The HTS undulator and wiggler development

Daniel Schoerling

Thanks to Axel Bernhard (KIT), Laura Garcia Fajardo (LBNL), Paolo Ferracin (LBNL), Yannis Papaphilippou (CERN), Sebastian Richter (CERN/KIT),

01st of February 2020

Outlook

- The CLIC damping rings
- The collaboration for undulators and wigglers
- CERN’s HFM program
- The HTS undulator development
- Conclusion

The CLIC collaboration

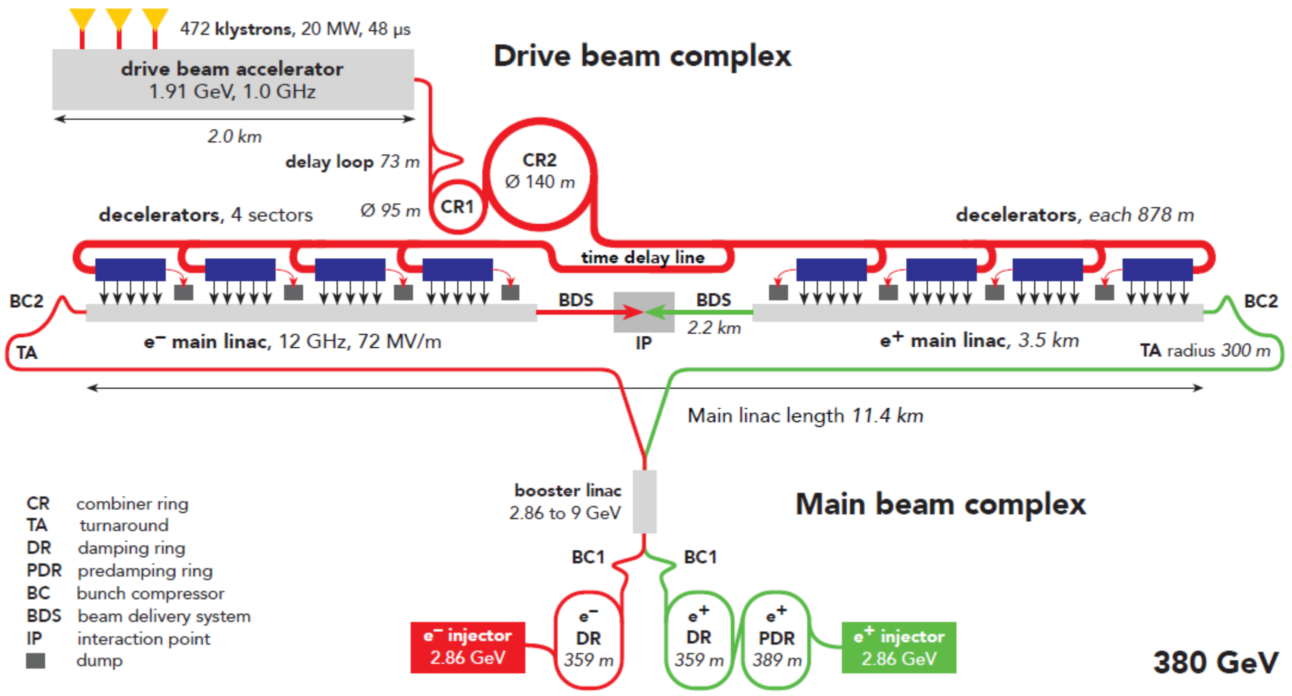


Figure 2.1: Overview of the CLIC layout at $\sqrt{s} = 380\,\mathrm{GeV}$.

Wiggler peak field, B_w [T]	3.5
Wiggler length, L_w [m]	2
Wiggler period, λ_w [cm]	4.9

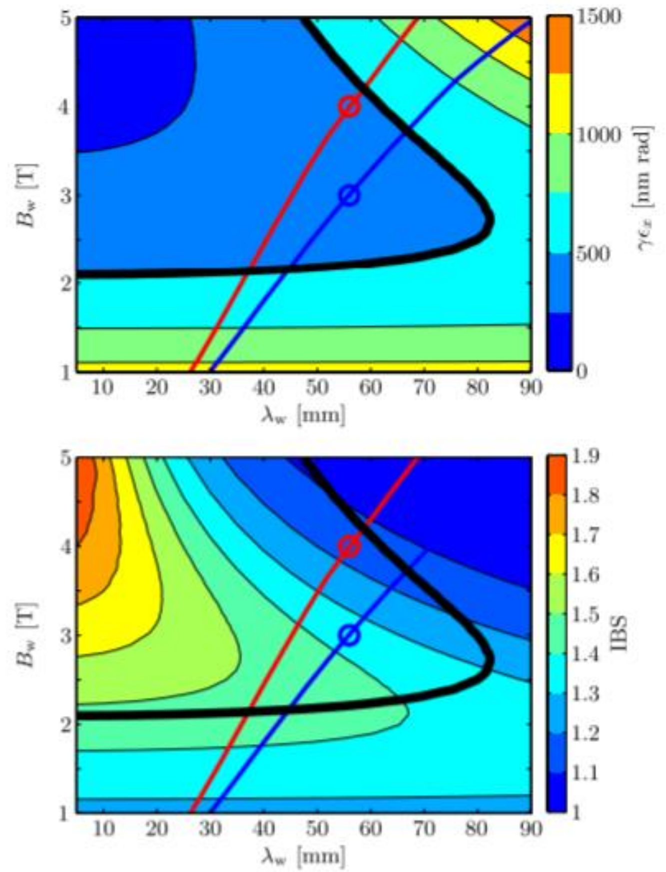
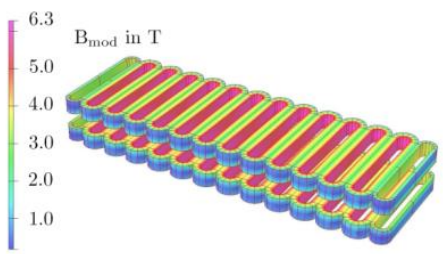
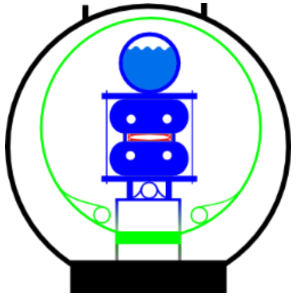


FIG. 6. Equilibrium normalized horizontal emittance $\gamma\epsilon_x$ (top) and the effect of IBS ($\gamma\epsilon_x/\gamma\epsilon_{x,0}$). The red and the blue curves show the maximum achievable magnetic flux density for superconducting wiggler magnets with Nb_3Sn and Nb-Ti wire technology, respectively.

The CLIC collaboration





Designing

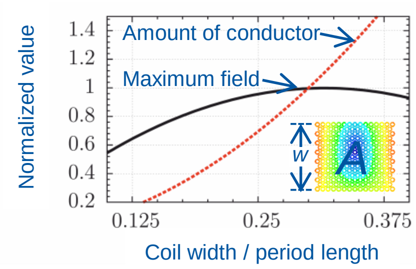
damping wiggler magnets with analytical equations and FE software

Manufacturing

Nb-Ti and Nb_3Sn short models for proof-of-principle

Developing

a technical concept for the SC CLIC damping wigglers



Collaborations

Budker Institute of Nuclear Physics

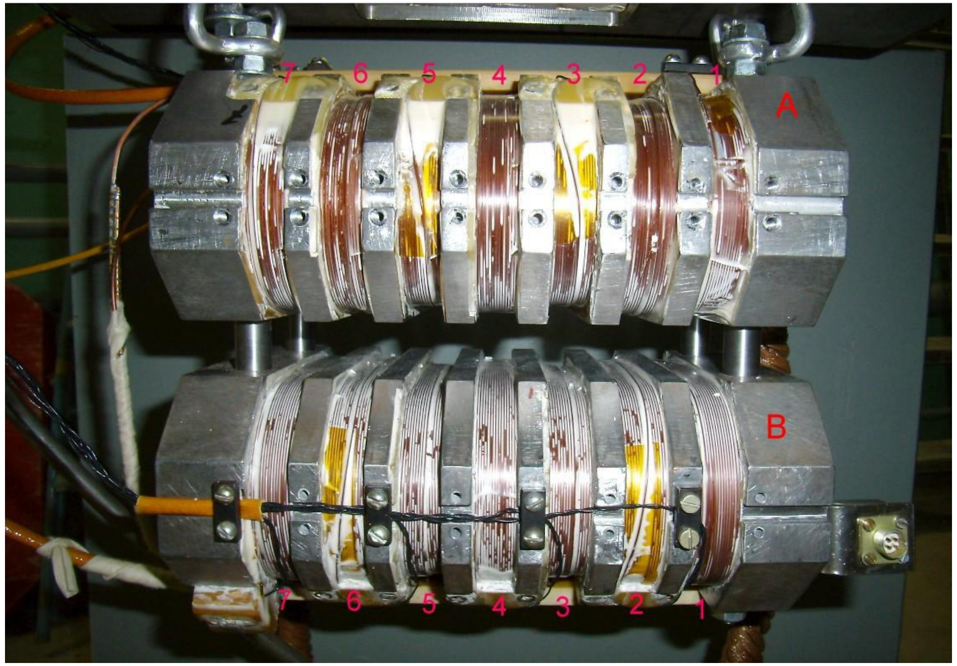
KIT Karlsruher Institut für Technologie

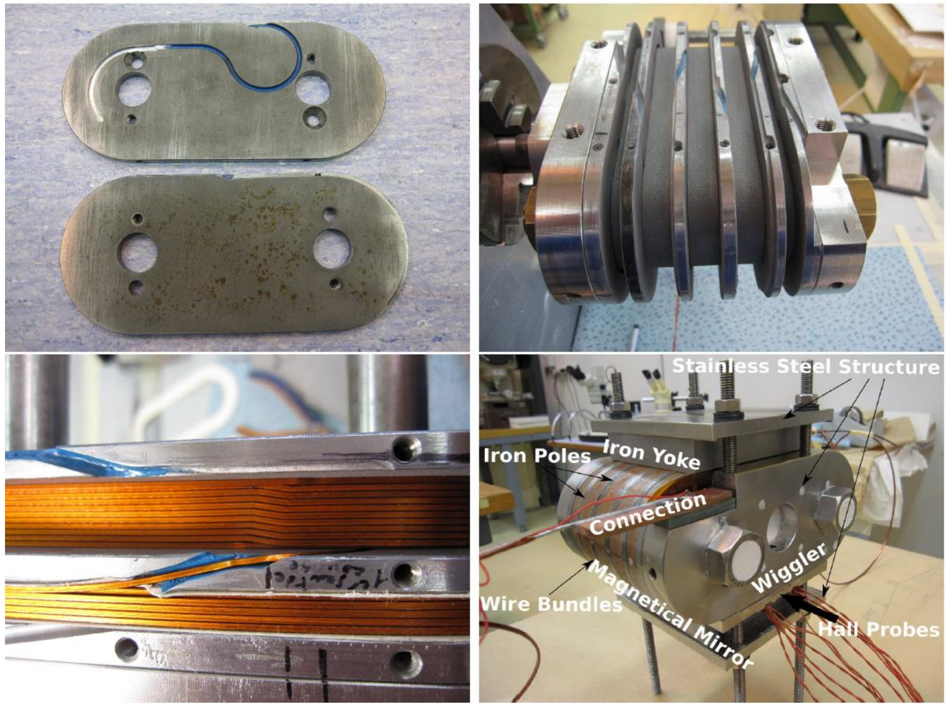
CERN

CLIC

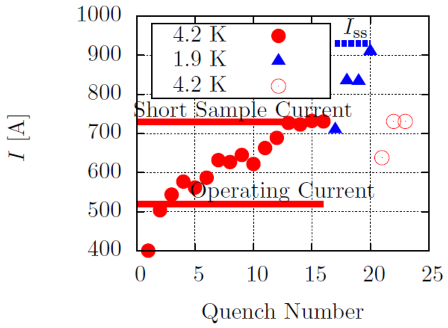
TU Bergakademie Freiberg

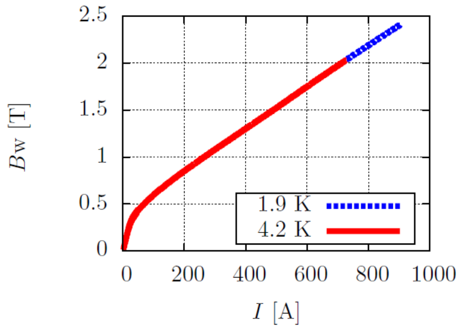
The first steps, now more than 10 years ago





This Nb-Ti superconducting wiggler reached only 60% of the critical current, that is, a maximum mid-plane flux of 1.6 T instead of 2.5 T (Courtesy BINP)





Moving from VR to HR

Workshop at CERN on 3rd December 2010 [1] and following discussions:

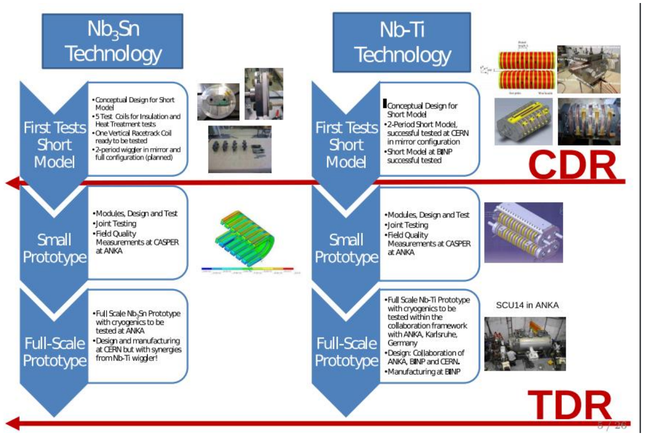
- HR or VR wiggler?
- Prepare KIT to test after the Nb-Ti a Nb_3Sn wiggler: cryostat is built such that coils can be relatively easily be exchanged
- A second cryostat was seriously discussed but never built/financed

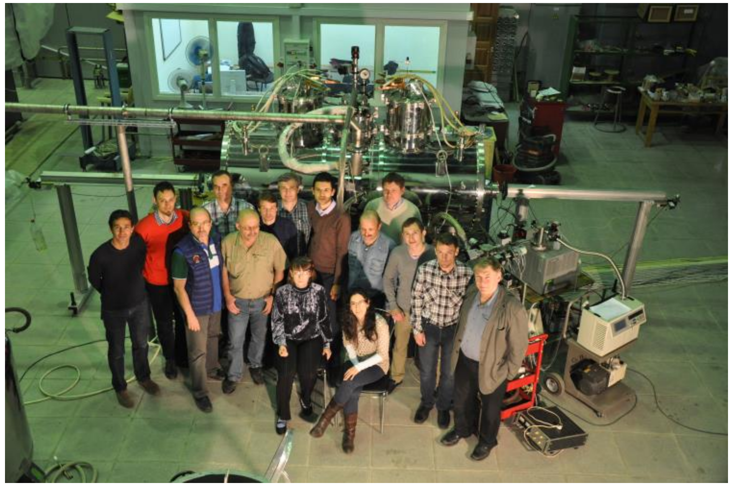
After many discussions and technical work, only 4 years later a CLIC damping wiggler was successfully built and tested.
We had agreed on a conduction cooled Nb-Ti HR wiggler with graded coils:

Period	51	mm
Nominal magnetic field	≥ 3	T
k	< 15	
Vacuum gap cold	13	mm
Magnetic length	1900	mm
Maximum Ramping Time	≤ 5	min
Power supply stability	$< 10^{-4}$	

The magnet was successfully tested and is used in KARA, KIT

Roadmap





CLIC damping wiggler FAT, 21.05.2014

The Nb-Ti prototype wiggler

- The cryogenic performance of the conduction cooled system was excellent reaching around 3 K
- In the case of indirect cooling, however, holding quenches occur after periods of seconds to several hours in the outer, high current coil sections for fields above 2.9 T. These holding quenches are basically uncorrelated with the magnet temperature.

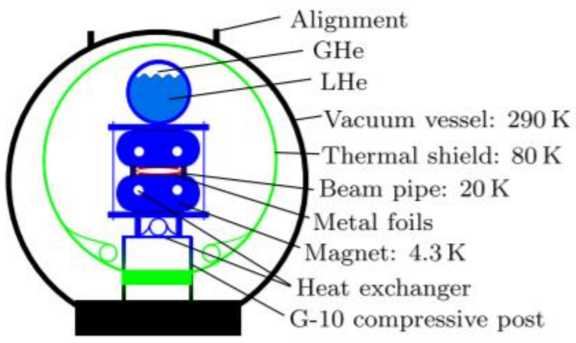
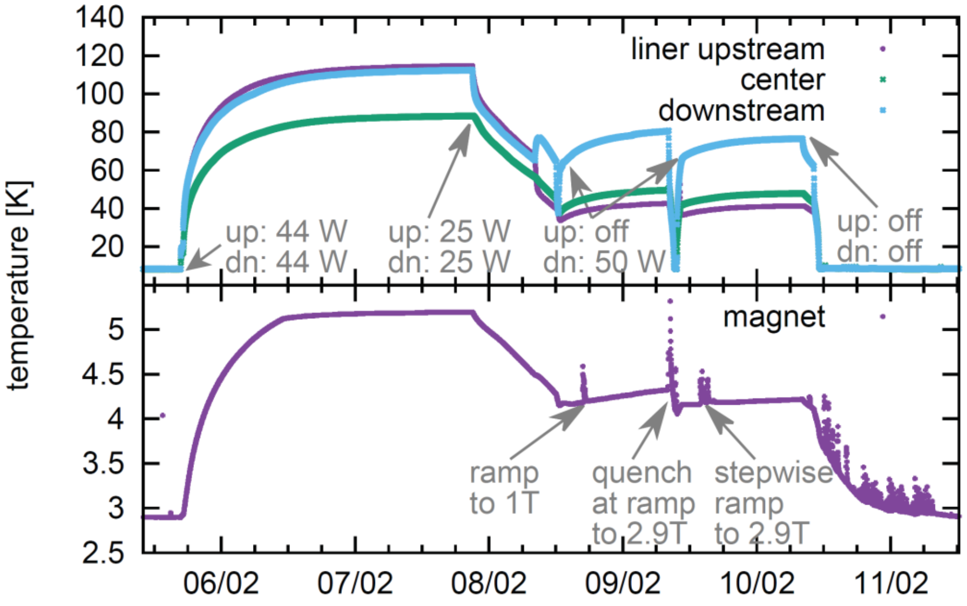
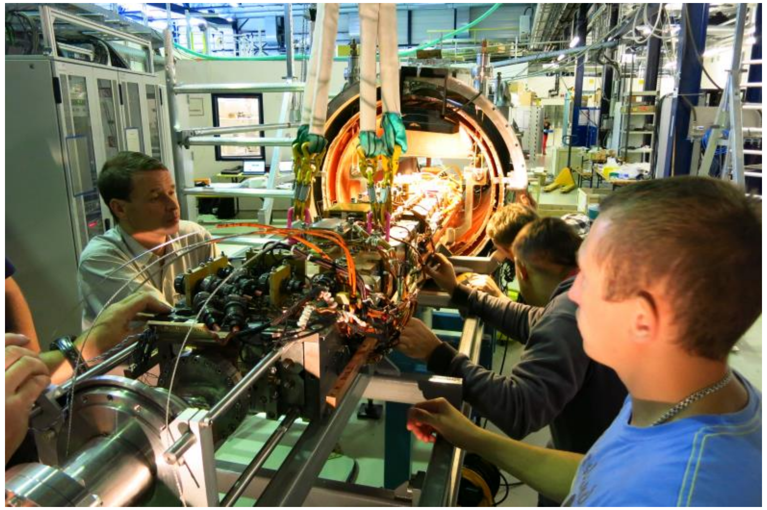
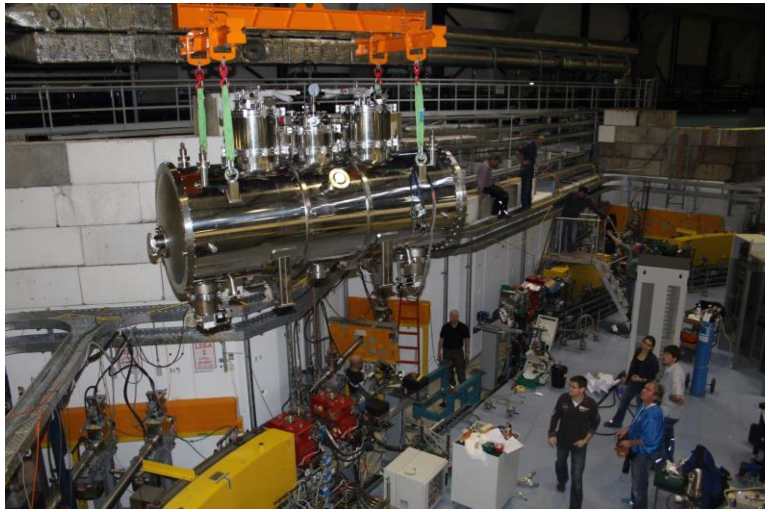


FIG. 3. Conceptual design of cryostat.

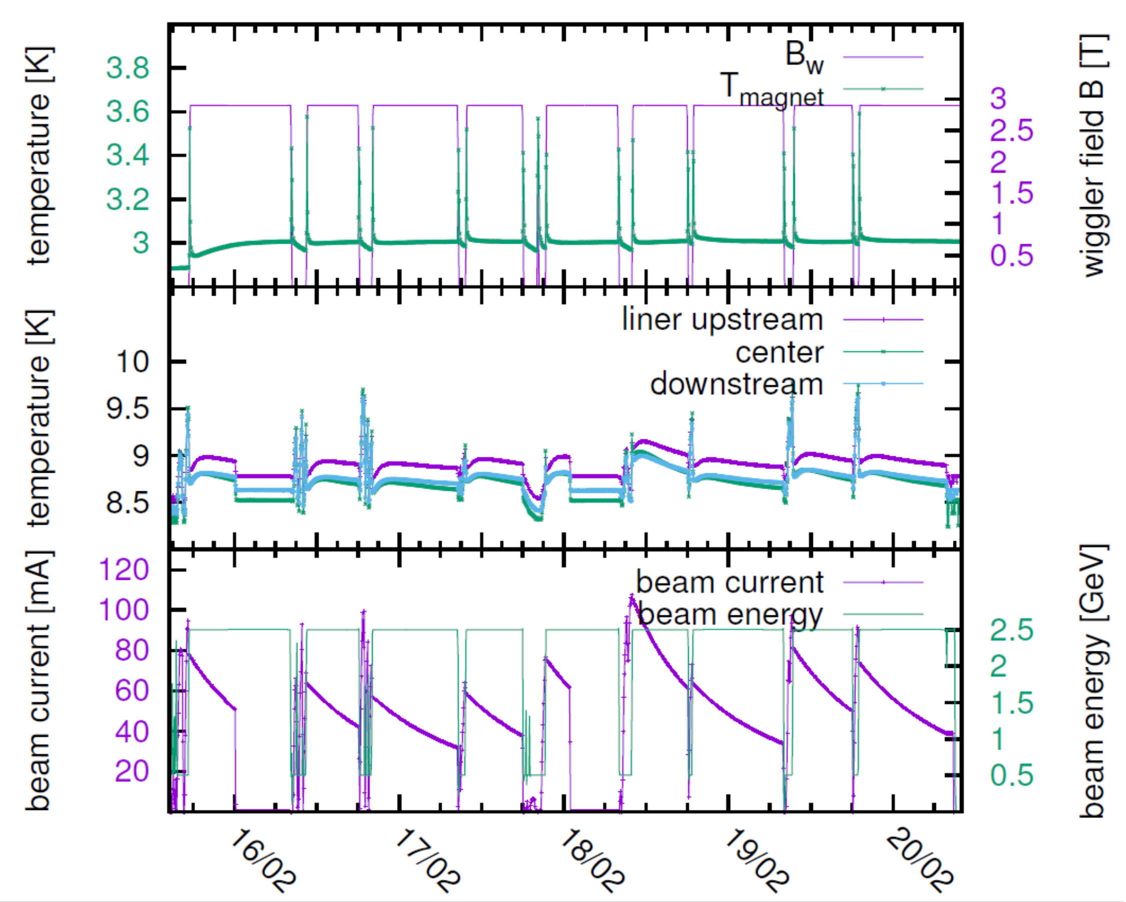






Beam tests in KARA

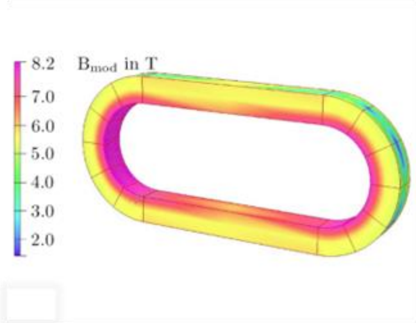
- The wiggler can be operated with beam in ANKA/KARA
- Experiments with beam indicated higher-field components; not measured with stretched wire measurements
- The presence of sextupole components, measured with beam, shows that there is room for further optimization of the magnetic design (e.g., the iron in the extremities could be shimmed to reduce the sextupolar component)
- The presence of quadrupole and octupole (non-allowed harmonics), measured with beam, indicates an asymmetry of the wiggler. For a future CLIC damping ring, limits for these multipoles shall be established and the manufacturing and assembly tolerances shall be revisited

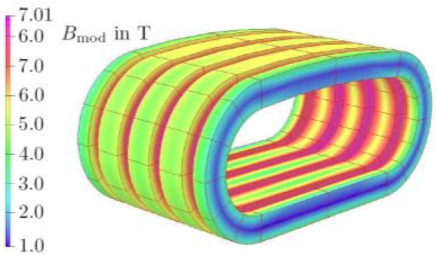


IPAC: WEPMW002 (2016), WEPIK068 (2017), WEPAB011 (2017), THPMF070 (2018), THPAK029 (2018)

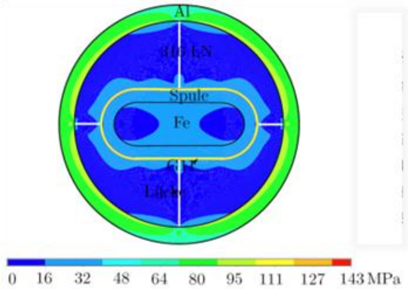
Nb_3Sn wiggler 1/2

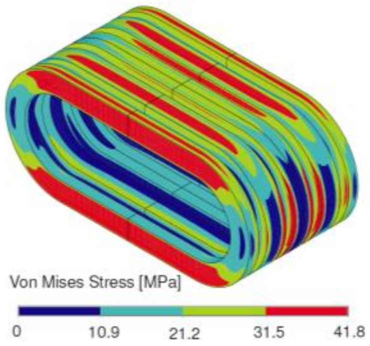
EM Design



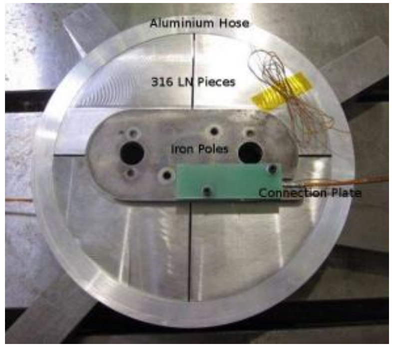


Mechanical Design

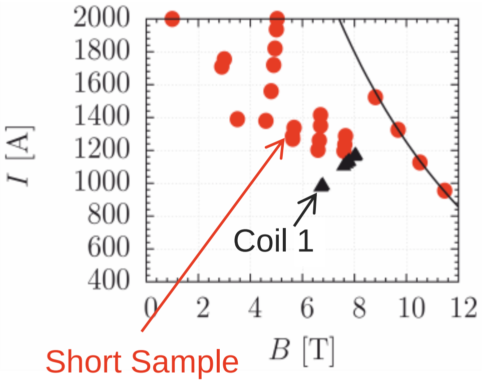


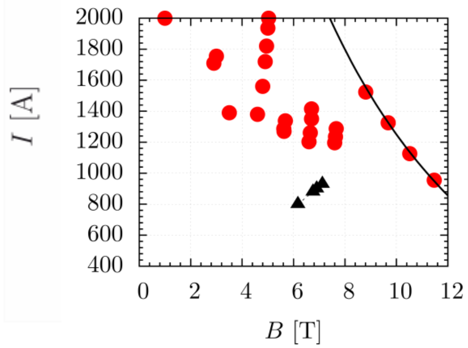


Prototype



Test Results





Achievements

- For the first time, Nb_3Sn damping wigglers have been built and successfully tested
- A fully fledged technical concept for CLIC damping wigglers has been developed (PhysRev STAB, Vol. 15:4, 04/2012) and is tested in ANKA

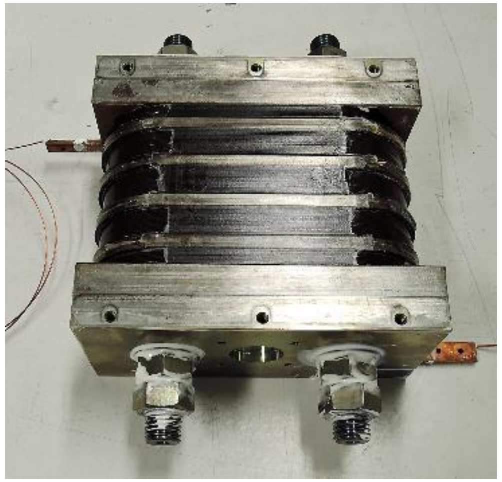
Nb_3Sn wiggler 2/2

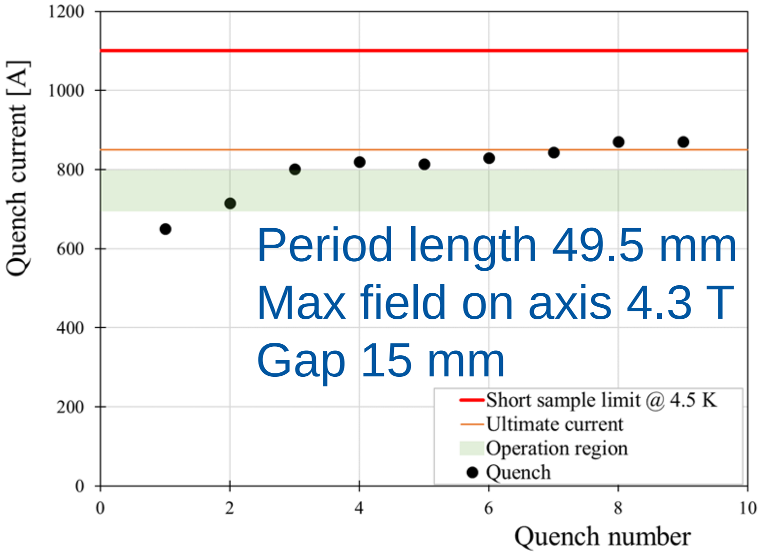
During first test (November 2017):

- No quench up to 600 A (limit of power supply at that time)

During second test (limited to 900 A due to rod strength, October 2018):

- First quench at 650 A, 60% SS
- Reached beyond operation region (690-800 A) after 2 quenches
- Ultimate current (850 A) after 7 quenches
- Two last quenches at 871 A, 79% SS
- Performance within expectations





Period length 49.5 mm
Max field on axis 4.3 T
Gap 15 mm

Summary history

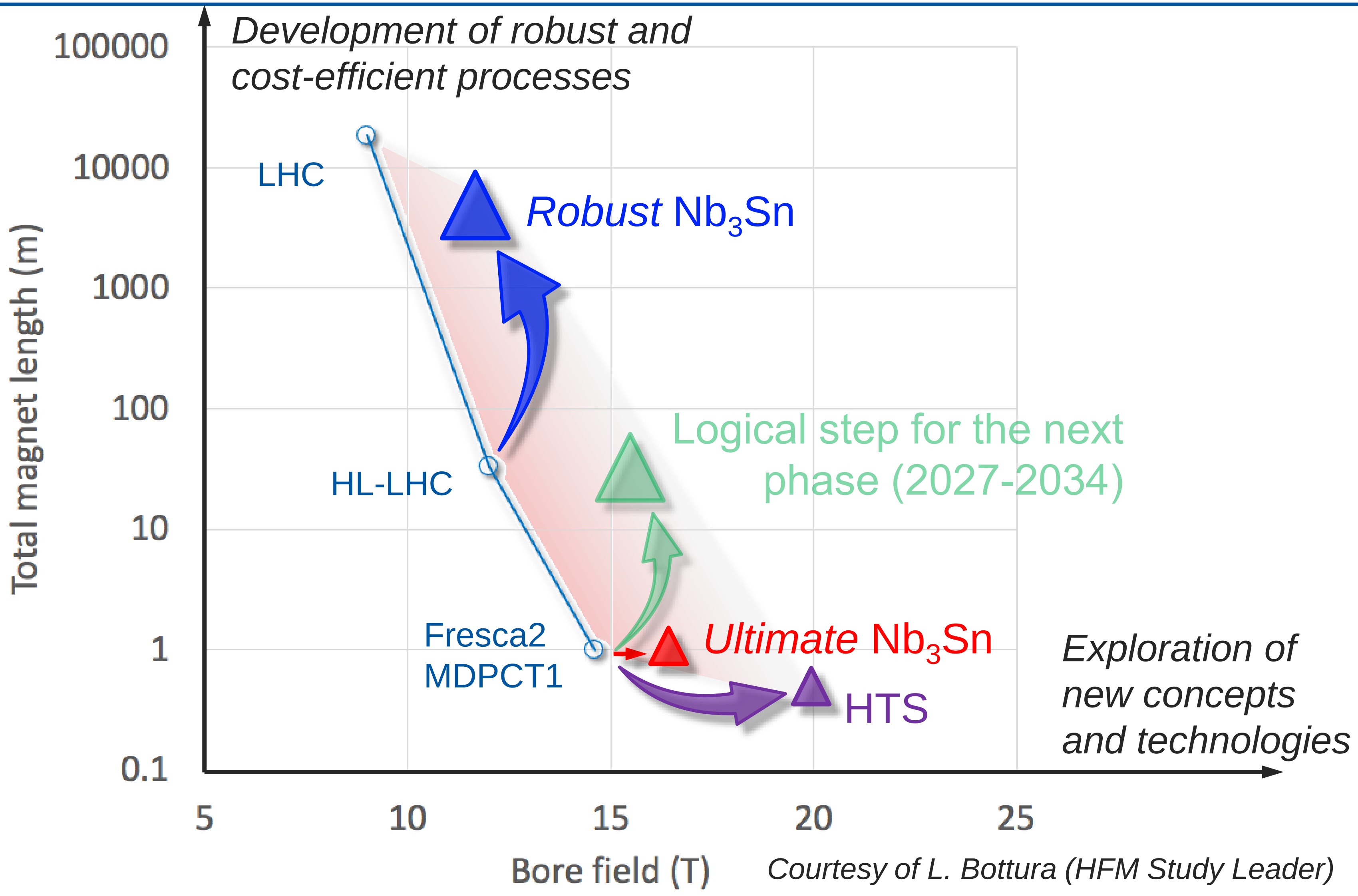
- A Nb-Ti prototype magnet was built and successfully tested in KARA at KIT
- Nb_3Sn wiggler magnets: VR magnets to reduce the number of joints. One HR test coil was built
- The Nb_3Sn short model wigglers are built from single strands, which are difficult to insulate and prone to breakage after heat treatment
- The second prototype Nb_3Sn magnet reached its operating region after the second quench! However, both wiggler models were plagued with technical issues: the first one had performance issues and both models had insulation issues.

In conclusion a working Nb-Ti CLIC damping wiggler prototype was built. On the other hand, the use of Nb_3Sn for wigglers is considered complicated and thanks to the impressive progress of ReBCO tape conductors interest in this technology for wigglers diminished over the years

- In 2018/2019 the activity was refocused on HTS (with a focus on undulators for CompactLight, a free electron laser design study)
- This activity was integrated into the HFM program of CERN

CERN's HFM project

- Undulator and wigglers might be the perfect candidate to test HTS magnets with beam
- This application may be mutually beneficial for HEP application and light source applications (free electron laser, synchrotrons)
- The open questions and challenges on the choice of the HTS material (ReBCO vs BSCCO), the cable type (Roebel/Rutherford, CORC®, (twisted) tape-stacks and the level of transposition), and the insulation system (fully insulated, partially insulated, diode-type insulation) are yet to be tackled.

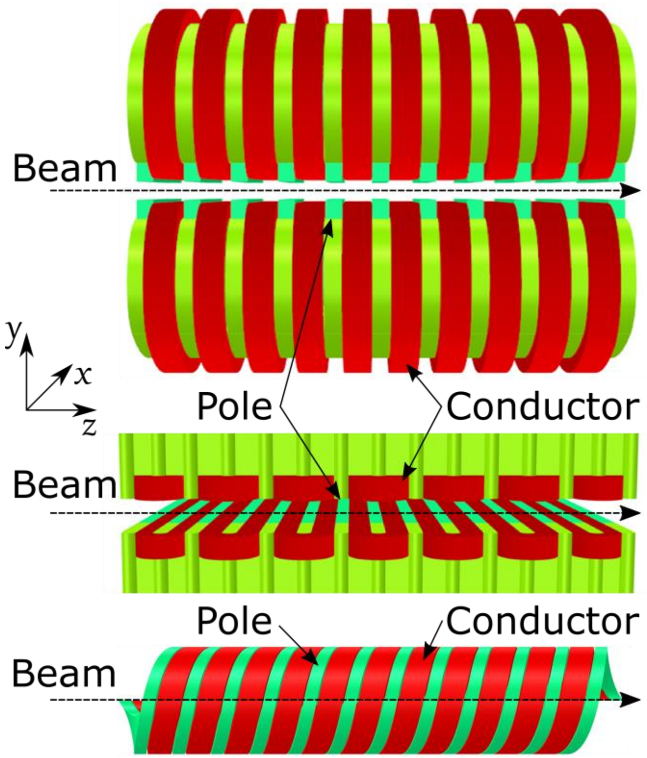


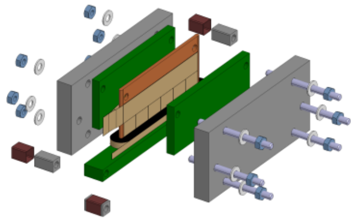
Courtesy of L. Bottura (HFM Study Leader)

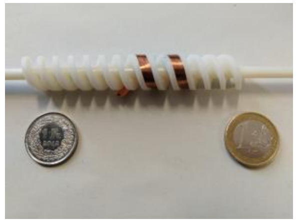
High-field accelerator magnets for leptons: Wiggler/Undulator

- Vertical planar undulator
  - Standard design for undulators, bending radius adjustable
  - Large number of joints for tape probably unavoidable
- Horizontal planar undulator
  - Advantages: High tape efficiency, relatively easy to repair in case of problems
  - Disadvantages: Large number of joints (~250 joints/m), very small bending radius of tape (1.25-6 mm)
- Helical undulator
  - √2 more efficient than a planar undulator, very compact magnet design
  - No feasible winding scheme yet developed

The aim is to build a short 4-5 prototype magnet and prove that the predicted fields can be reached, the magnet can be protected. Moreover, the field quality shall be predicted and measured.



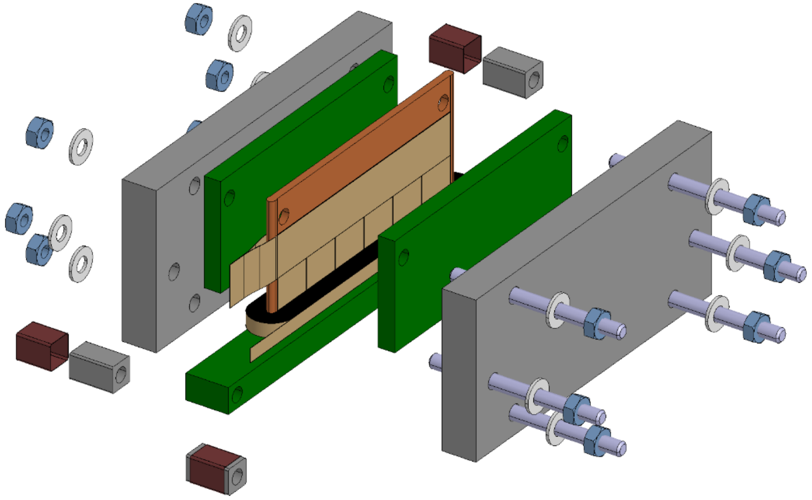


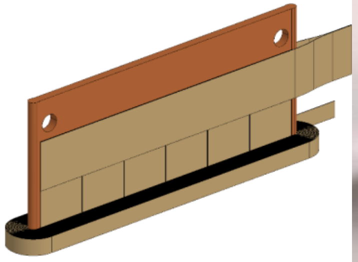


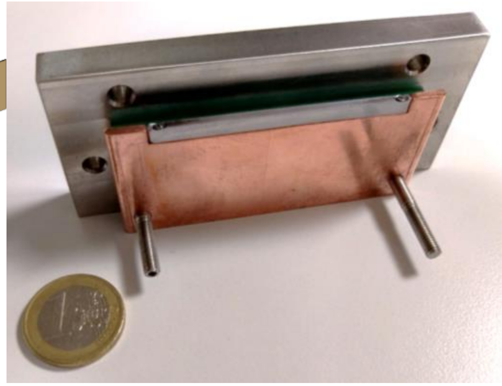
Small prototype program is funded from FCC, CLIC, and TE

Prototype coils

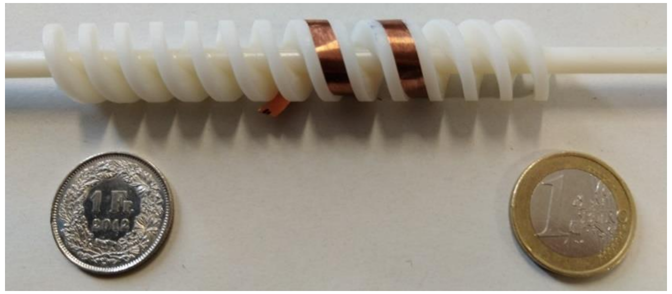
Horizontal planar undulator

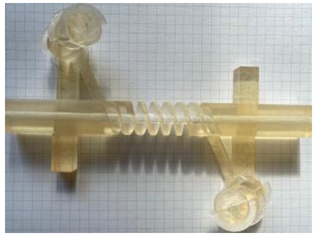


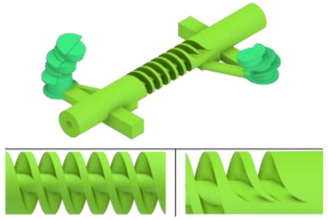




Helical undulator

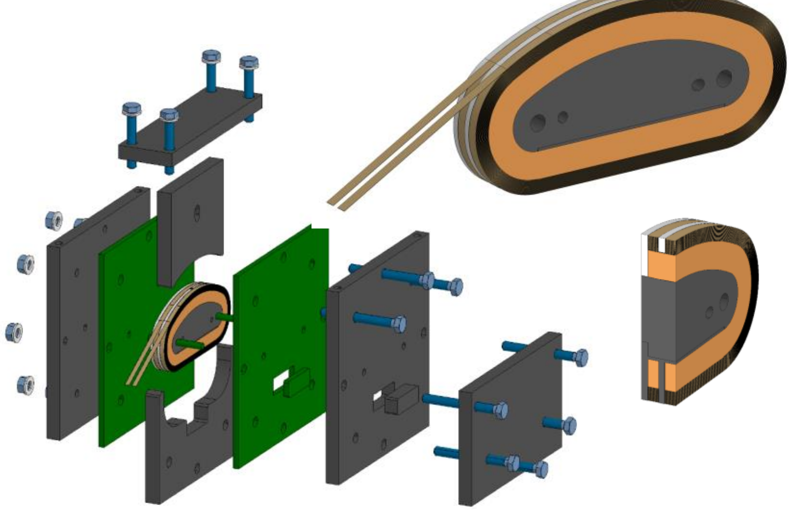


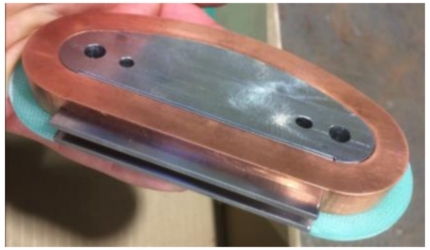


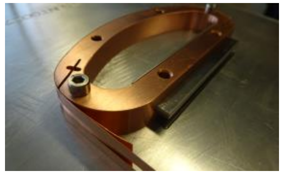


Undulator type	tape length /period, λ = 13 mm, tape width 4 mm
Horizontal	~20 m
Helical	~17 m
Racetrack	~60 m

Horizontal vertical undulator



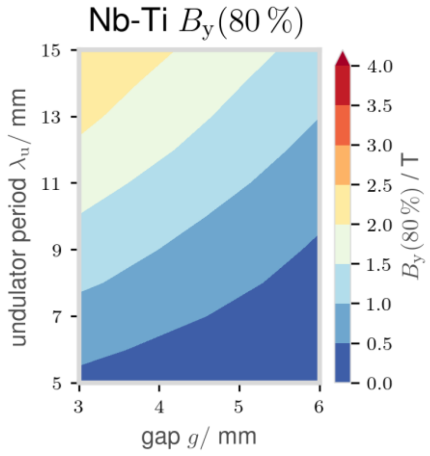


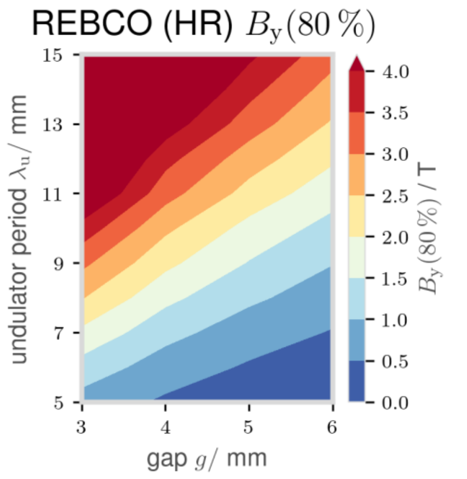


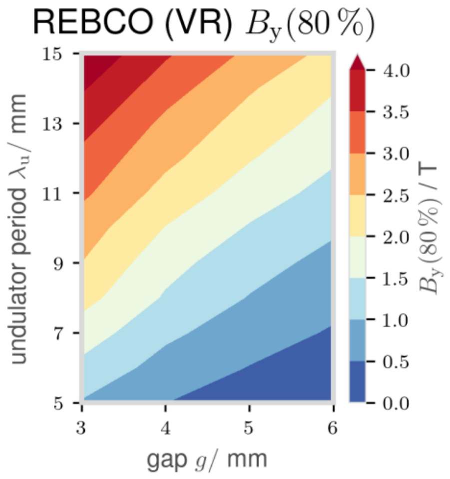
Potential field reach of HTS undulators

Table 13: Optimum magnetic peak field values for 6 mm gap and operation at 80 % of J_c, respectively. *Helical data is given for a 10 mm gap. An average peak field increase of up to 77 % may be possible by using coated REBCO conductor. HR and VR data is based on 2D simulations whereas Nb-Ti and the helical design were investigated in 3D.

period length λ_u / mm	HTS (VR) B / T	HTS(HR) B / T	HTS(hel.) B / T	HTS(hel.*) B / T	Nb-Ti B / T	Ratio HTS(VR+HR) / 2 x Nb-Ti
13	1.8	2.3	2.3	1.0	1.2	1.67
15	2.3	3.0	2.8	1.5	1.5	1.77

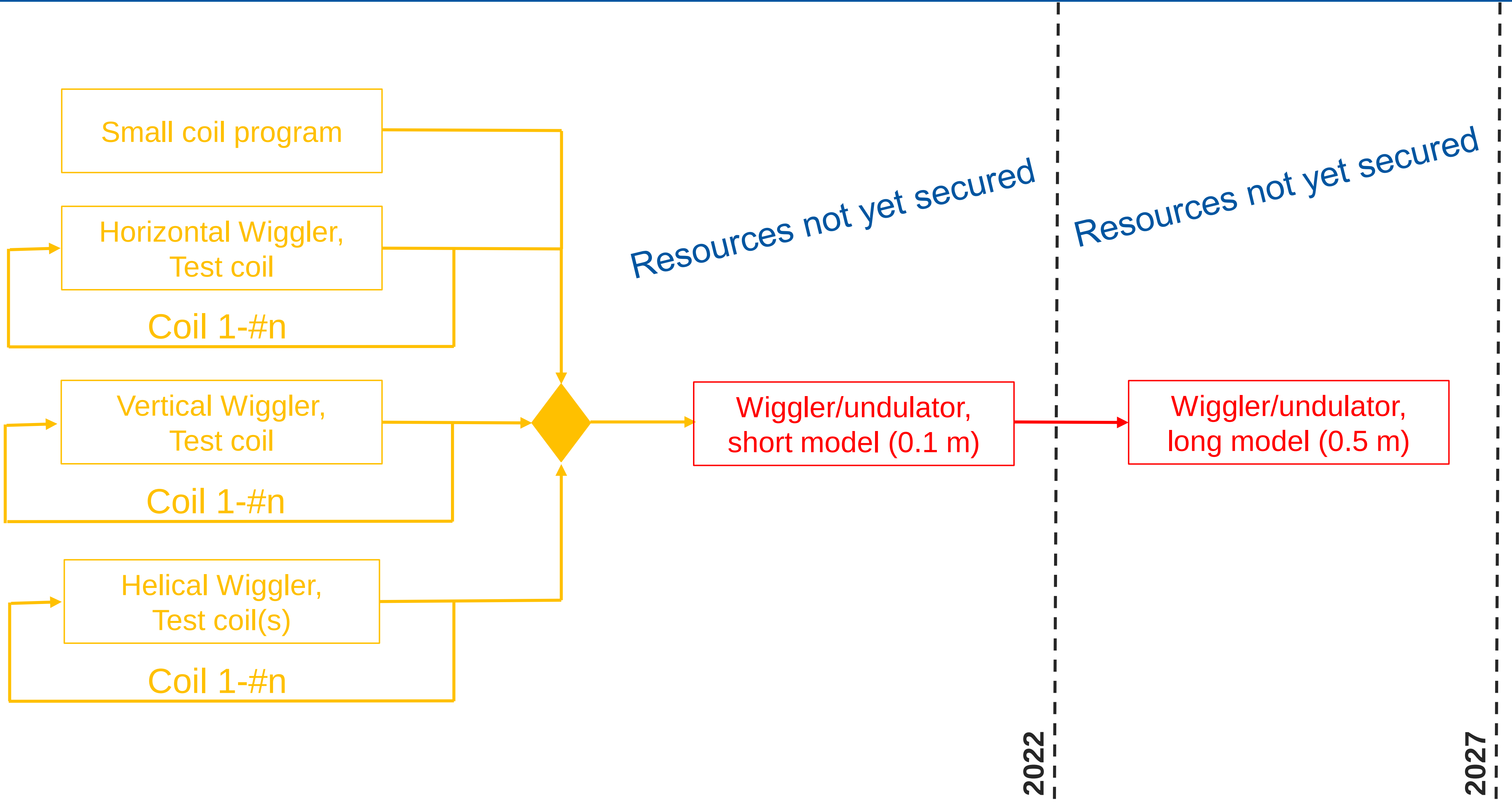






Similar increase in field is expected for non-insulated HTS damping wiggler magnets [1]

The HTS program: Undulators/Wigglers Flowchart



Conclusion

- Since more than 10 years we are developing in a collaboration between CERN and KIT and with other partners SC wiggler and undulator magnets
- We have built several prototypes and with BINP a full scale Nb-Ti wiggler installed and successfully operated in KARA
- Recently, we started to refocus our activities towards HTS undulators and wigglers. For wigglers and undulators, the required amount of conductor (and so the cost) is limited, the benefit from working at a slightly higher operation temperature (above 4.5 K) is great, and the performance gain compared to 'standard' technologies is large. Therefore, we consider it a perfect application for HTS.
- CERN is aiming to build this year vertical HTS test coils, and two short 5-period prototypes (helical & vertical)
- If funding & resources permit, a 0.5-1 m long prototype might be built in collaboration between CERN and KIT
- This program is now part of the HFM project of CERN and mutually benefits other lines of HTS magnet development.