Exploration of a Tevatron-Sized Ultimate Light Source

Michael Borland

Argonne National Laboratory

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Outline

- Introduction
- Generalities
  - Optimization of emittance
  - Scaling of lattice and collective effects
  - Emittance ratio
  - PEP-X MBA modules
- Possible Tevatron-sized light source
  - Design concept
  - Analysis of microwave instability
  - Choice of beam energy
  - Nonlinear dynamics optimization
  - Performance predictions
  - Short-pulse x-rays
- Conclusion

Introduction

- Not long ago, widely accepted that rings had reached the end of the road
- However, there are continuing improvements
  - PETRA-III: 1nm emittance at 6 GeV
  - NSLS-II: targeting 0.5 nm at 3 GeV
  - MAX-IV: targeting 0.25 nm at 3 GeV
  - SPRing-8 upgrade targeting 0.07 nm at 6 GeV
- Improvements are driven by
  - Advances in lattice design
  - Improved understanding of nonlinear dynamics
  - Improved lattice correction techniques
- Tevatron was recently shut down for good
  - Emittance scales like $1/C^3$
  - What can we do with a 6.28 km tunnel?
  - We present a snapshot of on-going work on this question

Methods of Decreasing Emittance

- To decrease the natural emittance, we can
  - Reduce the energy
  - Decrease $\mathcal{H}$
    - Stronger focusing
    - More frequent focusing
  - Increase damping
    - Damping wigglers

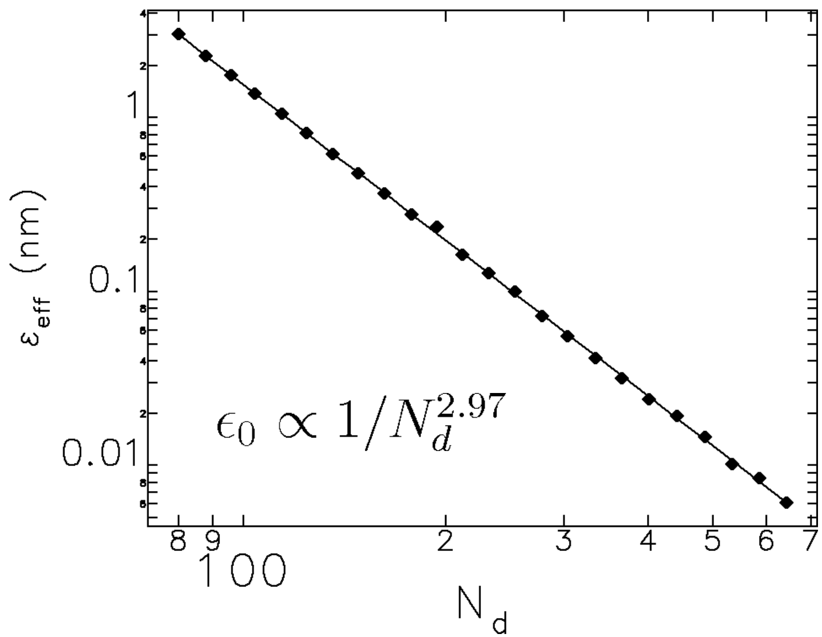
$$\epsilon \propto E_0^2 \frac{\langle \mathcal{H}/\rho^3 \rangle}{\langle 1/\rho^2 \rangle}$$

Used **elegant** to simulate scaling APS to larger circumference by adding more fixed-length cells.

Emittance scaling is as expected.

- A useful approximation[1]

$$\epsilon = F(\nu_x, \text{lattice}) \frac{E_0^2}{J_x N_d^3}$$



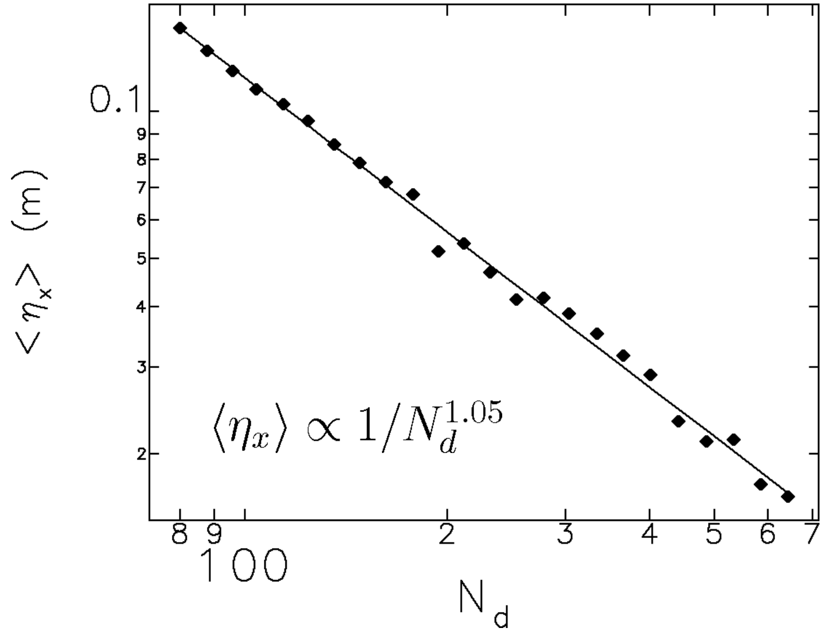
[1]J. Murphy, Light Source Data Book, BNL.

Nonlinear Dynamics

- More dipoles and/or stronger focusing ➔
  - smaller dispersion ($1/N_d$)
  - higher tunes, chromaticity (N_d)
- Chromatic sextupole strength scales like N_d^2
  - Expect $1/N_d^2$ scaling of dynamic and momentum aperture[1]
  - Smaller dynamic aperture ➔ injection problems
  - Smaller momentum aperture ➔ lifetime problems
- Use of additional sextupole families or octupoles necessary, but there are limits.

More data from the scaling simulation. Again no surprise.

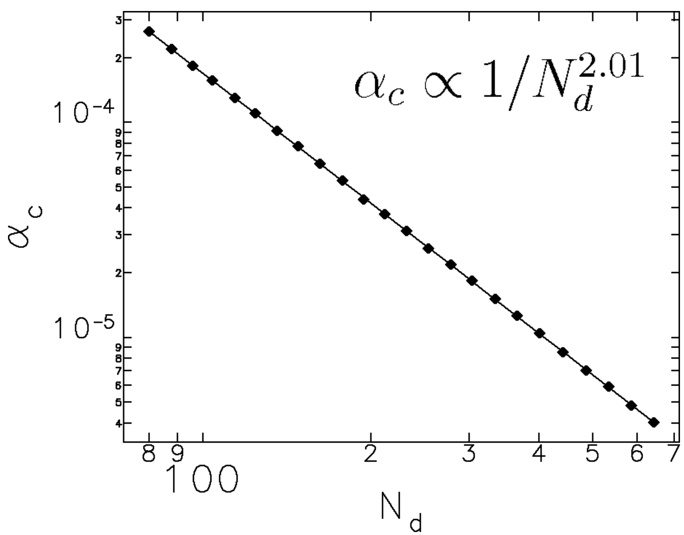
Sextupole strengths are inversely proportional to average dispersion.

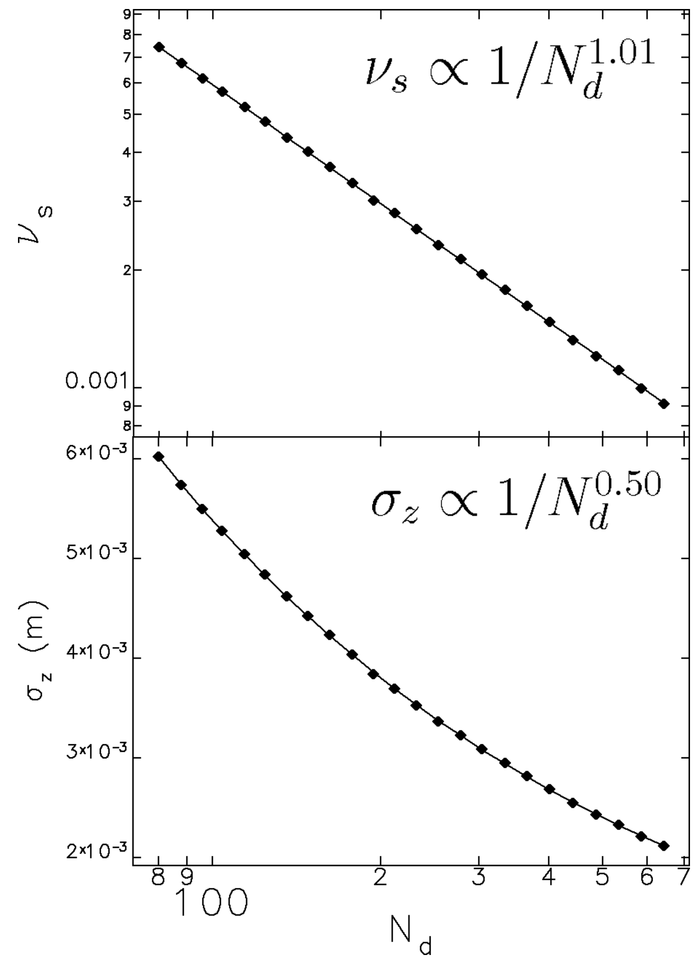


[1]L. Emery, private communication.

Collective Effects

- Smaller dispersion ➔ smaller momentum compaction α_c ➔ shorter bunch, reduced synchrotron tune ➔ increased collective effects





Simulations assume rf voltage adjusted for constant rf acceptance.

Collective Effects

- Touschek scattering

$$\frac{1}{\tau} \sim \frac{N_b N_d^{1.8}}{E^{4.1}}$$

- Intrabeam scattering

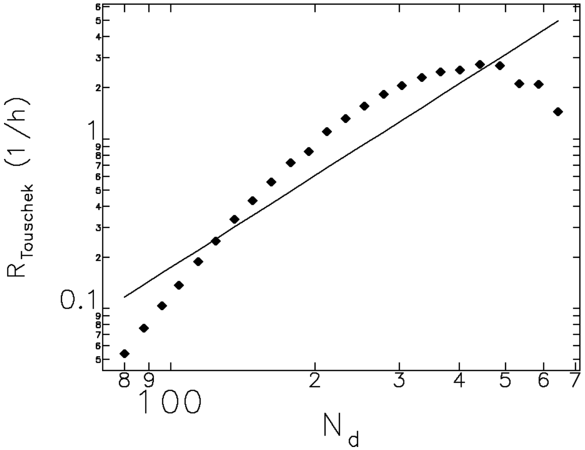
$$\frac{1}{\tau} \sim \frac{N_b N_d^{5.5}}{E^{8.1}}$$

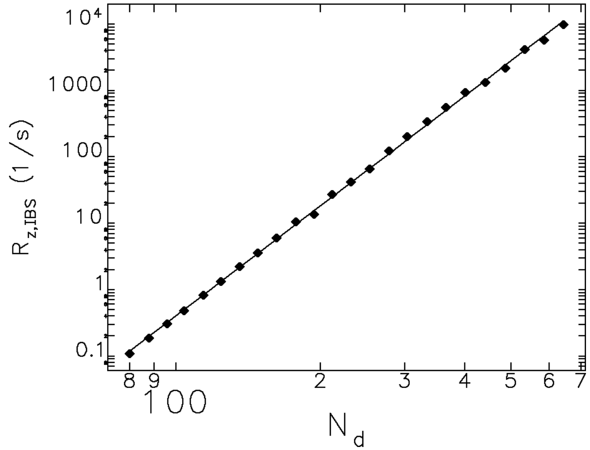
- TMCI[1]

$$I_{fht} = \frac{\pi \nu_s b^2 E}{R\langle\beta\rangle|Z/n|} \sim \frac{E}{N_d^{1.5}\langle\beta\rangle}$$

- Microwave instability[2]

$$I_{mw} = \frac{\sqrt{2\pi}\alpha_c E \sigma_l \sigma_\delta^2}{R|Z/n|} \sim \frac{E^{3.3}}{N_d^{5.5}}$$





Computed with **toushekLifetime** and **ibsEmittance** (A. Xiao *et al.*)
1: B. Zotter, Handbook of Accel. Phys. and Engineering.
2: H. Weidemann, Particle Accelerator Physics, Vol. 1.

Implications for a Tevatron-Sized Ring

- At 7 GeV, APS (C=1.1 km) has[1,2]
  - Microwave instability at 5 mA
  - TMCI at 2 mA (low chromaticity)
  - ~8 hour Touschek lifetime with 15 nC bunches, 1% coupling, and ±2.2% momentum aperture
  - Negligible IBS
- For 7 GeV, C=6.28-km APS-like ring, we expect
  - Microwave instability at 0.3 μA (!)
  - TMCI at 150 μA
  - 0.25 h Touschek lifetime
  - Non-negligible IBS
- What can we do?
  - Raise beam energy
  - Increase emittance ratio
  - Run *many* weak bunches
  - Lengthen the bunch
  - Dig into details

1: K. Harkay *et al.*, EPAC02, 1505.
2: Y.C. Chae *et al.*, PAC03, 3014.

Effect of Emittance Ratio

- Scaling for IBS and Touschek assumes emittance ratio is fixed
- For very low natural emittance, this is pointless
  - Intrinsic emittance from undulator is[1]

$$\epsilon_r = \frac{\lambda}{2\pi}$$

  - Pointless to make either horizontal or vertical emittance significantly less than this
- For 10 keV photons, threshold is about 10 pm
- Tevatron-sized APS-like lattice has 16 pm natural emittance
  - Set emittance ratio $\kappa \sim 1$ without harming brightness much
  - More about this later

[1]See, e.g., O. Chubar, FLS2012.

Injection Issues

- All present-day ring light sources use beam accumulation
  - Each stored bunch/train is built up from several shots from the injector
  - Incoming beam has a large residual oscillation after injection
    - Requires horizontal DA of ~10 mm or more
  - Because of x-y coupling, residual oscillations result in loss on vertical small-gap chambers
    - Incompatible with large x-y coupling
- We proposed to use “swap-out” injection[1,2]
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train
  - Injector requirements and radiation issues seem manageable[3]
- This was the operating mode of the first dedicated SR source, TANTALUS[4]

[1] M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
[2] L. Emery, M. Borland, ”Possible Long-term Improvements to the APS,” Proc. PAC 2003, 256-258 (2003)
[3] M. Borland, Proc. SRI09, AIP Conf. Proc. 1234, 2010.
[4] E. M. Rowe and F. E. Mills, Particle Accelerators **4**, 211 (1970).

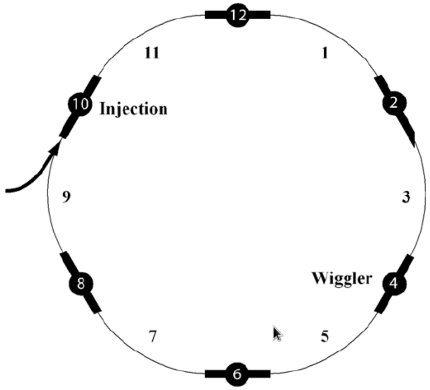
MBA Concept

- The APS lattice used for this scaling study is a double-bend design
  - We increased N_d by increasing the number of cells
  - Circumference increases with N_d
- Could also scale cells down while keeping fixed circumference
  - Hard to get very far with this approach
- Best approach is to make Multi-Bend Achromats[1]
  - Allows more dipoles in the same circumference
  - Smaller number of comparable-length straights
- MAX-IV ring[2] now under construction will be the first MBA ring

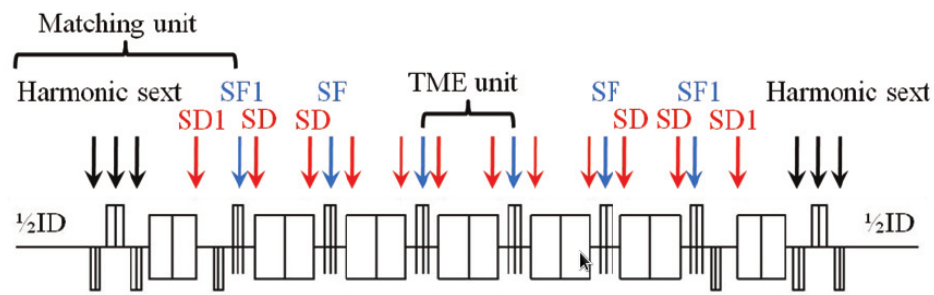
[1] D. Einfeld et al., Proc. PAC 95, 177-179 (1996).
[2] S.C. Leeman *et al.*, PRSTAB **12**, 120701 (2009).

PEP-X USR Design

- PEP-X group at SLAC has developed a robust 7BA lattice for a proposed light source in the PEP tunnel[1,2]



Courtesy Y. Nosochkov



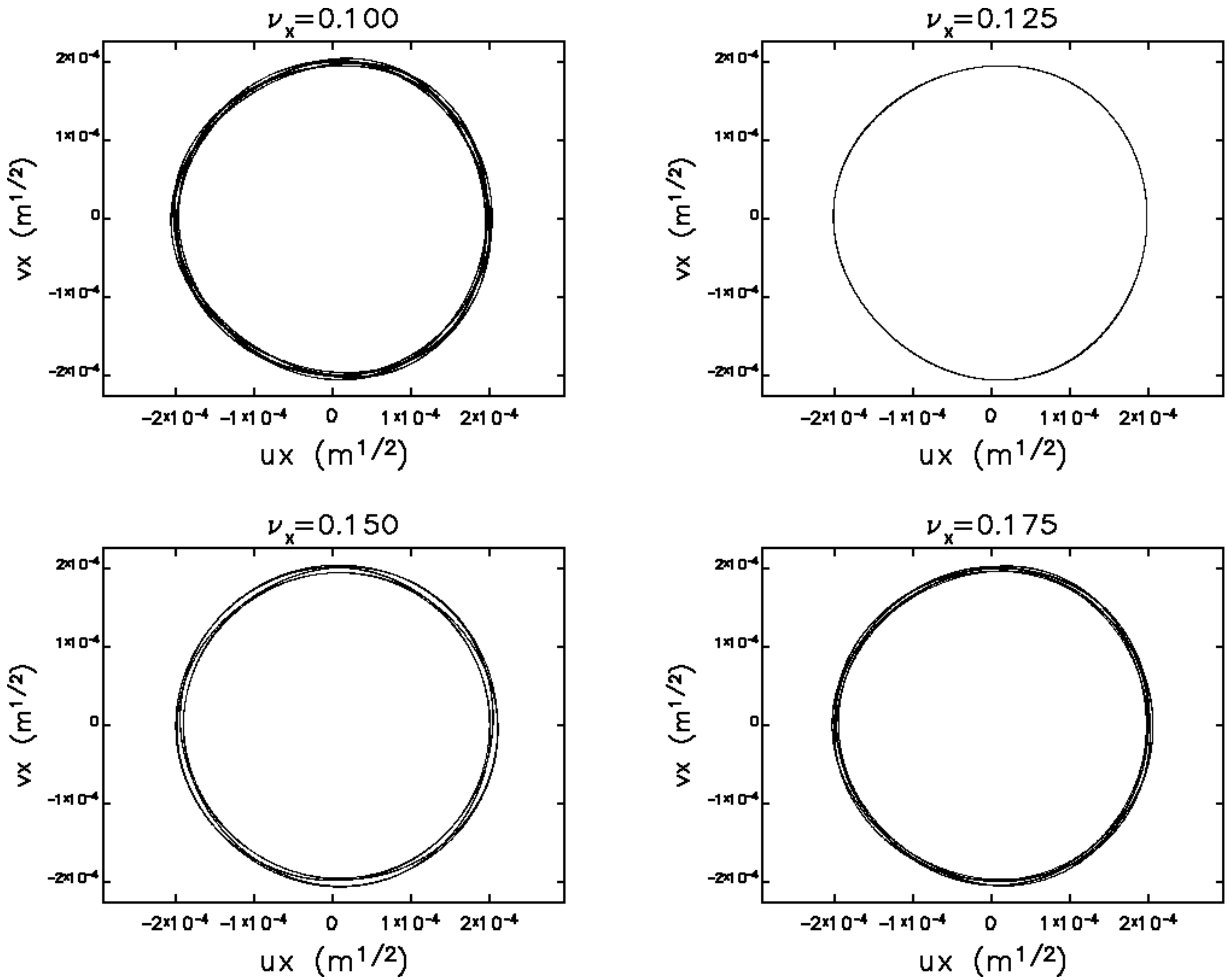
Courtesy M.-H. Wang

- Choose cell phase advance to make +I transform for each arc of N cells:
  - ν_x=2+m/N and ν_y=1+n/N
  - This results in cancellation of many 2nd-order geometric and chromatic aberrations[3,4]
  - For PEP-X, N=8 and m=n=1

[1]M.-H. Wang *et al.*, Proc IPAC11, THPC074.
[2]Y. Nosochkov *et al.*, Proc. IPAC11, THPC075.
[3]K. Brown, SLAC Rep. 75, June 1982.
[4]Y. Cai, NIM A 645:168-174 (2011).

Illustration of Effect of Right Phase Advance

Distortion of phase-space ellipse in PEP-X arc with 8 cells



Running with Round Beams

- There are various ways to make "round beams", i.e., $\kappa \sim 1$
  - Run on the $\nu_x - \nu_y = N$ resonance:
    - Pro: $\epsilon_x = \epsilon_y = \epsilon_0/2$
    - Con: hard to control
  - Add a vertically-deflecting damping wiggler
    - Pro: wiggler will provide damping
    - Con: strong, long-period wiggler will impact energy spread, no sharing of ϵ_0 between planes
  - Add x-y emittance-exchange insertions outside of arcs
    - Pro: simple implementation, doesn't mess up cancellation of driving terms inside arcs
    - Con: $\epsilon_x = \epsilon_y = \epsilon_0/\sqrt{2}$
- Of these, the EEX insertion seems preferable
  - Need to explore beam dynamics effects, however
  - Is it actually different from running on $\nu_x - \nu_y = N$?

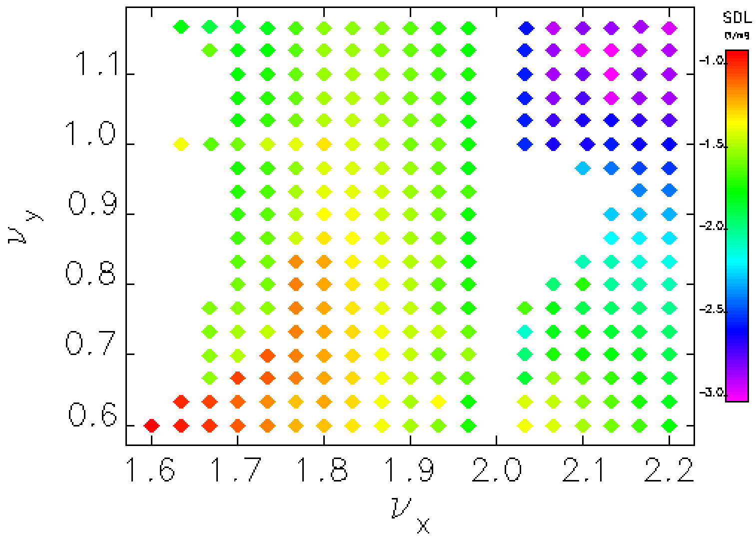
Exploratory "TevUSR" Lattice

- All lattice modules are taken from the PEP-X design[1,2,3]
  - N=30 MBA cells in each of six arcs
    - 180 ID straight sections (!)
  - Straight sections use FODO cell
  - Six matching quads between arc and FODO cells
- Differences from PEP-X design
  - Larger bending radius
  - Higher energy
    - Improves damping times, reduces IBS etc.
  - No high-beta insertion for injection
    - Will use on-axis injection, so not needed
- For cell tunes, started with Y. Cai's suggestion of ν_x=2.166, ν_y=1.166
  - 2.1 pm natural emittance at 9 GeV
  - Nonlinear dynamics too difficult

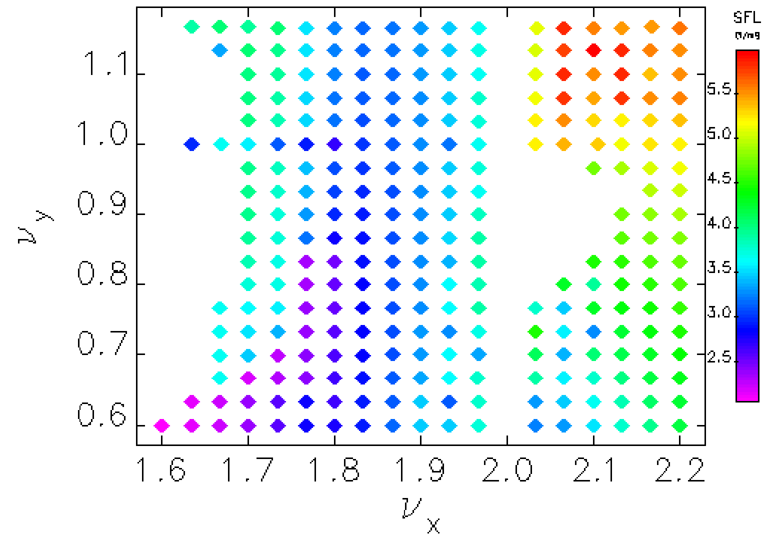
[1]M.-H. Wang *et al*., Proc IPAC11, THPC074.
[2]Y. Nosochkov *et al*., Proc. IPAC11, THPC075.
[3]Y. Cai, NIM A 645:168-174 (2011).

Scan of Cell Tunes (9 GeV)

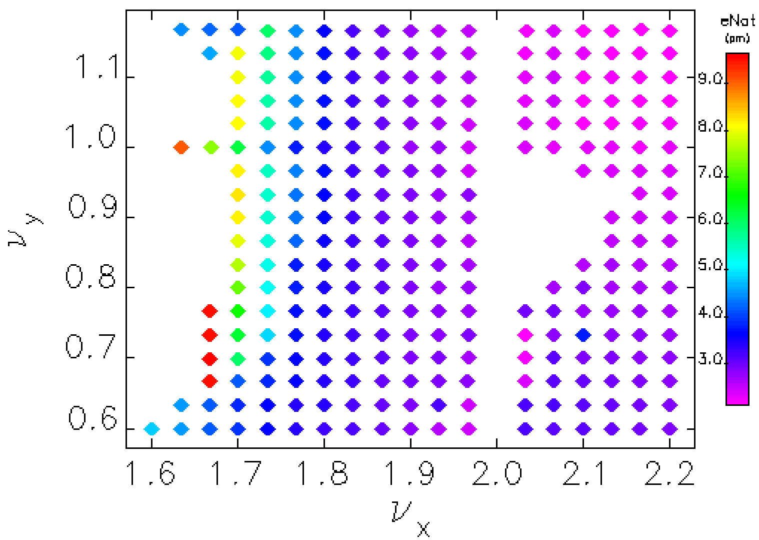
Integrated SD strength



Integrated SF strength



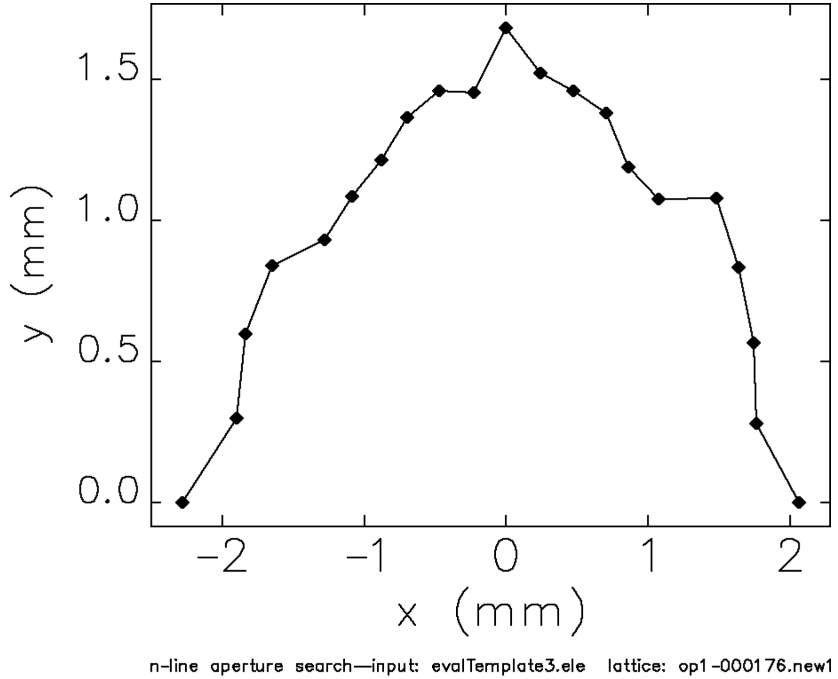
Natural emittance

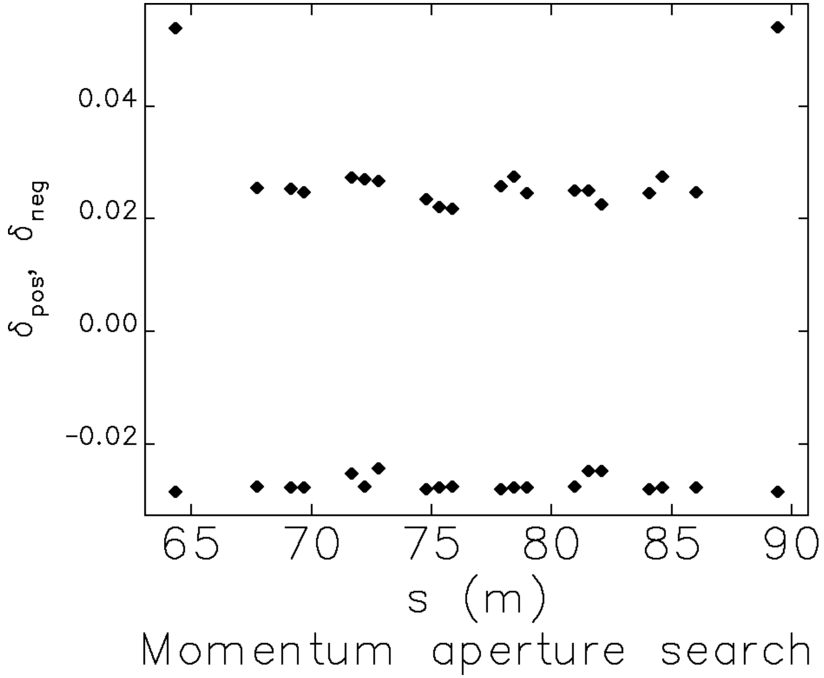


- Tunes per cell were 2.17, 1.17 (x, y)
- Now lowering to 1.90, 0.90
  - 2.9 pm emittance
  - Sextupoles 40~50% weaker

Preliminary MOGA Optimization with New Tunes

- Starting condition
  - All sextupoles except SF and SD set to 0
  - SF and SD set to give chromaticity of 1 in x and y
- Better results immediately, but no errors included
  - More later...



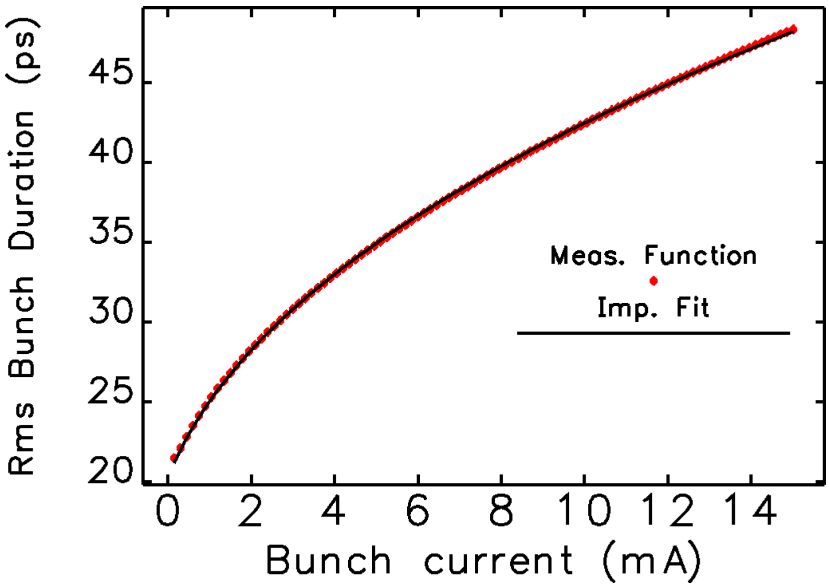


Analysis of Microwave Instability

- Recall the basic MWI equation

$$I_{mw} = \frac{\sqrt{2\pi}\alpha_c E \sigma_l \sigma_\delta^2}{R|Z/n|}$$

- Need value for |Z/n| to use here
  - We determined |Z/n|=0.28Ω for APS from measurement of bunch length vs current
- Gives MWI threshold of ~2 μA
  - Improved from scaling analysis
  - Would need S-band rf system to get 100 mA

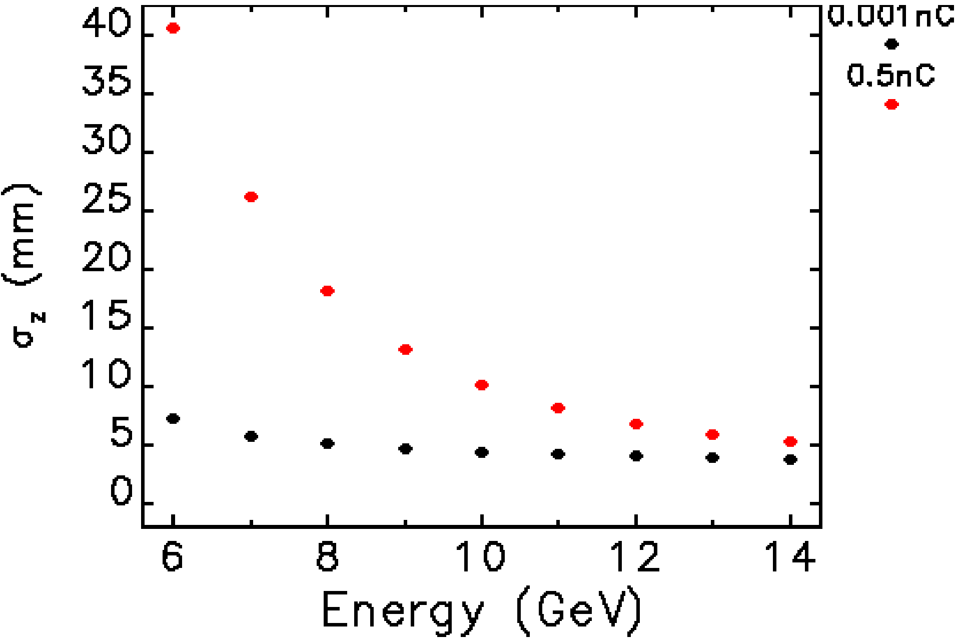


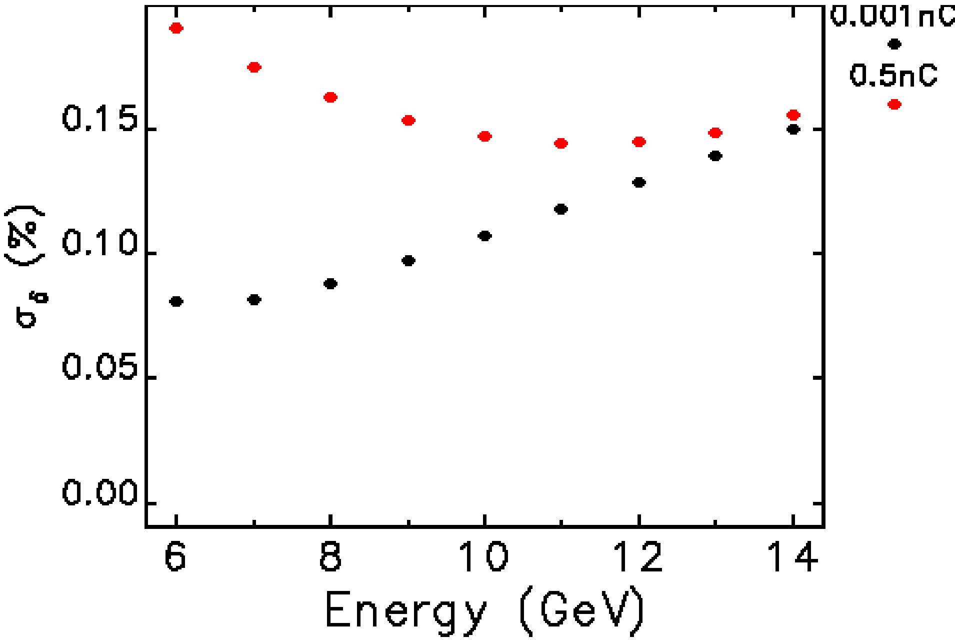
Problems with this analysis

- APS MWI threshold well above predicted value
  - Using simple formula, predicted MWI is 0.9 mA
  - Measured MWI[1] is ~5 mA
- Problem is that equation is too simple
  - Ignores resistive part of impedance
  - Ignores detailed frequency dependence
- For simplicity, just apply a 5x fudge factor
- Also, need to include
  - Bunch lengthening due to impedance and IBS
  - Energy spread increase due to IBS
  - Vary the beam energy
- We use some programs that come with **elegant**
  - **haissinki[2]**: potential well distortion
  - **ibsEmittance[3]**: intrabeam scattering
  - **touschekLifetime[3]**: Touschek lifetime
  - Assume κ=1

1: L. Emery *et al.* 2: A. Xiao *et al.*
3: K. Harkay *et al.*, EPAC02, 1505.

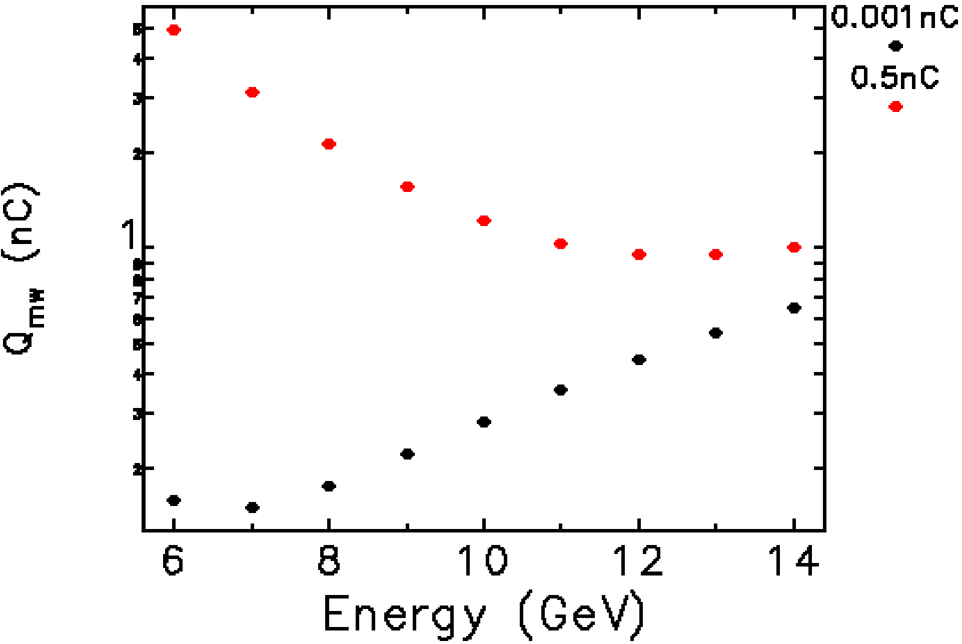
Trends in longitudinal parameters

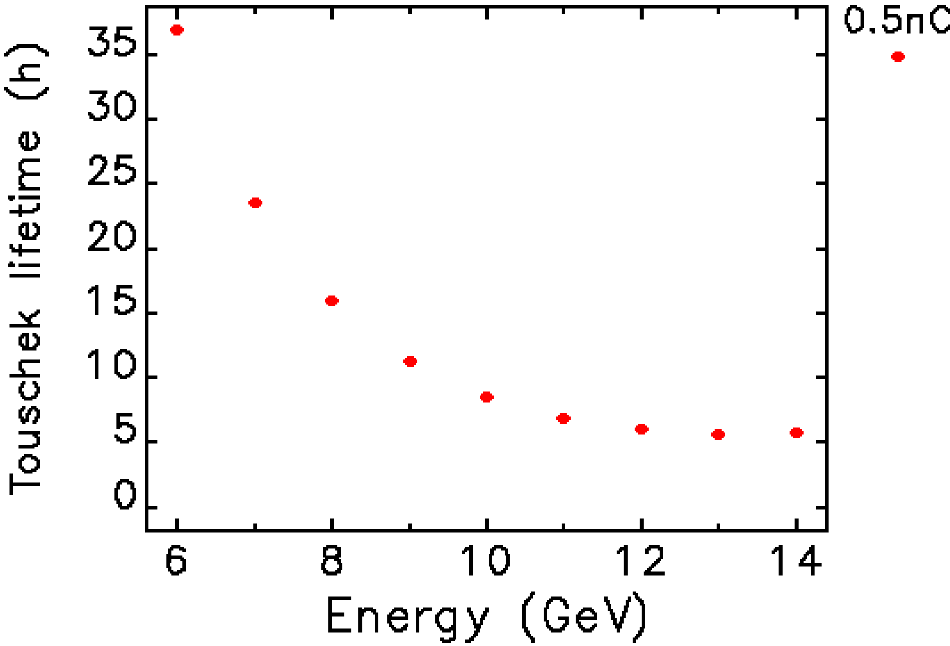




- For 0.5 nC case, trends are promising
- E.g., for 9 GeV
  - Energy spread increases by 50%
  - Bunch lengthens nearly three-fold
- Hints of an advantage to *lower* energy

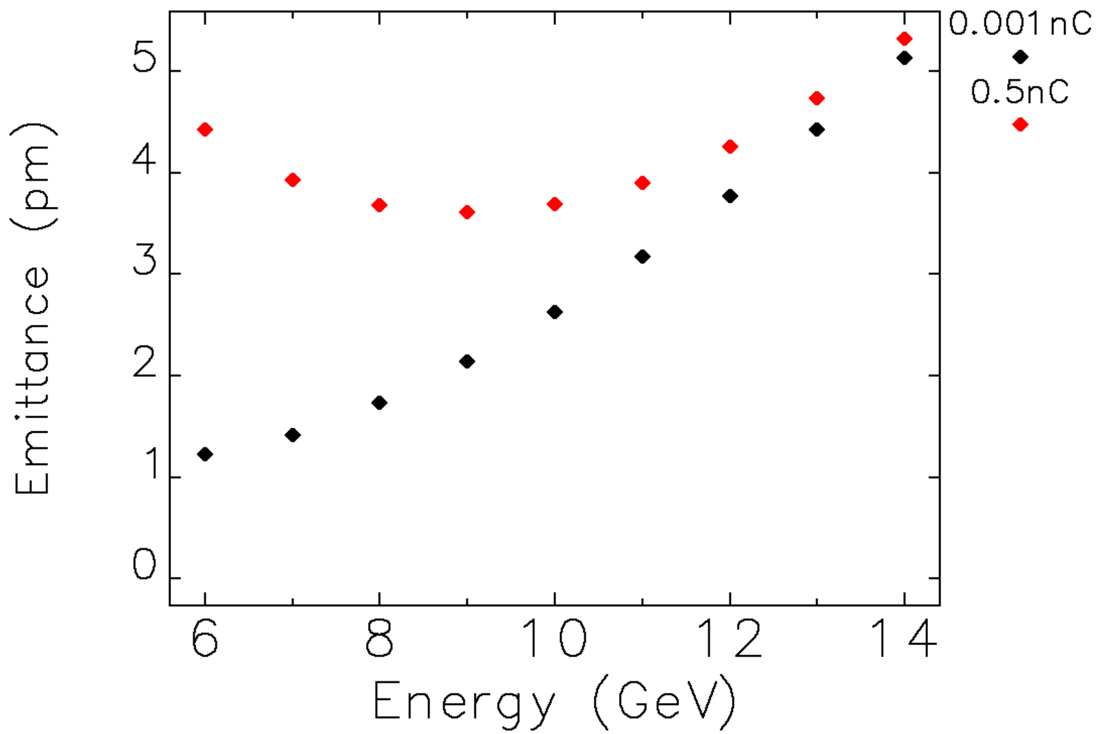
Surprising trends in MWI and Touschek





- MWI threshold is >0.9 nC throughout range
- Threshold generally *increases* with decreasing energy
  - Completely contrary to scaling results
  - Due to PWD and IBS, ignored before
- Touschek lifetime calculation assumes ±2% momentum acceptance
  - Also increases at lower energy!

Trend for Emittance



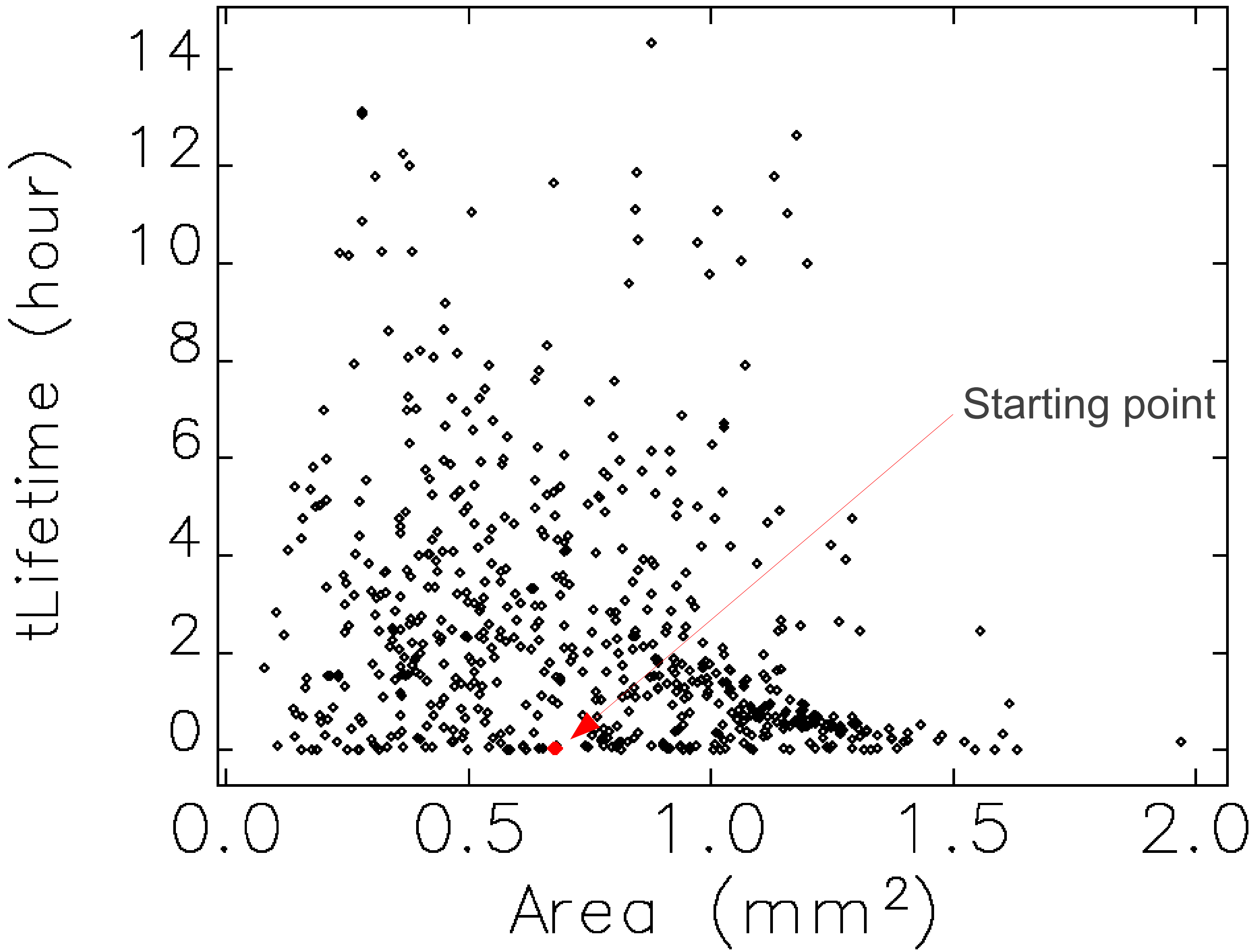
- For 0.5 nC, broad minimum centered on 9 GeV
  - <4 pm in both planes is not too bad…
- Appears that increased Touschek lifetime *does not* result from transversely colder beam at low energy
- We'll take 9 GeV as our working energy

Nonlinear Dynamics Optimization[1]

- Use tracking-based Multi-objective Genetic Algorithm (MOGA) to directly improve
  - Dynamic acceptance area
  - Touschek lifetime computed from local momentum acceptance for first arc cell
  - Uses parallel **elegant**[2] and geneticOptimizer[3]
- Variables
  - Integer tunes
  - Fractional tunes
  - Three SF families
  - Five SD families
  - Three harmonic sextupole families
- Add errors to give ~1% lattice function beats, κ~0.2
- ID chambers with ±18mm by ±3mm gaps
- Chromaticities corrected to +1 in both planes

1: M. Borland *et al.*, APS LS-319, 2010.
2: Y. Wang *et al.*, Proc. ICAP2009, 355-358.
3: M. Borland, H. Shang, unpublished.

Snapshot of on-going results

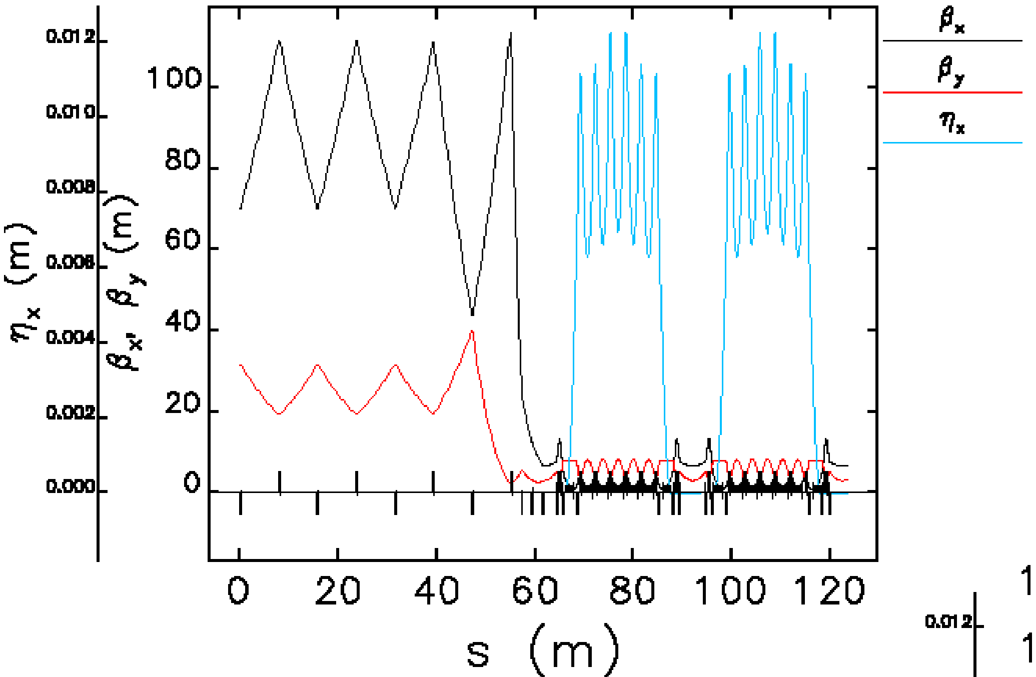


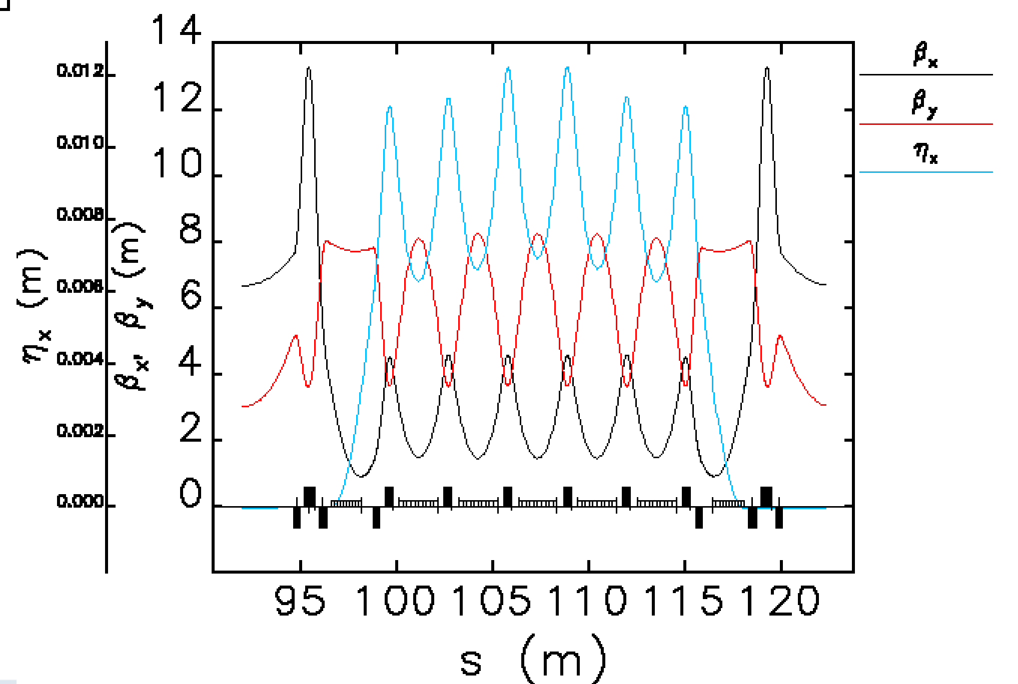
N.B.: lifetime calculation is for 100 mA, ignoring IBS, κ=1
Beam dynamics effects of undulators are ignored.

Lattice parameters

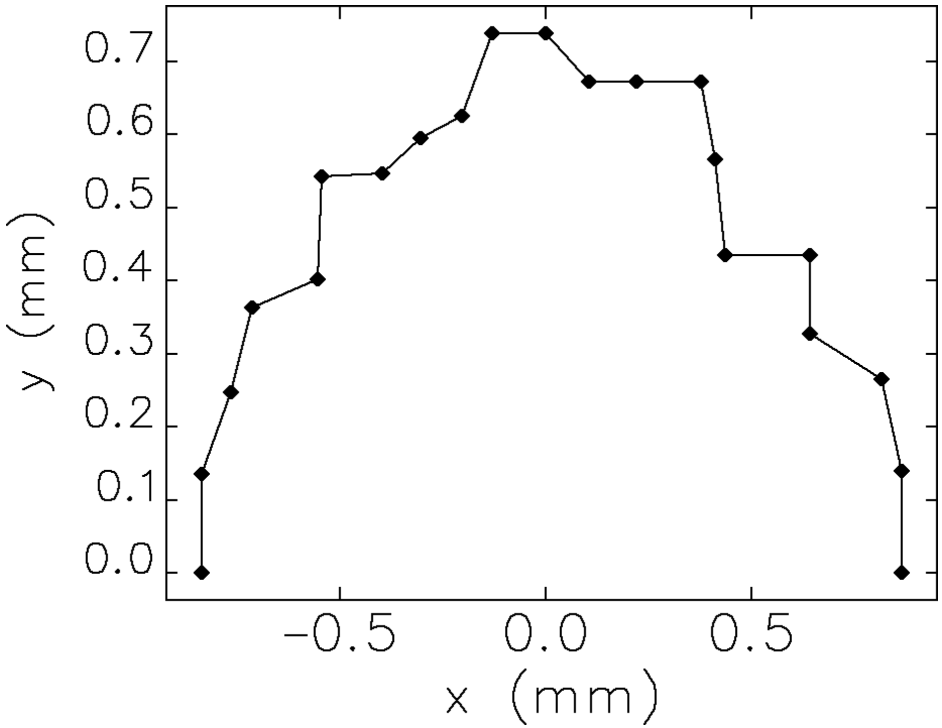
Betatron Tunes		
Horizontal	344.100	
Vertical	171.164	
Natural Chromaticities		
Horizontal	-476.675	
Vertical	-274.241	
Lattice functions		
Maximum β_x	113.354	m
Maximum β_y	39.925	m
Maximum η_x	0.012	m
Average β_x	13.542	m
Average β_y	7.555	m
Average η_x	0.007	m
Radiation-integral-related quantities at 9 GeV		
Natural emittance	2.918	pm
Energy spread	0.096	%
Horizontal damping time	91.382	ms
Vertical damping time	243.007	ms
Longitudinal damping time	713.162	ms
Energy loss per turn	1.535	MeV
Miscellaneous parameters		
Momentum compaction	5.979×10^{-6}	
Damping partition J_x	2.659	
Damping partition J_y	1.000	
Damping partition J_δ	0.341	

Lattice functions



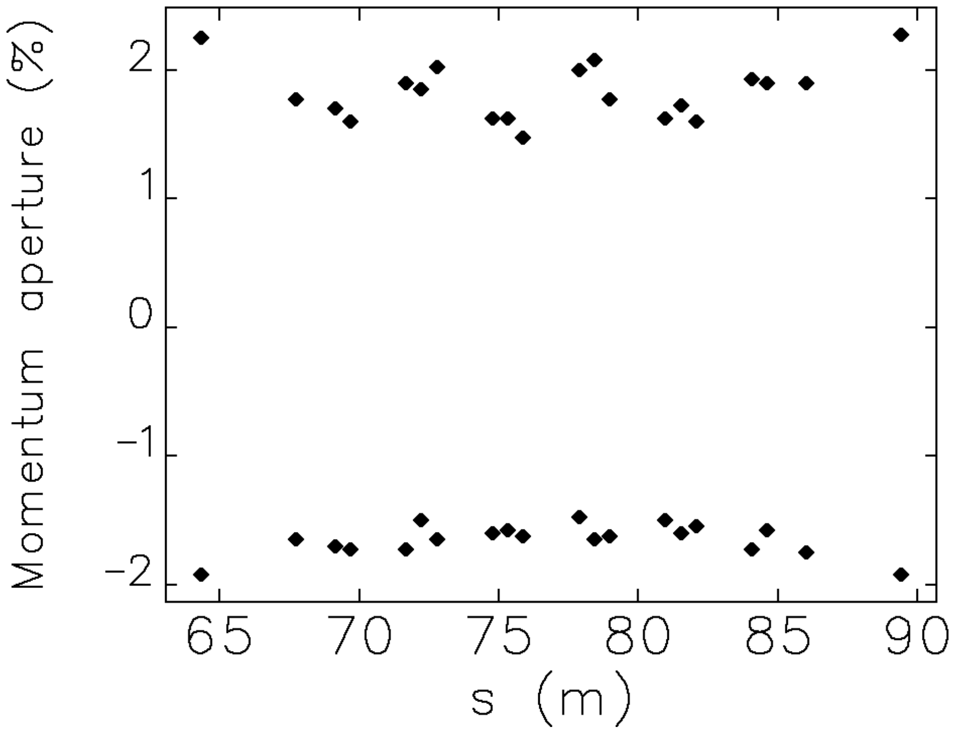


Dynamic acceptance



- Adequate for injection and quantum lifetime
- Impacts gas scattering lifetime
  - Assume 0.5 nT and same partial pressures as APS
  - Predict 4.5 hour gas scattering lifetime

Local momentum acceptance



- This is lower than the ±2% target
- Predicted Touschek lifetime is 8 hours for 0.5 nC bunches
  - Combined lifetime with gas scattering is ~3 hours
- Next step: add octupoles (?)

Magnet Strengths

- PEP-X design has combined function quadrupoles and sextupoles
- Here, we just look at strengths separately
- Sextupoles require ~12mm bore radius (using L=0.35m)

Name	Length	Gradient
		T/m
QD1	0.15	-53.79
QD2	0.17	-51.48
QD3	0.15	-59.37
QDS1	0.15	-13.00
QDS2	0.15	-39.93
QDS3	0.15	-15.29
QDSE	0.15	-6.61
QF1	0.28	62.62
QF2	0.20	93.26
QF3	0.20	71.71
QFC	0.20	72.04
QFS1	0.15	-6.15
QFS2	0.15	30.22
QFS3	0.15	7.58
QFSE	0.15	5.43

Name	Integrated Strength
	T/m^2
SD1	-4139.60
SD2	-4066.24
SD3	-4014.99
SD4	-4140.59
SF1	6650.50
SF2	6730.27
SF3	6618.28
SH1	-9.43
SH2	2.02
SH3	25.70
SH4	-21.24
SH5	-3.77
SH6	10.65

Injection Parameters

- For 200 mA and 0.5 nC/bunch, need ~8300 bunches
  - 500 MHz rf, fill 80% of 10360 buckets
  - 4.1 µs of 20.7 µs revolution time available for kicker rise/fall
  - If $T_{rise} = T_{fall} = 10$ ns, need N_T=202 trains of 41 bunches
  - Kicker flat-top is 82 ns long
- Droop between replacements of a given train is

$$D \approx \Delta T_{\mathrm{inj}} N_{\mathrm{T}} / \tau$$

- Assuming τ=3 h and D=0.1, need $\Delta T_{inj} = 5.3$ s
- Inject 41 bunches of 0.5 nC each time
  - Average power of 34 W
  - A photoinjector could easily provide the needed bunch trains

Low-Emittance Booster Injector

- A large-circumference booster can have emittance close to that of the ring (e.g., SLS booster)
  – Optics is "easy" since there are no user straights
  – Can occupy the same tunnel as the user ring to reduce cost
- Like USR itself
  – Ultra-low emittance
  – On-axis injection

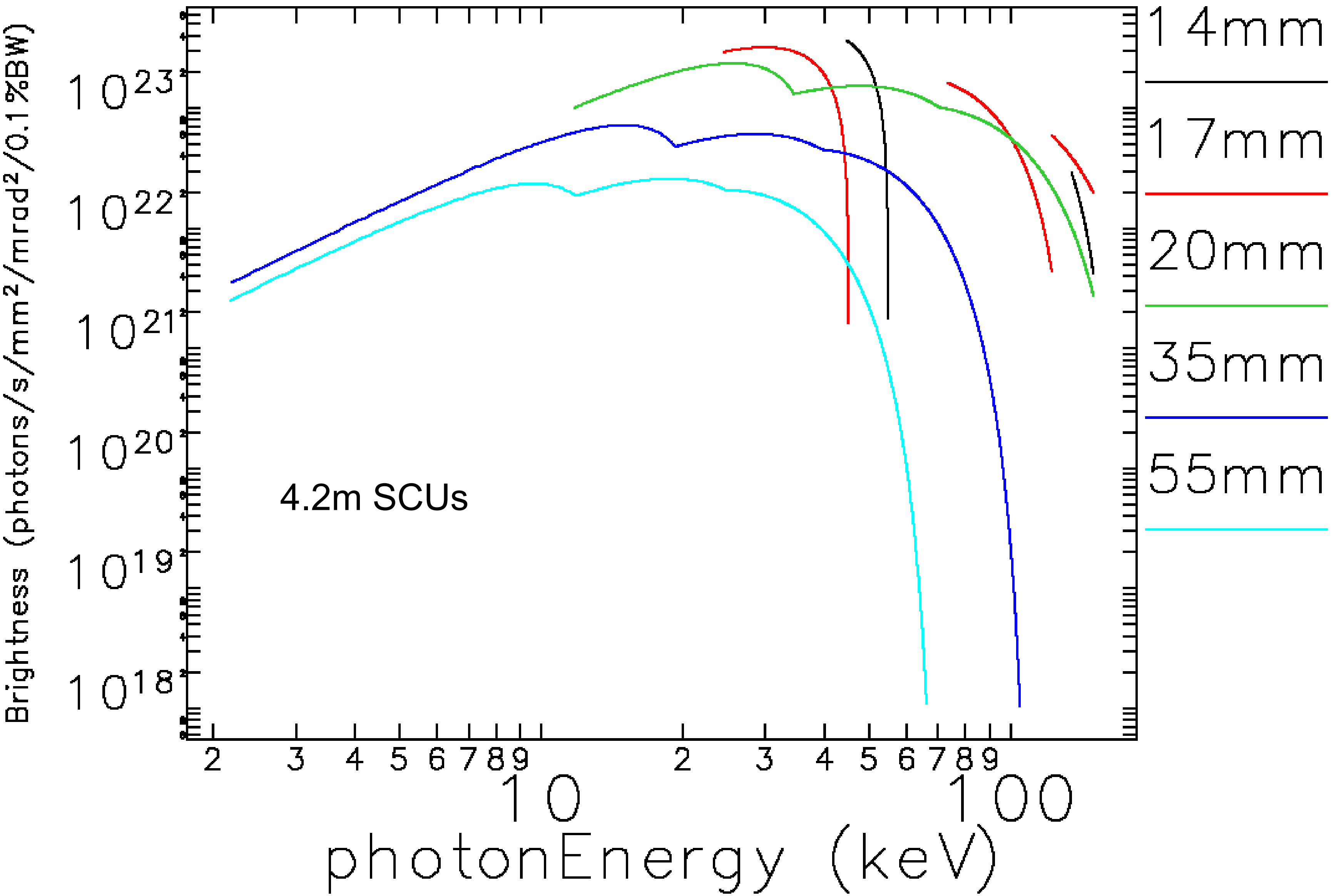
Full-Energy Linac Injector

- In principle, could fill the ring in one shot or using trains
- Probably not the optimum choice
  - 9 GeV emittance would be ~30 pm for typical ~0.5 nC bunches
    - Probably can do better with in-tunnel booster
  - Short bunches may be a problem
    - Collective effects may accentuate beam-quality blip
  - Long linac requires costly separate tunnel
  - Linac structures, rf systems more costly and less reliable than booster
- However
  - Might use linac for 10~100 turn mode with short pulses
  - The linac could also drive an FEL in its spare time

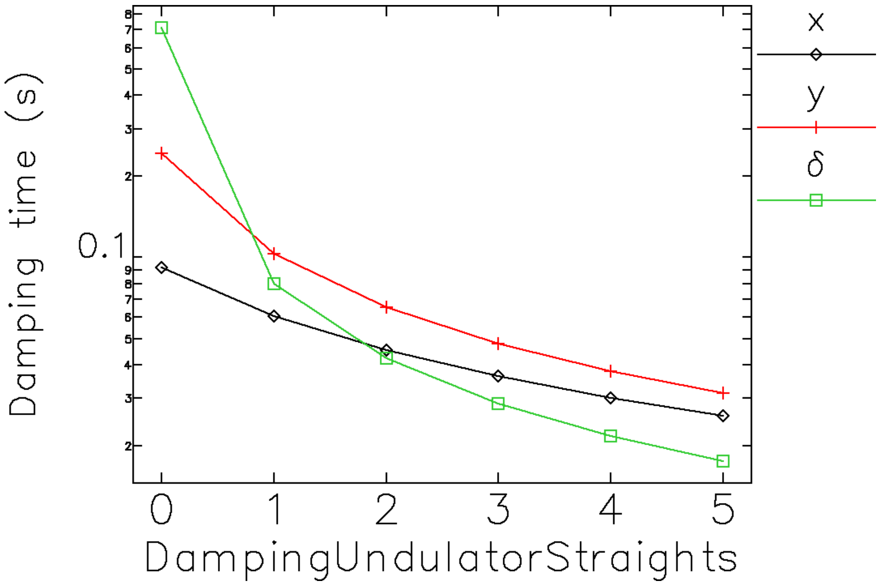
Radiation Load

- Radiation from extracted trains is small
  - Again, only about 30 W
  - No problem to design a dump for this
- Radiation load from 3 hour lifetime is more worrisome
  - 3.5 W predicted average power
  - For APS, have only 0.15 W at worst
  - Collimation for Touschek losses is presumably straightforward
  - How to intercept gas-scattered electrons without cutting into dynamic acceptance?

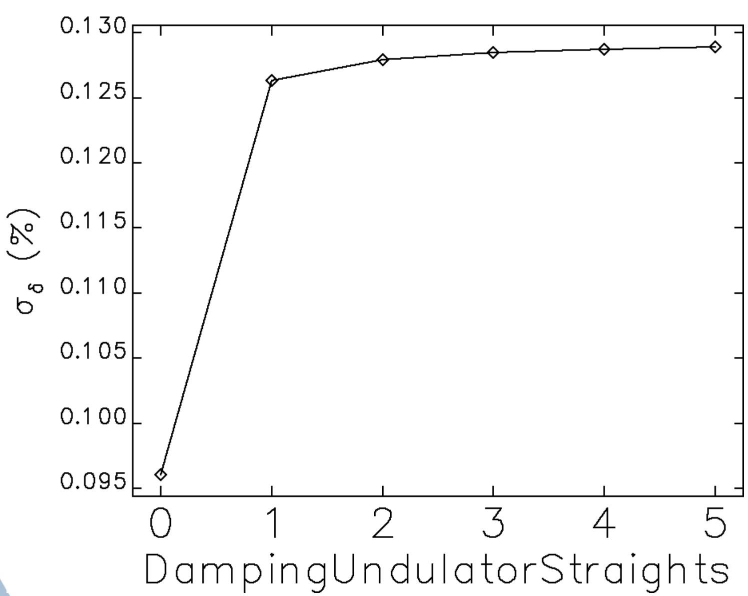
Brightness (200 mA, 9 GeV)

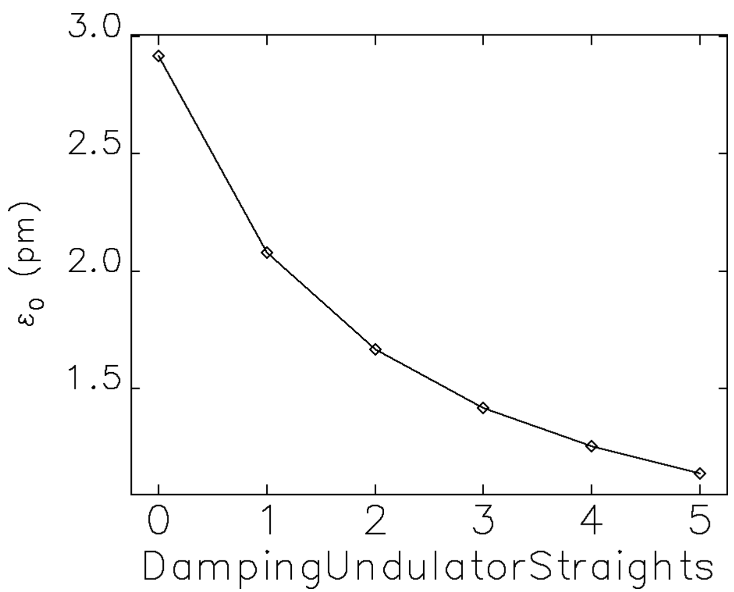


Use of damping undulators

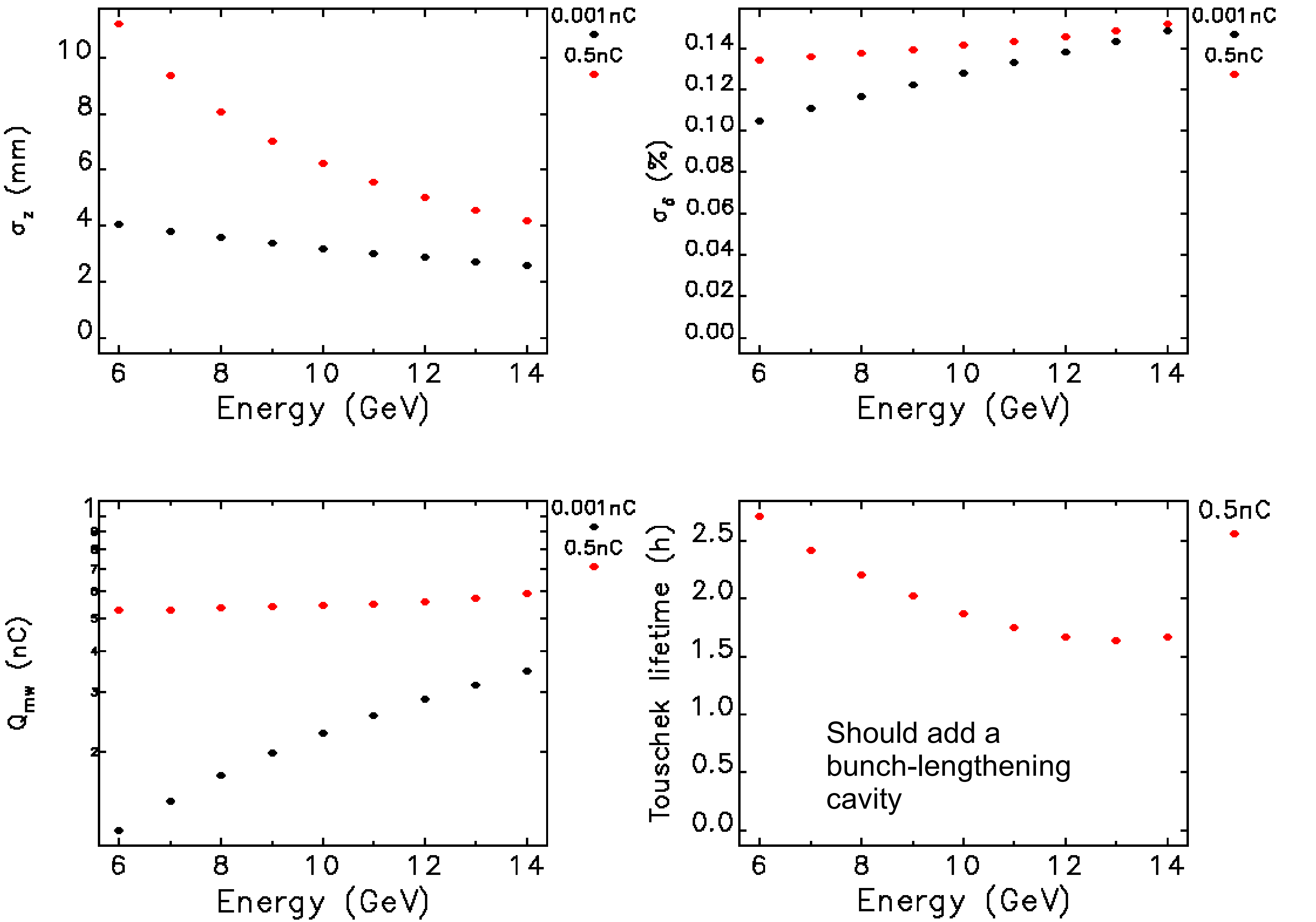


- Damping times are very long
- Explored use of SCU as damping devices
  - 1T, 17mm period
  - 6.7m long
  - 14 devices per long straight
- 420 kW radiation power per straight at 200 mA

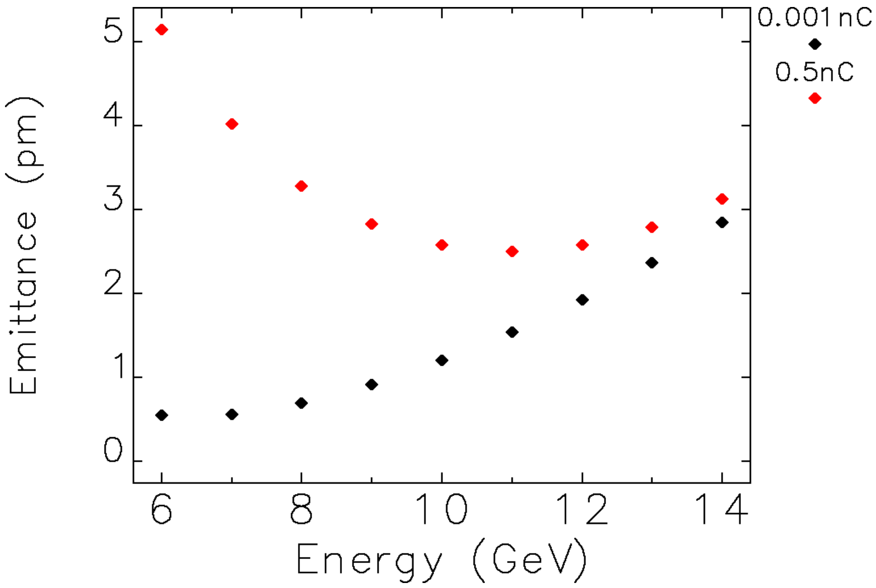




Collective effects with 1 DU straight

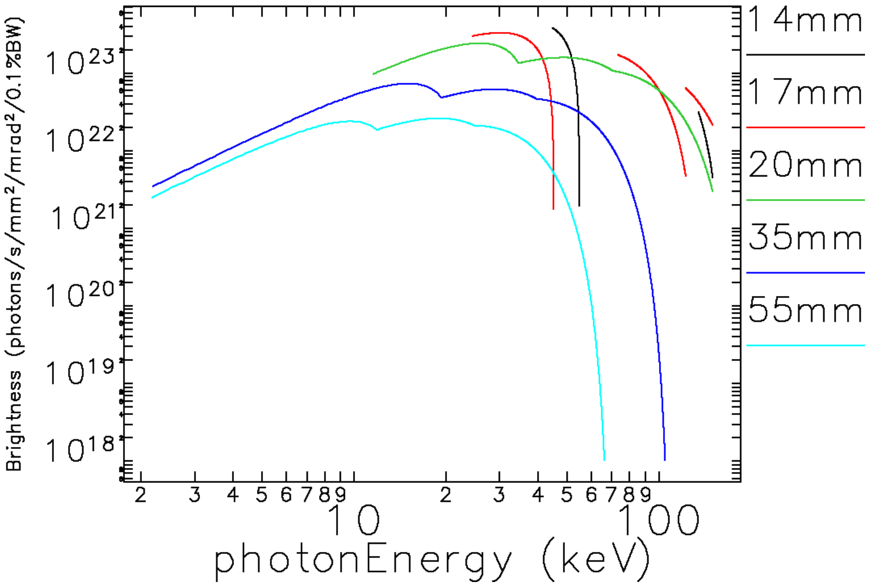


Collective effects with 1 DU straight

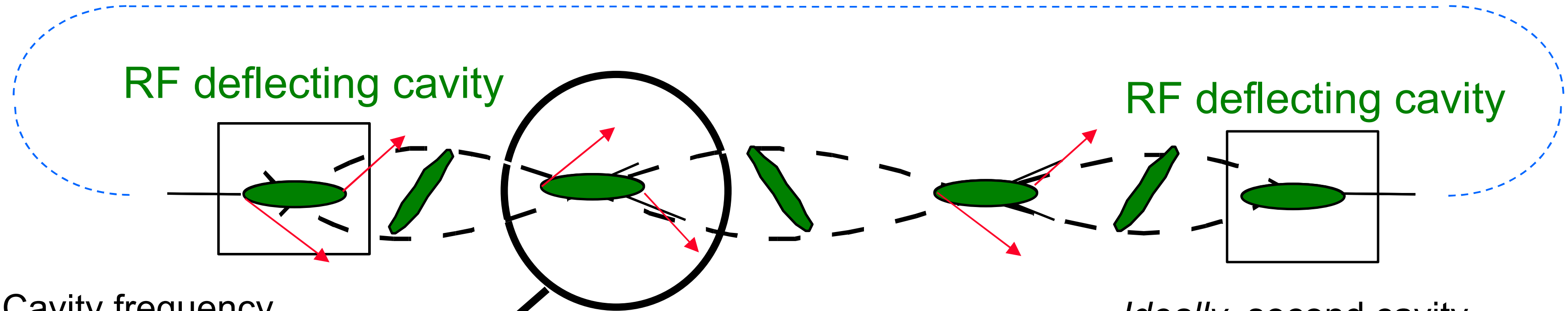


- Emittance at 9 GeV drops from 3.6 pm to 2.8 pm

- No significant improvement from before

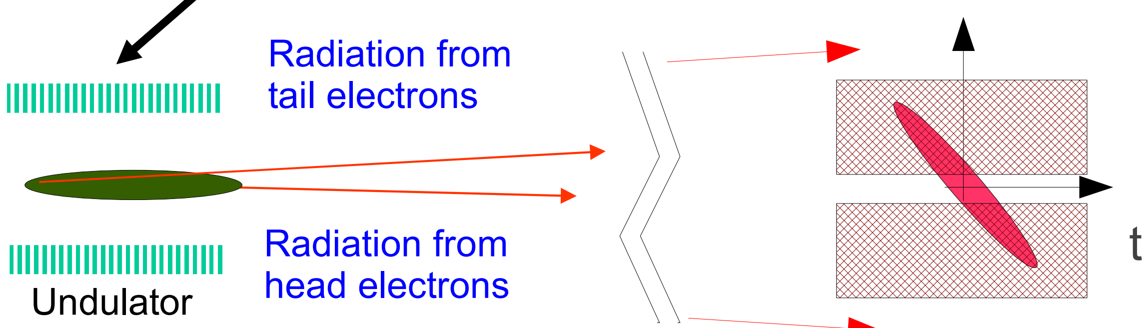


Zholents' Transverse Rf Chirp Concept[1]



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is n*180 degrees



Pulse can be sliced or compressed with asymmetric cut crystal

[1]A. Zholents *et al.*, NIM A 425, 385 (1999).

Pulse Duration Estimate

- Minimum pulse duration is[1]

$$\sigma_t \approx \frac{E}{V\omega}\sqrt{\frac{\epsilon}{\beta}+\frac{\lambda}{\pi L}}$$

- The intensity is reduced by (approximately) the ratio of the bunch duration to the x-ray pulse duration
- For TeVUSR, take some parameters similar to APS-U[2]
  - 2815 MHz with 8MV (APS-U uses 2 MV)
  - 12 keV radiation (1 A)
  - Taking 4 pm emittance gives <u>0.2 ps rms</u>
  - Intensity is ~0.5% of nominal
  - Average rate is ~400 MHz
- Unlike APS-U, could put this in a long straight to avoid nonlinear dynamics issues[3]

[1] L.Emery *et al.*, PAC11, 2348 (2011)
[2] K. Harkay et al., PAC05, 668 (2005)..
[3] M. Borland, PRSTAB 8(7), 074001, (2005).

Conclusion

- We presented a snapshot of on-going work on a Tevatron-sized USR
  - PEPX-based lattice design starting to show good results for nonlinear dynamics
  - Microwave and other (?) instabilities seem workable
  - Extremely high brightness promised from a 9 GeV ring
  - Chirping scheme provides very short x-ray pulses
- Much work still needed
  - more detailed analysis of collective instabilities
    - is higher current possible?
  - magnet design and lattice iteration
  - further error studies and nonlinear dynamics optimization
  - effects of damping undulators and insertion devices
  - cost reduction
  - science case

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  - K. Bane, Y. Cai, R. Hettel, Y. Nosochkov, M.-H. Wang
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