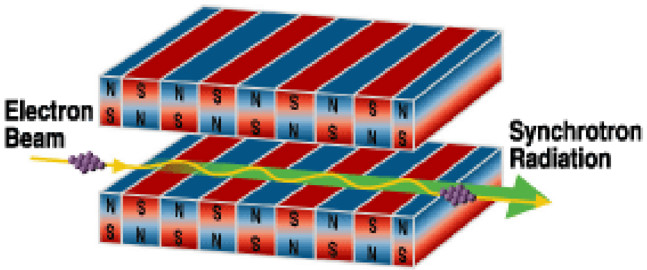
Superconducting wigglers and undulators

Nikolay Mezentsev
Budker Institute of Nuclear Physics
Russia

Contents

Introduction

Superconducting (SC) wigglers (SCWs) and undulators (SCUs) are high performance IDs suitable for extending the spectral range of SR storage rings towards shorter wavelengths and harder x-rays, increase brightness of photon sources.



The SCWs can be either wave length shifters (WLS) with a few magnet poles with very high magnetic field or multipole wigglers (MPW) with a large number of poles with high magnetic field.

The maximum magnetic field in SCWs and SCUs is defined by the critical curve of the SC wire. SC MPWs fabricated with use of Nb-Ti/Cu wire provide magnetic fields that are 2-3 times higher than what can be obtained using permanent magnets for the same pole gap and period length.

SCWs and SCUs, as a rule, have zero first and second magnetic field integrals along electron orbit and their operation does not affect the working reliability of the storage ring.

There is no any basic difference between multipole wiggler and undulator. Phase errors in a magnetic field are more important for undulators as spectrum-angular properties of radiation are formed by all undulator length.

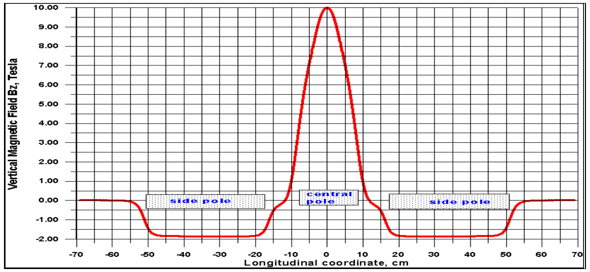
The main parameter of alternating-sign magnetic field which defines radiation property is K-value:

$$K = 0.934 \cdot \lambda_0[\text{cm}] B_0[\text{T}]$$

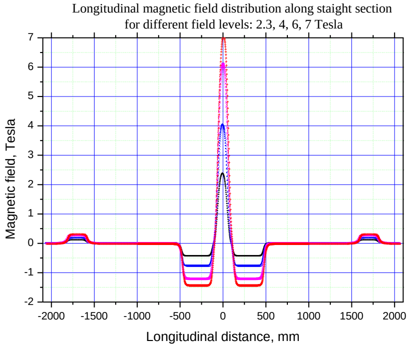
K~1 - undulator.
K>>1 - wiggler

Introduction

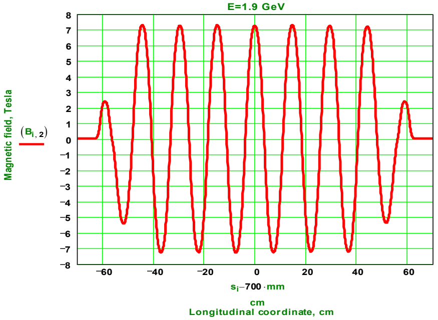
3-pole wiggler (shifter) –main objective is an increasing of radiation rigidity. The central pole is used as a radiation source. The point of radiation is shifted of relatively initial orbit. All three bending magnets are superconducting.



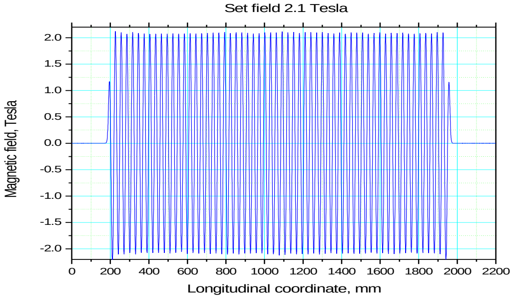
Shifter with the fixed radiation point – The same objective as previous one. The central pole is used as a radiation source. The external normally conducting magnets are used to keep beam orbit on a straight section axis at change of the main field.



Superconducting multipole wiggler – main objective - generation of powerful synchrotron radiation with high photon flux density in the rigid X-ray range. (K>>1)



Superconducting undulator – a basic purpose – generation of spatially coherent undulator radiation of high. (K ~ 1)



History

First superconducting multipole wiggler, BINP, Russia (1979)

The history of SC wiggler used for generation of SR started more than 35 years ago in Budker INP where the first SC MPW was designed and fabricated in 1979. The first SC MPW was installed on the 2 GeV storage ring VEPP-3 to increase photon flux density with higher energy. The cross section of the vacuum chamber of the SCW was like a keyhole where a wide vertical area was used for injection (30 mm), and narrow area (8 mm) was used for creation of magnetic field by the wiggler. The wiggler cryostat was built in the traditional scheme of those times with use of liquid nitrogen and liquid helium with a consumption of approximately 4 l/hr.

Nuclear Instruments and Methods 177 (1980) 239–246
© North-Holland Publishing Company

FIRST RESULTS OF THE WORK WITH A SUPERCONDUCTING "SNAKE" AT THE VEPP-3 STORAGE RING

A.S. ARTAMONOV, L.M. BARKOV, V.B. BARYSHEV, N.S. BASHTOVOY, N.A. VINOKUROV, E.S. GLUSKIN, G.A. KORNIUKHIN, V.A. KOCHUBEI, G.N. KULIPANOV, N.A. MEZENTSEV, V.F. PINDIURIN, A.N. SKRINSKY and V.M. KHOREV
Institute of Nuclear Physics, 630090, Novosibirsk, USSR

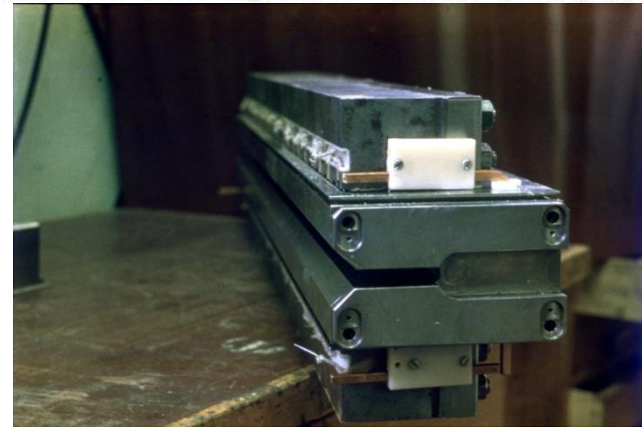
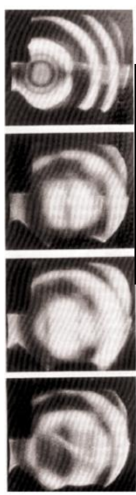


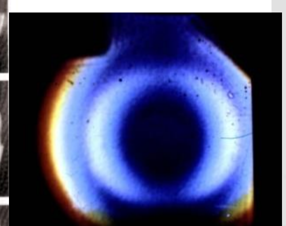
Photo of the wiggler magnet

Pole number	20
Pole gap, mm	15
Period, mm	90
Magnetic field amplitude, T	3.5
Vertical beam aperture, mm	7.8

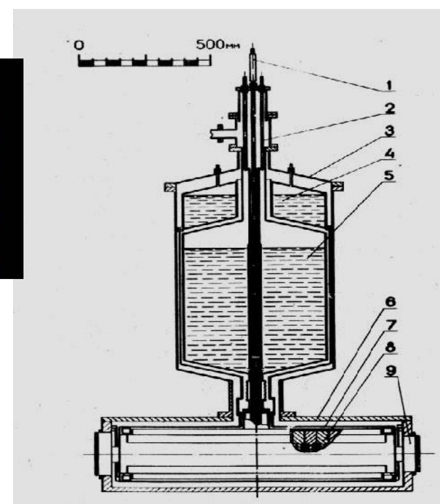
(A)



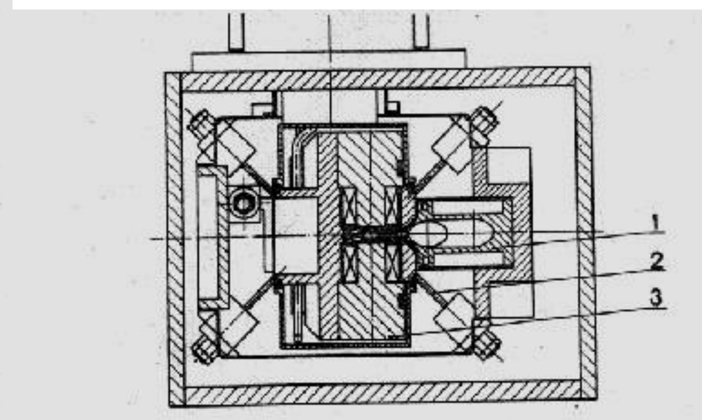
(B)



A) The wiggler cryostat with magnet
B)Undulator radiation from the wiggler



Sketch of the wiggler cryostat



Cross section of the magnet with vacuum chamber

First superconducting undulator, ACO, Orsay, France (1980)

Tome 41 N° 23 1er DÉCEMBRE 1980

LE JOURNAL DE PHYSIQUE-LETTRES

J. Physique — LETTRES 41 (1980) L-547 - L-550 1er DÉCEMBRE 1980, PAGE L-547

Classification
Physics Abstracts
41.70 — 42.72

First results of a superconducting undulator on the ACO storage ring (*) (**)

C. Bazin (1), M. Billardon (2), D. Deacon (3) (†), Y. Farge, J. M. Ortega (2), J. Pérot (4), Y. Petroff and M. Velghe (5)

LURE, Bât. 209 C, Université de Paris-Sud, 91405 Orsay, France.

Abstract. A superconducting undulator has been fixed on the ACO storage ring. It has been observed that the electron beam is stable in the small gap of the vacuum chamber and unperturbed by the magnetic field of the undulator. Light emission has been observed at 140 and 240 MeV in the visible and ultra-violet. First results indicate that its geometrical as well as spectral distribution agree with theoretical predictions; small disagreements
very probably arise from the fact that the electrons are not travelling exactly on the axis of the undulator.

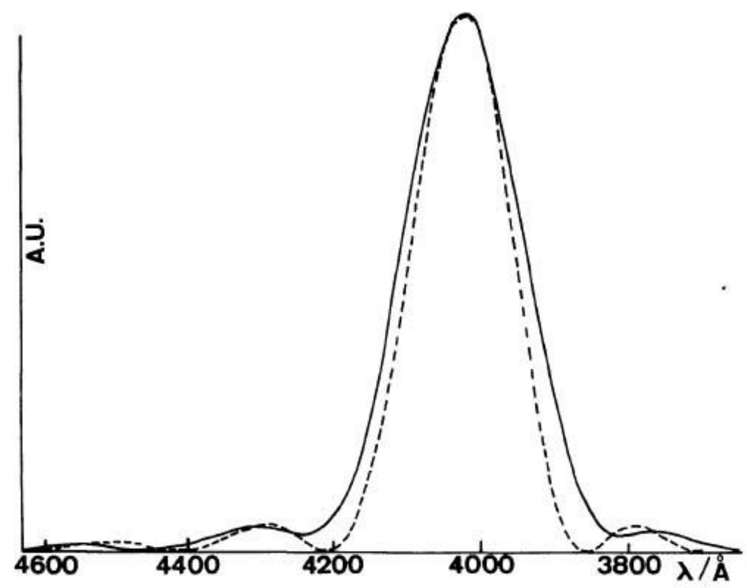
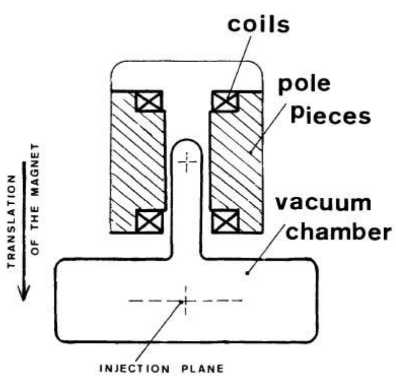


Fig. 4. — Spectral distribution of the emitted light (E = 150 MeV, K = 1.2) through a very small pinhole in the horizontal plane. Experiment : full lines ; Theory : dashed lines.

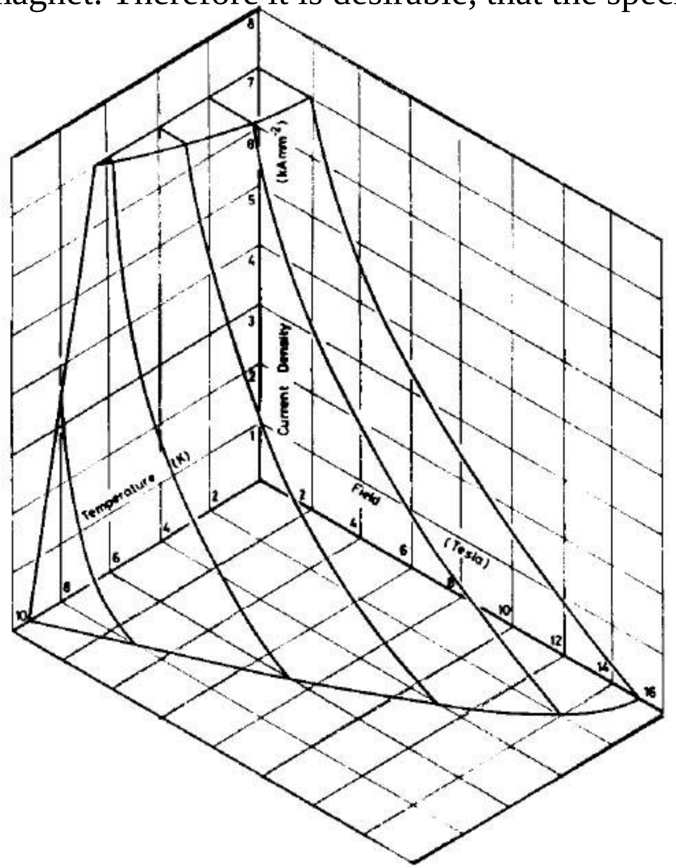


Period	40 mm
Number of periods	23
Effective length	0.96 m
Maximum field Bo	0.45 T (K = 1.68).

Superconducting materials

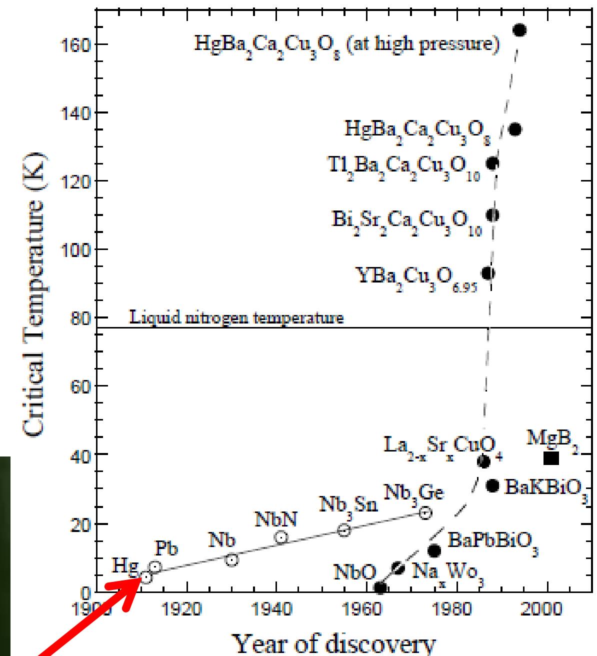
Main properties of SC materials

The greatest interest from the point of view of creation of superconducting magnets represents such properties of superconductors, as critical temperature T_c, density of current J_c and field B_c. These parameters define position of critical surface in space with coordinates T, J and B and, hence, limiting characteristics of a magnet. Therefore it is desirable, that the specified critical parameters had higher values.



The critical surface of niobium titanium: superconductivity prevails everywhere below the surface and normal resistivity everywhere above it.

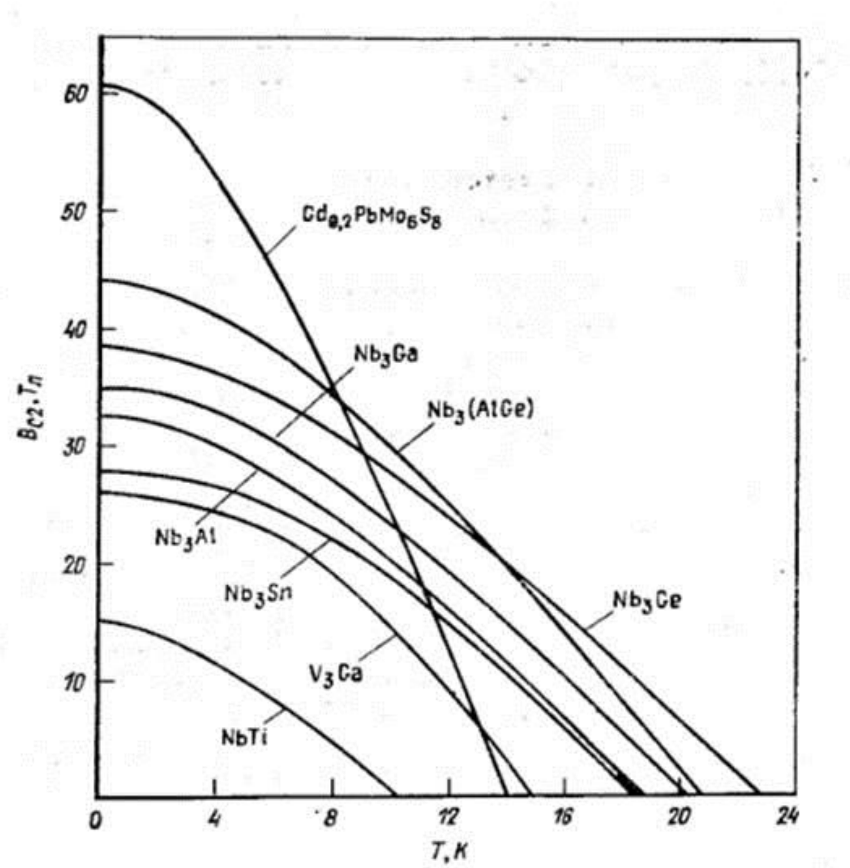
Kamerlingh Onnes



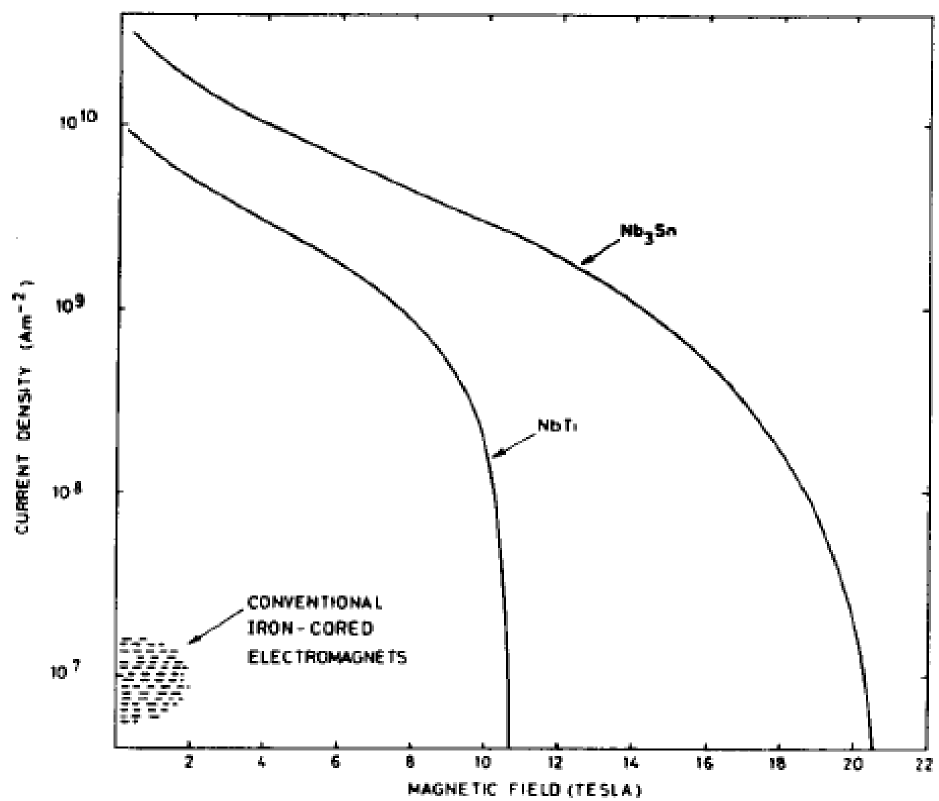
History of critical temperature of SC materials

Main properties of SC materials

B-T (critical field-critical temperature) and B-J (critical field – critical current) diagrams are shown in the figures below for best low temperature superconductors. Most of them exceed superconductors NbTi and Nb_3Sn by maximal magnetic field. However they, as a rule, essentially are more complex in manufacturing, and only two materials V_3Ga and Nb_3Al are possible to receive in the comprehensible form and the sufficient length for winding.



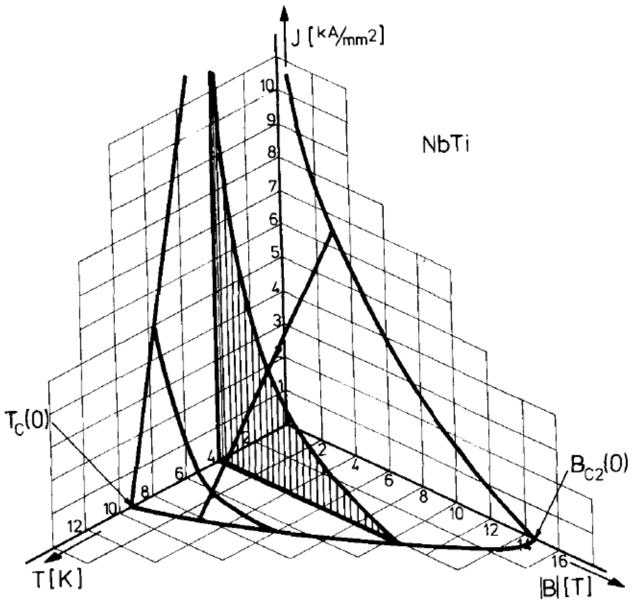
B-T critical curves of most popular SC materials for current in superconductors J=0A

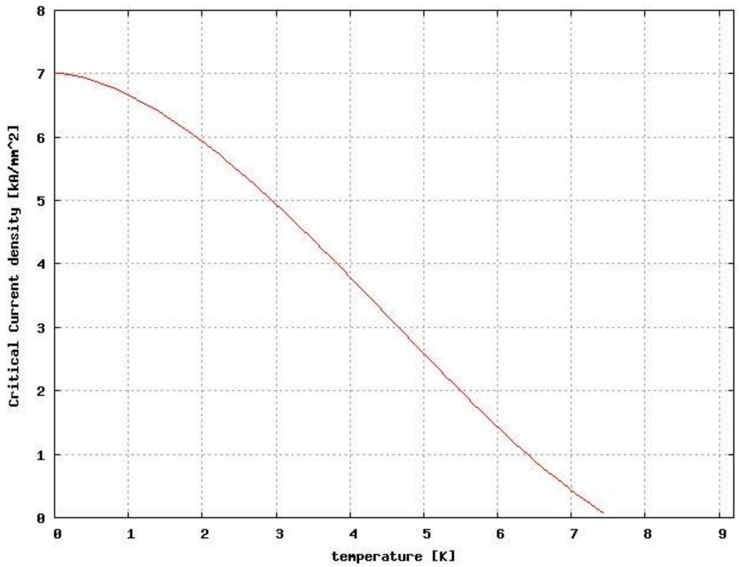


B-J diagrame of Nb_3Sn and NbTi superconductors for 4.2K temperature

Nb-Ti/Cu SC wire

NbTi/Cu superconductor began one of the first to be used as a material suitable for magnet manufacturing. Owing to reliability and simplicity of windings manufacturing it still is the basic superconducting material for various magnets with field up to 8T.





$$B_{C2}(T) = B_{C20}\left[1 - \left(\frac{T}{T_{C0}}\right)^{1.7}\right]$$

Bottura's formula

B_{C2} ~ 14.5 Tesla at T=0K, T_{C0} ~9.2K at B=0T.

$$\frac{J_C(B,T)}{J_{Cref}} = \frac{C_0}{B}\left[\frac{B}{B_{C2}(T)}\right]^{\alpha}\left[1 - \frac{B}{B_{C2}(T)}\right]^{\beta}\left[1 - \left(\frac{T}{T_{C0}}\right)^{1.7}\right]^{\gamma}$$

C_0, α, β и γ – empirical parameters
Typical values: C_0=30T, α=0.6, β=1 и γ=2

NbTi/Cu wire cross section

Nb-Ti/Cu SC wire

There are two basic processes for Nb-Ti/Cu which are used for manufacturing of windings:

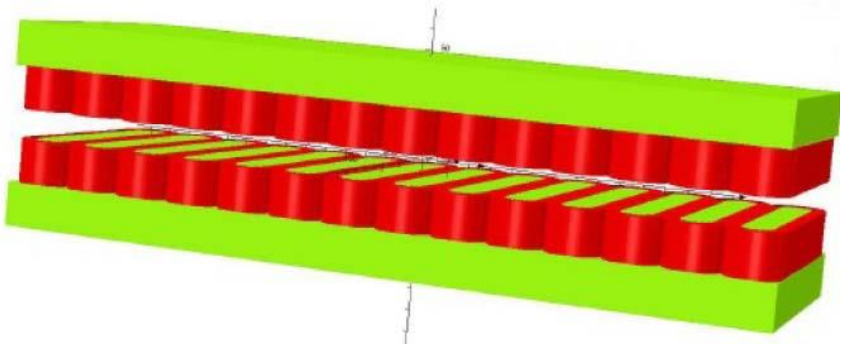
•Wet winding – epoxy coating is used during winding with special fillers for alignment of contraction coefficients between superconducting wire and epoxy coating, for increasing of heat capacity (Al_2O_3, Gd_2O_2S etc)

•Dry winding - vacuum impregnation or impregnation under pressure with hot (120^0C) hardening epoxy coating with corresponding fillers.

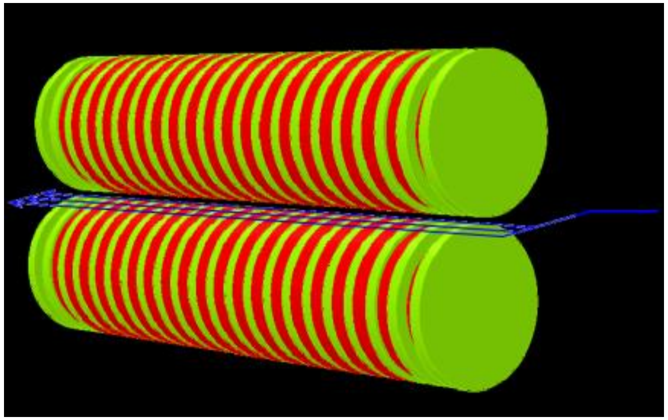
SC coils for multipole wigglers and undulators

Planar coils:

•Horizontal racetrack coils



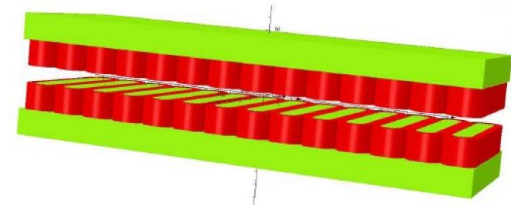
•Vertical racetrack coils

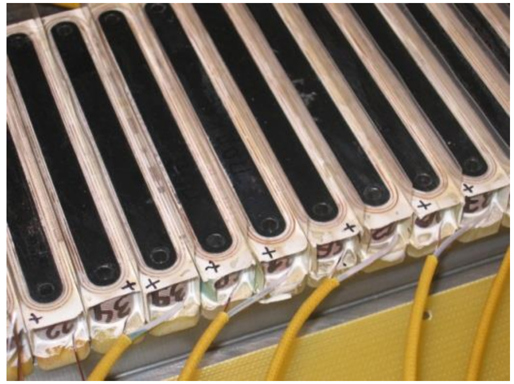


Horizontal racetrack	Vertical racetrack
Short SC wire is required	Long SC wire is required
Large number of splices for large number of poles.	Less number of splices.
Total SC wire length is minimal	Total SC wire length is 3-4 time more.
There is a possibility to make multi sections coils	There is no possibility to make multi section coils
The coils are stressed by bronze rods to compensate magnetic pressure in coils.	There is no possibility to stress coils by external compression
Minimal stored magnetic energy and inductance	Stored energy and inductance is more by 3 times
The coils have good thermo contacts with iron yoke after cooling down due to external compression	The thermo contacts became worth after cooling down. This is important disadvantage for indirect cooling magnets

Horizontal racetrack type (SC wigglers)

Budker Institute of Nuclear Physics

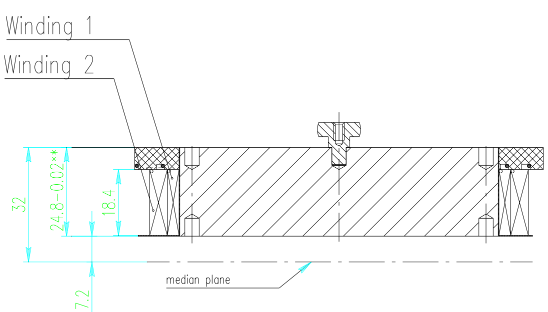


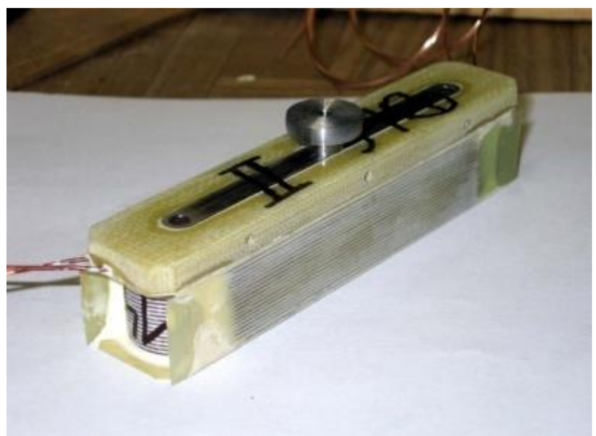


Magnet array of horizontal racetrack type poles (example of 30 mm period SC 2.1T wiggler)

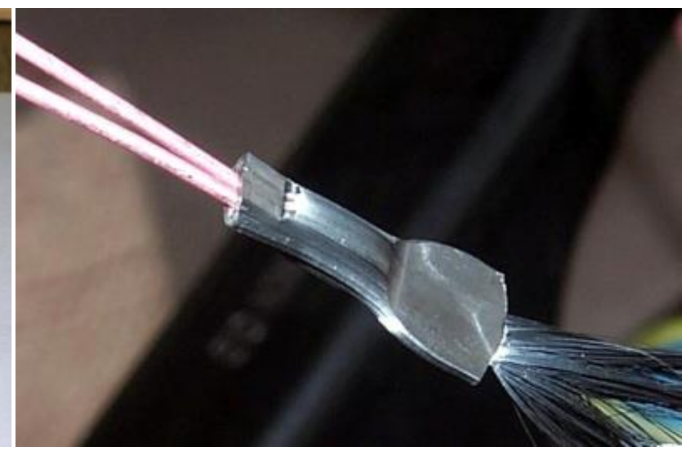
Horizontal racetrack coils assembly allows :

- to pre-stress all coils together for compensation of magnetic pressure
- to use 2 or more sections coils, which gives a possibility to obtain higher field for the same SC wire.





Drawing and photo of racetrack type poles (example of 2-sections coil of 48 mm period 4.2T wiggler



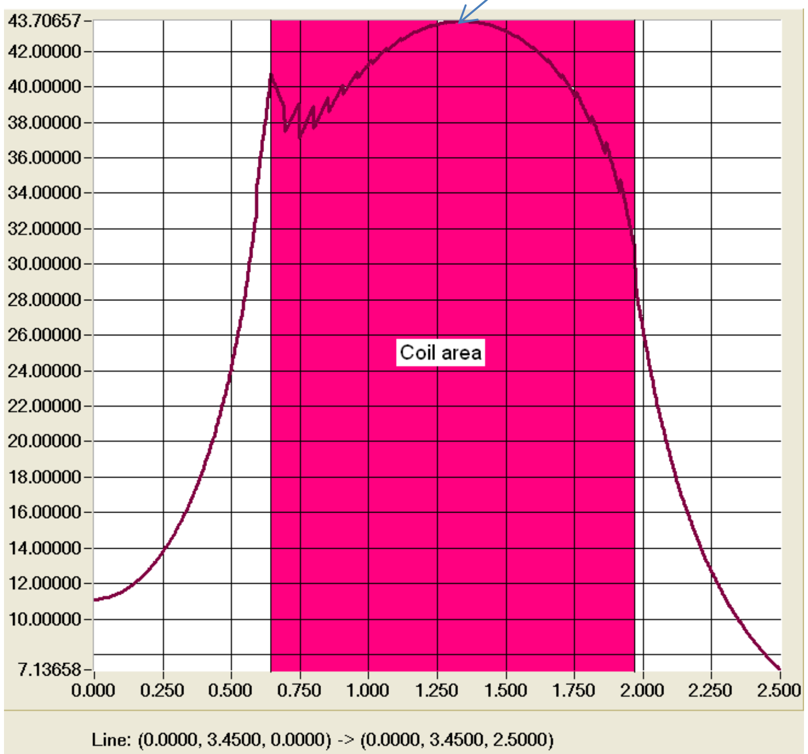
Cold welding method of wires connection gives resistance of the connection 10^{-10}-10^{-13} Ohm

1-section coils (example, SC wiggler)

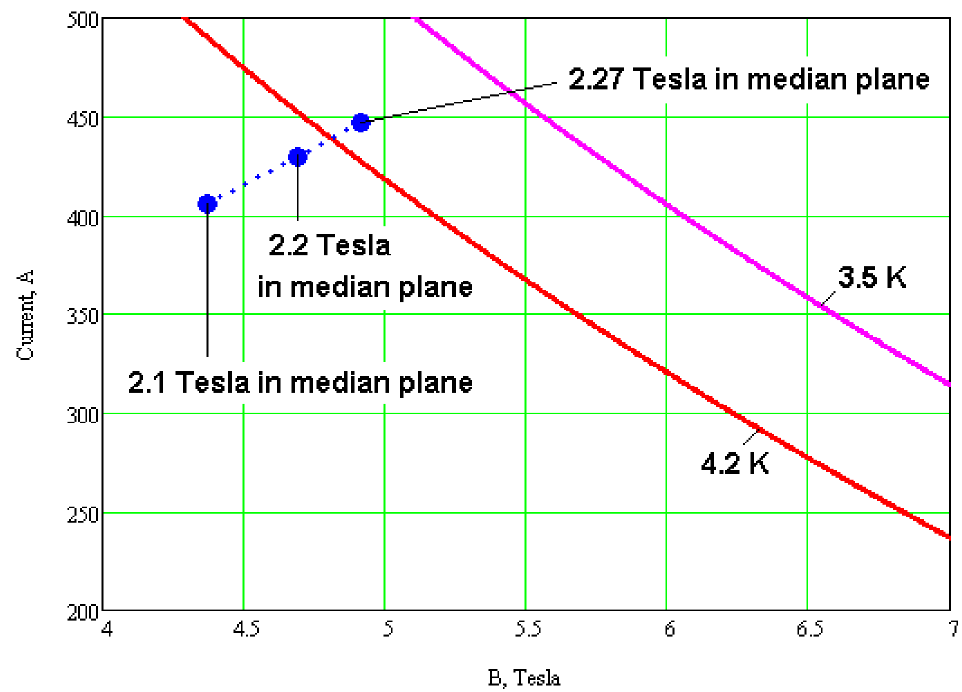
Period, mm	30
Pole gap, mm	12.6
Pole number	119
Nominal field ,T	2.1

Wire parameters:

Wire diameter with/without insulation, mm	0.55/0.5
NbTi/Cu ration	1.4
Number of filaments	312
Diameter of filament, micron	37
Critical current at 7 Tesla, A	236



Magnetic field distribution at the inner radius of the coil along vertical coordinate (B, kGs; z, cm).



Critical current curve of used superconducting Nb-Ti and field-current critical points inside coil correspond to magnetic field in median plane. Temperature decreasing gives a possibility to increase field.

Comparison of one and two sections coils

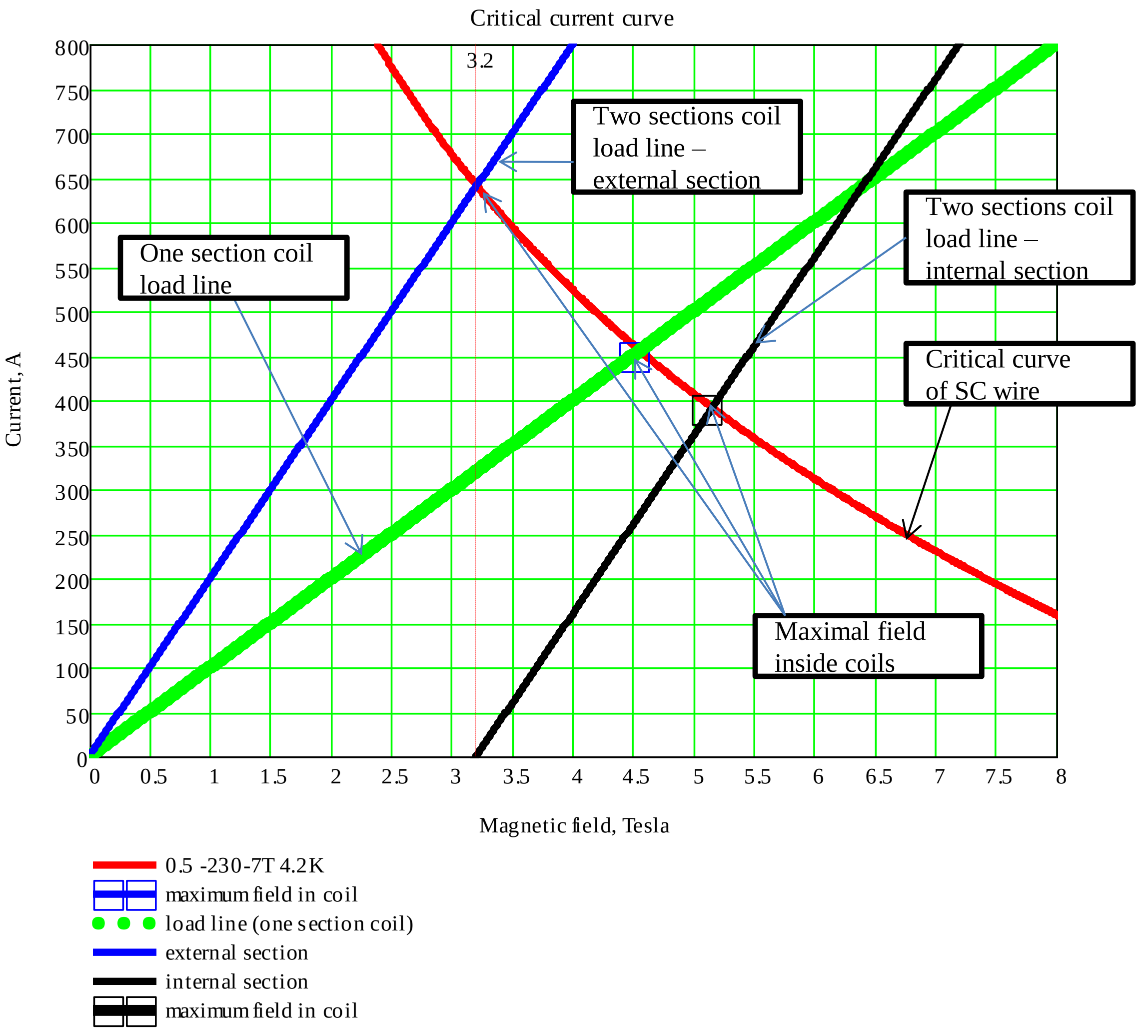


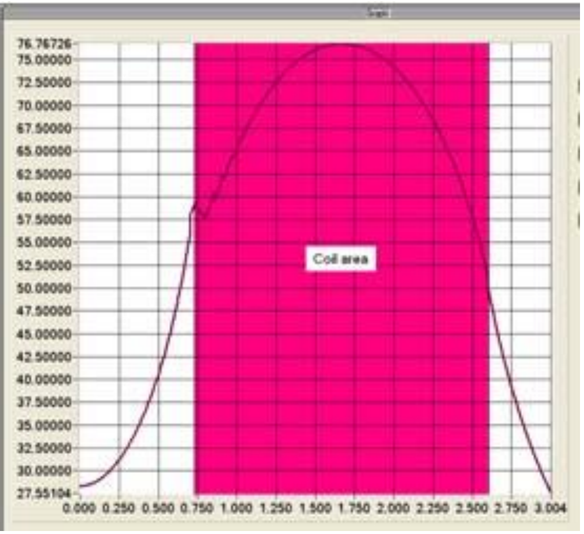
Figure shows a comparison of one and two section coils with identical layer numbers in the coils. The one-section coil reaches a critical current at 450A and field of 4.5T at internal layer. The two-section coil has different currents in sections which simultaneously reach critical values. The external section reaches a current of 649A and field of 3.2T at internal layer of the section. The internal section reaches a current of 380A and field of 5.2T at internal layer of the section. Due to splitting the coil into two sections with equal layer numbers and feeding section with different currents the field value increases by 15 % (5.2T and 4.5T) in comparison with an one-section coil.

2-sections coils (example, SC wiggler)

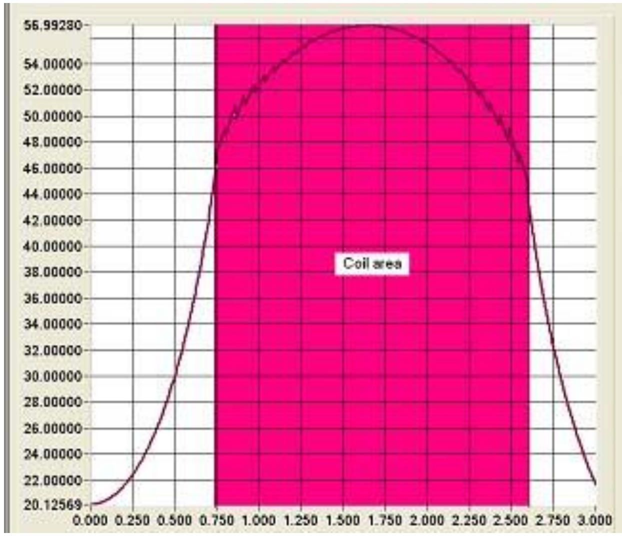
Period, mm	48
Pole gap, mm	14.4
Pole number	49
Nominal field, T	4.1

Wire parameters:

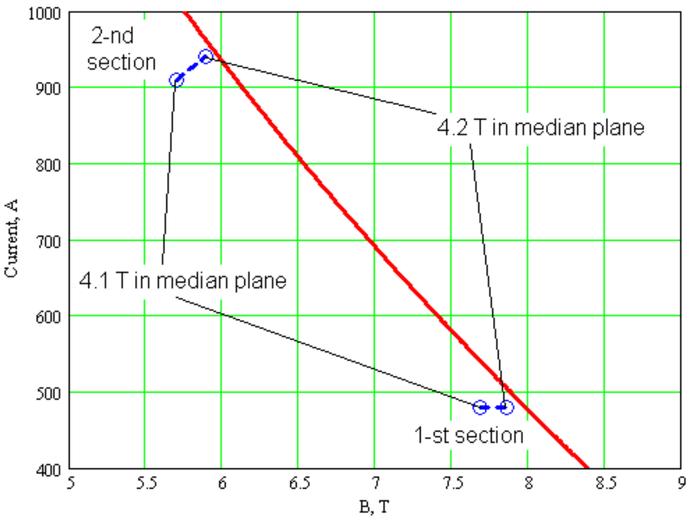
Wire diameter, mm	**0.91/0.85**
NbTi/Cu ration	**1.4**
Number of filaments	**312**
Diameter of filament, micron	**37**
Critical current at 7 Tesla, A	**700**



Magnetic field distribution at the inner radius of the coil 1-st section along vertical coordinate (B, kGs; z, cm).



Magnetic field distribution at the inner radius of the coil 2-nd section along vertical coordinate (B, kGs; z, cm)



Critical current curve of used superconducting Nb-Ti wire (red line) and field-current critical points inside coil correspond to magnetic field in median plane

Two-sections coil gives up to 15% higher field for the same SC wire.

Interpolation formula for the fabricated planar, horizontal racetrack SC wigglers

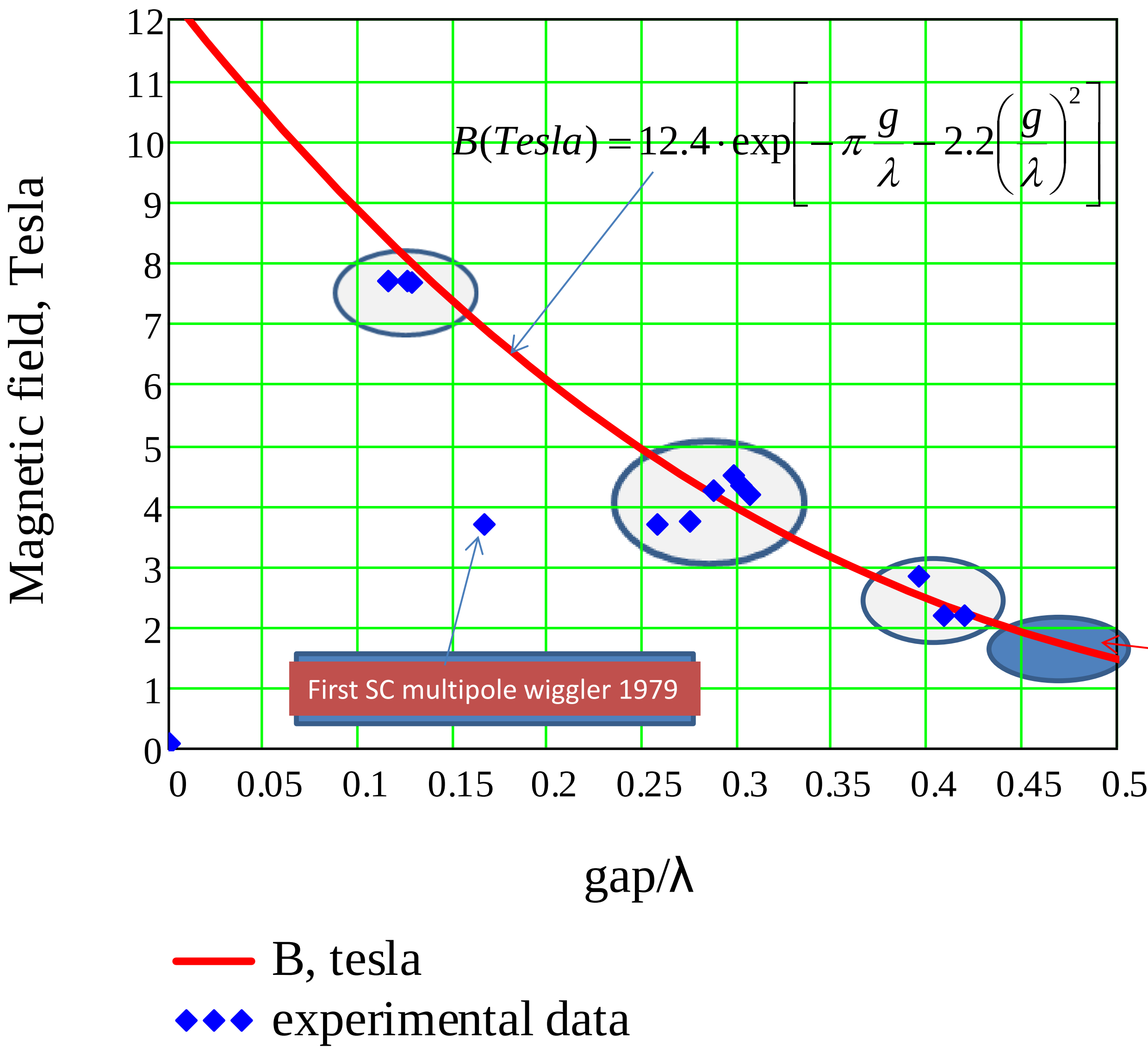


Figure shows the dependance of maximum magnetic field versus gap/λ by the interpolating curve and experimental data of different SC wigglers listed in the table above.

The region which we have a plan to master in the nearest future

Influence of SC ID field on beam dynamics

Orbit inside ID

$$I_1^x(s) = \int_{-L/2}^{s} ds' B_z(s'),$$

First field integral

$$x_0'(s) = \frac{I_1^x(s)}{B\rho}$$

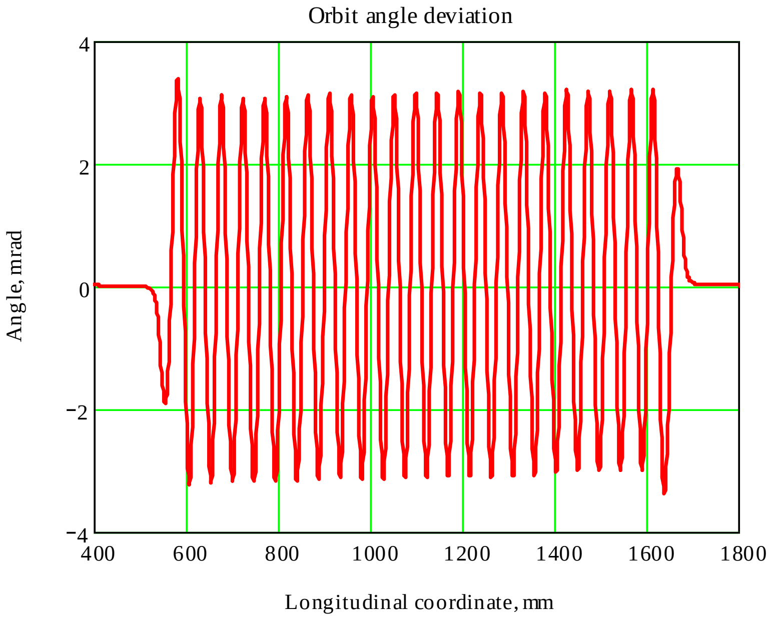
Angle of electron orbit
Inside a wiggler

$$I_2^x(s) = \int_{-L/2}^{s} ds' \int_{-L/2}^{s'} ds'' B_z(s'')$$

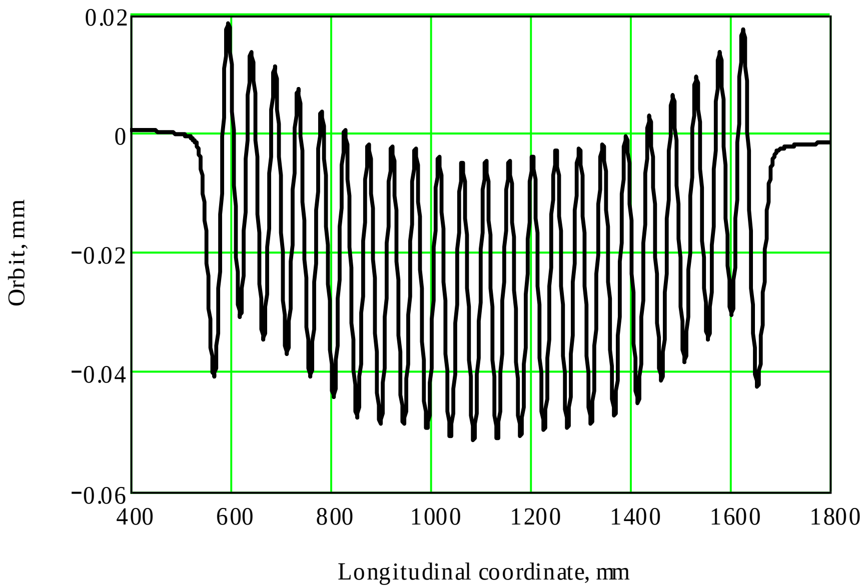
Second field integral

$$x_0(s) = \frac{I_2^x(s)}{B\rho}$$

Electron orbit
Inside a wiggler



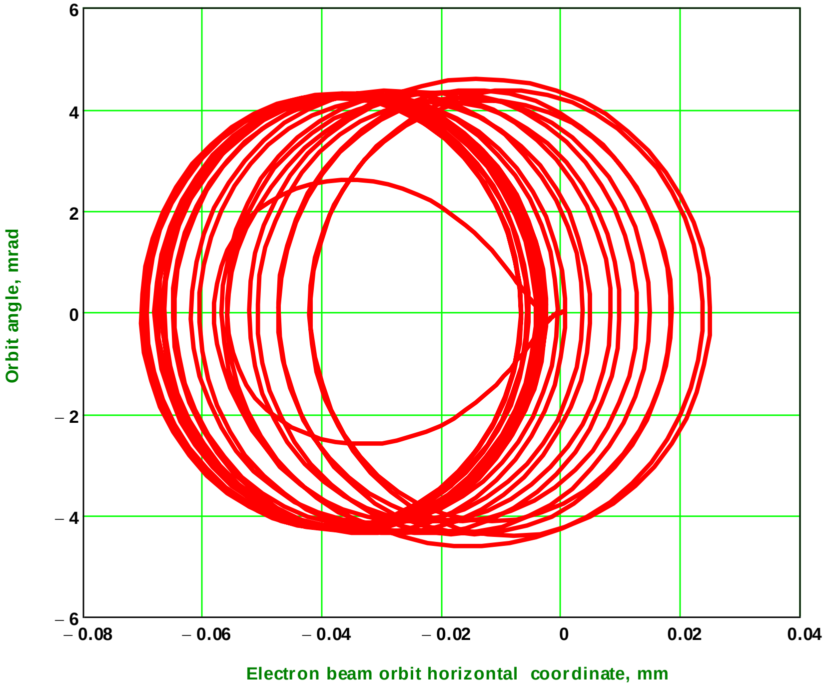
Angle orbit deviation inside 49-pole wiggler at field setting 4.2 Tesla, E=3 GeV



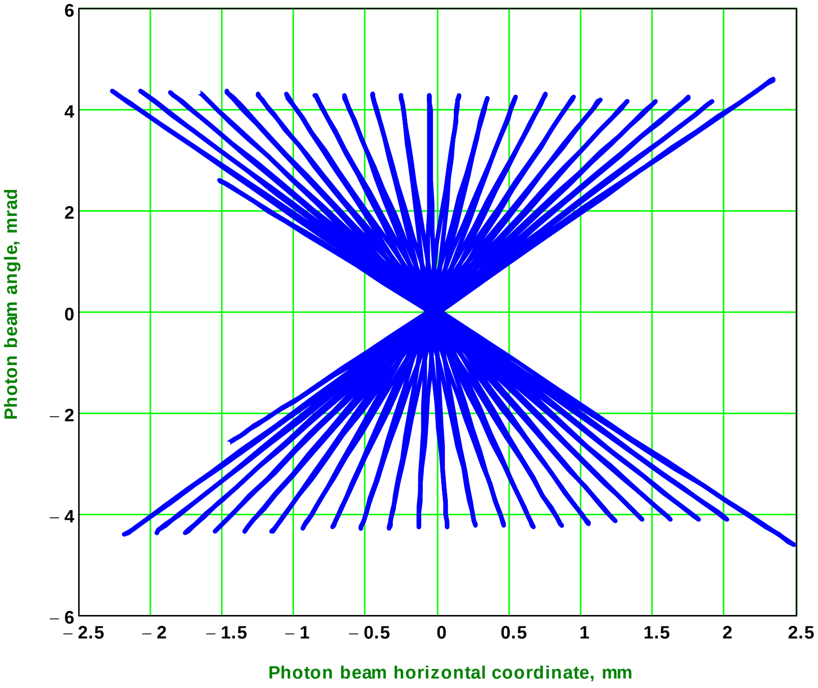
Orbit distortion inside 49-pole wiggler at field setting 4.2 Tesla, E=3 GeV

Phase space of electron orbit and photon beam

Electron beam orbit phase space



Photon beam phase space reduced to the wiggler center



Focusing property of SC ID

$$x'' + K_x \cdot x = 0$$

$$z'' + K_z \cdot z = 0$$

Betatron motion equations

Local and integral focusing rigidity

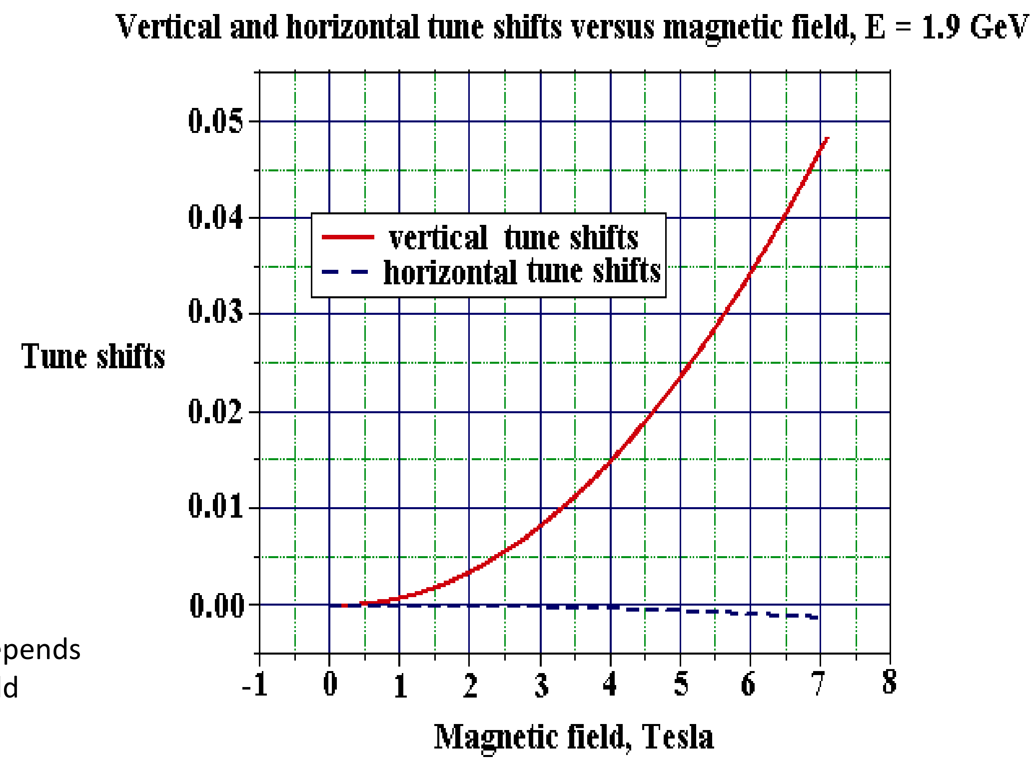
$$K_x = \frac{B_z^2}{(B\rho)^2} + \frac{1}{B\rho}\left(x' \frac{\partial B_z}{\partial s} - \frac{\partial B_z}{\partial x} \right)$$

$$K_z = -\frac{1}{B\rho}\left(x' \frac{\partial B_z}{\partial s} - \frac{\partial B_z}{\partial x} \right)$$

$$\int_{-L/2}^{L/2} K_x ds = -\frac{\partial}{\partial x} \int_{-L/2}^{L/2} \frac{B_z ds}{B\rho}$$

Integral value of *Kx* depends on gradient of first field integral

$$\int_{-L/2}^{L/2} K_z ds = \int_{-L/2}^{L/2} \frac{B_z^2}{B\rho^2} ds - \int_{-L/2}^{L/2} K_x ds$$



Vertical and horizontal betatron tune shifts for BESSY SC 7 T WLS versus magnetic field level.

Radiation (structural) integrals:

$$\Delta I_1 = \int_L \frac{(\eta_{x0} - x(s))B_z(s)}{B\rho} ds$$

$\alpha_x, \beta_x, \gamma_x$ are Twiss parameters

$$\Delta I_2 = \int_L \frac{B_z^2(s)}{B\rho^2} ds$$

$$\Delta I_3 = \int_L \frac{|B_z(s)|^3}{B\rho^3} ds$$

$$\Delta I_4 = \int_L \left(\frac{B_z^3(s) \cdot}{B\rho^3} - \frac{2K_x}{B\rho} \right)(\eta_{x0} - x(s)) ds$$

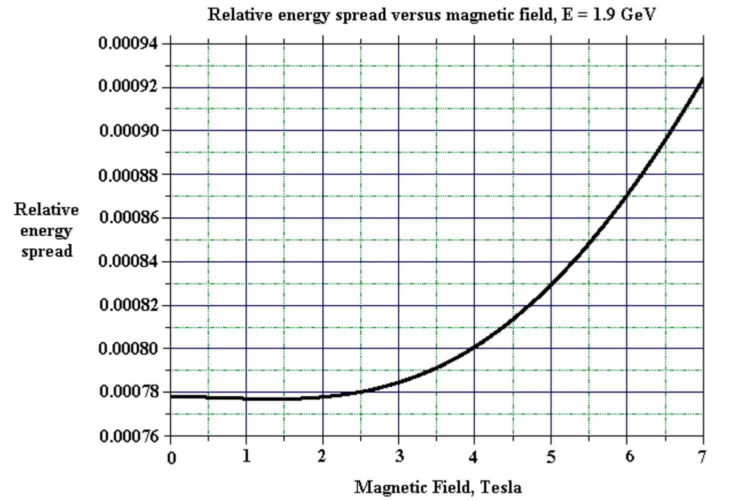
$$\Delta I_5 = \int_L \frac{|B_z(s)|^3}{B\rho^3} \left(\gamma_x(\eta_{x0} - x(s))^2 + 2\alpha_x(\eta_{x0} - x(s))(\eta'_{x0} - x'(s)) + \beta_x(\eta'_{x0} - x'(s))^2 \right) ds$$

$$\left(\frac{\sigma'_E}{\sigma_E} \right)^2 = \frac{1 + \dfrac{\Delta I_3}{I_3^0}}{1 + \dfrac{2\Delta I_2 + \Delta I_4}{2I_2^0 + I_4^0}} \approx 1 + \frac{\Delta I_3}{I_3^0} - \frac{\Delta I_{24}}{I_2^0}$$

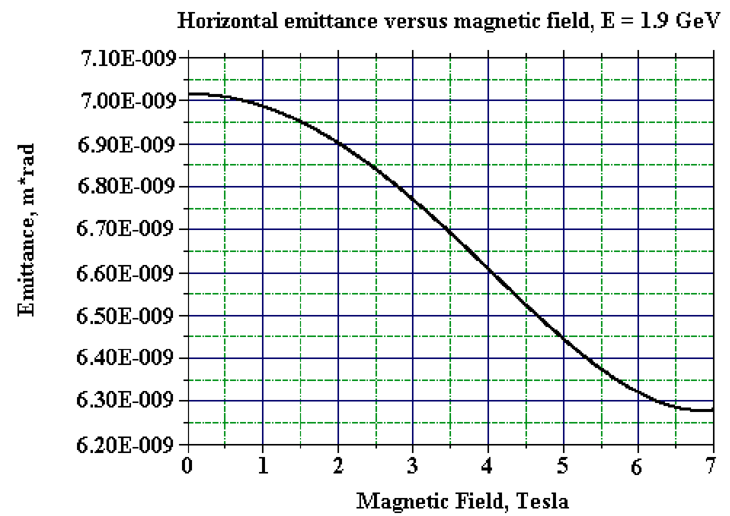
Energy spread change

$$\frac{\varepsilon'_x}{\varepsilon_x} = \frac{1 + \dfrac{\Delta I_5}{I_5^0}}{1 + \dfrac{\Delta I_2 - \Delta I_4}{I_2^0 - I_4^0}} \approx 1 + \frac{\Delta I_5}{I_5^0} - \frac{\Delta I_2}{I_2^0}$$

Emittance change



Energy spread in BESSY storage ring versus magnetic field level in SC 7 T WLS.



Horizontal emittance BESSY storage ring versus magnetic field level in SC 7 T WLS.

SC wiggler field, multipole components

$$B_z = B_0 \cos(k_0 s)\cos(k_x x)\cosh(k_z z)$$
$$B_x = -\frac{k_x}{k_z} B_0 \cos(k_0 s)\sin(k_x x)\sinh(k_z z)$$
$$B_s = -\frac{k_0}{k_z} B_0 \sin(k_0 s)\cos(k_x x)\sinh(k_z z)$$
$$k_z^2 = k_0^2 + k_x^2$$

Magnetic field measurements of an ID are usually carrying out in Cartesian coordinates which will have designations ***x, z, s***, thus the axis ***s*** coincides with a longitudinal axis of an ID, ***x*** and ***z*** are horizontal and vertical directions correspondingly. Planes z = 0, x = 0, s = 0 are corresponding planes of symmetry of magnetic systems:

If magnetic system is homogeneous enough so that orbit deviation is much less than characteristic size of field decrease, the formulas may be simplified:

δ **–** a shift off wiggler axis in x direction, ***Lw*** – wiggler length, ***Bρ*-** beam rigidity

First field integral

$$\int B_z(s)ds = \frac{B_0^2}{2B\rho}\frac{k_x^2}{k_0^2}L_w\delta$$

Gradient integral in x-direction

$$\int G_v(s)ds = \frac{B_0^2}{2B\rho}\left(1+\frac{k_x^2}{k_0^2}\right)L_w$$

Gradient integral in z-direction

$$\int G_h(s)ds = -\frac{B_0^2}{2B\rho}\frac{k_x^2}{k_0^2}L_w$$

Sextupole integral

$$\int S(s)ds = \frac{B_0^2}{2B\rho}\left(2+\frac{k_x^2}{k_0^2}\right)k_x^2\cdot\delta\cdot L_w$$

Octupole integral

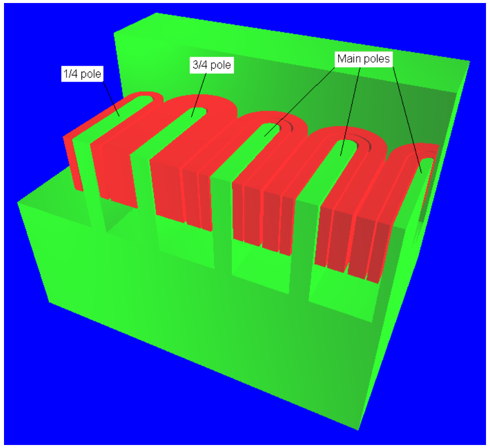
$$\int O(s)ds = -\frac{3B_0^2}{8B\rho}\left(4k_x^2+\frac{B_0^2}{B\rho^2}\right)L_w$$

High field superconducting wigglers (7-10 Tesla)

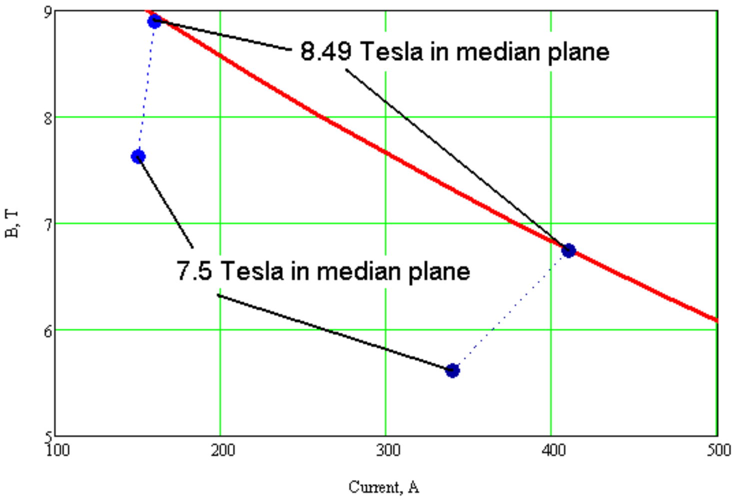
High field superconducting wigglers

Superconducting wire for high field wigglers:

Diameter (mm)	0.85 (0.91 with insulation)
Ratio of NbTi:Cu	0.43
Critical Current of modified/enhanced SC wire (A)	>360 (at 7 Tesla)
Number of NbTi filaments	8600



Two sections coils are used in high field wigglers. Period of the multipole wigglers is 148-200 mm.



Critical curve of SC wire and load lines for 1st and 2nd sections of a winding

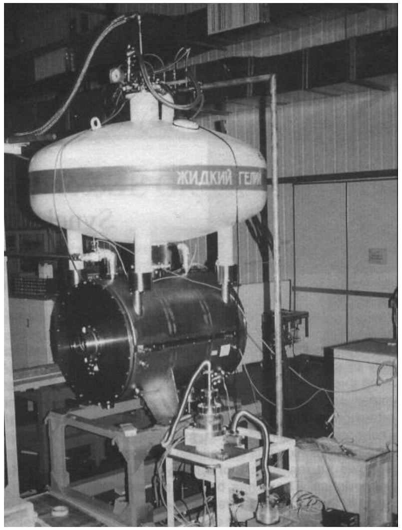
The main features of high field wigglers:

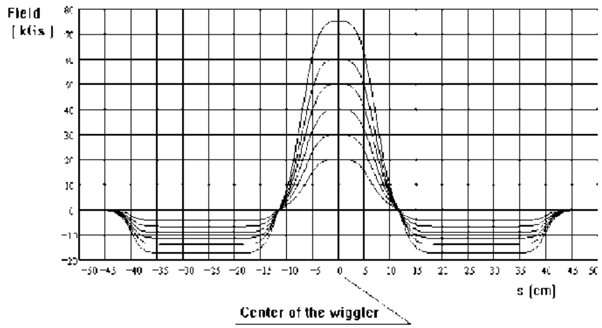
- High stored energy 400-900 kJ;
- Protection system contains cold diods and energy extraction system
- High pressure inside coils > 400 bar;
- Wide vacuum chamber due to large fan angle of radiation;
- Large influence of wiggler field on beam dynamics;
- High radiated power
- Bath cryostat with cryocoolers is used for this type of wiggler

High field superconducting wigglers

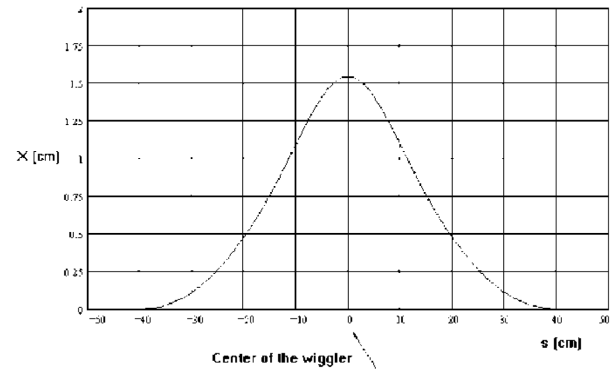
1993-1995

7.5 T SC WLS for Pohang Light Source





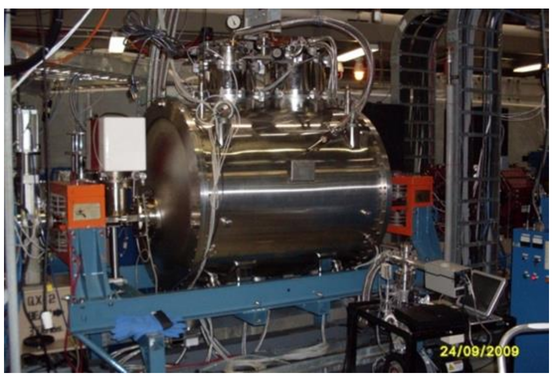
Longitudinal field distribution



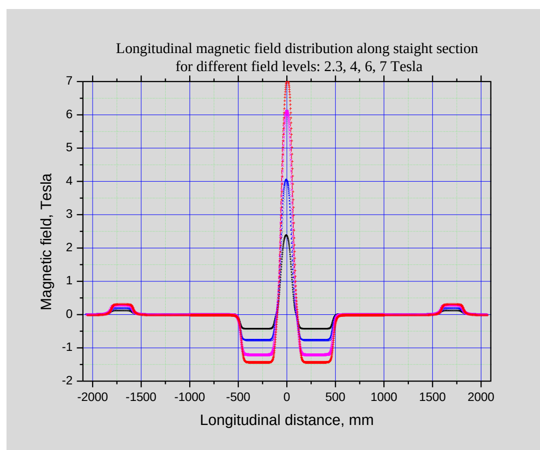
Orbit inside the WLS

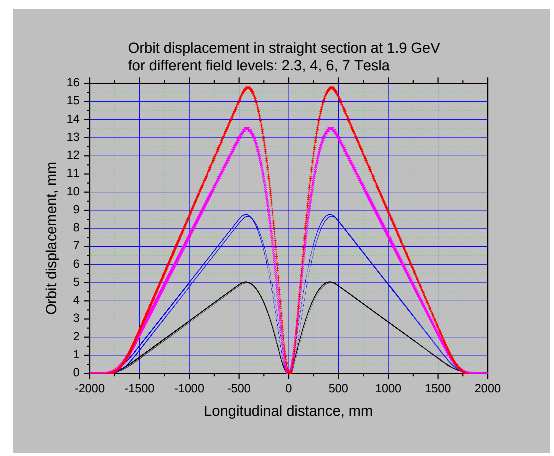
1995-1998

7T SC WLS for CAMD LSU with fixed point of radiation



2009 – cryostat upgrade

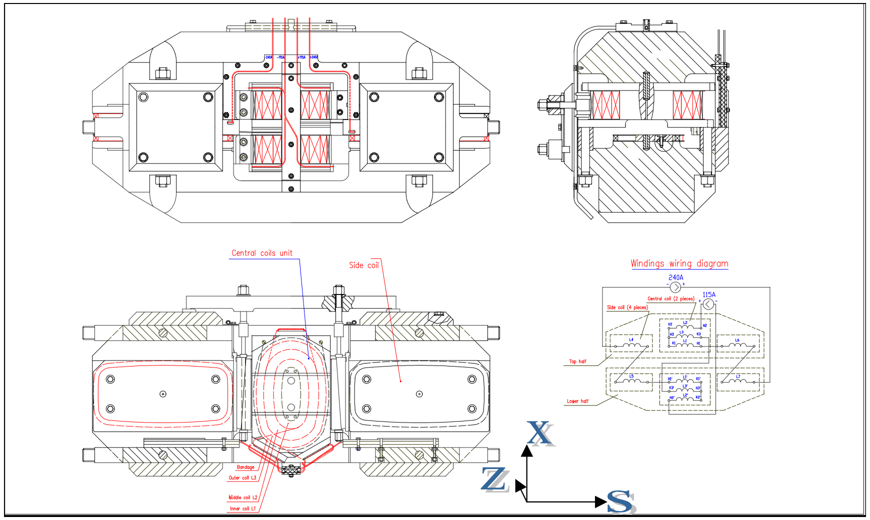




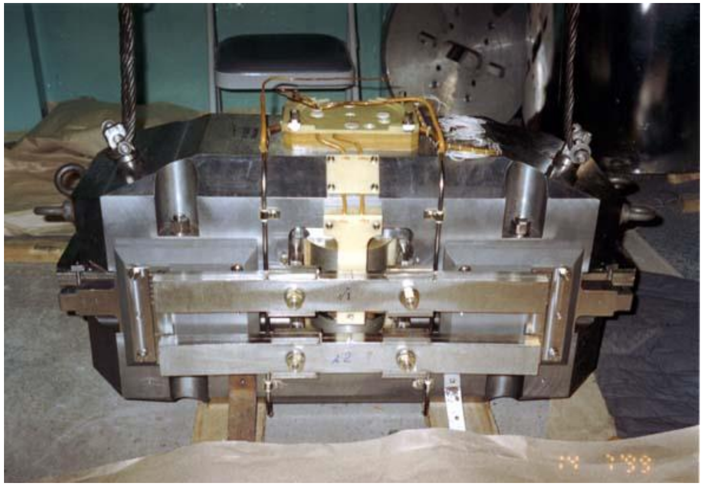
Two more similar WLSs successfully are functioning more than 16 years in BESSY-2 storage ring

High field superconducting wigglers

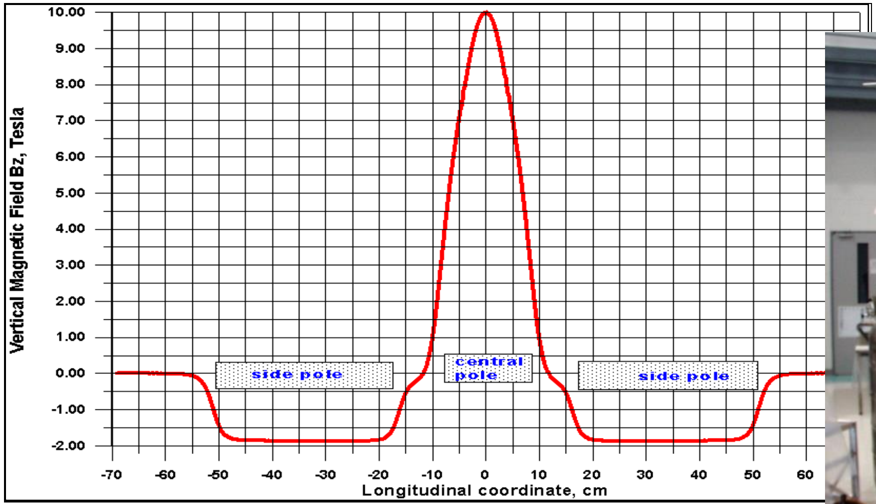
10 Tesla WLS for Spring-8, Japan



Superconductor Nb3Sn/Cu +NbTi/Cu



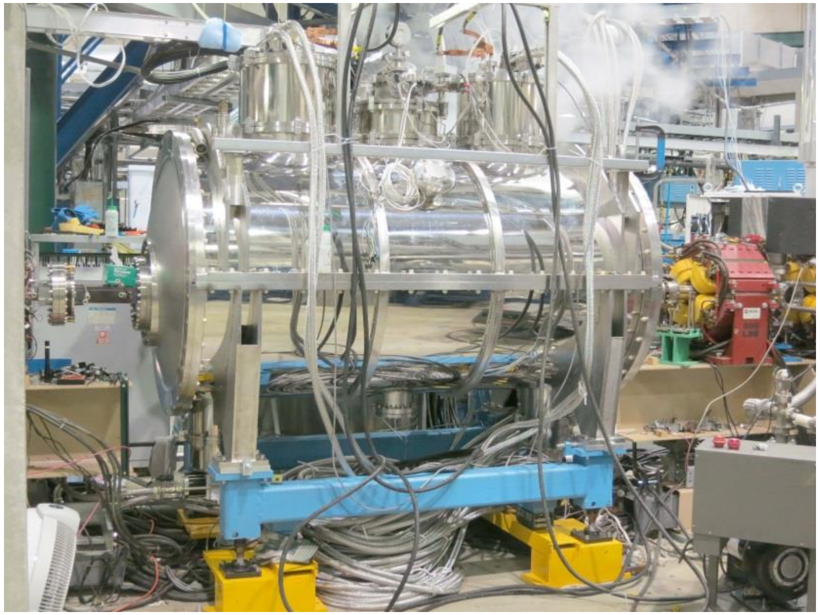
Superconducting 10 T WLS magnet

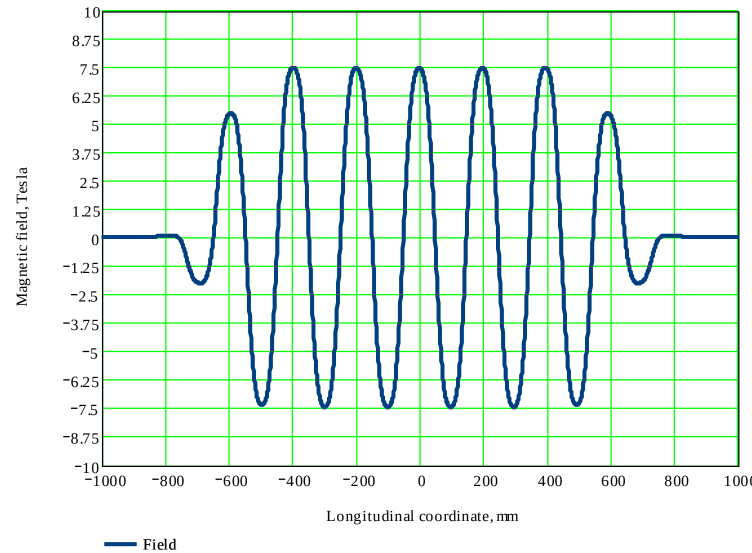


Longitudinal field distribution

Magnetic field measurements of 10 T WLS

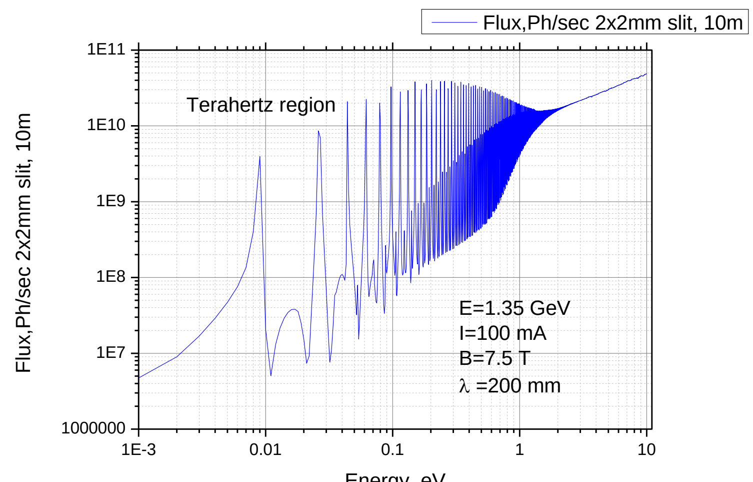
High field superconducting wigglers





Longitudinal magnetic field distribution in the wiggler

CAMD LSU, USA 2013
15pole SC wiggler
Field 7.5 T
Pole gap 25.2 mm
Period 193 mm
Beam energy 1.35 GeV



Low photon energy spectrum of 7.5 T wiggler at CAMD 1.35 GeV (K=148)

Similar wigglers are successfully working at BESSY-2 (7T, 17 pole, 2002) and Siberia-2 (7.5T, 21 pole, 2007) .
7 T wiggler is planned to build for DELTA, Germany

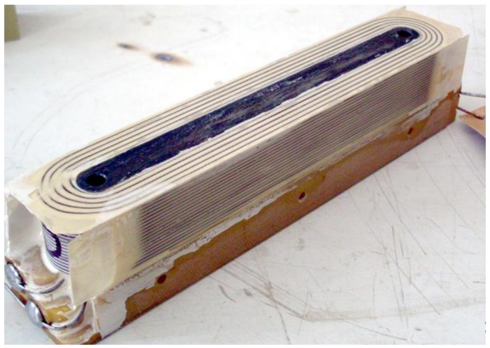
Medium field superconducting wigglers (2.5-4.5 Tesla)

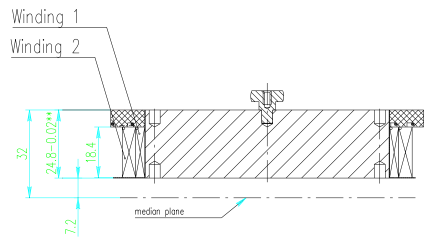
Medium field superconducting wigglers

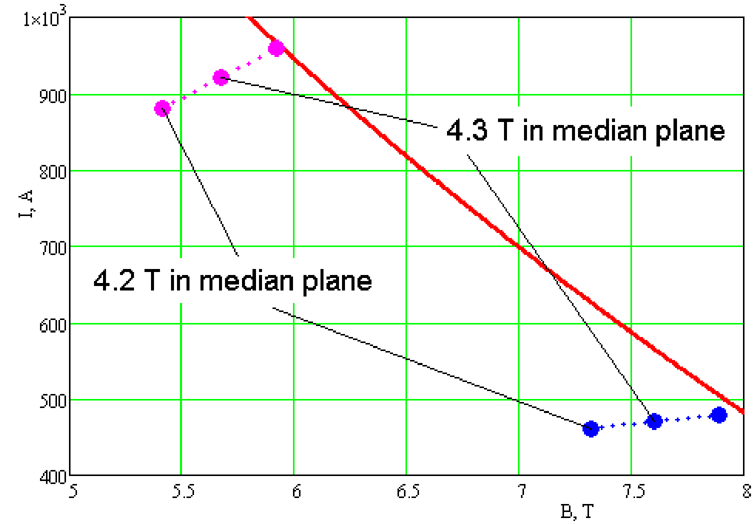
Parameters of the superconducting wire:

Wire diameter, mm	0.91/0.85
NbTi/Cu ration	1.4
Number of filaments	312
Diameter of filament, micron	37
Critical current at 7 Tesla at 4.2K, A	700

Two sections coils are used in high field wigglers.
Period of the multipole wigglers is 48-60 mm.



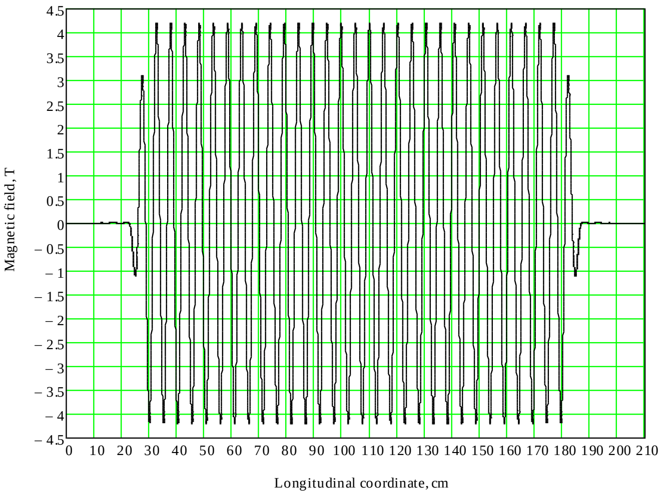




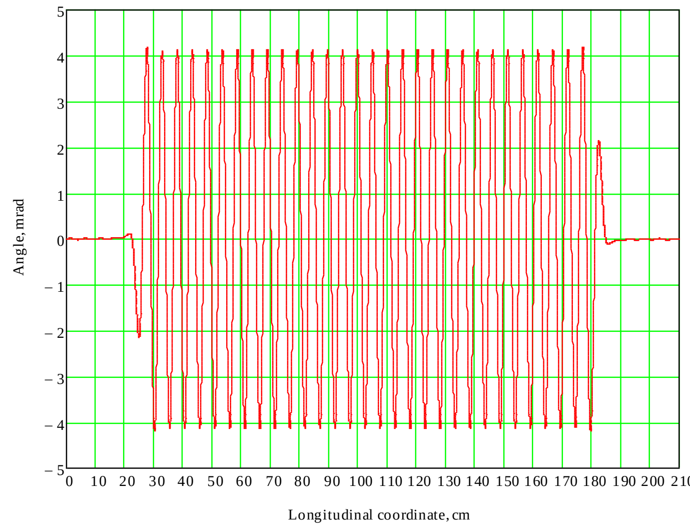
Critical current curves (4.2K) for superconducting wire (red curve). Pink dots – maximal field inside external section of the coil, blue dots - maximal field inside internal section of the coil for field level on median plane 4.2T and 4.3T for wiggler period 52 mm and pole gap 15.2 mm.

- **1979 – first 3.5 T 20 pole superconducting wiggler for VEPP-3 storage ring**
- **2002 - 3.5 T superconducting 49-pole wiggler (SCW) for ELETTRA, Italy – 2013 – cryostat ugrade**
- **2006 - 3.5 T superconducting 49-pole SCW for DLS, England**
- **2007 - 4 T superconducting 27- pole SCW for CLS, Canada**
- **2008 - 4 T superconducting 49-pole SCW for DLS, England**
- **2009 - 4 T superconducting 35 - pole SCW for LNLS, Brasil**
- **2012 – 4.2 T superconducting 63 - pole SCW for AS, Australia**
- **2014 - 2.5 T superconducting 44-pole wiggler for ANKA-CATACT, Germany**
- **2015 – 3 T superconducting 72-pole wiggler for ANKA/CLIC, Germany**

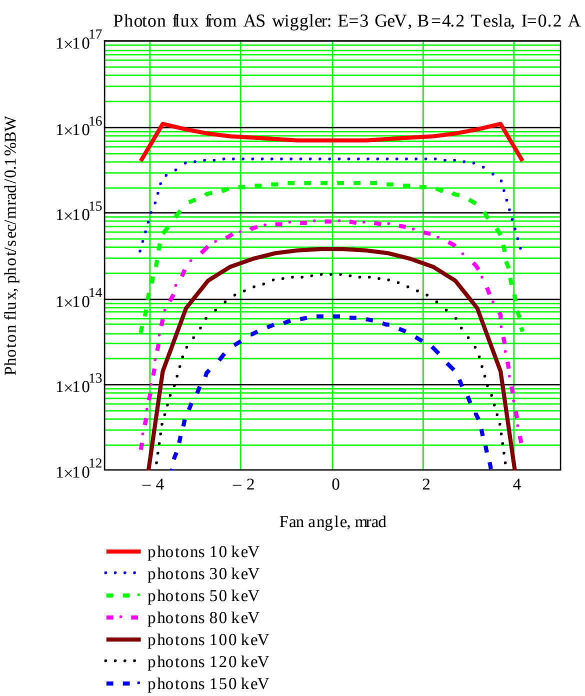
Medium field superconducting wigglers



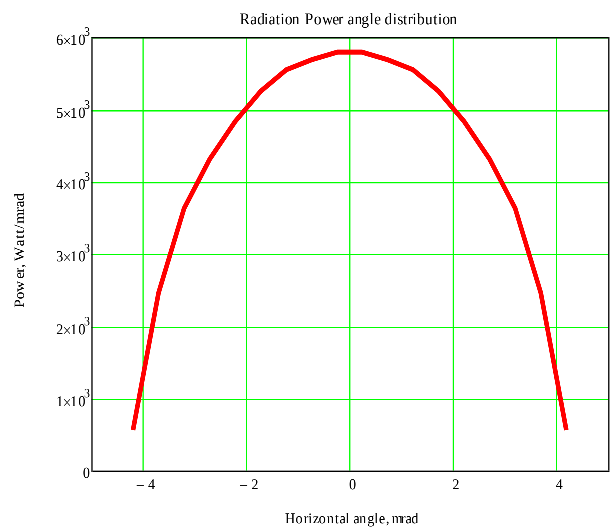
Magnetic field distribution for magnet with field 4.2 T Stored energy is about 35-45 kJ



Orbit angle deviation inside the wiggler: B0=4.2 T, E=3 GeV



Angle-spectral photon distribution from the wiggler: B0=4.2T, E=3 GeV, I=0.2 A

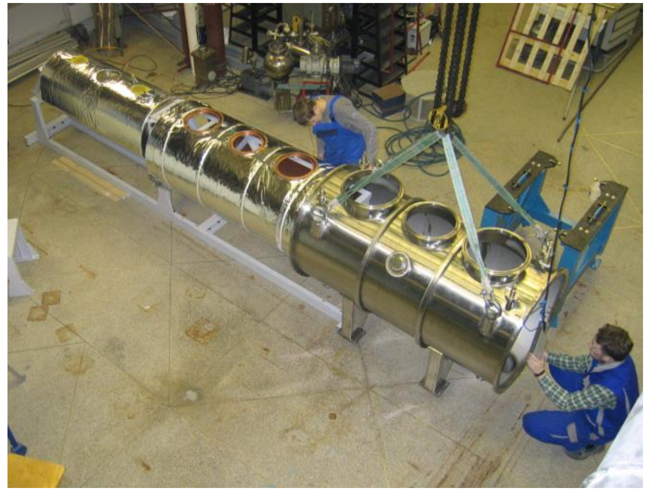


Angle power distribution from the wiggler: B0=4.2T, E=3 GeV, I=0.2 A (total radiated power ~37.5 kW)

Medium field superconducting wigglers

4.2 Tesla 49-pole superconducting wiggler DLS (England)

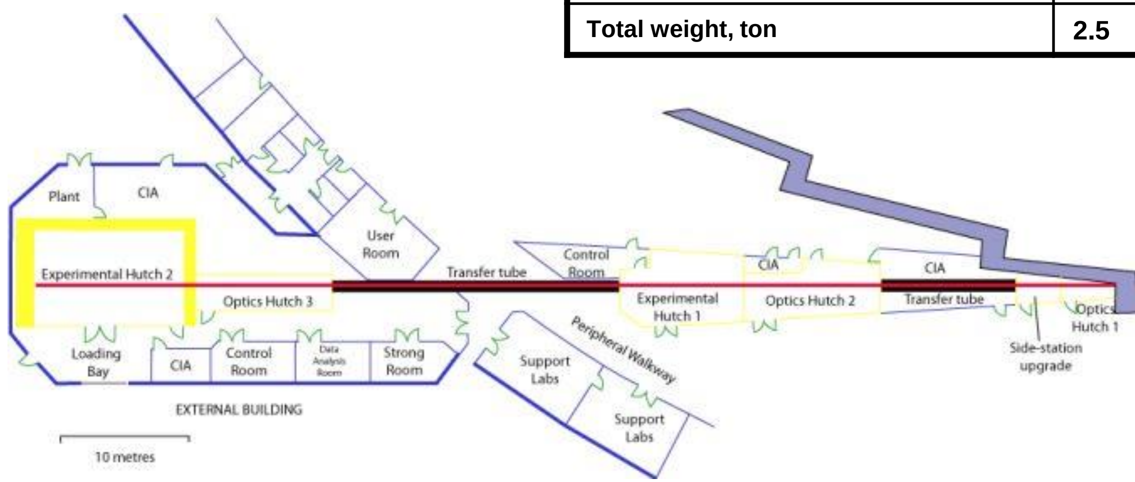
I12 beamline - JEEP: Joint Engineering, Environmental and Processing



Wiggler assembling on site

Pole number (main + side)	45+4
Vertical beam aperture, mm Horizontal beam aperture, mm	10 60
Pole gap, mm	14.4
Period, mm	48
Maximal field, Tesla Nominal field, Tesla	4.34 4.2
Two section windings, material – Nb-Ti Currents in sections at 4.2 Tesla, A internal section external section	 415 870
Stored energy, kJ	47
Liquid helium consumption, liter/ hour	<0.03
Total weight, ton	2.5

Main Research Techniques: (50-150 кэВ)
Imaging and tomography, X-ray diffraction, Small Angle X-ray Scattering (SAXS), Single Crystal Diffraction, Powder diffraction



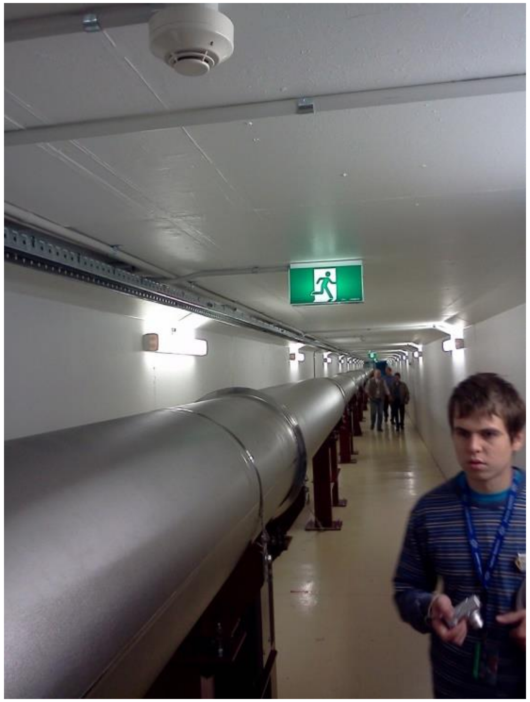
Medium field superconducting wigglers

4.2 Tesla 63 pole superconducting wiggler ASHo(Australia)

Field Direction	Vertical
Nominal peak on axis field, B_o	4.2 T
Maximum peak on axis field	4.3 T
Period length	52 mm
Number of pole pairs @ full field	59
Number of pole pairs @ ¼ field	2
Number of pole pairs @ ¾ field	2
Field sequence	¼, -¾, 1, -1, 1… 1, -¾, ¼
Transverse field homogeneity at all field levels	$\leq$ 0.03% at x = $\pm$ 5 mm $\leq$ 0.50% at x = $\pm$ 10 mm at z = 0
Max. Stray field on axis at each end of the cryostat	10^{-3} T
Ramping time, 0 to nominal peak field, up or down	$\leq$ 5 min
Full vertical aperture available to the electron beam on axis	10mm
Full horizontal aperture available to the electron beam on axis	60 mm

Medium field superconducting wigglers

4.2 Tesla 63 pole superconducting wiggler ASHo(Australia)



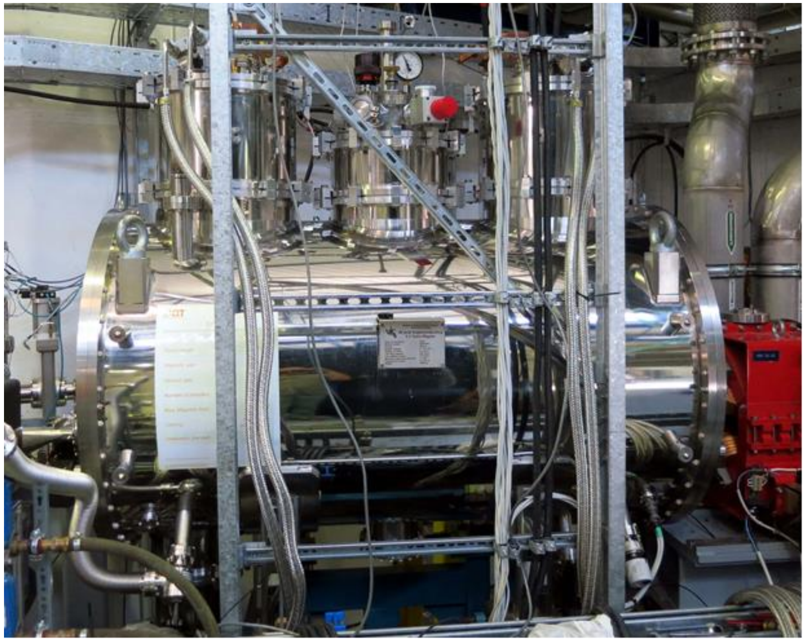
140 m long Imaging and medical beamline

First photon beam at the beamline end.

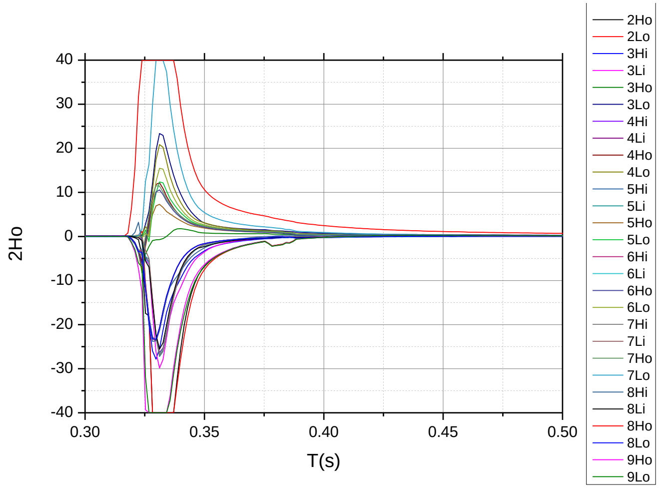
End of beamline- extraction window

Medium field superconducting wigglers

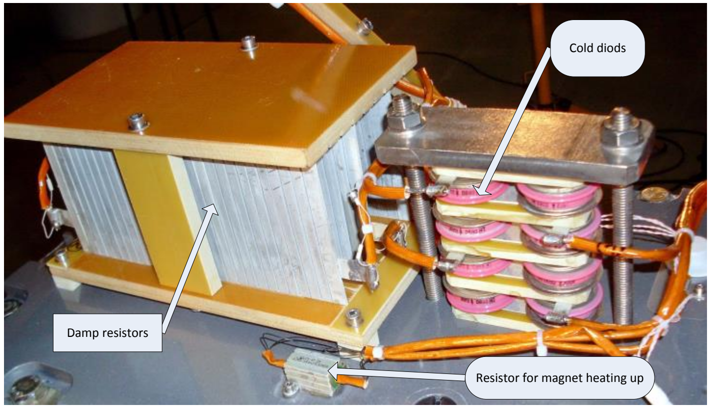
2.5 T superconducting 40-pole wiggler for ANKA-CATACT



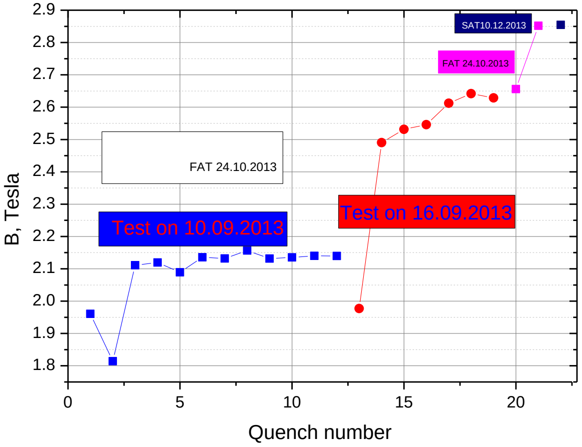
The wiggler installed on the ANKA ring



Tap signals from all magnet sections during quench



Cold diods quench protection system



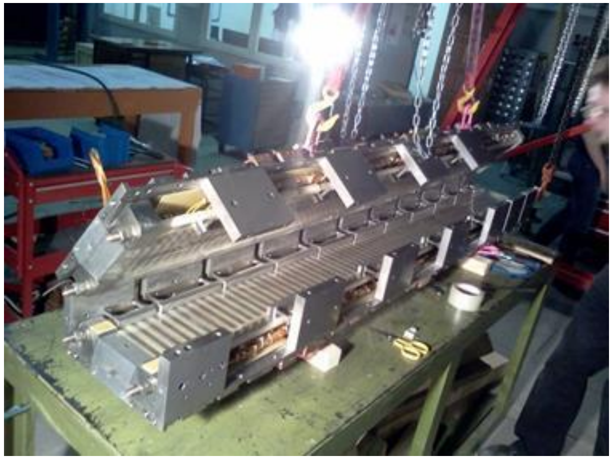
Quench history of ANKA-CATACT wiggler

Medium field superconducting wigglers

3 T superconducting 72-pole wiggler for ANKA-CLIC (indirect cooling magnetic system)

Heat sinks of the magnet poles

Assembled magnet



Open magnet for vacuum chamber installing

The magnet inside the cryostat

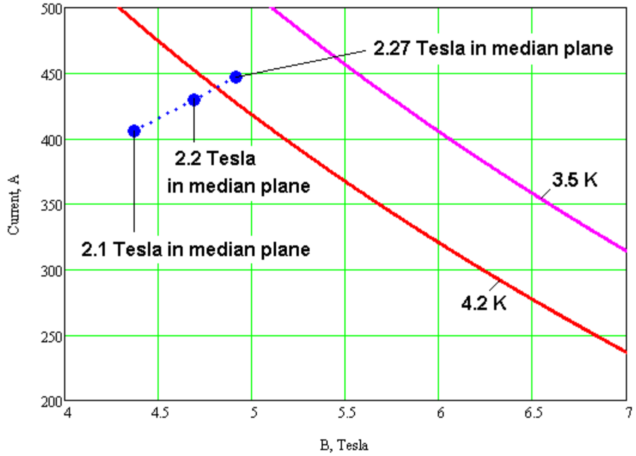
Short period superconducting wigglers (λ~3-3.3 cm, B~ 2-2.2T)

Short period superconducting wigglers

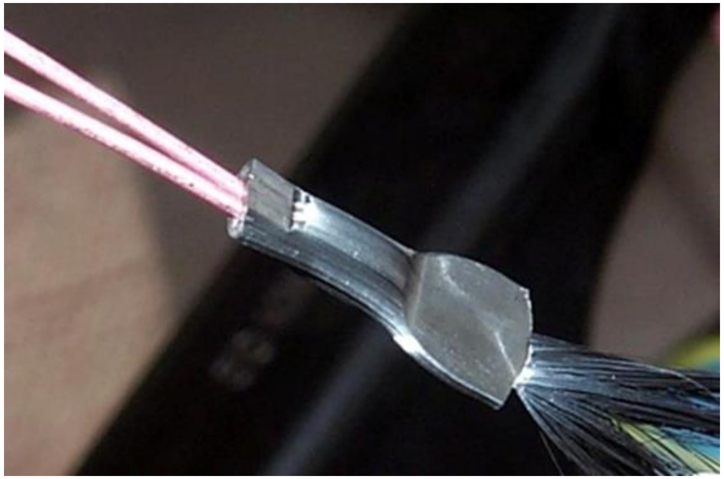
Parameters of the superconducting wire.

Wire diameter, mm	0.55/0.5
NbTi/Cu ration	1.4
Number of filaments	312
Diameter of filament, micron	37
Critical current at 7 Tesla, A	236

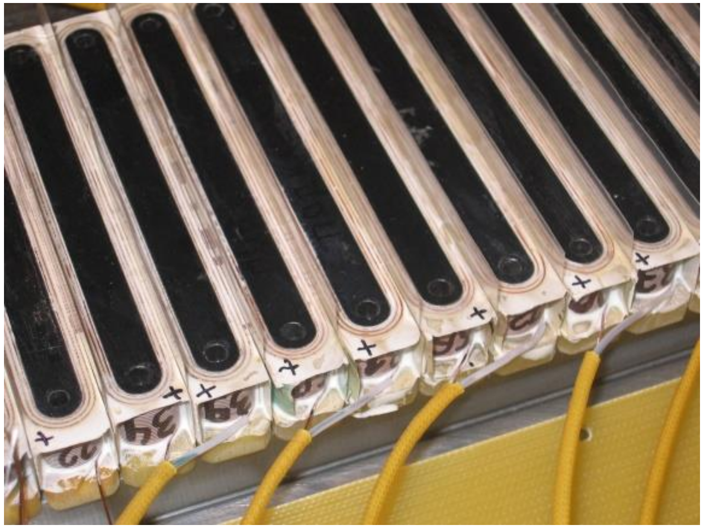
One section coils are used.



Critical current curve of used superconducting Nb-Ti wire (red line) and field-current critical points inside coil correspond to magnetic field in median.



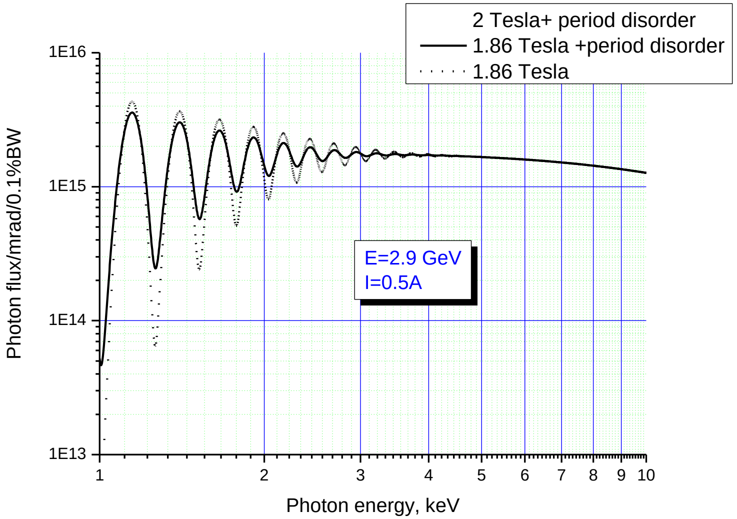
Large number of splices does not increase heat in-leak if to use cold welding method of wire connections 10^{-10}- 10^{-13} Ohm



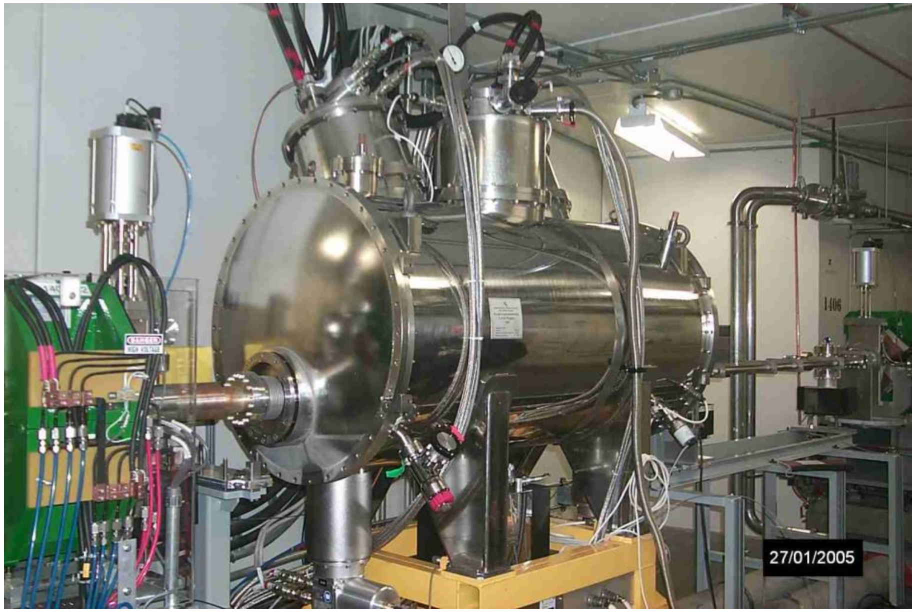
The coils and yoke of the ALBA-CELLS wiggler.

Short period superconducting wigglers

Parameter	Value
Operating Field on the Beam Axis	1.94 Tesla
Number of Poles	63
Gap between Poles	13.5 mm
Period Length (average)	33.5 mm
Operating Temperature of the Magnet	below 4.2 °K
Covered Range of Energy	5 to 40 keV
K-value	~ 6
Current of 1st power supply (I_s) at 1.94 T	400.0 Amp
Current of 2nd power supply (I_c) at 1.94 T	299.6 Amp
Ramping up time of Magnet (up to 1.94 T)	~ 5 min
Ramping down time of Magnet (to 0 T)	~ 10 min
Capacity of the Helium tank	350 Liters
High Vacuum Chamber Vertical Aperture	9.5 mm
High Vacuum Chamber Horizontal Aperture	50.0 mm



63-полюсный, 2 Тесла вигглер для CLS, Канада



A 2 Tesla Superconducting Wiggler with a period length of 33 mm and 63 poles was designed and fabricated as an X-ray source for HXMA Beamline at the Canadian Light Source Inc.

The specification required a critical energy range > 10keV and k-value ~6. Using the random shimming the periodicity was destroyed to get a smooth and featureless spectrum.

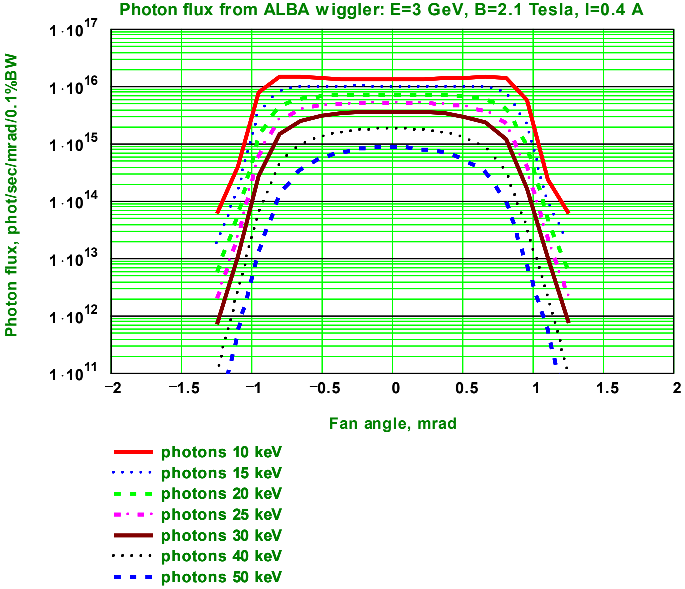
The cryogenic system for the Wiggler is capable of keeping Helium consumption close to zero.

Short period superconducting wigglers

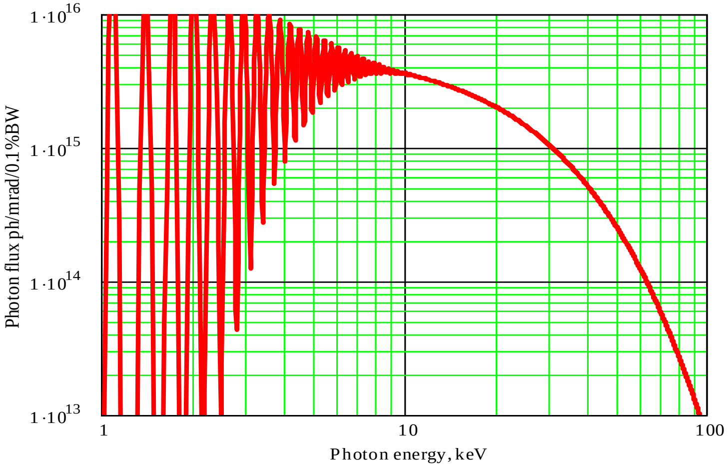
2.1 T superconducting 119-pole wiggler for ALBA-CELLS

The wiggler installed on ALBA-CELLS ring

Nominal peak on axis field, B_o	2.1 T
Maximum peak on axis field	2.2 T
Period length	30 mm
Number of pole pairs @ full field	119
Number of pole pairs @ ½ field	2
Magnetic gap, mm	12.4
Currents of power supplies at 2.1 Tesla, A	823 = 423+400
Stored energy, kJ	28
Ramping time, 0 to 2.1 T up or down	≤ 5 min
Field stability $\Delta B_z / B_z$ over two weeks	≤ 10^{-4}
Vertical aperture for electron beam, mm	8
Horizontal aperture for electron beam, mm	40



Angular-spectral photon distribution

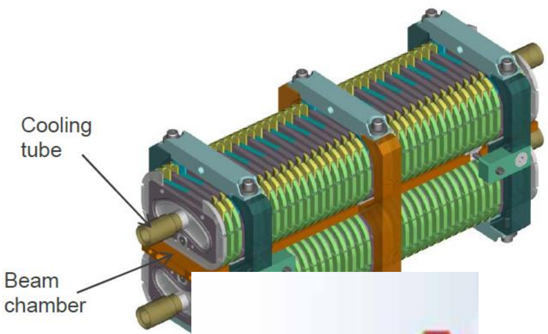


Wiggler spectrum for regular period of 30 mm

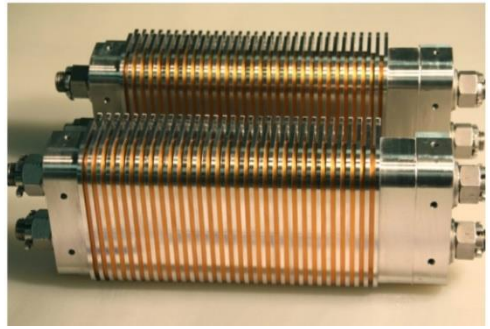
Superconducting undulators

Superconducting undulators

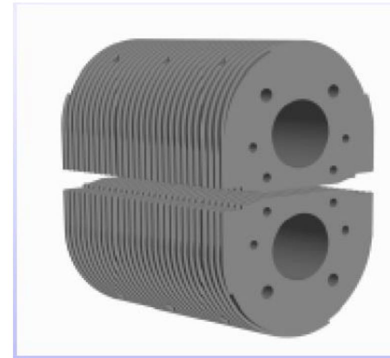
Vertical racetrack coils



Argonne NATIONAL LABORATORY

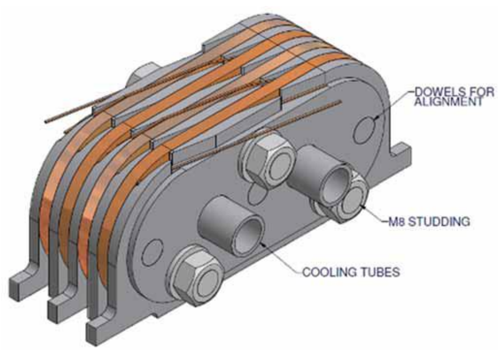


BABCOCK NOELL

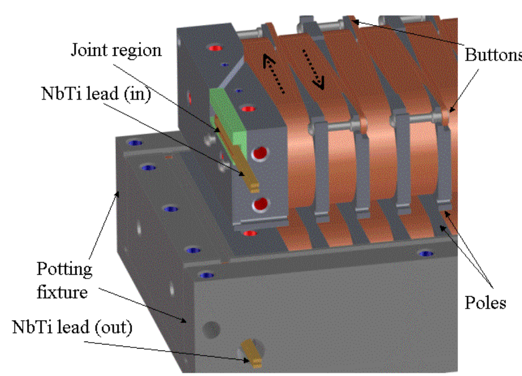


Prototype undulator (Mock-up)

ACCEL



ASTeC



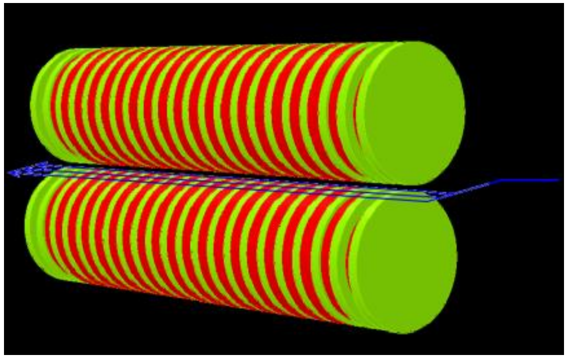
LBNL

Main requirements:

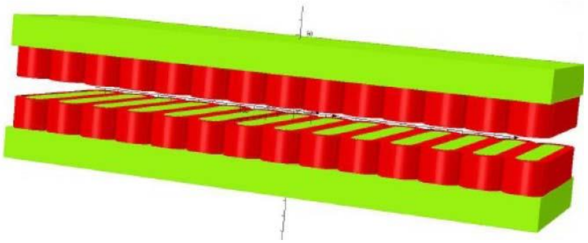
- Period length – 15-20 mm
- Pole number >100
- K-value >1
- Vertical aperture 4.5-10 mm
- Phase error

Superconducting undulators

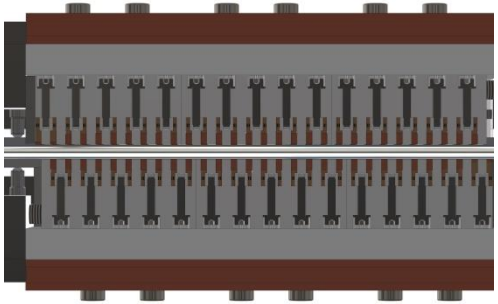
Vertical racetrack coils



Horizontal racetrack coils



Horizontal racetrack coils with neutral poles

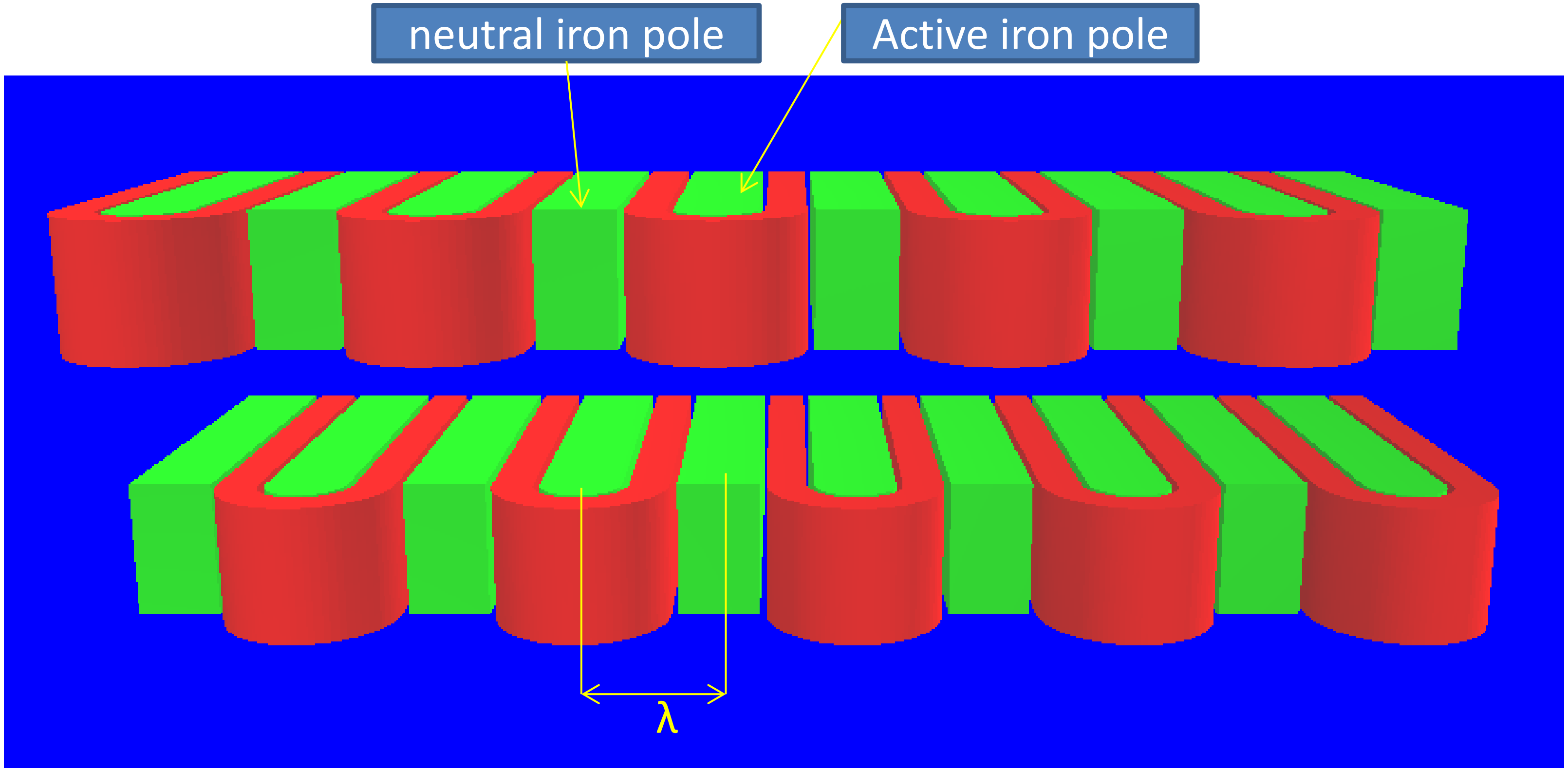


The main field of an undulator is created by horizontal cross currents.
In a 2-dimensional case when in the cross direction of a winding have the infinite size it doesn't matter how currents are closed.
For windings of the final sizes currents can be closed in the vertical plane (vertical racetrack coils) or in the horizontal plane (horizontal racetrack).

The way of windings with a current closing in the horizontal plane with use of a neutral pole was proposed in BINP.

Horizontal racetrack coils with neutral poles

The magnet consists of two identical top and bottom halves. Windings are reeled up on the iron core. Between windings the iron core without windings (a neutral pole) is inserted. A combination a winding + a neutral pole make one period of an undulator. Halves of an undulator are powered equally and turned to each other so that magnetic fields are directed towards to each other. For creation of the cross field in the median plane one half is shifted concerning another on a half of the period.

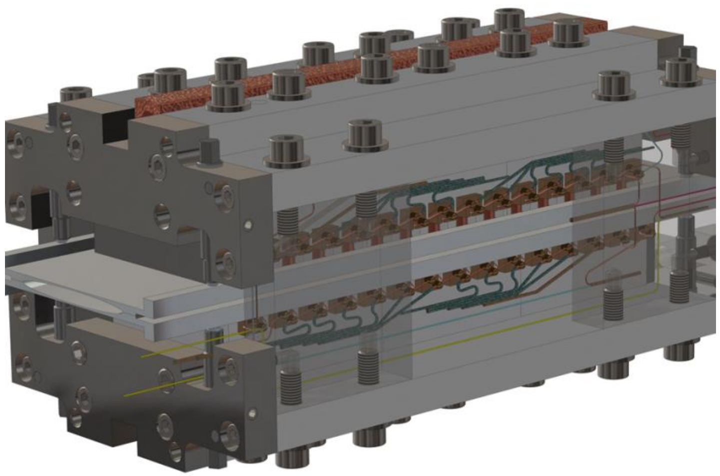


Horizontal racetrack undulator with neutral poles

The prototype of superconducting undulator with the period of 15.6 mm is designed, fabricated and successfully tested in BINP. Windings type of the prototype are made as horizontal racetrack. Pole gap - 8 mm, number of the periods 15, maximal field was achieved 1.2 T.

The superconducting NbTi/Cu wire with diameter of 0.5/0.55 mm was used for production of single-section windings.

The maximum current 590 A that corresponds to a magnetic field of 1.2 T in the median plane. Cooling of Undulator assumes use of cryocoolers of with use of thermal tubes and materials with high heat conductivity.



Model of the 15 periods superconducting undulator prototype

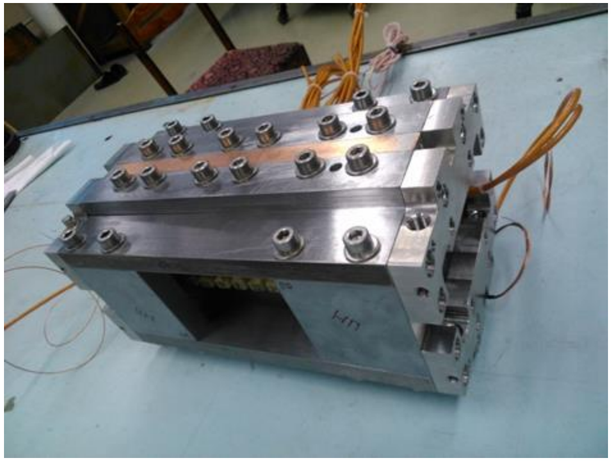
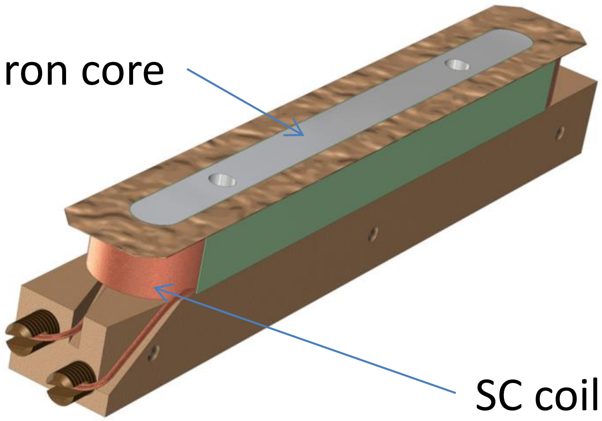


Photo of the undulator prototype

Superconducting undulators



Pole -main element of the undulator (model)

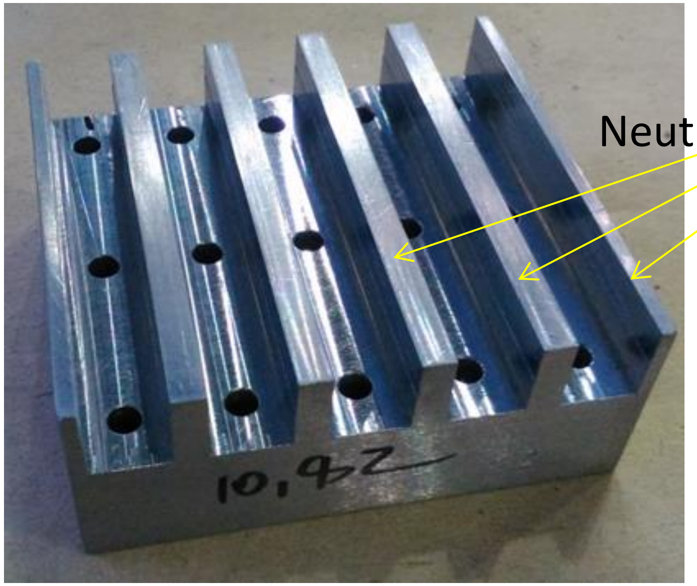
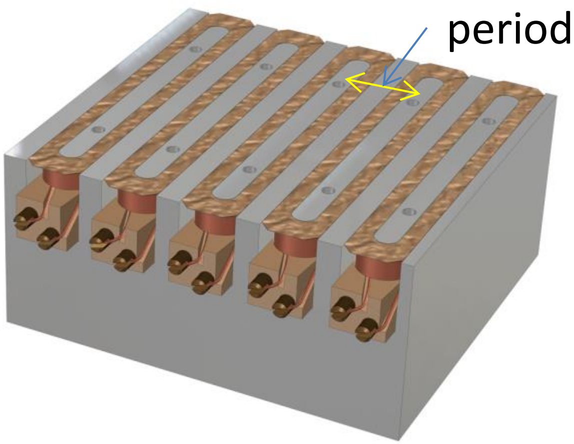
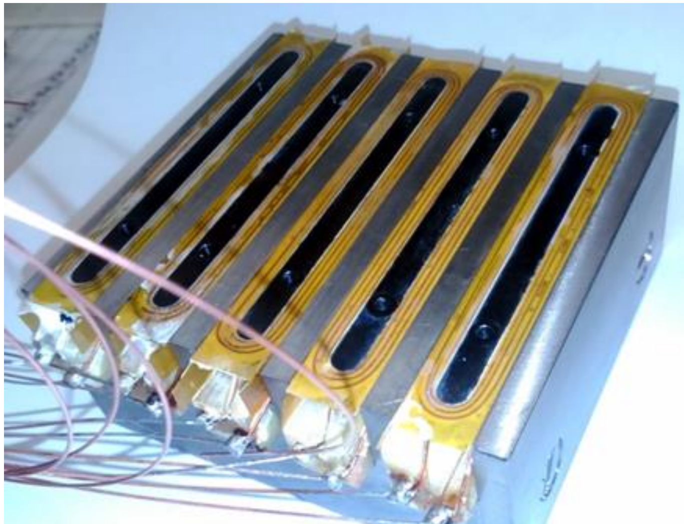


Photo of iron frame for 5 undulator poles

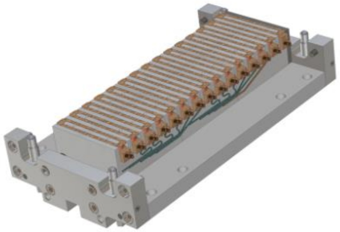


Iron frame filled by poles (model)

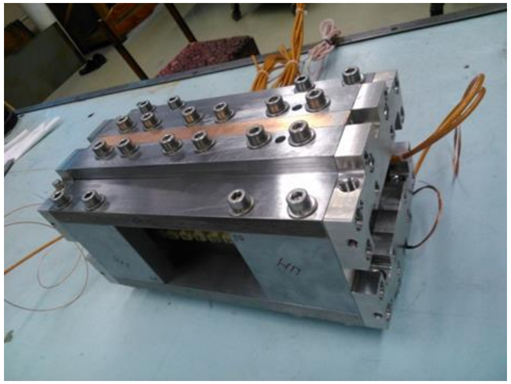


Iron frame filled by poles (photo)

Superconducting undulators



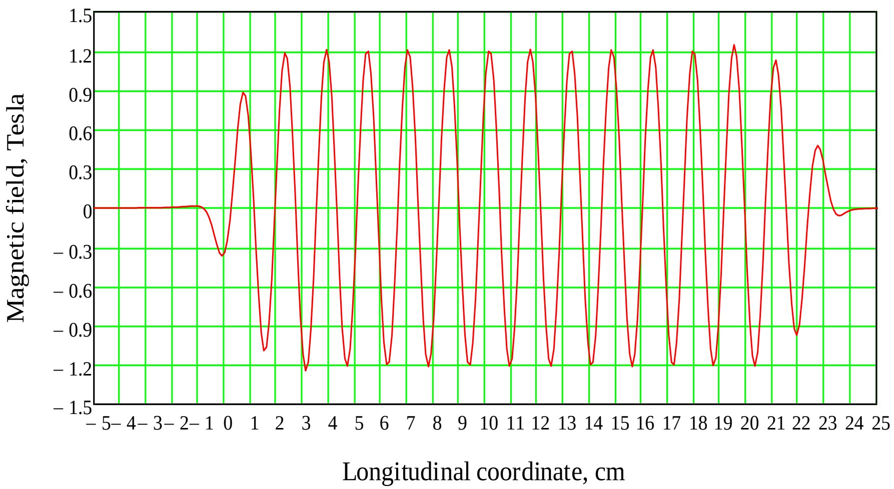
Model of ½ 15 periods undulator



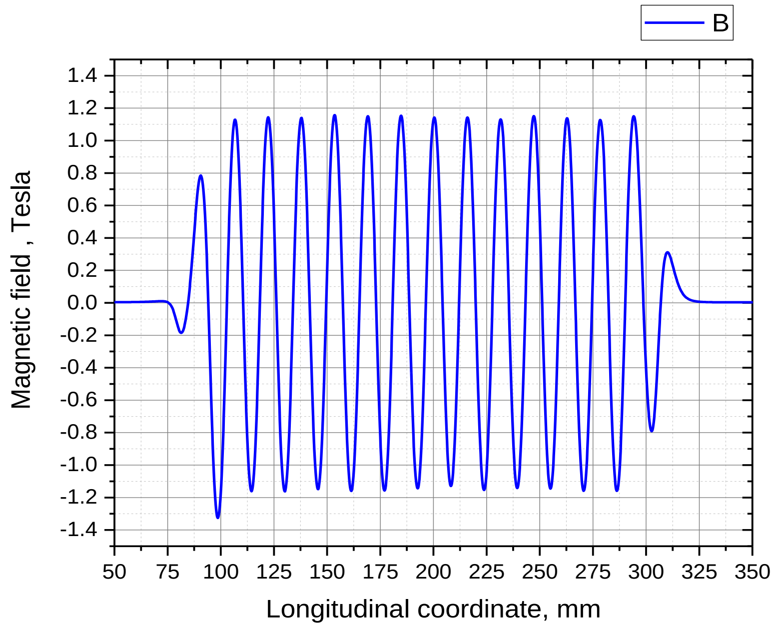
Photos of SC undulator with neutral poles

Position of the frames. Upper and bottom frames are shifted of ½ period

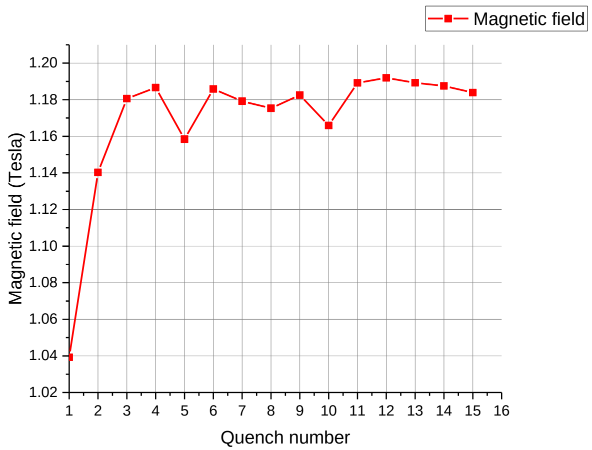
Superconducting undulators



Calculated field: λ=15.6 mm, gap=8 mm, I=550 A



Measured field: λ=15.6 mm, gap=8 mm, I=512 A



Quench history of the prototype inside vacuum cryostat with indirect cooling system

Comparison with other types of undulators

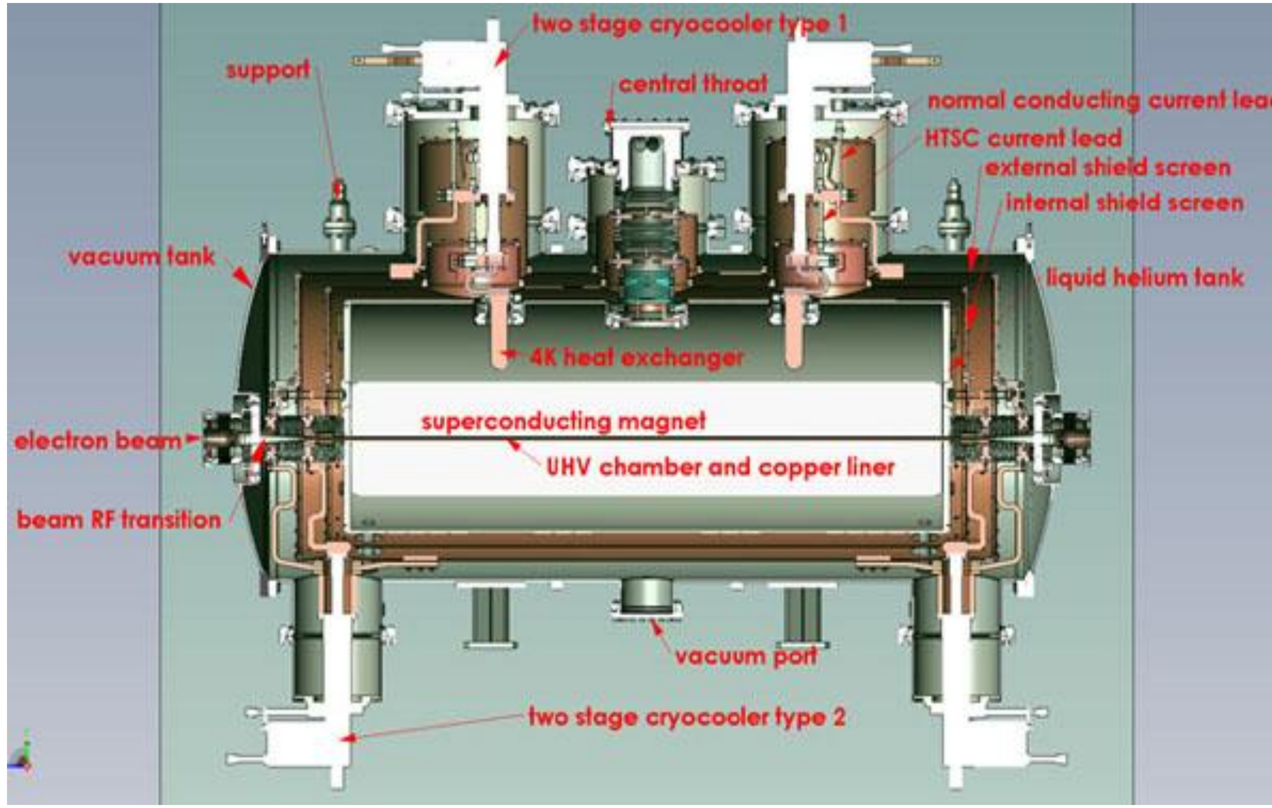
- The main magnet element (pole) is very simple. It is easily to provide mass production, high quality of pole fabrication, control of key dimensions and quality for every pole.
- Iron frame provides high precision of regular structure of the undulator. Horizontal racetrack winding improves precision of coils dimensions. It should minimize phase errors.
- There is no limitation of undulator length.

Cryogenic system

Cryogenic system

BATH CRYOSTAT WITH CRYOCOOLERS

The primary goal of the cryostat design is to create reliable safe systems with the possibility of long term independent work with close to zero liquid helium consumption. Cryocoolers are used for cooling the shield screens and heat coming from normal conducting current leads due to their heat conductivity and Joule heat.

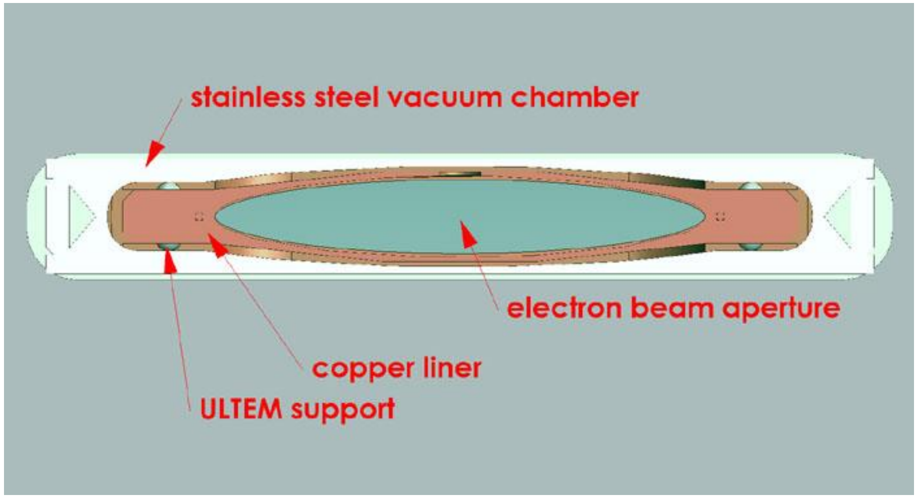


Horizontal bath cryostat for a wiggler magnet

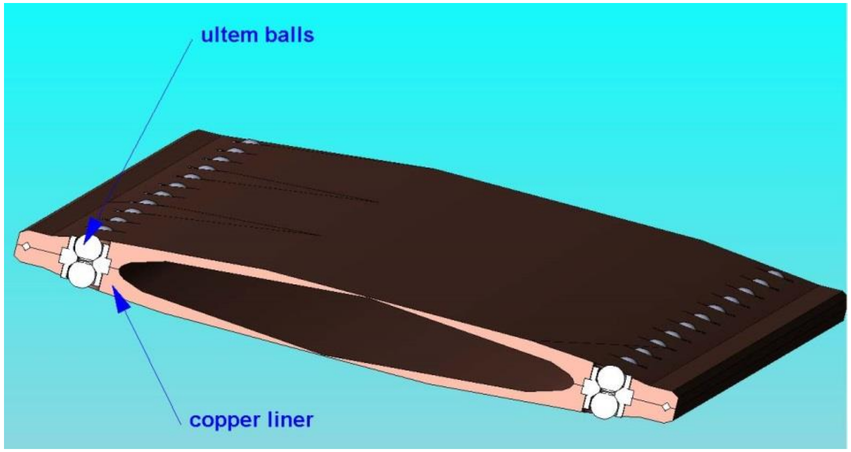
In order to provide zero liquid He consumption four 2-stage cryocoolers are used symmetrically situated relatively of the wiggler ends. The basic cryostat is to prevent of any heat to penetrate into the liquid He tank intercepting it by heat sinks connected to the cryocoolers stages. Two cryocoolers with stages of 4K and 50K (type 1) and two cryocoolers with stages of 10K and 50K (type 2) are used for this aim.

Cryogenic system   Beam vacuum chamber and copper liner for medium field wiggler

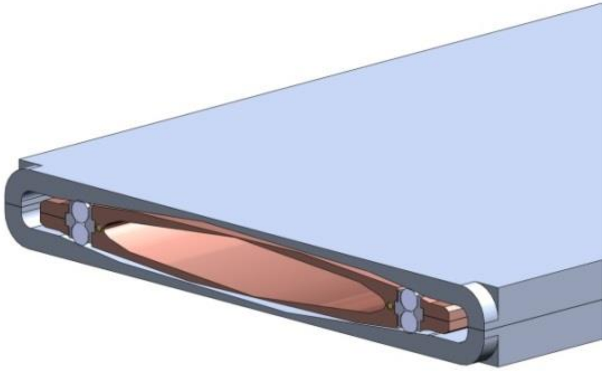
The second stages of the cryocoolers with 20K stage are used for cooling down of 20K shield screen and for interception of released heat in the copper liner when the electron beam is passing through the liner.



Cross section of cold vacuum chamber with copper liner inside for wiggler with medium magnetic field

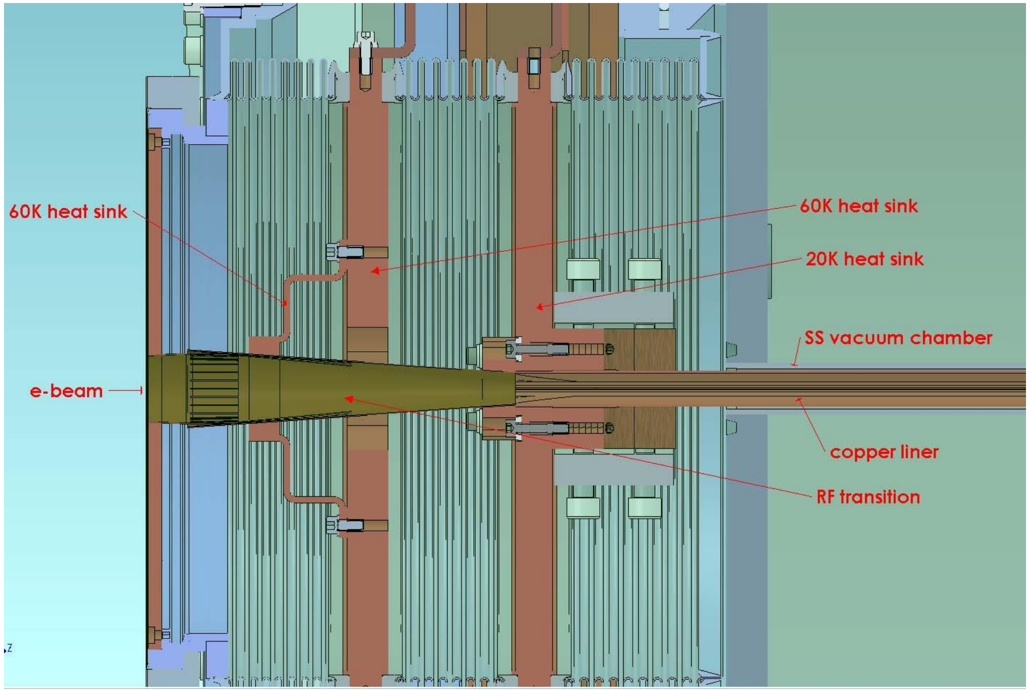


Copper liner with ULTEM support

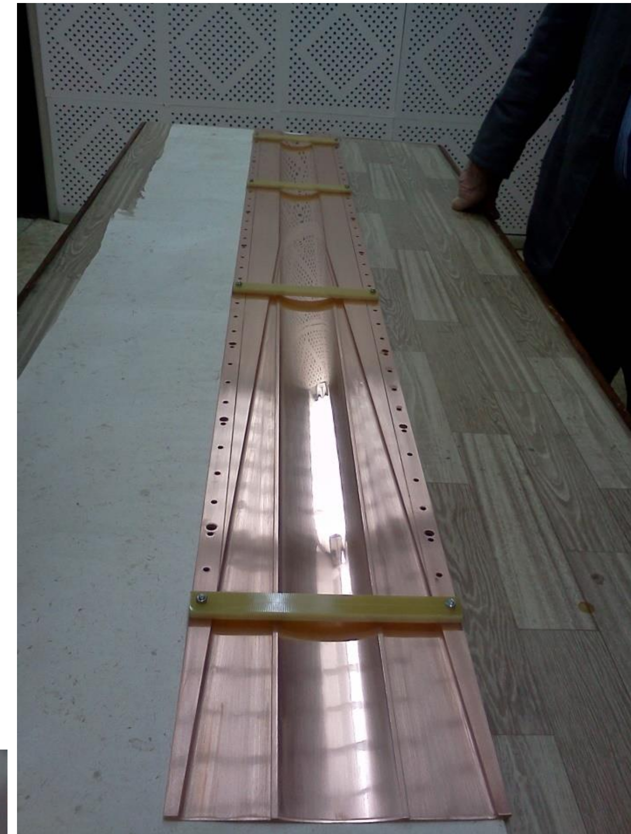


Copper liner assembled with vacuum chamber

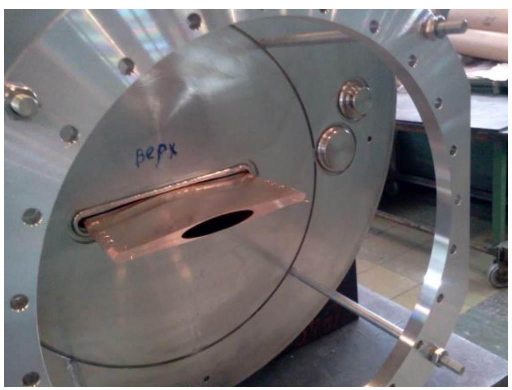
Cryogenic system Beam vacuum chamber and copper liner for high field wiggler



Cross-section of beam entry/exit of the LSU CAMD wiggler cryostat



Half of copper liner for 7.5 T Wiggler CAMD LSU

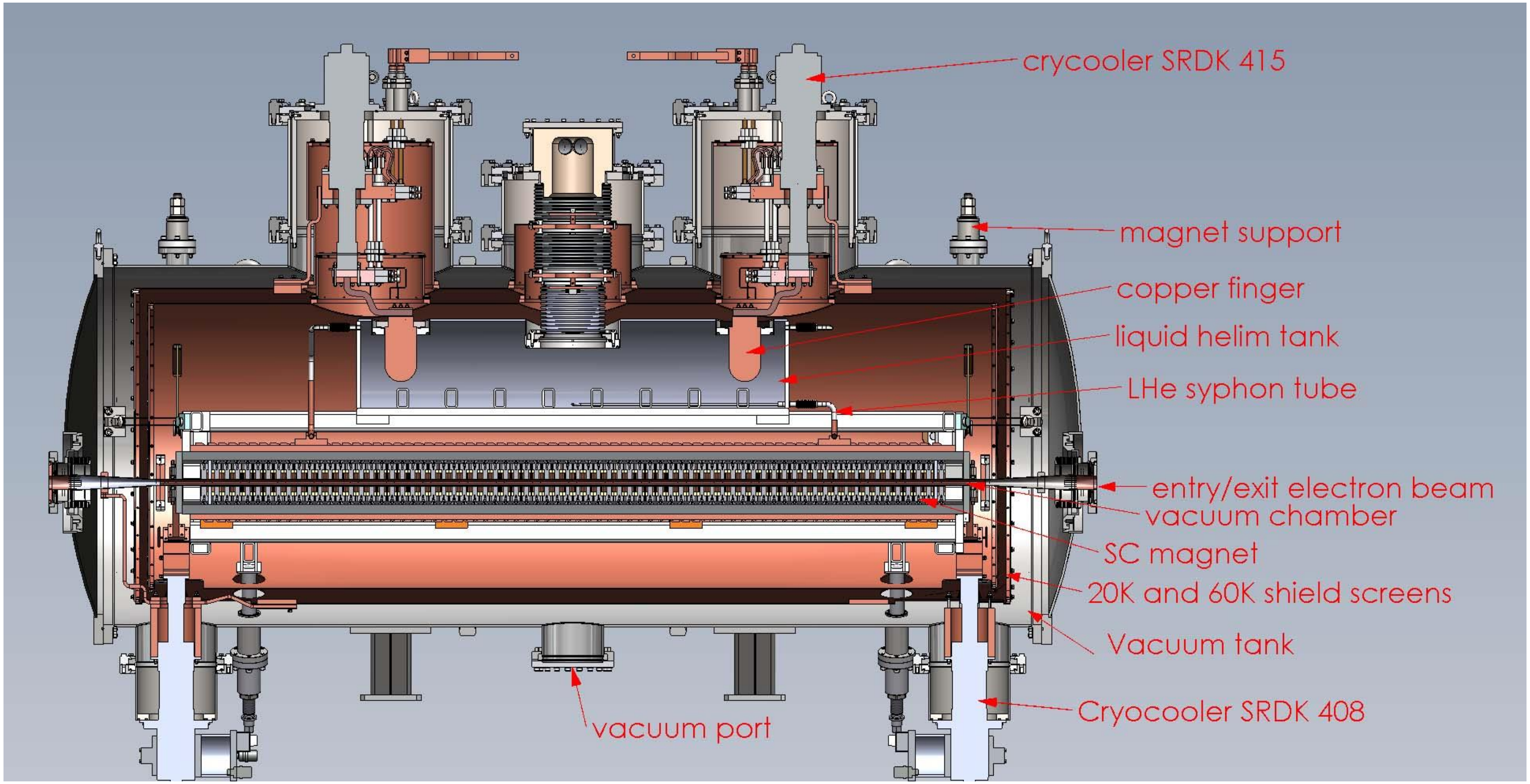


Entry and exit of beam of 7.5 T wiggler CAMD LSU

Cryogenic system

Cryostat with indirect cooling system

The wiggler cooling system is based on indirect cooling of the superconducting wiggler by LHe boiling in two copper tubes. In the current design, there are ***two*** cooling tubes attached to the copper plate of the upper half of the wiggler. The lower half is cooled via copper links of high thermal conductivity. Liquid helium is stored in the LHe vessel positioned above the wiggler.



Cryogenic system

Vacuum chamber for magnets with indirect cooling system

The vacuum chamber is made of OF copper tube. The tube was deformed to ellipse shape with required parameters. The copper ribs were soldered to increase the chamber rigidity.

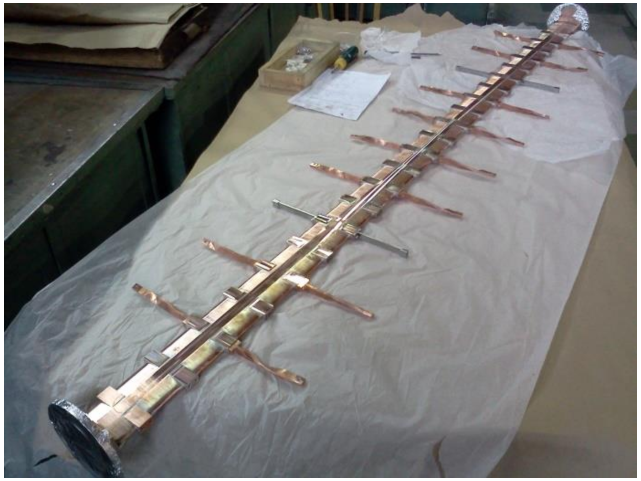
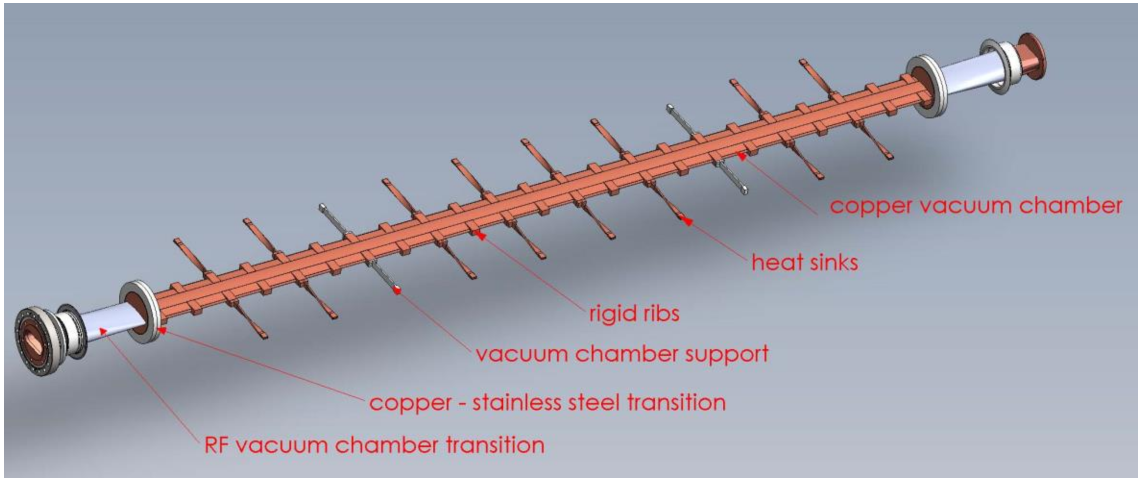
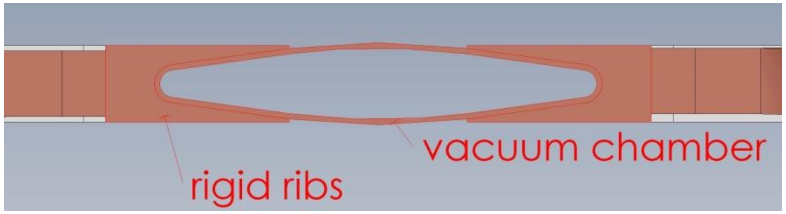


Photo of copper vacuum chamber for CLIC wiggler



Model of the copper vacuum chamber



Ross section of the copper vacuum chamber

Resume

- The technology of fabrication of horizontal racetrack coils for multipole magnetic systems with the period from 30 mm and above is debugged. About 20 superconducting multipole magnetic systems are successfully working in the various SR centers as SR generators.
- Use of horizontal racetrack coils in multipole magnetic systems have shown the reliability and simplicity in manufacturing. Almost all defects of some coils caused by defect of a wire or errors at winding are finding at room temperature. If a defective pole is found during low temperatures tests in bath cryostat it is replaced easily.
- Large number of splices also does not represent any problem due to very small contact resistance with use of a cold welding technics.
- The magnetic system with horizontal racetrack coils has no any length limitation.
- Bath cryostat with liquid helium and cryocoolers has proved as a reliable cryogenic system able during years to work independently in the conditions of limited access
- Based on the experience of the fabricated short period wigglers it is possible to assert that the minimum period of magnetic system with horizontal racetrack coils can be limited by 12 mm.
- The magnetic system with horizontal racetrack coils with indirect cooling was developed and created
- Cryostat for magnet with indirect cooling was developed , created and installed on ANKA storage ring.
- **Prototype of superconducting undulator with horizontal racetrack coils ,with the period of 15.6 mm and with indirect cooling system was designed, fabricated and successfully tested.**

Thanks for attention