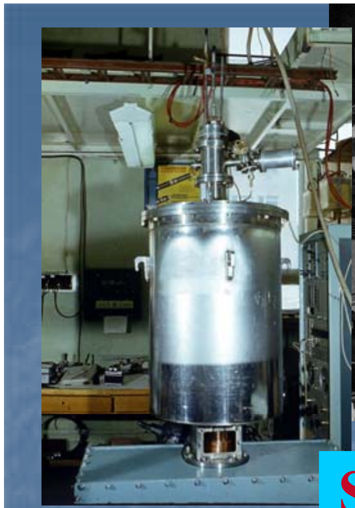
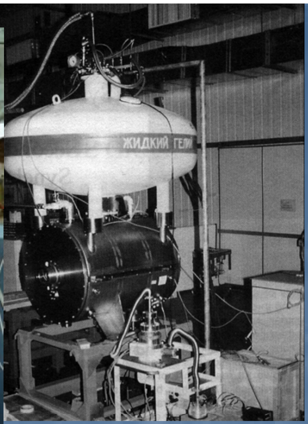
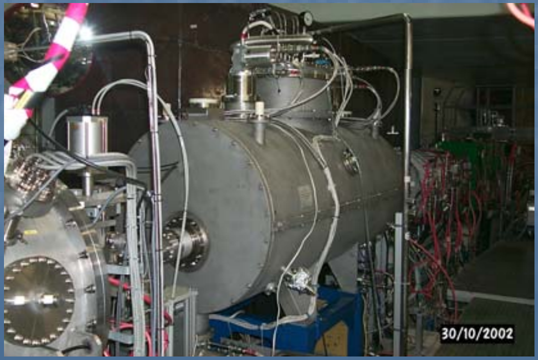


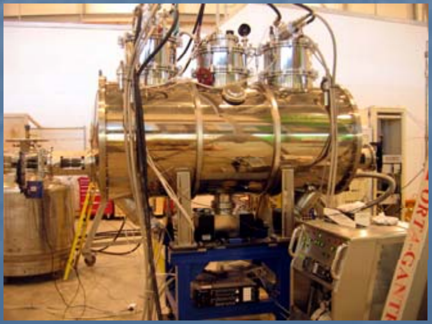


Survey of Superconducting Insertion Devices In Budker INP

Mezentsev N.A.

Budker Institute of Nuclear Physics,
Novosibirsk, Russia



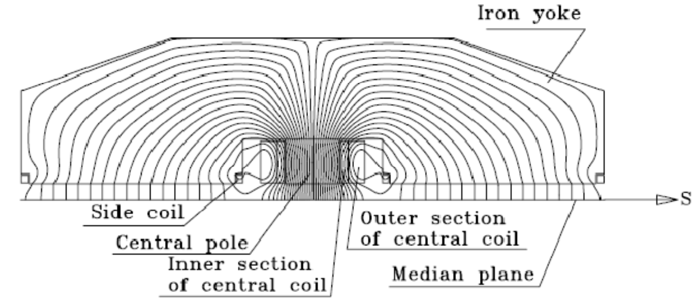


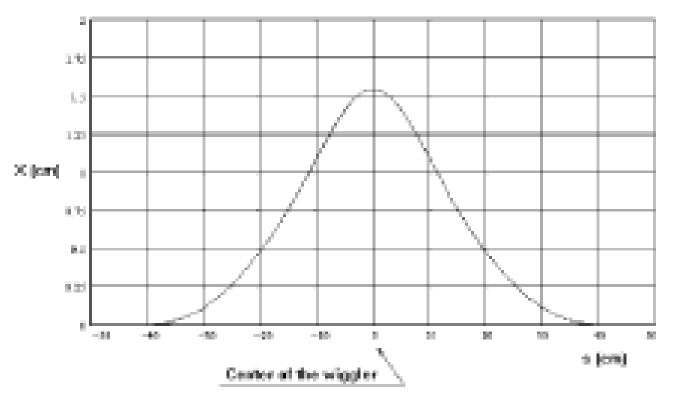
History

- 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 Tesla 27 pole SCW for CLS, Canada
- 2008 - 4 Tesla 49 pole SCW for DLS, England
- 2009 - 4 Tesla 35 pole SCW for LNLS, Brasil
- 2009 - 2.1 Tesla 121 pole SCW for ALBA, Spain

Standard 3-pole Superconducting Wave Length Shifters

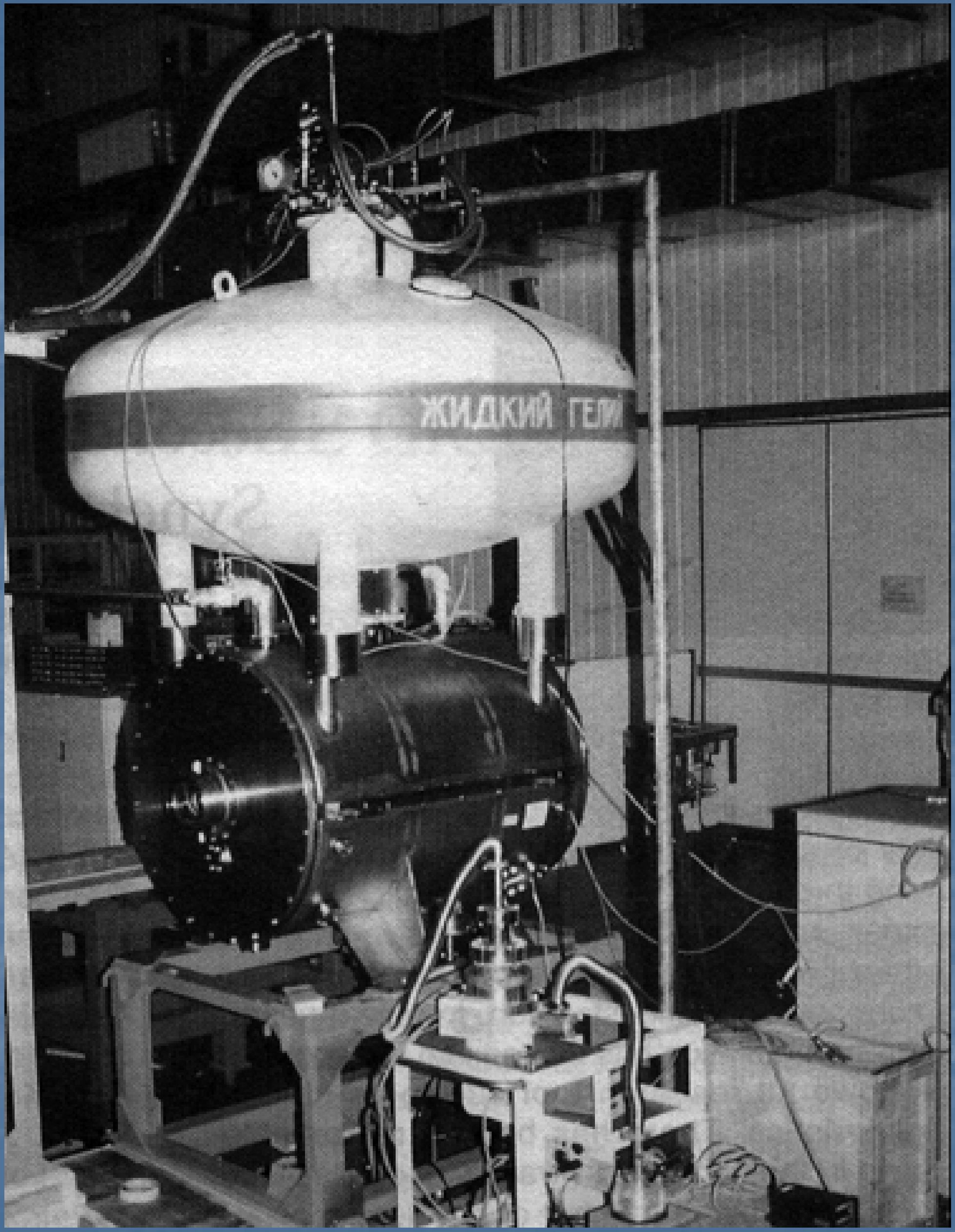
In three-pole magnets only the central magnet with high field is used as a source of radiation. Two others are used for compensation of orbit distortion by the central pole. The compensation puts two conditions: vanishing first and second field integrals over the magnetic system:



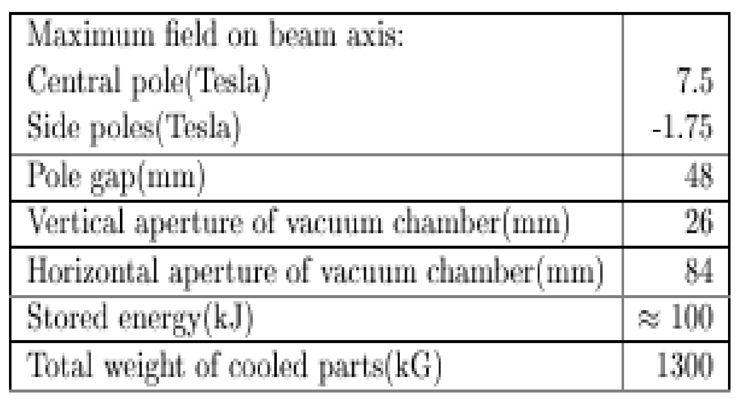


$$I_1 = \frac{1}{H\rho} \int_{-L/2}^{L/2} B_z(s)ds = 0$$

$$I_2 = \int_{-L/2}^{L/2} ds' \int_{-L/2}^{s'} \frac{B_z(s'')}{H\rho} ds'' = 0$$



7.5 Tesla SC WLS for Pohang Light Source, South Korea 1996



Maximum field on beam axis:	
Central pole(Tesla)	7.5
Side poles(Tesla)	-1.75
Pole gap(mm)	48
Vertical aperture of vacuum chamber(mm)	26
Horizontal aperture of vacuum chamber(mm)	84
Stored energy(kJ)	≈ 100
Total weight of cooled parts(kG)	1300

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

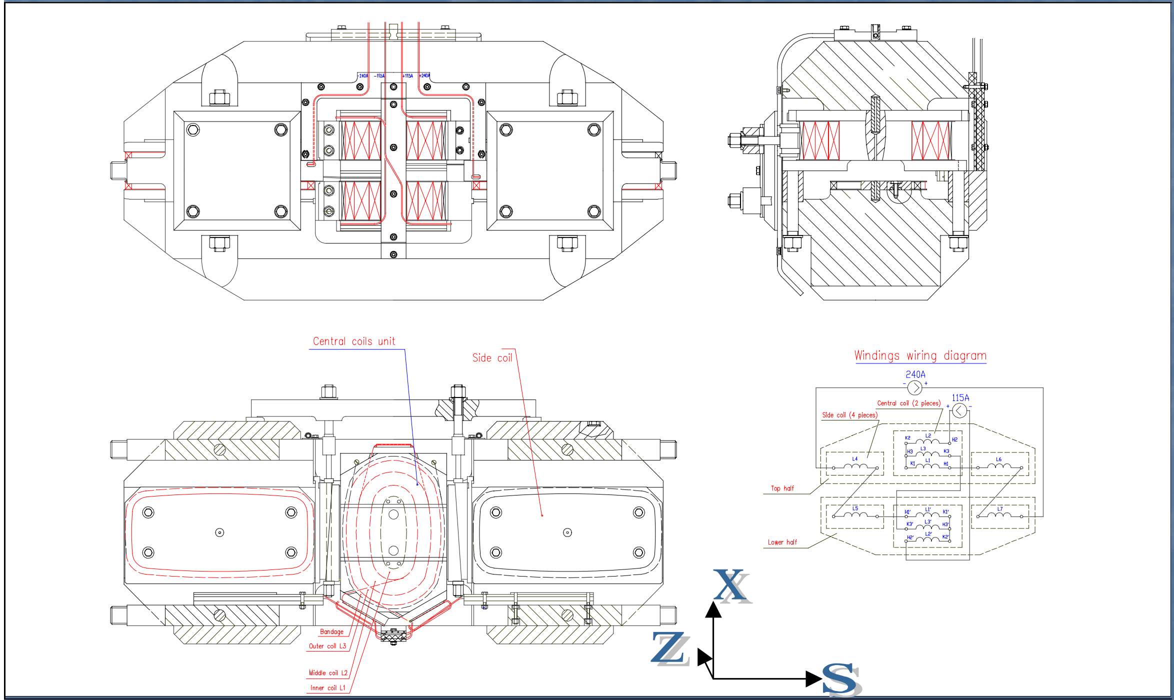
January 2000

10 Tesla WLS for Spring-8 Slow Positron Source

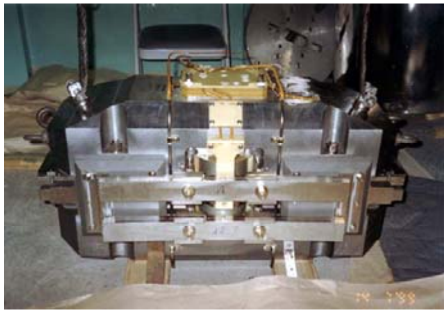
Magnetic field measurements during
Site Acceptance Test

10 Tesla WLS installed on SPrimg-8

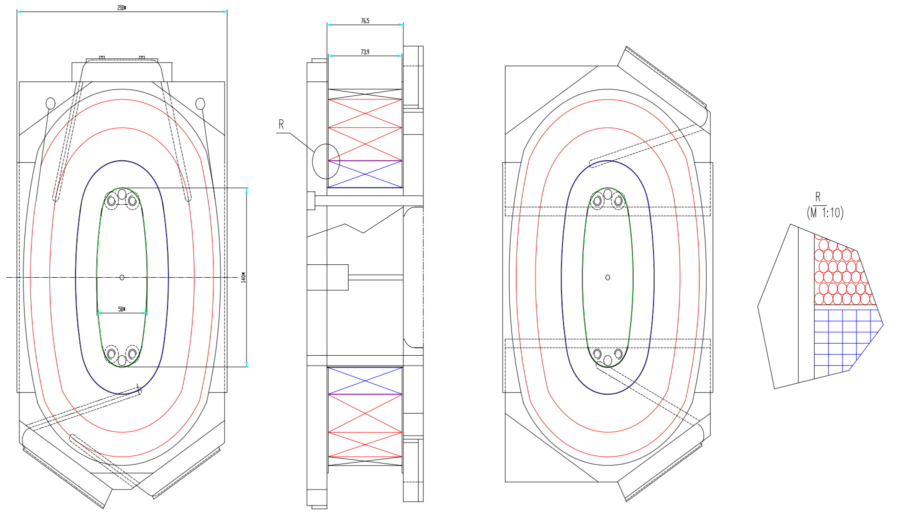
Pole number	3
Magnetic field in central pole (median plane)	10 Tesla
	(10.3 Tesla) Magnetic
field in side poles (median plane)	1.9 Tesla
Stored energy at 10 Tesla field	~400 kJ
Weight of wiggler cold part	~1000 kG
Windings of the central pole	
Nb$_3$S – Rectangular wire by the size	0.85x1.2 мм^2
Nb-Ti – Round wire by a diameter	0.92 мм
Full length of the magnet	1000 mm
Pole gap	42 mm
The size of the electron vacuum chamber	100x20 mm^2



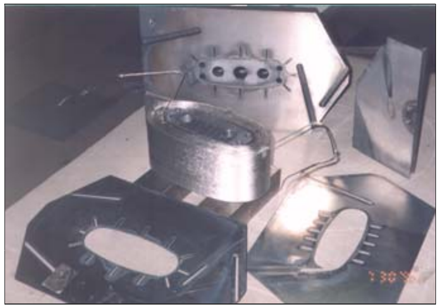
The iron yoke of the wiggler is intended to mechanically support the superconducting windings and the whole magnetic system as well as to reinforce of magnetic field in the orbit and to close the magnetic flux. In this case, the iron yoke is designed to completely close in it the magnetic flux and to exclude influence of stray magnetic fields upon the electron beam of the storage ring outside the superconductive wiggler. The core is made of a magnetically soft material (ARMCO) to diminish influence of the residual magnetic fields.



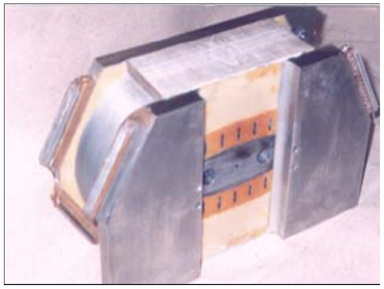
The central pole is a three-section winding, reeled up on a core of a magnetically soft metal with high magnetic permeability (the ARMCO grade). Electric contacts between the sections are taken outward and connected to each other with a rectangular superconducting tie. To be reeled up, the coil is placed in a special technological mandrel. The inner section of the central pole is manufactured by the "dry reeling" method from a rectangular Nb-Sn tie 1.4x0.87 mm in size.



Nomer katu[ki	Provod	Koli'estvo sloev	Koli'estvo vitkov v sloe	Koli'estvo vitkov v kat.
1	[inka sverh-provod. 0.87h1.4	24	52	1248
2	Provod sverh-provodq]ij ø0.92	32	79,78	2512
3		24		1884
Bandax	Provolokaø1 mm 12H18N10T	8	74,73	596

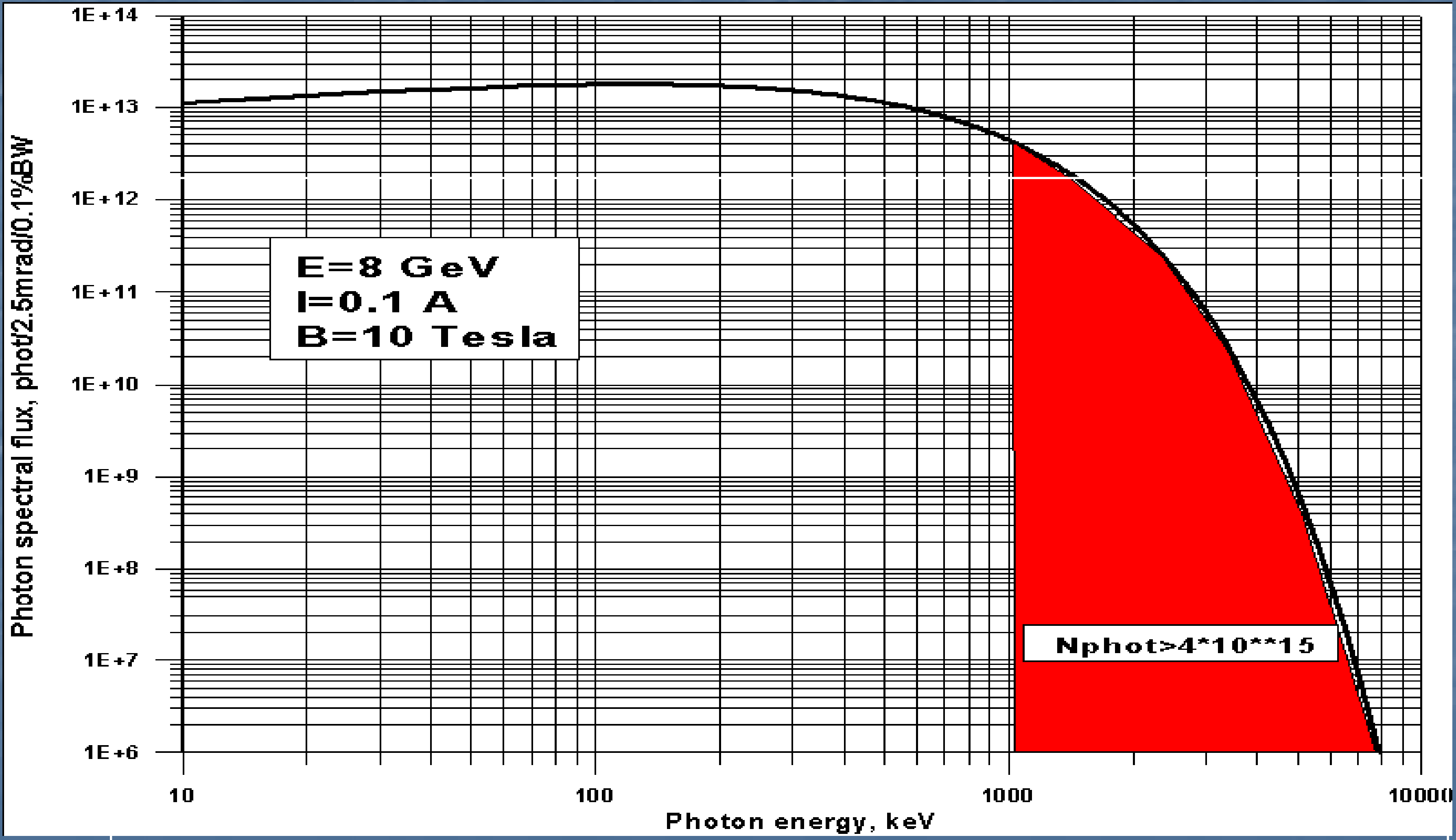


Nb-Sn coil disassembled after baking out



½ of central pole of 10 Tesla WLS

High energy of electron in SPring-8 gives a possibility to obtain wide spectrum of synchrotron radiation and hard part of the spectrum rich of MeV region. Critical energy of synchrotron radiation for electron energy of 8 GeV and magnetic field in central pole of the wiggler of 10 Tesla is equal to 450 keV.



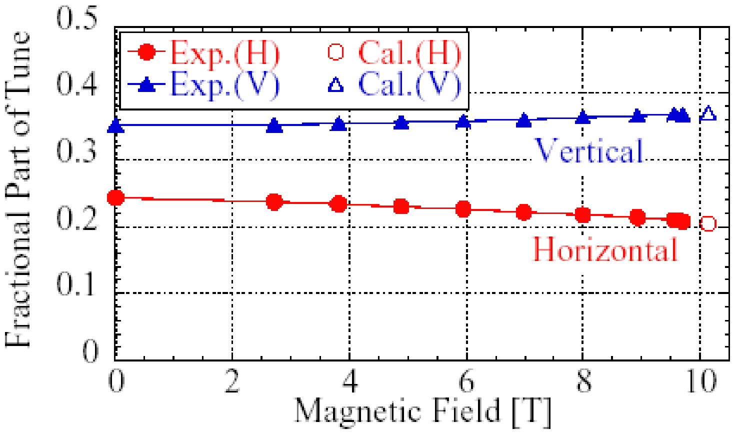


Figure 2: Betatron tunes as a function of the SCW peak field.

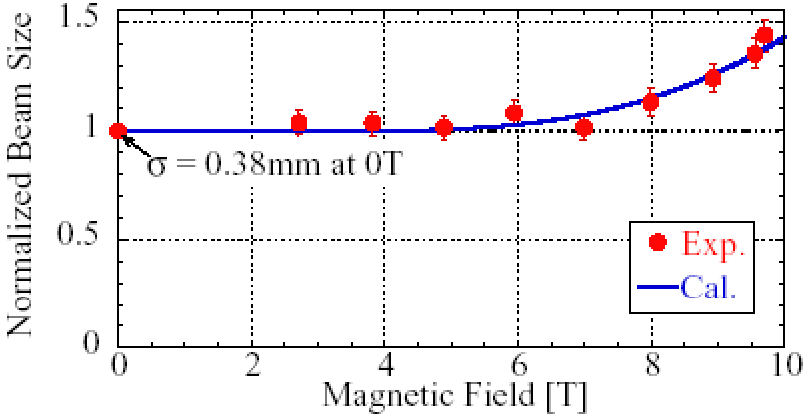


Figure 3: Horizontal beam size normalized at 0T.

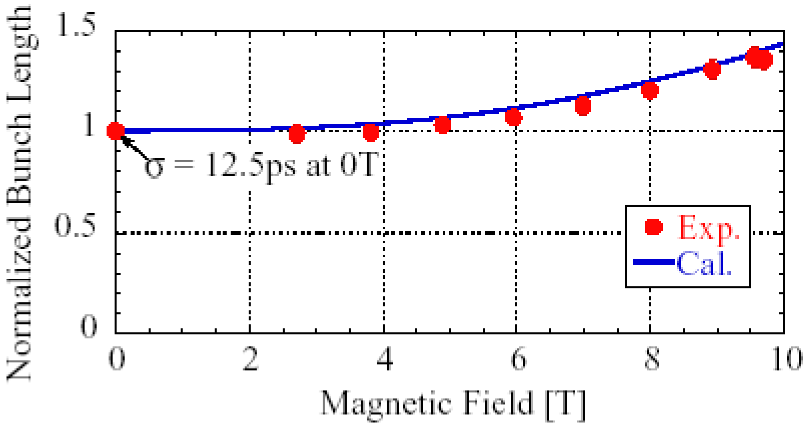


Figure 4: Bunch length normalized at 0T.

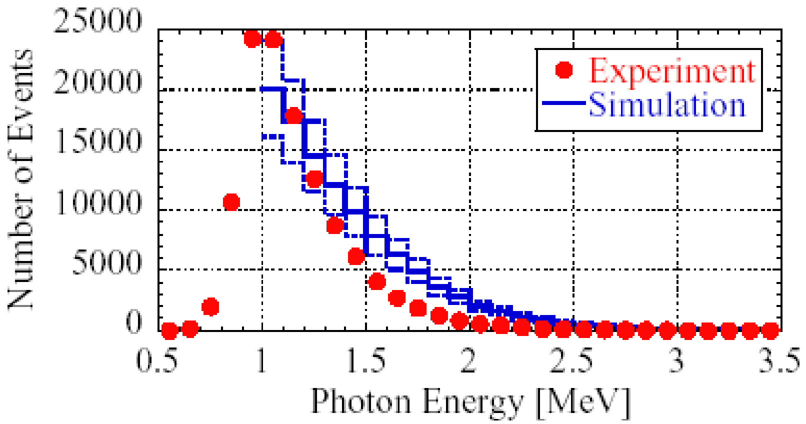
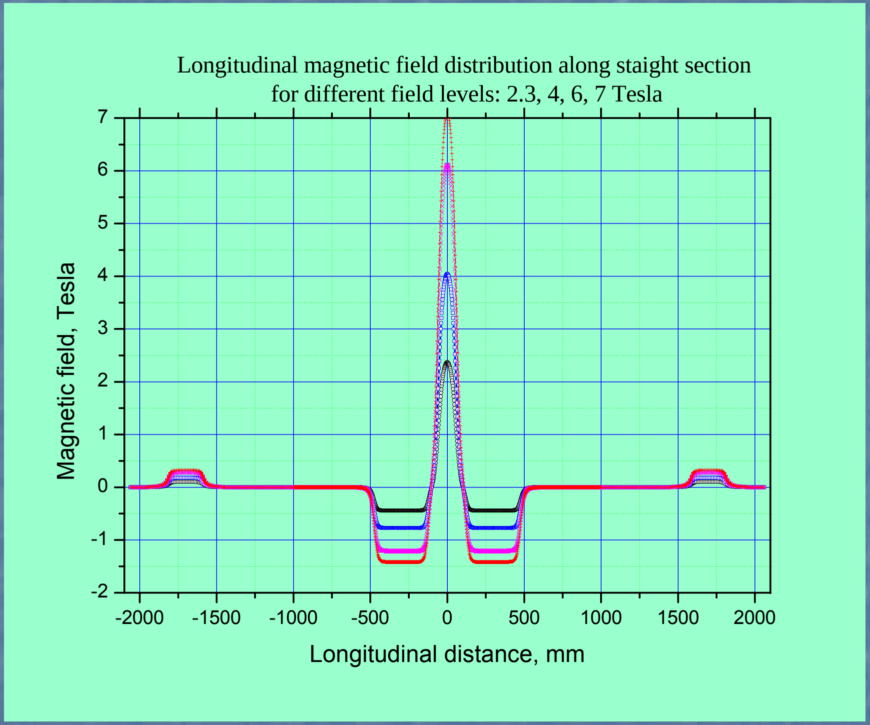


Figure 6: Photon spectrum at the field 9.5T.

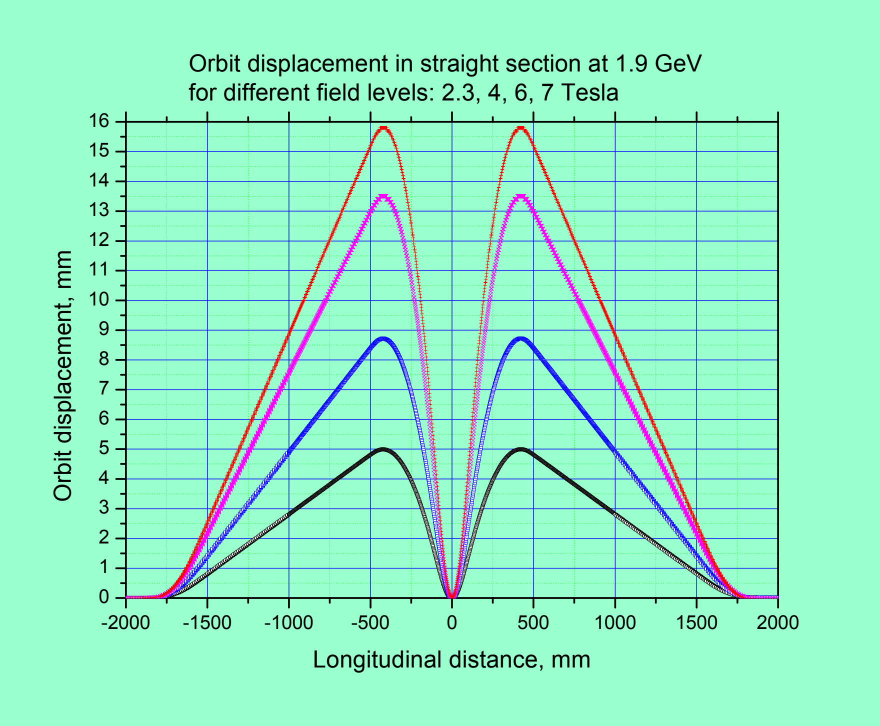
Wave Length Shifters with fixed point of radiation

There is a variant of 3 pole shifter (shifter with fixed radiation point) where the superconducting part of magnet has non-zero field integrals 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.

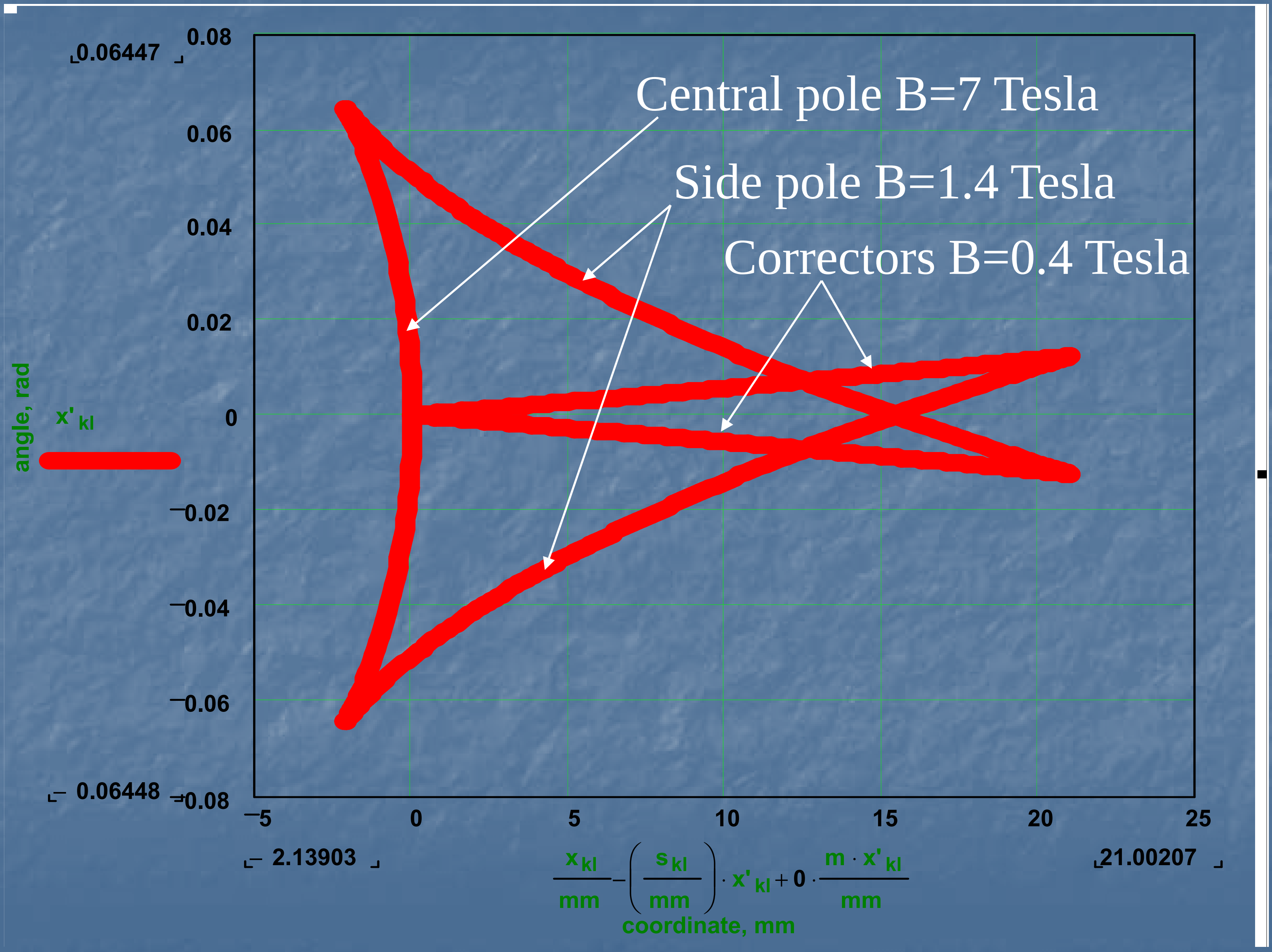


Magnetic field distribution of 7 Tesla WLS for BESSY-2



Orbit distortion inside 7 Tesla SC WLS for BESSY-2

Phase diagram of photon beam from 3 pole WLS

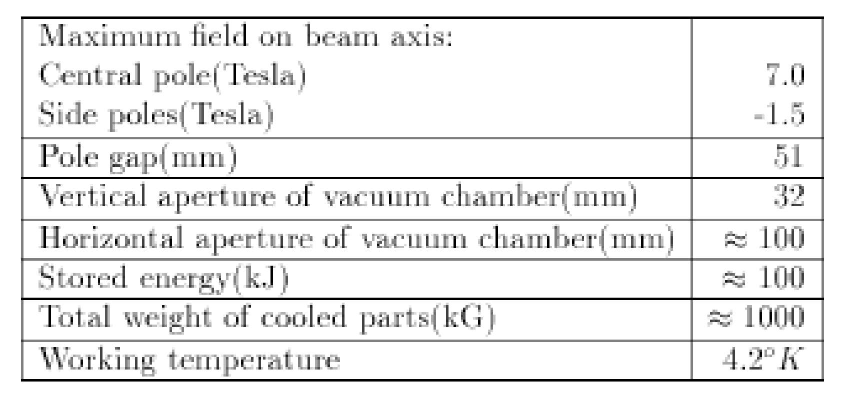


Central pole B=7 Tesla

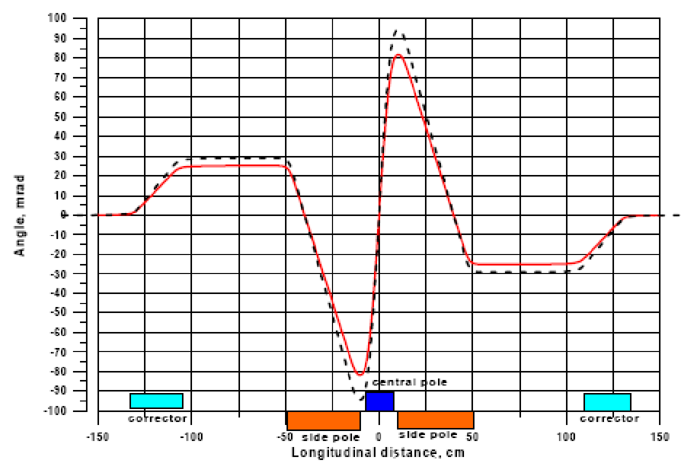
Side pole B=1.4 Tesla

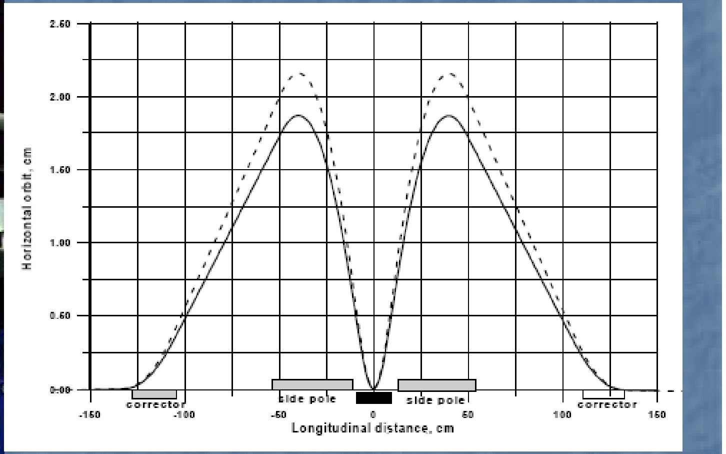
Correctors B=0.4 Tesla

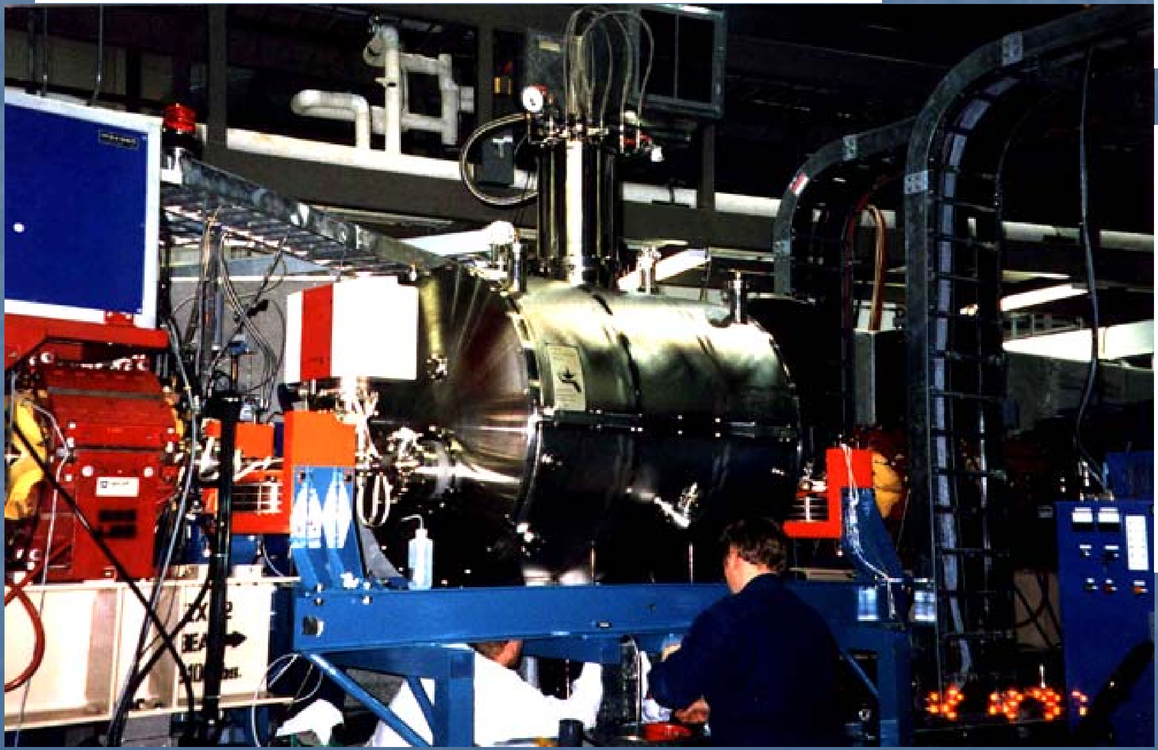
7 T superconducting wiggler at CAMD-LSU (USA) storage ring (1997)



Maximum field on beam axis:	
Central pole(Tesla)	7.0
Side poles(Tesla)	-1.5
Pole gap(mm)	51
Vertical aperture of vacuum chamber(mm)	32
Horizontal aperture of vacuum chamber(mm)	≈ 100
Stored energy(kJ)	≈ 100
Total weight of cooled parts(kG)	≈ 1000
Working temperature	$4.2^\circ K$

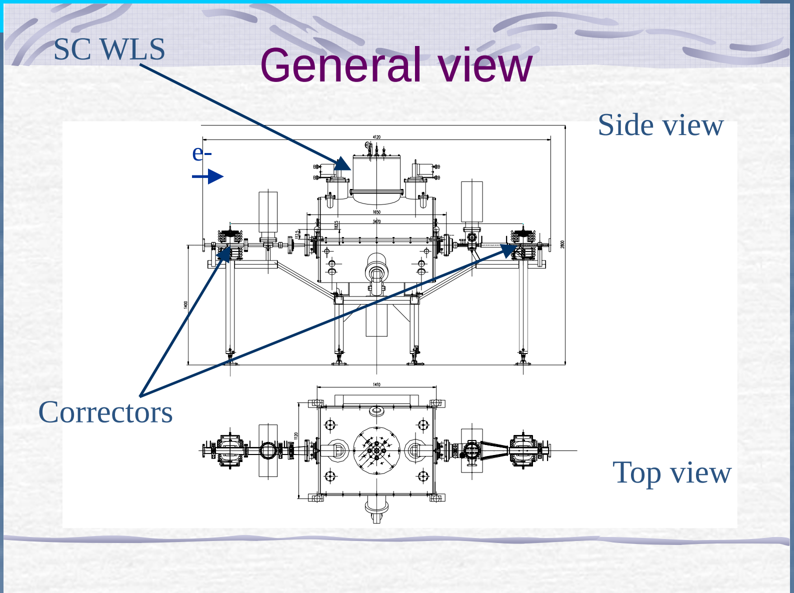






7 Tesla WLSs for BESSY-2 (Germany 2000, 2002)

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



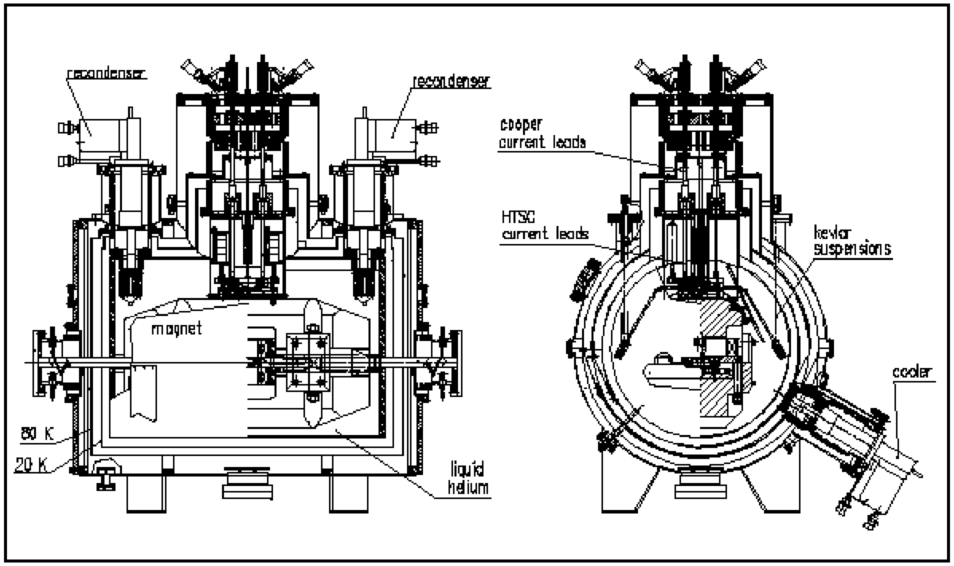
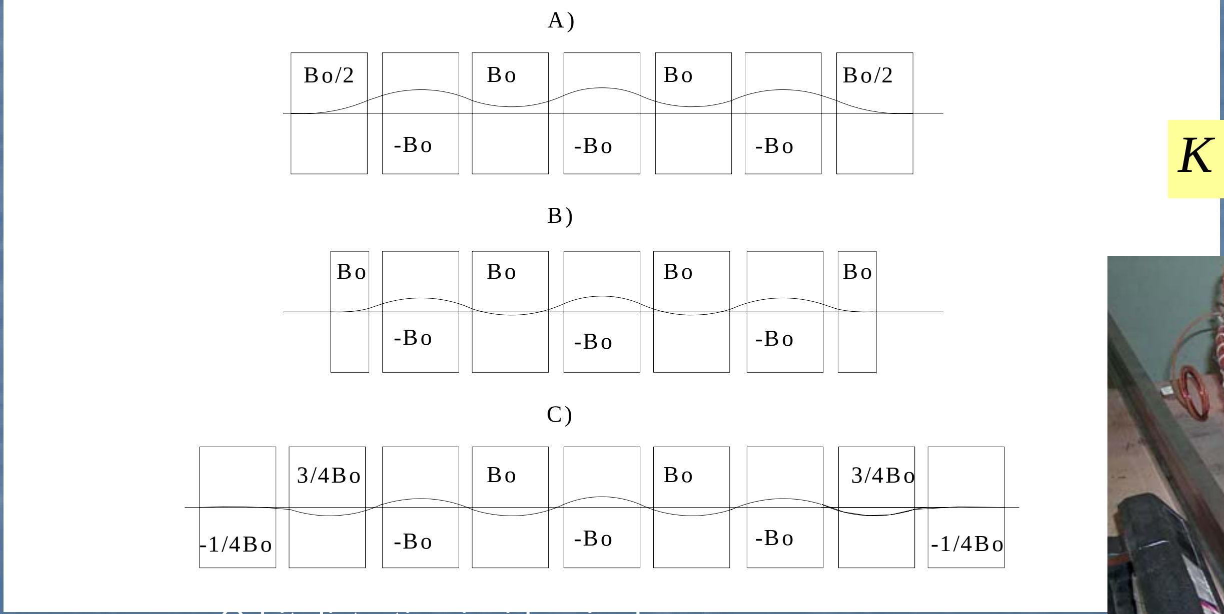


Fig. 2-1 General view of WLS system

Superconducting multipole wigglers

A superconducting wiggler presents a sign-alternating magnetic structure satisfying first field integral to be zero. To satisfy this condition, the field integral of side poles should be twice less than that of the main pole, having magnetic structure like ½,-1,1,-1 …..-1, ½ for symmetrical magnetic structure with an odd number of main poles, and ½,-1,1,-1 …..1, - ½ with an even main pole number.

A symmetrical magnetic system with an odd pole number satisfy condition of second field integral to be zero automatically and does not disturb orbit outside the wiggler while an asymmetric magnetic structure with an even pole number has non-zero second field integral and disturbs the electron orbit; hence it needs additional correctors.

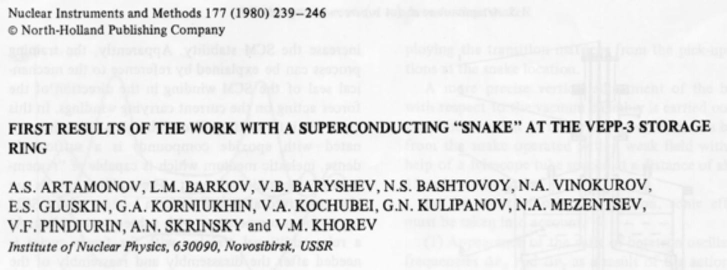


Orbit distortion inside wigglers with different magnetic structures.

$$K = 0.934 \cdot \lambda_0[cm]B[Tesla]$$

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



Nuclear Instruments and Methods 177 (1980) 239–246
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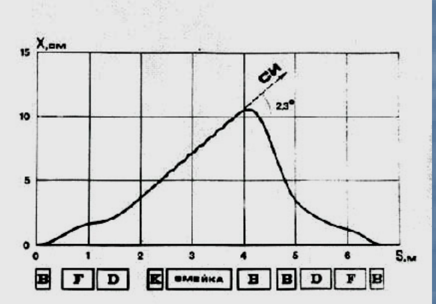
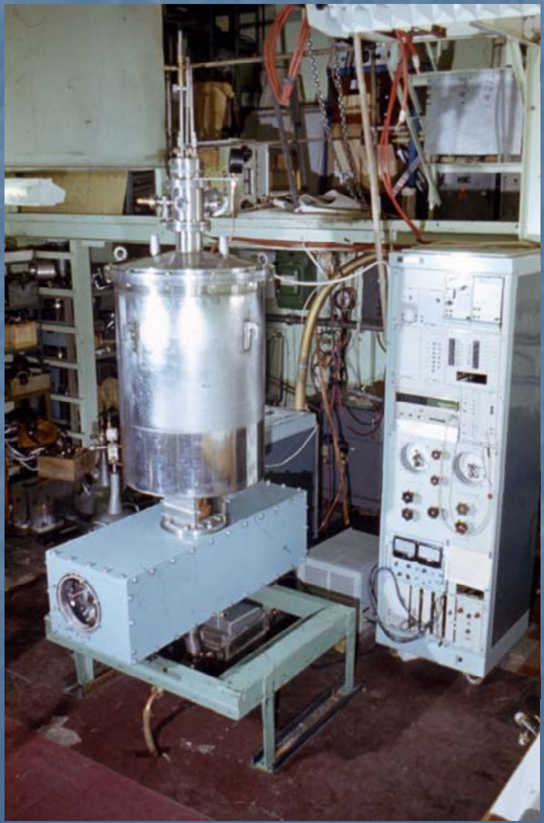
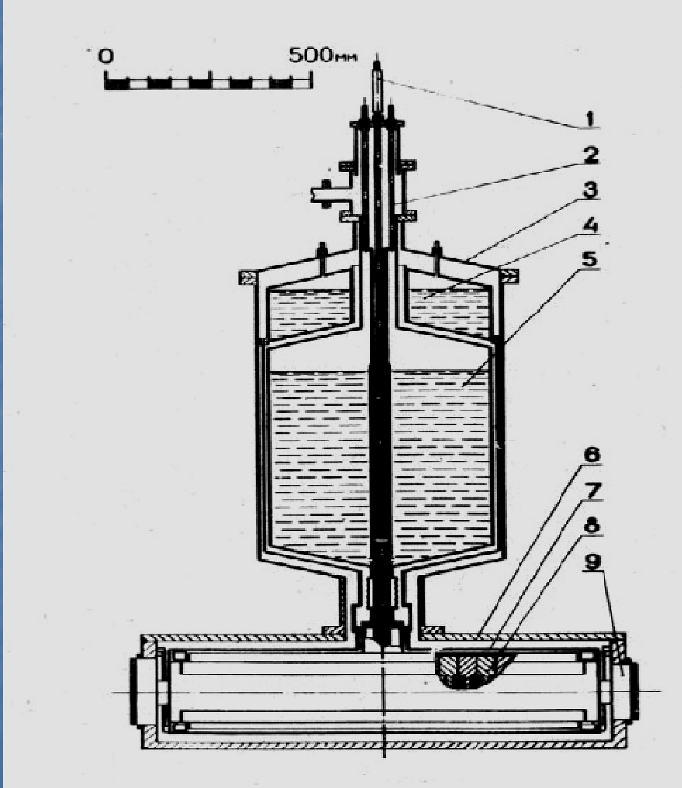
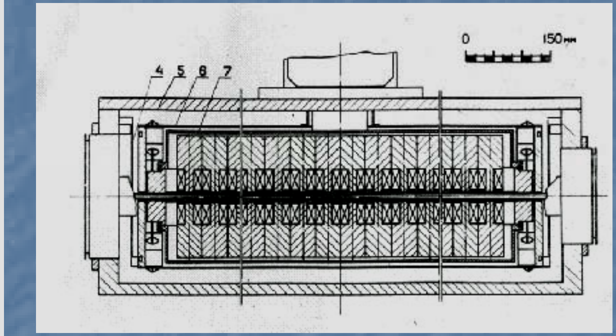
FIRST RESULTS OF THE WORK WITH A SUPERCONDUCTING "SNAKE" AT THE VEPP-3 STORAGE RING

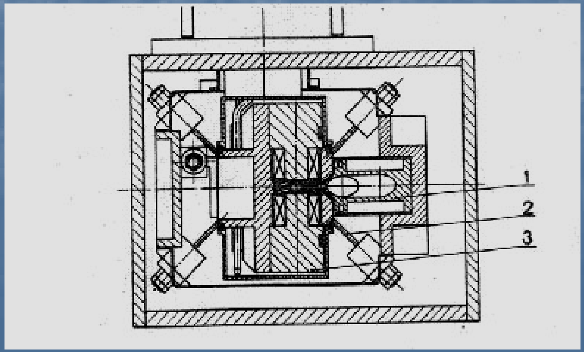
A.S. ARTAMONOV, L.M. BARKOV, V.B. BARYSHEV, N.S. BASHTOVOY, N.A. VINOKUROV,
E.S. GLUSKIN, G.A. KORNIUKHIN, V.A. KOCHUBEI, G.N. KULIPANOV, N.A. MEZENTSEV,
V.F. PINDIURIN, A.N. SKRINSKY and V.M. KHOREV
Institute of Nuclear Physics, 630090, Novosibirsk, USSR

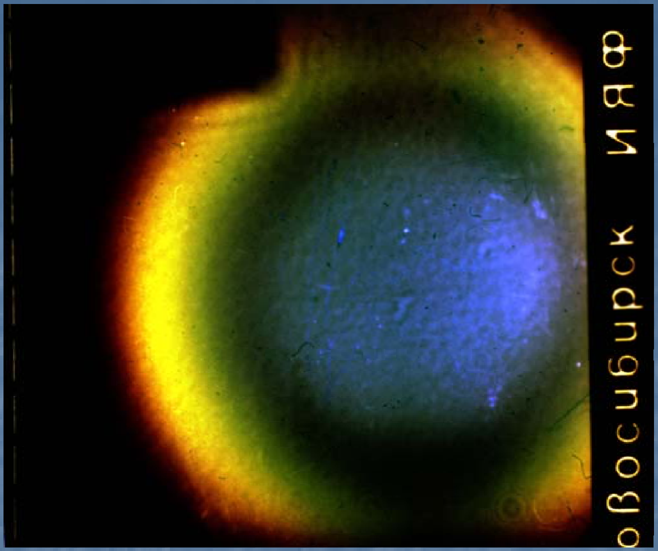


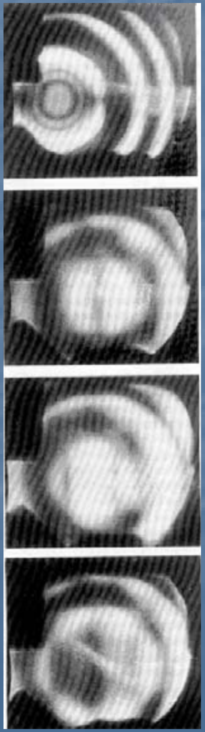




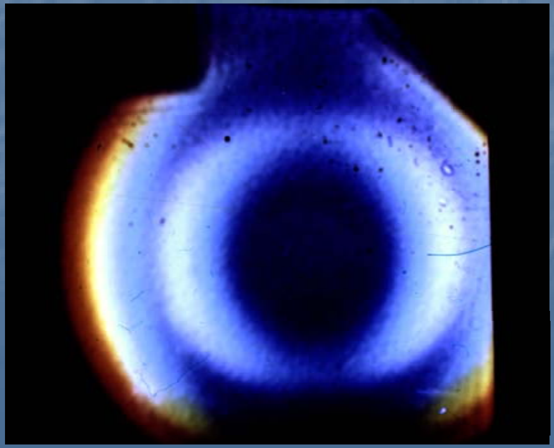




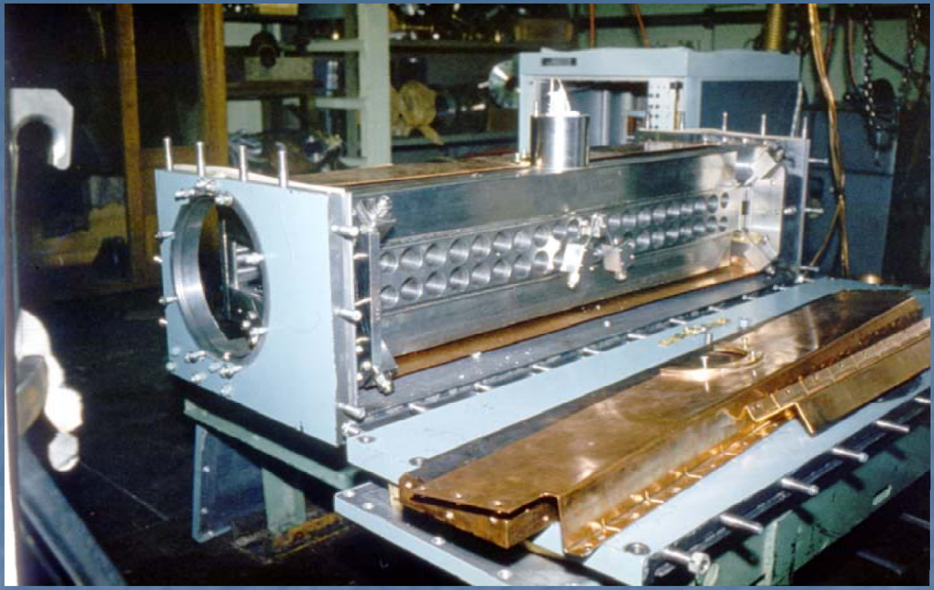




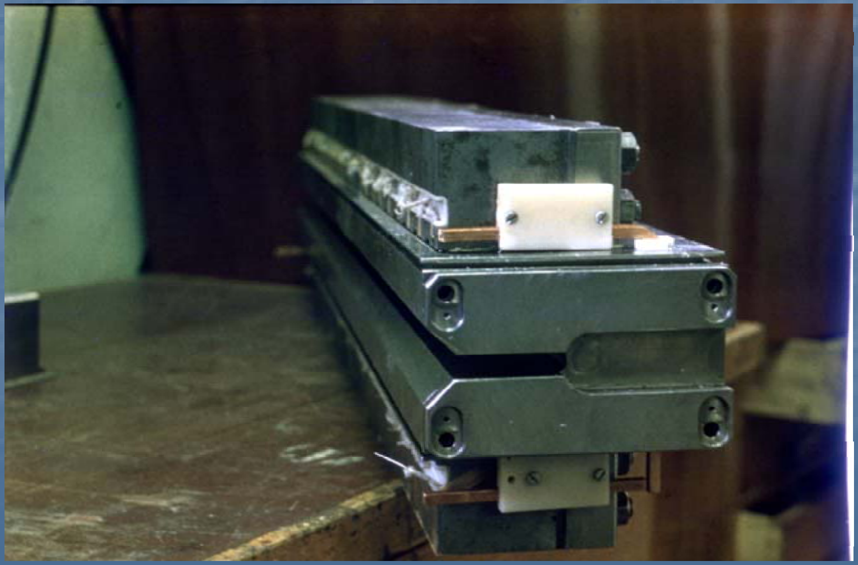
Undulator light from
The wiggler



Nitrogen shield screen



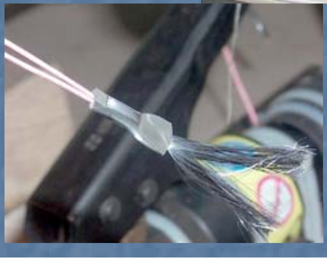
Superconducting magnet

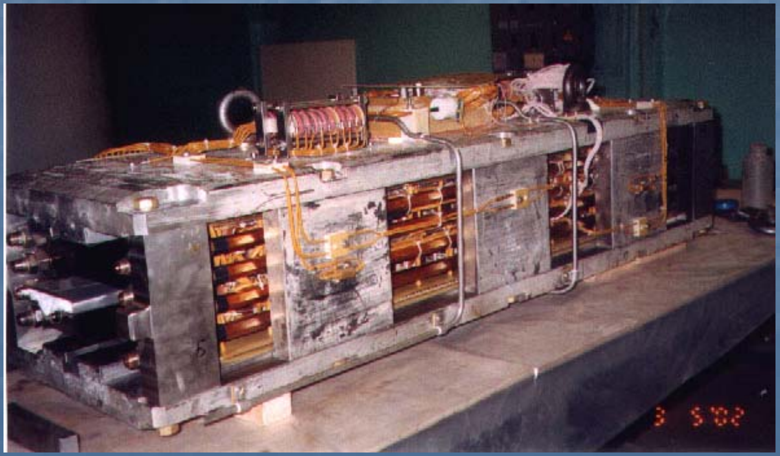


Multipole wigglers main parameters

	ELETTRA	BESSY-HMI	CLS-1	DLS-1	CLS-2	Сибирь-2	DLS-2	LNLS	ALBA
	Italy	**Germany**	**Canada**	**England**	**Canada**	**Москва**	**England**	**Brasil**	**Spain**
Magneic field, Tesla	3.5	7	2	3.5	4	7.5	4	4	2.1
Max. magnetic field, Tesla	3.67	7.45	2.2	3.77	4.31	7.67			
Pole number	45/49	13/17	61/63	45/49	25/27	19/21	45/49	31/35	121/123
Pole gap, mm	16.5	19	13.5	16	13.9	20.2	14.4	16.2	13.4
Period, mm	64	148	33-34	60	48	164	48	60	30.16
Beam aperture,VxH mm	10.7x81.3	13x110	окт.50	10x80	9x50	14x120	10x60	12x80	8.5x72
Currents, A	210/288	145/232	400/400	332/285	460/490	160/240	430/470	400/400	423/400
Stored energy, kJ	240	400	15	25	27.4	520	47	39	31
Year	2002	2002	2005	2006	2007	2007	2008	2009	2009

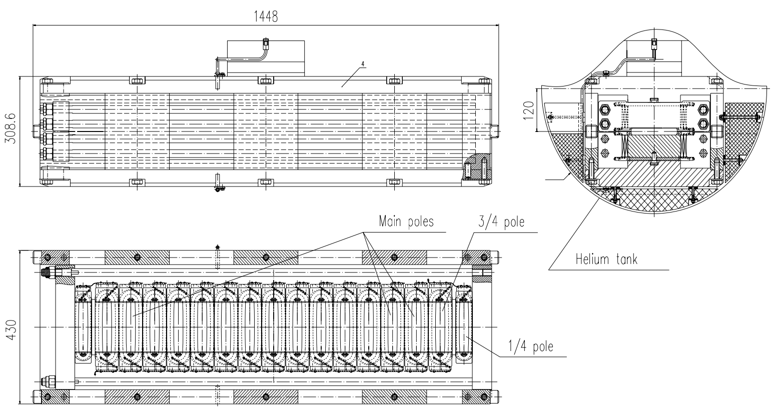
7 Tesla 17 pole wiggler for BESSY-2(Germany) (2002)





Number of poles (main+side)	13+4
Vertical aperture, mm	14
Magnetic gap, mm	19
Period length (main pole length), mm	148 (74)
Maximum magnetic field, T	7.45 (7.0)
Currents for 7 T magnetic field, A First current Second current	 145 197
Electron energy, GeV	1.9
Beam current, A	0.5
Radiation power, kWatt	60

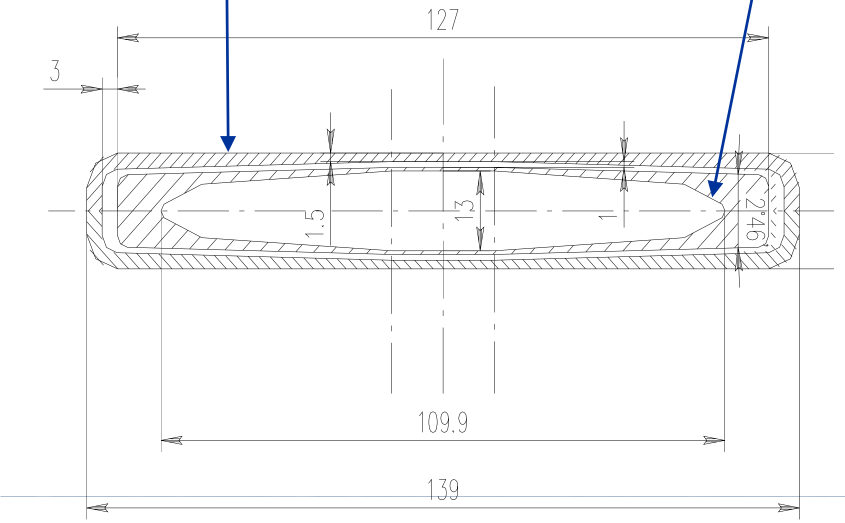
Magnet system of 17-poles superconducting wiggler

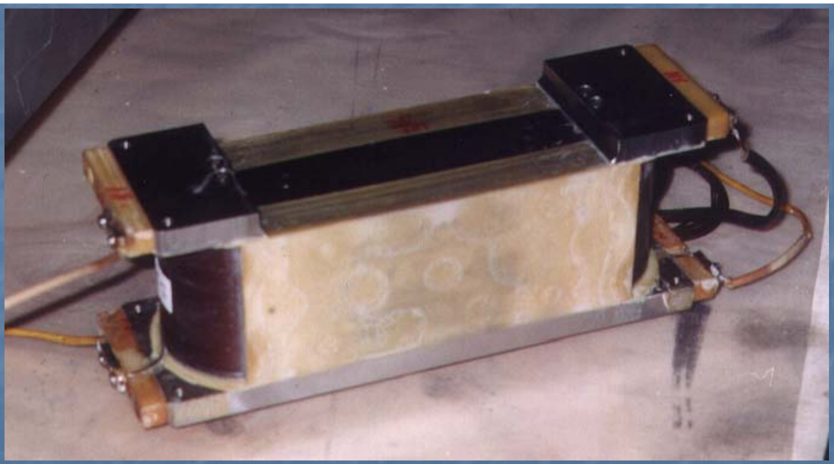


Stainless steel LHe vessel 4 K

Copper liner

Copper liner into helium vessel vacuum tube

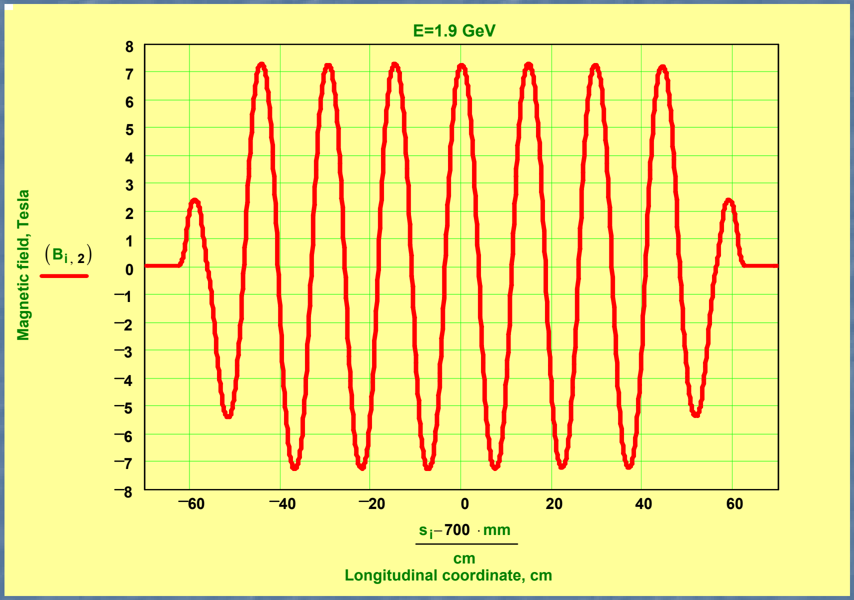




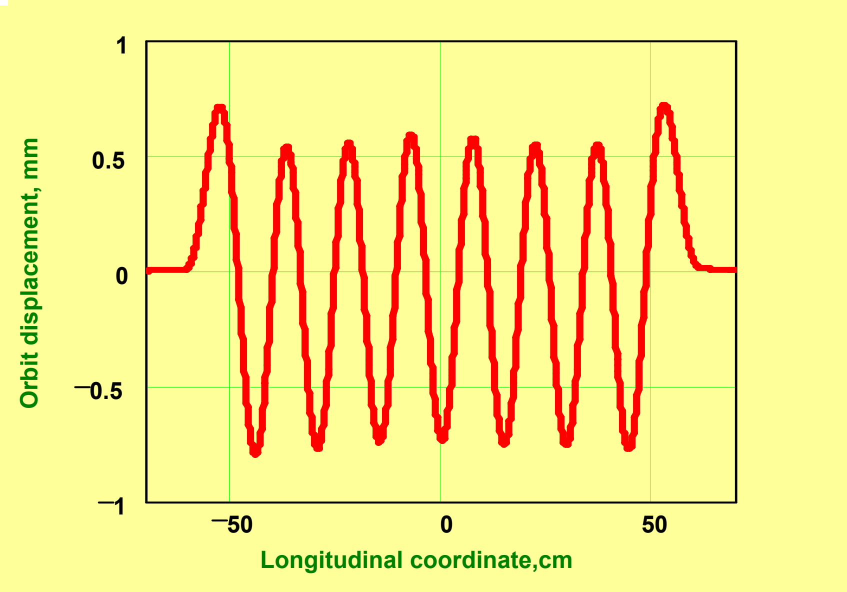
½ wiggler pole

The electron orbit inside a wiggler with ½ side poles oscillates with respect to the axis line horizontally, with a shift equal to the oscillation amplitude. In order to avoid this orbital shift, the end poles may have a structure 1/4,- 3/4,1,-1,….1,-3/4, 1/4.

As example of this structure, the magnetic field distribution of the 7 Tesla BESSY-2 wiggler and the orbit distortion inside the wiggler is shown in Figures below.

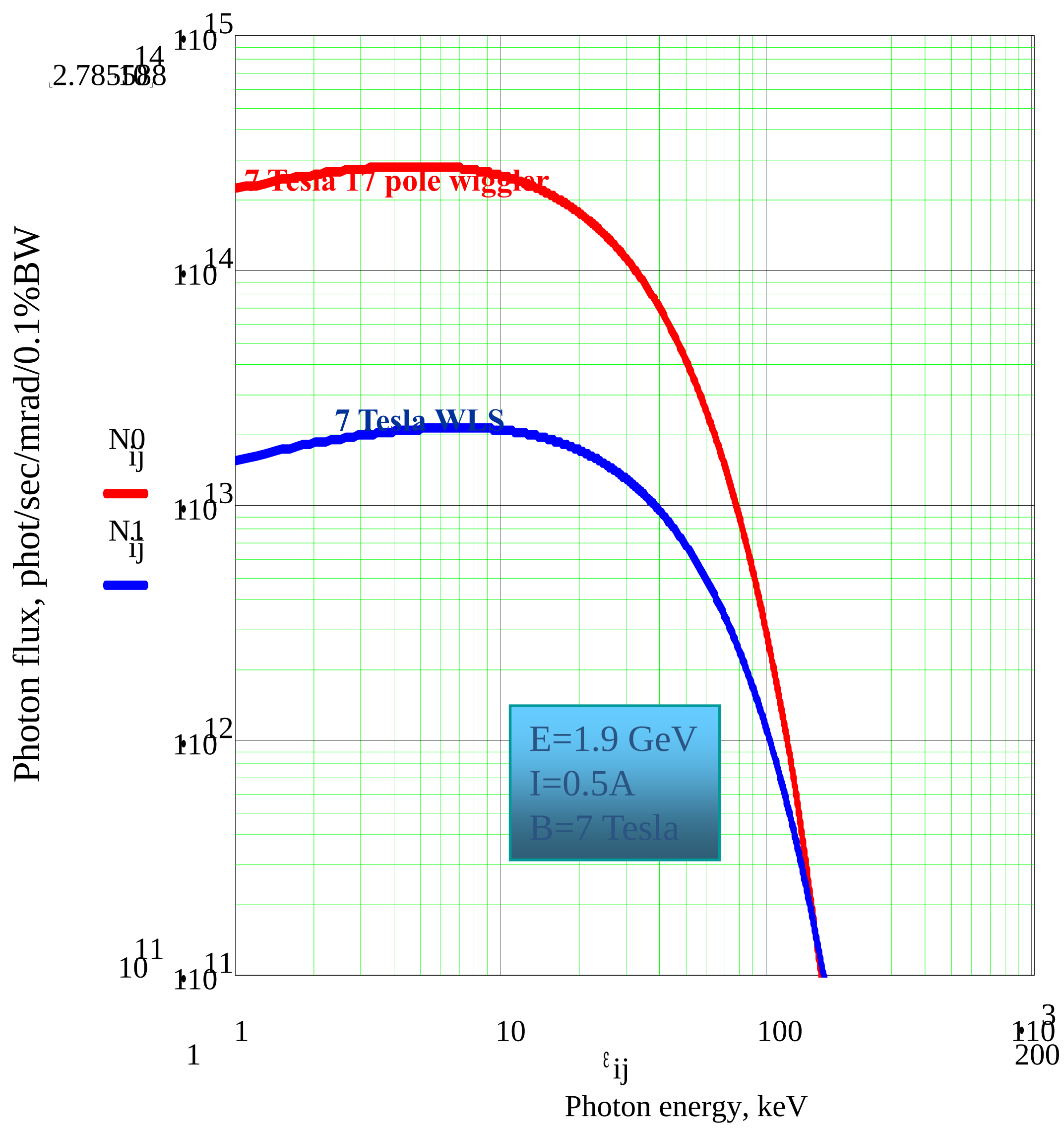


Magnetic field distribution of 7 Tesla wiggler for BESSY-2

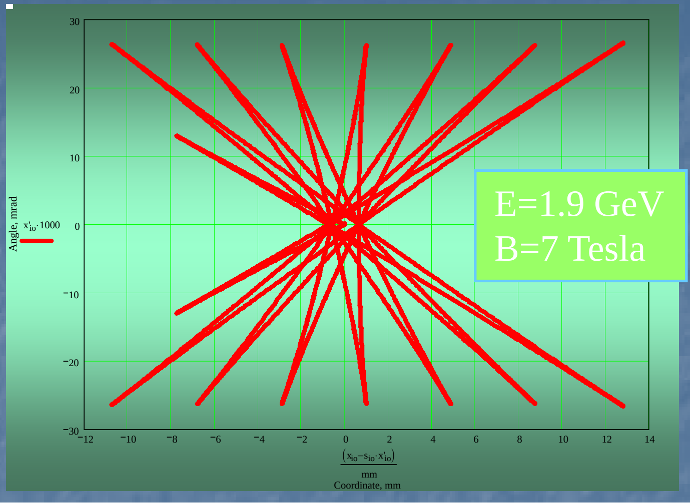


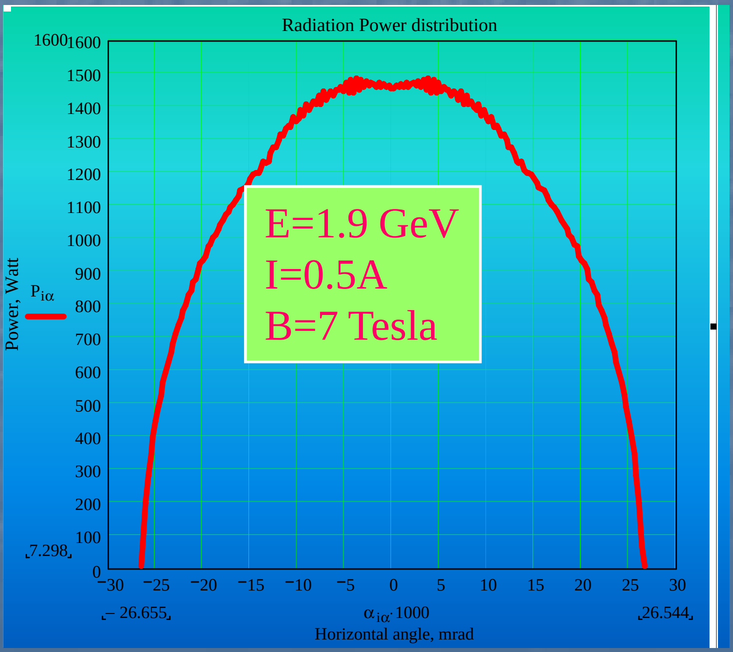
Orbit distortion inside 7 Tesla wiggler for BESSY-2

Radiation property of Superconducting multipole wiggler for BESSY-II - HMI



Photon phase-space reduced to center of the wiggler





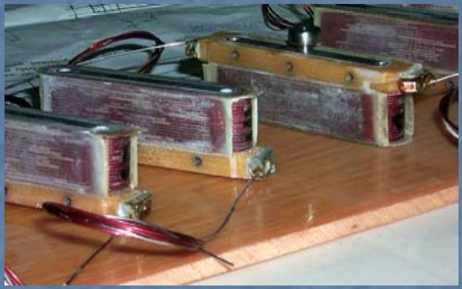
A superconducting 3.5 T 49-pole wiggler for ELETTRA (Italy) (2002)

3/10/2002

27/10/2002

Superconducting 63 pole 2 Tesla wiggler for CLS (Canada, 2005)

27/1/2005



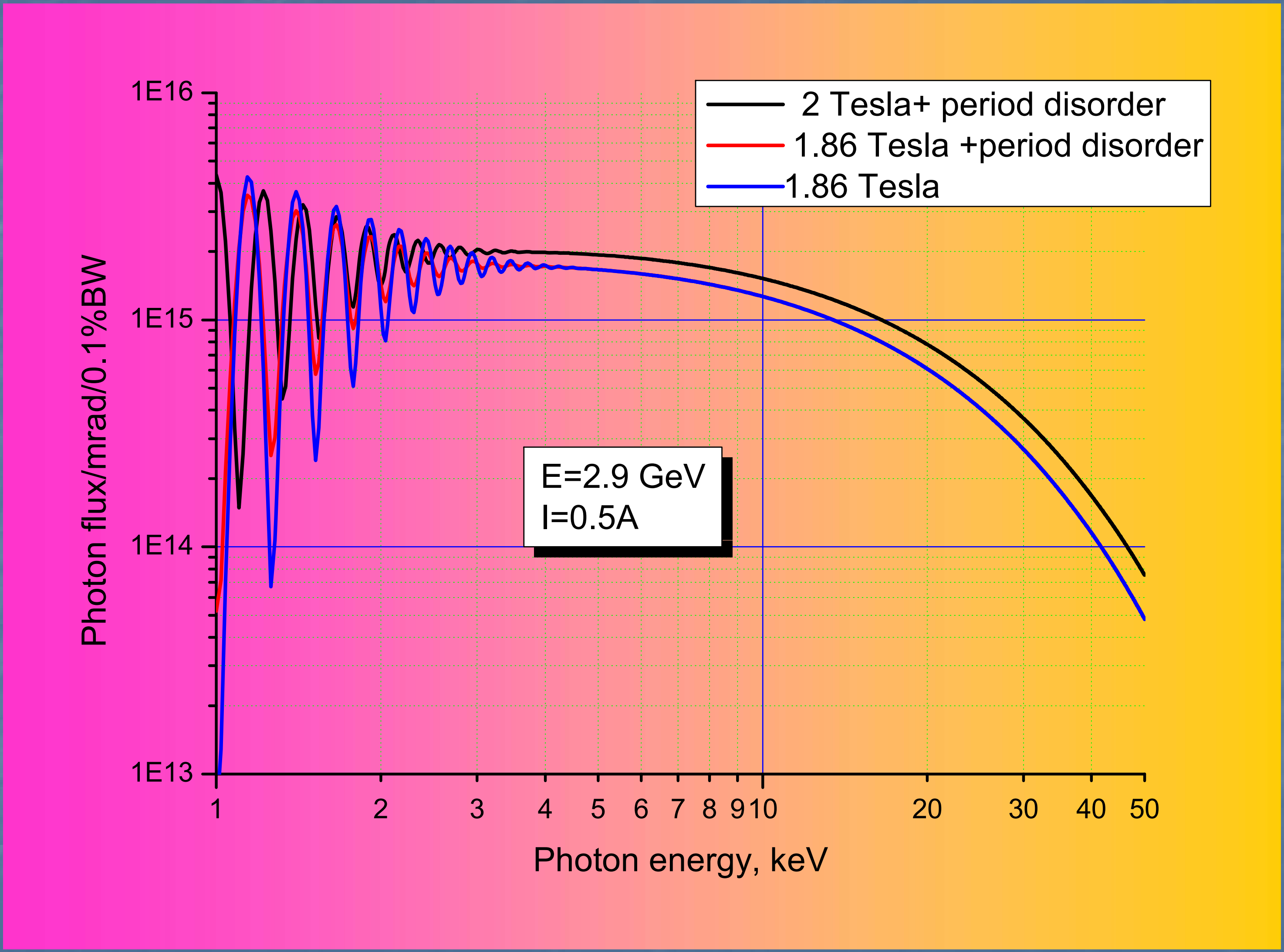
8/7/2004

SPECTRAL CHARACTERISTICS OF WIGGLER RADIATION

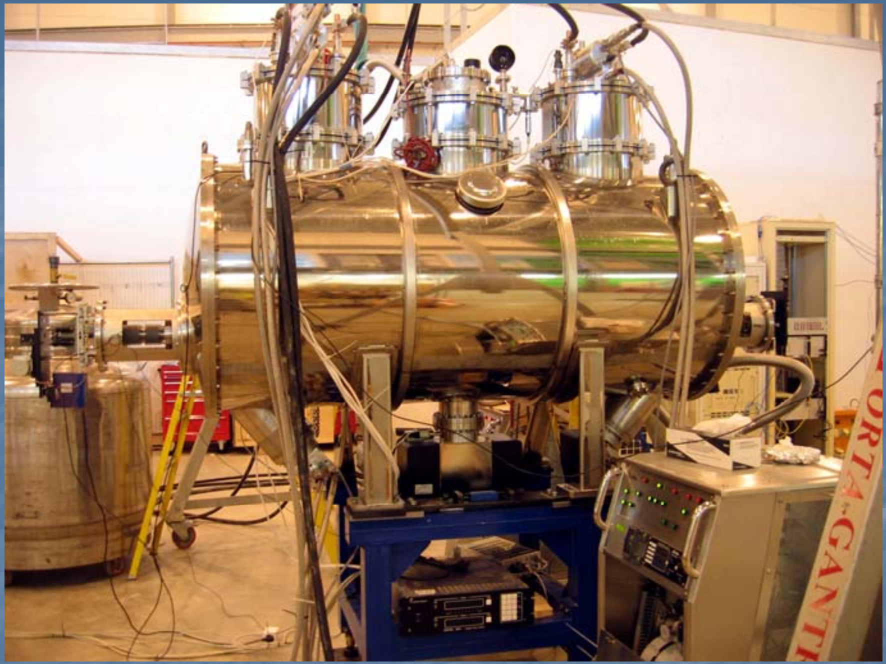
$K = 0.934 \cdot \lambda_0[cm]B[Tesla]$

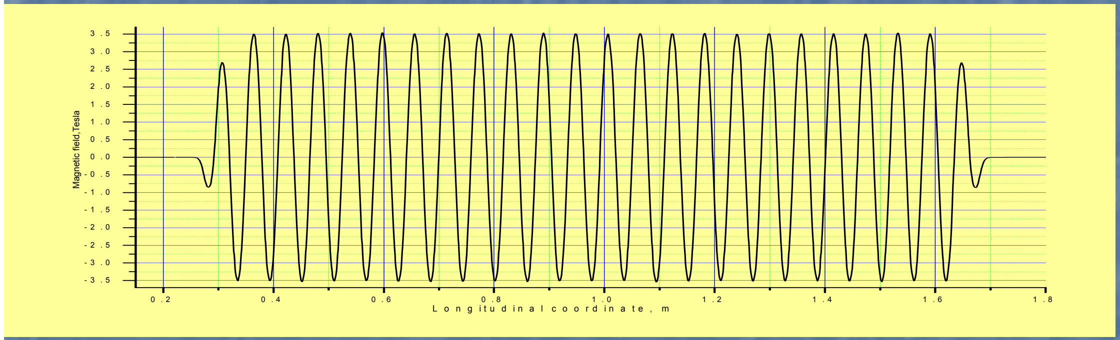
$$\varepsilon_n = \frac{2\gamma^2 \hbar n}{\lambda_0(1+K^2/2)}$$

$N_{\max} \approx 3/8K^3$



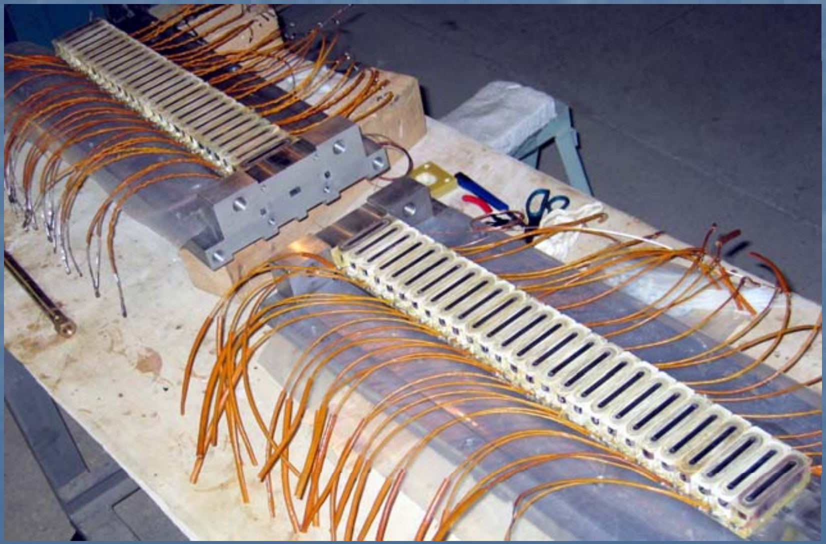
Superconducting 49 pole 3.5 Tesla wiggler for DLS (England, 2005)



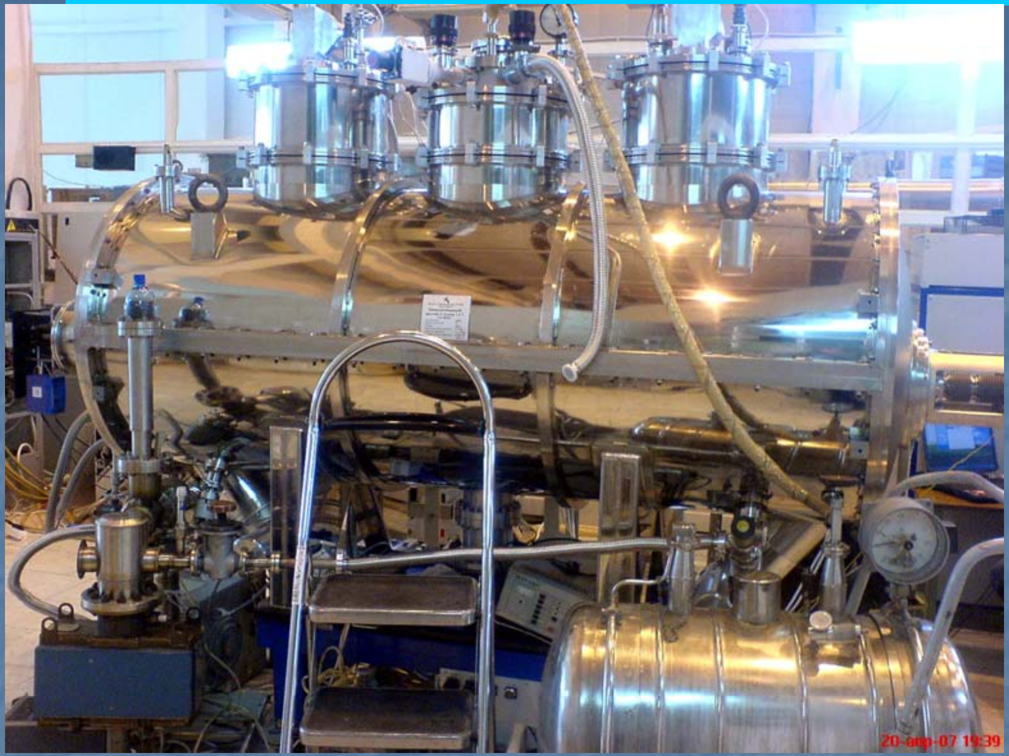


Longitudinal SC wiggler magnetic field distribution at 3.5 Tesla

Superconducting 27 pole 4 Tesla wiggler for CLS (Canada, 2007)



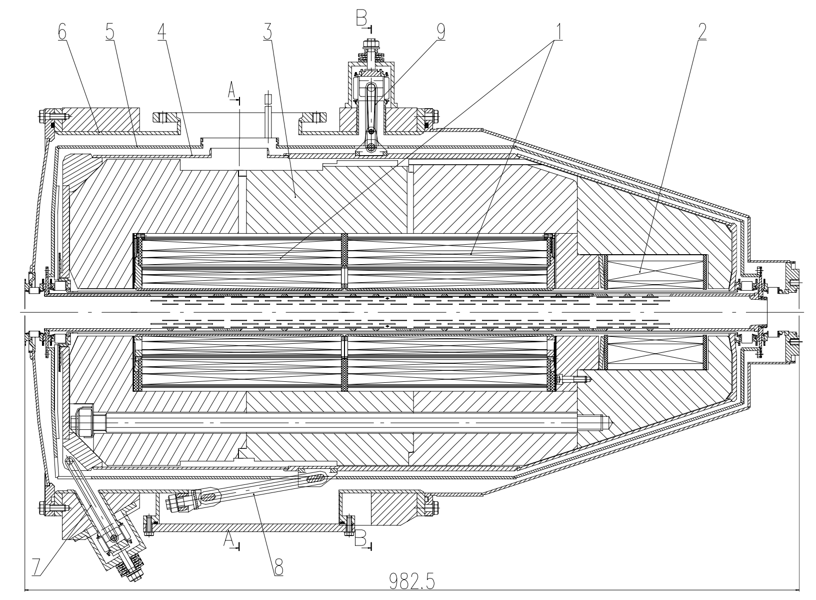
Superconducting 21 pole 7.5 Tesla wiggler for Siberia-2 (Moscow, 2007)

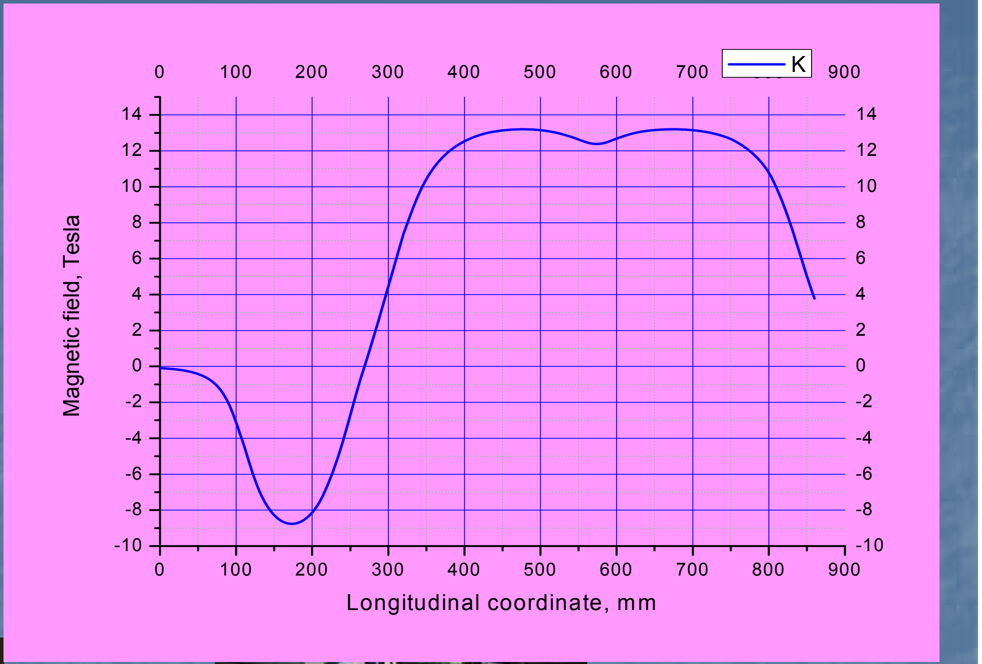


Superconducting magnets for accelerators

- 13 Tesla solenoids for VEPP-2000
- 9.6 Tesla Superbend for BESSY-2
- 2 Tesla Curved bending magnet for GSI

13 Tesla solenoids for VEPP-2000





9 Tesla superbend for BESSY-2 (2003)

Main parameters of SuperBend

Maximum Field (required /reached), T	9 .0 / 9.6
Magnetic gap, mm	46
Beam vacuum chamber: Vertical, mm Horizontal, mm	 30 75
Current in superconducting coils, A	300
Storage energy, kJ	220
Cold mass, kg	~1300
Liquid helium consumption, l/h	<1
Ramping time to 9 T	~15 min
Bending angle, degree	11.25
Bending radius, m	0.905 m
Edge angle, degree	1.3
Effective magnetic length, m	0.1777
Distance from flange to flange, m	0.55

Figure 97 Photograph of assembled superconducting magnet.

Fabrication of superconducting coilsof 9T SuperBend

Parameters of coils

Coil Sections	Wire Type	Number of layers	Number of turns	Total Turns	Current density in coil, A/mm^2	Fields at wire, T
1	Nb_3Sn (80%), d=1.24mm	10	77, 76	765	217	9.19
2	Nb_3Sn (50%), d=1.24mm	10	77, 76	765	217	7.05
3	Nb-Ti, d=0.92 mm	18	105, 104	1881	346	6.14
4 (correction)	Nb-Ti, d=0.92 mm	4	105, 104	418		
5 (bandage)	Stainless steel , d=1 mm	4	95, 94	378		

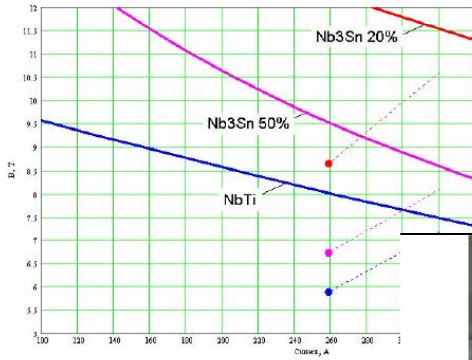


Figure 83 Critical curves for different wires, used in coils and load 9 Tesla

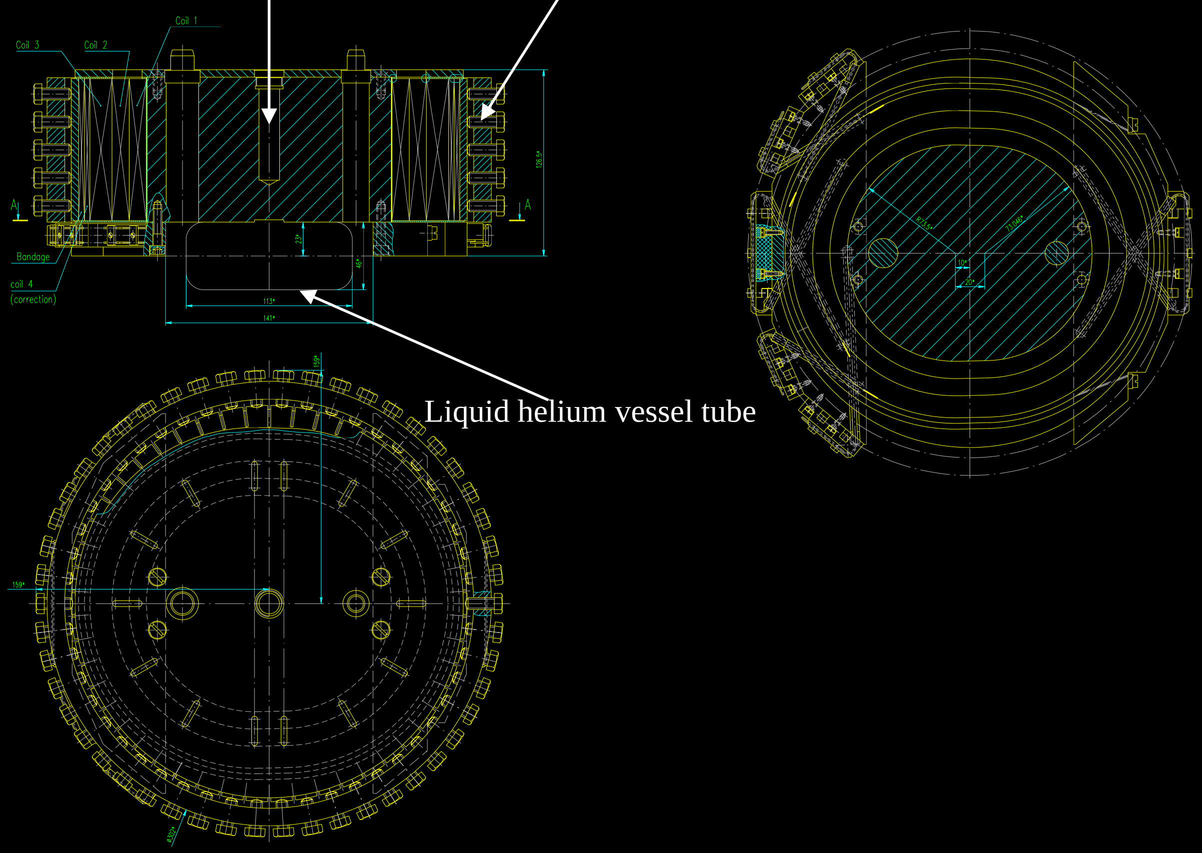
Figure 89 External bandage system of coils.

Figure 90 Assembled ½ part of superbend pole.

Figure 93 Assembling of pole coils with yoke.

Figure 91 Assembled pole of superbend without yoke.

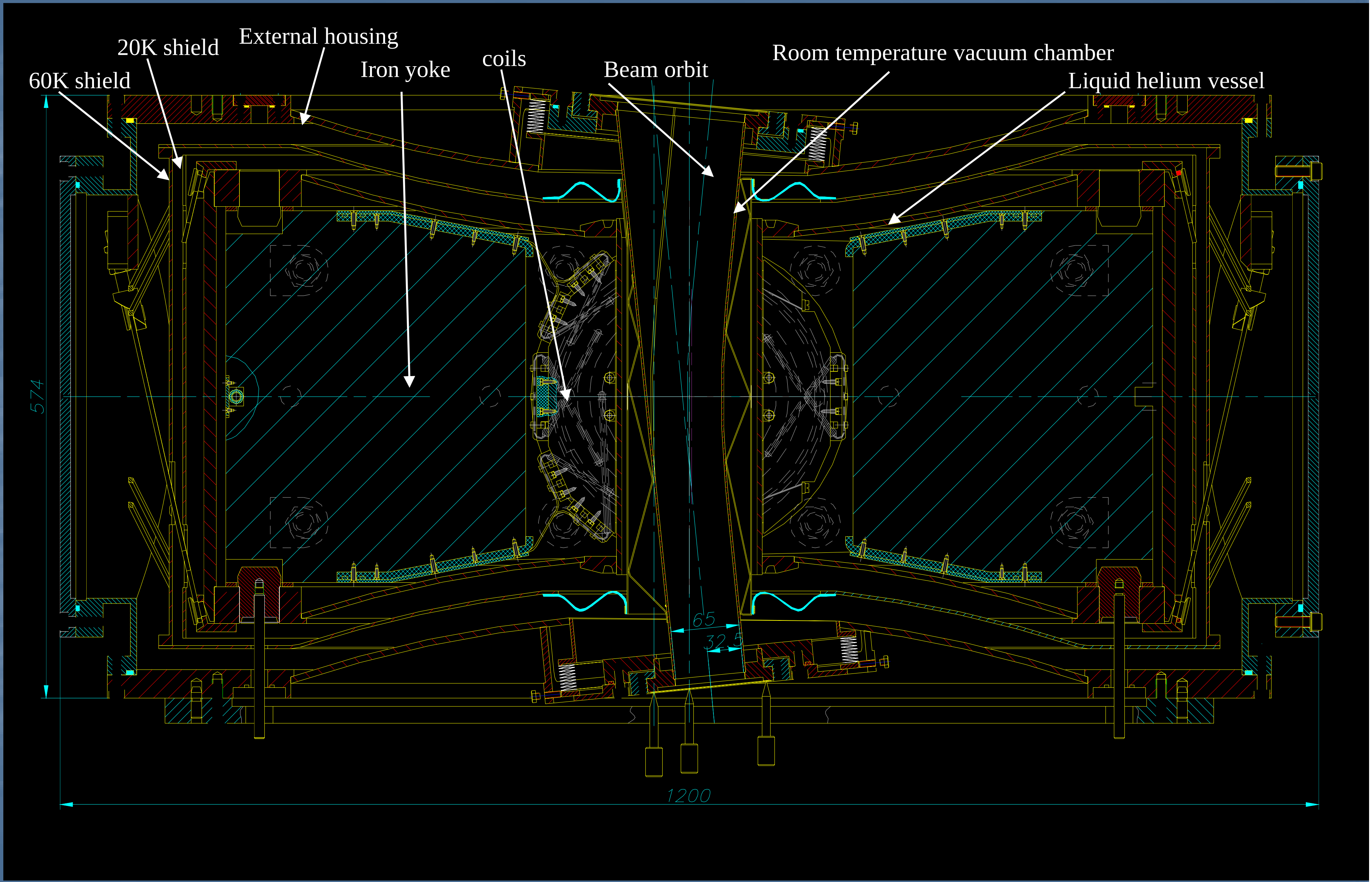
Superconducting coil design of superbend


NMR probes

Bandage-stainless steel ring

Liquid helium vessel tube

Superbend cross -section in median plane



60K shield

20K shield

External housing

Iron yoke

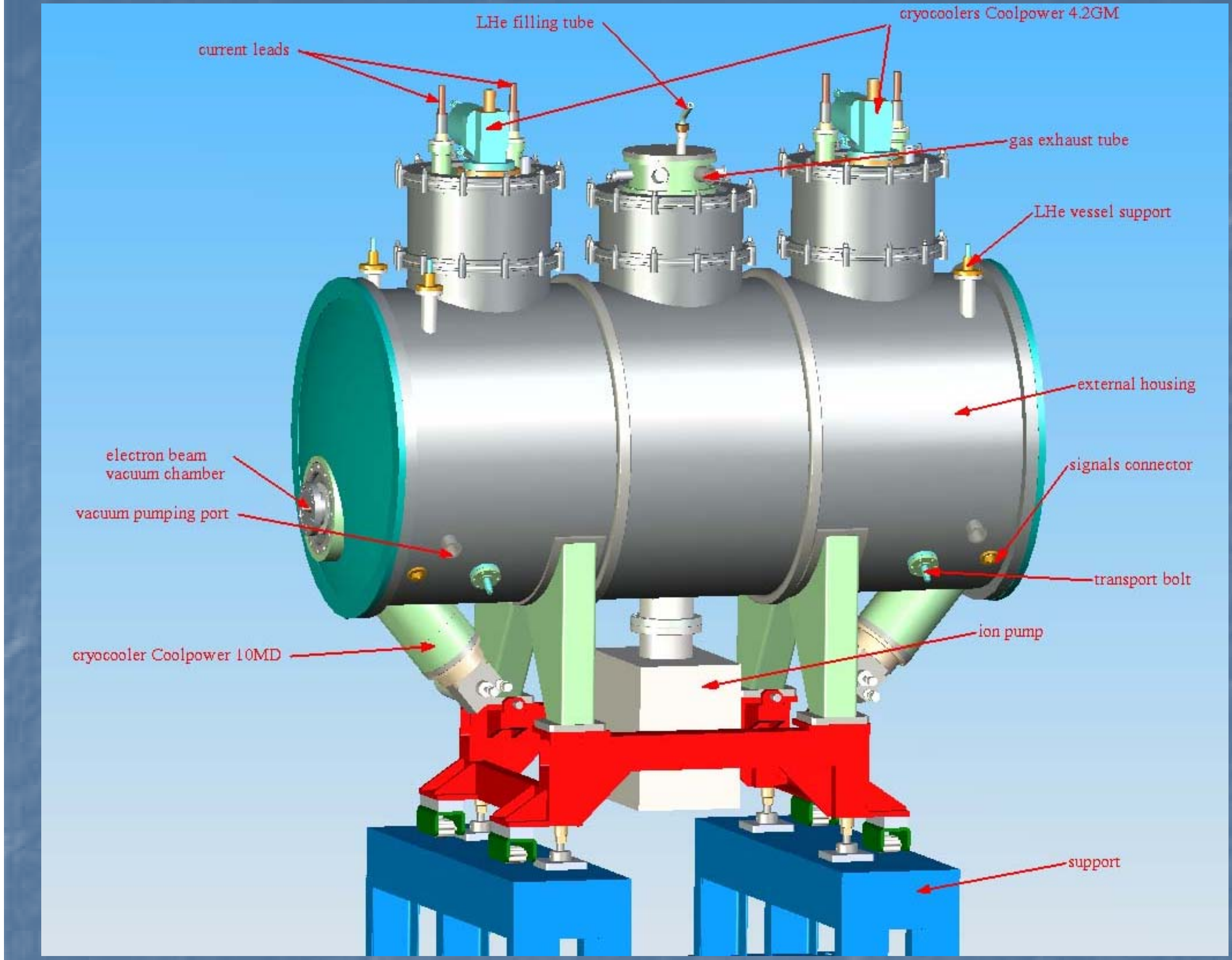
coils

Beam orbit

Room temperature vacuum chamber

Liquid helium vessel

WIGGLER CRYOGENIC SYSTEM

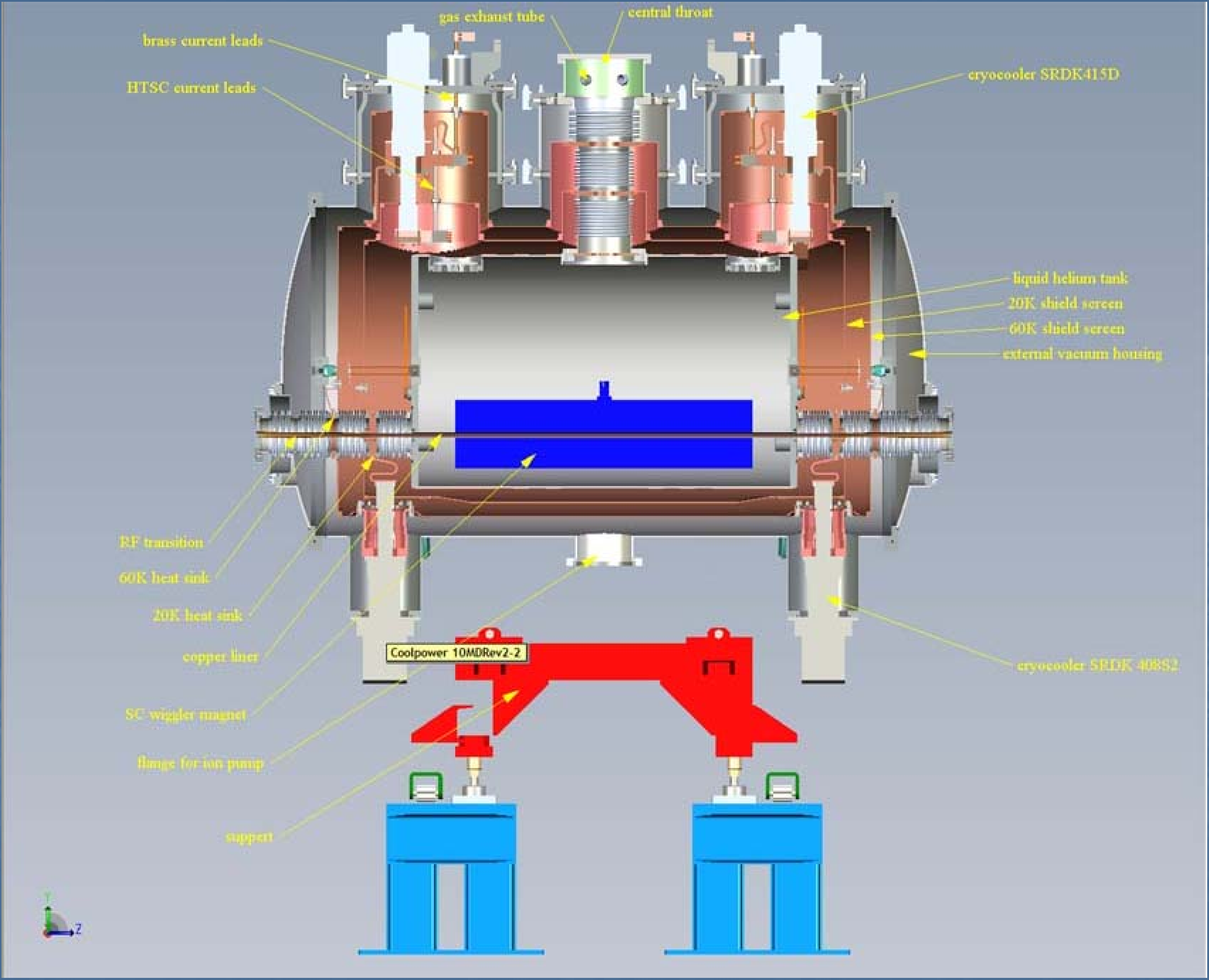


The cryogenic system consists of:

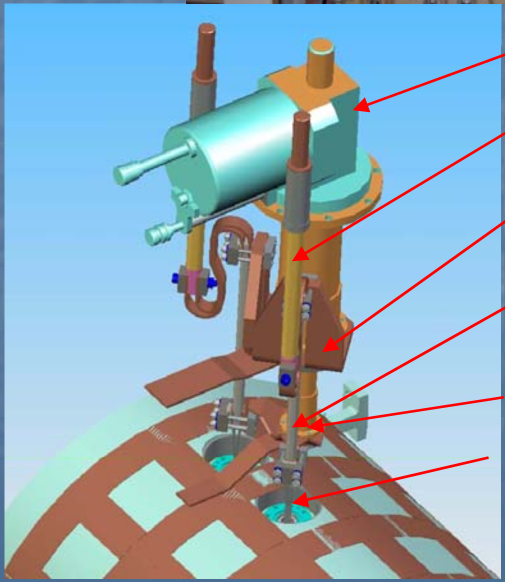
- **external housing,**
- **60K shield,**
- **20K shield,**
- **liquid helium vessel,**
- **throat,**
- **vacuum chamber with copper liner,**
- **upper flange,**
- **filling tube,**
- **2 Leybold 4.2GM One Watt System coolers**
- **2 shield Leybold Coolpack 10MD coolers**

Cryostat parameters

Working magnet temperature, K	**4.2**
Temperature of shield screens, K	**20, 60**
Temperature of copper liner, K	**20**
Liquid helium volume, liter	**330**


gas exhaust tube
central throat
brass current leads
HTSC current leads
cryocooler SRDK415D
liquid helium tank
20K shield screen
60K shield screen
external vacuum housing
RF transition
60K heat sink
20K heat sink
copper liner
SC wiggler magnet
flange for ion pump
support
Coolpower 10MDRev2-2
cryocooler SRDK 408S2
Y
Z

WIGGLER CRYOGENIC SYSTEM



Coolpower 4.2GM

Brass current lead

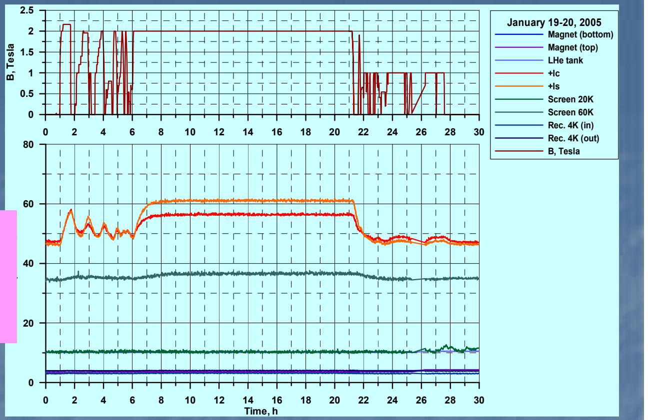
60K stage

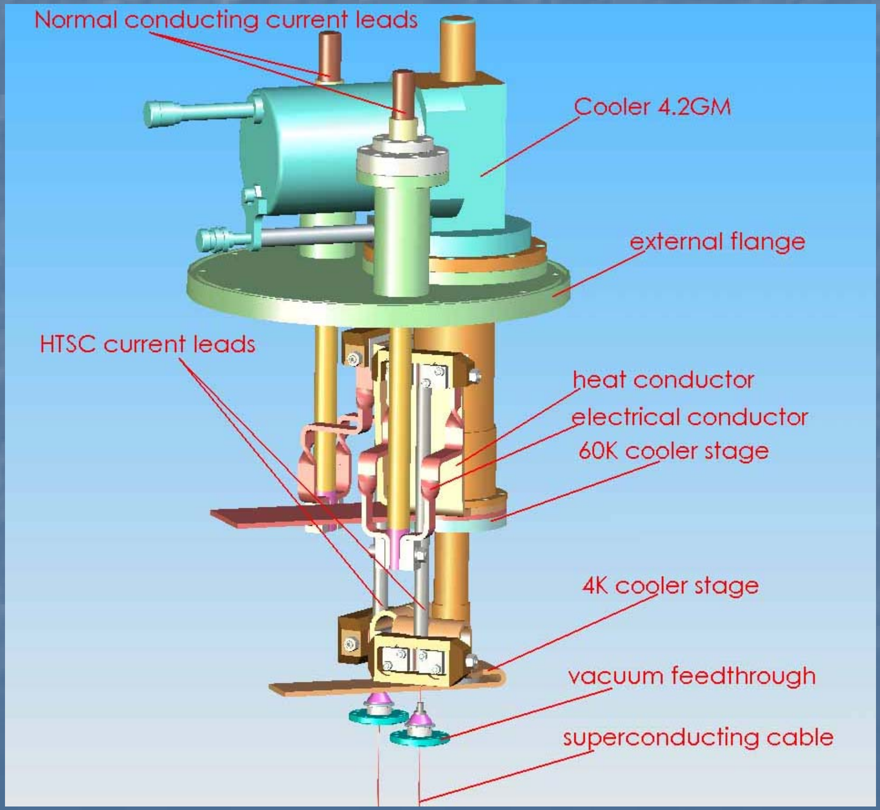
HTSC current lead

4K stage

Vacuum-LHe feedthrough

Main temperature probes values versus time at different field level of the wiggler.

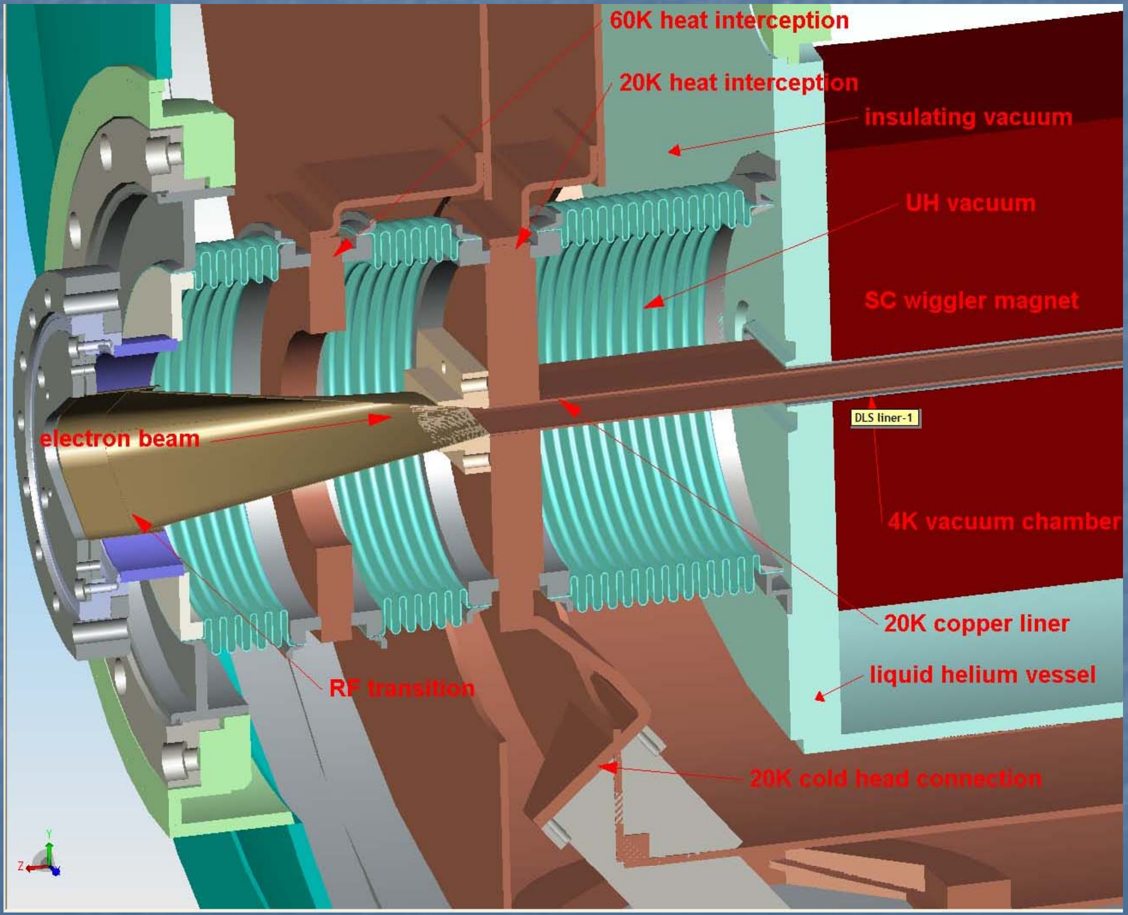




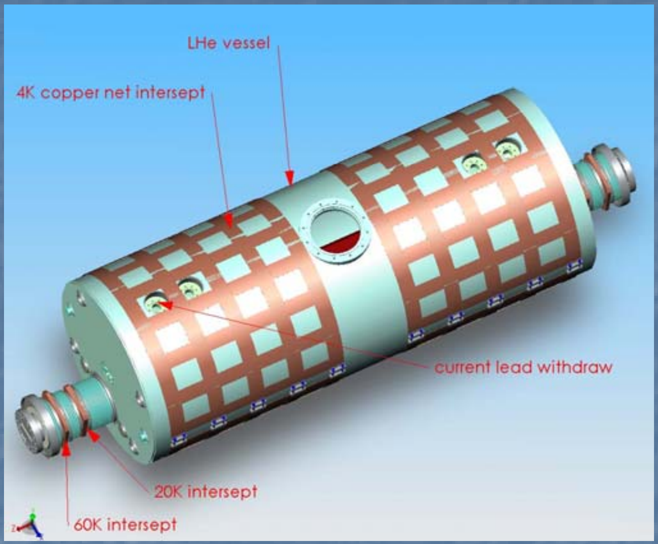
Vacuum chamber and copper liner

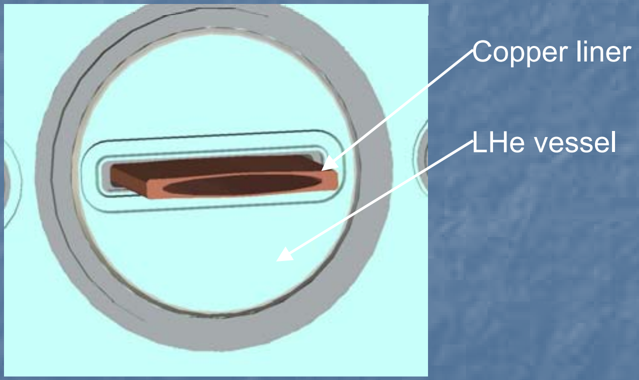
Insulating vacuum is separated from UH vacuum of a storage ring and keep at vacuum level 10^{-6} – 10^{-7}Torr by 300l/s ion pump

Beam vacuum chamber system



Liquid helium vessel with vacuum chamber fittings

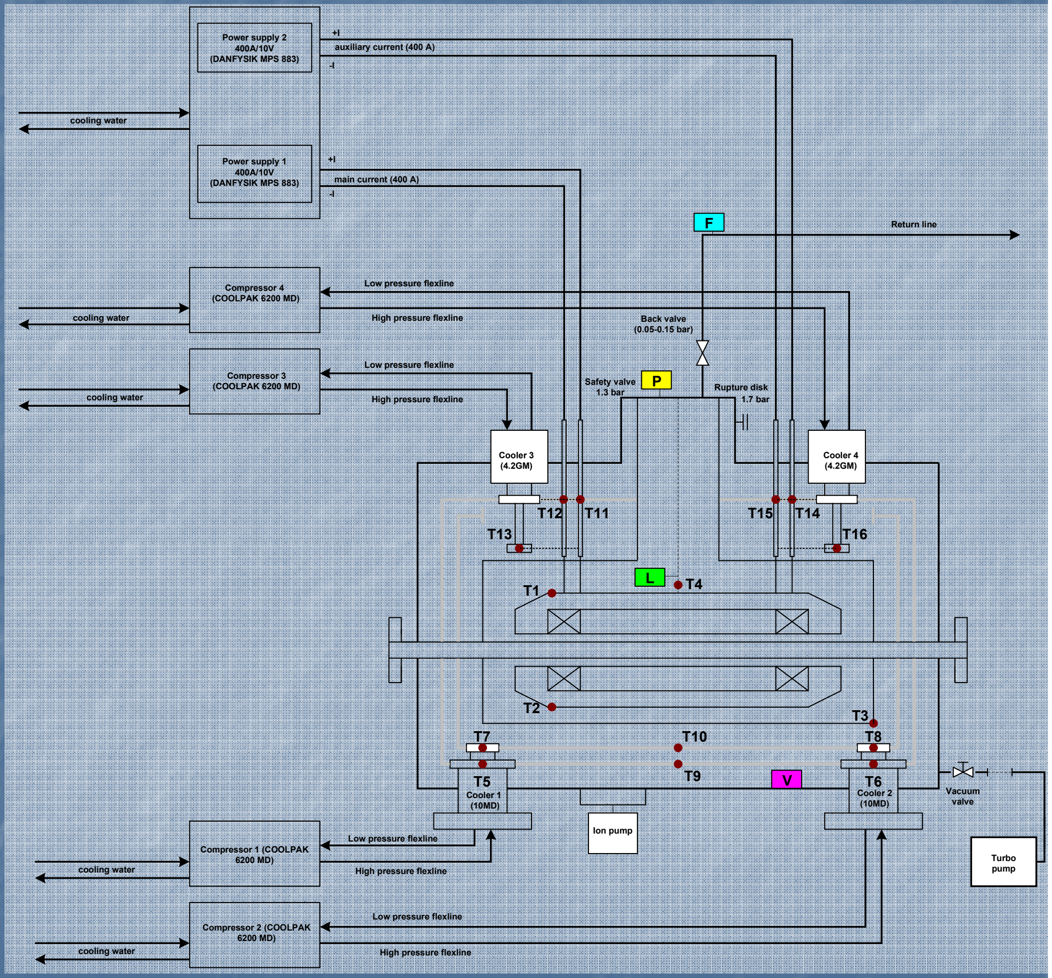




Control system

Description	Legend	Data
magnet top (4K)	T1	4.2 K
magnet bottom (4K)	T2	4.2 K
LHe vessel bottom (4K)	T3	~ 5K
minimum level of LHe (4K) - interlock	T4	max 4.5 K
60K stage of 10MD cooler 1	T5	~ 40K
60K stage of 10MD cooler 2	T6	~ 40 K
20K stage of 10MD cooler 1	T7	~ 15 K
20K stage of 10MD cooler 2	T8	~ 15 K
60K shield screen	T9	~ 40K
20K shield screen	T10	~ 15 K
HTSC 1 main current lead upper end (60K) - interlock	T11	max 70 K
HTSC 2 main current lead upper end (60K) - interlock	T12	max 70 K
HTSC main current leads bottom end (4K)	T13	~ 5 K
HTSC 1 auxiliary current lead upper end (60K)- interlock	T14	max 70 K
HTSC 2 auxiliary current lead upper end (60K)- interlock	T15	max 70 K
HTSC auxiliary current leads bottom end (4K)	T16	~ 5 K
LHe level	L	5 – 100%
pressure inside LHe vessel, bar	P	1 – 1.3
Insulating vacuum, Torr	V	$<10^{-6}$
LHe consumption rate	F	< 0.05 l/h

P&I diagramm



Future plans

- Facility for measurement of low temperature material property (thermoconductivity, resistivity, heat capacity, critical currents etc)
- High field superconducting magnets with indirect cooling

Thanks for attention