Low Emittance Upgrade for Existing Mid-size Light Source

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Outlines

1. Introduction to Light Source.

2. 3rd Generation Light Source in Operation.

3. Low Emittance Upgrade for Existing Mid-size Light Source.
   - USR upgrade (Many facilities on study)
   - Practical upgrade (Three upgrade cases: SPEAR-3, PLS-II, ALS)

4. Summary.

Today Light Sources' Chart

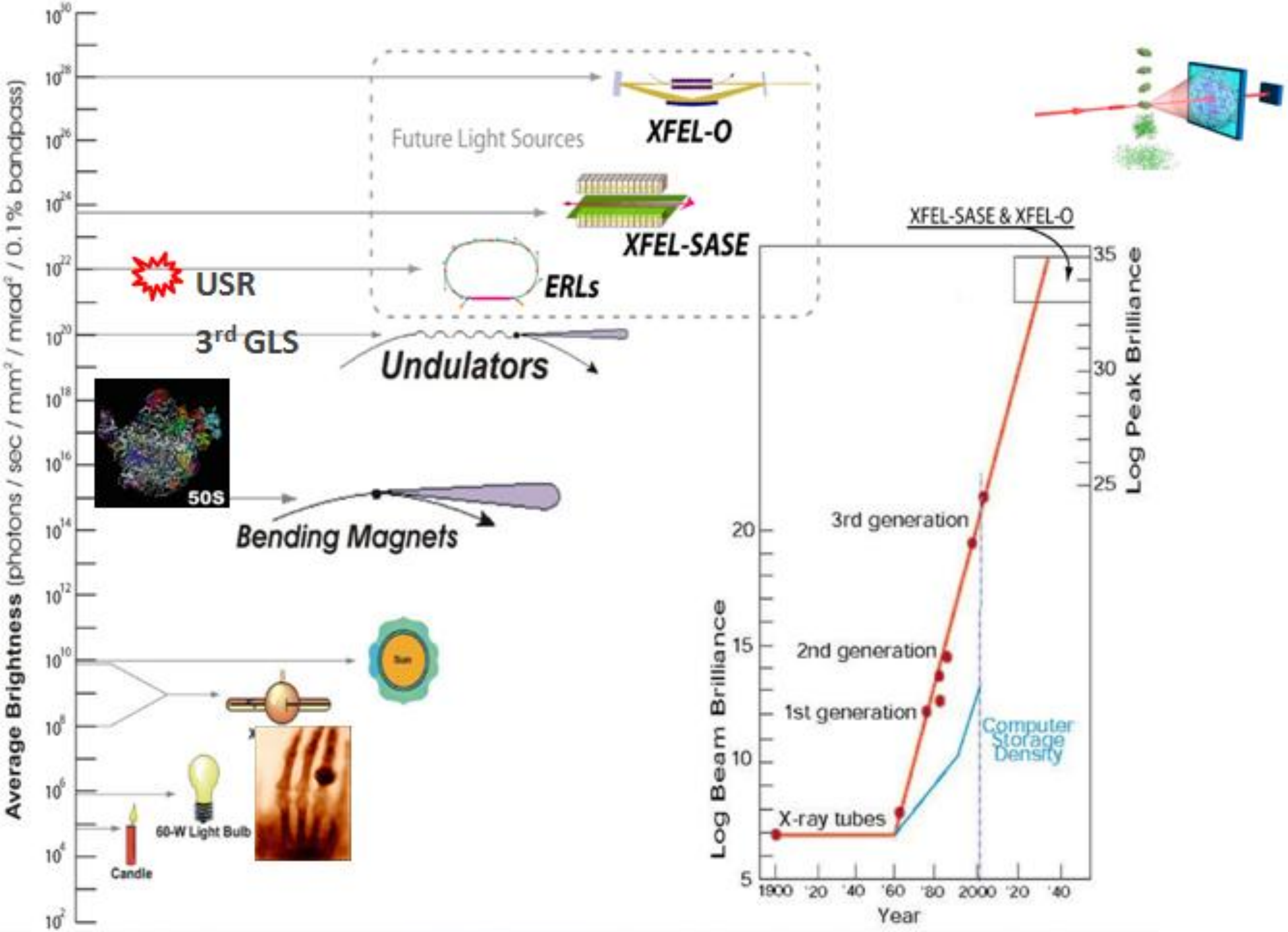
(Courtesy of L. Nadolski)

Nearly 80 facilities producing synchrotron light

Brief History

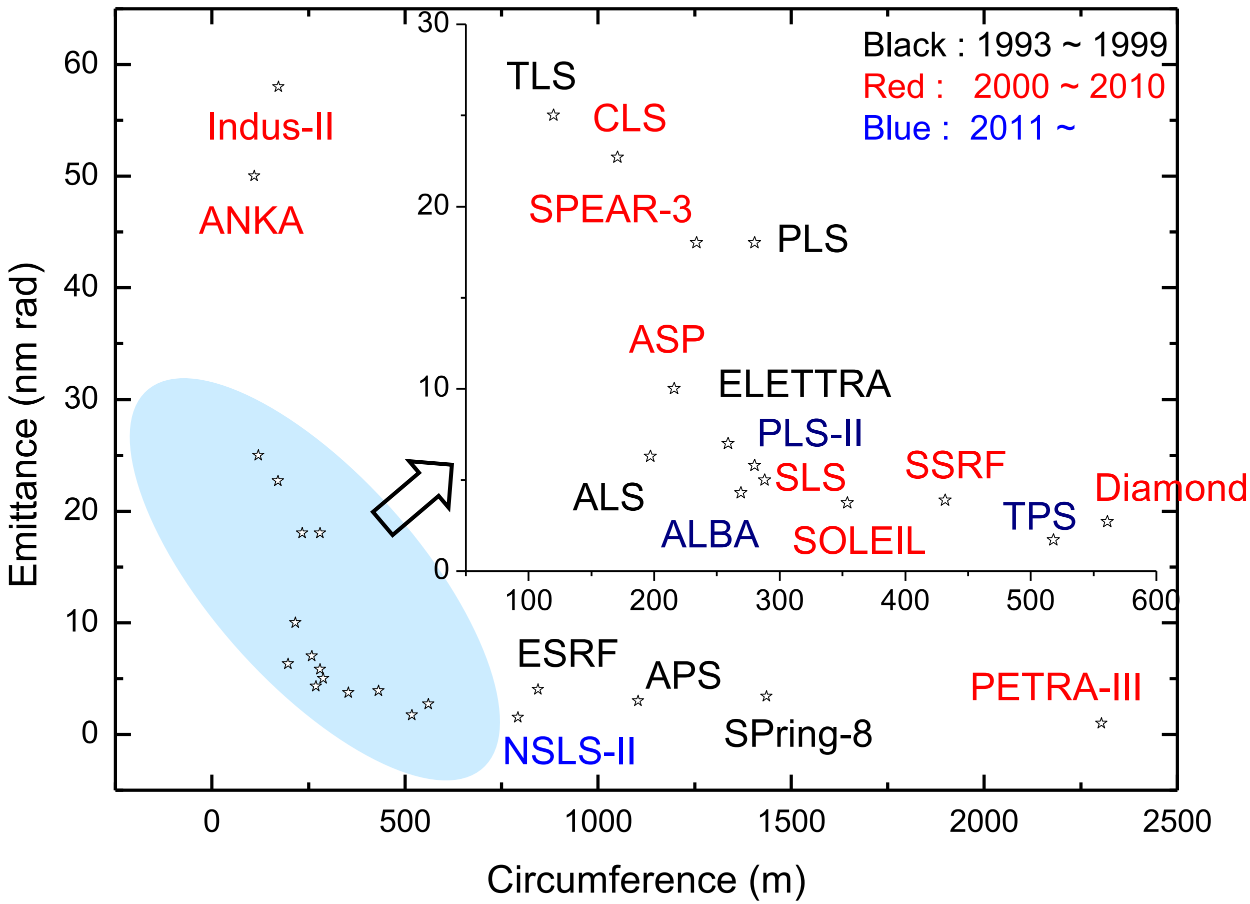
1. 1st Generation SR Source.
   - Parasitic operation: 1961, electron synchrotron UV source at NBS
   - 1974, SOR (1st ring designed for SR). SPEAR (1st x-ray beam line)
2. 2nd Generation SR Source.
   - dedicated for SR with dipole source.
   - PF, NSLS, BESSY, SPEAR-II, SUPER-ACO (1981 ~ 1990)
3. 3rd Generation SR Source.
   - High brightness & low emittance
   - ESRF (1st 3GLS in 1992), ALS, PLS (1996), APS, SPring-8, … PLS-II (2011)
   - Undulator source.
4. 4th Generation SR Source.
   - Higher brightness, higher coherence, shorter bunches.
   - LCLS, SCSS, Euro-XFEL, Swiss-XFEL, PAL-XFEL, …
5. Ultimate Storage Ring (Existing 3rd GLS, New LS)
   - Diffraction limited emittance, high average brightness, stable CW operation.
   - MBA and small horizontal aperture

The progression of bright x-ray sources



3rd Generation Light Sources in Operation

Most 3rd generation light sources are in the intermediate energy range and mid-size ring.
Execption
- ESRF, APS, SPring-8 in the early part
- PETRA-III: Converted source from a former high energy physics machine.
- NSLS-II: "Green field" project



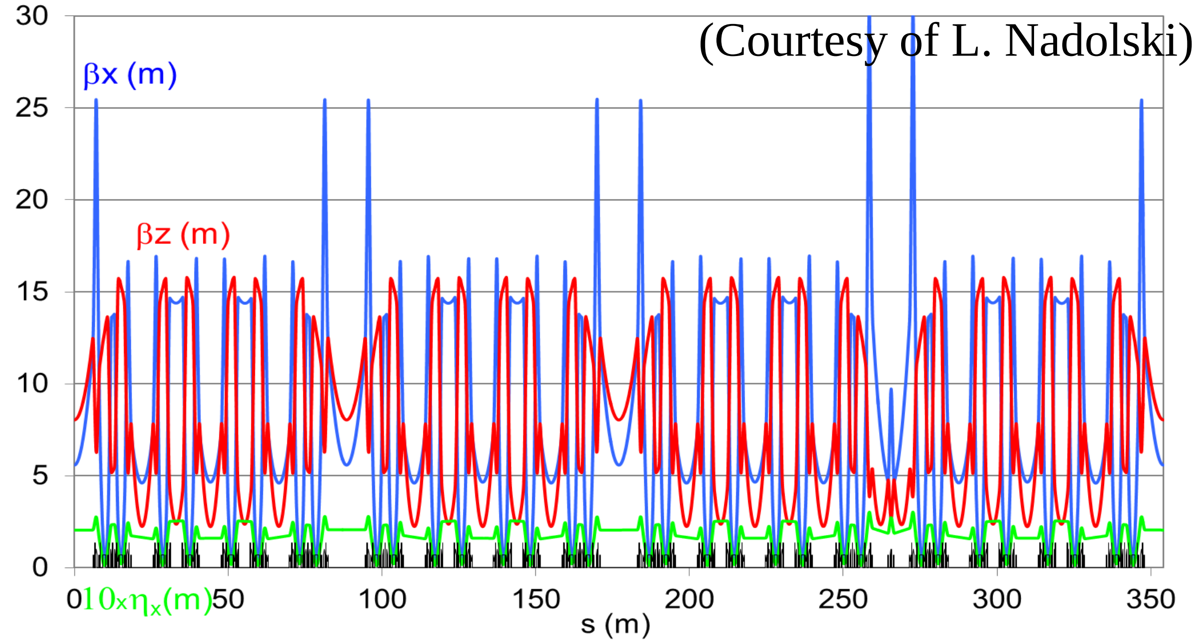
Technology and Experience on 3rd Generation Sources

1. Extended spectral range.
   - Around 3 GeV operation energy. (High flux, 6-12 keV)
   - Reduce undulator period. (In-vacuum undulator)
2. Stability.
   - Sophisticated feedback systems. (no longer submicron stability but 200 ~ 300 nm.
   - Top-up operation. (mandatory)
3. High availability (Target: 98~99% with 96% as low limit, MTBF: 50~100 h)
   - Reliable software and hardware.
4. Advanced diagnostics.
   - Bunch motion analysis from post-mortem.
   - Beam position monitor electronic
5. SC cavities.
6. Automated beam-based optimization.
7. Alignment precision.
8. Small vacuum pipe.
9. Magnet technology.
10. Modeling improvement.

Performance of 3rd Generation Light Source

SOLEIL SYNCHROTRON

Circumference = 354 m
24 straight sections
4 × 12 m
12 × 7 m
8 × 3.6 m
45 % of the circumference available for straight sections



Parameters	Design	Achieved as of Oct 2013
Energy (GeV)	2.75	2.739
Emittance H (nm•rad)	3.9	3.9
Coupling, $\varepsilon_V/\varepsilon_H$	<1%	0.7% (w/o corr.) 1% (w/ V dispersion)
Current Multibunch mode (mA)	500	500 (430 for Users operation)
Beam Lifetime (h)	16 h	14h @ 500 mA

5 Modes of Operation for the Users (All in Top-up injection)

5 feedbacks simultaneously in operation: TFB, SOFB, FOFB, BTUNE-FB, Coupling.-FB

PAUL SCHERRER INSTITUT PSI

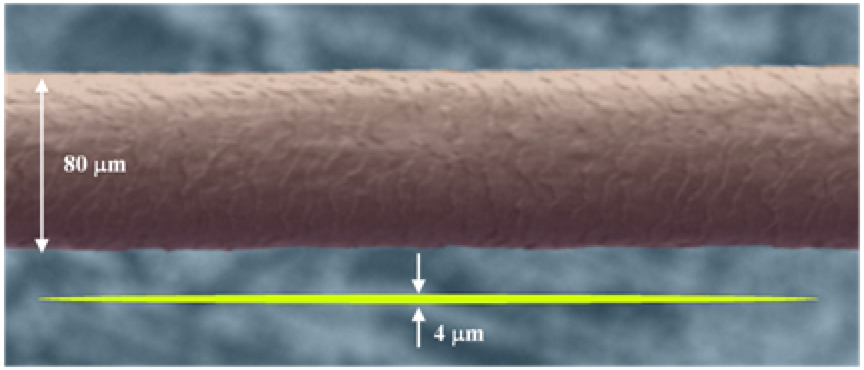
(Courtesy of A. Streun)

SLS world record for smallest vertical emittance

Coupling minimization at SLS

M. Aiba et al., *Ultra low vertical emittance at SLS through systematic and random optimization*, NIM A 694 (2012), 133-139

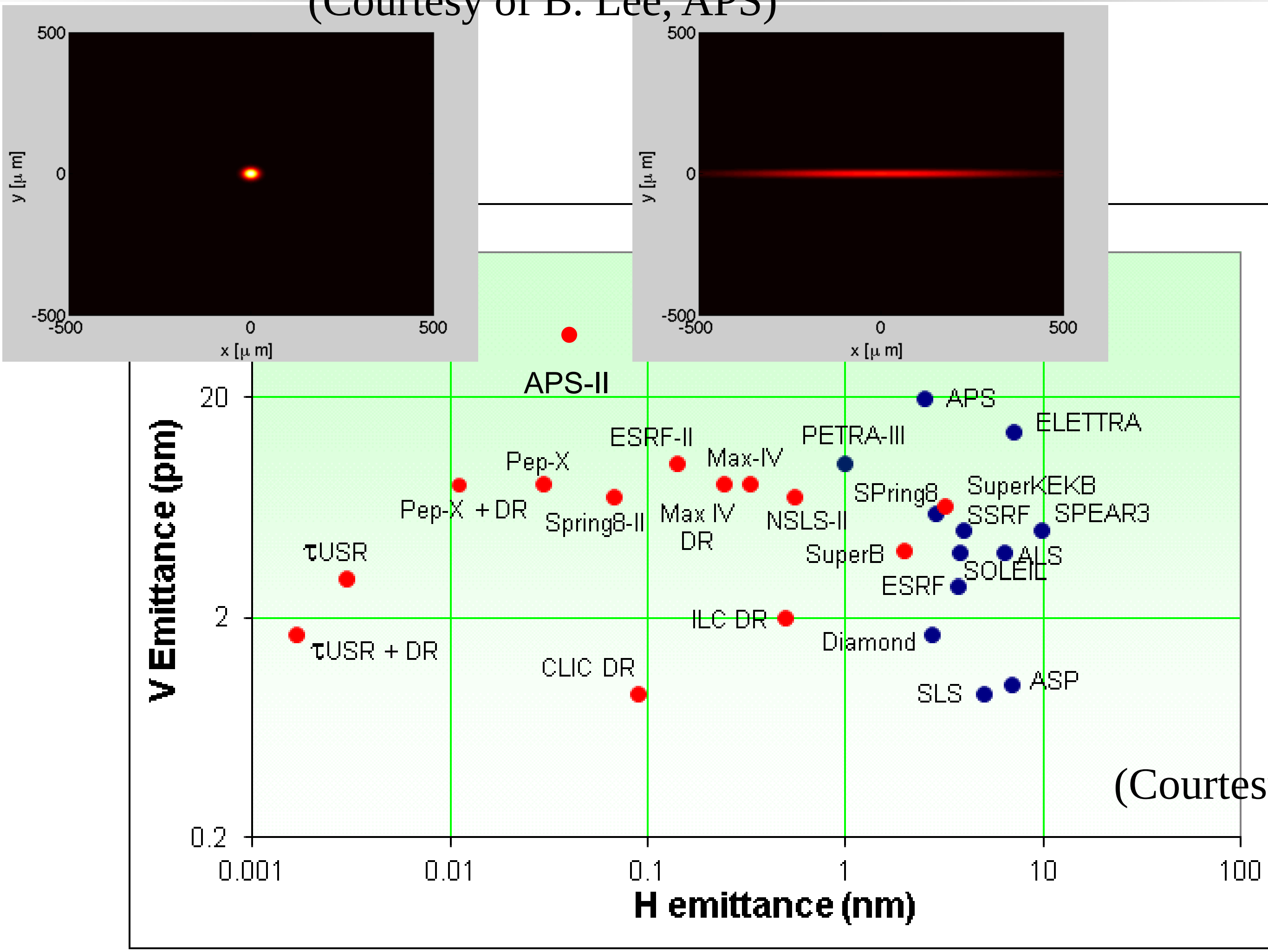
- observable: vertical beam size from monitor
- knobs: 24 skew quadrupoles
- random optimization: trial & error (small steps)
- Start: model based correction: $\varepsilon_y = 1.3$ pm
- 1 hour of random optimization $\varepsilon_y \rightarrow 0.9\pm0.4$ pm
- Measured coupled response matrix off-diagonal terms were reduced after optimization.



⇨ Model based correction limited by model deficiencies rather than measurement errors.

H emittance vs V emittance

(Courtesy of B. Lee, APS)



(Courtesy of R. Bartolini)

Transverse coherence requires small emittance

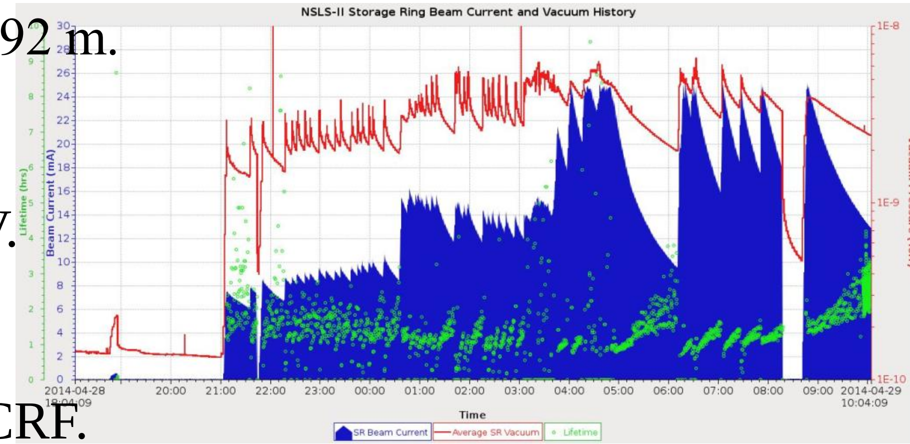
Diffraction limit at λ = 0.1 nm requires 8 pm emittance

$$\varepsilon \le \frac{\lambda}{4\pi}$$

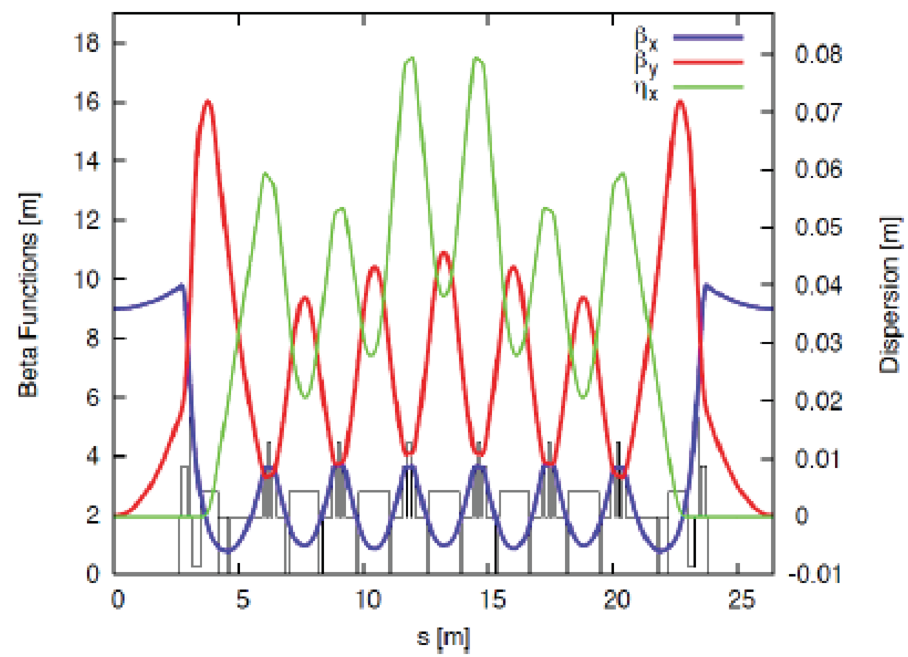
New 3rd Generation Light Source

1. NSLS-II
   - "Green field" project with ring size 792 m.
   - 30 Double Bend Cell.
   - Emittance in X with DWs < 1 nm.
     diff. limited emittance in Y at 10 keV.
   - Finished commissioning Phase-1
     25 mA Beam store (April 2014)
   - Start commissioning Phase-2 with SCRF.

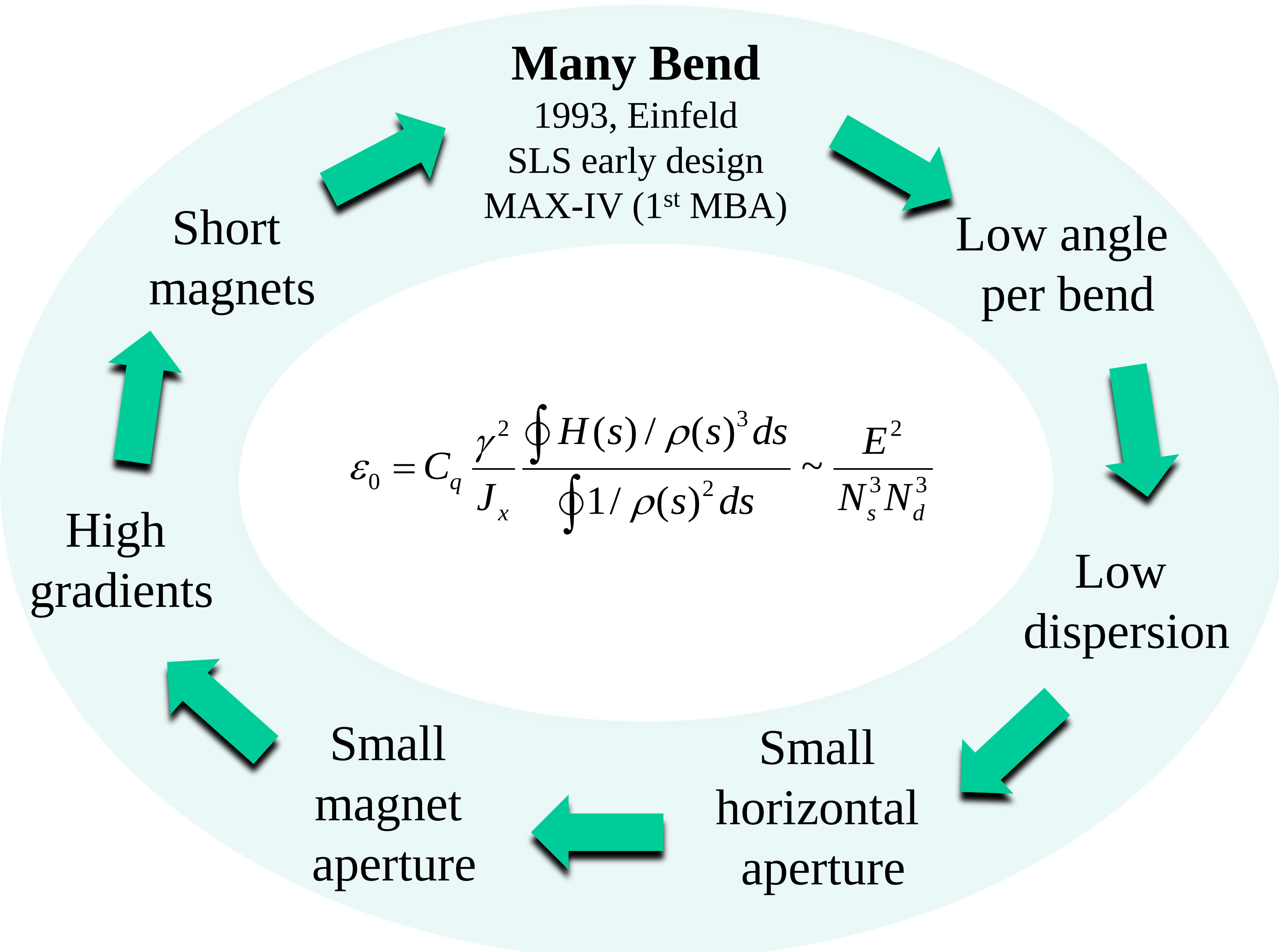
NSLS-II **Storage Ring** Beam Current and Vacuum History



2. MAX-IV
   - First 3 GLS using MBA.
   - 20 7BA (zero dispersion in SS) cell
   - 3 GeV, 528 m, 0.34 nm emittance
   - Small magnet bores
     NEG pumped round chamber in arcs.
   - Commissioning in early 2015

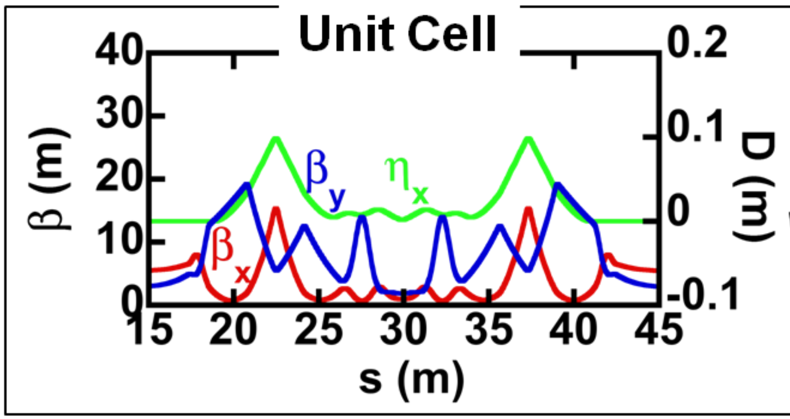


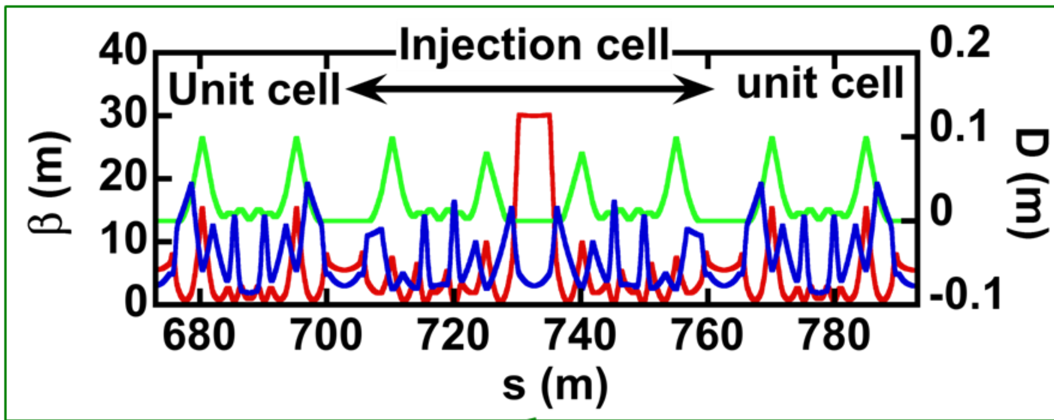
Ultimate Storage Ring: MBA

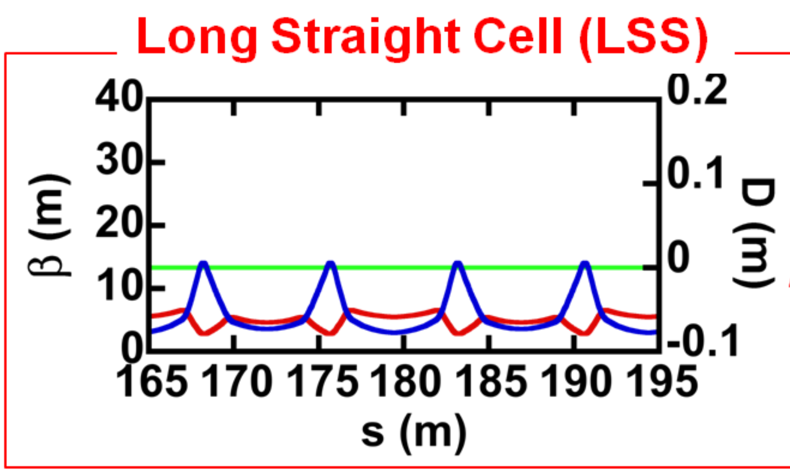


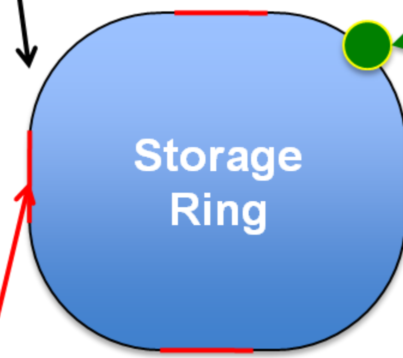
Ultimate Storage Ring: Large size ring

1. SPring-8 upgrade study (Courtesy of Y. Shimosaki)









Injection Point

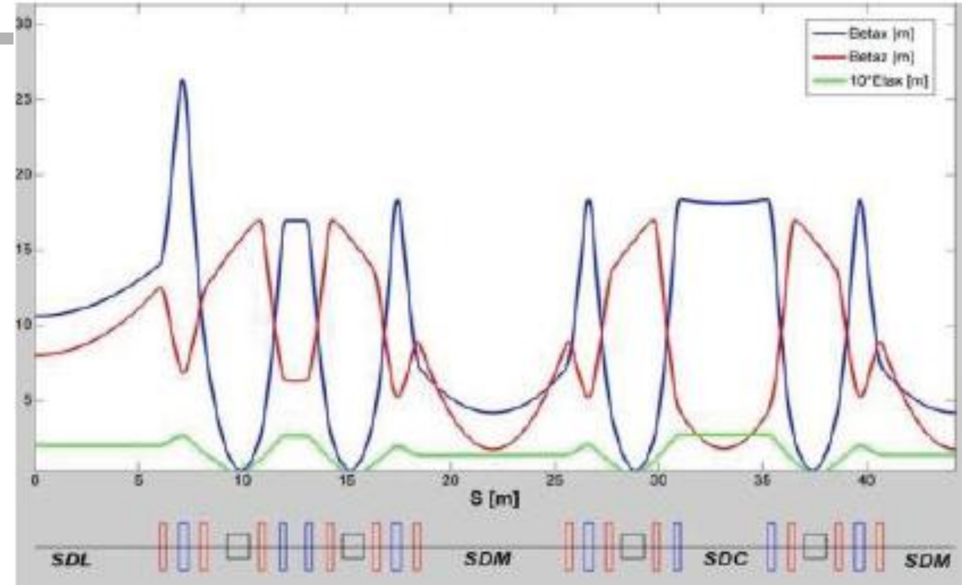
Double bend -> 5 Bend Achromat
2.4 nm -> 100 pm (w IDs)

Basic ring structure is ("Unit cell" x 11 + "LSS") x 4, but it is locally modifed at injection point.

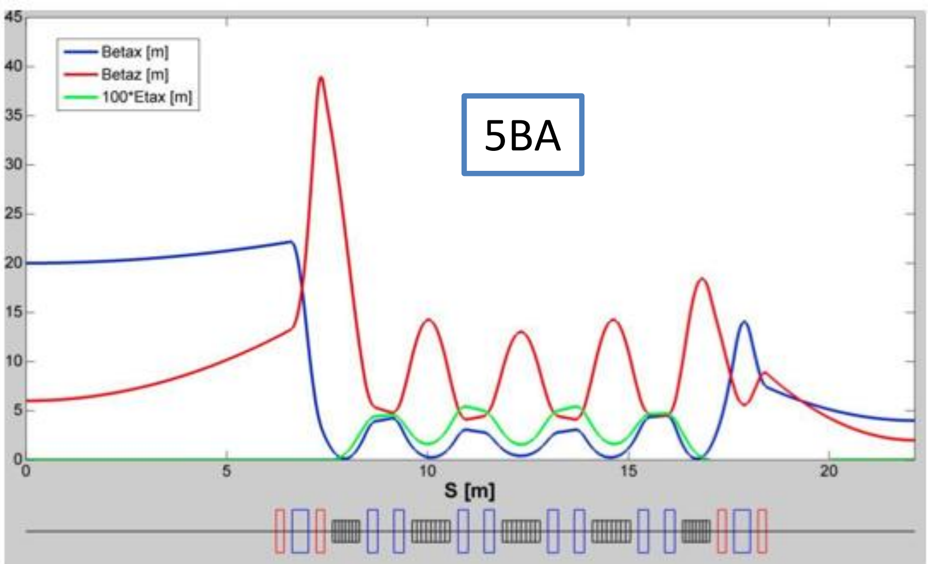
2. APS (~100 pm), ESRF (~150 pm)

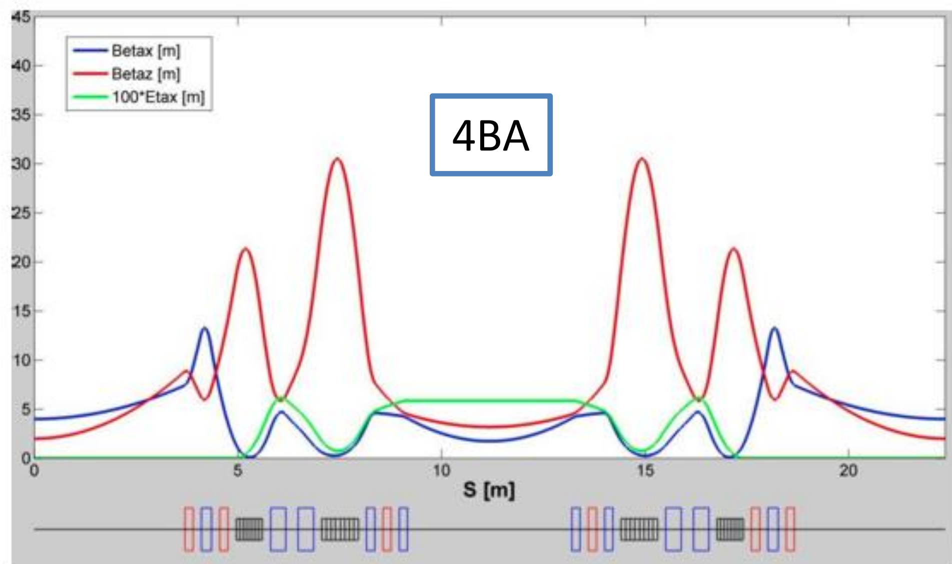
Ultimate Storage Ring: Mid-size ring

1. SOLEIL upgrade study
   1) Keep BL and SS.
   2) 520 pm emittance @ 2.75 GeV
   3) Maximum gradient 50 T/m.
   4) Reasonable chromaticities.
   5) Combined function dipole.



R. Nagaoka et al. Study Of Lower Emittance Optics Using Multi-Bend Achromat Lattice At SOLEIL. In Pro- ceedings of the fourth International Particle Accelerator Conference, pages 76–78, Shanghai, China, May 2013.





Lattice and envelop functions for the SDL-SDM (left) and SDM-SDC-SDM cells (right), altogether representing 1/8th of the ring

Ultimate Storage Ring: Mid-size ring

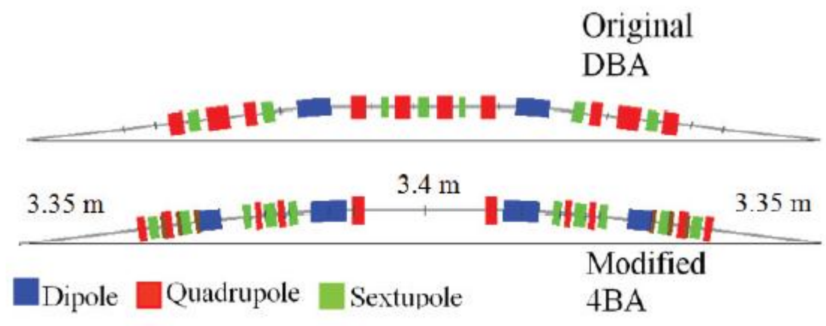
2. DIAMOND upgrade study

   1) 2750 -> 280 pm emittance @ 3 GeV

   2) Modified 4BA.

   3) Doubling capacity.

   4) Feasibility studies for the current ring
      - replacing the existing cell2 with a Modified 4BA.
      - serves as a prototype for low emittance lattice upgrade.



3. ALS upgrade study

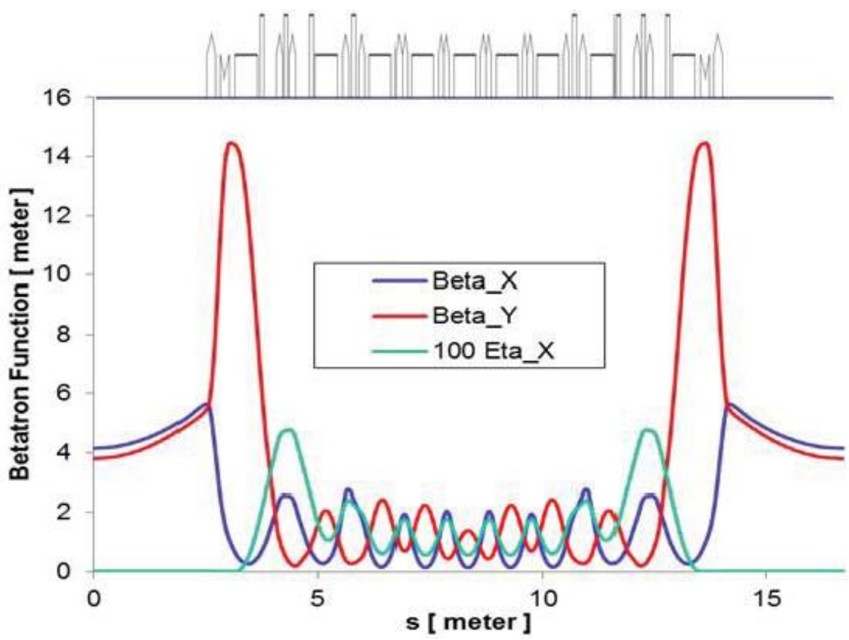
   1) MBA (Similar to MAX-IV concept)

   2) 50 pm at 2 GeV in 200 m ring.

   3) Emittance with IBS < 70 pm at 400 mA

   4) Keeping the existing straight.

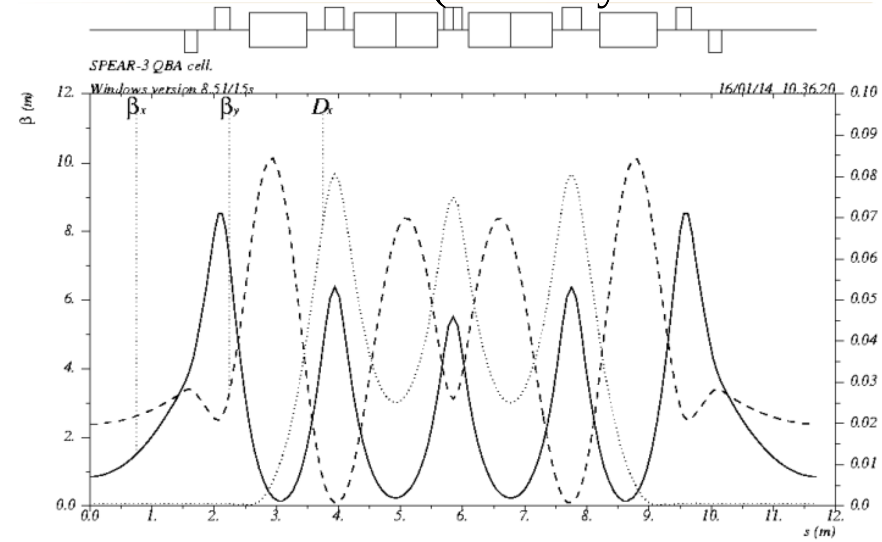
   5) High magnet strength
      - 80 T/m for quadrupole
      - 3000 T/m^2 for sextupole



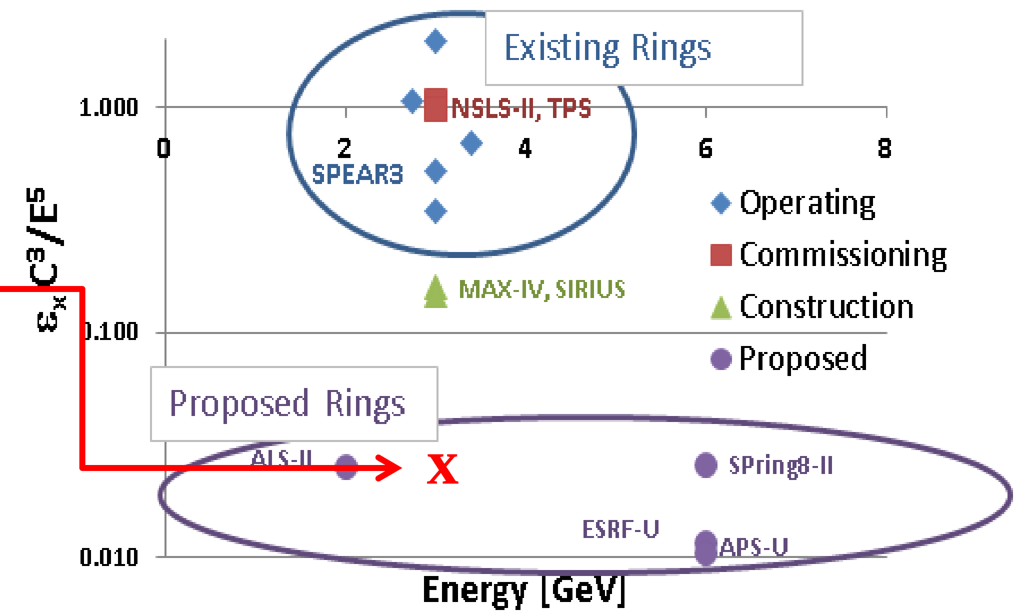
Ultimate Storage Ring: Mid-size ring

(Courtesy of J. Safranek)

4. SLS upgrade study
   1) Keep all beam lines.
   2) re-use girder, injector system
   3) 100 ~ 150 pm @ 2.4 GeV in 288 m.
   4) Longitudinal gradient super bend
   5) On study for 1st budget in 2017.



5. SPEAR-3 upgrade study
   1) 234 m size for 3 GeV.
   2) 11.5 m celll is short.
   3) 0.7 nm emittance
   4) Low scaling emittance.
      - $\varepsilon_x \sim E^2/N_{dip}^3$
      - $N_{dip} \sim C/E$ (B-field limit)
      - $\varepsilon_x \sim E^5/C^3$



Ultimate Storage Ring: Issues

1. Lower Emittance: Damping wiggler, Magnet type
2. Dynamic aperture

   1) Strong sextupole.

   2) Beam injection
      - Multipole injection (but still off-axis injection)
      - On-axis injection
3. Round beam

   1) Diffraction limit in H and V plane.

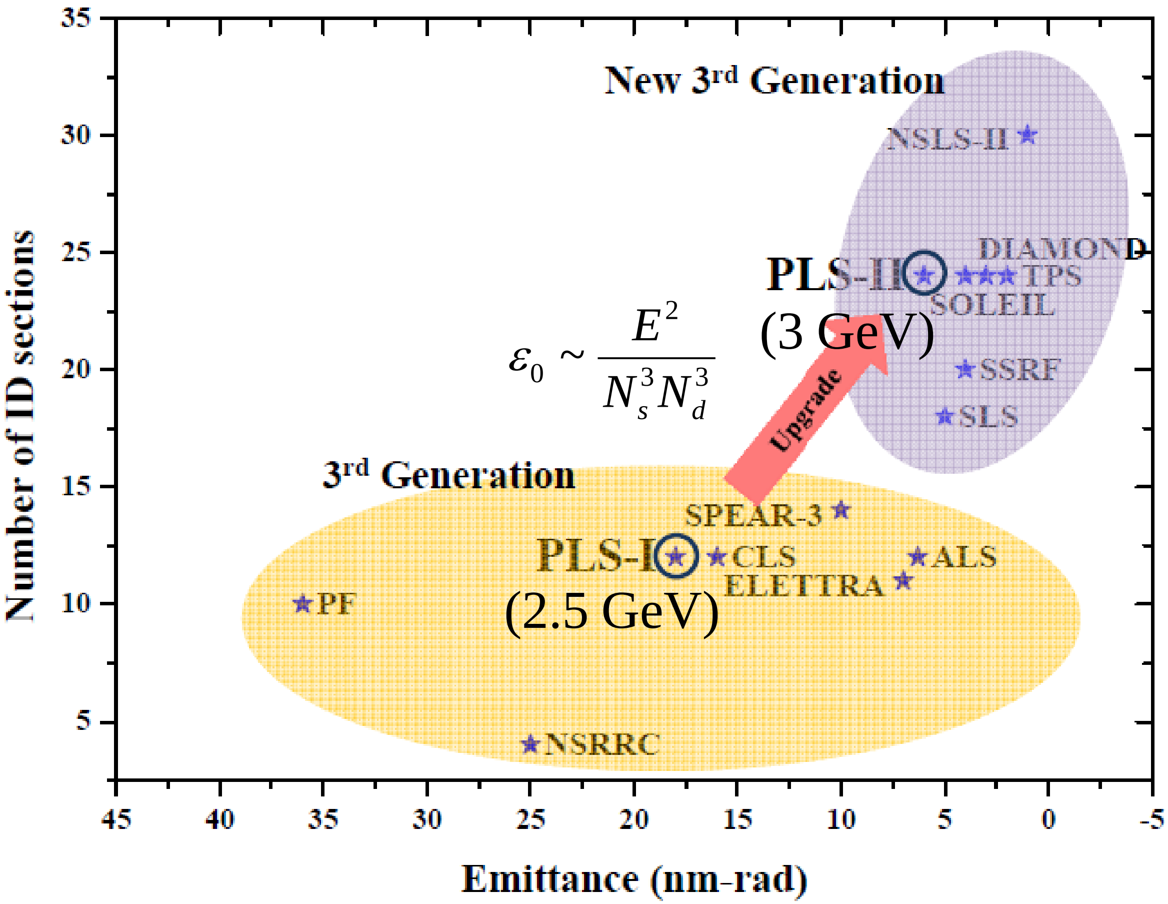
   2) Simplication of the optics in beam line.
4. Beam current: IBS, Harmonic cavity
5. High strength magnet

   1) Quadrupole: MAX IV (40 T/m), USR study (~ 100 T/m)

   2) Sextupole: MAX IV (4000 T/m^2), USR study (~ 13000 T/m^2)
6. Constraint existing ring and BLs.
7. Schedule and budget.

Low Emittance Upgrade for Existing Mid-size Ring

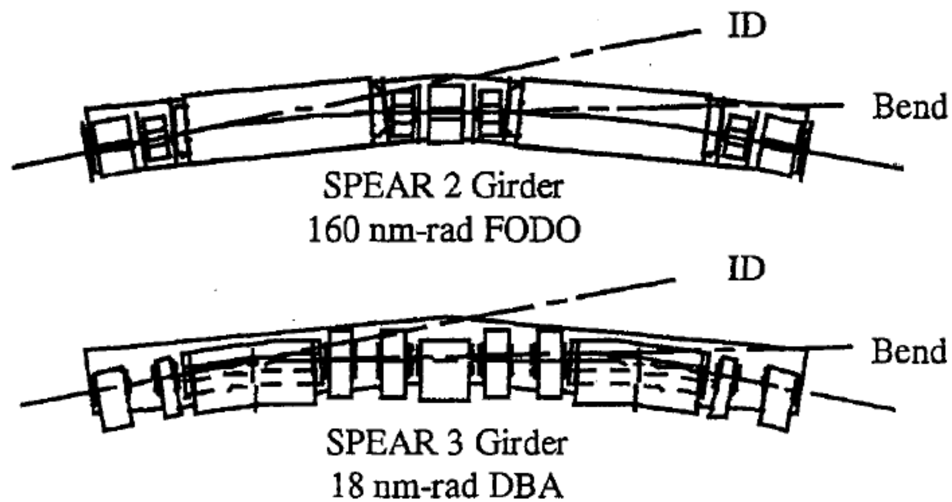
1. SOLEIL, DIAMOND, SLS, ALS etc. on study for USR
2. Many 3rd GLS facilities have potential capacity to be upgraded.
3. SPEAR-3 (2004) / PLS-II (2011) / ALS (2013, partial replacement)



SPEAR-2 Upgrade (SPEAR-3)

1. Major Parameter

	SPEAR 2	SPEAR 3
Energy	3 GeV	3 GeV
Current	100 mA	500 mA
Emittance (w/ID)	160 nm-rad	18 nm-rad
RF frequency	358.5 MHz	476.3 MHz
RF gap voltage	1.6 MV	3.2 MV
Lifetime @ Imax	30 h	>17h
Critical energy	4.8 keV	7.6 keV
Tunes (x,y,s)	7.18,5.28,.019	14.19,5.23,.007
e- σ (x,y,s) - ID	2.0,.05,23 mm	0.43,0.3,4.9 mm
e- σ (x,y,s)-dipole	.79,.20,23 mm	.16,.05,4.9 mm
Injection energy	2.3 GeV	3 GeV

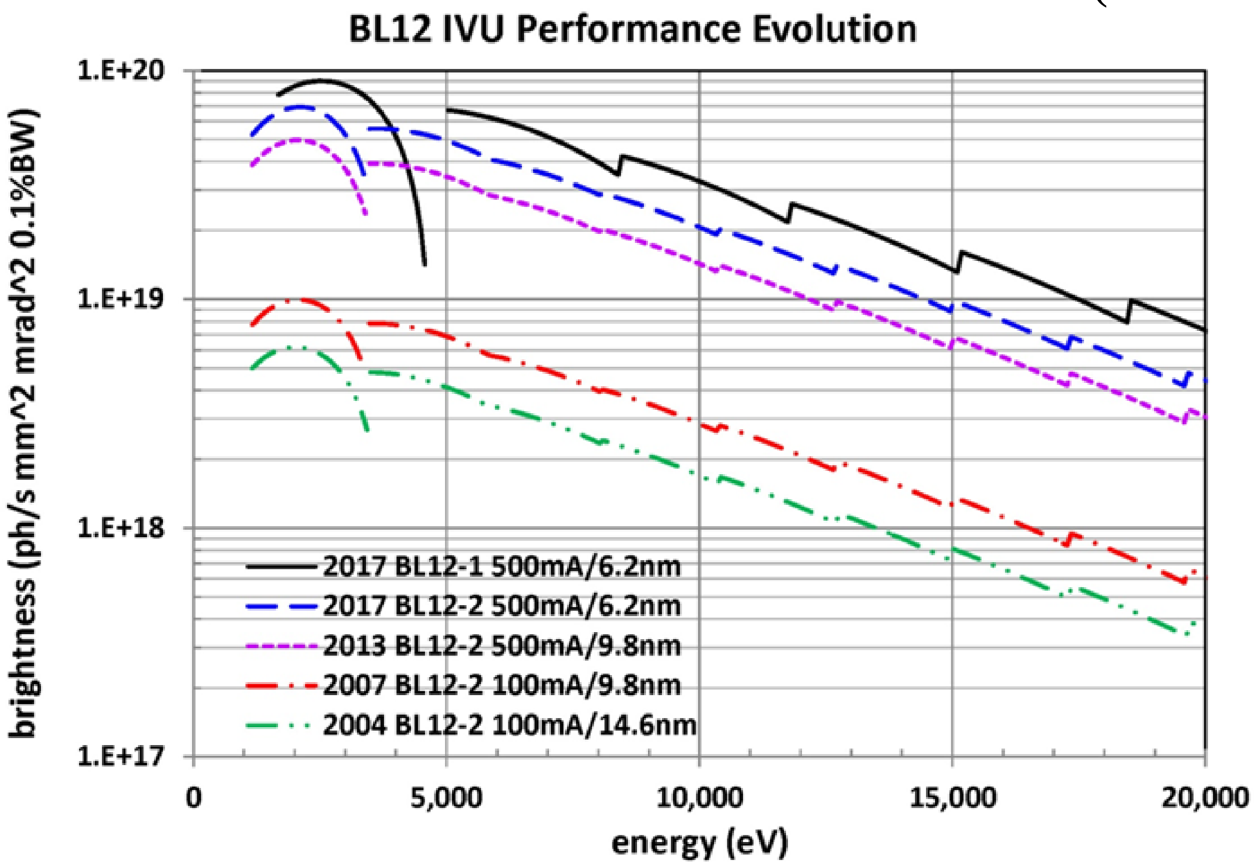


2. 1st Existing ring Upgrade (replacement from 2nd GLS to 3rd GLS)
3. 4 bending BLs and 7 ID BLs
4. Emittance (~9 fold reduction)
5. 7 month dismantling and installation and 5 month commissioning.
6. Completion on schedule.
7. Budget: 58 M$

Increasing SPEAR-3 Brightness

1. Brightness improvement: ~18 × total

(Courtesy of J. Safranek)



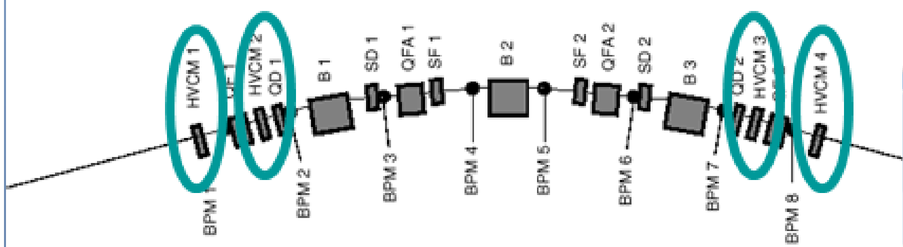
2. Requirement for 6 nm ε_x : Must capture the injected beam.
   - Improve dynamic aperture: Sextupole PS from 4 to 10.
   - Septum wall reduction and improvement of injected beam control.

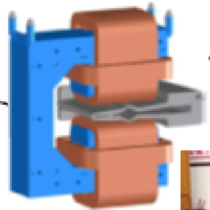
Emittance Reduction @ ALS

(Courtesy of H. Tarawneh)

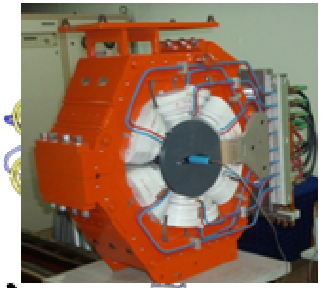
ALS

Project History



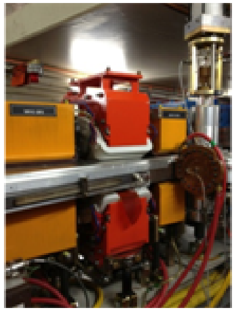


Existing Correctors



Sextupole / Corrector Multimagnets

- Received funding (summer 09)
- Comprehensive project review (12/09)
- Awarded magnet contract (9/10)
- Detailed magnet design review (3/11)
- Prototypes of 3 magnet types complete (12/11)
- First set of 13 production magnets shipped (4/12)
- All magnets received (8/12)
- Pre-Installed 13 of 48 sextupoles (1/13)
- Remaining magnets and power supplies installed (3/13)
- User operation in high brightness mode (2.0 nm emittance) – since (4/13)

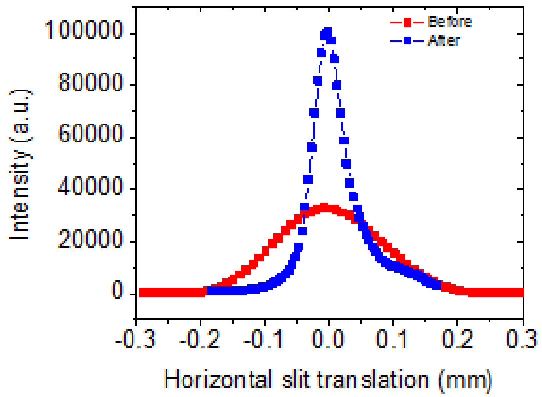


Advanced Light Source H. Tarawneh, C. Steier, A. Madur, D. Robin. L.E. Workshop, July 9, 2013 25 U.S. DEPARTMENT OF ENERGY Office of Science

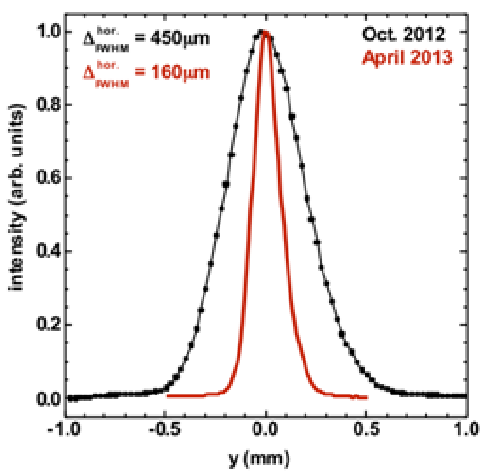
(Courtesy of H. Tarawneh)

ALS

Commissioning Results



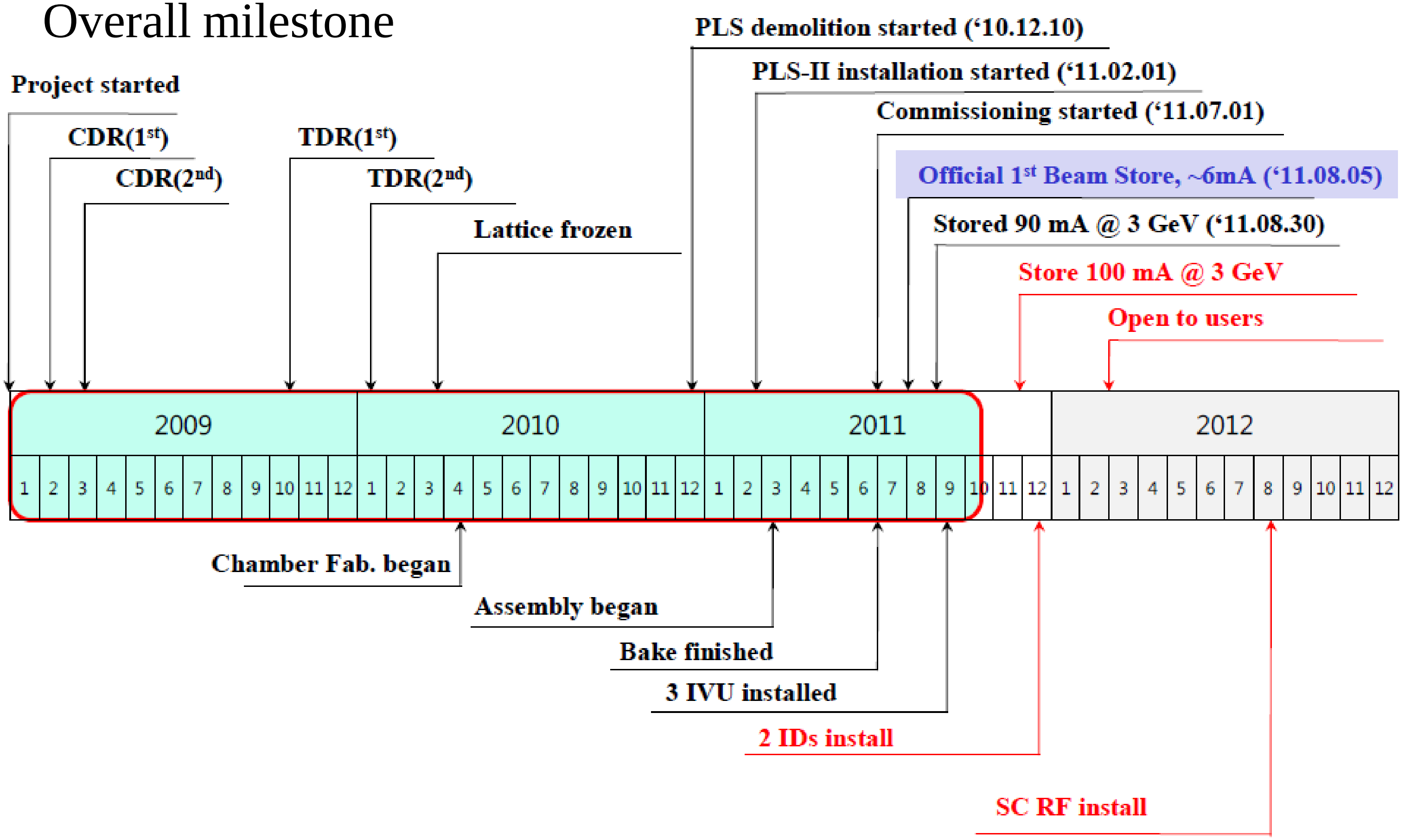
Measured horizontal photon beam profiles showing the reduction in size and increase in brightness. Above: BL 12.3.2, Below: BL 6.3.1



- Installation completed on time (Mar/Apr 2013)
- Quick Commissioning Progress
  - Benefit of pre-installation and commissioning: orbit feedbacks, detuned upgrade lattice
- Managed to deliver low emittance beam during BLC shifts – and continue into user operations
  - 3 months ahead of schedule
- Beamlines able to resolve brightness increase
- Reliable operation (no faults due to new lattice or hardware so far)

PLS Upgrade (PLS-II) : Project overview

1. Period : 3 year (One year break in user service)
2. Budget : 100 M $
3. Critical path : All PLS beam lines (30) should be operated in PLS-II after one year shutdown.
4. Overall milestone



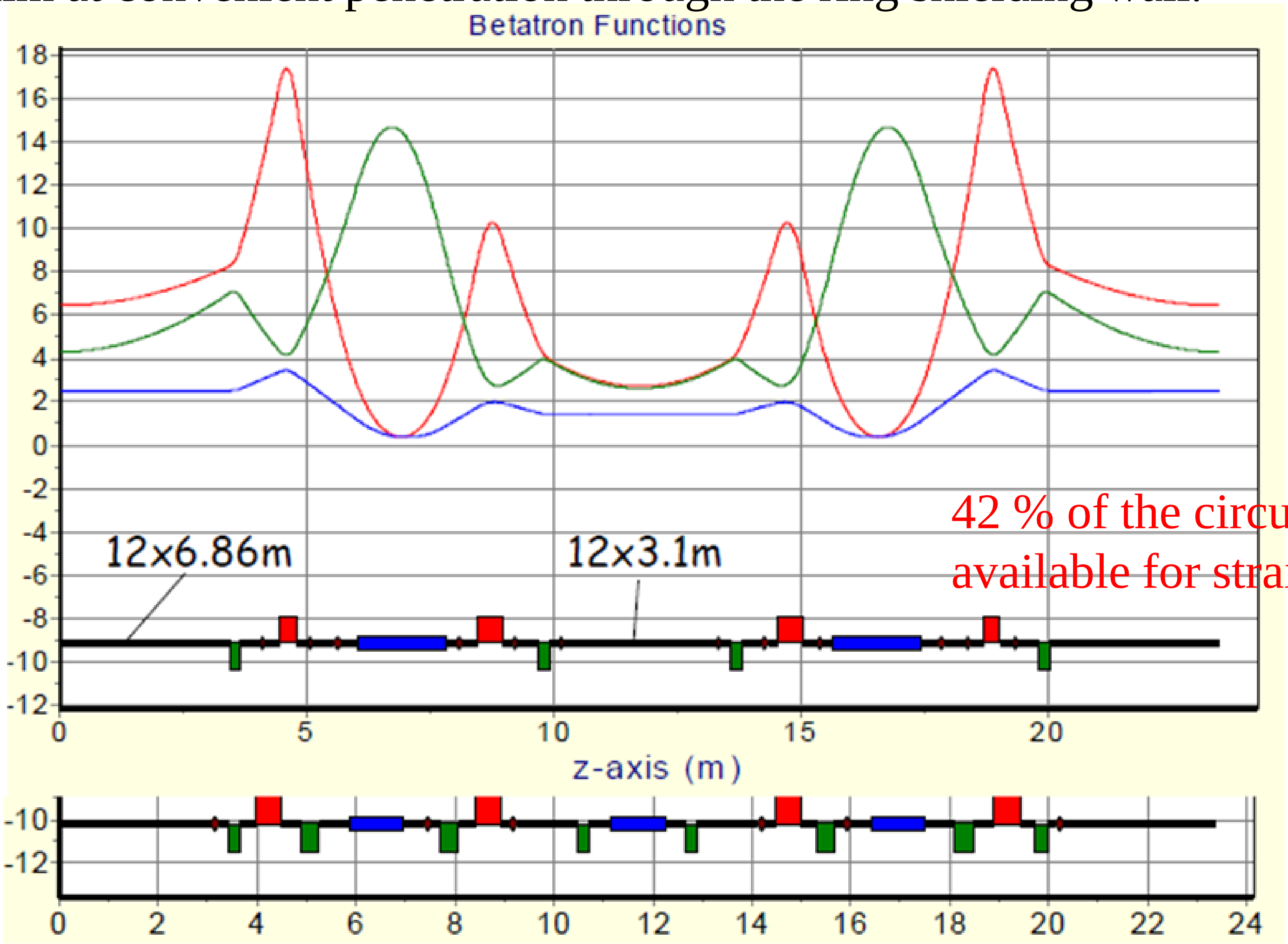
PLS Upgrade (PLS-II) : Major Parameter

Parameter	PLS	PLS-II
Beam Energy (GeV)	2.5	3.0
Beam emittance (nm)	18	5.8
Beam Current (mA)	200	400
IDs	10	20
Tune (H/V)	14.28 / 8.18	15.24 / 9.17
Natural Chromaticity (H/ V)	-23.36 / -18.19	-32.95 / -14.88
Harmonic Number	468	470
Circumference	280	281
RF voltage (MV)	NC/2.0	SC (3)/3.3
Lattice	TBA	DBA
Operation	Decay	Top-Up
Brightness	$\sim 2 \times 10^{18}$	$\sim 10^{20}$

PLS Upgrade (PLS-II) : Lattice Design

Design Challenges

- biggest challenge is the doubling of ID SSs.
- ring shielding wall cannot be changed / moved (all possible beam lines should aim at convenient penetration through the ring shielding wall.



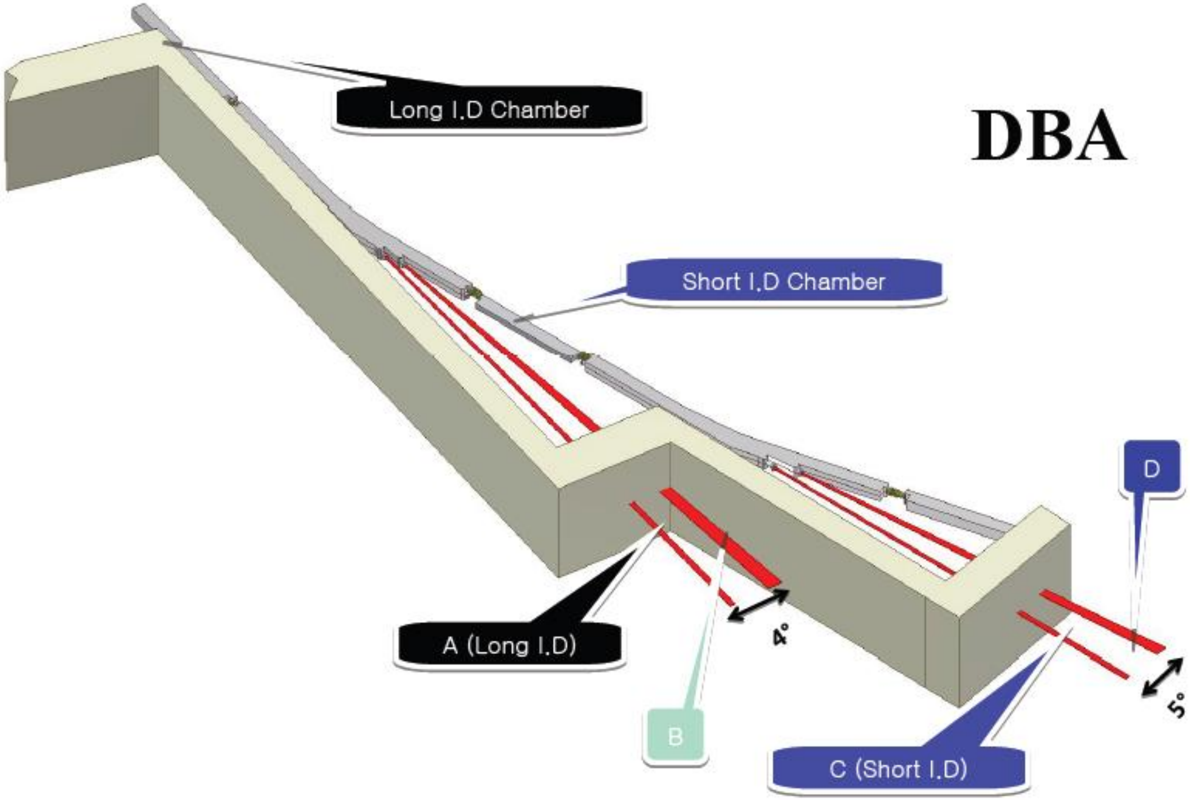
42 % of the circumference available for straight sections

PLS-II

⇧

PLS

1. Adjustment of Ring Geometry
   - to accommodate easy transit to experimental hall through existing shielding wall.
   - need to expand avg. ring radius by 0.20 m.
   - rotate ring against beam direction by 1.5 degree.
   - causing the need for small adjustments in injection line.

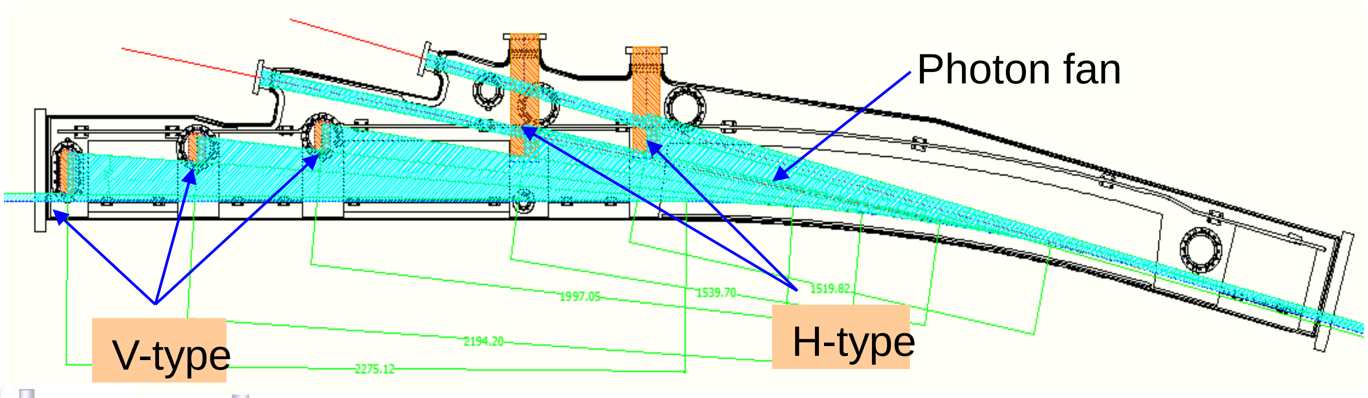


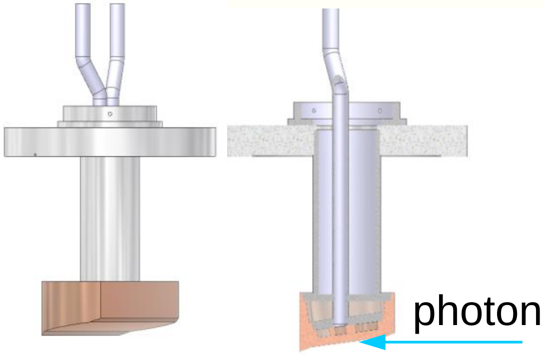
2. Vacuum

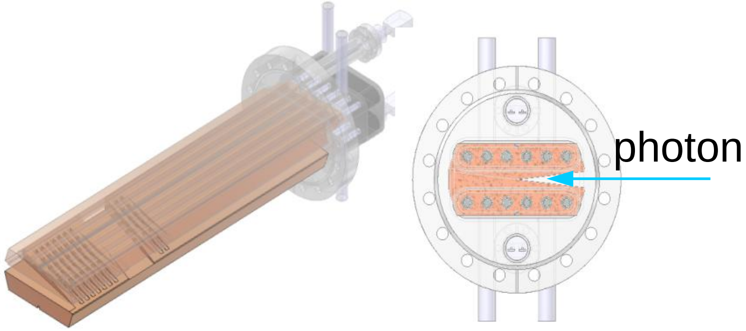
- Total synchrotorn radiation power is increased from 110 kW to 417 kW.

$$P[kW] = 88.463 \cdot \frac{E[GeV]^4}{\rho[m]} \cdot I[A]$$

- To accommodate such high heat flux in the limited space, complicated design of several different types for the photon absorbers is unavoidable .

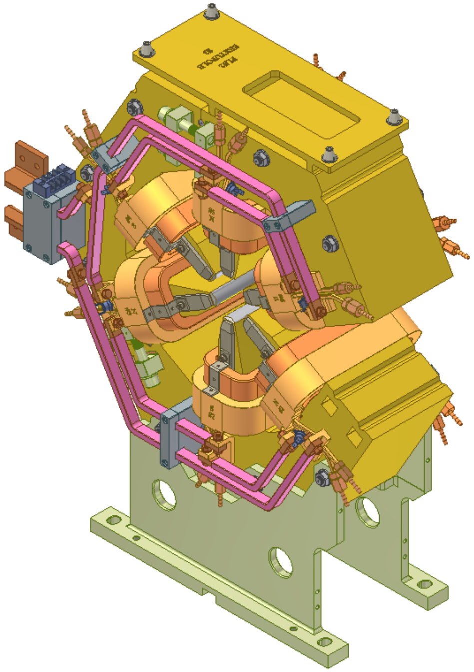






PLS Upgrade (PLS-II) : Technical Issues

3. Radiation Shielding.
   - No change of storage ring tunnel from PLS to PLS-II.
   - Additional 10 cm local Lead block (beam height)
4. Magnet. (Reuse quadrupoles and sextupoles)

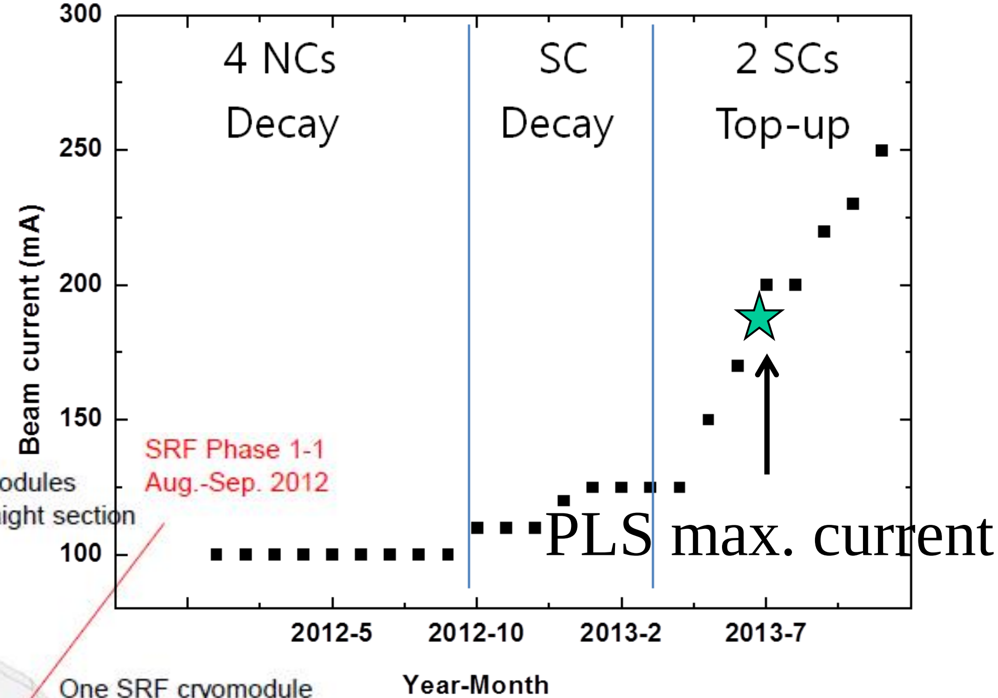


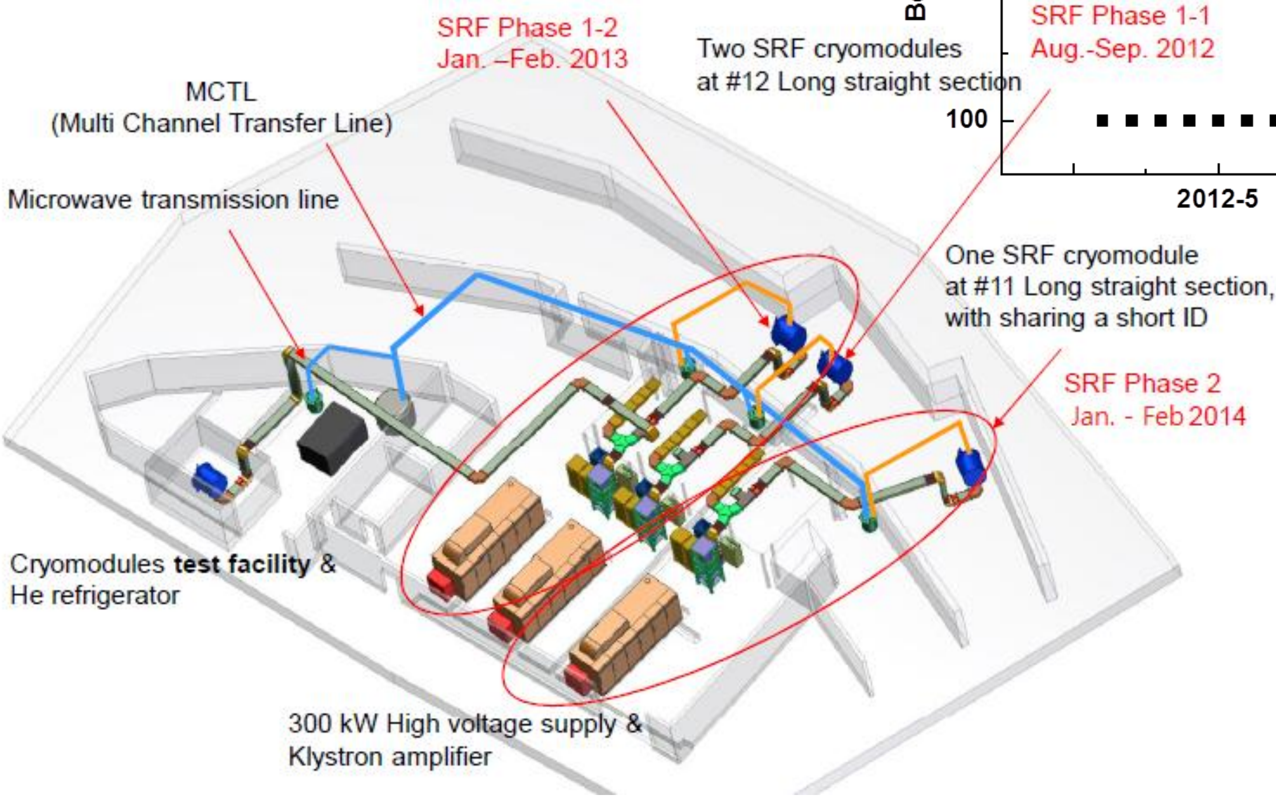
	PLS	PLS-II
# of bending magnets	36	24
length each (m)	1.10	1.80
field (T)/gradient(T/m)	1.2/0.0	1.455/-0.4
crit Photon Energy (keV)	5.52	8.73
# of quadrupoles	144	96
length (m)	0.25/0.35/0.54	use PLS magnets
# of sextupoles	72	96
families	2	4

sextupole magnets include H/V correctors and skew quadrupole fields

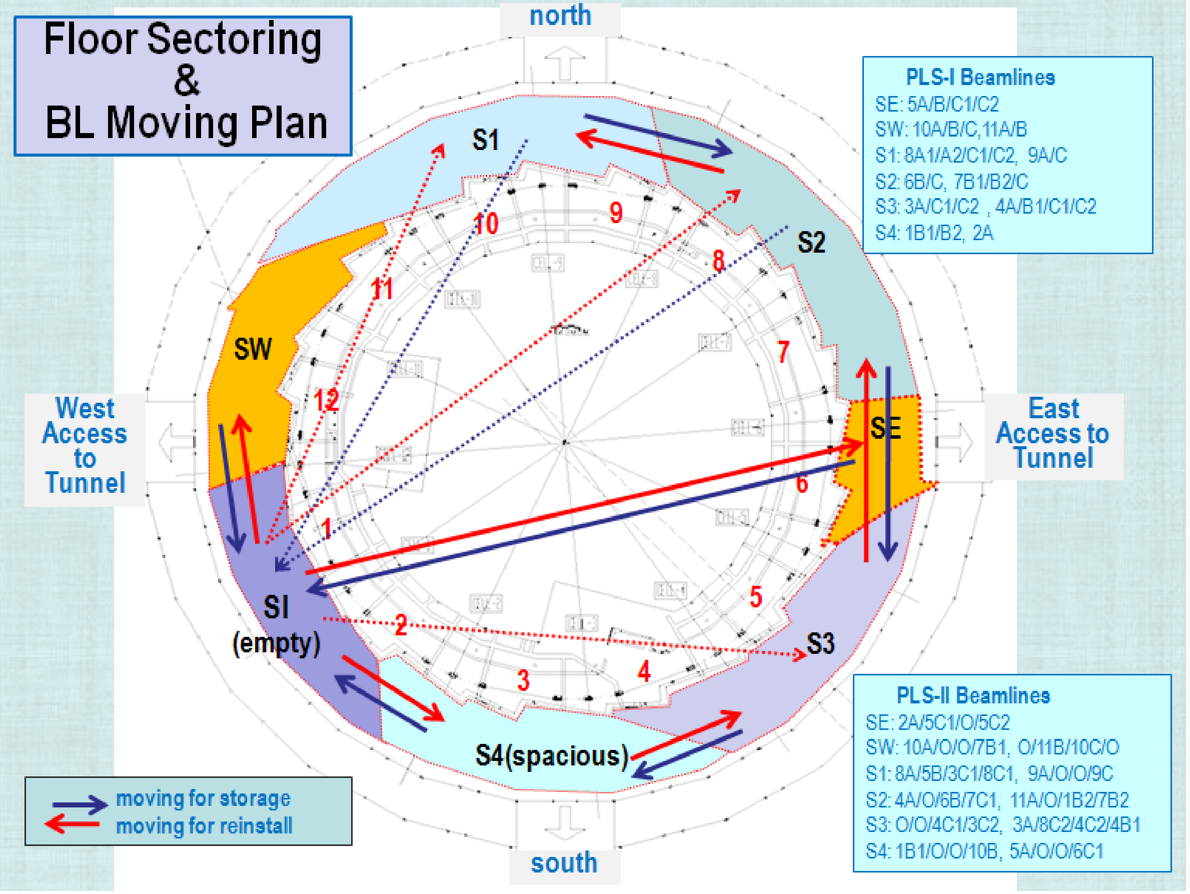
PLS Upgrade (PLS-II) : Technical Issues

5. RF system.
   - 3 SC system
   - Phased installation.



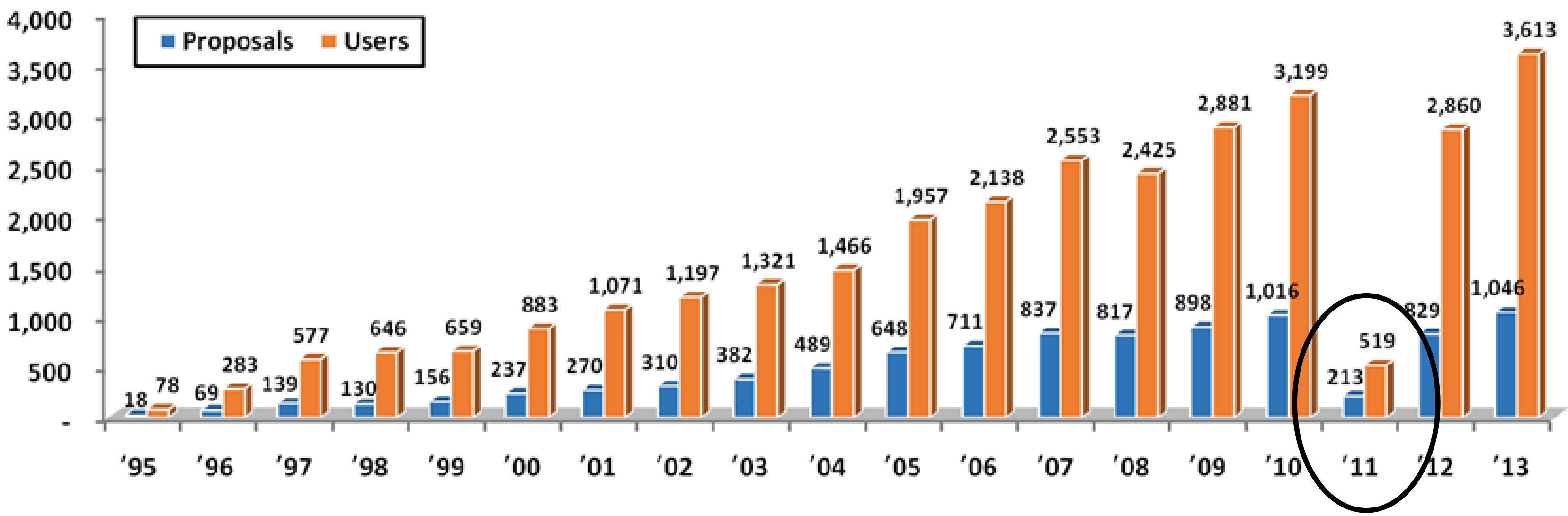


1. DCM development
2. Beam line allocation.
   - BM BL-> ID BL : 6 BLs (SAXS, Nanoscopy, etc.)
   - New ID BL : 6 BLs
2. Beam line dismantling and installation. (Total 30 BLs)



PLS Upgrade (PLS-II) : User support

1. User Statistics.



One year shutdown

2. Block Beamtime Program in foreign facilities.
   - Budget U$ 100,000.
   - In total of 213 experiments.
   - PF, RIKEN, SSRF, NSRL.

Summary

1. There is no argument that 3rd generation light sources have been operated and developed successfully for 20 years.
2. Most technologies related with 3rd generation light sources are matured.
   - for instance, no revolution is needed but steady improvement on what already achieved for beam stability and feedback system)
3. Now it's time to push horizontal emittance of existing ring to ultimate regime (diffraction limited ring).
4. Some cases of low emittance upgrade for existing mid-size ring imply
   - Short break in user service. (On schedule operation)
   - Performance increase.
     (Not only emittance reduction but also energy, IDs, stability, current, etc.)
   - Relatively low budget. (Same building and utility)

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