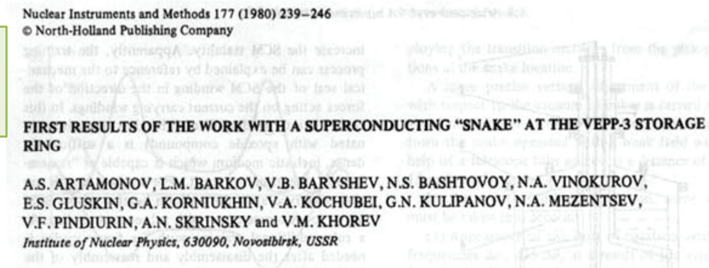
STATUS OF DEVELOPMENT OF SUPERCONDUCTING INSERTION DEVICES FOR GENERATION OF SYNCHROTRON RADIATION IN BUDKER INP

Shkaruba Vitaliy

Budker Institute of Nuclear Physics, Novosibirsk

4 October 2018, RuPAC-2018, Protvino, Russia

The first SC 20-pole 3.5 T wiggler with the period of 90 mm was installed on the 2 GeV storage ring VEPP-3 in 1979.


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

The main parameters of first SCW:

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

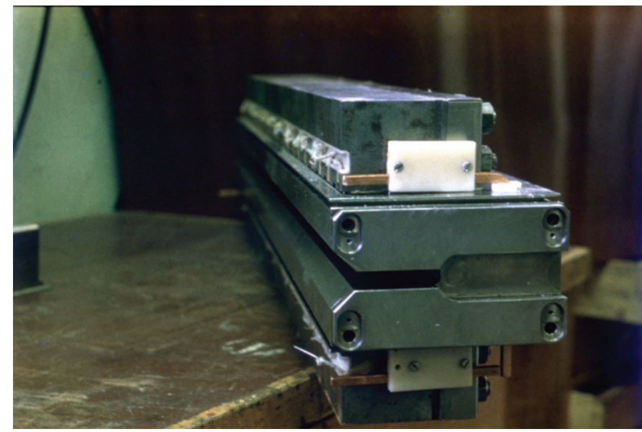
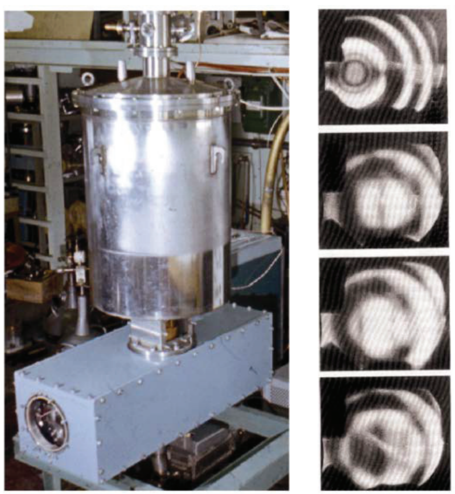
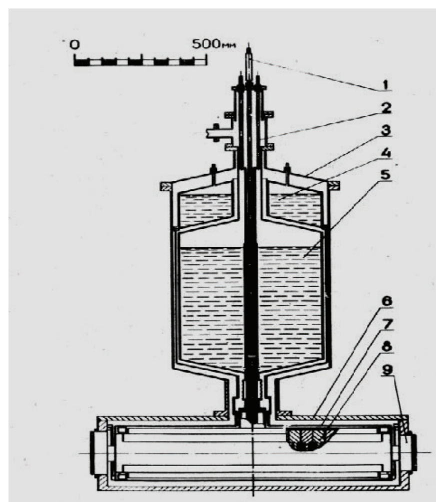


Photo of the wiggler magnet



(A) (B)

The wiggler cryostat with magnet

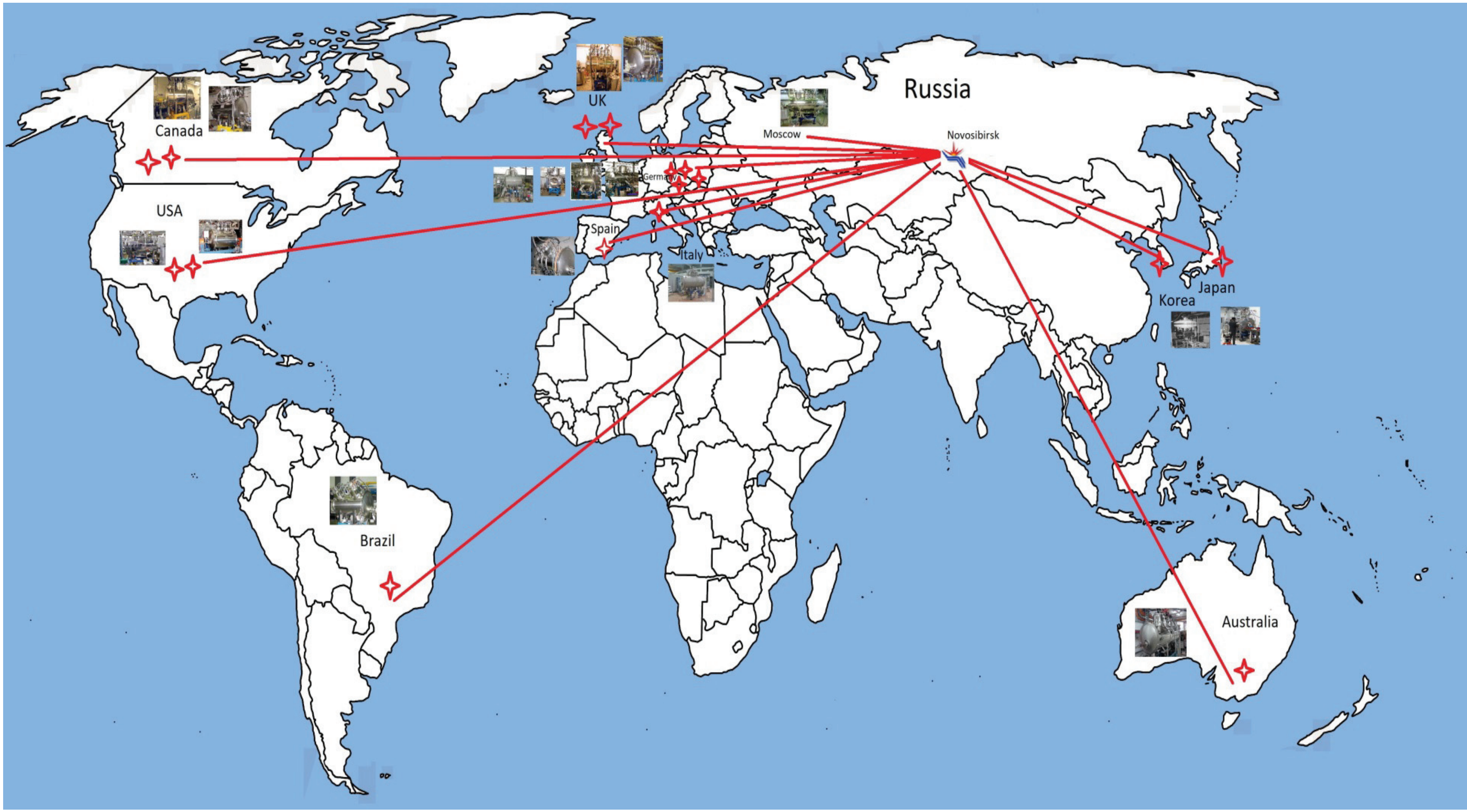


Design of the wiggler cryostat

The wiggler cryostat with using of liquid nitrogen and liquid helium consumption of ~ 4 l/h.

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Since 1995 ~ 20 SC ID was created in BINP for more then 10 SR sources:



Advantages of Super-Conducting ID – possibility increase magnetic field level:

- Extending the spectral range of SR storage rings to **harder x-rays**:
- **Increase brightness** of photon sources (for MPW):

$$\varepsilon_c = 0.665 \cdot E_e{}^2[GeV] \cdot \boldsymbol{B[T]}$$

$$B_\lambda = \frac{\boldsymbol{N[Photon]}/\Delta t[sec]}{\Delta S[mm^2] \cdot \Delta\Omega[mrad^2] \cdot 0.1\% \Delta\lambda/\lambda}$$

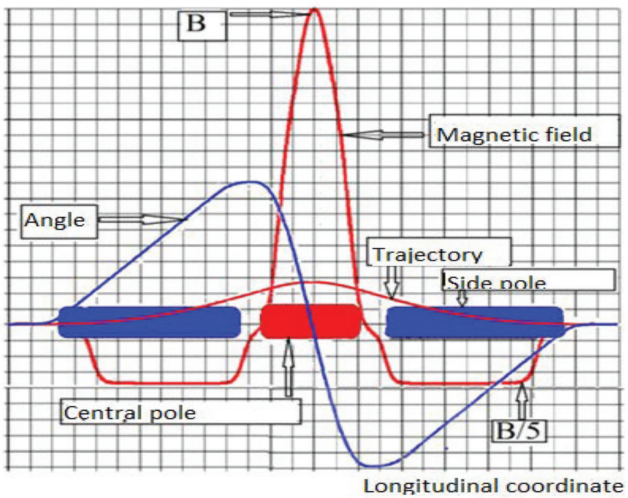
Disadvantage: need to use of cryogenic system.
But BINP created SCW cryostats with zero Lhe consumption.

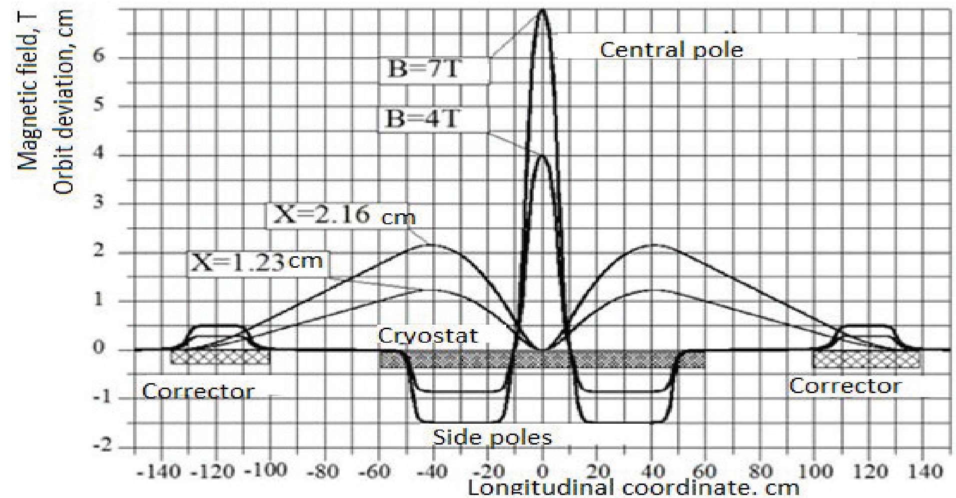
- ID inserts to straight section and is not an element of Storage Ring structure;
- ID must not to disturb the orbit outside;
- The conditions for **closed orbit**:

$$I_{first} = \int_{-L/2}^{L/2} B_z(s)ds = 0$$

$$I_{second} = \int_{-L/2}^{L/2} sB_z(s)ds = 0$$

3-pole Wave Length Shifter (WLS) - The central pole is used as a radiation source:
Disadvantage: Offset of radiation point from exes in depending of magnetic field level;
Decision: The using of 2 usual correctors for fixing of radiation point in the center of WLS.

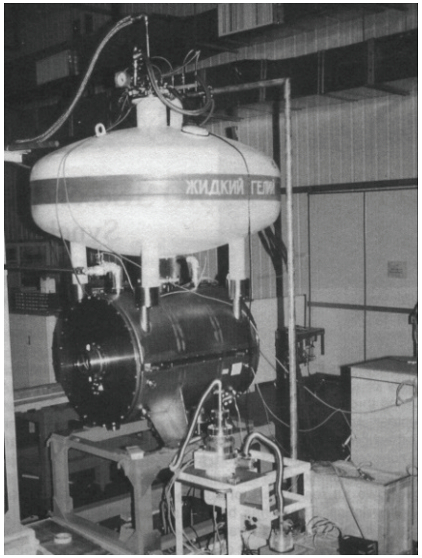




List of SC WLS fabricated by Budker INP:

Storage ring, location	Year	Magnetic field, (B_{Max}) B_{work}, T	Pole gap/beam gap, mm	LHe consumption, l/hour
7.0T shifter PLS, Korea	1995	(7.68) 7.5	48(26)	2
7.0T shifter LSU-CAMD, USA	1998	(7.55) 7.0	51(32)	1.5
10.0T shifter SPring-8, Japan	2000	(10.3) 10.0	40(20)	0.6
7.0T shifter BESSY-II, Germany	2000	(7.5) 7.0	52(32)	0.6
7.0T shifter BESSY-II, Germany	2001	(7.5) 7.0	52(32)	0.6

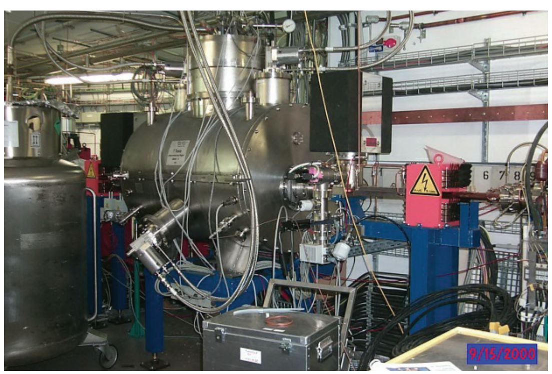
SC 3-pole WLS fabricated by Budker INP:



7.5 PLS-WLS,
Korea, **1995**

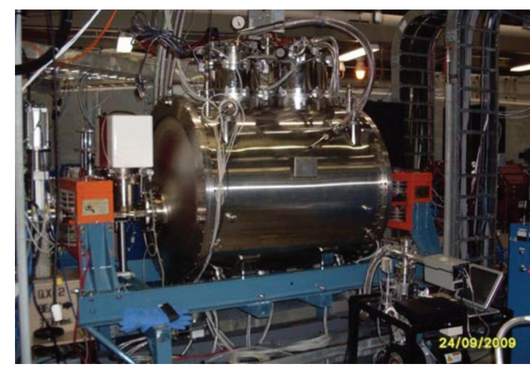
10.3 T Spring-8 WLS,
Japan , **1999**

7.5 T LSU-CAMD WLS,
USA, **1998**



7.5 T BAM- WLS,
BESSY-II, Germany, **2000**

7.5 T PSF- WLS,
BESSY-II, Germany, **2002**

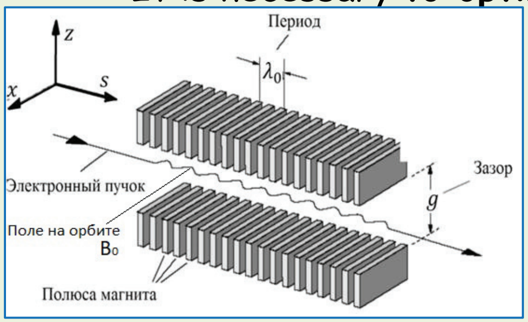


7.5 T LSU-CAMD WLS,
USA, **2009** (upgrade of cryogenic system)

Advantages of Multi-Pole Super-Conducting Wiggler (MPSCW):

- **Increase of photon flux** is proportional to N - number of poles.

It is necessary **to optimize the wiggler parameters** for given:

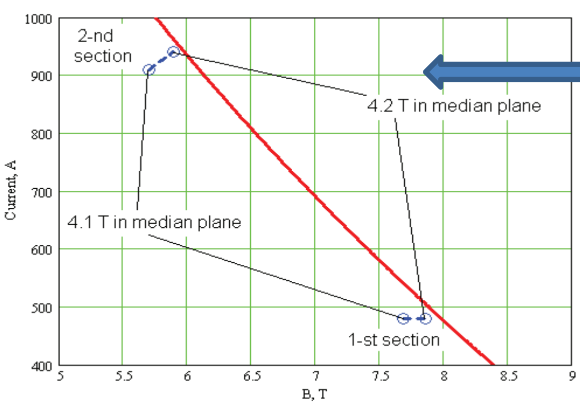


λ_0-period of wiggler;
B_p - magnetic field on pole;
g – magnetic gap;

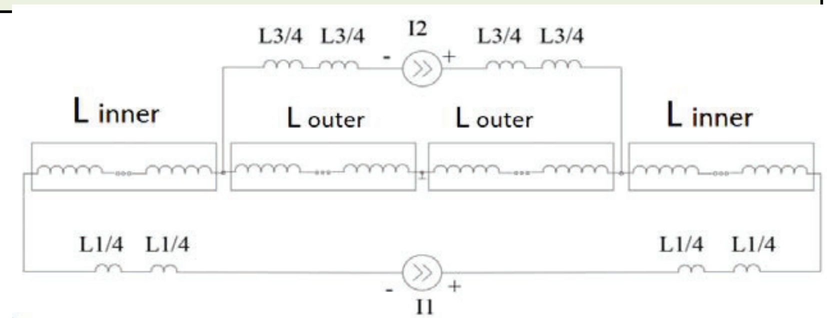
E**[GeV]** – beam energy
ε **[Kev]** – phonon energy;
L**[m]** – length of wiggler

Features of the MPSCW created in BINP:

- The using **of two sections coils** – to increase max. field on the pole up to ~15% due to the addition of current to the outer section;
- The feeding of coils by **two independent power supplies** – opportunity to zeroing of field integrals (redistributing of currents);



Critical current curve of Nb-Ti wire and field-current critical points inside coil correspond to magnetic field in median plane



Simplified circuit of wiggler coils supply

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

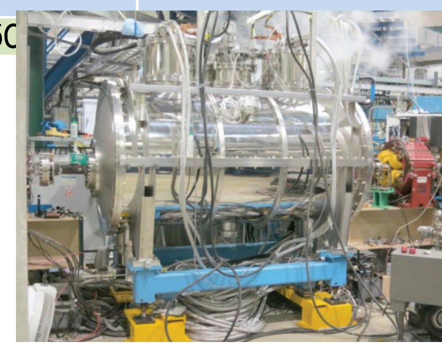
High field (7–7.5 T) and long period (140 – 200 мм) MPSCW created in BINP:

- ❑ Increase photon flux at harder x-rays region - prolongation of "life" of old SR sources;
- ❑ Wide horizontal angle - opportunity to install of several beam lines;

SR source, Energy, GeV, location, year	BESSY-II, 1.9 GeV, Germany, 2002	КИСИ 2.5 GeV, Moscow, 2007	CAMD-LSU, 1.3 GeV, USA, 2013	DELTA, 1.5 GeV, Germany, 2018
Magnetic field, $B_{nominal}$ (B_{max}), T	7.0 (7.67)	7.5 (7.7)	7.5 (7.75)	7.0 (7.25)
Pole Number (main+ side)	13 + 4	19 + 2	11+4	18+4
Period, mm	148	164	193.4	128
Magnetic gap (beam gap), mm	19 (13)	19 (14)	25.2 (15)	16.5 (10)
Critical energy, Kev	16.8	31	8.53	10.5
K-parameter	~97	~115	~136	~83
Power, kW	56 (0.5 A)	36 (0.1 A)	17 (0.2 A)	17 (0.13 A)
	450		850	

BESSY, Germany, **2002**, 17-poles, 7 T

Moscow, Siberia-2, **2007**
21-pole 7.5 T



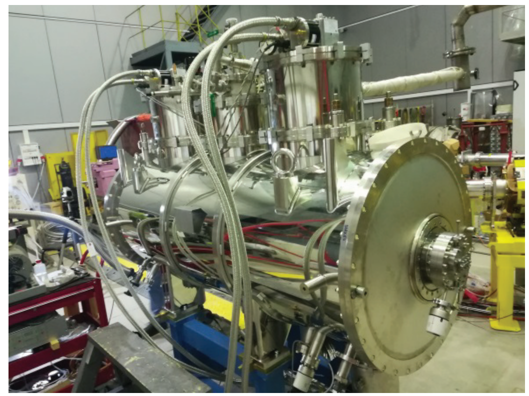
LSU-CAMD,USA, **2013**
15-pole 7.5 T

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

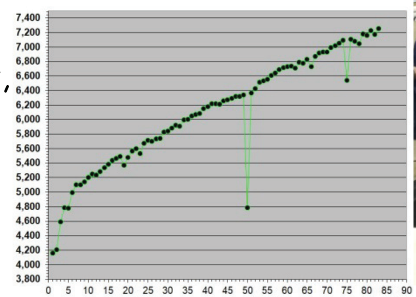
22-pole 7 T wiggler with period of 127 mm for DELTA SR source (Dortmund, Germany):

N.Mezentsev, A.Bragin, S.Khrushchev, V.Lev, A.Safronov, V.Shkaruba, O.Tarasenko, V.Tsukanov, A.Volkov, A.Zorin (BINP SB RAS, Novosibirsk), Shaukat Khan (DELTA, Dortmund), **"Superconducting 7 Tesla Wiggler for Delta Synchrotron Radiation Source"** (THPSC05, RuPAC-2018).

Magnetic field, $B_{nominal}$ (B_{max}), T	7.0 (7.25)
Pole Number (main+ side)	18+4
Period, mm	128
Magnetic gap (beam gap), mm	16.5 (10)
Horizontal aperture, mm	90/110
Magnet length, mm	~1500
Critical energy, Kev	10.5
K-parameter	~83
Power, kW	~13 (0.1 A)
Currents, A	180/(180+230)
Stored energy, kJ	~250
Ramping time, min	~10



Overall view of 22-pole 7 T wiggler for DELTA (Factory Accepted Test, **June 2018**)



Quench history of 22-pole 7 T wiggler for DELTA SR source (Bmax=7.25 T, **15 June 2018**)

Inserting SC magnet to Lhe vessel

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Middle field (2.5 –4.2 T) and middle period (46 – 64 мм) MPSCW created in BINP:

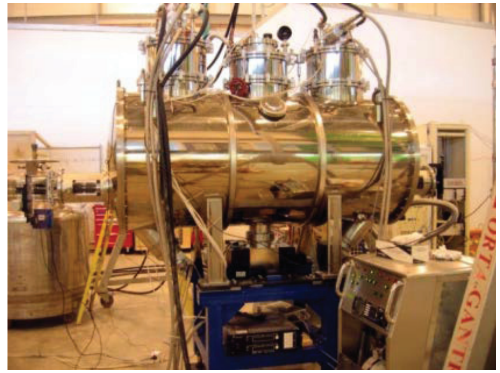
- ❑ Most in demanded parameters – generate SR flux at in the most used x-rays region;

Storage ring, Energy, location, year	ELETTRA,2 GeV Italy, 2002	DLS,3 GeV, UK, 2006	CLS, 2.9 GeV, Canada, 2007	LNLS, 1.37 GeV, Brazil, 2009	DLS, 3 GeV, UK, 2009	AS, 3 GeV, Australia, 2012
Magnetic field, B_{oper} (B_{max}), T	3.5 (3.7)	3.5 (3.8)	4.0 (4.3)	4.1 (4.2)	4.2 (4.3)	4.2 (4.4)
Pole number (main+side)	45+4	45+4	25+2	31+4	45+4	59+4
Period, mm	64	60	48	60	48	52
Magnetic gap (beam gap), mm	16.5 (11)	16.4 (10)	13.9(9.5)	18.2 (14)	14.4 (10)	15.2 (10)
Horizontal aperture, mm	84	80	60	80	60	60
Magnetic length, mm	1680	1544	1000	1162	1304	1758
Critical phot. energy, Kev (Wavelength, Å)	9.3 (1.33)	21 (0.59)	23 (0.54)	5 (2.48)	25 (0.49)	25 (0.49)
K – value	21	19.6	19	18	18.8	18.8
Power, (Beam current, A), KW	8.8 (0.2)	60 (0.5)	12 (0.2)	4.45 (0.3)	55 (0.5)	37.5 (0.2)
Current in coils, A	288 (288+210)	327+290	411 (411+445)	436 (436+414)	455 (455+415)	447 (447+432)
Critical current of wire ø 0.9 mm at 7 Тл	380	520	700	520	700	700
Stored energy, KJ	240	70	20	60	25	70
Lhe consumption, l/h	0.45	<0.05	<0.05	<0.05	<0.03	<0(0.7 bar)

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Middle field (2.5 –4.2 T) and middle period (46 – 64 мм) MPSCW created in BINP:

ELETTRA,Italy,**2002**
49-pole 3.5 T

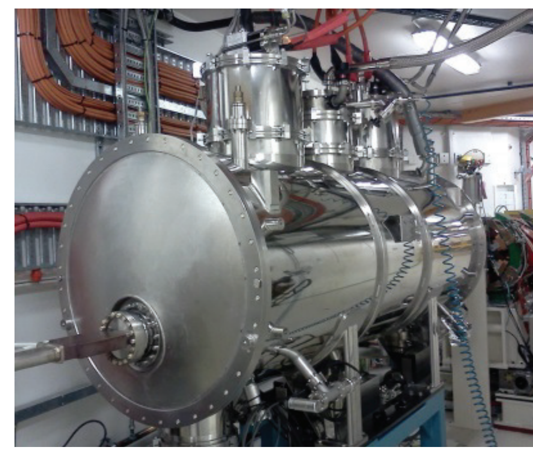


DLS,England,**2006**
49-pole 3.5 T

CLS,Canada,**2007**
27- poles 4 T

DLS, England,**2008**
49-pole 4.2 T

LNLS, Brazil,**2009**
35-pole 4.2 T

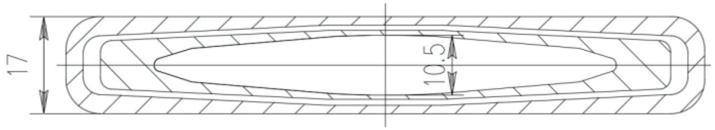


AS, Australia, **2012**
63-pole 4.2 T

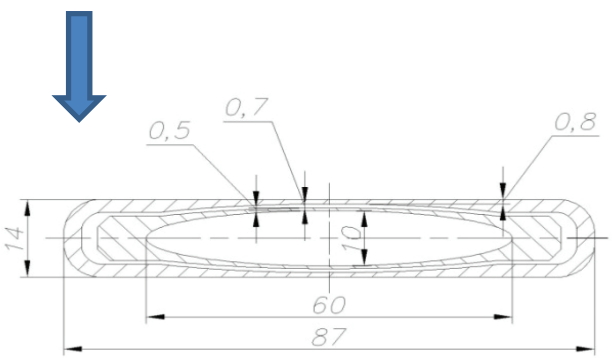
Middle field (2.5 –4.2 T) and middle period (46 – 64 мм) MPSCW created in BINP:

- The main task – increase max magnetic field at the minimal period length: it is possible to place more periods at an accessible place in straight section);

- The ways for increase of magnetic field:
- Decreasing the thickness of vacuum chambers and the gaps inside of magnetic gap down to technological and mechanical limits (~0.5 mm) ($\frac{\Delta B_0}{B_0} \approx e^{-\pi\frac{\Delta g}{\lambda_0}} - 1 = e^{-\pi\frac{3\,[mm]}{50\,[mm]}} - 1 = 0.2$);



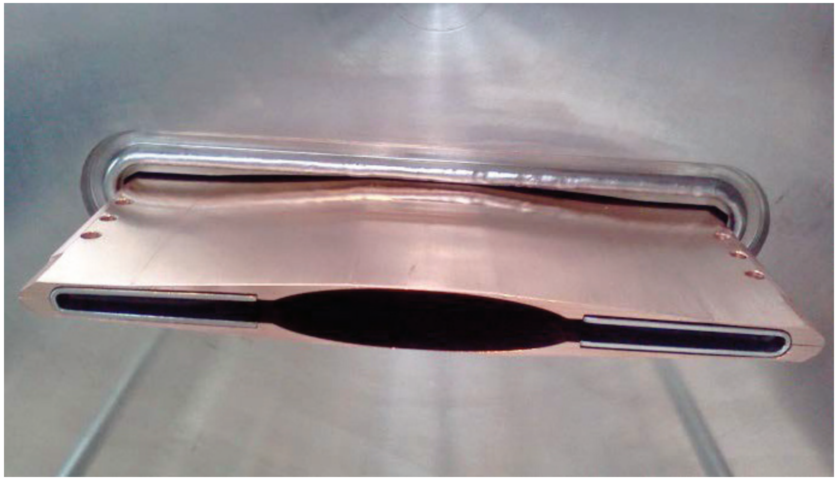
ELETTRA SCW (**2002**)



CLC SCW (**2007**)

$$B_0 = \frac{B_p}{\cosh\left(\pi \frac{g}{\lambda_0}\right)}$$

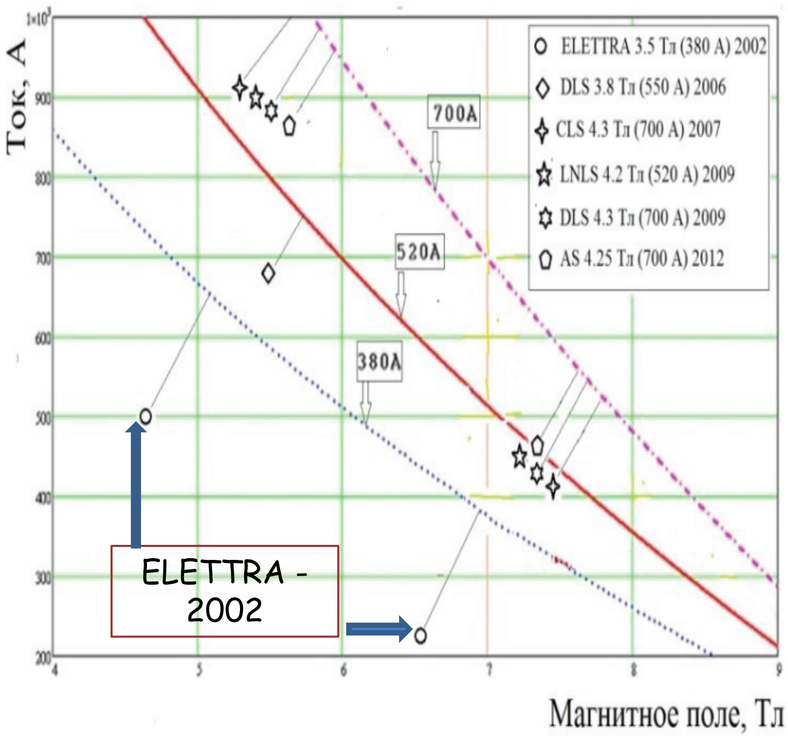
B_p - поле на полюсе;
B_0 - поле на орбите
g – магнитный зазор;
λ_0 - период.



Design of magnetic gap of LSU-CAMD 7T 15-pole SCW. (Horizontal aperture 200 mm, vertical gaps between chambers ~0.5 mm along of ~2 m) (**2015**)

Middle field (2.5 –4.2 T) and middle period (46 – 64 мм) MPSCW created in BINP:

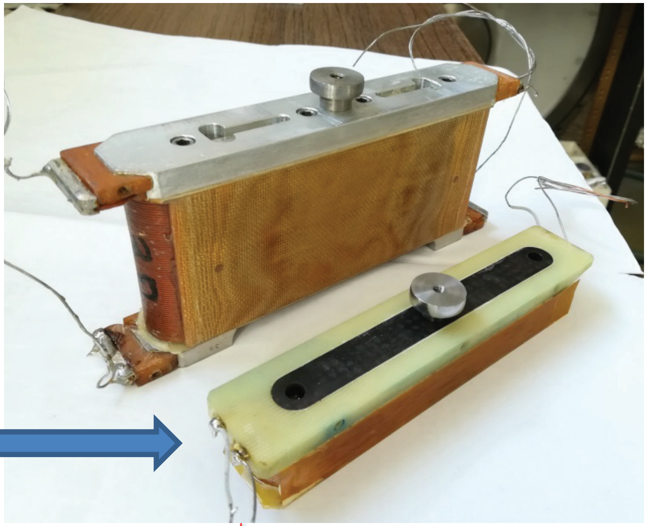
- The progress in the field-current parameters of SC Nb-Ti wire (from 360A to 700A at 7T). For all wire parameters it was reached 90-95% from critical currents;



The location of field-current critical points relatively of critical current curves of used Nb-Ti wire.

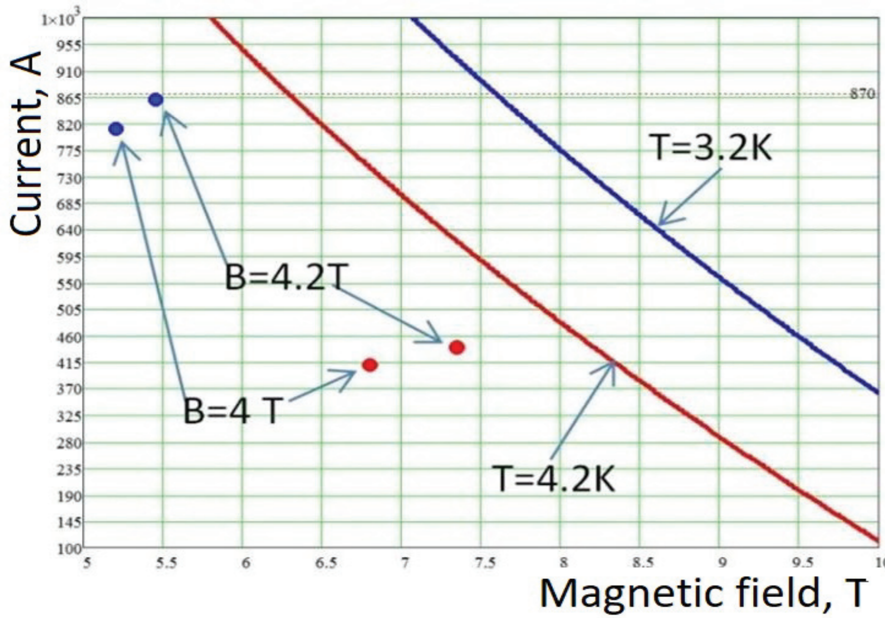
- Except for ELETTRA 3.5T 45-pole SCW. But in January 2018 the ELETTRA magnet was upgraded (new optimal design of the coils - three times lower inductance and stored energy);
- A.Bragin, E.Karantzouliss, S.Khrushchev, N.Mezentsev, O.Tarasenko, V.Tsukanov, A.Volkov, V.Lev, A.Safronov, V.Shkaruba, D.Zangrando, "**The upgrade of the superconducting wiggler magnet installed at the ELETTRA storage ring** (SFR-18, Novosibirsk)".

SC coils of ELEETRA-2002
and ELETTRA-**2018** (upgrade)

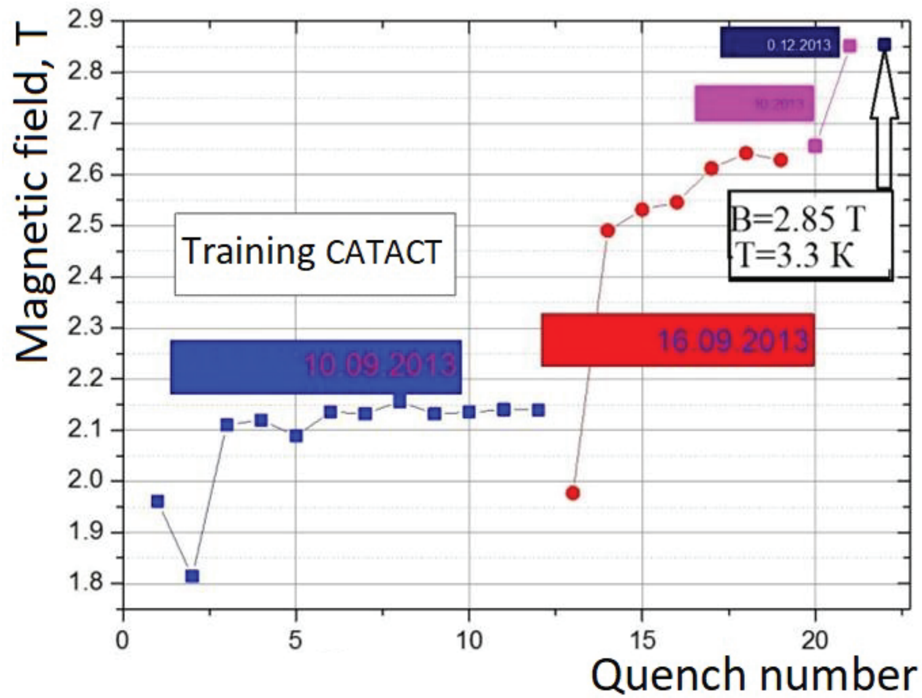


Middle field (2.5 –4.2 T) and middle period (46 – 64 мм) MPSCW created in BINP:

- The progress at the cryocoolers parameters – cooling power increase from 0.5W to 1.5W at 4.2K (on SRDK-415 Sumitomo cold head) and simultaneous upgrade of cryogenic system. The possibility of low pressure inside of Lhe vessel (compared to the atmosphere) and shifting of field-current parameters of SC Nb-Ti wire (for tens of amperes): increase magnetic field;



The shifting of field-current curves of Nb-Ti wire at overcooling down 3.2 K and the corresponding moving of critical points at the SCW coils.

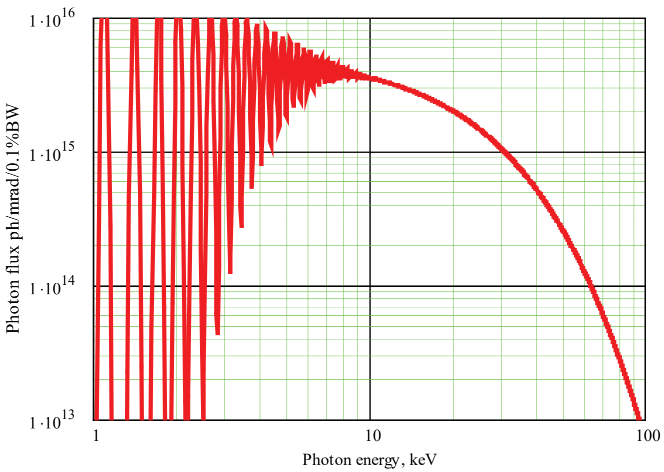


Quench history of 2.5 T ANKA-CATACT SCW (the max field of 2.85T at 3.3K):

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

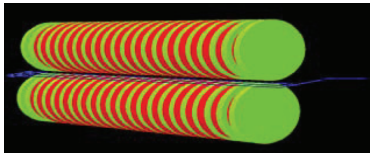
Low field (2 – 2.1 T) and short period (30 – 34 мм) MPSCW created in BINP:

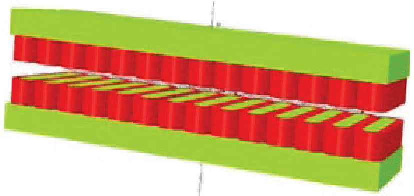
- Feature: The undulator type (line) spectrum at low energy region. The wiggler type (continuous) spectrum at high energy region;
- In opposite to traditional approach for short period SCW (vertical rays-track) it was used horizontal rays-track;
- Advantages: Wire length, stored energy and inductances 3-4 time smaller;
- Disadvantage: Large number of splices. Decision: Cold welding method for wires connection with resistance of 10^{-13} Ohm;



Spectrum of 2.1 T SCW for ALBA with the period of 30 mm (K~6)

Cold welded connection with resistance of 10^{-13} Ohm



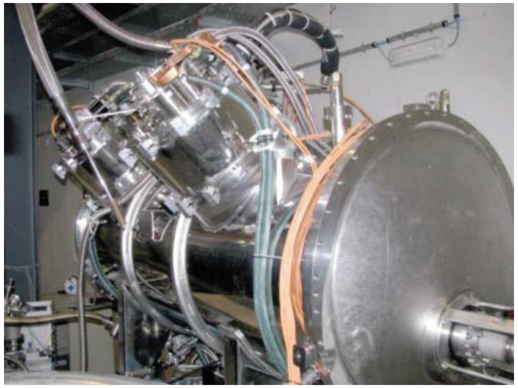


Short period magnet array of horizontal racetrack type poles (for ALBA 2.1 T SCW with 30 mm period

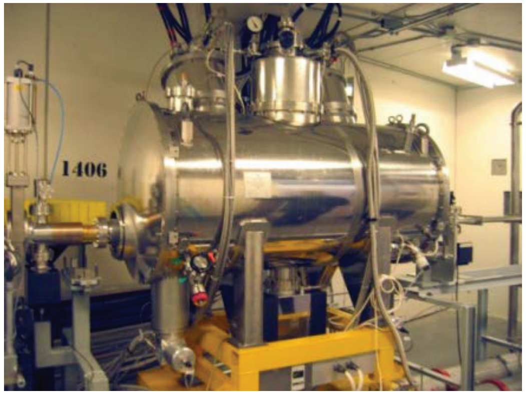
STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Low field (2 – 2.1 T) and short period (30 – 34 мм) MPSCW created in BINP:

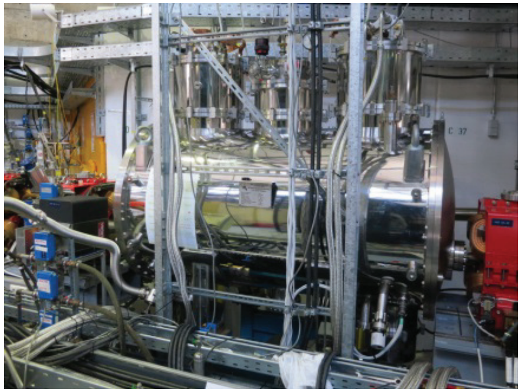
Storage ring, Energy location, year	CLS, 2.9 GeV, Canada, 2005	ALBA, 3 GeV, Spain, 2010	ANKA-CATACT, 2.5 GeV, Germany, 2013
Magnetic field, B_{oper} (B_{max}), T	2 (2.2)	2.1 (2.27)	2.5 (2.85)
Pole number (main+side)	61+2	117+2	36+4
Period, mm	34	30	47
Magnetic gap (beam gap), mm	13.5 (9.5)	12.6 (8.5)	19 (15)
Critical phot. energy, Kev (Wavelength, Å)	12.4 (1.01)	13.1 (0.94)	15.5 (0.79)
K – value	6.5	6	12
Power, (Beam current, A), KW	12 (0.5 A)	20 (0.4)	4.5 (0.4)
Current in coils, A	800	430	540+460
Critical current of wire at 7 Тл	520 A (dia. 0.9 mm)	230 A (dia. 0.55 mm)	520 A (dia. 0.9 mm)
Stored energy, KJ	15	19	30



ALBA, Spain, 2010
119-pole 2.1 T



CLS,Canada,2004
63-pole 2 T

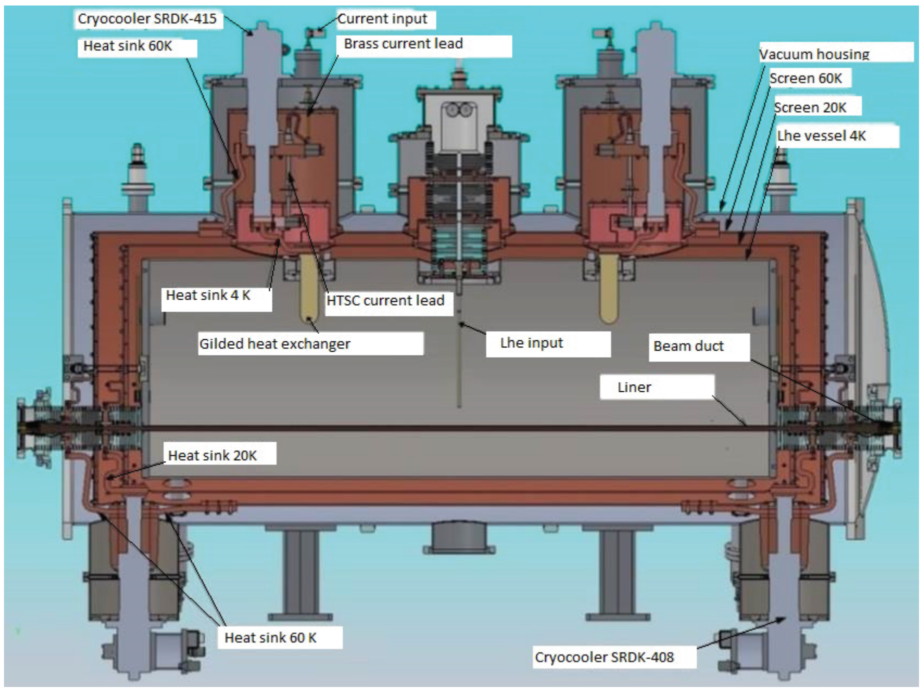


ANKA-CATACT, Germany, 2013, 40-pole 2.5 T

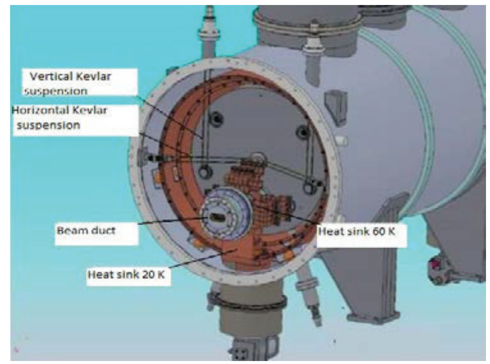
STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Cryogenic system of SCW with zero boil-off Lhe. Specialty of SCW cryostat:

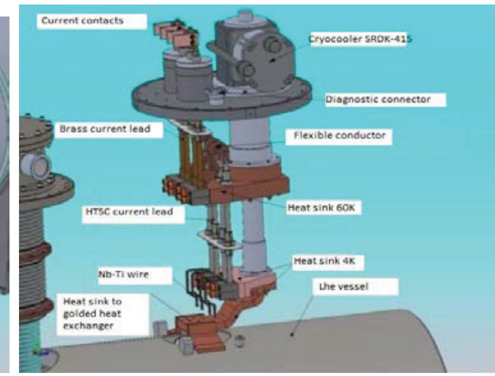
- Additional heat load from electron beam and SR; While it is necessary to decrease the magnetic gap for high field and to increase one for lower heat load;
- **Main concept**: Full interception of heat in-leaks to Lhe in critical points onto 60K, 20K and 4K cryo-coolers stages to prevent Lhe evaporation;



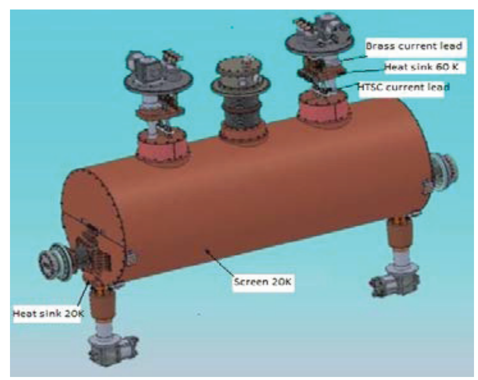
Cross-section of zero boil off cryostat for SCW



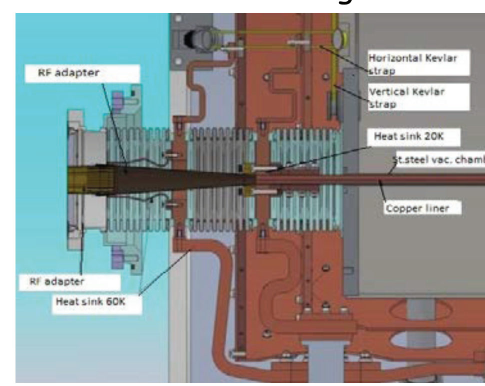
Kevlar suspensions (power to Lhe ~10 mW)



Power inleak from outside ~0.3W
Power of Joule heating ~0.3W



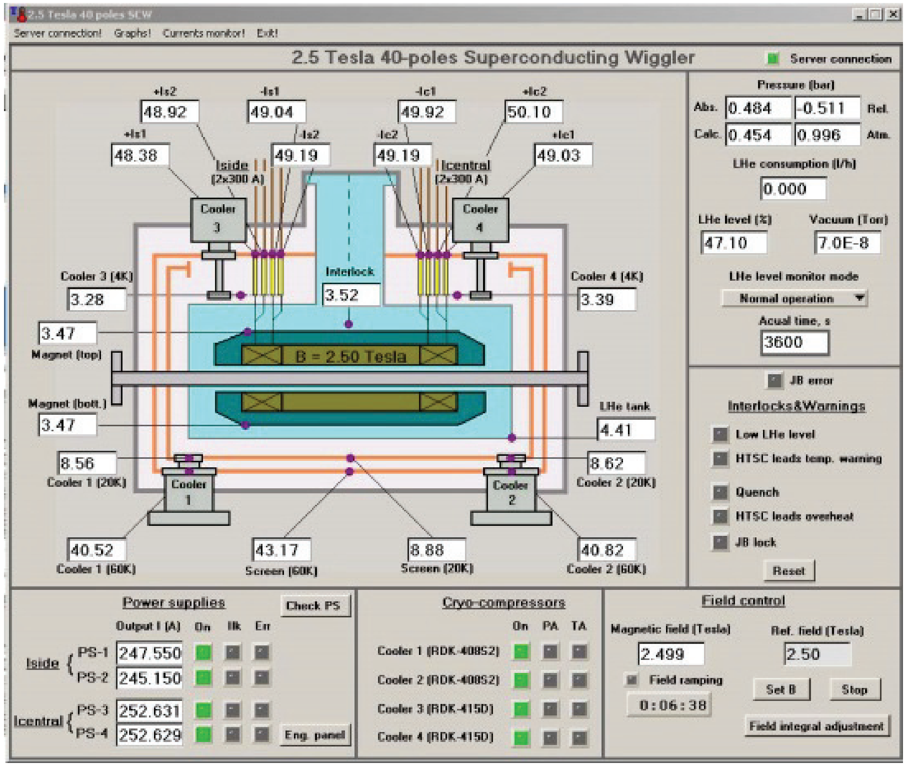
Radiation screens 20K and 60K with superinsullation (power to Lhe ~10 mW), Total cooling power at 60K ~180W



Power inleak through bellows ~ 40mW

Heat budget of zero boil off cryostat for SCW:

	Outer screen (60 K), W	Inner screen (20 K), W	Lhe vessel (4 K), W
Thermal radiation	8	0.05	0.0002
Central throat	2.5	0.3	0.06
Bellows of vacuum chamber	5.3	0.25	0.04
Suspension system	0.5	0.1	0.01
Current leads (thermal conductivity)	50	0	0.3
Current leads (Joule heating)	50	0	0.3
Diagnostic wires	5	0.1	0.01
Liner	10	10	0.2
Total	131.3	10.8	0.92
Cooling power	180 (at 50 K)	15 (at 20 K)	3 (at 4.2 K)



Temperature distribution at zero boil off cryostat

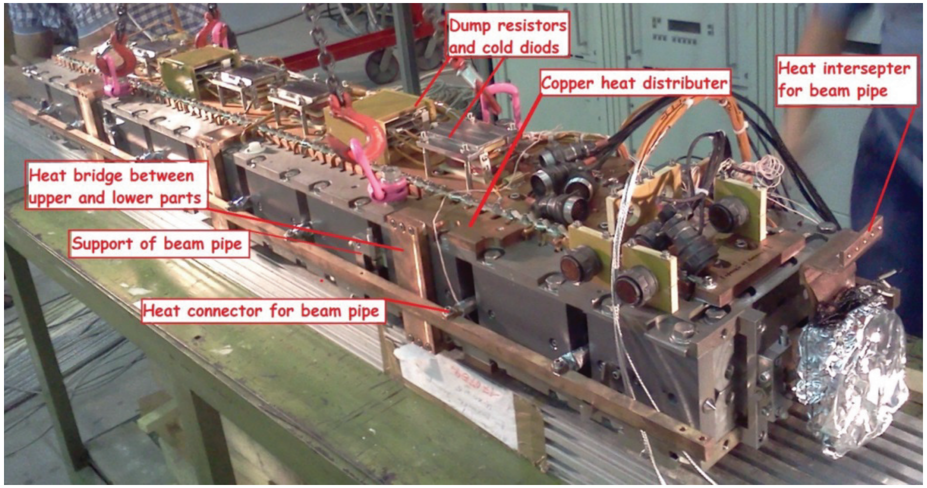
- ❑ Heat budget: The total cooling power of all cryocooler stages exceeds the corresponding heat inleaks;
- ❑ The cooling power of 4K stages exceeds (in factor 3) the heat inleaks. Excess power capacity goes to the overcooling of helium vessel with SC magnet and a decrease pressure relative to the atmosphere;
- ❑ Prevention of helium losses during a quench, recondensation and increase of LHE level in SCW cryostat.

The directions for further progress:

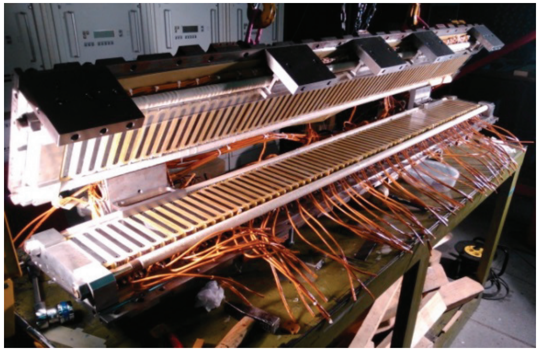
- **Indirect cooling**: Removing one of the vacuum chamber (wall of helium vessel) - the possibility to increase of field level due to decreasing of the magnetic gap. The coils located in vacuum and are cooled by copper heat links;

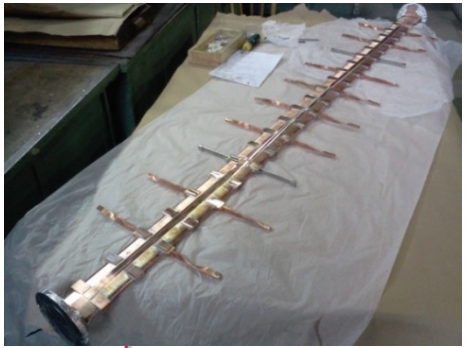
72-pole indirect cooling 3Tesla wiggler for CLIC dumping ring

The main parameters:	
Magnetic Field, T	3
Period, mm	51
Magnetic gap cold, mm	18
Vacuum gap cold, mm	13
Number of poles	68+4
Cold mass, kg	700
Ramping time, min	‹ 5
Beam heat load (acceptable), W	50



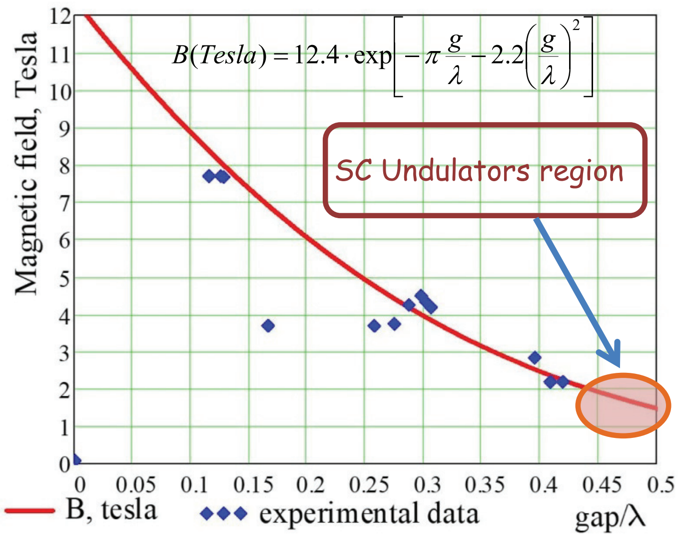
Magnetic system of 72-pole indirect cooling 3Tesla wiggler for CLIC dumping ring.

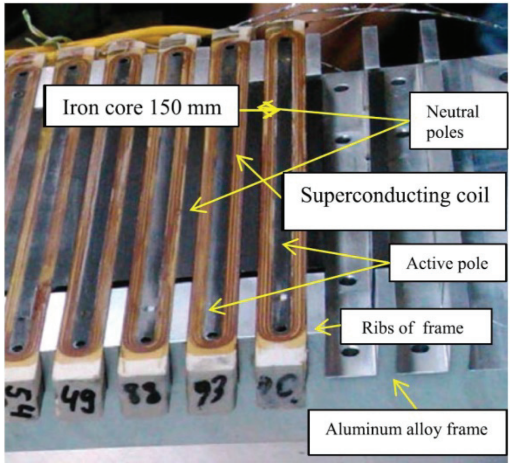




The directions for further progress: Superconducting indirect cooling SC undulator

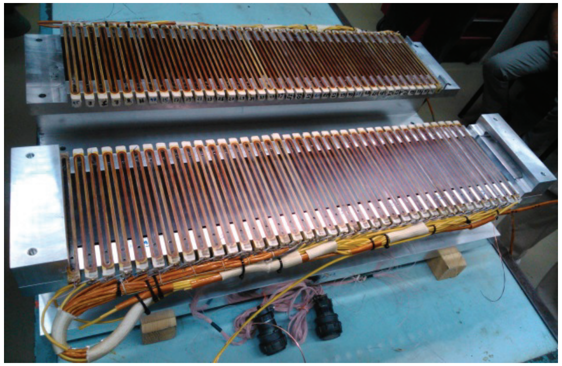
Prototype of 1.2 Tesla SC undulator with 15.6 mm period and neutral poles based on indirect cooling



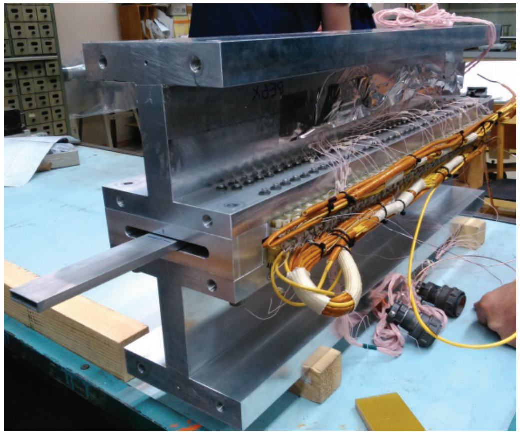


Magnetic structure of SC undulator with neutral poles

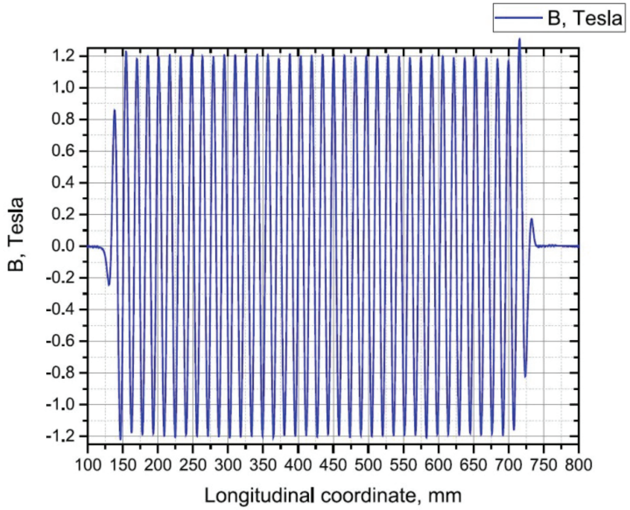
The main parameters:	
Magnetic Field, T	1.2
Period, mm	15.6
Magnetic gap cold, mm	8
Vacuum gap cold, mm	6
Number of periods	40
Current, A	470



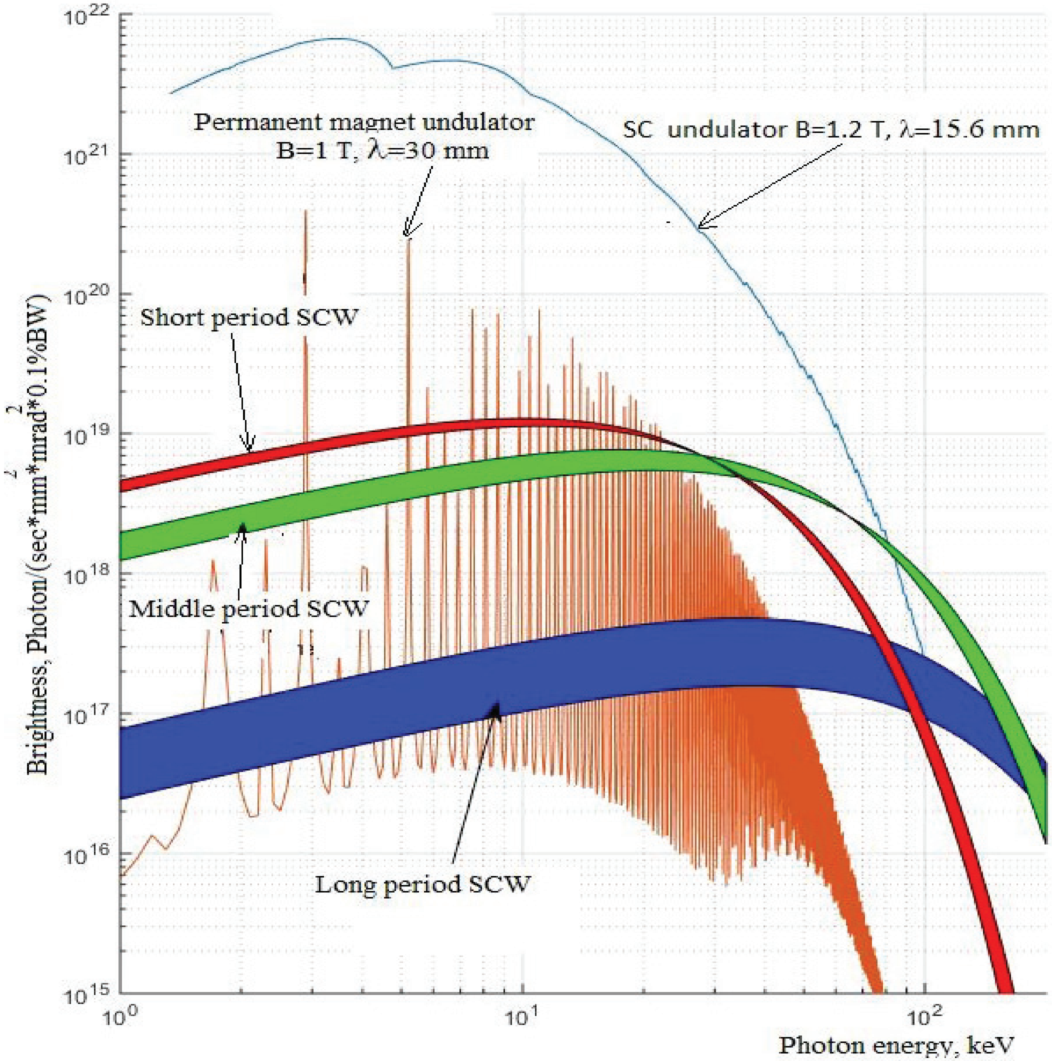
Two halves of SC undulator



40 period SC undulator-prototype



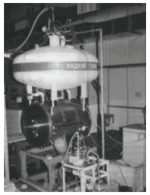
Magnetic field of SC undulator



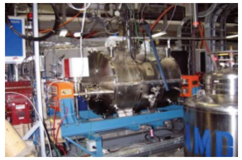
Comparison of spectral characteristics for different types ID for generating of synchrotron radiation (E=3GeV).

STATUS OF DEVELOPMENT OF SUPERCONDUCTING ID FOR SR GENERATION IN BINP

Storage ring, location	Year	Magnetic field, (B_{Max}) B_{work}, T	Poles number (main + side)	Pole gap/beam gap, mm	Period mm	LHe consumption, l/hour
3.5T wiggler BINP, Russia	1979	3.5	20	15	90	4
7.0T shifter PLS, Korea	1995	(7.68) 7.5	1+2	48(26)	-	2
7.0T shifter LSU-CAMD, USA	1998	(7.55) 7.0	1+2	51(32)	-	1.5
10.0T shifter SPring-8, Japan	2000	(10.3) 10.0	1+2	40(20)	-	0.6
7.0T shifter BESSY-II, Germany	2000	(7.5) 7.0	1+2	52(32)	-	0.6
7.0T shifter BESSY-II, Germany	2001	(7.5) 7.0	1+2	52(32)	-	0.6
7.0T wiggler BESSY-II, Germany	2002	(7.67) 7.0	13 + 4	19(13)	148	0.5
3.5T wiggler ELETTRA, Italy	2002	(3.7) 3.5	45 + 4	16.5(11)	64	0.4
2.0T wiggler CLS, Canada	2005	(2.2) 2.0	61 + 2	13.5(9.5)	34	<0.03
3.5T wiggler DLS, England	2006	(3.75) 3.5	45 + 4	16.5(11)	60	<0.03
7.5T wiggler SIBERIA-2, Russia	2007	(7.7) 7.5	19 + 2	19(14)	164	<0.03
4.2T wiggler CLS, Canada	2007	(4.34) 4.2	25 + 2	14.5(10)	48	<0.03
4.2T wiggler DLS, England	2009	(4.25) 4.2	45 + 4	13.8(10)	48	<0.03
4.1T wiggler LNLS, Brazil	2009	(4.19) 4.1	31 + 4	18.4(14)	60	<0.03
2.1T wiggler ALBA-CELLS, Spain	2009	(2.27)2.1	117 + 2	12.6(8.5)	30	<0.03
4.2T wiggler AS, Australia	2012	(4.5) 4.2	59+4	15.2(10)	50.5	<0 (0.7 bar)
7.5T wiggler CAMD LSU, USA	2013	(7.75) 7.5	11+4	25.2(15)	193.4	<0 (0.5 bar)
2.5T wiggler KIT, Germany	2013	(2.85) 2.5	36+4	19(15)	46.9	<0 (0.3 bar)
7T wiggler DELTA, Germany	2018	(7.25) 7.0	18+4	16.5(10)	128	<0 (0.2 bar)



7.5 PLS-WLS,
Korea, **1995**



7.5 T LSU-CAMD WLS,
USA, **1998**

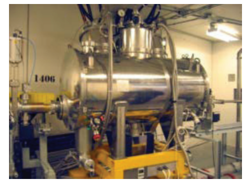
10.3 T Spring-8 WLS,
Japan , **1999**

7.5 T BAM- WLS,
BESSY-II, Germany, **2000**

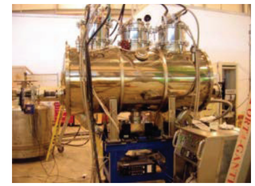
7.5 T PSF- WLS,
BESSY-II, Germany, **2002**

BESSY, Germany, 2002,
17-poles,7.5 T

ELETTRA,Italy,2002
49-pole 3.5 T

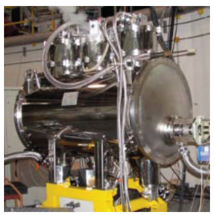


CLS,Canada,2004
63-pole 2 T



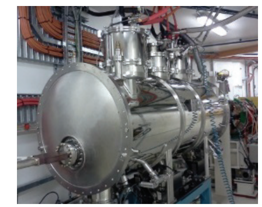
DLS,England,2006
49-pole 3.5 T

Moscow, Siberia-2, 2007
21-pole 7.5 T



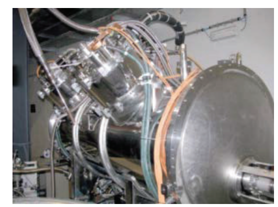
CLS,Canada,2007
27- poles 4 T

LNLS, Brazil,2009
35-pole 4.2 T

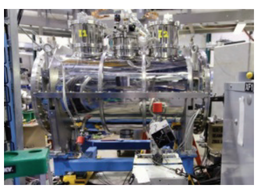


AS, Australia, 2012
63-pole 4.2 T

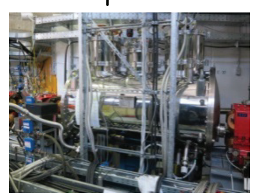
DLS, England,2008
49-pole 4.2 T



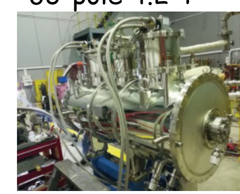
ALBA, Spain, 2010
119-pole 2.1 T



LSU-CAMD,USA, 2013
15-pole 7.5 T



ANKA-CATACT, Germany,
2013, 40-pole 2.5 T



DELTA,Germany, 2018,
22-poles,7 T

Thanks for attention