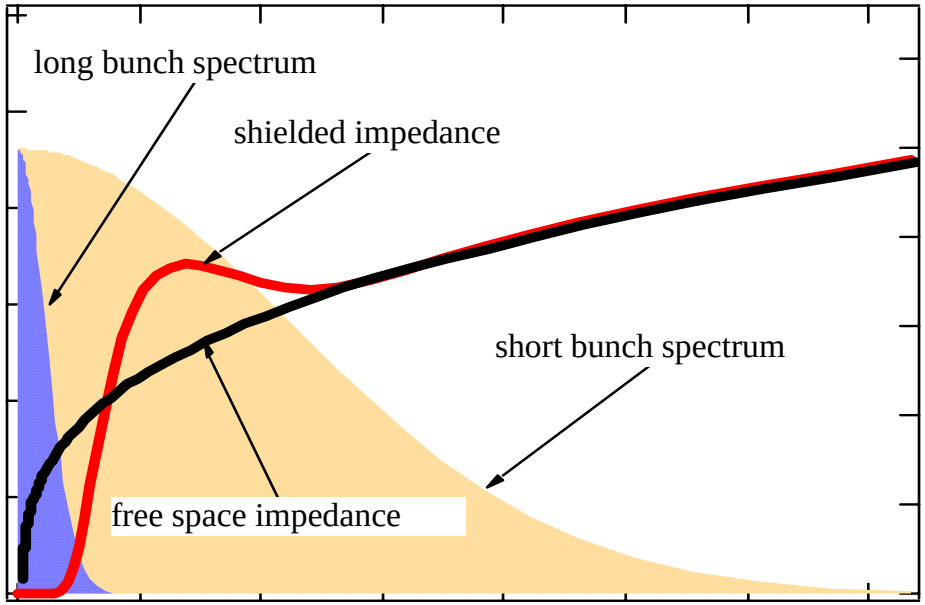
Vacuum chamber as high pass filter

Vacuum Chamber acts as a High Pass Filter



When the effective size of the SR source is equal to the height of the vacuum chamber, SR is suppressed.

Most rings can not make short enough bunches to generate CSR!



Frequency

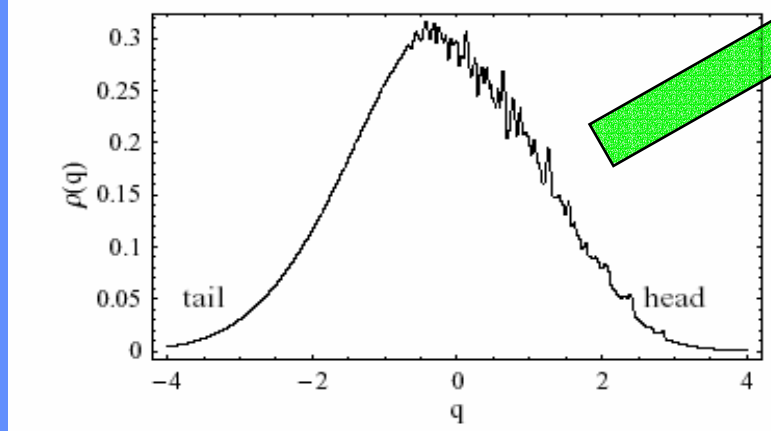
Nodvick, Saxon, Phys. Rev. **96**, 1, p. 180 (1954)

Shielding by the vacuum chamber limits the SR emission to wavelengths above the waveguide cutoff condition

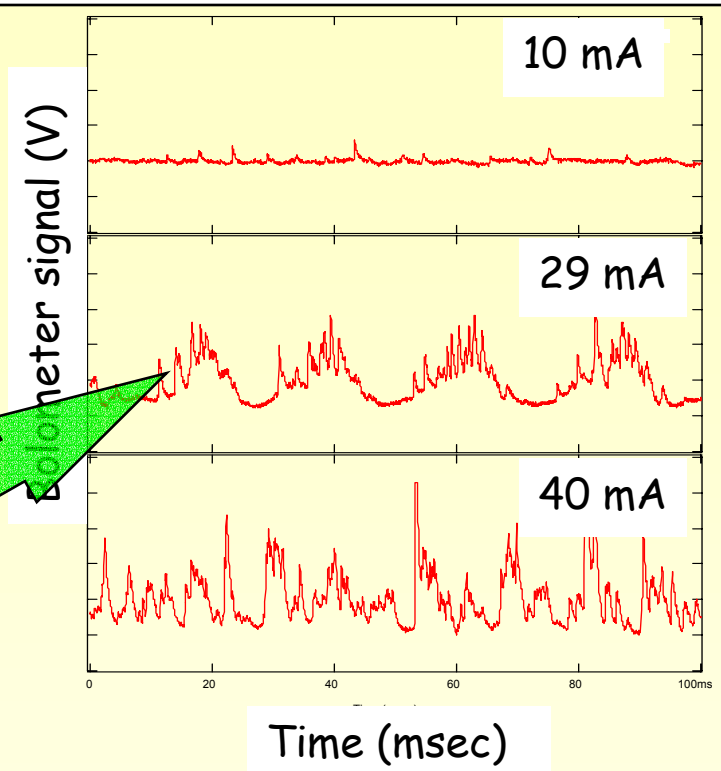
$$\pi\sigma < \lambda < 2h\left(\frac{h}{\rho}\right)^{1/2}$$

CSR Instabilities

CSR can drive a microbunching instability in the electron bunch, resulting in a periodic bursts of terahertz synchrotron radiation, resulting in a noisy source.



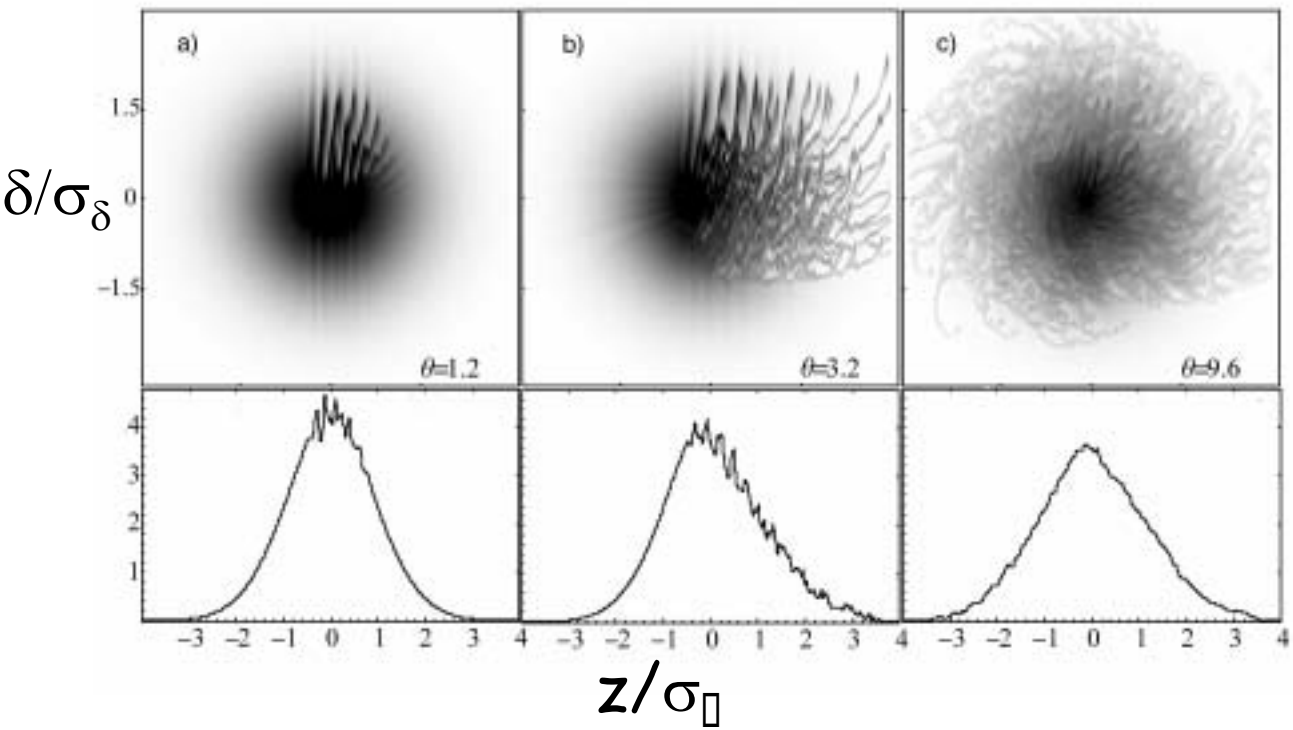
Simulated instability showing bunch shape



Bursts of far-IR CSR observed on a bolometer. Threshold depends on beam energy, bunch length, energy spread, and wavelength.

Microbunching Model

Small perturbations to the bunch density can be amplified by the interaction with the radiation. Instability occurs if growth rate is faster than decoherence from bunch energy spread.

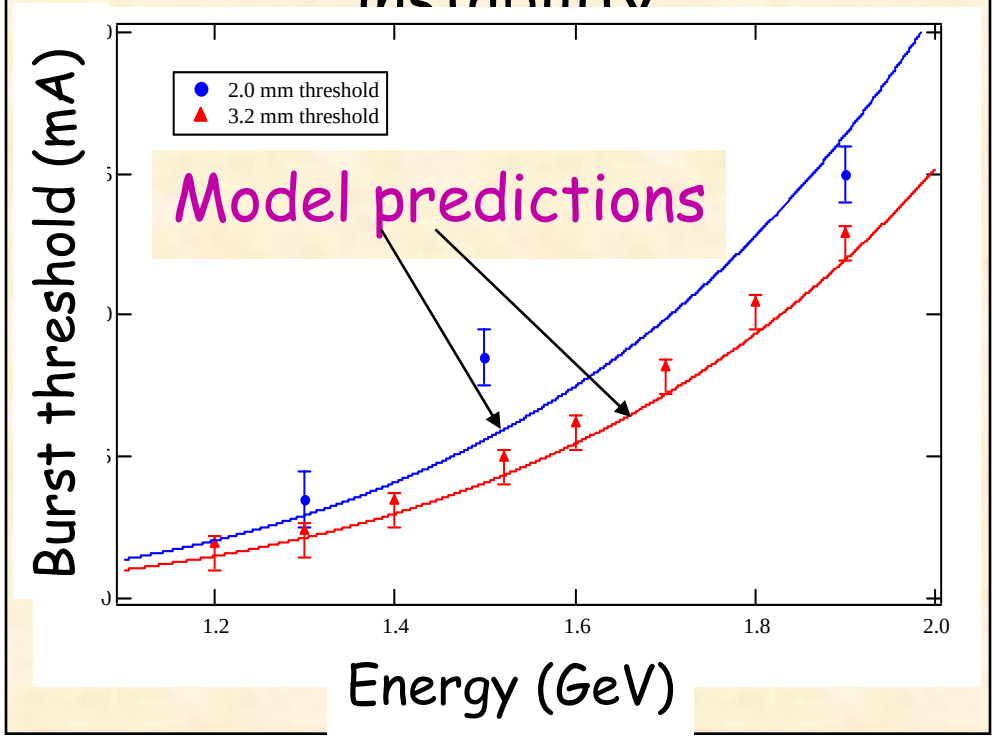


Nonlinear effects cause the instability to saturate. Radiation damping damps the increased energy spread and bunch length, resulting in a 'sawtooth' instability.

S. Heifets and G. Stupakov, PRST-AB **5**, 054402 (2002).
M. Venturini and R. Warnock, PRL **89**, 224802 (2002).

ALS microbunching results

ALS studies show first confirmation of CSR driven sub-microwave instability

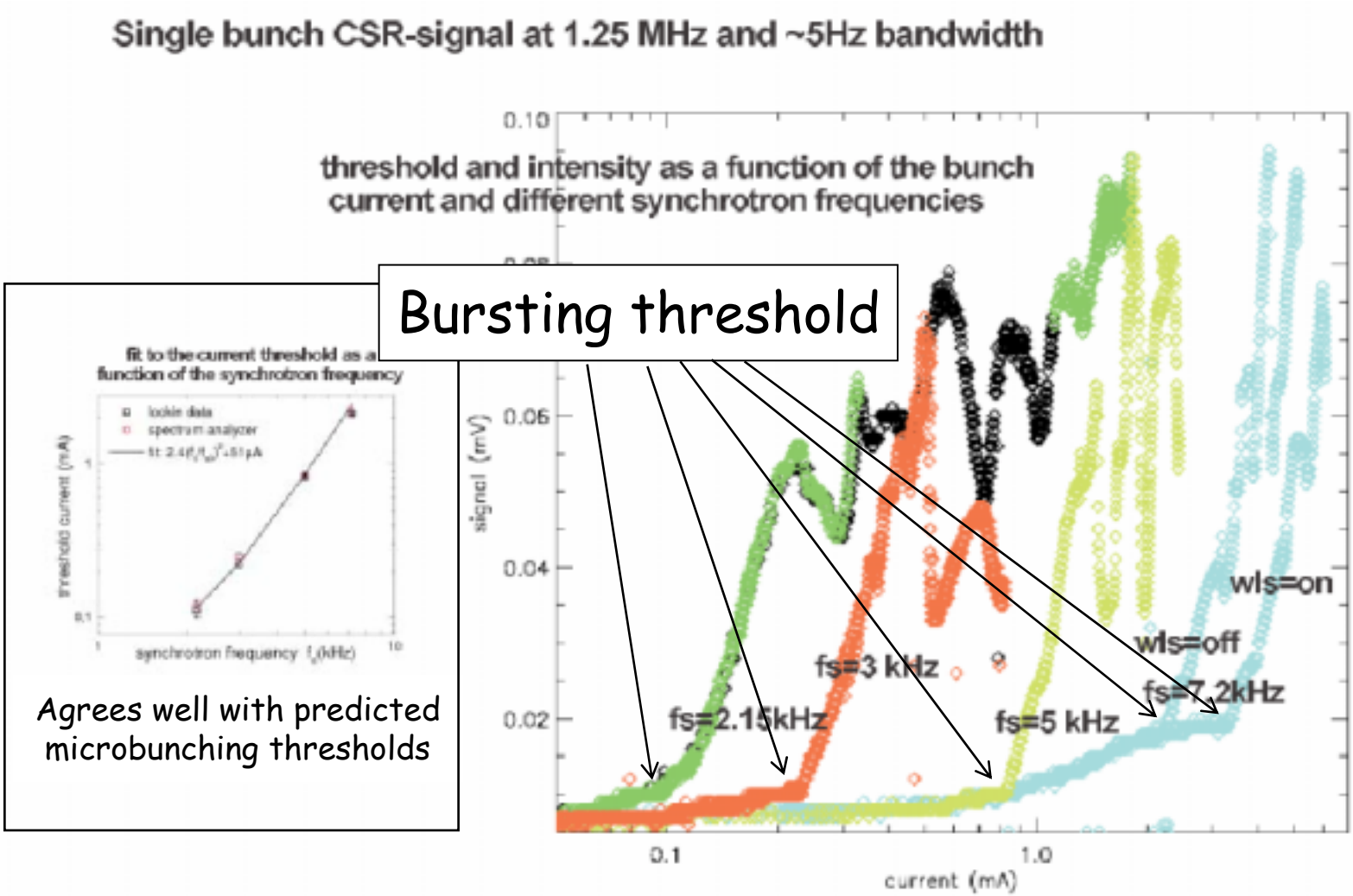


Instability thresholds understood:
- -agreement w/observations at other sources
- -coherent power enhanced w/lower S/N
- -possibility of raising threshold using nonlinear momentum compaction

NB: This is the same effect on which the LCLS is based!

J. Byrd, et. al. PRL 89, 224801, (2002).

Bessy-II Microbunching



G. Wuestefeld, Napa CSR Workshop, Oct. 2002

APS μbunching threshold

John Byrd

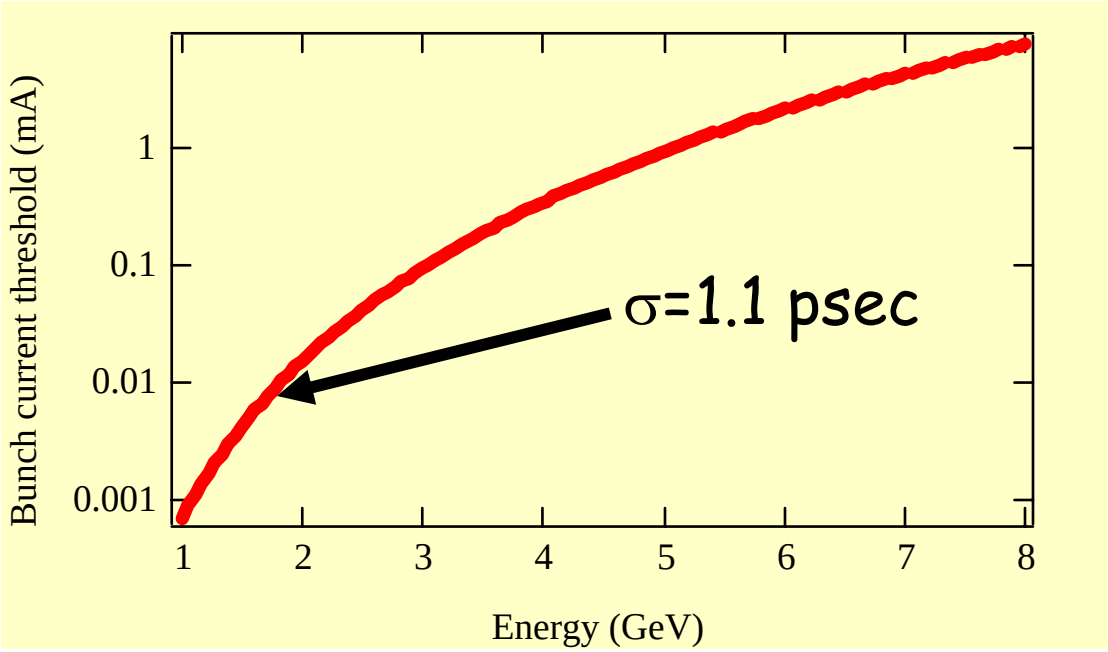
$$I > \frac{\pi^{1/6}}{\sqrt{2}} \frac{ec}{r_0} \frac{\gamma}{\rho^{1/3}} \alpha_C \delta_0^2 \sigma_z \frac{1}{\lambda^{2/3}}$$

Vacuum Chamber Cut-off limits the wavelength:

$$\lambda \lesssim 2b\,(b/\rho)^{1/2}$$

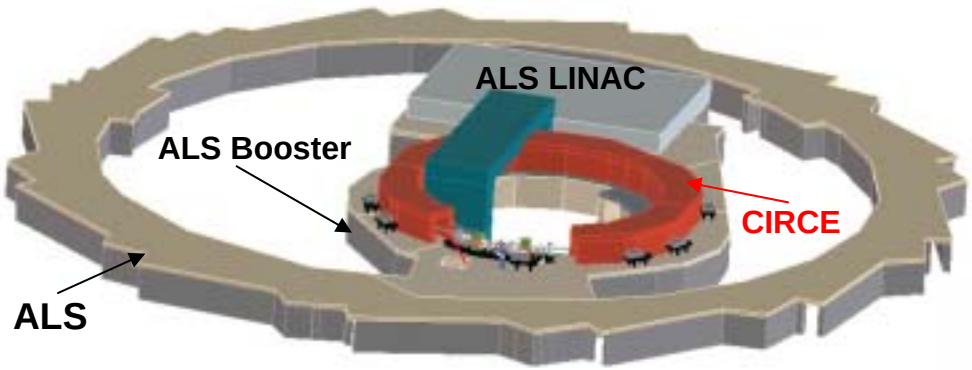
What is the instability threshold for 1 psec bunch in APS?
V=11 MV, α=2.3e-4,ρ=39 m, b=2 cm

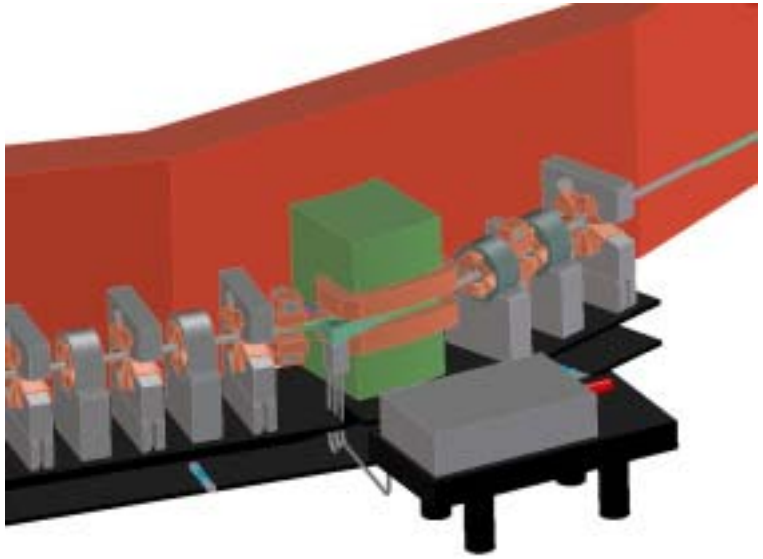
Thresholds for bunches ~1 psec are typically below 100 μA. Evolution above threshold is not yet fully explored

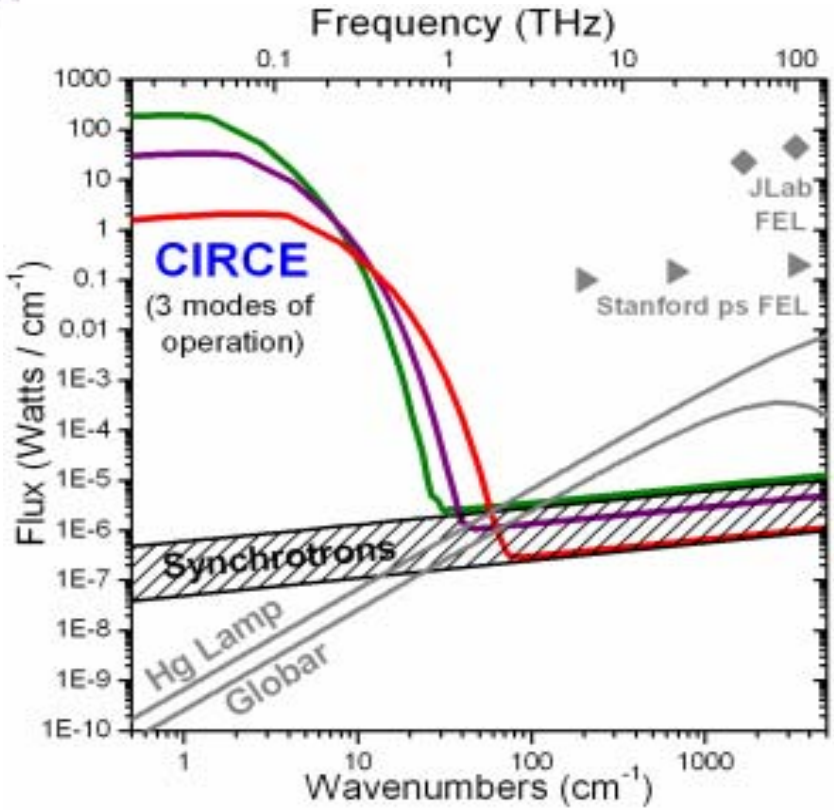


CIRCE: Coherent InfraRed CEnter

John Byrd

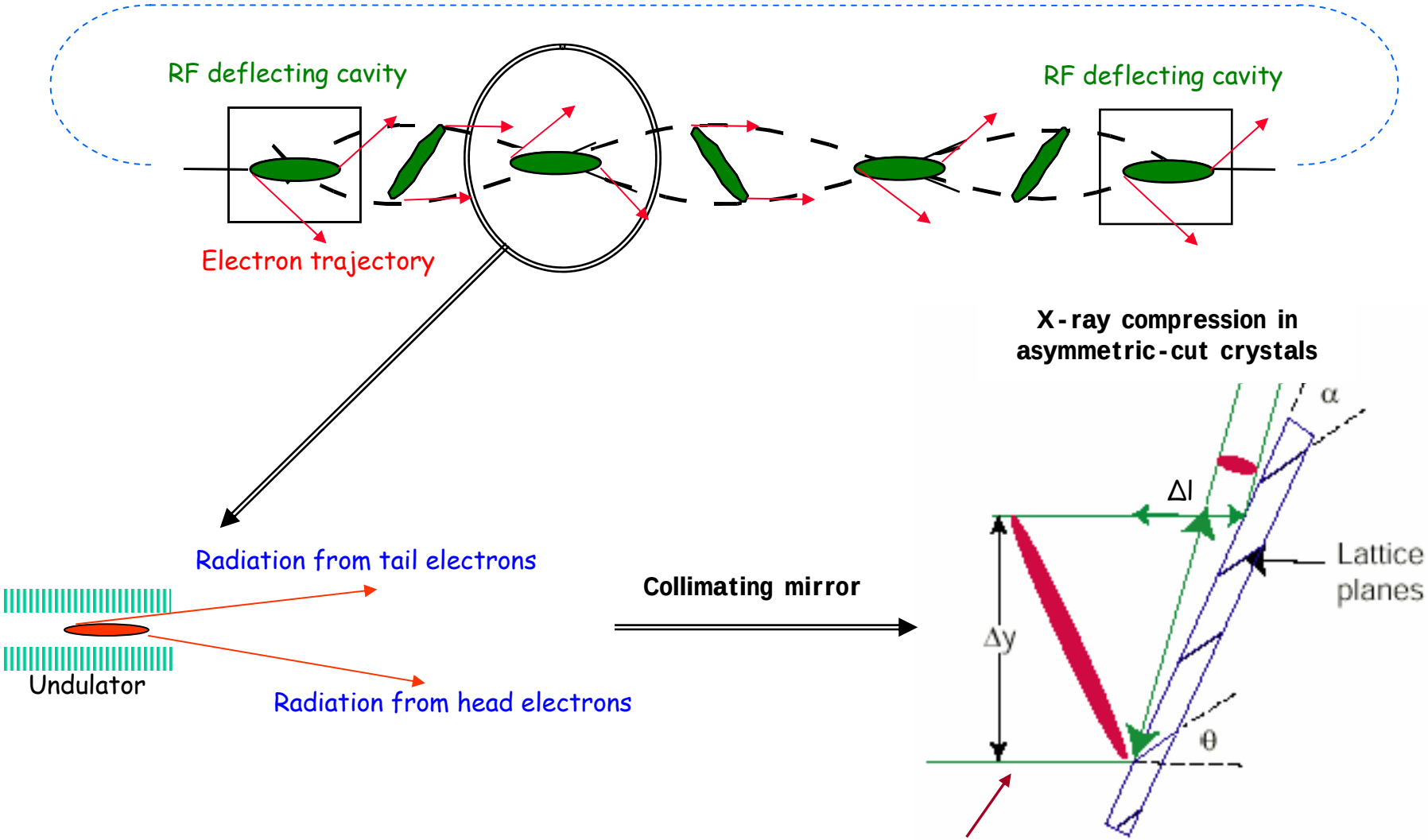






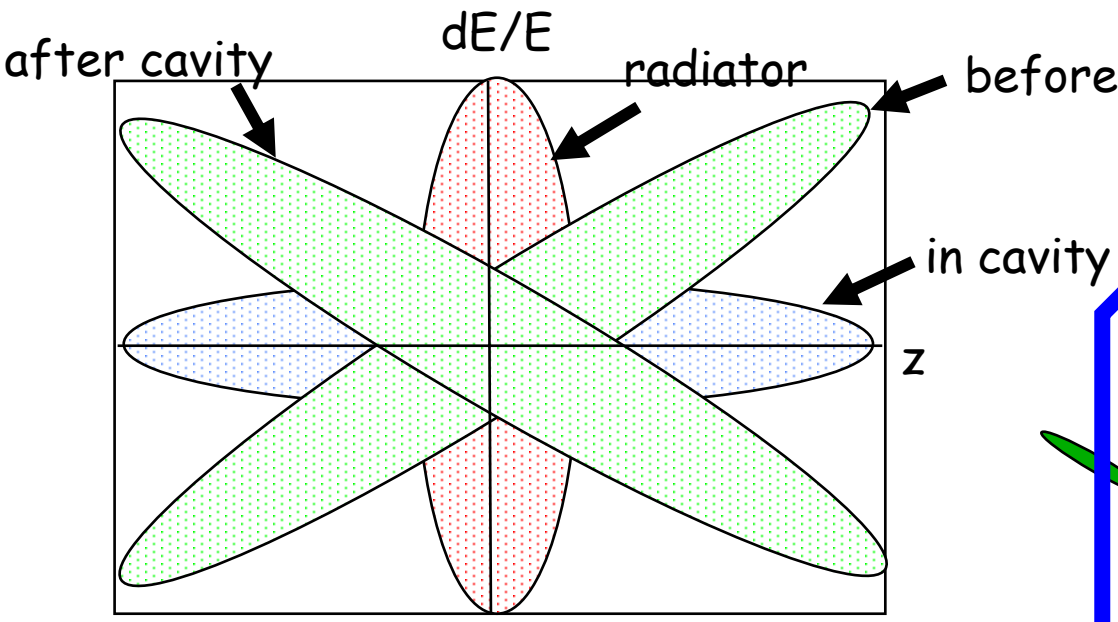
Pulse compression techniques

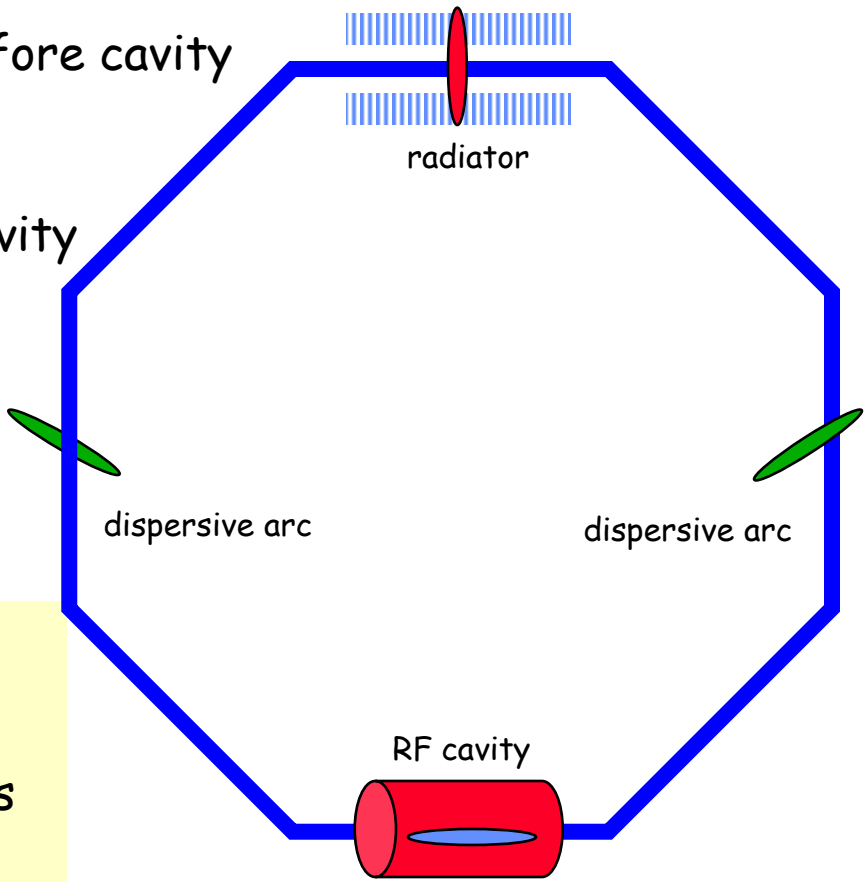
John Byrd



Strong Focussing

John Byrd





- Short bunch only at point of interest
- High dispersion arcs compress correlated energy spread into short bunch (but generates transverse emittance)
- Relatively high V needed or high ω
- Requires low energy spread to achieve short bunches
- Increased energy spread at radiator

It may be possible to make this work in pulsed mode

Example ring: DAFNE

E=510 MeV

		$\sigma_z(IP) = 3\ mm$	$\sigma_z(IP) = 2\ mm$	$\sigma_z(IP) = 1\ mm$
Bunch length at the RF position	$\sigma_z(RF)$	12 mm	12 mm	12 mm
One-turn synchrotron phase advance	μ	151°	161°	170°
Energy spread in the strong RF focusing regime	$\frac{\sigma_E}{E}$	1.2 ‰	1.4 ‰	1.4 ‰
One-turn normalized path elongation (total $\boldsymbol{R_{56}}$)	$R_{56}(L) = \alpha_c L$	19.4 m	16.9 m	17.1 m
Natural energy spread ("weak" focusing regime, μ <<1)	$\left.\frac{\sigma_E}{E}\right\|_0$	0.45 ‰	0.45 ‰	0.45 ‰
A function	$A[\mu, \rho(s), \beta_l(s)]$	0.446	0.263	0.074
RF wavelength - RF frequency	$\lambda_{RF} - f_{RF}$	0.6 m - 500 MHz	0.6 m - 500 MHz	0.6 m - 500 MHz
RF Voltage	V_{RF}	9.43 MV	11.19 MV	11.28 MV
Energy acceptance (@ IP - RF)	$\left.\frac{\Delta E}{E}\right\|_{max}$	0.98 % - 0.41%	1.16% - 0.45%	1.2% - 0.47%

Dedicated ring

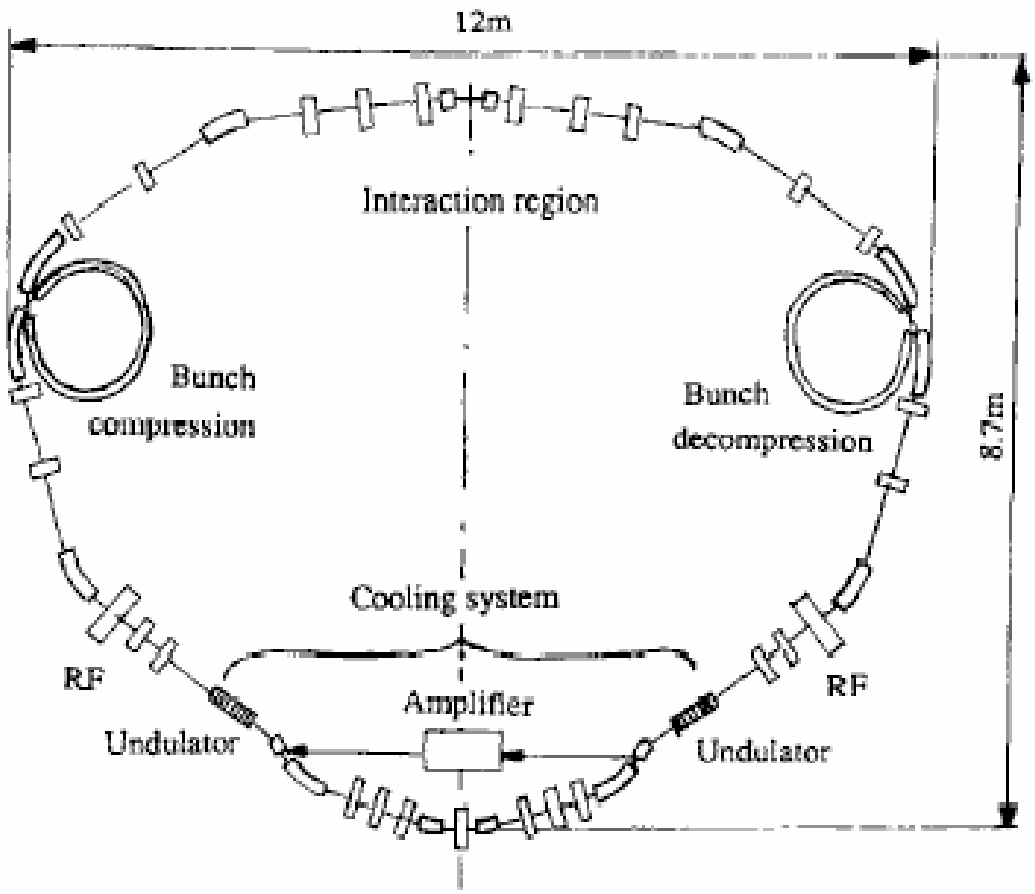


Fig. 1. The layout of the storage ring.

Beam parameters in the interaction region	
Bunch length, σ_z / c	100 fs
Energy spread, σ_E / E_0	9×10^{-4}
Horizontal beam size, σ_x	0.6 mm
Vertical beam size, σ_y	0.6 mm
Beam parameters in the cooling insertion	
Bunch length, σ_z	1 cm
Energy spread, σ_E / E_0	3×10^{-6}
Compression factor	300

X-rays generated via Compton scattering of a 150 MeV electrons and 10.5 micron CO_2 laser.

Zholents and Zolotorev, NIMA 358 (1995), 455-458

Summary

- Static bunches <1 psec are possible in rings but at low currents and relatively low beam energies (<few GeV)
- Limited by instabilities. For bunches <1 psec this effect dominated by interaction of beam with its own radiation and is independent of vacuum chamber.
- Bunch phase rotation: possible but yet to be demonstrated. Requires low energy spread and thus low energy beam and relatively high RF voltage.
- x-ray pulse compression: See Sacha's talk.
- laser slicing: See Sacha's talk.

Acknowledgements: Fernando Sannibale, Cecile Limborg, Sacha Zholents, Max Zolotorev, Alessandro Gallo, Karl Bane, John Corlett