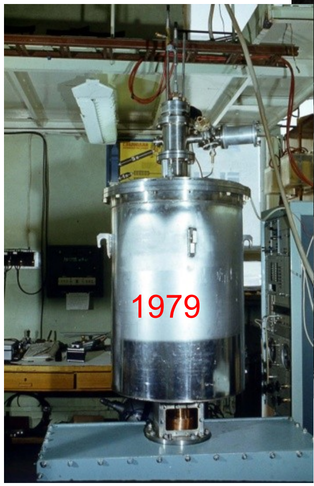
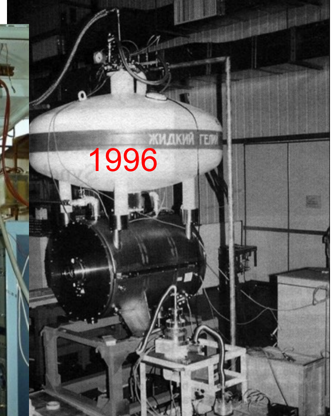
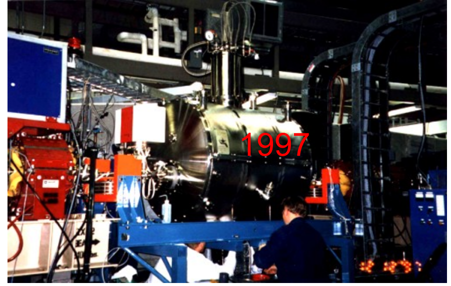




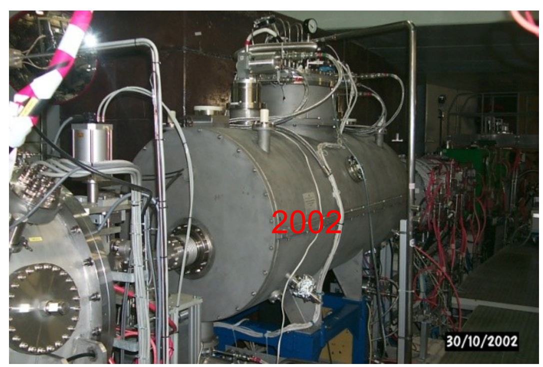


Superconducting wigglers fabricated in Budker INP

Konstantin ZOLOTAREV

Budker Institute of Nuclear Physics

December, 2010



History of superconducting magnet activity in Budker INP

- 1979 – first in the world 3.5 Tesla superconducting 20 pole wiggler (SCW) for VEPP-3
- 1984 – 5 pole 8 Tesla superconducting wiggler for VEPP-2
- 1985 – 4.5 Tesla Superconducting Wave Length Shifter (WLS) for Siberia-1, Moscow
- 1992 – 6 Tesla superbend (SB) prototype for compact storage rings
- 1996 - 7.5 Tesla superconducting WLS for PLS, South Korea
- 1997 - 7.5 T superconducting WLS with fixed point of radiation for CAMD-LSU (USA)
- 2000 – 10 Tesla WLS for Spring-8, Japan
- 2000 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany
- 2001 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany
- 2002 – 3.5 Tesla 49 pole SCW for ELETTRA, Italy
- 2002 – 7 Tesla 17 pole SCW for BESSY-2, Germany
- 2004 – 9 Tesla Superbend for BESSY-2, Germany
- 2005 – 13 Tesla superconducting solenoids for VEPP-2000
- 2005 – 2 Tesla 63 pole SCW for CLS, Canada
- 2006 – 3.5 Tesla 49 pole for DLS, England
- 2006 – 7.5 Tesla 21 pole SCW for Siberia-2, Moscow
- 2007 – 4.2 Tesla 27 pole SCW for CLS, Canada
- 2009 – 4.2 Tesla 49 pole SCW for DLS, England
- 2009 – 4.1 Tesla 35 pole SCW for LNLS, Brasil
- 2010 - 2.1 Tesla 119 pole SCW for ALBA, Spain

Superconducting Wave Length Shifters

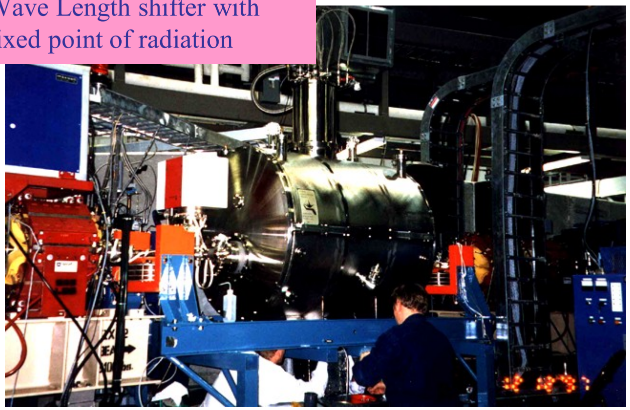
List of Superconducting Wave Length Shifters

Shifter represents 3-pole magnet with zero first and second field integrals along a trajectory. The central pole of the magnet has strong magnetic field and is used for generation of hard X-ray SR, while side poles are used for orbit correction.

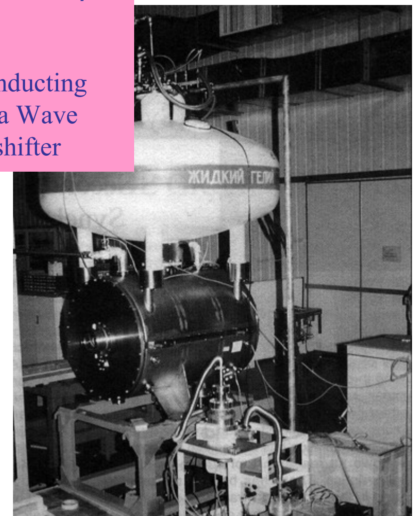
	Year	Magnetic field, T Max/ normal	Magnetic gap, mm	Magnetic length	Vertical aperture, mm	Cryostat type, Liquid helium consumption, LHe liter/hr
WLS for Siberia-1 (Moscow)	1985	(5.8) 4.5	32	350	22	Liquid nitrogen, Liquid helium, 2-2.5
WLS for PLS (Korea)	1995	(7.68) 7.5	26.5	800	26	Liquid nitrogen, Liquid helium, 1.5-2
WLS for LSU-CAMD (USA)	1998	(7.55) 7	51	972	32	Liquid nitrogen, Liquid helium, 1.2-1.6
WLS for SPring-8 (Japan)	2000	(10.3) 10	40	1042	20	Cryocoolers, Liquid helium 0.4-0.6
BAM WLS (BESSY, Gernany)	2000	(7.5) 7	52	972	32	Cryocoolers, Liquid helium 0.4-0.6
PSF-WLS (BESSY, Germany)	2001	(7.5) 7	52	972	32	Cryocoolers, Liquid helium 0.4-0.6
Superbend (BESSY, Germany)	2004	(9.6) 8.5	46	177	32	Cryocoolers, Liquid helium <0.5

Superconducting strong field magnetic system fabricated in Budker INP

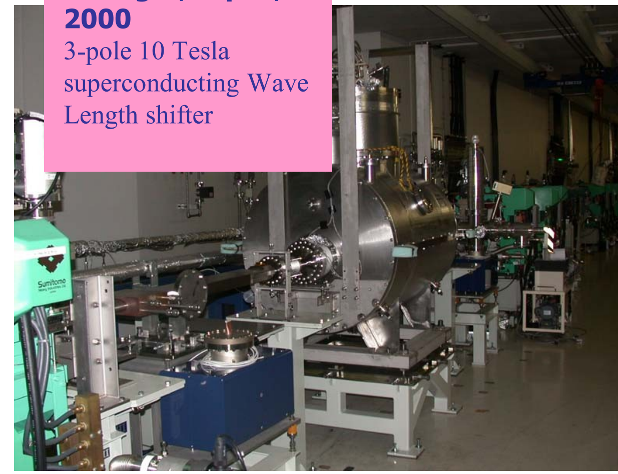
CAMD LSU, USA, 1996
superconducting 3-pole 7.5 Tesla superconducting Wave Length shifter with fixed point of radiation



PLS, S.Korea, 1997
3-pole superconducting 7.5 Tesla Wave Length shifter



SPring-8, Japan, 2000
3-pole 10 Tesla superconducting Wave Length shifter



BESSY, Germany, 1999, 2001
Two Superconducting Wave Length Shifters with fixed point of radiation

Fig. 2-4 Photo of 7 Tesla WLS inserted into BESSY-2 straight section.

BESSY, Германия, 2002
Superconducting 8.5 Tesla bending magnet

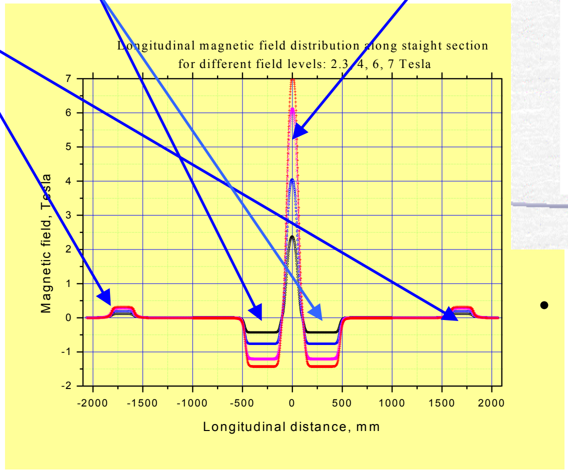
7 Tesla WLS for BESSY-2 (2000, 2001)

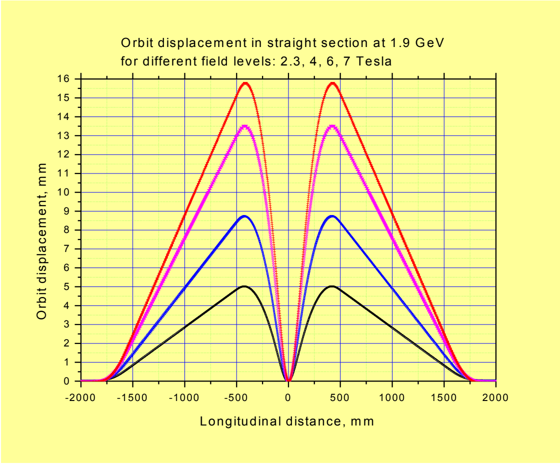
Normal conducting Corrector-magnets

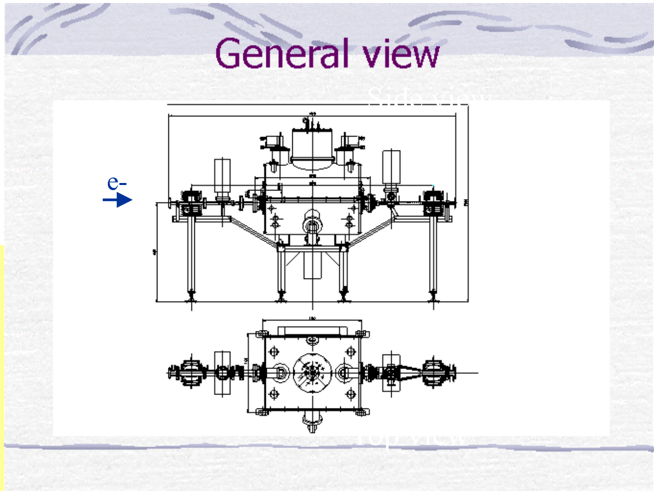
Superconducting Side magnets

Central pole

Fig. 2-4 Photo of 7 Tesla WLS inserted into BESSY-2 straight section.







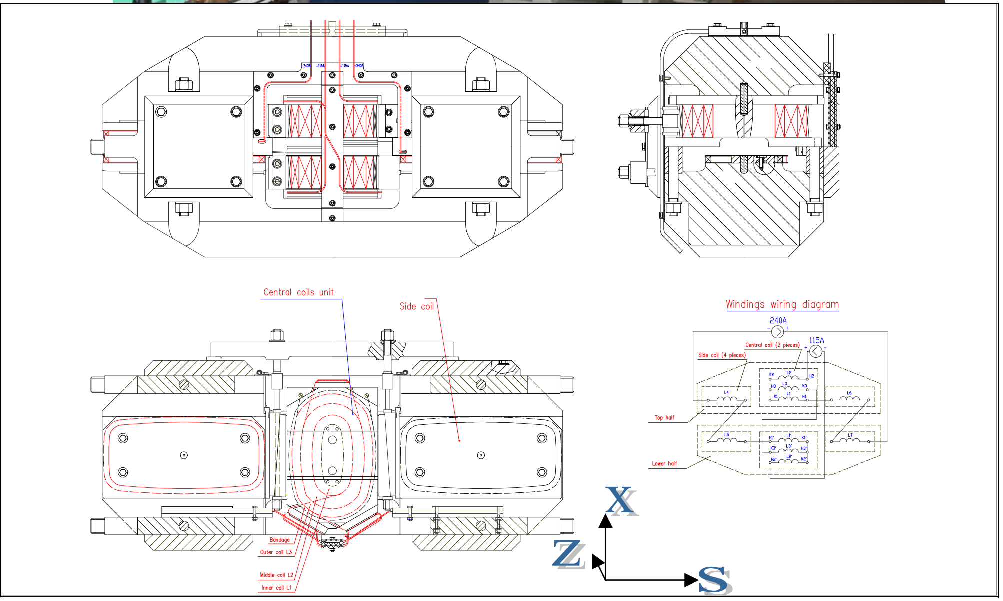
- Wave Length Shifter with fixed radiation point, where the superconducting part of magnet has non-zero first field integral and requirements of zero field integrals are performed by normally conducting correcting magnets which are outside of shifter cryostat.

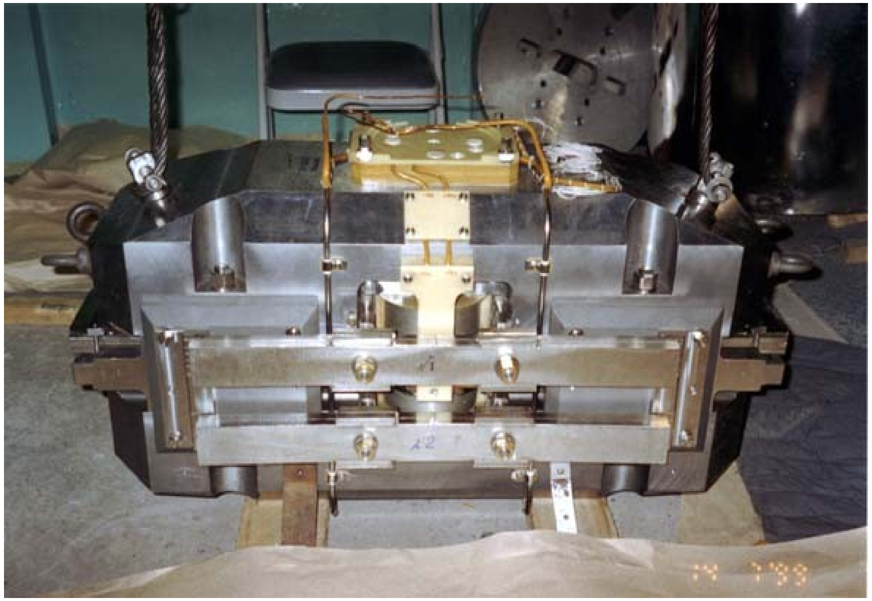
  This variant of shifter allows to compensate for the first and second field integrals over each ½ shifter parts so that in the central pole the radiation point will be always on an straight section axis at any field level of the shifter.

10 Tesla 3 pole WLS for SPring-8 (Japan)

January 2000

Pole number	3
Magnetic field in central pole (median plane)	10 Tesla
side poles (median plane)	1.9 Tesla
Stored energy at 10 Tesla field	~400 kJ
Weight of wiggler cold part	~1000 kG
Windings of the central pole	
Nb_3S – Rectangular wire by the size	0.85x1.2 мм^2
Nb-Ti – Round wire by a diameter	0.92 мм
Full length of the magnet	1000 m
Pole gap	42 mm
The size of the electron vacuum chamber	100x20 mm^2

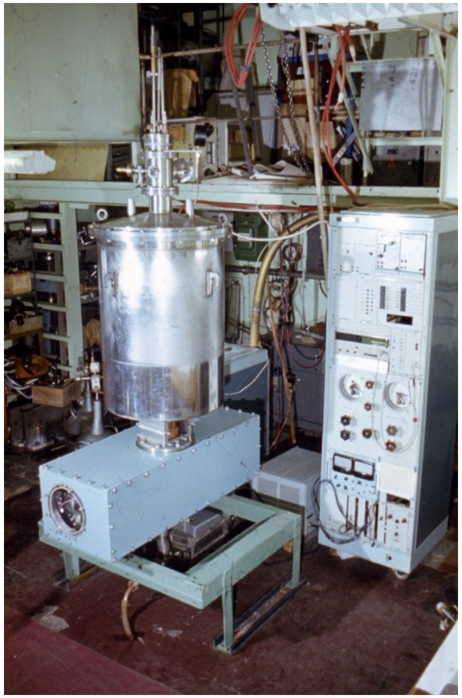


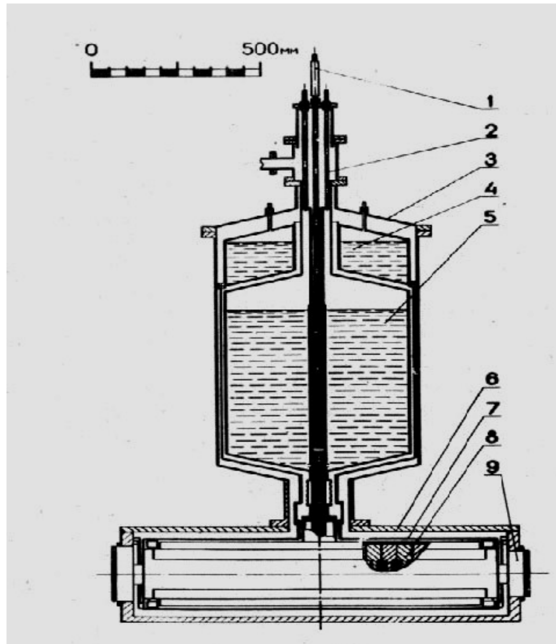


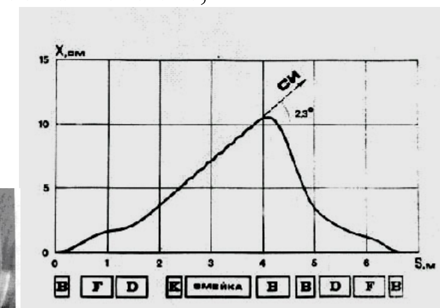
Superconducting multipole wigglers

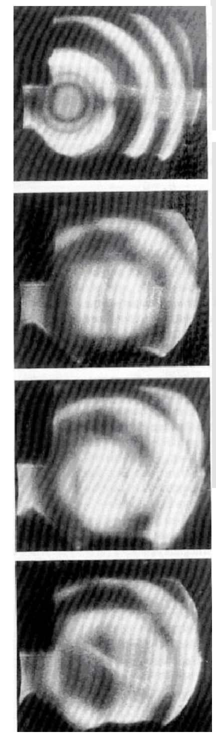
SC 20-pole 3.5 Tesla wiggler VEPP-3, Novosibirsk, Russia, 1979

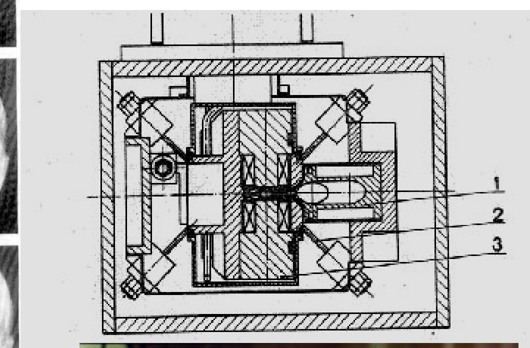
Pole number	20
Pole gap,mm	15
Period, cm	9
Field amplitude, Tesla	3.5
Vacuum chamber dimensions, mm	8 x 20

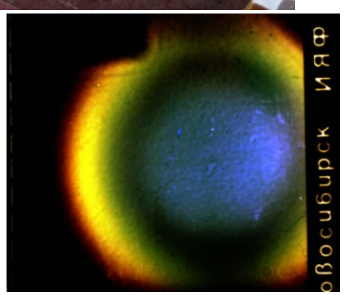


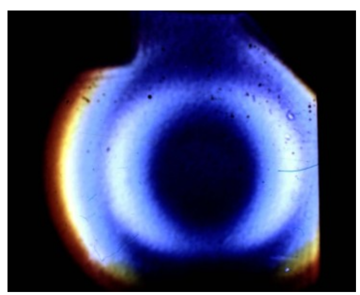










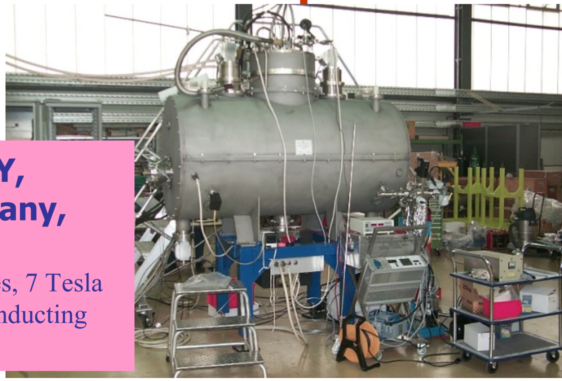


Undulator light from the wiggler

SC multipole wigglers fabricated in Budker INP last 8 years

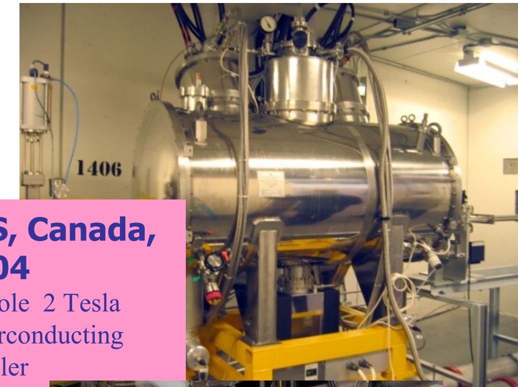
	Year	Magnetic field, T (Max) normal	Poles number (main + side)	Pole gap, mm	Period mm	Vertical aperture, mm
7 Tesla wiggler (BESSY-II, Germany)	2002	(7.67) 7	13+4	19	148	13
3.5 Tesla wiggler ELETTRA (Italy)	2002	(3.7) 3.5	45+4	16.5	64	11
2 Tesla wiggler CLS (Canada)	2005	(2.2) 2	61+2	13.5	34	9.5
3.5 Tesla wiggler DLS (England)	2006	(3.75) 3.5	45+4	16.5	60	10
7.5 Tesla wiggler SIBERIA-2 (Russia)	2007	(7.7) 7.5	19+2	19	164	14
4.2 Tesla wiggler CLS (Canada)	2007	(4.34) 4.2	25+2	14.5	48	10
4.2 Tesla wiggler DLS (England)	2009	(4.25) 4.2	45+4	13.8	48	10
4.1 Tesla wiggler LNLS (Brazil)	2009	(4.19) 4.1	31+4	18.4	60	14
2.1 Tesla wiggler ALBA-CELLS (Spain)	2010	2.1	117+2	12.6	30.0	8.5

Superconducting multipole wigglers

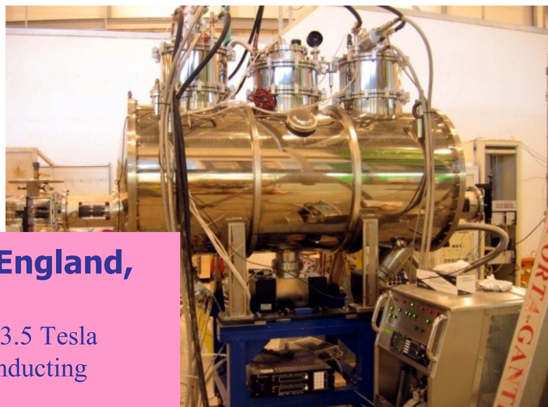


BESSY, Germany, 2002
17-poles, 7 Tesla superconducting wiggler

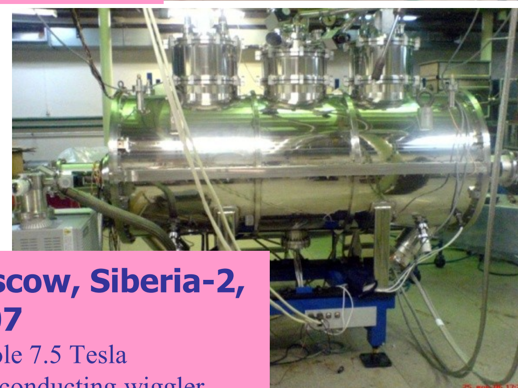
ELETTRA, Italy, 2002
49-pole 3.5 Tesla superconducting wiggler



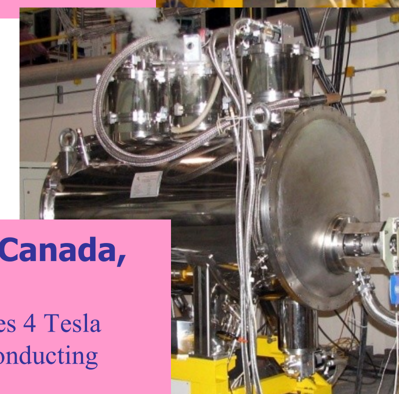
CLS, Canada, 2004
63-pole 2 Tesla superconducting wiggler



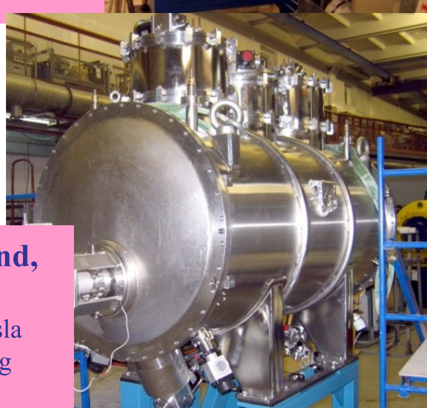
DLS, England, 2006
49-pole 3.5 Tesla superconducting wiggler



Moscow, Siberia-2, 2007
21-pole 7.5 Tesla superconducting wiggler

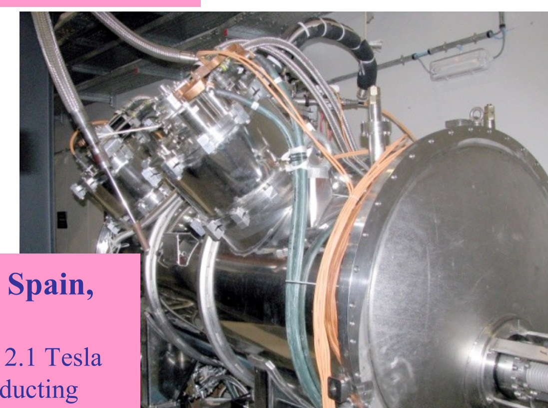


CLS, Canada, 2007
27- poles 4 Tesla Superconducting wiggler



DLS, England, 2008
49-pole 4.2 Tesla superconducting wiggler

LNLS, Brazil, 2009
35-pole 4.2 Tesla superconducting wiggler

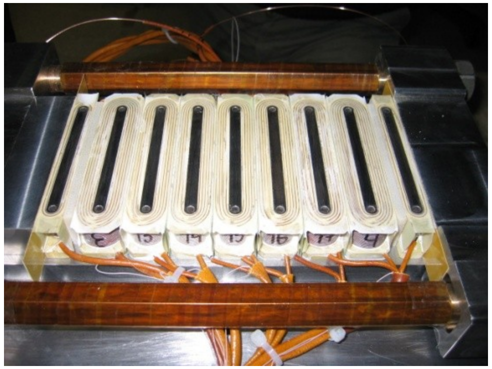


ALBA, Spain, 2010
119-pole 2.1 Tesla superconducting wiggler

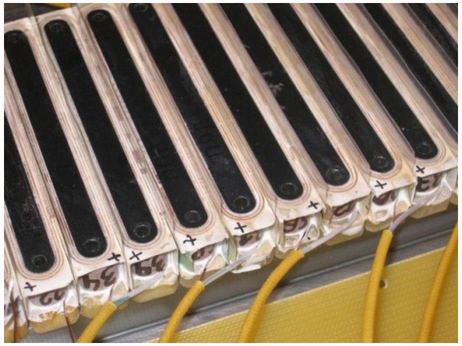
3 groups of SC wiggler

Long period SC multipole wigglers
(B_0 =7-7.5 Tesla, λ_0~150-200 mm)

Medium period SC wigglers
(B_0 =3.5-4.2 Tesla, λ_0~48-60 mm)



Short period SC wigglers
(B_0 =2-2.2 Tesla, λ_0~30-34 mm)

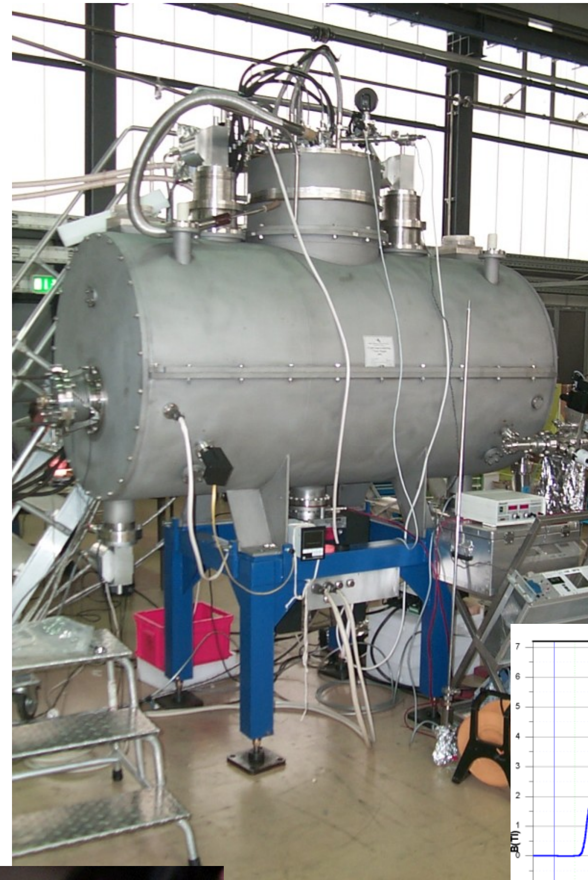


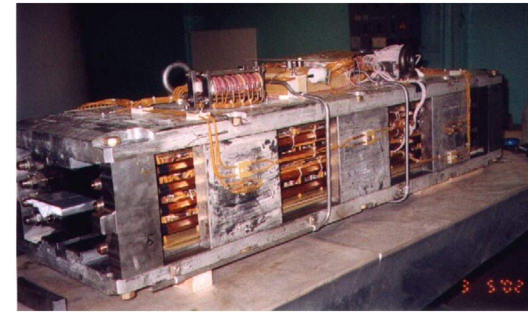
Long period (LP) superconducting multipole wigglers

7 Tesla 17 pole superconducting wiggler (BESSY-2(Germany, 2002))

Main parameters

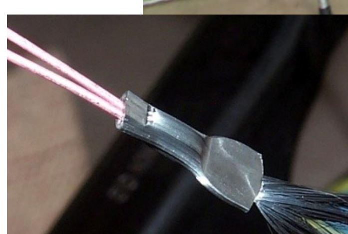
Pole number (main+side)	13+4
Vertical beam aperture, mm Horizontal beam aperture, mm	13 110
Pole gap, mm	19
Period, mm	148
Maximal field, Tesla Nominal field, Tesla	7.45 7.0
2-sections coil, material – Nb-Ti/Cu Currents in sections at 7 Tesla field, A internal section external section	 145 342
Stored energy, kJ	400
Liquid helium consumption, l/hour	0.5
Total weight, tonn	2.5





Assembled wiggler magnet

2 sections coil

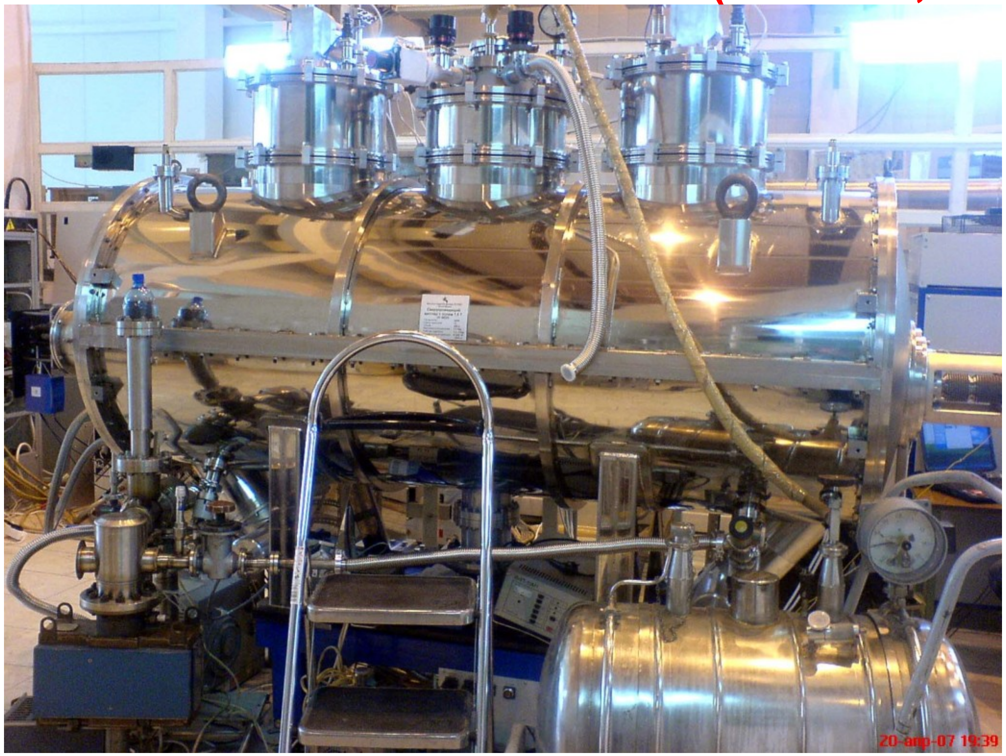


Coils connection by cold welding method

Resistance of the connection
10^{-10}- 10^{-13} Ohm

Longitudinal field distribution in the wiggler

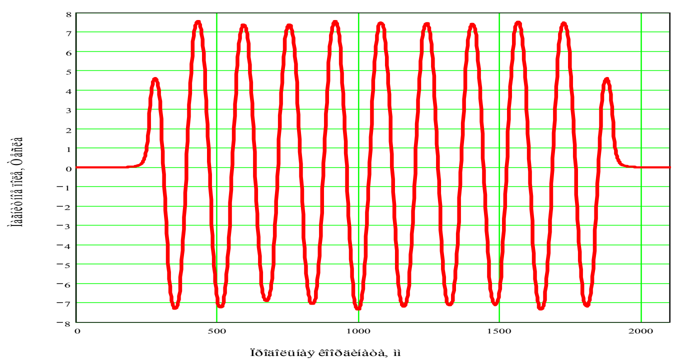
7.5 Tesla 21 pole superconducting wiggler (Moscow, Siberia-2)



Main parameters

Pole number (main + side)	19+2
Vertical beam aperture, mm Horizontal beam aperture, mm	14 120
Pole gap, mm	20.2
Period, mm	164
Maximal field, Tesla Nominal field, Tesla	7.67 7.5
2 sections coil material – Nb-Ti/ Cu Currents in sections at 7.5 Tesla, A internal section external section	 160 400
Stored energy, kJ	520
Liquid helium consumption, l/hour	<0.03
Total weight, tonn	3

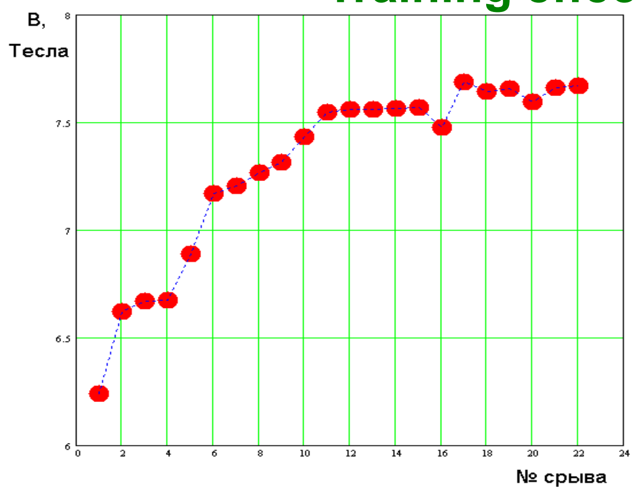
Test in bath cryostat



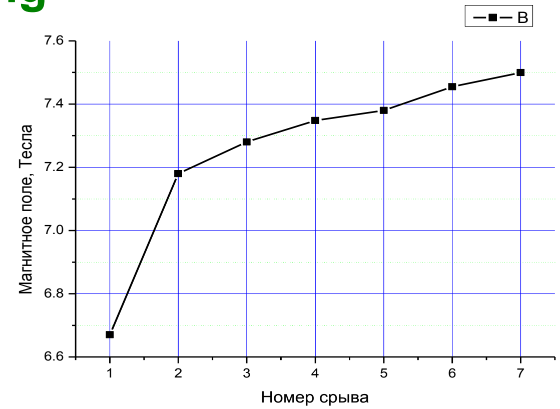
Longitudinal field distribution

Lower part of the wiggler magnet

Training effect by quenching



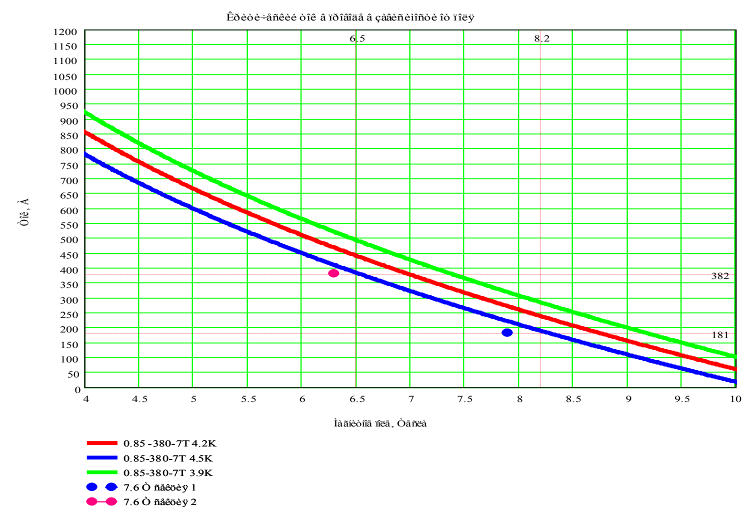
Quench history 7T superconducting wiggler for BESSY-HMI during test in bath cryostat



Quench history 7.5T superconducting wiggler for Siberia-2 during test in bath cryostat

Superconducting wire parameters for wigglers with high stored energy

wire diameter,mm	0.85 (0.92 with insulation)
Ratio NbTi:Cu	1:1.4
Critical current, A	380 (at 7 Tesla)
filaments number in the wire	8910

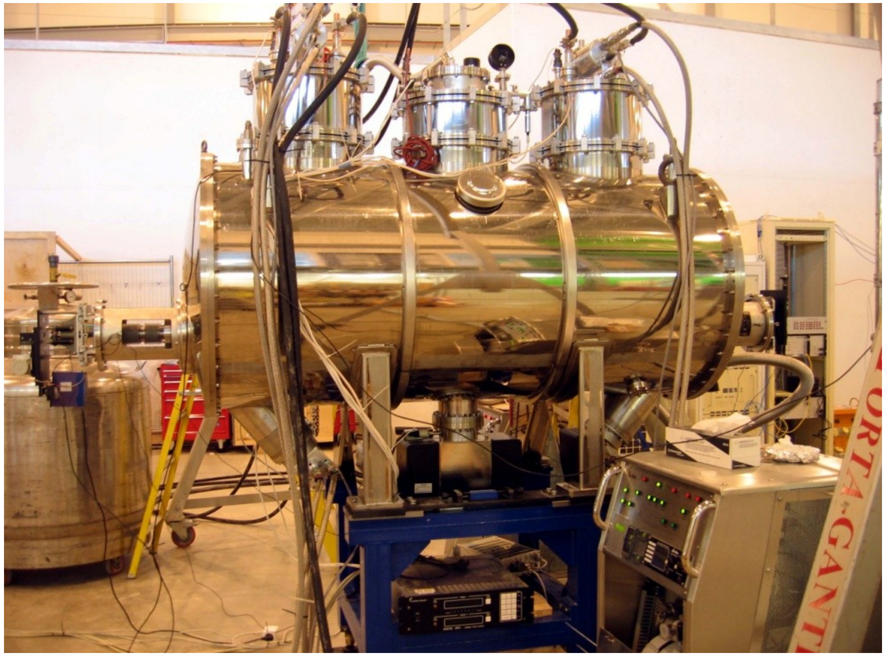


Critical curve of the SC wire at various temperatures. Points represent values of currents and the maximal fields on a winding in 1-st and 2-nd sections at the maximal field in median planes of 7.5 Tesla.

Medium period (MP) superconducting multipole wigglers

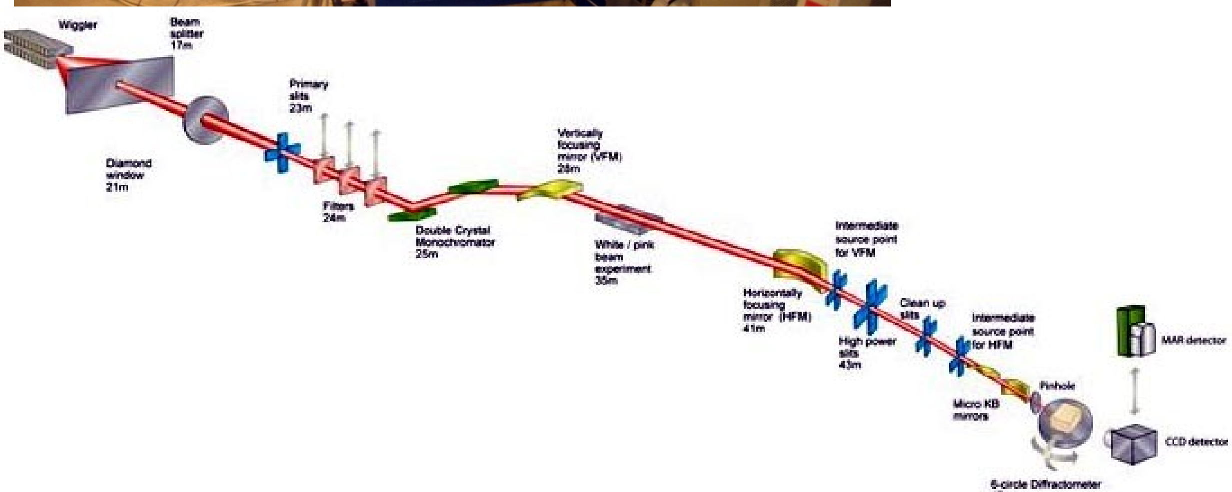
Superconducting 49 pole 3.5 Tesla wiggler for DLS (England, 2005)

I15 beamline - Extreme Conditions



Half pole of SC wiggler

Pole number (main + side)	45+4
Vertical beam aperture, mm Horizontal beam aperture, mm	10 60
Pole gap, mm	16.2
Period, mm	60
Maximal field, Tesla Nominal field, Tesla	3.77 3.5
One section windings, material – Nb-Ti Currents in sections at 3.5 Tesla, A	 650
Stored energy, kJ	35
Liquid helium consumption, liter/ hour	<0.03
Total weight, ton	2



Beamline Design Specifications

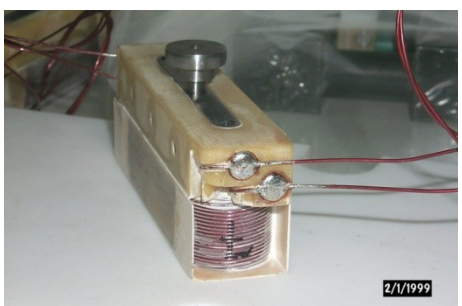
Energy range	20 - 80 keV (mono beam). Beam size conditions apply for high energies > 30 KeV. Minimum beam size >30 keV is 80-100 microns.
Energy resolution (Δ E/E)	1.0×10^{-3}
Photon beamsize at sample	Variable, from a few tens of microns to mm
Beam divergence at 50 keV	Variable with focusing elements
Flux at sample at 50 keV (ph/s)	10^9

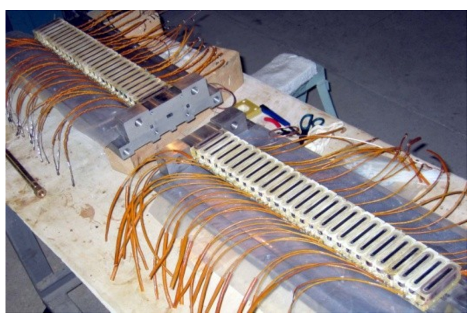
03.12.2010

4.2 Tesla 27 pole superconducting wiggler
CLS (Canada)

Biomedical Imaging and Therapy (BMIT-ID) 05ID-2 (POE-2 & SOE-1)

Pole number (main + side)	**25+2**
Vertical beam aperture, mm **Horizontal beam aperture, mm**	**9** **50**
Pole gap, mm	**13.9**
Period, mm	**48**
Maximal field, Tesla **Nominal field, Tesla**	**4.31** **4.2**
Two section windings, **material – Nb-Ti** **Currents in sections at 4.2 Tesla, A** **internal section** **external section**	 **460** **950**
Stored energy, kJ	**27.4**
Liquid helium consumption, liter/ hour	**<0.03**
Total weight, ton	**2**

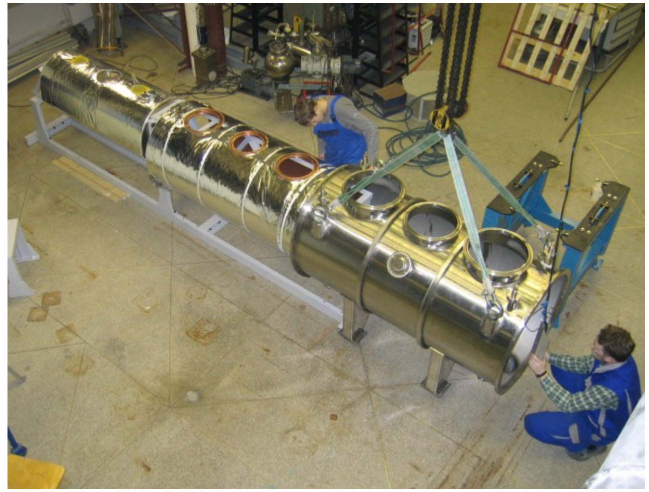




Maximal field of 4.3 Tesla, period – 48 mm

4.2 Tesla 49-pole superconducting wiggler DLS (England)

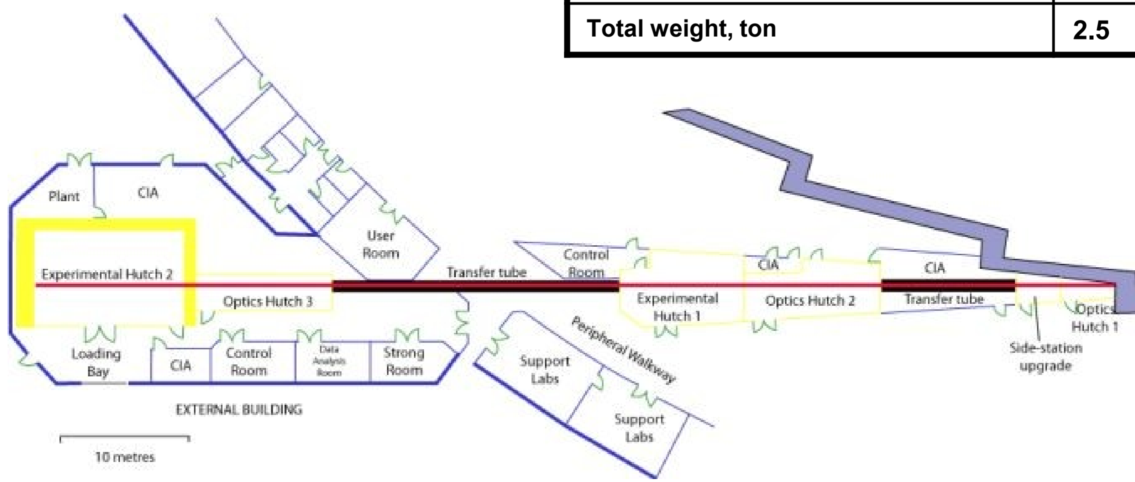
I12 beamline - JEEP: Joint Engineering, Environmental and Processing



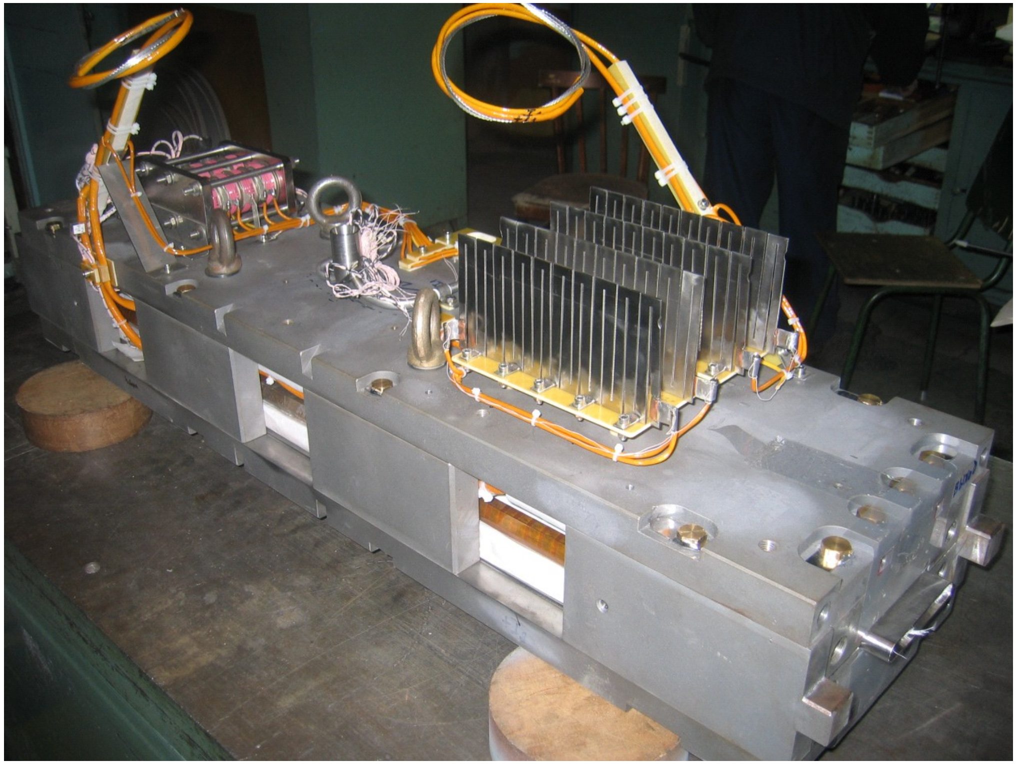
Wiggler assembling on site

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



4.1 Tesla 35 pole superconducting wiggler
LNLS (Brazil)



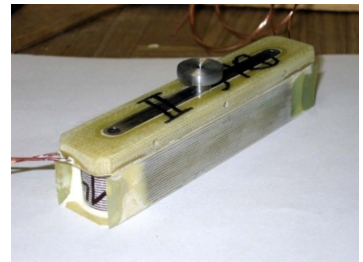
Pole number (main + side)	31+4
Vertical beam aperture, mm Horizontal beam aperture, mm	14 80
Pole gap, mm	18.4
Period, mm	60
Maximal field, Tesla Nominal field, Tesla	4.19 4.1
Two section windings, material – Nb-Ti Currents in sections at 4.2 Tesla, A internal section external section	 441 882
Stored energy, kJ	39
Liquid helium consumption, liter/ hour	<0.03
Total weight, ton	1.9

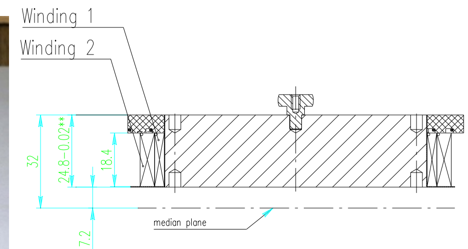
Beamline for Materials Science

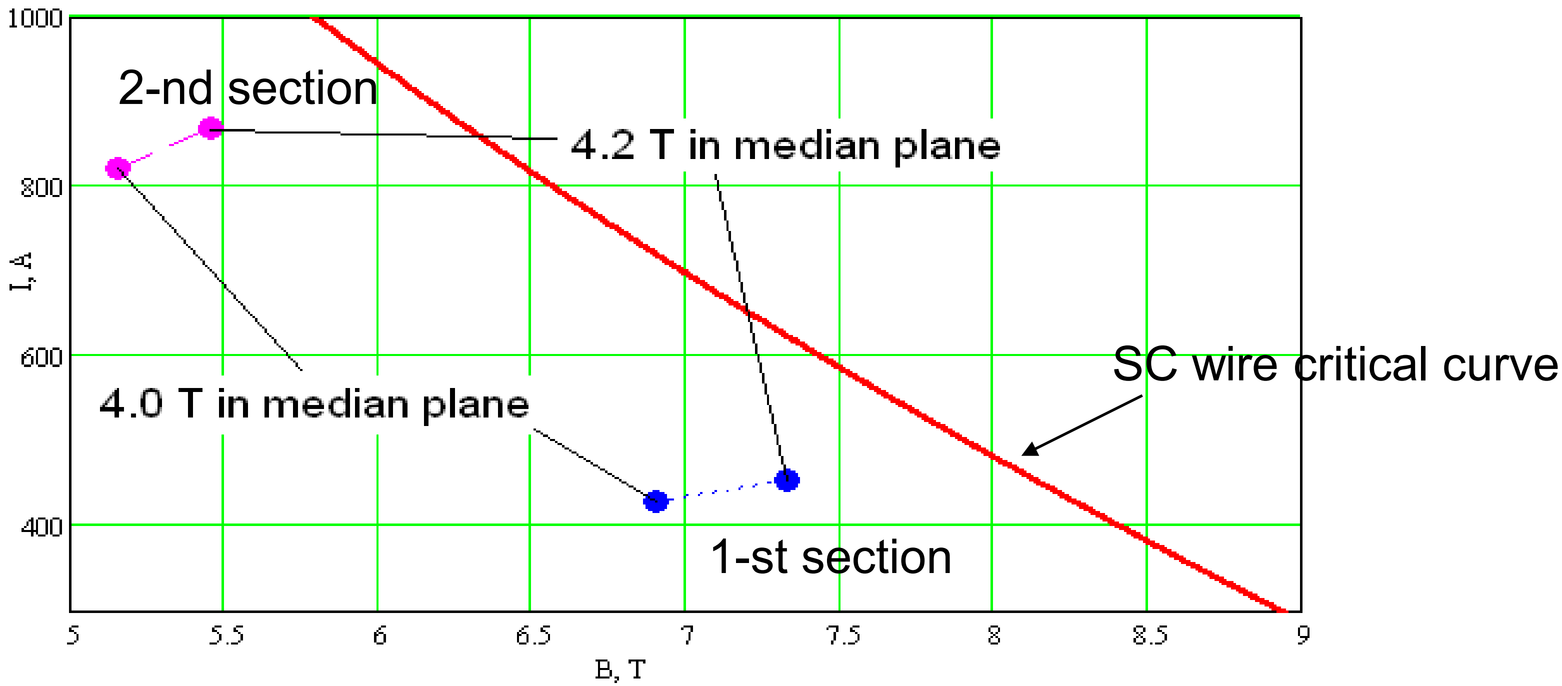
Studies of new materials, specially nanostructured materials, in high conditions (temperature, magnetic field and pressure). The wiggler was designed to produce hard x-rays with 100 times more intensity for photons of 10 keV and 1000 times more intensity for photons of 20 keV, when compared to the typical emission obtained in conventional dipole magnets.

Superconducting wire properties used for MP SC wigglers

Wire diameter with/without insulation, mm	0.91/0.85
Ratio of NbTi : Cu	1.4
Number of filaments	312
Critical current (Amp)	700 (at 7 Tesla)
Number of filaments in wire	312



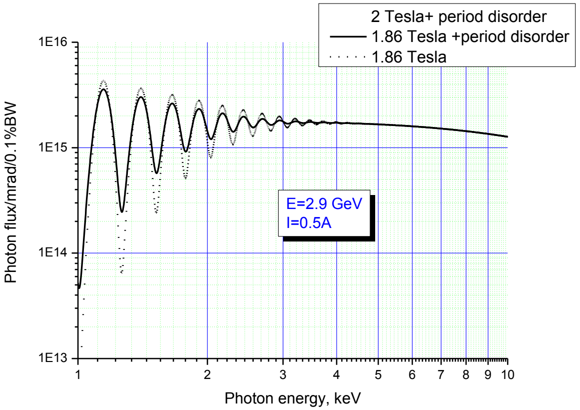




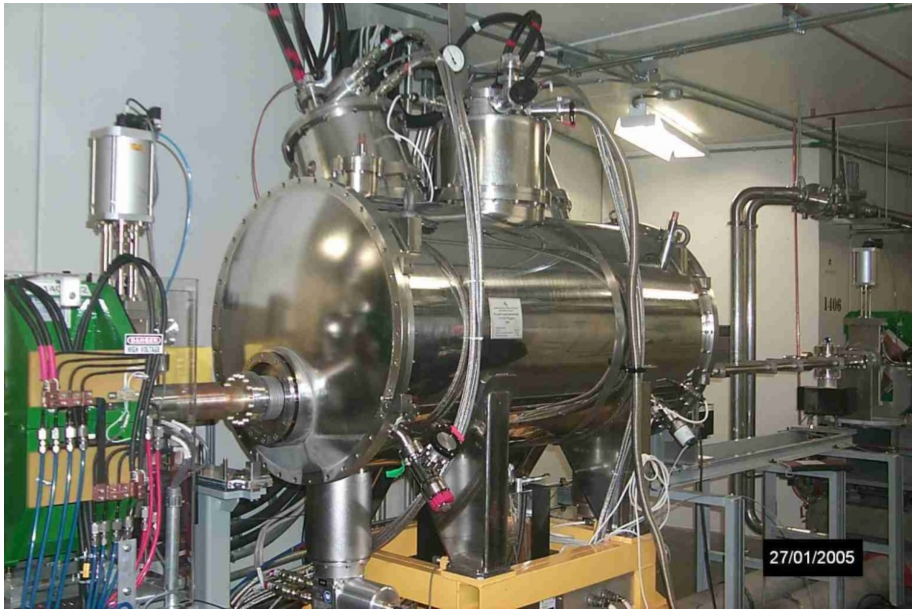
Short period (SP) superconducting multipole wigglers

63-pole, 2 Tesla wiggler for CLS, Canada

Parameter	Value
Operating Field on the Beam Axis	2 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 ^{o}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



Hard X-ray MicroAnalysis (HXMA) beamline

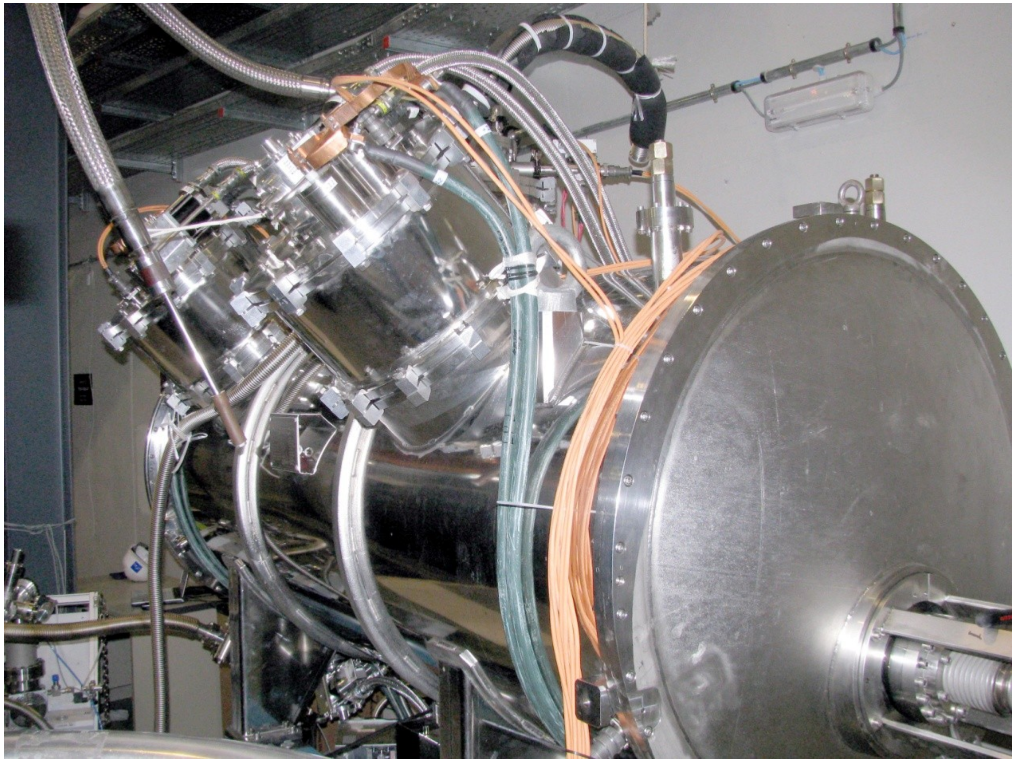


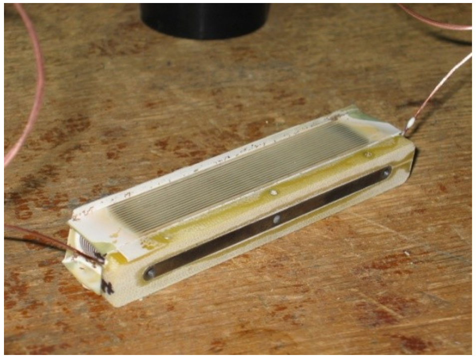
A 2 Tesla Superconducting Wiggler with a period length of 33 mm and 63 poles was designed and fabricated as an X-ray source for HXMA Beamline at the Canadian Light Source Inc.

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.

2.1 Tesla 119-pole superconducting wiggler
ALBA-CELLS (Spain)





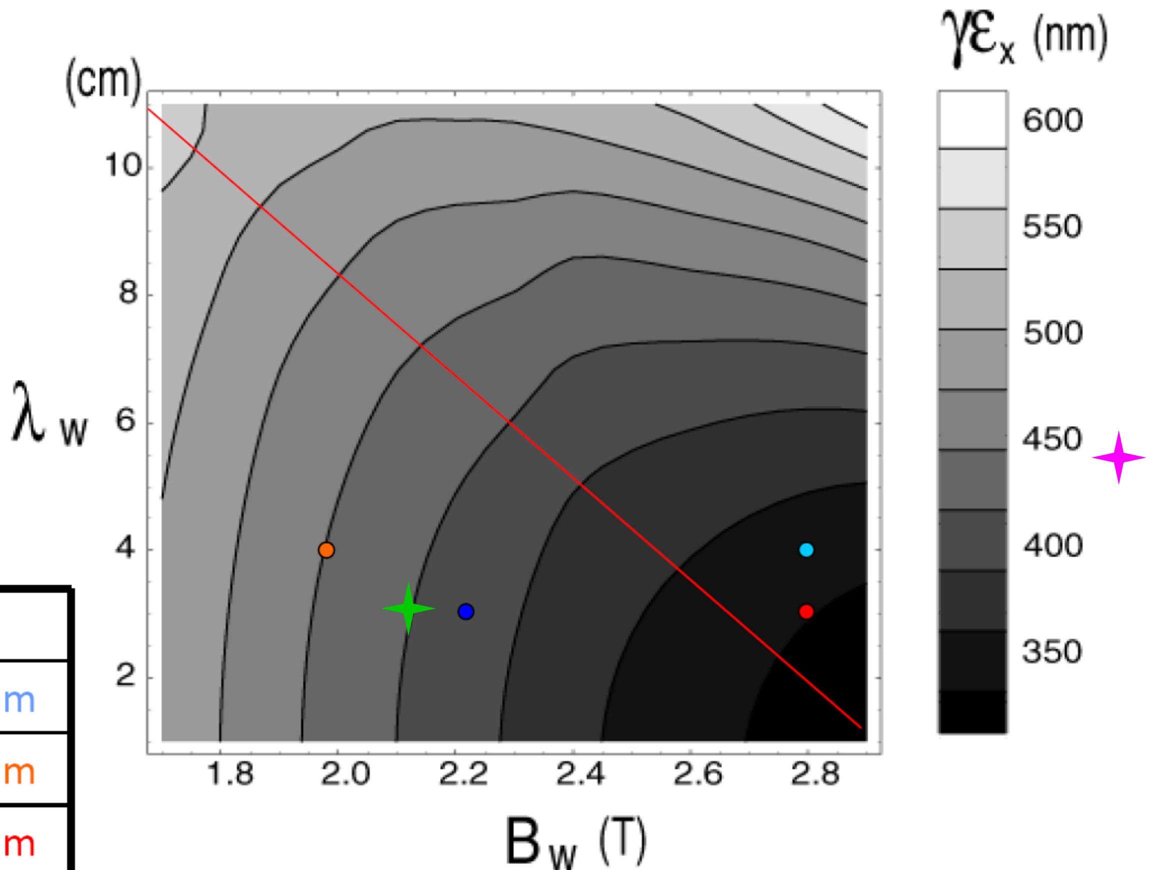
Materials Science and Powder Diffraction (MSPD) beamline

Pole number (main + side)	117+2
Vertical beam aperture, mm Horizontal beam aperture, mm	10 60
Pole gap, mm	12.6
Period, mm	30.3
Maximal field, Tesla Nominal field, Tesla	2.15 2.1
One section windings, material – Nb-Ti Current in section at 2.1 Tesla, A	 440
Stored energy, kJ	36
Liquid helium consumption, liter/hour	<0.03
Total weight, ton	2.5

Wigglers comparison

Type	B_{max}, T	Period, cm	Gap, mm
ALBA wiggler	**2.1**	**3**	**12.6**
DLS wiggler	**4.2**	**4.8**	**14.4**

Type	Bmax	Period	Gap
Nb_3Sn	2.8 T	40 mm	16 mm
NbTi	2.0 T	40 mm	16 mm
Nb_3Sn	2.8 T	30 mm	10 mm
NbTi	2.2 T	30 mm	10 mm

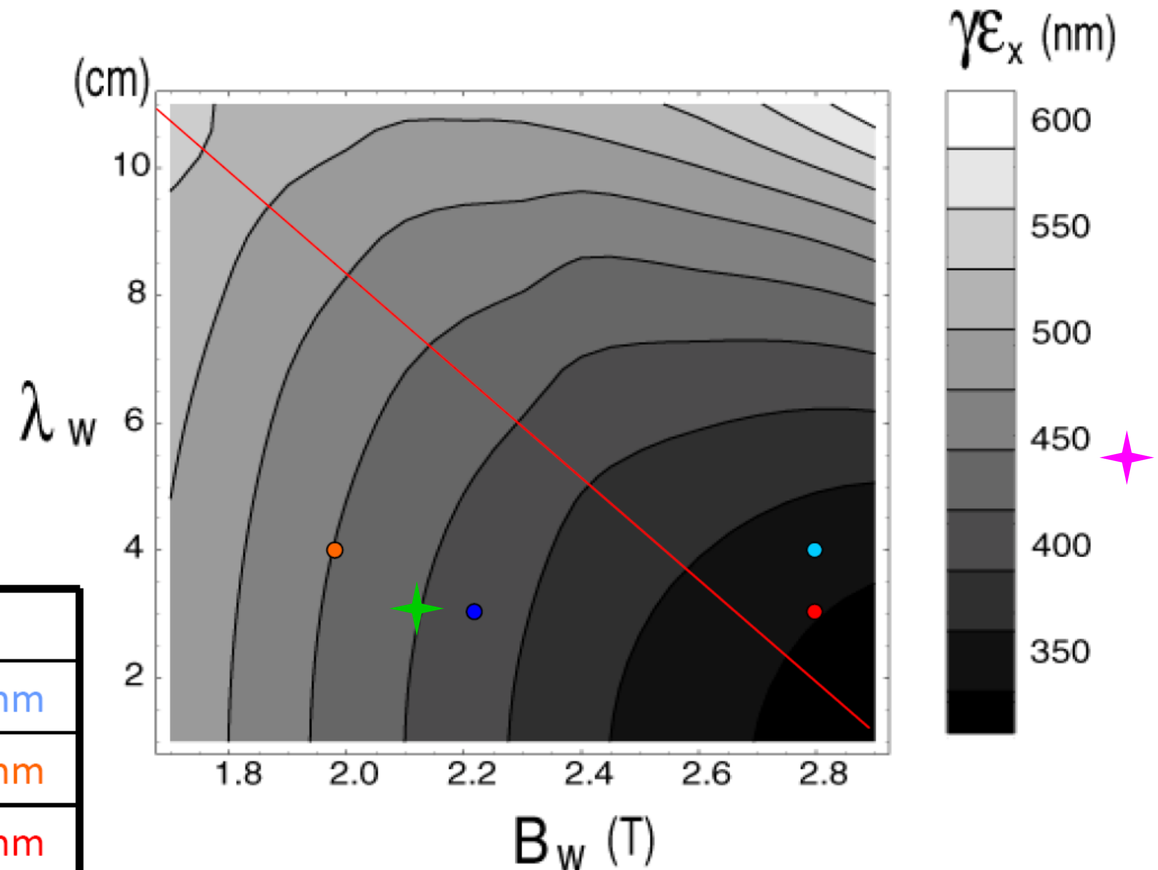


Wigglers comparison

$$B_m = B_p\, e^{-\frac{\pi g}{\lambda_w}}$$

Type	B_p, T	Gap, mm	B_{max}, T
ALBA wiggler	**8**	**10**	**2.7**
DLS wiggler	**10.8**	**18**	**3.3**

Type	Bmax	Period	Gap
Nb_3Sn	2.8 T	40 mm	16 mm
NbTi	2.0 T	40 mm	16 mm
Nb_3Sn	2.8 T	30 mm	10 mm
NbTi	2.2 T	30 mm	10 mm



Advantages of horizontal racetrack coil technology

- Simplicity of the design
- Simplicity manufacturing and testing of single coil
- Field quality
- Reliability
- Lowest inductivity and stored energy
- Possibility to good thermo stabilization of the coil with using Gd_2O_2S powder addmixture to the epoxy compaund (in wet wireing technology)

Cost and rate coil production

- Our current facility permits to produce 3 coils per one 12 hours shift (3 persons are involved in the wiring operation)
- The personal salary is about 30-50 SF per every coil
- Due to simplicity of this facility (turning machine) in a case of big necessity the facility and wiring team can be dublicated

Resume

- BINP has a big experience in the superconducting wigglers manufacturing
- BINP horizontal racetrack wigglers are suitable for CLIC damping ring and can be effectively used in ANKA researc
- BINP can make prototype wiggler
- BINP has not interest for developing vertical racetrack technology

Thanks for attention