ERL Parameter Review and Overview of Physics Issues

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Outline

- Why consider an ERL?
- ERL overview
- Operating modes for ERL upgrade
- Assumptions and ERL physics issues
  - Emittance production and preservation
  - Energy spread and recovery
  - Linac optics principles
  - Arc optics principles
  - Beam breakup
- Short pulse issues and options
- Beam loss concerns
- Magnet designs
- Stability and diagnostics issues
- Conclusion.

Why Consider an Energy Recovery Linac[1]?

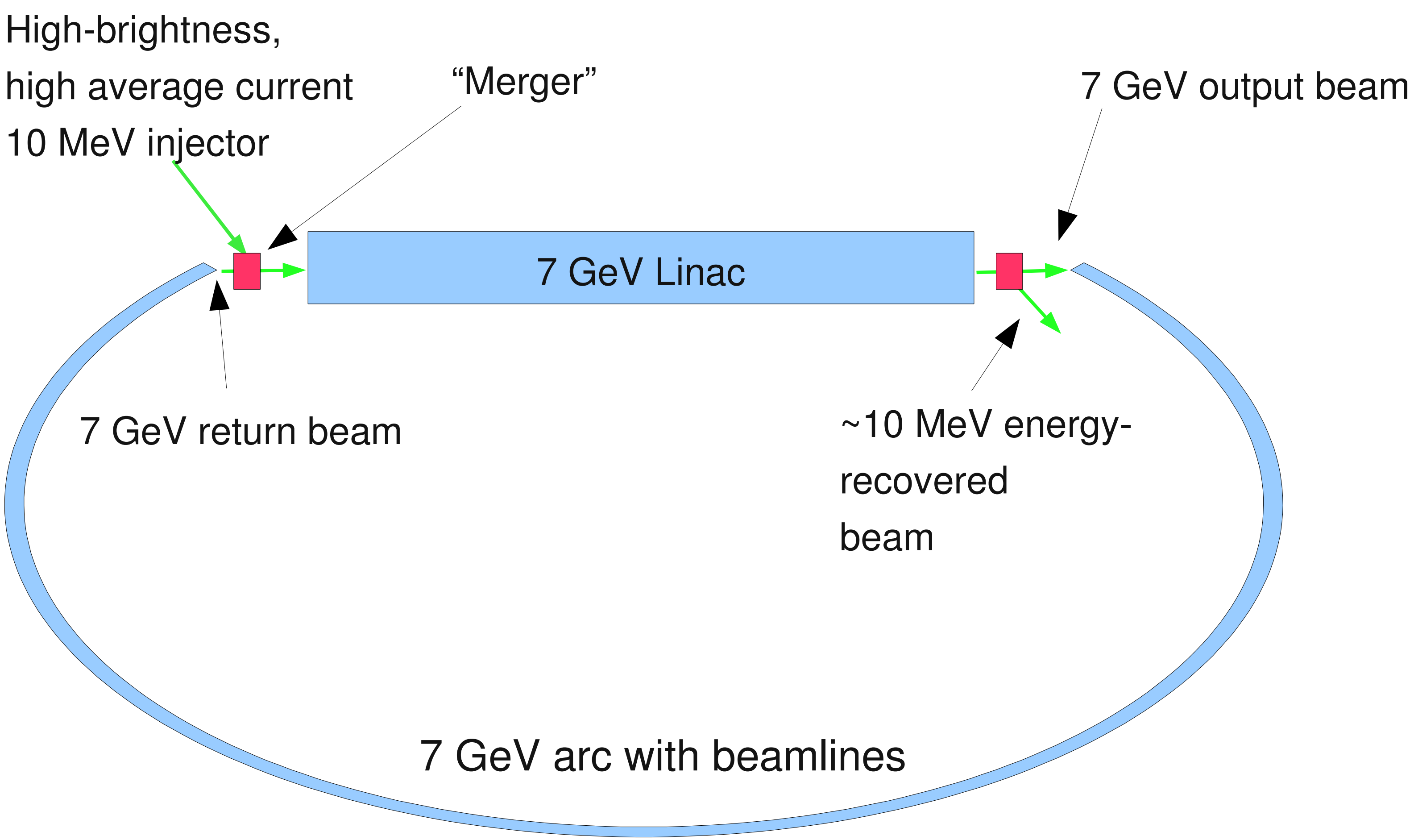
- Unlikely to get revolutionary improvements in accelerator performance for APS storage ring upgrade
  - Constrained by the present circumference
    - *Dramatic emittance reductions are very difficult*
    - *Desire for long straight sections further increases difficulty*
  - Nonlinear dynamics issues increasingly difficult
  - Need new booster, long dark time
- ERL promises revolutionary performance
  - Emittance in both planes comparable to present APS minimum vertical emittance
    - *Very high degree of spatial coherence*
  - Electron bunches of few ps duration or less
  - No long dark time
- We find that adapting the ERL concept to APS maintains these advantages.

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

ERL vs Ring in a Nutshell

- Facts about storage rings vs linacs:
  - Emittance scaling favors high-energy linac: ~E^2 for ring, ~1/E for linac
  - Energy-spread scaling favors high-energy linac: ~E for ring, ~1/E for linac
  - Linac can much more easily produce short (ps or less) pulses
  - Single-pass systems (e.g., linac) can more easily support optics flexibility
  - Ring can much more easily produce high current
- A 7 GeV, 100mA linac nominally consumes GW of wall plug power
  - Energy recovery allows high current from a high-energy linac.

Basic ERL Concept



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 with ultra-low emittance, ps pulses
- Option for less current with high charge, fs pulses.

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

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Guns for ERLs

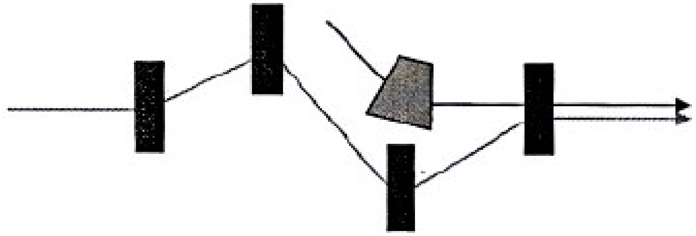
- Challenges:
  - Very low emittance desired (~0.1 μm normalized)
    - *Even 1 μm would be good: 80 pm emittance at 7 GeV*
    - *Can start with a lesser gun and gradually improve*
  - CW operation with high average current (100 mA)
    - *Vacuum must be extremely good to preserve cathode lifetime*
- Many gun types
  - DC photocathode gun is most common (JLAB, JAERI, Cornell, Daresbury)
  - Several normal and superconducting rf gun projects underway

Ranges of design and achieved values (A. Todd, NIM A 557 (2006) 36-44).

Output energy	2~15 MeV	CW average current	100-500 mA (5~32)
Bunch charge	0.075~3 nC (0.13~4.75)	Normalized emittance	0.1~ 6 um (7~30)
Bunch length	2~7 ps (3~50)	Energy spread	0.1 ~ 0.5 % (0.1~3)
Rf frequency	500~1300 MHz	Rf power	50~500 kW

Emittance Preservation in Injector

- Two notable simulation efforts
  - Cornell[1] gets 0.1 μm emittances for ~100 pC without merger
  - JAERI[2] gets 0.1 μm emittances for ~10 pC with merger
- High-coherence mode (0.1 μm, 19 pC) seems plausible
- The injector must be carefully optimized to preserve the gun emittance against
  - Space charge
  - Merger bends
- Not APS-specific, so for now assume these designs work
  - Cornell has built a prototype gun and is testing now
    - *Most important issue probably high voltage (750 kV)*
  - Improved merger concepts under development.



"Zigzag" merger (V. Litvinenko et al., NIM A 557 (2006) 165-175.)

[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.

Emittance Preservation at High Energy

- Issues at high energy all related to bending
  - Mismatch due to average energy loss in arcs
  - Coherent synchrotron radiation (CSR) in arcs
  - Quantum excitation (ISR) in arcs
- These also affect the energy spread
  - Impacts brightness
  - Impacts beam loss and energy recovery
- The methods of dealing with these are well known
  - Similar to high-brightness ring design in many respects
- Site-specific issue, related to accelerator geometry
  - Considerable APS-specific detail shown later.

Average Energy Loss

- In large, high-energy ERL, the beam loses considerable energy traversing arcs
  - E.g., ERL@APS might have 10~15 MeV loss
  - Reduces energy recovery efficiency (see below)
- Optics mismatch unless magnet strengths are tapered
  - If no tapering, emittance growth and beam loss will be worse
  - Solving this requires more power supplies
    - *APS already has individual PS for all quads and sextupoles*
    - *APS also has trim supplies for all dipoles*
    - *Hence, so far we taper only in the APS portion*
- Loss also varies as users change undulator gaps
  - This is a fraction (~20%) of the fixed losses
  - We have not explored the impact of this.

Quantum Excitation (Incoherent Synchrotron Radiation)

- ISR concerns
  - Emittance growth reduces brightness
  - Energy spread growth reduces brightness, affects losses/ER
- Scaling is different than for storage ring equilibrium properties
- For isomagnetic separated function lattice[1,2]

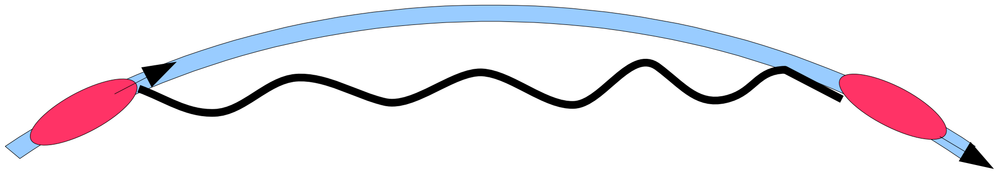
$$\Delta\epsilon_x \propto I_5\gamma^5 \propto \Delta\theta \frac{\gamma^5}{\nu_x^3\rho} \qquad \Delta\sigma_\delta^2 \propto \Delta\theta \frac{\gamma^5}{\rho^2}$$

- Lessons
  - Don't bend the beam more than necessary at high energy
    - *Bending at low energy is much, much better*
  - Keep bend radius large
  - Use strong-focusing lattice.

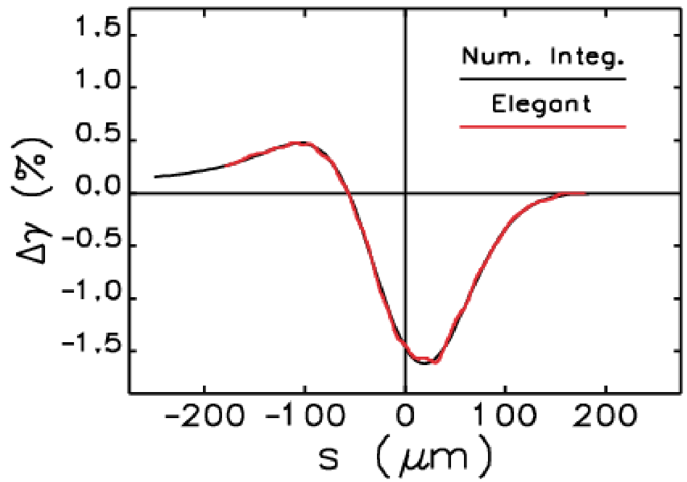
[1] M. Sands, The Physics of Electron Storage Rings, SLAC-121, November 1970.

[2] M. Borland, OAG-TN-2006-045, 10/5/2006.

Coherent Synchrotron Radiation[1,2]



Steady-state
CSR "wake" for
1nC gaussian bunch



$$\Delta\sigma_\delta \approx \frac{r_e Q L_b}{4 e \gamma (\rho^2 \sigma_s^4)^{1/3}} = \frac{r_e Q \theta \rho^{1/3}}{4 e \gamma \sigma_s^{4/3}}$$

$$\Delta\epsilon \sim \beta_x \theta \Delta\sigma_\delta$$

- Gets *better* linearly with increasing energy
- For fixed angle, weak dependence on radius
- Like ISR: strong focusing, many weak dipoles helps emittance.

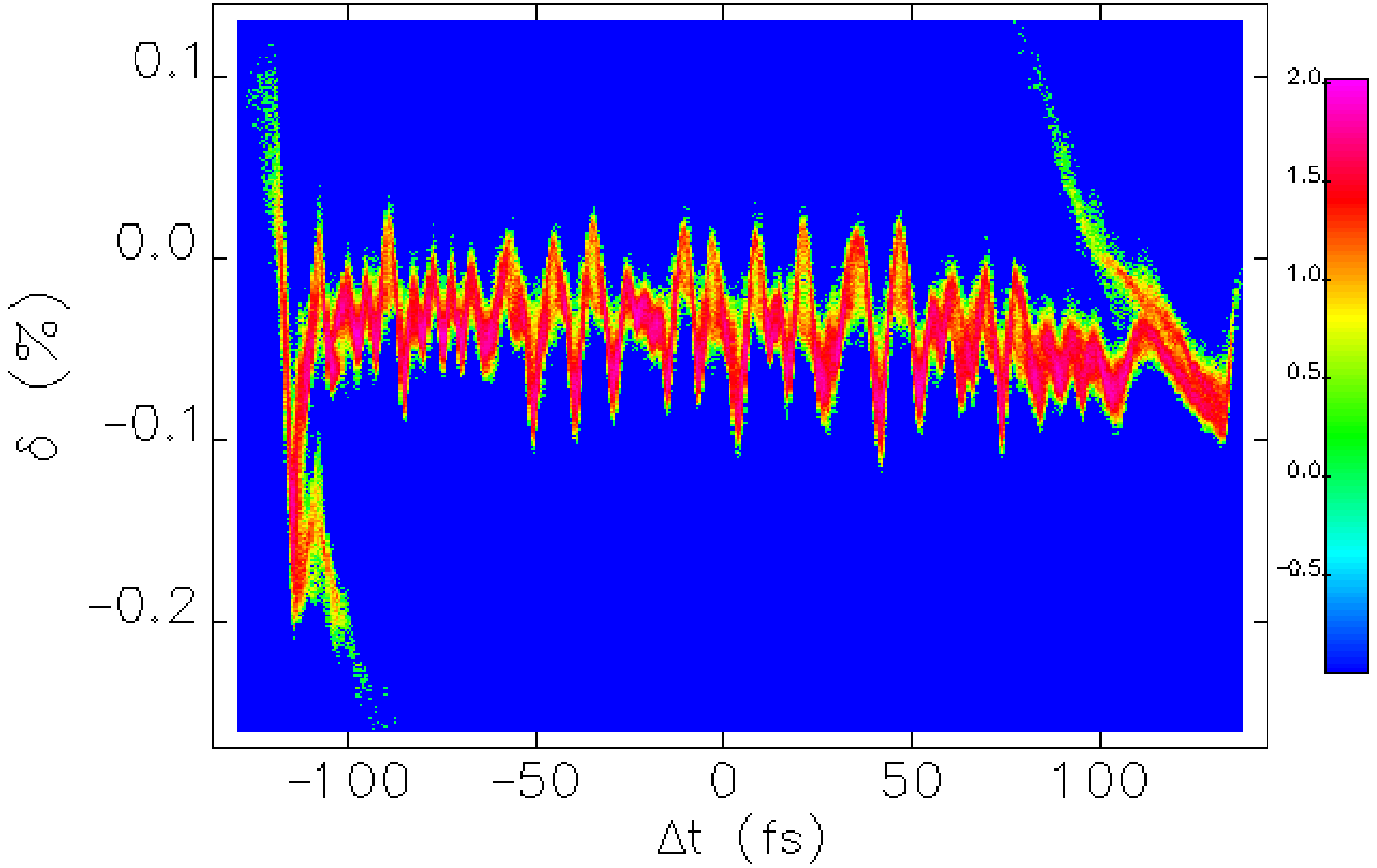
[1]B. Carlsten et al., Phys. Rev. E 51,1995.
[2]M. Borland, Phys.Rev.ST Accel. Beams **4**, 070701 (2001).

CSR Microbunching Instability[1]

- CSR wake strongly driven by local derivative of current
  - Accelerates the head
  - Decelerates the tail
- If $R_{56}<0$
  - Head falls back, tail moves forward
  - Density clump gets enhanced if CSR wake larger than local energy spread
- $R_{56}<0$ for low-emittance double-bend cell (e.g,. APS arcs)
- At high intensity, this can significantly corrupt longitudinal phase space
- Simulations with smooth Gaussian beams can be highly misleading.

[1]M. Borland et al., NIM A 483, 268 (2002).

CSR Microbunching Instability in Early LCLS Design[1]



[1]M. Borland et al., NIM A 483, 268 (2002).

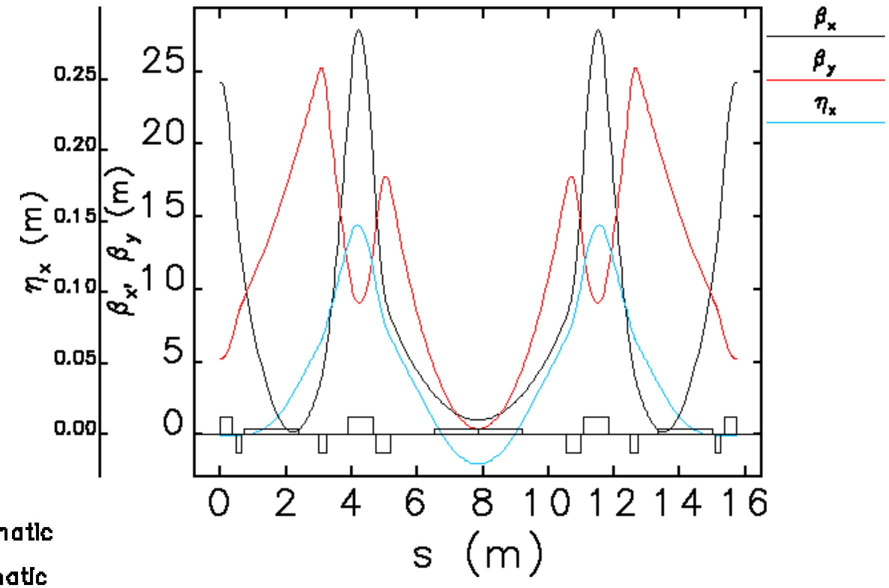
Arc Design for ERLs

- Need bending arcs for various purposes
  - Recirculation arcs
  - New user arcs
  - Arcs into and out of the APS
- Based designs on triple-bend cells[1]
  - Emittance-preserving (strong focusing)
  - Achromatic
    - *Necessary for user beamline arcs to avoid effective emittance (growth) due to energy spread (growth)*
    - *Not generally optimal for beam-transport arcs*
  - Isochronous
    - *Rigid longitudinal distribution mitigates CSR instability*
    - *Horizontal phase advance of $2\pi N/m$ per cell with $M{*}m$ cells gives emittance growth cancellation[1].*
- In APS, we use zero-dispersion tuning of the existing double-bend cells (see below).

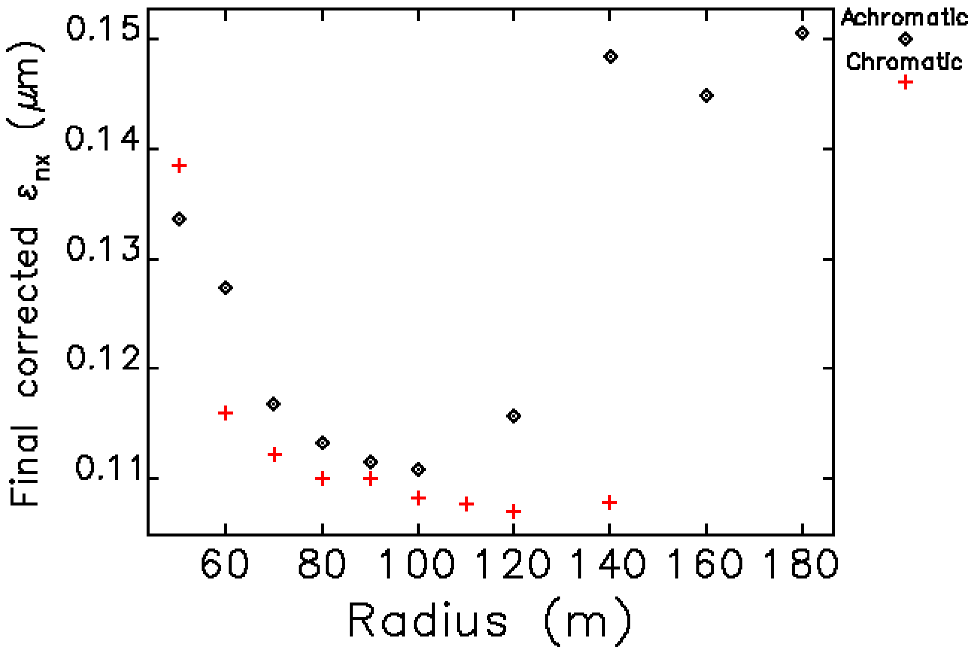
[1]J. Wu et al, Proc 2001 PAC; G. Bassi et al, NIM A 557 (2005).

7 GeV Transport Arc Designs for ERLs

- Typical ischronous achromatic transport cell
- Three non-gradient dipoles
- Five quadrupole families



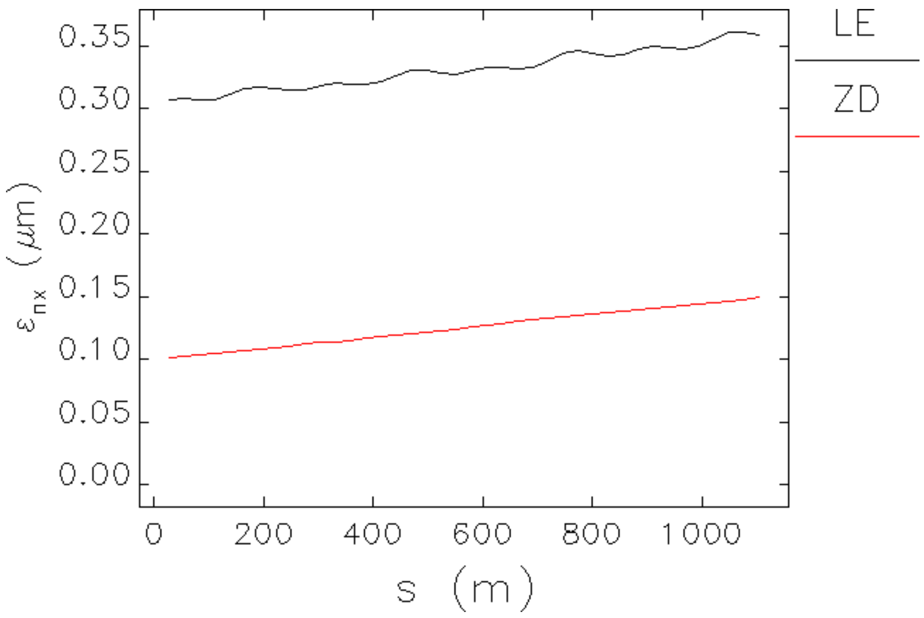
Results for 10-cell 90-deg arcs



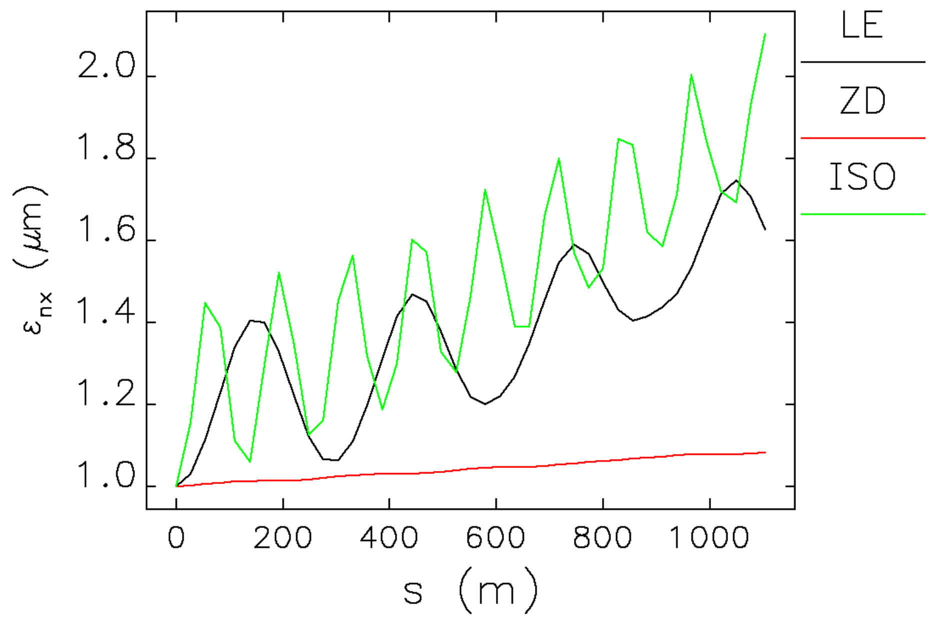
- R>110m: achromatic solution performs poorly without more, shorter cells
- For 80~110m average radius, get similar results
- We've used achromatic arcs in this range
  - Easier to match to user arcs

APS Lattice for ERL[1]

- APS uses distributed dispersion low-emittance (“LE”) lattice
  - Minimizes the effective beam emittance
- In spite of tiny energy spread, need achromatic cells (“ZD” lattice) for ERL even ignoring ISR/CSR



Emittance growth in APS w/o CSR, Cornell high-coherence parameters.



Example with Q=50 pC, 0.17 ps rms bunch length: ZD much better.

[1]M. Borland, NIM A 557 (2005) 224.

Optics Correction

- Optics correction is a serious issue for emittance preservation in ILC[1]
- Effective emittance can be enlarged by
  - Mismatched horizontal dispersion
  - Spurious vertical dispersion
- Typical beta functions at IDs are ~10 m with ~7 pm geometric emittance at 7 GeV
  - ~8 μm mono-energetic beam size
- Less than 10% emittance increase means beam size of increase of under 5%

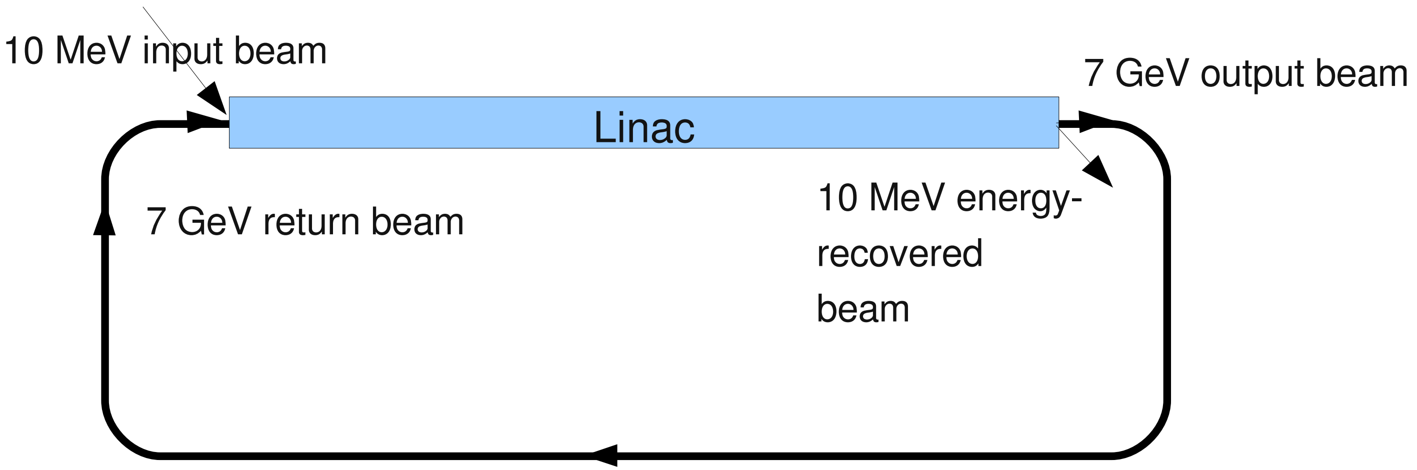
$$\eta \sigma_{\delta} < \sqrt{\epsilon \beta} (1.05^2 - 1)^{1/2}$$

- With 0.02% rms energy spread, need η<0.01 m.
  - In APS we correct[1] dispersion at IDs to ~0.003 m
- Appears not to be a major issue.

[1]L. Emery, private communication.

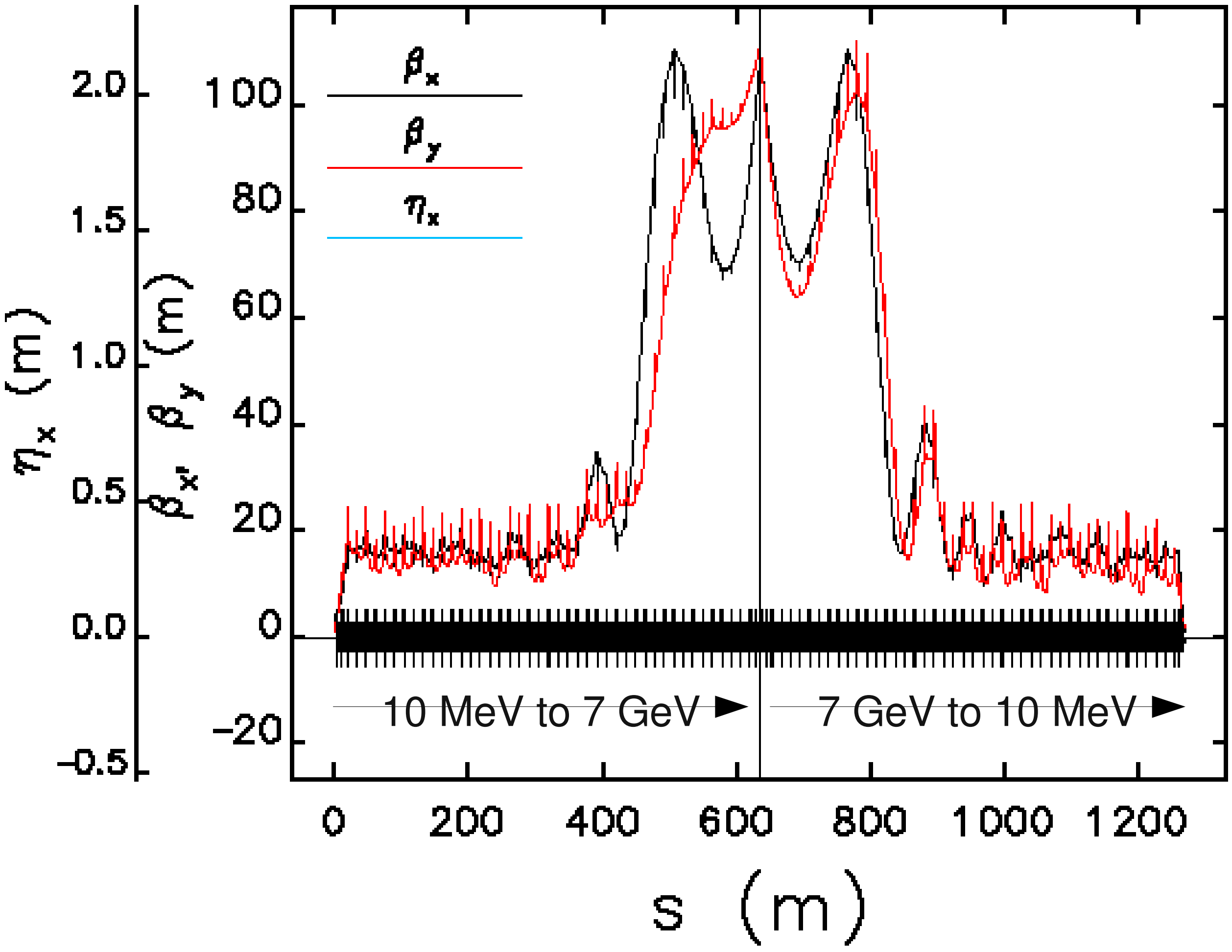
ERL Linac Optics Design

- ERL linac must support beams of multiple energies in the same location
  - Single-pass ERL linac must support 10 MeV and 7 GeV beams together
  - The "graded gradient"[1] principle was applied and works well
    - *Quadrupoles have constant focal length for lowest energy beam at any location*



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

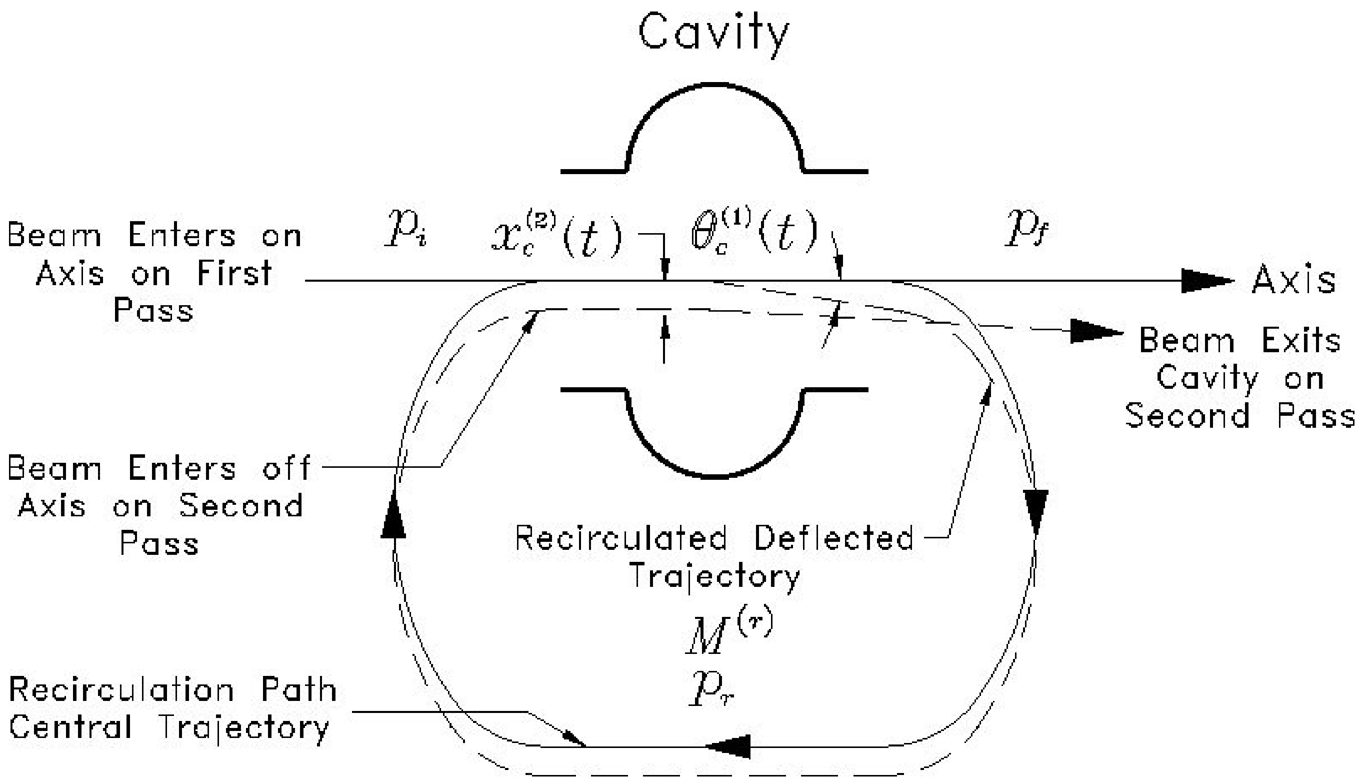
Example of Doublet-Based ERL Linac Optics Design



- Linac is 600m long with ~0.6 packing fraction
- Graded-gradient gives starting point
  - Optimizer chooses best initial constant gradient and quad separation
- Then use **elegant** to optimize everything at once to reduce maximum beta functions for both beams.

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

Multipass Beam Breakup



N. Sereno, Univ. of Illinois Urbana Ph. D. Thesis, 1994.

Initially on-axis beam gets a small kick from HOM.

Beam returns with large offset that dumps more energy into the HOM.

Solutions to BBU[1,2]

- Linac optics
  - Small beta functions using graded gradient design
  - R_{12} and R_{34} matrix elements for one pass should be small
    - *Trajectory from cavity's kick crosses near zero when beam returns to same cavity*
    - *Can be done by adjustment of external phase advance*
- HOM control
  - Damping
    - *Requires space between cavities for HOM dampers*
    - *Decreases the cavity fill factor*
  - Stagger tuning
    - *This was done for the APS storage ring, but with far fewer cavities*[3]
- Cornell/JLAB effort[1] shows a >200 mA threshold is possible using these techniques for a single-pass ERL.

[1] S. Gruner and M. Tigner eds., CHESS Tech. Memo 01-003.
[2] N. Sereno, “Beam Breakup in ERLs,” 11/2/06.
[3] L. Emery, PAC 1993, 3360-3362.

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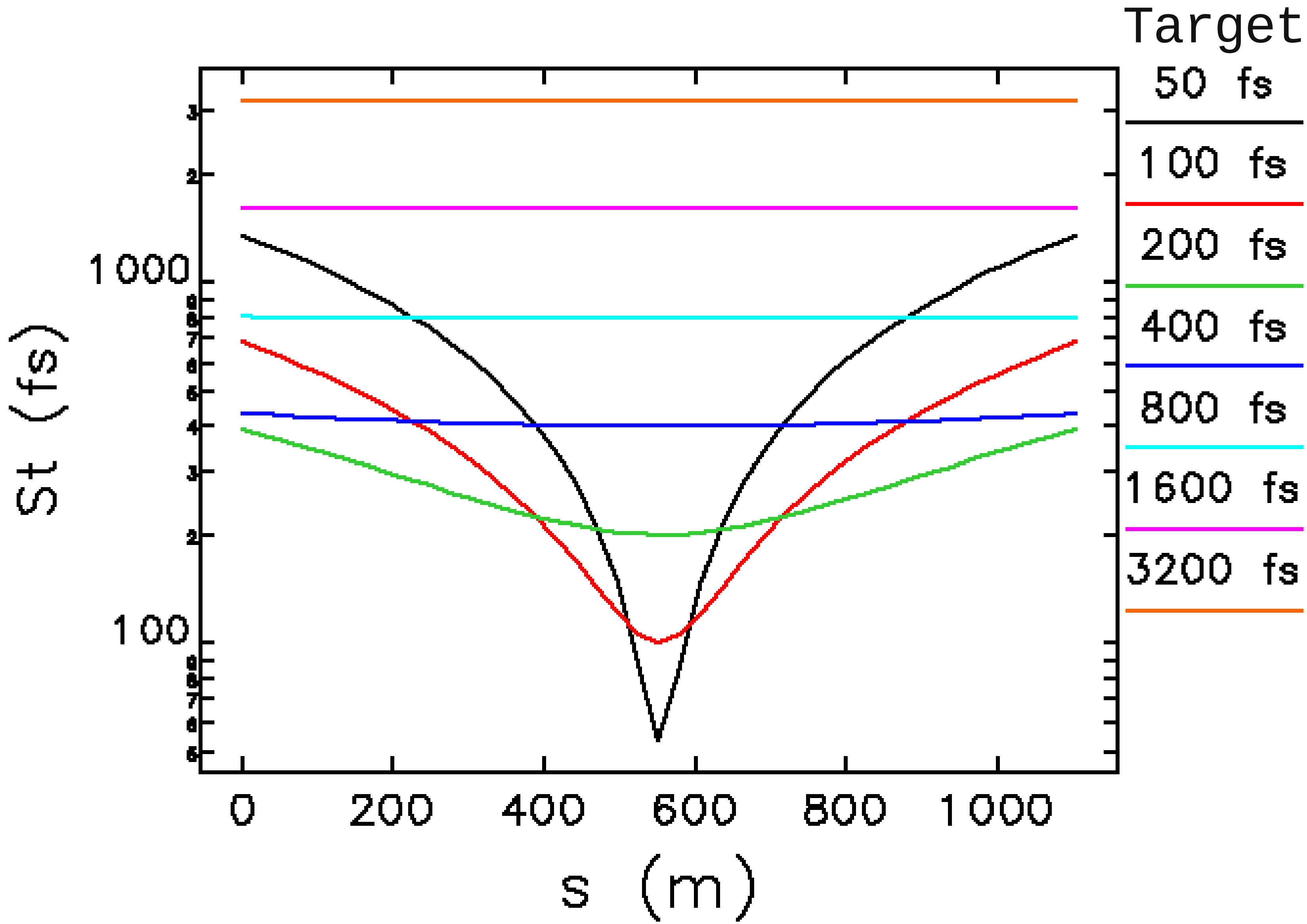
ERL Ultrafast Mode

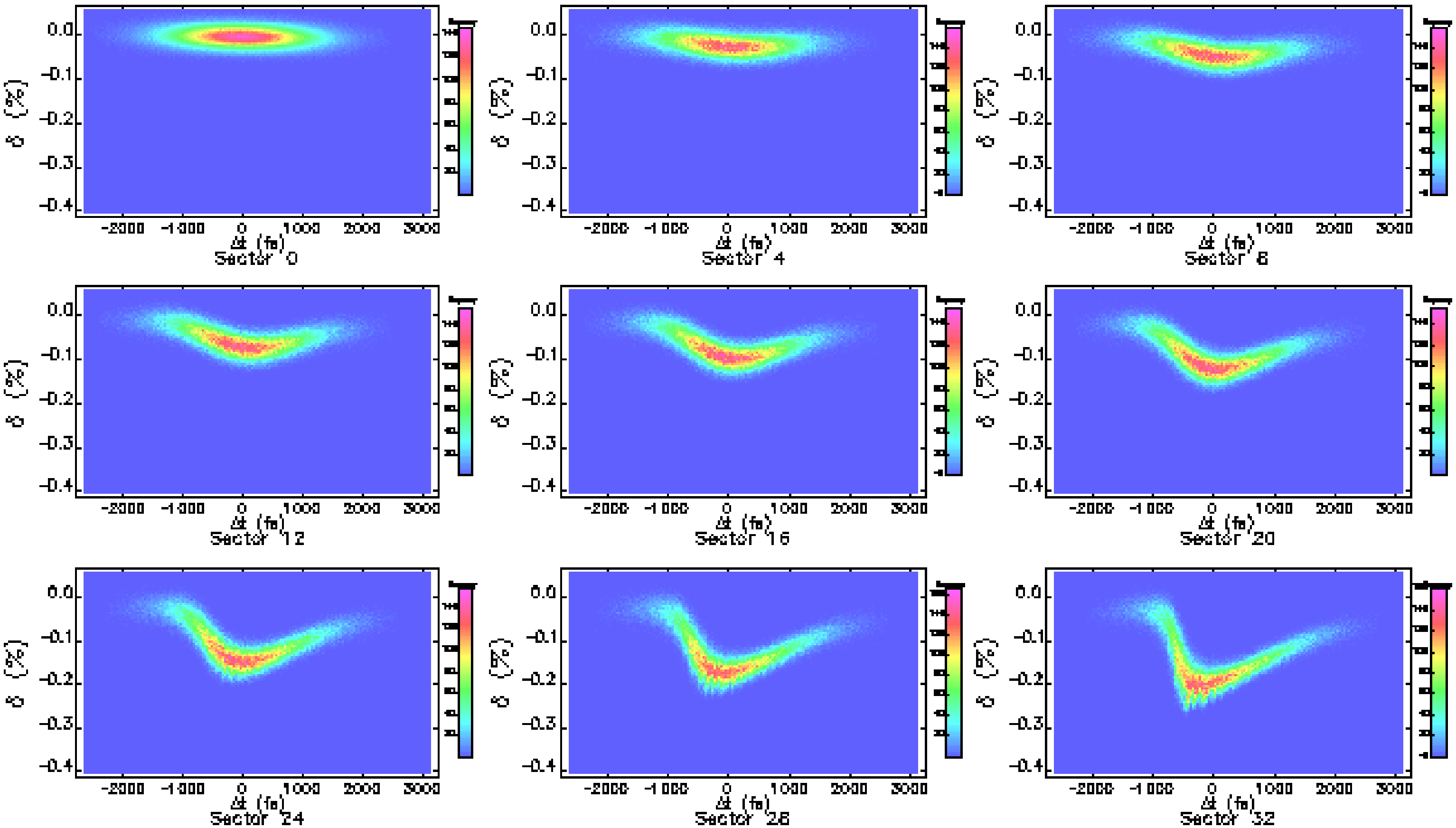
- Cornell ERL group[1] lists the following parameters for "ultra-fast" operating mode:
  - 0.35 nm emittance in both planes (at 7 GeV)
  - 1 mA average current
    - *1 nC per bunch at 1 MHz*
  - Very short bunch length: 50 fs rms
  - Energy spread of 0.3% rms
- Can these values be delivered to APS users?
  - Assume that we'll use the APS itself as the bunch compressor
  - Assume we can arbitrarily transform the initial longitudinal phase space with emittance 50fs*0.3%
    - *Varying the initial chirp varies the target bunch length.*

[1] G. Hoffstaetter, FLS-2006.

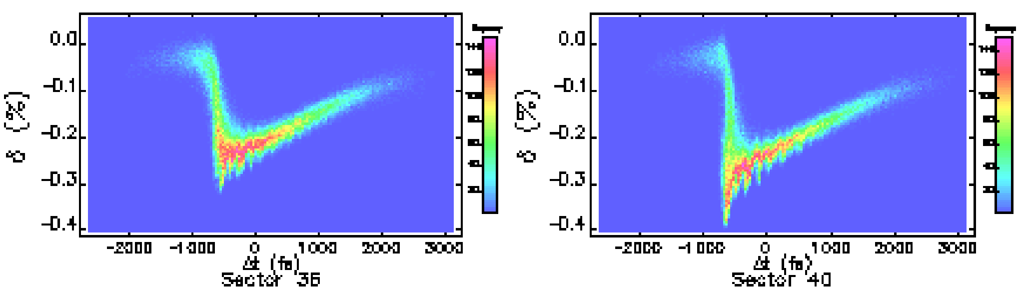
Ideal Result without CSR or ISR



Impact of Coherent Synchrotron Radiation: 800fs Target

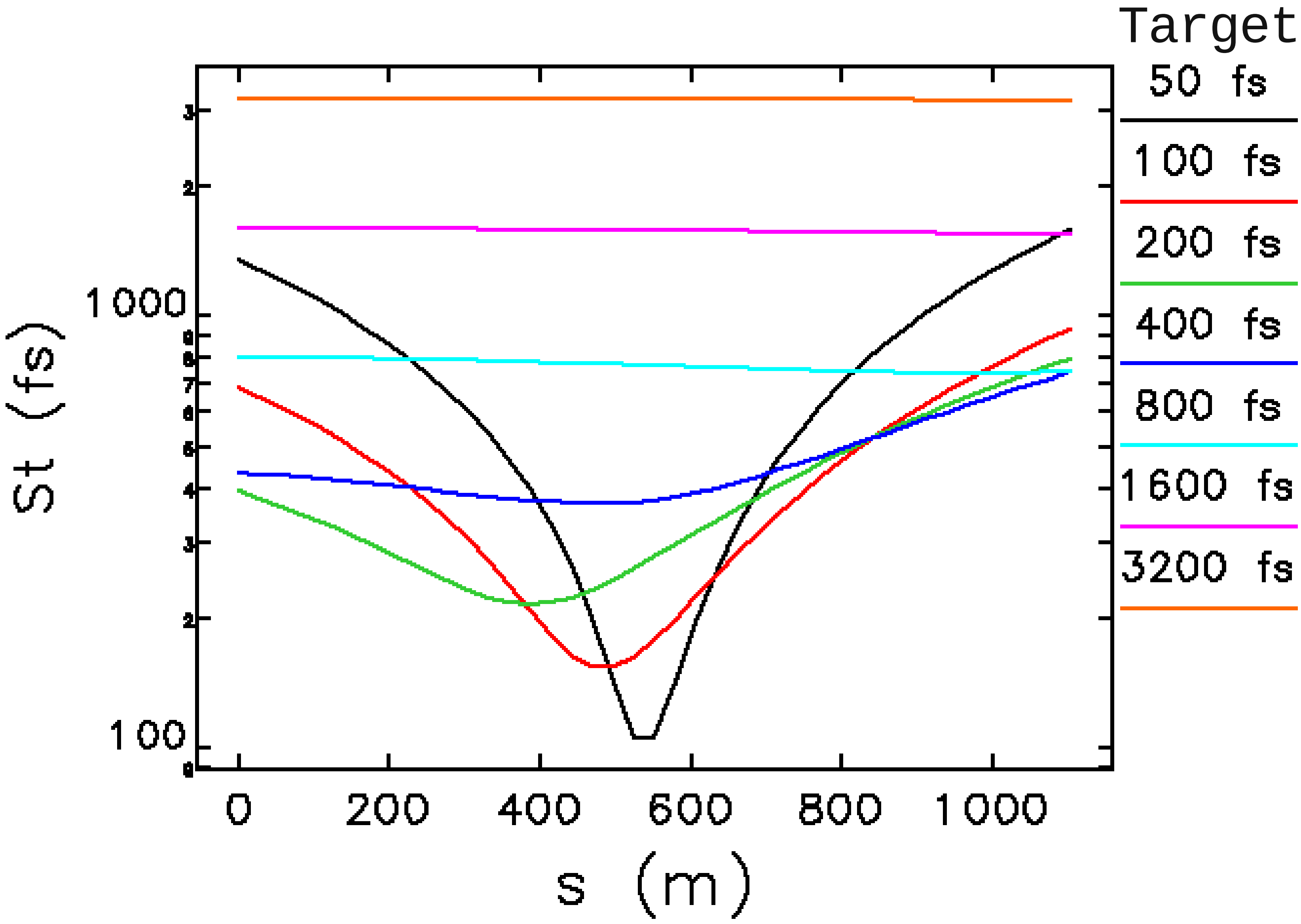


Longitudinal phase space at 4 sector intervals.

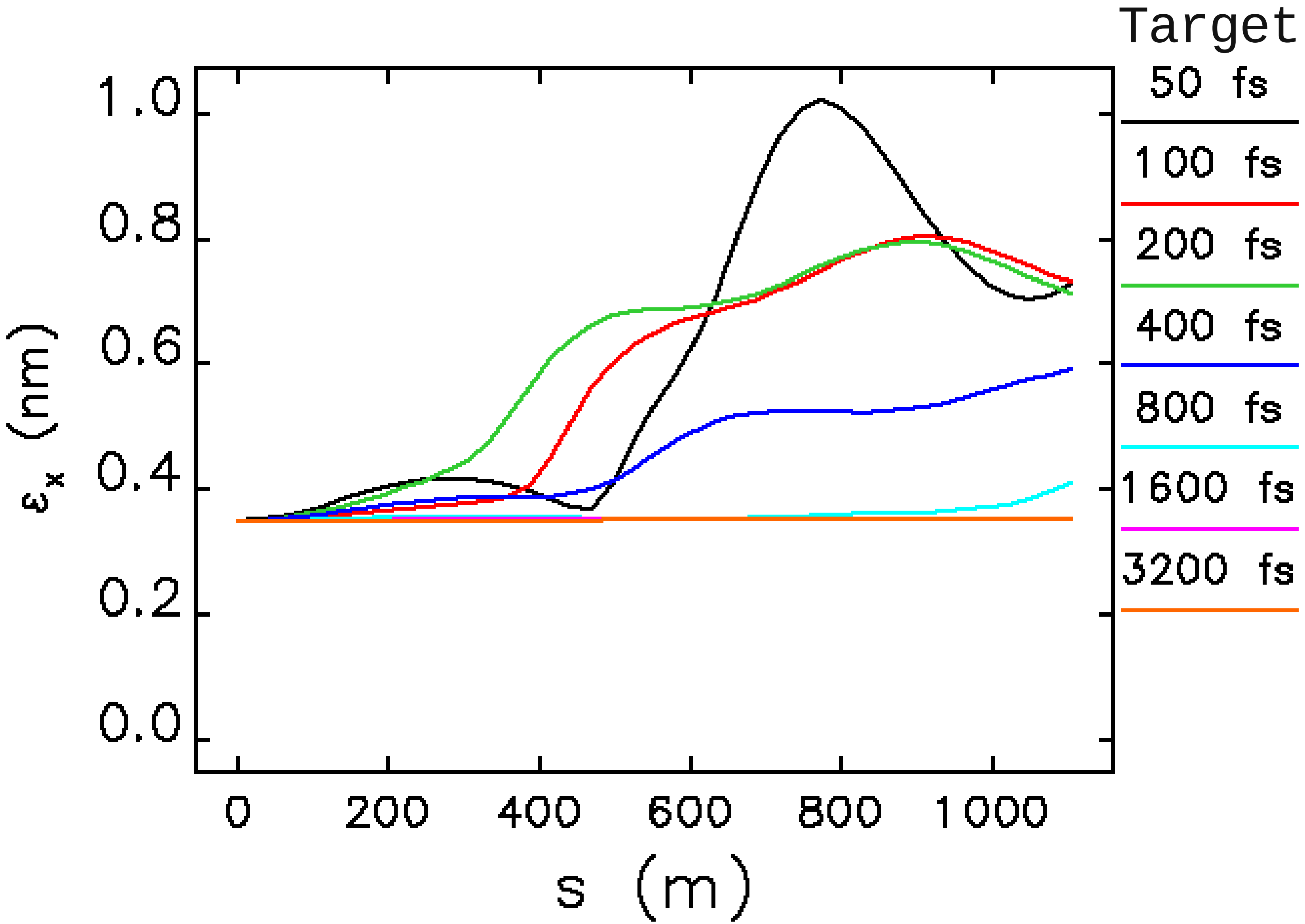


Hint of microbunching instability seen.

Evolution of Rms Bunch Duration



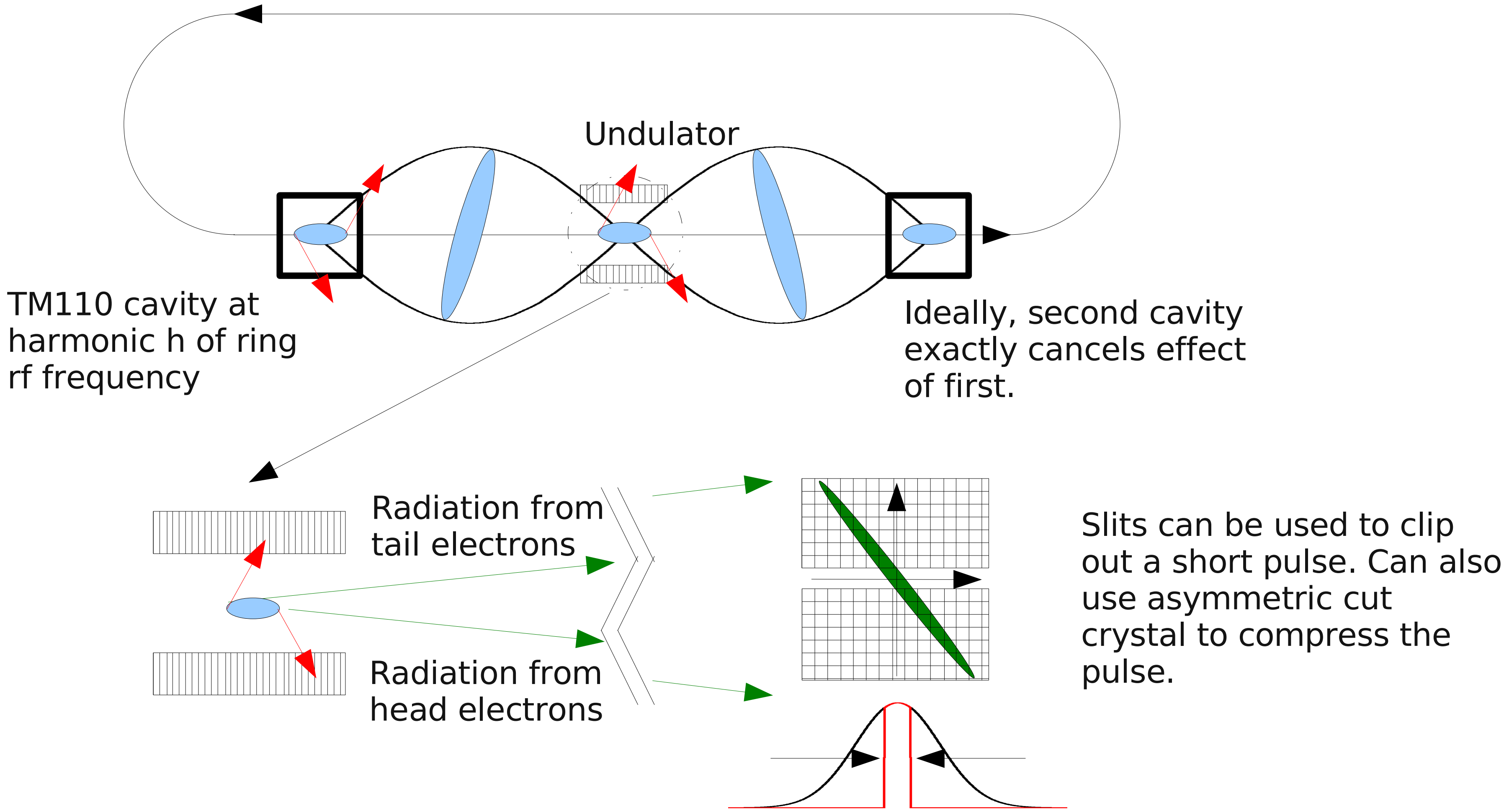
Horizontal Emittance Evolution



Discussion of ERL Ultrafast Mode

- For ~1ps, seems ok, but
  - Assumed smooth, gaussian input bunches
- Average current is 1 mA, so flux down 100-fold
- Brightness is down even more
  - Vertical emittance ~14-fold bigger (0.025 nm now)
  - Horizontal emittance ~6-fold smaller
  - Average brightness down ~200-fold
- Charge per bunch down 60-fold, so peak brightness basically unchanged
- This mode would put almost all APS users off the air.

Short Pulses from a Storage Ring: Zholents' Concept[1]



[1]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.

Crab Cavities with ERL?

- X-ray pulse duration for Zholents' crab cavity scheme[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

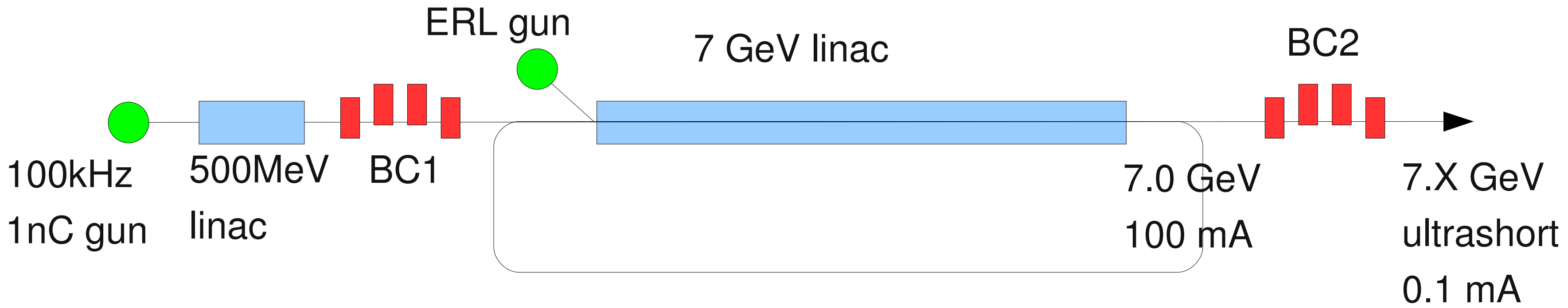
0.3A and L_u=10m

- 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 somewhat limited but intriguing.

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

Ultrashort Mode with Second Gun

- Bazarov[1] suggests that ultrashort pulses should be delivered with a separate gun to a separate user hall

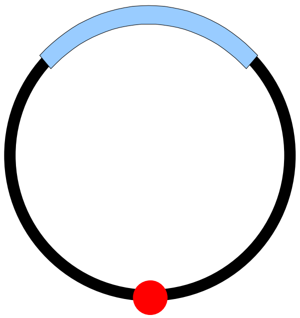


- Due to low repetition rate of high charge gun, don't need energy recovery
- Limitation on average current is from beamloading
- Advantage: ERL runs normally for rest of user community
- Disadvantage: must build new beamlines for timing users
- Some of our options (see Decker's talk) accommodate this mode.

[1] I. Bazarov, private communication.

Short Pulse Option: Hybrid ERL/SR Mode

- Can we mix Ultrafast ERL and stored beam?
- Partial solution to ERL operating mode issues
- 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
  - Need fast 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
- Average current would be up to 0.27 mA
  - Up to 2 MW beam power, maybe don't need ER
- No physics reasons this won’t work.



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Beam Loss Issues[1,2]

- Possible problems include
  - Inefficient energy recovery
  - Cryogenic load in linac
  - Radiation hazard to users
  - Radiation damage to equipment
  - Catastrophic damage to equipment from beam strike
- APS injector delivers a mere 10 nA
  - Efficiency of charge transfer is 80 to 90%
  - "Maximum Credible Incident" is a 44 nA loss at one spot in ring
    - *11 rem/hour radiation outside shield wall*
  - Even 1 PPM loss from 100 mA ERL corresponds to 100 nA
- *Should we just run and hide from the ERL?*

[1]CY Yao, "Beam Loss Issues of ERL Accelerators," 10/12/06.
[2]M. Borland and A. Xiao, OAG-TN-2006-052, 10/16/06.

Continuous Beam Loss Mechanisms[1]

- Optical mismatch in beam transport systems
- Beam halo, from many sources
  - Space charge
  - Scattered drive-laser light
  - Field emission
  - Gas scattering
  - Touschek scattering
  - Non-linear optical elements
- These are either
  - Present (mostly) at low energy (space charge, laser scatter, field emission)
  - Controllable through proper design (Touschek, nonlinear optics)
- If we can collimate effectively at low energy, we may find losses are controllable.

[1]CY Yao, "Beam Loss Issues of ERL Accelerators," 10/12/06, and references therein.

Implications of MCI for ERL

- MCI gives us a dose/power or dose/current relationship for the existing SR shielding
- To reduce radiation to 1 mrem/hour, limit loss to 4.4 pA
  - That's 0.044 parts-per-billion compared to 100 mA!
- Another way to think about issue is in terms of limiting power/meter[1]
- Put another way, we may have losses at each of 36 to 40 sectors
  - Total loss allowance of up to 170 pA or 1.7 PPB
- Presently for stored beam in 24 bunch mode
  - 100 mA has lifetime of $\tau \approx 6$ hours
  - Losses in a single turn are T_{rev}/τ = 0.17 PPB or 17 pA.

[1] R. Gerig, private communication.

Gas Scattering

- A possible source of beam halo is gas scattering
- We can estimate gas scattering rate from known gas scattering lifetime of the APS
  - ~120 hours for ~1 nT pressure

$$\frac{dI}{dt} = \frac{I}{\tau} \rightarrow \Delta I = \frac{I}{\tau} T_0$$

- For APS, T_0=3.68 μs so for 100 mA, loss current is 0.9 pA
- Expect a somewhat larger value for entire ERL
  - Probably much longer than APS
  - Not all at 7 GeV
- Overall doesn't appear to be serious.

Touschek Scattering[1]

- Touschek scattering is a worry for low-emittance bunches
- We can use Piwinski's lifetime formula to get the loss rate for ERL

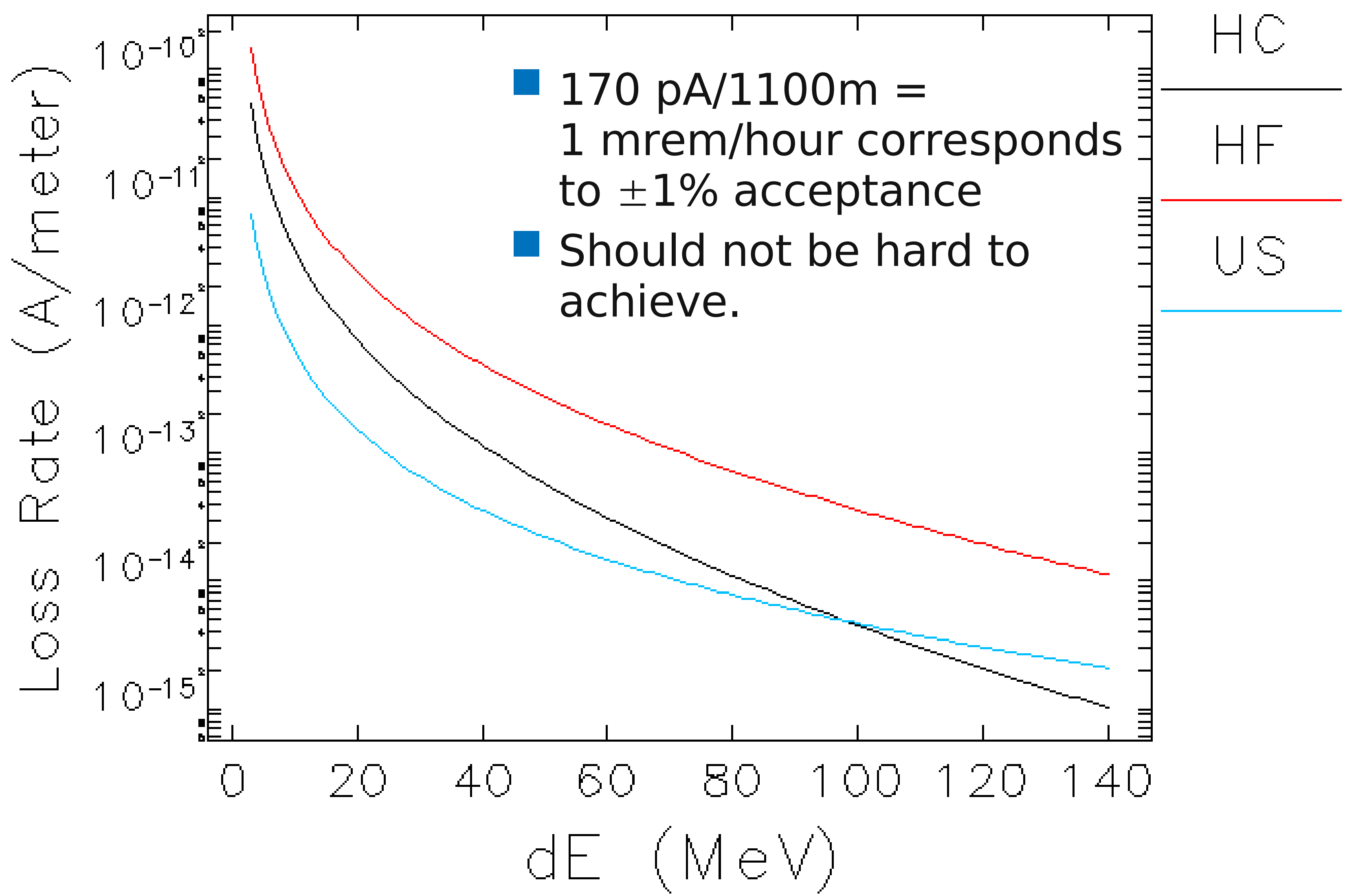
$$\frac{1}{T} = \left\langle \frac{r_p^2 c N_p}{8\pi\gamma^2\sigma_s\sqrt{\sigma_x^2\sigma_y^2 - \sigma_p^4 D_x^2 D_y^2}\,\tau_m} F(\tau_m, B_{1,} B_2) \right\rangle$$

where $\tau_m = (\beta \Delta p/p)^2$

- Piwinski's formula gives the rate of scattering outside of a particular momentum aperture Δp
- We can estimate the loss rate by assuming a constant energy acceptance
  - Later, we optimize the acceptance and estimate loss distribution.

[1]A. Xiao, OAG-TN-2006-048, 10/10/06.

Cumulative Loss Rate in APS for Different ERL Modes[1]



[1]M. Borland, A. Xiao, OAG-TN-2006-052, 10/16/06.

Energy Aperture Optimization

- Purpose of energy aperture optimization is to reduce losses in user arcs due to Touschek scattering
- Initially, we tried simply correcting chromaticity, but results were not very good
- Used method that more directly simulates the problem
  - Put energy scattering elements after each magnet to model Touschek scattering
    - *Each particle gets scattered once only*
    - *Energy offset scattering distribution is uniform ±2%*
  - Put in realistic physical apertures
  - Track from the start of the turn-around arc to the exit of APS
    - *Don't include exit transport line or linac*
  - Using tracking, optimize for
    - *Maximum transmission to the end of the arcs*
    - *Centroid of final momentum distribution equal to 0*
- We used the parallel version[1] of **elegant** for this task.

[1]Y. Wang and M. Borland, Proc. AAC06, to be published.

Discussion

- Outlook for beam loss issues:
  - Touschek scattering is main loss mechanism at high energy
  - Touschek-scattered particles are lost quasi-uniformly around the circumference
  - We can probably keep loss rates under 170 pA and doses under 1 mrem/hour with
    - *Sufficient energy aperture (±1%)*
      - See later talk for results.
    - *Halo collimation (at low energy).*
- Using the high-coherence mode gives a 10-fold reduction in Touschek rate
  - Also gives higher spectral brightness[1]

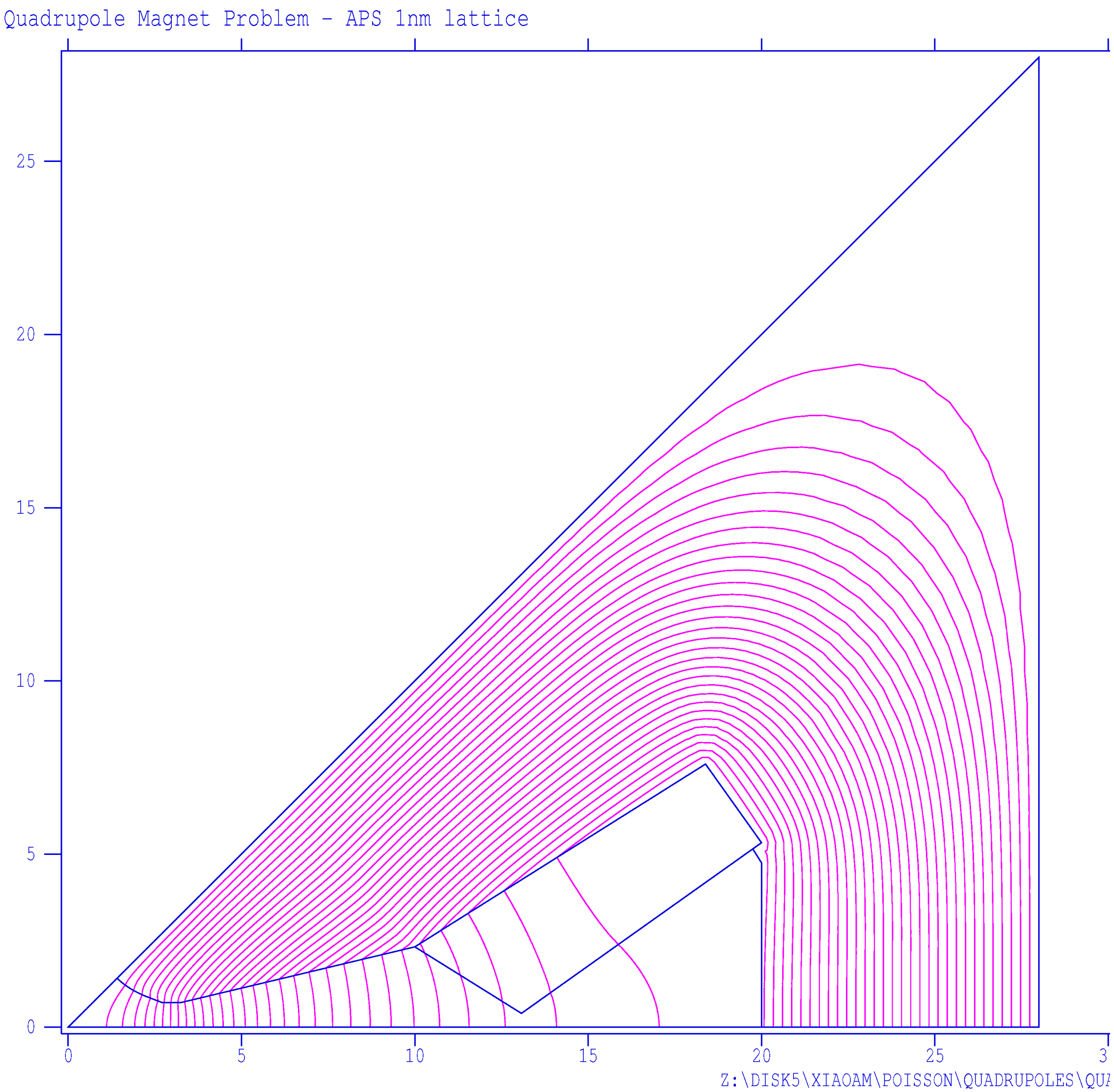
[1]R. Dejus, private commication.

Magnet Designs for ERL and SR Work

- APS magnets are quite conservative
  - 40 mm bore radius
  - Quadrupoles up to $K_1 = 0.9\ 1/m^2$ or 21 T/m
  - Sextupoles up to $K_2 = 30\ 1/m^3$ or 700 T/m^2
- We find we need stronger magnets for ERL (and SR) upgrades
  - Need many short, strong-focusing cells
  - Forces magnets to be short, therefore stronger
  - Sextupoles must be strong because new ERL arcs have very low dispersion
- We've designed around a 20 mm bore radius. Feasible[1] designs found
  - Quadrupoles up to $K_1 = 2.35\ 1/m^2$ or 55 T/m
  - Sextupoles up to $K_2 = 183\ 1/m^3$ or 4.3 kT/m^2

[1]A.Xiao, M. Jaski.

2D Quadrupole Design[1]



Maximum gradient:
54.9 T/m

Maximum K_1 @ 7GeV:
2.35 1/m^2

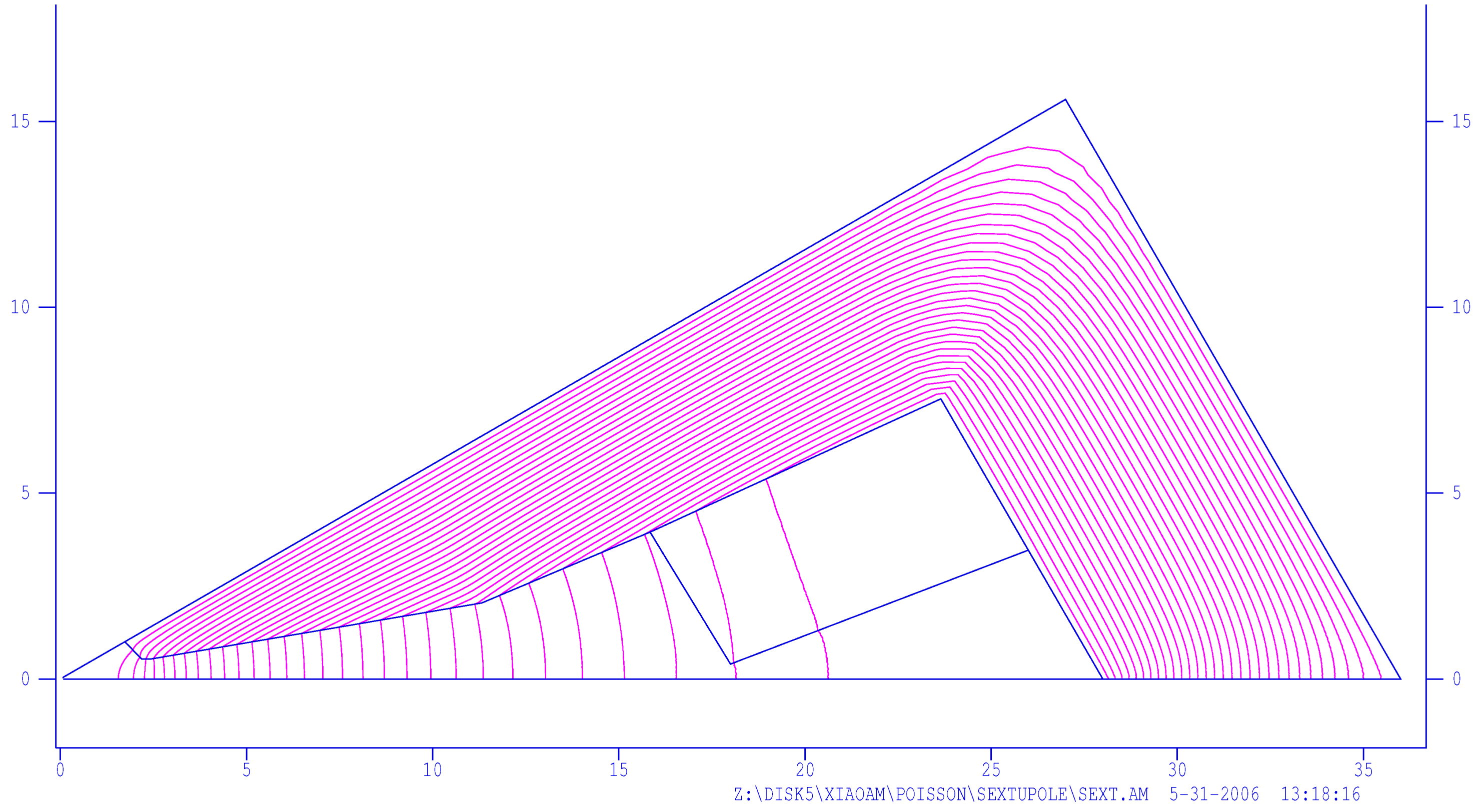
Maximum field in iron:
2.1 T

Current density:
3.4 A/mm^2

Vacuum chamber[2]:
Round, 30 mm ID

[1]A.Xiao, M. Jaski
[2]G. Goeppner

2D Sextupole Design[1]



Maximum strength:
4.3 kT/m^2

Maximum field in iron:
2.0 T

Vacuum chamber[2]:
Round, 30 mm ID

Maximum K_2 @ 7GeV:
183 1/m^3

Current density:
2.0 A/mm^2

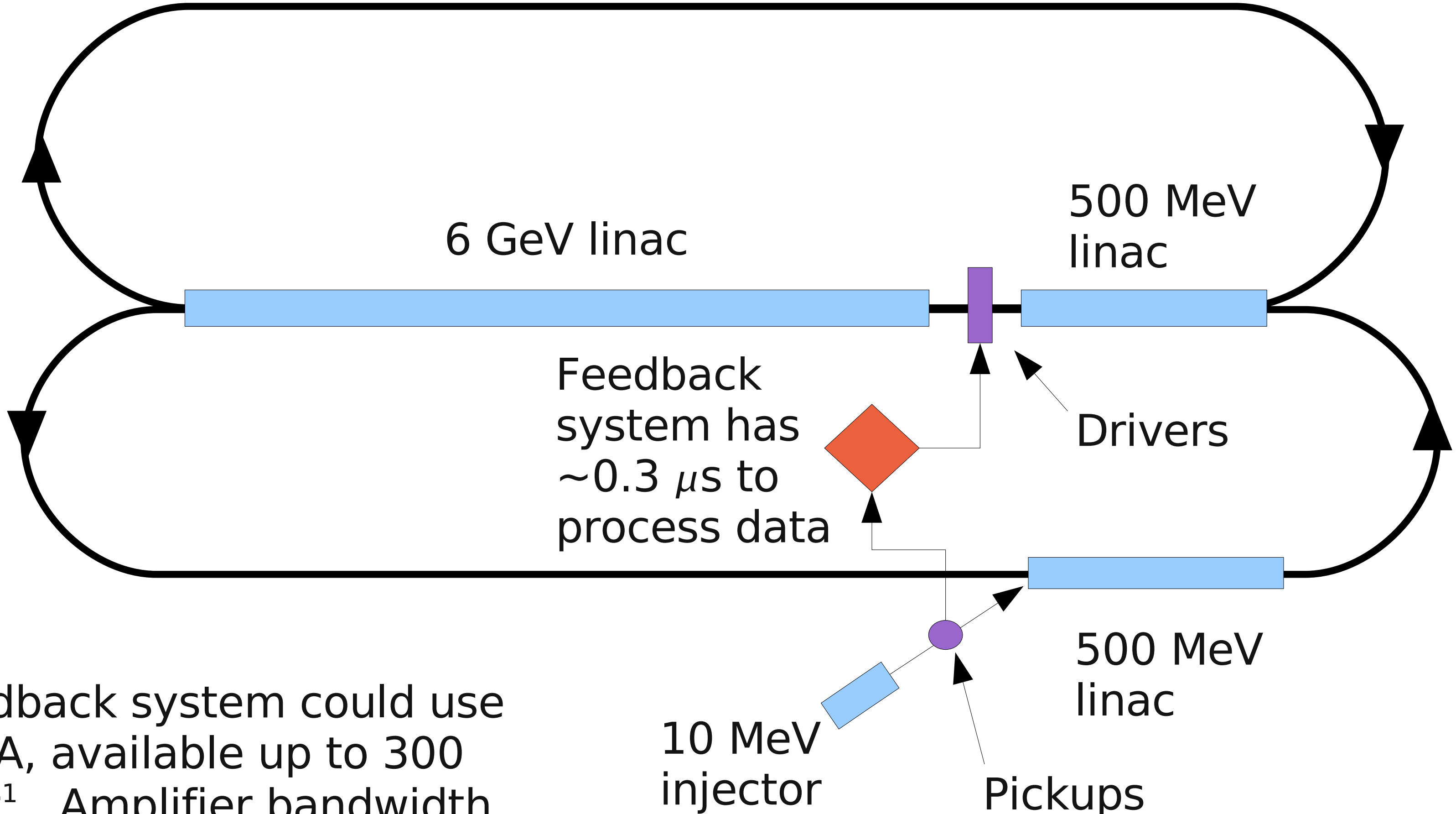
[1]A.Xiao, M. Jaski
[2]G. Goeppner

Stability and Diagnostics Issues

- Typical ID beta functions are ~10 m with ~7 pm geometric emittance
  - Typical beam size of 8 μm
- APS beam sizes at ID now are 280 μm and 8.7 μm
  - Should be able to measure emittance of ERL beam using ID35 beamline[1]
- APS stability now is 1.5 μm horizontal and 0.9 μm vertically in 0.016~30 Hz band
  - Scaling to ~10m beta function, this is equivalent to 1.1 μm horizontally and 1.6 μm vertically
    - *These are ~20% of the ERL 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 ground vibration*
    - *Good signal for BPMs*
  - Advancing technology should allow much faster data collection and feedback.

[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.

Conclusion

- ERL promises very bright beams for x-ray production
- For some ERL issues that are not APS-specific, we've assumed that on-going research will provide solutions
  - Gun design for ultralow emittance
  - Emittance preservation at low energy
  - Cathode lifetime for 25~100 mA CW
  - Beam break-up
- Site-variable issues were reviewed
  - Linac length and optics
    - *10 MeV to 7 GeV and back in one pass linac is feasible*
  - Emittance preservation in arcs
    - *ISR and CSR are concerns (more in later talk)*
    - *IBS is not a problem (see supplemental slide)*
  - Ultrafast ERL beam in APS has issues
    - *Beam corruption, low average current*
    - *Several options available to address this and keep more users happy*

Conclusion

- Site-variable issues (continued)
  - Beam loss is a serious concern
    - *Gas scattering is negligible*
    - *Indicated how to compute Touschek losses (more later)*
    - *Touschek loss rates for APS stored beam already lower than required for ERL*
    - *Assume we can collimate at low energy to eliminate halo*
- Magnets appear feasible, though quite strong
  - Assuming a 30 mm ID chamber
- Diagnostics and beam stability seem within reach
- APS-specific details in subsequent talks
  - Layout options
  - Designs and performance.

Supplemental Slides Follow

Conclusions of A. Todd's Review[1]

- Normal conducting rf guns are the least viable technology
  - Gradient limited by power load
  - Cathode technology (lifetime, reliability) not there
- Superconducting rf guns are least mature but promising
  - Unproven at high average current
  - In principle will deliver better performance than DC guns
  - No demonstrated cathode technology
- DC guns are in use now at 10 mA level
  - Extrapolation to the 100 mA level looks likely
  - GaAs cathodes are key, but they need periodic recesiation
    - *100 mA with ~100 hour lifetime "within reach"*[2]
- DC guns appear to be the best bet.

[1] A. Todd, NIM A 557 (2006) 36-44.
[2] C. Sinclair, NIM A 557 (2005) 69-74.

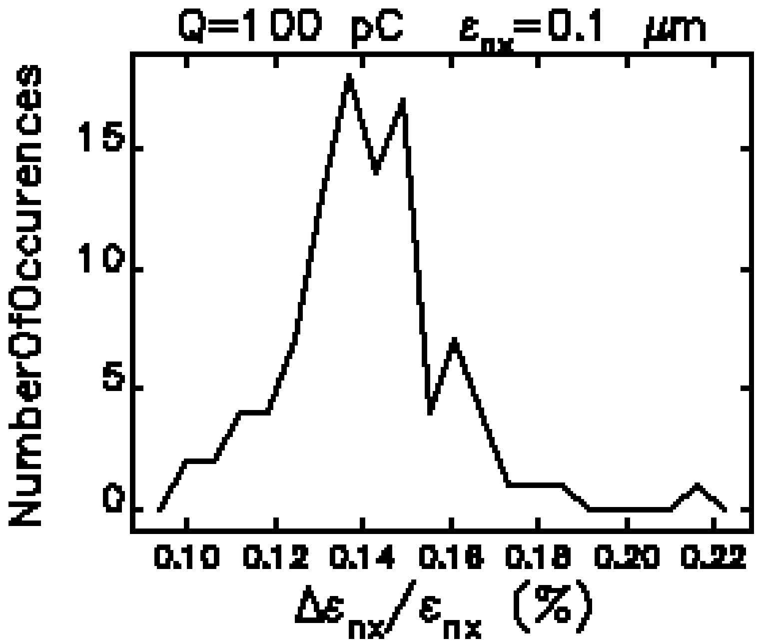
Radiation Opening Angle Effect on Emittance

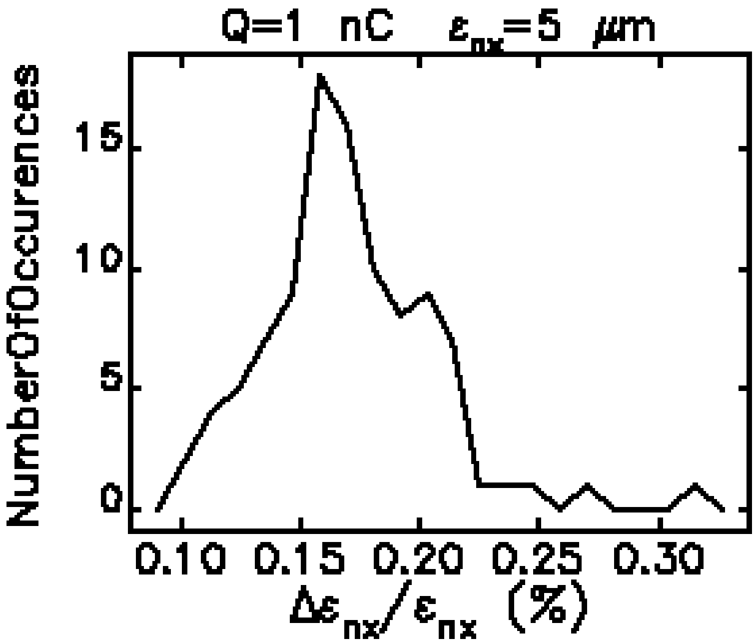
- ERL emittances are 7 GeV are extremely small compared to present storage rings
- Do radiation opening angle effects have an impact?
- Mean photon energy is u_a=0.32 u_c
  - For a 2T dipole and 7 GeV beam, u_a = 22 keV
- Typical emission angle is $1/\gamma \sim 75\ \mu$rad
- Typical transverse momentum change is $u_a/\gamma \sim 1.5$ eV
- Typical slope change is thus ~0.2 nrad
- Even if $\beta \sim 1000$m, beam divergence is ~90 nrad, so effect is neglible
- Tracking with model of detailed photon distributions using **elegant** confirms this conclusion[1].

[1]M. Borland, OAG-TN-2006-043, 10/4/06.

Emittance Preservation at High Energy: Wakes

- Short-range wakefields may impact ultra-small emittances
- Checked this by tracking with **elegant**[1]
  - 7 GeV single-pass linac design (shown later)
  - TESLA cavity wakefields[2]
  - 1 mm rms cavity misalignments
- Transverse wakes not an issue.





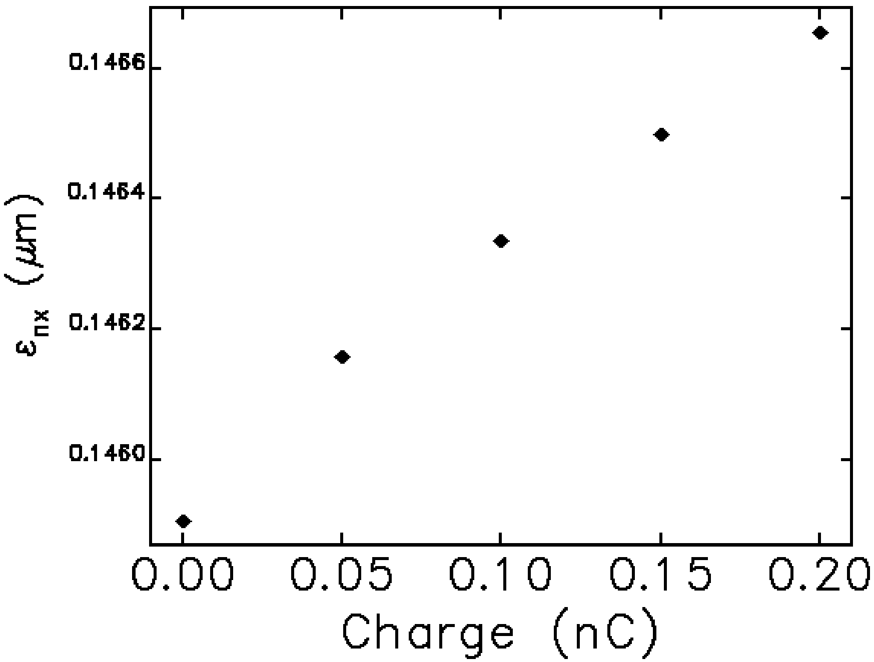
[1]M. Borland, APS LS-287, September 2000.

[2]T.Weiland, I. Zagorodnov, TESLA 2003-19.

Intrabeam Scattering

- Intrabeam scattering is a well-known barrier to low emittance in storage rings
  - What about even smaller ERL emittances?
- Tracking program **elegant** includes calculation of IBS growth rates using Bjorken-Mtingwa method
  - Designed for multiturn tracking but applicable here
  - Assumes periodic lattice functions
  - Computes growth rate using turn-by-turn emittances
- Apply to ERL case to estimate effect
  - Simulate the APS ZD lattice only
  - Insert IBSCATTER element at each straight section with 1/40 strength
- Results show IBS not an issue.

IBS Results for ERL Beam in APS ZD Lattice



Emittance increase from 0.1um dominated by ISR.

IBS gives <0.01 um additional at 0.2 nC

Energy spread increases by only 0.18 MeV due to IBS at 0.2 nC