Undulators and bending magnet sources at the ALS-U

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Contents

Acknowledgments and references

- The material is presented on behalf of the groups working with ALS and ALS-U at Lawrence Berkeley National Laboratory.
- Material has been copied from the ALS-U CDR with contributions from, for example, A. MacDowell, S. Morton, H. Padmore, D. Robin, F. Sannibale, C. Steier, C. Sun, C. Swenson, M. Venturin, S. Leemann, and W. Waldron.

- The software Radia has been used for magnet models of insertion devices [O. Chubar, P. Elleaume and J. Chavanne, "A 3d magnetostatics computer code for insertion devices," Journal of Synchrotron Radiation, 5:481-484, 1998.].
- The software Spectra has been used for calculation of synchrotron radiation [T. Tanaka and H. Kitamura, Journal of Synchrotron Radiation 8, 1221 (2001).].
- The software SRW has been used for calculation of synchrotron radiation [O. Chubar and P. Elleaume, Proceedings of EPAC 1998 , 1177 (1998).]..

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FACILITY FACTS

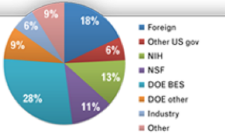
- **22** Years in operation
- **~200** Total ALS staff
- **>800** Refereed publications per year
- **$60M** Average operating budget per year
- **5000** Average number of operating hours per year
- **40** Number of beamlines

USER STATS

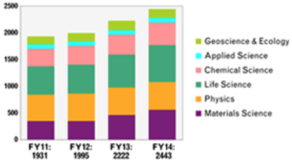
50-100 Users on site at any one time

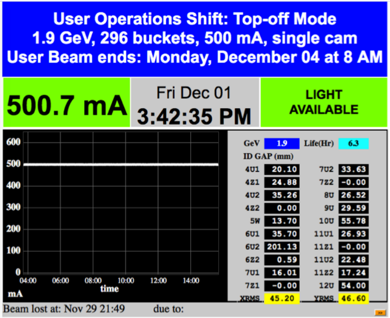
1 hour to 10 days Average stay of users

Users by Funding

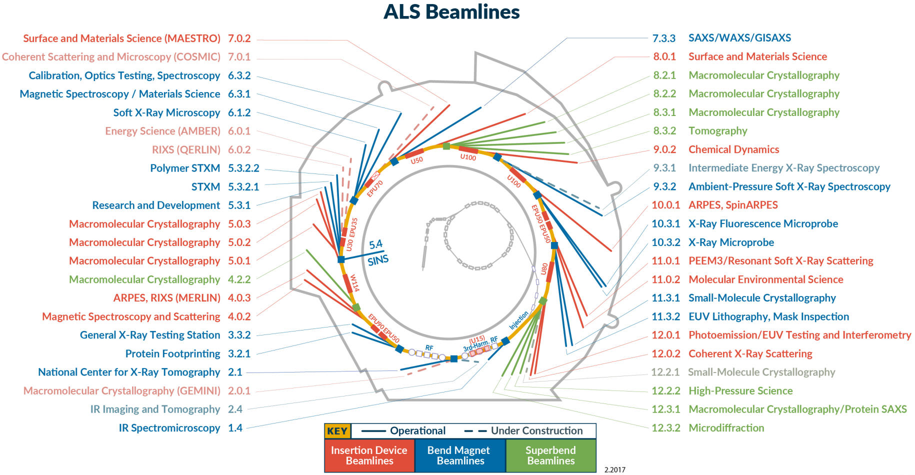


Users per Discipline per Fiscal Year (includes remote users)



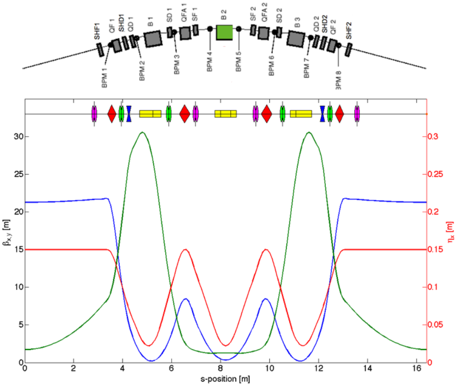


ALS has 28 bend magnet end stations and 22 insertin device end stations

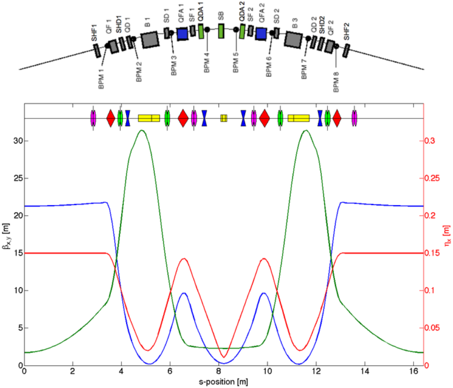


The 3 superbends (6 T superonducting dipole) is a unique feature of the ALS

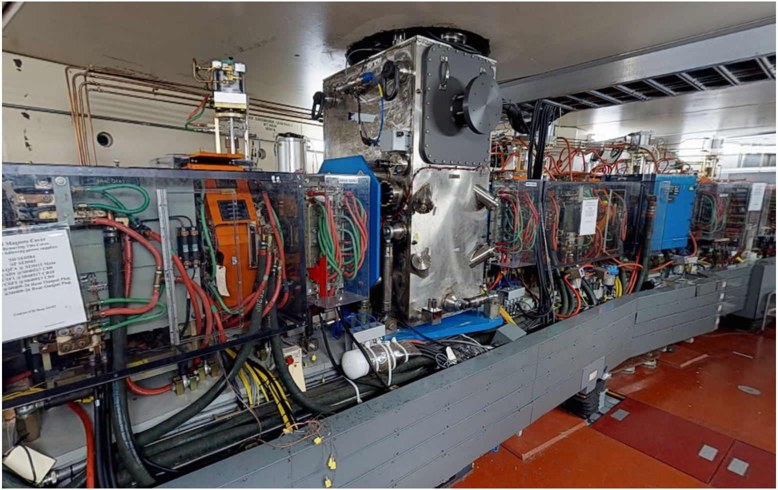
Normal ALS Sector



Modified Superbend ALS Sector



ALS sector with superbend



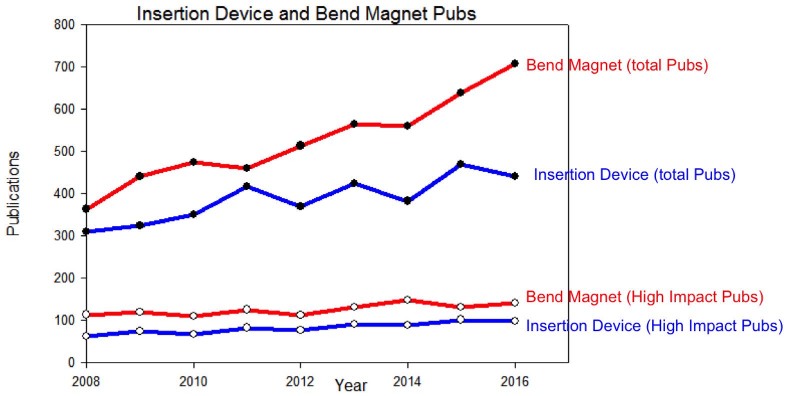
ALS insertion devices, 14 IDs, 17 beamlines, 22 end stations

Device	BL	P. L. [mm]	No. of Periods	ID Gap [mm]	ID Eff. Field [T]	ID Ph.En. [eV]
U15	2.0.1	15	131	4.3-20	1.05-0.15	7000-15000^{a}
EPU50	4.0.2	50	37	14-55	0.80-0.10 ^{v} 0.58-0.10 ^{h}	73-3000
QEPU90	4.0.3	90	20.5	14.5-99	1.18-0.06 ^{v} 0.78-0.06 ^{h}	8-1600
W114	5.0.1 5.0.2 5.0.3	114	29	12.5-180	1.94-0.03	6-21000
U30 U30-w	6.0.1	30	50	5.5-27	1.5-0.13	120-5000 4-11 keV
EPU35	6.0.2	35	52.5	12-40	0.71-0.06	265-4000
EPU38	7.0.1	38	44.5	12.5-75	0.89-0.11 ^{v} 0.67-0.11 ^{h}	150-2500
EPU70	7.0.2	70	26.5	12.5-75	1.18-0.07	16-2000
U50	8.0.1	50	89	14-45	0.85-0.10	80-3000
U100	9.0.1	100	43	22.7-116	0.98-0.05	8-1500
U100	10.0.1	100	43	23.1-116	0.80-0.05	12-1500
EPU50	11.0.1	50	36.5	14.3-55	0.85-0.10 ^{v}	75-3000 0.57-0.10 ^{h}
EPU50	11.0.2	50	37	13.8-55	0.86-0.10 ^{v} 0.58-0.10 ^{h}	71-3000
U80	12.0.1 12.0.2	80	55	24.7-83	0.80-0.07	20-1900

^{a} Harmonic 5-11 ^{b} Harmonic 11 ^{v} Vertical Field ^{h} Horizontal Field

ALS publications from insertion device straights and bend magnet beamlines

-60% ALS publications from Bend Magnet beamlines (including Super bends @ 24%)



Bend End stations (**28**) 14, 21, 321, 332, 422, 531, 5321, 5322, 54, 612, 6311, 6312, 632, 731, 733, 821, 822, 831, 832, 931, 932, 1031, 1032, 1131, 1132, 1222, 1231, 1232

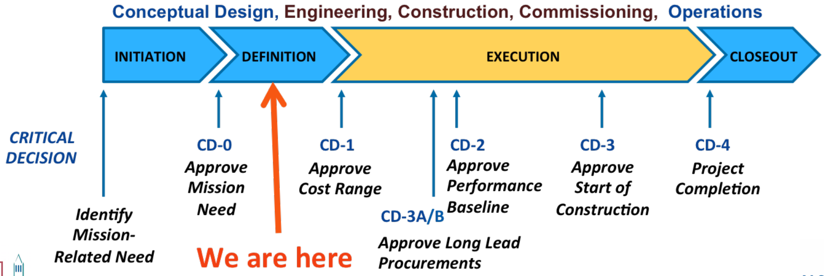
ID End stations (**22**) 402, 4031, 4032, 501, 502, 503, 601, 602, 7011, 7012, 801, 901, 902, 10011, 10012, 11011, 11012, 11021, 11021, 12011, 12012, 1202

High-level performance goals of the upgrade of ALS

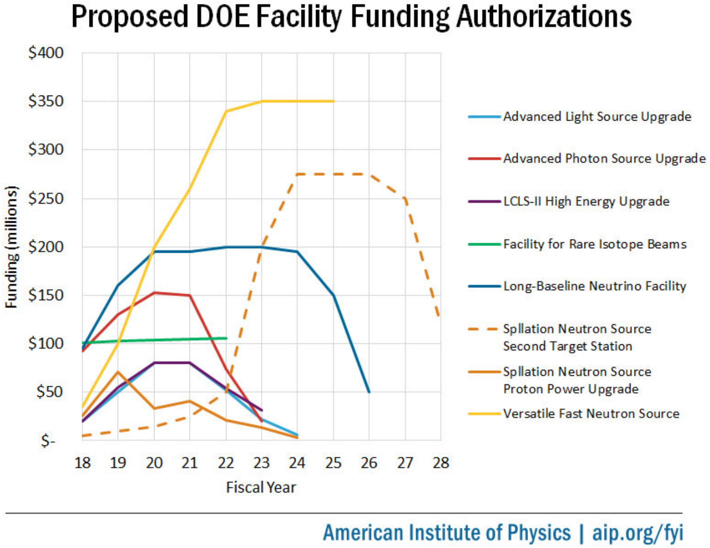
- Achieve an increase in the brightness and coherent flux for soft x-rays at 1 keV photon energy of at least two orders of magnitude beyond today's ALS capabilities
- Develop a set of experimental capabilities that will enable leadership in soft x-ray science
- Provide infrared capability that extends across the wavelength range provided at present day ALS
- Provide hard x-ray capability comparable to present-day ALS

Stages of a DOE project – ALS-U is working towards CD-1

- Finished first (partial) CDR draft in May 2017
- First ESAC+MAC meetings in early summer 2017
- Currently working on system integration and second CDR draft
- Completed first technical design review (Dipole B, R+D magnet) planning round of technical conceptual design reviews for spring



Funding situation as propsed in a bill from the House of Representatives (dynamic)

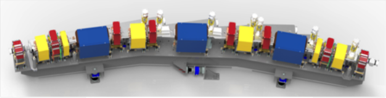


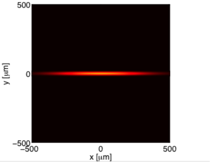
Scope of ALS-U

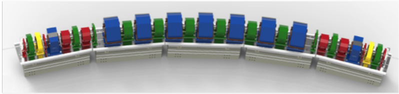
1. **Replacement** of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a **multi-bend achromat**.
2. **Addition** of a low-emittance, full-energy **accumulator ring** in the existing storage-ring tunnel to enable on-axis, **swap-out injection** using fast magnets.
3. **Upgrade** of the optics on existing beamlines and realignment or relocation of beamlines where necessary.
4. **Addition** of three new undulator beamlines that are optimized for novel science made possible by the beam's high coherent flux.

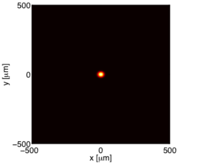
Existing ALS ring New accumulator ring New ALS-U ring

ALS and ALS-U in numbers



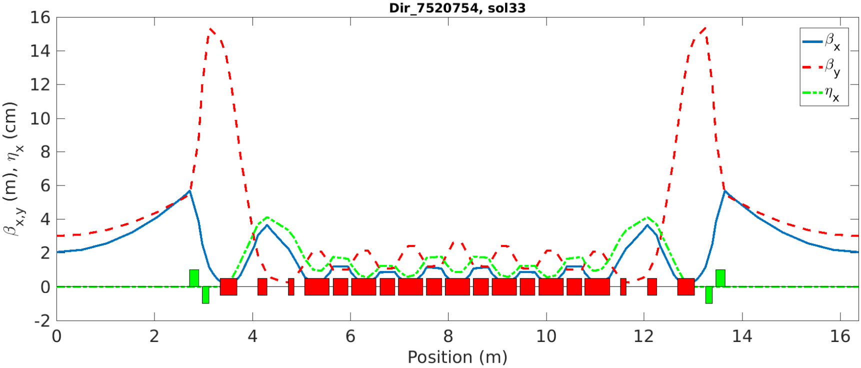






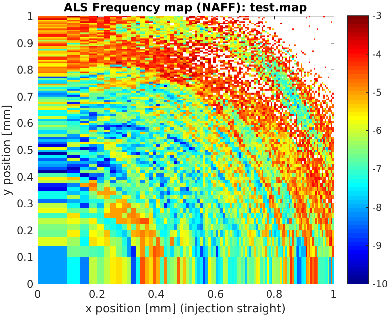
Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Horiz. emittance	pm	2000	<70
Vert. emittance	pm	30	<70
Beamsize @ ID center (σ_x/σ_y)	mm	251 / 9	<13 / <13
Beamsize @ bend (σ_x/σ_y)	mm	40 / 7	<7 / <10
bunch length (FWHM)	ps	60-70 (harmonic cavity)	100-200 (harmonic cavity)
RF frequency	MHz	500	500
Circumference	m	196.8	~196.5

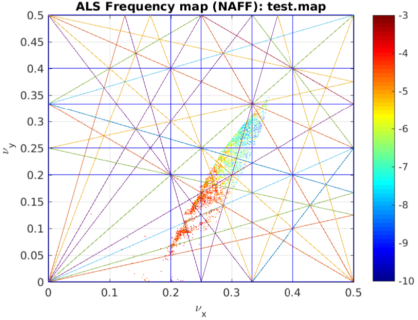
Multibend achromat with 9 bend magnets with reverse bends from QF with offset

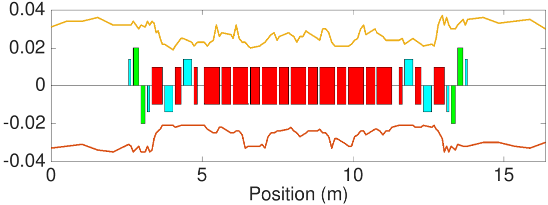


Twiss functions for lattice v20r. The lattice has 12 fold symmetry.

Lattice v20r frequency-map, tune footprint, and momentum aperture (with errors)





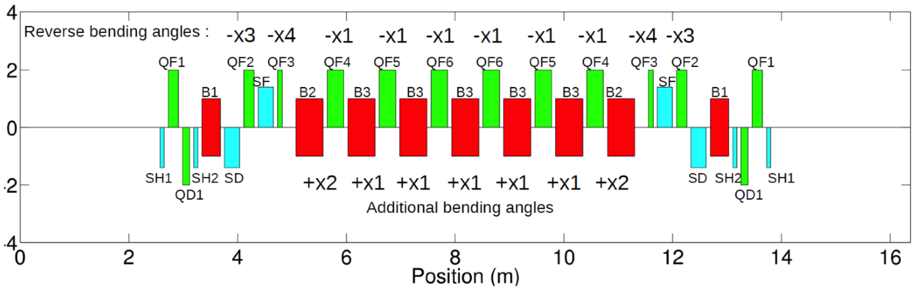


Storage ring parameters for lattice v20r

Lattice parameters	
Lattice type	9BA(w/ rev. bend)
Lattice version	v20r
Tunes, ν_x/ν_y	41.357/20.354
Natural chromaticities, ξ_{0x}/ξ_{0y}	-65.2 /64.84
Chromaticities during operation, ξ_x/ξ_y	1/1
Beta functions at IDs, β_x/β_y	$\sim$ 2/ 3 m
Dispersion functions at IDs, η_x / η_y	<1/1 mm
Circumference, C	196.5 m
Revolution time, T_0	0.655 µs
Momentum compaction, α_c	2.11×10^{-4}
Radiation and related parameters	
Natural rms emittance, ε_{0x}	92 pm
Rms emittances w/ full coupling, $\varepsilon_x = \varepsilon_y$	62 pm
Rms natural relative energy spread, σ_δ	9.43×10^{-4}
Radiation energy loss per turn from dipoles, U_D	217 keV
Radiation energy loss pet turn from IDs, U_{ID}	<70 keV
Total energy loss pet turn, U_0	<287 keV
Partition numbers, $J_x/J_y/J_z$	2.08/1/0.91
Damping times (dipole radiation), $\tau_x/\tau_y/\tau_z$	5.8/12.1/13.8 ms

RF and related parameters	
Electron energy, E	2.0 GeV
Harmonic number, h	328
Main rf cavity resonance frequency,	500 MHz
Main rf cavity voltage (HC tuned out),	0.60 MV
RF Harmonic cavity frequency,	1,500 MHz
RF Harmonic cavity voltage,	0.17 MV
Natural rms bunch length (no HC), $\sigma_{\tau 0}/\sigma_{z0}$	11.8 ps (3.55 mm)
Bunch length (FWHM, with HC)	112 ps (33.4 mm)
RF relative momentum acceptance, δ_{RF}	3.7%
Synchrotron-oscillation tune, ν_s	1.75×10^{-3}
Synchrotron-oscillation frequency, f_s	2.68 kHz
Other parameters	
Total no. of bunches	284
Total no. of trains	11
Min. separation between bunches	2 ns
Min. separation between trains	10 ns
Average current, I_{avg}	500 mA
Single-bunch current, I_b	1.76 mA
Touschek lifetime, τ_s	≈1 h

Reverse bend configuration



- Reverse bending is achieved by offset quadrupoles QF2(-x3), QF3(-x4), QF4-QF6(-x1)
- Additional bending in the magnet B2(+x2) and B3(+x1) to set overall bending angle to 30 deg per sector
- 3 knobs for reverse bending angles: x1, x2, x3, x4 = x2-x1/2-x3

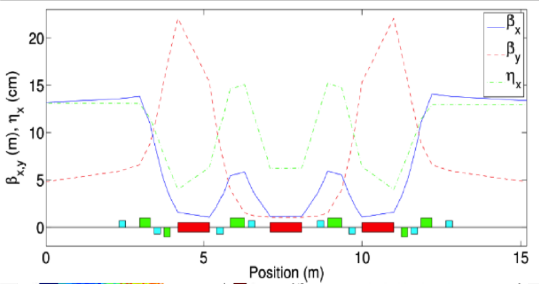
Reverse bend magnet parameters

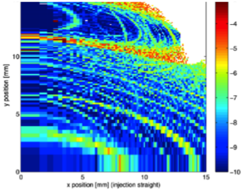
Storage-ring v20r lattice specifications for the magnet effective length (L), bending angle (θ), bending field B_0, quadrupole and sextupole unnormalized (B', B'') and normalized (K_1, K_2, MAD convention) gradient-field components. All magnets have two counts in each of the 12 sectors, except for $B3$ (five counts per sector.) Negative signs for the bending angle and B−field denote reverse bending.

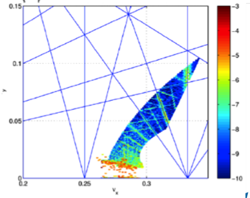
Name	L (m)	θ (deg)	B_0 (T)	K_1 (m^{-1})	B' (T/m)	K_2 (m^{-2})	B'' (T/m^2)
B1	0.34	3.333	1.141	−3.000	−20.000	-	-
B2	0.5	3.646	0.848	−7.057	−47.050	-	-
B3	0.5	3.763	0.848	−7.057	−47.050	-	-
QF1	0.18	-	-	13.768	91.785	-	-
QF2	0.19	−0.0914	−0.056	10.224	68.160	-	-
QF3	0.115	−0.0062	−0.006	10.546	70.307	-	-
QF4	0.305	−0.429	−0.164	15.282	101.884	-	-
QF5	0.305	−0.429	−0.164	15.795	105.305	-	-
QF6	0.305	−0.429	−0.164	15.761	105.075	-	-
QD1	0.14	-	-	−13.432	−89.545	-	-
SF	0.28	-	-	-	-	1562.9	10,419
SD	0.28	-	-	-	-	−1280.4	8,535
SHF	0.075	-	-	-	-	77.72	518.1
SHD	0.075	-	-	-	-	−1156.4	7,709

Accumulator ring with triple bend achromat lattice

Accumulator Ring	
Lattice parameters	
Lattice type	TBA
Tune, ν_x/ν_y	15.345/8.106
Natural chromaticity, ξ_{0x}/ξ_{0y}	-34.9/-30.4
Chromaticity during operation, ξ_x/ξ_y	1/1
Circumference, C	182.122 m
Revolution time, T_0	0.607 µs
Revolution frequency, f_0	1.64 MHz
Momentum compaction, α_c	1.31×10^{-3}
Radiation and related parameters	
Natural rms emittance, ε_{x0}	2 nm
Rms natural energy spread, σ_δ	0.8×10^{-3}
Radiation energy loss per turn, U_0	247 keV
Partition numbers, $J_x/J_y/J_z$	1.42/1/1.57
Damping times (dipole radiation), $\tau_x/\tau_y/\tau_z$	6.92/9.83/6.22
RF and related parameters	
Electron energy, E	2.0 GeV
Harmonic number, h	304
Main rf cavity frequency, f_{r1}	500 MHz
Main rf cavity voltage, V_1	1.3 MV
Rms natural bunch length σ_z	4.8 mm
RF relative momentum acceptance, δ_{RF}	2.7×10^{-2}
Synchrotron oscillations tune, ν_s	6.37×10^{-3}
Synchrotron oscillations frequency, f_s	10.49 kHz
Other parameters	
Touschek lifetime, τ_s	N/A ≈h
Gas scattering lifetime,	N/A





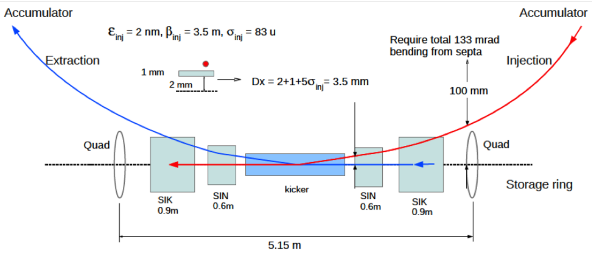


ALS-U Technical challenges

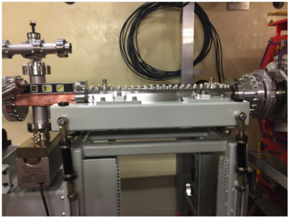
- Emittance increase due to intrabeam scattering
- Swap-out injection
- Tightly packed MBA lattice
- Very high magnet packing density
- Alignment of the magnets
- Small (20 mm) aperture NEG-coated vacuum chambers for the acclerator sectors
- Vacuum system to allow all dipole and straight section light ports
- Very small (4 to 6 mm) aperture NEG-coated vacuum chambers for the straight sections

Accelerator R&D: Swap-out injection technology demonstrated on ALS

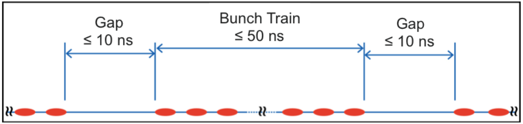
Injection swap-out concept

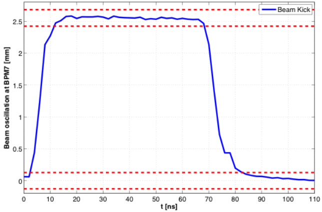


Fast kicker installed



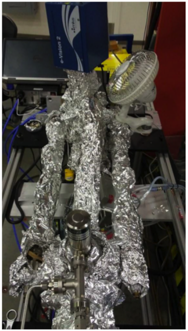
Swapping out a bunch train



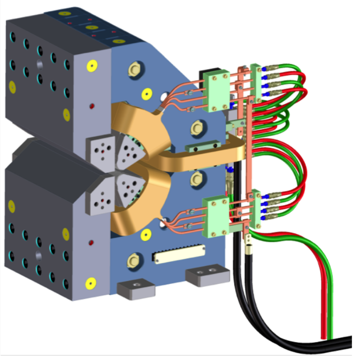


Accelerator R&D: Vacuum and magnets

Successfully activated first LBNL-coated small-gap (6 and 9 mm) NEG vacuum chambers



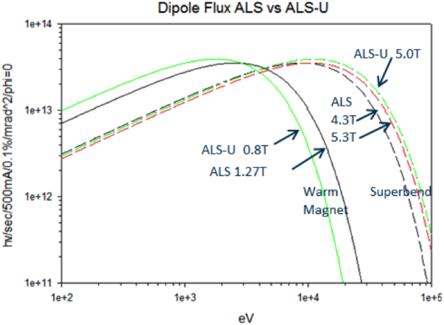
Completed design of R&D storage ring lattice magnet

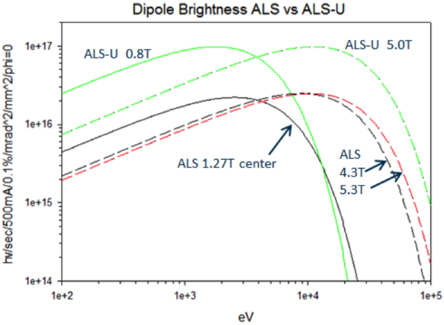


Scope of bend magnet beamline move suggests about 25 beamlines to move

	Beamline	Name	Technique		Existing source	Angle from Straight Deg	Angle from Straight mrad	delta from nominal mrad	eV min	eV max	Publications 2016 (HI)
1	1.4	IR	IR		bend	22.60	394.44	0.00	0.05	1.2	7(0)
2	2.1	NCXT	Bio Tomography		bend	6.30	109.96	0.00	400	1300	5(1)
3	2.4	new IR	IR	Commisioning	bend	22.60	394.44	0.00	0.05	1.2	0
4	3.1	Ring Diagnostics			bend	6.30	109.96	0.00	500	2000	0
5	3.2.1	LIGA	lithography		bend	11.97	208.91	-11.00	3000	20000	2(0)
6	3.2.2	Undeveloped	thro the wall	undeveloped	Bend	13.23	230.91	11.00			0
7	3.3.1	Footprinting	Footprinting	Commisioning	bend	16.77	292.69	-11.00	3000	20000	0
8	3.3.2	Brookhaven detector	Detector development		bend	18.03	314.69	11.00	5000	20000	4(1)
9	4.2.1	Undeveloped	thro the wall	undeveloped	superbend .2	11.97	208.87	-11.04			0
10	4.2.2	MBC	MAD MX		superbend .2	13.23	230.85	10.94	5500	16000	38(5)
11	5.3.1	R&D	Tender X-ray		bend	16.74	292.19	-11.50	1000	13000	11(0)
12	5.3.2.1	High Energy STXM	Ptychography	| split single port	bend	18.03	314.69	11.00	600	2000	7(2)
13	5.3.2.2	Low energy STXM			bend	18.03	314.69	11.00	250	800	37(6)
14	5.4	BSISB	IR		bend	22.60	394.44	0.00	0.07	1.25	12(2)
15	6.1.2	XM-1	Microscopy (MSD/CXRO)		bend	6.95	121.30	11.34	500	1300	4(2)
16	6.3.1	Magnetic/PIPO	Spectroscopy		bend	16.82	293.58	-10.11	250	2000	28(5)
17	6.3.2	EUV Calibration	Reflectometry		bend	18.07	315.47	11.78	25	1300	8(2)
18	7.3.1	Soft X-ray	Spectroscopy	Commisioning	bend	16.92	295.39	-8.30	180	1500	0
19	7.3.3	SAXS/WAXS			bend	17.41	303.79	0.10	8000	11000	152(29)
20	8.2.1	HHMI	MAD MX		superbend .2	11.97	208.86	-11.05	5500	16000	42(9)
21	8.2.2	HHMI	MAD MX		superbend .2	13.23	230.86	10.95	5500	16000	19(8)
22	8.3.1	UCB-UCSF	MAD MX		superbend .3	16.77	292.69	-11.00	5500	16000	30(13)
23	8.3.2	Tomography	Tomography		superbend .3	18.03	314.69	11.00	5000	70000	37(3)
24	9.3.1	Chem. Materials	Spectroscopy		bend	16.94	295.66	-8.03	30	850	25(5)
25	9.3.2	Materials	Spectroscopy		bend	17.48	305.16	1.47	2320	5600	8(1)
26	10.3.1	Microprobe			bend	16.71	291.57	-12.11	3000	20000	5(0)
27	10.3.2	micro-EXAFS			bend	18.10	315.97	12.28	2400	17000	18(6)
28	11.3.1	Small-Molec. XTAL	Crystallography	Moving to 1221	bend	16.77	292.69	-11.00	6000	17000	92(17)
29	11.3.2	SHARP	EUV Inspection		bend	18.03	314.68	11.00	50	1000	9(0)
30	12.2.1	Small-Molec. XTAL	Crystallography	Commissioning	superbend .2	11.97	208.86	-11.05	6000	25000	0
31	12.2.2	High Pressure	Crystallography		superbend .2	13.23	230.86	10.95	6000	40000	30(6)
32	12.3.1	SIBYLS (PBD/LSD)	MAD MX		superbend .3	16.70	291.44	-12.25	5000	17000	44(11)
33	12.3.2	Microdiffraction	Crystallography		superbend .3	18.03	314.69	11.00	6000	22000	33(7)

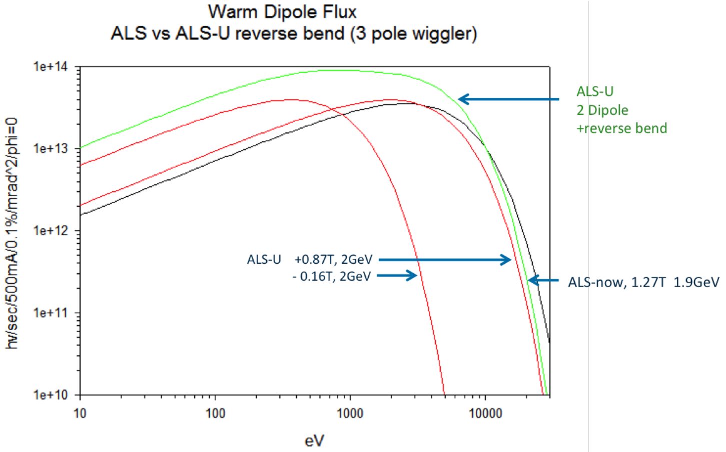
ALS-U bend magnet performance



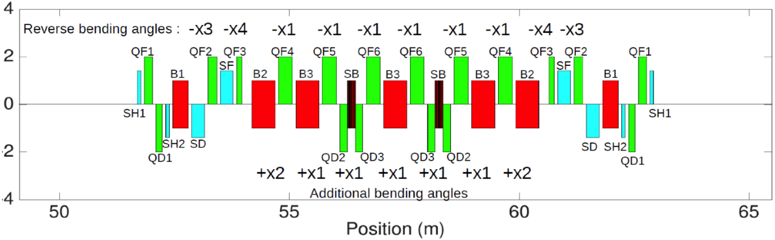


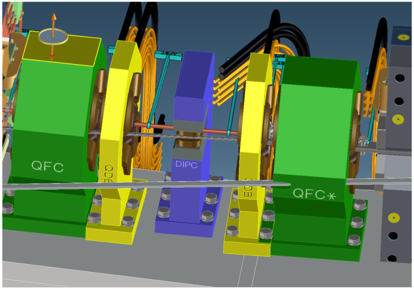
Beam port	Magnet	Source size µm FWHM HxV	
		ALS (2017)	ALS-U
BL x.1	Warm	76x76	20x20
BL x.3	Warm	94x17	20x20
BL x.2	Superbend	62x23	20x20
BL x.3	Superbend	62x23	20x20

ALS-U reverse bend source – More Fluxe



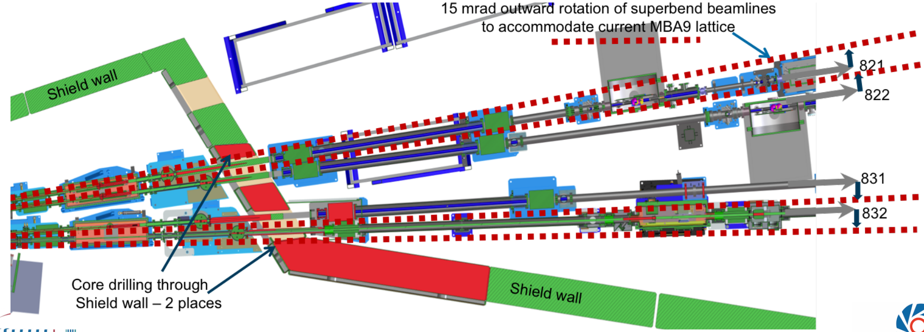
Initial modeling for installing 3 superbends with 6 beamlines has started





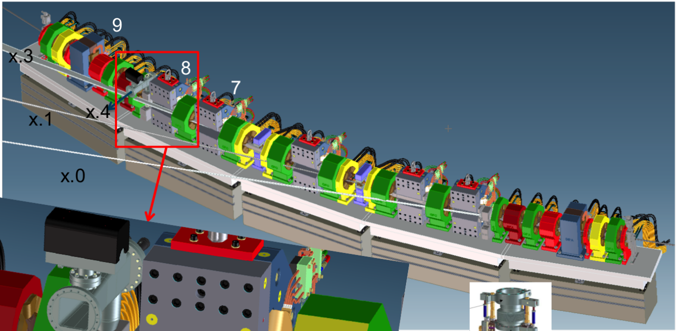
There is a 15mrad shifts on BL8 superbends

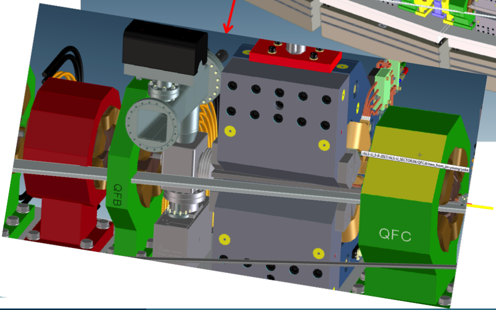
- Will require core drilling the shield wall at 2 places
- Translate 4 hutches 375mm to side - expensive
- All superbend beamlines are productive

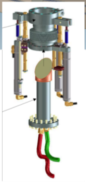


Infra-Red Beamlines 1.4, 2.4, 5.4

-IR beamlines require large opening angle , Currently 69x17 mrad (hxv)
- Location space for M1 between MBA magnets 8 & 9 using light from #7
- Modify optics in ring tunnel to steer beam from a new source point but through same shield hole.







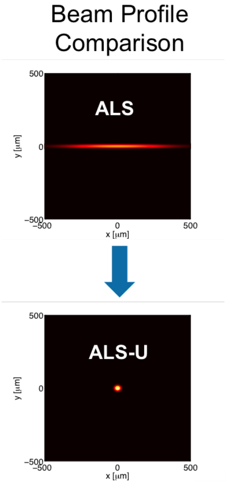
Re-Use M1
mirror assembly

Defining the detailed plan for moving of the bend magnet BLs is work in progress

- The bend magnet beamlines are highly productive and cannot be left out from the ALS-U
- Matching the dipole source points between ALS-U and ALS is not trivial
- It may be possible to use the reverse bend to increase the flux at warm magnet bend magnet BLs
- Modeling the superbend lattice and the superbend magnets has started and is work in progress

Undulators for the ALS-U

- The small dimensions of the ALS-U beam allows the installation of circular vacuum chambers with down to 4 mm vacuum stay clear diameter
- The small vacuum chamber gives freedom to choose undulator type and period length.
- Polarization control is needed for several of the new undulators, which gives EPUs, Delta type, X-type, or superconducting undulators.
- The circular vacuum chamber can be used on complete straight section and the first section of a canted straight section



Interesting development is taking place at SR and FEL sources. Two examples:

X-Type undulator

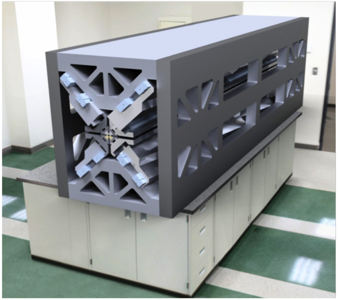


Figure by H.-D. Nuhn, SLAC, shown at ID2017 workshop at LBNL

Arbitrary Polarizing SCU—SCAPE

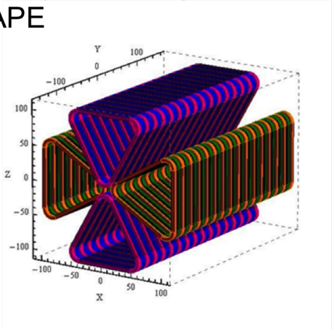
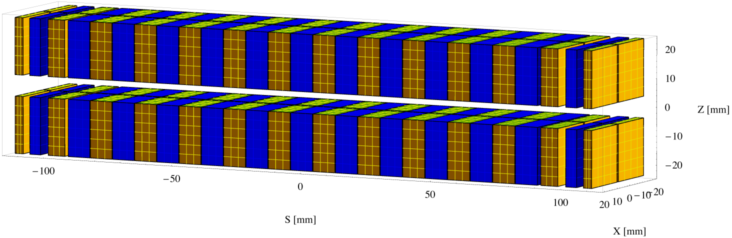
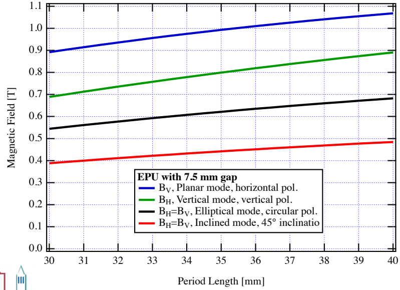
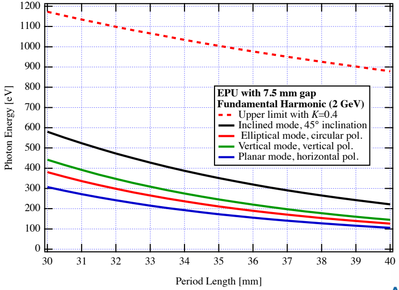


Figure by Y. Ivanyushenkov, APS, shown at ID2017 workshop at LBNL

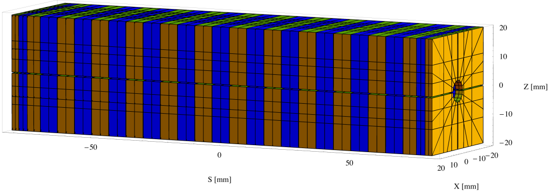
Parameter studies of EPUs

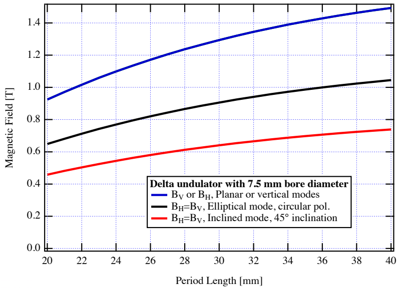


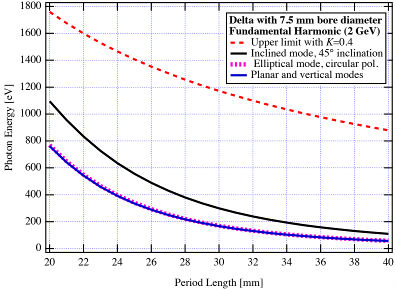




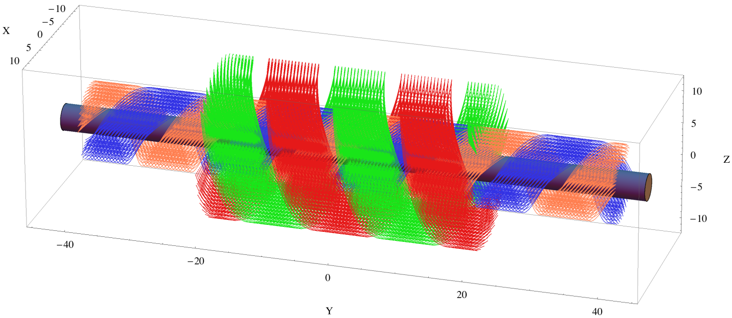
Parameter studies of Delta type undulators





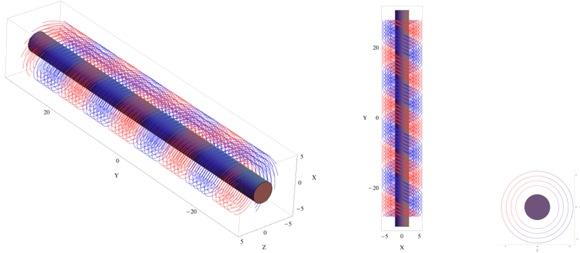


Parameter studies of double helical superconducting undulators

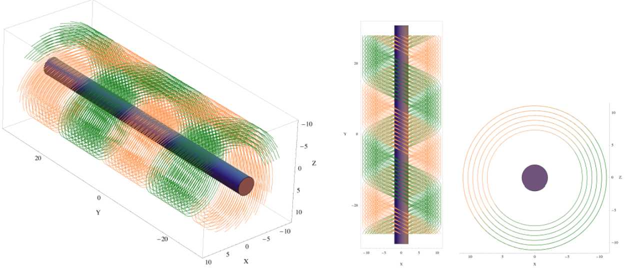


Parameter studies of two period superconducting undulators

Inner coil with 14 mm period length



Outer coil with 28 mm period length

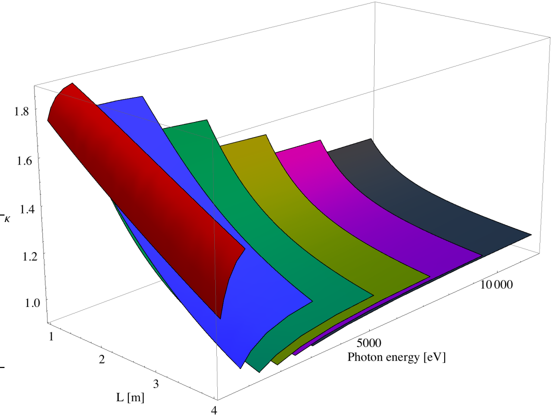


The undulators are optimized to give the maximum brightness

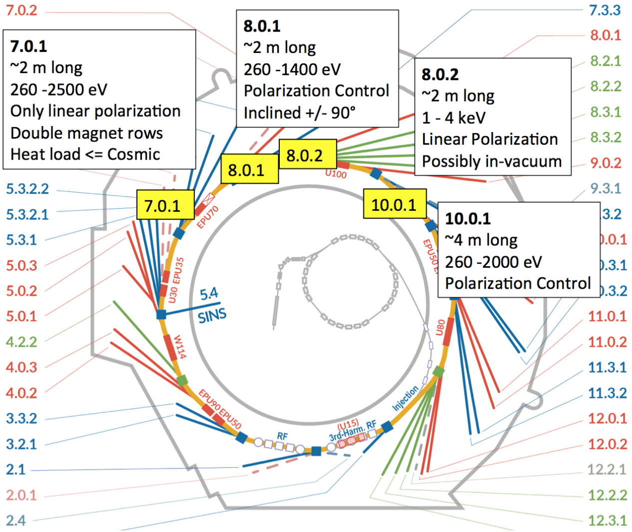
Scaling of the brightness increase with increasing undulator length depends on the photon energy, undulator length, and harmonic, the beam parameters.

Horizontal Emittance	ε_H	64	pmrad
Vertical Emittance	ε_V	64	pmrad
Horizontal β-function	β_H	3	m
Vertical β-function	β_V	3	m
Beam Energy	E	2	GeV
Energy Spread	σ_γ	8.13	$\times 10^{-4}$
Undulator Period	λ_0	32	mm
Undulator Strength	K	2	

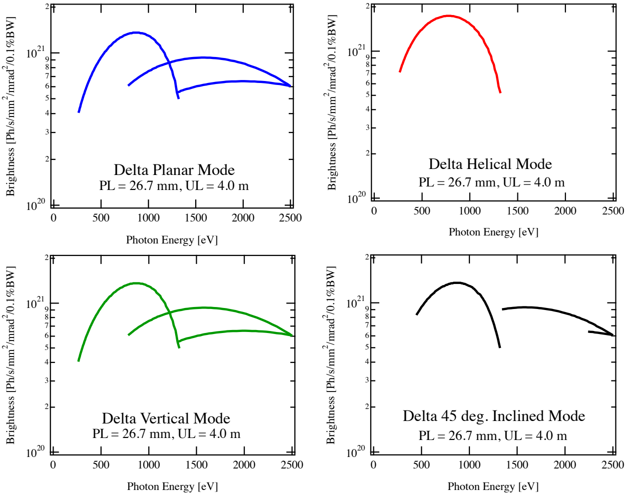
$$\mathfrak{B}_{nReal} \propto L^{\kappa}$$



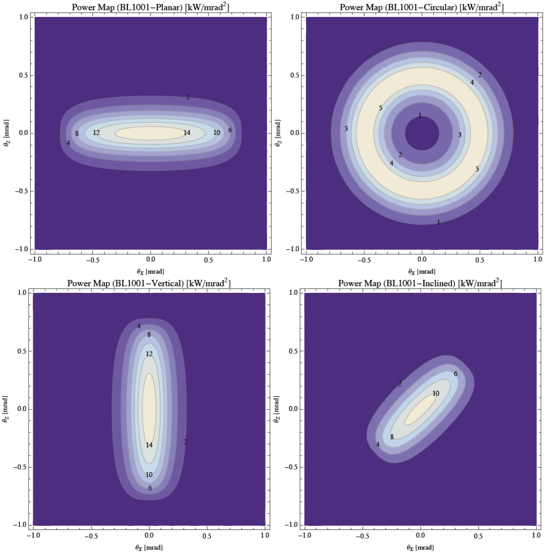
A selection process over the coming 6-9 months will determine the final undulator configuration of the ALS-U. A tentative selection of undulators is shown below.



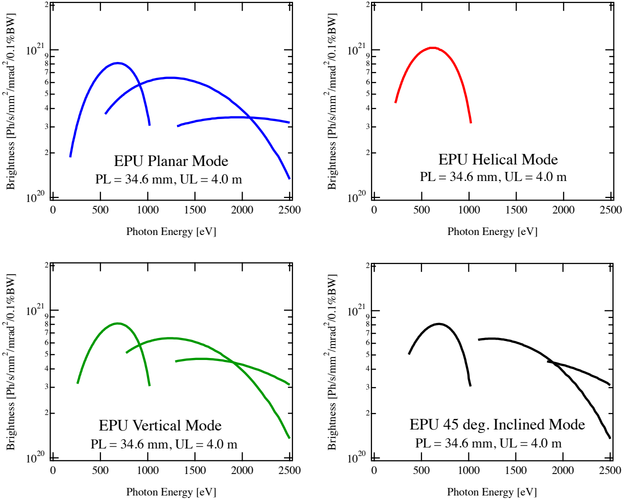
Beamline 10.0.1 using a 4 m long Delta type undulator



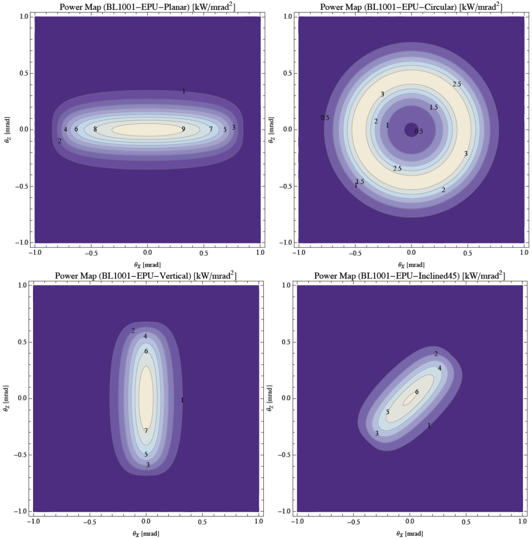
Beamline 10.0.1 using a 4 m long Delta type undulator



Beamline 10.0.1 using a 4 m long EPU



Beamline 10.0.1 using a 4 m long EPU



Insertion device challanges and prototyping

Vacuum system	Refurbishment of ALS IDs	Magnetic measurements	Robust designs	Prototyping
The Delta or Type-X undulators requires 4.5 m long vacuum tubes with an inner diam of 4 mm. The vacuum level must be guaranteed by distributed pumping by NEG coatings. The long narrow vacuum tube will require adequate mechanical support for straightness and cooling to avoid overheating. Other parts of the vacuum system, such as front ends, may be exposed to high power densities of synchrotron radiation	The undulators that are reused from the existing ALS will operate at 0.5-1.7 mm smaller gaps and the heat load will be 23 % higher for the same photon energy. The mechanical systems of the undulators must stand 11% higher magnetic forces and be able to move to the smaller gap. The gap and phase motion control systems of the undulators must be updated for the future operation.	The reused undulators from the existing ALS shall be magnetically measured and if needed also tuned. For the large 4.5 m long undulators the magnetic measurements is best carried out in situ leaving the undulator in the ring. For standard undulators the UMF Hall probe bench can be used. For the in-situ magnetic measurements and for Delta type undulators a new closed bore meas. system is needed	The new undulators for ALS-U will be used over the coming 20 years. The undulators must stand frequent gap and phase changes over extended time periods. The undulators must stand the expected radiation levels without degraded performance. The chosen undulator technology should not dramatically increase the technical risk of the beamline or accelerator.	The main path for the prototyping will be to make prototype studies, possibly in collaboration with other labs, of the chosen Delta or X-type undulator. Prototyping of an alternative design using superconducting coils has great potential and shall be carried out if resources are available. A magnetic measurement system for closed bore geometries for Deltas, SCUs and in-situ meas. will be developed.

Summary

- The baseline lattice for the ALS-U is a 9 bend achromat with reversed bends from offset of the focusing quadrupoles in between the defocusing quad bender magnets.
- The natural emittance ε is 92 pmrad (without IBS)
- The fully couple H/V emittance $\varepsilon_H / \varepsilon_V$ is 62 pmrad and the beta functions in center of the SS are $\beta_H = 2.2$m and $\beta_V = 2.7$ m.
- An accumulator ring and swap injection will be used. A prototype fast kicker magnet has been built and tested.
- It is challenging to accommodate all bend magnet and superbend beamlines when installing ALS-U
- Undulators with cirular vacuum chamber can be used on ALS-U.
- The funding situation looks promising with a chance of receiving $20M already fro FY 2018. The funding schedule would be the similar tor APS.

Thank you for your attention!

Biannual Undulator Conference at the yearly SPIE August meeting in San Diego

SPIE is the international society for optics and photonics and the groups working with beamlines optics attend conferences arranged by SPIE.

A biannual conference series on undulators will be arranged at the SPIE August meetings in San Diego starting year 2019.

At the August 2019 meeting in San Diego there will also be a conference called "X-Ray Lasers and Coherent X-Ray Sources: Development and Applications".