New Designs of Short-Period Undulators for Producing High-Brightness Radiation in Synchrotron Light Sources

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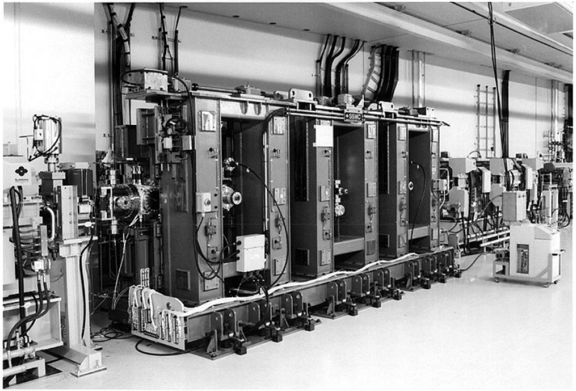
Contents

Introduction

- Today's state of the art light sources, such as 3rd generation synchrotron radiation storage rings, diffraction limited storage rings, and linear accelerator free electron lasers are all using undulators for the production of high brightness synchrotron radiation.
- In order to push the photon energy spectrum to higher photon energies, without increasing the energy of the accelerator electron beam, the period length should be as short as possible.
- For short wavelength planar polarization, in-vacuum undulators is the main workhorse at light sources. For elliptically polarized light, small gap elliptically polarizing undulators are installed around a thin extruded aluminum vacuum chamber.
- A recent development is that the new diffraction limited storage rings, as well as free electron lasers, allow the installation of round small diameter vacuum chambers.
- The intention with this presentation is to give an overview of the development of short period undulators, both planar and elliptically polarizing.

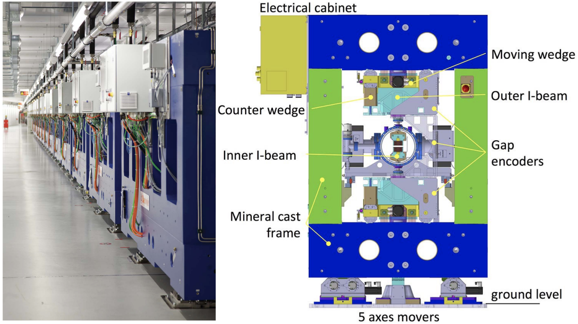
In-Vacuum Undulators

- After the first proposal to build and install an in-vacuum undulator at KEK in Japan [1], there has been a tremendous evolution of the in-vacuum technology.
- The main initial driver of the development of in-vacuum undulators was SPring8 in Japan [2, 3].
- Other laboratories have followed and in-vacuum undulators have been further developed at, for example, the ESRF in France [4] and PSI in Switzerland [5].



Examples of In-Vacuum Undulators at Free Electron Lasers

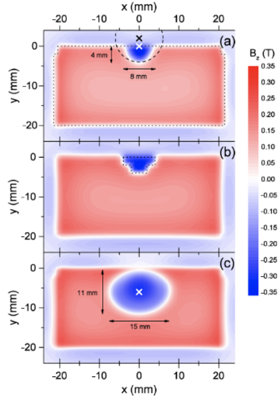
The SACLA undulator Hall [6] at RIKEN SPring-8 Center. with two 100 m rows of in-vacuum unulators



The row of U15 undulators for the ARAMIS beamline at the SwissFEL at PSI [5]

Issues with In-Vacuum Undulators

- The in-vacuum undulator technology is fully mature and industrial partners can deliver complete undulator systems with individual undulator lengths of 5 m or more.
- The grade of magnet material used in the hybrid type magnet structure stands the elevated temperatures during the initial vacuum bake-out after installation and vacuum problems are rare.
- Mechanical problems are rare [7] and the main problem with in-vacuum undulators is that, being close to the smallest aperture in the accelerator, they may be exposed to demagnetization, showing reduced radiation properties and changing multipole contents.
- The maximum magnetic field strength is limited by the maximum remanence of the rare earth alloys used. Some enhancement of the field is obtained by carefully surround the poles, which are made of soft magnetic material, with permanent magnet material.

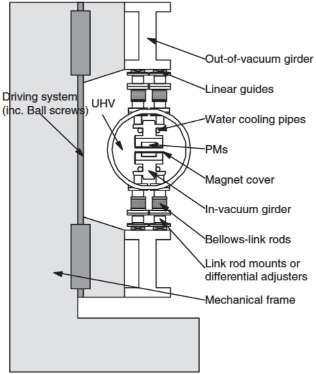


Demagnetization, or field reversal, in a SACLA in-vacuum unulator [8]

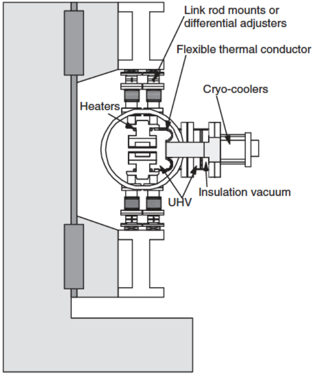
Cryogenically Cooled In-Vacuum Undulators

- The shortcomings of the in-vacuum undulator, with sensitivity to radiation induced demagnetization and the limit put by rare earth materials at room temperature, were addressed by suggesting to cool the magnet rows down to cryogenic temperatures and that make use of the increased remanence and intrinsic coercivity of the magnet material at low temperatures [9].
- In principle, the change from running cooling water to keep the in-vacuum undulator at room temperature to instead run a cryogenic fluid or install cryocoolers to keep the magnet rows at cryogenic temperatures, is minor. In practice, however, it is rather complicated and the various thermal expansion rates of the mechanical supports structure, the magnet material properties that change with temperature, and the necessity of carrying out magnetic measurement in-situ under vacuum in the undulator have been challenging.
- By a major effort carried out at several laboratories [10, 11, 12, 13, 14, 15, 16], the challenges have been overcome and the cryogenically cooled undulator technology is now a mature technology and it is possible to order cryogenically cooled undulators from industry. The maximum undulator length is however limited to about 4 m.

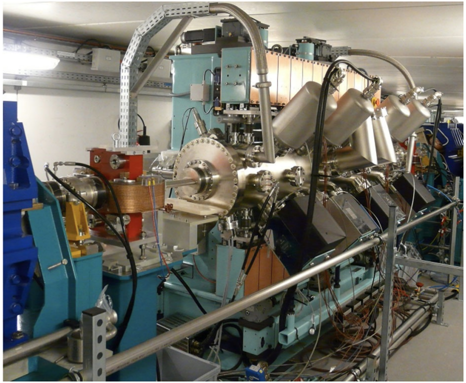
Working Principle of a Cryogenically Cooled In-Vacuum Undulator [11, 15]



In-Vacuum Undulator

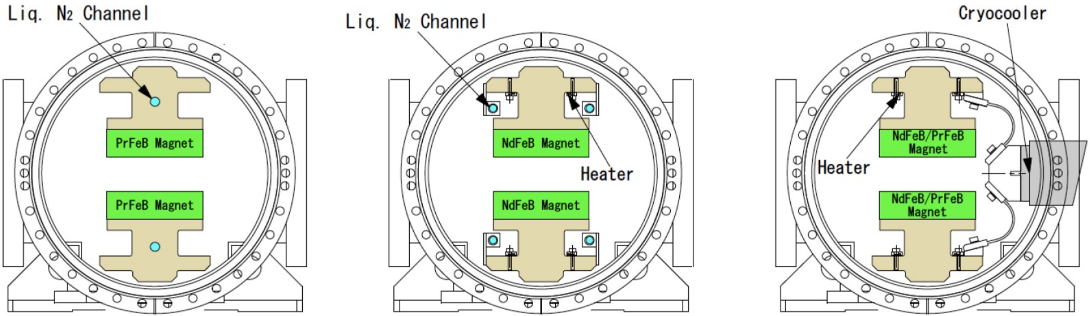


Cryogenic Permanent Magnet Undulator for TPS



Installation of a Cryogenically Cooled In-Vac at Soleil

Cooling of a Cryogenically Cooled In-Vacuum Undulator [11]



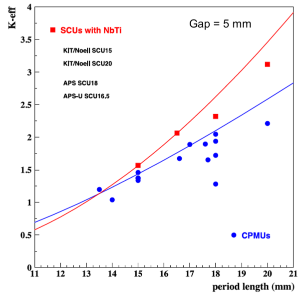
(a) Direct cooling of PMs with LN_2, (b) indirect cooling of PMs with LN_2 and temperature control, (c) indirect cooling of PMs with cold head and temperature control

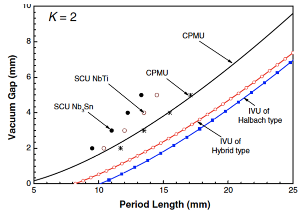
Overview of Cryogenically Cooled In-Vacuum Undulators Installed at Light Sources [16]

Facility	#	Status	λ_0 (mm)	Gap (mm)	N	L (m)	Magnets	Grade	Br (T)	HcJ (kA/m)	T (K)	B (T)	Cryogenics	References
Diamond LS	1	Operation	17.7	5.0 4.0	114	2.0	$Nd_2Fe_{14}B$	Vacodym 776 TP	*1.32*	*>1670*	147	1.04 e 1.26 e	Thermosiphon	[52–55]
Diamond LS	2–4	Construction	17.6	5.0			$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.20	Cryocooler LN	[55], and private communication
Diamond LS	5	Construction	16.6	4.5			$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.25	Cryocooler LN	Private communication
ESRF	1	Operation baked at 120°	18.0	6.0	107	2.0	$Nd_2Fe_{14}B$	Nerorem 595t	*1.16*	*>2400*	150	0.88	Cryocooler LN	[11,56–59]
ESRF	2	Operation	18.0	6.0	107	2.0	$Nd_2Fe_{14}B$	Vacodym 764 TP	*1.37*	*>1275*	150	0.99	Cryocooler LN	[60–62]
ESRF	3	Operation	14.4	5.0		2.0	$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1	Cryocooler LN	[62,63]
HEPS-TF/IHEP	1	Construction	13.5	5.0	140		$Pr_2Fe_{14}B$	P50SH	Under development		<85	1	Cryocooler LN	[64–67]
HZB	1	Construction	17.0	5.5	80		$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.12 e	Cryocooler LN	[68–70]
HZB/UHH/Desy	1	Construction	15.0	2.0	127		$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	2.08 e	2 × coldhead	[68,71]
NSRRC	1	Construction	15.0	2.8 3.8	133		$Pr_2Fe_{14}B$	NMX-68CU GBD	1,67	6200	77	1.77 e 1.32 e	2 × coldhead	[5,72–74]
SOLEIL	1	Operation	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.57	6090	77	1.15	Cryocooler LN	[13,75–79]
SOLEIL	2	Operation cryo-ready	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.15	Cryocooler LN	[77–80]
SOLEIL	3	Construction	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.15	Cryocooler LN	[79,80]
SOLEIL	4	Construction	15.0	3.0	200		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.74	Cryocooler LN	[77–82]
SPring-8	1	Beam tests 2013 at SPring-8	15	3.0	93	1.4	$Nd_2Fe_{14}B$	NMX-49CH	1.48	3025	140	1.64	2 × coldhead	[51,5]
SPring-8/SLS	1	Operation at SLS	14	3.8 5.0	120	1.7	$Nd_2Fe_{14}B$	NMX-S45SH	>1.5	>4000	135	1.186 0.835	Cryocooler LN	[12,83–85]
SSRF	1	Operation 2015	20	6	80		$Nd_2Fe_{14}B$	N48H	1.53	4000	135	1.06 1.03 e	Cryocooler LN	[86]

Superconducting Undulators

- Superconducting wavelength shifters and wiggler shave with success been used at synchrotron light sources for decades and the experience from these application regarding cryostats, cryocoolers, heat loads, winding techniques, and current leads was valuable for the development of superconducting undulators.
- Superconducting undulators can reach even higher fields that cryogenically cooled in-vacuum undulators. Superconducting undulator are radiation hard and can stand lost electron beams and hard x-rays without degrading. The superconducting coils will quench at the radiation incident but recovers after coils have cooled down again.
- The development of superconducting undulators using NbTi to the level of commercialization has been driven by the Karlsruhe Institute of Technology [17] and APS at Argonne [18].
- The performance can be further enhanced by using Nb3Sn wires that, however, requires an elaborate heat treatment after winding, which leads to further technical complications [19].





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Superconducting Undulator Coils, example from APS [18]

- The superconducting coils are wound with a bobbin winding around a core of iron with grooves for the wire. The winding is without interruption and the required wire length is about 5 km.
- The end sections consist of a gradual decrease of the number of turns in the last few slots.
- Small superconducting correction coils are installed in the beginning and end of the undulator.
- The achievable phase error of the undulator depends greatly on the mechanical precision obtained during machining and winding.

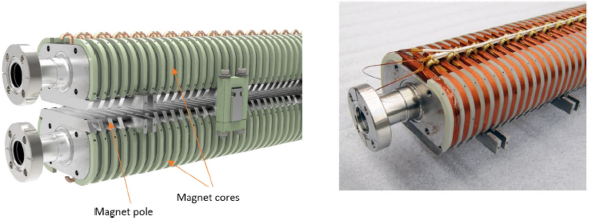
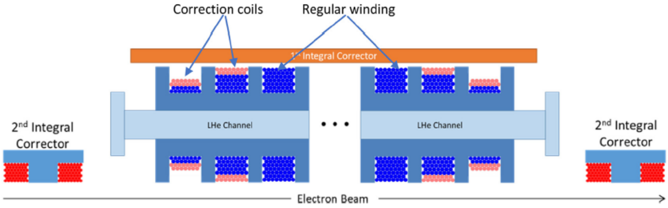


Fig. 9. Rendering and picture of APS SCU magnet core.



The RMS phase error is brought down by using adjustable spacers between upper and lower coils [18]

J. Bahrdt, E. Gluskin

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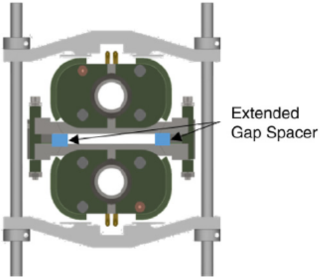
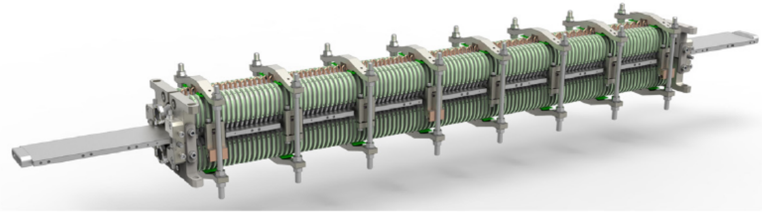
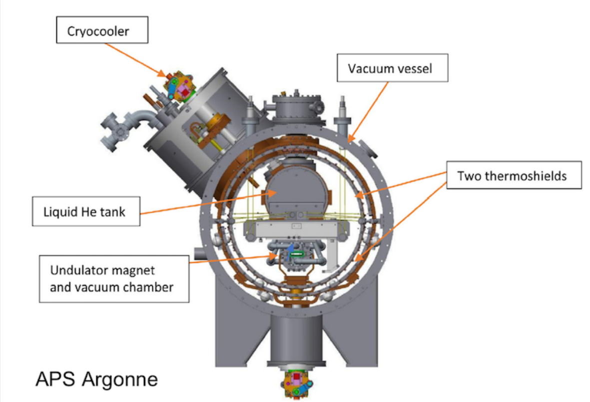




SCU magnet with gap spacers and gap-adjusting clamps. The vacuum chamber extends from both sides of the magnet.

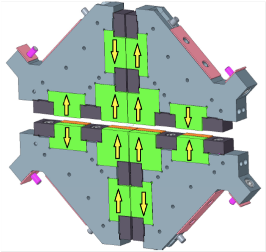
Cryocoolers are used in combination with a liquid He bath [17] or conduction cooling [18]

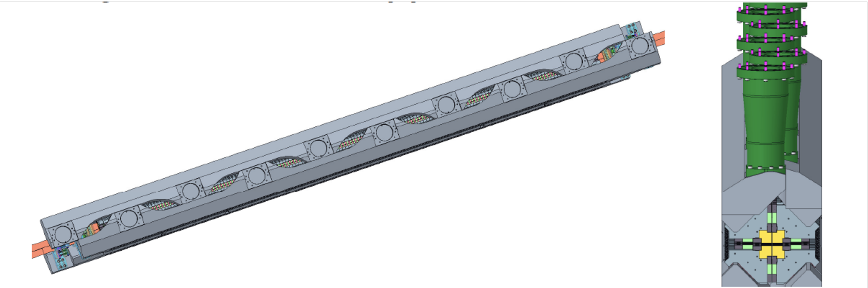


Elliptically Polarizing Undulators

- Elliptically polarizing undulators (EPU) give control of the polarization of the emitted light. With four rows of magnets arbitrary polarization, both elliptical and inclined planar polarization, can be achieved.
- In the same way as for undulators with planar polarization, there is a quest for the shortest possible period length for elliptically polarizing undulators (EPU), which means that the magnetic gap should be as small as possible.
- EPUs are normally mounted at the straight sections using an extruded aluminum vacuum chamber that allows the magnet rows operate down to a gap of about 10 mm. Recently, the first in-vacuum EPU was installed at a storage ring [20].
- The recent development of diffraction limited storage rings and free electron lasers has made it possible to use a round vacuum chamber and bring the permanent magnets closer to the beam compared to standard EPUs, which has enabled a new development trend.

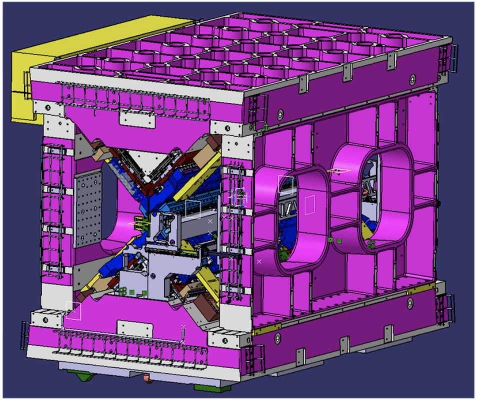
Short period In-vacuum APPLE-II EPU developed at HZB [20]

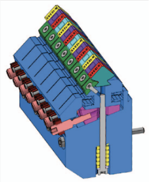


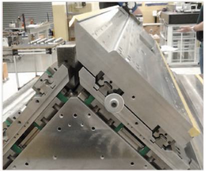


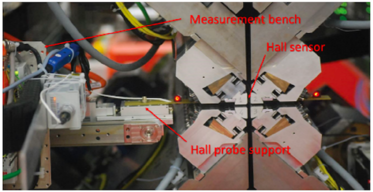
The In-vacuum APPLE-II EPU is featuring force compensating magnets (left), interlaced support points for the magnet rows (middle), and a staggered arrangement of the support columns through the vacuum tank(right).

Development of X-type undulators at the PSI [21, 22, 23, 24]



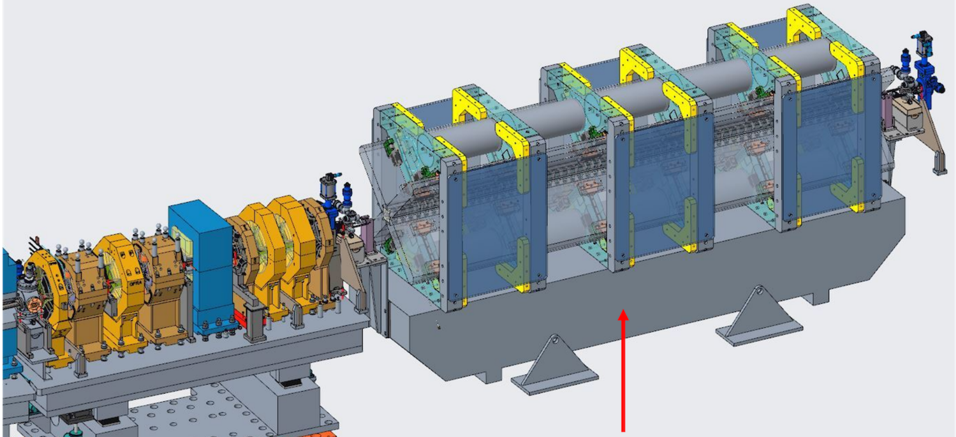






The PSI X-type undulator is featuring a cast iron frame, a round vacuum chamber, adjustable magnet holders for robot tuning, and a moveable wedge system to adjust the radial position of the magnet rows.

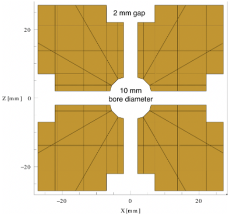
Development of X-type undulators at Lawrence Berkeley National Laboratory (LBL)

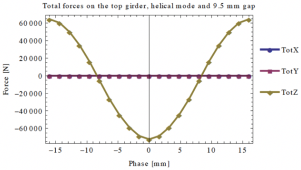


Granite Base Plate with a flat polished top surface acts like the frame usually used for undulators

Magnetic concept and magnetic forces of the LBL X-type undulator

Geometry of magnets



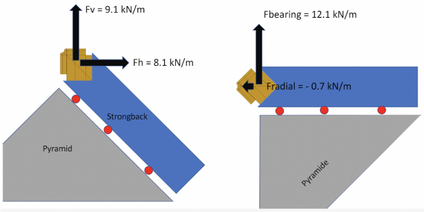


- No longitudinal magnetic force for the phase drive motion when being in the helical mode of operation
- Inclined mode operation by radial motion removes a challenging force load situation
- The only force of importance is the attractive/repulsive force between magnet rows

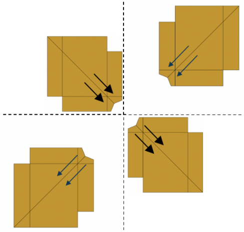
The major force load goes into the bearings holding the strongbacks.

The radial force is low.

Typical forces at minimum gap



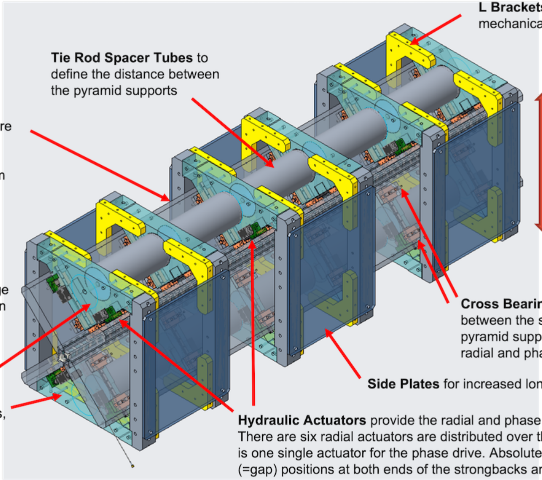
Inclined mode operation by radial motion



No phase position change and hence no longitudinal forces

The transverse, attractive/repulsive, and radial forces are negligible

Mechanical design overview of the LBL X-type undulator



L Brackets for increased transverse mechanical stability

Tie Rod Spacer Tubes to define the distance between the pyramid supports

Magnet Strongbacks are holding the four rows of magnets.
The strongbacks are 4 m long and they are the largest machined parts manufactured.
The strongbacks are moved radially for a gap change and along the beam for a phase change changing the polarization

The force direction is attractive/repulsive 72 kN / 65 kN between upper and lower row of pyramids to be distributed over 12 support points
There are no forces acting along the beam direction
The transverse forces in the inclined mode of operation are negligible

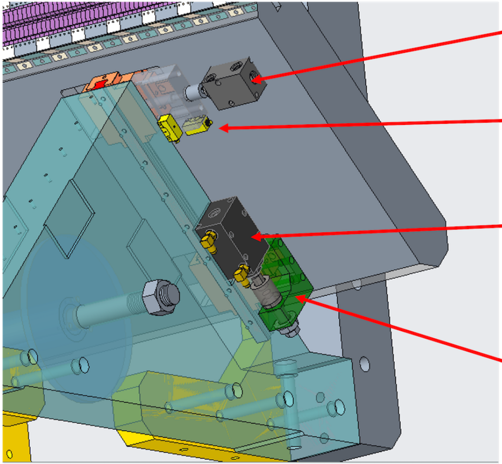
Cross Bearings control the distance between the strongbacks and the pyramid supprts while allowing the radial and phase motions.

Side Plates for increased longitudinal stability

Pyramid Supports are the basic building blocks, and they are the seats the bearing rails

Hydraulic Actuators provide the radial and phase position motion of the strongbacks. There are six radial actuators are distributed over the six sets of pyramids while there is one single actuator for the phase drive. Absolute linear encoders give the the radial (=gap) positions at both ends of the strongbacks and also the phase position.

Hydraulic actuator system of the LBL X-type undulator



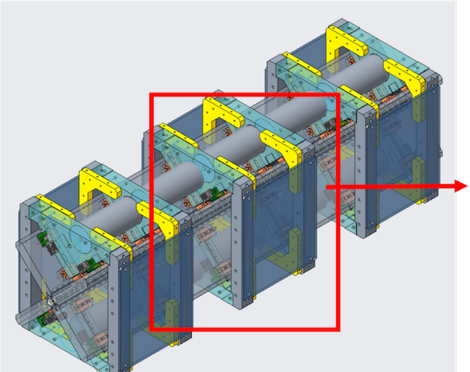
Hydraulic Actuator for the phase position. There is one phase actuator per strongback.

Encoders for the radial and phase positions. There is one phase encoder and two radial (one in each end) for the radial position.

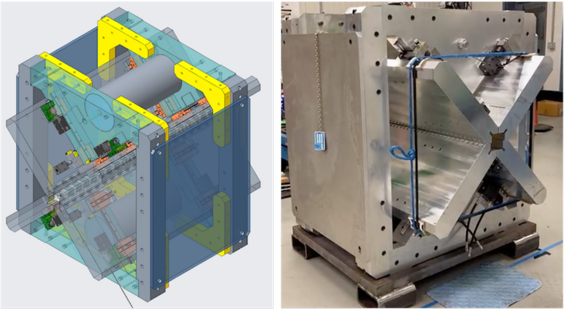
Hydraulic Actuator for the radial position. There are six radial actuators per strongback. The actuation is done in two cells with the first and last three actuators making up a control cell controlled by the entrance or exit radial encoder.

Radial Motion Bracket with internal set screw with jam nut. The hardstop, which is the end position of actuator cylinder, position is set by adjusting the set screw and then lock with the jam nut.

Demonstrator unit of the LBL X-type undulator



Full Size Undulator, 4m long



Demonstrator unit ~1/3 of full size

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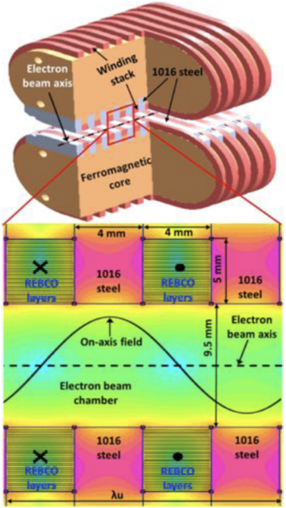
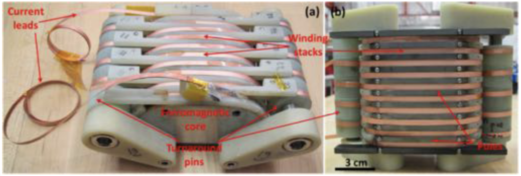
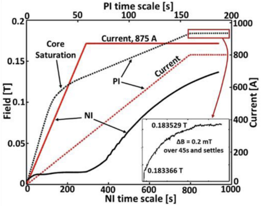
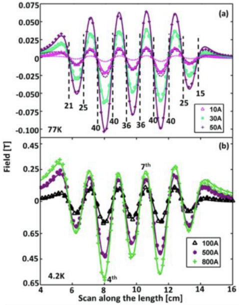
REBCO HTS tape used for superconducting undulators with high current density [25]



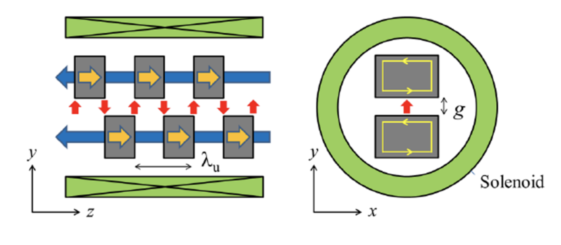


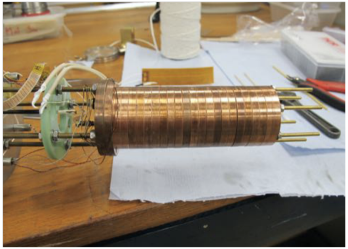


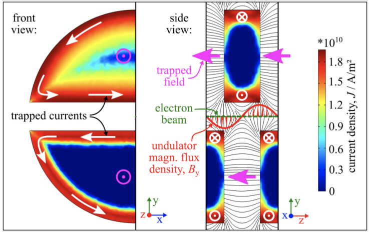


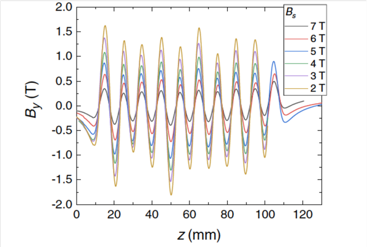
Demonstrated Je = 2.2kA/mm2
Very good agreement with simulations
16mm period 9.5mm magnetic gap
→ ~1T undulator field on axis

Staggered superconducting undulator with possible high field strength [26, 27, 28, 29, 30]

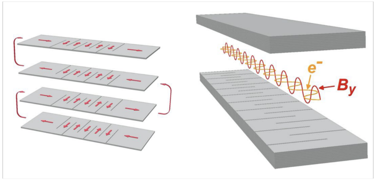


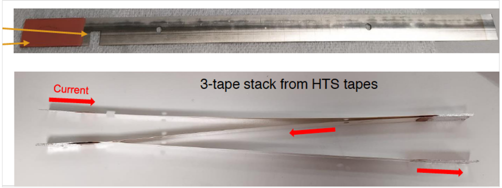


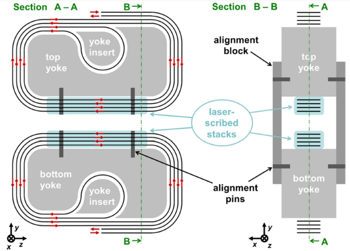


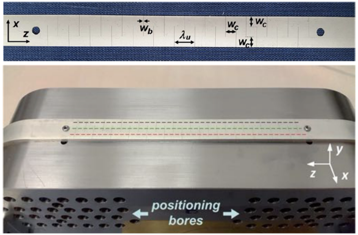


Undulator using structured REBCO HTS tape [31, 32]









Conclusions

- Since its introduction 30 years ago, the in-vacuum undulator technology has gone through a tremendous evolution and is now a fully mature technology. In-vacuum undulators populate 3rd and 4th generation light sources all around the world.
- The cryogenically cooled in-vacuum undulators have over the past decade evolved to a mature technology. Compared to in-vacuum undulators, they have even higher magnetic fields and radiation hardness.
- Superconducting undulators have over the past few years matured into mature technology. Superconducting undulators have even higher fields than cryogenically cooled in-vacuum undulators.
- The 4th generation light sources with diffraction limited storage rings have opened up the possibility to have small circular vacuum chambers in the straight sections of storage rings in addition to linac based FELs, which has led to a development of X-type undulators.
- The above mentioned workhorses for synchrotron radiation production will likely dominate the field of undulators for light sources over the foreseeable future.
- A possible breakthrough in the application of high temperature superconductors may lead to a new direction for the development of short period undulators.

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