LBNL Instrumentation Colloquium

Reaching the Soft X-ray Diffraction Limit: ALS-U, A Revolutionary Upgrade of the ALS

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Advanced Light Source, Accelerator Technology and Applied Physics

for the ALS-U team

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Outline

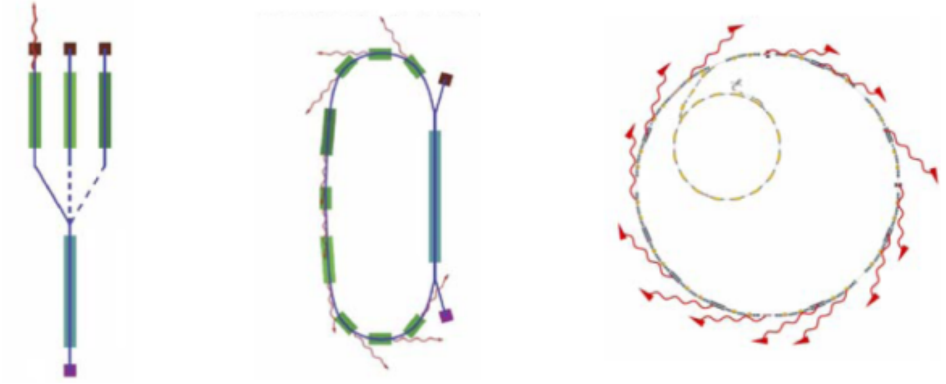
ALS-U is a cost effective and innovative upgrade and will be a world leading facility for soft x-ray science enabling nanoscale microscopes with chemical, magnetic, and electronic contrast.

- Synchrotron Radiation – Coherence – Diffraction Limit
- Advances of Synchrotron Light Sources
  - Transverse Dynamics
  - Synchrotron Radiation
  - Dynamic Aperture
- Diffraction Limited Storage Rings
  - Lattice Design
- Advanced Light Source – ALS-Upgrade
  - Technology Challenges
- R+D Program

DOE Report on Future Light Sources (2008/2009)

Options for Future Light Sources:

- **Diffraction Limited Storage rings**
- **Energy recovery linac (ERL)**
- **Free electron laser (FEL)**



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 continue to utilize novel techniques for producing photons tailored to applications:

Different operating modes

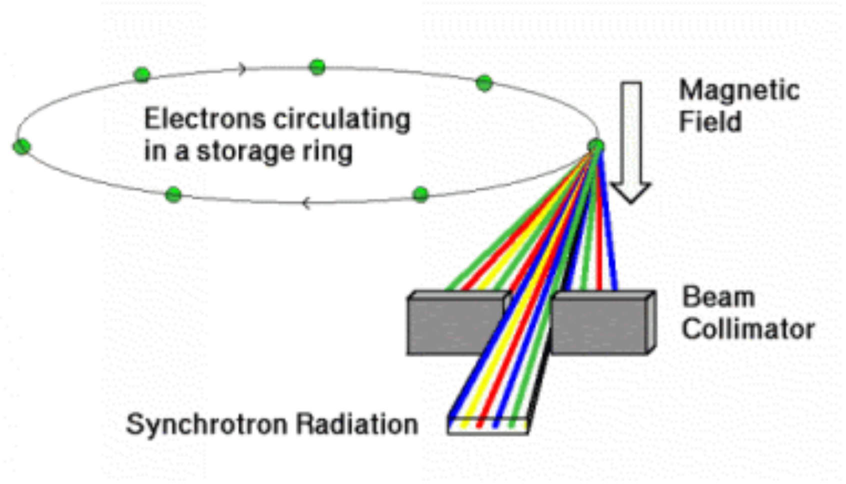
Optical manipulation of particle beams

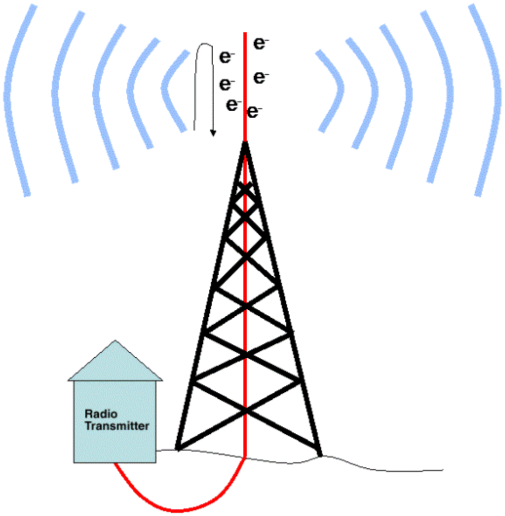
Use of multiple, complementary facilities

What is Synchrotron Radiation?

- Synchrotron radiation is electromagnetic radiation emitted when charged particles are radially accelerated (move on a curved path).

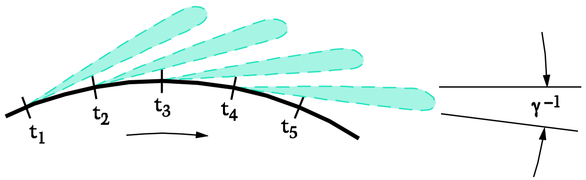
Electrons accelerating by running up and down in a radio antenna emit radio waves (long wavelength electromagnetic waves)





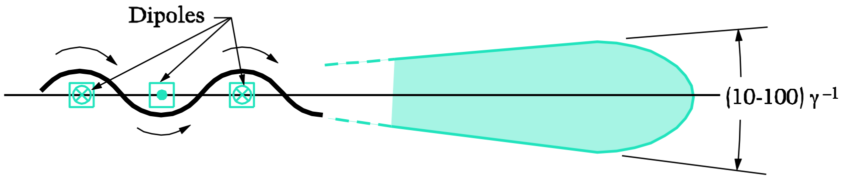
Both cases are due to the same fundamental principle:
Charged particles radiate when accelerated.

How is Synchrotron Radiation generated



bending magnet

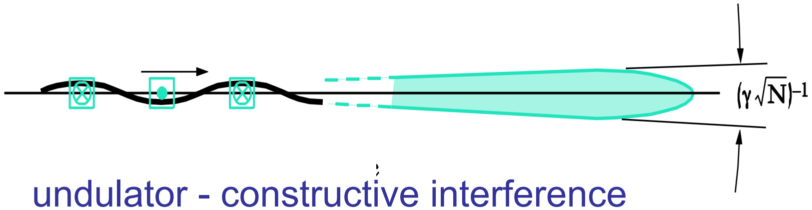
Flux ~ Current



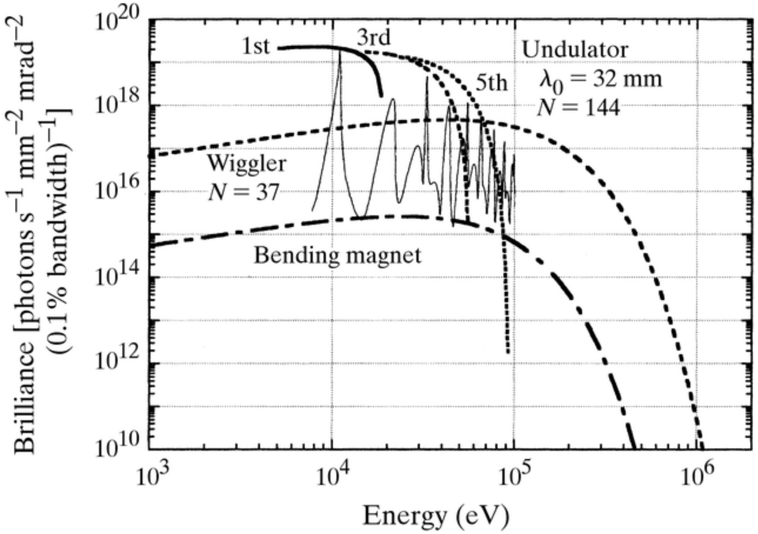
Flux ~ Current * N_{period}

wiggler - incoherent superposition

Flux ~ Current * N^2_{period}

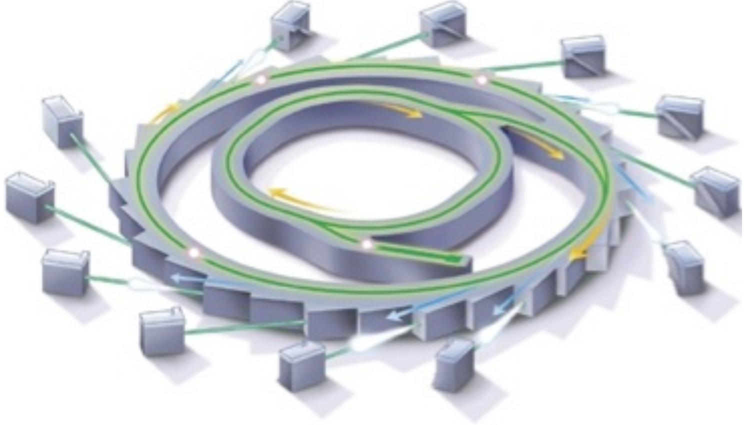


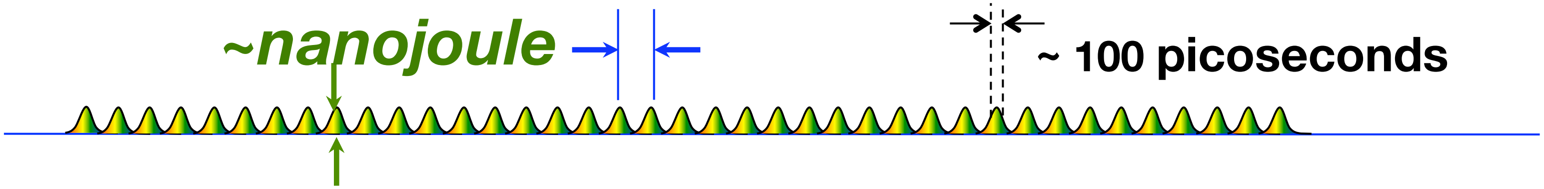
undulator - constructive interference



Strengths of Ring Based Light Sources

- **Stability:** High positional and photon energy stability
- **Tunability:** Easy and rapid photon energy tunability
- **Access:** Serves ~ 40 instruments simultaneously
- **Quasi-CW Operation -** Long pulses at high repetition rates:
  - Advantage for important classes of experiments





~ 2 nanoseconds

~nanojoule

~ 100 picoseconds

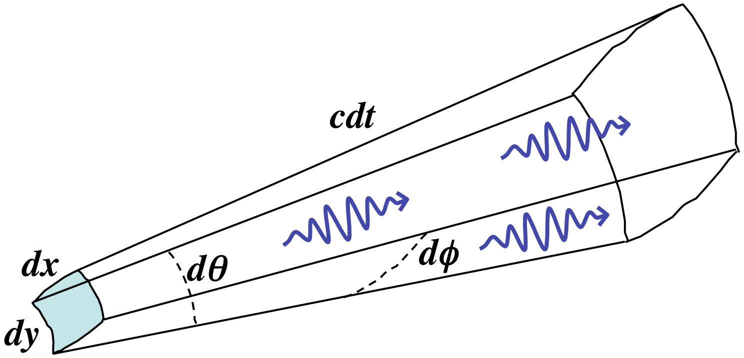
Brightness of a Light Source

- Brightness is the one of the main parameters for the characterization of a particle/light source
    - Determines achievable resolution (space, time, energy) within a given measurement time

- Brightness is defined as the density of particles in 6-D phase space = Flux normalized by emission area and divergences

$$\textbf{Flux} = \frac{\textbf{\# of photons in given } \Delta\lambda/\lambda}{\textbf{sec}}$$

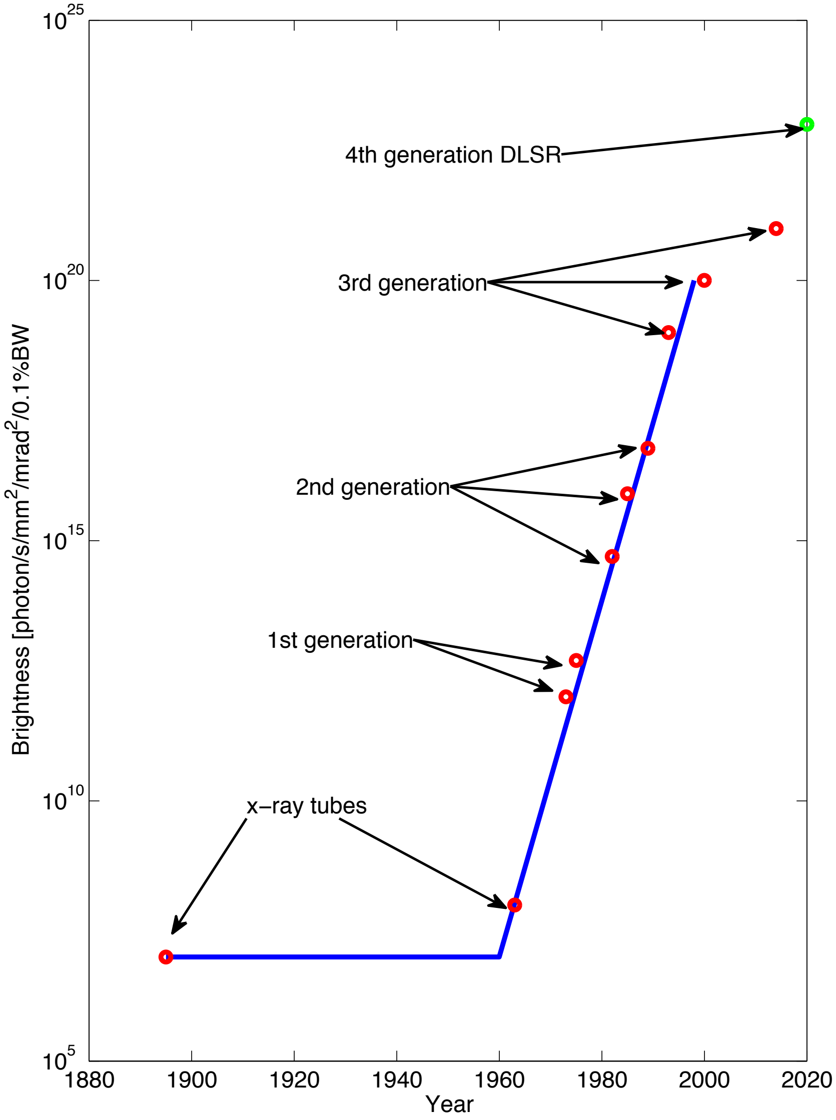
$$\textbf{Brightness} = \frac{\textbf{\# of photons in given } \Delta\lambda/\lambda}{\textbf{sec, mrad } \theta\textbf{, mrad } \varphi\textbf{, mm}^2}$$



Advances in Light Source Performance

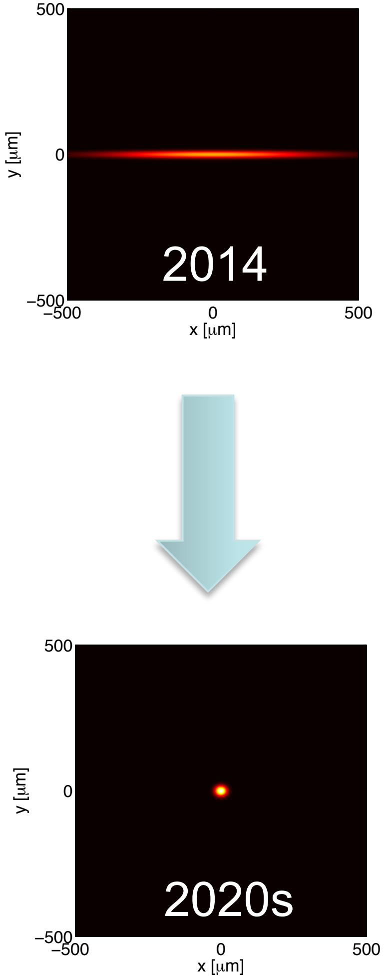
≥2 orders of magnitude progress in brightness between generations

- First Generation: Parasitic, use of dipole sources
- Second Generation: Dedicated, dipoles, later wigglers, higher flux
- Third Generation: Dedicated, optimized for undulators, high average brightness
- Fourth Generation: three approaches (linear/ring); high coherence



Recent Advances Enable Ultra-Bright Rings

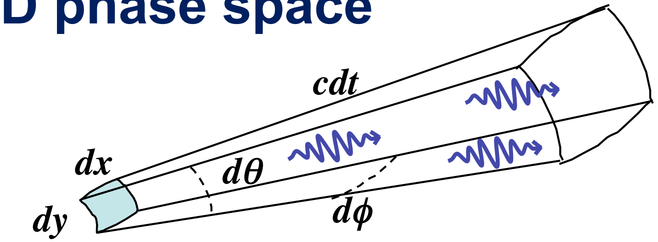
- Storage ring light sources have not reached their practical limits of brightness and coherence.
- Dramatic improvements are possible due to transformational advances in accelerator design.
- What Has Changed:
  - Tightly-packed multi-bend achromat lattices via new magnet and vacuum technology.
  - Success of top-up, better understanding of storage ring scaling, advances in simulation, optimization, and alignment.
- International community is now upgrading existing facilities and building new facilities with diffraction limited capability that will enable new science.



Brightness and Equilibrium Emittance

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

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

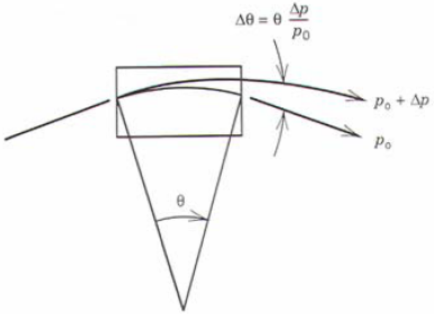


$\varepsilon_{x,y}$ = electron emittance

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**

Background: Transverse Beamdynamics

There are several magnet types that are used in storage rings:

Dipoles → used for guiding

$B_x = 0$

$B_y = B_o$

Quadrupoles → used for focussing

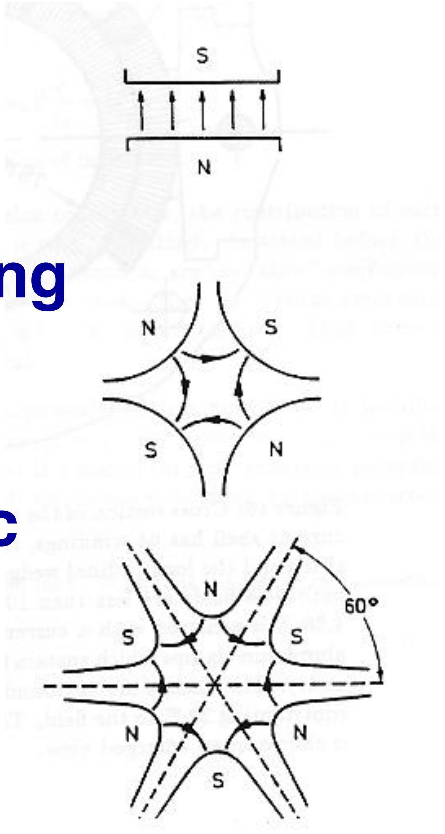
$B_x = Ky$

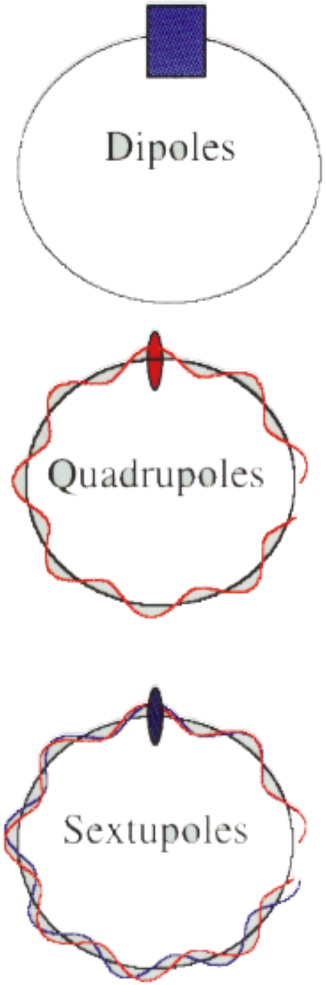
$B_y = -Kx$

Sextupoles → used for chromatic correction

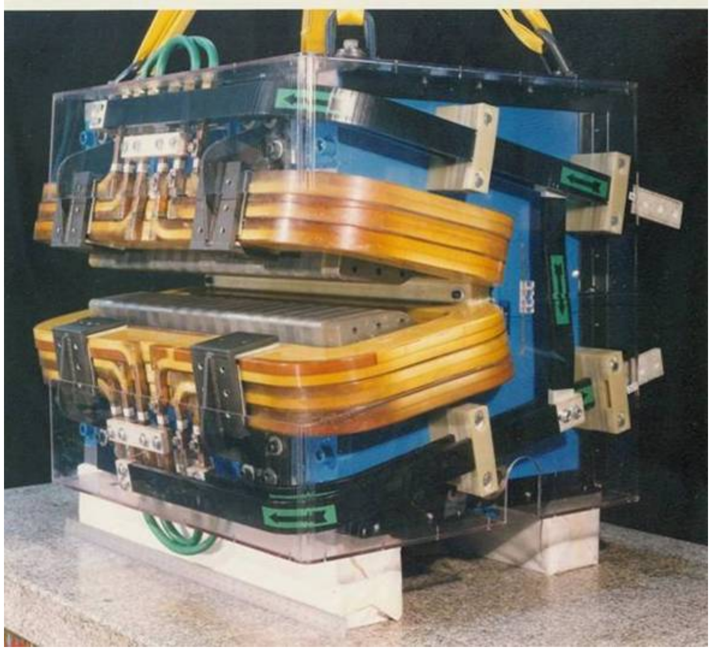
$B_x = 2Sxy$

$B_y = S(x^2 - y^2)$





Practical Magnet Examples at the ALS



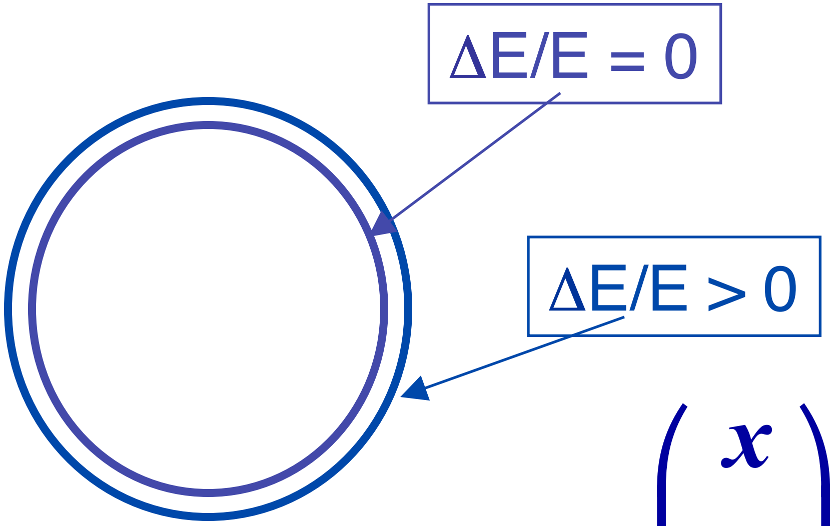
Dipoles

Quadrupoles

Sextupoles

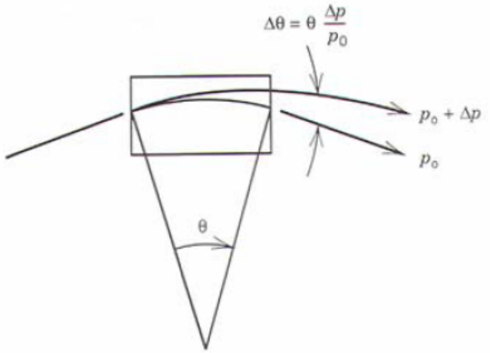
Dispersion

Dispersion, *D*, is the change in closed orbit as a function of energy


ΔE/E = 0

ΔE/E > 0

$$x = D_x \frac{\Delta E}{E}$$



$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_f = \begin{pmatrix} C & S & D_x \\ C' & S' & D'_x \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_i$$

Radiation damping

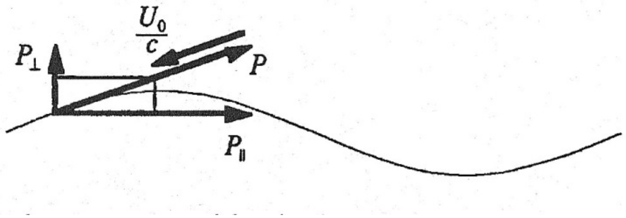
Energy damping:

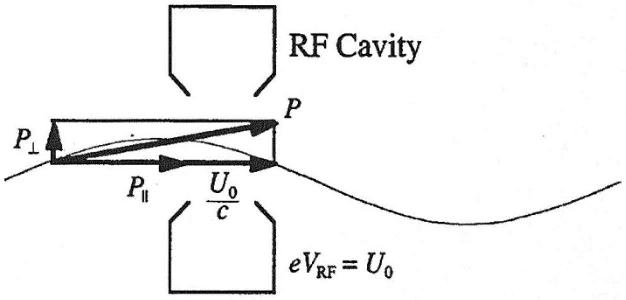
Larger energy particles lose more energy

$$P_{SR} = \frac{2}{3}\alpha \mathrm{h} c^2 \frac{\gamma^4}{\rho^2}$$

Transverse damping:

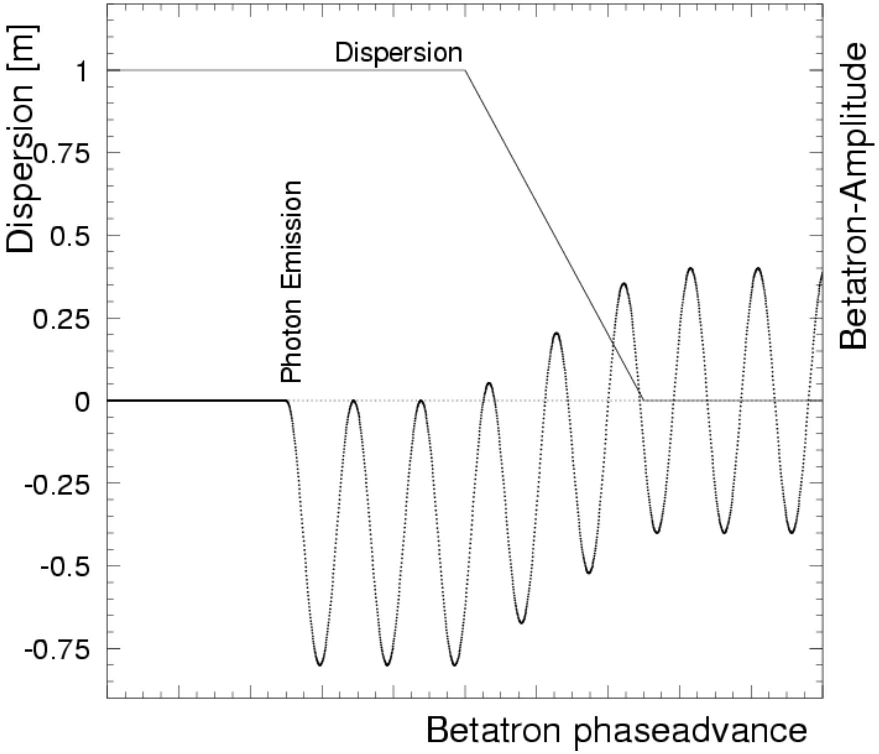
Energy loss is in the direction of motion while the re-acceleration in RF cavities is only longitudinal



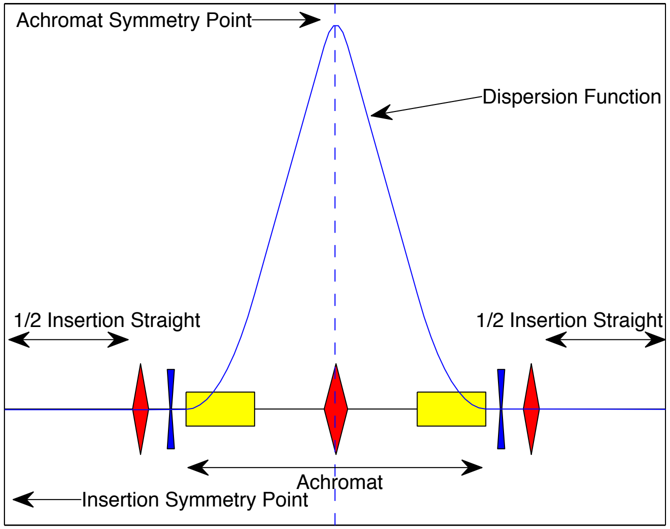


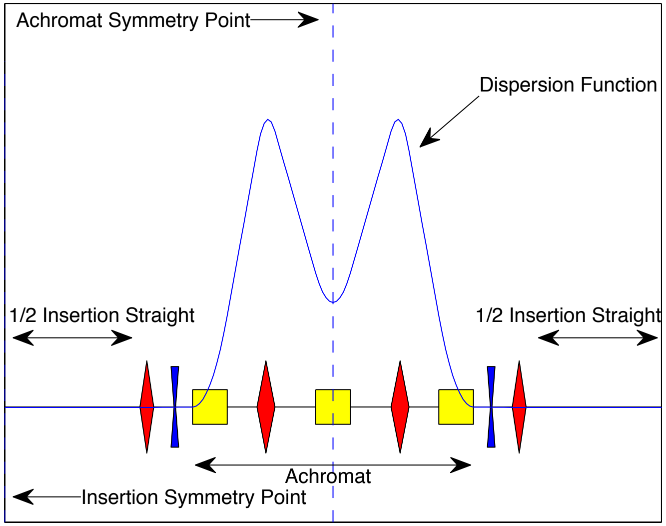
Quantum Excitation / Transverse Equilibrium Emittance

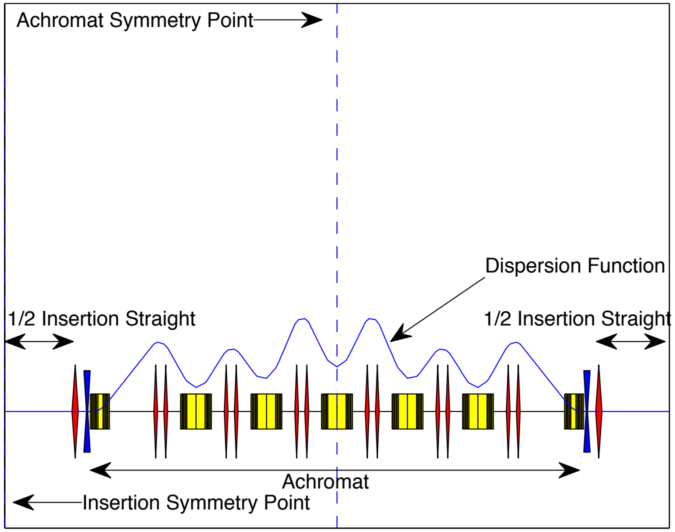
Particles, which change their energy in a region of dispersion starts transverse oscillations. This balanced by damping gives the equilibrium emittances.



Common Lattice Options



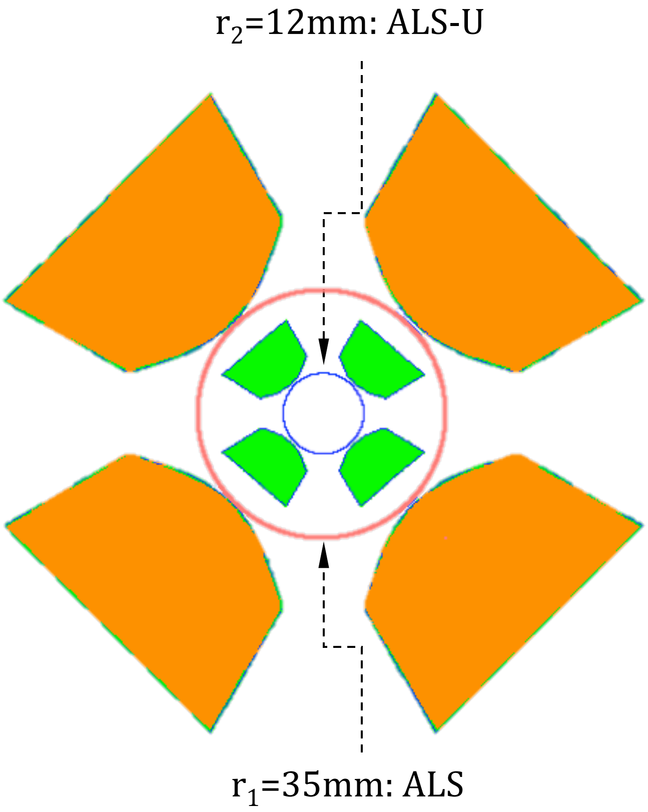




- Early 3rd generation SR sources all used double/triple bend achromats (some with gradient dipoles)
- Later optimization included detuning from achromatic condition (Optimizing effective emittance)
- New designs (including DLSRs) employ MBA
- Damping wigglers can help (emittance, damping time, IBS)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

Design choices/Challenges of ALS-U

- Design Choices:
  - Enabled by decade of progress in nonlinear dynamics, instabilities, magnet+vacuum technology:
    - Smaller magnet and vacuum apertures
    - Advanced Lattice
    - New Injection Method
- Challenges:
  - Physics: Stability, Lifetime, Injection – integrated design optimization
  - Engineering: Magnets, vacuum systems, insertion devices
- All challenges are manageable.

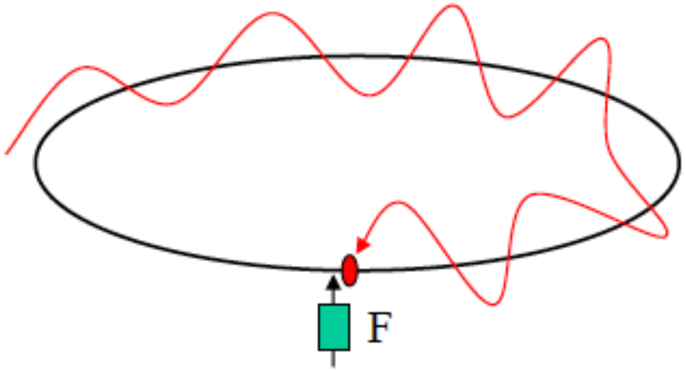


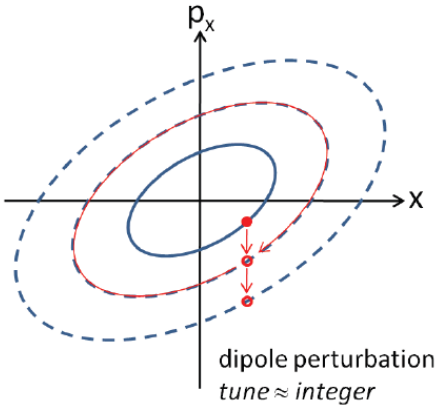
Nonlinear Dynamics / Particle Losses

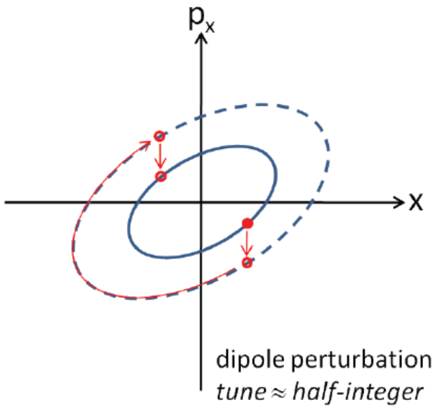
- Particles are lost in accelerators because of finite apertures, potentially limiting
  - Injection efficiency, or
  - Beam lifetime

- Limiting apertures can be *physical* or *dynamic*:
  - Vacuum chamber → physical aperture
  - Nonlinear single particle dynamics → dynamic (energy) aperture
- Loss process typically involves two steps:
  - Scattering process (or injection) launching particles to large amplitudes outside core of beam
  - Resonant or diffusive processes (nonlinear dynamics) leading to growth of oscillation amplitudes

Betatron Resonances





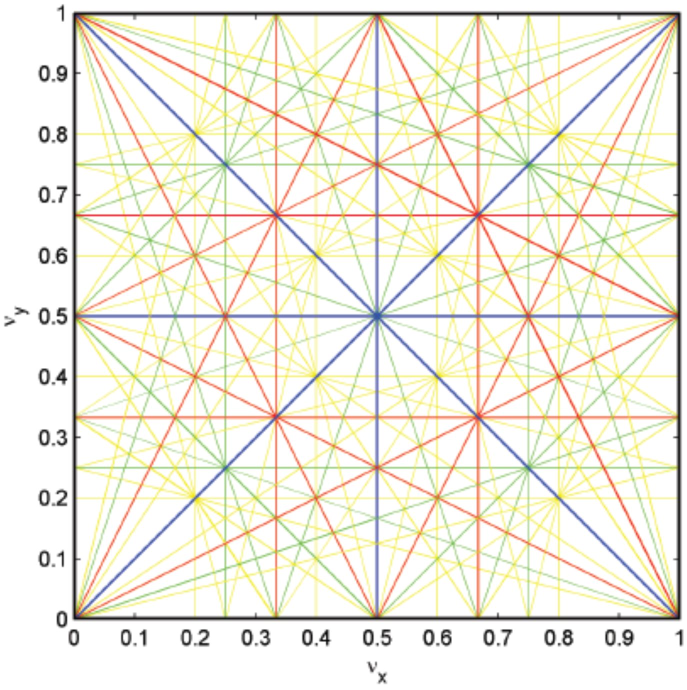


- Resonances can occur when the tunes satisfy:

$$m\nu_x + n\nu_y = q$$

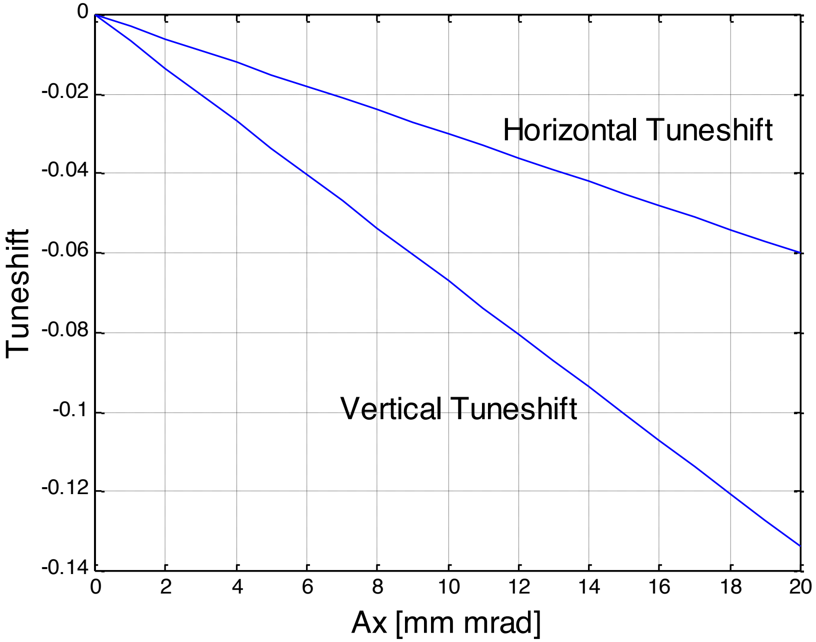
where m, n and q are integers

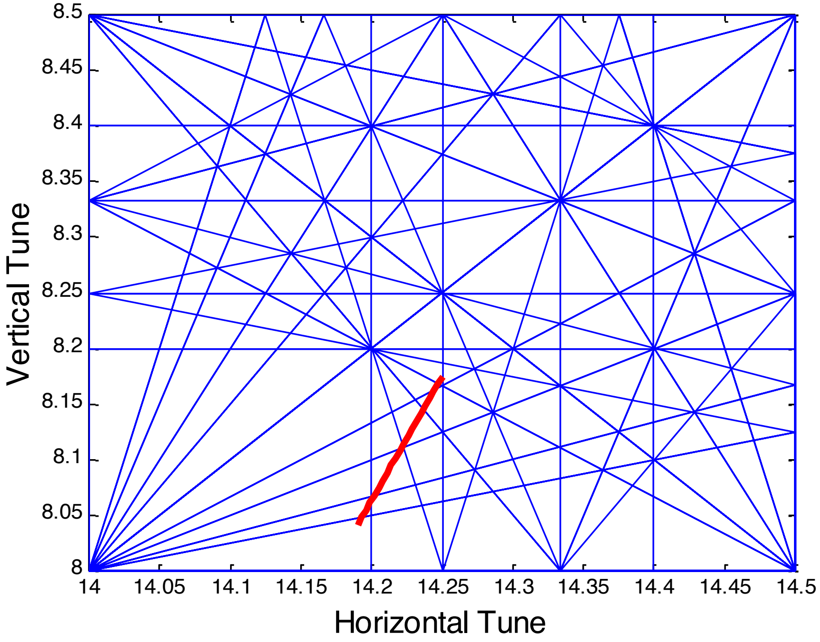
- Generally resonances are weaker the higher their order
- Integer resonances driven by dipole errors, half-integer by quadrupole errors, third-integer by sextupoles, …



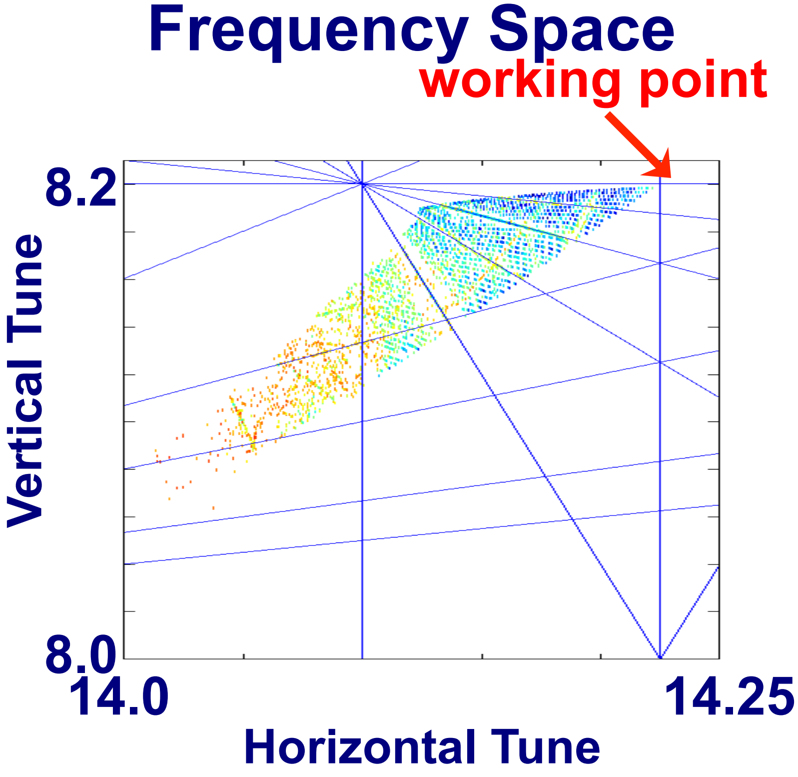
Tune shift with amplitude

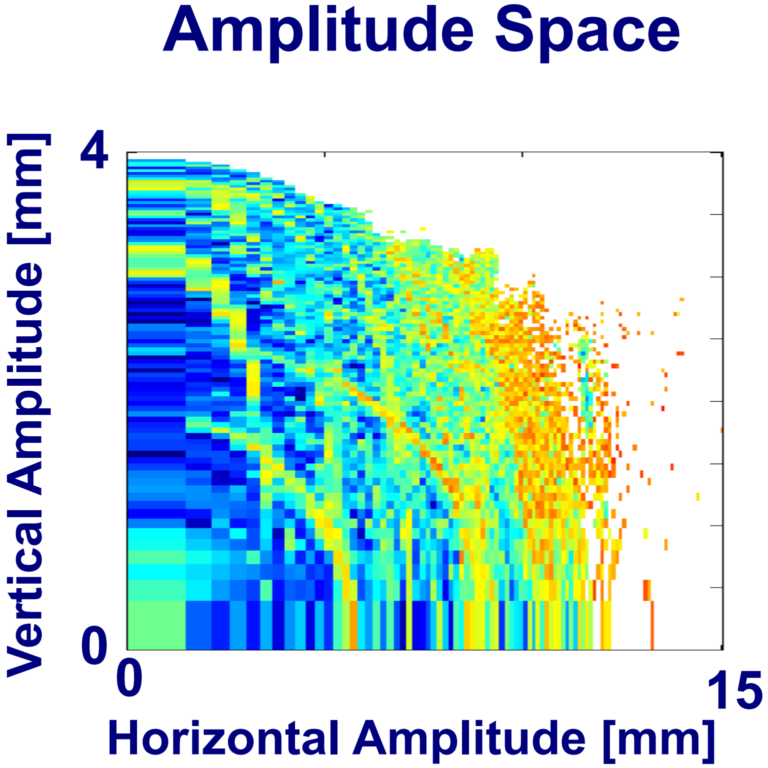
Particle tune get shifted with amplitude





Frequency Map Analysis





Brightness, Coherent Fraction, Diffraction Limit

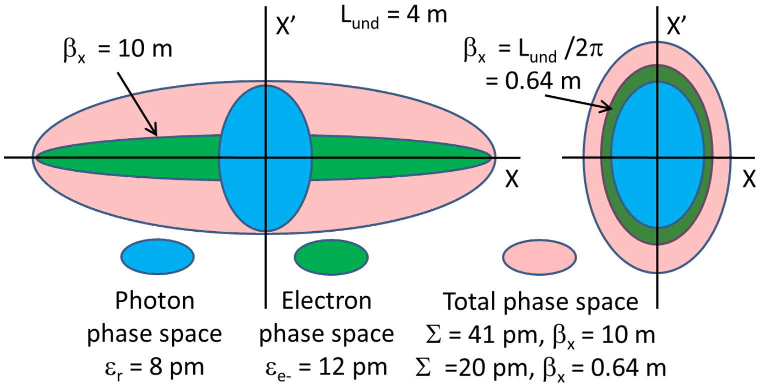
$$\varepsilon_r = \text{diffraction limited emittance} = \sigma_\gamma \sigma'_\gamma = \frac{\lambda}{4\pi} = \begin{cases} \text{80 pm @ 1 keV} \\ \text{8 pm @ 10 keV} \end{cases}$$

Brightness is inversely proportional to convolution of electron beam sizes and divergences and diffraction emittance

$$\text{Brightness} = \frac{\text{Spectral Flux}}{(2\pi)^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}$$

$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_\gamma^2}$$

Electron Photon



Coherent fraction = ratio of diffraction-limited emittance to total emittance

$$f_{coh} = \frac{F_{\mathrm{coh,T}}(\lambda)}{F(\lambda)} = \frac{\sigma_\gamma \sigma'_\gamma}{\underbrace{\sigma_{\mathrm{Tx}}\sigma_{\mathrm{Tx'}}}} \frac{\sigma_\gamma \sigma'_\gamma}{\sigma_{\mathrm{Ty}}\sigma_{\mathrm{Ty'}}}$$

DLSRs produce photon beams with dramatically larger coherent fraction due to reduced horizontal emittance

International Context – New Rings + Upgrades

Large circumference + damping wigglers

BNL**: NSLS-II** (2015): 3 GeV,
1000pm x 8 pm, 500 mA (New, **Operational**)

First new multi-bend achromat rings

Sweden: **MAX-IV** (2016): 3 GeV,
230 pm x 8 pm, 500 mA (**New**)

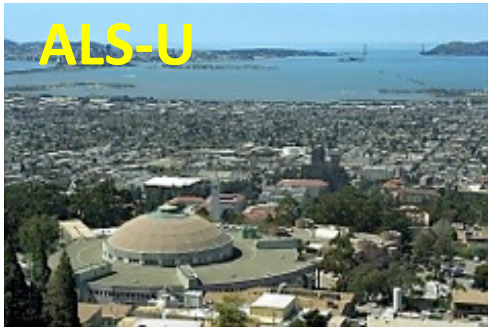
Brazil**: SIRIUS** (2016/17): 3 GeV,
280 pm x 8 pm, 500 mA (**New**)

1st multi-bend achromat upgrade

France: **ESRF-II** (2020): 6 GeV,
160 pm x 3 pm, 200 mA (**Upgrade project**)

U.S. upgrade landscape for the future

APS-U: 6 GeV, 60 pm x 8 pm,
200 mA (**Upgrade project**)

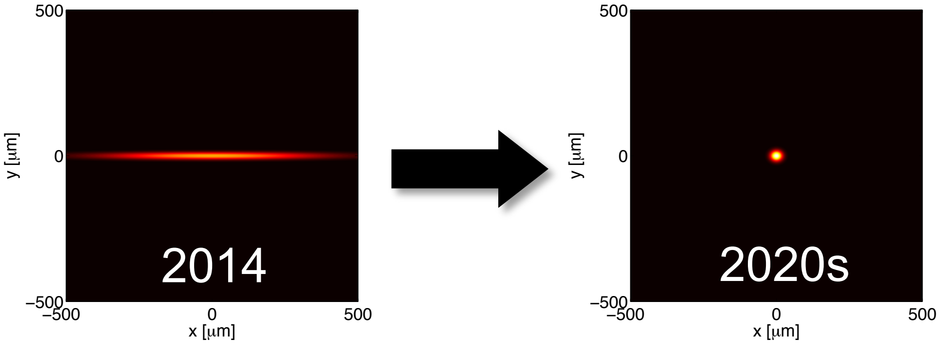


ALS-U: 2 GeV, 50 pm x 50 pm,
500 mA (**Pre-Conceptual design**)

Other international plans: *Japan (Spring 8, 6 GeV), China (BAPS, 5 GeV), Germany (PETRA-III), France (SOLEIL), Switzerland (SLS, 2.4 GeV), Italy (ELETTRA) are developing brightness upgrade plans*

Goals for ALS-U

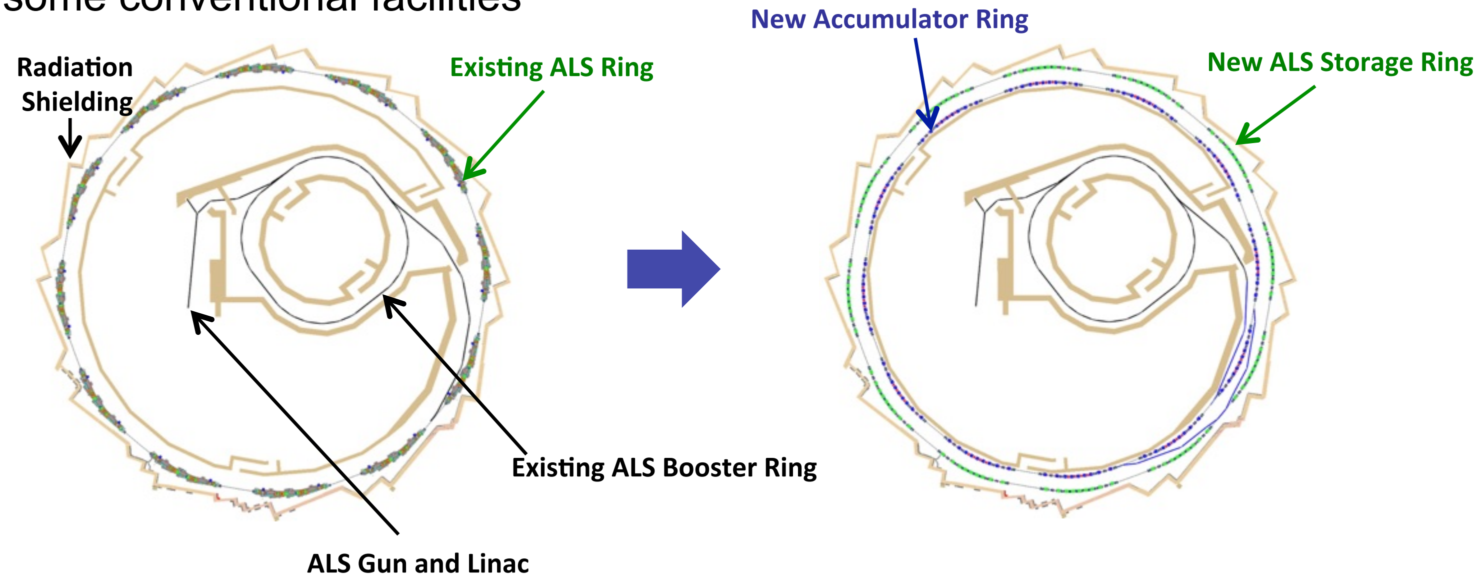
- Develop the highest brightness and most capable soft x-ray synchrotron facility
  - SXR brightness beyond any synchrotron, current, planned, under construction
  - up to 1000x increase in brightness over current ALS



- Use advanced imaging techniques to address essential science and technology
  - chemical, electronic, and magnetic maps of functional systems
  - nanometer resolution in 3-dimensions
  - dynamics and kinetics on natural timescales from picoseconds to minutes
- Execution:
  - Finish in 6 years from CD-0
  - Minimize dark time to less than one year
  - Most beamlines operational at end of project

Scope of the ALS-U Project

- **Replace** storage ring with new high performance storage ring based on multi bend achromat: same straight section length, location, and symmetry as original storage ring
- **Add** full energy accumulator ring in existing storage ring tunnel
- **Modify** existing beamlines: optics upgrades and beamline relocation
- **Add** two new world-class undulator beamlines optimized for science case
- **Upgrade** some conventional facilities

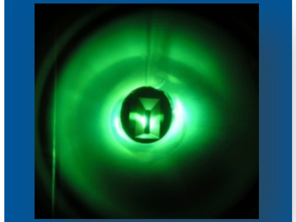


Cost effective solution:

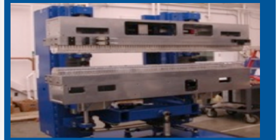
- Will reuse existing building, shielding, injector, and most beamlines
- Will have operational costs similar to ALS

Successful ATAP and ALS Innovation in Providing Exquisite X-Ray Beams and Developing Next Generation Light Sources

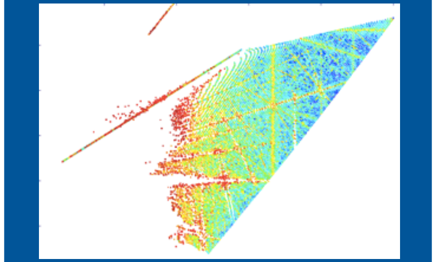
first ALS light



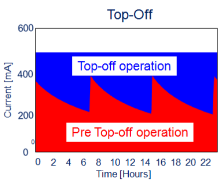
elliptically polarizing undulator



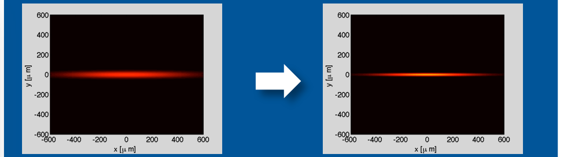
frequency maps



top-off at 500 mA



brightness upgrade 3x emittance reduction

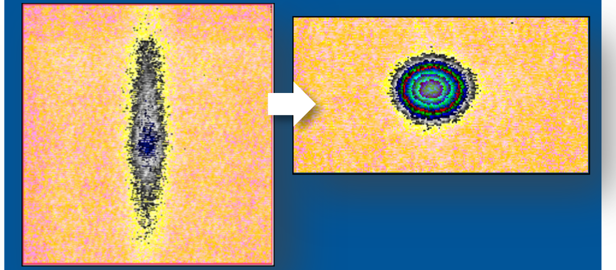


1993

2003

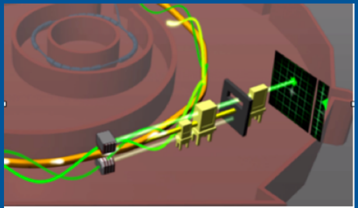
2013

2020s

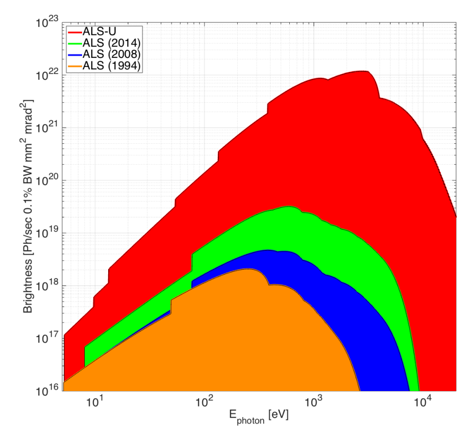


multi-bunch feedback for high-current and high-brightness

pseudo single bunches for pulses on demand



ready for generational leap: ALS-U



Mounting Interest in ALS-U

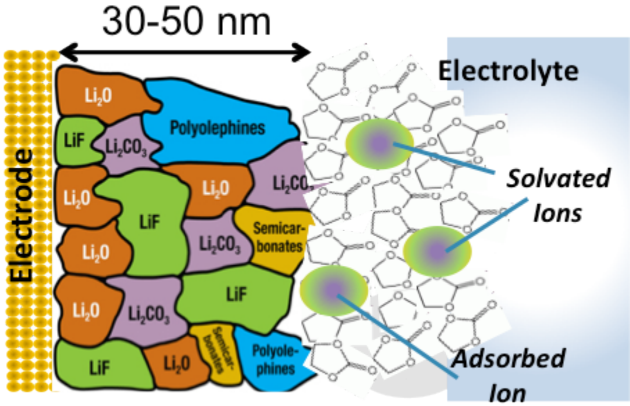
Jul 2013	*BESAC Subcommittee on Future X-ray Light Sources:* "The Office of Basic Energy Sciences should **ensure that U.S. storage ring x-ray sources reclaim their world leadership position**. […] It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments of storage rings in other countries. Such developments include **diffraction-limited storage rings**. […]"
Oct 2014	*Workshop on Soft X-ray Science Opportunities using Diffraction-Limited Storage Rings, LBNL*
Feb 2015	Roger Falcone presentation at BESAC: *Soft X-Ray Workshop Report: Scientific opportunities enabled by coherent soft x-rays*
May 2015	*Senate's FY16 Energy & Water appropriations bill includes the statement,* "Further, $5,000,000 is provided for research and development for the Advanced Light Source Upgrade."

ALS-U Connects Nanoscale Landscapes to Function

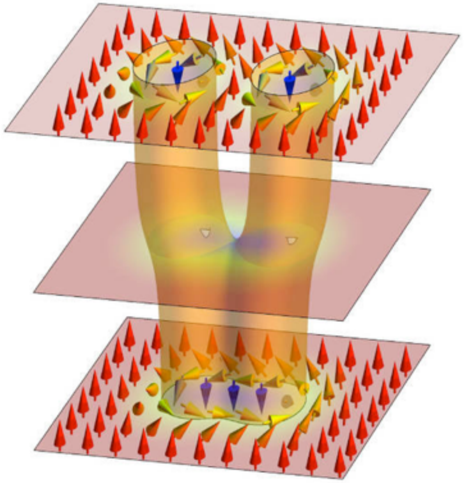
Measuring & directing nanoscale chemistry

Materials to enable low power processing

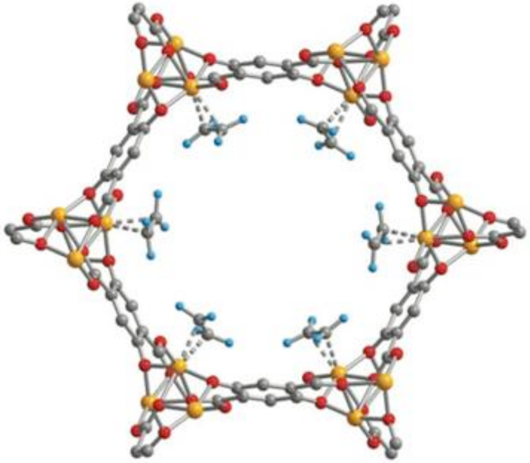
Global biological & environment challenges



Electrochemical landscape controls ion transport, SEI stability, cell lifetime



Magnetic landscape controls spin and skyrmion transport, processing



Chemical landscapes in MOFs controls catalysis, CO_2 capture

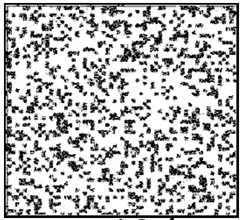
ALS-U tools will

- - map *nanoscale landscapes* with chemical, electronic, magnetic contrast

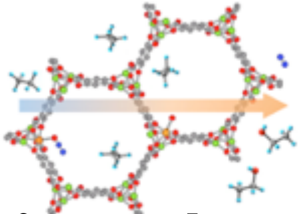
- - probe *nanoscale motion* of mass, charge, spin, elementary excitations

Brightness allows capture of spontaneous nanoscale kinetics: approaching the h/k_BT timescale

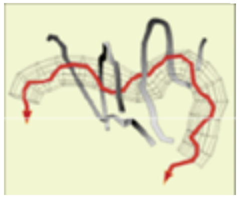
Nucleation kinetics
10.1126/science.1230915



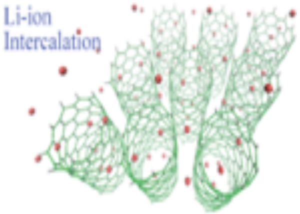
Selective Catalysis
10.1038/nchem.1956



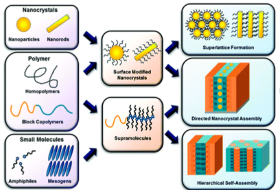
Polymer reptation

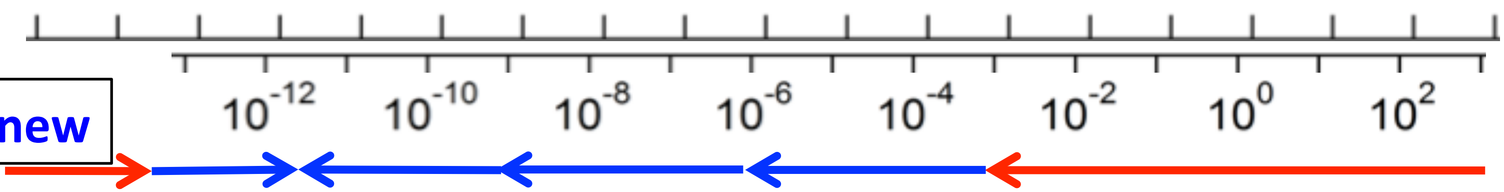


Intercalation kinetics,
10.1039/C0EE00473A



Self assembly



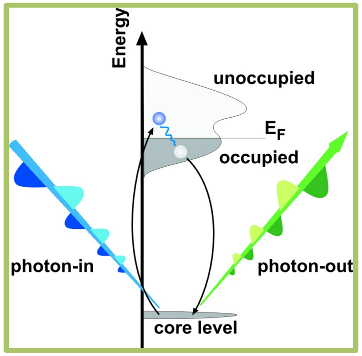


10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11} 10^{-13} 10^{-15} 10^{-18} Energy Scale (eV)

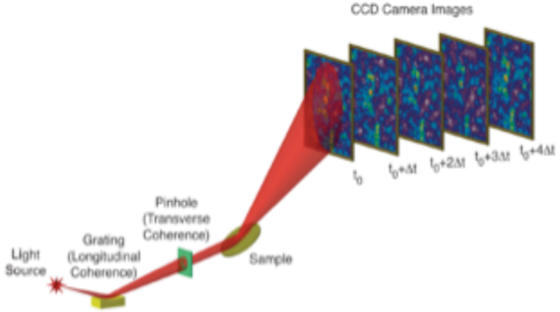
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} Time Scale (sec)

now/new

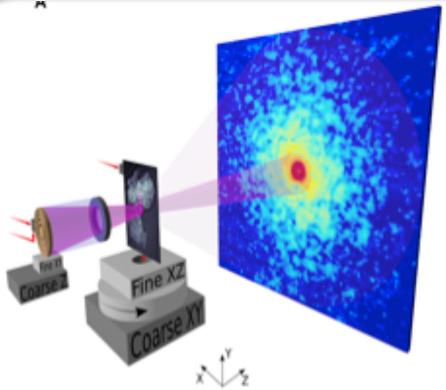
RIXS FT-RIXS Fast XPCS XPCS movies movies/XPCS



Resonant Inelastic X-Ray Scattering: S(q,ω)



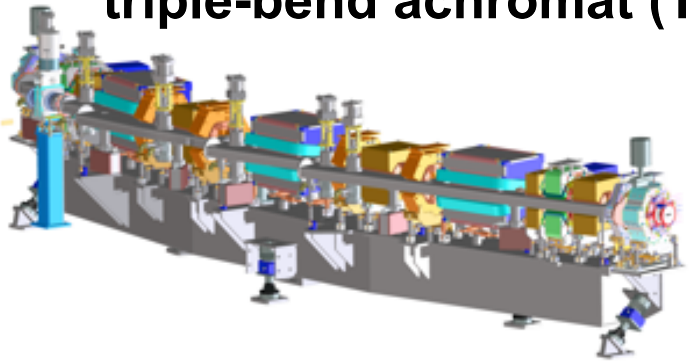
X-ray Photon Correlation Spectroscopy: S(q,t)

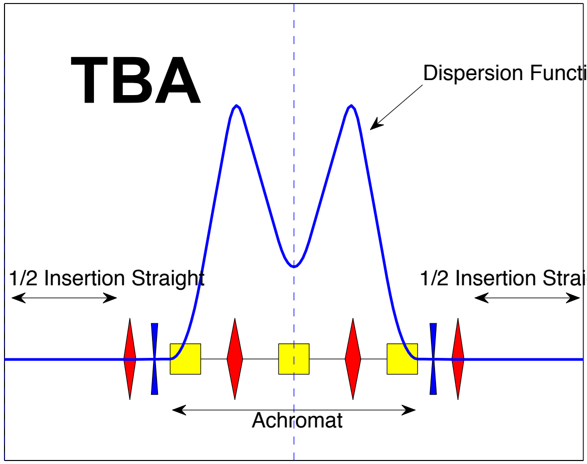


Time-resolved X-ray Microscopy: G(r,t)

Multi-Bend Achromat Lattices Enable Small Electron Emittance and High X-Ray Brightness

ALS today
triple-bend achromat (TBA)

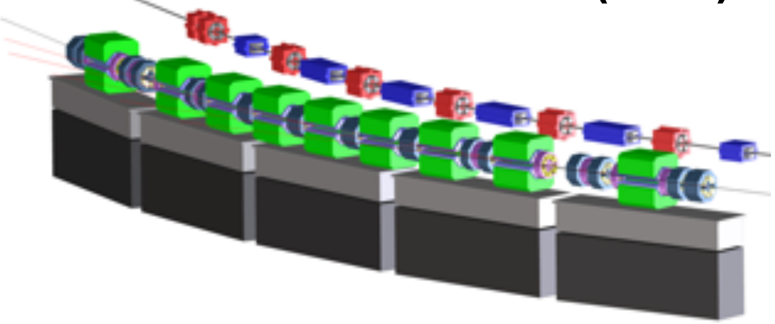


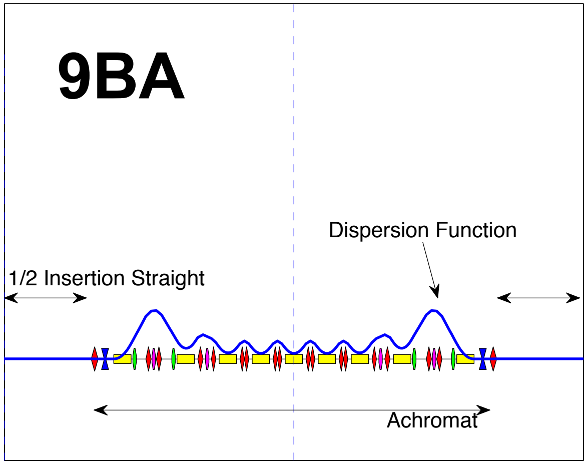


$$\varepsilon_x = \boxed{2000\ \mathrm{pm}}\ @\ 1.9GeV$$

$$\varepsilon_x = C_L \frac{E^2}{\boxed{N_D^3}}$$

ALS-U
multi-bend achromat (9BA)





$$\varepsilon_x = \boxed{52\ \mathrm{pm}}\ @\ 2.0GeV$$

ALS and ALS-U in numbers

Parameter	Units	Current ALS	ALS-U
Electron Energy	GeV	1.9	1.9-2.2 (2.0 baseline)
Horiz. Emittance	pm rad	2000	~50
Vert. Emittance	pm rad	30	~50
Beamsize @ ID center (σ_x/σ_y)	μm	251 / 9	<10 / <10
Beamsize @ Bend (σ_x/σ_y)	μm	40 / 7	<5 / <7
Energy Spread	ΔE/E	9.7×10^{-4}	$<9\times10^{-4}$
Typical Bunch Length (FWHM)	ps	60-70 (harmonic cavity)	150-200 (harmonic cavity)
Circumference	m	196.8	~196.5
Bend Magnet Angle	degree	10	3.33

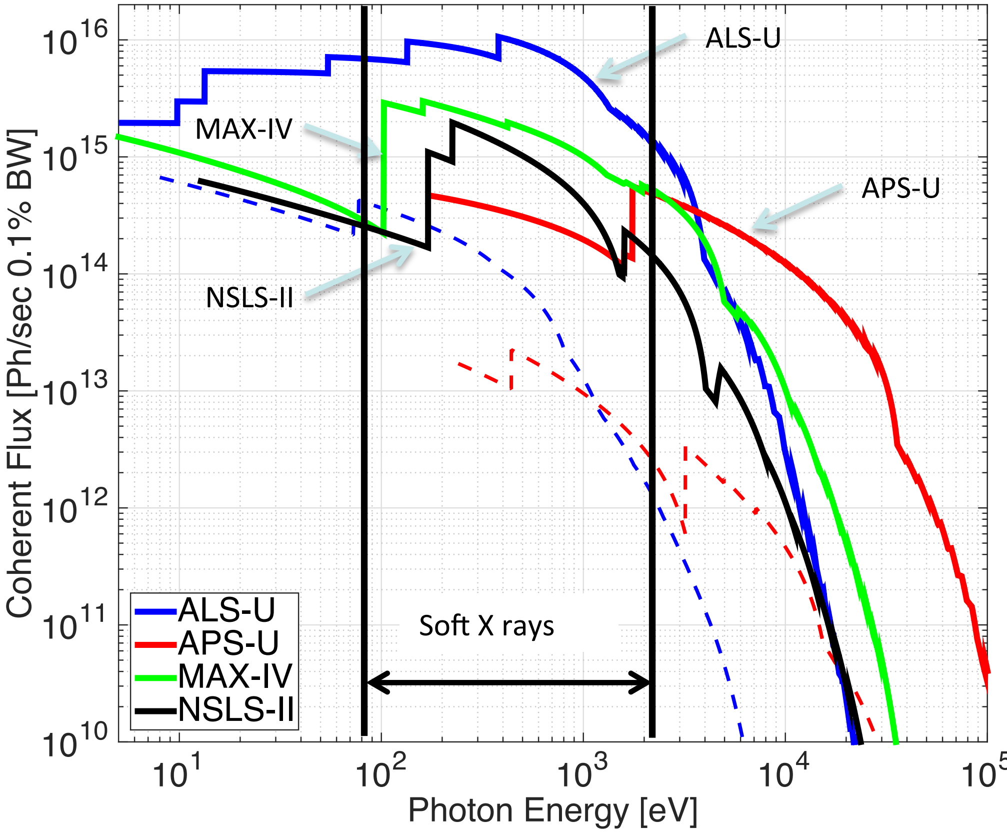
ALS-U is Optimized for Soft X-Ray Science

- **Choices are made to optimize brightness for photon energy range:**
  - Electron beam energy
  - Undulator technology

- **Features of ALS 2 GeV ring compared with higher energy ring:**
  - Larger beam current
  - More undulator periods for given photon energy
  - Lower heat load on beamline components

✓ALS-U design results in:

Highest coherent soft x-ray flux



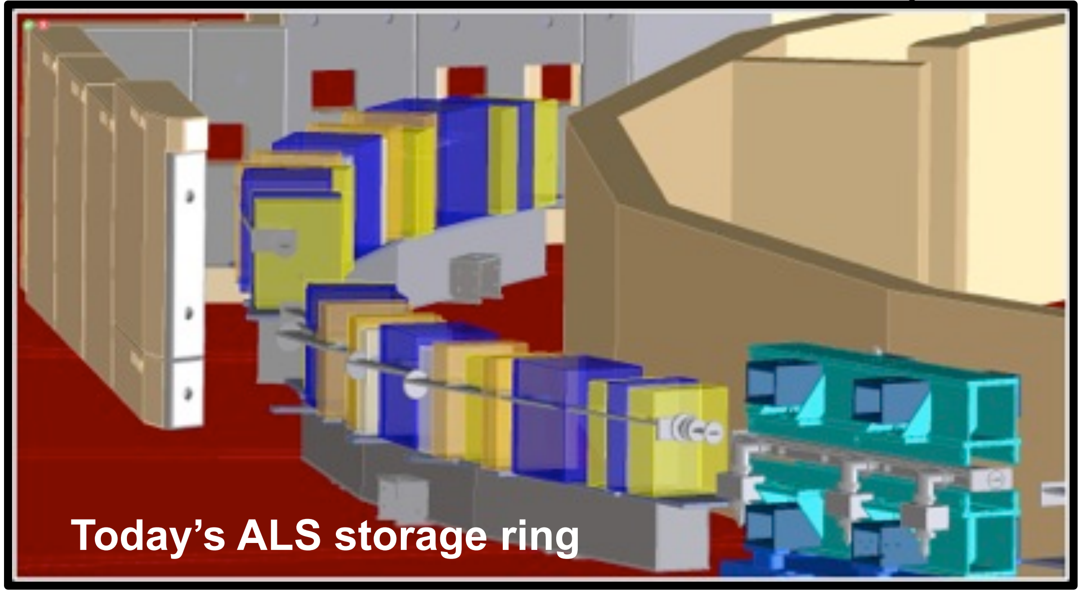
--- --- current ALS, APS

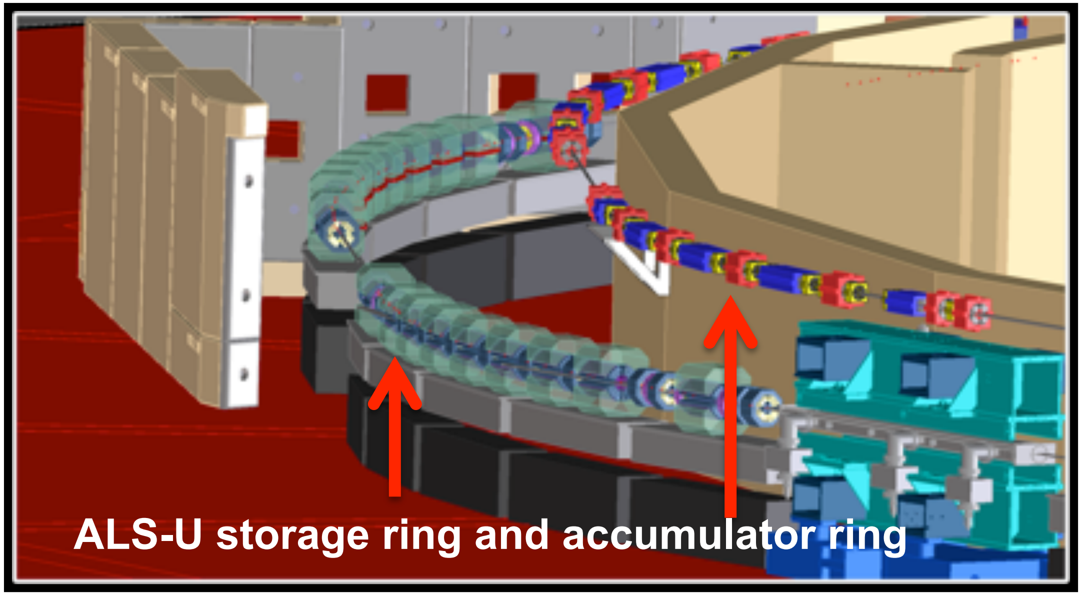
Use of Swap-Out Enables Generational Leap

– **On-axis swap-out injection:**
- **Further optimization of lattice** (smaller emittance)
- **Round beams** (more useful shape and reduced emittance growth)
- **Magnet field requirements relaxed** (cost benefit)
- **Vacuum chambers with small and round apertures** (better undulator performance)
- **Reduced injection losses** (better performance)

Only ALS-U and APS-U include swap-out

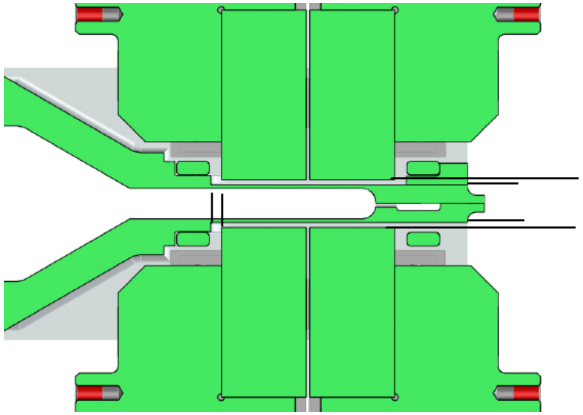
Swap out initially proposed by M. Borland


Today's ALS storage ring

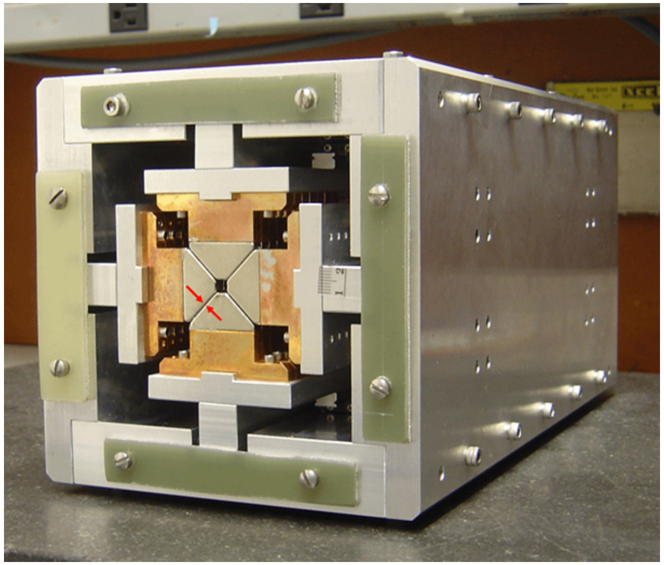

ALS-U storage ring and accumulator ring

Advantage of smaller apertures

- Smaller apertures in DLSR arcs enable strong gradients to minimize emittance
- However, DLSRs also allow smaller apertures in straights
  - Smaller gaps allow higher performance (shorter period, i.e. more flux) undulators
  - Round beam allows to go from flat undulator geometries (which were fine for linear polarization) to round ones
  - Potentially large advantage for polarization control undulators (could be both permanent magnet or s/c)
  - Will evaluate substantially cheaper undulators



ALS: MAESTRO EPU



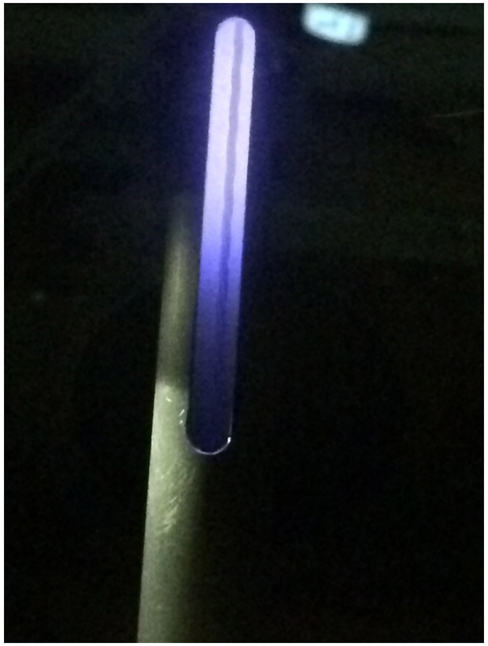
A. Temnikh – Delta Undulator

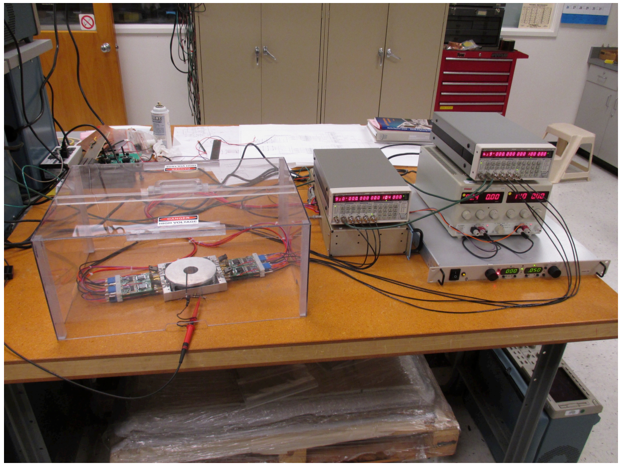
R+D Areas

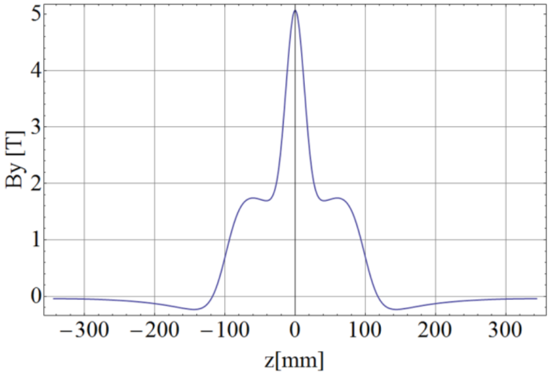
Topics selected to cover areas with highest technical risks – well aligned with community consensus

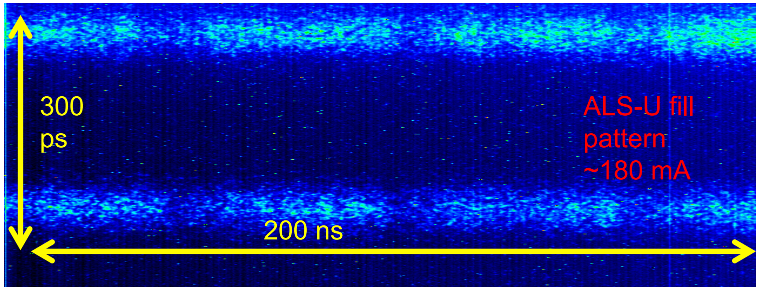
Funded by LDRD:

- Pulsed Magnets/Injection
- Vacuum System, small gap NEG coated chambers
- RF system, harmonic RF, transients, fill pattern
- Magnets, Radiation Production
- Optimization of Physics Design, Staging
- Emittance preserving photon optics

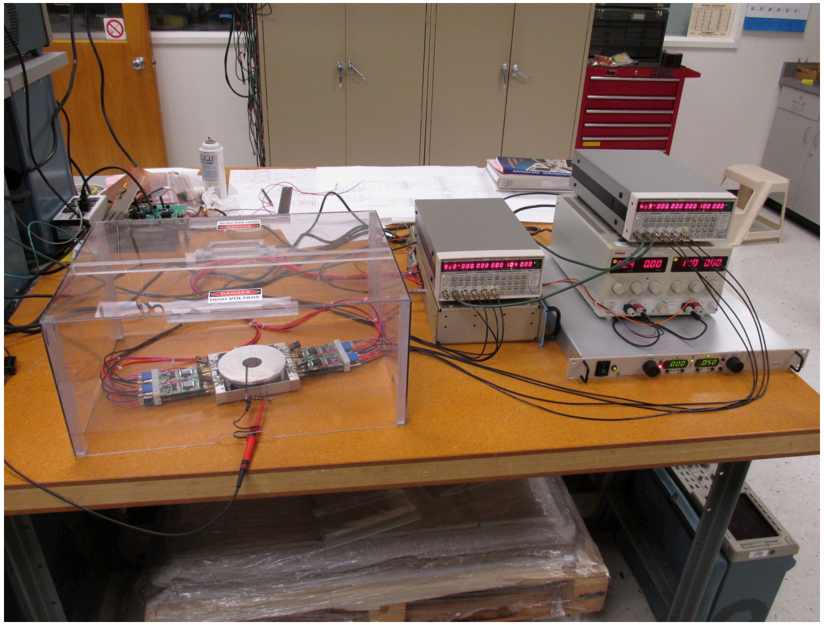


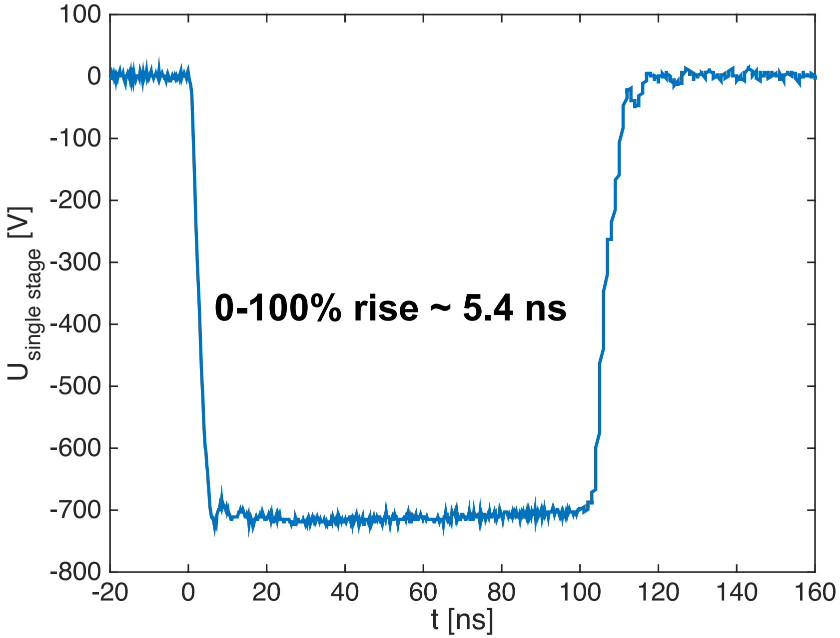






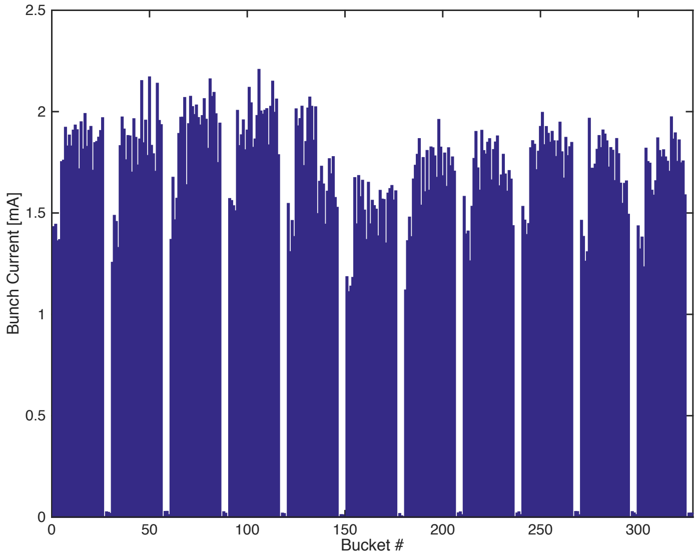
R+D Success (1) - Injection

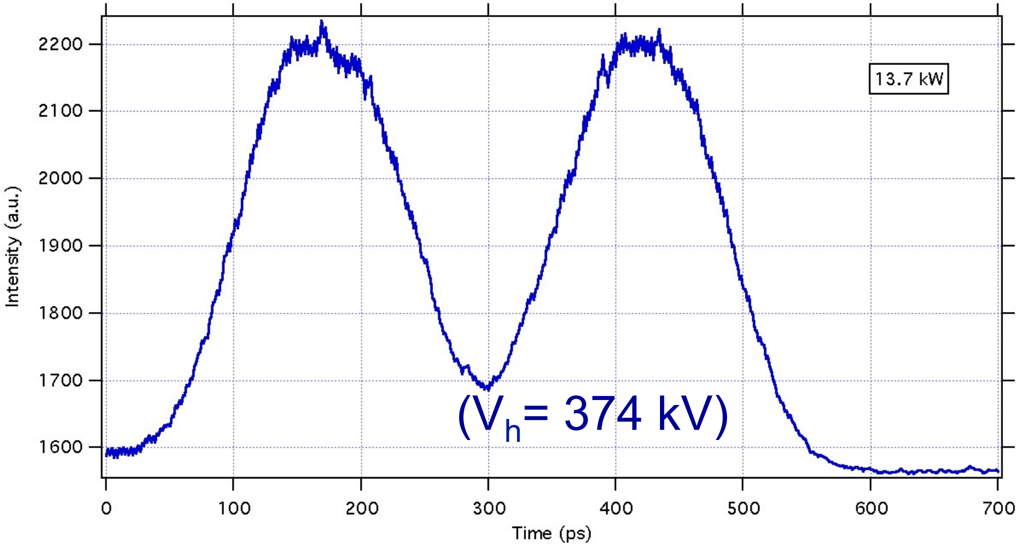




- **Single module with ALS-U parameters has been tested successfully** (<<10 ns rise/fall time)
  - Consistent with RF / THC design
  - Full pulser almost complete; test with beam in FY16

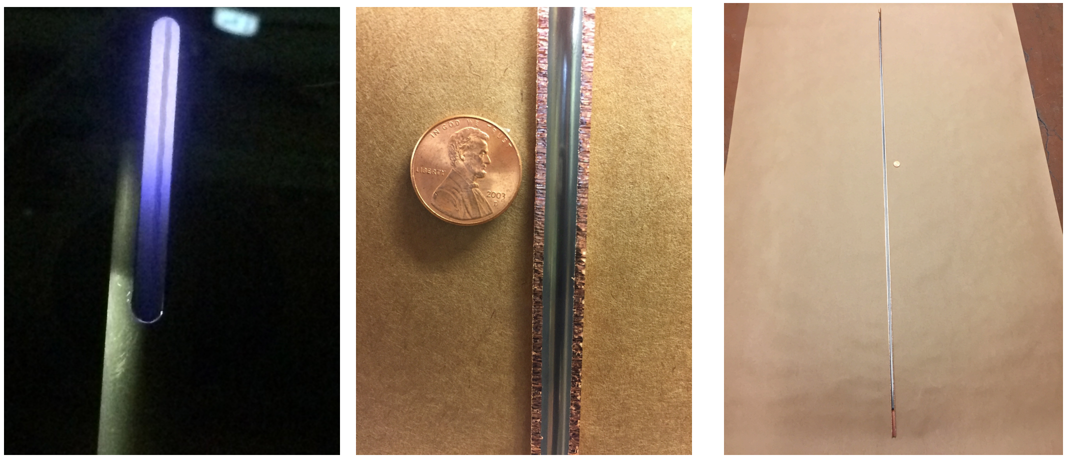
R+D Success (2) – Bunch Lengthening

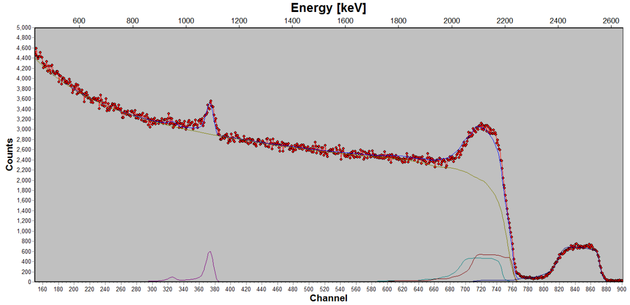


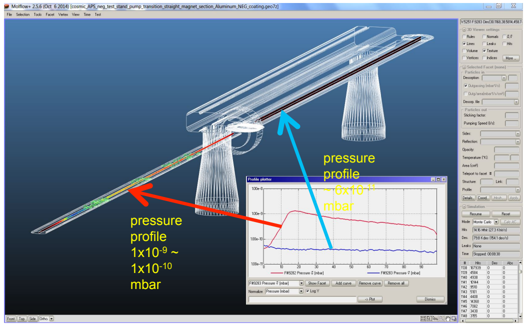


- **Large bunch lengthening factors (>4) essential (IBS), but not routinely achieved before**
- Extensive simulations (finite element, multi particle tracking)
- Measurements with ALS harmonic cavity system in parameter regimes close to ALS-U (fill pattern, lengthening factor) – **Achieved factor 4.5, retiring large risk.**

R+D Success (3) - Vacuum

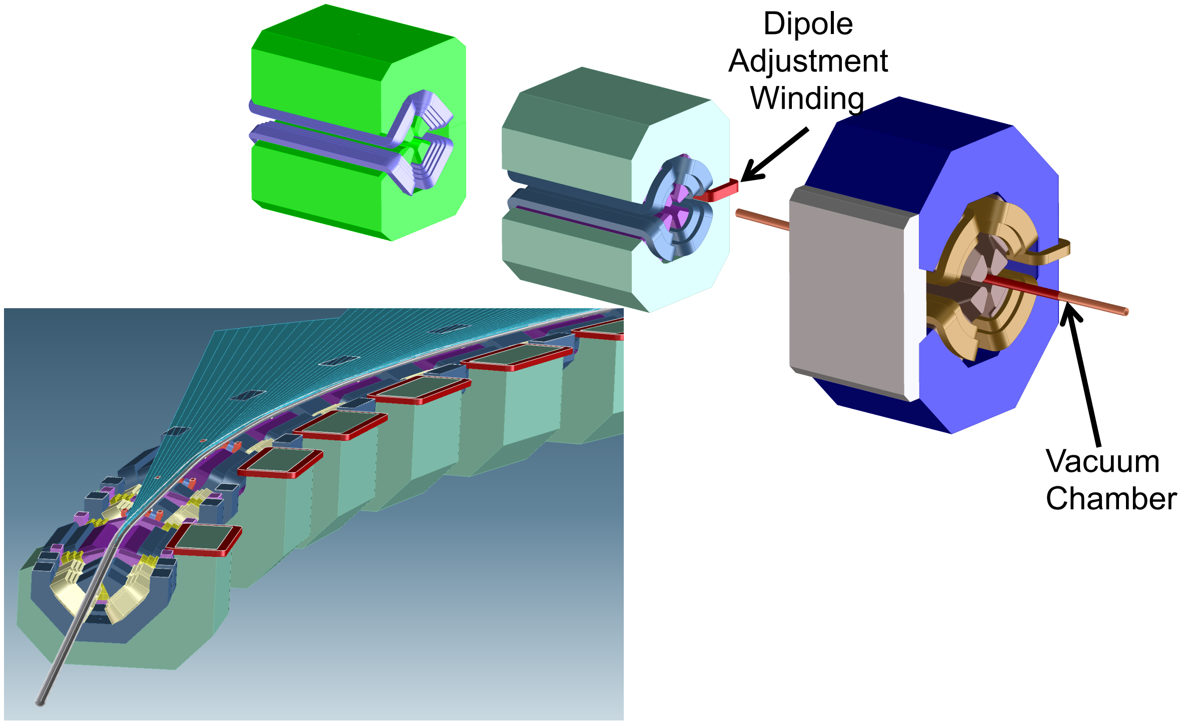


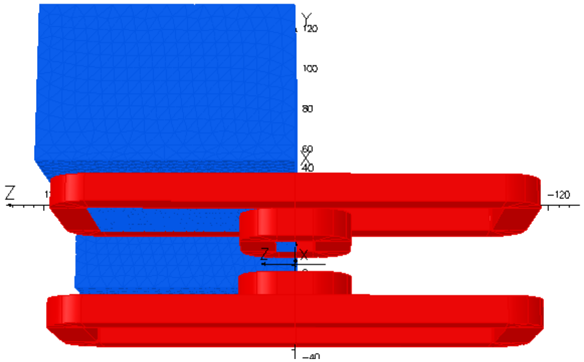


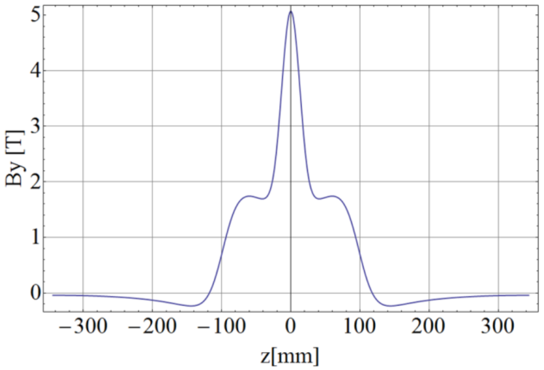


- Concentrating on small apertures and unusual shapes
  - Industry capabilities evaluated in parallel as part of COSMIC project.
- First small copper chamber (6 mm) NEG coated at LBNL, currently being characterized – activation tests in spring
  - As far as we know this is the **smallest chamber ever coated**
  - Developing in-house knowledge to model dynamic vacuum systems

Magnet Design Progress

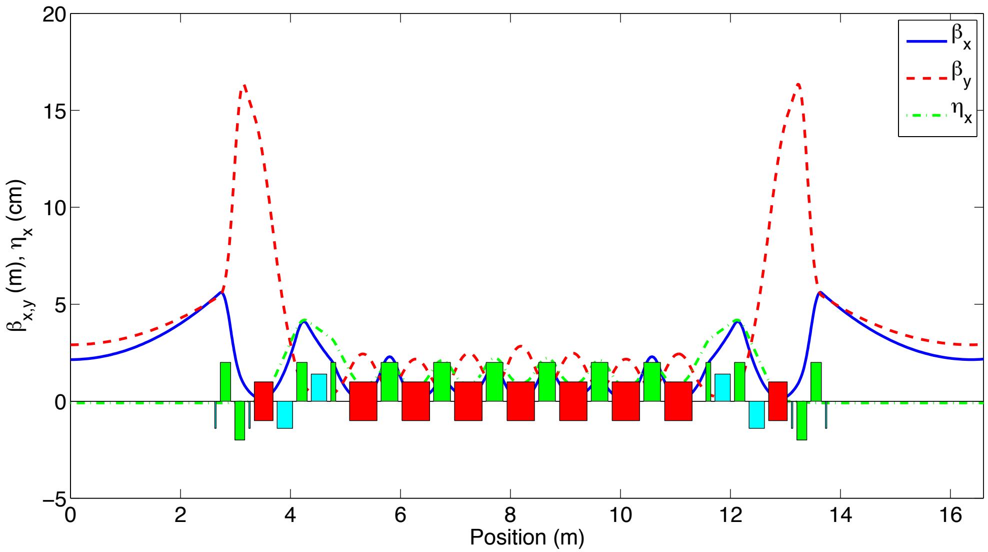


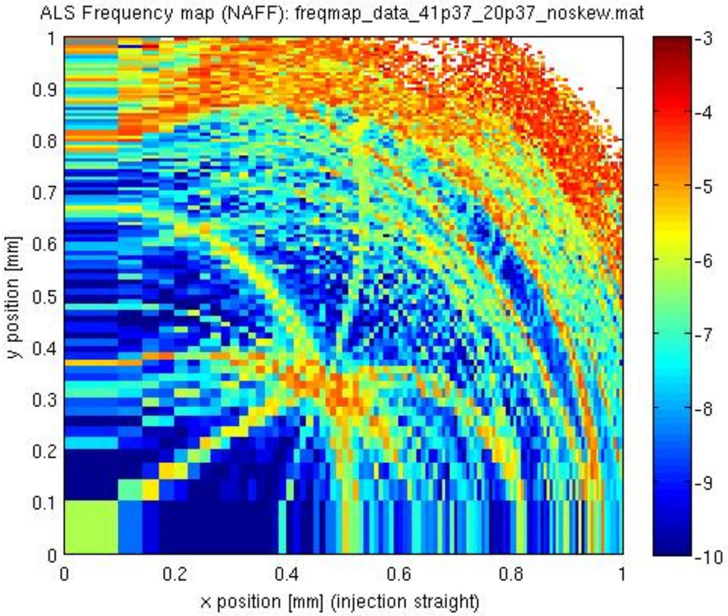




- Magnets, Radiation Production
  - Established feasibility of basic accelerator magnets (quadrupoles, gradient dipoles) – advanced materials and 3d pole shape
  - Studying various hard x-ray options (permanent magnet and s/c Superbends, 3PW, multiple field strengths)
  - Studying Insertion Devices for small/round chambers

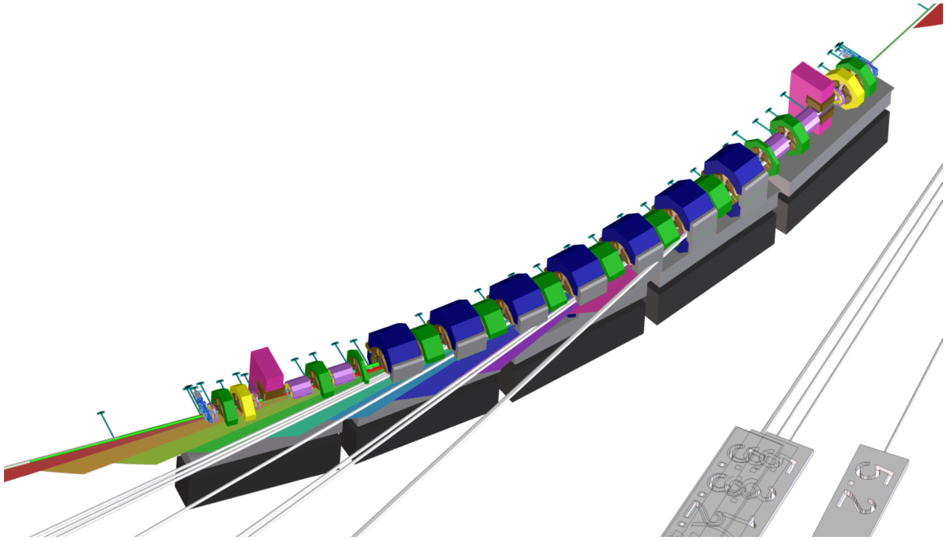
ALS-U Baseline Lattice

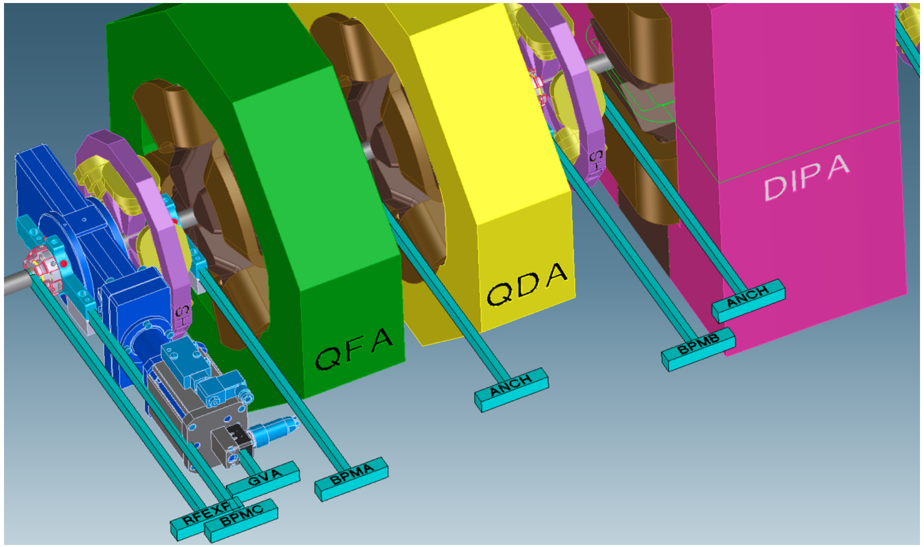


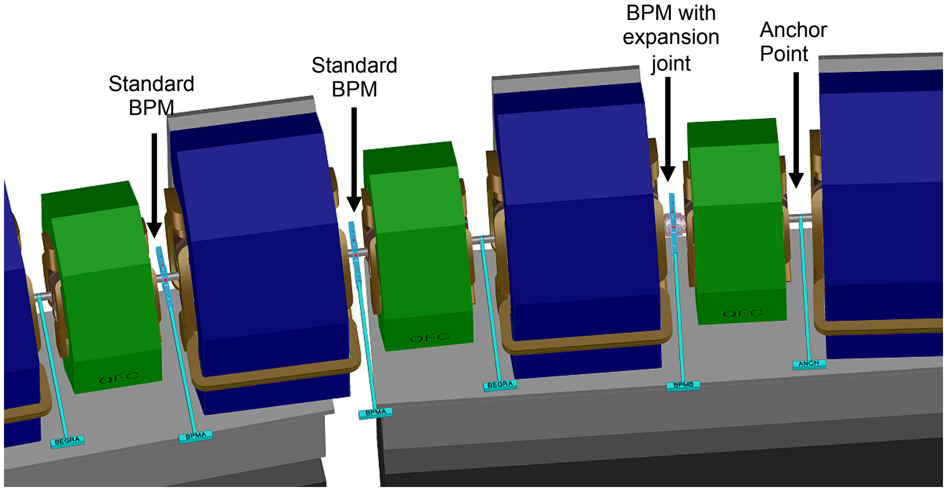

ALS Frequency map (NAFF): freqmap_data_41p37_20p37_noskew.mat

- Finished physics design and released baseline lattice
  - Baseline lattice allows to study all engineering/layout/geometry questions and interdependencies in sufficient detail
  - Baseline lattice achieves basic design goals – but further improvements desirable and tolerance studies under way
    - Emittance, Dynamic Aperture, Momentum Aperture

Efficient Physics – Engineering Integration





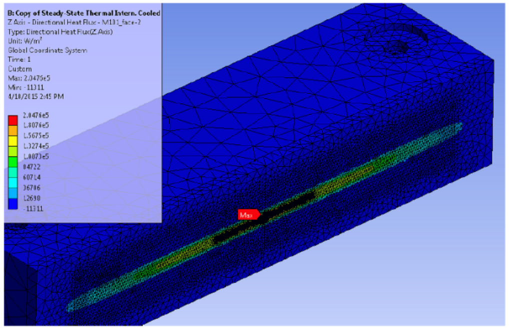


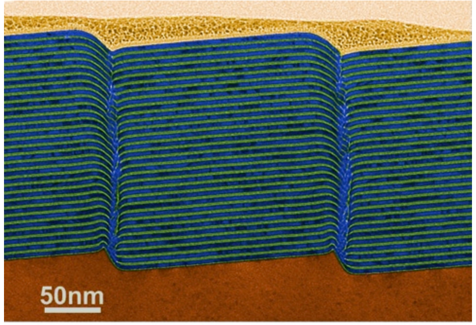
Developed automated scripts to move from physics design to 3D CAD model

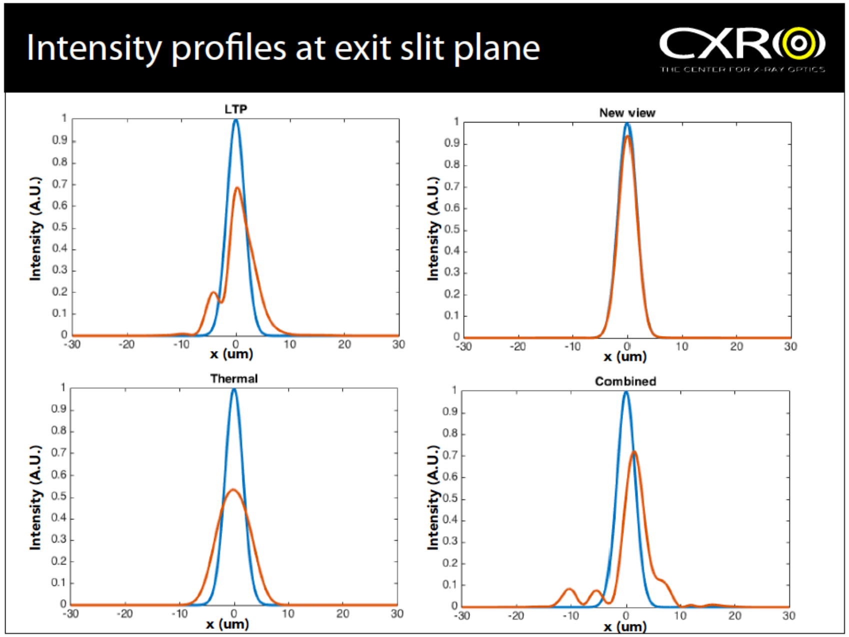
- Using Pre-conceptual designs for magnets
- Combining with sample designs for all necessary vacuum components

Allows evaluation of space constraints/ interference and photon beamline needs

X-ray Optics Development

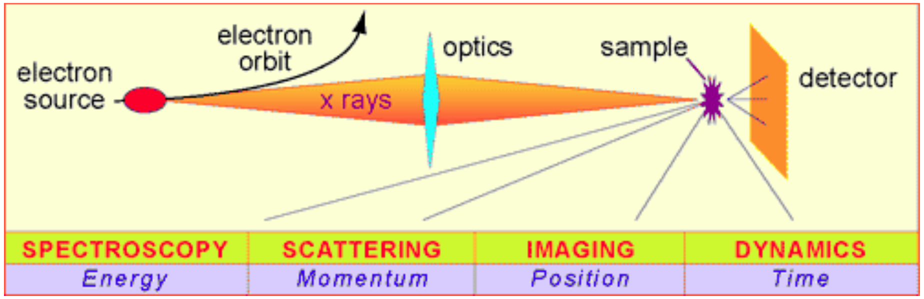





Intensity profiles at exit slit plane

- Challenge to preserve photon brightness/coherent wavefronts horizontally +vertically:
  - Surface quality
  - Thermal distortions
- Work integrated as part of LDRD
  - Team of ALS/ENG/CXRO/ATAP
- Advanced simulation tools
- Studying different cooling schemes, including LN cooled Si
  - Will include hardware tests
- No show-stoppers identified, but much more work needed

Instrumentation Example: Beam Stability

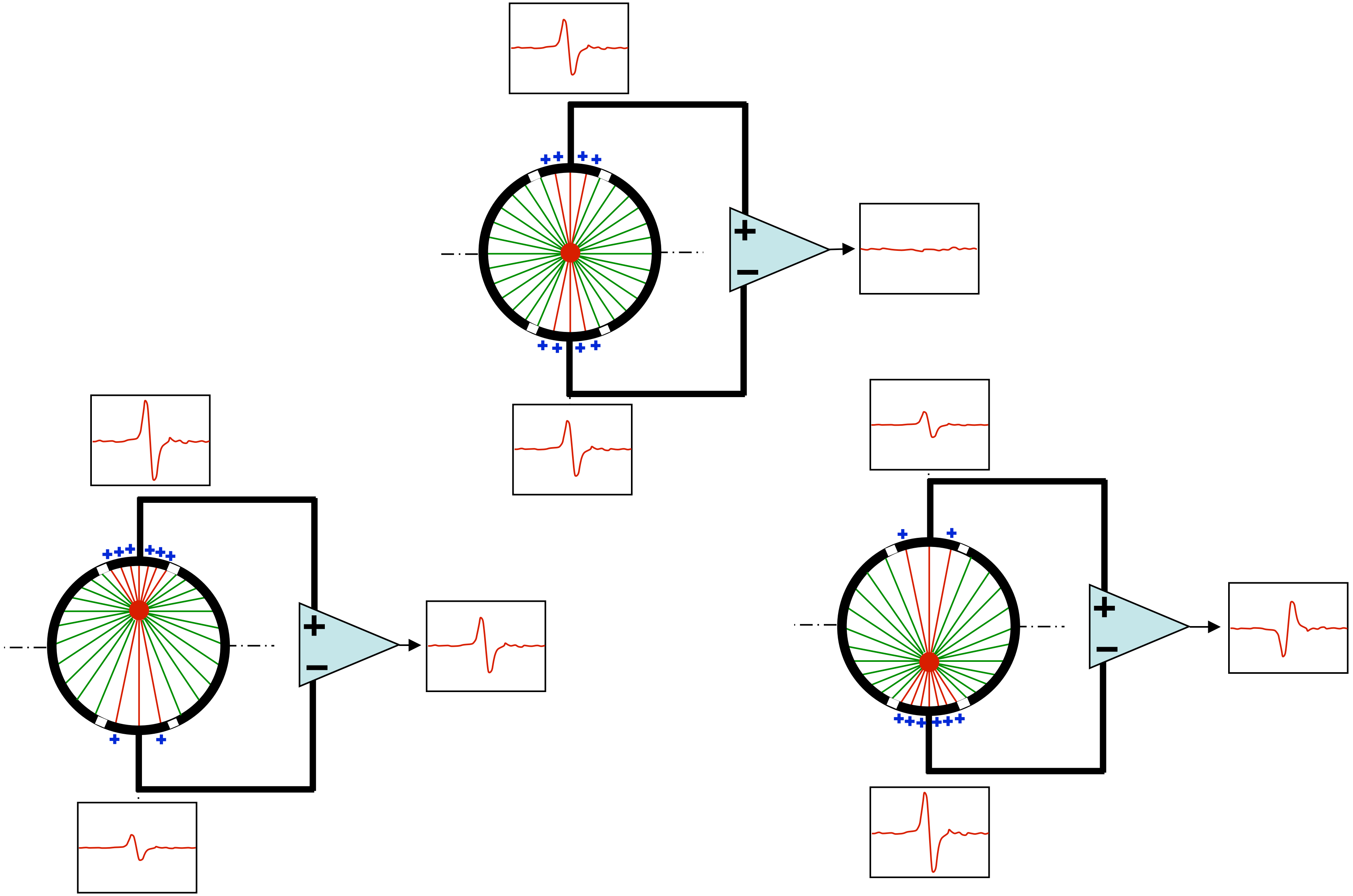


Typical requirements of modern SR user experiments:

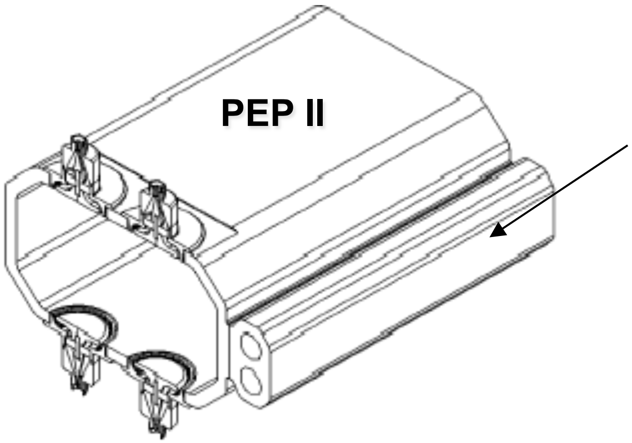
Measurement parameter	Stability Requirement
Intensity variation $\Delta I/I$	<<1% of normalized I
Position and angle	<2-5% of beam σ and σ'
Energy resolution $\Delta E/E$	$<10^{-4}$
Timing jitter	<10% of critical time scale
Data acquisition rate	$10^{-3} - 10^{5}$ Hz

- All of those requirements relate back into stability requirements for beam position + angle, beamsize + emittance, beam energy, beam energy spread, …
- Often stability can be more important to SR users than brightness+flux
- For current SR sources, this means for example submicron orbit stability (for ERLs in both planes)

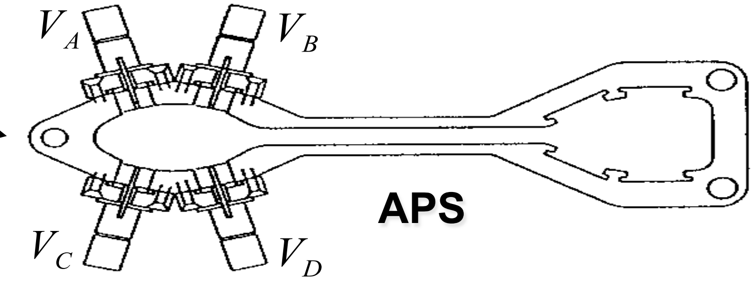
Electromagnetic Beam Position Monitors



Capacitive Pickups

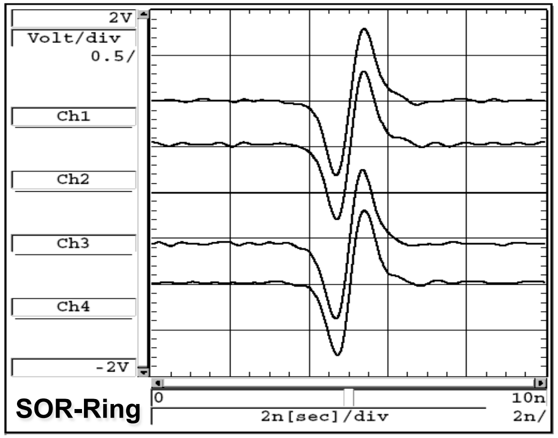


- **Typical geometry used in the presence of synchrotron radiation.**

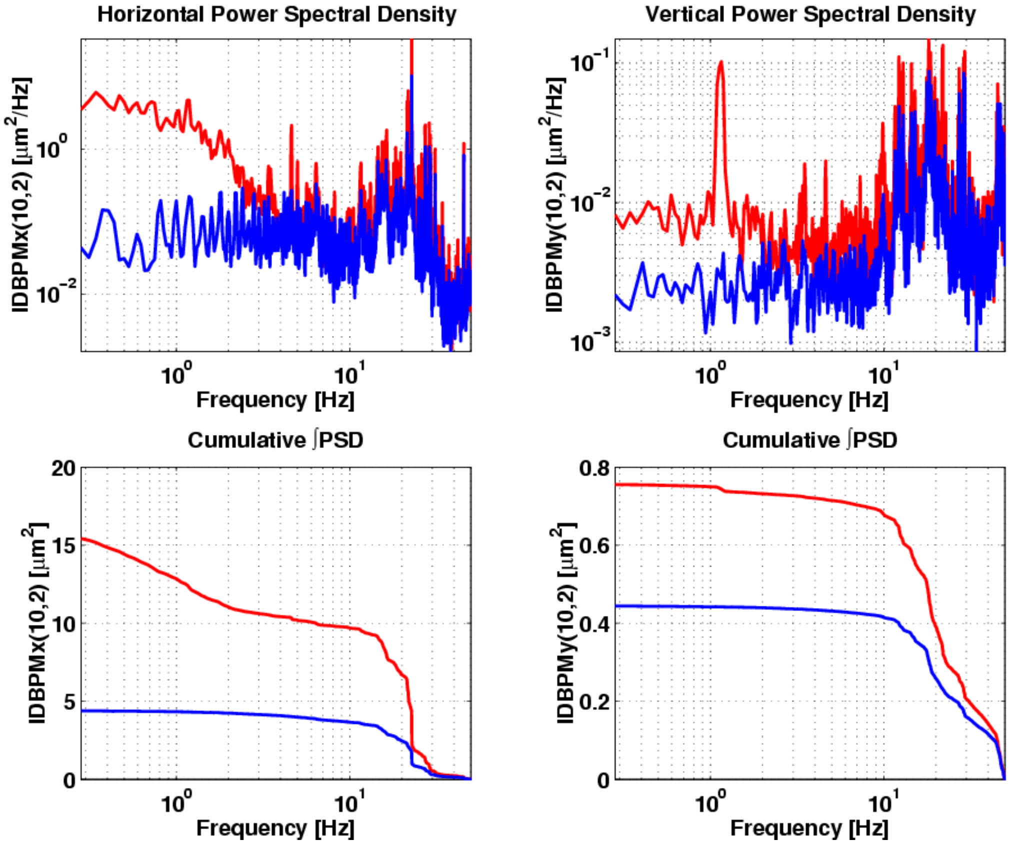


$$\Delta x = K\frac{(V_A + V_C) - (V_B + V_D)}{V_A + V_B + V_C + V_D}, \qquad \Delta y = K\frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D}$$

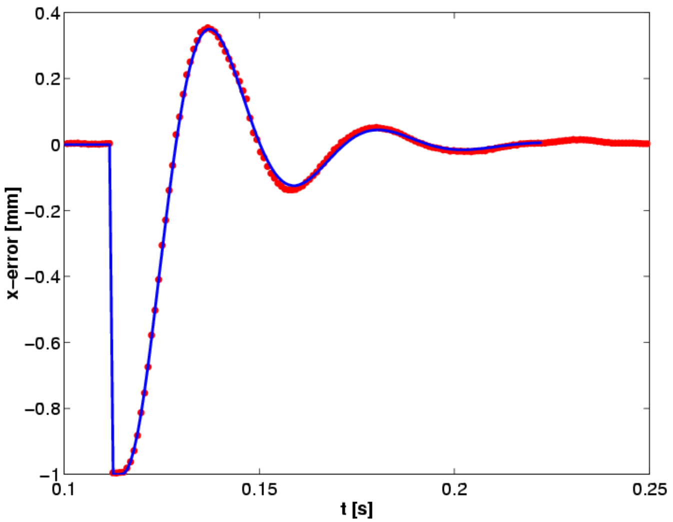
- **Capacitive type (derivative response), low coupling impedance, relatively low sensitivity, best for storage rings.**



Performance of Fast Orbit Feedback at ALS



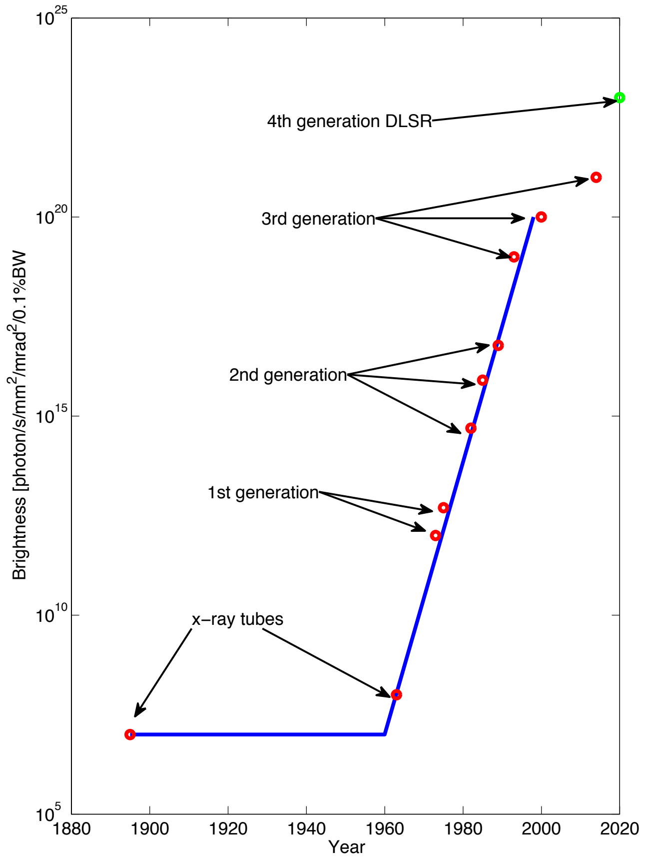
Comparison of orbit PSDs with and without fast feedback.
Fast orbit feedbacks are in use at most light sources: APS, NSLS, ESRF, SLS, …



Comparison of simulated (Simulink) and measured step response of feedback system in closed loop in a case where PID parameters were intentionally set to create some overshoot.

Longer Term Options

- Diffraction limited source might appear as end of development for rings
  - That will likely change
  - 3^{rd} generation was seen as endpoint
- Possible directions include:
  - Partial lasing, special single/few turn modes, beam manipulations
- Having ALS-U as starting point makes any such options much more attractive and easier



Summary

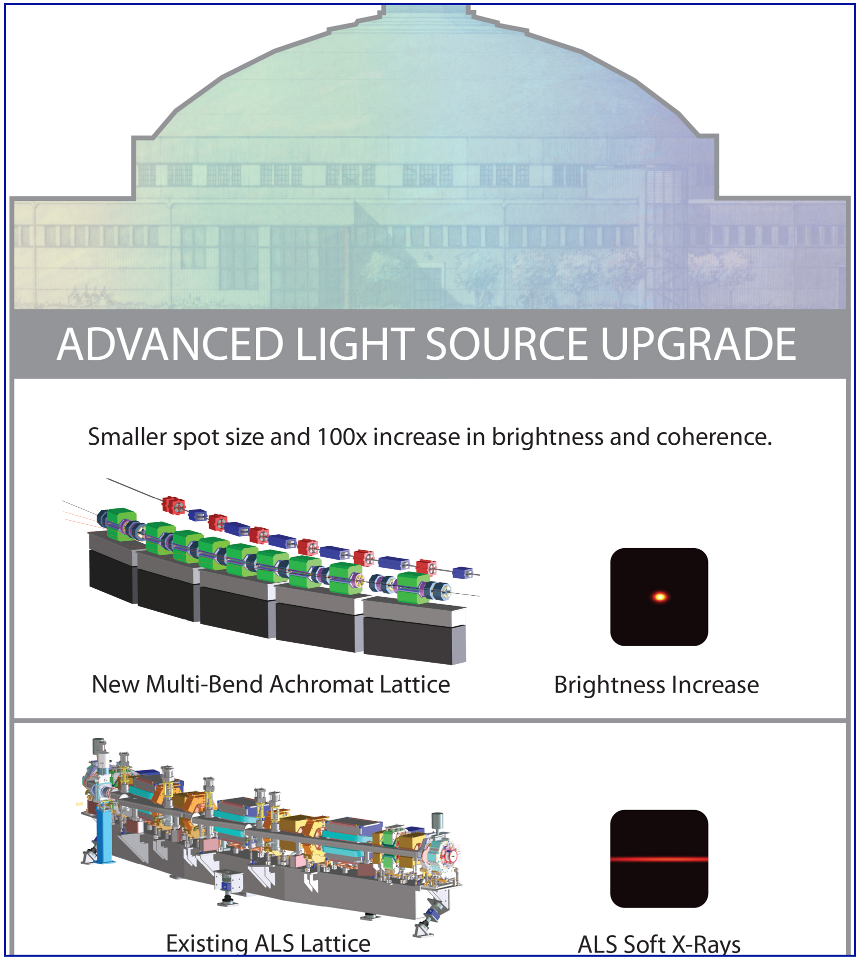
- Dramatic and cost effective performance improvements beyond ALS are possible.
- Enabled by dramatic progress in accelerator physics, modeling and engineering in the last 20 years
- Exciting accelerator R+D program underway, also performing pre-conceptual design
- ALS-U will be world leading facility for soft x-ray science enabling nanoscale microscopes with chemical, magnetic, and electronic contrast.

Backup Slides

National Need

Report of the BESAC Subcommittee on Future X-ray Light Sources (July 2013)

- Given the impressive advances in accelerator technologies during the last five years, it is likely that the best approach for a light source with the characteristics just enumerated would be a linac-based, seeded, free electron laser (FEL).
- At the same time, the Office of Basic Energy Sciences should ensure that U.S. storage ring x-ray sources reclaim their world leadership position. […] It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments of storage rings in other countries. Such developments include diffraction-limited storage rings […] .



ADVANCED LIGHT SOURCE UPGRADE

Smaller spot size and 100x increase in brightness and coherence.

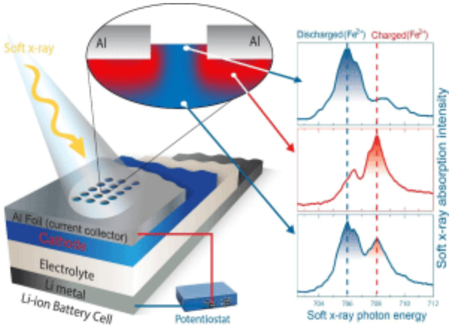
New Multi-Bend Achromat Lattice

Brightness Increase

Existing ALS Lattice

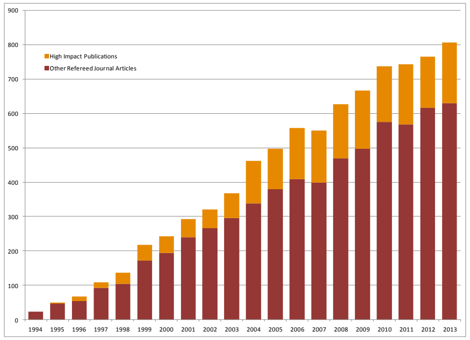
ALS Soft X-Rays

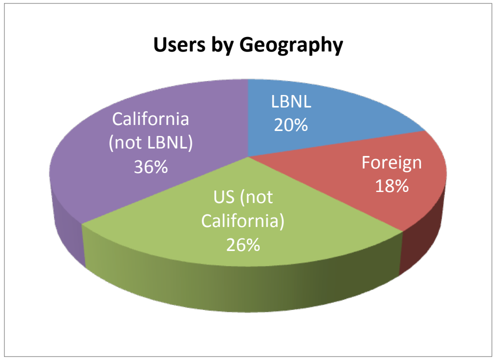
ALS Performance at a Glance



Scientific leadership

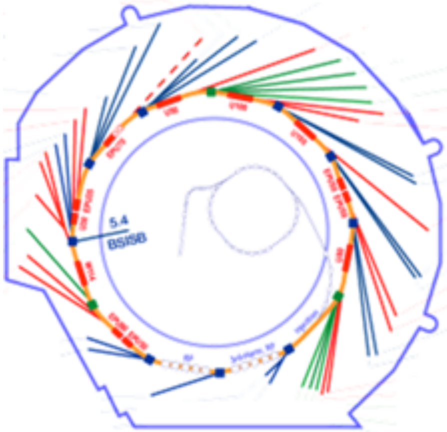
- world-class infrared to x-ray science
- world-leading soft x-ray science
- spectroscopy, scattering, and imaging techniques





Outstanding annual metrics

- 2400 users
- Growing at 10%/year
- 800 science publications
- 5000 operating hours



20 years of growth

- 40 instrument beamlines
- continual upgrade of machine brightness
- continual upgrades of science capabilities

History of TME / MBA

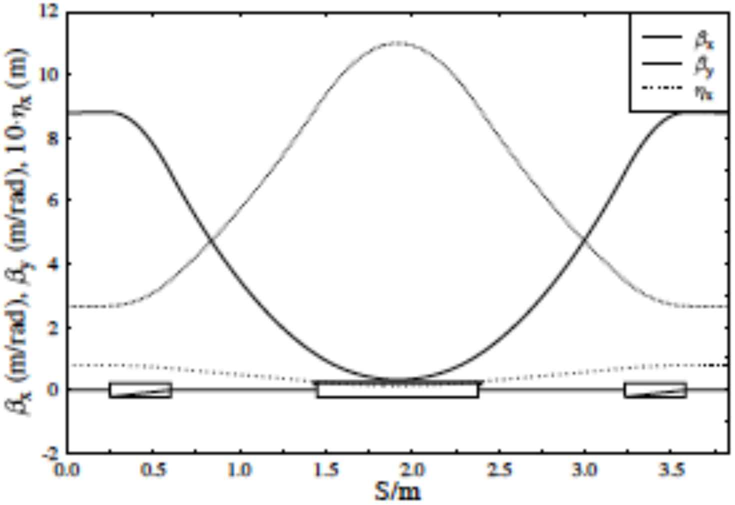
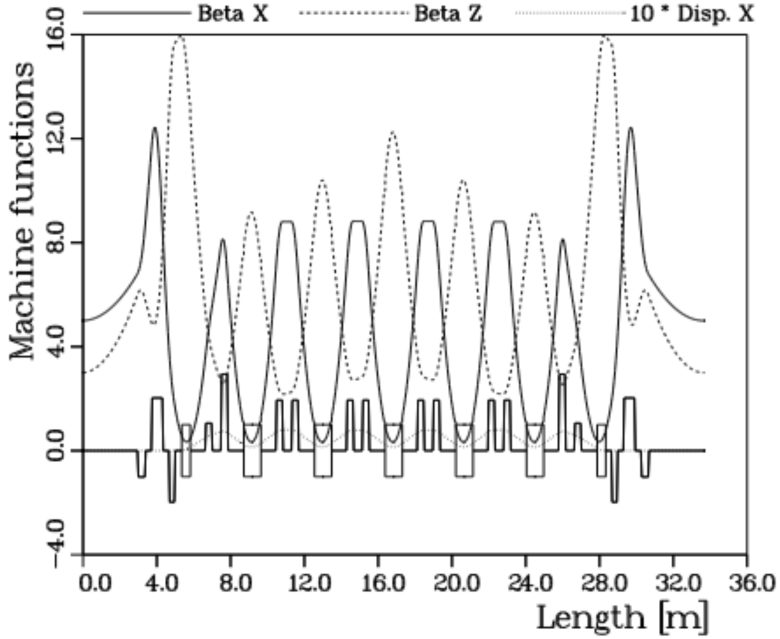


Figure 4: Lattice of a simplified TME-structure

$$\beta_x(0) = \frac{1}{2\cdot\sqrt{15}}\cdot L \qquad \eta_x(0) = \frac{L^2}{24\cdot\rho}$$

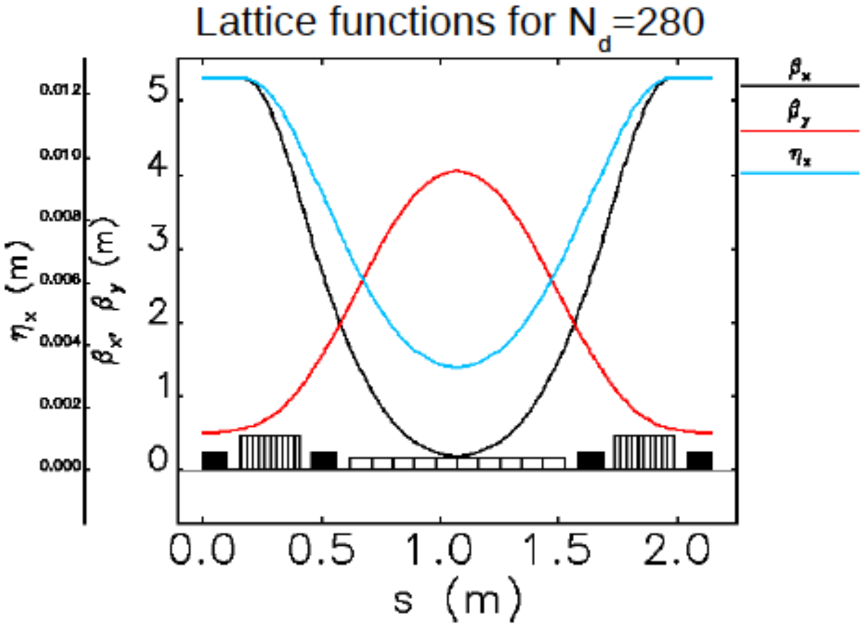
$$\varepsilon_{x0} = C_q\cdot\gamma^2\cdot\frac{1}{J_x}\cdot\frac{1}{3\cdot4\sqrt{15}}\cdot\varphi^3$$

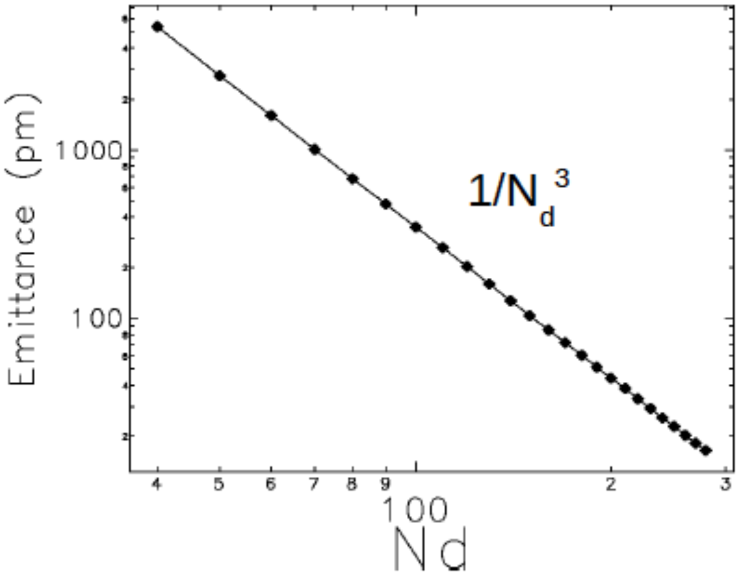


- Work in 1990 to find theoretical minimum emittance structures – Einfeld, et al. (NIM 1993, PAC 1995, EPAC 1996)
- MBA is a modification of this, with (detuned) TME structure in the middle of the arc and (short) matching sections at ends
- Originally considered challenging ("chromaticity wall")
- Max-4 is first full implementation of MBA

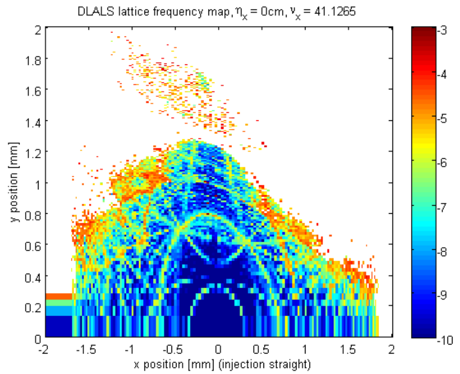
Scaling

M. Borland


Lattice functions for N_d=280

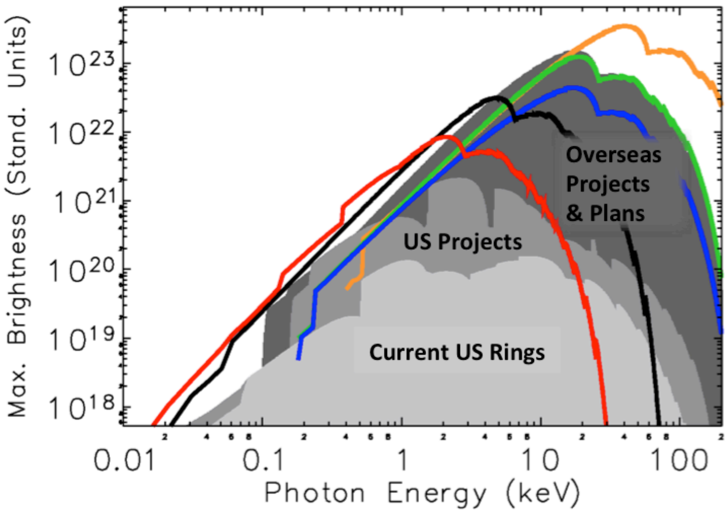


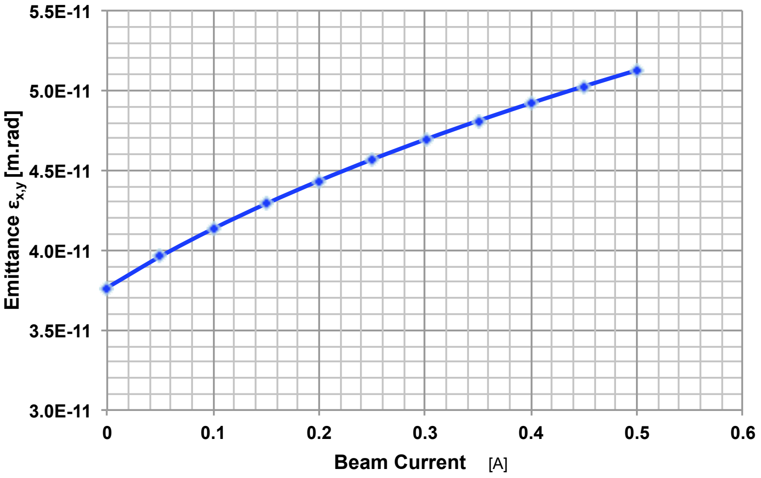
- However, more and more magnet require magnets to become stronger (quadupoles about quadratically, sextupoles even quicker)
  - Engineering limits
  - Nonlinear dynamics
- Energy scaling is complex (magnet strength, C)


DLALS lattice frequency map, η_x = 0cm, ν_x = 41.1265

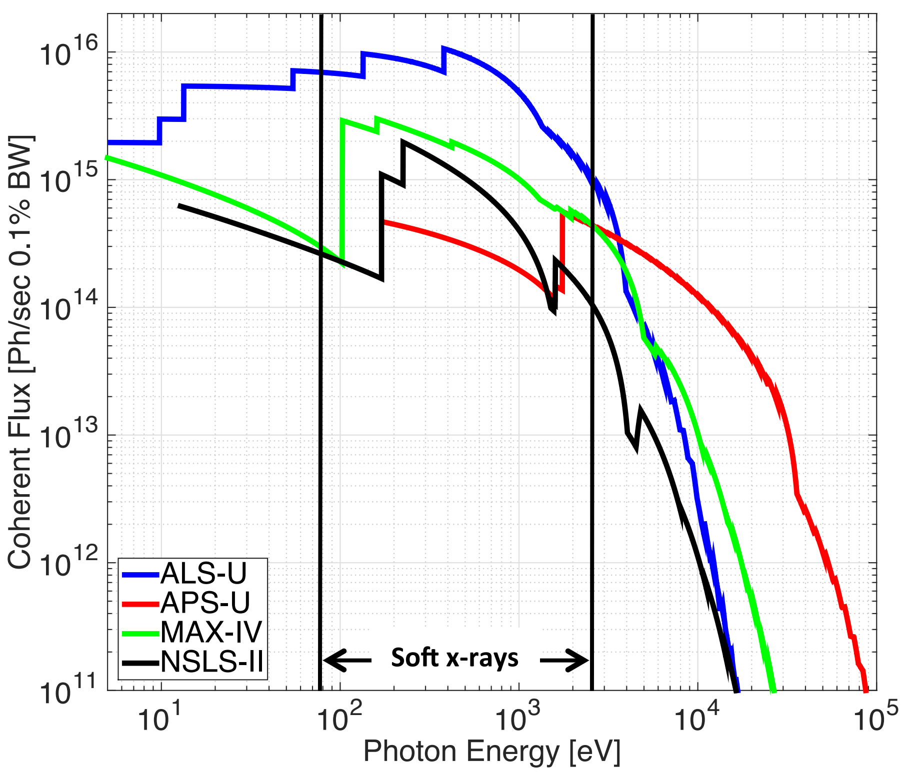
Optimizing for Soft X-rays

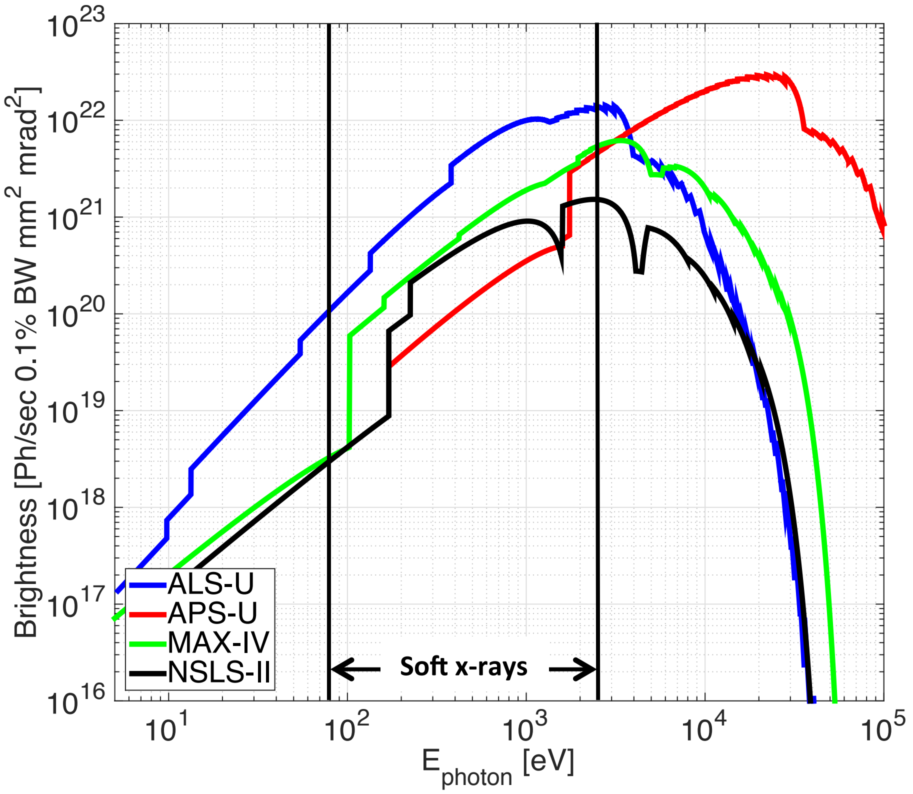
- Brightness peak in soft x-rays allows lower electron beam energy (3 keV-2 GeV)
- Diffraction limited emittance larger (2 keV-50pm) – reachable with 200m ring
  - Vertical plane diffraction limited at same ('large') emittance - round beam
- Lower beam energy-shorter focal lengths-more magnets, lower emittance
  - Smaller ring-less unit cells-larger dispersion-weaker sextupoles
- Intrabeam scattering much worse
  - need to fill all buckets and lengthen bunches aggressively
- Heatload on optics depends on beam energy





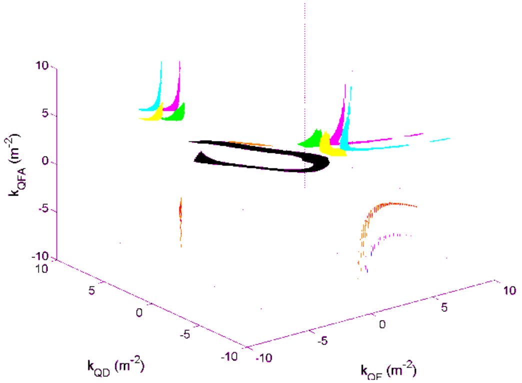
ALS-U has Highest Coherent SXR Flux from a Synchrotron

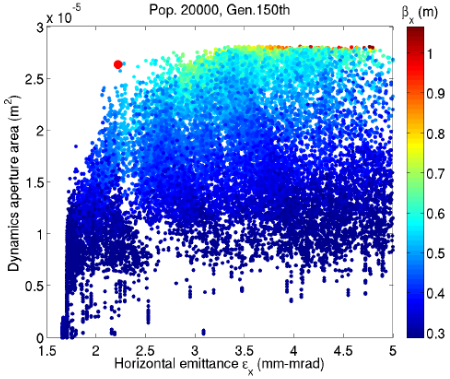


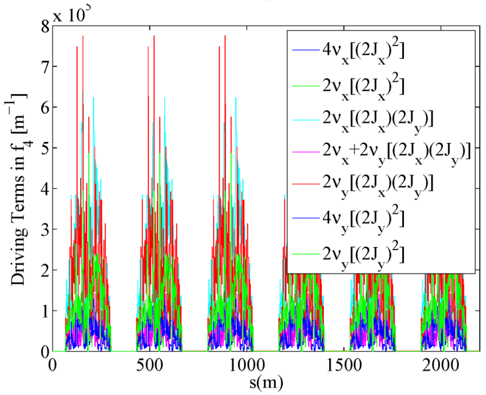


Highest coherent flux will be best
for imaging and understanding dynamic systems

Lattice optimization – Some examples







- GLASS – Global Analysis of All Stable Solutions
  - •Tool to look for optimum lattice solution for highly periodic lattices (few parameters)
- MOGA – Multi Objective Genetic Algorithms
  - •Usefulness for accelerators first demonstrated for photo injectors (Bazarov et al./Cornell)
  - •Optimum solution with moderate computation time for larger dimensional parameter spaces
  - •Integrated optimization of linear+nonlinear lattice possible

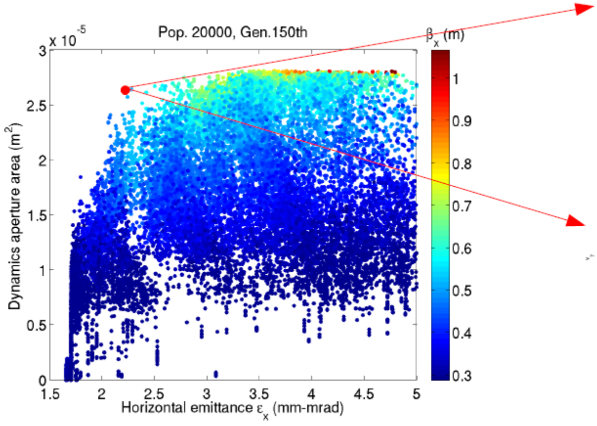
•Resonance Driving Terms

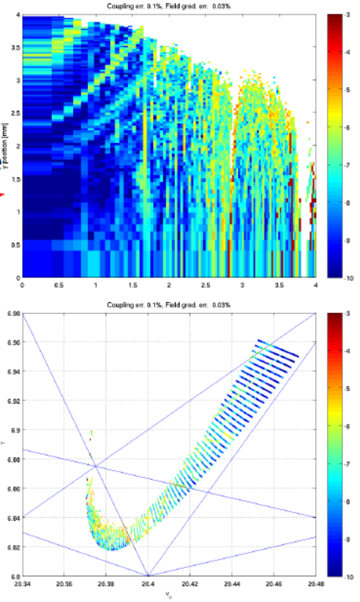
- •High order achromats
- •Phase cancellation
- •Multi-sector cancellation

Simultaneous Optimization of linear and nonlinear Lattice

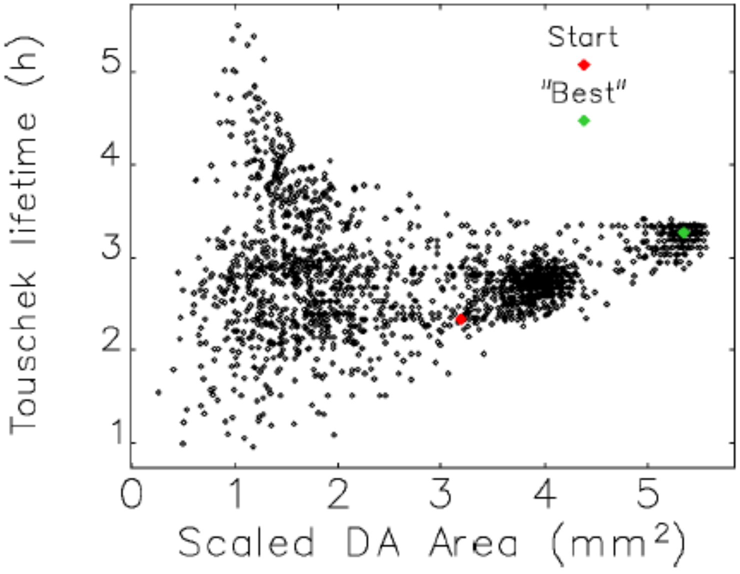
Linear and nonlinear properties of the lattice are optimized simultaneously using GA.

- 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.



Normalized to $\beta_x=\beta_y=3$m

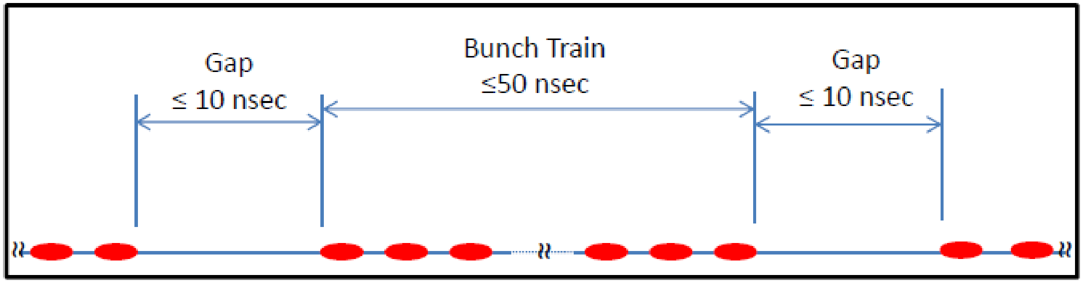
ALS, C. Sun

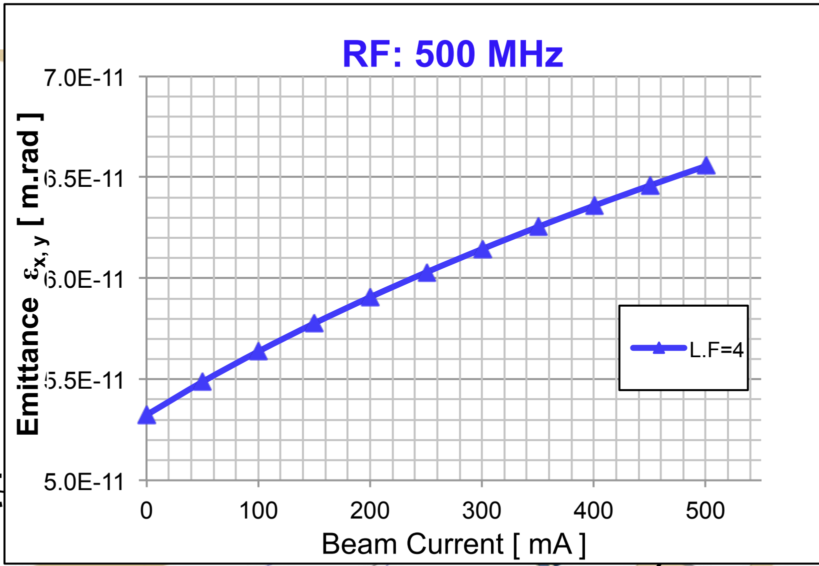
APS-U, M. Borland

- Challenge: space of stable solutions vs. quadrupole gradients very sparse
- In general case not possible to just include quads as parameters, but rather lattice parameters + lattice fit

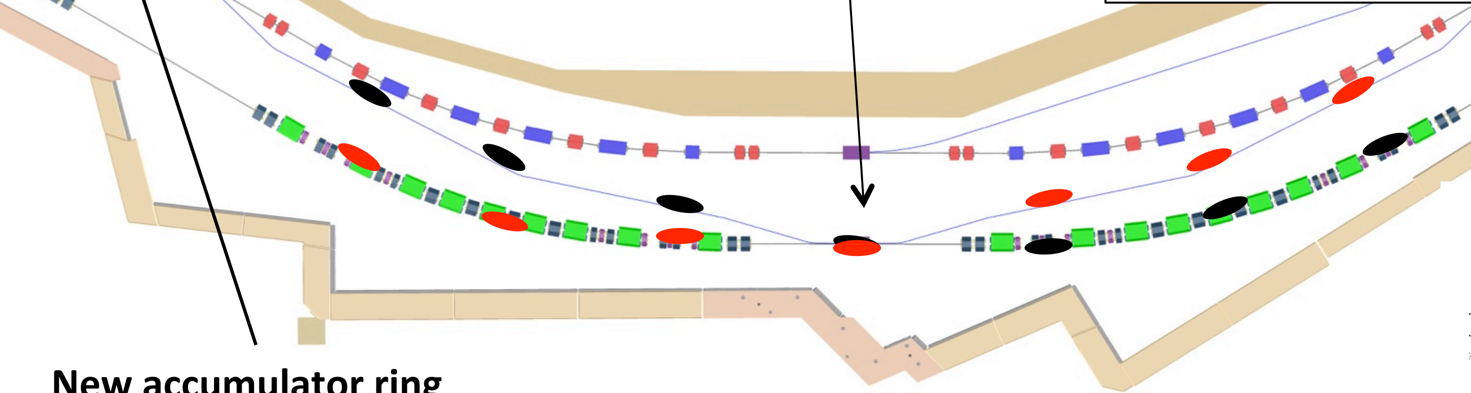
Swapping accumulator and storage ring beams

- ● storage ring bunches transferred to accumulator
- 🔴 accumulator bunches transferred to storage ring



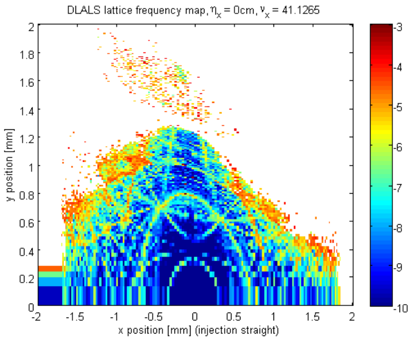


Fast kicker magnet



New accumulator ring

New ALS storage ring



Swap-out injection was first proposed by M. Borland for possible APS upgrades

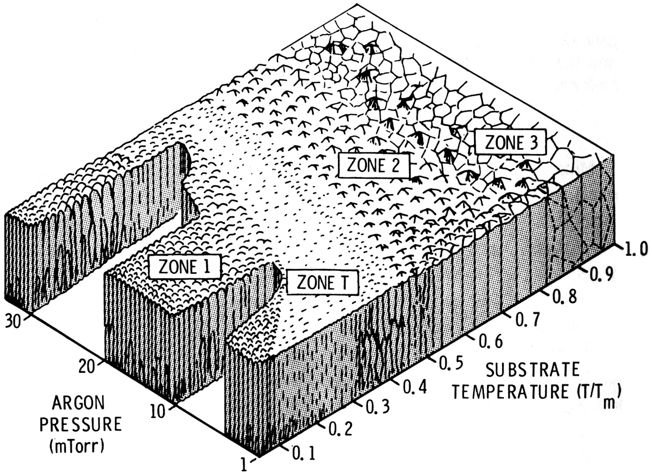
Goals for R+D program

- Reduce technical risks + explore new technologies for performance advantage of soft x-ray DLSR
  - Concentrate on areas with highest technical risk
  - Approach: Demonstrate necessary technology at subsystem level or through advanced simulations
- Selection of R+D topics covers main areas of risk and opportunity:
  - Low emittance ➔ compact, **small aperture magnets** ➔ very small vacuum chamber diameter ➔ need for **NEG coating**
  - Low energy ring ➔ intrabeam scattering is severe ➔ **aggressive bunch lengthening** as well as filling as many buckets as possible ➔ **pulsers with very small rise and fall times**
  - Highest possible brightness ➔**need for optics that preserve coherent wavefronts**.
  - Small apertures (both planes) open new opportunities for **radiation production devices**.

Vacuum System / NEG chambers

The challenges are:

- NEG coatings for very small (< 10 mm) aperture
- Integration of ports for many beamlines
- NEG activation challenges
  - In-situ (SIRIUS, Soleil, …)
  - Ex-situ (Max-IV)



J. A. Thornton, *J. Vac. Sci. Technol.* **11** (1974) 666

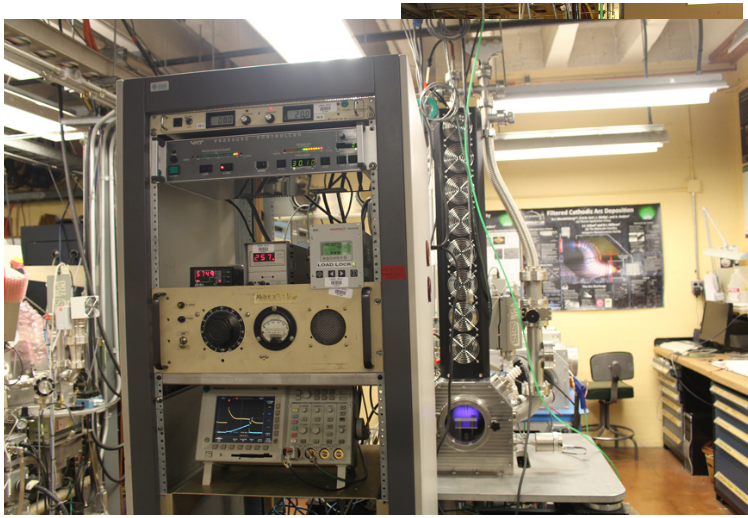
Concentrate our R+D effort where no industrial solution available, yet:

- Smaller apertures (<10 mm)

Also improving process where we see problems:

- Complex geometries
- Activation
- Cleaning

But work in parallel with industry (ID chamber, development process)



Bunch Lengthening / (harmonic) RF

- Bunch lengthening factors of >=4 essential
- Demonstrated (s/c or low frequency RF) but difficult
- Fill pattern important
- Pursuing various options
  - (100/500/1500 MHz, n/c or s/c)
- Conducting beam tests on ALS to verify simulation codes