ICFA Workshop on Future Light Sources: FLS 2012

Ultimate Storage Ring Based Light Sources, Comparison and Potential Synergies with ERLS

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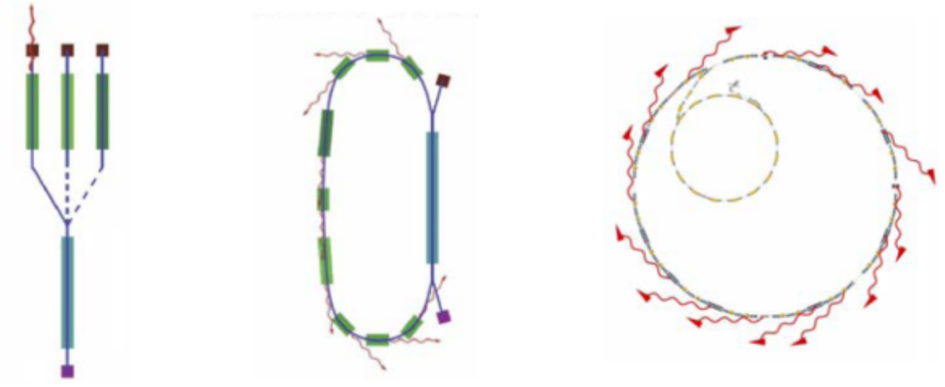
Topics

- Ring Based Light Sources
  - Near term developments
  - Ultimate Sources
    - Soft/Intermediate/Hard x-rays
- Comparison with ERLs
- Potential Synergies
- Summary

Variety of synchrotron radiation source concepts being pursued

- **(Ultimate) Storage rings**
- **Energy recovery linac (ERL)**
- **Free electron laser (FEL)**
- Laser wakefield accelerator
- Optical manipulation of electron beams



Figures of merit

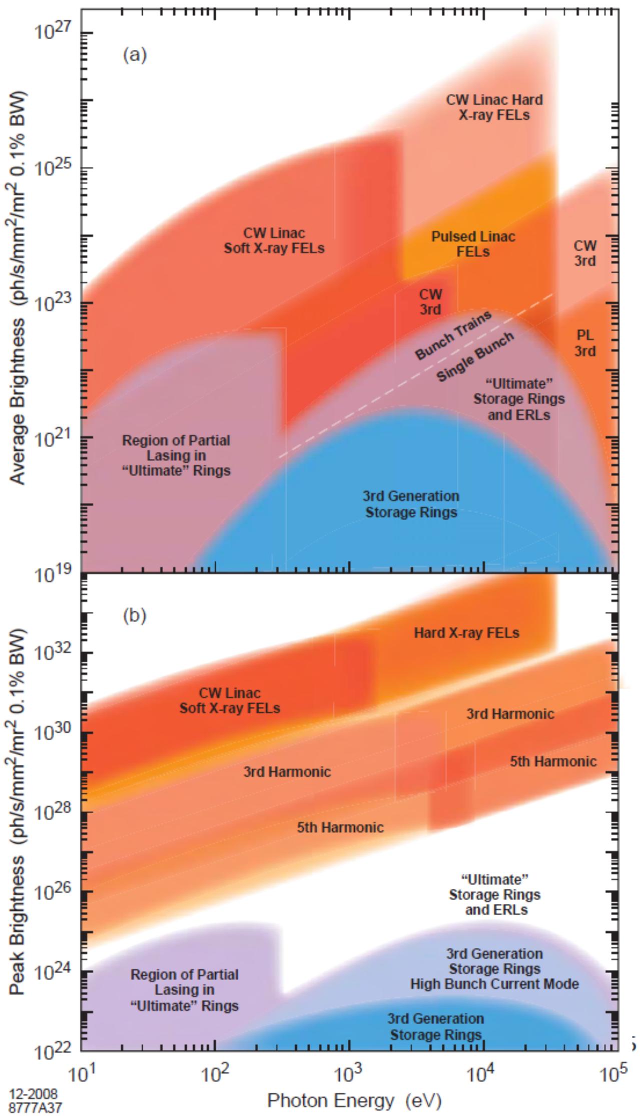
- Average and peak flux
- Average and peak brightness
- Pulse repetition rate
- Temporal coherence
- Bandwidth
- Spatial coherence
- Pulse duration
- Synchronization
- Tunability
- # beamlines
- Beam stability

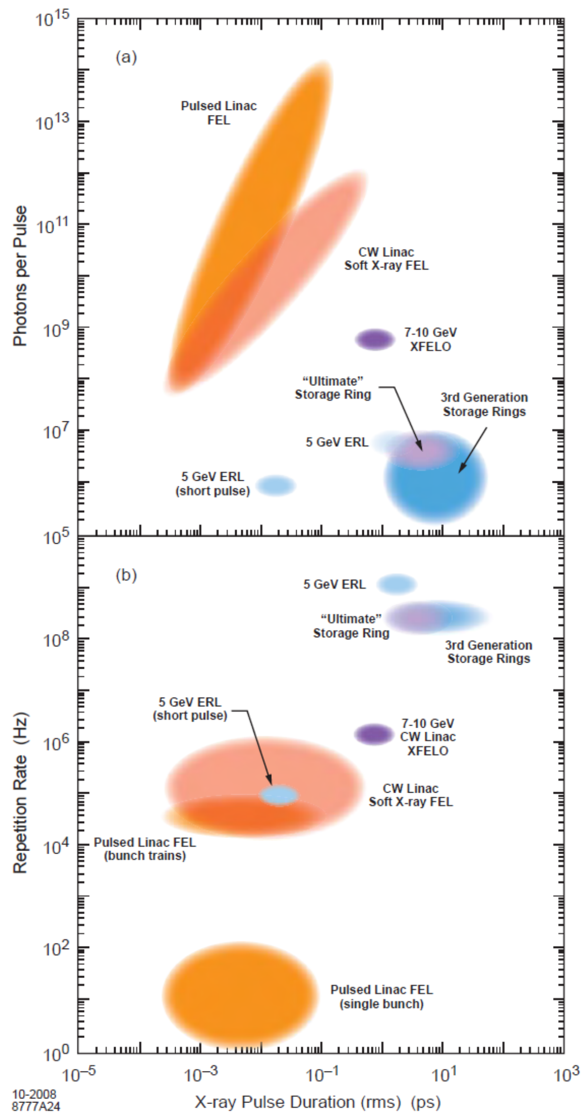
Future generations of light sources will likely utilize novel techniques for producing photons tailored to application needs

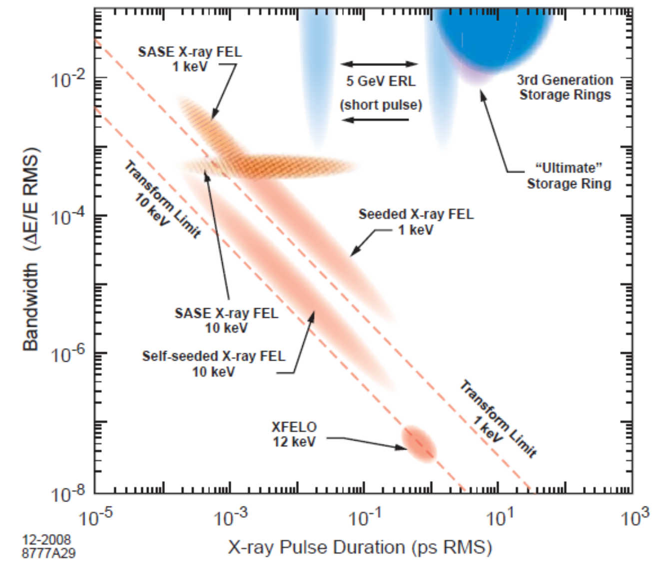
Different operating modes

Different facilities

Rings are Complimentary to FELs







Specific properties of interest for USRs and any X-ray light source include:

- spectral brightness and flux (average and peak)
- coherent fraction and coherent flux
- beam size, divergence and pulse length
- pulse repetition rate and pulse train structure
- energy spectrum and energy spread
- spatial, temporal and spectral stability
- photon polarization

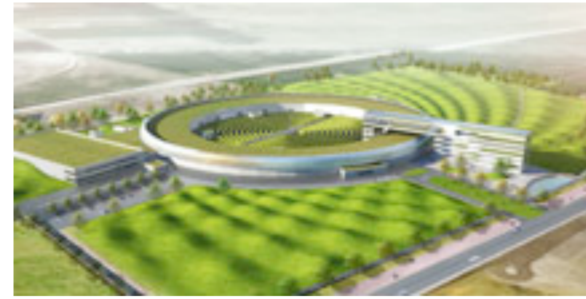
3rd Generation Rings (Current and Future)

SLS (2002) 2.4GeV

ε_x= 3.9 nm, ε_y=72 pm, I=300 mA

ALS (1993) 1.9GeV

ε_x= 6.3 (2.2) nm, ε_y=30 pm, I=500 mA



MAX-4 (2016) 3GeV

ε_x= 0.2-0.3 nm, ε_y= 8 pm, I=500 mA

NSLS-II (2013) 3GeV

ε_x= 0.6-1.1 nm, ε_y= 8 pm, I=500 mA

Soleil (2006) 2.75 GeV

ε_x= 3.7/5.6 nm, ε_y=37 pm, I=400(500) mA

APS (1995) 7GeV

ε_x= 2.5/3 nm, ε_y=25 pm, I=100 mA

Diamond (2007)

3.0 GeV

ε_x= 3.0 nm,

ε_y= 30 pm,

I=300(500) mA

Brightness, Diffraction Limit, Natural Emittance

- **Spectral brightness: photon density in 6D phase space**

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(s \cdot \% BW)}$$

$\varepsilon_{x,y}$ = electron emittance ε_r = photon emittance **= $\lambda/4\pi$**

- **Horizontal (natural) emittance determined by balance between radiation damping and quantum excitation due to synchrotron radiation in all magnets:**

$$\varepsilon_x = Q_x \tau_x \ , \quad Q_x \approx E^5 \oint B^3 \frac{\eta^2 + (-\frac{\beta_x'}{2}\eta + \beta_x \eta')^2}{\beta_x} ds \ , \quad \frac{1}{\tau_x} \approx J_x E^3 \oint B^2 ds$$

- **How to minimize emittance?**
  - **Reduce dispersion and beta function in bend magnets (wigglers/undulators)**
  - **Achieved by refocusing beam 'inside' bending magnets -> need space**
  - **'Split' bending magnets -> multi bend achromats**

Natural Emittance / Coupling

Emittance scaling with energy and circumference:

$$\varepsilon \propto E^2\theta^3 F(\text{lattice}) \qquad \theta = \text{dipole bend angle}$$

$$\Rightarrow \varepsilon \propto \frac{E^2 F(\text{lattice})}{N^3} \qquad N = \text{number of dipoles} \propto \text{ring circumference}$$

Coupling / Transverse Emittance Redistribution:

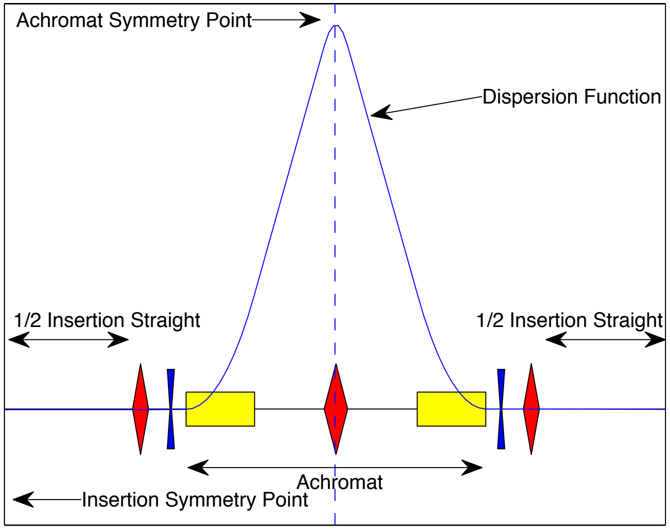
$$\varepsilon_x = \frac{\varepsilon_{nat}}{1+\kappa}, \varepsilon_y = \frac{\kappa \cdot \varepsilon_{nat}}{1+\kappa}$$

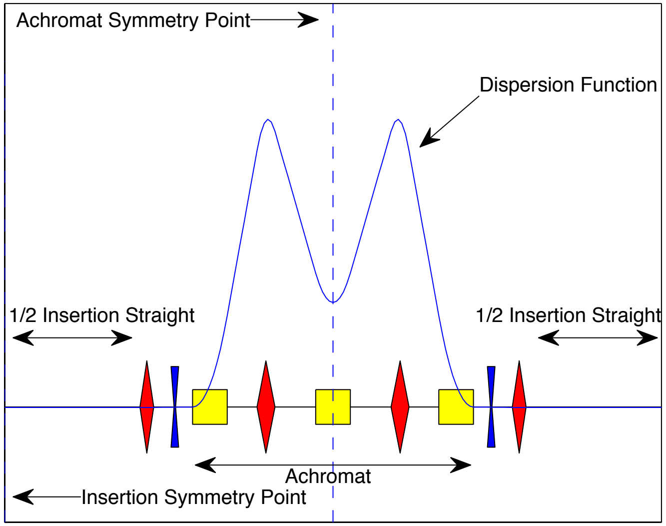
Emittance reduction with damping wigglers:

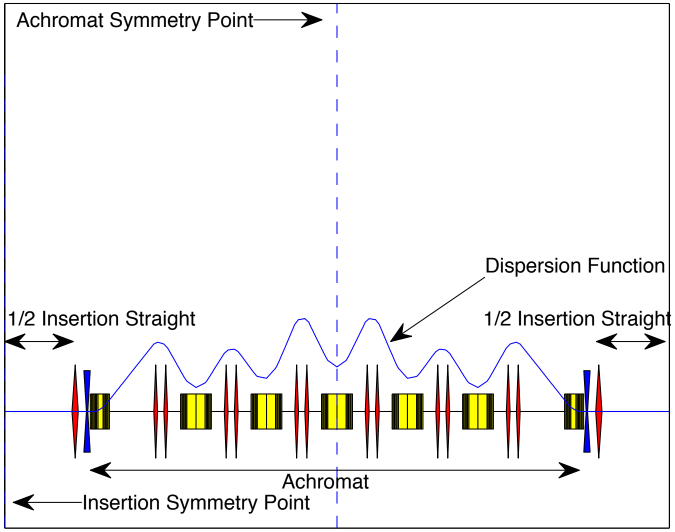
$$\frac{\varepsilon_w}{\varepsilon_o} = \frac{1+f}{1+\frac{L_w}{4\pi\rho_o}\left(\frac{\rho_o}{\rho_w}\right)^2} \approx \frac{1}{1+\frac{U_w}{U_o}}$$

Need to find optimum balance between emittance, energy spread, momentum compaction factor, collective effects (e.g. microwave instability, intra beam scattering

Common Lattice Options







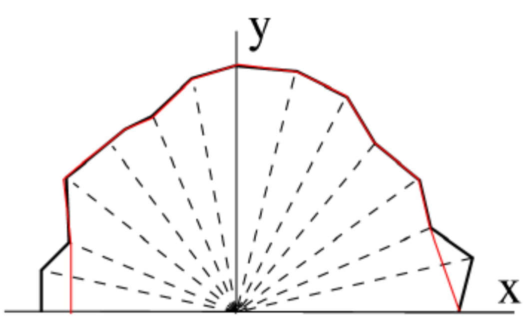
- Early 3rd generation SR sources all used double/triple bend achromats (some with gradient dipoles)
- Later optimization included detuning from achromatic condition (Optimizing effective emittance)
- New designs (including USRs) employ MBA
- Damping wigglers can help (emittance, damping time, IBS) but trade energy spread

Features of Ultimate Rings

- Some enabling features for further evolution of rings geared towards delivering diffraction limited (i.e. transversely coherent) spontaneous emission – very high average brightness:
- Multi Bend Achromat design
  - Advanced lattice design techniques as well as beam based optimization techniques
    - Multi objective genetic algorithms, simultaneous linear+nonlinear lattice optimization, driving terms, higher order achromats, frequency maps, parallel computing, use of octupoles, …
- Compactness and high magnet strength enabled by smaller magnet apertures
  - better vacuum system design (NEG coating, …)
  - better magnet tolerances (wire edm, laser cutting, …)
- State-of-the-art Insertion Devices
- Low impedance vacuum system (based on ability to accurately model components)

Comparison of merit functions for dynamics optimization

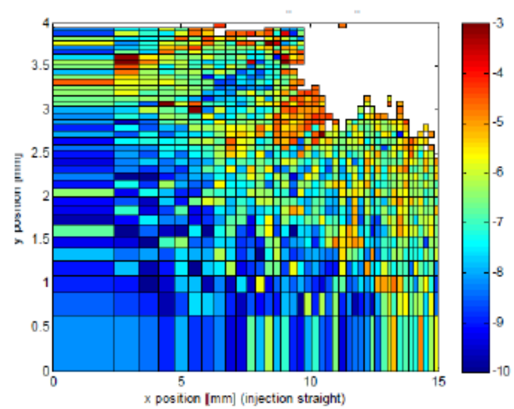
- Dynamics aperture area *[M. Borland, Elegant V 23.1]*
  - ➔ 21 line, and 11 steps for each line
  - ➔ 4 interval splitting to refine the boundary
  - ➔ 512 turns
  - ➔ Boundary is clipped to avoid the island



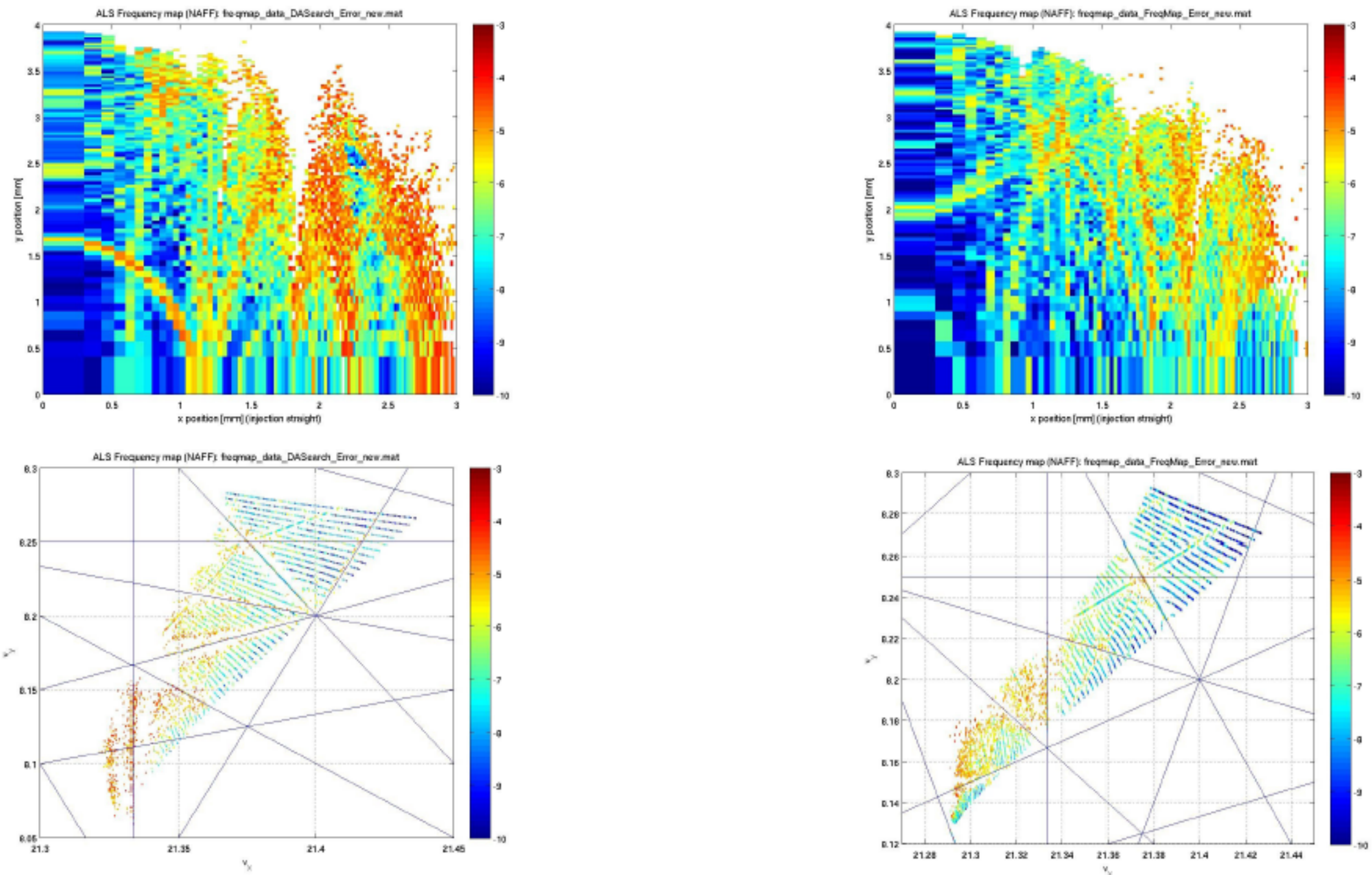
- Total diffusion rate *[C. Steier and W. Wan, IPAC 2010]*
  - ➔ Frequency Map Analysis
  - ➔ 21 by 21 non-uniform grid search
  - ➔ 512 turns for each grid.
  - ➔ Diffusion rate is calculated according to

$$d = \log\left(\frac{\sqrt{(\nu_{x,1}-\nu_{x,2})^2+(\nu_{y,1}-\nu_{y,2})^2}}{N}\right)$$

  - ➔ Diffusion rate is assigned to -3 for lost particle
  - ➔ Boundary is clipped to avoid the island



Example optimization



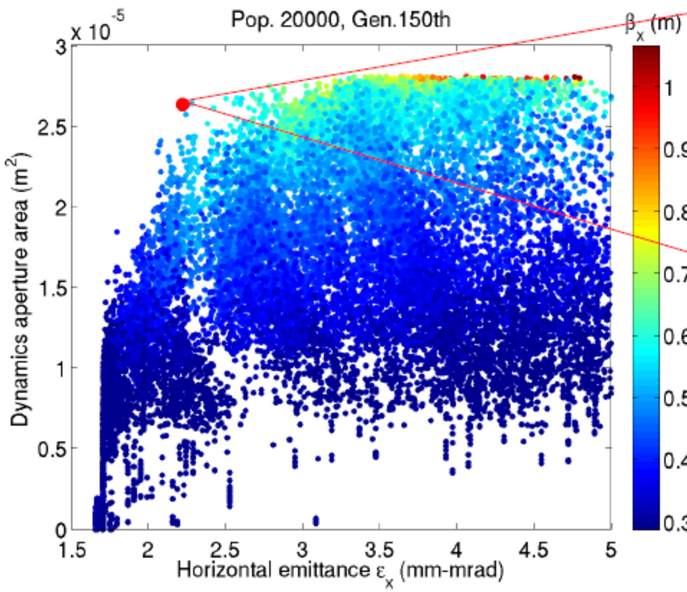
C. Sun

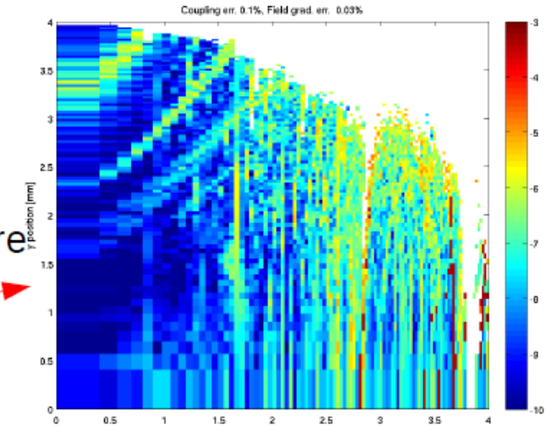
- In this particular example, optimized solution using diffusion rates looks better (maybe not surprising) – but fairly comparable in most cases
- Also allows generally for faster calculation (less initial conditions, fewer turns)

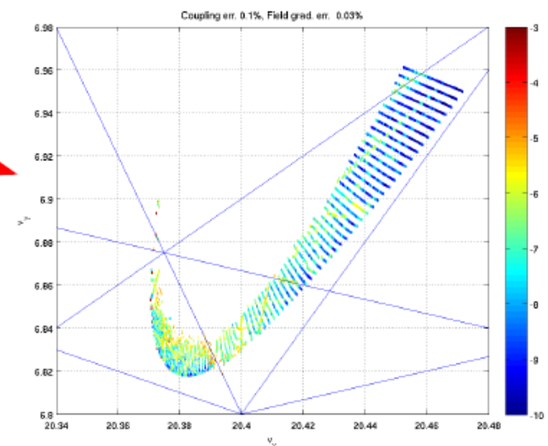
Simultaneous Optimization of linear and nonlinear Lattice

Linear and nonlinear properties of the lattice are optimized simultaneously using GA.

- 7 parameters: 3 Quads + 4 Sextupoles
- 7 constraints: stability, positive partition number, maximum beta and dispersion functions
- 3 objectives: emittance, betax and dynamics aperture







A trade-off between the dynamics and emittance is found.

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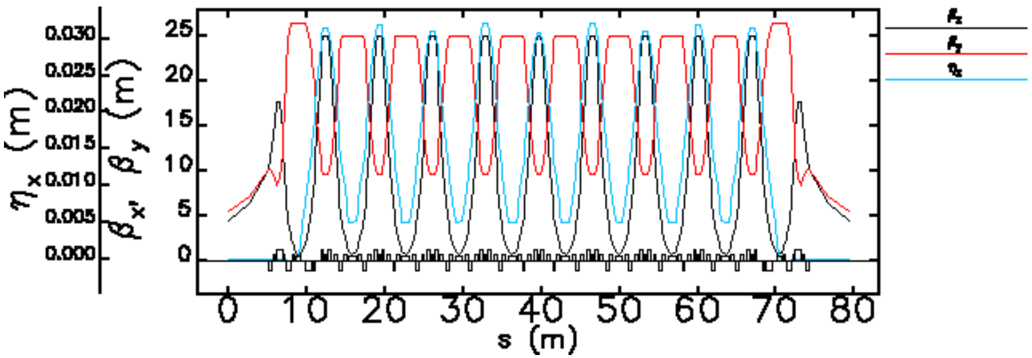
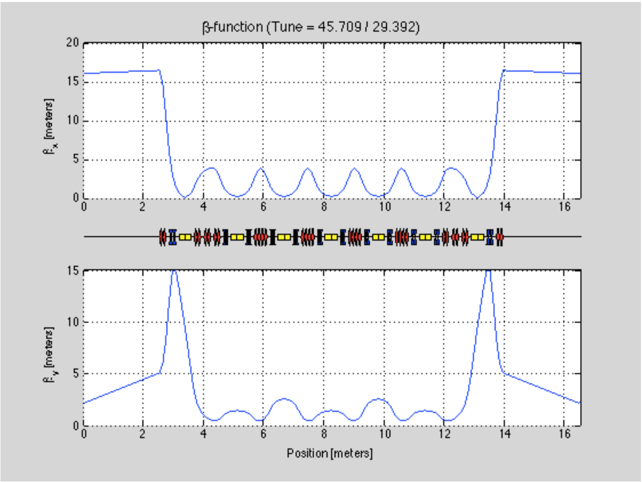
Example USR Lattices

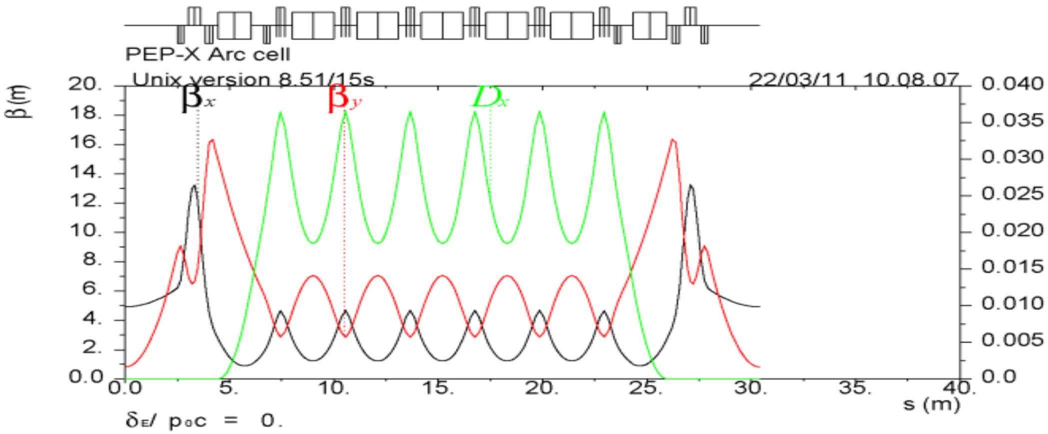


USR7 M. Borland



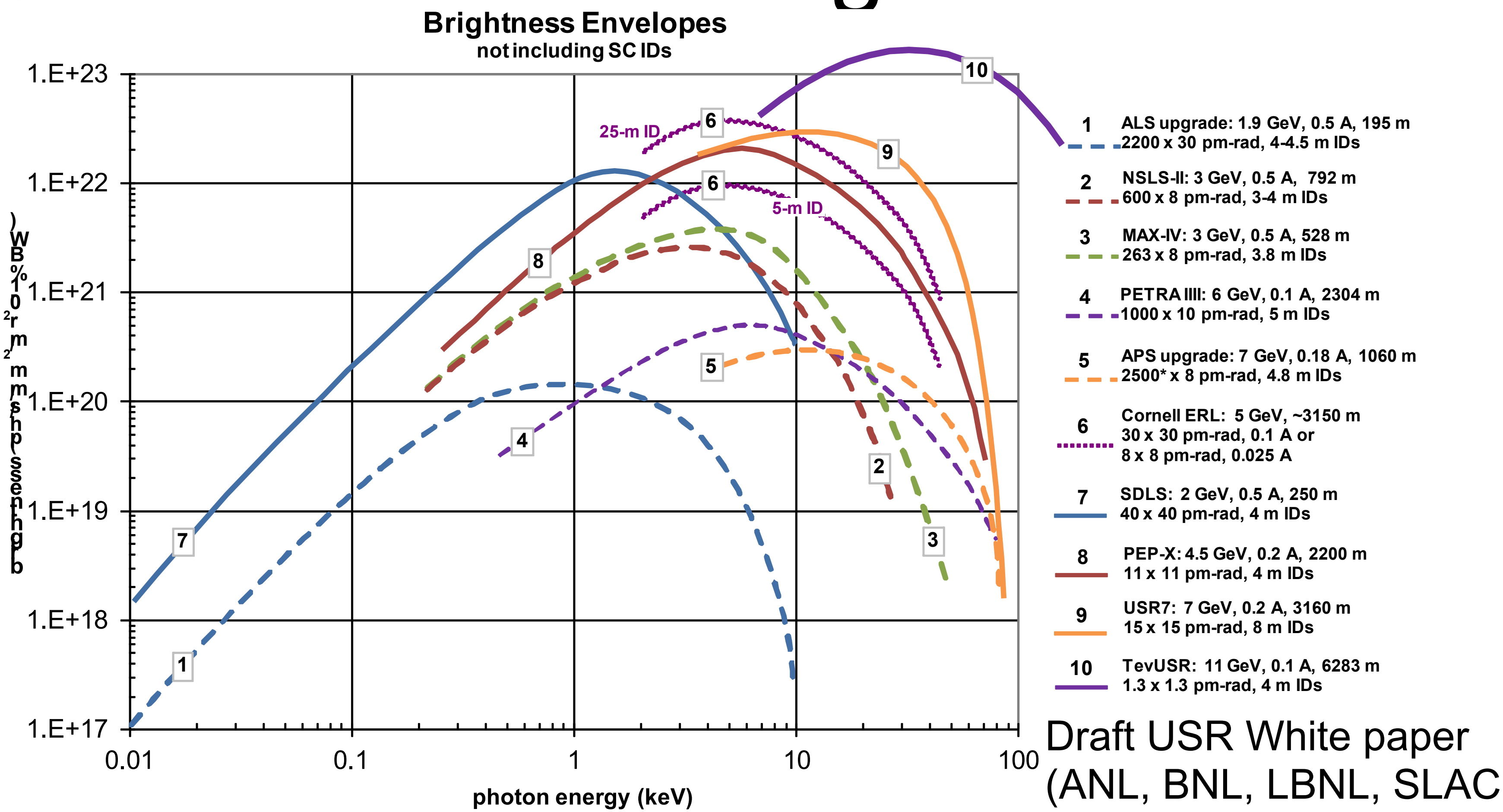
SDLS C. Steier, W. Wan

7BA cell



Y. Cai, et al. modified from MAX-4

USR/ERL Brightness



Draft USR White paper (ANL, BNL, LBNL, SLAC)

Spectral brightness, coherent fraction and beam dimensions will reach unprecedented levels for storage ring sources having emittances approaching the X-ray diffraction limit

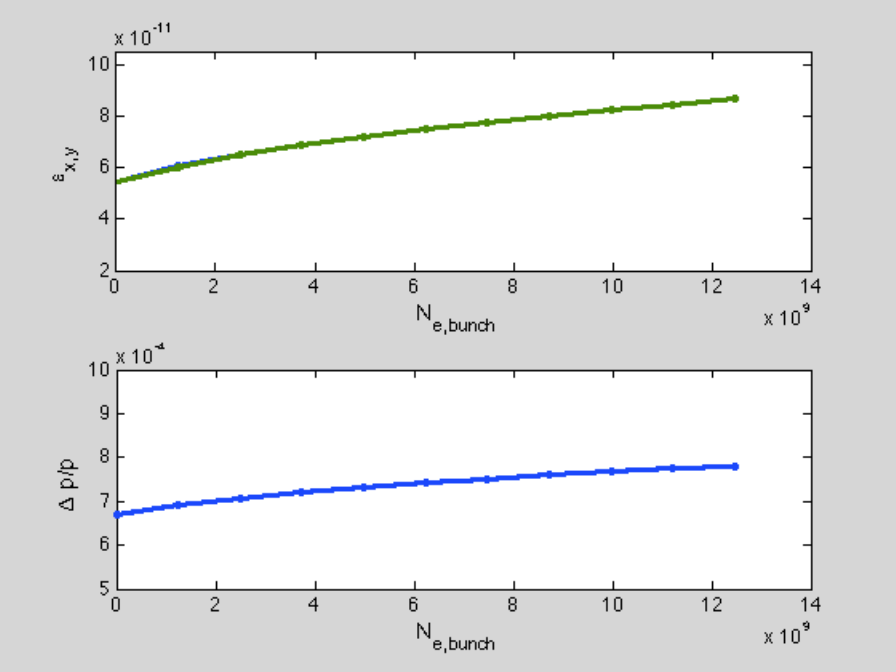
Parameter Range of Candidate Designs

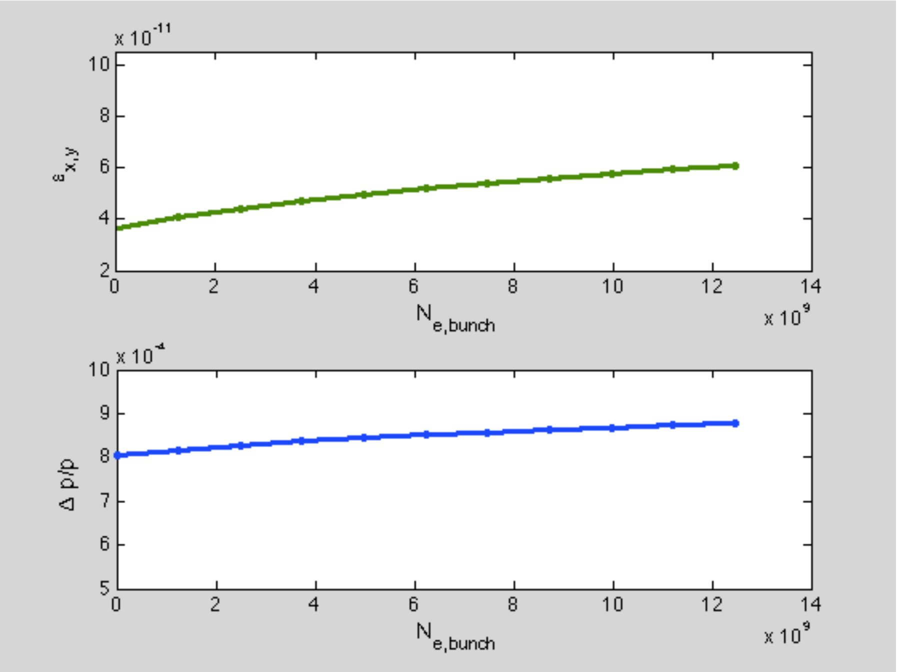
Parameter	< 2 keV[(1)]	2-20 keV[(2)]	>20 keV[(3)]
Electron energy (E_{e-}, GeV)	2	4.5	11
Circumference (C, m)	250	2200[(4)]	2π x 1000
Beam current (I, mA)	500	200[4]	100
Emittance ($\varepsilon_{x,y}$ @ I, pm-rad)	40/40	11/11	1.3/1.3[5]
Diffract-lim photon energy @ $\varepsilon_{x,y}$ (E_{phdiff}, keV)	2.5	9	76[5]
Number of bunches	420	3300	8300
e- size @ ID ($\sigma_{x,y}$, μm RMS)	6.0 / 8.5	7.4 / 3.3	2.5 / 1
e- divergence @ ID ($\sigma'_{x,y}$, μrad RMS)	6.6 / 4.7	1.5 / 3.3	0.5 / 1.3
e- bunch length (σ_s, ps RMS)	6 (18 with HC)	10	10
e- energy spread (σ_δ, RMS)	0.9×10^{-3}	1.25×10^{-3}	1.43×10^{-3}
RF voltage (V_{RF}, MV)	1	8.7	25
Damping wiggler length (L_{DW}, m)	<10	90	188[5]
Lifetime @ I (τ, h)	1.5	2.4	4.5

(1) Very preliminary estimates for the SDLS [C. Steier, W. Wan].
(2) From PEP-X study [Y. Cai, et al.].
(3) From preliminary study of Tevatron-sized USR [M. Borland].

Intra Beam Scattering

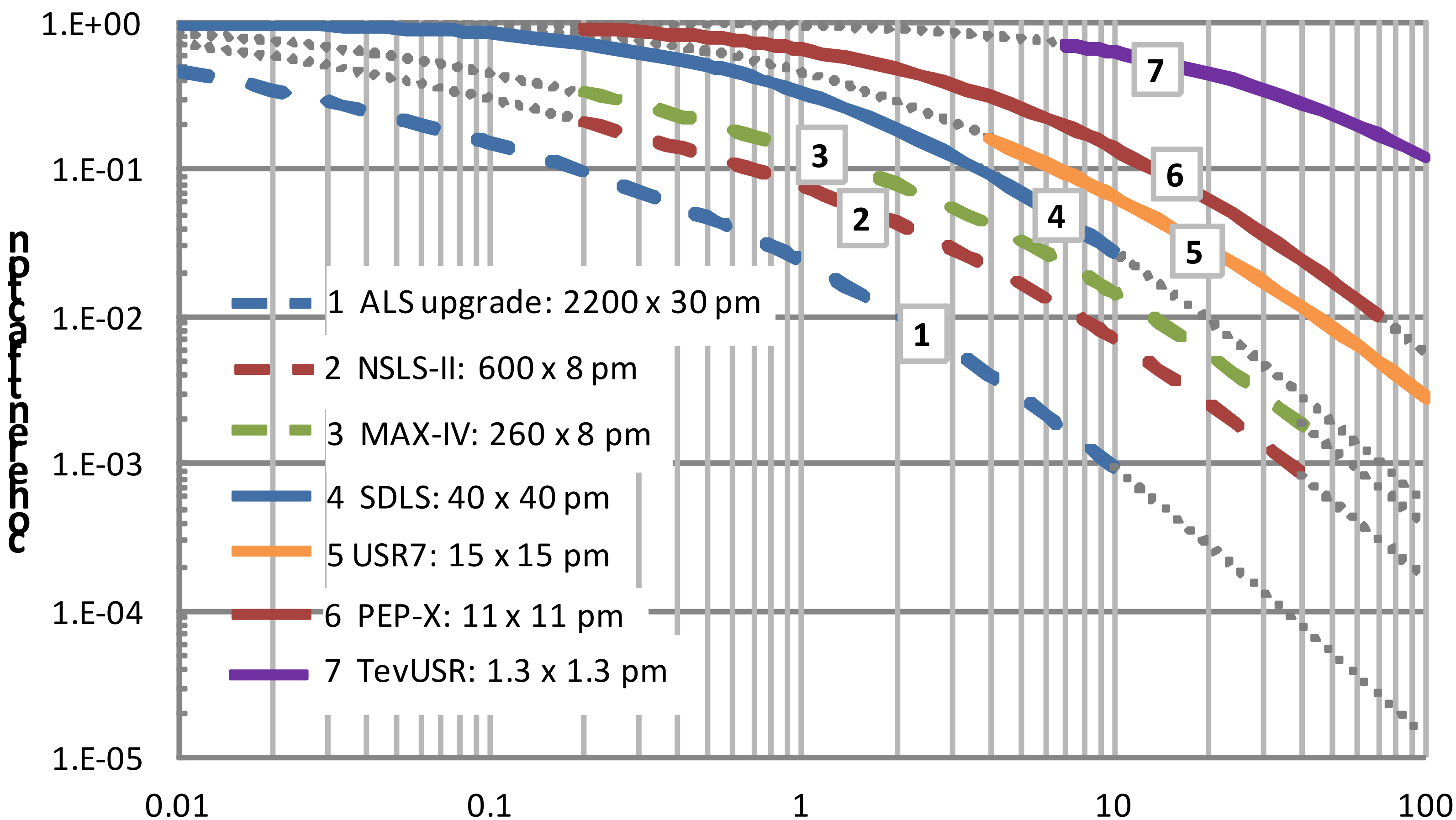
- Intra Beam Scattering is potentially a very significant effect at USRs
  - Higher energy design: Running with full coupling is sufficient mitigation
  - Lower Energies: Combination of harmonic cavities and (some) damping wigglers necessary





Example: pre-conceptual SDLS, 2 GeV, Harmonic Cavities, left no DW, right 10 m DW, 500 mA is 6.5×10^9 e-/bunch

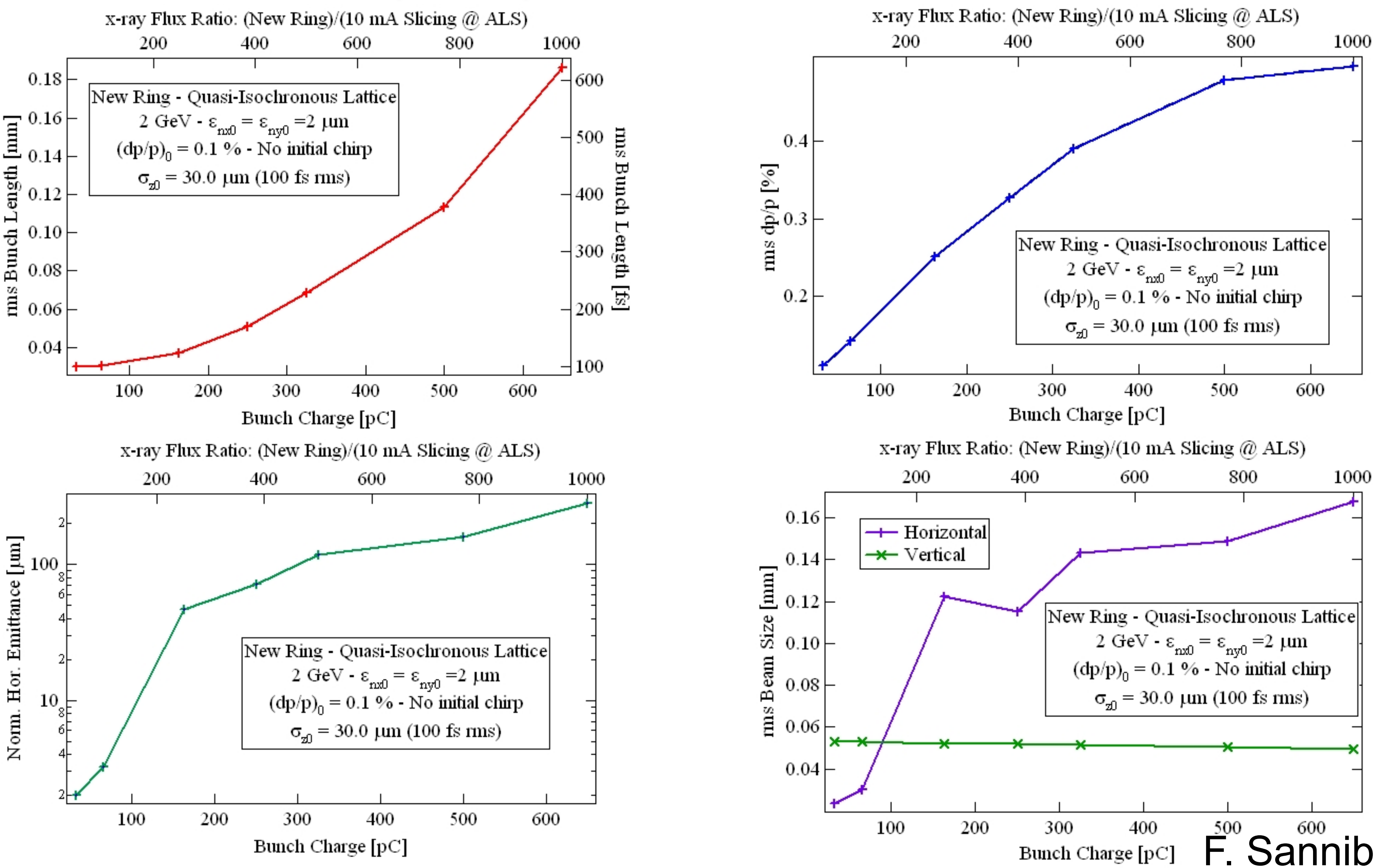
Coherent Fraction



Features of Ultimate Rings

- Besides having diffraction limited emittance (and “round beams”), other features of USRs and their photon beams include:
- **Short bunches:** momentum compaction factor for USRs is factor of >10 lower, allowing (quasi) isochronous transport (but: harmonic cavities)
- **Special operating modes:** USRs open up the potential of implementing many special modes of operation (with potential for simultaneous use), including
  - Single/few-turn, sub-ps bunch mode
  - Crab cavity short pulse scheme (shorter bunches plus smaller emittance might allow much shorter pulses compared to SPX)
  - 100-1000 turn mode, enabling very low emittance with reduced dynamic aperture, requiring injection of fresh electrons from a superconducting linac operating without energy recovery (e.g. ~1 mA @ few GeV)
  - localized bunch compression systems with components located in long straight sections
  - bunch tailoring with low alpha, non linear momentum compaction, multiple RF frequencies
  - lasing in an FEL located in a switched bypass, where the post-lasing electron bunches are returned to the storage ring for damping
  - partial lasing at soft X-ray wavelengths using the stored beam, requiring high peak current created by localized bunch manipulation

Example of Single–Pass Short Bunch Performance: 2 GeV, 5BA, Quasi-Isochronous Lattice

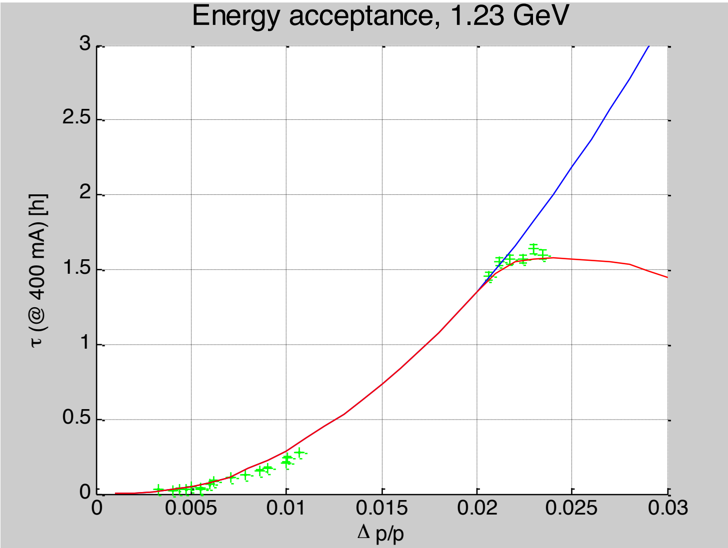


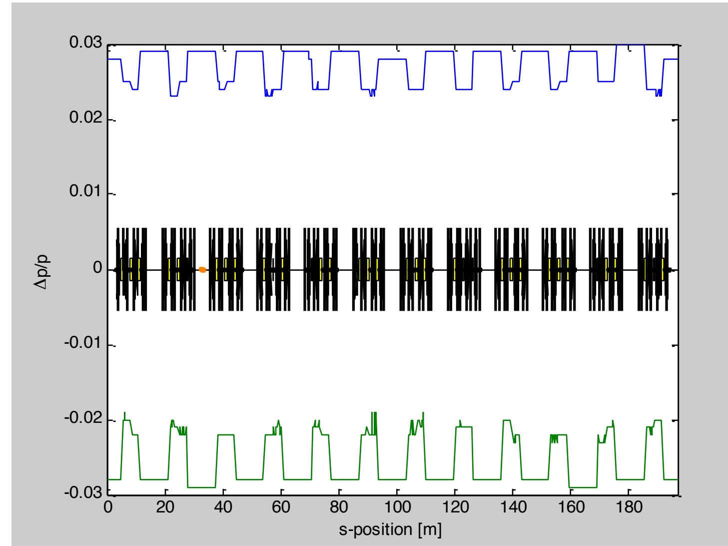
F. Sannibale

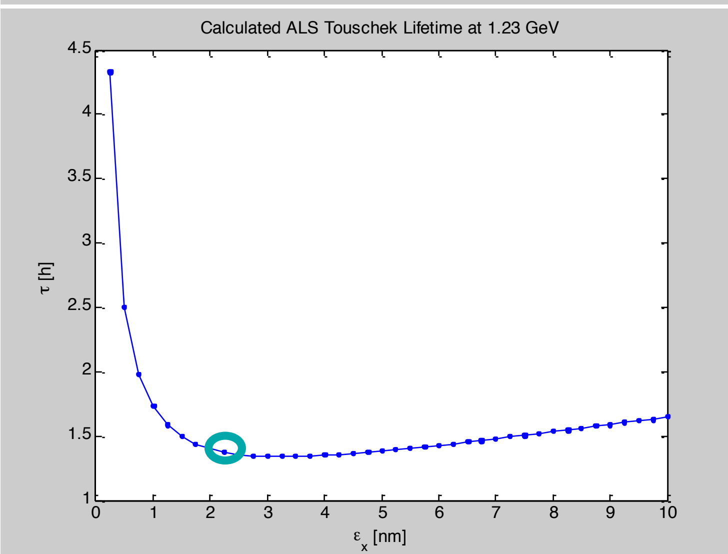
More Supporting Technology …

- **"Long" lifetime:** If transverse emittances are small enough the available transverse momentum is insufficient to scatter outside of momentum acceptance, so fewer particles are lost from the bucket, and Touschek lifetime increases to a few hours. Can be helped by damping wigglers and harmonic cavities (bunch length/density, IBS)
- **Damping wigglers:** If a low field strength of dipole magnets in large-circumference, low- to medium-energy USRs is chosen, the electron energy loss per turn from the dipoles is low, leading to long damping times. These damping times can be reduced by adding high-field wigglers which, if situated in straight sections having no dispersion, also reduce beam emittance by a factor of 2 or more.
- **On-axis injection:** As ring emittance is reduced, so is the dynamic acceptance for injected particles. Beam can be injected into a small dynamic acceptance on-axis if necessary ("swap-out" injection).

Touschek Lifetime @ Small ε_x







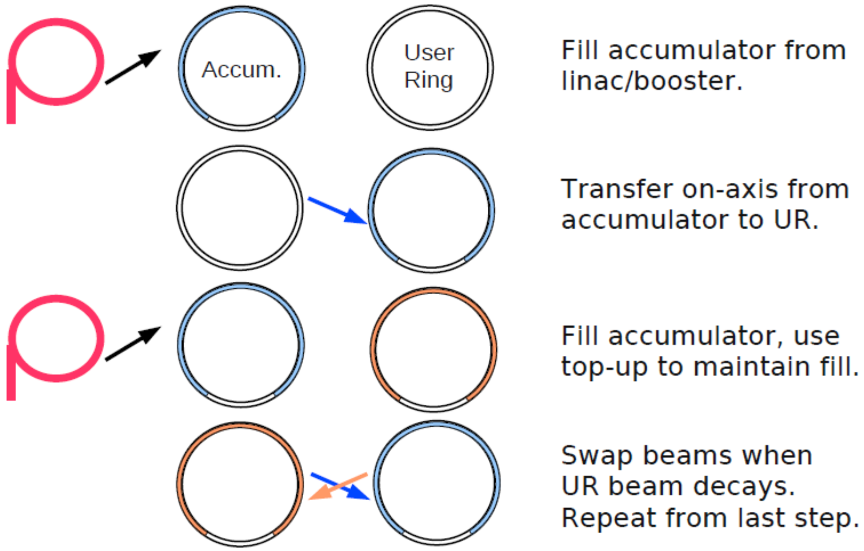
$$\frac{1}{\tau} = \frac{r_e^2 cq}{8\pi e\gamma^3\sigma_s}\frac{1}{C}\oint_C \frac{F\left(\left[\frac{\delta_{acc}(s)}{\gamma\sigma'_x(s)}\right]^2\right)}{\sigma_x(s)\sigma'_x(s)\sigma_y(s)\delta_{acc}^2}ds$$

$$\sigma'_x(s) = \frac{\varepsilon_x}{\sigma_x(s)}\sqrt{1+\frac{H(s)\left(\frac{\Delta p}{p}\right)^2}{\varepsilon_x}}$$

$$F(x) = \int_0^1 \left(\frac{2}{u} - \ln\frac{1}{u} - 2\right)\exp\left(-\frac{x}{u}\right)du$$

Swap Out- Injection

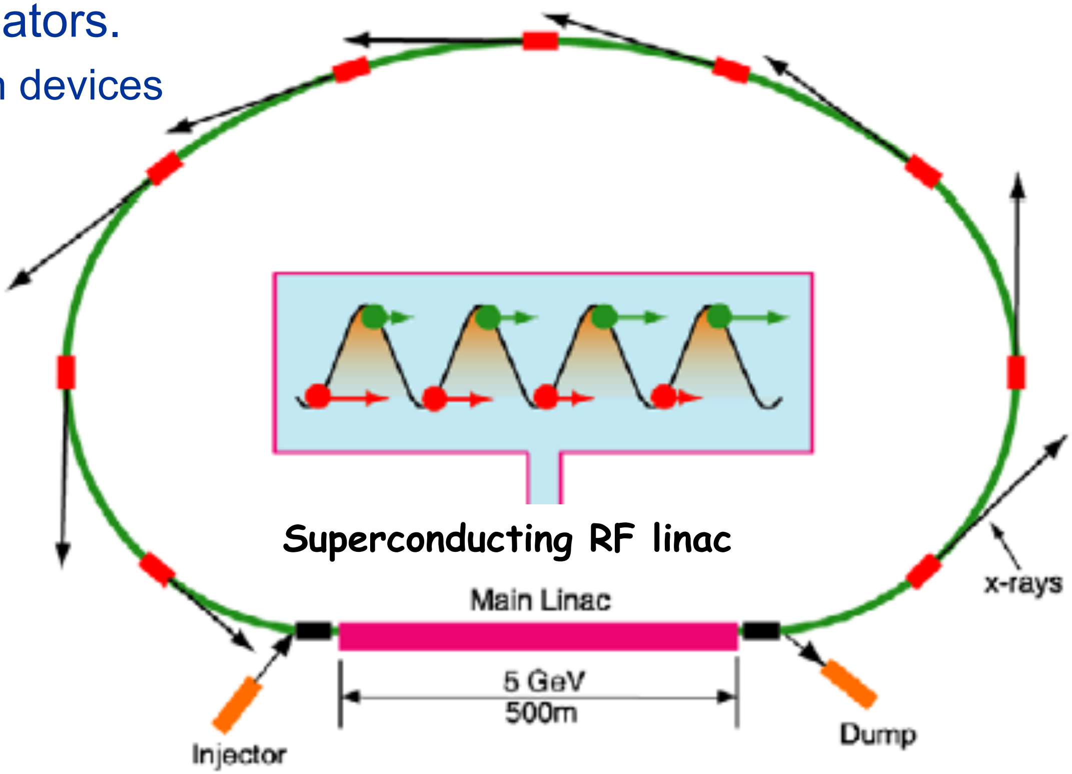
- Once the lattice is pushed to achieve ultrasmall emittances, the dynamic aperture usually shrinks, potentially making beam accumulation (even top-off) impossible. A scheme first proposed by Borland and Emery and later studied elsewhere promises to potentially overcome this obstacle. In this scheme, the whole beam in the storage ring is replaced at once (using either an accumulator ring or a full energy linac with a long bunch train – see figure below).



- [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).

Energy Recovery Linac (ERL)

- An ERL accelerates high-brightness electron beams in a linac and recovers the energy from the beam after it radiates
- High-brightness electron bunches from a photocathode gun + adiabatic damping
- Diffraction-limited radiation into the hard x-ray regime (with a high-energy electron beam)
- Small energy spread = long undulators.
  - Spontaneous emission in insertion devices
  - Multiple operating modes
    - Spatial coherence
    - High brightness
    - Short pulses
  - High bunch repetition rate
    - ~ MHz - GHz
  - High average power
    - Need to recover beam energy
    - 100 mA @ 5 GeV
      - 500 MW

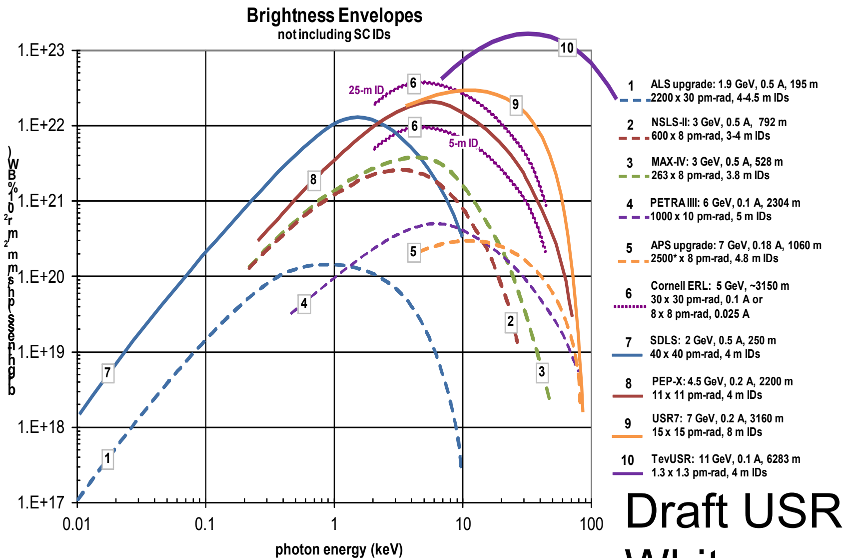


Comparison ERL/USR

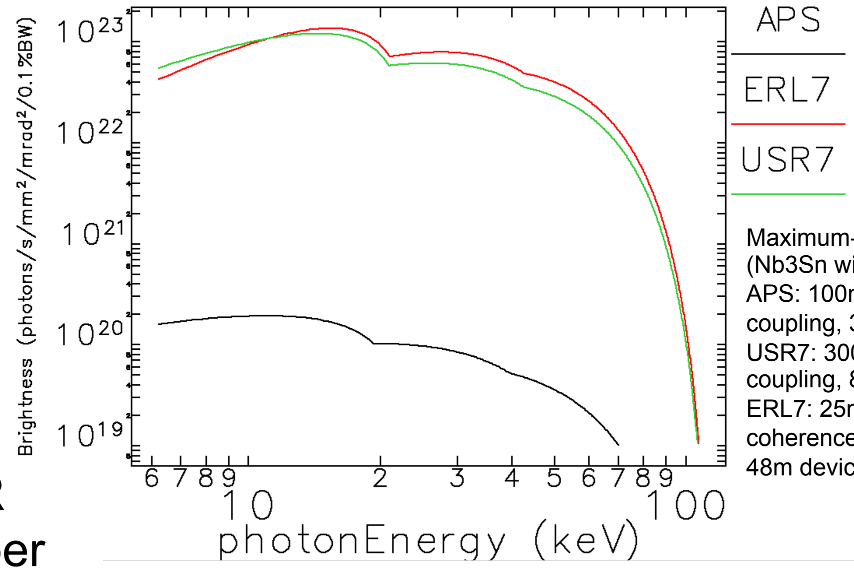
Performance Metric	Advantage	Reason / Comment
Average Brightness	Similar	25 m undulators in ERL, 4-8 m in USR
Average Flux	USR	ERL would require currents >> 100 mA
Transverse Coherence	ERL?	ERL might have matching advantage
Stability	USR	ERL has additional jitter sources
Reliability	USR	Cryoplant, Multiple RF systems for ERL
Short Pulses	ERL	But seeded FELs supplant both – reasonable add-on for USR possible
Useful repetition rate	USR?	ERLs need higher rep rate for high brightness
Photon Energy Tunability	Similar	USRs can have similar ID apertures
Tailored lattice functions	ERL?	MOGA methods allow non-symmetric ring designs
Effects of Undulators on other users	USR?	Long IDs in ERL produce substantial energy loss for downstream beamlines
Cost / Beamline	USR	Number of beamlines, cryoplant, …
Operating Cost	USR	Large Cryoplant, Power consumption for ERL
Maturity of Design	USR	Technical components are ready
Risk	USR	

Overall USRs appear to have (slight) advantage and seem to complement FELs better

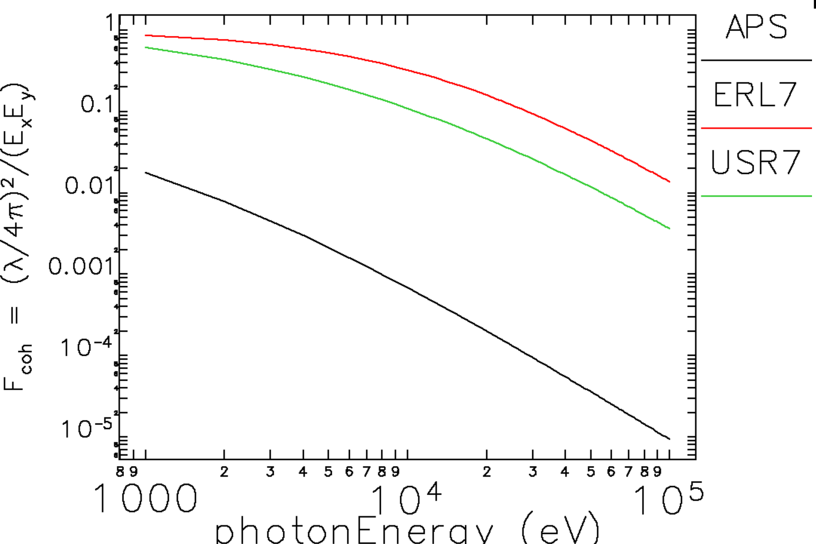
Some Comparison Plots

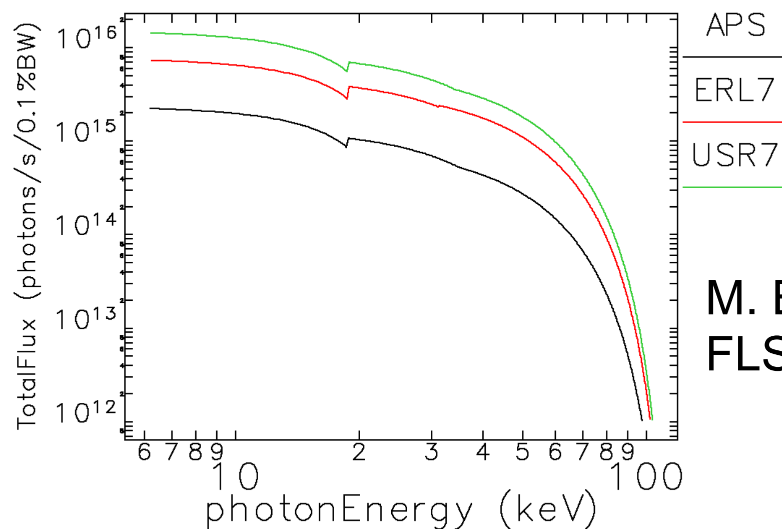


Draft USR White paper



Maximum-length SCU20 (Nb3Sn wire)
APS: 100mA, 1.3% coupling, 3.8 m device
USR7: 300mA, 100% coupling, 8.0 m device
ERL7: 25mA, “high-coherence” parameters, 48m device





M. Borland FLS 2010

Synergies ERL/USR

- Developing the science case for both is very synergistic, since most science drivers for both are fairly similar – of course that also means that there will be (friendly) competition
- Additionally there are several technical areas where synergies exist (a different subset than the ERL/FEL synergies)
  - Stability design, beam diagnostics, feedback systems
  - Beamline design, emittance preserving optics, …
  - Insertion Devices (small, round apertures, …)
  - Low impedance designs
  - …

(Partial) Table of Synergies

Topic	USR	Present ring light sources	All light sources (FELs, compact, etc)	General accelerator applications
Stability in accelerator and beam lines	X	X	X	X
RF cavities (including harmonic)	X			X
RF power sources	X	X	X	X
Alignment	X	X	X	X
Combined function magnets	X			X
Impedance of vacuum chamber	X	X	X	X
Kickers for on-axis injection	X			X
Pulsed multipoles for off-axis injection	X	X		
High power absorbers	X	X	X	
X-ray optics cooling	X	X	X	
Mirror metrology	X	X	X	
Waverfront error detection/correction	X	X	X	
Minimal optics techniques (lensless, etc)	X	X	X	
Photon beam monitors and transducers	X	X	X	
Superconducting IDs (low and high Tc)	X	X	X	X
Low phase error undulators for very high harmonics	X	X	X	
ID designs that minimize unused power on optics	X	X	X	
Novel magnetic ID structures for unique applications	X	X	X	X
Vertical undulators	X		X	

Summary

- Rings have been work horses of synchrotron radiation research
- Rings are mature technology, nevertheless significant growth potential still exists and exploring this remains exciting
- PETRA-III, NSLS-II, Max-4 are first steps on this way, but USRs (like USR7, PEP-X, TevUSR, SDLS, …) promise substantial further progress
- Science case and developments in many technical areas have clear synergies with ERLs
- Ultimate Ring based Sources can compare favorably with ERLs in most relevant performance metrics and have lower risk and cost