Diffraction-Limited Storage Ring Workshop: DLSR 2014

Overview of Lattice Options for Diffraction-Limited Storage Rings

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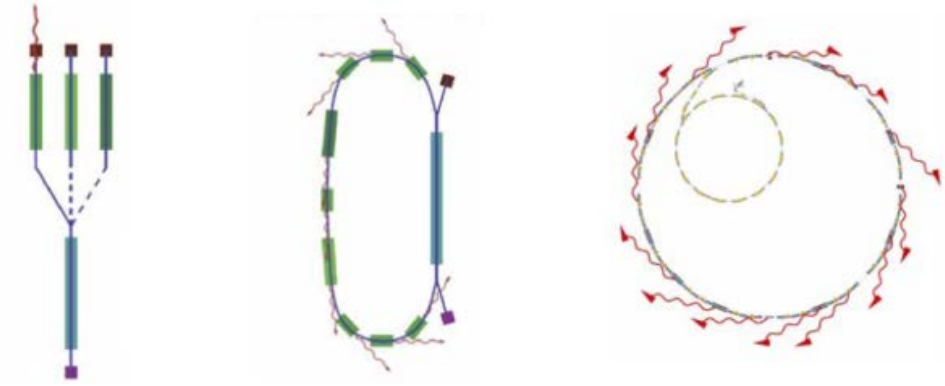
Topics

- Introduction
- General Lattice Choices
  - Scaling
- Lattice Optimization
  - Design
  - Specific Lattice Solutions
- Related Topics
  - Emittance Control
  - Injection Methods
  - Beam-based Correction
- Summary

Report on Future Light Sources (2008/2009)

- **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

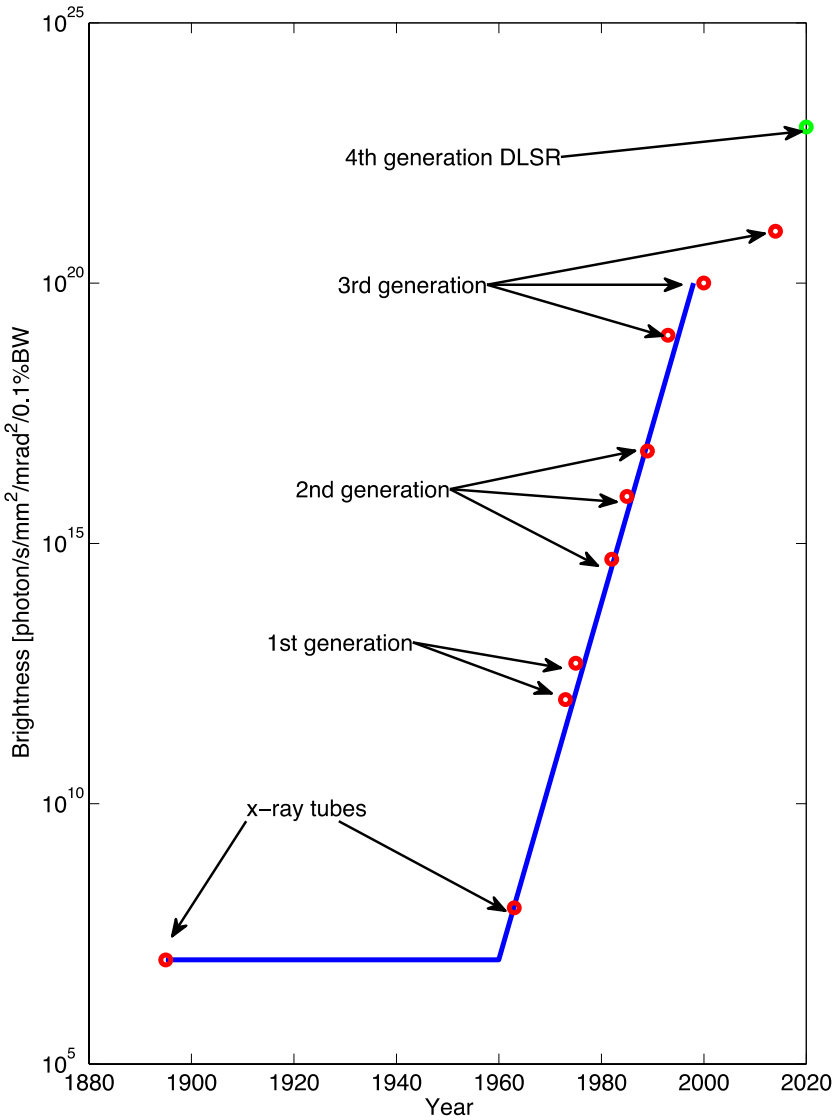
Future generations of light sources will likely utilize novel techniques for producing photons tailored to application needs

- Different operating modes
- Optical manipulation of particle beams
- Use of multiple, complementary facilities

Advances in Light Source Performance

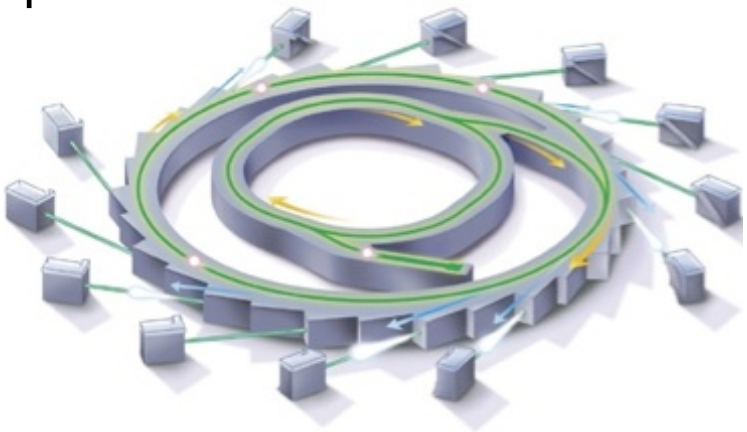
≥2 orders of magnitude progress in brightness between generations

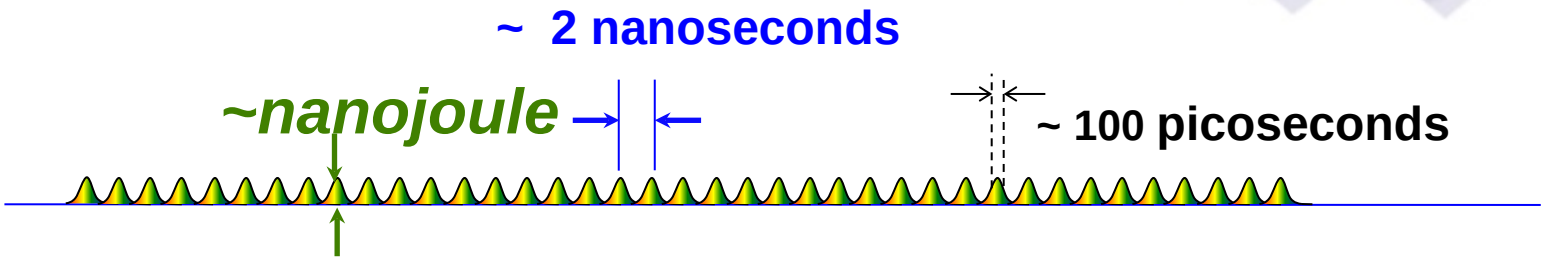
- First Generation: Parasitic, use of dipole sources
- Second Generation: Dedicated, dipoles, later wigglers, higher flux
- Third Generation: Dedicated, optimized for undulators, high average brightness
- Fourth Generation: three approaches (linear/ring); high coherence



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





Moving to Ever Brighter Ring Sources

Double-bend achromat + damping wigglers

BNL: **NSLS-II** (2014): 3 GeV, 1000pm x 8 pm, 500 mA (**New**)

First new multi-bend achromat rings

Sweden: **MAX-4** (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 ring upgrade

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

U.S. Proposals

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

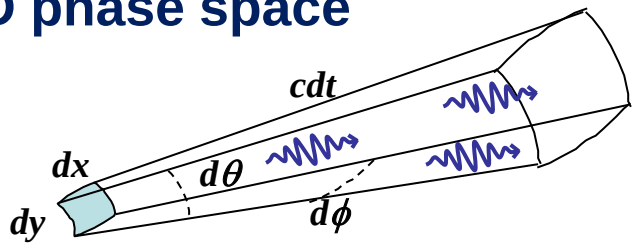
ALS-U: 2 GeV, 50 pm x 50 pm, 500 mA (**Upgrade proposal**)

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

Brightness and Equilibrium Emittance

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

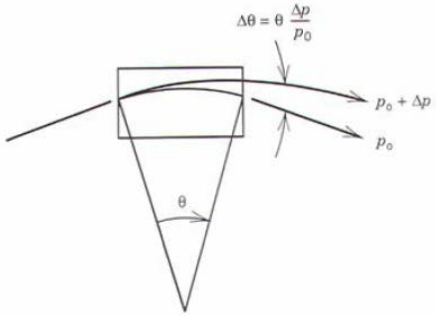
$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(s \cdot \%BW)}$$



$\varepsilon_{x,y}$ = electron emittance ε_r = photon emittance **= 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**

Brightness, Coherent Fraction, Diffraction Limit

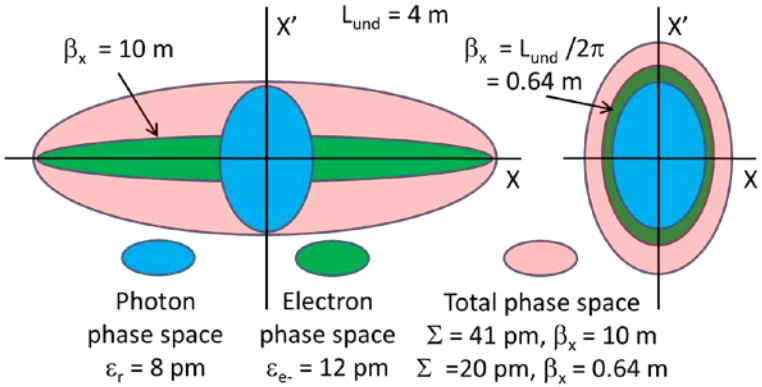
$$\varepsilon_r = \text{diffraction limited emittance} = \sigma_\gamma \sigma'_\gamma = \frac{\lambda}{4\pi} = \begin{cases} 80 \text{ pm @ 1 keV} \\ 8 \text{ pm @ 10 keV} \end{cases}$$

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

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:

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

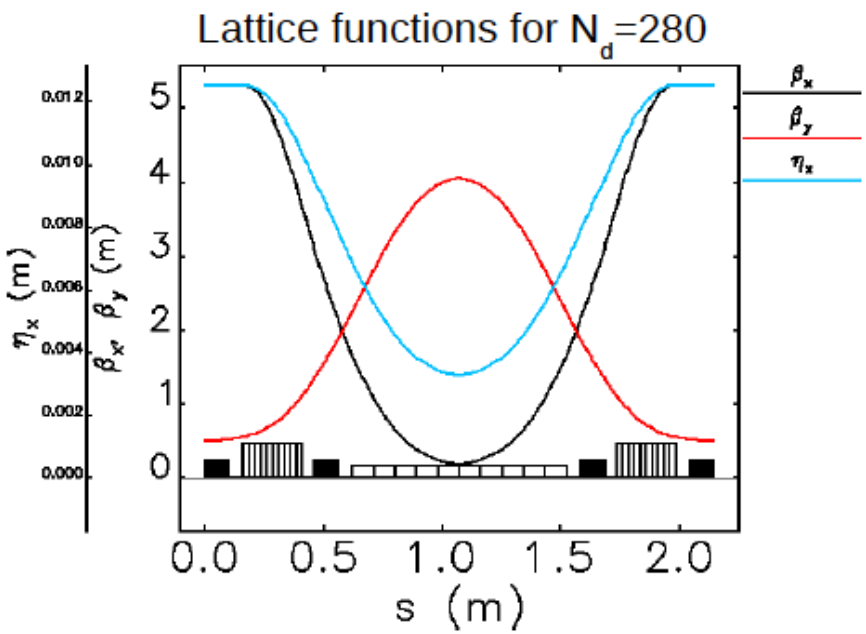
Emittance reduction with damping wigglers:

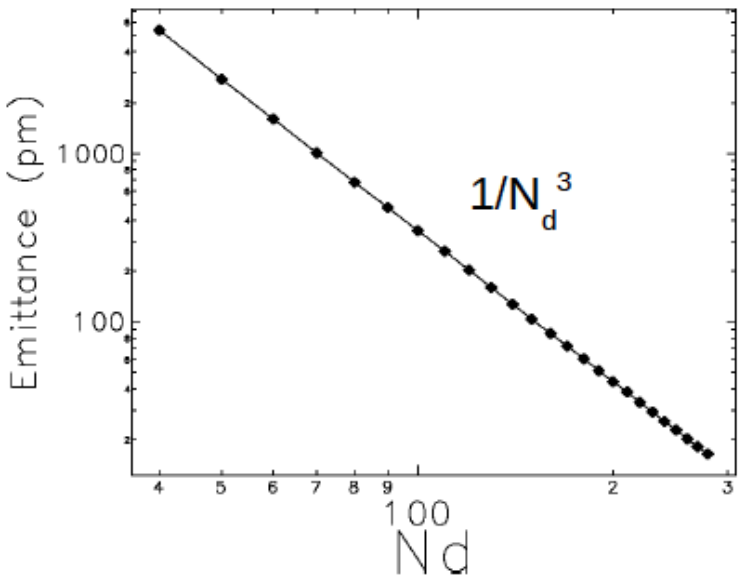
$$\frac{\varepsilon_w}{\varepsilon_o} = \frac{1+f}{1+\frac{L_w}{4\pi\rho_o}\left(\frac{\rho_o}{\rho_w}\right)^2} \approx \frac{1}{1+\frac{U_w}{U_o}}$$

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

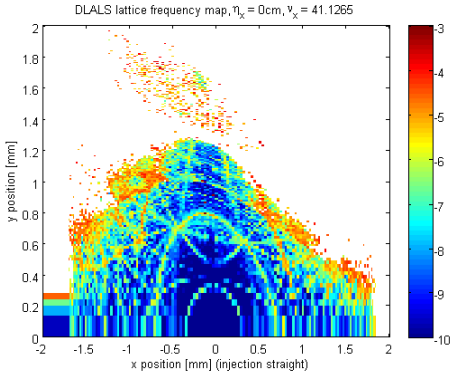
Scaling

M. Borland

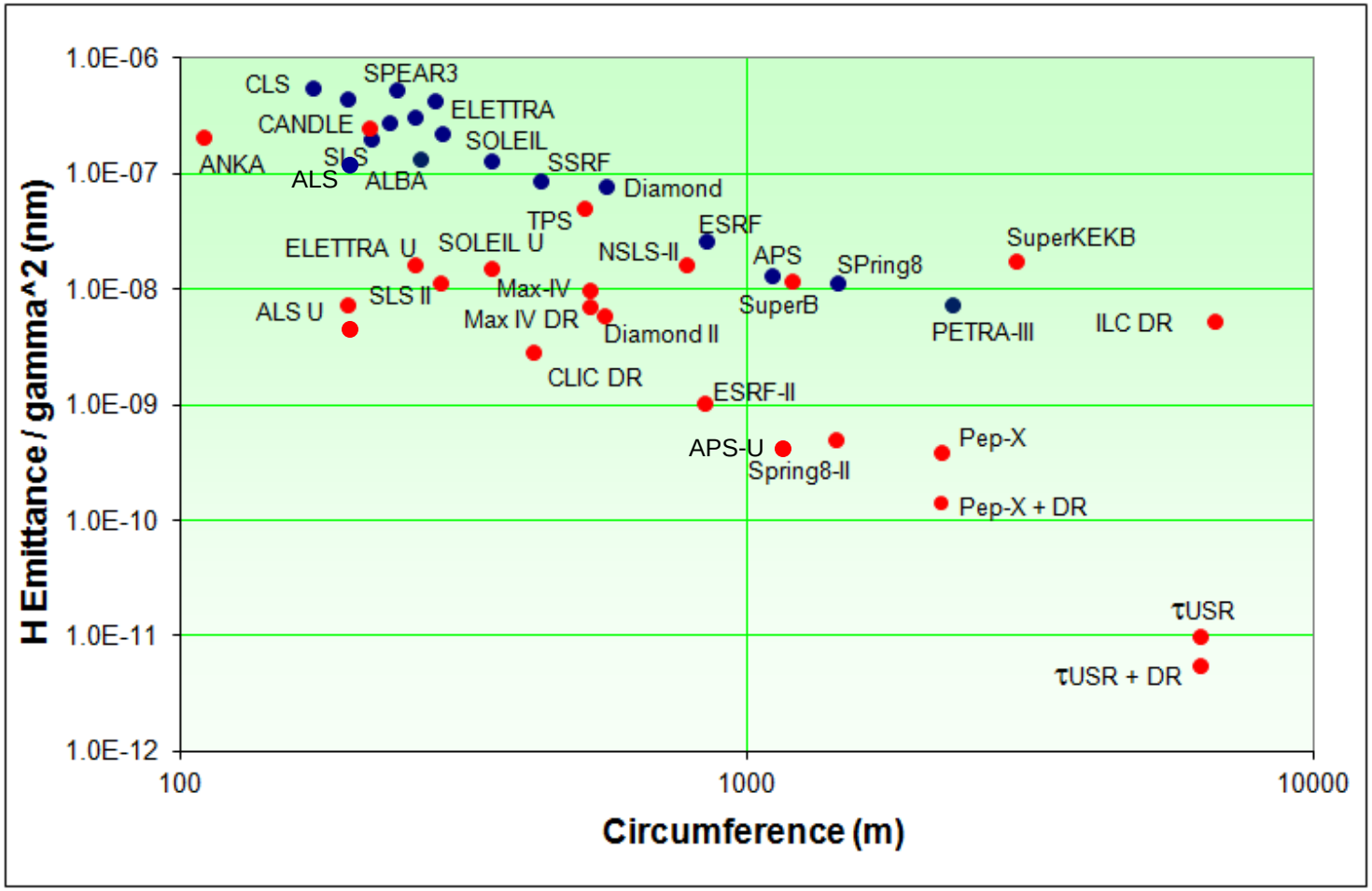




- However, more and more magnet require magnets to become stronger (quadupoles about quadratically, sextupoles even quicker)
  - Engineering limits
  - Nonlinear dynamics
- Energy scaling is complex (magnet strength, C)



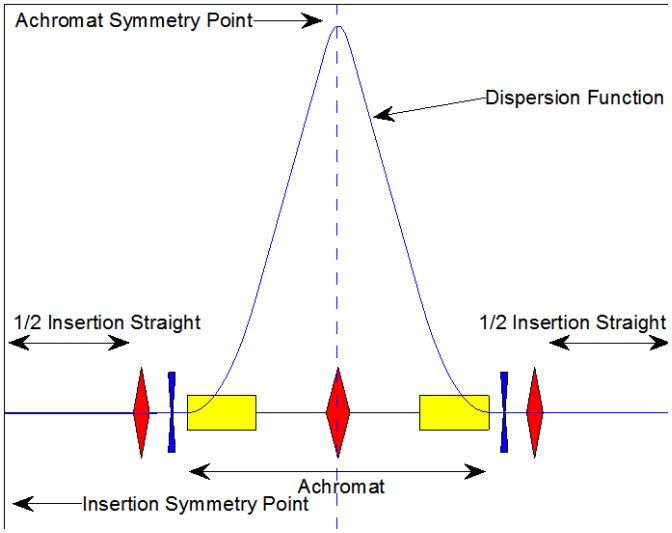
Scaling (2)

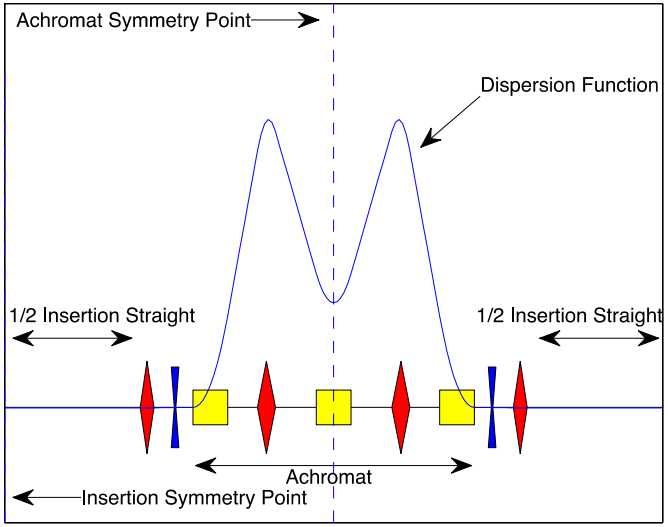


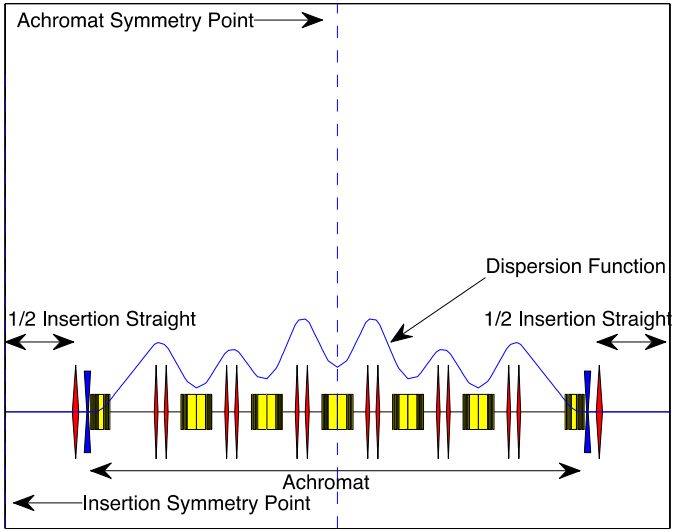
- Slope of optimized parameter sets indicates that this merit function is too simple

R. Bartolini

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

History of TME / MBA

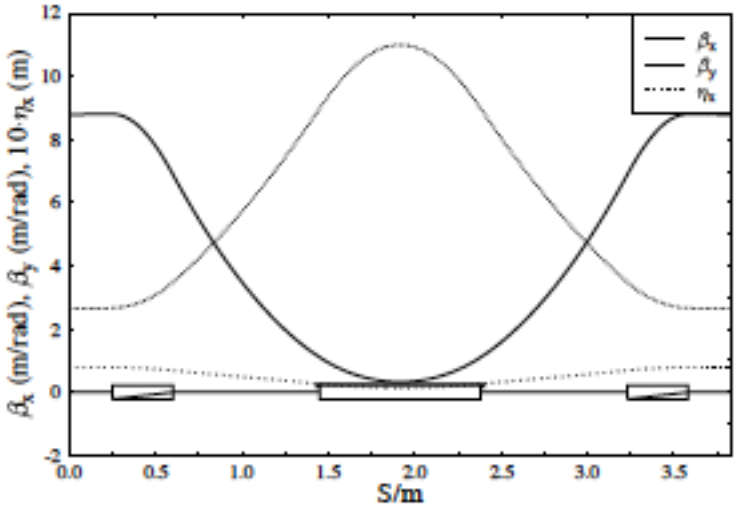
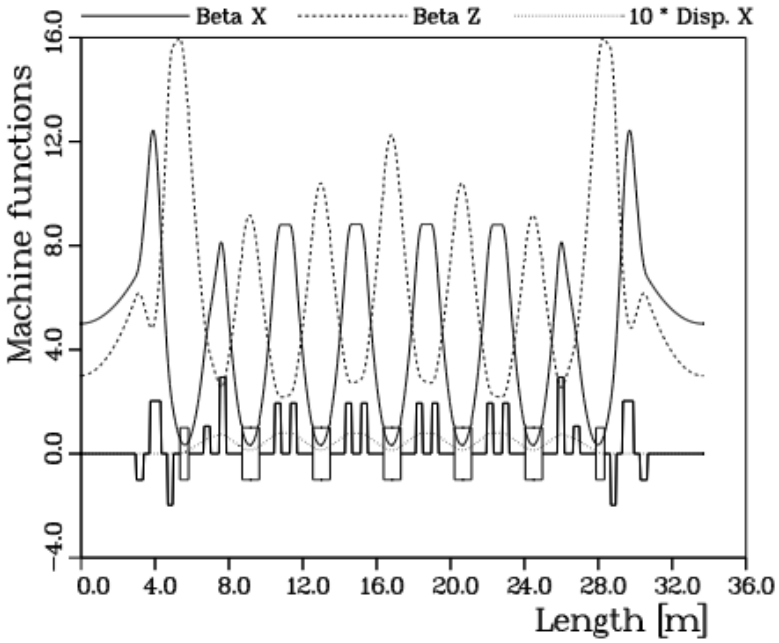


Figure 4: Lattice of a simplified TME-structure

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

$$\varepsilon_{x0} = C_q\cdot\gamma^2\cdot\frac{1}{J_x}\cdot\frac{1}{3\cdot 4\sqrt{15}}\cdot\varphi^3$$



- Work in 1990 to find theoretical minimum emittance structures – Einfeld, et al. EPAC 1996, PAC 1997
- 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

Lattice Optimization Methods

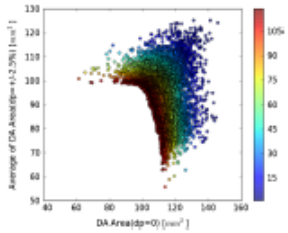


FIG. 1. The last generation of objective functions: DA of on-momentum (horizontal axis) and off-momentum (vertical axis) particles. Points are colored according to their rank.

Symplectic Tracking based methods

DA, MA separated

DA, MA together

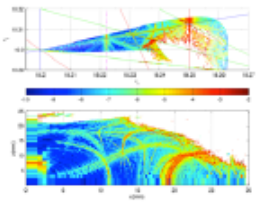
from L. Nadolski, ICFA LowEring, Oxford 7/13

Direct tracking based optimization

GLASS

Analytical based method

Genetic Algorithm
MOGA



Lie Algebra/Differential Algebra

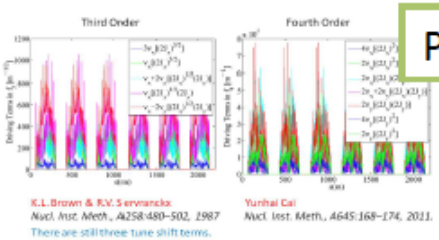
Resonance Driving Terms
RDT minimization

Amplitude Tuneshift
minimization

Frequency Maps
FMA
Diffusion factor

Nonlinear
"LOCO"

Canceling
Sextupole
Resonances



Phase advances

Interleaved
sextupoles

Resonance identification

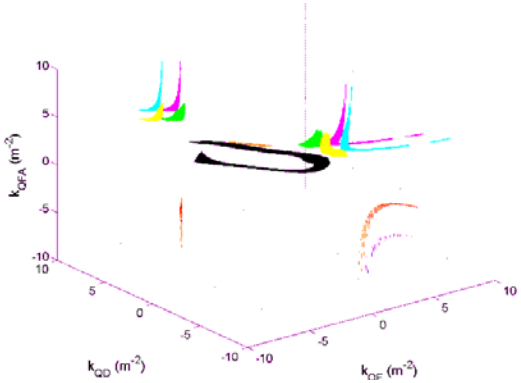
Robustness to magnetic, alignment errors

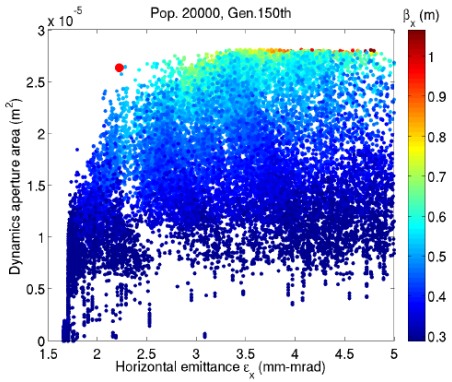
Robustness ID configurations

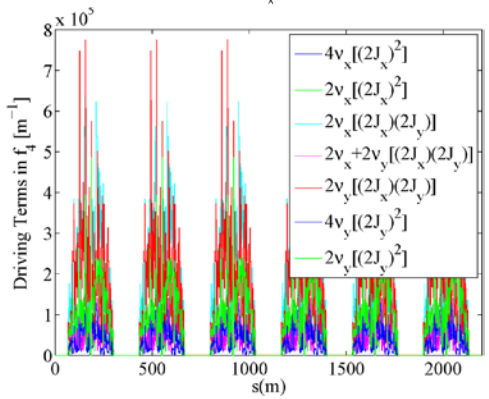
Tracking codes: PTC MADX TRACY AT LEGO OPA ELEGANT

Collective Effects

Lattice optimization – Some examples





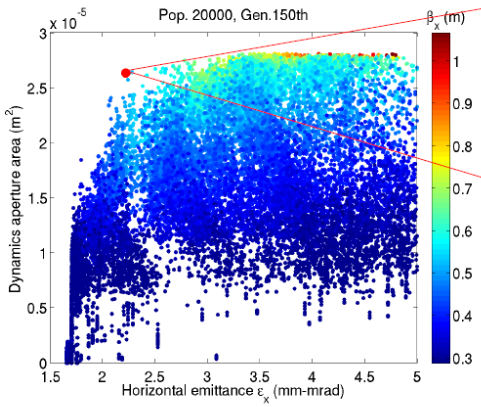


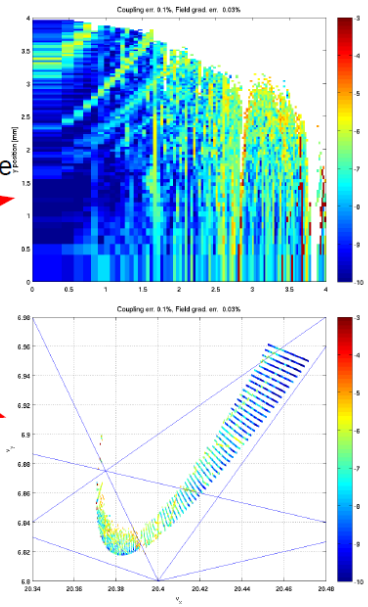
- GLASS – Global Analysis of All Stable Solutions
  - Tool to look for optimum lattice solution for highly periodic lattices (few parameters)
- MOGA – Multi Objective Genetic Algorithms
  - Usefulness for accelerators first demonstrated for photo injectors (Bazarov et al./Cornell)
  - Optimum solution 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.

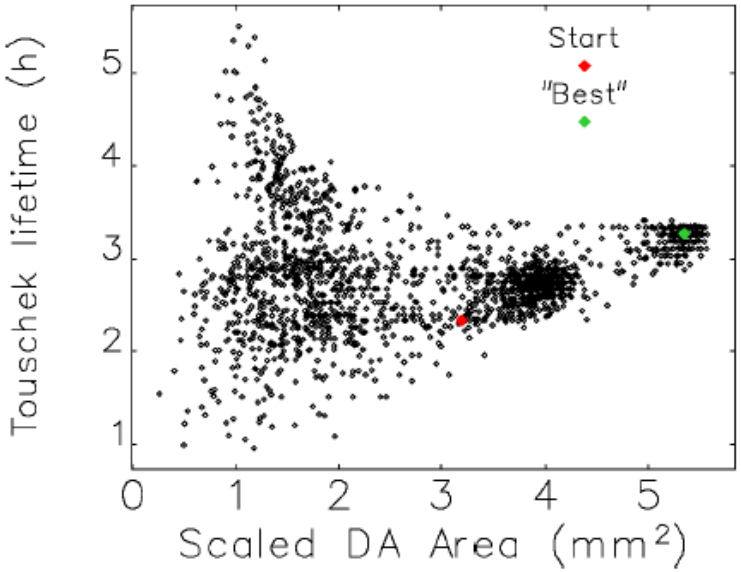
- 7 parameters: 3 Quads + 4 Sextupoles
- 7 constraints: stability, positive partition number, maximum beta and dispersion functions
- 3 objectives: emittance, betax and dynamics aperture





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

ALS, C. Sun

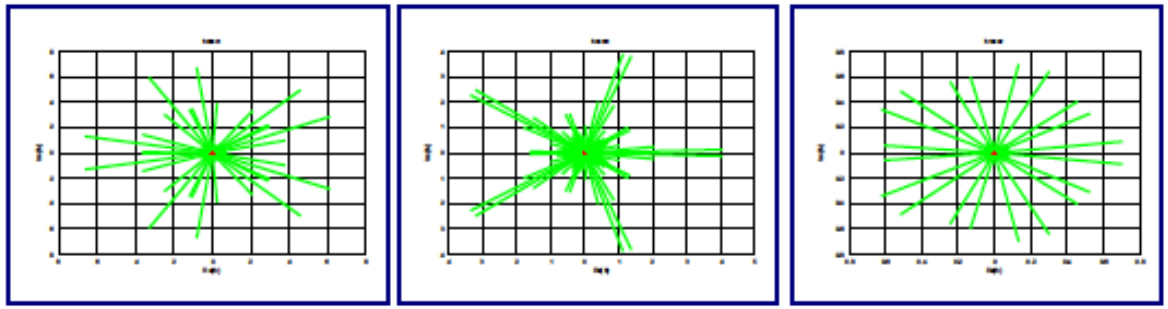


Normalized to $\beta_x=\beta_y=3$m

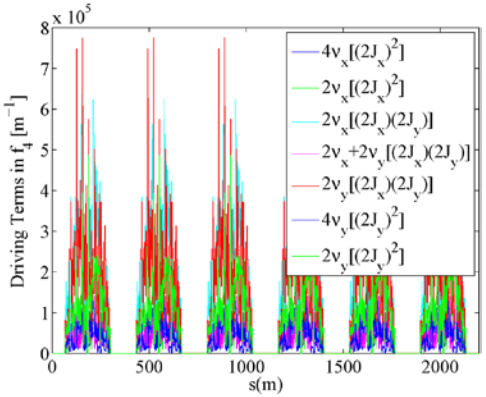
APS-U, M. Borland

- 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

Resonance Driving Terms



h_{20001} h_{00201} h_{10002}



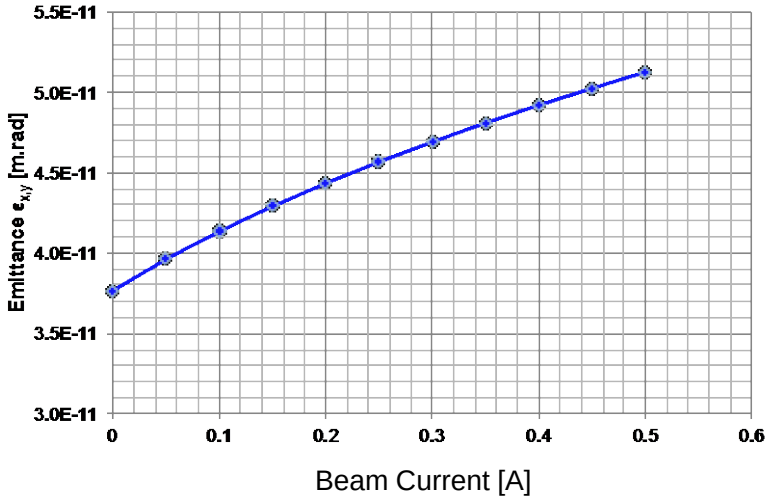
J. Bengtsson: 5 cell 2nd order achromat, Chromatic driving terms

Y. Cai: 4th order achromat

- Quite effective, but often not the global optmimum (as shown by subsequent MOGA optimization)
- Optimization can have choices: Which driving terms to miminize?
  - Example: optimize for small/large detuning with amplitude? Folds in frequency map?

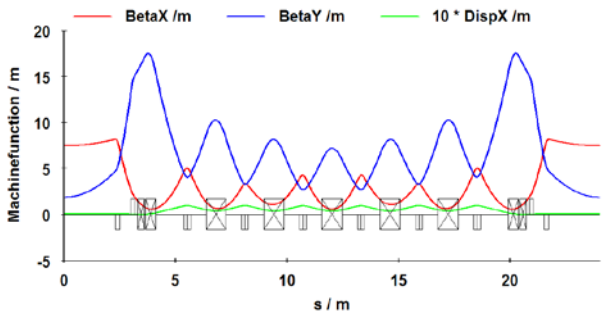
Intra Beam Scattering

- Intra Beam Scattering is potentially a very significant effect at DLSRs
  - Mitigation typically involves some combination of increased vertical emittance, bunch lengthening (harmonic cavities), faster damping times (damping wigglers, normal IDs, …).
  - Optimum solution for smallest quantum excitation does not necessarily minimize IBS emittance growth -> include in lattice optimization

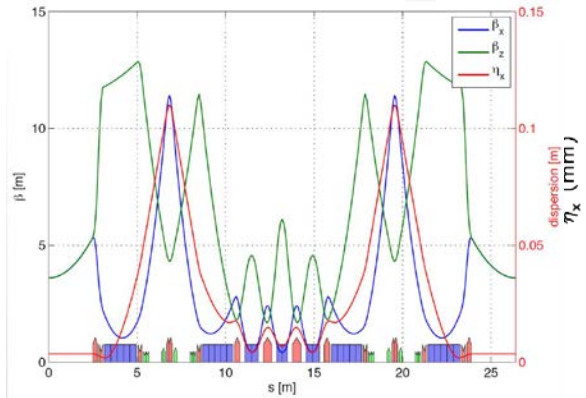


Example: ALS-U, 2 GeV, Harmonic Cavities, full coupling, full set of insertion devices, no damping wigglers

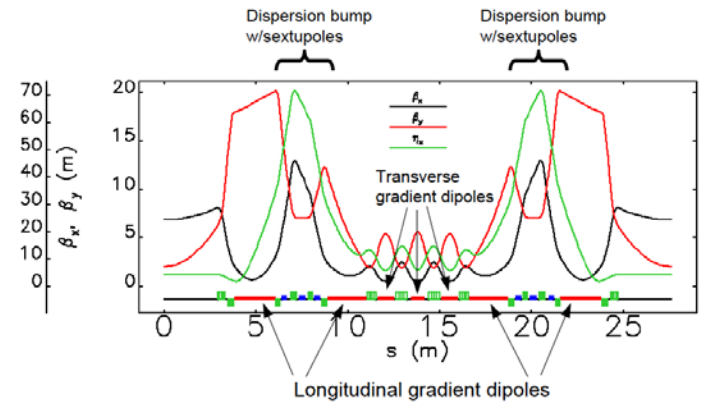
Example MBA Lattices



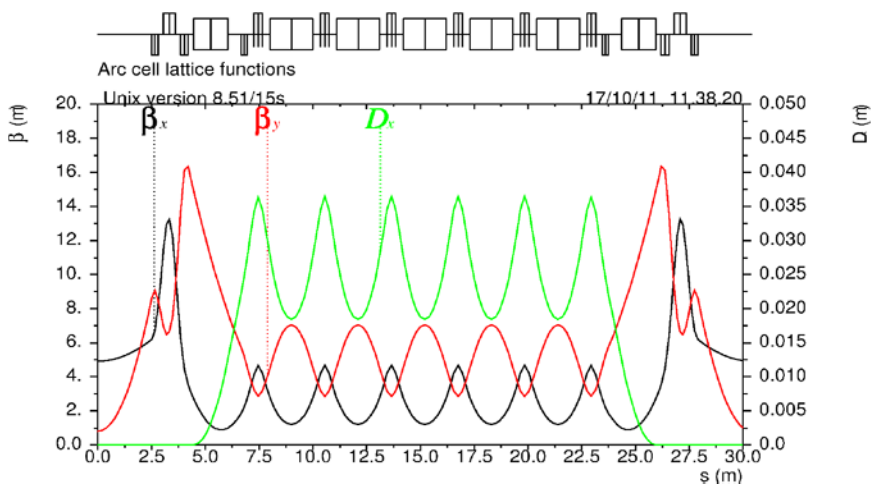
Max-4 – 7BA, octupoles, M. Eriksson



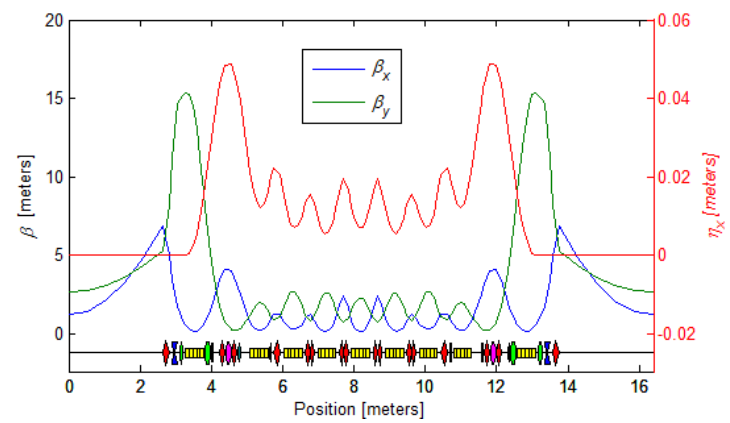
ESRF-2- HMBA, P. Raimondi



APS-U - HMBA, swap-out, M. Borland

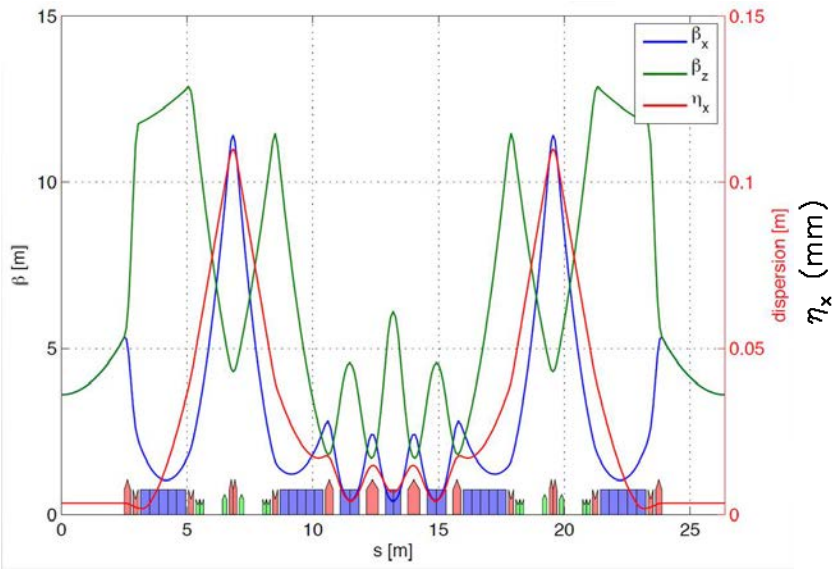


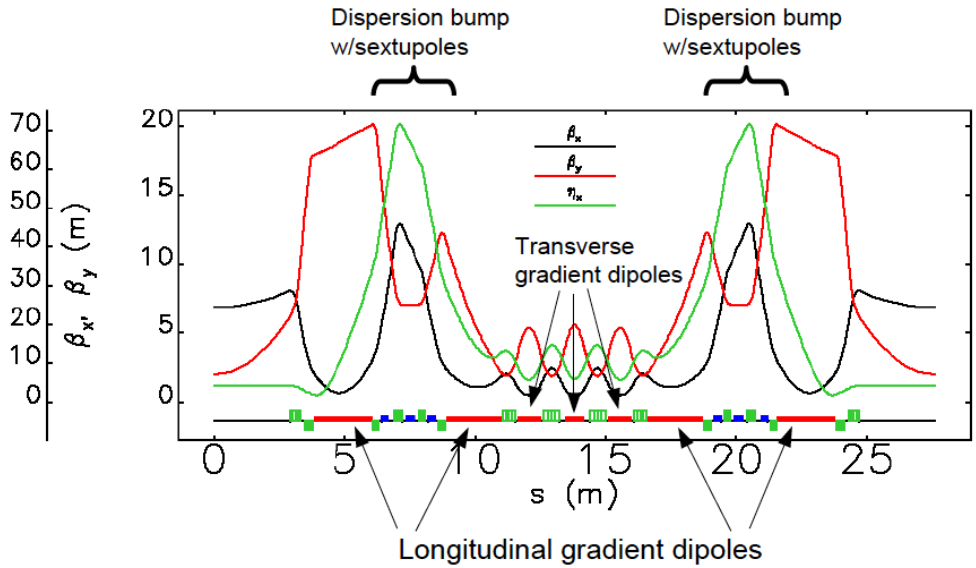
PEP-X – 7BA, 4th order achromat, Y. Cai



ALS-U – 9BA, octupoles, swap-out, H. Tarawneh, C. Steier

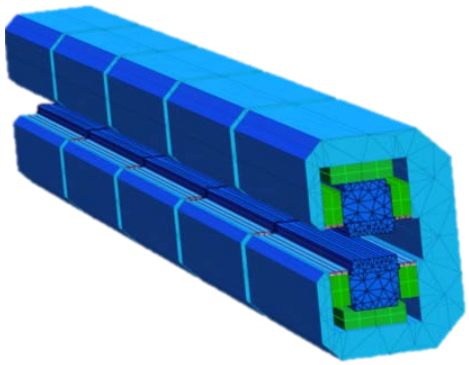
(Hybrid) Multibend Achromat



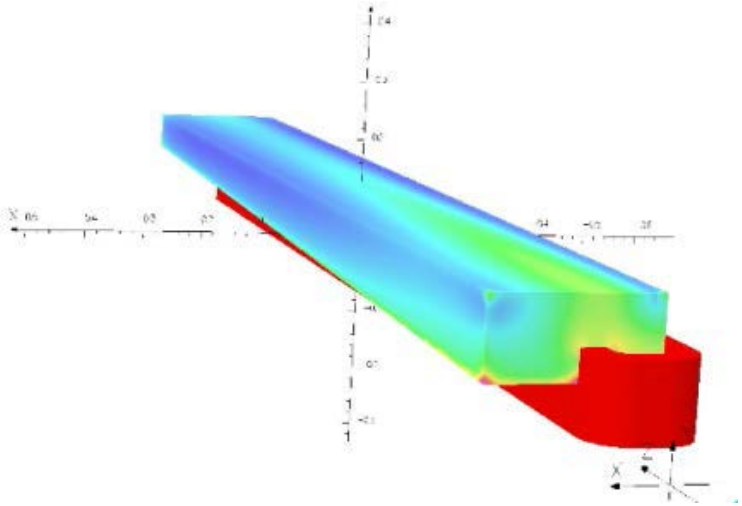


- Chromaticity correction only in high dispersion area
  - Acceptable sextupole strength
- Fixed phase advance between 2 high dispersion areas (sextupole chancellation)
- Use of longitudinal gradient dipoles
  - Helps to reduce emittance further
  - Longer than other dipoles, highest field radiation in straights
- Use of special high beta straight for accumulation (ESRF), swap-out in symmetric straight (APS-U)

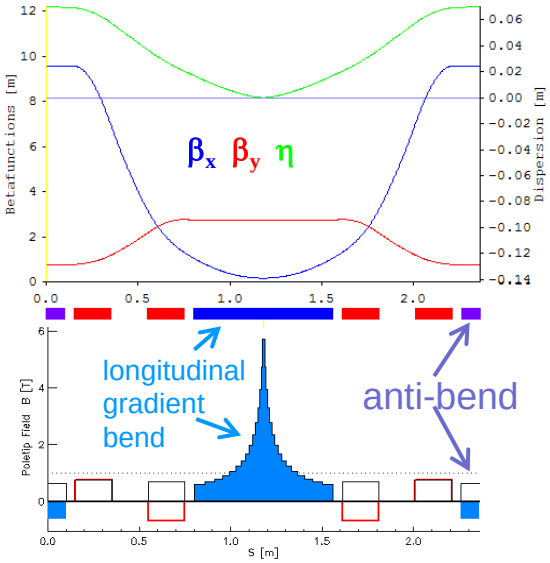
Longitudinal Gradients



ESRF-2



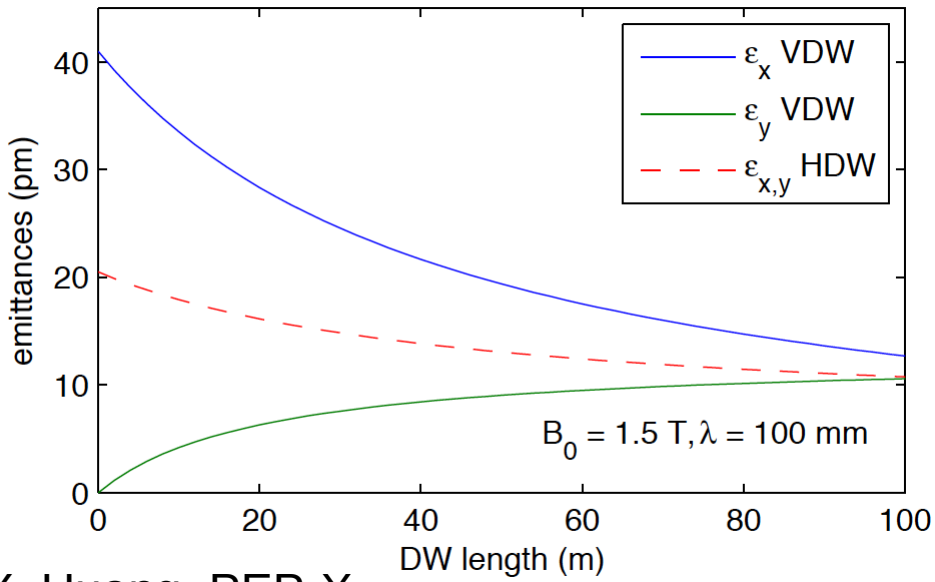
APS-U



A. Streun

- Allow reduction in emittance and larger dispersion in chromatic correction section
- Potential draw backs:
  - Non-trivial to build
  - Longer
  - Highest field in line with straights (for HMBA)

Damping Wigglers



X. Huang, PEP-X

NSLS-2

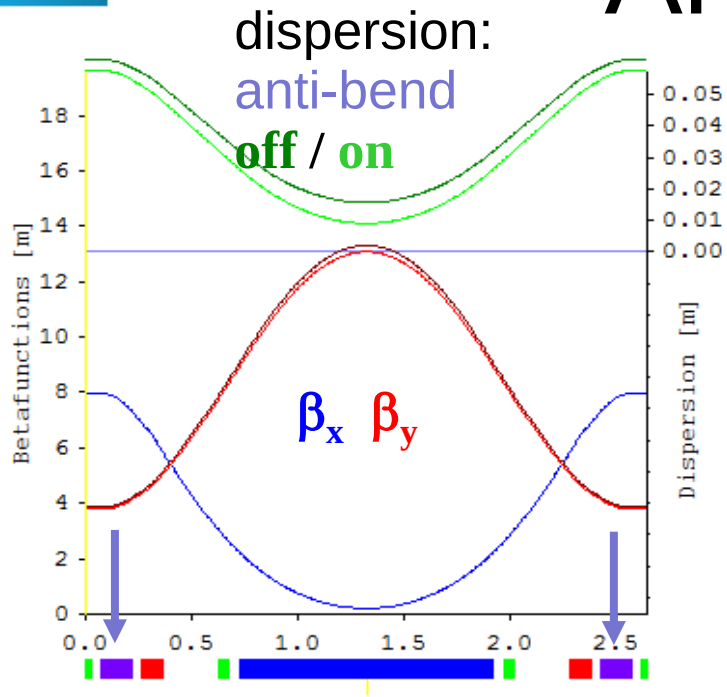
$$\frac{\varepsilon_w}{\varepsilon_o} = \frac{1+f}{1+\frac{L_w}{4\pi\rho_o}\left(\frac{\rho_o}{\rho_w}\right)^2} \approx \frac{1}{1+\frac{U_w}{U_o}}$$

- Help to reduce the equilibrium emittance – without reducing momentum compaction factor
- Also decrease damping time (beneficial for IBS)
- Possible tool to control vertical emittance (vertical wiggler, vertical dispersion)
- Increase energy spread (reduces higher undulator harmonics)
- Can impact dynamic aperture
- Occupy space, increase RF need, need to handle high power synchrotron light

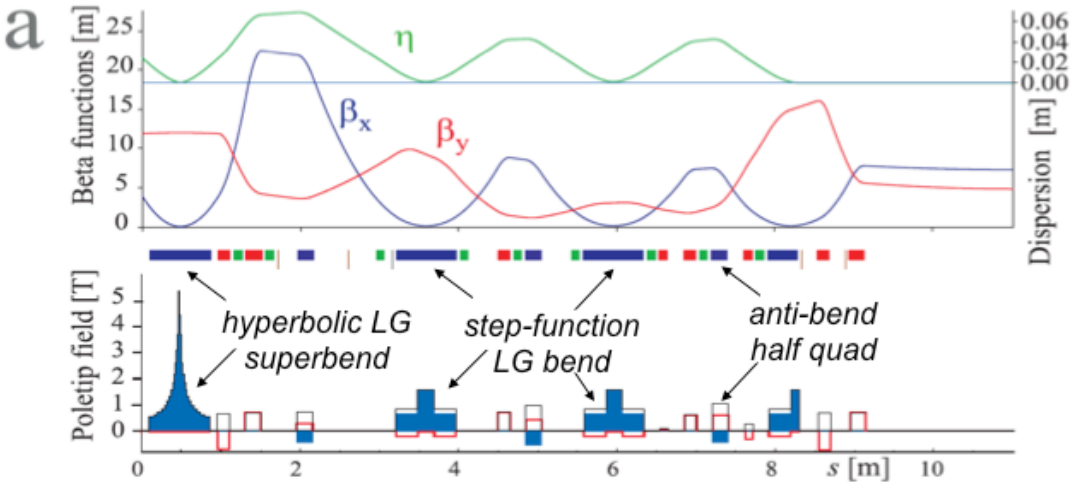
Other Methods of Emittance Control

- If ring is diffraction limited in horizontal plane, vertical emittance does not need to be smaller
  - Very different from current rings which run with emittance ratios between 0.1% - few %
  - Intrabeam scattering and Touschek lifetime require the vertical emittance to not be too small
- User experiments sometimes prefer round beams
- Control of vertical emittance is needed
  - Coupling control (reduces horizontal emittance, fine with swap-out, but challenging with asymmetric apertures for off-axis injection, limits tune choices)
  - Vertical Dispersion (local/global) – routinely used in light sources right now, but only up to maybe 10% emittance ratio
  - Damping Wigglers (spurious or intrinsic vertical dispersion)
  - Moebius ring / emittance exchange / …

Anti-Bends



A. Streun, SLS

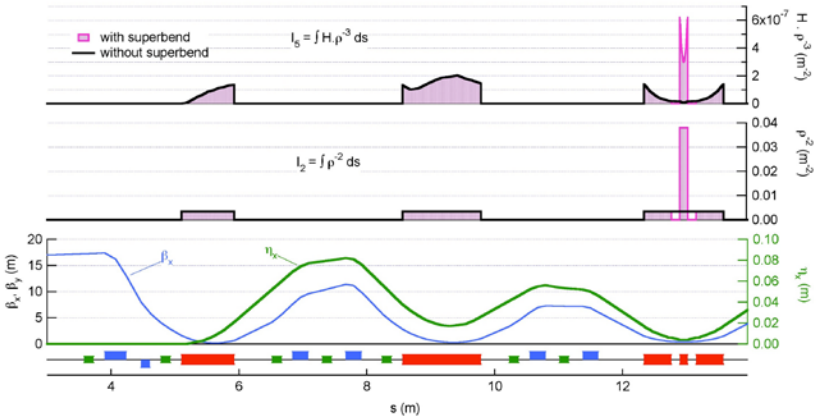


relaxed TME cell, 5°, 2.4 GeV, $J_x \approx 2$

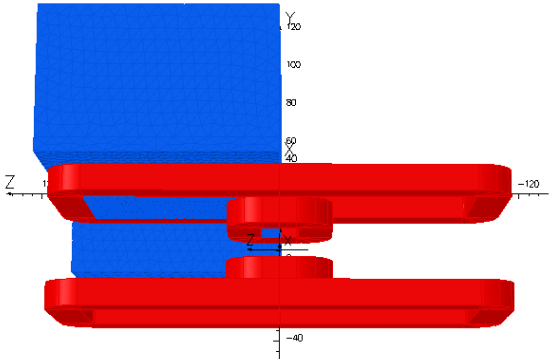
Emittance: **500 pm** / **200 pm**

- Very new proposal
- Allows more control over momentum compaction factor as well as separate control of beta-function and dispersion

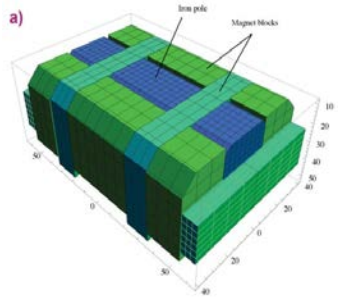
3PW, Superbends, …

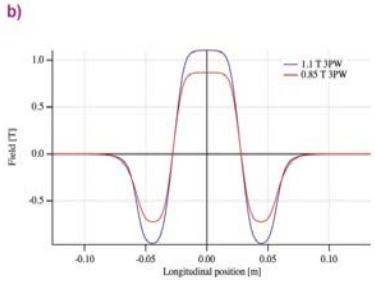


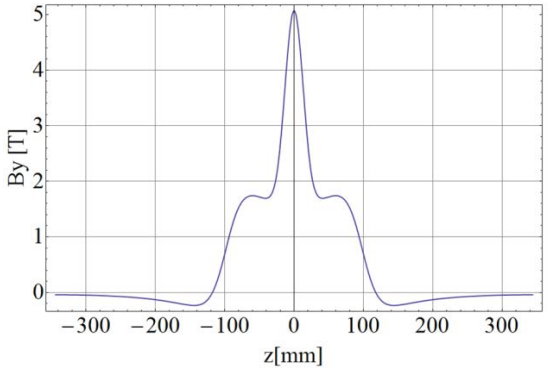
L. Liu, SIRIUS



ESRF-II







ALS-U

- MBA lattices might have weak field dipoles
- 3PW or Superbends allow to extend spectrum to harder photon energies
- Can also help to reduce the emittance (longitudinal gradient dipole) – if done right
- Need to create space in lattice, correct for potential symmetry distortion

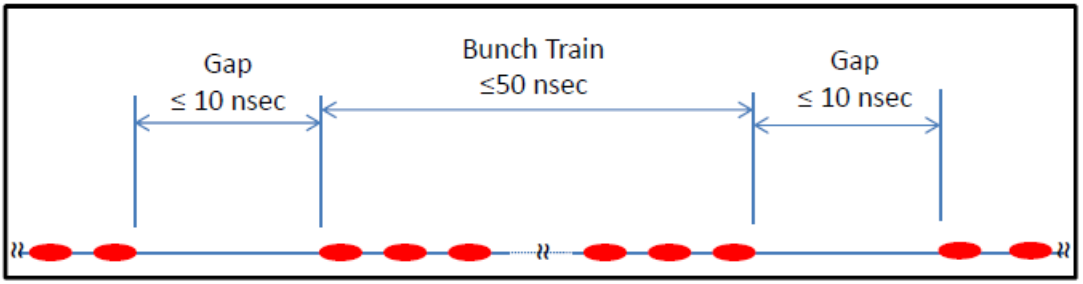
Injection Methods

- Accumulation
  - Traditional injection scheme for light sources
  - Requires sufficiently large dynamic aperture (at injection point)
  - Smallest emittance lattices might have sufficient momentum aperture (lifetime) but not sufficient dynamic aperture

- On-Axis Swap-out
  - Bunch (or bunch-train) is replaces with fresh bunch (or bunch-train)
  - Recycle or dump spent buncges
    - Added complexity
  - Requires fast kickers to minimize (potential) fill pattern gaps
    - Might impact the range of possible fill patterns
  - In use for commissioning or damping rings
  - Many potential advantages

Swapping accumulator and storage ring beams

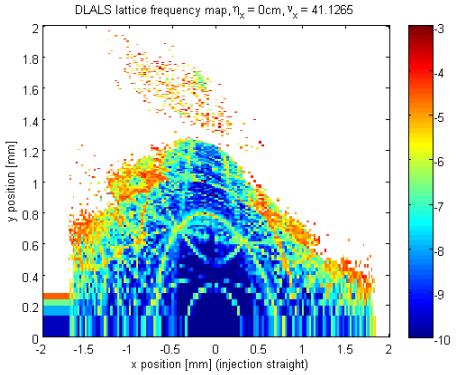
- storage ring bunches transferred to accumulator
- accumulator bunches transferred to storage ring



Fast kicker magnets

New ALS storage ring

New accumulator ring

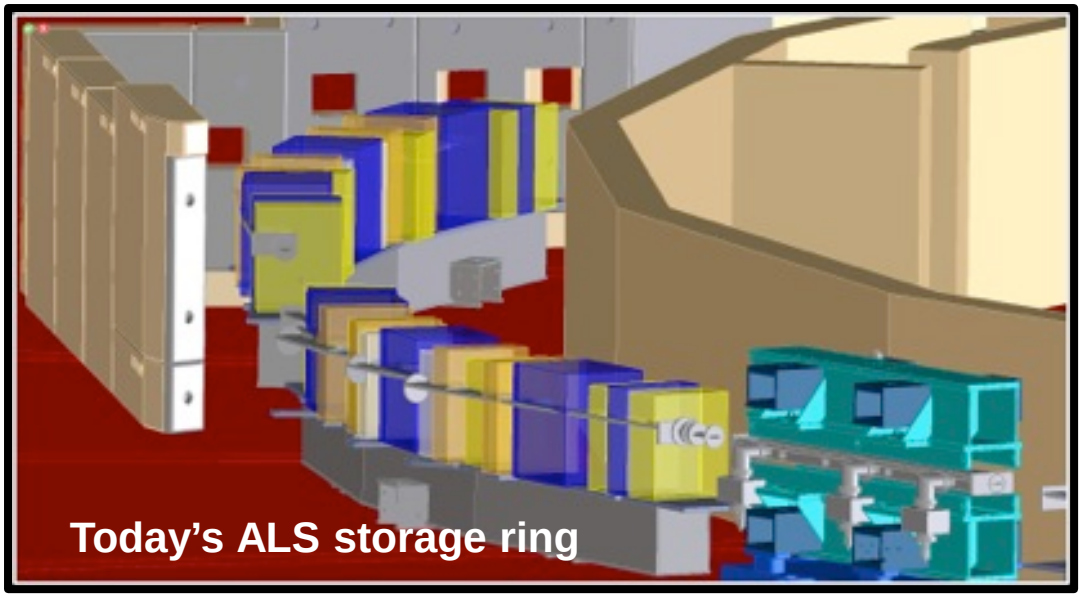


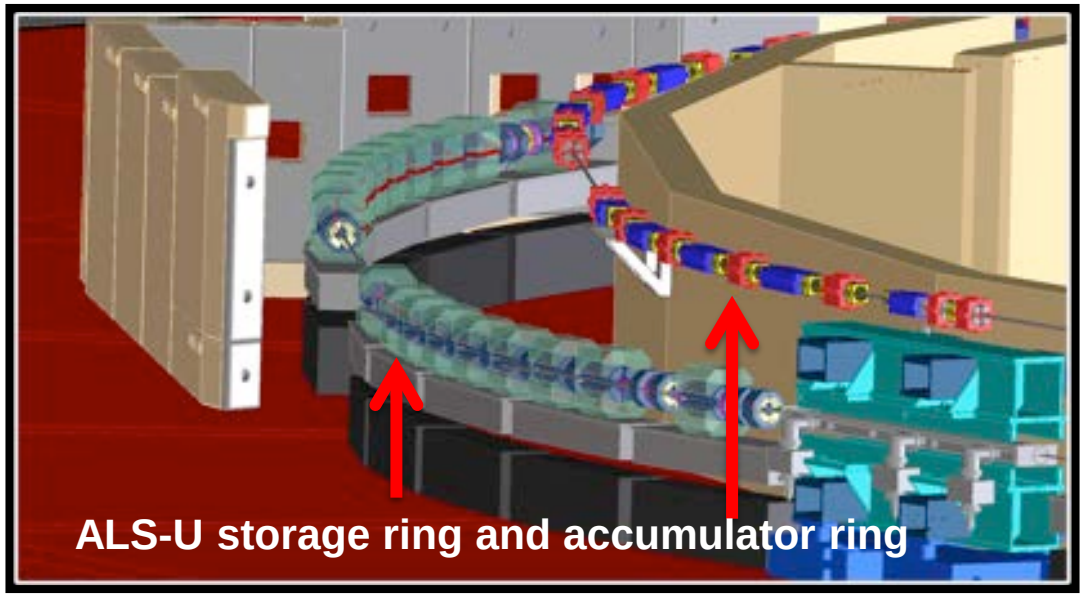
Swap-out injection was first proposed by M. Borland for possible APS upgrades

Use of Swap-Out Enables Many Advantages

On-axis swap-out injection:

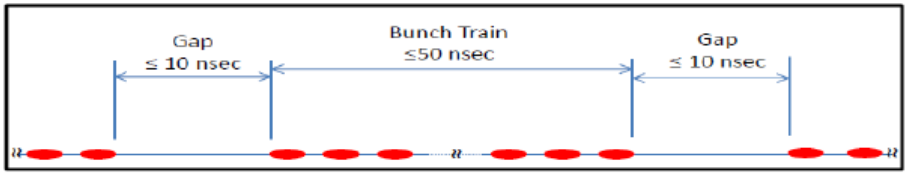
- **Further optimization of lattice** (smaller emittance)
- **Round beams** (more useful shape and reduced emittance growth)
- **Magnet field requirements relaxed** (cost benefit)
- **Vacuum chambers with small and round apertures** (better undulator performance)
- **Reduced injection losses** (better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



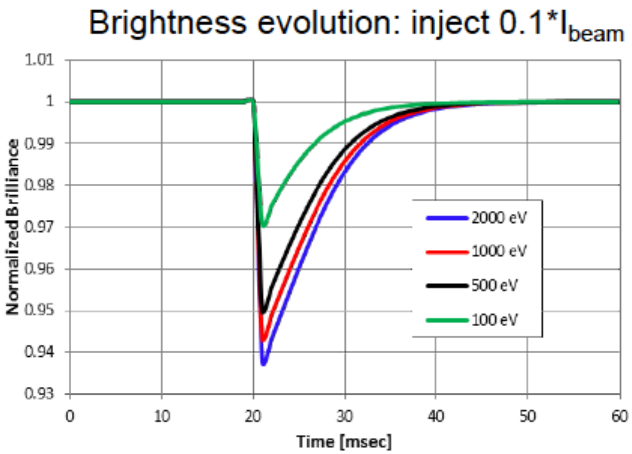


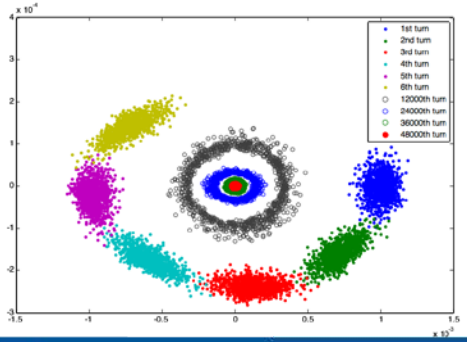
Swap-Out Options

Choose to swap-out
- Single bunch
- Bunch train
- Full beam



Impacts
- Kicker parameters (rise time, flat top)
- Stress on the injector
- Current in the accumulator
- Possible fill patterns
- Transparency of injection





100% injection efficiency in simulations for realistic lattice errors and large kicker errors

Beam Based Correction is Important

- Beam based measurements are essential to improve performance of low emittance lattices
- Allow calibration of linear, coupled, nonlinear models
- Based on model predictions, can optimize lattices (symmetrization, coupling correction, …)
- Some measurements also provide model independent guidance for optimization (tune, chromaticity choice, …)
- Standard bag of tools – developed over the last 15 years
  - First turn trajectories, Turn-by-turn data, Response matrix analysis, frequency maps, tunescans, rf-scans, resonance driving terms, …
  - Improvements in diagnostics (BPMs, …) have improved resolution substantially (particularly of first turn measurements)
- Quantitatively evaluating these methods at the design stage of a lattice is essential to understand error tolerances for magnets, alignment, power supplies, … and how far one can push the lattice towards low emittance

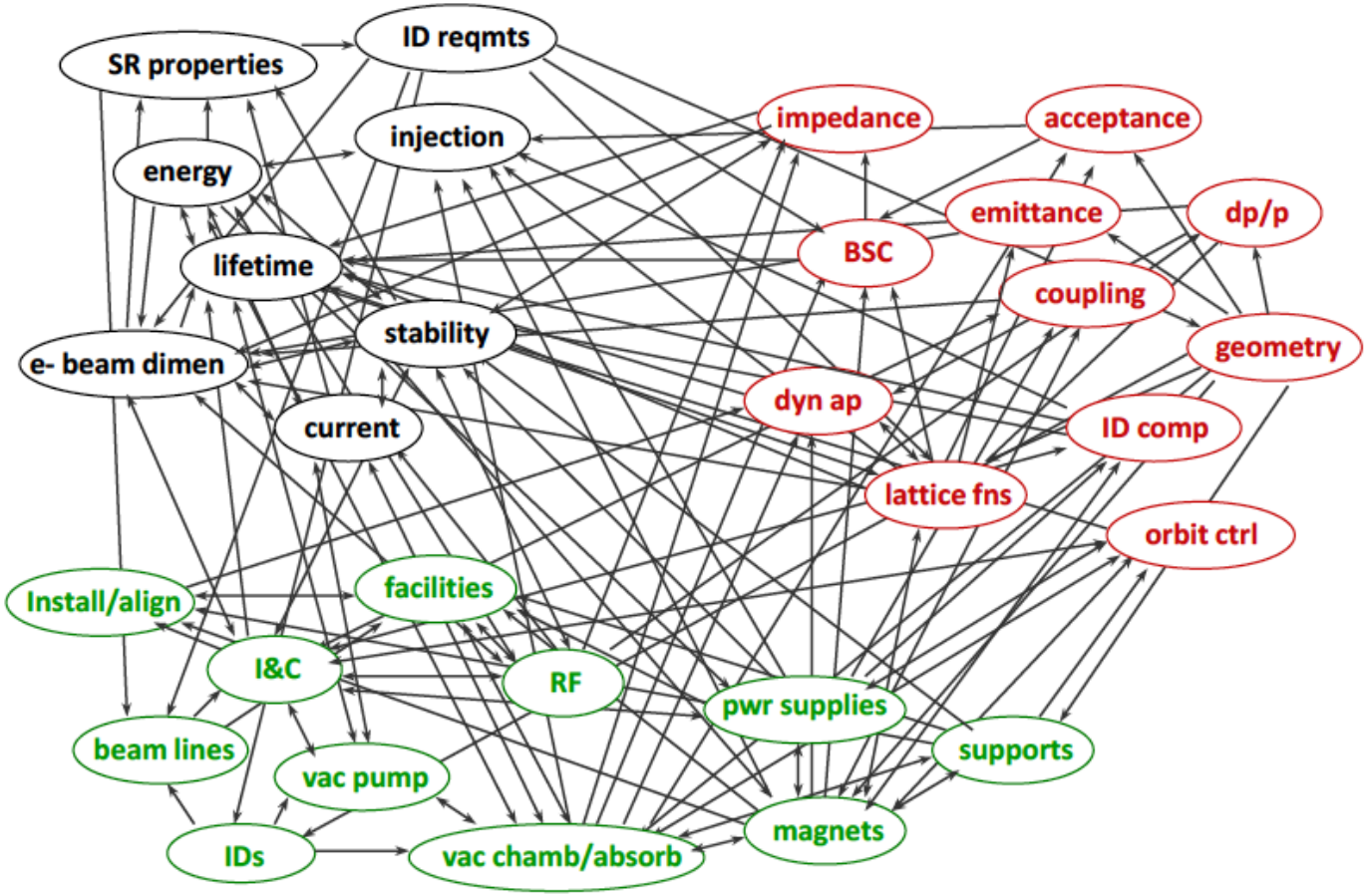
Summary

- Lattice design techniques have matured over last 20 years
  - Parallel computing as well as advanced methods
- Use of Multi-bend Achromat Lattices promises much smaller equilibrium emittances in moderately sized rings
- Many detailed lattice design choices can be made
  - All have their strengths and drawbacks
  - Diverse set of solutions will be with us for the future

- We can confidently look into a bright future

Backup Slides

Summary



R. Hettel

Draft

Features of DLSRs

- 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 DLSRs

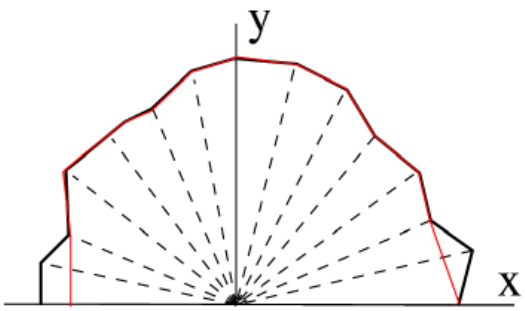
- Besides having diffraction limited emittance (and “round beams”), other features of USRs and their photon beams include:
- **Short bunches:** momentum compaction factor for USRs is factor of >10 lower, allowing (quasi) isochronous transport (but: harmonic cavities)
- **Special operating modes:** USRs 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

Features of DLSRs

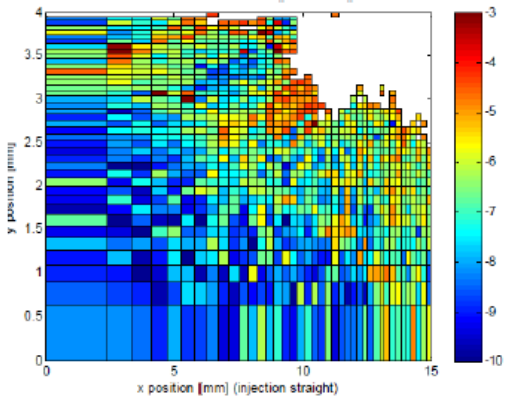
- **“Long” lifetime:** If transverse emittances are small enough the available transverse momentum is insufficient to scatter outside of momentum acceptance, so fewer particles are lost from the bucket, and Touschek lifetime increases to a few hours. Can be helped by damping wigglers and harmonic cavities (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).

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