Exploration of a Tevatron-Sized Ultimate Light Source

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Outline

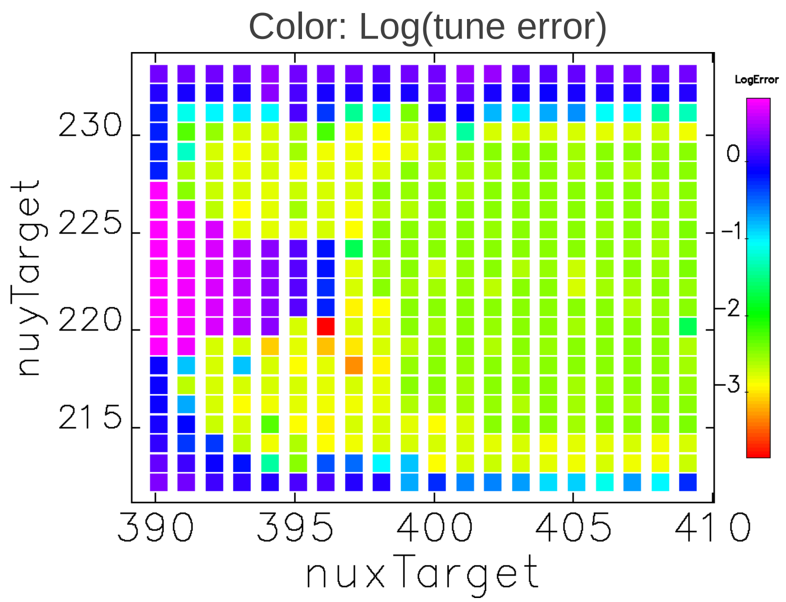
- Lattice concept
- Linear optics
- Choice of beam energy
- Effect of damping undulators
- Collective effects
- Performance predictions
- Preliminary MOGA optimization
- Short-pulse x-rays
- Issues (magnets, damping undulators, rf, injection)
- Conclusion

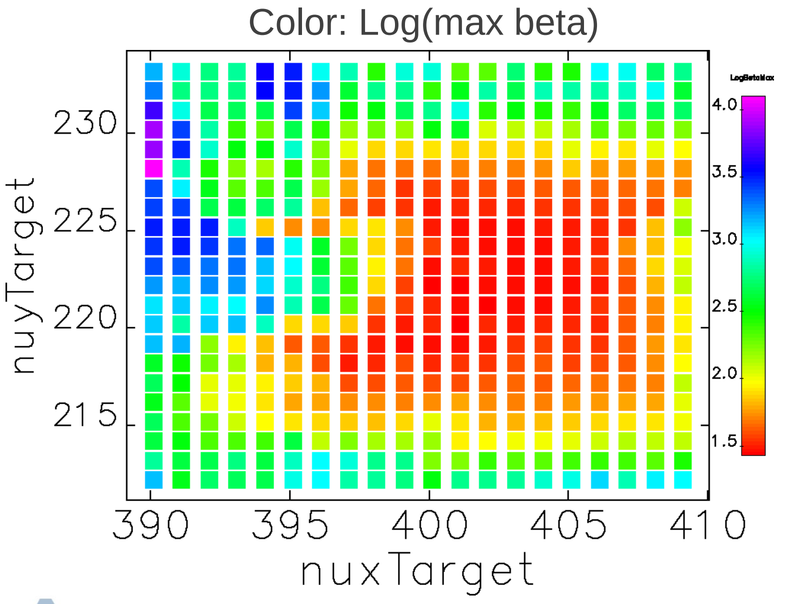
Exploratory "TeVUSR" Lattice

- 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 (!)
  - Start with Y. Cai suggestion of ν_x=2.166, ν_y=1.166
  - 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 (?)
  - No special optics for straights with damping undulators
    - For simplicity, turn off the (weak) vertical undulator focusing at this stage

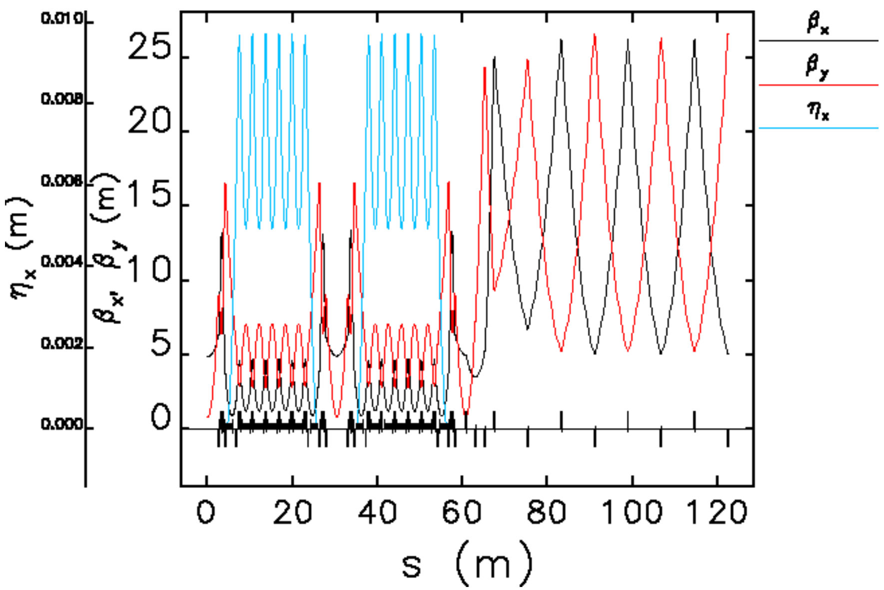
[1] M.-H. Wang *et al.*, Proc IPAC11, THPC074.
[2] Y. Nosochkov *et al.*, Proc. IPAC11, THPC075.
[3] Y. Cai, NIM A 645:168-174 (2011).

Integer Tune Scan with Matching/FODO Quads





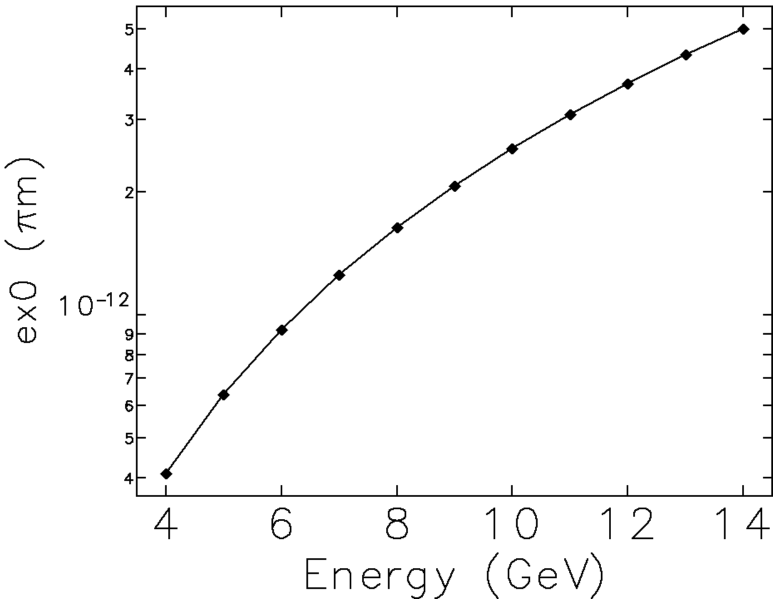
- Fairly wide region within which tune can be varied with matching and FODO quads only
- Start with ν_x=403.1, ν_y=222.2



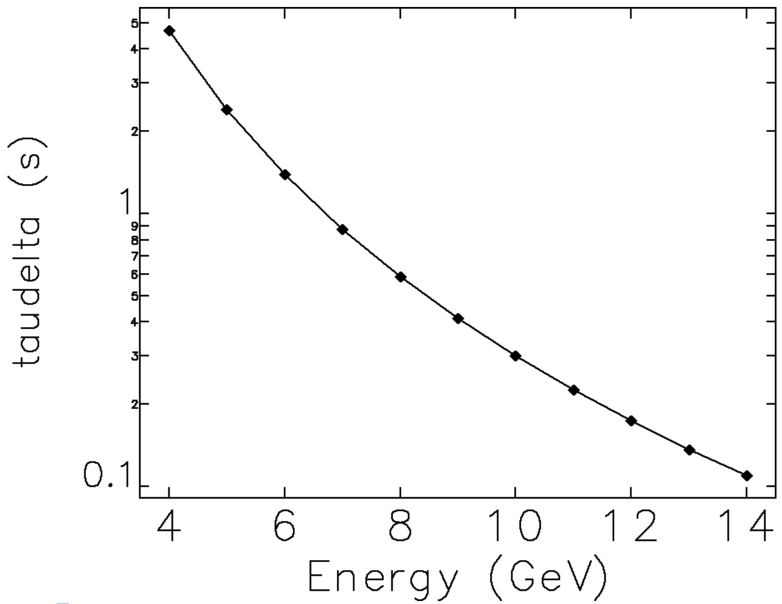
Lattice w/o Damping Undulators (DUs)

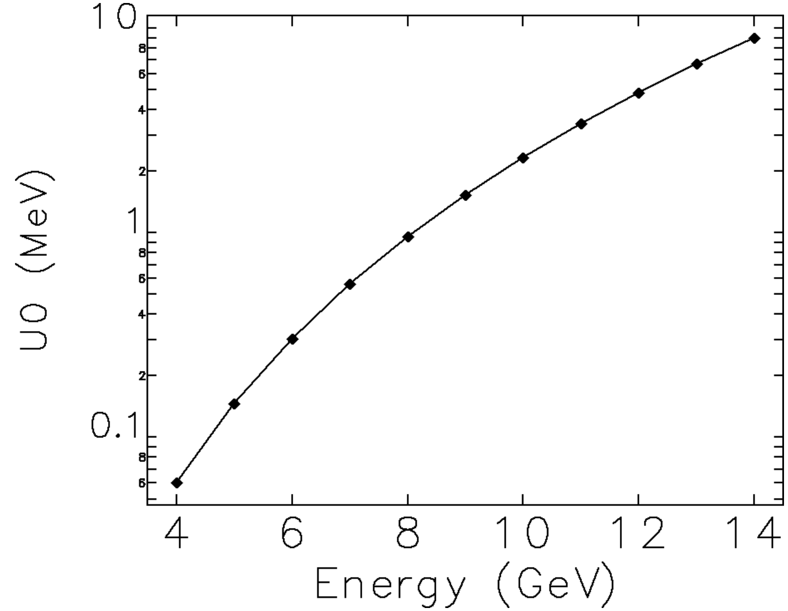
Betatron Tunes		
Horizontal	403.098	
Vertical	222.198	
Natural Chromaticities		
Horizontal	-580.114	
Vertical	-468.581	
Lattice functions		
Maximum β_x	26.341	m
Maximum β_y	29.000	m
Maximum η_x	0.009	m
Average β_x	5.199	m
Average β_y	7.112	m
Average η_x	0.006	m
Radiation-integral-related quantities at 11 GeV		
Natural emittance	3.092	pm
Energy spread	0.089	%
Horizontal damping time	55.241	ms
Vertical damping time	133.097	ms
Longitudinal damping time	225.349	ms
Energy loss per turn	3.425	MeV
Straight Sections		
Effective emittance	0.003	nm
β_x	4.922	m
η_x	-0.000	m
β_y	0.778	m
Miscellaneous parameters		
Momentum compaction	4.468×10^{-6}	
Damping partition J_x	2.409	
Damping partition J_y	1.000	
Damping partition J_δ	0.591	

Energy Scan with no DUs

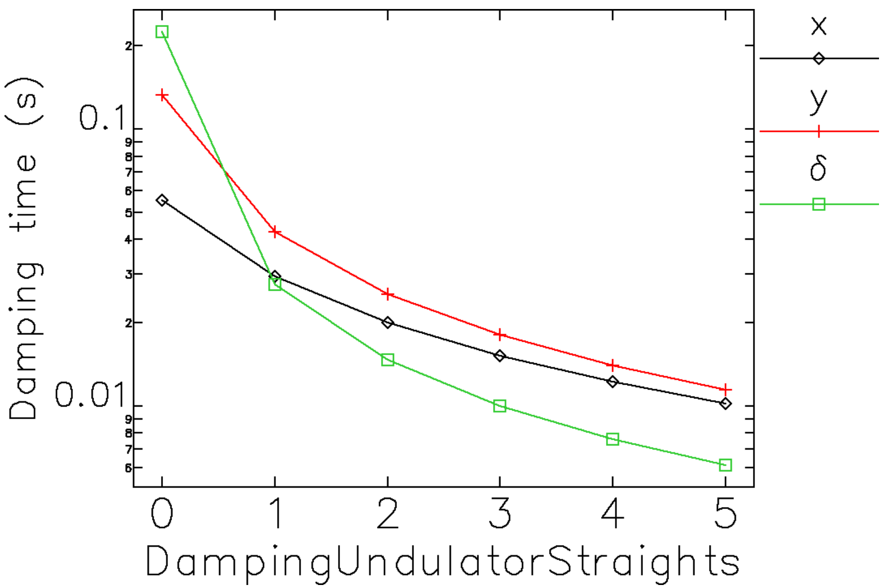


- Longitudinal damping time is very long
- <100ms is "desirable"
  - Means we need damping wigglers plus relatively high energy
- For 11 GeV electron beam, APS U55 can reach below 4 keV x-ray energy

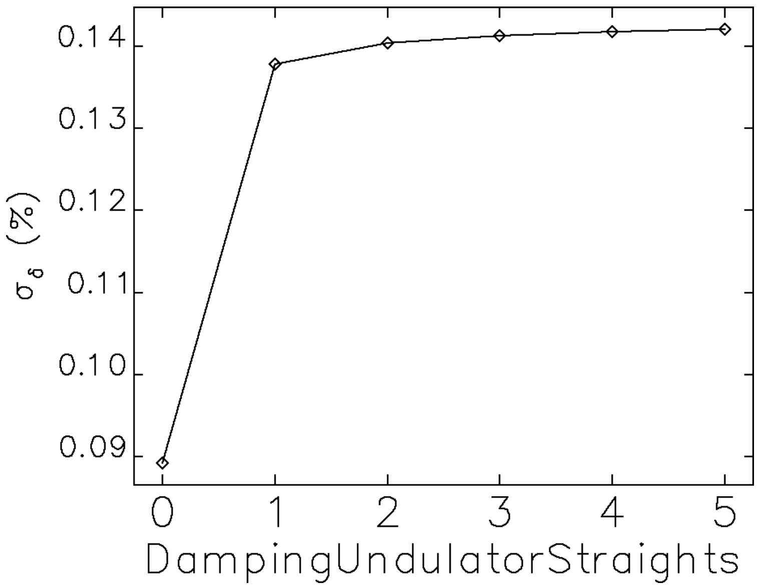


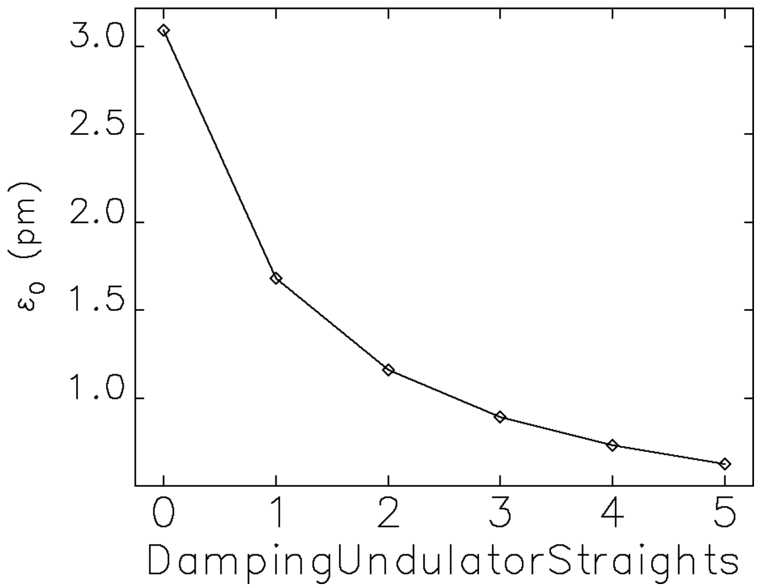


11 GeV with DUs in Several Straights



- DUs assumed to be 1T SCU with 16.7 mm period
- Fourteen 6.7m devices per straight
  - 0.8m per device for warm-to-cold transitions
- Probably 2 straights of DUs is sufficient



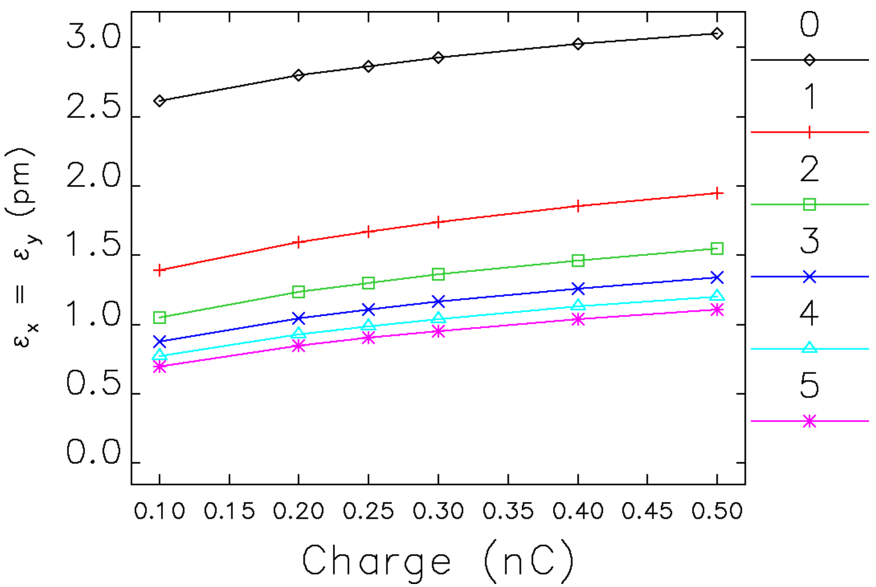


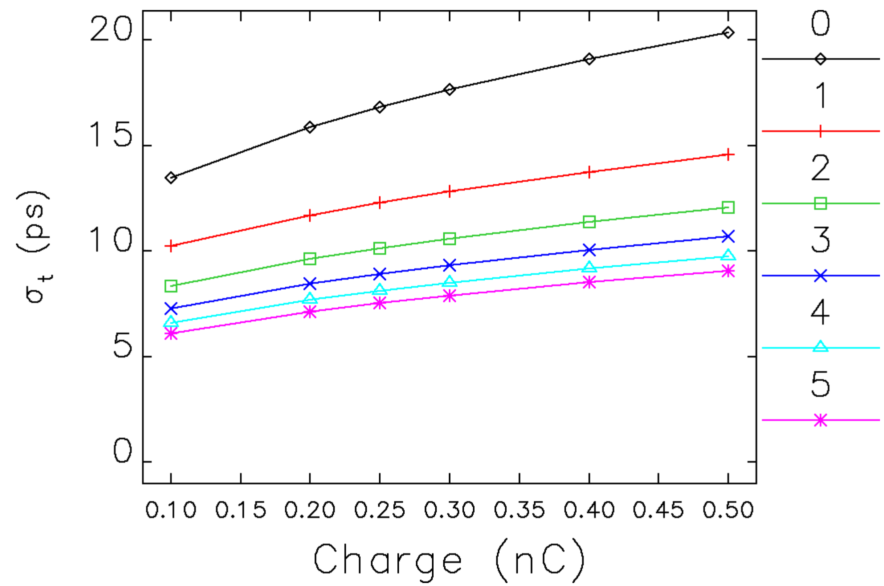
Collective Effects

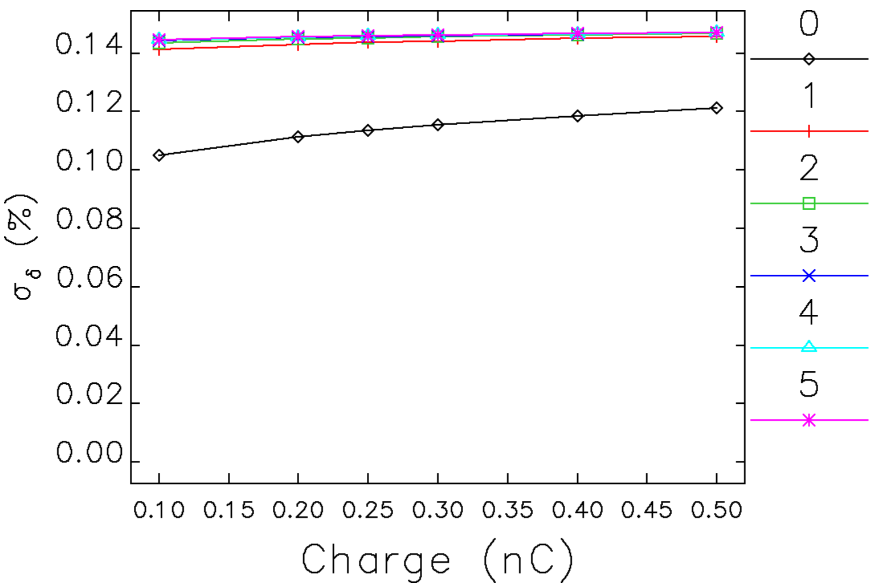
- Took very preliminary look at collective effects
- Solve[1] Haissinki equation assuming |Z/n| = 0.3 Ohm to get bunch length vs current
- Compute[2] equilibrium properties in presence of intrabeam scattering
  - Starting bunch length from Haissinki eqn.
  - Assumed 100% coupling
    - Reduces IBS, increases lifetime, round beams,…
- Computation[3] of Touschek lifetime, assuming
  - Beam parameters from IBS calculation
  - $\pm$2% constant momentum aperture

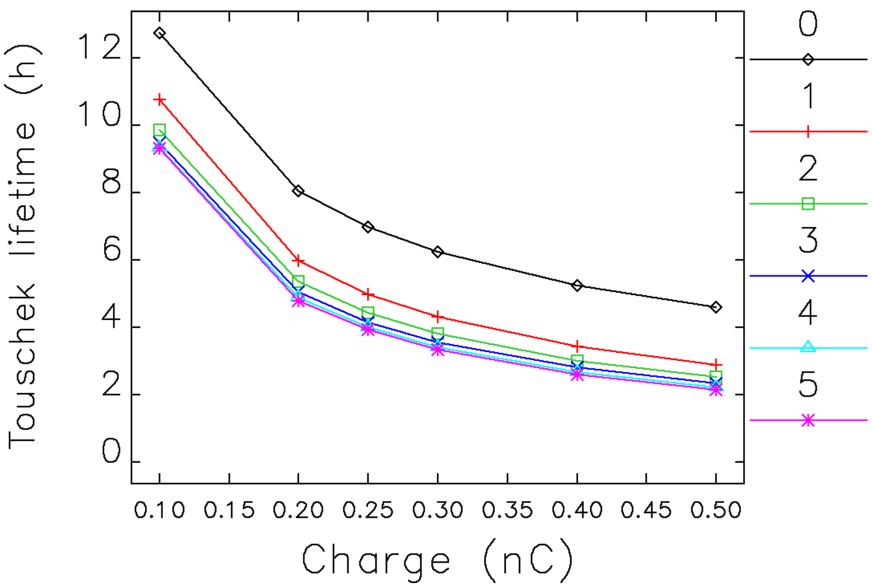
[1]Using **haissinski** (L. Emery, M. Borland).
[2]Using **ibsEmittance** (A. Xiao, L. Emery, M. Borland).
[3]Using **touschekLifetime** (A. Xiao, M. Borland).

Collective Effects for 0-5 DU-filled Straights

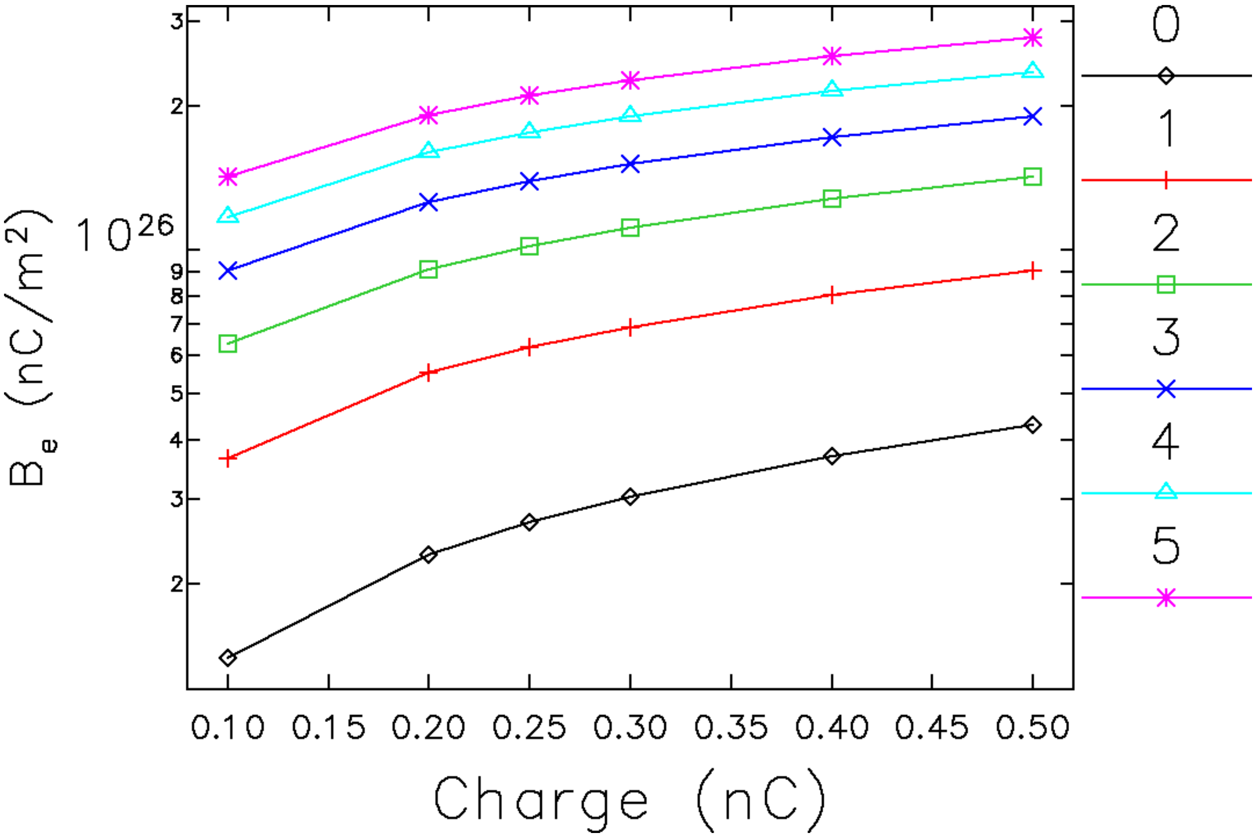








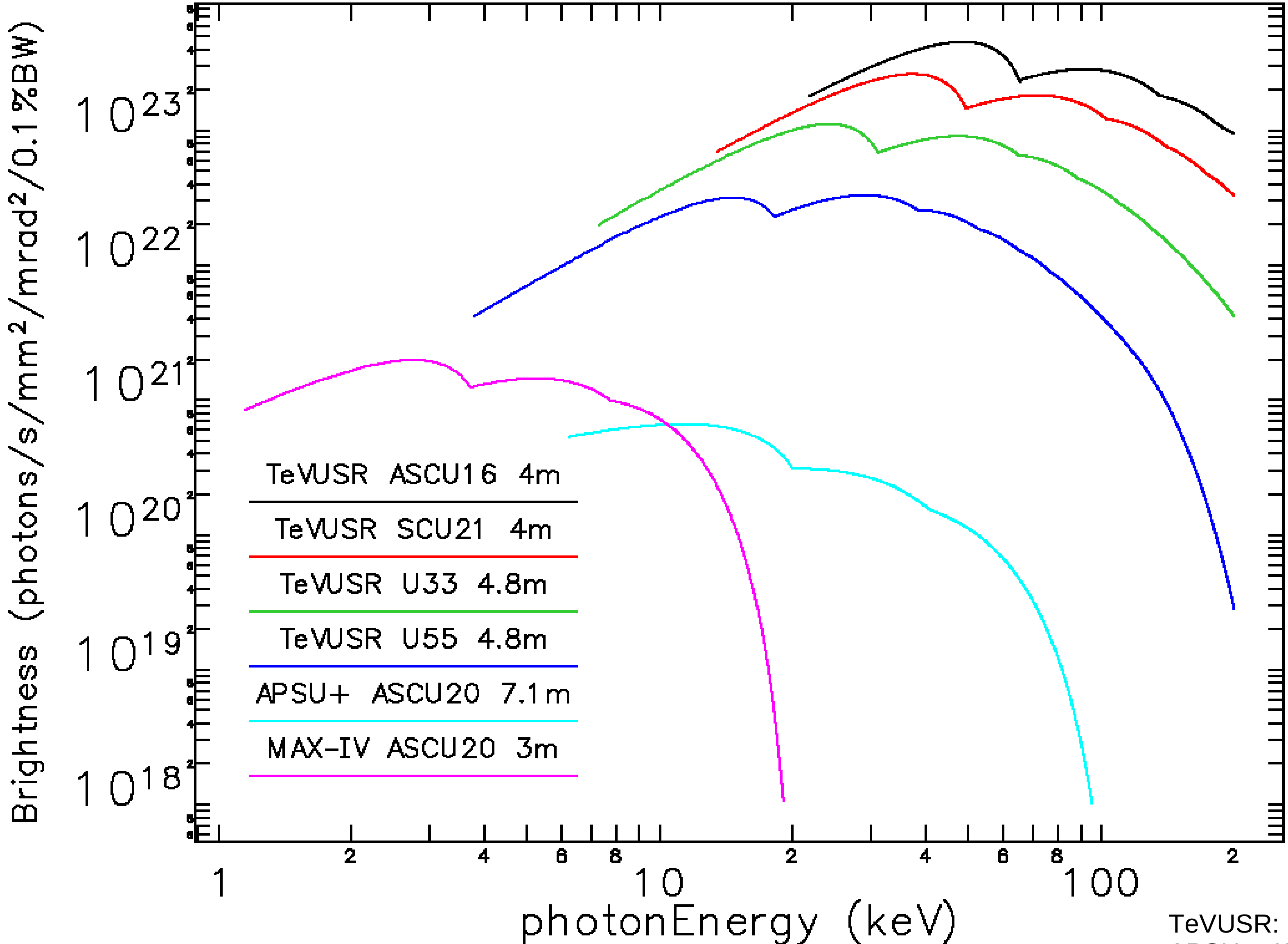
Electron Bunch Brightness



$$B_e = \frac{Q}{\epsilon_x \epsilon_y \sigma_\delta}$$

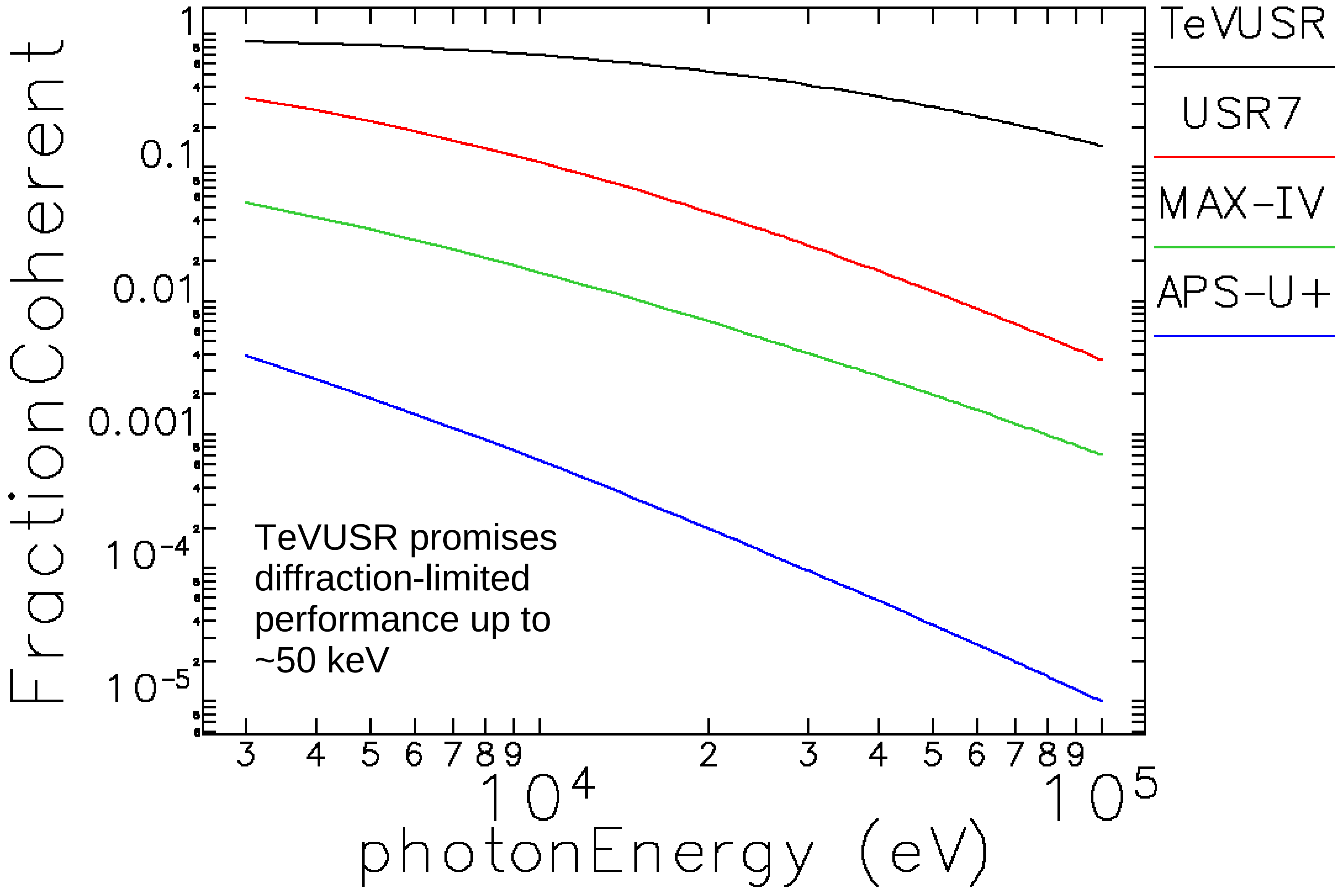
- Diminishing returns evident as more DUs are added
- Similarly as more charge is added
- We'll assume two DU straights

Brightness Performance (2 DU straights)



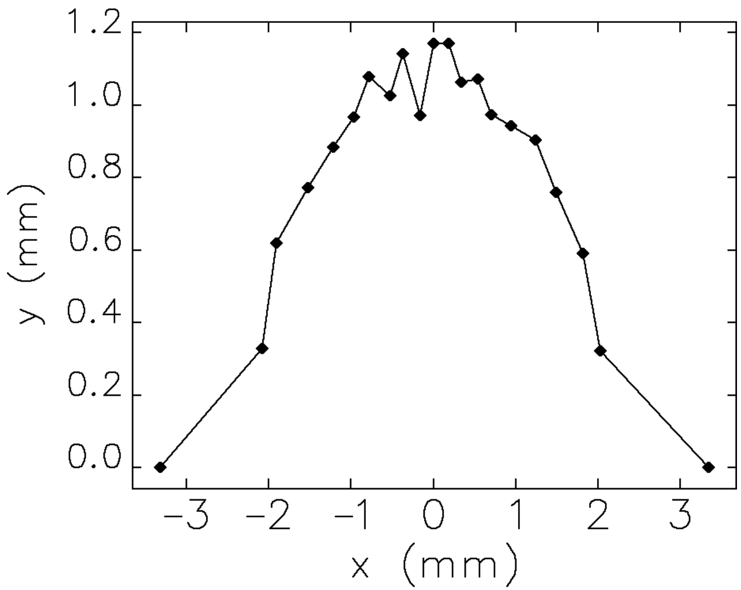
TeVUSR: 100mA
APSU+: 150mA
MAX-IV: 500mA

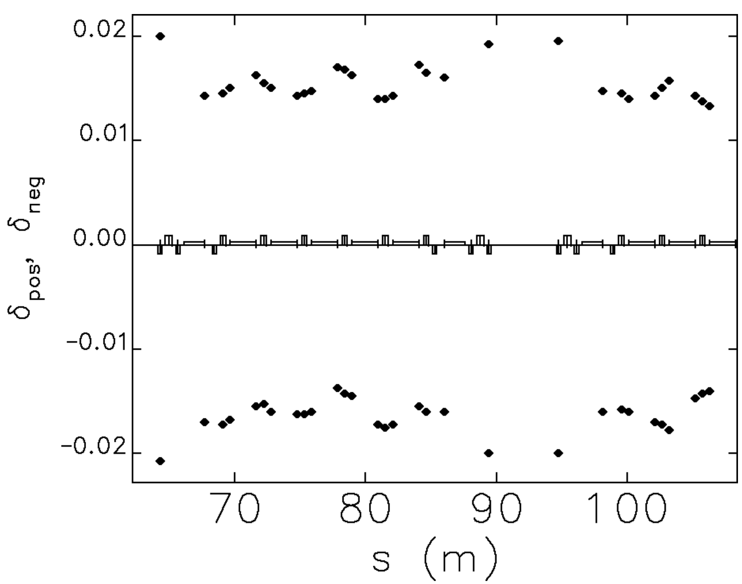
Coherent Fraction



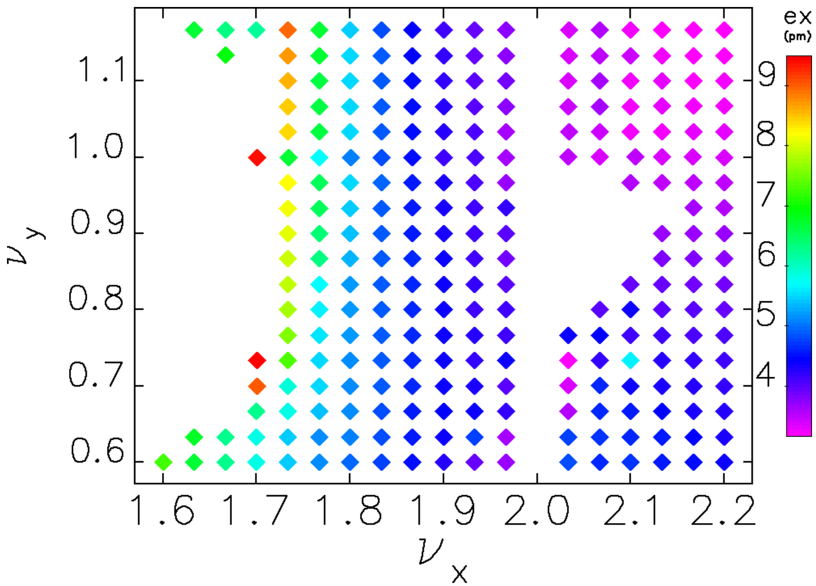
Preliminary MOGA Results (Perfect Machine!)

- MOGA performed with 15 variables
  - Integer and fractional tunes
  - 11 sextupole families
- DA is adequate for on-axis injection
- Momentum aperture is still too low
  - Touschek lifetime is ~2 hours
- Since we don't even have errors, this is not workable

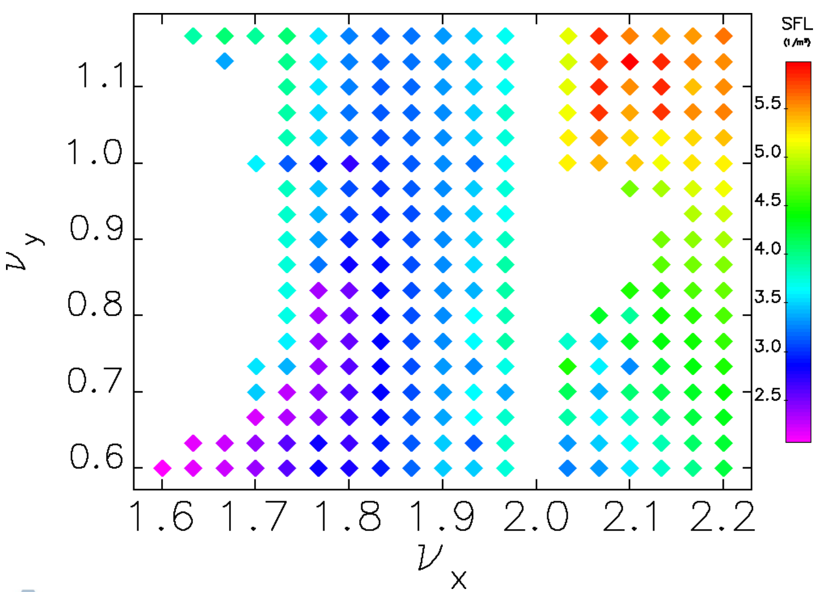


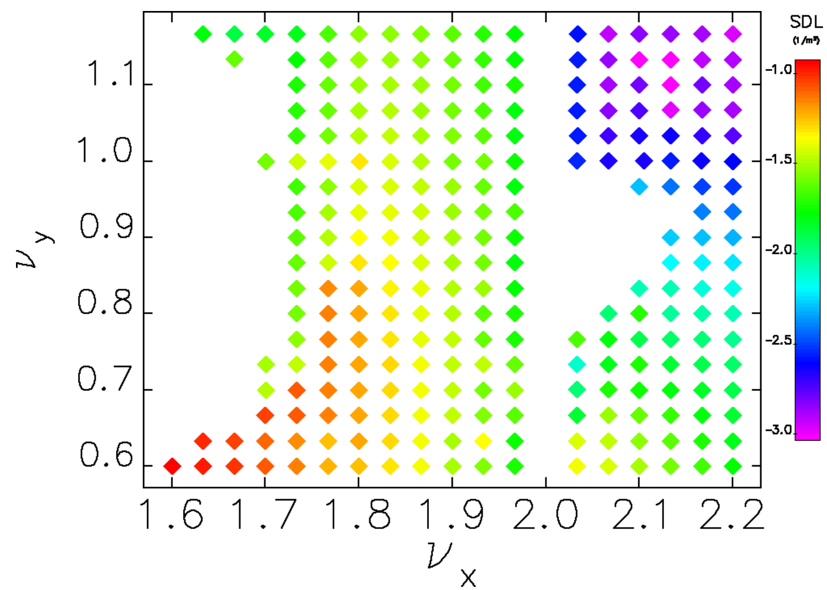


Scan of Cell Tunes



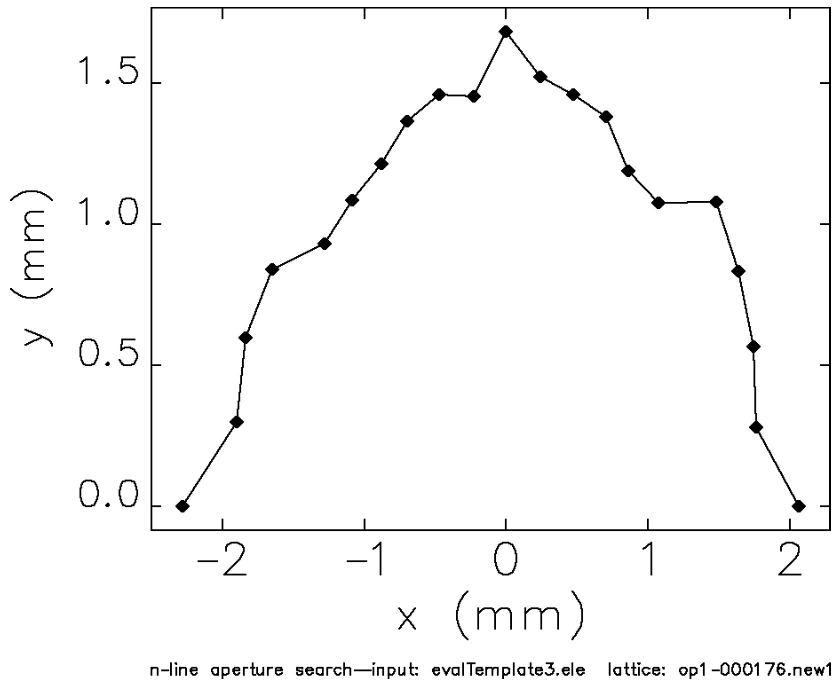
- Tunes per cell were 2.17, 1.17 (x, y)
- Now lowering to 1.90, 0.90
  - 4.4 pm emittance
  - Sextupoles 40~50% weaker

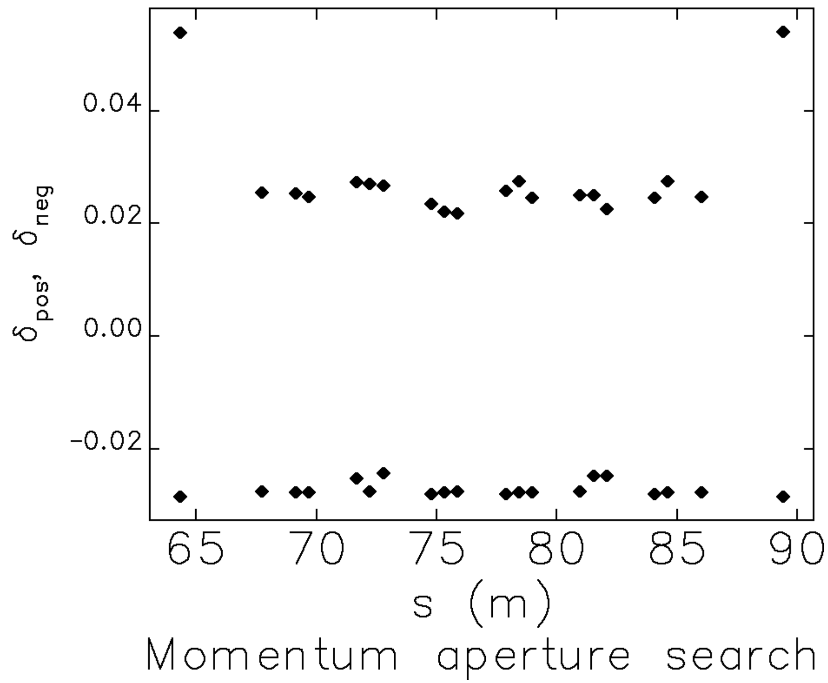




Preliminary MOGA Optimization with New Tunes

- Starting condition
  - All sextupoles except SF and SD set to 0
  - SF and SD set to give chromaticity of 1 in x and y
- Much better results immediately
- Hopeful that performance w/errors may be acceptable





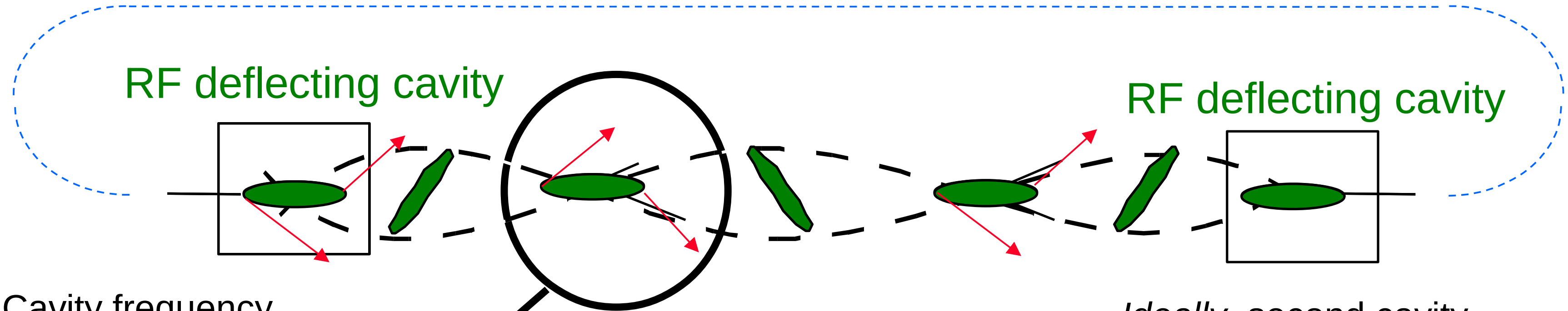
Magnet Strengths

- PEP-X design has combined function quadrupoles and sextupoles
- Here, we just look at strengths separately
- Sextupoles require ~10mm bore radius (using L=0.35m)

ElementName	Length	K_1	G_1	Count
		$1/m^2$	T/m	
QD1	0.15	-1.79	-65.73	720
QD2	0.17	-1.71	-62.92	720
QD3	0.15	-1.98	-72.56	720
QDS1	0.15	-0.41	-15.20	24
QDS2	0.15	-0.22	-7.96	24
QDS3	0.15	-0.44	-16.13	24
QDSE	0.15	-0.09	-3.29	60
QF1	0.28	2.09	76.53	720
QF2	0.20	3.11	113.98	720
QF3	0.20	2.39	87.64	720
QFC	0.20	2.40	88.05	720
QFS1	0.15	-1.05	-38.58	24
QFS2	0.15	0.77	28.22	24
QFS3	0.15	0.17	6.29	24
QFSE	0.15	0.09	3.24	48

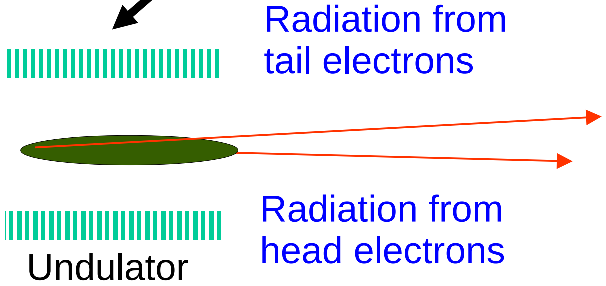
ElementName	$K_2L(B\rho)$	Count
	T/m	
SD1	-5026.41	360
SD2	-5022.90	720
SD3	-4963.88	720
SD4	-4829.27	360
SF1	8167.16	360
SF2	8200.90	360
SF3	7935.36	360
SH1	-25.94	180
SH2	9.20	180
SH3	19.39	180
SH4	-25.11	180
SH5	8.61	180
SH6	18.98	180

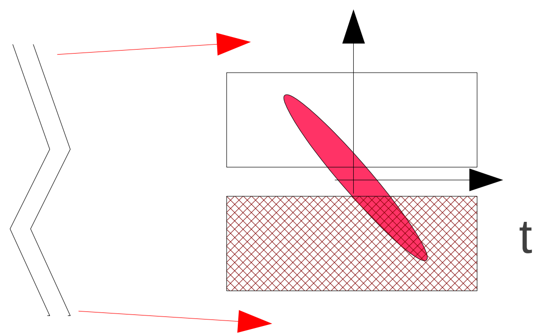
Zholents' Transverse Rf Chirp Concept[1]



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 2 pm emittance gives <u>0.2 ps rms</u>
  - Intensity is ~2% of nominal
  - Average rate is ~400 MHz
- Unlike APS-U, could put this in a long straight to avoid nonlinear dynamics issues[3]

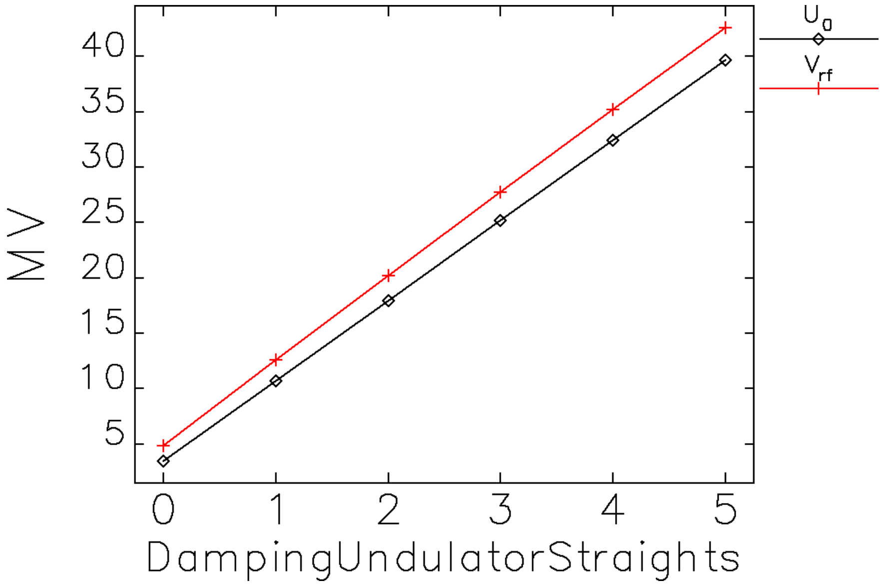
[1]L.Emery *et al.*, PAC11, 2348 (2011)
[2] K. Harkay et al., PAC05, 668 (2005)..
[3]M. Borland, PRSTAB 8(7), 074001, (2005).

Issues with DUs

- 1T field is an extrapolation
  - Present APS 16mm SCU achieves ~0.7 T
  - Can reasonably expect to double this in future:
    - Smaller gap
    - Thinner chamber walls
    - Better magnetic material
    - Better superconducting wire
- How to handle 725 kW/straight/100mA ?
  - Will probably need masking within the straights to protect each SCU from upstream SCUs
  - Might be able to cant the devices in order to spread out the power
    - Could then consider varying the device parameters to make useful radiation sources at popular energies (e.g., 12.4 keV)

Rf Voltage and Power Requirements

- Computed required rf voltage assuming 500 MHz and 3% bucket half-height
- With 2 DU straights, need 20MV rf voltage
  - APS 352 MHz cavities, when new, gave 0.75 MV each
  - Assuming same performance for equivalent 500 MHz cavities, would need ~27 cavities
  - Requires ~35m
  - Straights have more than enough room
- At 100 mA, beam power is ~70kW/cavity (not hard)



Running with Round Beams

- There are various ways to make "round beams", i.e., $\epsilon_x=\epsilon_y$
  - Run on the ν_x-ν_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 ν_x-ν_y=N?

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]

[1]M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
[2]M. Borland, L. Emery,”Possible Long-term Improvements to the APS,” Proc. PAC 2003, 256-258 (2003)
[3]M. Borland, Proc. SRI09, AIP Conf. Proc. 1234, 2010.

Injection Parameters

- For 100 mA and 0.25 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=2 h and D=0.1, need ΔT_{inj} = 3.6 s
- Inject 41 bunches of 0.25 nC each time
  - Average power of 31 W
  - A photoinjector could easily provide the needed bunch trains

Radiation Issues

- We worry about radiation from two sources
  - Extracted beam
  - Losses in the ring
- Beam dump power is “negligible” ~30W for 11 GeV beam
- Touschek losses in the ring are ~3 W total
  - In APS today, have 0.1 W
  - Can design collimation system to intercept these losses

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
  - Can fill bunch trains at few Hz repetition rates
- 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
  - 11 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

Conclusion

- Storage ring light sources are among the most successful scientific facilities in existence
- Reports that rings had reached the end of the road were premature
  - NSLS-II and MAX-IV under construction
  - MBA lattice design with genetic algorithms
  - New injection ideas: 100% coupling and swap-out
- Studies continue in Japan, US, Europe
  - Interest in a possible international collaboration on a large ultimate light source
- A Tevatron-sized USR is very intriguing, but much work needed
  - collective instabilities
  - magnet design
  - error studies and nonlinear dynamics optimization
  - cost reduction
  - science case

Acknowledgements

- Thanks to the PEP-X team for providing their lattice and helpful comments and suggestions
  - K. Bane, Y. Cai, R. Hettel, Y. Nosochkov, M.-H. Wang
- Thanks to A. Zholents for comments on earlier versions of this talk