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

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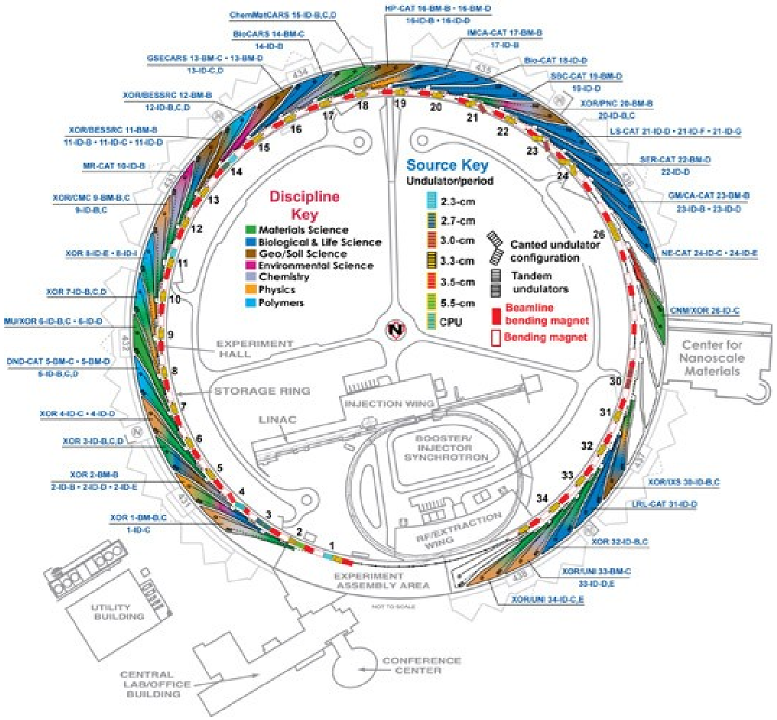
Outline

- 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

Why Upgrade the APS?

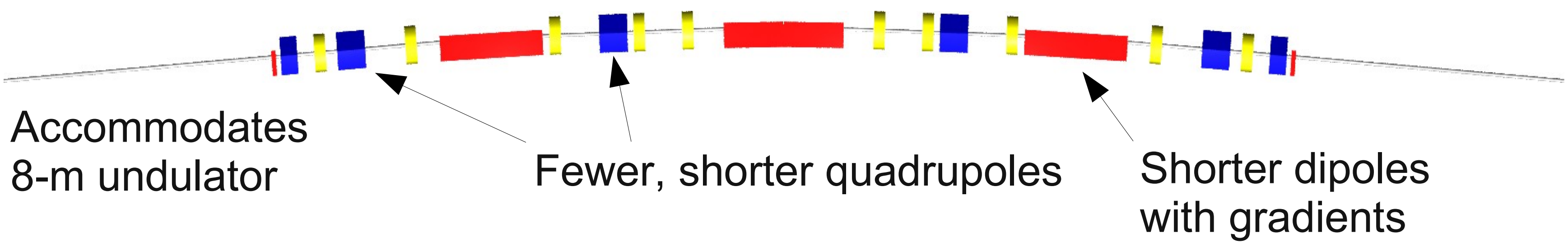


- APS has been in operation since 1996
  - ~98% availability
  - ~70 hour MTBF
  - Thousands of users per year
- Source performance meets the demands of most users
  - 7 GeV
  - 3.1 nm horizontal emittance
  - ~50 pm vertical emittance
  - 100 mA
  - ~80% of time in top-up
  - Various bunch patterns to support timing experiments
- APS is presently state of the art, but can't remain so indefinitely
  - New rings, ERLs, and FELs promise higher coherence, brightness, and/or flux
  - An upgrade in the not-to-distant future is needed to stay relevant.

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 great[1]
  - ~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.

<u>APS 1nm triple-bend replacement lattice</u>[1]



[1]A. 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/mm^2/mrad^2/0.1%BW
  - Hence, brightness benefits from high current, high energy, small emittance, and narrow energy spread

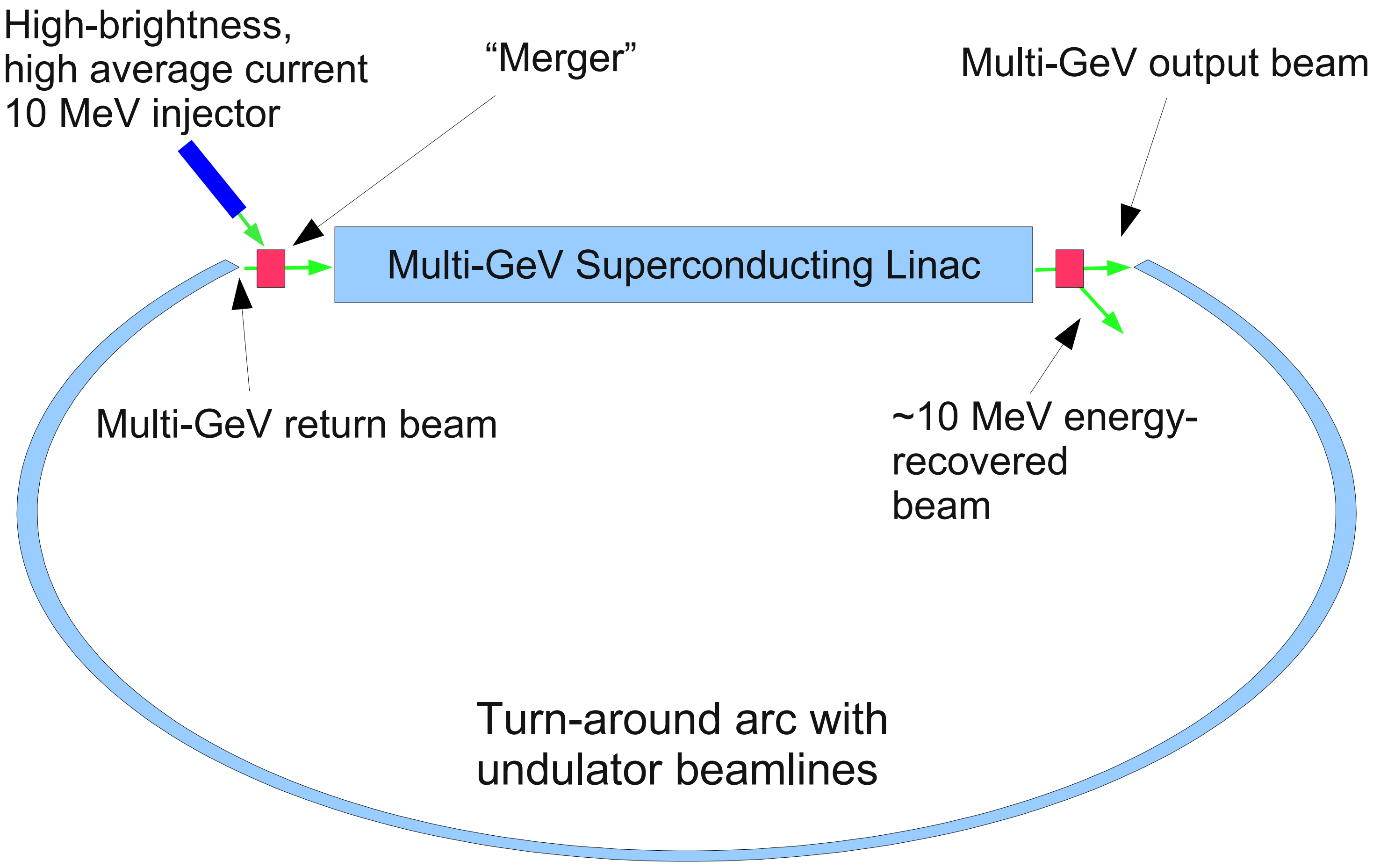
$$B \sim \frac{I_{beam}}{E_x E_y \sqrt{4\sigma_\delta^2 + \left(\frac{0.4}{hN_u}\right)^2}}$$

$$E_x = \sqrt{\left(\epsilon_x \beta_x + \frac{\lambda L}{8\pi^2}\right)\left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda}{2L}\right)} \geq \epsilon_x + \frac{\lambda}{4\pi}$$

(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]

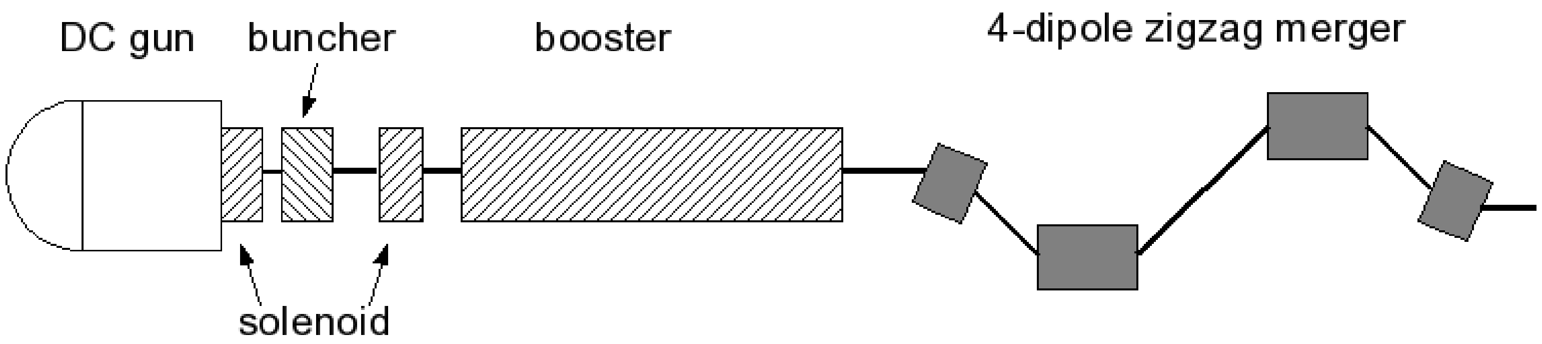


Energy recovery addresses the most significant advantage of rings over linacs.

[1]M. Tigner, *Nuovo Cimento* **37**, 1965.
[2]I. Bazarov *et al*., PAC 2001, 230.
[3]I. Ben-Zvi *et al*., PAC 2001, 350.

Simulations Give Promising Predictions for Injector

- Bazarov *et al.* performed optimizations[1] for a ultra-bright photo-injector based on a high-voltage DC gun
- Litvinenko *et al.* have developed the “zig-zag” merger[2], which maintains laminar beam motion and prevents emittance growth
- Sun *et al*. developed a design[3] 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.



[1]I. Bazarov et al., PRSTAB 8, 034202 (2005).
[2]V. Litvinenko et al., NIM A 557 (2006) 165.
[3]Y. Sun et al., Proc. Linac08, TUP100.

Predictions for Injector with Zig-zag Merger[1]

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.

[1]X. Dong, MO6RFP044.
[2]G. Hoffstaetter, “Status of the Cornell ERL Project,” fls2006.desy.de

Energy Choice for ERL@APS

- Previously[1], 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~1 and keeping the photon energy fixed, we find

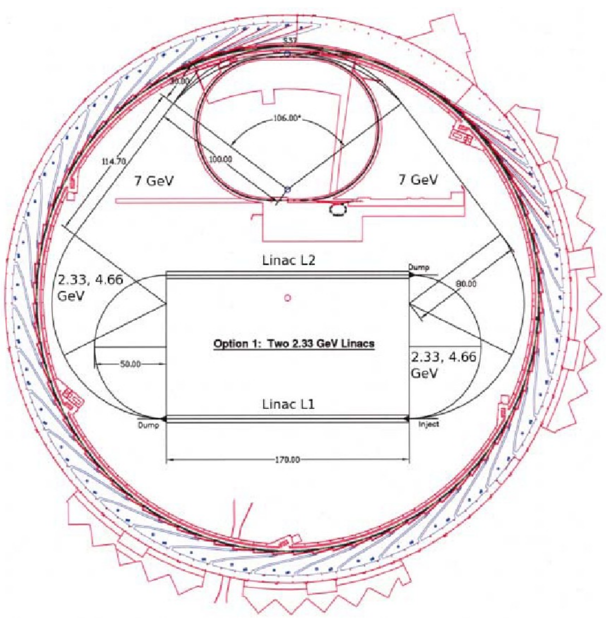
$$\Delta\sigma_{E,u}^2 \propto \frac{L_u}{E^2}$$

  where L_u is the total length of undulators.
- Hence, a higher energy electron beam can tolerate longer undulators.

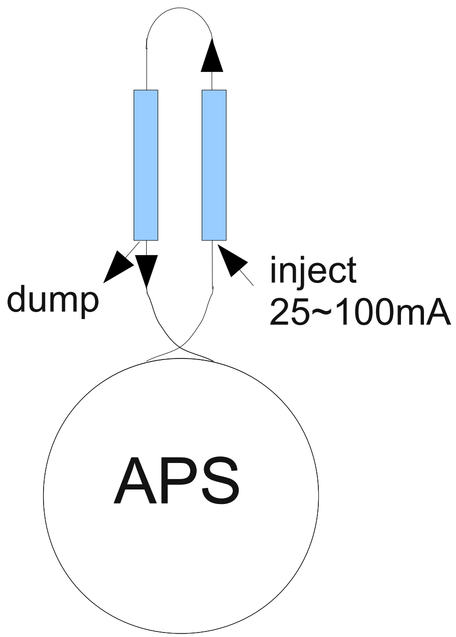
[1]M. Borland *et al.*, PAC 2007, 1121 (2007).

Some Configuration Options for ERL@APS

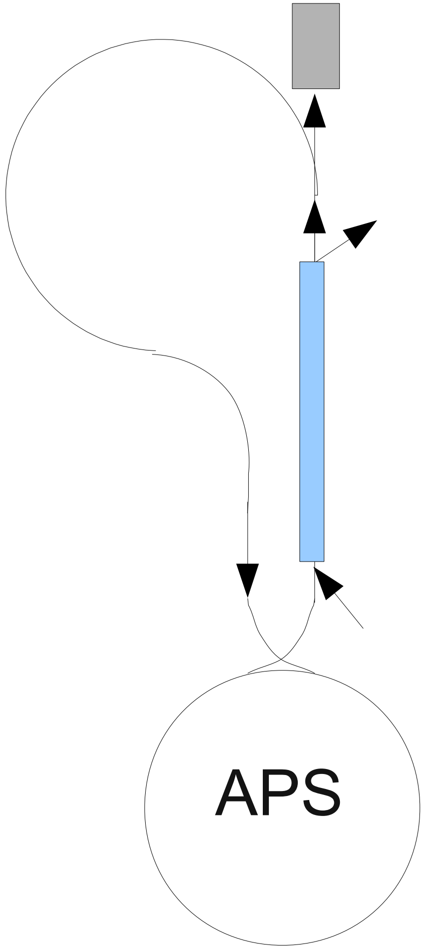
Infield[1,2]: Two 2.33 GeV linacs.



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



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

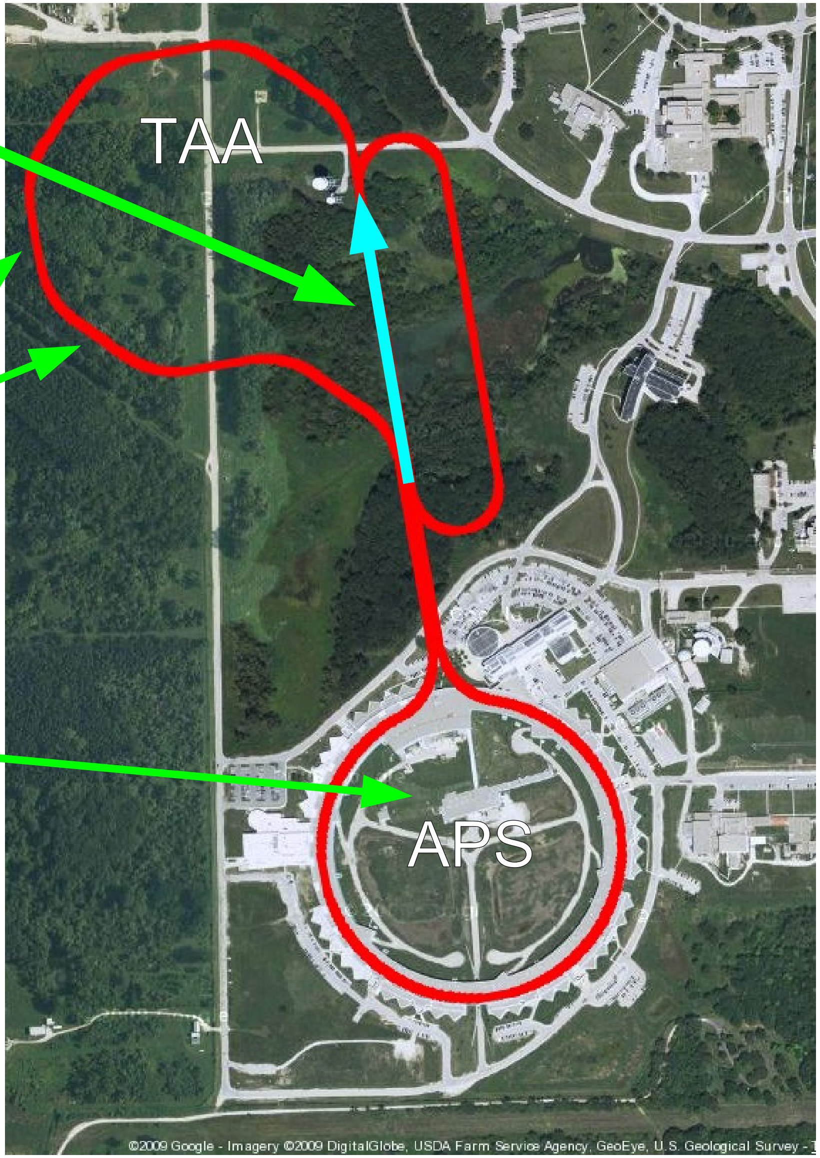


[1]M. White *et al*., SRF2003 (MoP42).
[2]N. Sereno *et al*., PAC2007, 1145 (2007).

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

An "Ultimate" ERL@APS Concept

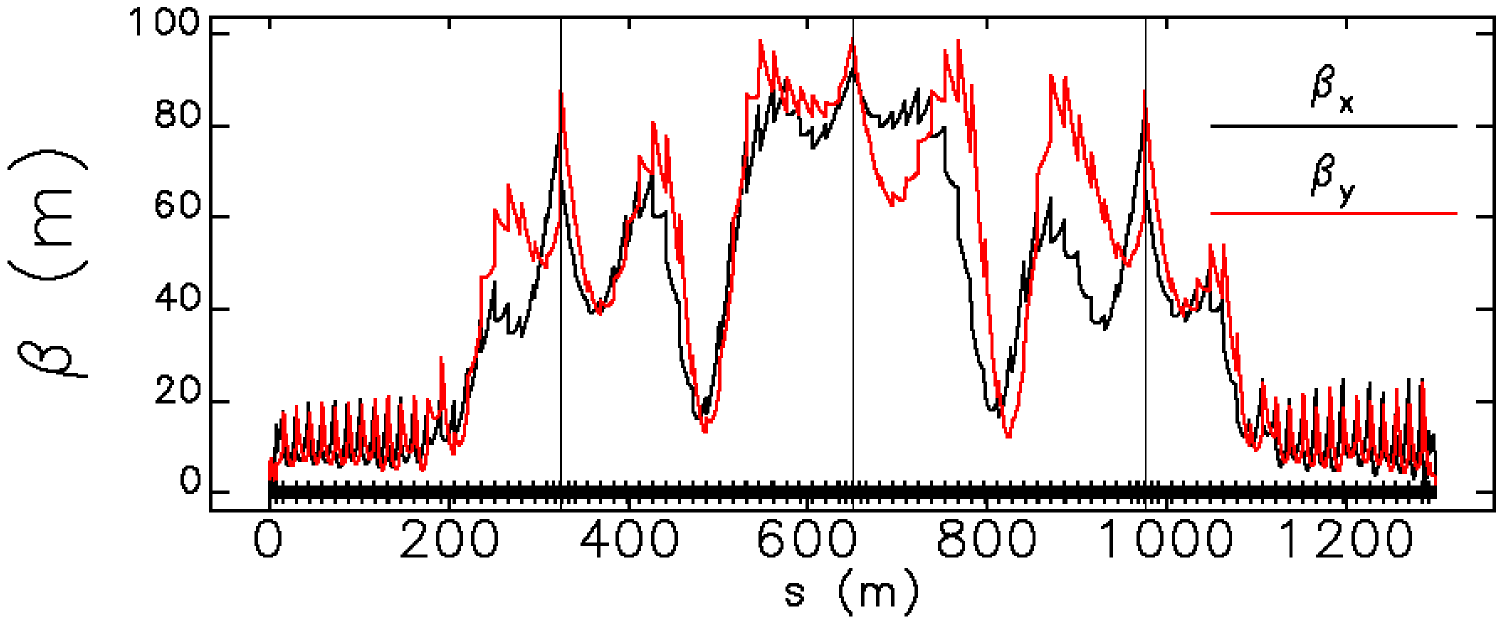
- Single- or two-pass 7 GeV linac with 7 GeV turn-around arc
  - Two-pass linac shown as cost-reducing measure
  - Accelerate away from APS to put highest-quality beam into TAA
- TAA has nine 50-m straight sections
  - Accommodates 48-m undulators to get maximum benefit from beam quality
- Ability to store beam is unchanged, using existing injector[2]
  - Envision a gradual change from 100% stored beam operation to 100% ERL operation.



[1]M. Borland *et al.*, NIM A 582 (2007) 54-56.
[2]G. Decker, private communication, September 2006.

Linac Design

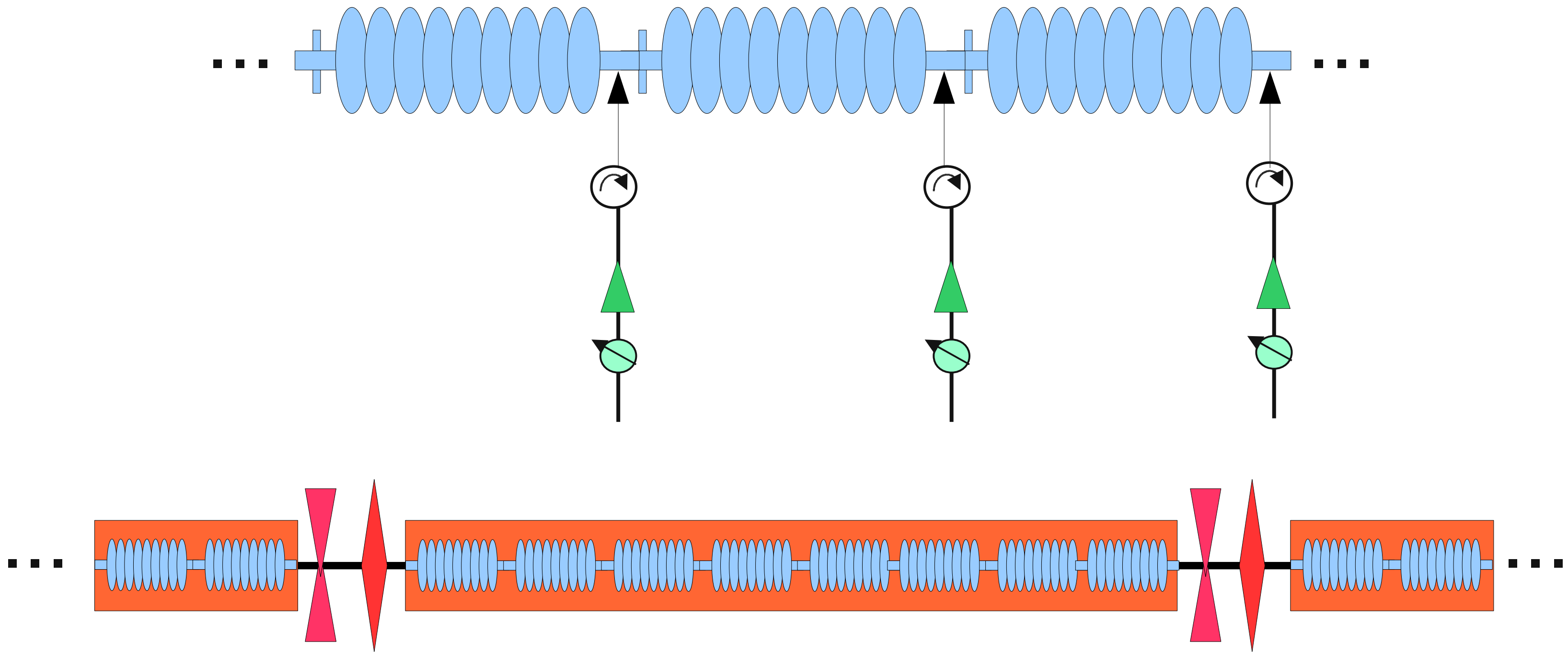
- The linac will see four beams
  - Accelerating from 10 MeV to 3.5 GeV, and from 3.5 GeV to 7 GeV
  - Decelerating from 7 GeV to 3.5 GeV, and from 3.5 GeV to 10 MeV
- Started with the graded gradient concept[1] to develop the optics
  - Constant focal lengths for the lowest energy beam at any location
- Used ELEGANT to optimize individual quads for four beams at once
  - Doublet configuration found to give good control of beam sizes



[1]D. Douglas, JLab-TN-00-27 (2000).

Linac Layout

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

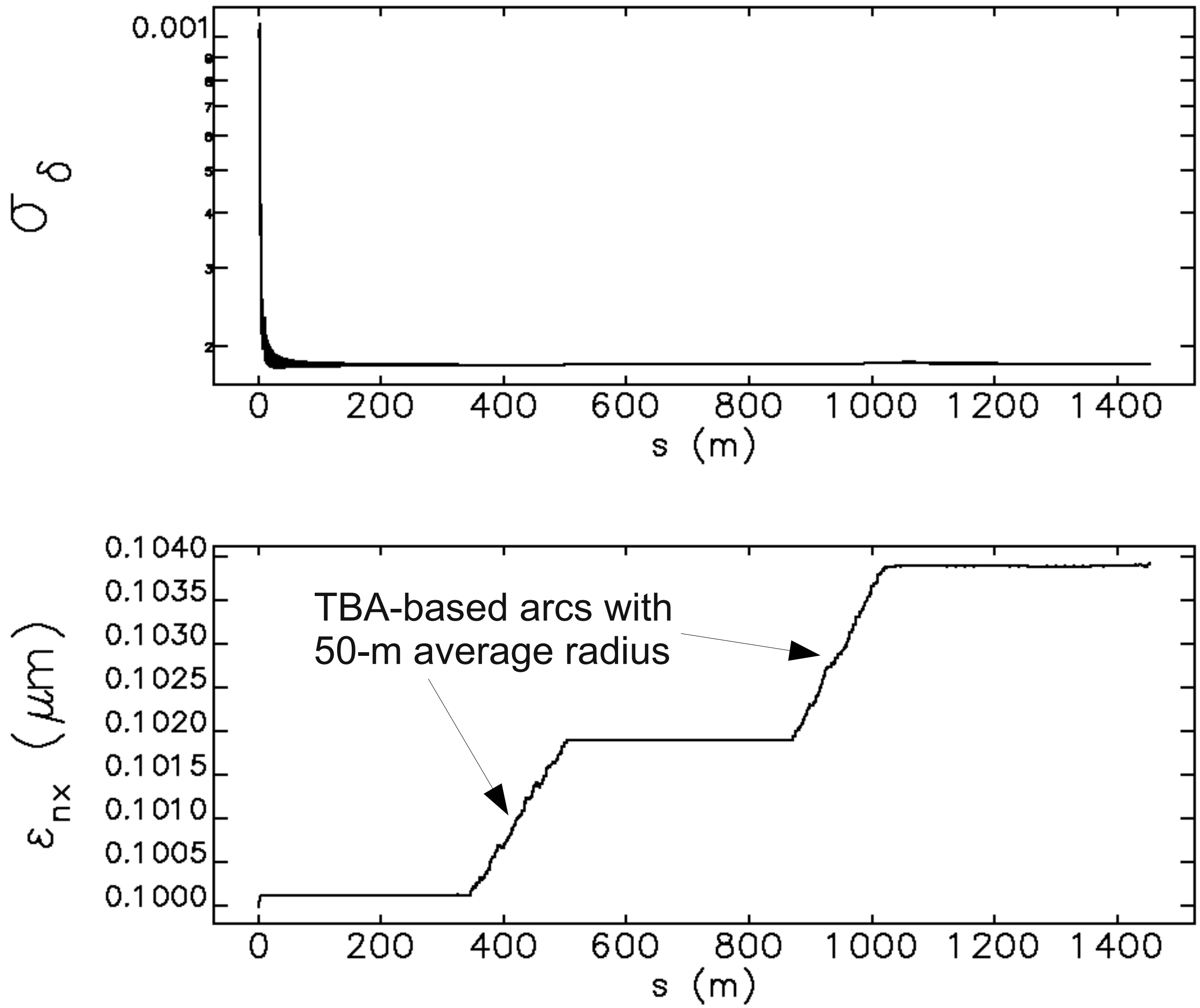


quad
doublet

8-cavity cryomodule (24 total)

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

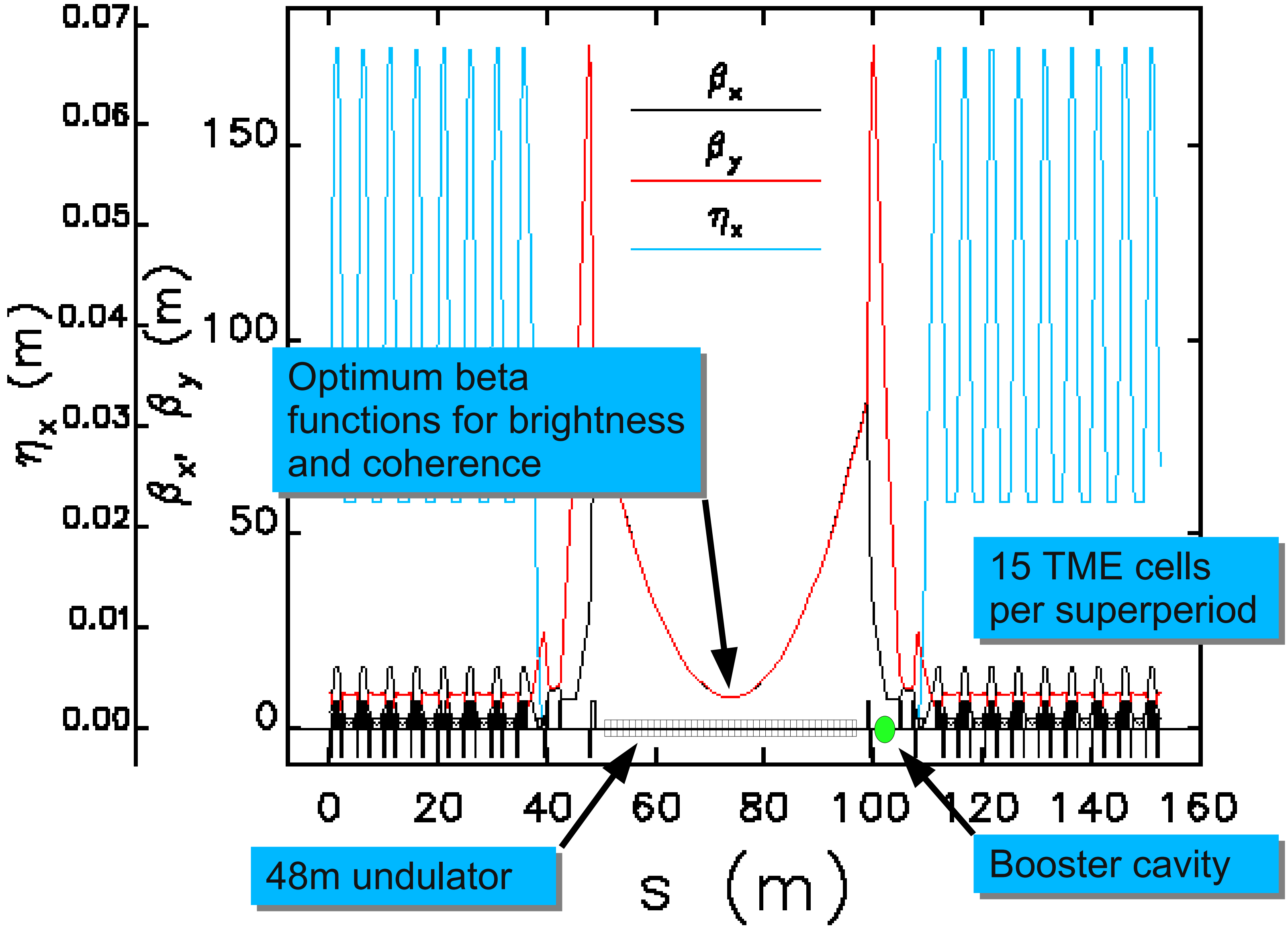
Beam Evolution Through the Linac (Acceleration)



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



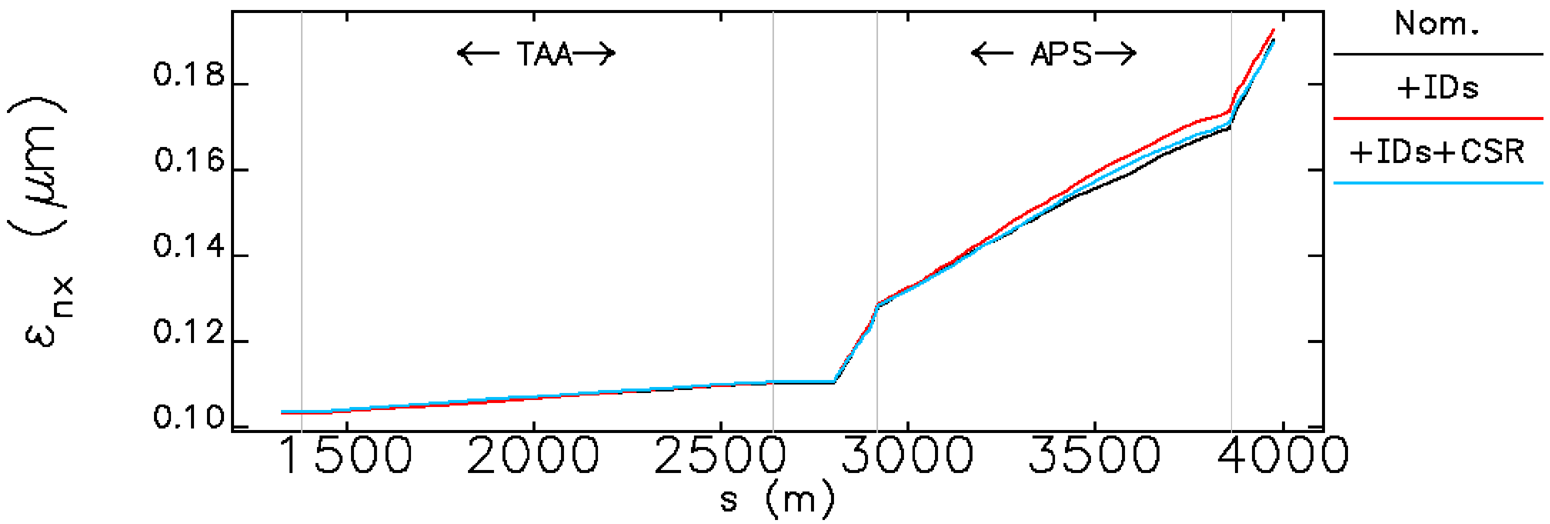
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
150
100
50
0
η_x (m)
β_x, β_y (m)
β_x
β_y
η_x
Optimum beta functions for brightness and coherence
15 TME cells per superperiod
0
20
40
60
80
100
120
140
160
s (m)
48m undulator
Booster cavity

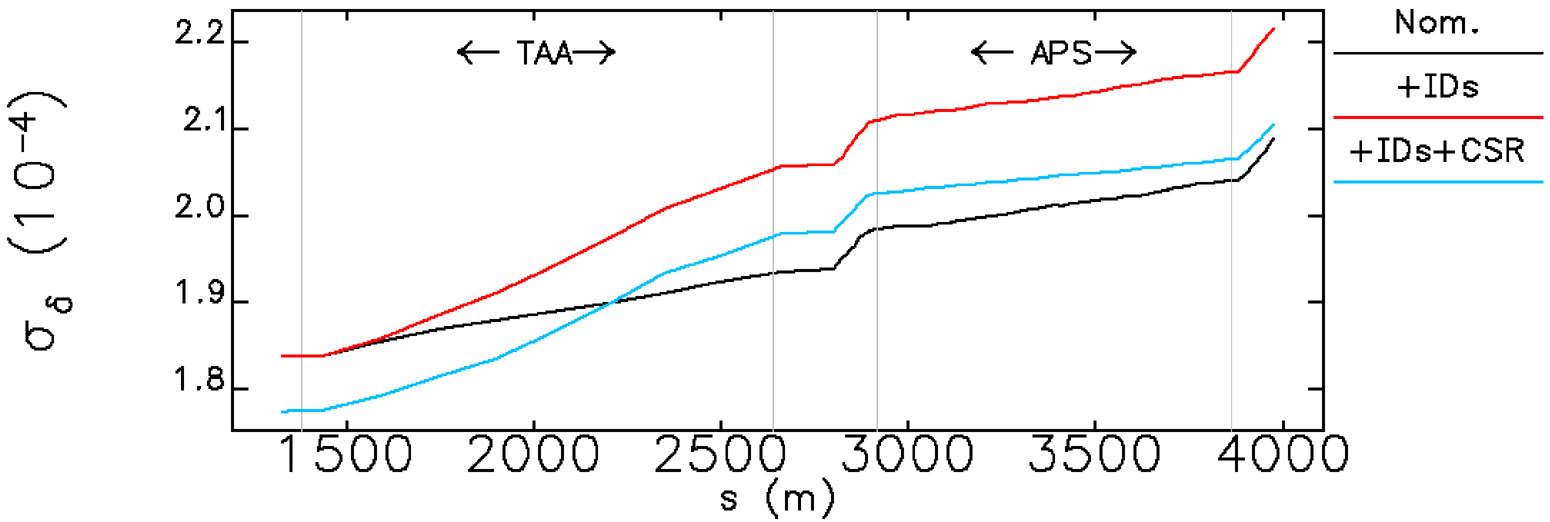
Need for Booster Cavities

- 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

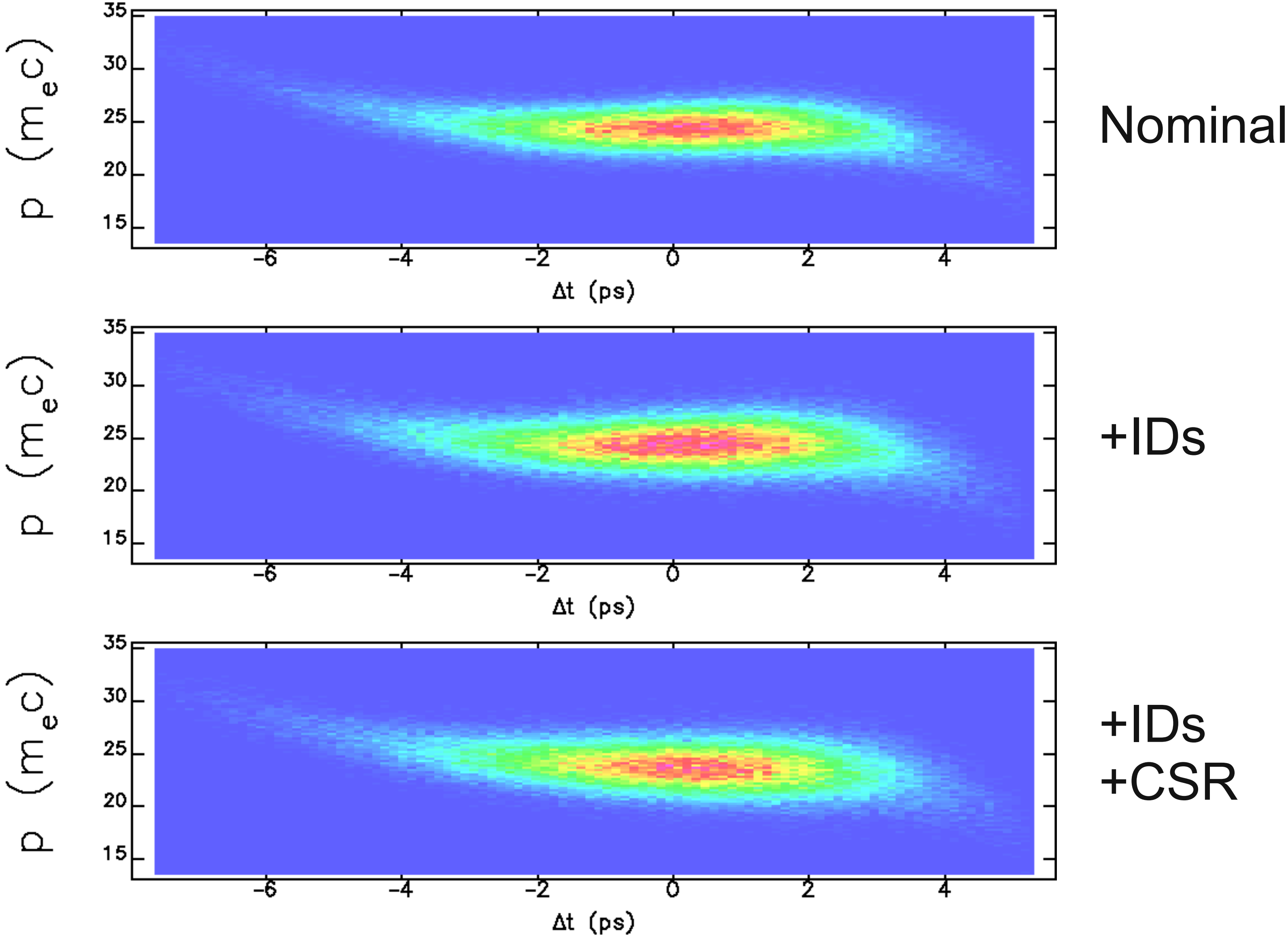
Undulator		Booster cavity		Number
Period mm	K max.	Voltage MV	Power kW	
18	0.45	0.11	2.7	1
23	1.20	0.46	11.6	1
27	1.78	0.74	18.5	2
30	2.20	0.92	22.9	1
33	2.74	1.18	29.4	2
35	3.08	1.32	33.0	1
55	4.97	1.39	34.8	1

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

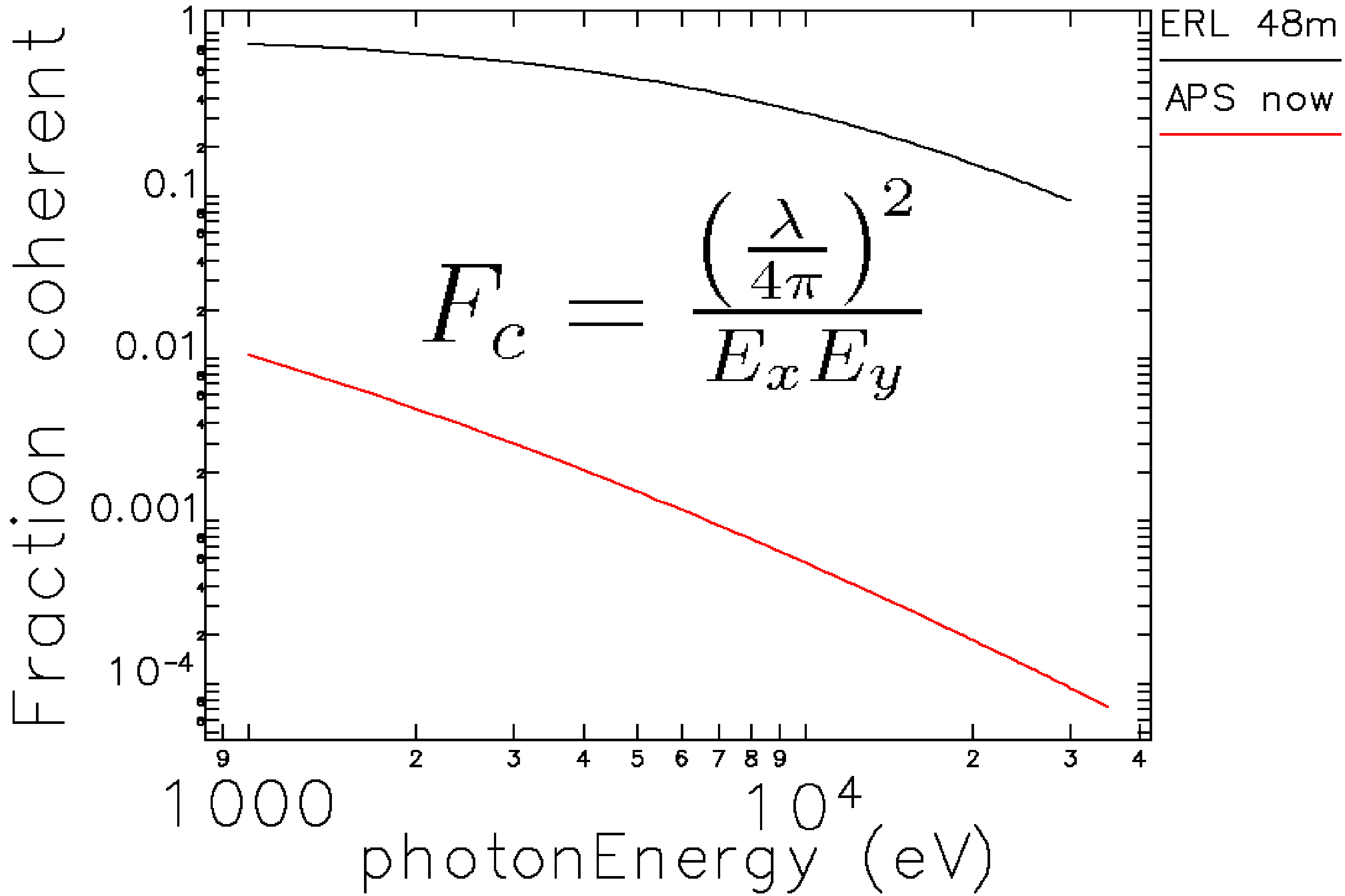




Final Longitudinal Phase Space

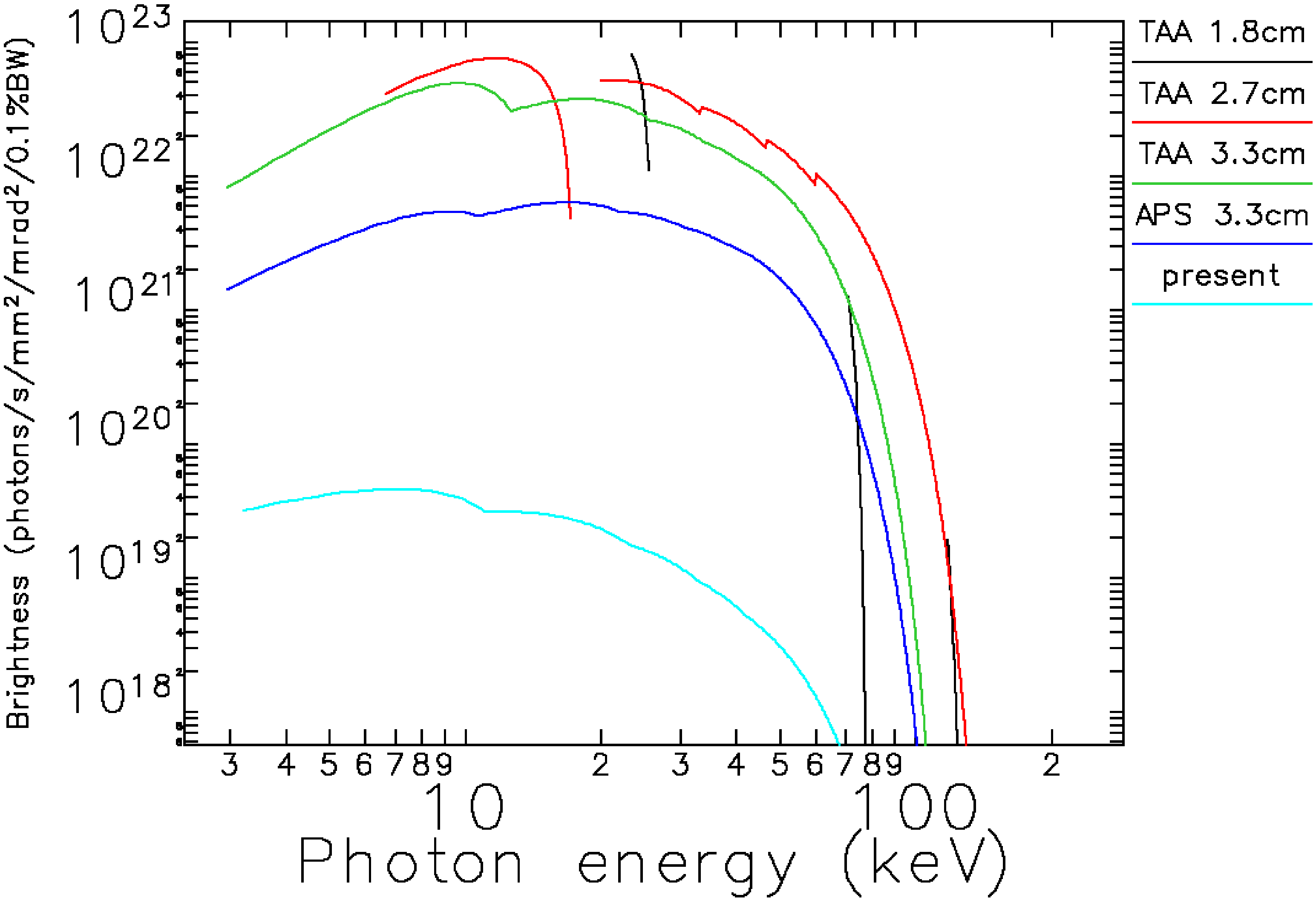


X-Ray Performance: Transverse Coherence



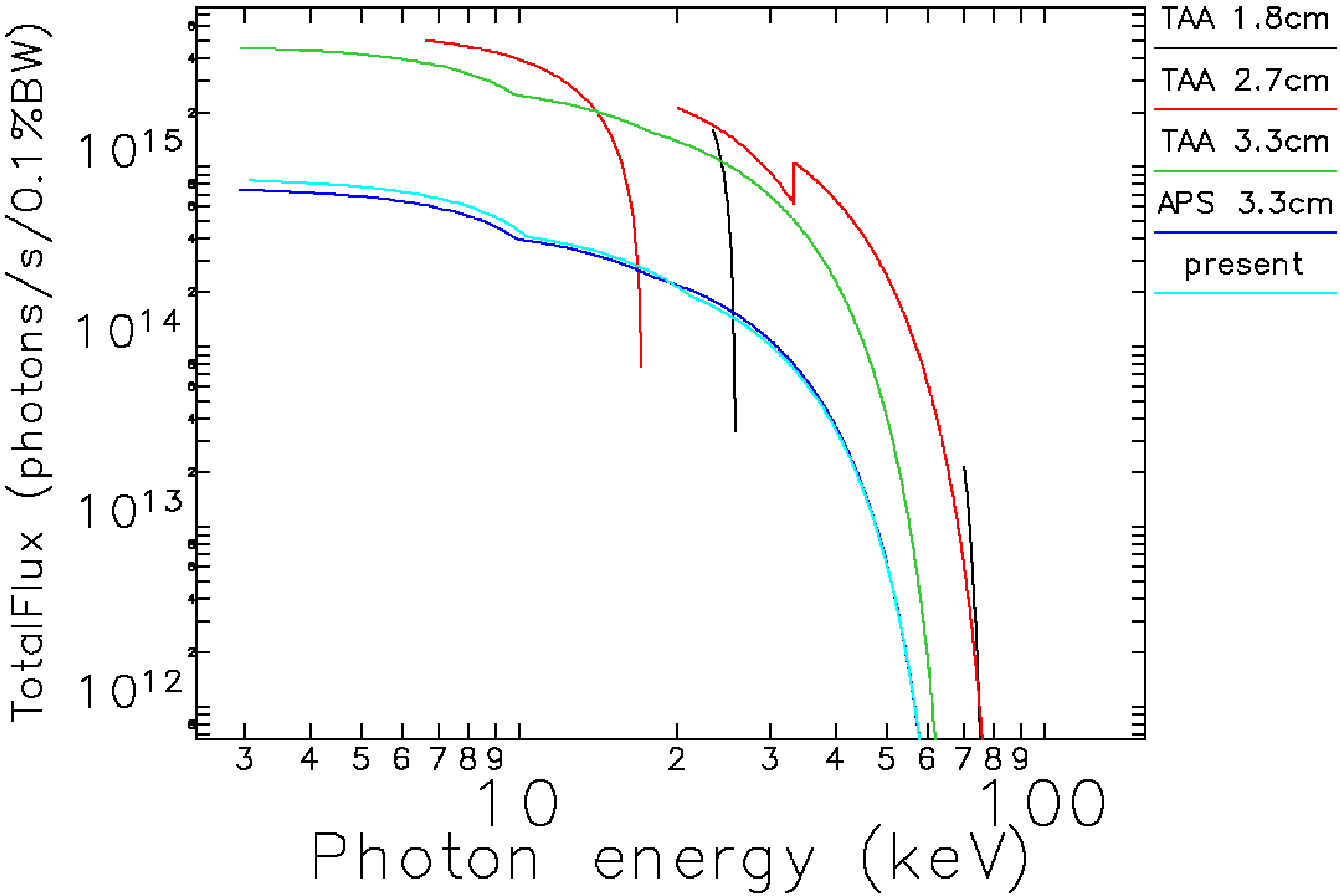
$$F_c = \frac{\left(\frac{\lambda}{4\pi}\right)^2}{E_x E_y}$$

X-ray Performance: Brightness



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

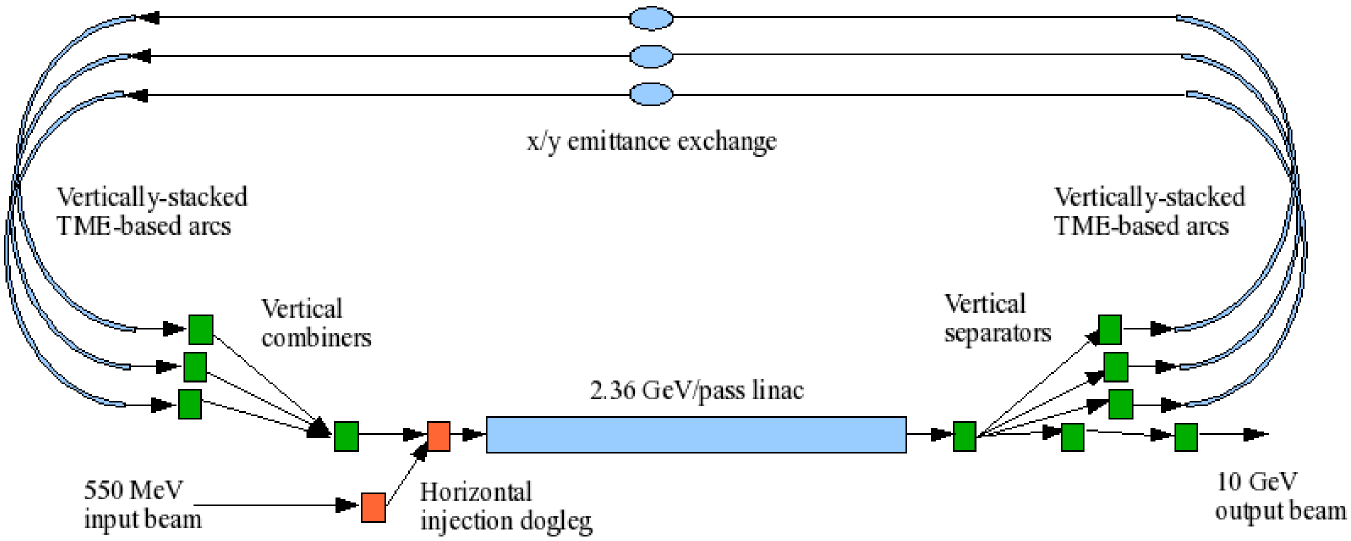
X-ray Performance: Flux



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

Other Options: XFEL-O[1]

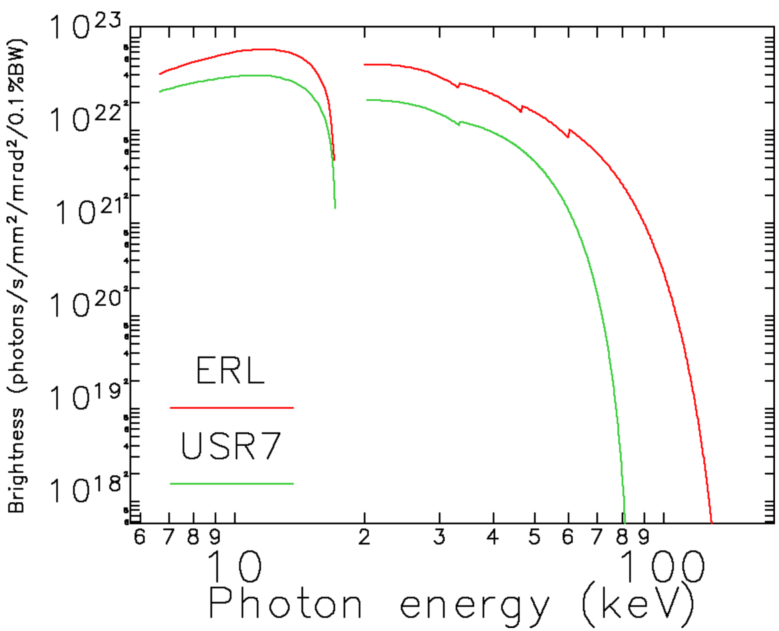
- X-ray FEL oscillator using x-ray crystals as mirrors
- Extremely high average brightness
- Fully coherent
- ERL-like beam requirements, but no recovery
- Serves fewer beamlines and less tunable than ERL
- See Ostroumov *et al.* (MO6RFP046), Lindberg *et al.* (TU5RFP049), Borland (TU5RFP048).

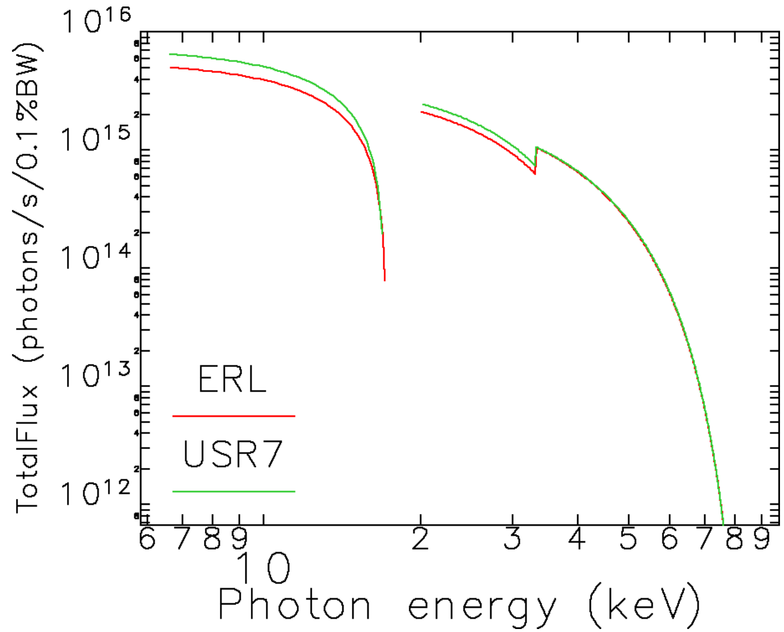


[1]K.-J. Kim *et al.*, PRL 100, 244802 (2008)

Other Options: USR7

- "Ultimate" storage rings (USRs) have been proposed several times[1,2,3]
- An APS design concept[4] approaches ERL performance
  - 7 GeV, 200 mA
  - 40 MBA[5] sectors, 3.1 km circumference, damping wigglers
  - Fully coupled beam, on-axis swap-out operation
  - Technology apparently not challenging





[1]A. Ropert *et al.*, EPAC2000, 83.
[2]M. Borland, NIM A 557 (2006) 230.
[3]K. Tusmaki *et al.*, NIM A 556 (2006) 394.
[4]M. Borland, LSU Grand Challenge Workshop.
[5]D. 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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