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An Exploration of Upgrade Options for the Advanced Photon Source

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U.S. DEPARTMENT OF ENERGY

Outline

- Rationale and goals for the upgrade
- Storage ring and ERL strengths and weaknesses
- Storage ring options
- ERL options
- Performance comparison
- Brief survey of ERL challenges.

Why Upgrade?

- There has been a massive investment in beamlines built up around the APS ring
- An increasing number of experiments could benefit from more than APS can presently deliver
- We are close to the end of what we can do to improve performance with the existing design
- If APS is not upgraded, it risks becoming obsolete
  - Planning and execution of such a project requires ~10 years...
  - Start now!

Goal for the Upgrade

- *Provide revolutionary new experimental capabilities for x-ray users*
- Accelerator changes can *potentially* support
  - Time-resolved studies requiring picosecond pulses
  - Higher flux
  - Higher brightness
  - Improved transverse coherence
  - Significantly longer straight sections
  - More beamlines
- We have investigated two major types of accelerator upgrades
  - Replacement storage ring
  - Energy recovery linac (ERL) injector
- Which is best depends on the x-ray science case and other factors.

Storage Ring Option

- Demonstrated strengths
  - High brightness (e.g., APS, ESRF, SPRing-8)
  - High current and flux (e.g., 1 A is not out of the question)
  - Stable and reliable
  - Well known technology
  - Safety issues well understood and controlled
  - Relatively inexpensive
- Known weaknesses
  - Difficult to be revolutionary:
    - *Difficult to make short bunches (e.g., <10 ps)*
    - *Difficult to get ultra-low emittance (e.g., < 1nm)*
    - *Hard to support sector-by-sector beam customization*
    - *Can't have ultra-low energy spread (e.g., <0.1%)*
  - Long dark time for installation (e.g., 1 year).

ERL Option

- Projected strengths
  - Ultra-high brightness
  - Short pulses (e.g., 1~2 ps rms)
  - Option for ultrashort pulses (e.g., 100 fs rms)
  - "No" dark time required for installation
- Known weaknesses
  - All strengths are *projected*, particularly
    - *Low emittance*
    - *Ultrashort pulses*
  - Difficult to achieve high average current
  - Multiple incompatible operating modes for different user communities
  - Operating reliability unlikely to be as high as ring
  - Very expensive.

Storage Ring Design Challenges

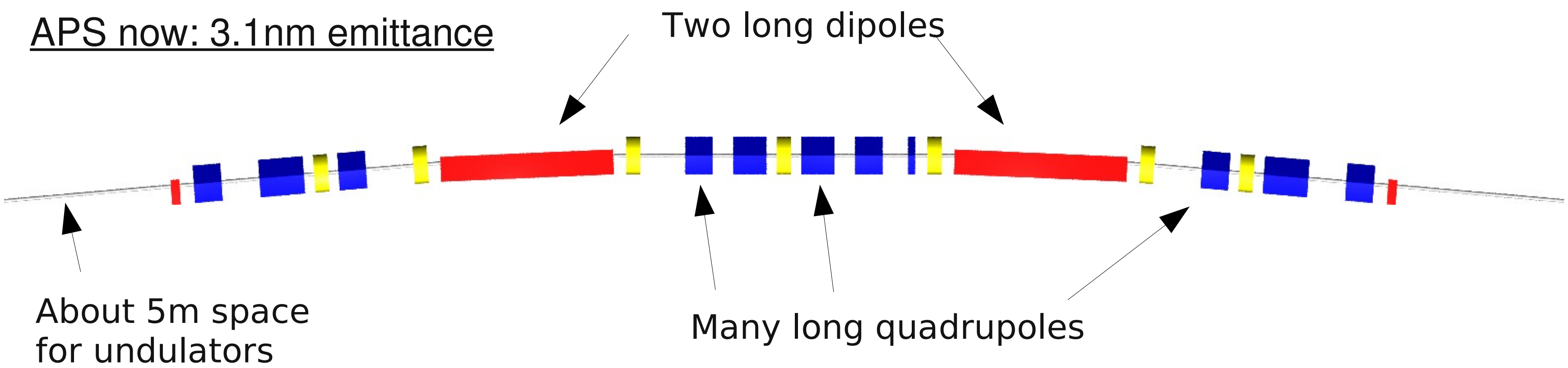
- For fixed-size ring, reduction of emittance requires strong focusing
  - This makes for strong chromatic aberrations and therefore strong sextupoles
  - These cause reduction of the transverse injection aperture
- Sextupoles and quadrupoles become difficult to build
  - Want them to be shorter, generally
  - Need them to have higher integrated strength
  - Forces us to smaller gaps
  - Makes alignment tolerances much tighter.

Storage Ring Design Challenges

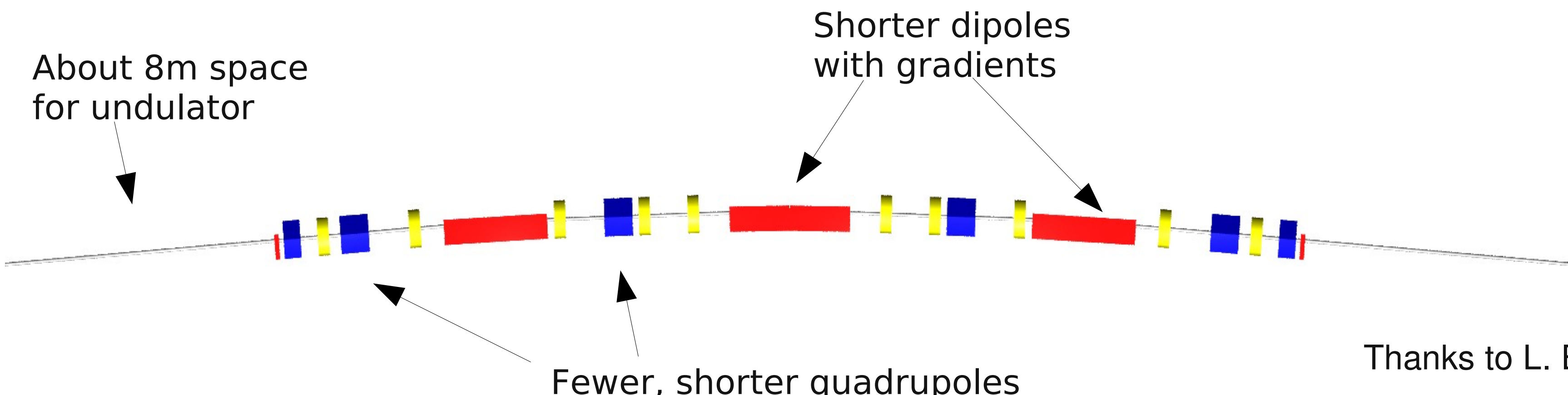
- Collective instabilities
  - Smaller magnet gaps mean smaller vacuum chambers
  - Beam interacts with itself through the vacuum chamber
    - *Geometric wakes caused by changes in VC cross section should be reduced*
    - *Resistive wakes caused by proximity of VC walls will increase*
- Lifetime
  - Primary concern is Touschek scattering
    - *APS lifetime already Touschek-dominated*
    - *Gets worse as emittance is reduced*
  - Gets worse if the momentum acceptance is lower
    - *Often happens whenever sextupoles are strong.*
  - Short lifetime means frequent top-up, radiation damage.

Triple-Bend Ring Design (APS1nm)

APS now: 3.1nm emittance

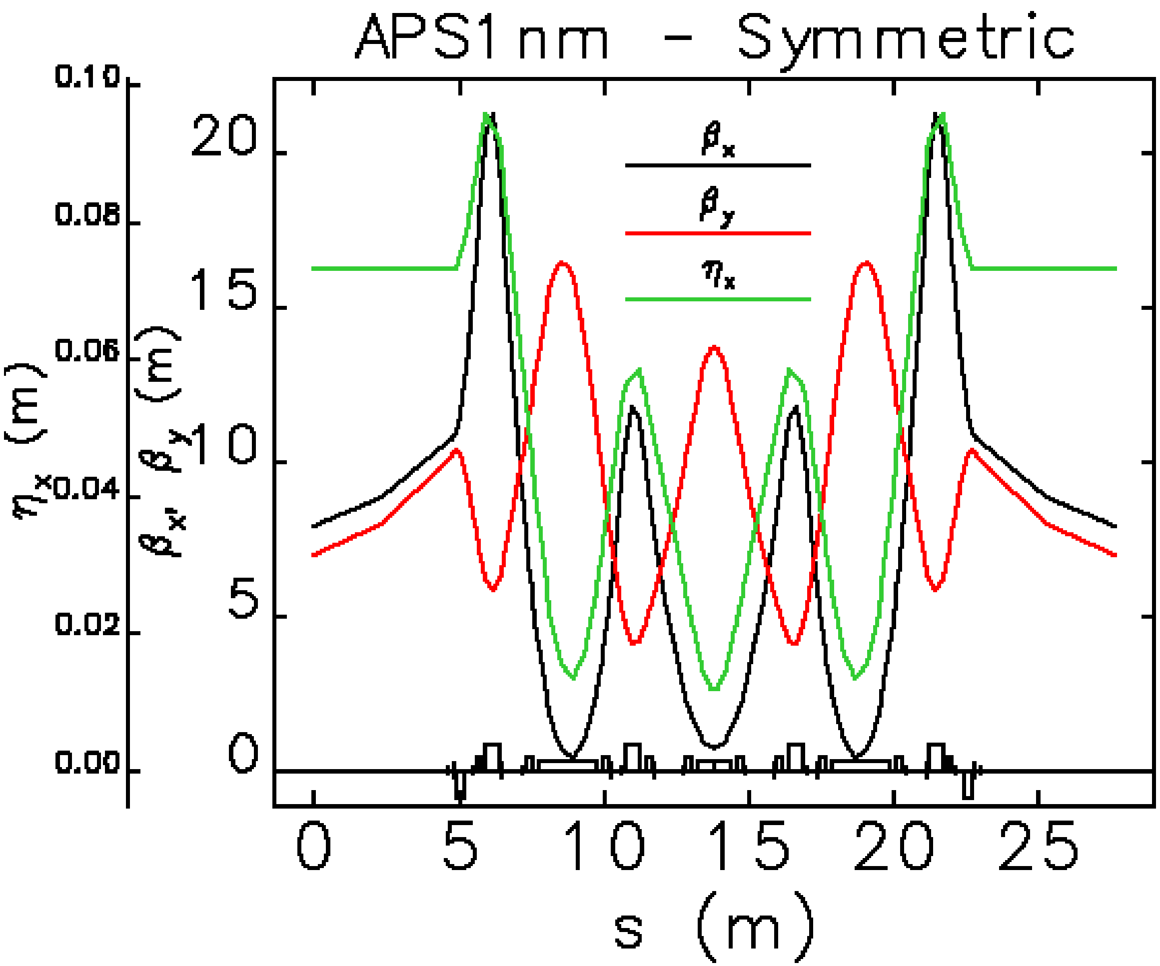


"APS 1nm": 1nm emittance



Thanks to L. Emery
for help with figures.

Symmetric Lattice – Optical Function



- Longer straight section ~8m for IDs
  - 4.8m max for APS now
- 0.9 nm effective emittance
  - Combined function dipoles
  - Stronger focusing

From A. Xiao, M. Borland, "APS 1nm Lattice," MAC Review, 11/15/06.

General Parameters of APS 1nm

	APS 1nm	APS
Energy (GeV)	7	7
Effective emittance (nm rad)	0.89	3.1
Betatron tune X	57.3	36.2
Betatron tune Y	21.4	19.26
Chromaticity X	-127	-92
Chromaticity Y	-45	-45
Energy spread	1.16×10^{-3}	0.96×10^{-3}
Energy loss per turn (MeV)	6.5	5.4
Momentum compaction	1.04×10^{-4}	2.81×10^{-4}

From A. Xiao, M. Borland, "APS 1nm Lattice," MAC Review, 11/15/06.

Magnets are Challenging but not Impossible

Table 2: Combined-function Bending Magnet Strength for APS1nm Lattice

Bend

			APS1nm - Sym.	APS1nm - Lowβ
Name	$L[m]$	$Angle[rad]$	$K1[m^{-2}]$	$K1[m^{-2}]$
B0	2	0.061	-0.277	-0.268
B1	1.132	0.035	-0.372	-0.384

Hard to get sufficient good field region

Table 3: Quadrupole Strength for APS1nm Lattice

Quadrupole

		APS1nm - Sym.	APS1nm - Lowβ		
			Normal	Type-A	Type-B
Name	$L[m]$	$K1[m^{-2}]$	$K1[m^{-2}]$	$K1[m^{-2}]$	$K1[m^{-2}]$
QI1	0.3	-1.185	-1.199	-1.612	-1.023
QI2	0.5	1.413	1.419	1.633	1.463
QDF	0.5	1.698	1.702	1.659	1.675

Magnet design gives 2.35

Table 4: Sextupole Strength for APS1nm Lattice

Sextupole

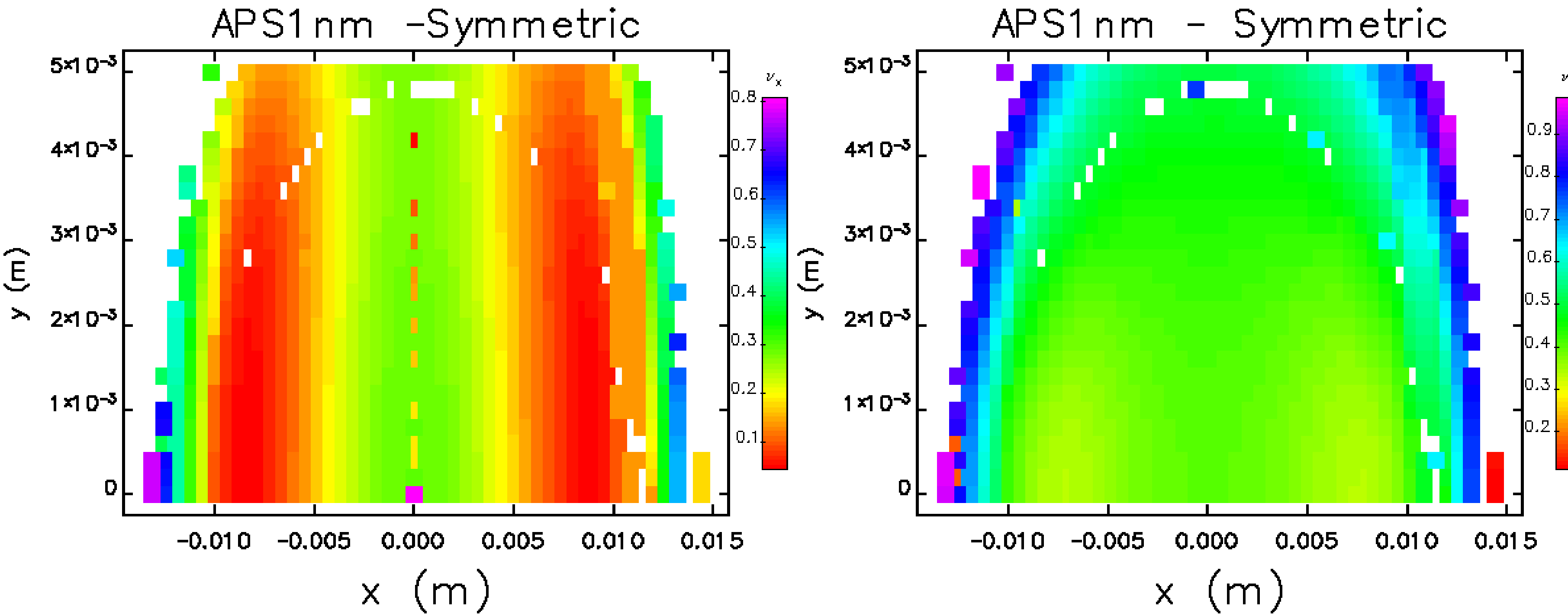
		APS1nm - Sym.	APS1nm - Lowβ		
			Normal	Type-A	Type-B
Name	$L[m]$	$K2[m^{-3}]$	$K2[m^{-3}]$	$K2[m^{-3}]$	$K2[m^{-3}]$
S1	0.2	56.8	71.0	66.5	47.3
S2	0.2	-101.8	-121.2	-93.3	-65.1
SD	0.2	-85.0	-89.4	-84.4	-99.0
SE	0.2	-98.2	-100.1	-51.4	-90.9
SF	0.2	136.8	132.5	87.9	130.0

Magnet design gives 175

From A. Xiao, M. Borland, "APS 1nm Lattice," MAC Review, 11/15/06.

APS 1nm Optimization

- Dynamic aperture optimized using geneticOptimizer[1]
  - Tunes, plus sextupole strength and positions are varied
  - Track many particles with dynamic aperture distribution and maximize the number that survive 50~100 turns
  - Include small errors to drive resonances
- Resulting 500-turn dynamic aperture is larger than ±10mm

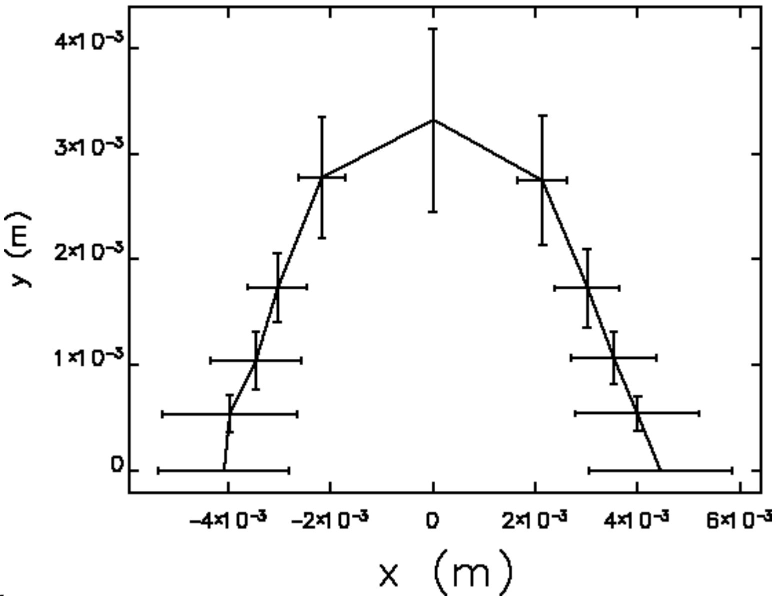


Adapted from A. Xiao, M. Borland, “APS 1nm Lattice,” MAC Review, 11/15/06.

[1] M. Borland

Performance with Errors

- Ran 50 seeds with full set of errors
  - Multipole errors (same as ILC DR)
  - Rms alignment: 100 μm, 0.1 mrad
  - Rms strength errors: 0.01%
- One-pass trajectory corrected first to get stored beam
- Tune and chromaticity corrected to design value by 2 sets of quadrupoles and sextupoles
- RMS beta beating is ~15% horizontal, ~30% vertical
- Dynamic aperture is sufficient to allow storing beam for lattice correction
  - Should get few % beta beats[1] and good dynamic/momentum aperture.



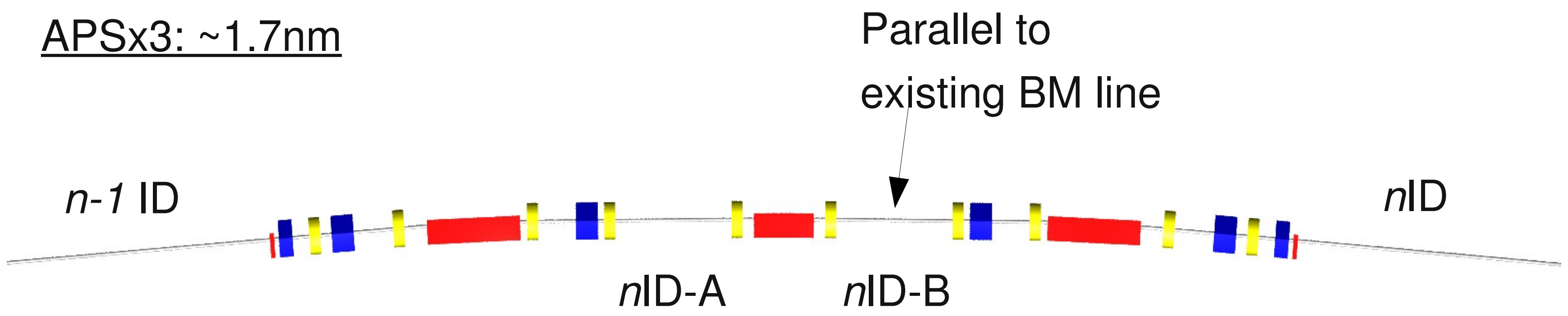
Adapted from A. Xiao, M. Borland, "APS 1nm Lattice," MAC Review, 11/15/06.

[1]V. Sajaev and L. Emery, EPAC 2002, p 742.

Another Option: APSx3[1]

- This is an evolution of the 1nm lattice
- Offers three times as many ID beamlines
- Could provide a three-pole wiggler for beamlines that still want bending-magnet-like source
- Acceptable dynamic/momentum aperture achieved[1]

<u>APSx3: ~1.7nm</u>

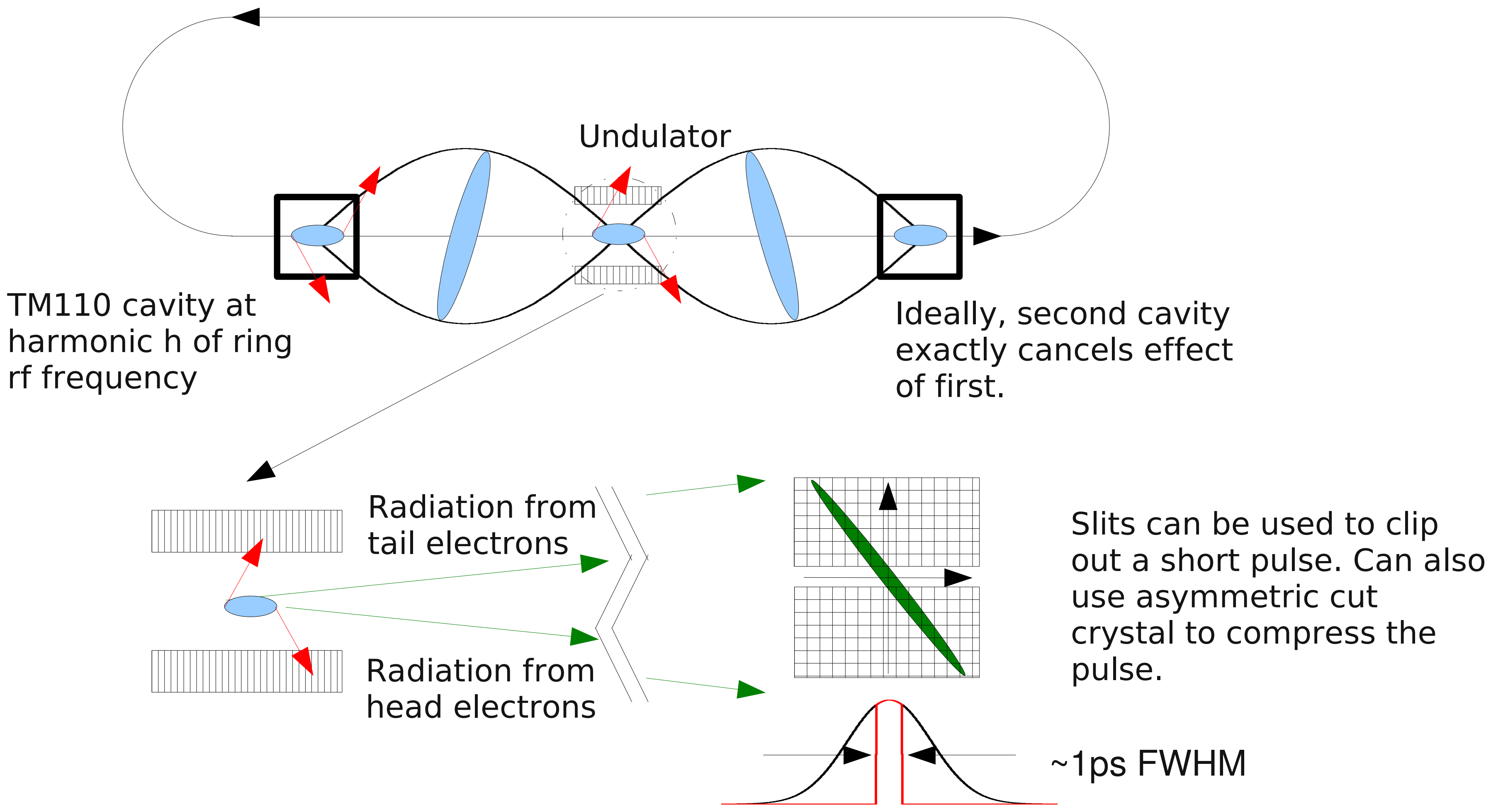


2.1m magnet-to-magnet
in new straight sections.

Thanks to L. Emery
for help with figures.`

[1]V. Sajaev, M. Borland, “APSx3 Lattice Design,” MAC Review, 11/15/06.

Short Pulses from a Storage Ring: Zholents' Concept



A. Zholents,et al,, Nucl. Instrum. Methods Phys. Res., Sect. A 425, 385 (1999)

See also, A. Zholents' talk at 2004 APS Strategic Planning meeting.

Pulsed vs. CW Cavities

- Zholents' concept was based on CW superconducting cavities
  - These have a long development time
  - Big footprint makes choice of location difficult
- A. Nassiri came up with "ultra fast-track" approach using
  - Pulsed-cavity approach[1,2]
  - 3 or 4 room-temperature cavities in one straight
  - Mostly existing rf hardware
  - Initial operation at 120 Hz, later at 1 kHz
- Cavity design in progress by V. Dolgashev (SLAC) and APS
  - 9-cell S-band cavities have ~0.5 m insertion length
  - Single bunch current limit[3] reduced 1~2 mA (10~20%)
  - Multibunch instabilities manageable[4] with mode de-Qing
- CW approach being pursued in parallel for future upgrade.

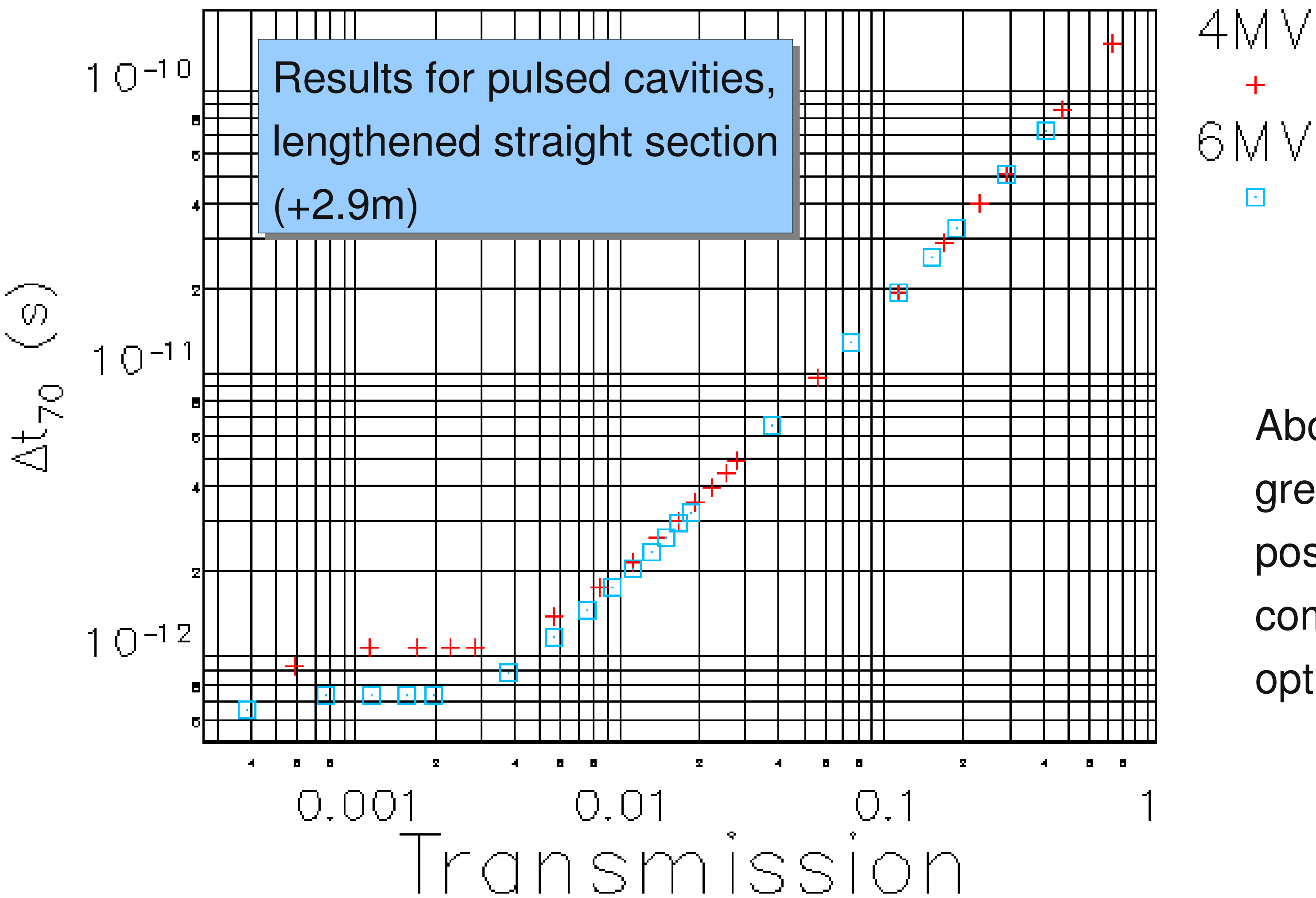
[1]P. Anfinrud, private communication.

[2]M. Borland, OAG-TN-2005-013, 6/16/06.

[3]Y-C Chae, private communication.

[4]L. Emery, private communication.

Expected Performance without Compression Optics[1]



About 10x greater intensity possible with compression optics.[2]

[1]M. Borland, OAG-TN-2006-049, 10/13/06.

[2]K. Harkay et al., PAC 2005, p 668.

Storage Ring Summary

- With APS 1nm lattice:
  - Would decrease the emittance 3-fold
  - 8 m undulators instead of 4.8
  - Would increase the beam current from 100 to 200 mA
  - Brightness will increase 1 order of magnitude
- We can also produce ~ 1 ps pulses for selected beamlines, with 1 to 10% of normal intensity
  - No significant impact on other users
- Would require a 1 year shutdown to replace the ring[1]
- We may need to replace the booster as well[2,3].

[1] J. Noonan, private communication.

[2] V. Sajaev, M. Borland, “APSx3 Lattice Design,” MAC Review, 11/15/06.

[3] N. Sereno, “Booster Upgrade Requirements and Possibilities,” MAC Review, 11/15/06.

Why Pursue a Linac-Based X-ray Source?

- For a high-energy source, it is very hard to increase storage ring brightness

$$B \propto \frac{I}{\epsilon_x \epsilon_y}$$

$$\epsilon_x \propto \frac{E^2}{\rho \nu_x^3}$$

Bending radius

Frequency of restoring force

- For a linac, the scaling is quite favorable

$$\epsilon_x \propto \frac{1}{E}$$

- Also, in a linac the energy spread is small and constant, whereas in a ring

$$\frac{\sigma_E}{E} \propto \frac{E}{\sqrt{\rho}}$$

See M. Sands, SLAC-121 for background.

Cornell ERL Parameters[1] Scaled to 7 GeV

	APS now	ERL High flux	ERL High coherence	ERL Ultrashort pulse
Average current (mA)	100	100	25	1
Repetition rate (MHz)	0.3~352	1300	1300	1
Bunch charge (nC)	0.3~60	0.077	0.019	1
Emittance (nm)	3.1 x 0.025	0.022 x 0.022	0.006 x 0.006	0.37 x 0.37
Rms bunch length (ps)	20 ~ 70	2	2	0.1
Rms momentum spread (%)	0.1	0.02	0.02	0.3

- Promise of very high brightness
  - Extremely low emittance, equal in both planes
  - Very low energy spread
  - Current from 25 to 100 mA
  - Picosecond pulses
- Option for less current with high charge, femtosecond pulses.

[1]G. Hoffstaetter, FLS 2006 Workshop, DESY.

An "Infield" Option (Sereno)[1,2]

- Advantages
  - No impact on external environment
  - Multi-pass linac shorter, cheaper
  - Recirculation feature for commissioning
- Disadvantages
  - Complex, crowded beam optics
  - Somewhat higher emittance growth expected[3]
  - No major expansion of beamlines

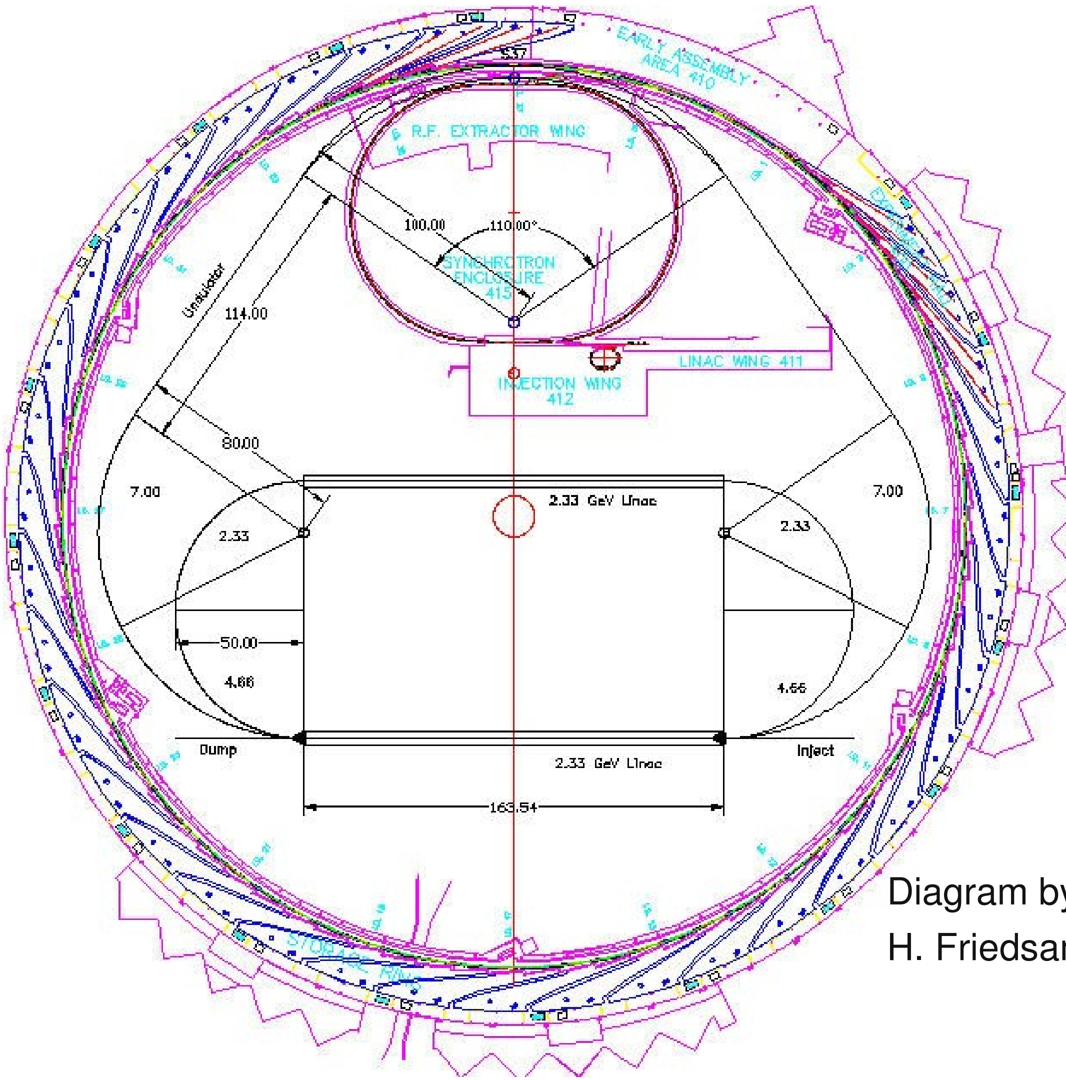


Diagram by H. Friedsam

[1]N. Sereno, "Infield ERL Option," 10/19/06.

[2]Evolved from suggestions by Y. Cho, D. Douglas, R. Gerig, M. White.

[3]V. Sajaev, ASD/APG/2006-20, 8/20/06.

An "Outfield" ERL Option (G. Decker[1])

- Advantages:
  - Linac points away from APS[2] to give straight-ahead short-pulse facility[3]
  - Beam goes first into new, emittance-preserving turn-around arc[4]
    - *Potential for many new beamlines*
  - Avoids wetlands etc. by using narrow corridor for linac and return line
- Issues:
  - Big, expensive
  - North turn-around should be *larger* than shown
  - Requires some changes to ring
  - No space for long undulators

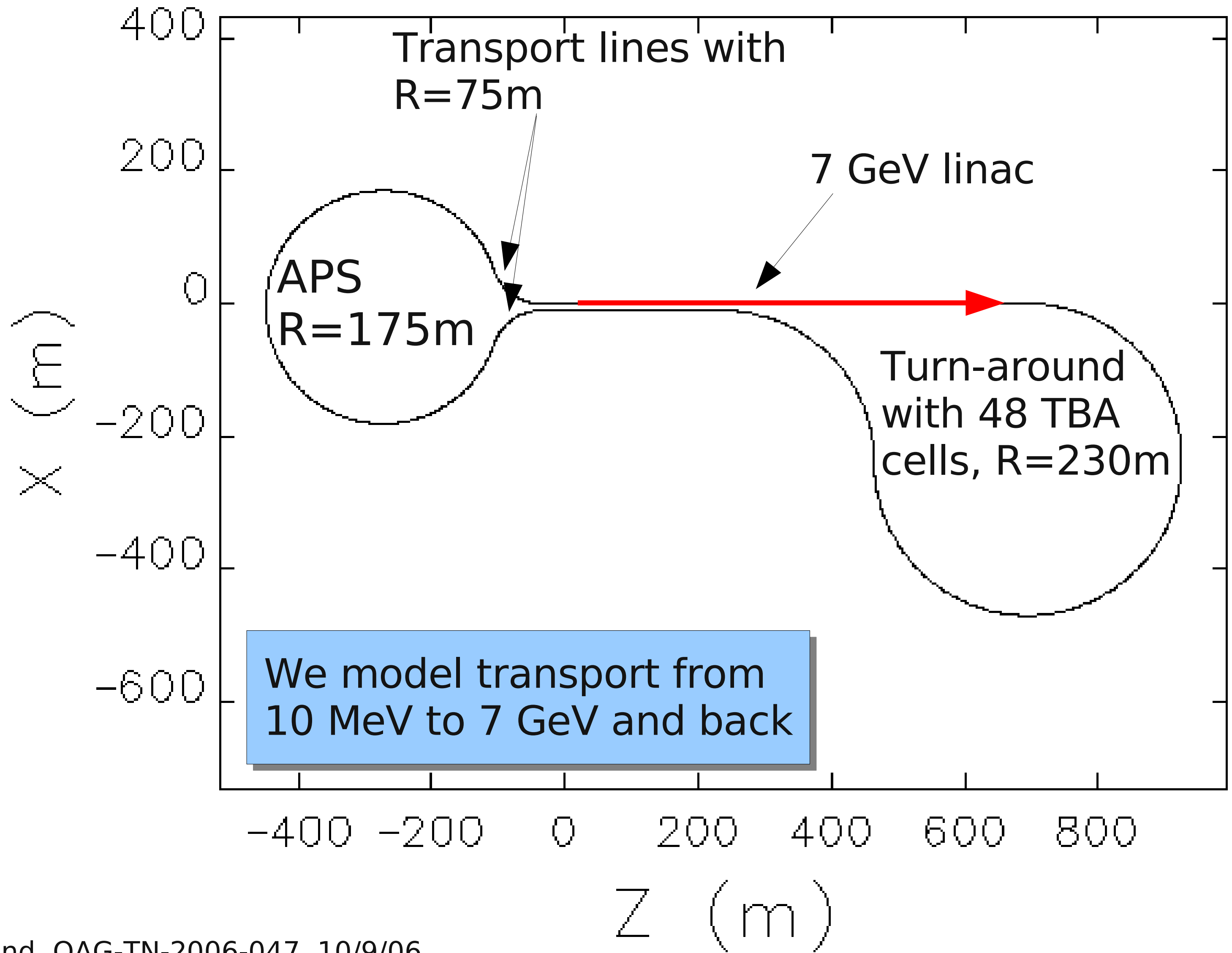
[1]G. Decker,OAG-TN-2006-058, 9/30/06.

[2]M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.

[3]M. Borland, "Can APS Compete with the Next Generation?", May 2002.

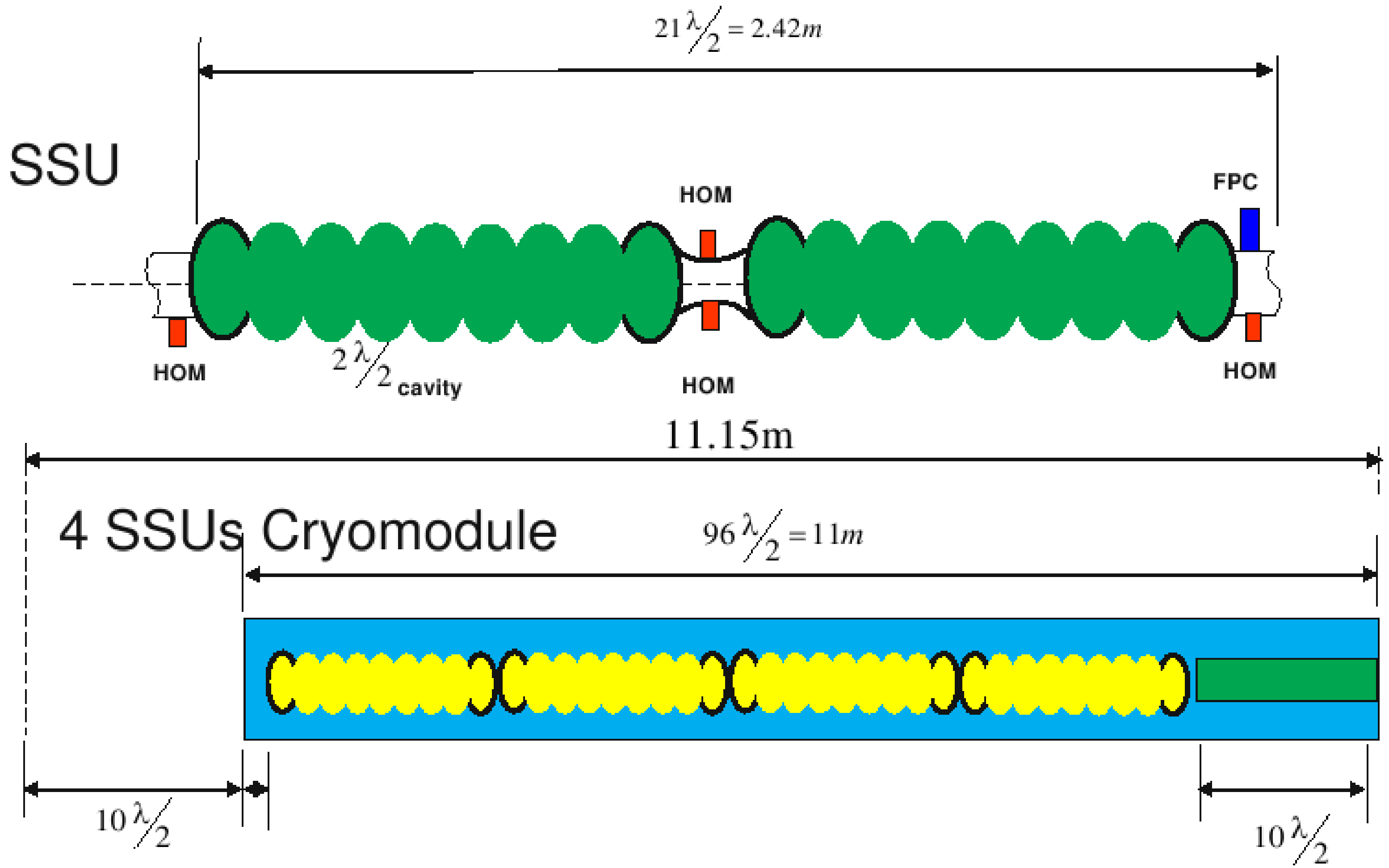
[4]M. Borland, OAG-TN-2006-031, 8/16/06.

Realization of Decker's Outfield ERL Concept[1]



[1]M. Borland, OAG-TN-2006-047, 10/9/06.

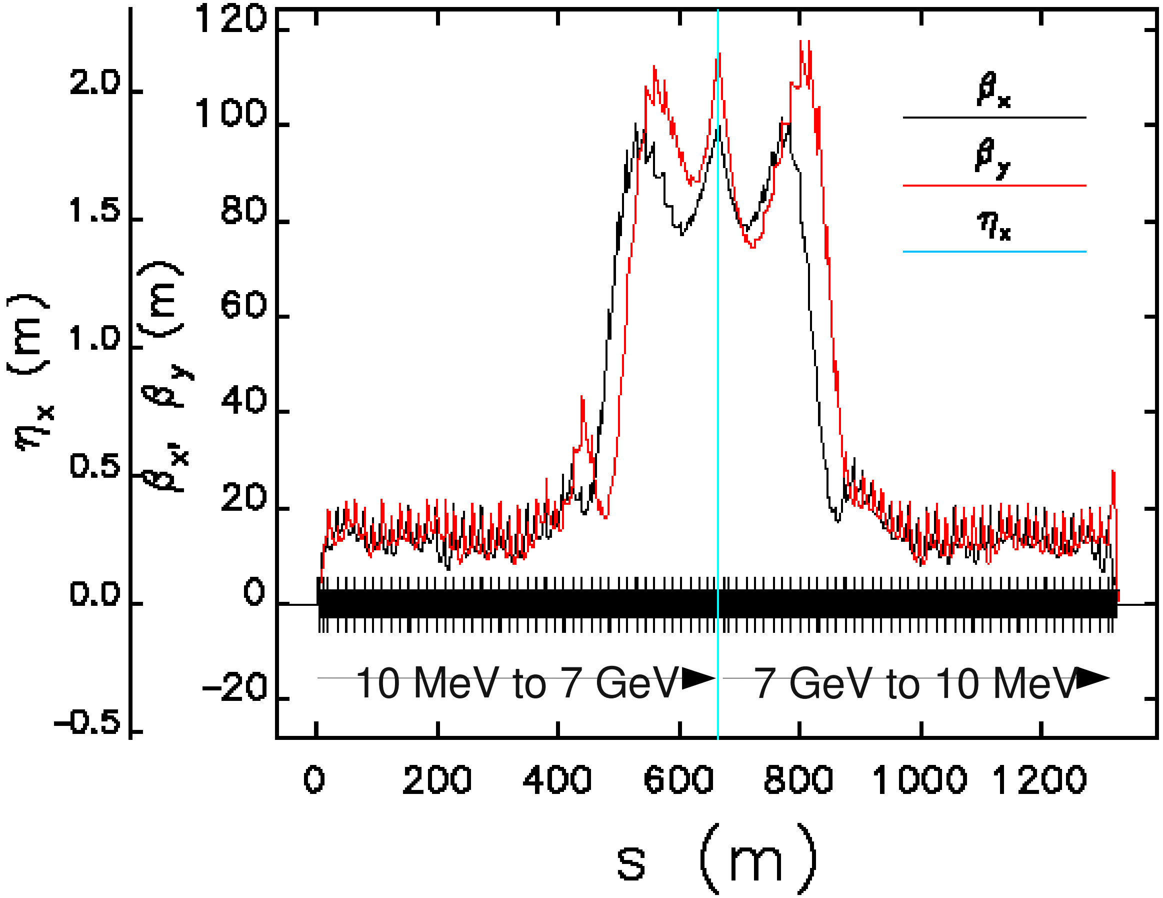
Rough APS ERL Linac Configuration[1]



~45 cryomodules are needed for a one-pass 7 GeV linac.

[1]A.Nassiri, “Overview of Superconducting Linacs,” 8/11/06.

Linac Design for 7 GeV ERL



- Inject at 10 MeV
- Start with graded gradient[1] doublet optics
- Optimize using elegant to further reduce maximum beta functions[2]
- Use Nassiri's configuration
  - 352 cavities
  - 20 MV/m
- Cavity filling factor 0.52
- 92 quadrupoles

[1]D. Douglas, JLAB-TN-00-027, 11/13/00.

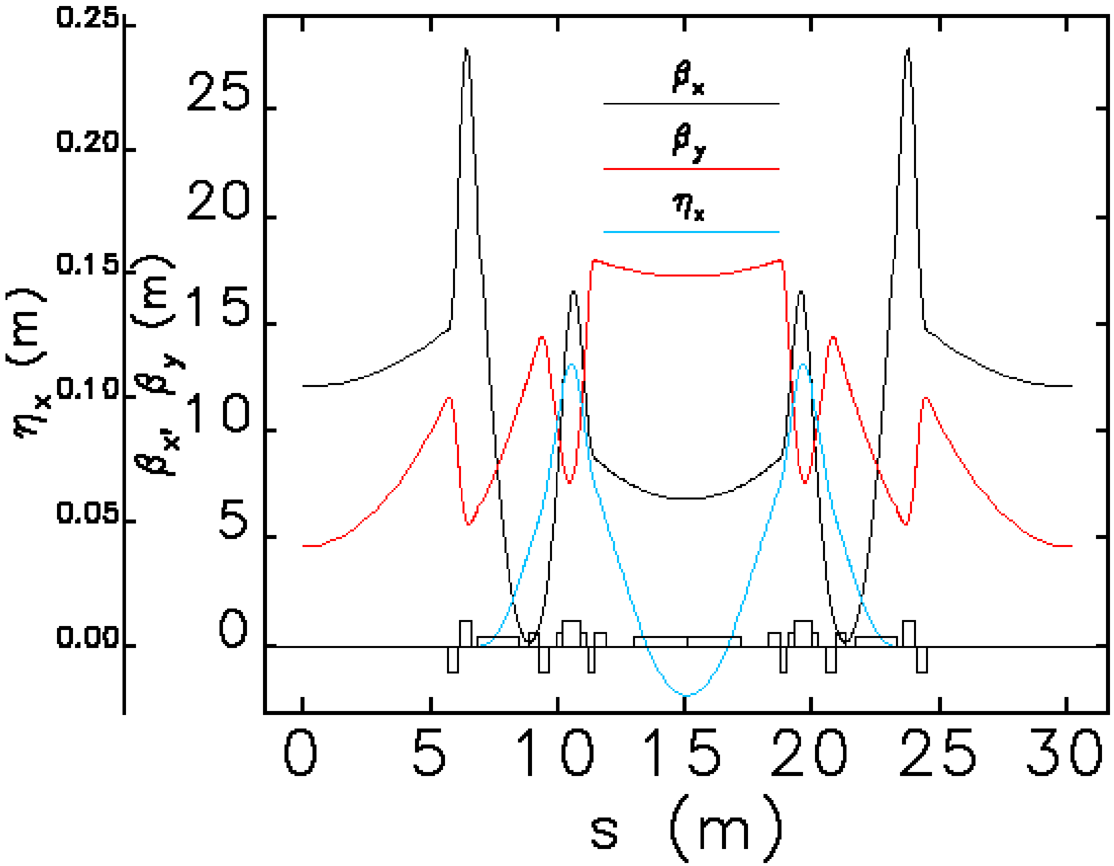
[2]M. Borland, OAG-TN-2006-041, 9/17/06.

Emittance-Preserving Arc Designs for ERLs

- Linac may produce very low emittance, but we have to deliver it to many users through
  - Turn-around arc
  - Injection transport line
  - APS ring itself
- Emittance can be degraded by (among others)
  - ISR: Incoherent synchrotron radiation (randomness of photon emission)
  - CSR: Coherent synchrotron radiation
- Emittance preservation is similar to low-emittance storage ring design
  - Gentle bending and strong focusing
- CSR control requires isochronous design as well[1]
  - Rigid bunch shape and judicious phase advance result in CSR cancellation.

[1] J. Wu et al, Proc 2001 PAC; G. Bassi et al, NIM A 557 (2005).

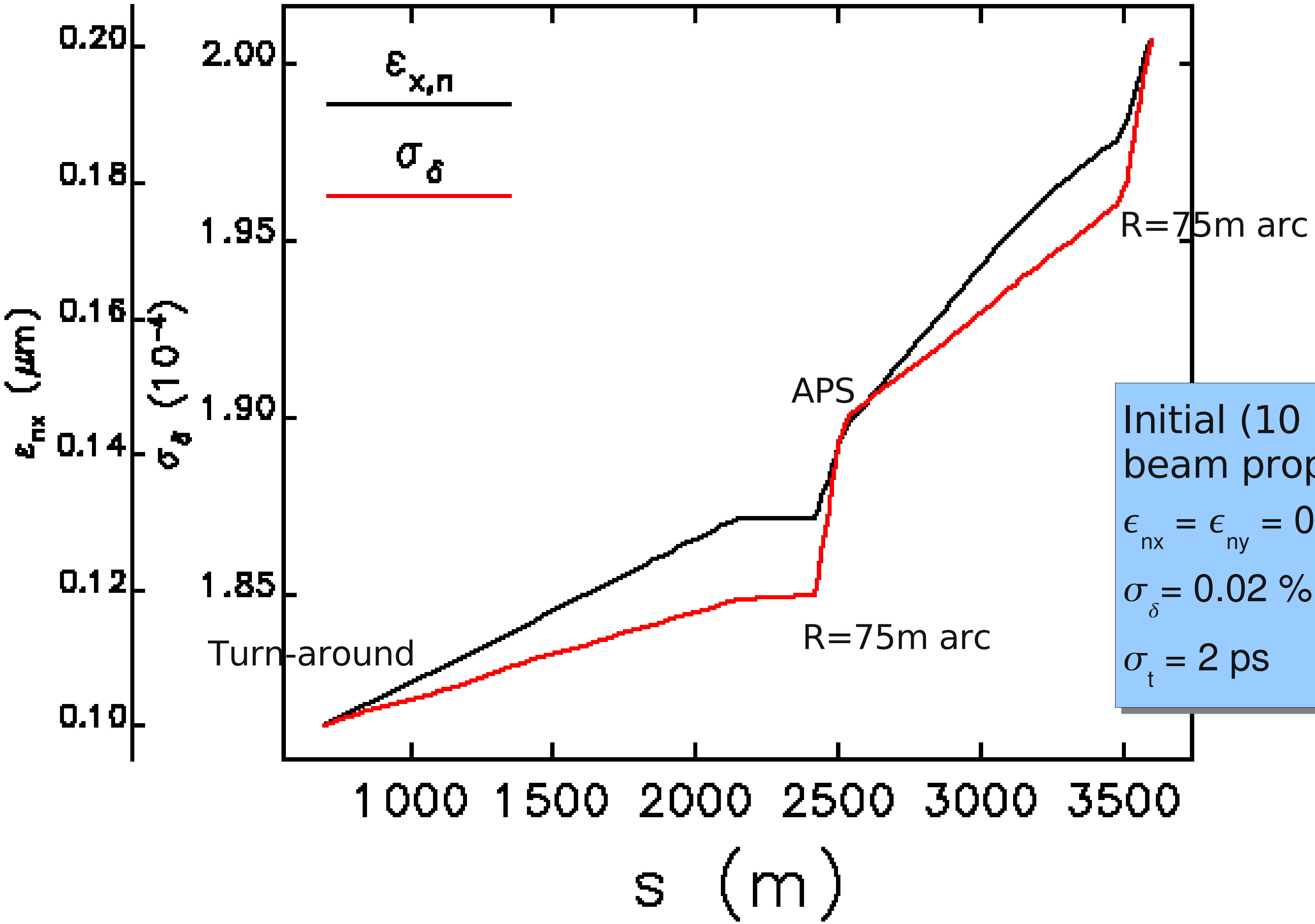
Arc Design for Turn-Around [1]



- 10 m straights for eventual new beamlines
- Average radius 230m
- Isochronous, achromatic triplet-bend cells
- $\Delta\nu_x$=1.25 per cell
- Excellent emittance preservation
- Four sextupole families for beam loss control

[1]M. Borland, “Comparison of ERL Options and Greenfield ERL,” MAC Review, 11/15/06.

Outfield ERL Tracking Results without CSR (7 GeV Portion)



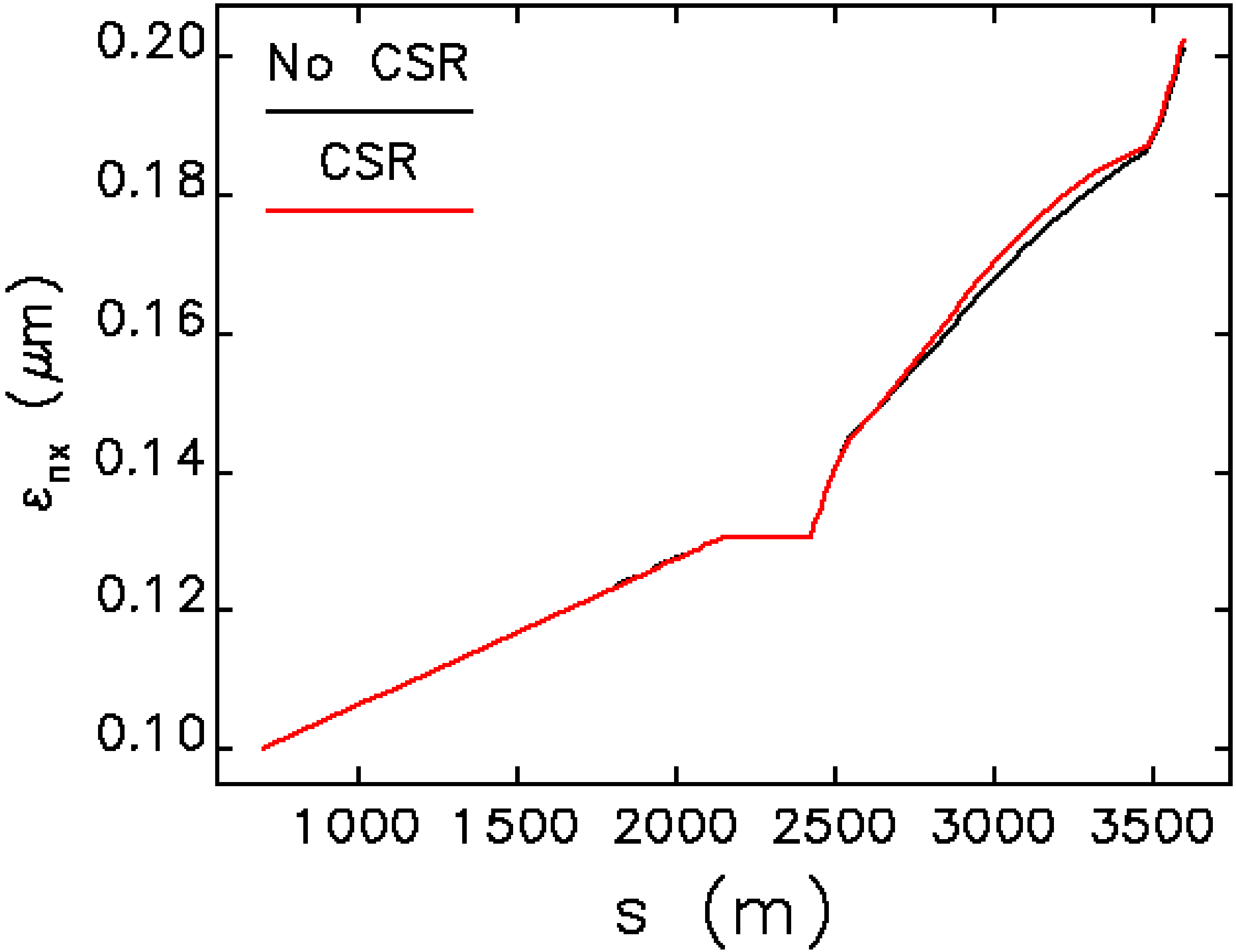
Initial (10 MeV) beam properties:

$\epsilon_{nx} = \epsilon_{ny} = 0.1\ \mu$m

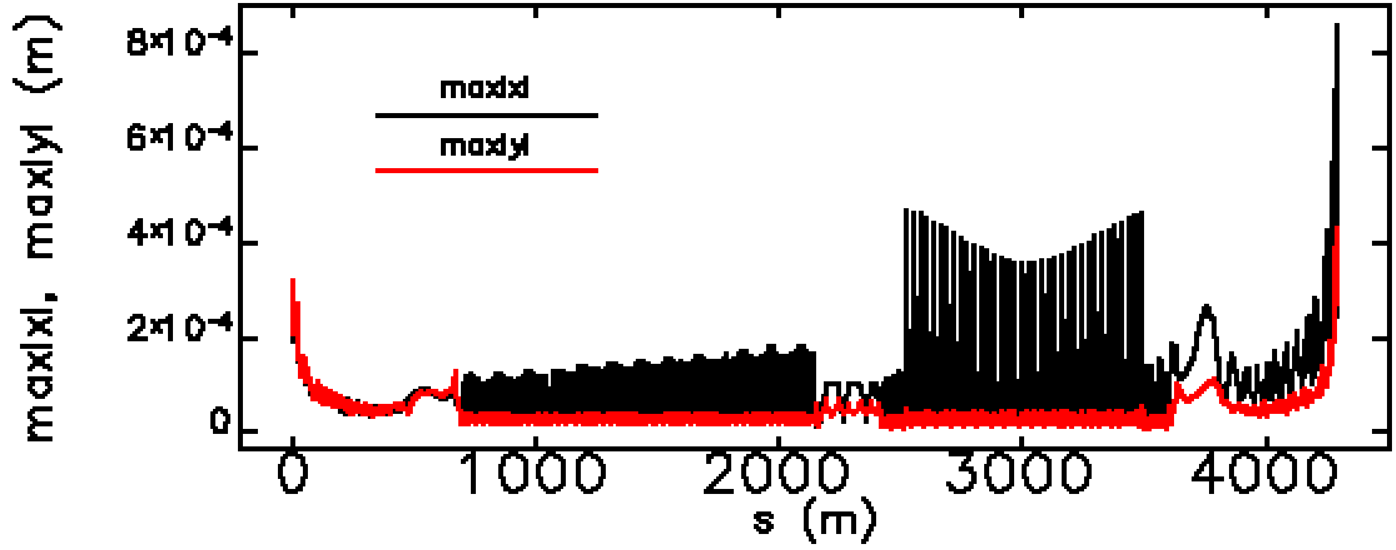
$\sigma_\delta = 0.02$ %

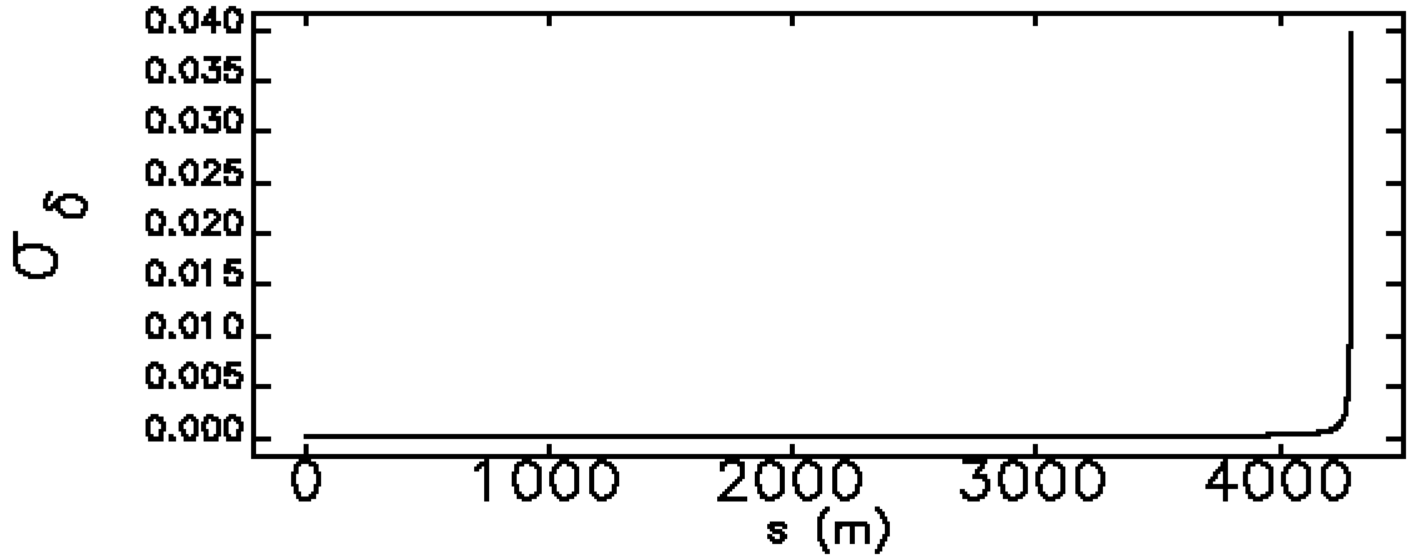
$\sigma_t = 2$ ps

Outfield ERL Tracking Results with CSR (77 pC/bunch)

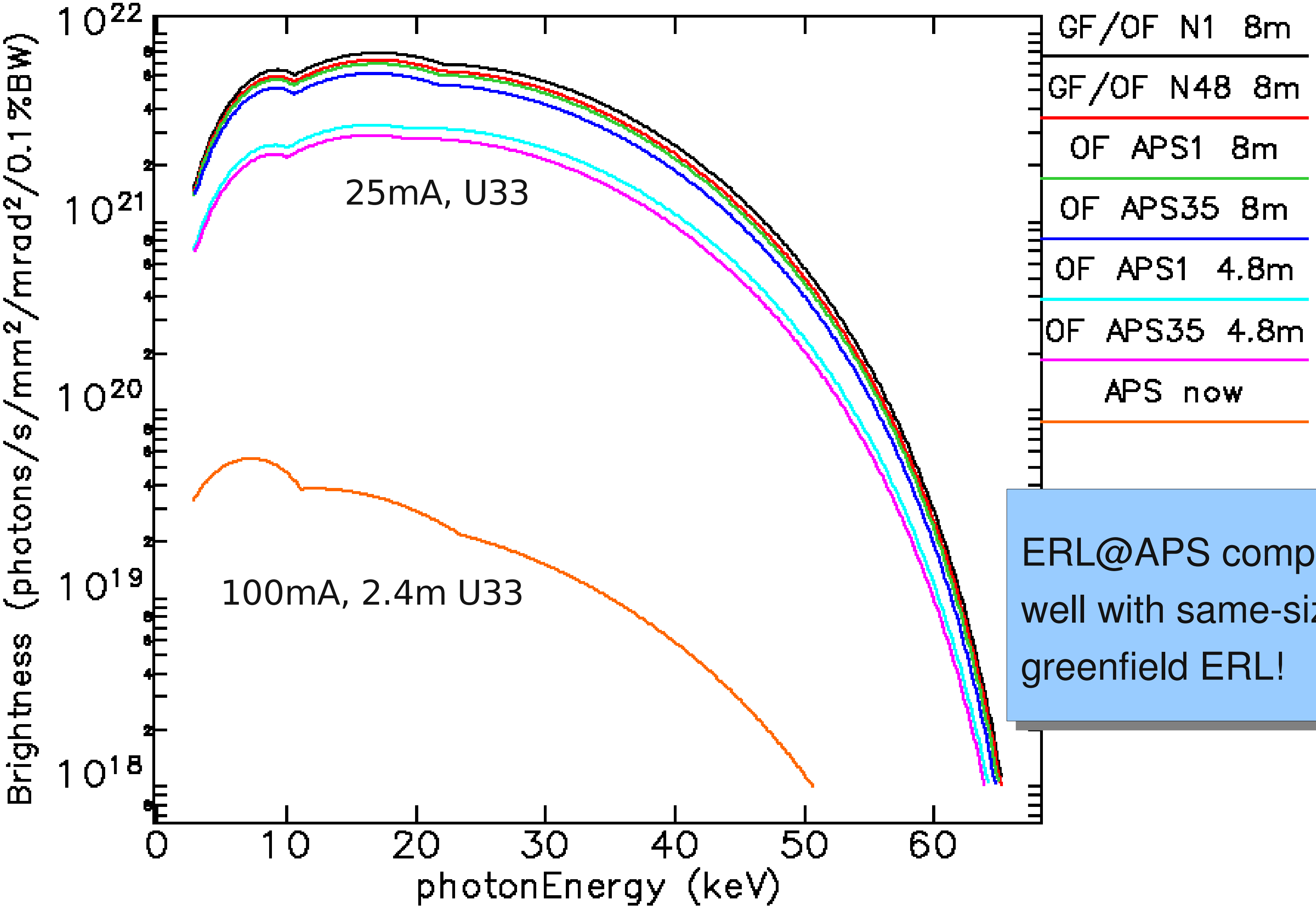


Good Beam Control to End of Linac (17 MeV)





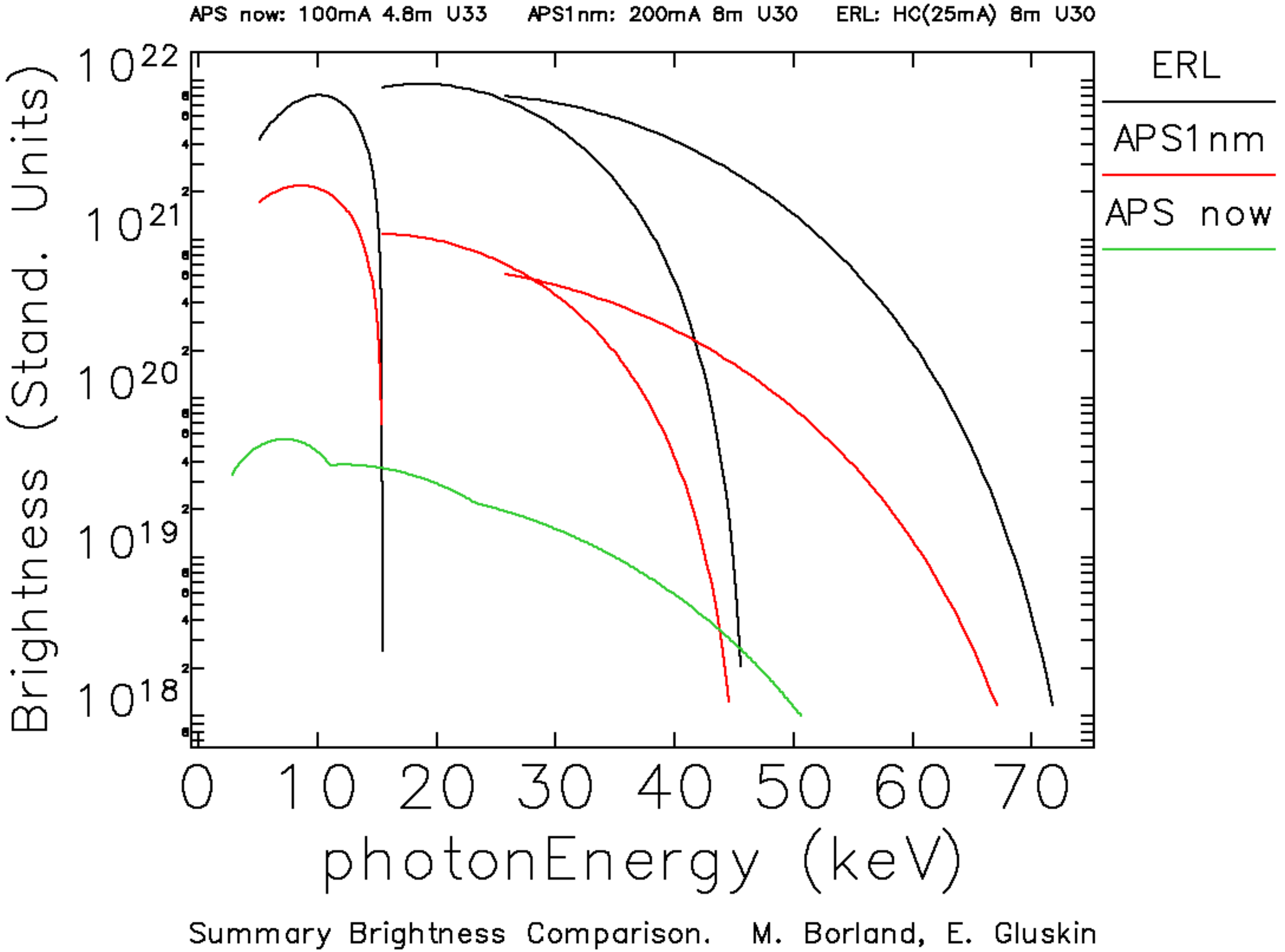
Brightness Comparison for High Coherence Mode



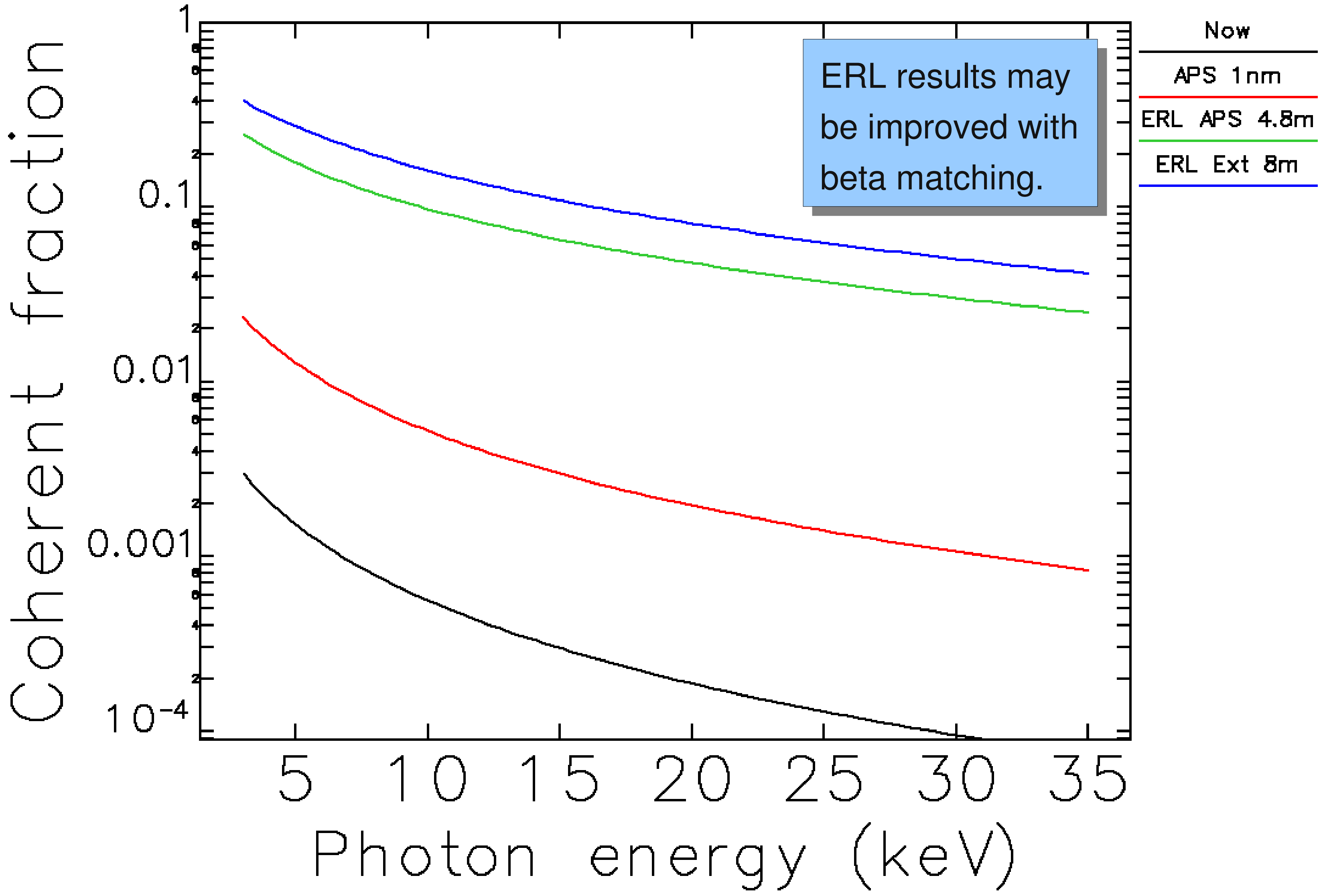
ERL@APS competes well with same-size greenfield ERL!

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

Comparison of ERL, APS 1nm, and APS now

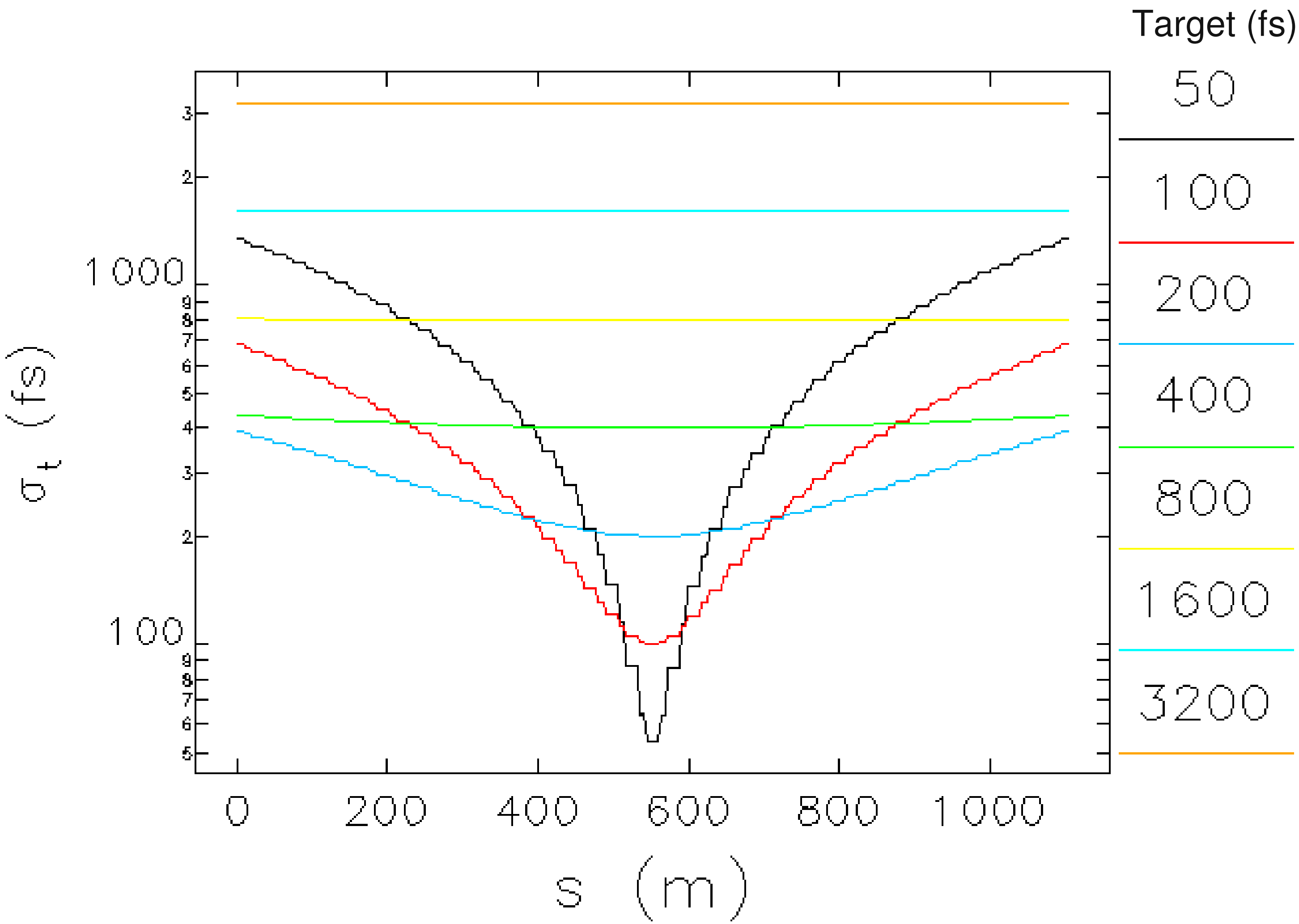


Coherent Fraction Comparison



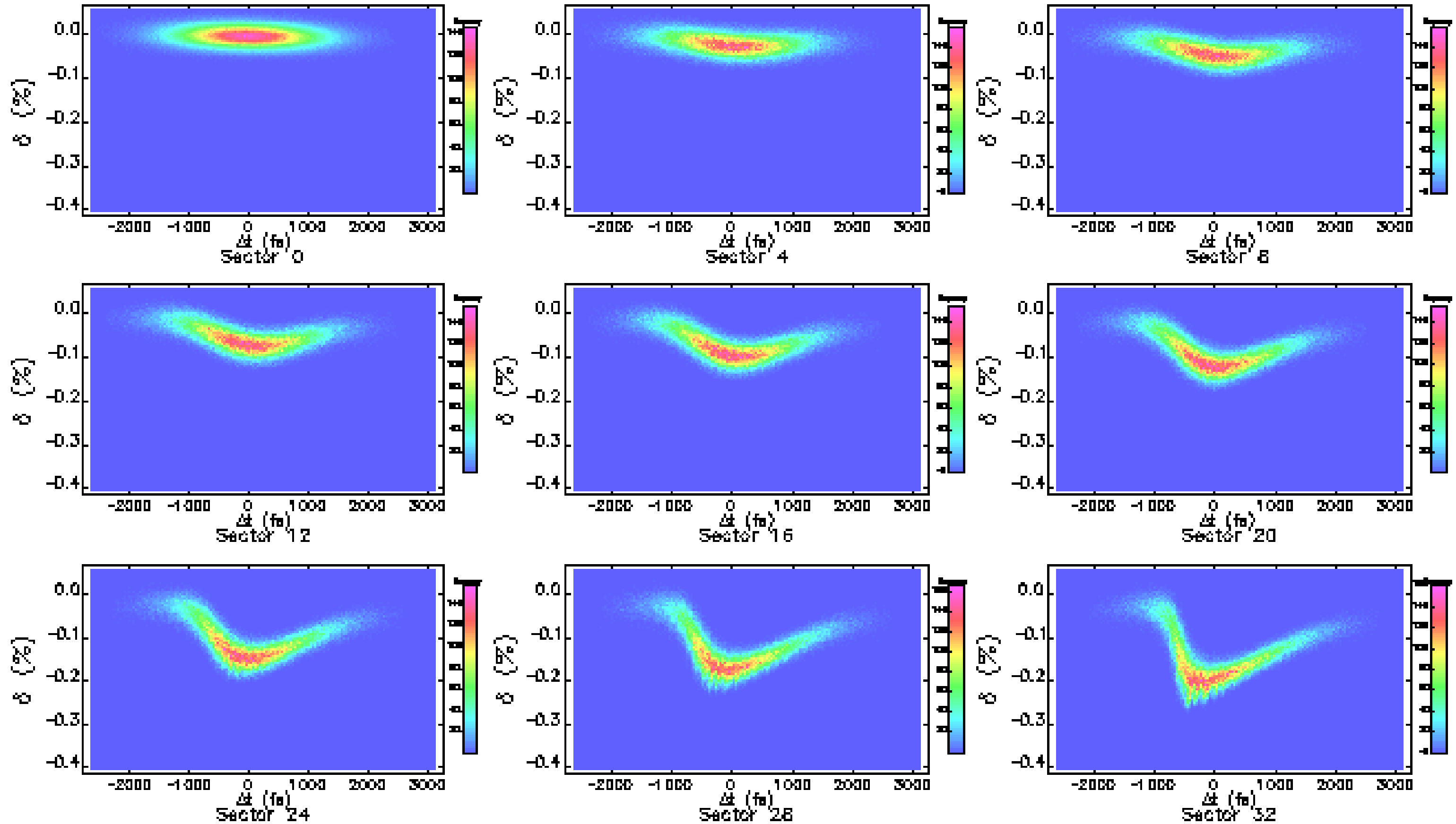
Short Bunches in APS from ERL?

- Can ultra-short pulses really be delivered?
- Can use APS as a bunch compression system (R_{56}=0.3 m)

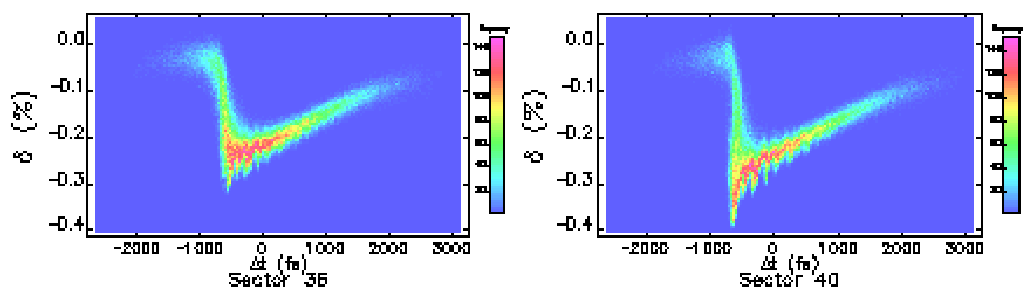


Ideal result without coherent SR

Impact of Coherent Synchrotron Radiation: 800fs Target



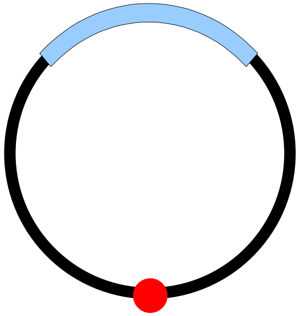
Longitudinal phase space at 4 sector intervals.



Energy spread is ~20 MeV, which impedes full energy recovery.

Hybrid ERL/SR Mode

- Concept:
  - Run ring with stored beam crowded on one side as in present hybrid mode
  - Pulse ERL gun at 271/N kHz to match ring revolution frequency
  - Inject short, intense pulse into ring for 1 turn
- Average current would be up to 0.27 mA
  - Up to 2 MW beam power, *maybe* don't need ER
- Challenging R&D for magnets and power supplies:
  - Need faster kickers (<3 us)
  - Need high rate kickers (kick in and out)
  - Need highly stable kickers due to small emittance
  - Kickers must have DC mode for normal ERL operation
- No obvious reasons this won't work
  - Still need more linac in order to chirp the pulse.



Crab Cavities with ERL?

- Approximate minimum compression of chirped pulse[1]

$$\sigma_{t,xray} \approx \frac{E}{V\omega_c}\sqrt{\sigma_{\gamma'}^2 + \sigma_{y'}^2}$$ ← <1.2 μrad for β>5m

$$\sigma_{\gamma'} \approx \sqrt{\frac{\lambda_\gamma}{2L_u}}$$ ← ~1.2 μrad for:

1A and L_u=35m

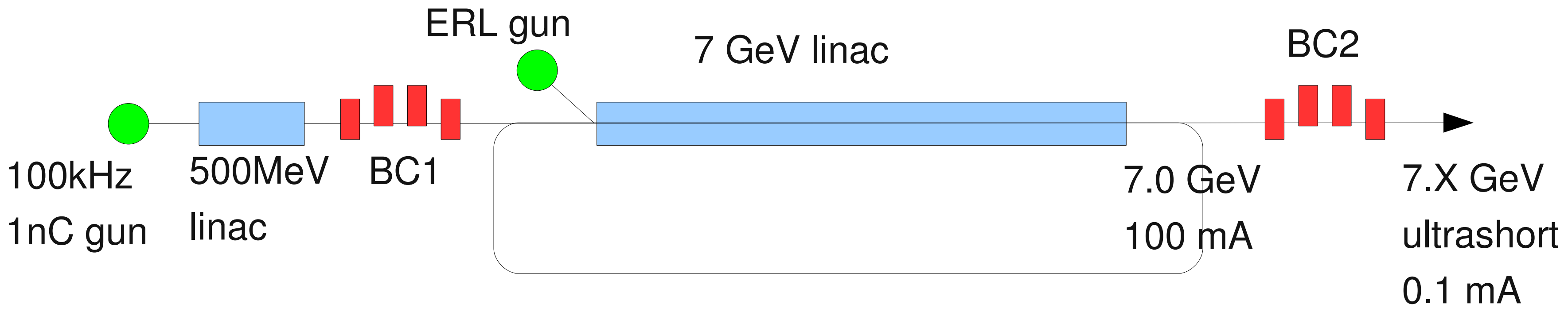
0.3A and L_u=10m

- For V=6 MV and 3 GHz cavity
  - ~100 fs rms for 1*A* and L_u=35m or 0.3*A* and L_u=10m
  - Intensity through slits is ~100fs/2ps = 5%
- Shouldn't harm beam: rms deflection only 32 μrad
  - Deflection is very linear, ideal for x-ray compression
- Applicability limited by wavelength/undulator restrictions.

[1]M. Borland, Phys. Rev. ST Accel Beams 8 074001 (2005).

Ultrashort Mode with Separate Injector

- Using Cornell's Ultrashort Mode in ERL@APS is fraught with problems
  - 1 mA average current
  - Much higher emittance
  - Serious beam degradation
- This isn't unique to APS
- Bazarov[1] suggests that ultrashort pulses should be delivered with a separate gun to a separate user hall:



Don't need ER for 1nC gun (low average current)!

[1] I. Bazarov, private communication.

Most Important R&D Challenges

- Gun/injector
  - For now we've assumed values predicted by Cornell simulations[1]
    - *0.1 μm emittance at 100 pC, but no merger*
  - Simulations at JAERI show comparable results[2]
    - *0.1 μm emittance at 10 pC including merger*
  - High-coherence mode is 0.1 μm emittance at 19 pC
  - High voltage on the gun is a problem (750 kV!)
- Cathode lifetime
  - Need to run 25 to 100 mA for ~48 hours to be comparable to APS today
    - *Probably can't do better than 1 hour with present cathodes[3]*
  - Time to change cathodes should also be short
    - *Two-gun system probably essentially to avoid gaps in service.*

[1]I.Bazarov and C. Sinclair, Phys. Rev. ST Accel. Beams 8 (2005) 034202.
[2]R.Hajima and R. Nagai, NIM A 557 (2006) 103-105.
[3]C. Sinclair, NIM A 557.

Beam Loss Issues[1,2,3]

- Possible problems from beam loss include
  - Inefficient energy recovery
  - Cryogenic load in linac
  - Radiation damage to equipment
  - Catastrophic damage to equipment from beam strike
  - Radiation hazard to users
- APS shielding[4] is such that a 44 nA beam loss at one spot creates ~2 rem/hour outside shield wall
- Even 1 PPM loss from 100 mA ERL corresponds to 100 nA
- Is it possible to get around ~1 PPB?
  - APS injectors are typically only ~90% efficient, but
  - Stored beam in 24 bunch mode has single-turn loss of 0.17 PPB.

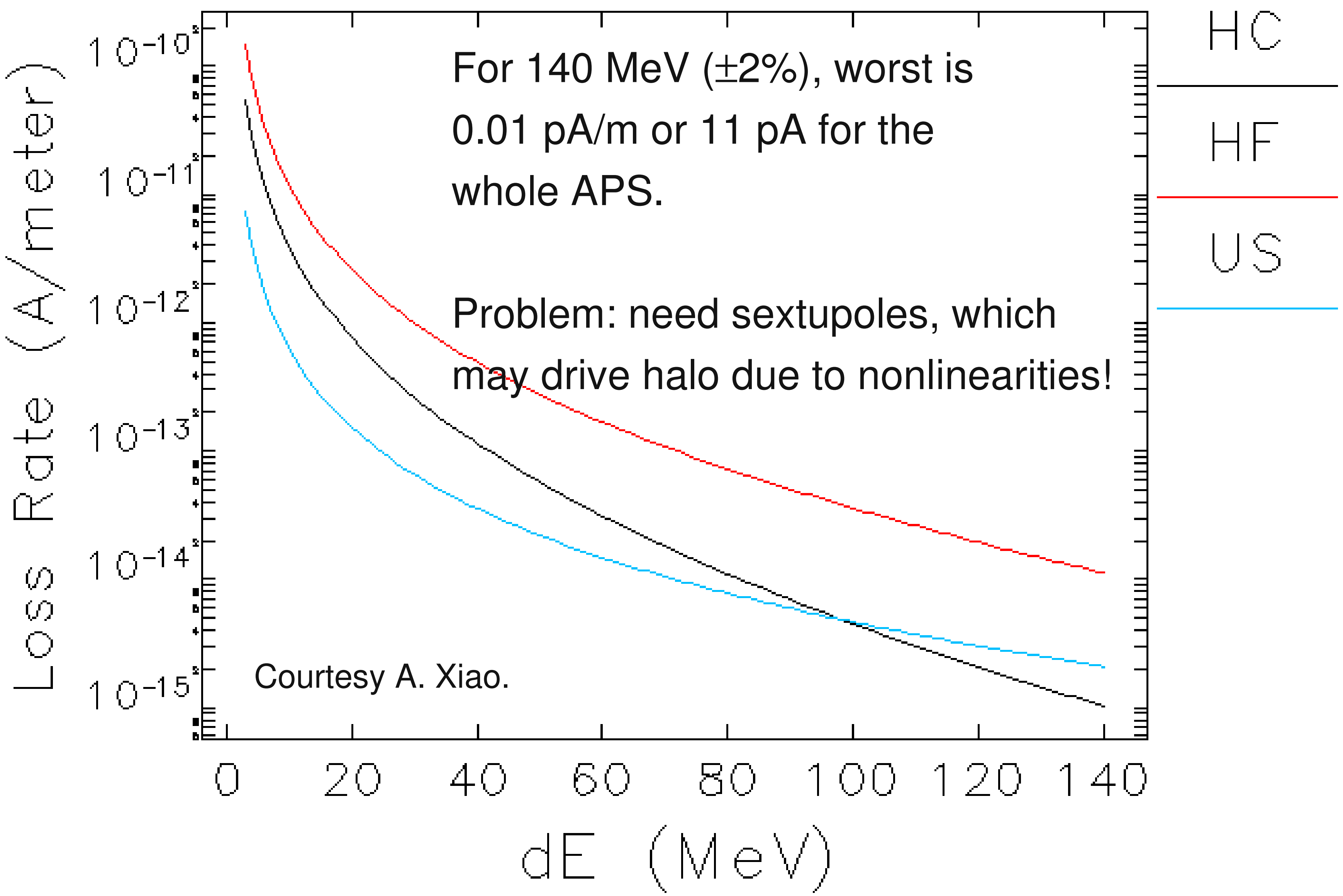
[1] G. Neil, "Beam Loss and Beam Abort Strategy," FLS 2006 Workshop.
[2] CY Yao, "Beam Loss Issues of ERL Accelerators," 10/12/06, and references therein.
[3] M. Borland and A. Xiao, OAG-TN-2006-052, 10/16/06.
[4] APS Safety Assessment Document, APS-3.1.2.1.0 and L. Emery, private communication.

Beam Loss Mechanisms[1,2]

- ERL beam will have a "halo," from e.g.
  - Space charge
  - Scattered drive-laser light
  - Field emission from the gun and linac
  - Intrabeam scattering
  - Non-linear optical elements
- Important R&D topics:
  - Quantitatively understand mechanisms of halo formation through theory, simulation, and experiment
  - Determine if it is workable to collimate halo and at what energy
  - Develop methods for reducing and managing halo, e.g.,
    - *surface quality and composition to reduce field emission*
    - *momentum aperture optimization to control IBS*
- If we can get the beam to high energy cleanly, may be able control beam losses in arcs.

[1]G. Neil, "Beam Loss and Beam Abort Strategy," FLS 2006 Workshop.
[2]CY Yao, "Beam Loss Issues of ERL Accelerators," 10/12/06, and references therein.

Cumulative Touschek Loss Rate in APS for Different ERL Modes

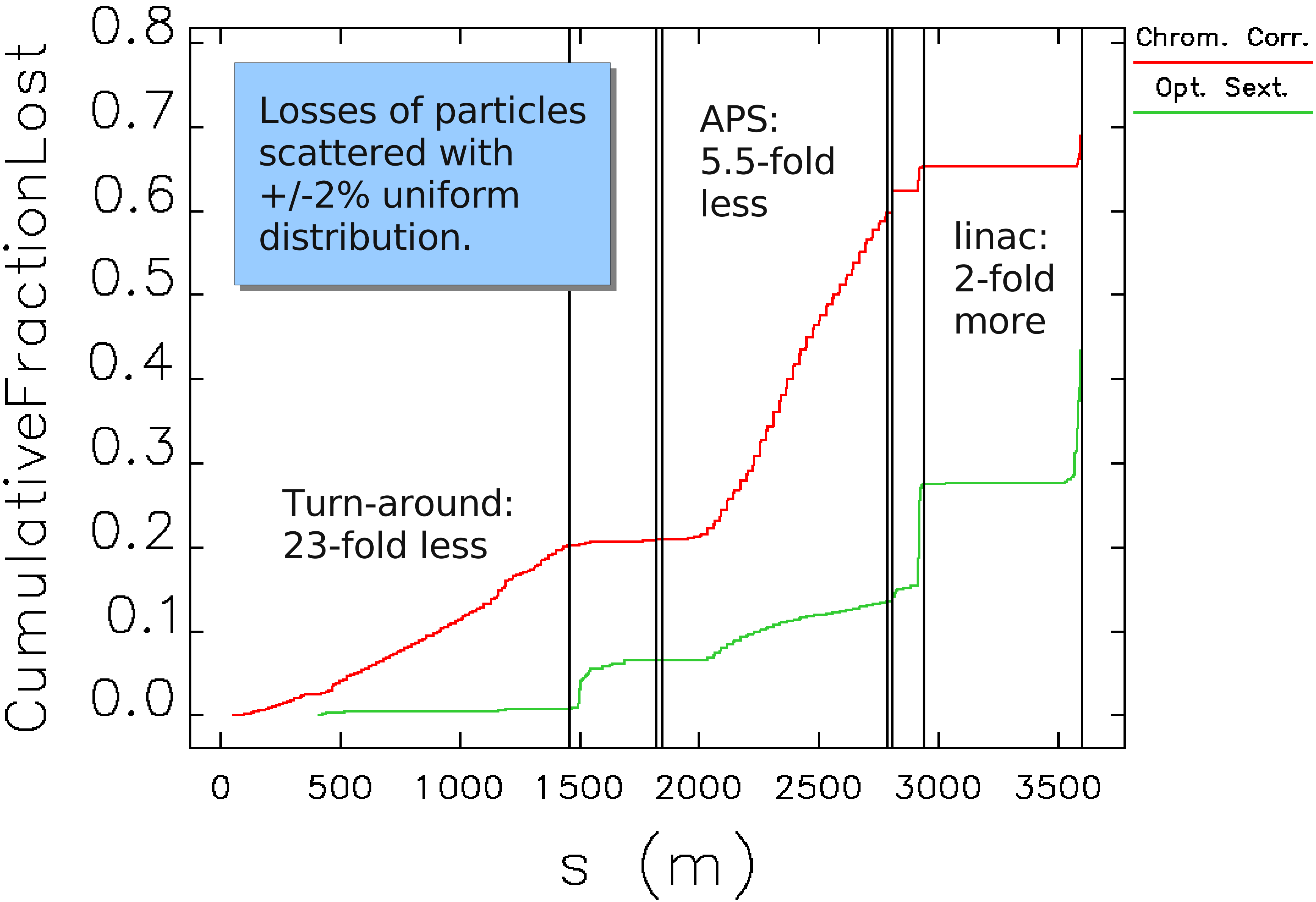


For 140 MeV (±2%), worst is 0.01 pA/m or 11 pA for the whole APS.

Problem: need sextupoles, which may drive halo due to nonlinearities!

Courtesy A. Xiao.

Sextupole Optimization Can Control Losses in Ring



Estimated APS ERL Linac Cost/Power Requirements[1,2,3,4]

- In spite of use of SC technology, power dissipation in the cavities is an issue
  - Power is ~40 W/m, but dumped at 2K
  - Require ~1kW of cryoplant power for 1W dumped at 2K!
  - Estimate we'd need a ~16 MW cyroplant for a one-pass linac
- Estimated cost is
  - ~250 M$ for the cryoplant
  - ~250 M$ for the linac itself

[1] A.Nassiri, "Overview of Superconducting Linacs," 8/11/06.

[2] A.Nassiri, "ERL Cost Update," 8/24/06.

[3] A.Nassiri, private communication.

[4] A. Nassiri, "ERL RF Systems," MAC Review, 11/15/06.

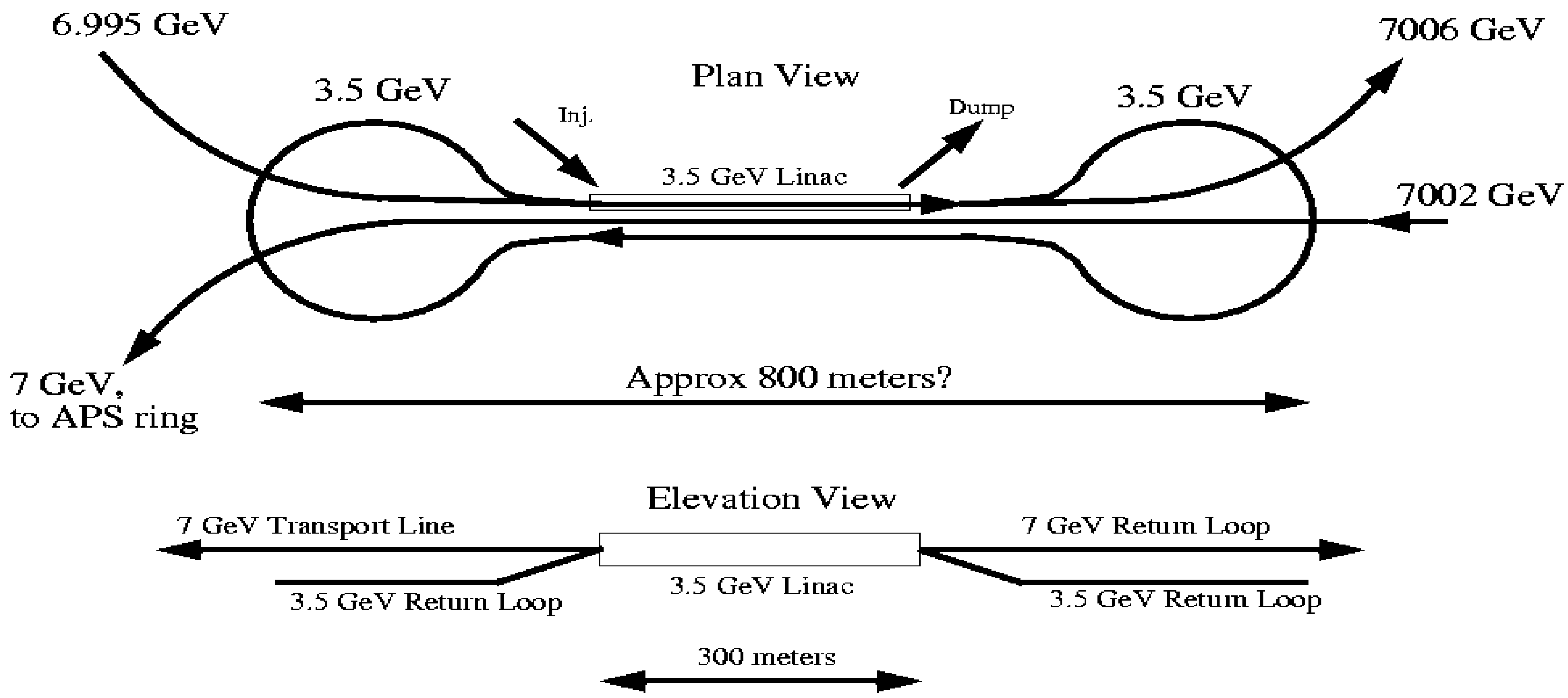
Linac R&D Topics

- Linac superconducting cavity design and fabrication[1]
  - Required gradients (20 MV/m) and Q's (10^{10}) are achievable
  - Higher gradients would reduce length, but increase cryogenic power
  - Higher Q's would reduce cryogenic power
  - R&D on this topic important in controlling cost and complexity
- Cryogenics
  - With present technology, ~16 MW cryogenic plant required[1]
  - Better cryoplant design may be possible and might pay off[2]
- Rf frequency choice
  - Higher frequency gives lower power consumption
  - Lower frequency (generally) better for beam dynamics
    - *Worse for CSR and Touschek scattering*
- Multi-pass vs single-pass linac.

[1] A. Nassiri, “ERL RF Systems”, MAC Review, 11/15/06.

[2] M. White, private communication.

Two-Pass Acceleration Scheme for ERL[1]



- Linac/cryoplant much cheaper, but overall cost impact unknown
- Much less accommodating to intense short-pulse schemes
- Need to look at BBU thresholds.

[1]N. Sereno, G. Decker, OAG-TN-2007-003, 1/15/07.

Other Issues

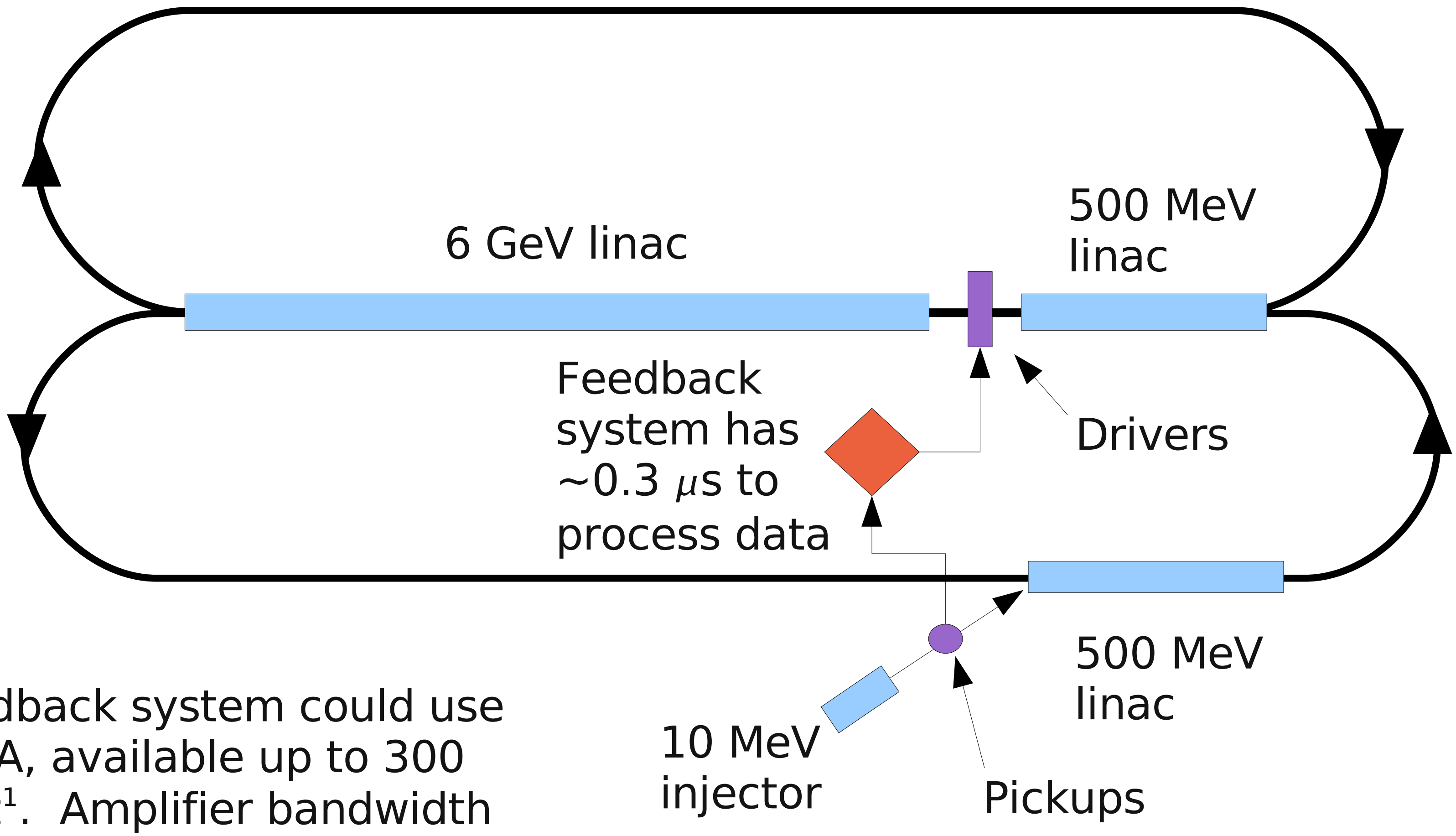
- Path length tuning
  - For ER to work, the returning bunches must enter the linac 180 degrees out of phase with new bunches
  - Exit transport line from the APS to the linac is a convenient location to adjust this
  - Need to understand survey tolerances and adjustment range
- ID impact has to be looked at
  - IDs will change beam energy
    - *Energy loss from IDs is about 20% of nominal energy loss*
    - *If uncompensated, will change path length and ER*
    - *Need to develop a compensation scheme to allow users to change gaps at will*
  - IDs will increase emittance and energy spread
    - *Needs to be evaluated, but probably small.*

Positional Stability

- Based on present APS performance (1 μm), we could stabilize ERL beam to ~20% of beamsize
  - We don't see to be far from required ~10% stability
- 1.3 GHz repetition rate of ERL beam will help
  - 1.3 GHz is much faster than power supply ripple, rf variation, and vibration
  - Good signal for BPMs
  - Existing APS BPMs work at 352 MHz, so may want to build 1.408 GHz linac
- Ability to do correlation analysis (beam and equipment) with high rate data needed
- Present APS feedback system (1.6 kHz data rate) probably too slow
- R&D into quieter power supplies should also be pursued
  - Otherwise, might need feedback at rates above chopper frequencies (20 kHz).

[1]A. Lumpkin.

Feedback Scheme for ERL to Compensate Gun Jitter



Feedback system could use FPGA, available up to 300 MHz[1]. Amplifier bandwidth is limiting factor.

[1]R. Lill, private communication.

Summary

- An APS Upgrade is being seriously investigated
- Storage ring upgrades are possible, but
  - Require long "dark time" (1 year or more)
  - Don't deliver revolutionary improvements
- ERL@APS promises revolutionary improvement in brightness and coherence
  - Simulation model "delivers" high quality beam to users
  - Enables major expansion of number of beamlines
  - Nearly identical performance to same-size greenfield ERL
- ERL needs heavy R&D to solve potential problems, e.g.,
  - Injector emittance requirements
  - Average current and cathode lifetime
  - Control of beam losses
  - Linac cost optimization
  - Short pulse production
- Initial results and world-wide R&D effort give reasons for optimism.

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Google “APS Upgrade” for MAC Review talks.