FIRST MAGNETIC TEST OF A SUPERCONDUCTING NB$_3$SN WIGGLER MAGNET FOR CLIC

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Abstract

To achieve high luminosity at the collision point of the Compact Linear Collider (CLIC) the normalized horizontal and vertical emittances of the electron and positron beams must be reduced to 500 nm and 4 nm before the beams enter the 1.5 TeV linear accelerators. An effective way to accomplish ultra-low emittances with only small effects on the electron polarization is using damping rings operating at 2.86 GeV equipped with superconducting wiggler magnets. Only superconducting wiggler magnets meet the demanding magnetic specifications of the CLIC damping rings. Although Nb-Ti damping wiggler magnets fulfill the specifications of CLIC, Nb$_3$Sn wiggler magnets would reach higher magnetic fields leading to even better beam properties for CLIC. Moreover, they have at the same time higher thermal and magnetic margins. Therefore, Nb$_3$Sn wiggler magnets are under investigation at CERN despite the challenging manufacturing process. This paper presents first results of Nb$_3$Sn coils and short model tests and outlines the further plans for developing Nb$_3$Sn wiggler magnets at CERN.

INTRODUCTION

The CLIC damping rings will be utilized to achieve the target emittances in the electron- and positron beams. While the achievable normalized equilibrium emittance improves with shorter period lengths and higher field strengths (Fig. 1 top), the effects of the intra-beam-scattering (IBS) also become more pronounced with short period lengths and strong fields (Fig. 1 bottom). Therefore, a trade-off between the two effects has to be found, taking into account the load-lines of the two conductor-material options Nb-Ti and Nb$_3$Sn.

Fig. 1 shows that the CLIC specifications can be fulfilled with Nb-Ti. However, with Nb$_3$Sn the effect of the IBS can be minimized even further. Moreover, Nb$_3$Sn will be operated at 68% of the critical current compared to 85% in case of Nb-Ti, offering a higher operational and thermal margin to quench. Therefore, the development of Nb$_3$Sn wiggler magnets was started at CERN and a short wiggler model was manufactured and tested at CERN and KIT. The test results from this Nb$_3$Sn short model are presented in this paper. The design and system integration of the superconducting CLIC damping wiggler magnets is published in [1].

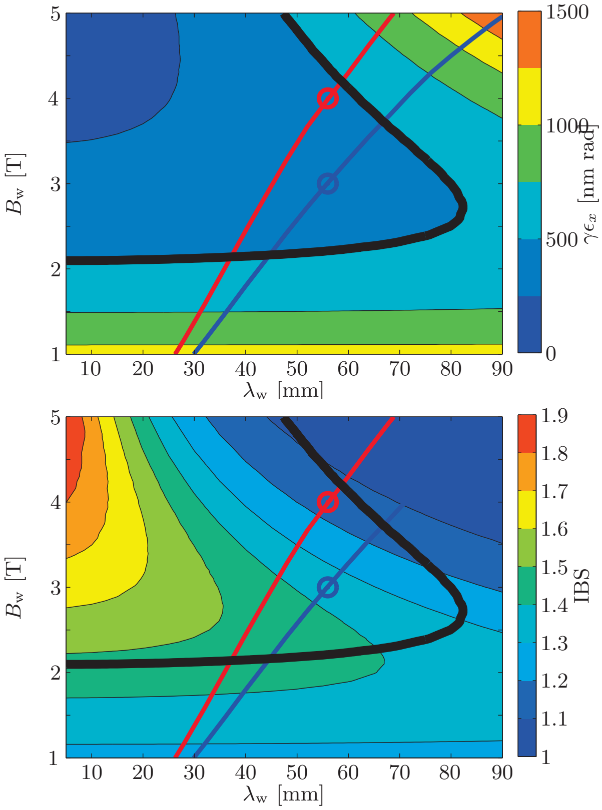

Figure 1: Equilibrium normalized horizontal emittance $\gamma\epsilon_x$ (top) and the effect of IBS versus the period length λ_w and versus the amplitude of the sinusoidal magnetic field B_w. The black line indicates the area where the emittance requirements are met. The red and the blue curves show the maximum achievable magnetic flux density for superconducting wiggler magnets with Nb$_3$Sn and Nb-Ti wire technology, respectively. The dots represent the proposed working points of the wiggler magnets [1].

A NB$_3$SN TEST COIL

Experiments with superconducting insertion devices have shown the importance of a reliable insulation of the wire to avoid eddy currents, inter-strand current loops and resistive heating of the iron body during a quench [2]. The wire used in the short model presented in this paper is a OST RRP wire insulated by S-glass braid. (Bare diameter: 0.81 mm, insulated diameter: 0.94 mm, Sc/Cu ratio: 1.1, No. of filaments: 54 [3]).

As a first step towards a wiggler, a single test coil was manufactured. The iron winding body was insulated by Al$_2$O$_3$ ceramic plasma spraying. Since past experiments

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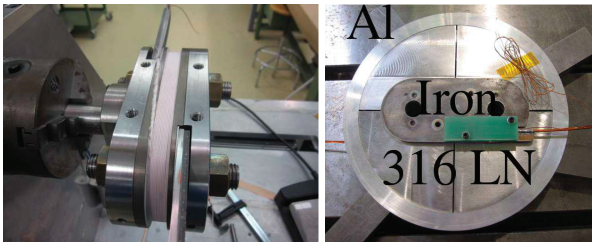

Figure 2: Left: the single test coil. Right: the mechanic clamping structure

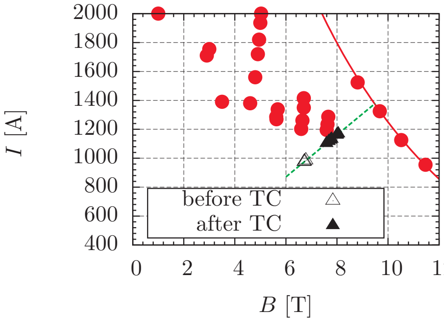

Figure 3: Measured quench current (triangles) of the test coil and short sample current (red dots) [7]. The solid red line shows the critical surface at 4.3 K of Nb_3Sn and the dashed green line shows the load line of the coil.

[4] showed that the different thermal expansion of the wire and the iron body leads to a loosening of the wire, a special heat-treatment mold was used to apply pressure to the straight wire parts during heat treatment. The coil was tempered at 205°C for 72 h, 400°C for 48 h and 695°C for 17 h, impregnated with Araldite MY740, Aradur HY906 and Accelerator DY073 and cured for 8 h at 120°C.

The Lorentz forces in a single coil are not compressive; therefore, a clamping structure in aluminum and stainless steel was built to encase the coil during operation to prevent wire movement. Fig. 2 shows the test coil and the clamping structure.

Fig. 3 shows the quench currents for the first test and after a thermal cycle. The black line shows the critical surface [5]. The red points show measurement results form a short sample measurement and the black triangles are the quench currents of the coil. The current in the coil reached 85% of the critical current. The coil is operated in the low-field-instability area of the superconducting material. Frequent voltage spikes during ramping (Fig. 4) occur in this area, which in turn can trigger a premature quench. Only a 2% increase of the current could be reached at 1.9 K compared to the current reached at 4.2 K due to magneto-thermal instabilities. Most recent strand development may overcome these limitations [6]. Although, the critical current is not reached, the current reached in the Nb_3Sn coil at 4.2 K (1163 A) still surpasses the one reached with a Nb-Ti wire with similar effective cross-section (730 A). Also, the quench current could be repeated with >1100 A over several thermal cycles.

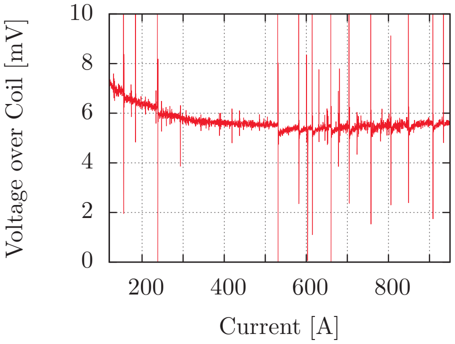

Figure 4: Measured voltage during ramping showing the effect of the instabilities at 4.2 K.

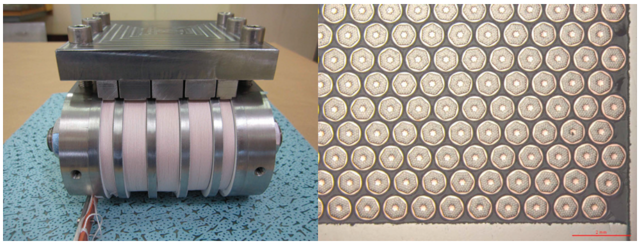

Figure 5: Left: The short model with the top part of the heat-treatment mold. Right: Cross-section of the wire bundle.

THE NB$_3$SN WIGGLER MODEL

After the encouraging result from the Nb_3Sn test coil, a vertical racetrack short model coil with a period length λ_w of 40 mm was manufactured using the same techniques. Fig. 5 (left) shows the short model including the part of the heat-treatment mold that applies pressure to the straight wire sections to ensure a straight wire bundle after heat treatment. Due to the shape of the winding body, the plasma spray insulation could not be applied everywhere in the grooves. Instead additional glass fiber was used to insulate the strands towards the iron, achieving a resistivity in the range of MΩ. However, after heat treatment and impregnation this resistivity was reduced to 60 Ω.

In this wiggler configuration the von-Mises stress acting on the coils due to the Lorentz force act mostly compressive. Therefore, a special clamping structure as it was designed for the single test coil is not necessary in this case.

The model was tested in the magnetic measurement setup CASPER at KIT. As discussed in the previous section, instabilities are expected to occur due to magneto-thermal instabilities. Since the total wire length is increased compared to the single coil, the occurrence of instabilities is more likely. Fig. 6 shows the measured voltage during ramping. The quench detection system was at first unable to distinguish between real quenches and these voltage spikes, so the voltage threshold had to be increased, thereby slightly increasing the quench-load. The first three training runs were made with a very low ramp rate of 25 A/minute and quenches occurred at 800 A, 900 A and 920 A (comparison: Nb-Ti current was 730 A). After

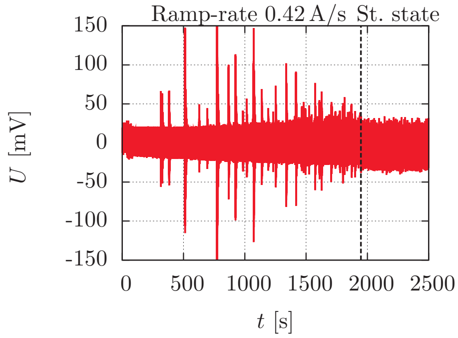

Figure 6: The measured voltage during ramping of the short model. A comparison with Fig. 4 shows that the noise level is increased.

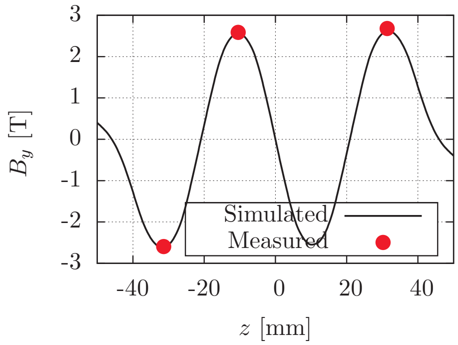

Figure 7: The magnetic field of the short model at 900 A.

this the ramp rate was increased to 100 A/minute, but this lead to an earlier quench at 900 A, probably due to warming of the iron, with a subsequent degradation of the coil. Around 75% of the critical current was reached with the wiggler short model.

The CLIC damping wiggler magnets will be operated at a constant current. Fig. 6 also shows that the voltage peaks occur only during ramping (ramp ends at $t \simeq 2000$ s). Therefore, this test has shown the feasibility of operating Nb_3Sn wiggler magnets at constant current. Should the wiggler operation mode involve ramping during operation, advanced power converter controllers would have to be developed to ensure that the current follows the specified value even in presence of such perturbations (effective changes of the resistance of the circuit). Also, the time stability was investigated by observing the field for 800 s before continuing the ramp. During this time no drift in the field could be observed.

During the training the magnetic field was measured by Hall probes mounted on the poles. The magnet was operated in a magnetic-mirror-configuration. Fig. 7 shows a comparision of the measured field values to the simulated field (at 900 A) and Fig. 8 shows the measured maximum field over the current during the ramp.

While the training of the short model could not be concluded and therefore the current reached was lower than in the single test coil, the current and field reached still surpasses the performance of a Nb-Ti wiggler of similar dimensions.

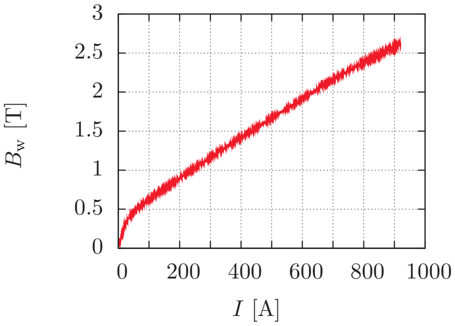

Figure 8: The amplitude of the sinusoidal magnetic field in the center of the gap B_w vs. current during ramping.

OUTLOOK & CONCLUSION

The development of Nb_3Sn wiggler magnets will be continued in order to fabricate a second model with a larger period from 40 to about 50 mm, and include in the design additional layers of insulation between the conductor blocks and the poles. In particular, the plan is to increase the thickness of the plasma spray insulation and add a layer of fiberglass over the poles and the winding posts, thus significantly reducing the risk of electrical shorts as observed during the test and in a series of electrical measurements performed after the warm-up. Redesign and optimization of the grooves where the wires transition from one coil to the other and of the current lead area is also in progress. At the time of the submission of this paper, the drawings of the components used in the first Nb_3Sn wiggler model have been reviewed and are in the process of being modified.

The presented tests showed the feasibility of Nb_3Sn wiggler magnets with a significantly improved performance over Nb-Ti wiggler magnets. The baseline design for the CLIC damping rings remains Nb-Ti wiggler magnets. A Nb-Ti damping wiggler magnet prototype will be tested in ANKA, Karlsruhe and is under construction with the technical concept presented in [1]. The development of a Nb_3Sn wiggler magnet will be continued.

REFERENCES

[1] D. Schoerling, et al., *Phys. Rev. ST Accel. Beams*, 15:042401, Apr 2012.

[2] S. Ehlers., el al., *Proceeding of IPAC 2010, Kyoto, Japan*, WEPD016, p. 3120, 2010.

[3] Oxford instruments, www.oxford-instruments.com.

[4] D. Schoerling. *Superconducting wiggler magnets for beam-emittance damping rings*. PhD thesis, CERN, 2012.

[5] L.T. Summers, et al., *IEEE Transactions on Magnetics*, 27(2):2041 –2044, 1991.

[6] B. Bordini, et al., *IEEE Trans. Appl. Supercond.*, 20:274–278. 6 p, Jul 2010.

[7] B. Bordini, et al., *Proceedings of EPAC08, Genoa, Italy*, WEPD003, p. 2406, 2008.