



... for a brighter future

Possible Upgrade of the Advanced Photon Source with an Energy Recovery Linac

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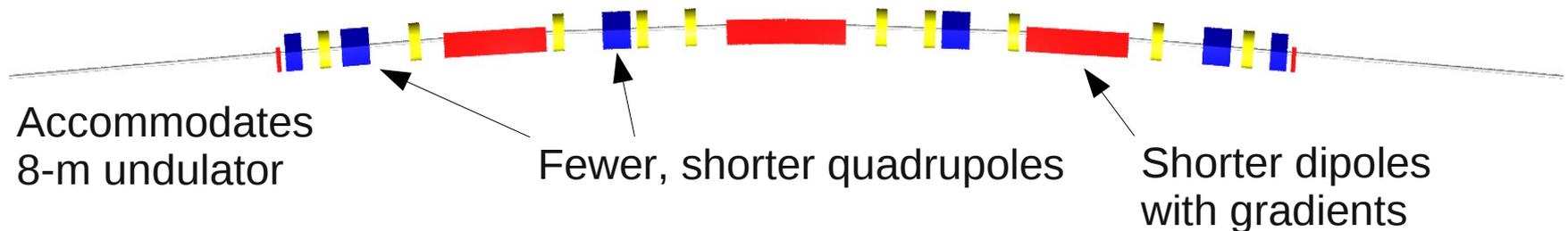
Outline

- Why upgrade the APS?
- Ring replacement
- Advantages of linacs and rings
- ERL basics
- Concepts and options for an ERL upgrade
- Injector design
- Linac design
- High energy transport
- X-ray performance
- Other options
- Conclusion

Ring Improvement or Replacement

- APS started out as a 8-nm light source
 - We've brought this down to 3.1 nm
 - We may be able to lower this ~15% more
- To go further requires replacing the ring itself
- Unfortunately, the up-side potential isn't that great¹
 - ~3 fold in transverse coherent fraction
 - ~40 fold in brightness
 - At least 1 year of dark time for users
- A different idea is needed for an eventual upgrade.

APS 1nm triple-bend replacement lattice¹



¹A. Xiao *et al.*, PAC07, 3447-3449; V. Sajaev *et al.*, PAC07, 1139-1141.

Importance of Emittance and Energy Spread

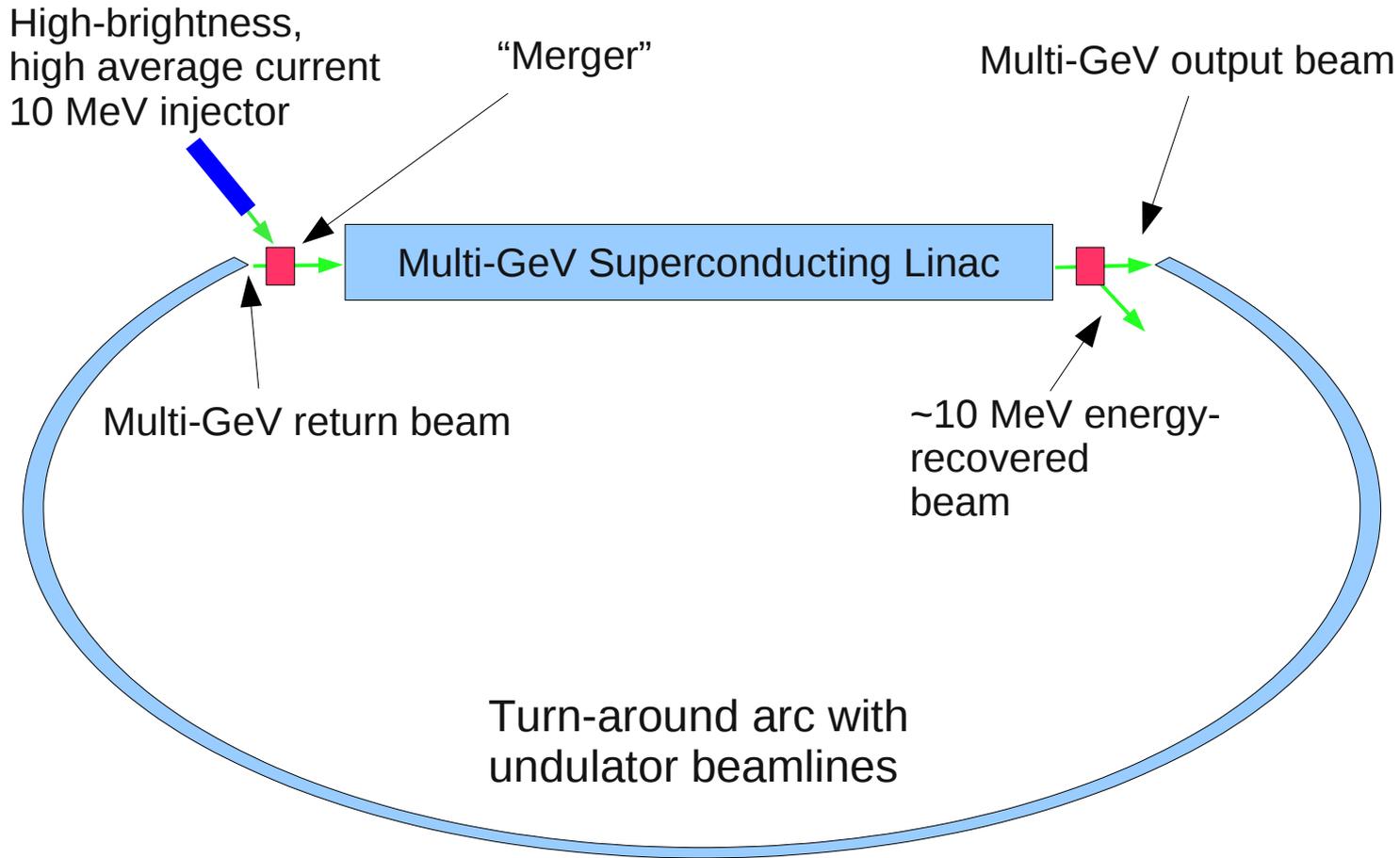
- Average spectral brightness is a primary measure of performance
 - The units of brightness are telling: photons/s/mm²/mrad²/0.1%BW
 - Hence, brightness benefits from high current, high energy, small emittance, and narrow energy spread

$$B \sim \frac{I_{beam}}{E_x E_y \sqrt{4\sigma_\delta^2 + \left(\frac{0.4}{hN_u}\right)^2}}$$

$$E_x = \sqrt{\left(\epsilon_x \beta_x + \frac{\lambda L}{8\pi^2}\right) \left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda}{2L}\right)} \geq \epsilon_x + \frac{\lambda}{4\pi} \quad (\text{Plus similar for y plane})$$

- Comparison of multi-GeV rings and linacs
 - Linac: Emittance comparable to 1Å/4π in both planes
 - Linac: Greater freedom in matching to ideal beta functions
 - Linac: Small energy spread allows capitalizing on long undulators
 - Ring: Easy to achieve high average current

Energy Recovery Linac X-ray Source Concept^{1,2,3}



Energy recovery addresses the most significant advantage of rings over linacs.

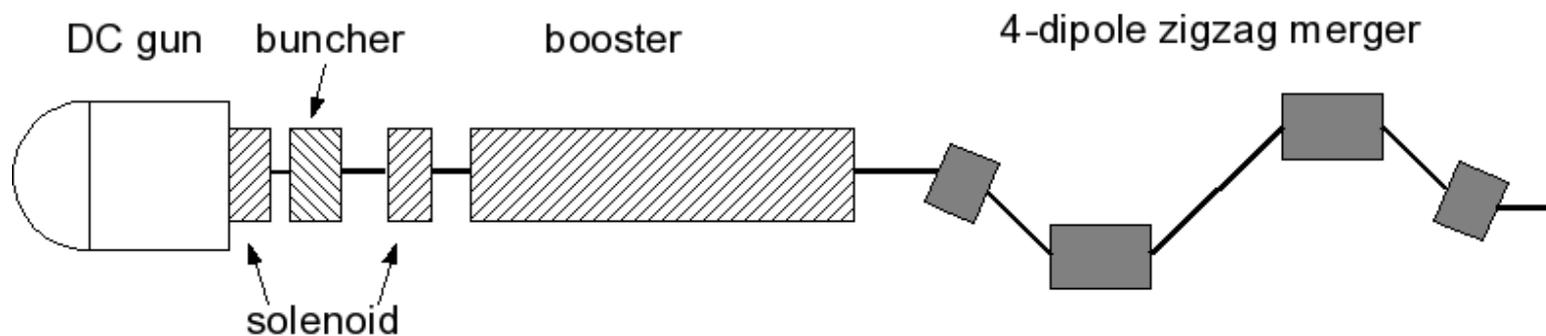
¹M. Tigner, *Nuovo Cimento* **37**, 1965.

²I. Bazarov *et al.*, PAC 2001, 230.

³I. Ben-Zvi *et al.*, PAC 2001, 350.

Simulations Give Promising Predictions for Injector

- Bazarov *et al.* performed optimizations¹ for a ultra-bright photo-injector based on a high-voltage DC gun
- Litvinenko *et al.* have developed the “zig-zag” merger², which maintains laminar beam motion and prevents emittance growth
- Sun *et al.* developed a design³ using an ellipsoidal electron beam that delivers similar performance
- We've combined these concepts into an injector design with a merger that gives the desired beam quality
 - See X. Dong *et al.*, MO6RFP044, this afternoon.



¹I. Bazarov *et al.*, PRSTAB 8, 034202 (2005).

³Y. Sun *et al.*, Proc. Linac08, TUP100.

²V. Litvinenko *et al.*, NIM A 557 (2006) 165.

Predictions for Injector with Zig-zag Merger¹

Beam properties scaled to 7 GeV and compared to APS today

Quantity	APS today	Injector design	
Average Current (mA)	100	25	100
Repetition Rate (MHz)	6.5 to 352	1300	1300
Bunch Charge (nC)	<59	0.019	0.077
Horizontal Emittance (nm)	3.1	0.006	0.020
Vertical Emittance (pm)	25~50	6	20
Rms Bunch Length (ps)	>20	2	2
Rms Energy Spread (%)	0.1	0.02	0.02

- These are equivalent to the High-Coherence and High-Flux parameter sets defined by Cornell.²
- We'll concentrate on the High-Coherence parameters.

¹X. Dong, MO6RFP044.

²G. Hoffstaetter, "Status of the Cornell ERL Project," fls2006.desy.de

Energy Choice for ERL@APS

- Previously¹, we showed the advantage of high beam energy
 - Initial geometric emittance decreases with energy
 - Photons more numerous and harder like E^2
 - Emittance and energy spread growth in arcs increases
 - We concluded that for photon energies over ~ 7 keV, we want a 7 GeV or higher electron beam
- Another consideration is energy spread growth due to undulators
 - A limiting factor in an ERL is how much energy spread can be tolerated after deceleration
 - This is a fixed value, independent of the linac energy
- For $K \sim 1$ and keeping the photon energy fixed, we find

$$\Delta\sigma_{E,u}^2 \propto \frac{L_u}{E^2}$$

where L_u is the total length of undulators.

- Hence, a higher energy electron beam can tolerate longer undulators.

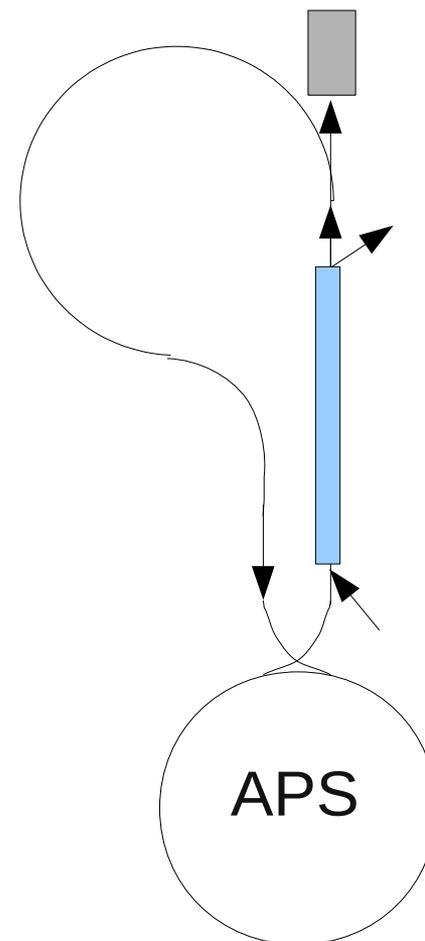
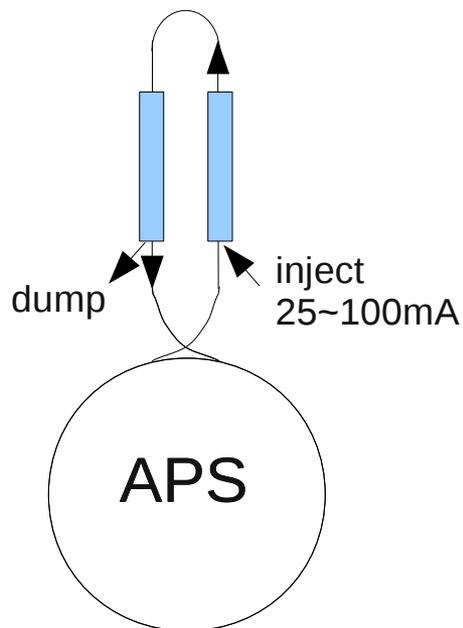
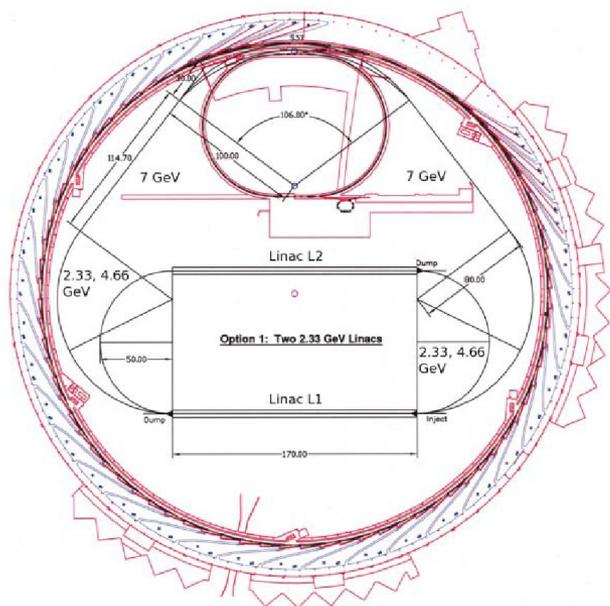
¹M. Borland *et al.*, PAC 2007, 1121 (2007).

Some Configuration Options for ERL@APS

Infield^{1,2}: Two 2.33 GeV linacs.

Outfield: Two 3.5 GeV linacs, budget turn-around system.

Ultimate: 7 GeV linac, new user arc, straight-ahead hall



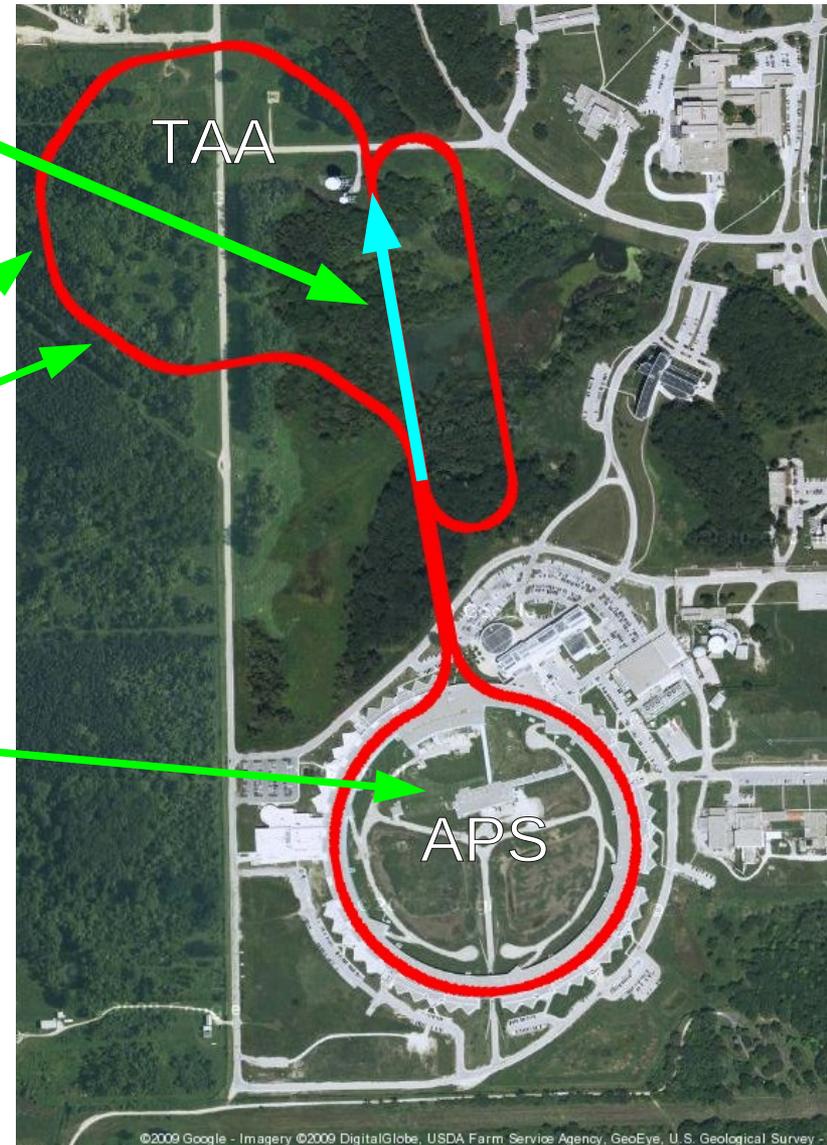
¹M. White *et al.*, SRF2003 (MoP42).

²N. Sereno *et al.*, PAC2007, 1145 (2007).

Based on ideas from M. Borland, G. Decker, N. Sereno.

An “Ultimate” ERL@APS Concept

- Single- or two-pass 7 GeV linac with 7 GeV turn-around arc
 - Two-pass linac shown as cost-reducing measure
 - Accelerate away from APS to put highest-quality beam into TAA
- TAA has nine 50-m straight sections
 - Accommodates 48-m undulators to get maximum benefit from beam quality
- Ability to store beam is unchanged, using existing injector²
 - Envision a gradual change from 100% stored beam operation to 100% ERL operation.

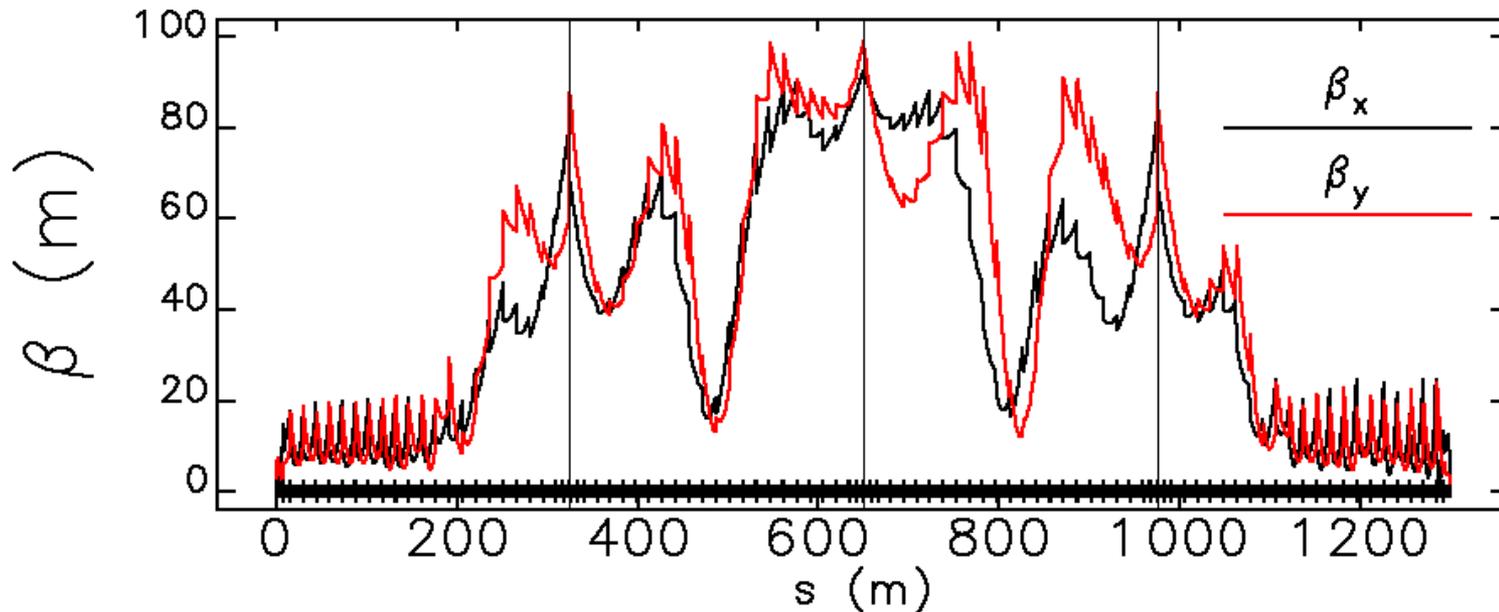


¹M. Borland *et al.*, NIM A 582 (2007) 54-56.

²G. Decker, private communication, September 2006.

Linac Design

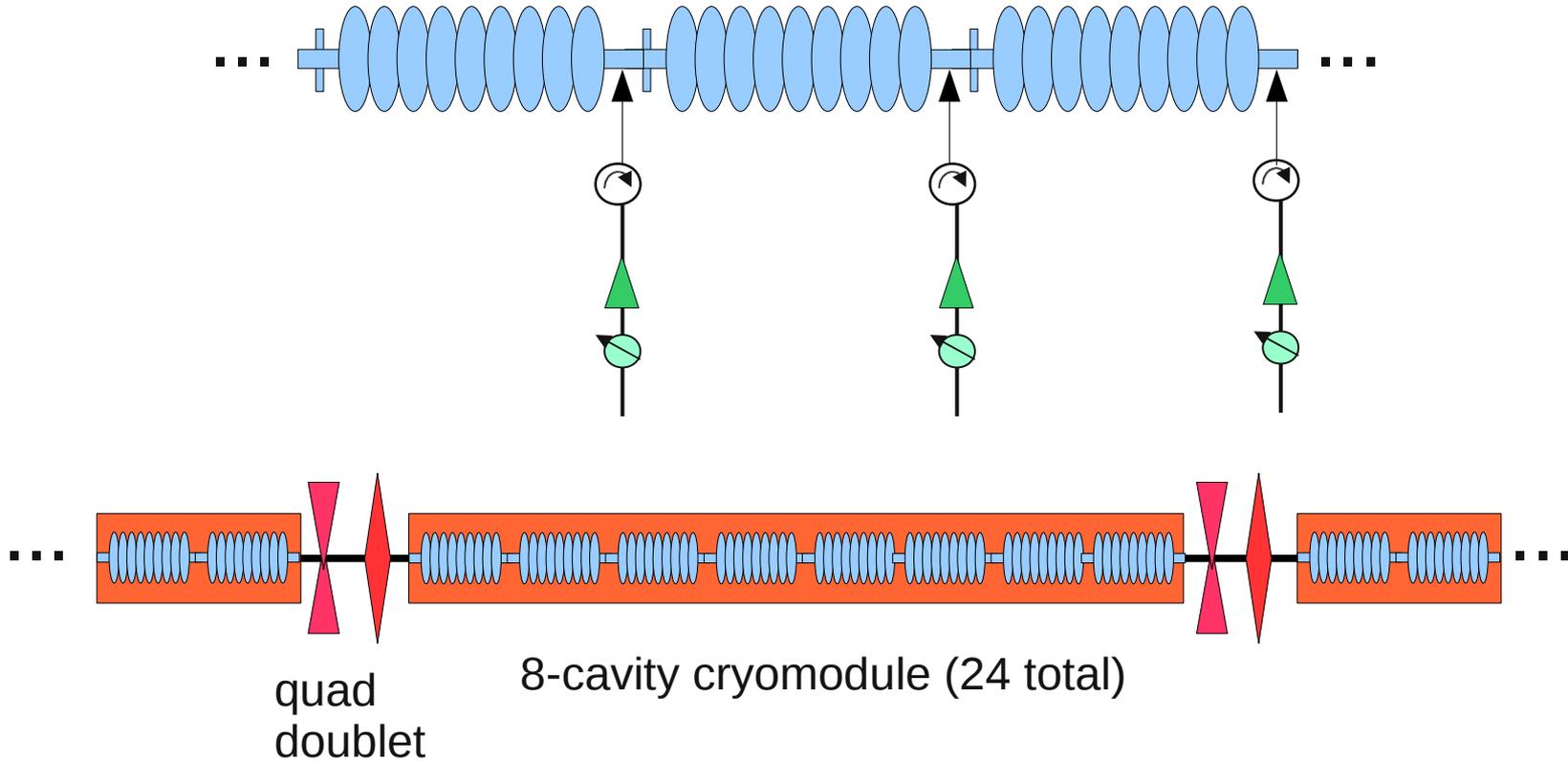
- The linac will see four beams
 - Accelerating from 10 MeV to 3.5 GeV, and from 3.5 GeV to 7 GeV
 - Decelerating from 7 GeV to 3.5 GeV, and from 3.5 GeV to 10 MeV
- Started with the graded gradient concept¹ to develop the optics
 - Constant focal lengths for the lowest energy beam at any location
- Used ELEGANT to optimize individual quads for four beams at once
 - Doublet configuration found to give good control of beam sizes



¹D. Douglas, JLab-TN-00-27 (2000).

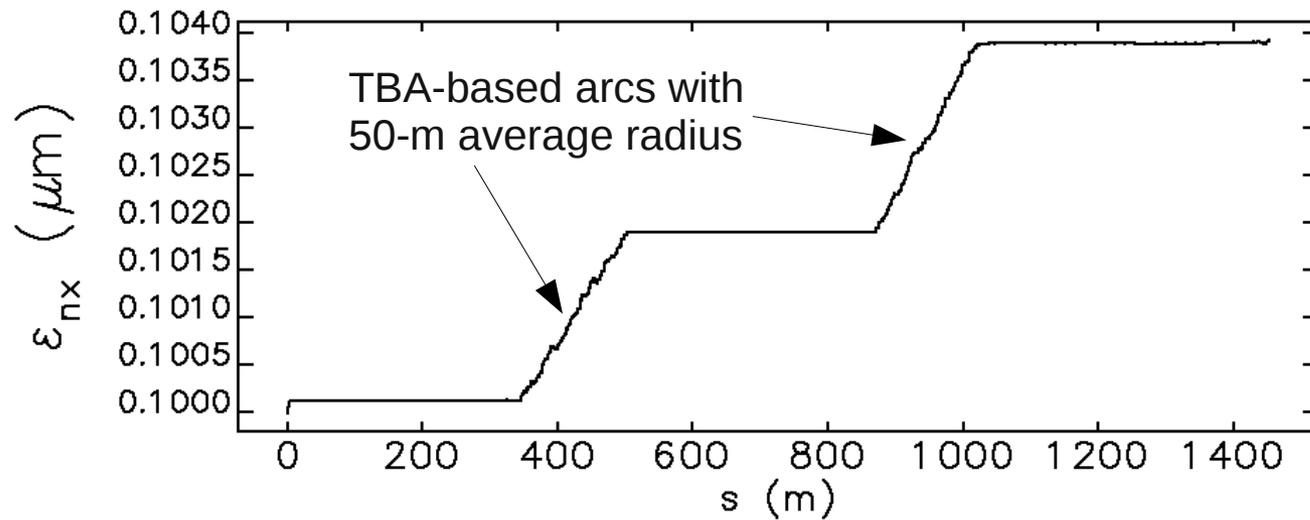
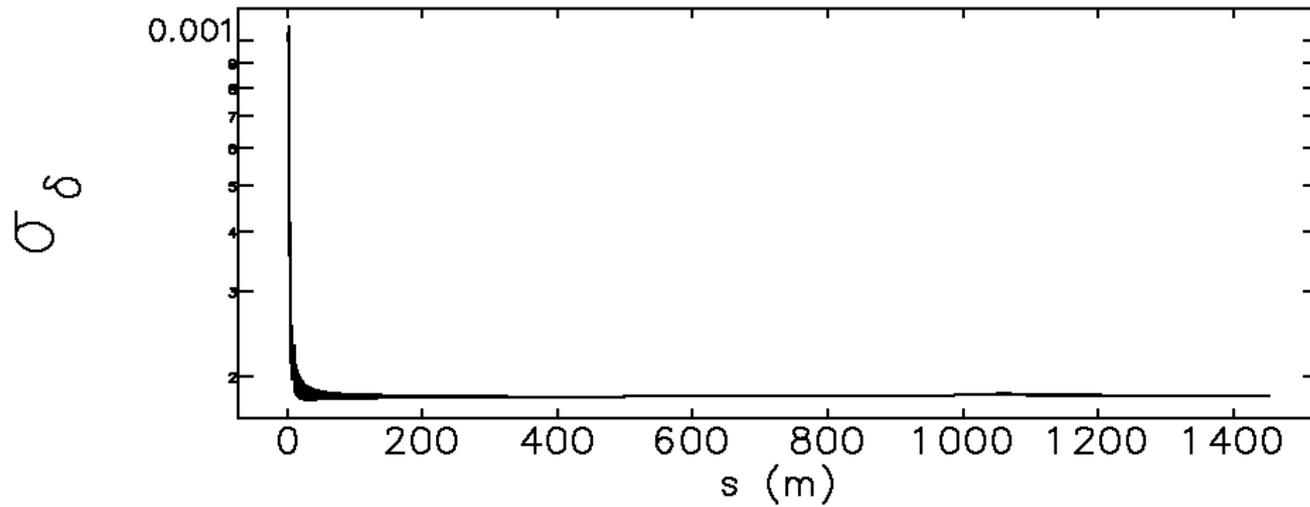
Linac Layout

1-m, 9-cell, 1.3 GHz cavities (TESLA-like¹)
with independent klystrons, @ 20 MV/m



¹B. Aune et al., PRSTAB 3, 092001 (2000).

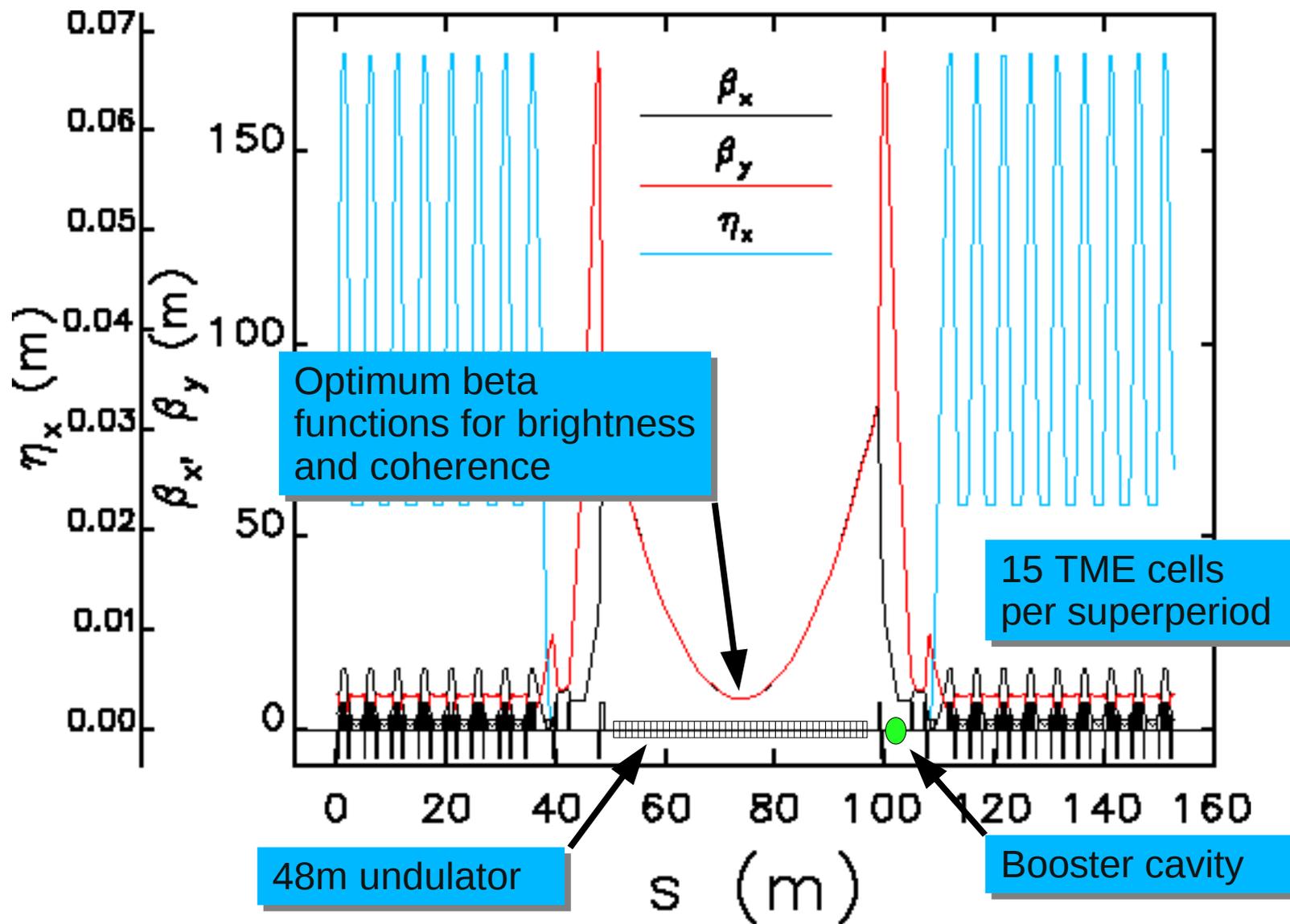
Beam Evolution Through the Linac (Acceleration)



Turn Around Arc (TAA) Design

- Our previous TAA designs provided a large number of additional straights
 - 48 TBA or DBA cells
 - 230m average radius
 - 10m straight sections to accommodate 8m undulators
 - This gave ~140 fold brightness increase over APS today
 - About 80% of present flux (HC mode)
- For this work, we sought to push the brightness and flux higher
 - Emphasize fewer, much-longer undulators
 - Room for “booster cavities” to restore energy lost to each undulator
 - Use TME cells to reduce emittance growth
 - 190m average radius (100m in arcs)
- Design was done with ELEGANT, which allows simultaneously optimizing floor coordinates, linear optics, emittance growth, and energy spread growth.

TAA Optics



Need for Booster Cavities

- Users must vary undulator gaps, causing energy variation downstream
 - With long devices, variation may exceed the energy spread (1.4 MeV)
 - If uncompensated, will adversely impact downstream users
 - We also need to limit variation in
 - *Time of flight through the TAA and APS*
 - *Energy offset in the 3.5 GeV arcs*
 - *Energy of recovered beam*

- We used a representative set of APS undulator designs

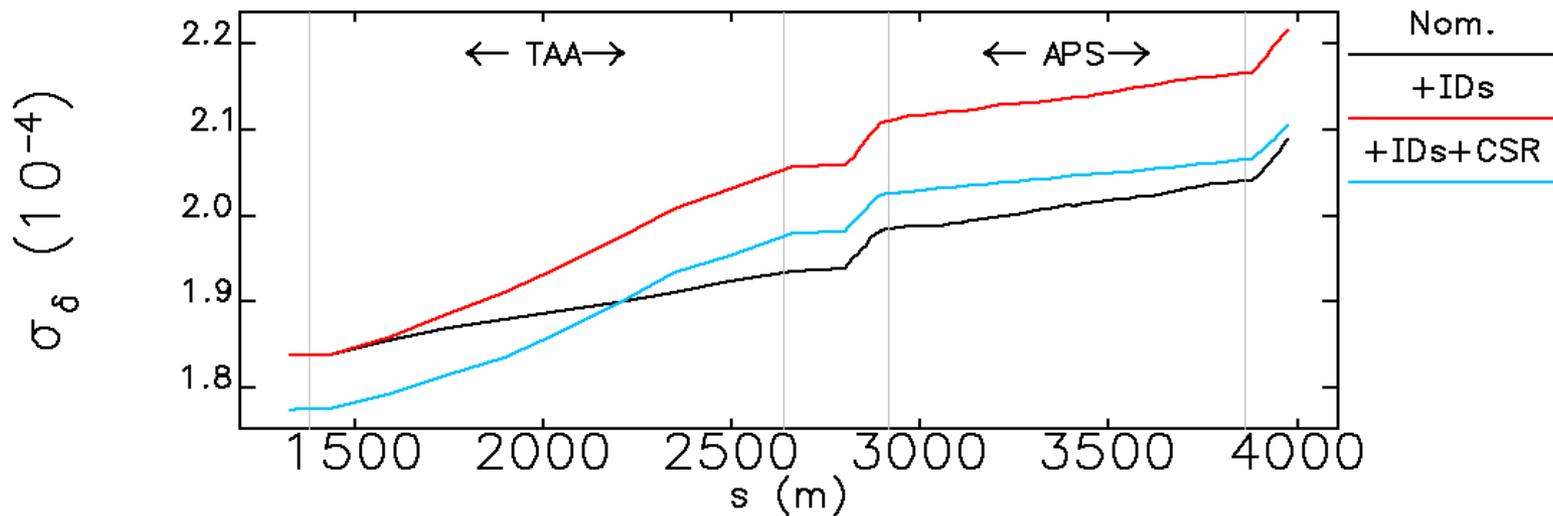
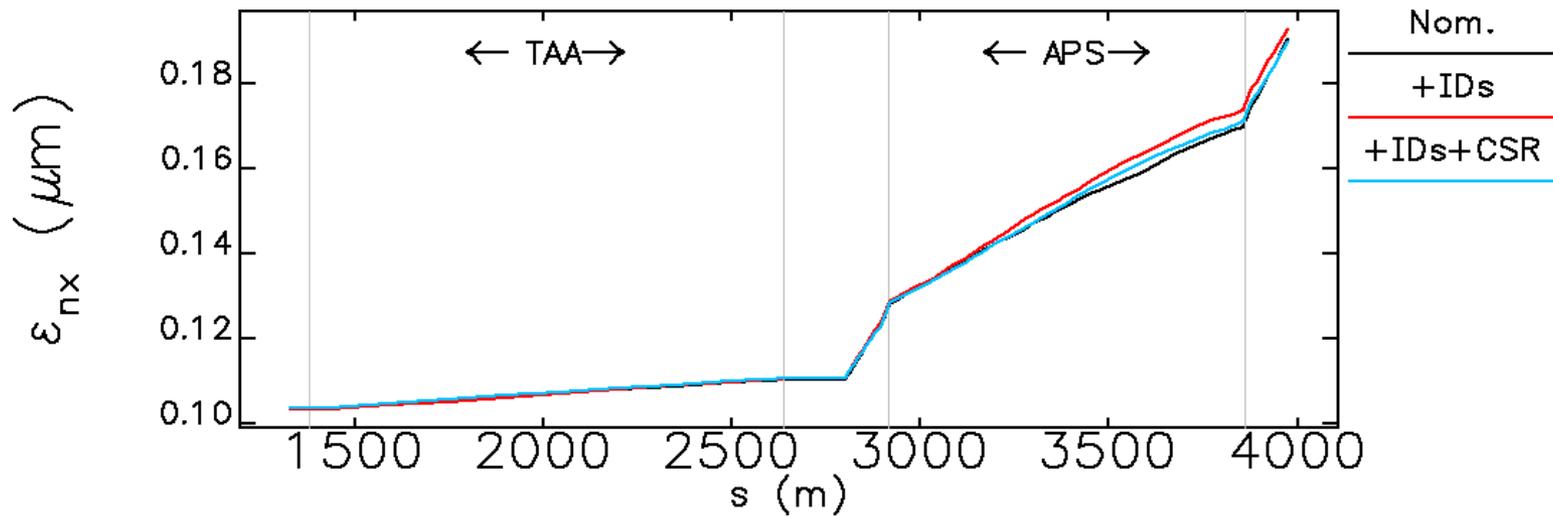
- Assess impact on beam dynamics
- Estimate booster cavity parameters

- Booster cavities may be needed in the APS ring portion as well

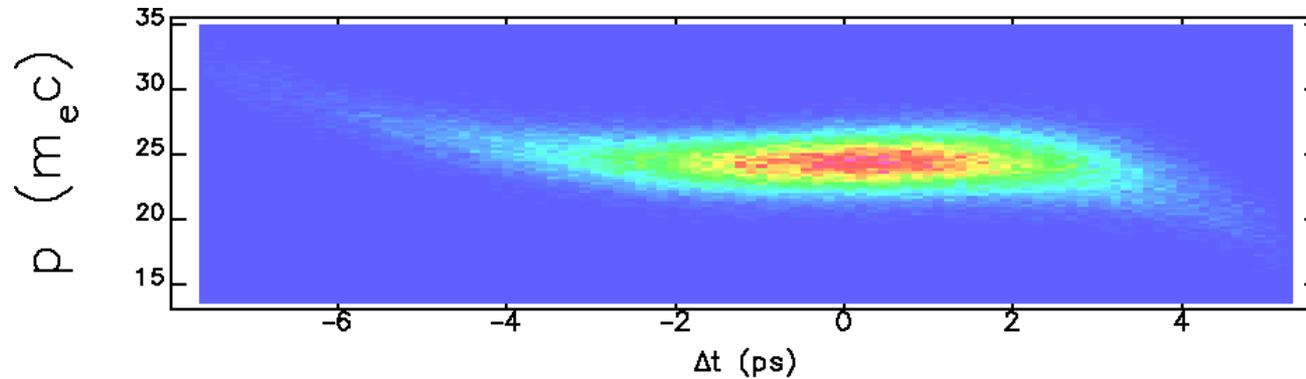
- Want to use 8m undulators
- Could devote every N^{th} straight section to a cavity

Undulator		Booster cavity		Number
Period mm	K max.	Voltage MV	Power kW	
18	0.45	0.11	2.7	1
23	1.20	0.46	11.6	1
27	1.78	0.74	18.5	2
30	2.20	0.92	22.9	1
33	2.74	1.18	29.4	2
35	3.08	1.32	33.0	1
55	4.97	1.39	34.8	1

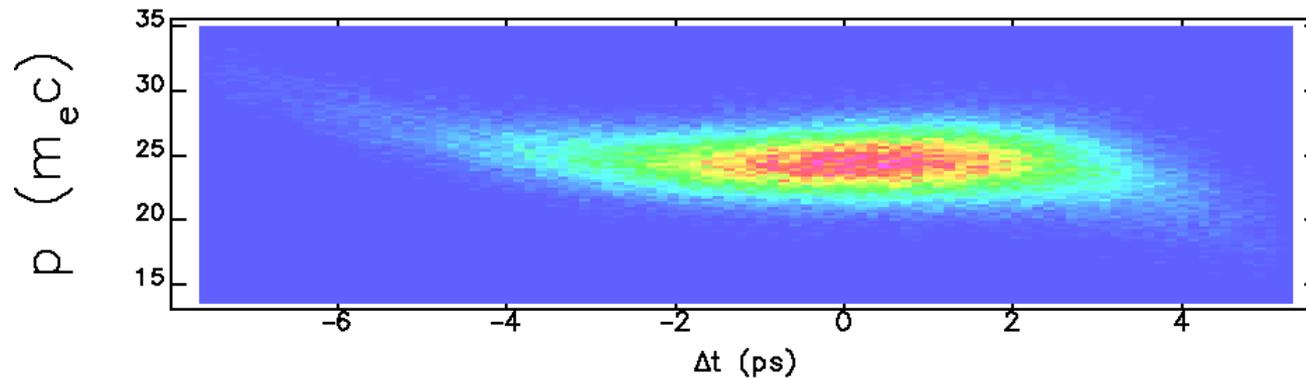
Beam Evolution in the TAA and APS Portion (19 pC)



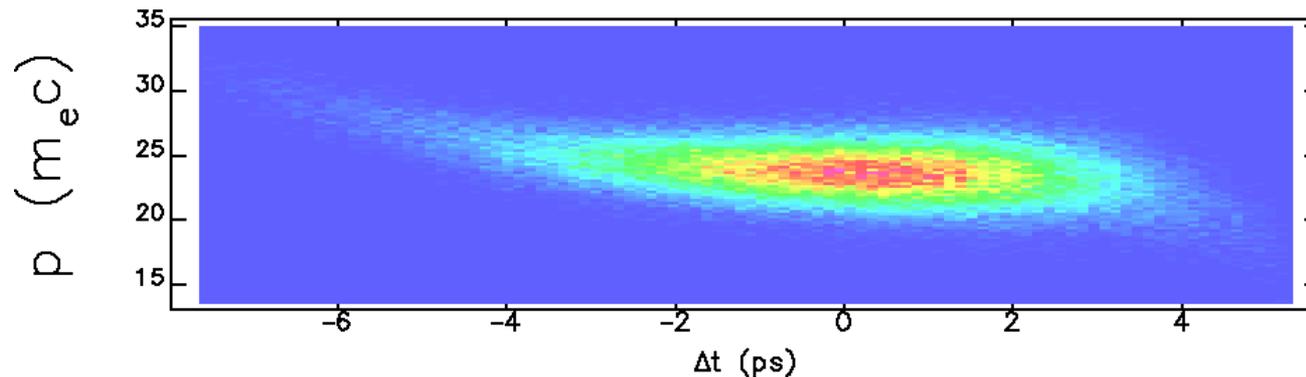
Final Longitudinal Phase Space



Nominal

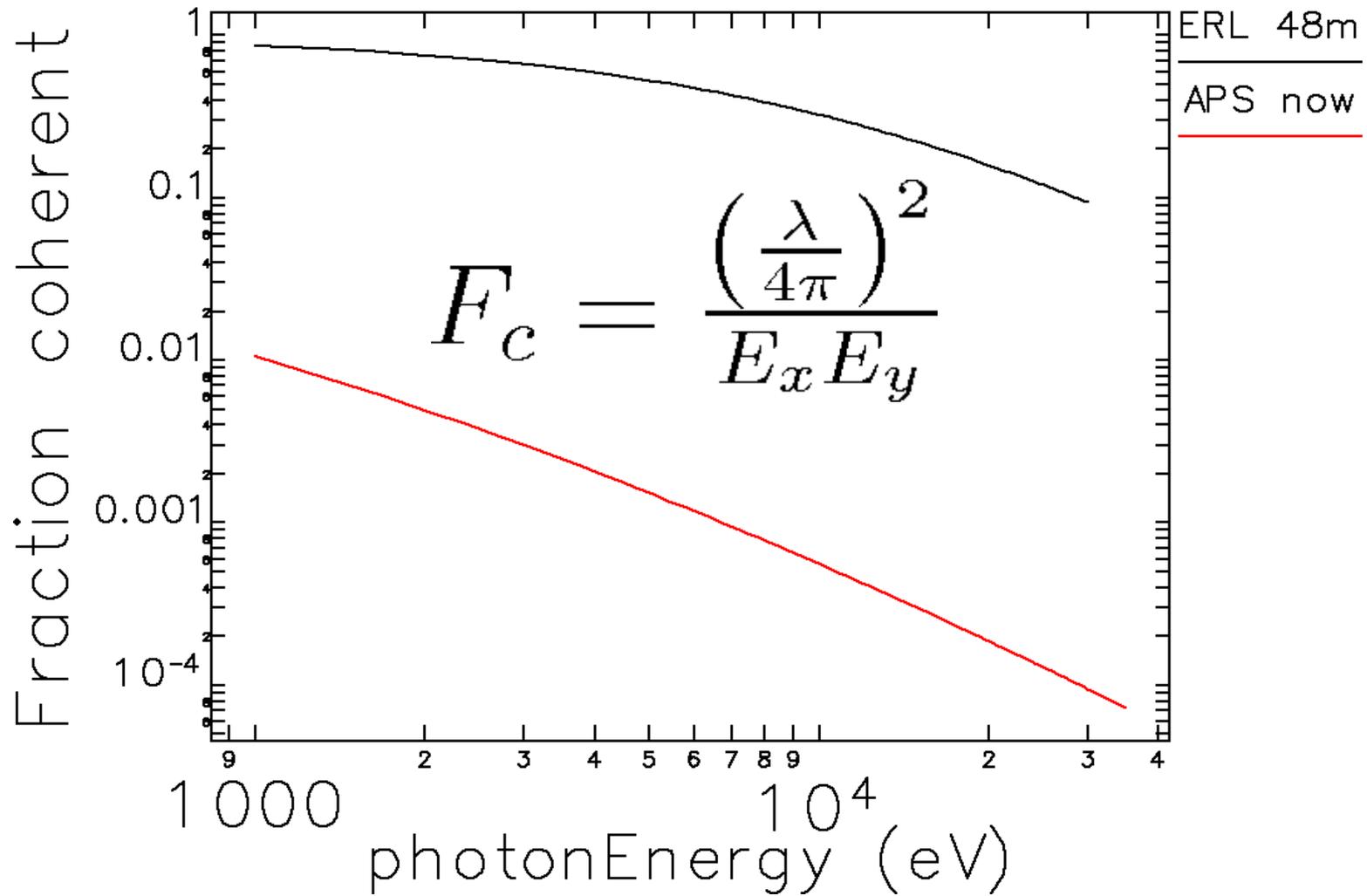


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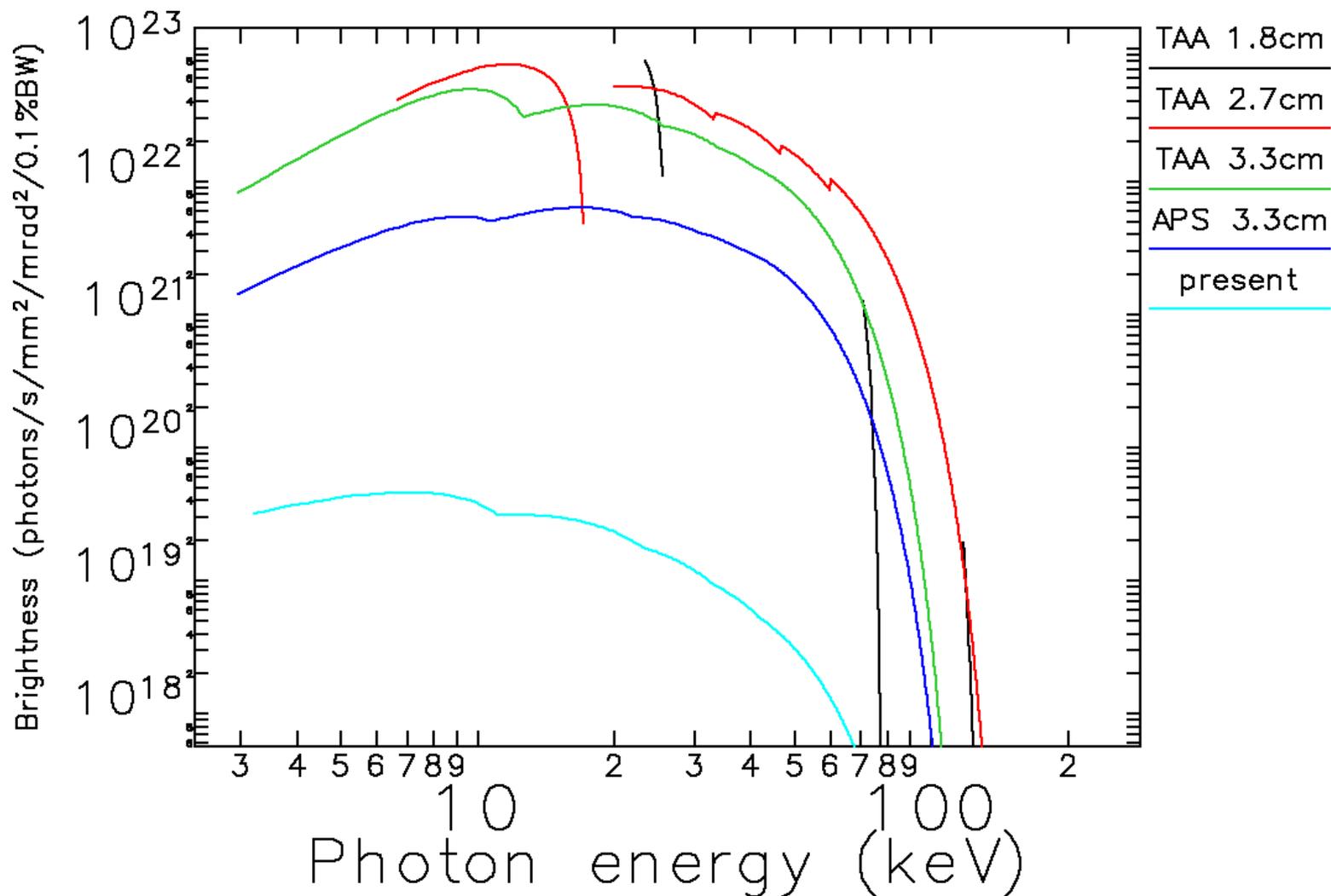


+IDs
+CSR

X-Ray Performance: Transverse Coherence

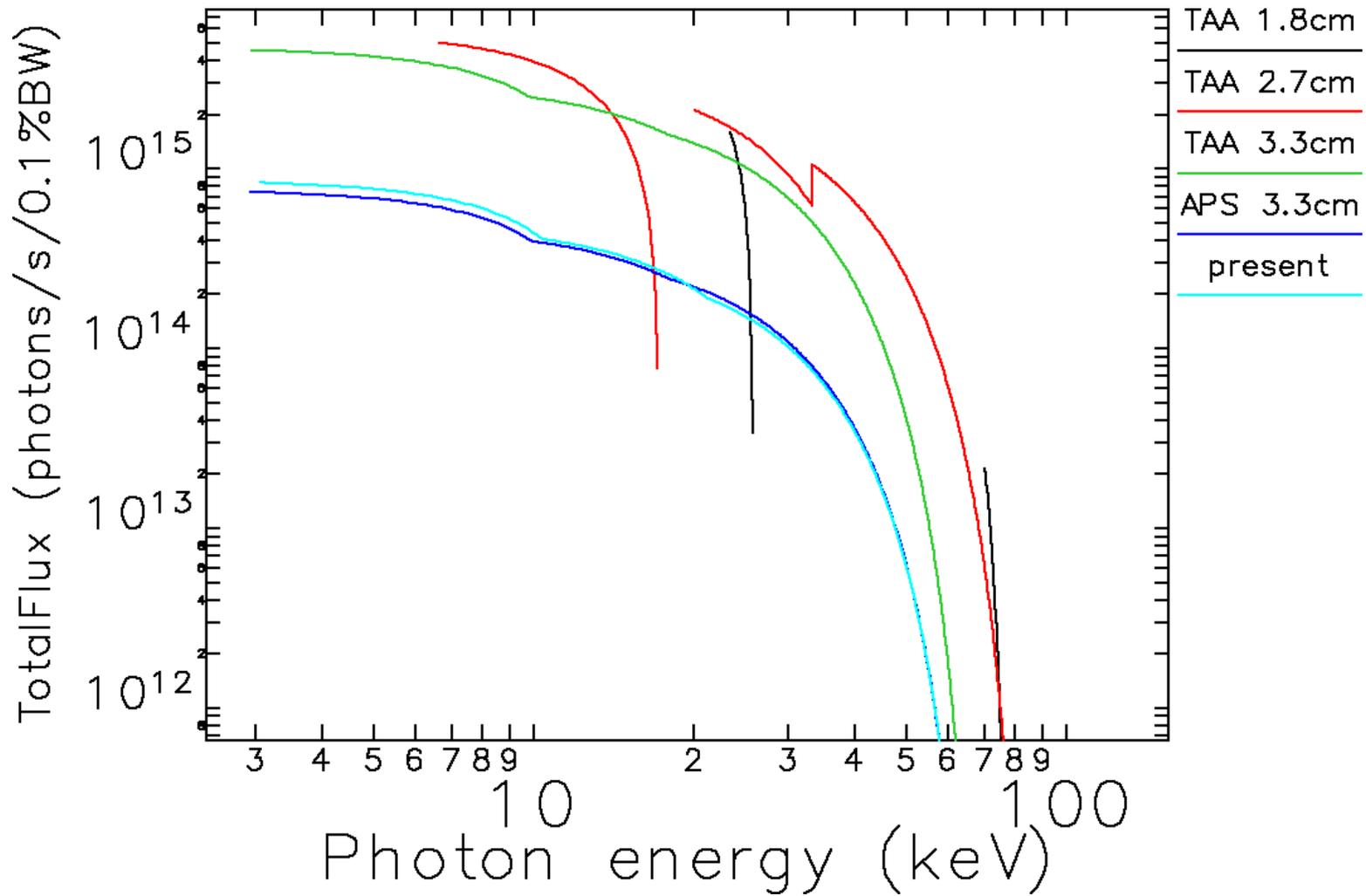


X-ray Performance: Brightness



Computed with sdsbrightness (H. Shang, R. Dejus, M. Borland).

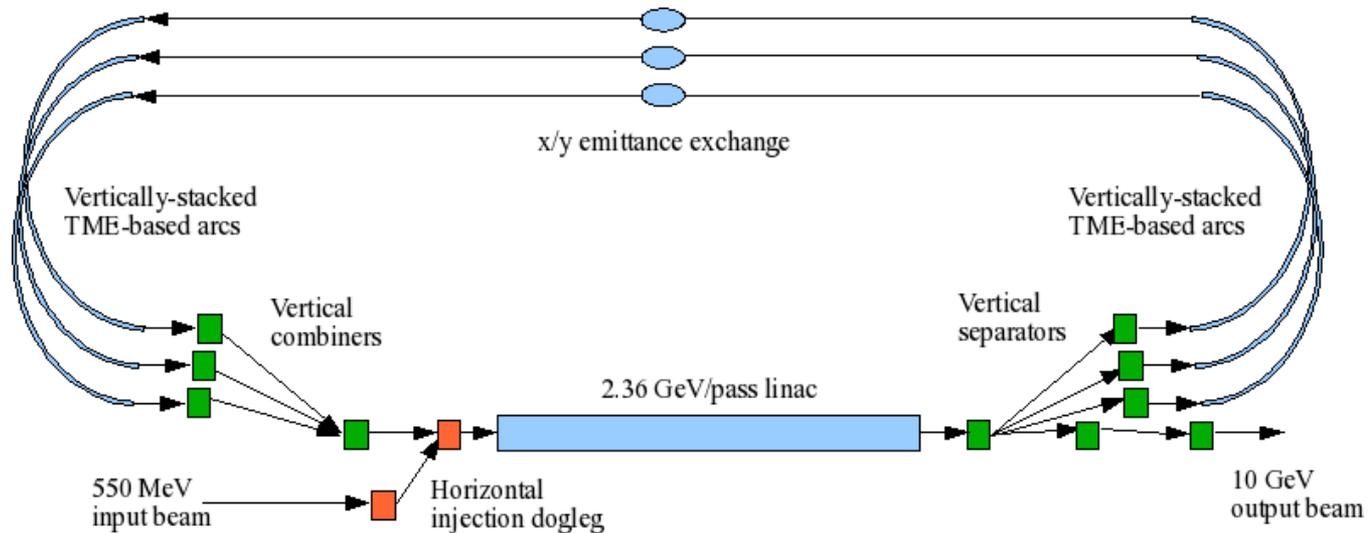
X-ray Performance: Flux



Computed with sddsfluxcurve (M. Borland, R. Dejus).

Other Options: XFEL-O¹

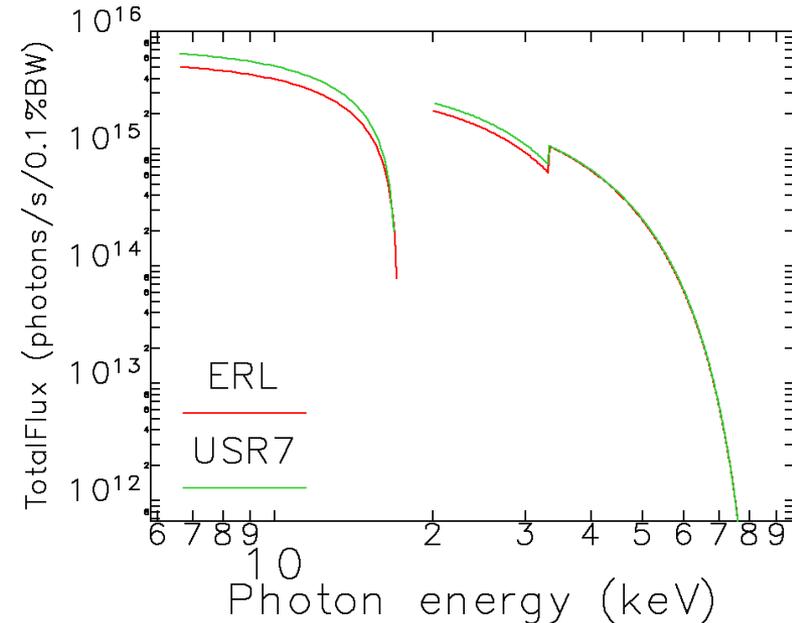
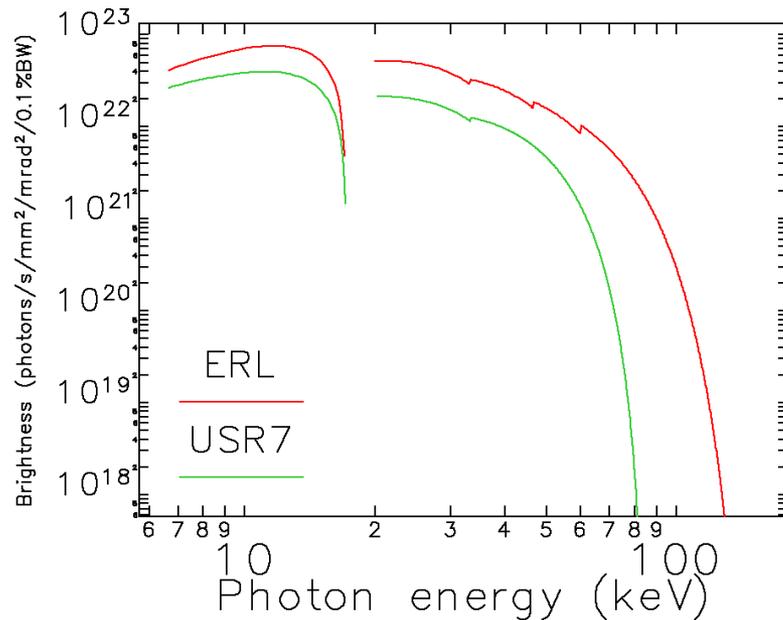
- X-ray FEL oscillator using x-ray crystals as mirrors
- Extremely high average brightness
- Fully coherent
- ERL-like beam requirements, but no recovery
- Serves fewer beamlines and less tunable than ERL
- See Ostroumov *et al.* (MO6RFP046), Lindberg *et al.* (TU5RFP049), Borland (TU5RFP048).



¹K.-J. Kim *et al.*, PRL 100, 244802 (2008)

Other Options: USR7

- “Ultimate” storage rings (USRs) have been proposed several times^{1,2,3}
- An APS design concept⁴ approaches ERL performance
 - 7 GeV, 200 mA
 - 40 MBA⁵ sectors, 3.1 km circumference, damping wigglers
 - Fully coupled beam, on-axis swap-out operation
 - Technology apparently not challenging



¹A. Ropert *et al.*, EPAC2000, 83.

²M. Borland, NIM A 557 (2006) 230.

³K. Tsumaki *et al.*, NIM A 556 (2006) 394.

⁴M. Borland, LSU Grand Challenge Workshop.

⁵D. Einfeld *et al.*, EPAC 96, jacow.org.

Conclusions

- An ERL upgrade appears to be a viable option for APS
 - In-tunnel storage ring replacement can't compete with next-generation sources
 - Injector modeling is very promising
 - Several system designs have been developed
- Latest design incorporates nine 48m undulators
 - 3+ orders of magnitude higher brightness
 - Higher flux than APS today
 - Use of booster cavities seems necessary, looks feasible
 - Energy spread after deceleration seems workable
- Other upgrades are still on the table
 - Greenfield ERL (similar performance)
 - XFEL oscillator
 - Ultimate storage ring
- Meanwhile, we are developing an APS “renewal” plan to better serve users through the intervening years

Acknowledgements

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- ANL: Y.-C. Chae, R. Gerig, E. Gluskin, K. Harkay, K.-J. Kim, V. Sajaev, N. Sereno, H. Shang, R. Soliday, C.-X. Wang, Y. Wang, M. White, A. Xiao, C.-Y. Yao
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