CONCEPTUAL DESIGN OF STORAGE RING MAGNETS FOR A DIFFRACTION LIMITED LIGHT SOURCE UPGRADE OF ALS, ALS-U*

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Abstract

Lawrence Berkeley National Laboratory (LBNL) has been engaged in an internal laboratory directed research and development project to define a suitable accelerator physics lattice to support the diffraction limited upgrade of the Advanced Light Source (ALS). [1] Diffraction limited lattices require strong focusing elements throughout. Magnetics design is challenging in that the high gradient magnetic structures are required to operate in close proximity. Lattice development requires a coordinated engineering design effort to ensure the lattice design feasibility. We will present a review of the results of our magnet scoping studies as well as conceptual design specifications for the ALS-U lattice dipole, quadrupole, and sextupole magnet systems.

INTRODUCTION

LBNL is developing a lattice design suitable for production of diffraction limited radiation in the VUV range of photon energies. The new lattice design will ultimately achieve a natural beam emittance on the order of 50 to 75 pm-rad with a 2.0 GeV beam. The objective of this work will ultimately be an upgrade of the ALS. A pre-conceptual design lattice was selected in summer 2015 to define the magnet design targets upon which to develop engineering specifications. The key design issue evaluated is the achievable gradients in dipole and magnets, and their dependence upon beam aperture.

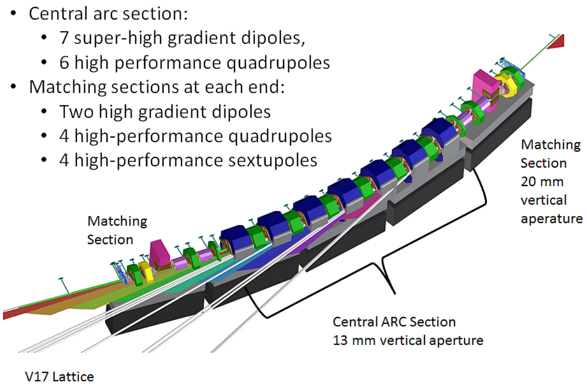

Figure 1: (ALS-U 9BA Lattice) The requirement is that the lattice configuration must provide radiation source points for both bending magnets and insertion devices.

DESCRIPTION OF ALS-U LATTICE

The most-general feature of the ALS-U lattice is that it is a 9 bend achromatic lattice (9BA). Each magnet sector is comprised by a central arc section with matching sections at each end. (See Fig. 1). The central arc section is comprised by 7 high defocusing gradient dipole magnets (Bend 2), and six high performance focusing quadrupoles. The nominal beam aperture in the central arc section is taken to be 13 mm. Each matching section contains a single high defocusing gradient dipole (Bend 1), three focusing and one defocusing quadrupole magnets, and four sextupole magnets. The nominal beam aperture in the matching sections is taken to be 20 mm.

STRATEGY FOR MAGNET DESIGN

One challenging aspect of the design integration for ALS-U is that the magnetic designs must support a lattice that must fit within an existing -197 m circumference facility. Diffraction limited light-source lattices have a high packing density of the focusing elements. The goal of integrating the lattice design with a practical magnetic and mechanical engineering requires that space be budgeted explicitly during the lattice development. For example, we have selected the spacing between magnets to be about 75 mm which corresponds to a minimum length of a BPM assembly or vacuum chamber anchor. The requirements for assembly have dictated that the electromagnetic windings minimally protrude into this space to allow practical installation. The resultant impact on the design is that the magnet poles have been developed with extensions that protrude axially in the beam direction. (See Fig. 2).

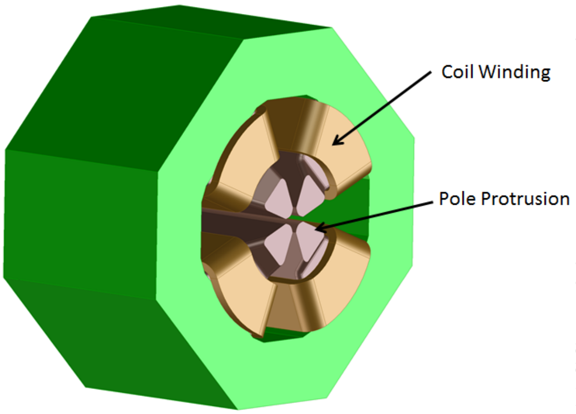

Figure 2: Illustration of axial pole extension employed in ALS magnets. Pole material can be pure iron or CoFe.

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*This work was supported by the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under U.S. Department of Energy Contract No. DE-AC02-05CH11231

The mechanical design of the lattice magnets also entails curved pole pieces for the dipole. For this reason the bulk of magnetic design process has entailed a full 3D modelling effort using OPERA 3D [2]. The 3D models were developed after analytical analysis and baseline investigations using the 2D magnetics code POISSON [3]. The modelling approach allows the magnetic fields to be simulated for two or three magnets in close proximity to each other allowing estimates of cross-talk and integral multipoles in the ALS Lattice. The magnet specifications presented here correspond to those values required for storage ring operation.

Table 1: Summary of ALS-U Dipole Specifications

Magnets	Bend 1	Bend 2	Bend 3
Function	Low Gradient Dipole	High Gradient Dipole	High Field Dipole
Geometry	Gradient Dipole	Offset Quadrupole	Super Bend
Family	DIPA	DIPB	DIPC
Number in Sector	2	7	2*
Lattice Length [mm]	340	500	76*
Bend Angle	3.3333	3.3333	3.3333
Pole Material	HP Iron	HP Iron	Holmium
Pole Tip Field [T]	0.95	1.5	5.3
Nominal Field [T]	-1.1407	-0.7757	5.0
Gradient [T/m]	16	46	0
Tip to tip Length [mm]	338	485	~100

* Bend 3 only used in super bend arc sections

DIPOLE MAGNETS

The NBA dipoles are presently described by two design families: “DIPA” the matching section dipoles, and the central arc section dipoles “DIPB”. There are seven dipoles in the central arc section and two matching section dipoles. The ALS presently deploys three nominally ~5 T superconducting super-bend magnets in three sectors. ALS-U design work has also covered a preliminary study to include a new super bend magnet design in the lattice.

The matching section DIPA dipoles are designed as conventional 1.14 T gradient dipoles in 2D. The specified gradient is 16 T/m. The pole cross sections are then swept in 3D. The poles of the gradient dipole are also extended to save space in the lattice. (See Fig. 3.) Design studies have indicated that this magnet can be constructed efficiently with pure iron or carbon steel poles.

The DIPC gradient dipoles in the central arc section are specified to have an operating gradient of 46 T/m. with a dipole field of -0.776 T. The high gradient is achieved by adopting an offset quadrupole geometry whereby the nominal beam offset is 15.6 mm. The design entails a back-leg winding to allow small adjustment of gradient and/or dipole fields. These dipoles may require CoFe poles if the vacuum aperture is large. (See Fig. 4.)

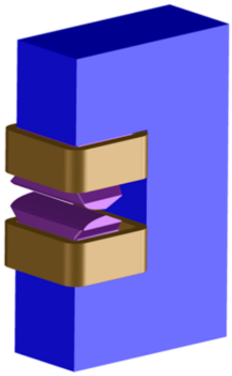
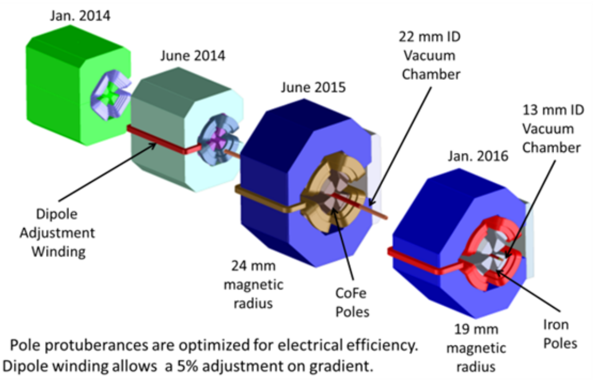


Figure 3: Illustration of gradient dipole magnet concept developed for matching sections in the ALS-U lattice.

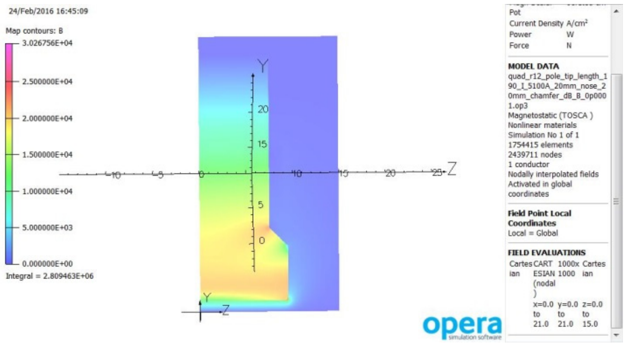


- Pole protuberances are optimized for electrical efficiency.
- Dipole winding allows a 5% adjustment on gradient.

Figure 4: Design evolution of ALS-U offset quadrupole bending magnets.

QUADRUPOLE MAGNETS

High gradient quadrupoles are essential to achieving a diffraction limited lattice. Lattice designs envision quadrupole gradients as high as 106 T/m. Design concepts have been developed that utilize either pure iron or CoFe pole materials to efficiently achieve these gradients. Material selection is largely determined by gradient and magnetic aperture. (See Fig. 5.) Table 2 summarizes lattice requirements for quadrupole magnets.



Pot
Current Density A/cm²
Power W
Force N

MODEL DATA
quad_r12_pole_tip_length_190_I_5100A_20mm_nose_20mm_chamfer_dB_B_0p0001.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
1754415 elements
2439711 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	1000x 1000	Cartesian
	x=0.0 to 21.0	y=0.0 to 21.0	z=0.0 to 15.0

Figure 5: Pole design example utilizing CoFe materials. Efficiency is estimated to be 96% for this structure. The radial extent of the pole extension is required to achieve both axial field uniformity and magnetic efficiency.

Table 2: Summary of ALS-U Quadrupole Specifications

Magnets	QF1	QF2	QF3	QF4	QF5	QF6	QD1
Family	QFA	QFA	QFB	QFC	QFC	QFC	QDA
Number in Sector	2	2	2	2	2	2	2
Lattice Length [mm]	190	190	90	305	305	305	180
Pole Material	CoFe	HP Iron	CoFe	HP Iron	HP Iron	HP Iron	HP Iron
Magnetic Radius [mm]	12	12	12	10	10	10	12
Pole Tip Field [T]	1.1	0.86	0.96	1.02	1.04	1.01	-0.91
Gradient on Axis [T/m]	-87.3	-71.3	-80.2	-101	-104	-101	75.5
Integral of Gradient [T]	-16.6	-13.5	-7.21	-31.0	-31.7	-30.8	13.6
Tip to tip Length [mm]	190	190	90	305	305	305	180
Bx, By Corrector Coils	No	No	No	Yes	Yes	Yes	No
Corrrector Angle [mR]	0.0	0.0	0.0	0.2	0.2	0.2	0.0

SEXTUPOLE MAGNETS

Sextupole magnet strength requirements are on the order of 5700 T/m^2. The magnetic radius required is 12 mm. The selection of CoFe alloy for the pole materials is necessary to accomplish the design. The multifunction sextupole magnets are still very early in their conceptual design. We anticipate using pole extensions in the chromatic sextupoles. (See Table3 below.)

Table 3: Summary of ALS-U Sextupole Specifications

Sextupole Magnets	SF1	SD1	SHD1	SHD2
Function	Chromatic Sextupole	Chromatic Sextupole	Multifunction Sextupole	Multifunction Sextupole
Family	SFA	SDA	SHDA	SHDB
#in Sector	2	2	2	2
Lat. Length [mm]	280	280	45	65
Pole Material	CoFe	CoFe	CoFe*	CoFe*
Mag. Rad. [mm]	12	12	12	12
Pole Tip Field [T]	-0.84	0.68	0.02	0.72
Sextupole [T/m^2]	-5831	4716	167.8	5014.2
Integral [T/m]	-1605	1421	7.55	325.92
Iron Len [mm]	280	280	25	45*
Bx, By Corrector	No	No	Yes	Yes
Cor. Angle [mR]	0.0	0.0	TBD	TBD
SKEW (x, y) Corrector	No	No	Yes	Yes
Cor. Grad. [T/m]	0.0	0.0	TBD	TBD

* Considering a CoFe laminate if required.

DISCUSSION OF PROXIMITY EFFECTS

The conceptual design of the ALS-U lattice has a 75 mm spacing between the poles of differing magnets. The symmetry axis of the offset quadrupole bending magnets is shifted by 15.6 mm in the existing design. Initial study work has been completed whereby the proximity effects between magnets is estimated by comparing the perturbations to the field integrals along the beam trajectory through the dipole while varying the neighbouring quadrupole field strengths by ± 5%. Initial calculations indicate that the field integrals are stable to within 0.05% without field clamps and ~ 0.003% with field clamps in the geometry. Additional criteria are being developed to qualify the magnetic design to allow spatial and magnetic fiducialization of the curved gradient dipoles. We have calculated trajectory errors of ~30 microns through the dipole for on energy particles. We note that the trajectory errors are quite small when compared to the 5 mm multipole expansion diameter. These errors are comparable to existing positioning errors for components at the ALS.

FUTURE WORK

Thus far we have examined the allowed multipole field errors associated with ideal magnet geometries. Near term work will entail an analysis the effects of construction errors to develop a sensitivity model to define construction tolerances for each of the magnet geometries envisioned. Magnet design development is being driven by the lattice requirements for the ALS-U. The ALS-U lattice is under development and subject to change. However, the magnet design concepts presented are now sufficient to define research and development hardware magnets to fully understand critical aspects of the magnet systems under consideration.

CONCLUSIONS

We have presented an overview of the lattice magnet design concepts for ALS-U. The key aspect of the design philosophy is the implementation of pole extensions “nose-cones” to manage axial space in the storage ring. Additionally our design studies have explored the trade-offs between a larger beam aperture and the selection of low or high-grade ferromagnetic pole materials. We have also started the characterization of proximity effects between magnets; and are developing criteria for fiducilization.

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