ibS 중이온가속기연구소
Institute for Rare Isotope Science

KOMAC Korea Multi-purpose Accelerator Complex

PAL POHANG ACCELERATOR LABORATORY

KAFAT Korea Association for Fusion Energy and Accelerator Technology

ICABU 2023

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ICABU 2023

The 25th International Conference
on Accelerators and Beam Utilization

Recent trends and developments in the field of accelerator physics and engineering for synchrotron light sources

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Abstract

Light source community is rapidly evolving in the past decades, pushing towards reliable operations with highest brightness to meet growing demands from the users.

The growth in reliability and capabilities is fueled by ongoing developments of concepts in accelerator physics and new technologies in engineering.

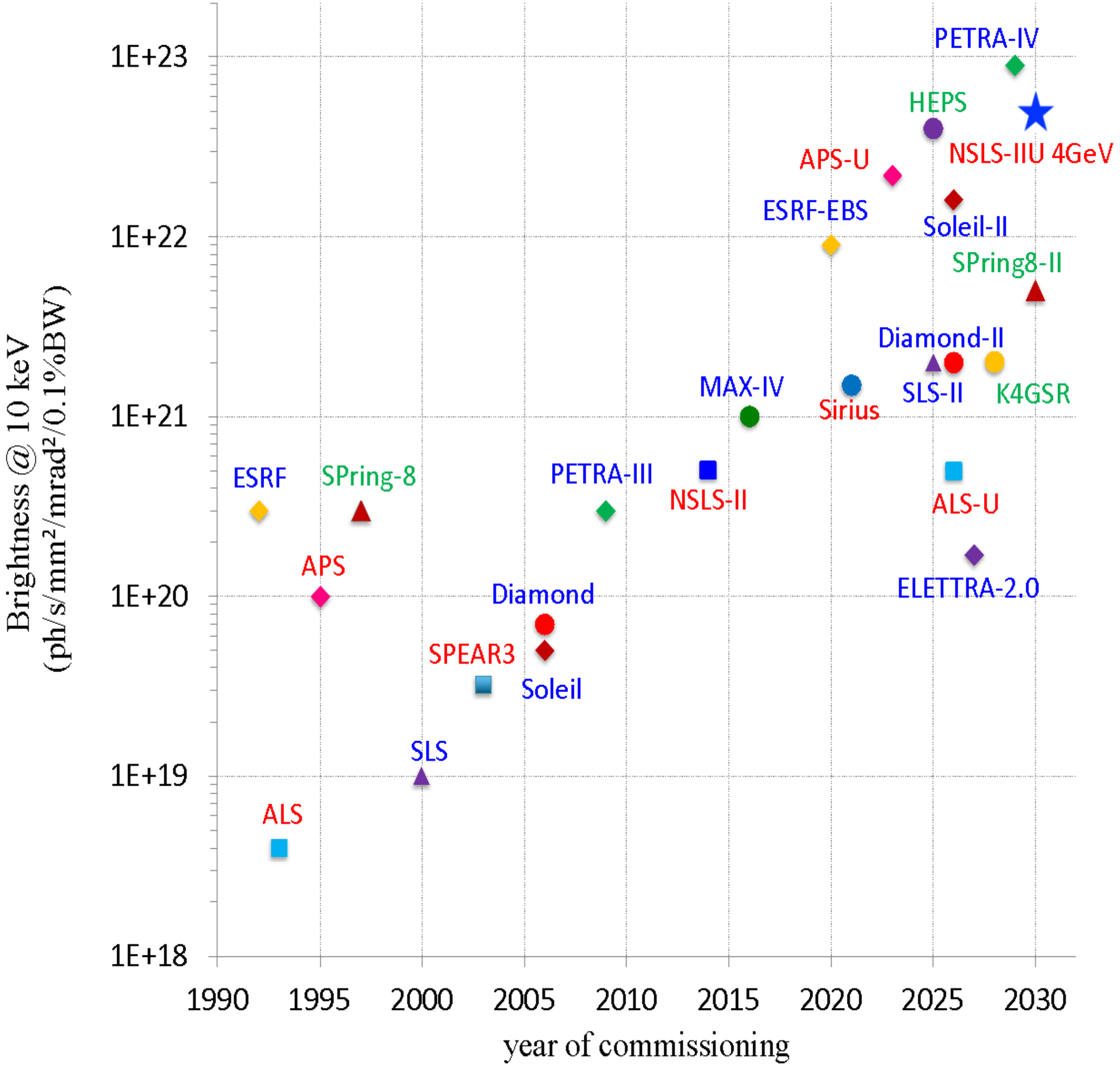
This presentation is intended to provide an overview of recent developments and give a few highlights of new approaches in producing bright X-ray beams for advanced user applications.

Outline

- Trends in development of Synchrotron Light Sources
- Ways to Increase Brightness
- Evolution of Accelerator Subsystems
    - Lattice Design
    - Insertion Devices
    - Magnet Design
    - Intensity-dependent Effects
    - Vacuum Systems
    - Diagnostics and Instrumentation
    - Injection Schemes
- Model analysis and simulations
- Summary

Trends in development of Synchrotron Light Sources

- R&D challenges in the 21st century:
  - Biological and medical sciences
  - Efficient energy
  - Advances in computing
  - Advanced manufacturing
  - Environmental science
- These complex, dynamic, and heterogeneous problem s require the instruments providing:
  - multiple scales of length, time, and energy
  - ability to work in a multimodal fashion
  - exquisite resolution and sensitivity
  - in-operando conditions
- Synchrotron light sources deliver means for solving these and other problems
  - Imaging, spectroscopy, coherent X-rays for complete characterization of samples
  - Ultimate brightness of light sources is one of the keys in advancing to a smaller scale, faster response, and higher rate of data measurement and processing



Ways to Increase Brightness

$$\text{Brightness} \propto \frac{\text{Beam Intensity} \times \text{Insertion Devices}}{\text{Electron Beam Emittance}}$$

- Increasing intensity of the electron beam:

  This approach is limited by technical problems: high RF power, beam-induced heating, collective instabilities

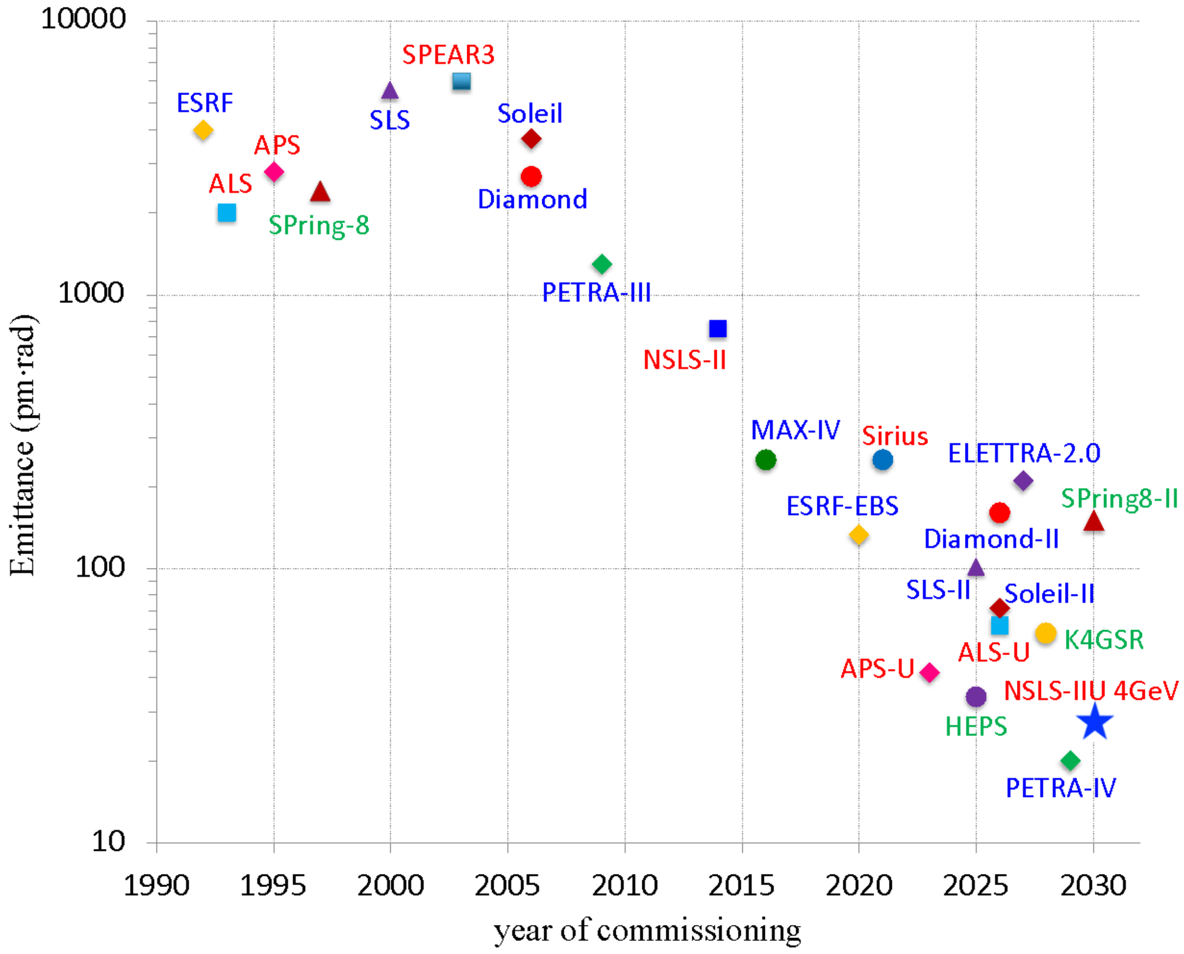
  There are no light sources operating with the beam current exceeding 500 mA.

- Advanced undulators
- Reducing emittance of the electron beam:

$$\varepsilon_x = F(\text{lattice})\frac{E^2}{J_x \boxed{N_d^3}}$$

- General trend: increasing number of dipoles

  - From DBA & TBA to MBA and Complex Bend lattices:

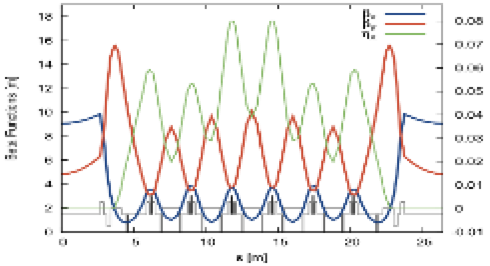


Lattice Design

- Transition from DBA / TBA to MBA
  - Strong focusing calls for high-gradient quadrupoles
  - High natural chromaticity
- Small dynamic aperture:
  - Typical DBA: $\gtrsim \pm 10$ mm
  - Typical MBA: $\gtrsim \pm 1$ mm
- Small momentum aperture & strong Touschek effect
  - Typical DBA: beam lifetime of about 10 hours
  - Typical MBA: beam lifetime of about 1 hour
- New approach: complex bend (NSLSII)
  - A magnet consisting of many poles: bending and strong focusing
  - A compact design provides more space for insertion devices and other components
  - Quadrupole gradient < 130 T/m ⇒ use of permanent magnets

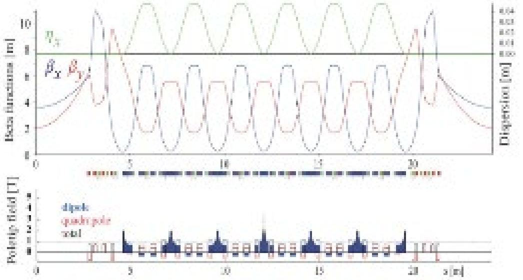
"Classic" MBA

MAX-IV
E=3 GeV
C=528 m
ε_x=250 pm



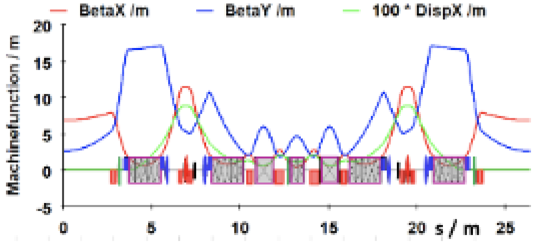
Compact MBA

SLS-2
E=2.4 GeV
C=290 m
ε_x= 102 pm



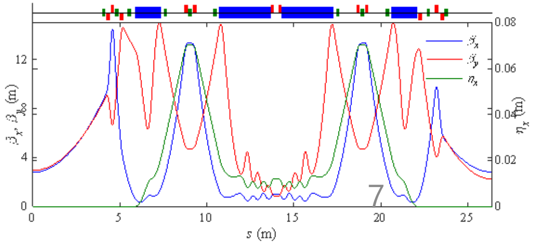
Hybrid MBA

ESRF-EBS
E=6 GeV
C=844 m
ε_x= 132 pm



Complex Bend

NSLS-IIU
E=3 GeV
C=792 m
ε_x= 23 pm



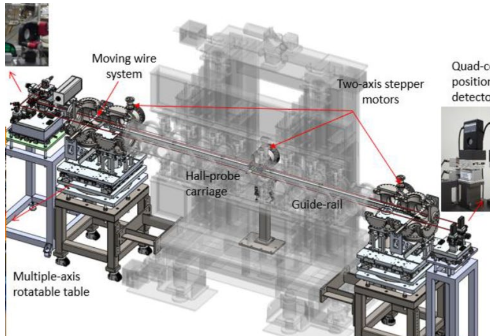
Insertion Devices

- High brightness requires long undulators with short period
- Heat loads: self-imposed undulator radiation + wakefields
- Active R&D in the area of short period CPMUs or SCUs
  - APS-U double ID prototypes
  - ALS-U 4 m long IVU and EPU
- Use of separate short IDs, integrated into the same magnetic structure
  - Segmented Adaptive Gap in-vacuum Undulator (NSLS-II)
  - Tandem IVUs/EPUs (TPS)
  - SCUs with SC focusing triplet, corrector and phaser in double-beta minimum straights (NSLS-II)
- Gain in brightness by using phasers
  - Beam test at CSX beamline at NSLS-II

4.8 m 2xSCU (APS)

M. Kasa, et al., Proc. of IPAC2019, Melbourne, TUPRB095

Y. Ivanyushenkov, et al., Phys. Rev. Accel. Beams 20, 100701 (2017)



J.-C. Huang, et al., AIP Conf. Proc. 2054, 030022 (2019)

Cryo-PM undulators (NSRRC)

CSX phaser (NSLS-II)

SC-SAGU (NSLS-II)

Magnet Design

- Modern low-emittance lattices rely on quadrupole gradients $\gtrsim$ 100 T/m
- Magnet gaps reduced to <2 cm
- Trend towards complex combined magnets with field profiles tailored to the lattice requirements
  - MAX-IV: single yoke with dipole and quadrupole magnets
- Advances in precise machining and integration
  - Longitudinal gradient bends with multipole coils (SLS)
- Use of permanent magnets (ESRF-EBS, SIRIUS)
  - Transition to PM bending / focusing elements to save space and advance to gradients $\gtrsim$ 200 T/m
  - Permanent magnets ⇒ reduced power consumption
  - Superconducting magnets (ELBE)

Longitudinal gradient dipole (ESRF)

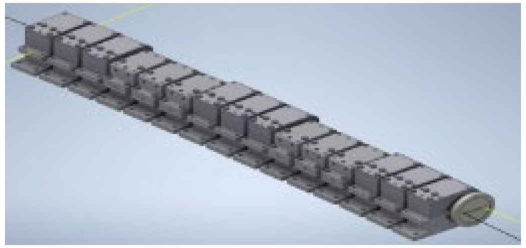
ESRF Highlights 2016

Compact magnets (MAX-IV)

M. Johansson, et al., J Synch. Rad. 2014 21: 884–903

PM superbend (SIRIUS)

J. Citadini, et al., IEEE Trans. on Applied Superconductivity 28(3), 1-4 (2018)



Complex Bend magnets (NSLS-II)

S. Sharma, et al., Proc.of IPAC2019, Melbourne, THPTS094

Intensity-dependent Effects

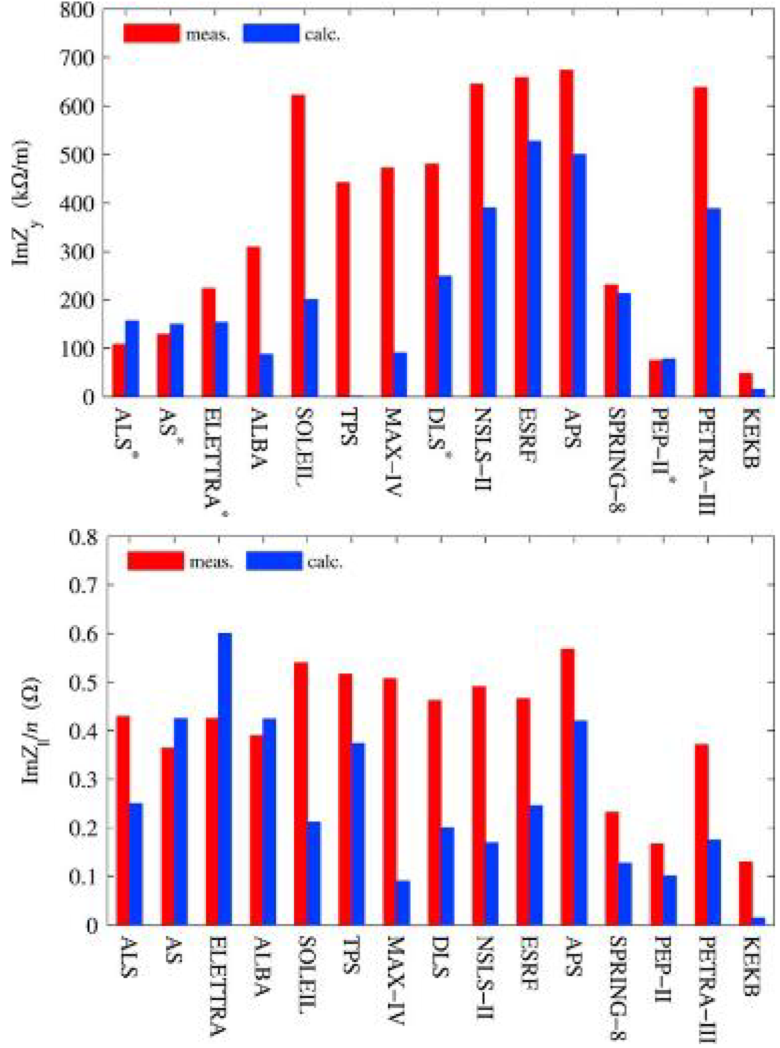
Challenges

- Intra-beam scattering
  - intensity-dependent growth of emittance, energy spread, and bunch length
- Impedance
  - beam-induced heating;
  - energy spread growth;
  - single-bunch and multi-bunch instabilities
- Ions
  - multi-bunch instabilities and impact on lifetime

Mitigation

- Reducing peak beam current
  - bunch lengthening by higher-harmonic RF cavities
- Reducing impedance
- Complex fill patterns

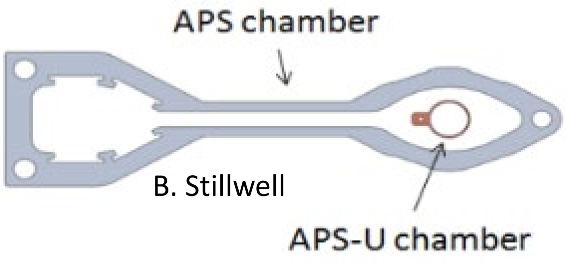
Longitudinal and vertical impedance: measurements and calculated budgets at different facilities

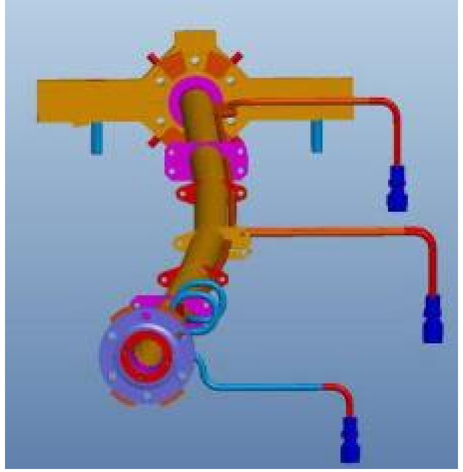


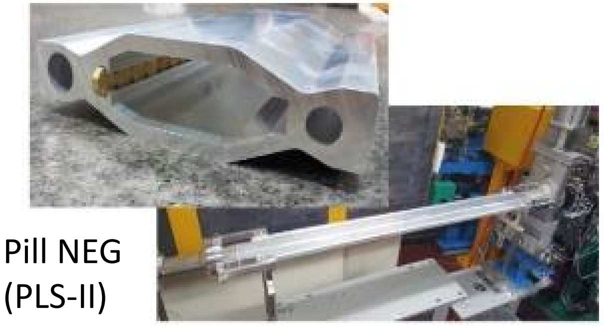
V. Smaluk NIMA 888, pp. 22-30 (2018)

Vacuum Systems

- High gradients ⇒ small apertures and tight arrangement of magnets
  - Short space for pumping
  - Extraction of synchrotron radiation from inside magnets
- Strong reliance on NEG coating
  - 5% (DBA) to 50% (MBA) of ring chambers are NEG coated
  - Reliable coating of small (Ø5 mm) chambers (ALS-U)
  - Alternative NEG configurations: Pill NEG (PLS-II)
- Vacuum-friendly low-emittance lattices: complex bend approach
- Design of Front-ends capable of handling high peak radiation power
  - APS-U: 500 kW/mrad^2
  - New materials: CuCrZr vs OFC Cu
- Minimizing ring impedance and reducing heating
  - Large number of flanges in low-emittance rings
  - Advanced designs of RF contacts, bellows, etc.





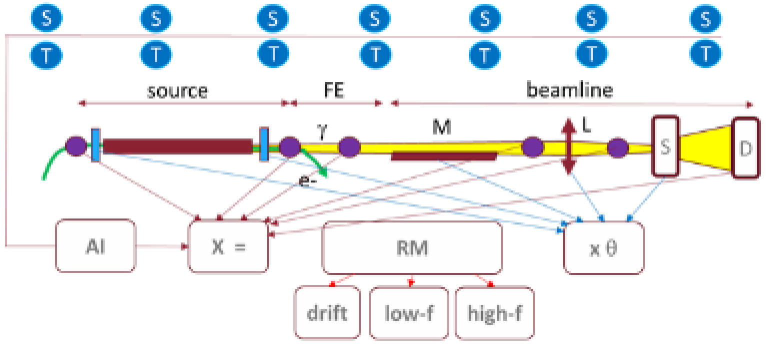


Pill NEG (PLS-II)

Diagnostics and Instrumentation

High X-ray beam stability required in future light sources

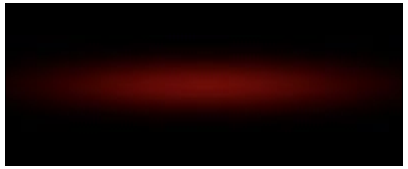
- Integrated electron and X-ray feedback system
  - high flexibility and broad bandwidth
  - RF BPMs + X-ray BPMs
  - environmental data (vibrations, temperature, etc.)
  - data processing using Artificial Intelligence and Machine Learning algorithms



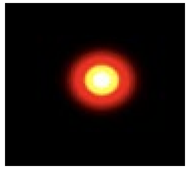
- High-resolution BPMs are needed for high-precision characterization and correction of the lattice

- BPM electronics with bunch-by-bunch capability for continuous monitoring of collective instabilities

Control of beam emittance, energy spread, and bunch length



NSLS-II beam

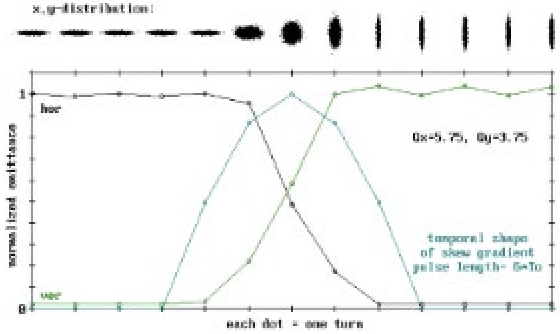


NSLS-IIU beam

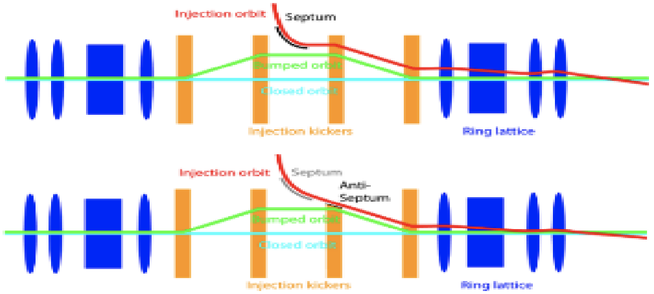
- Advanced optical diagnostics (visible light & X-rays)

Injection

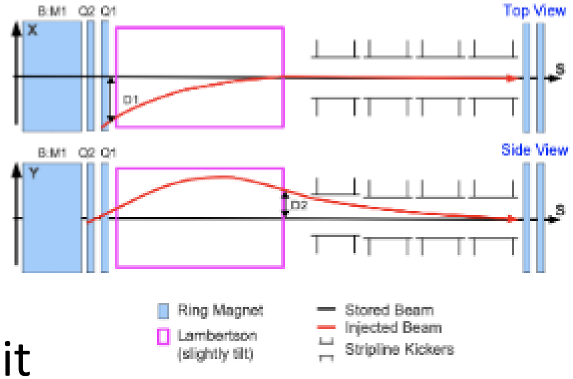
- Top-off injection: stringent requirements
  - Tolerance of $\Delta I/I \sim 0.2\%$
  - Frequency of injections <1 minute
- Off-axis injection:
  - relatively large dynamic aperture is required
  - transverse emittances exchange to improve efficiency (HZB)
  - antiseptum to bring the injected bunch closer to the stored beam (PSI)
- On-axis swap-out injection:
  - works with small DA (APS-U)
  - fast kicker magnets dump the stored bunch and put the injected bunch onto the equilibrium orbit
  - accumulation in a separate ring to perform swap-out injection of bunch trains (ALS-U)
  - Injection with deflecting cavity (PLS-II)



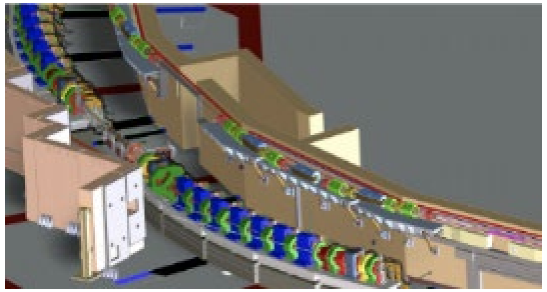
P. Kuske, F. Kramer, Proc. of IPAC2016, Busan, WEOAA01



C. Gough, M. Aiba, Proc. of IPAC2017, Copenhagen, MOPIK104



APS-U PDR, 2017, p. 111



S. DeSantis, 2nd RULe Topical Workshop on Injection, 2019

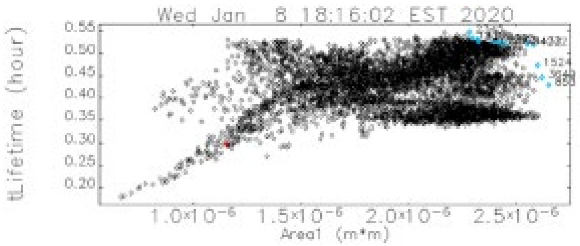
Tools for Analysis and Simulations

- Low-emittance lattice requires strong focusing resulting in highly nonlinear beam dynamics

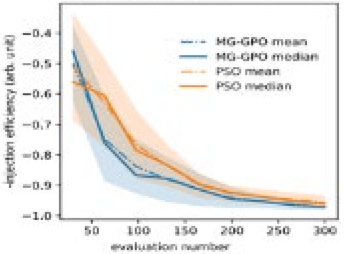
  Goal: design of a robust lattice with a large dynamic aperture and momentum aperture.

  Method: optimization of linear optics and nonlinear beam dynamics
  - Analytical approach (optimization of resonance driving terms)
  - Advanced techniques for characterization of nonlinear beam dynamics
  - Multi-objective genetic algorithms
  - Machine learning techniques
- Advanced simulations of collective effects (impedance + ions + IBS + HHC + feedback + …)
- Realistic simulation of storage ring commissioning with errors and automated commissioning procedure (APS-U, ALS-U)
- Trends in increasing computing power

MOGA (APS)

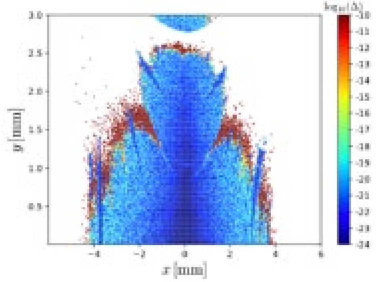


Injection efficiency optimization using ML algorithms

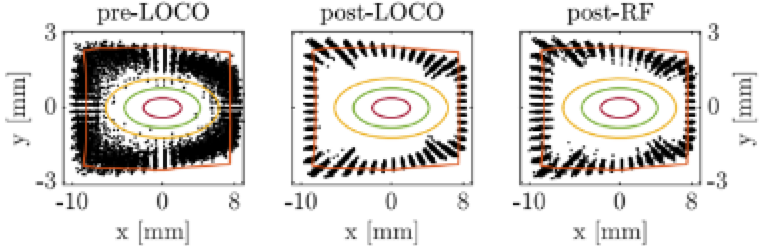


Z.Zhang et al., Mach. Learn.: Sci. Technol. 2 (2021) 015014

Chaos map (NSLS-II)



Simulation of machine commissioning (ALS-U)



T.Hellert et al., PRAB 22, 100702 (2019)

Summary

- The quest for the highest brightness is continuing
- Low-emittance synchrotrons with highly nonlinear beam dynamics result in challenges to achieving the required beam lifetime and injection efficiency
- High beam intensity for flux-limited beamlines requires a high average current of electron beams
- Horizons for future light source development
  - Reaching diffraction limit at photon energy of 10 keV and higher
  - Enabling new experimental capabilities of light sources
    - Short-pulse and timing modes of operation
    - Integration of FEL capabilities to the storage ring light sources
  - Modern light sources are major hubs for user science
    - Increasing beamline capacity to evolve the productivity of the facilities
  - High reliability and high stability
    - Ever-changing standards of electronics open new perspectives
    - Using recent advances in the area of AI and ML