Workshop on Accelerator R&D for Ultimate Storage Rings : Beijing / IHEP, October 2012

Possible USR Upgrade of the ALS (pre-conceptual)

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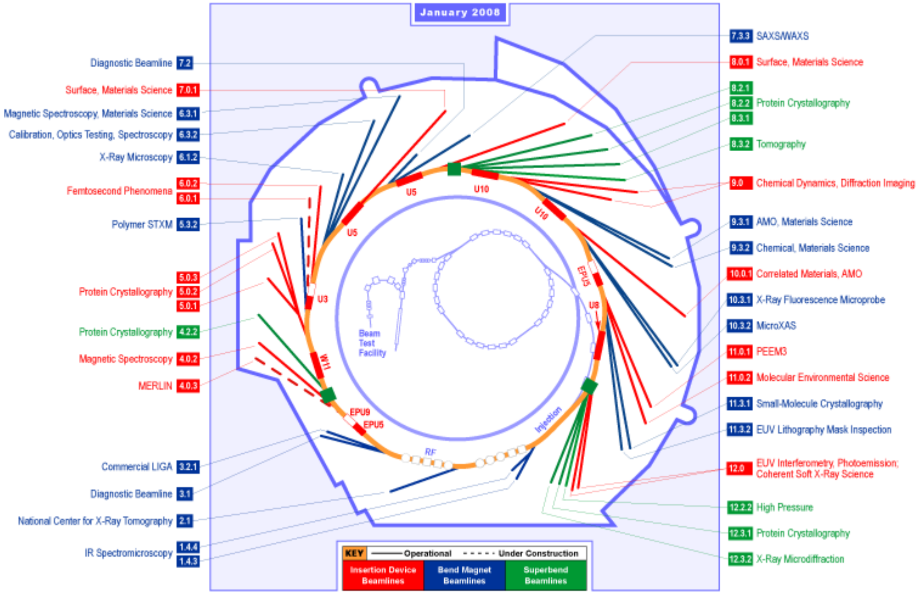
Topics

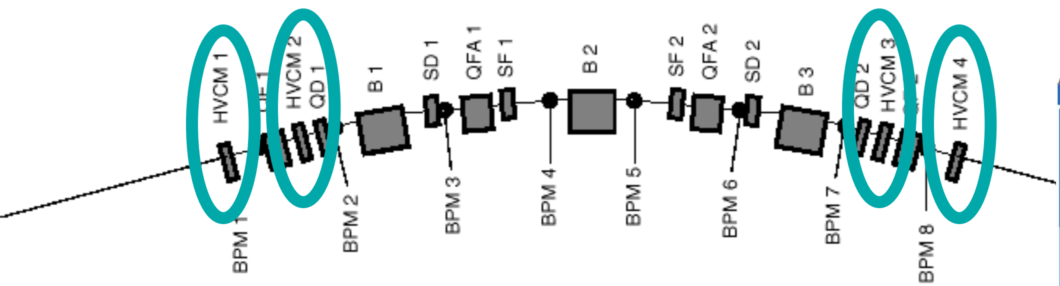
- Advanced Light Source
  - Recent Upgrades
  - LBNL Light Source Strategy
    - NGLS is highest priority
- Potential ALS Upgrade
  - Looked at 5BA years ago (flat beam)
  - Now revisited 7BA (round beam)
- Summary

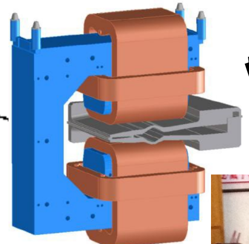
ALS Parameters and Beamlines

Nominal Energy	1.5-1.9 GeV
Circumference	196.8 m
RF frequency	499.642 MHz
Harmonic number	328
Beam current	500 mA multibunch 35-50 mA two-bunch
Nat. emittance	6.3 nm (future 2.2) at 1.9 GeV
Vert. Emittance	30 œ50 pm (user ops), 4-5 pm (dedicated AP)
Nat. energy spread	0.097%
Refill period	Top-off every 30-60 s (current stability 0.3%)
User Beamlines	>40 simultaneous (11 insertion devices)



Brightness Upgrade

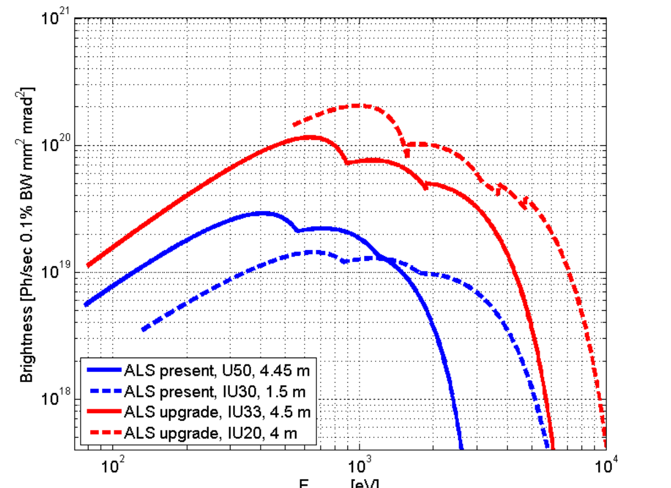




Sextupoles / Correctors

Existing Correctors

- By changing magnet lattice, horizontal emittance is reduced from 6.3 nm rad to 2.2 nm rad
- Brightness is inversely proportional to emittance
- Currently installing magnets
  - Completion in March 2013

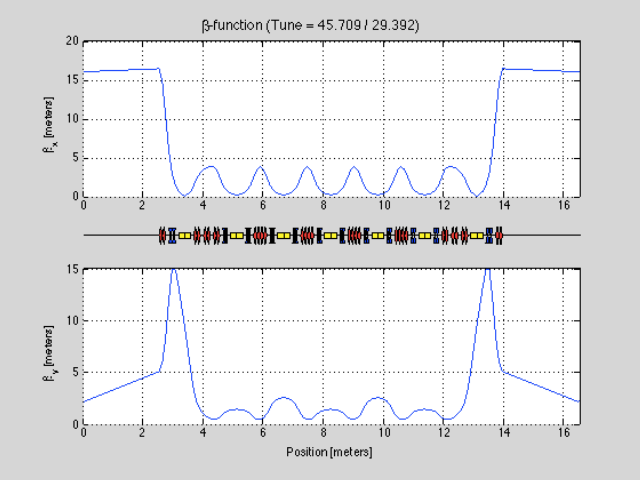


C. Steier, et al., NIM A, DOI: 10.1016/j.nima.2010.11.077.

LBNL Light Sources

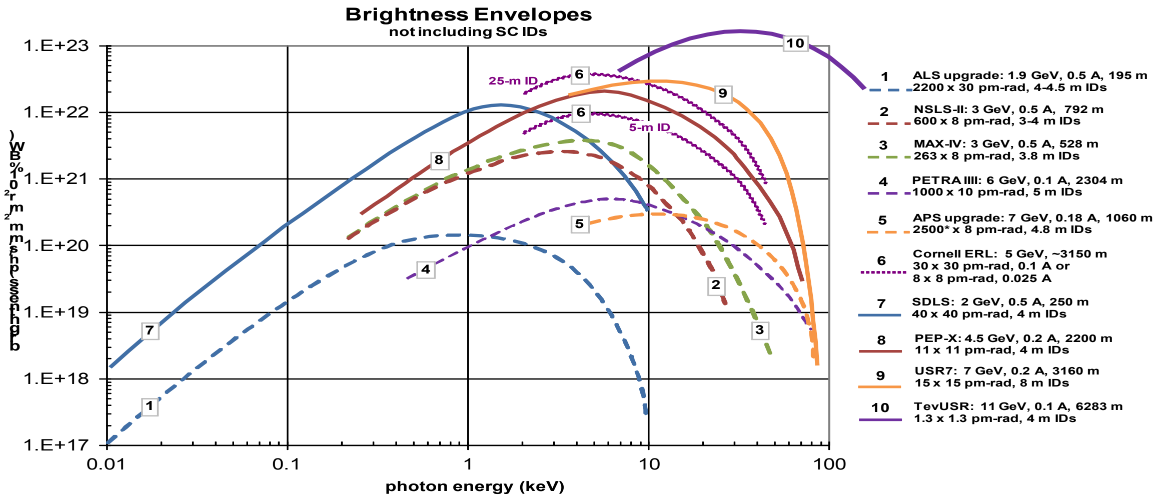
– Highest Priority: Develop revolutionary capability in time resolved studies (or studies that need transverse and longitudinal coherence) – NGLS

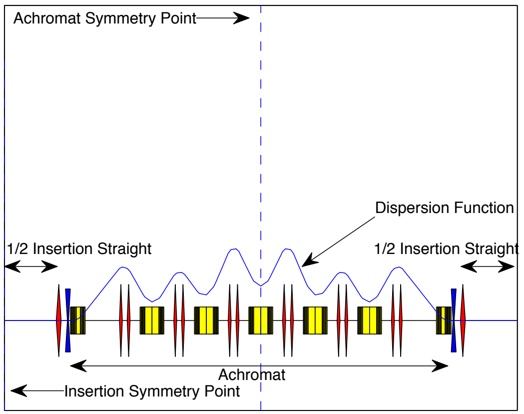
– Retain (via cost-effective upgrades) the complimentary world class capability in experiments needing transverse coherence only and benefit from ultimate repetition rate – (SD)-ALS



Opportunity

- NGLS promises revolutionary science opportunities, but large development potential still exists for storage ring based light sources
  - New lattice ideas leading to (potentially) transverse diffraction limited performance
  - Science case is complementary to FELs and ALS soft x-ray user community is key strength of LBNL to attract NGLS
  - Upgrade cost for ring of ALS size moderate (order 100 M$) – Dark time of order of 1 year.
- Upgrade is a way for ALS to stay relevant in parallel to NGLS
  - Skilled workforce retenton
  - Synergies in User Support, Engineering resources, Operations Staff

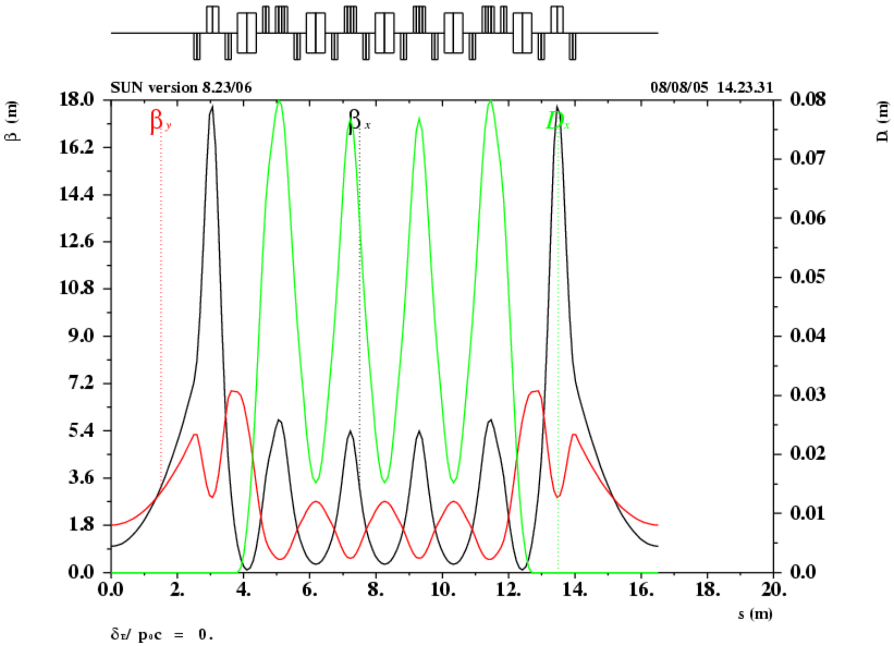


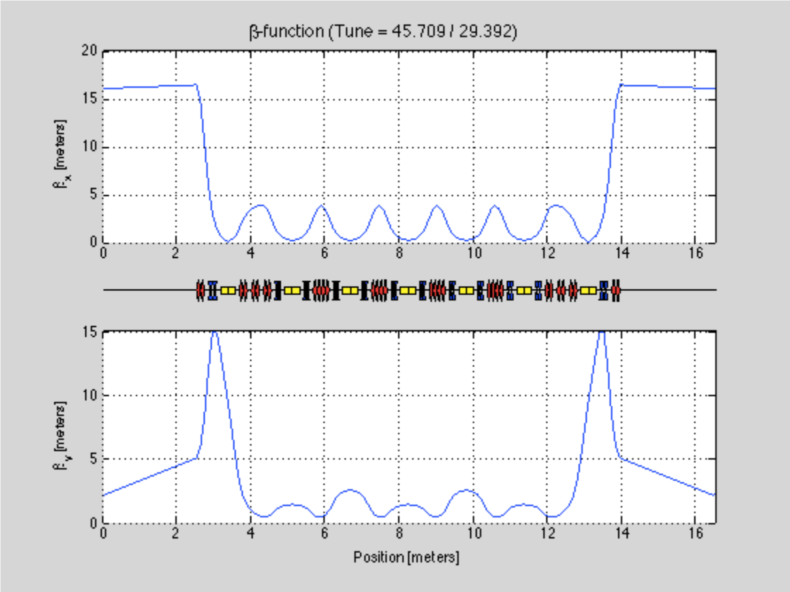


Design choices of (SD)ALS – common

- Third generation light sources originally designed with generous physical apertures everywhere (except for IDs) – smaller apertures (factor 3) allow much stronger magnets
- TME/MBA lattices provide smaller natural emittances than double or triple bend achromats
- NEG coating on vacuum chambers allow distributed pumping in small aperture chambers (good vacuum, cheaper vacuum system)
- Fitting the electron beam ellipse better to photon ellipse (diffraction limit) using small beta functions
- (Frequent) on axis injection (a step beyond top-up) allows to relax requirements on dynamic aperture – requires powerful full energy injector – prefer accumulator ring
- Lattices yield small momentum compaction factors allowing to transport very short bunches at least for single turn
- Complications: Shorter lifetimes, radiation safety/damage, current stability, lattice control/correction, tougher demands on orbit/ beamsize stability, …

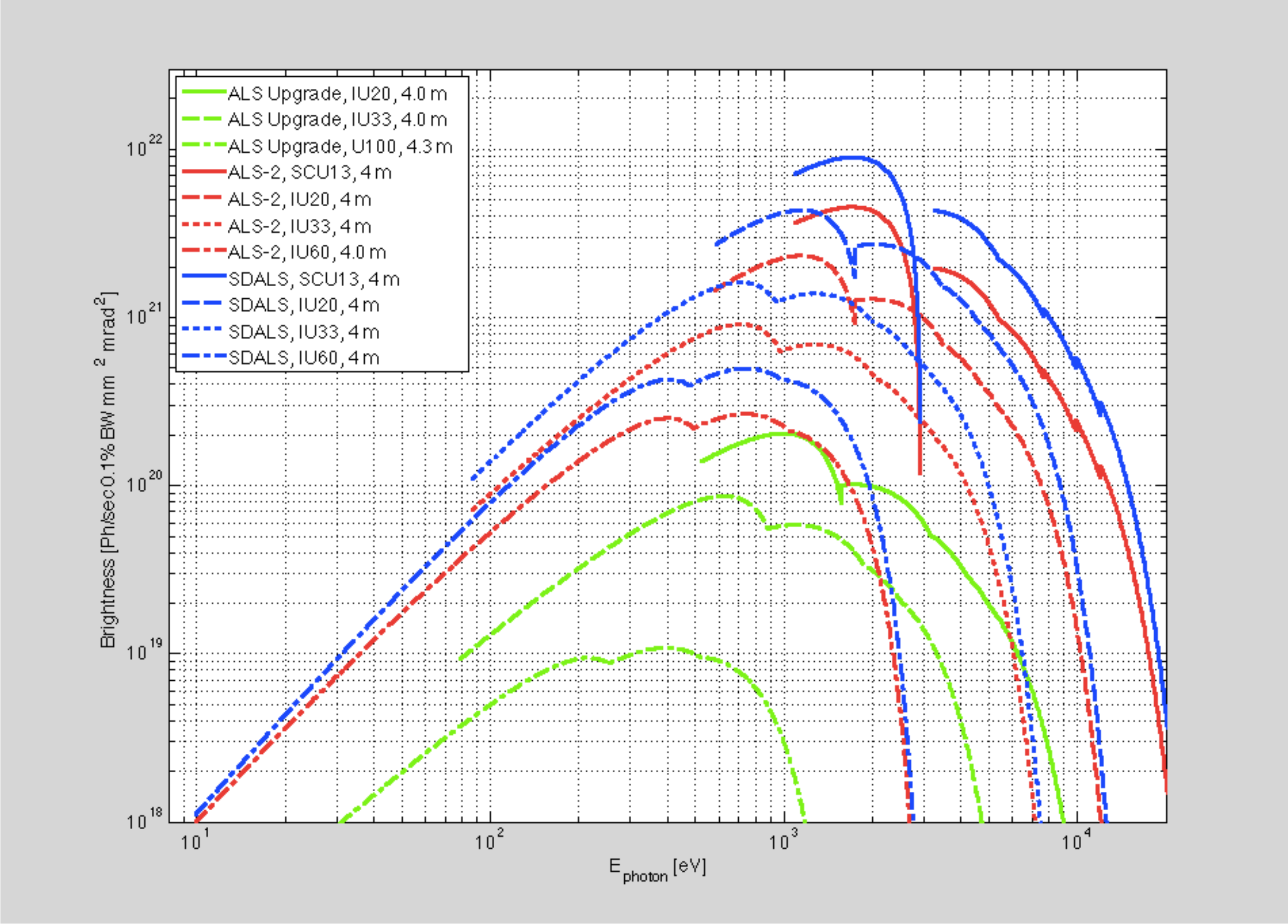
(SD)ALS lattice





- Keep circumference, as well as straight section location, number and length of ALS
- Most (de-)focusing in arcs is concentrated in dipoles (similar to TME)
- ALS has k value of 3.5 m^{-2} (22 T/m) for quads, 0.8 m^{-2} (5 T/m) for bends 75 m^{-3} (480 T/ m^2) for sextupoles with 32.5 mm pole tip radius
- New lattices would be very compact, use magnets with small aperture (13 mm pole tip radius) -> quads and dipoles in candidate lattices are factor 2.5 stronger gradient
  - Magnets are very challenging and space constraints might require some integrated sextupoles (loss in flexibility)

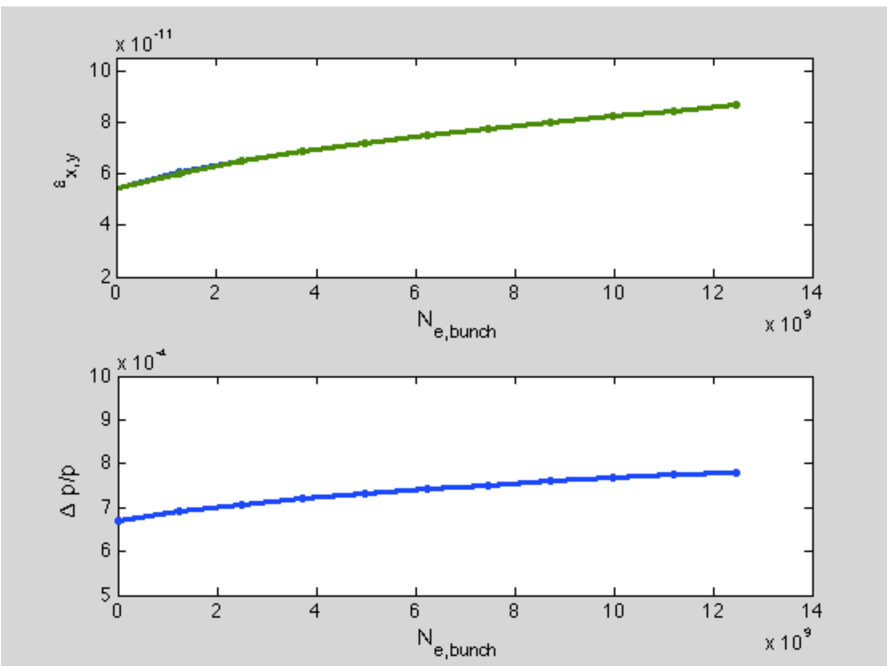
Brightness

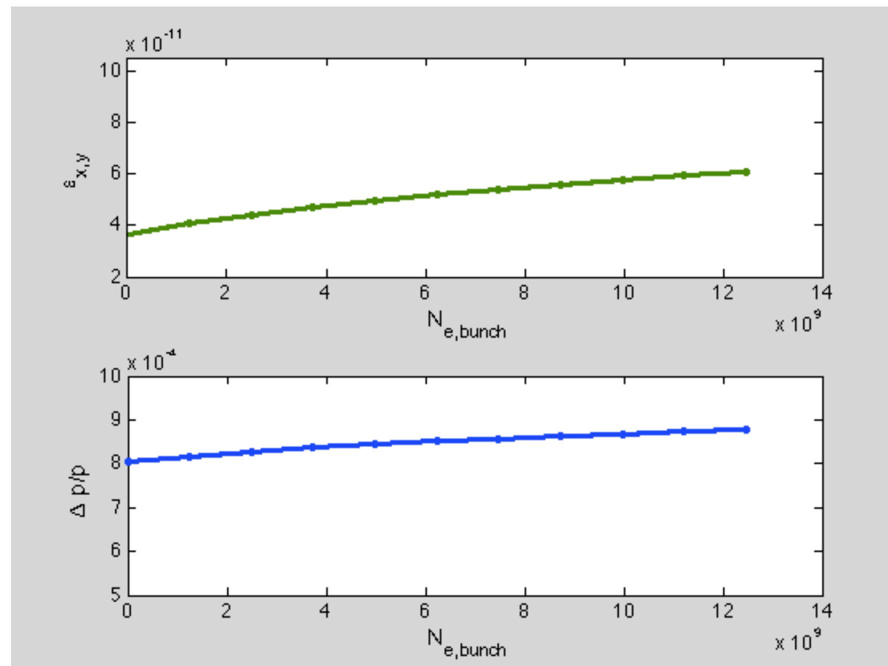


ALS Upgrade, IU20, 4.0 m
ALS Upgrade, IU33, 4.0 m
ALS Upgrade, U100, 4.3 m
ALS-2, SCU13, 4 m
ALS-2, IU20, 4 m
ALS-2, IU33, 4 m
ALS-2, IU60, 4.0 m
SDALS, SCU13, 4 m
SDALS, IU20, 4 m
SDALS, IU33, 4 m
SDALS, IU60, 4 m
Brightness [Ph/sec 0.1% BW mm 2 mrad2]
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{1}
10^{2}
10^{3}
10^{4}
E_{photon} [eV]

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 (250 m), 2 GeV, Harmonic Cavities, left no DW, right 10 m DW, 500 mA is $6.5*10^9$ e-/bunch

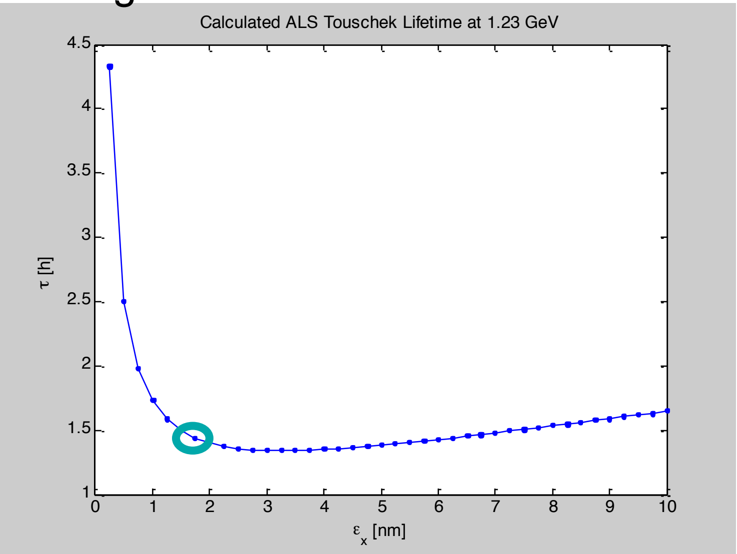
Touschek Lifetime @ Small ε_x

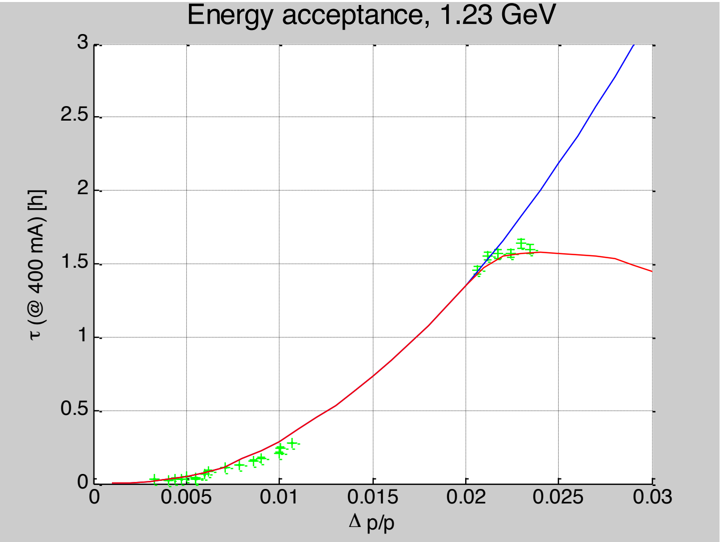
- Dynamic aperture of small beta function lattices we studied so far) is 2-3 mm – only sufficient for on-axis injection
- Momentum aperture is good enough that lifetime is acceptable (>2 h) with harmonic cavities
- Interesting side remark: Because of low emittance increase in lifetime, harmonic cavities in presence of intra beam scattering increase lifetime much more than bunchlength
- Conducted lifetime measurement in transition regime at ALS

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

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

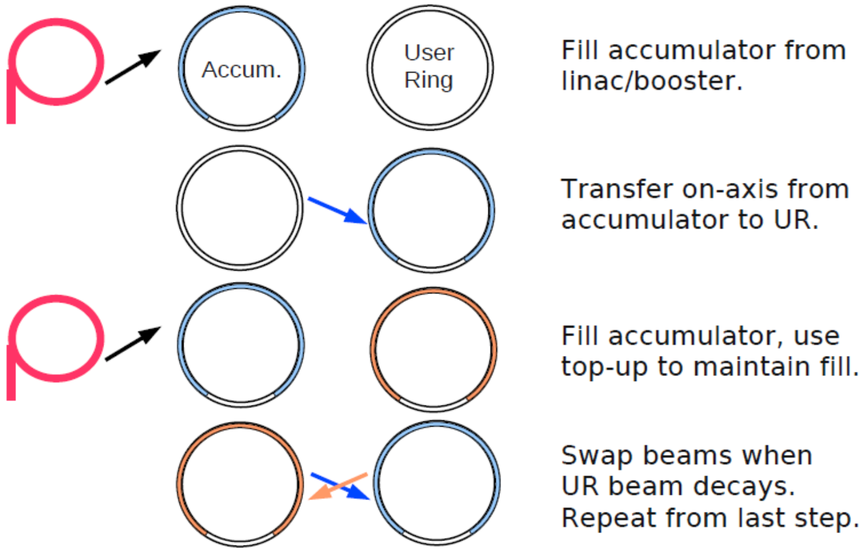
$$F(x) = \int_0^1\left(\frac{2}{u} - \ln\frac{1}{u} - 2\right)\exp\left(-\frac{x}{u}\right)du$$





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).

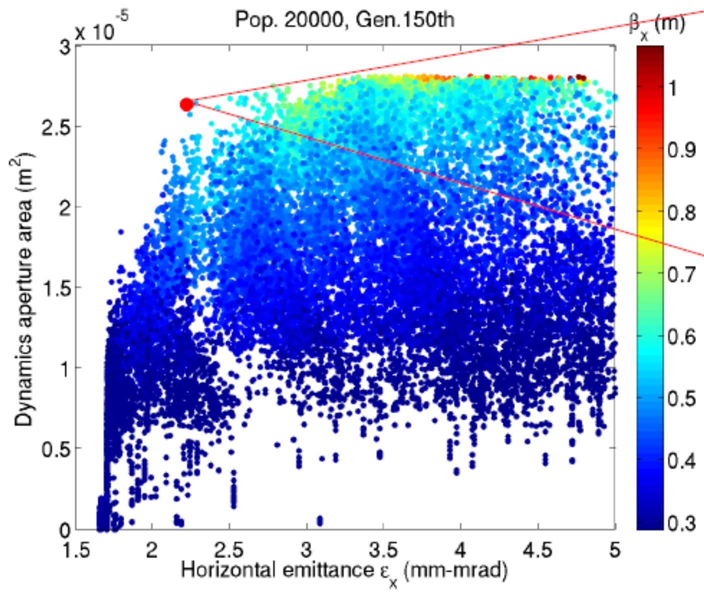


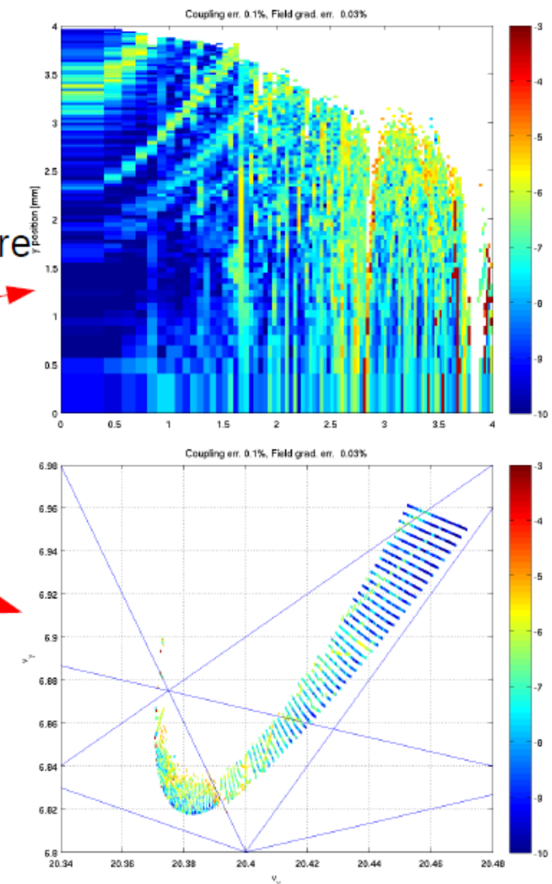
- [1] M. Borland, "Can APS Compete with the Next Generation?", APS Strategic Retreat, May 2002.
- [2] M. Borland, L. Emery,"Possible Long-term Improvements to the APS," Proc. PAC 2003, 256-258 (2003).

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.

C. Sun

Optimum Photon/Electron Energy

- With better and better undulators (phase shimming, higher fields) it has become feasible to significantly extend photon energy reach.
- ALS (<2 GeV) cannot reach beyond about 15 keV with high brightness undulator sources
  - But even a USR in 2 GeV class could be small and cost effective
- New 3 GeV type sources can get into original ESRF/APS/Spring-8 domain beyond 20 keV.
- On the other hand, higher energy sources try to extend to lower energies …
  - I believe, they are not quite optimized. Either need long period and very high field (huge heat load) or extremely long period and weak field (with lower brightness).
- No big improvement on the horizon for photon energies significantly below 100 eV.

Summary

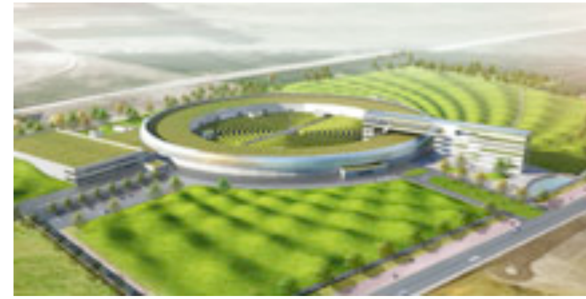
- ALS has been a tremendous success as soft x-ray source for almost 20 years
- Continuous Upgrades have kept it state-of-the-art
- NGLS is highest LBNL priority moving forward
- Diffraction limited soft x-ray ring (USR upgrade of ALS: 195m, 2 GeV) has potential to complement NGLS well
  - Moderate Cost
  - Goal for emittance is 50-100 pm @ 2 GeV

Backup Slides

Selection of 3rd Generation Rings (Current/Future)

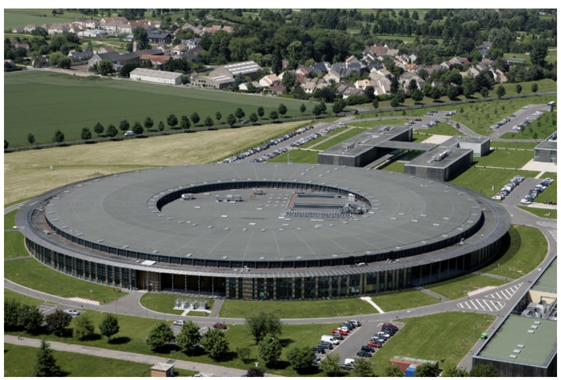
SLS (2002) 2.4 GeV
ε_x= 3.9 nm, ε_y=72 pm, I=300 mA

ALS (1993) 1.9 GeV
ε_x= 6.3 (2.2) nm, ε_y=30 pm, I=500 mA



MAX-4 (2016) 3 GeV
ε_x= 0.2-0.3 nm, ε_y= 8 pm, I=500 mA

NSLS-II (2013) 3 GeV
ε_x= 1.1 (0.6) nm, ε_y= 8 pm, I=300(500) mA



Soleil (2006) 2.75 GeV
ε_x= 3.7/5.6 nm, ε_y=37 pm, I=400(500) mA

APS (1995) 7 GeV
ε_x= 2.5/3 nm, ε_y=25 pm, I=100 mA

Diamond (2007)
3 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 **= λ/4π**

- **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**

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)

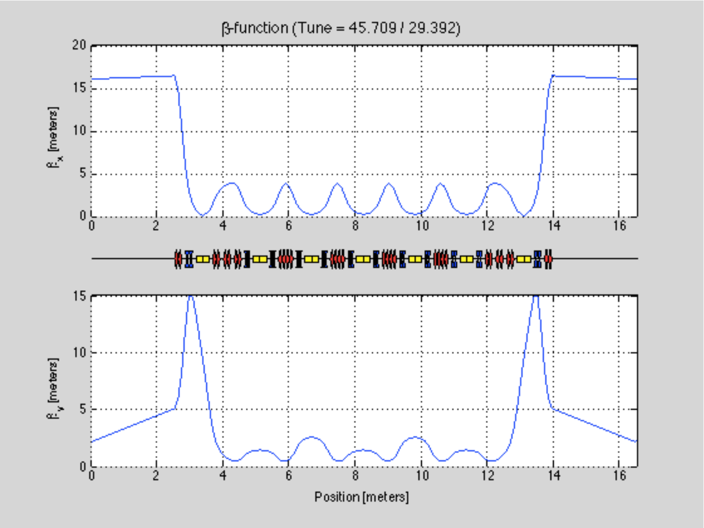
Features of Ultimate Rings

- 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

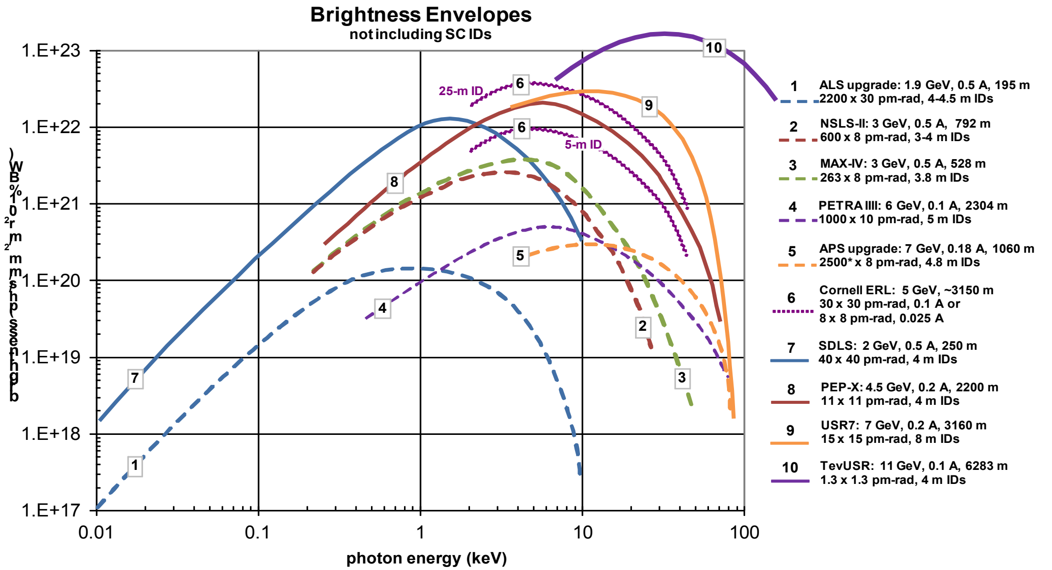
More Supporting Technology …

- **"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).

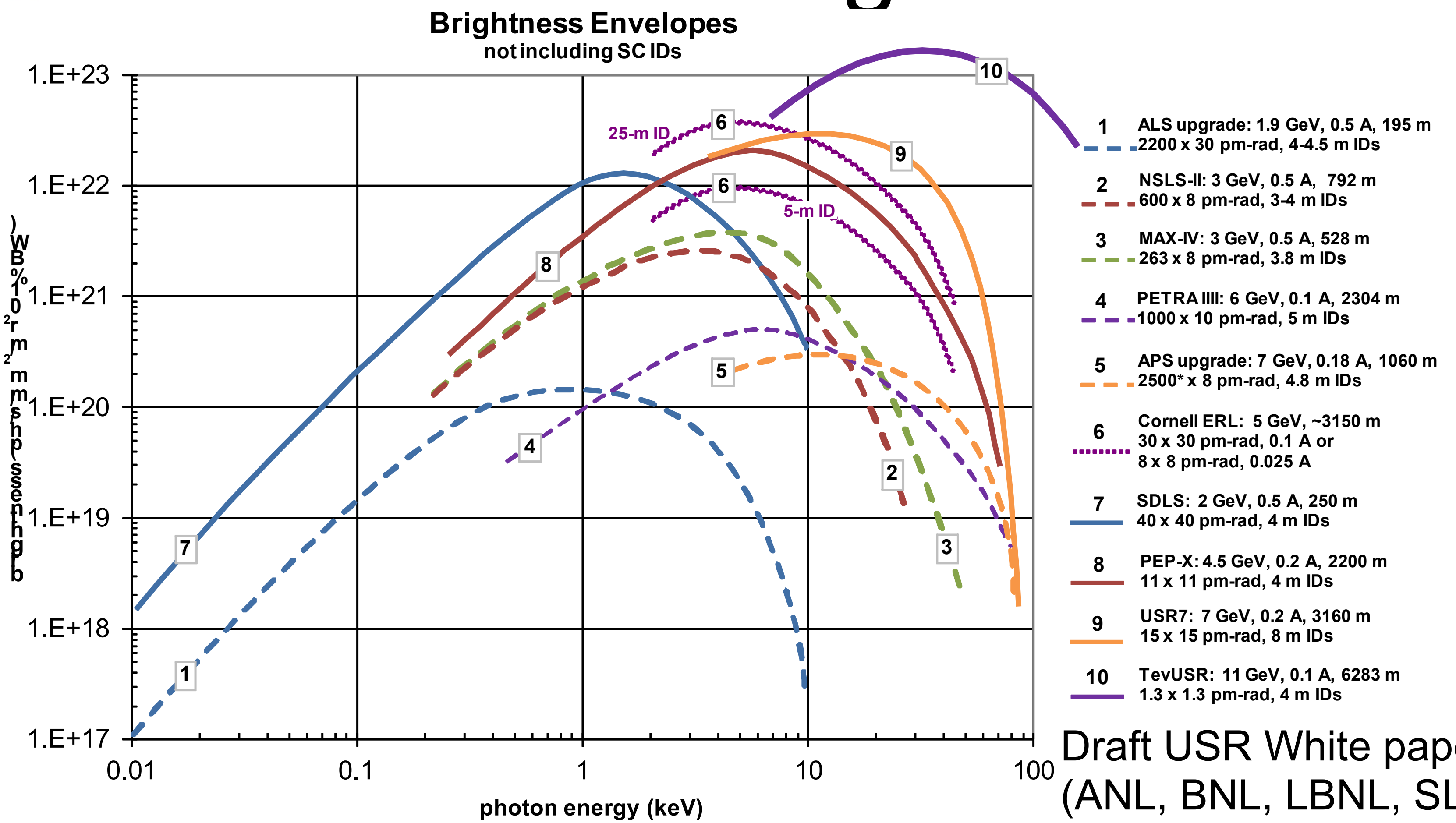
Ultimate Storage Rings



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 x 10^{-3}	1.25 x 10^{-3}	1.43 x 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



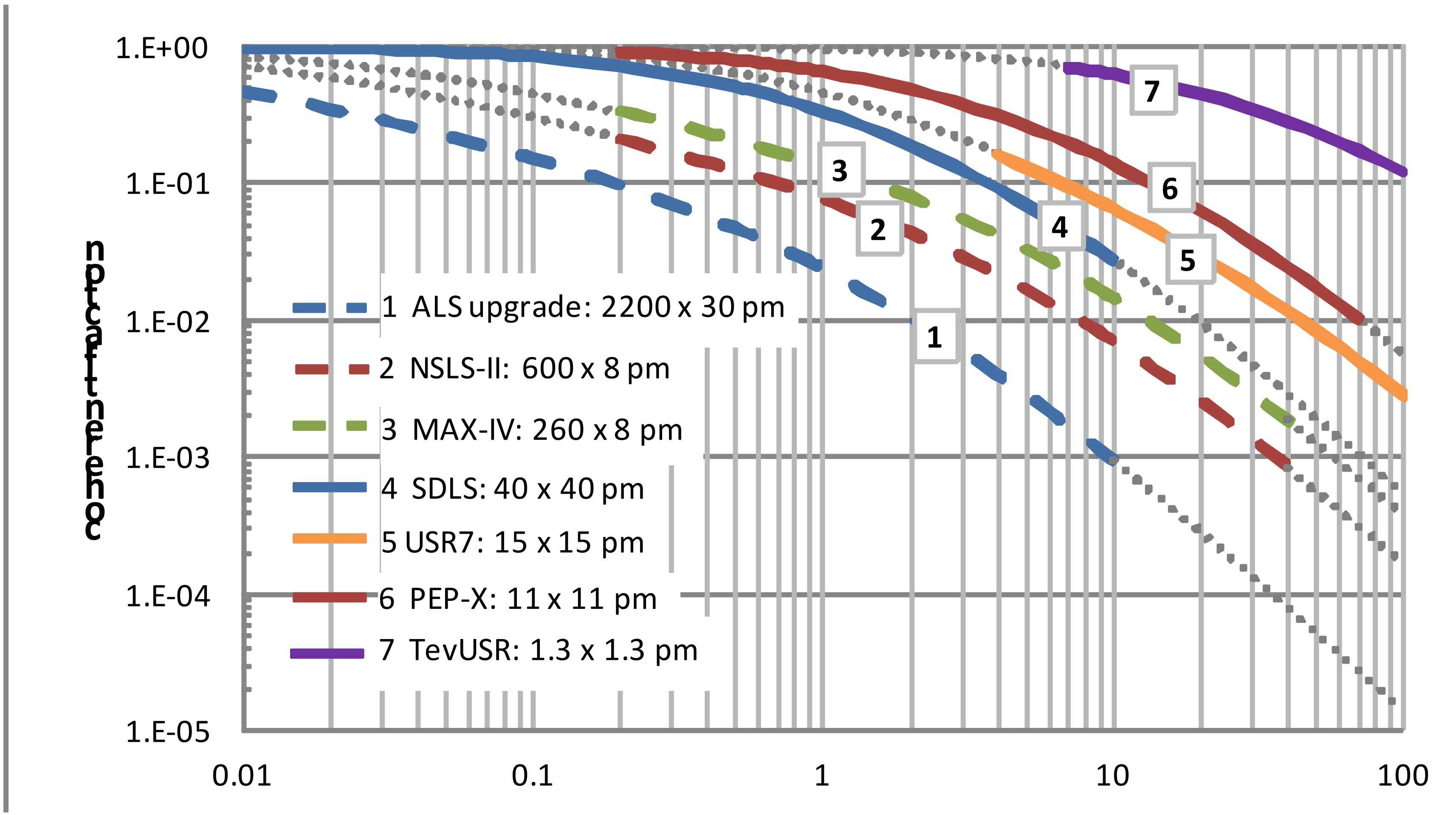
USR/ERL Brightness



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

Coherent Fraction



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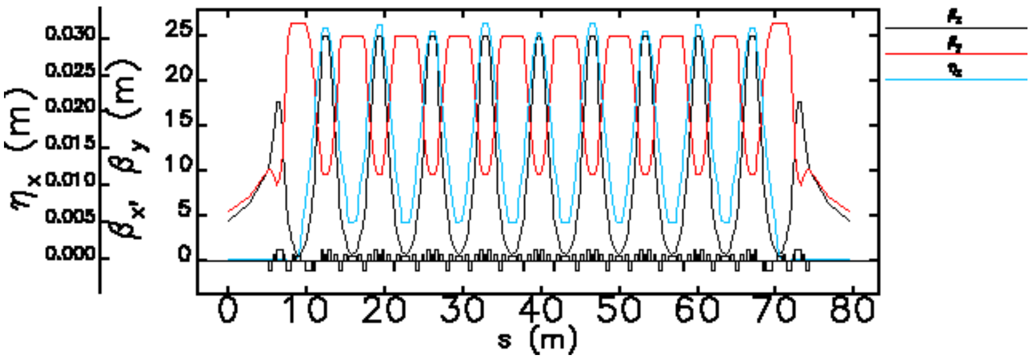
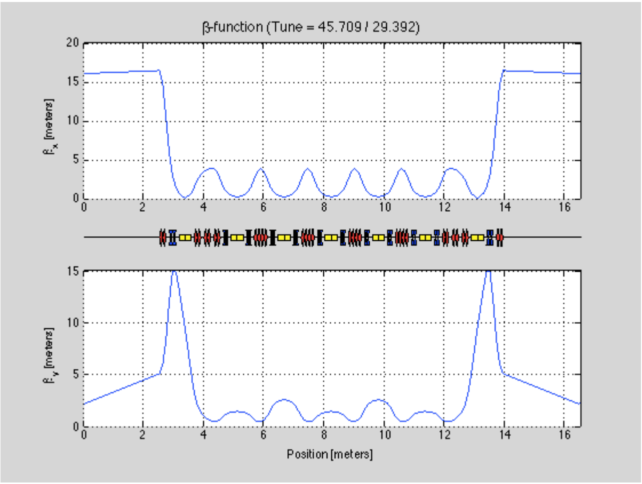
(1) Very preliminary estimates for the SDLS [C. Steier, W. Wan].
(2) From PEP-X study [Y. Cai, et al.].
(3) From preliminary study of Tevatron-sized USR [M. Borland].

Example USR Lattices

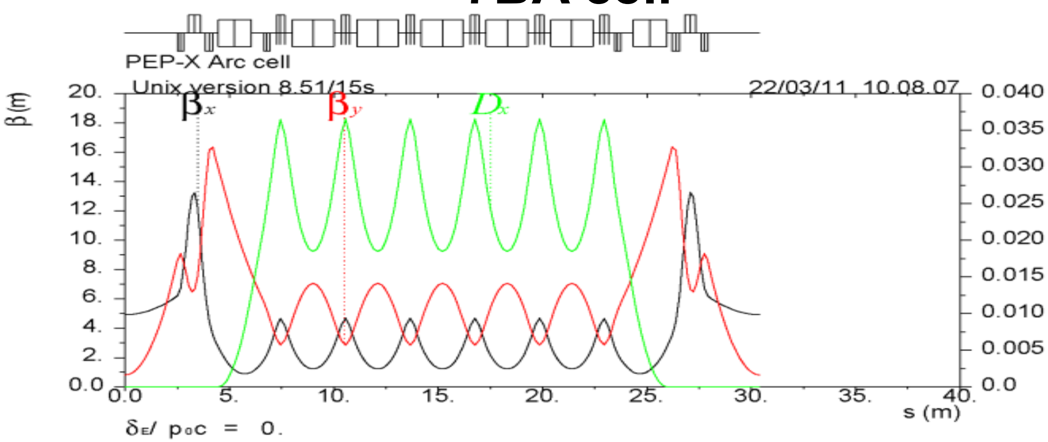


USR7 M. Borland



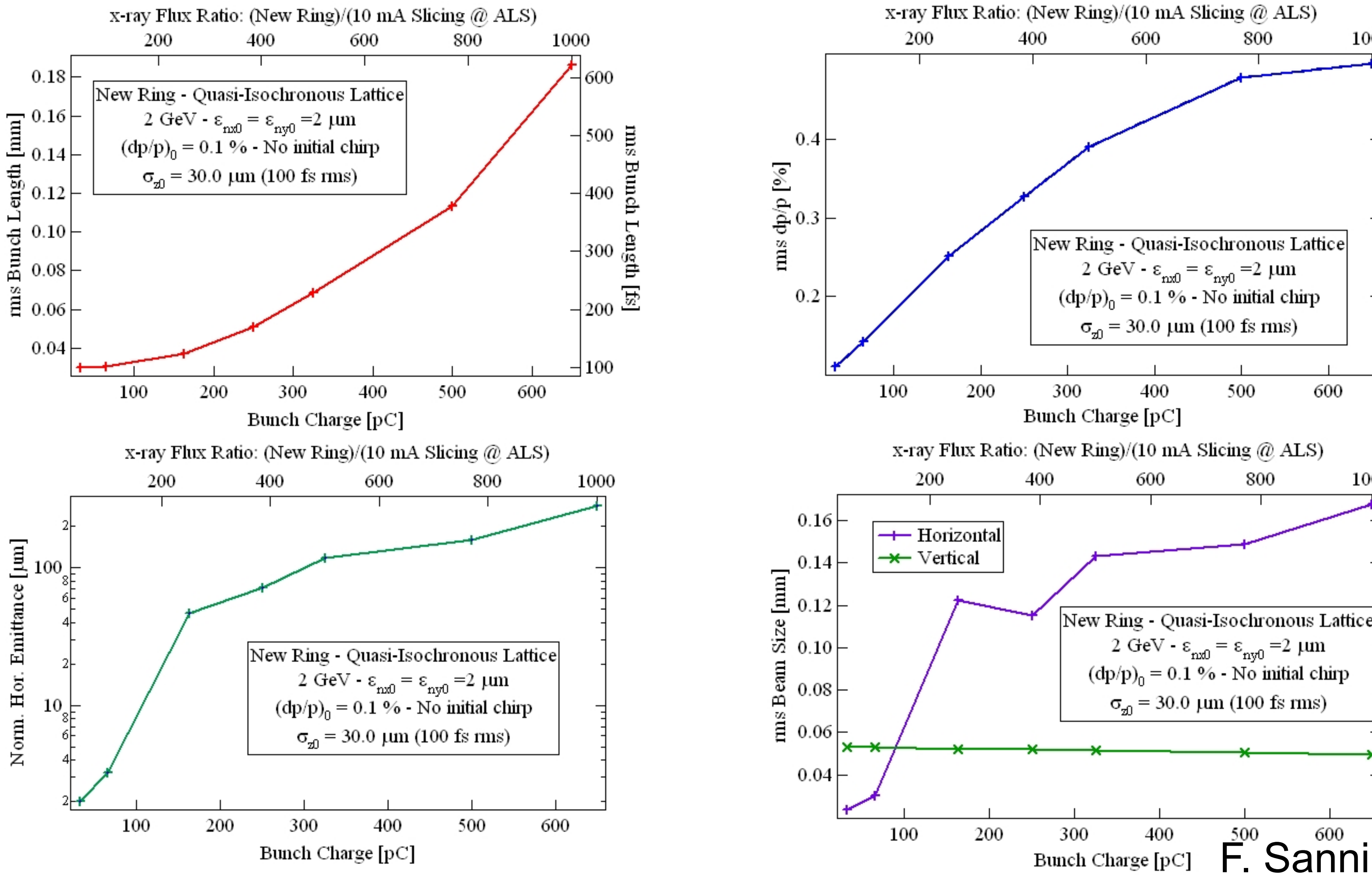
SDLS C. Steier, W. Wan

7BA cell



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

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



F. Sannibale