Low-emittance lattice for the PEP-II tunnel

Donish Khan / SSRL

October 8, 2025

PEP-X @ SLAC

- The Positron-Electron Project (PEP-II) is a decommissioned (late 2000's) storage ring once used to collide beams as a part of SLAC's high-energy physics programs.
- A next generation, storage ring light source has been proposed since the late 2000's in the existing PEP tunnel to inherit SSRL's scientific program.
- Work on PEP-X since ~2008:
  - Initial lattice design: DBA + TME
  - DA/MA/TL studies
  - Magnet lattice refinements
  - Insertion device compatibility
  - Injection scheme development
  - RF system design
  - Collective effects analysis

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Lattice design and optimization for the PEP-X ultra low emittance storage ring at SLAC

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Single-particle dynamics in electron storage rings with extremely low emittance

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IDEAS FOR A FUTURE PEP-X LIGHT SOURCE†

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PEP-X: AN ULTIMATE STORAGE RING BASED ON FOURTH-ORDER GEOMETRIC ACHROMATS

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DLSR design and plans: an international overview

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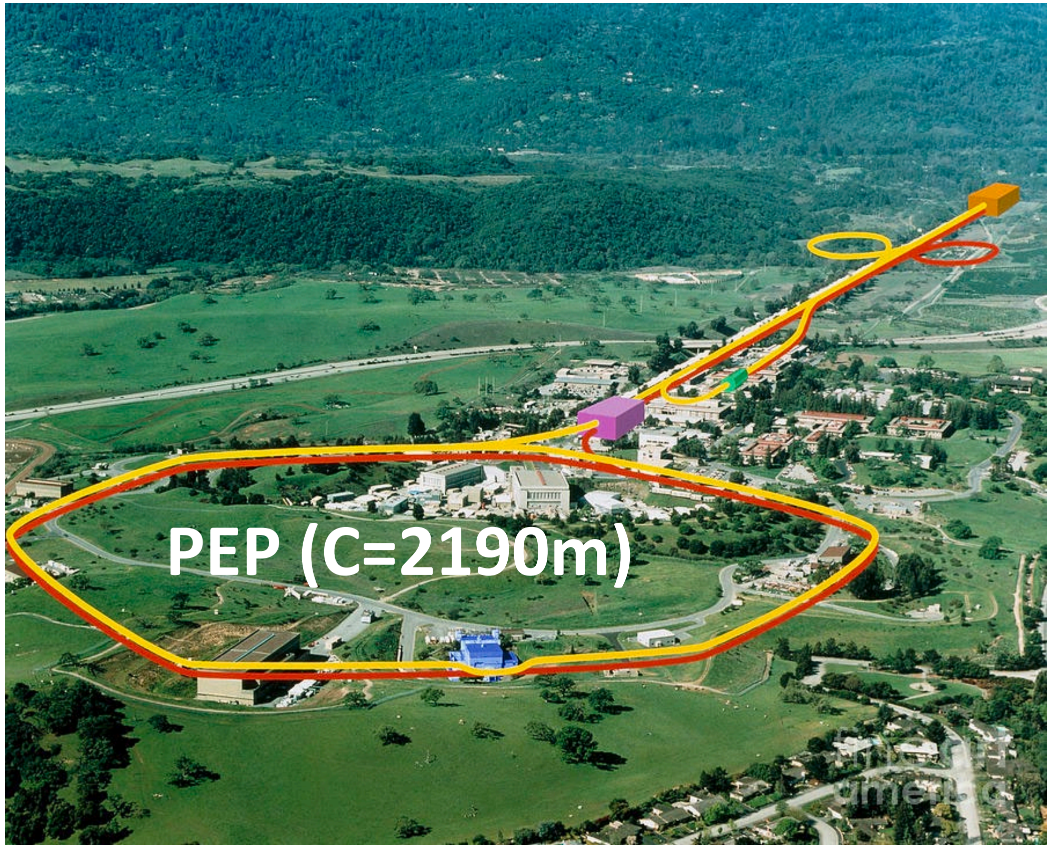
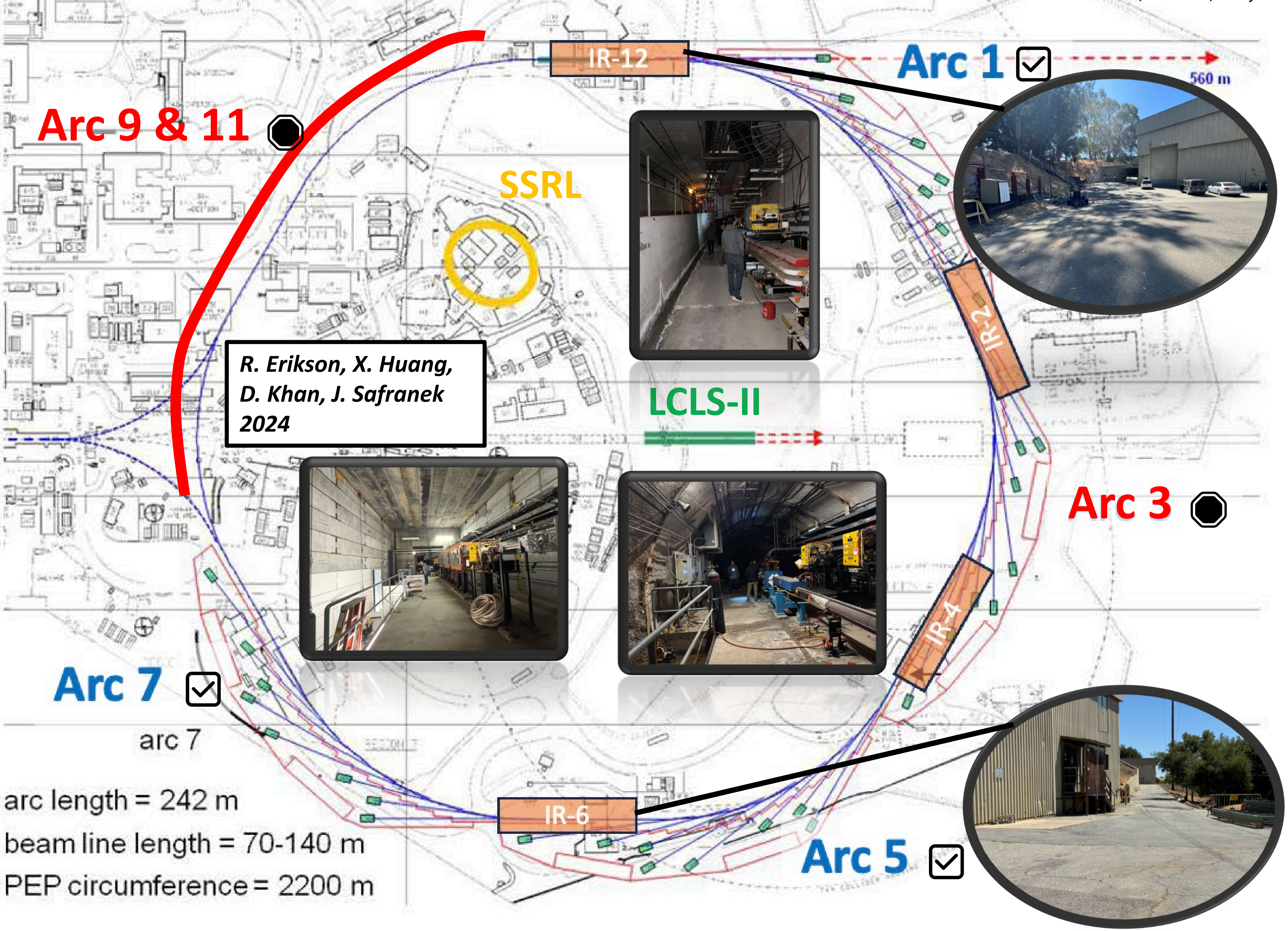


T. Rabedeau, R. Hettel, J. Safranek

PEP-X

- The PEP-II ring is located underground with a large circumference of ~2.2 km.
- It's proximity to LCLS/LCLS-II affords interesting parasitic injection schemes.
- Multiple areas of research for beamlines:
  - A balance between cost (avoiding excavation) and beamline potential.
  - Standard ID beamlines.
  - Soft-arc premium beamlines.
  - Storage ring-based FEL options.



Cell Innovations: The Hybrid 6 Bend Achromat (H6BA)

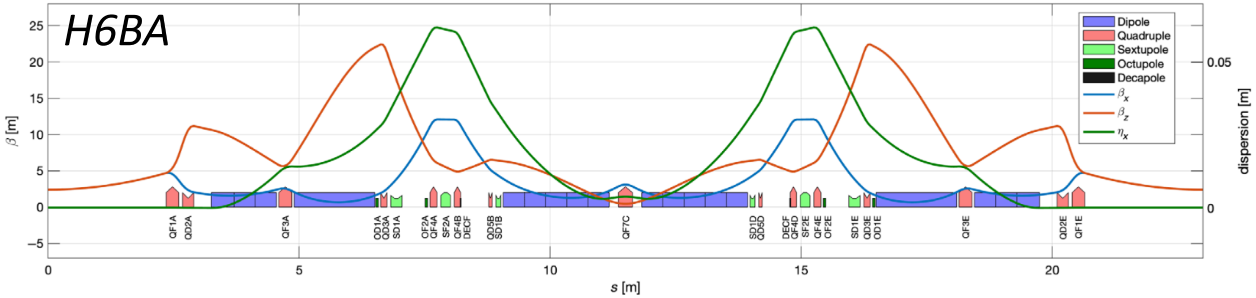
- The H6BA is a cell that combines the features of the DBA and MBA while maintaining chromaticity correction:
  - Multi-bend → lower ϵ_x.
  - η bumps separated by $-\mathbb{I} \rightarrow \xi_{x,y}$ correction.
  - Weak sextupoles enhanced by η bumps.
  - Orthogonal optics knobs for nonlinear dynamics tuning.
- Recent design work (2023) by Pantaleo R. et al on the cell has open doors for PEP-X.
- The Stanford Diffraction Limited Light Source (SDLS) is the adaptation of the H6BA cell into PEP-X.
- H6BA characterized by its performance in nonlinear dynamics…

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 021601 (2023)

Toward a diffraction limited light source

Pantaleo Raimondi and Simone Maria Liuzzo

ESRF, Grenoble, France

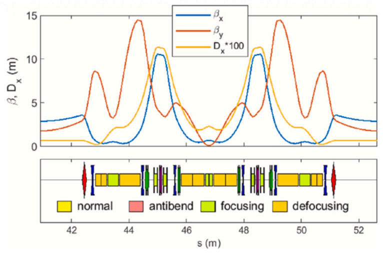


ELSEVIER

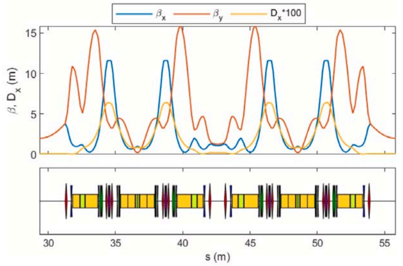
Advanced storage ring lattice options based on hybrid six-bend achromat for Stanford Synchrotron Radiation Lightsource upgrade

Pantaleo Raimondi, Xiaobiao Huang, Jaehyun Kim, James Safranek, Tom Rabedeau

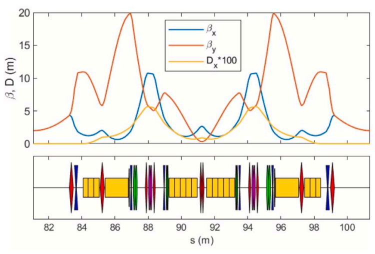
SSRLUP (234m)



SSRLX (587m)



SDLS (2190m)

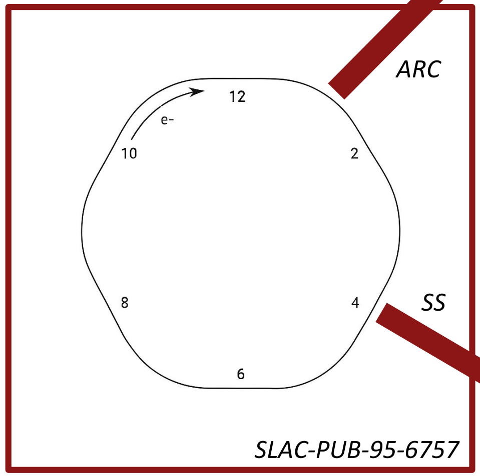


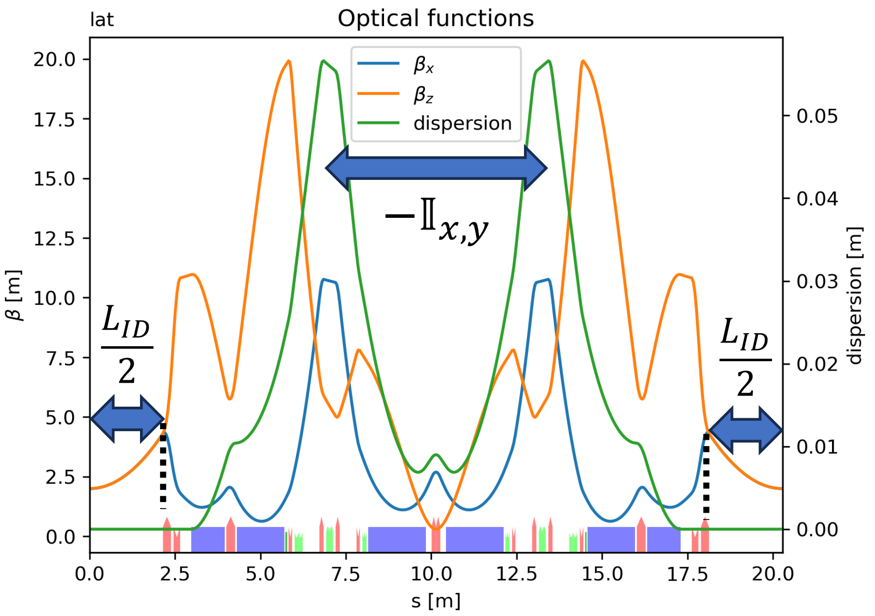
SLAC

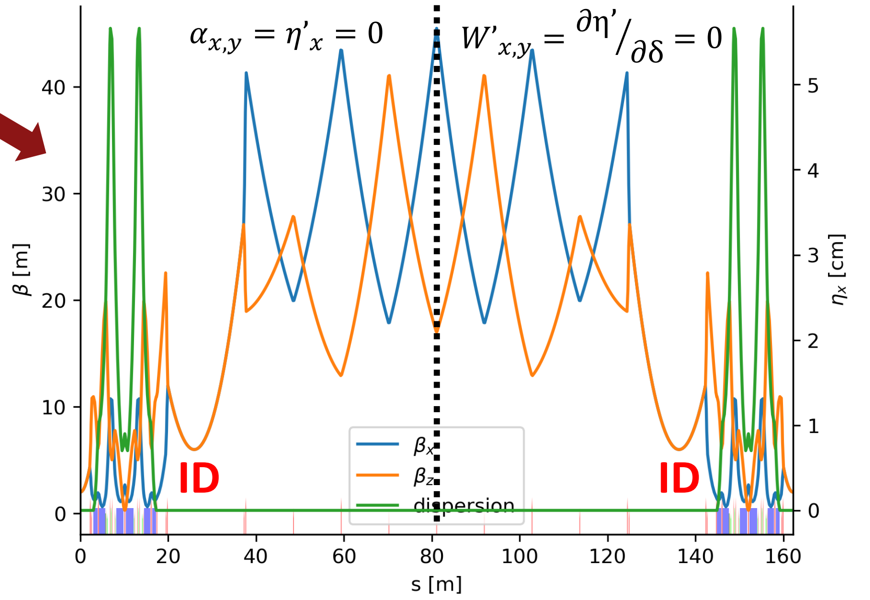
Stanford Diffraction -limited Light Source: SDLS

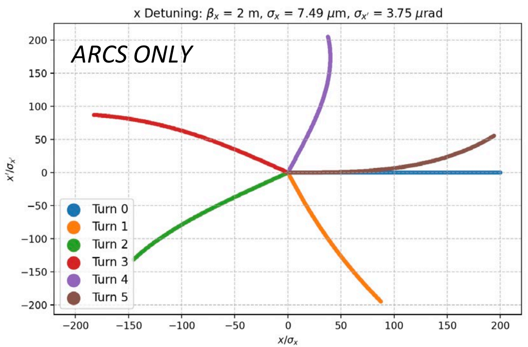
The SDLS is the adaptation of the H6BA cell into the PEP-X:

1. 6 Arcs (12 H6BA cells i.e. "12cell")
   a. $-\mathbb{I}_{x,y}$ transform between dispersion bumps.
   b. 3 families of sextupoles: 1 SF & 2 SD.
   c. Octupole (high β_y) and Decapole for high-order nonlinearities correction.
   d. $L_{ID} = 4.3$ m between cells for ID.
2. 6 Long (~120 m) Straight Sections (SS)
   a. Two long (12 m) ID sections (left/right).
   b. <u>**Transparency conditions (TC)**</u> at center of the SS:
      - On-energy: $\alpha_{x,y} = \eta'_x = 0$ & $\Delta\mu_{x,y} = (2,1) \times n\pi$.
      - Off-energy: $W'_{x,y} = {}^{\partial\eta'}/_{\partial\delta} = 0$.

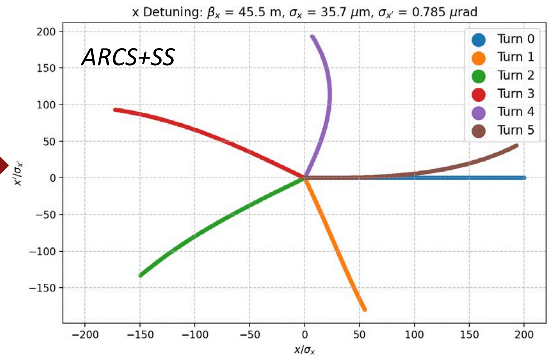






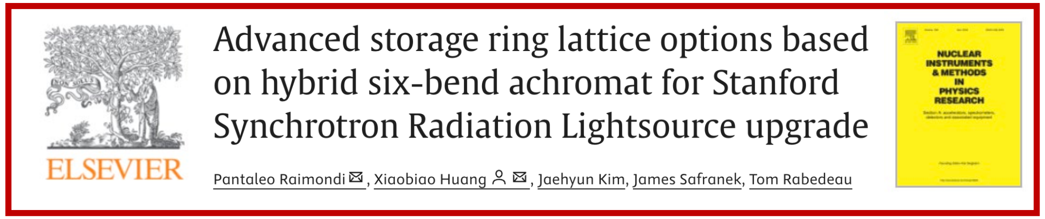


TC preserves performance

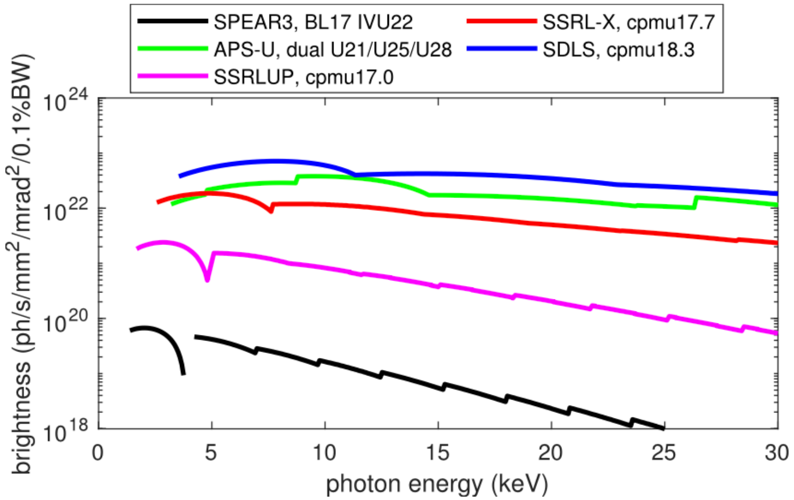


SDLS Performance Highlights

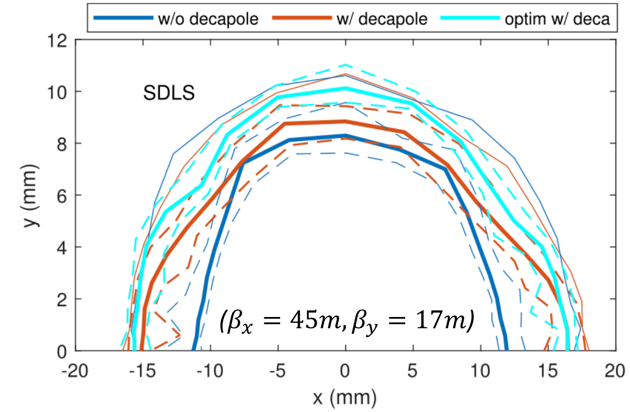
- Some performance highlights of the SDLS:
  1. Large DA (~12mm) enables off-axis injection.
  2. The Touschek lifetime (TL) is ~100 hours for a 300 mA beam current (0.1 mA/bunch).
  3. Diffraction limited for 10 keV photons (fully coupled electron beam with ~10pm).

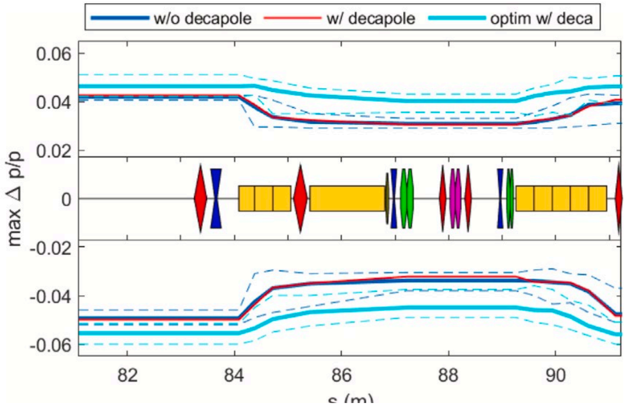

Advanced storage ring lattice options based on hybrid six-bend achromat for Stanford Synchrotron Radiation Lightsource upgrade

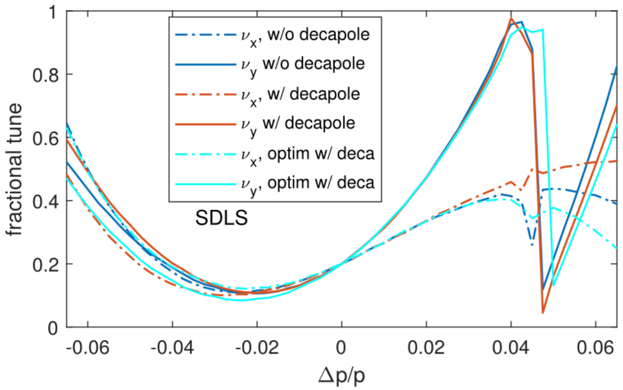
Pantaleo Raimondi, Xiaobiao Huang, Jaehyun Kim, James Safranek, Tom Rabedeau

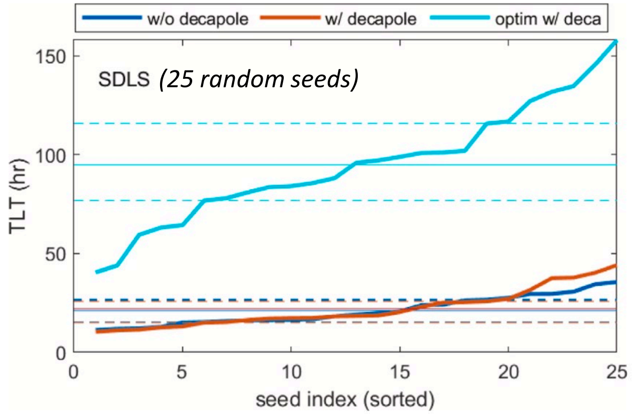


Parameter	Units	Value
Energy	GeV	5.000
Tune (x, y)	2π	1.766667, 0.905556
Chromaticity (x, y)	n/a	0.240214, 0.199434
Nat. Emittance (x)	pm	28.055
σ_E/E_0	n/a	6.38016E-04
Energy Loss	keV	9.47348
α_c	n/a	3.93017E-05



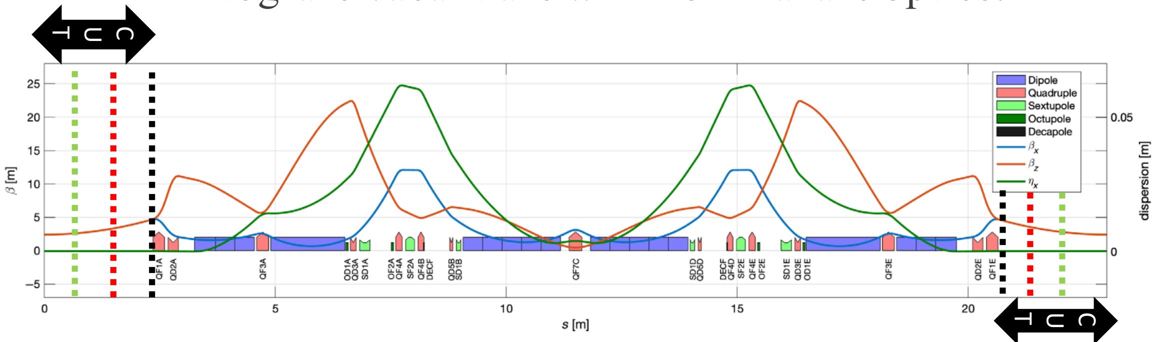


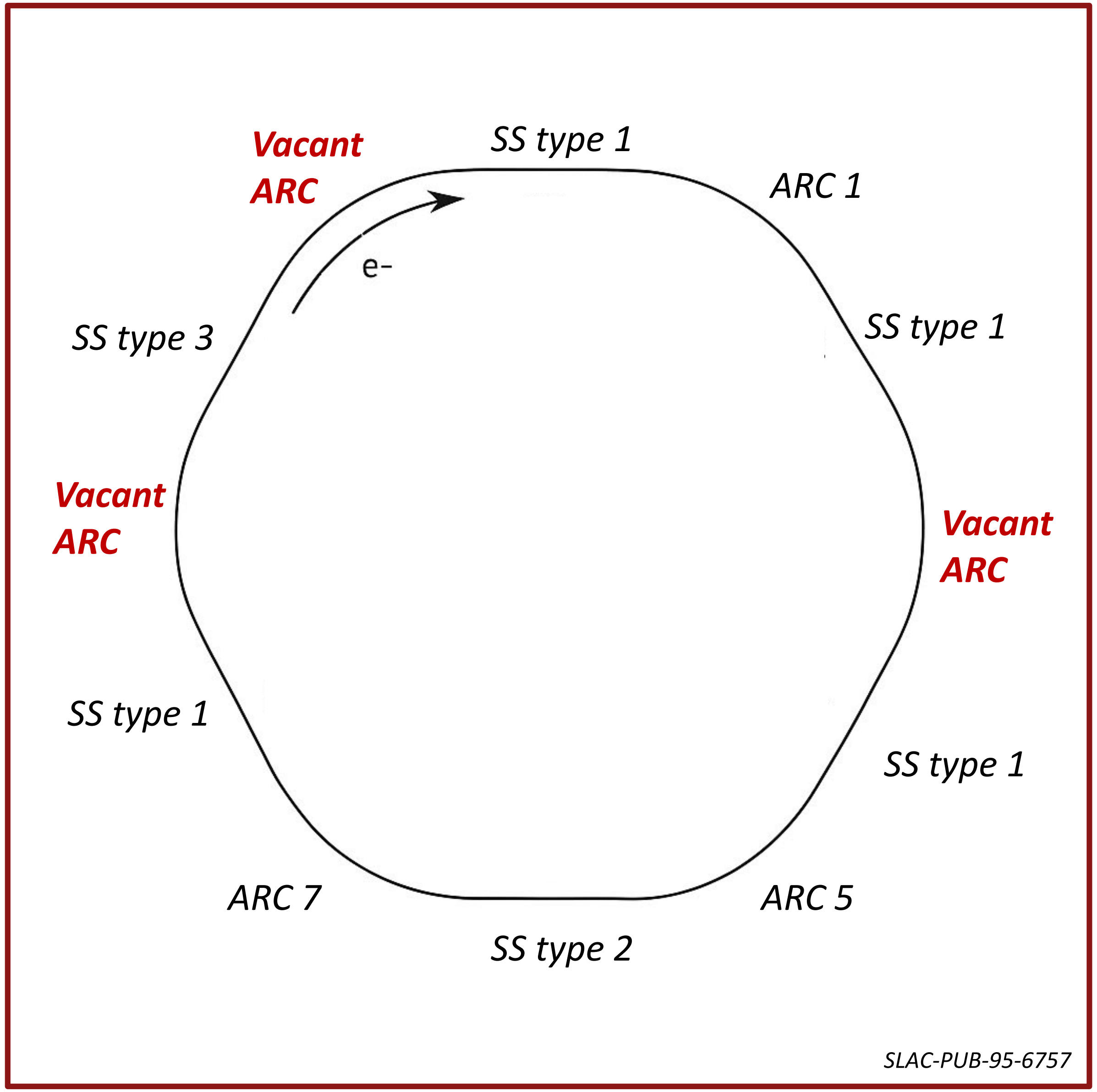




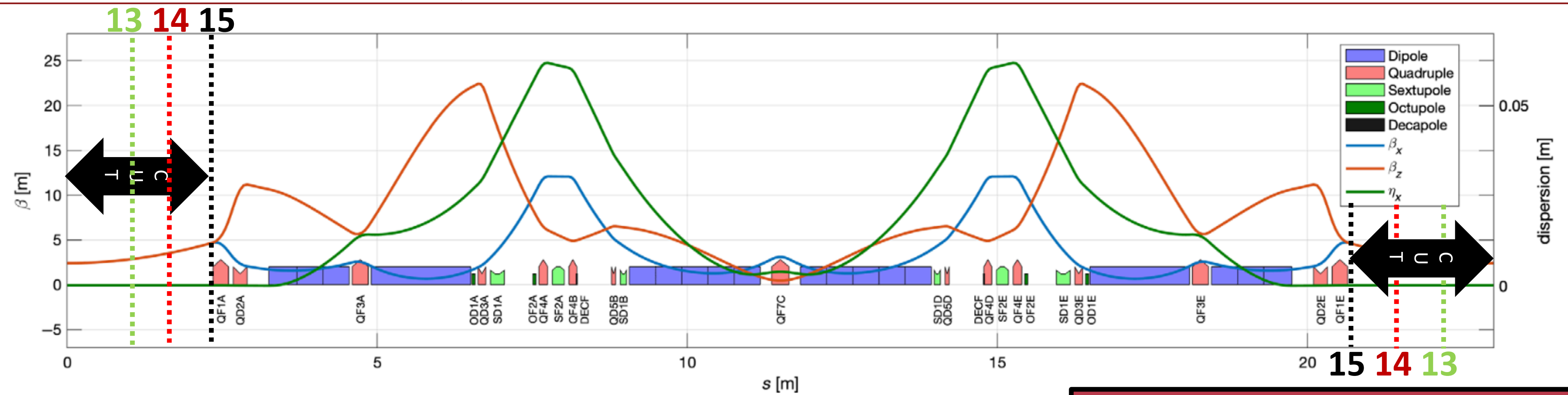
Improving Upon The SDLS

- Now, the goal is to continue to push performance of the nominal SDLS design.
- Not all arcs (only 3 of 6) in the PEP ring will be used to host beamlines.
- The **"vacant" arcs** can be further optimized:
  - Cut/shorten ID-dedicated drift sections in cell (**15**, **14**, **13**).
  - Following the scaling law, $\epsilon_x \propto \frac{\gamma^2}{C^3}$, increase the number of cells (i.e. dipoles) to minimize ϵ_x.
  - Optimized linear optics and magnet distribution within cell.
  - Integrate vacant arc with nominal arc optics.





The Compact H6B~~A~~ cell: “15 cell”



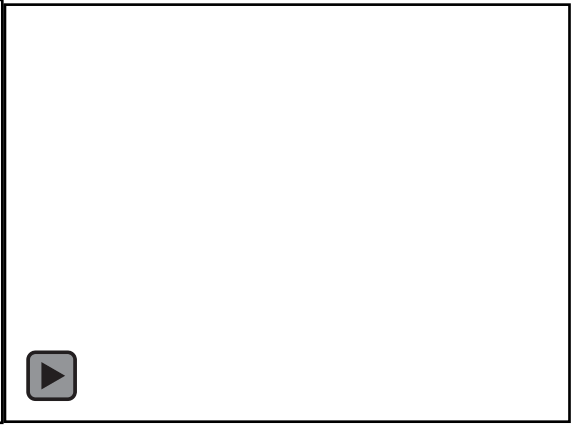
- 15cell design stage(s):
  1. Remove the ID drift(s).
  2. Convert end quadrupole to a half-magnet; adjacent cells share a triplet.
  3. Reduce emittance by a factor of $(12/15)^3 \sim 0.5$.
  4. Optimize linear and nonlinear optics for performance
  5. Dispersion suppressor
  6. Match into SS’s:
     a. SS type 1: 12cell-to-15cell
     b. SS type 2: 12cell-to-12cell
     c. SS type 3: 15cell-to-15cell

} Non-achromatic cell!

Parameter	Units	Value
Energy	GeV	5.000
Tune (x, y)	2π	1.591111, 0.613333
Chromaticity (x, y)	n/a	0.180076, 0.149954
Nat. Emittance (x)	pm	13.728
σ_E/E_0	n/a	5.65784E-04
Energy Loss	keV	6.0630299999999995
α_c	n/a	3.10415E-05

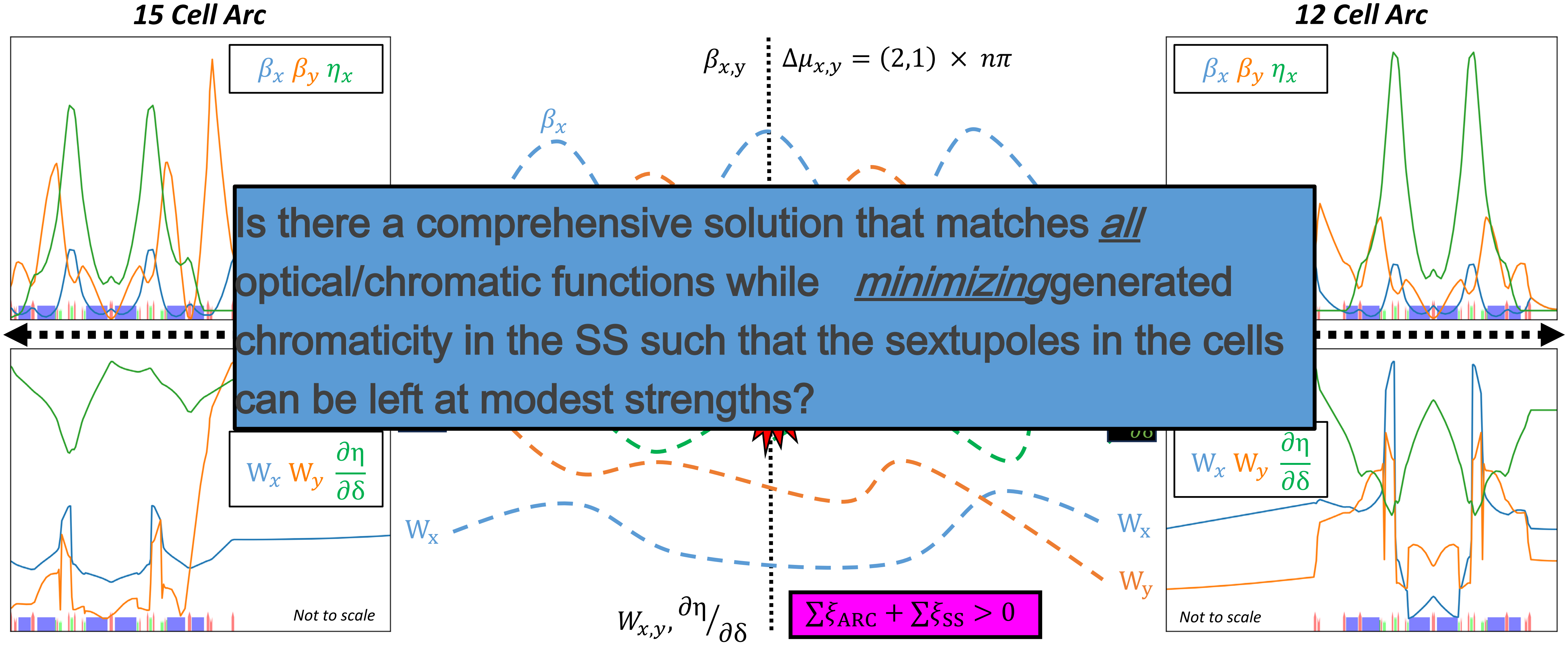
Various Challenges:

1. Matching linear optics along with chromatic functions $(W_{x,y}, \frac{\partial\eta}{\partial\delta})$!
2. Preserving nonlinear dynamics performance of 12cell.



15 Cell Challenges: Linear/Chromatic Optics Matching

- There is a break in periodicity between the 12cell & 15cell arcs each having different intrinsic optical/chromatic functions.
- Straight sections need to provide matching of all terms each with its own phase space invariant, $\mathcal{J}_i = \gamma i^2 + 2\alpha i i' + \beta i'^2$:



Is there a comprehensive solution that matches _all_ optical/chromatic functions while _minimizing_ generated chromaticity in the SS such that the sextupoles in the cells can be left at modest strengths?

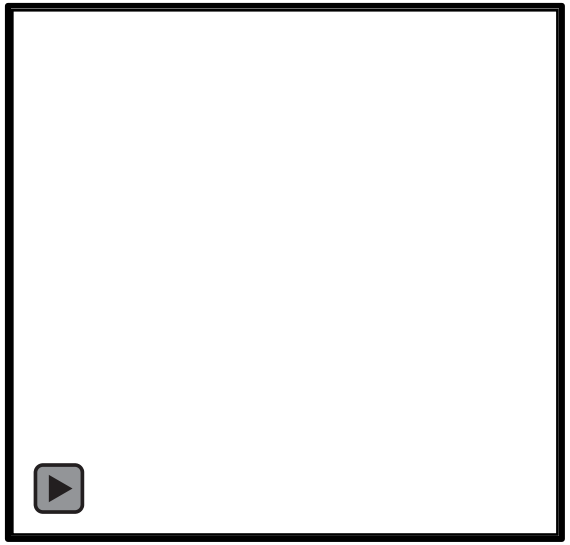
15 Cell Challenges: Nonlinear Dynamics Performance

Legend

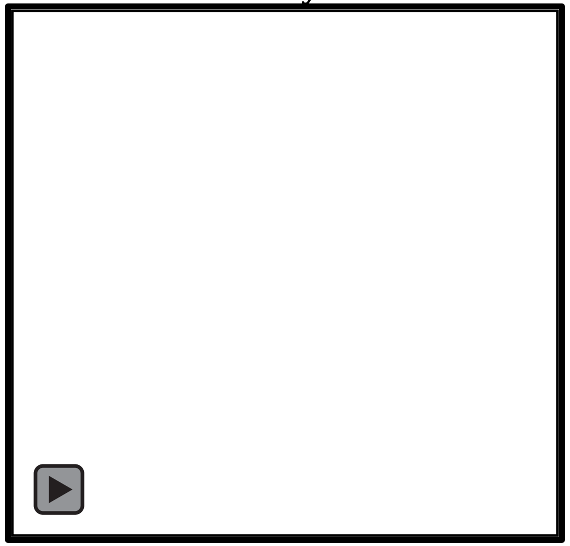
x	y
x-y	y-x

- Nonlinear dynamics optimization is computationally expensive task.
- Strong linear optics optimization as a 1st step could get close to an optimal solution subsequently found with Multi Objective Genetic Algorithm (MOGA) like numerical optimizations.
- "Starfish" plots are a relatively fast-proxy for tune-shift with amplitude nonlinear dynamics.
  a. Use H6BA optics knobs: $\Delta\mu_{x,y}$ between SF's, Sextupole (K_2), Octupole (K_3).
  b. Optimize starfish for "*anharmonicity*" i.e. straight lines for each arm of starfish i.e. after N-turns $\vec{x}_0 = \vec{x}_N$.

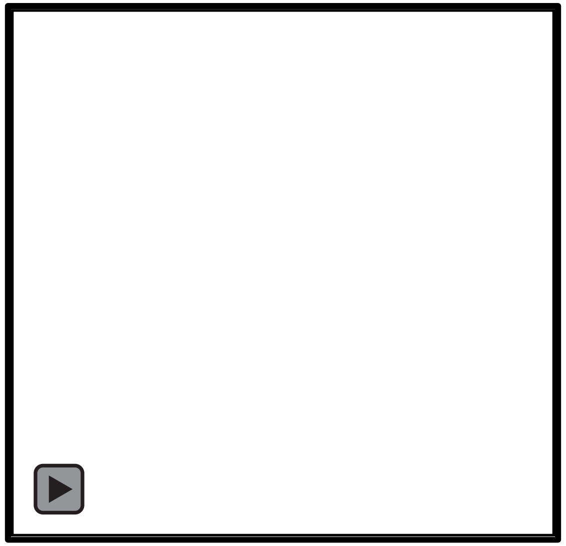
$\Delta\mu_x$



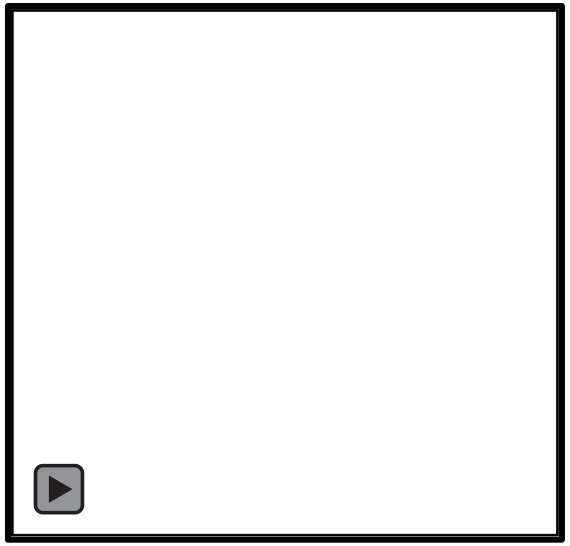
$\Delta\mu_y$



ΔK_2



ΔK_3



SLAC

Beam Energy & IBS Studies

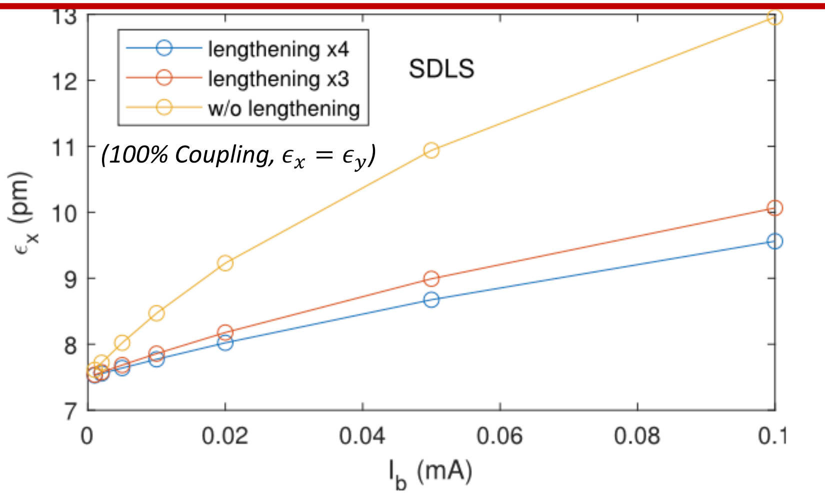
Advanced storage ring lattice options based on hybrid six-bend achromat for Stanford Synchrotron Radiation Lightsource upgrade

Pantaleo Raimondi, Xiaobiao Huang, Jaehyun Kim, James Safranek, Tom Rabedeau

- Reducing γ reduces the lattice ϵ_x via $\epsilon_x \propto \frac{\gamma^2}{C^3}$ scaling law.
- Reduction in γ not only affects photon energy range but exacerbates ϵ_x dilution via intra-beam scattering (IBS).
- IBS's affect on ϵ_x could nullify the compact H6BA cell ("15cell") optimization efforts.
- IBS scales ***strongly*** with γ: IBS Growth Rate $(1/\Gamma_x) \propto E^{-11.5}$ for a scaled lattice(s) →

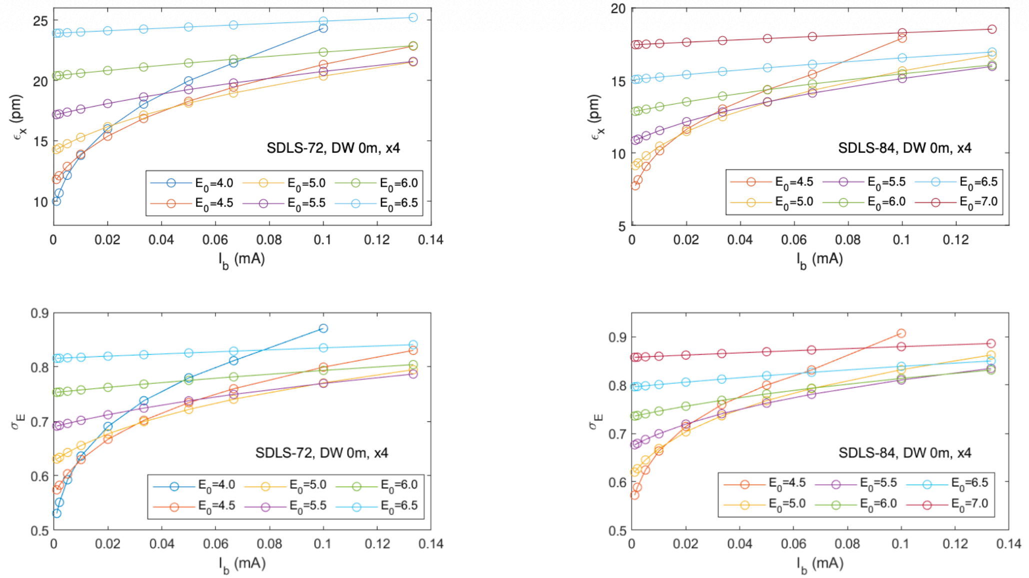
  IPAC17 POTENTIAL PERFORMANCE LIMIT OF STORAGE RINGS *

  Xiaobiao Huang†, SLAC, Menlo Park, CA 94025, USA
- Increases of γ helps IBS but hurts ϵ_x .
- Choice of beam energy plays a big role in machine performance.



IPAC25 OPTIMAL BEAM ENERGY FOR ULTRA LOW EMITTANCE STORAGE RINGS *

Xiaobiao Huang†, SLAC, Menlo Park, CA 94025, USA



Future Steps

1. Beamline layout and accelerator orientation (clock-wise vs. counter clock-wise)
    a) Minimize cost & maximize flexibility
2. Research injection options
    a) Electron source: LCLS? Dedicated e-Gun/linac?
3. Comprehensive lattice and beam dynamics studies (elegant, Bmad, AT):
    a. Push for lower emittance – higher gradients, shorter magnets, more cells.
    b. Lattice & nonlinear dynamics design/optimization.
    c. Insertion device performance/impact studies.
    d. Collective effects and long-term stability.
4. Monochromator-less beamlines
5. Study ring-based FEL options
6. Investigate timing mode options (crab cavities, single bunch limits)