Flat Beam Dynamics

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Introduction

- The high field VLHC has a "usefully" short **radiation damping time** $\tau_d \simeq 2.6$ hr.

- There is some freedom in selecting the **equilibrium horizontal emittance**

$$\epsilon_x \simeq 0.5\mu\text{m} \propto B^3 L_{hc}^3 \gamma^0 \tag{1}$$

  where L_{hc} is the half FODO cell length.

- **Magnet technology** limits L_{hc} and ϵ_x from above, eg through arc dipole systematic harmonics at injection.

- There may be considerable freedom to reduce the **equilibrium emittance ratio**

$$\kappa = \epsilon_y/\epsilon_x \leq 0.1 \tag{2}$$

  to **make the beams flat.**

Luminosity performance

- For flat beams, assume that

$$\kappa = \frac{\epsilon_y}{\epsilon_x} = \frac{\beta_y^*}{\beta_x^*} = \frac{\sigma_y^*}{\sigma_x^*} \ll 1 \qquad (3)$$

so that the *flat* beam-beam parameter

$$\xi = \xi_x = \xi_y \approx \frac{N}{\epsilon_x}\frac{r}{2\pi\gamma} \qquad (4)$$

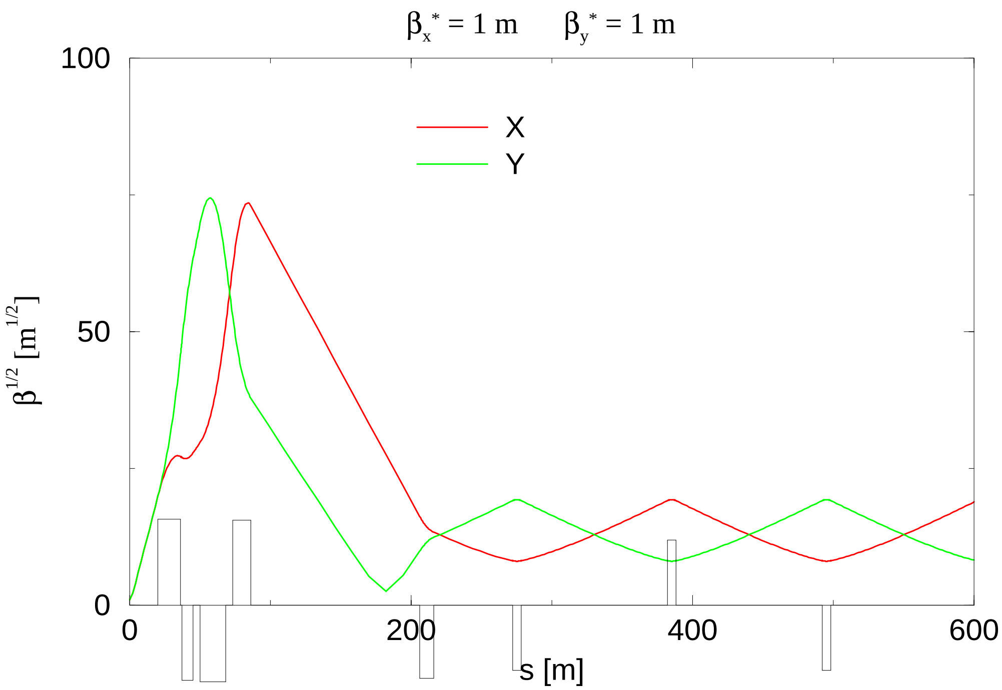
and the flat luminosity is simply

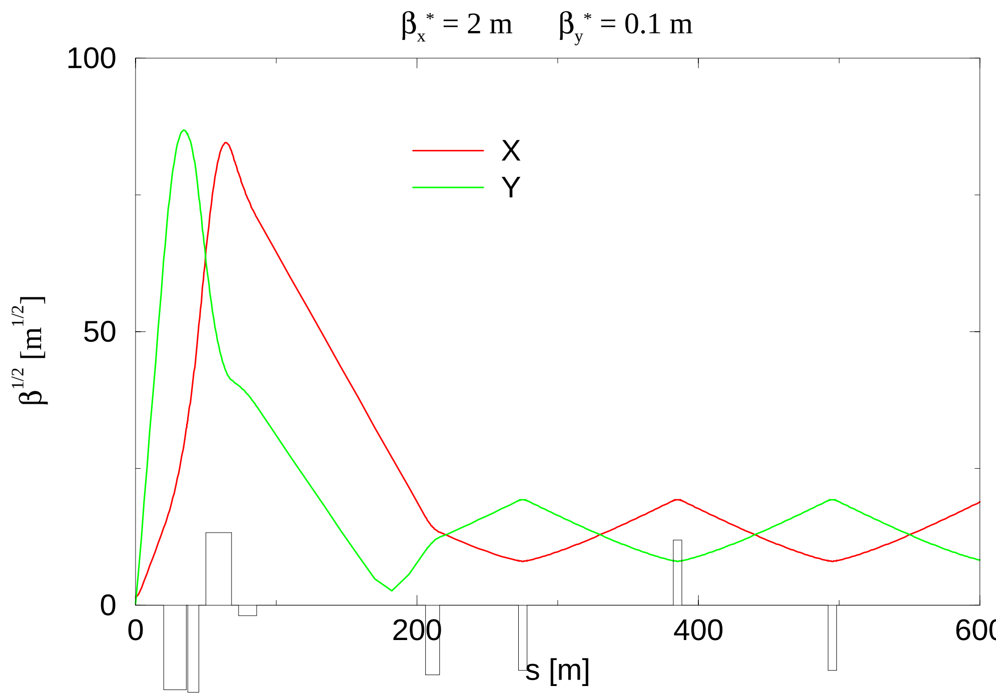
$$L = M\xi^2 \frac{\sigma_x'^{*2}}{\kappa} \left(\frac{\pi F \gamma^2}{r^2}\right) \qquad (5)$$

- The **flat beam luminosity scales like**

$$L \propto \frac{1}{\kappa} \qquad (6)$$

because the maximum value of the horizontal rms angular beam size $\sigma_x'^*$ is set by the IR optics.

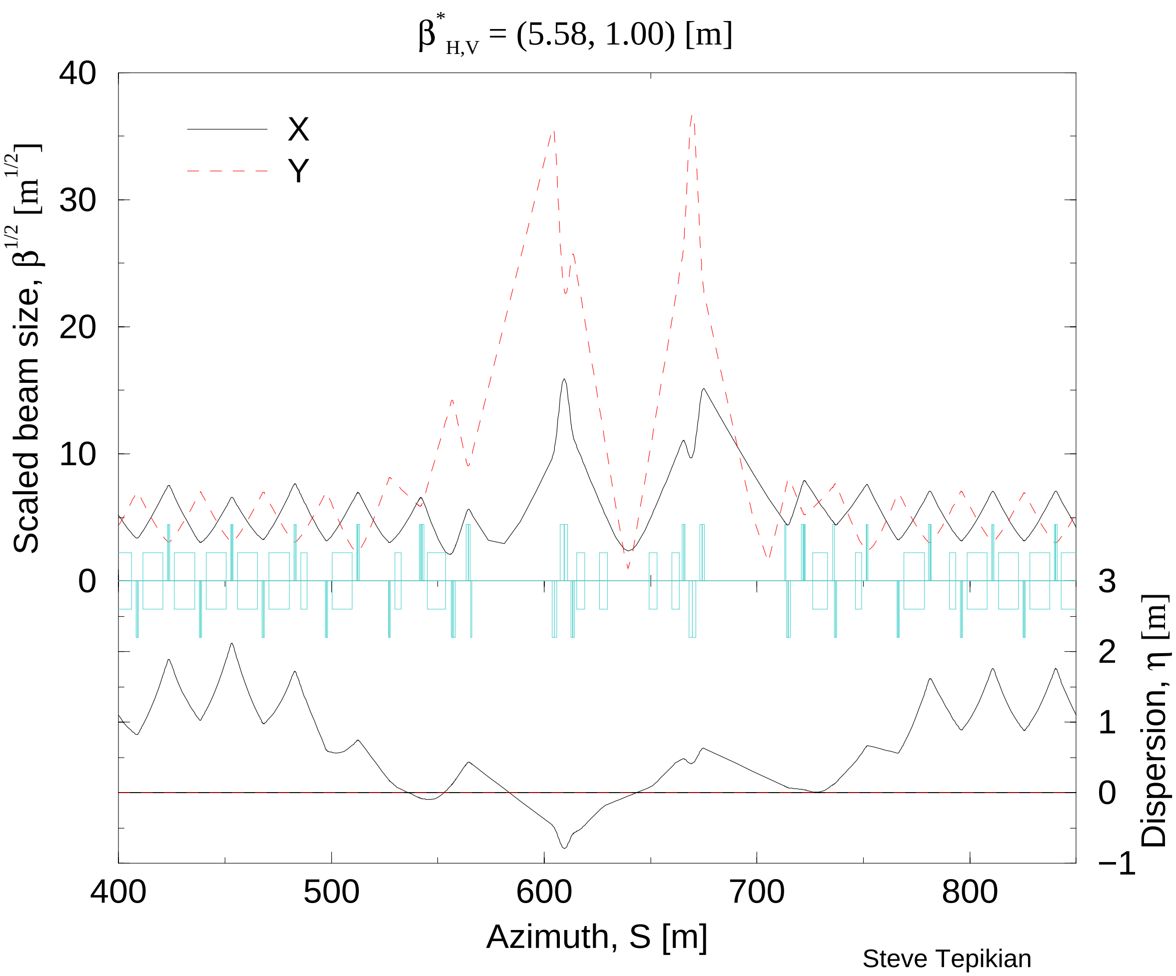




- The same 4 quads ($G = 500$ T/m !) as a triplet ($\kappa = 1$) on the left, and as a doublet ($\kappa = 0.05$) on the right.

- **The doublet outperforms the triplet by a factor of** $20 * (74/119)^2 = 7.7$

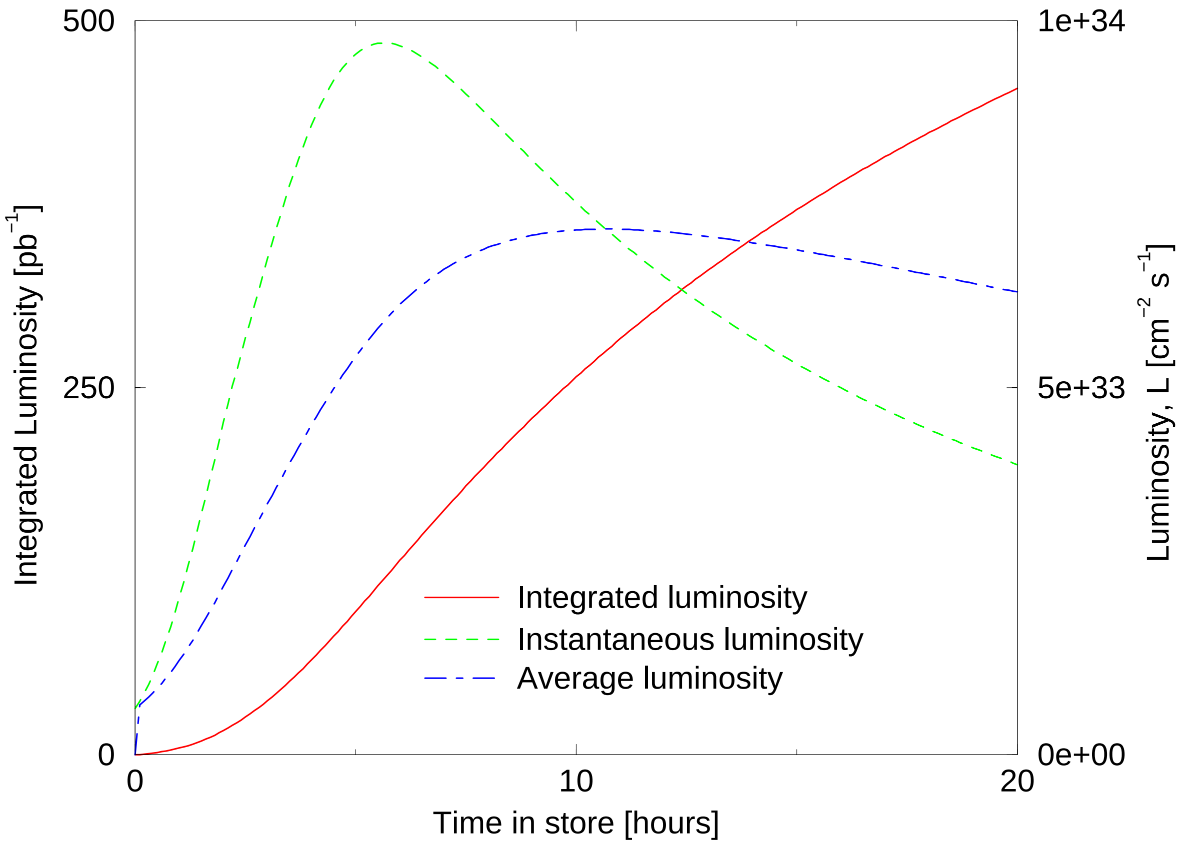
Flat beam collision optics in RHIC



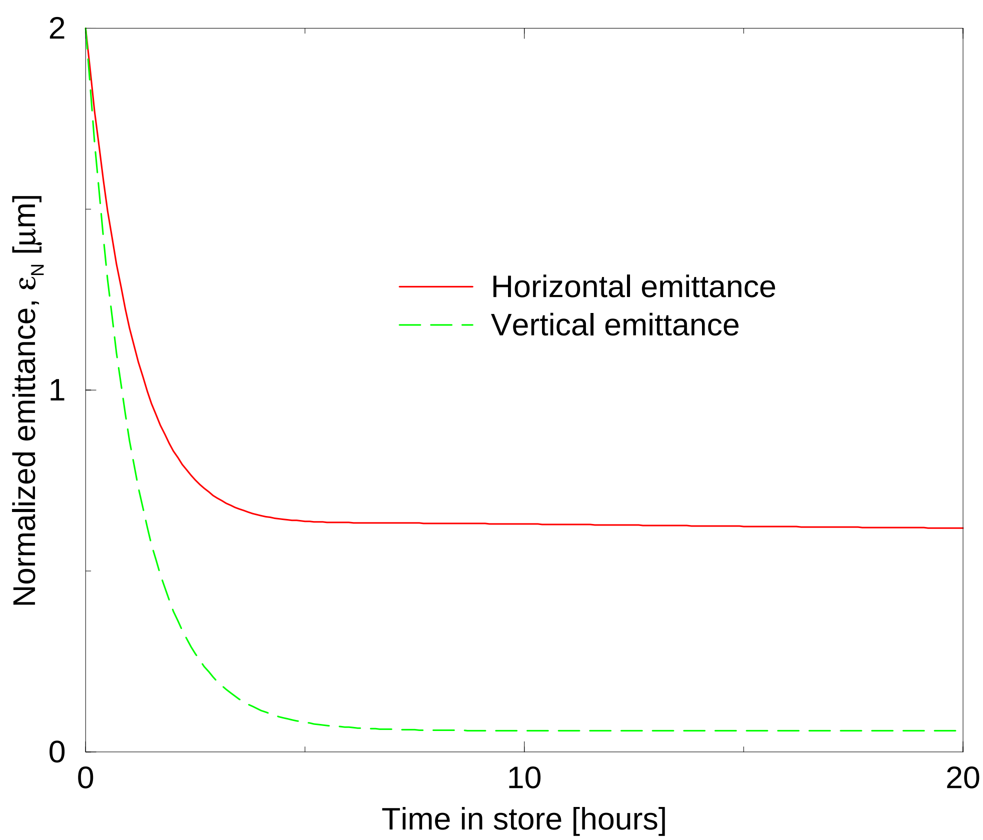
- **RHIC can achieve $\kappa \leq 0.18$.**
- IBS flattens RHIC emittances (especially at low energies).

Flat beam store evolution using *almost* the same parameters as Mike Harrison ...

Energy, E_s	50.0	TeV
Peak luminosity, L	10^{34}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Circumference, C	89.0	km
Dipole field, B	12.5	T
Damping time, τ_d	2.26	hr
Half cell length, L_{hc}	260	m
Horz. emittance, ϵ_x	0.59	μm
Emittance ratio, κ	0.1	
Collision betas, β_x^*, β_y^*	5.0, 0.5	m
Number of bunches, M	20,000	
Initial bunch intensity, N	12.5×10^9	
Synch. rad. power, P_{SR}	0.49	MW
Dipole linear heat load	5.9	W/m

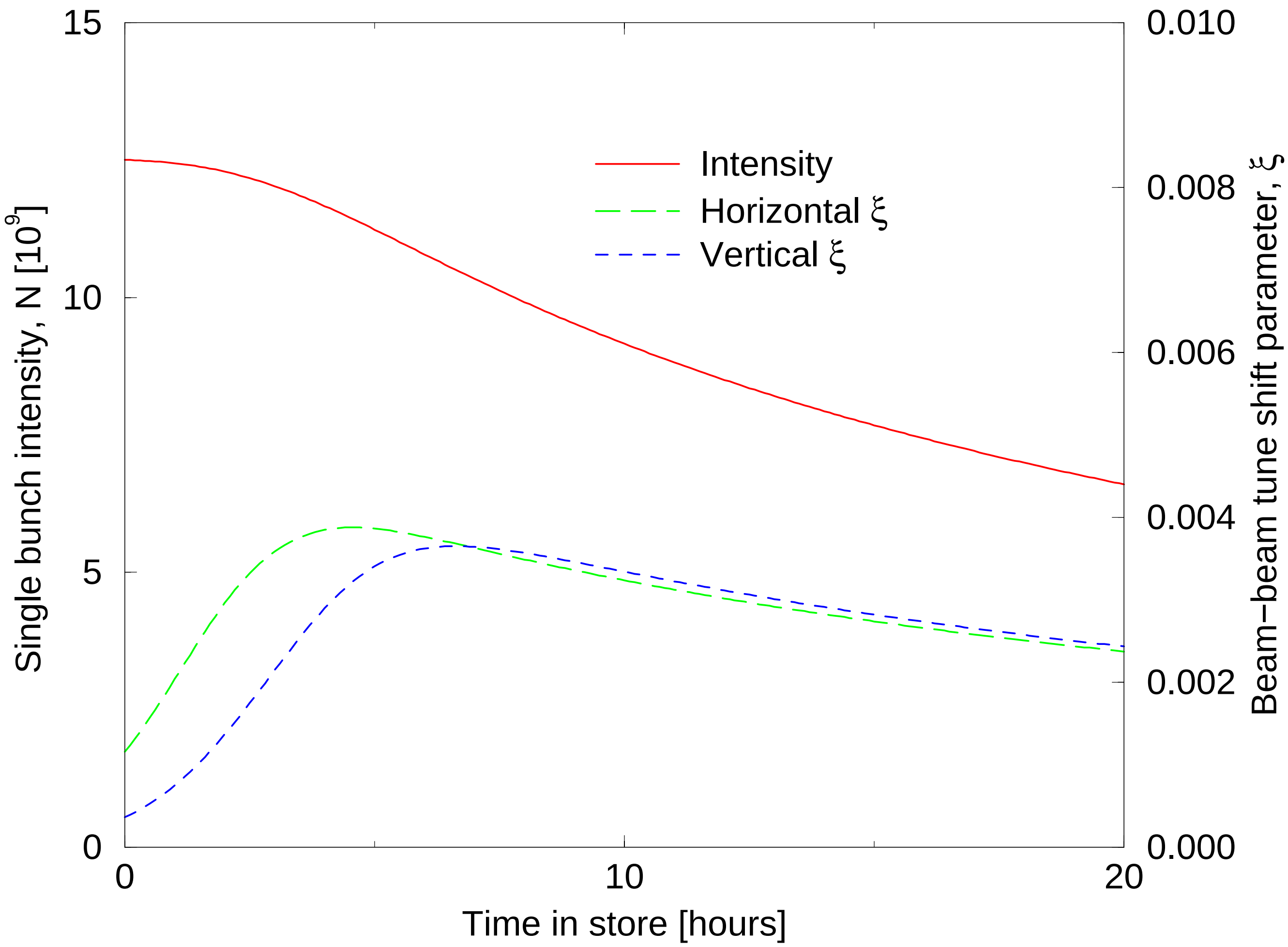


500
250
0
1e+34
5e+33
0e+00
0
10
20
Integrated Luminosity [pb^-1]
Luminosity, L [cm^-2 s^-1]
Time in store [hours]
Integrated luminosity
Instantaneous luminosity
Average luminosity



2
1
0
0
10
20
Normalized emittance, ε_N [µm]
Time in store [hours]
Horizontal emittance
Vertical emittance

Beam-beam tune shift parameter ξ



- Horizontal and vertical ξ's are well behaved.
- **Half the beam is "burned off"!!**

Synchrotron Radiation Effects Workshop

Sept. 18-20, 2000, BNL

"Round or Flat Beams?" & "Damping Dynamics" working groups met jointly, led by Chao & Talman:

A. Chao (SLAC)
J. Johnstone (FNAL)
P. Limon (FNAL)
J. Murphy (BNL)
B. Parker (BNL)
S. Peggs (BNL)
T. Sen (FNAL)
R. Talman (Cornell)
J. Wei (BNL)

"We have (almost) no definite answers to these questions, but we had 2 fun days discussing them."

Talman topics:

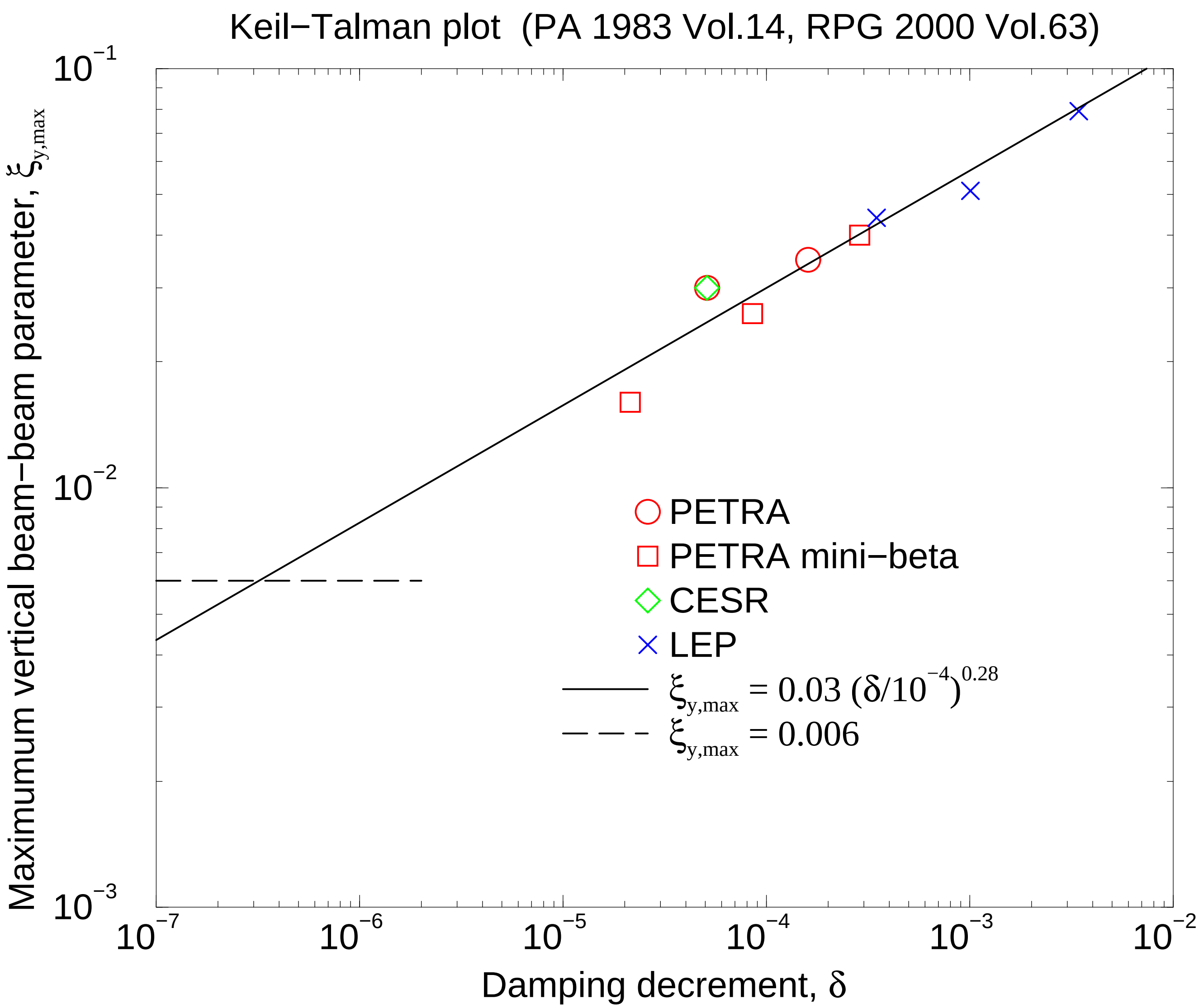
1. Does damping enhance beam-beam stability?
2. Synchrotron Radiation heat load economy.
3. Future experiments & theoretical investigations.

Chao challenges:

1. Does Synchrotron Radiation help or hurt?
2. Is high field or low field better?
3. Are flat beams better than round?

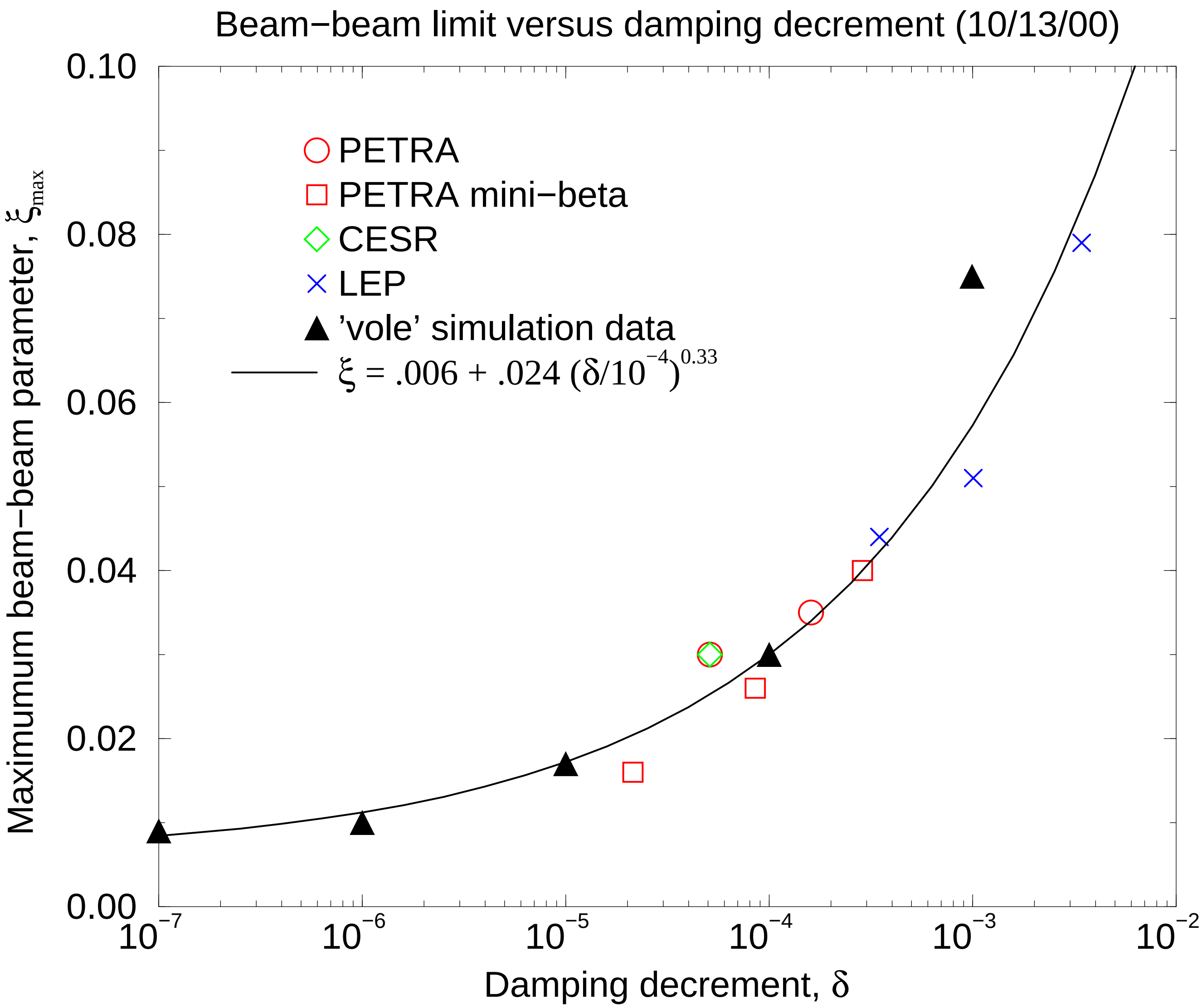
(with some re-organization to aid narrative flow)

1. Does damping stabilize beam-beam?



- Electron data are straight on a log-log plot
- SPS, TeV, HERA (no damping): $\xi_{max} \approx 0.006$
- What happens when damping decrement $\approx 10^{-7}$?

Add simulation data ...



Damping not much help to beam-beam.

2. SR heat load economy

- The total SR power is

$$P_{SR} = \frac{U_0}{T_0} N \tag{7}$$

- **Most protons burn off**, so

$$N \approx L\, \sigma_{tot}\, \tau_{store} \tag{8}$$

- Luminosity evolution has a **timescale of τ_d**

$$\frac{\tau_{store}}{\tau_d} \equiv n_1 \sim 5 \tag{9}$$

- But since

$$\tau_d = \frac{T_0 E}{U_0} \tag{10}$$

then

$$P_{SR} \approx L\, \sigma_{tot}\, n_1\, E \propto E \tag{11}$$

This is a remarkably simple scaling result!

Suppose that

- $\eta_{liner} = 0.95$ is the fraction of SR absorbed in an 80 K beam pipe liner,
- $\eta_{80} = 0.25(80/300)$ is the warm refrigeration efficiency, and
- $\eta_4 = 0.25(4/300)$ is the cold efficiency.

The wall plug power is then

$$\begin{aligned} P_{plug} &= \left(\frac{1-\eta_{liner}}{\eta_4} + \frac{\eta_{liner}}{\eta_{80}}\right) P_{SR} \\ &\approx (15+14) \quad P_{SR} \qquad (12) \end{aligned}$$

For example, with $P_{SR} = 0.49$ MW per ring from the standard parameters quoted above, then

$$P_{plug} \approx 15 \text{ MW per ring.} \qquad (13)$$

3. Future experiments and theoretical investigations.

Investigate κ_{min} with respect to:

1. **Intra Beam Scattering**

2. **Noise sources:** *See Chao challenges, below.*

3. **Flat beam optics:** investigate/confirm the appearance that

$$\frac{L_{flat,max}}{L_{round\,max}} \simeq 5 \tag{14}$$

1. Does SR help or hurt?

1. SR relaxes the demand on ϵ_{inj}, so long as the beam doesn't scrape.

2. SR relaxes the demand on magnet nonlinearities and injection errors.

3. SR is a large heat load on the cryosystem. If 6 W/m is absorbed at 80 K, the wall plug power is $\approx$ 15 MW per ring.

4. An SR heat load of 30 MW suggests beam energy can be increased! 20 W/m => 160 TeV ??

5. SR at $\geq$ 100 keV can be a significant source of
   (a) radio-activation
   (b) DC heat load to the magnet coils

   These effects need to be evaluated.

6. SR has the potentially **very important advantage of allowing manipulations of** ϵ_x, ϵ_y to optimize L. The following need to be fully explored:
   (a) Add combined function wigglers in the arcs to control the partition numbers J_x, J_s.
   (b) Control J_x, J_s by f_{RF}.
   (c) Add wigglers in non-dispersive regions to increase the radiation damping (shorten τ_d).

7. Does shorter τ_d allow a higher head-on beam-beam limit? SR either doesn't help, or helps only a little bit. This issue remains to be resolved.

2. Is high field or low field better?

1. Overall, SR seems to hurt more than help.

3. Are flat beams better than round?

1. When the bunch population is limited (eg SR load), the smaller $\kappa = \epsilon_y/\epsilon_x$ the better for L.

2. What happens if κ is "too small"?
   (a) IBS $\propto 1/\kappa$. Control IBS by longitudinal heating.
   (b) Can lose flexibility in choosing either H or V beam separation.
   (c) Long range beam-beam $\Delta Q \propto 1/\kappa$. This needs more quantitative evaluation.

3. Two IR optics options:
   (a) triplet, round beam, $\kappa \approx 1$
   (b) doublet, flat beam, $\kappa \ll 1$

   No clear advantages of triplet option.

4. **It's crucial to fight for small κ.** This realization is a highlight of the workshop.

5. How small will κ be? It is determined by

$$\frac{d\epsilon_y}{dt} = -\frac{\epsilon_y}{\tau_d} + \frac{\epsilon_{y0}}{\tau_d} + \dot{\epsilon}_{y,noise} \qquad (15)$$

   Need to study $\dot{\epsilon}_{y,noise}$ in theory and experiment. Design experiments at RHIC (for IBS) and Tevatron (for other noise sources)!

6. It's likely that $\epsilon_{y0}/\tau_d \ll \dot{\epsilon}_{y,noise}$. Should design the lattice (eg L_{hc}) to minimize $\dot{\epsilon}_{y,noise}$.

7. IBS calculations need to be performed for flat beams!

Conclusions

1. "SR has the potentially **very important advantage of allowing manipulations of** ϵ_x, ϵ_y to optimize L."
2. **"It's crucial to fight for small κ."**
3. Flat beams produce denser bunches, so luminosity scales like $L \propto 1/\kappa$.
4. Flat beams permit doublet IR optics.
5. $P_{SR} \approx$ 15 MW/ring, and $P_{SR} \propto E$. Much higher energies are possible?
6. Damping has little effect in stabilizing the beam-beam effect?
7. RHIC can achieve $\kappa \leq 0.18$, allowing flat beam experiments – with IBS emittance flattening.

8. Experimental studies:

(a) IBS

(b) noise

(c) flat beam optics

9. Theoretical studies:

(a) Flat IBS

(b) arc optics resilient to noise

(c) IR optics

(d) high energy photons: radio-activation, magnet coil heat load

(e) wigglers

(f) beam-beam: damping, long range