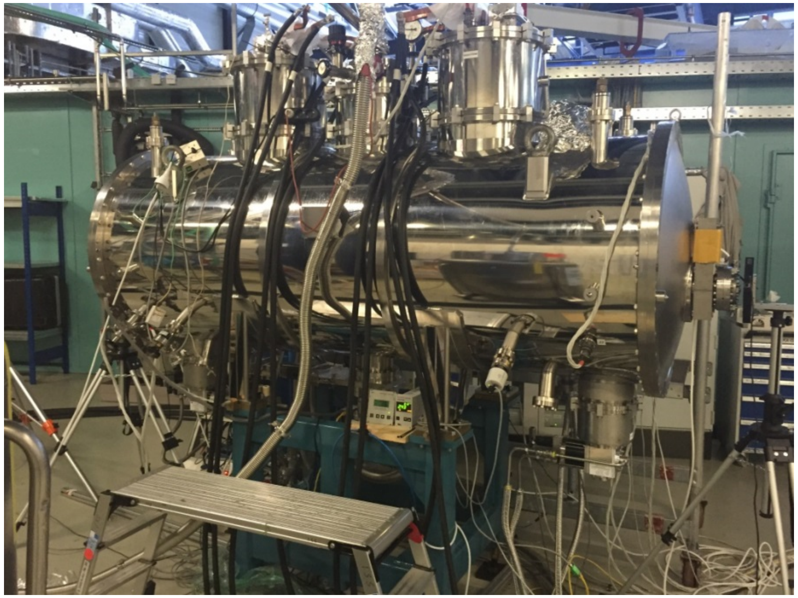
Budker INP



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Superconducting 72-pole indirect cooling 3Tesla wiggler for CLIC dumping ring and ANKA image beamline

Shkaruba Vitaliy (Budker Institute of Nuclear Physics)

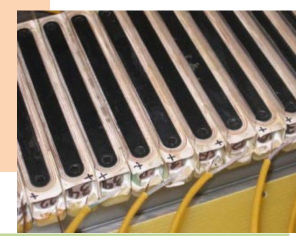
SFR-2016, Novosibirsk, Russia, 4 - 7 July 2016

List of SC insertion devices fabricated by Budker INP

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	
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 (-0.3 atm)
7.5T wiggler CAMD LSU, USA	2013	(7.75) 7.5	11+4	25.2(15)	193.4	<0 (-0.5 atm)
2.5T wiggler KIT, Germany	2013	(2.85) 2.5	36+4	19(15)	46.9	<0 (-0.7 atm)

Three groups of multipole SC wigglers fabricated by Budker INP

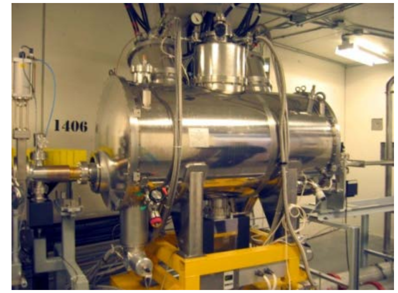
Storage ring, location	Magnetic field, (B_{Max}) B_{work}, T	Poles number (main + side)	Pole gap/beam gap, mm	Period mm	
Long period (High field) wigglers (B =7-7.5 T, λ ~150-200 mm): High radiated power and hard X-ray spectrum					
7.0T wiggler BESSY-II, Germany	(7.67) 7.0	13 + 4	19(13)	148	
7.5T wiggler SIBERIA-2, Russia	(7.7) 7.5	19 + 2	19(14)	164	
7.5T wiggler CAMD LSU, USA	(7.75) 7.5	11+4	25.2(15)	193.4	
Medium period (Medium field) wigglers (B =3.5-4.2 T, λ~48-60 mm): High photon flux at 10 -100 KeV					
3.5T wiggler ELETTRA, Italy	(3.7) 3.5	45 + 4	16.5(11)	64	
3.5T wiggler DLS, England	(3.75) 3.5	45 + 4	16.5(11)	60	
4.2T wiggler CLS, Canada	(4.34) 4.2	25 + 2	14.5(10)	48	
4.2T wiggler DLS, England	(4.25) 4.2	45 + 4	13.8(10)	48	
4.1T wiggler LNLS, Brazil	(4.19) 4.1	31 + 4	18.4(14)	60	
4.2T wiggler ASHo, Australia	(4.5) 4.2	59+4	15.2(10)	50.5	
Short period (Low field) wigglers (B =2-2.2 T, λ~30-34 mm): close to undulator					
2.0T wiggler CLS, Canada	(2.2) 2.0	61 + 2	13.5(9.5)	34	K ~6
2.1T wiggler ALBA-CELLS, Spain	(2.27)2.1	117 + 2	12.6(8.5)	30	K ~ 6
2.5T wiggler KIT, Germany	(2.85) 2.5	36+4		46.9	K ~ 11



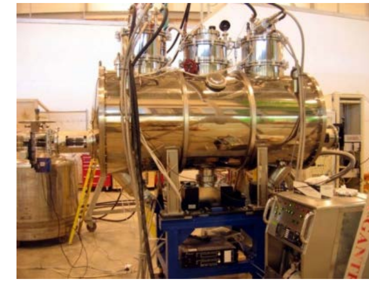
Photos of SC multipole wigglers fabricated by Budker INP

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

ELETTRA,Italy,2002
49-pole 3.5 T



CLS,Canada,2004
63-pole 2 T



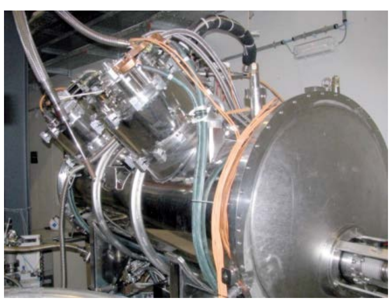
DLS,England,2006
49-pole 3.5 T

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

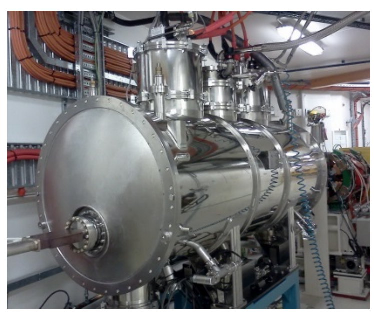
CLS,Canada,2007
27- poles 4 T

DLS, England,2008
49-pole 4.2 T

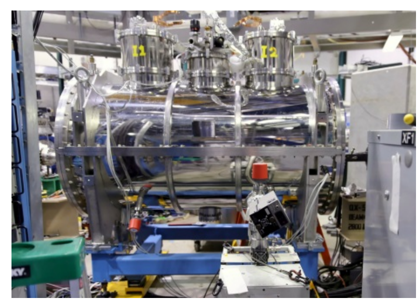
LNLS, Brazil,2009
35-pole 4.2 T



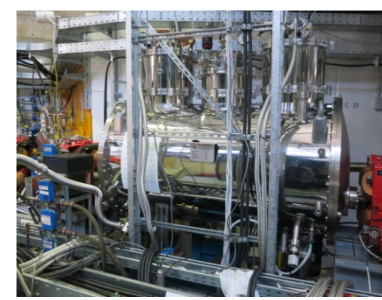
ALBA, Spain, 2010
119-pole 2.1 T



AS, Australia, 2012
63-pole 4.2 T



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



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

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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
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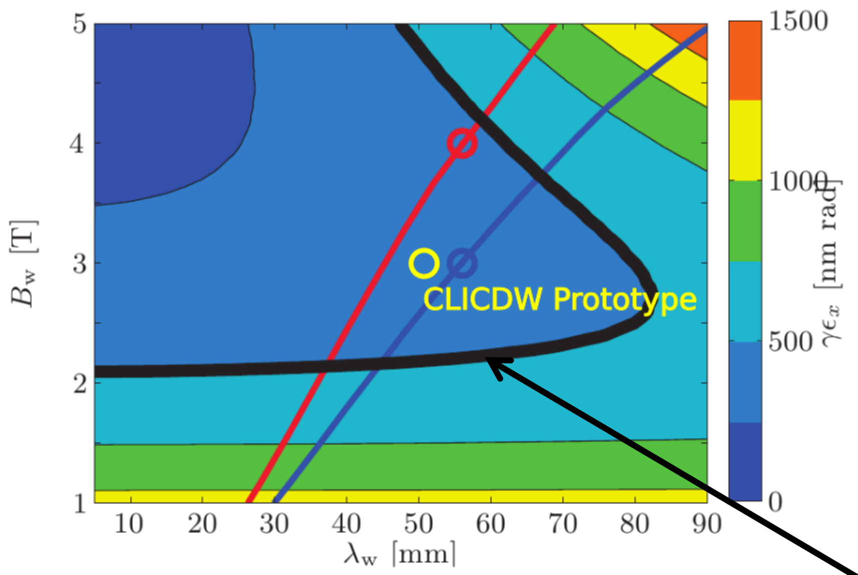
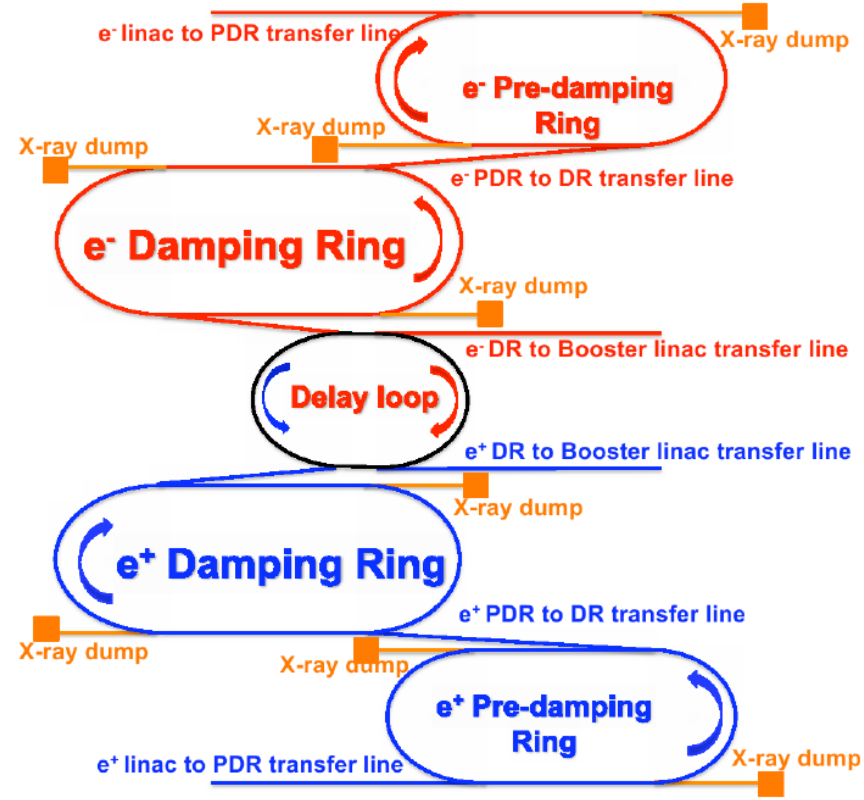
Required magnetic parameters of CLIC dumping wiggler

Magnetic field	3 (2.95)* T
Period	51 (51.4)* mm
Magnetic gap	18 (17)* mm
Beam gap	13 mm
Number main poles	68
Side poles	$+\frac{1}{4},-\frac{3}{4},\ldots,+\frac{3}{4},-\frac{1}{4}$

*-real final parameters of BINP prototype



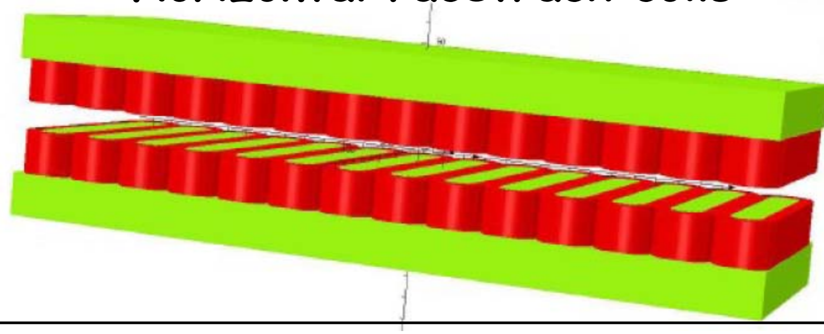
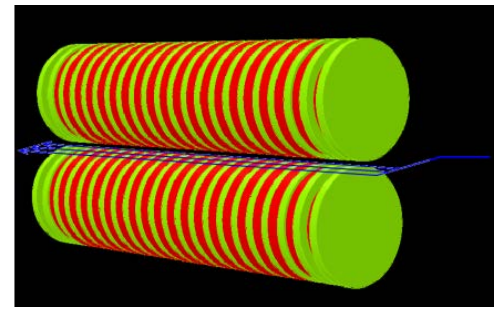
F. Antoniou; D. Schoerling et al, PRSTAB 15 (2012)

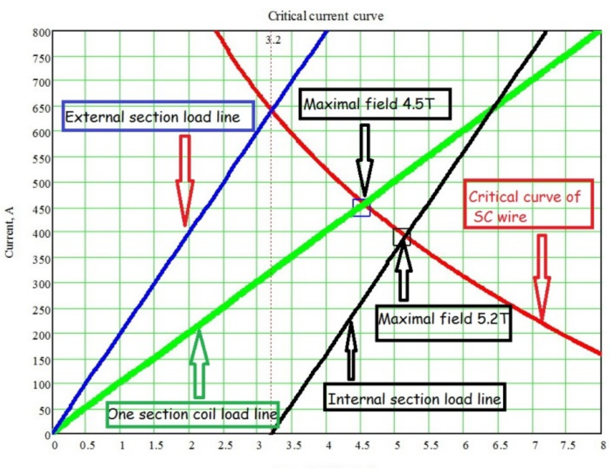


- electron and positron beams with ultra-low emittance due to emission of synchrotron radiation
- 2 x 52 superconducting Damping Wigglers (DW) for two dumping rings (DR)
- Horizontal Normalized Emittance (target): < 500[nm·rad]

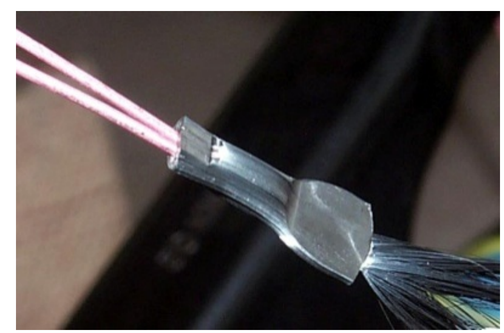
Budker INP

Choice between horizontal and vertical racetrack coils design

Horizontal racetrack coils	Vertical racetrack coils
	
Short SC wire is required	Long SC wire is required (3-4 time more)
Minimal stored magnetic energy and inductance	Stored energy and inductance is more by 3 times
Possibility of multi sections coils (+15% for two sections)	No possibility to make multi section coils
Possibility to replace of broken coils and easy mass production	Need to replace the whole coils block
Large number of splices for large number of poles	Less number of splices



- Comparison of one and two section coils with identical layer numbers. Due to feeding section with different currents the field value increases by 15 % (5.2T and 4.5T)

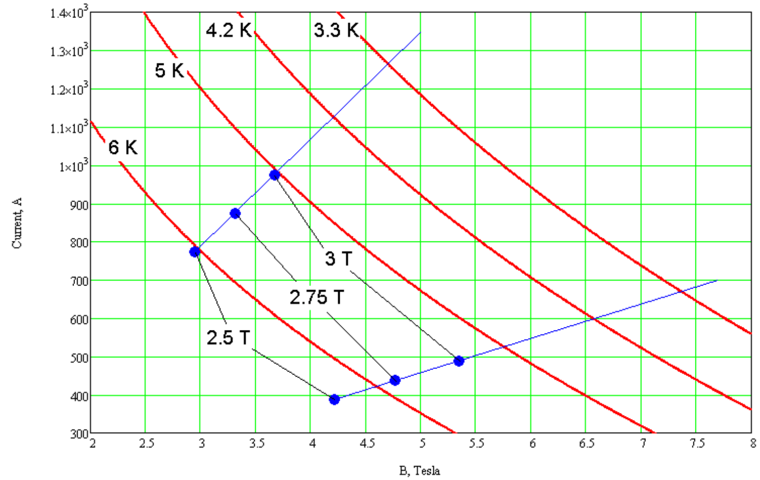


- Cold welding connection of SC wires ($R<10^{-12}$ Ohm)

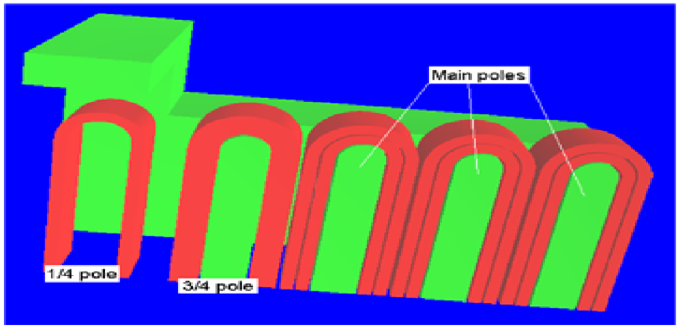
Magnetic system of CLIC dumping wiggler prototype

Magnetic Field, T	≥ 3
Period, mm	51
Magnetic gap cold, mm	18
Vacuum gap cold, mm	13
Number of poles	68+4
Stored energy, kJ	60
Cold mass, kg	700
K	< 16
Magnet length, mm	1836
Length flange to flange, mm	2590
Maximum ramping time, min	< 5
Beam heat load (acceptable), W	50
Period for LHe refill with beam	> 1 year
LHe boil off for 1 quench, L	< 15
Field stability for two weeks	$\pm 10^{-4}$

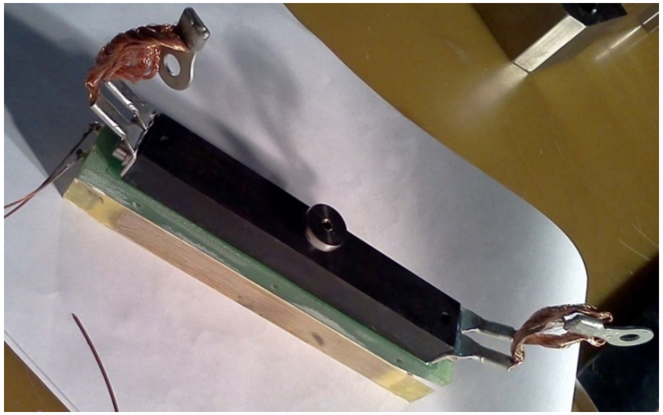
- Winding geometry: horizontal racetrack
- Wire: Nb-Ti Diam.0.85 (0.91) mm with 520A at 7T
- Inner Section: 487A x 62 turns
- Outer Section: (487A + 487A) x 62 turns



- Critical curve of used SC wire at different temperature (red). Blue dots – maximal field inside of outer and inner sections for 3.0 T magnetic field on the median plane for the wiggler period of 51 mm and the pole gap of 18 mm.



- 3D model (MERMAID code) for optimization of magnetic field of CLIC dumping wiggler



- Two-sectional horizontal racetrack central pole with copper heat links

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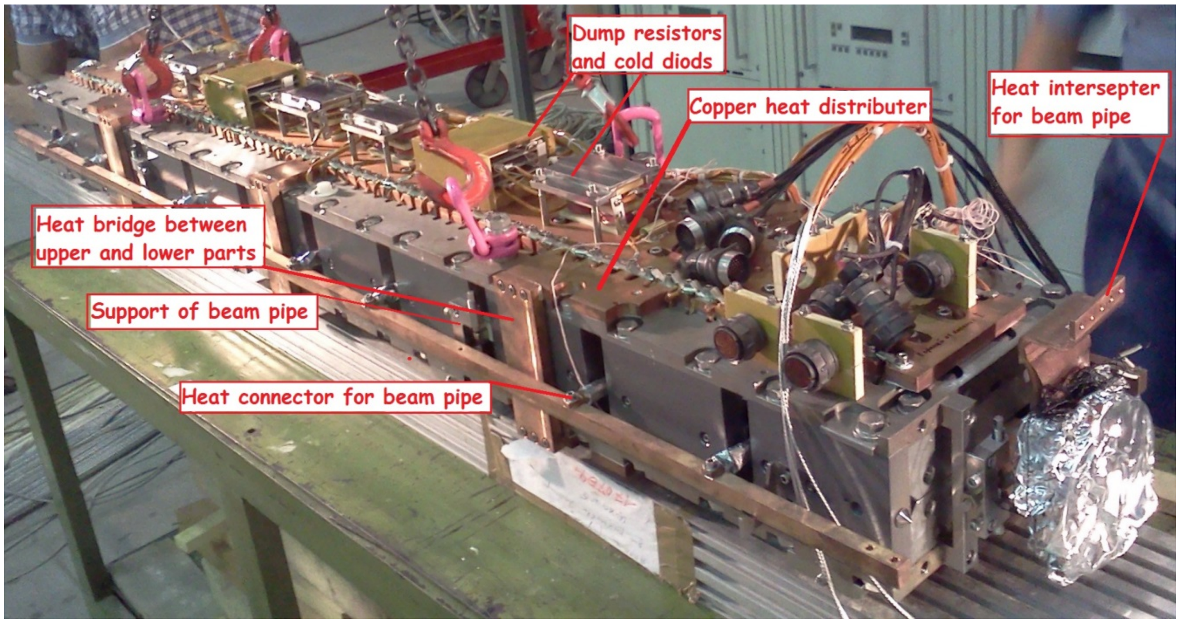
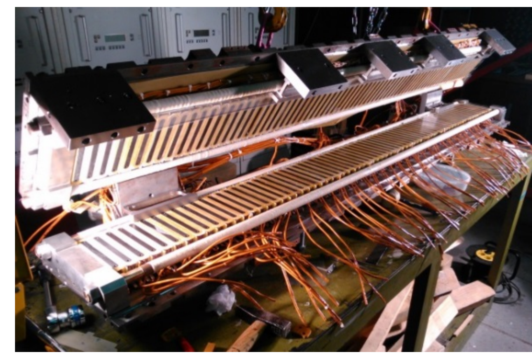
Magnetic system of CLIC dumping wiggler prototype

- **Cooling concept:** Main problem of indirect cooling - reliable cooling of SC coils by using only termo-conductivity of applied materials. The coils (located in vacuum) are cooled by copper heat links from each core to copper heat distributer extended along the magnet.



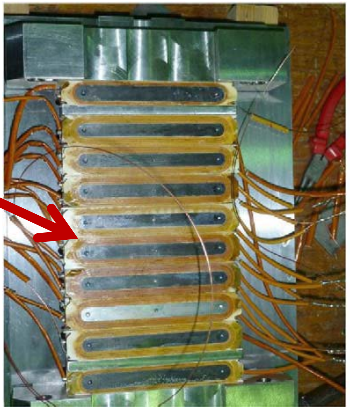


- **Principal design advantage:** Removing of useless vacuum chamber (wall of helium vessel) gives the possibility to increase of field level due to decreasing of the magnetic gap
- **"Open-able" design feature:**
- Easy access for large number of heat sinks (to improve cooling) and supports of the vacuumchamber (for reliable positioning).
- Possibility to exchange of coils and of vacuum chamber

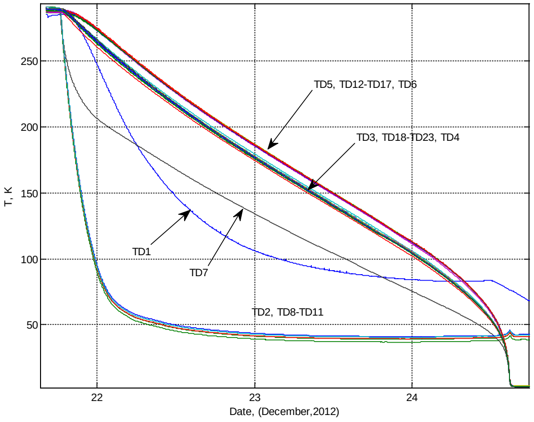
Testing of "Short prototype" CLIC wiggler with indirect cooling

- Short model (10 pairs of poles) was directly attached to 1W cooling stage of cryocooler by copper thermal links and cooled down to ~3K for ~2 days.

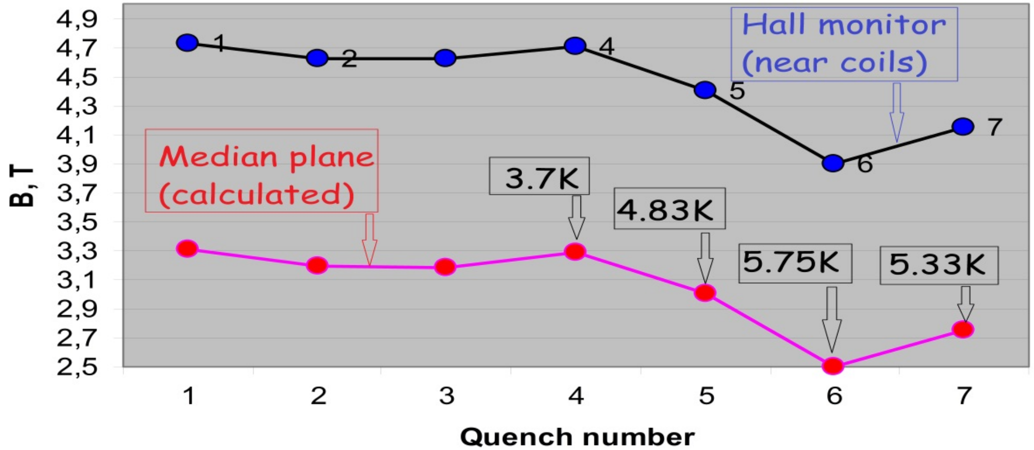
- 10-pole short prototype before assembling



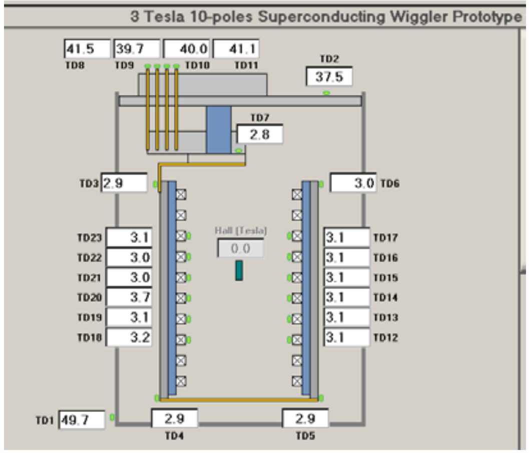
- SUMITOMO SRDK-408 D2 1W at 4.2K



- Process of indirect cooling of short prototype down to ~3K



- Dependence of field level B(T) from temperature is in good agreement with critical curve of SC wire.
- Quenching of short prototype at different temperatures (3.7K-5.75K)
- Maximal field of 3.3T for 3.7K.



- Temperature distribution of indirect cooled short prototype

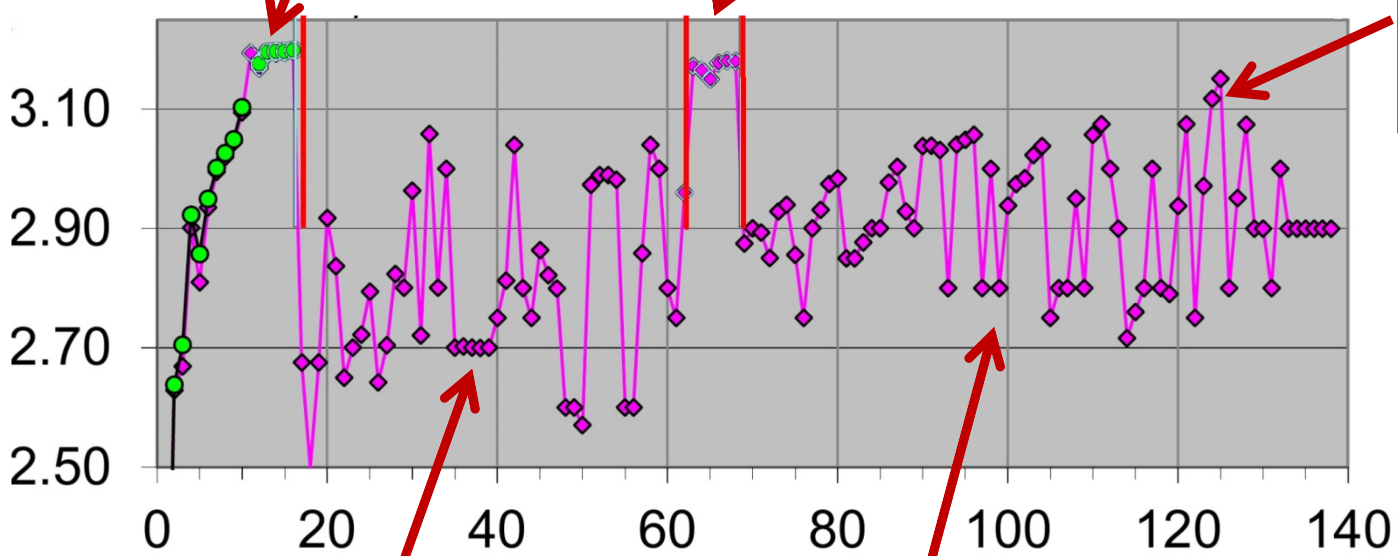
Quenching of "Full Size" prototype of CLIC wiggler

- Full size magnet was tested at liquid helium and with indirect cooling method
- Training in liquid helium: the field level is reached to 3.2T
- Training with indirect cooling : the field level is reached to 3.1T during ramping
- But: No stable operation if the ramping stopped at 2.7 –3.0T. Unpredictable quenches after period from minutes to hours uncorrelated with the magnet temperature. The quenched coils are different.

- **First** quenching in Liquid Helium 4.2K: stable 3.2T after training

- **Second** quenching in Liquid Helium 4.2K: stable 3.2T without training

- quenching with indirect cooling: field > 3.1T during ramping



- quenching with indirect cooling: no stable field after stopping ramping at > 2.7T

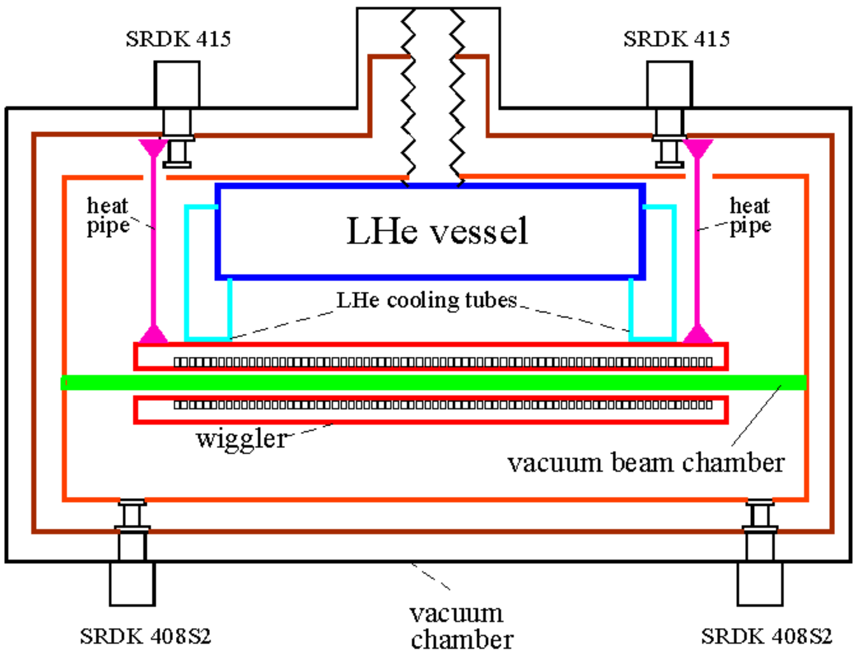
Activities for troubleshooting of premature quenching before 3T

Actions	Results (stable level of magnetic field)
Replace of often quenched coils	2.7T
Additional heat links for interception of heat in-leaks through signal wires and elements of cryostat. Installation of additional sensors for monitoring of temperatures	2.7T
Additional super-insulation at questionable places	2.8T
Additional increasing of mechanical rigidity of magnet	2.8T
Preventive maintenance of questionable cold welded splices	2.8T
Each splice (~300) were thermally connected to heat sinks	2.8T
Decrease of magnetic gap from **18 mm to 17 mm** and period **from 51 to 51.4 mm** (additional 0.2 mm Cu-foils between the coils for cooling) (Beam gap remained required **13 mm!)**	**~2.95T stable at 3.1 K to 4.5 K**

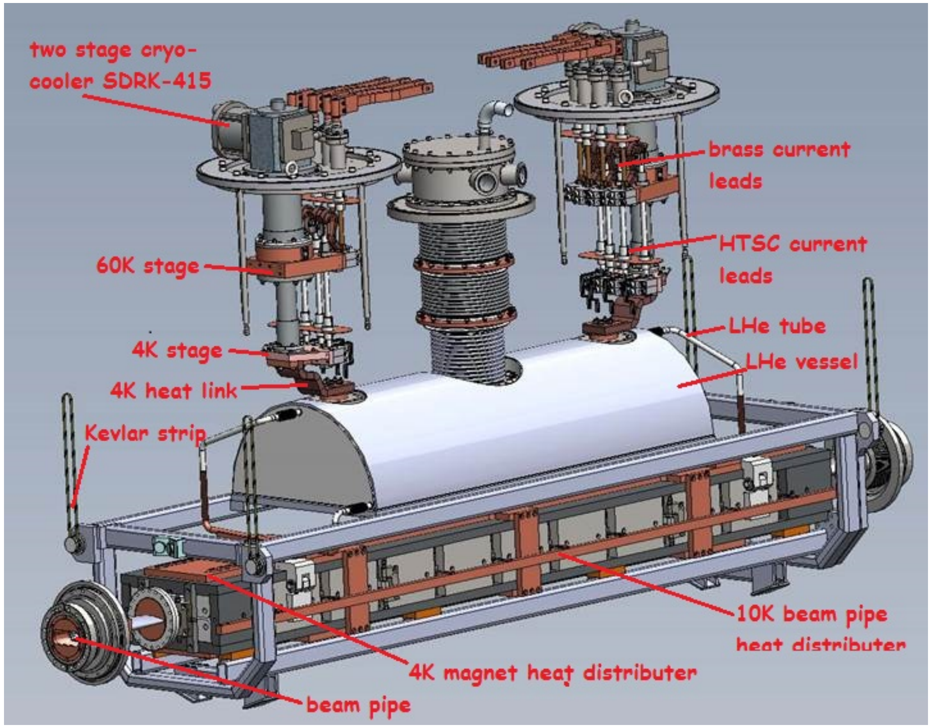
- Improvement of cooling, interception of heat in-leak and removing of heating generated by current.
- All taken actions haven't resulted in elimination of premature quenching (Max stable field was ~2.8T)
- The decision was made: to decrease of magnetic gap from 18 mm to 17 mm (reached field ~2.95T)
- The reason of unstable operation of indirect cooling magnet (in opposed to cooling by liquid helium) is still not explained and remaining the subject investigation!

Cryogenic system of CLIC wiggler with indirect cooling

- **Cooling concept:** Indirect cooling of the magnet (located in vacuum) by copper heat links connected with copper plate along the magnet
- The copper plate is cooled by thermo- siphon tubes with circulating helium
- Helium is re-condenses inside of helium vessel by heat exchangers cooled by 4K stage of cryo-coolers
- Vacuum chamber is cooled with heat links by 10 K stage of cryo-coolers. Current lead block which is combined from HTSC and brass parts allows input current t of ~1000 A



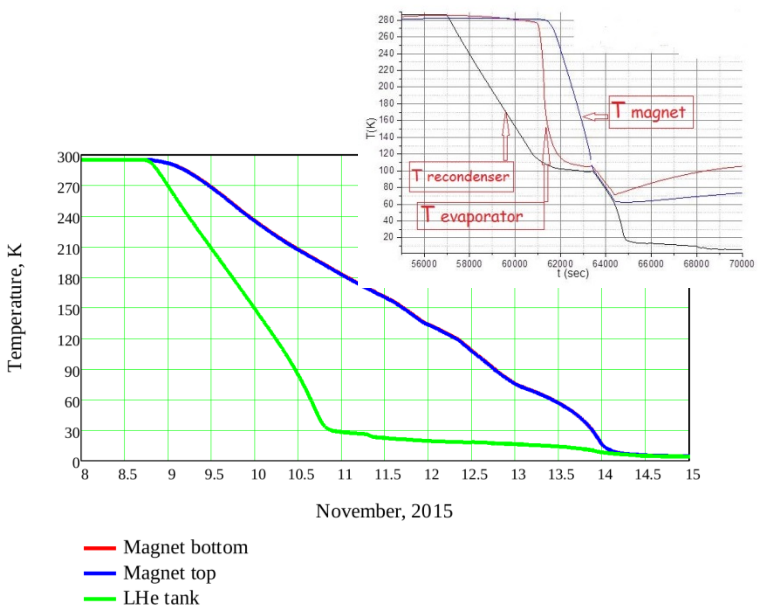
- Indirect cooling conception of CLIC DW cryostat



- 3D model of indirect cooled cold mass of CLIC DW cryostat

Cryogen-free precooling down with nitrogen heat pipes

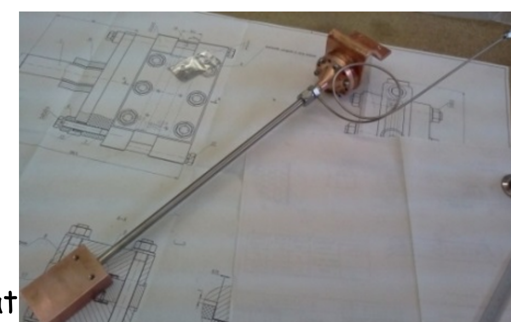
- Cryostat advantage: Pre-cooling down of ~1000 kg cold mass with using of two nitrogen heat pipes (thermo-siphon type) as a heat conduction elements between 60K stage of the cryo-coolers (re-condensers) and the magnet.
- Heat pipe is operated as a "thermal switch" which automatically freeze when the temperature is dropped down to nitrogen freezing point (64K). After that thermal connection is cut of.
- Special heaters with feedback is used to prevent anticipatory freezing of nitrogen and prolongation of cooling. Maximal extracted power: ~100W for each pipe.
- Cryogen-free cooling down and condensation of He gas



- It takes ~5 days to cool down the magnet down to LHe temperature. Then wiggler can operate without any service during some years.

- Cooling upper end of nitrogen heat pipe (60K cryo-cooler stage)

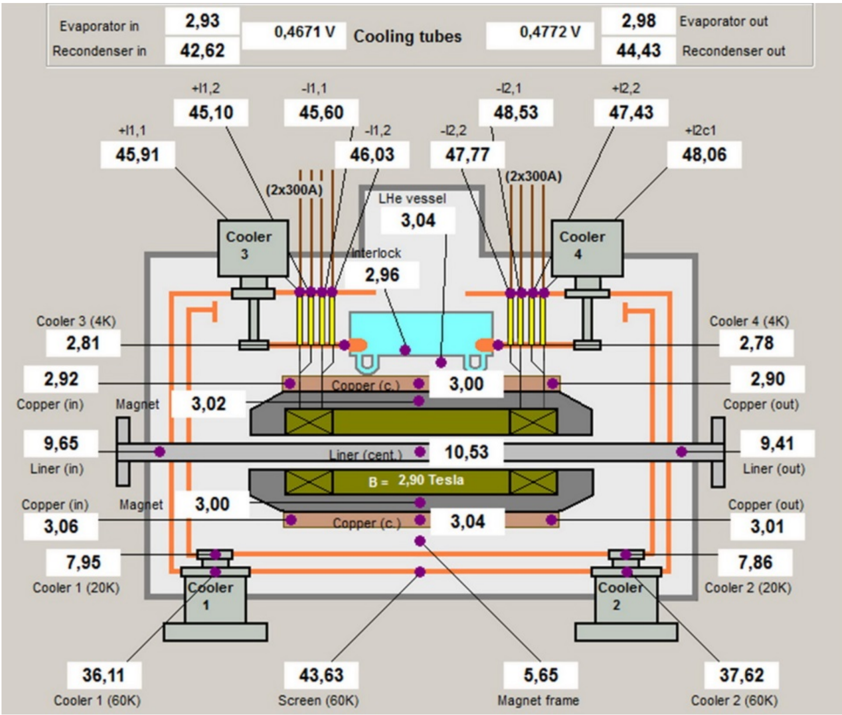
- Cooled lower end of nitrogen heat pipe (magnet)



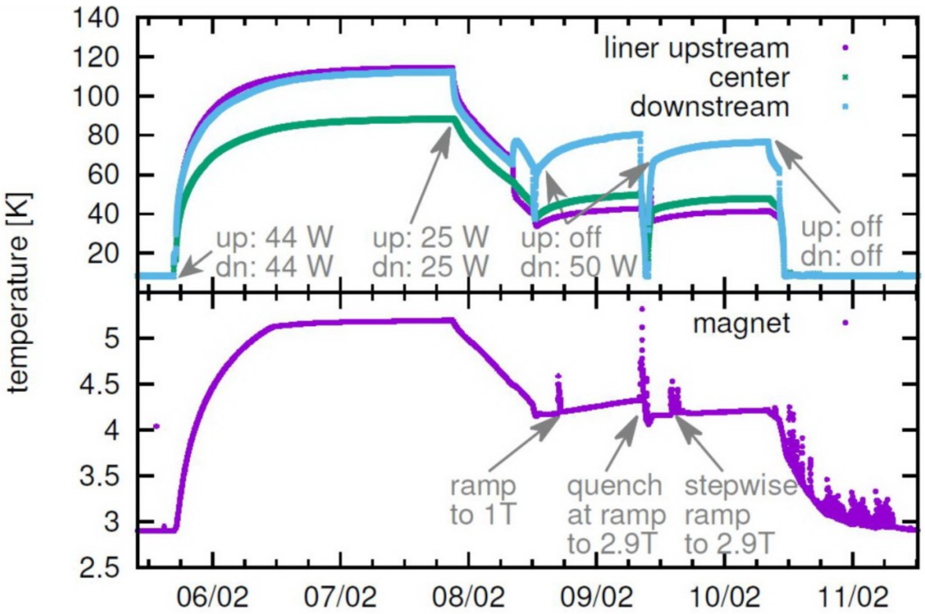
- Overall view of nitrogen heat pipe (re-condenser)

Cryogenic system performance

- The minimal temperature reaches ~3K on the magnet and ~10K on the beam pipe
- In the damping rings the heat load from synchrotron radiation on beam pipe from upstream wigglers expected up to ~50W
- So heat load test with ~90W was conducted by simulation of heating using resistive heaters attached to the beam pipe
- The temperature was stabilized at ~100 K at beam pipe and ~5K at the magnet (with full field and without quench)



- Temperature distribution of indirect cooled CLIC dumping wiggler prototype (the field of 2.9T)



- Temperature on beam pipe and on magnet during of heat load test. (A. Bernhard et al, ProcIPAC-2016)

Current status and conclusions

- CLIC damping wiggler prototype with indirect cooling was successfully installed and commissioned in ANKA storage ring on 2016 Feb.

- The wiggler will be used for ANKA image beamline and for testing as dumping wiggler prototype for CERN.

- Now wiggler is under study of effects on the beam dynamics

- The maximum field amplitude reached during ramping was 3.2 T, both in the bath cryostat and in the wiggler's own cryostat

- But the stable field is limited to 2.95 T during long operation. The physical reason of this instability is not yet satisfactorily explained

Acknowledgements

BINP

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CERN

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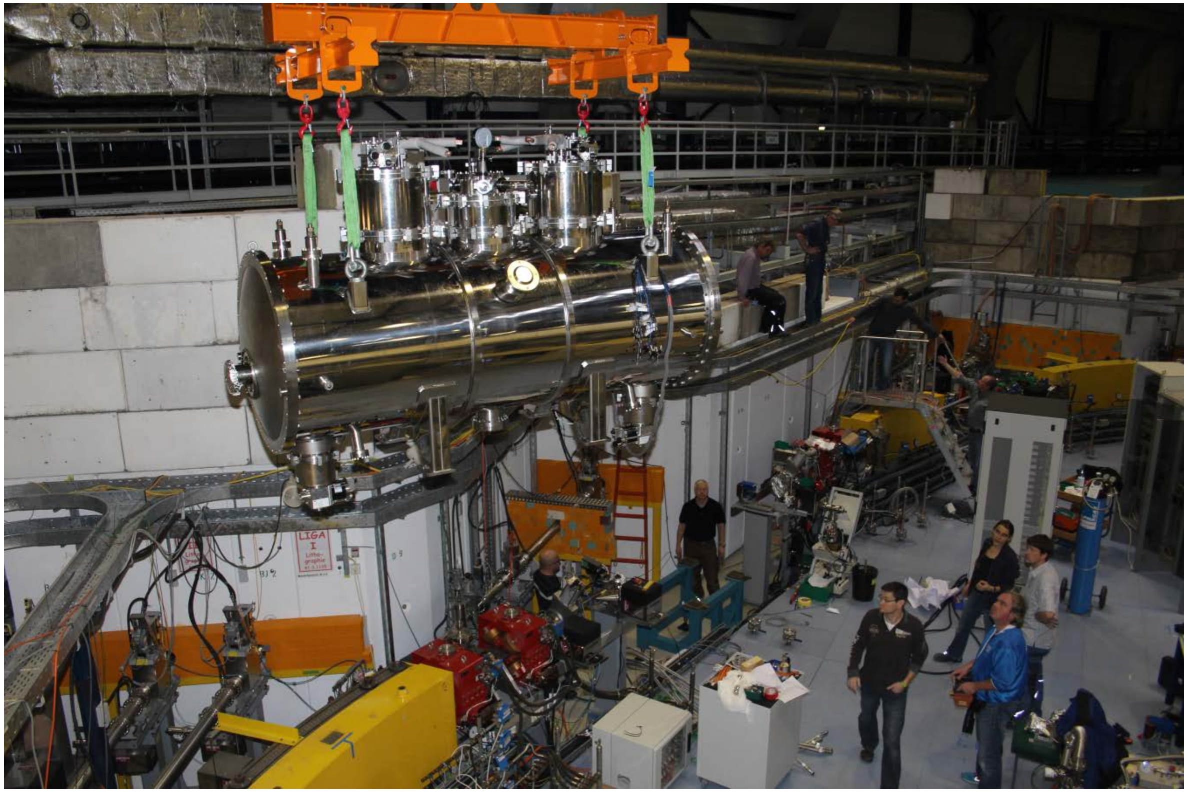

Thank for attention