FIELD OPTIMIZATION FOR SHORT PERIOD UNDULATORS

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Abstract

Undulators dedicated to low energy electron beams, like Laser Wakefield Accelerators, require very short period lengths to achieve X-ray emission. However, at these short period lengths ($\lambda_U \simeq 5$ mm) it becomes difficult to reach magnetic field amplitudes that lead to a K parameter of $\geq$1, which is generally desired. Room temperature permanent magnets and even superconductive undulators using Nb-Ti as conductor material have proven insufficient to achieve the desired field amplitudes. The superconductor Nb_3Sn has the theoretical potential to achieve the desired fields. However, up to now it is limited by several technological challenges to much lower field values than theoretically predicted. An alternative idea for higher fields is to manufacture the poles of the undulator body from Holmium instead of iron or to use Nb-Ti wires with a higher superconductor/copper ratio. The advantages and challenges of the different options are compared in this contribution.

INTRODUCTION

The shorter the period length of an electromagnetic insertion device is, the lower is the flux density at the conductor. To optimize the achievable fields for short period devices, one has therefore to look for a conductor material that performs well in low (~1 T) magnetic fields. The standard conductor material for superconductive insertion devices is Nb-Ti. This material can be wound like copper wire and its handling is therefore relatively easy. The critical current density depends on the flux density at the conductor and is, for short wire samples, given by a fit of measured data shown in Fig. 1 [1].

For high magnetic fields Nb_3Sn is superior to Nb-Ti. It has been in use for high field magnets for some time and was also shown to perform well for ~50 mm period lengths wigglers [2]. Figure 2 shows the values for short samples. For high magnetic fields, the measured short sample points lie on a common fit, but for low magnetic fields the measured points deviate from the fit and only considerably lower critical current densities than predicted can be reached. Lowering the temperature to 1,9 K does not increase the achievable current density significantly, because at 1,9 K the flux jumps are so large, that they tend to offset the theoretical gain in critical current density [3].

An additional challenge of Nb_3Sn is, that it has to be wound in the form of a non-reacted progenitor wire and then has to be heat treated at ~700°C and is very brittle afterwards. Moreover, the correct wire fixation technique is important. Figure 3 shows a Nb_3Sn coil after

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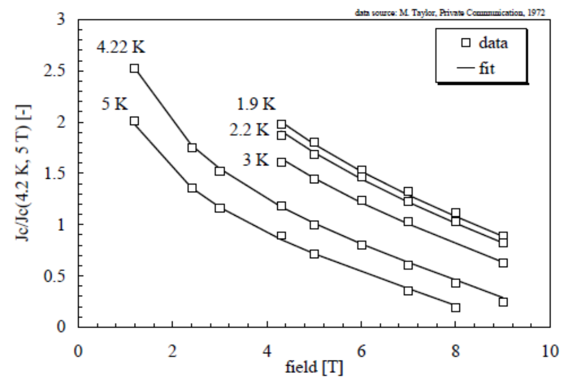

Figure 1: Critical current density vs. flux density at the conductor for Nb-Ti at different temperatures.[1]

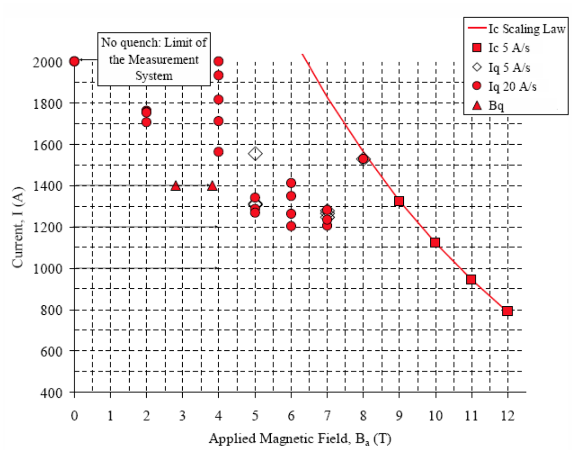

Figure 2: Critical current density vs. flux density at the conductor for Nb_3Sn. The red curve plots the values predicted from a fit. The dots are short sample measurement values for different ramp rates. It is visible that the low-field values are considerably lower than predicted from the fit. [4]

heat treatment. The wire, which was wound with a tension of 3 kg, has become tension-less and a gap is visible between wire bundle and iron body. This is explained by a non-reversible elongation of the Nb_3Sn strands due to a mismatch in the thermal expansion coefficients of the iron body and the wire. This can cause a mobility of the wire under stress, which in turn leads to friction heating and a possible quench. However, these problems can be solved by a ceramic impregnation developed at CERN, that withstands the tempering procedure and holds the wire in place [5]).

Figure 3: The gap between a Nb_3Sn wire bundle and the winding body after heat treatment.

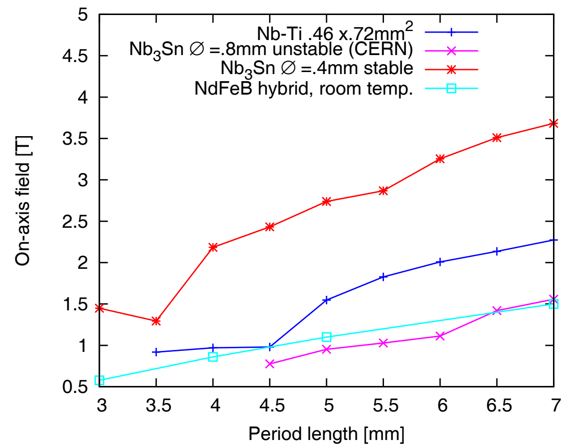

Figure 4: Actually achievable magnetic flux densities for different materials. For comparison the theoretical values for a thinner Nb_3Sn wire with the same isolation and crossection profile, but without low-field instabilities are also shown (red line). The steps in the lines occur, where the number of wires per groove changes.

Table 1: Achievable on-axis magnetic flux density for short period lengths with Nb-Ti and Nb_3Sn in an ideal scenario (short sample currents, filling factor=1, gap=1.2 mm)

Period length [mm]	B_{max}(Nb-Ti)	B_{max}(Nb_3Sn)
3	0.77 T	0.78 T
4	1.18 T	1.26 T
5	1.54 T	1.74 T

THEORETICAL FIELD VALUES

Without the low field instabilities, i.e. with the critical current densities taken directly from the fit in Fig. 2, Nb_3Sn would obviously be the best choice for short period undulators. But even assuming that it is consistently possible to reach the measured short sample values and to attain a filling factor (wire crossection/groove crossection) of close to one, Nb_3Sn would be the best conductor material down to $\sim$3 mm. Table 1 shows some theoretically achievable field values vs. period length for a 1.2 mm gap undulator.

INSULATION AND FILLING FACTOR

For Nb-Ti a filling factor close to one is a valid assumption. Nb-Ti is available in rectangular wires with a varnish type insulation, which is very thin compared to the dimensions of the wire. However, for Nb_3Sn the assumption of a filling factor of one is not valid. Since Nb_3Sn needs to be reacted at $\sim$700°C, most varnish type insulations would not survive the tempering process. There have been experiments with ceramic powder insulation [6]. However, that is not yet scratch resistant enough to reliably survive the winding process. So the best currently commercially available solution is the insulation of the Nb_3Sn wires by glass braids. But these are typically $\sim$100 μm thick, which means that for thin wires a relatively large proportion of the filling factor will be lost to the insulation. Moreover thin Nb_3Sn wires are not yet available with a rectangular cross-section, but only with a circular cross-section.

Taking into account these limitations and the low-field instabilities, the actually achievable field values change drastically for short period lengths. As can be seen in Fig. 4, Nb-Ti significantly outperforms Nb_3Sn for short period undulators and below 6.5 mm Nb_3Sn is even inferior to permanent magnets. However, research is ongoing to improve Nb_3Sn wires towards the ideal properties. One important goal is, to combat the low-field instabilities. These originate most likely from flux jumps and it is expected, that these decrease with filiament thickness due to the improved pinnig of fluxoids. This means that wires with thinner filaments are expected to display less severe low-field instabilities. As an example Fig. 4 also shows the values for a circular Nb_3Sn wire with the same number of filiaments but half the diameter of both filaments and wire. Under the assumption that no low-field instabilities occur, the increased current density would be more than enough to offset the loss in filling factor due to the decreased conductor/insulation ratio.

HOLMIUM AND SHAPED POLES

Another idea to increase the field on axis was to use a material with a higher saturation point like Holmium as material for the poles. But simulations with the finite element software Opera 2D show, that there is no significant field increase. See Fig. 5. This is due to the fact that, while Holmium does increase the field on-axis for a fixed current, it also increases the field at the conductors. This leads to a reduced critical current, so that the resulting net field on axis stays approximately the same.

An analysis of the field distribution across the conductor (Fig. 6) shows that the maximal field is close to the edge of

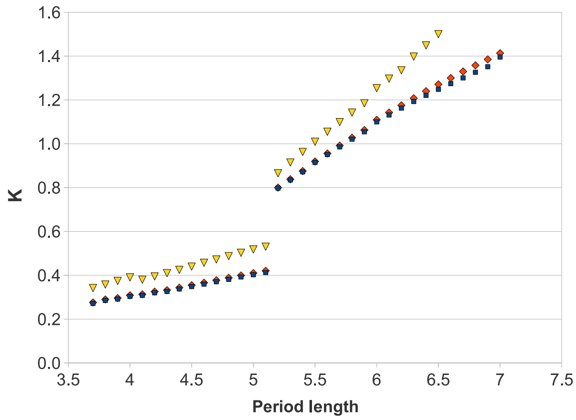

Figure 5: The achievable K-factor for a fixed Nb-Ti conductor (0.51×0.77 mm^2), 1,3 mm gap and different poles. The blue dots are with regular iron poles, the red dots are with holmium poles and the yellow triangles are with rounded iron poles. The step in all lines is at the point where there is enough space in the model to use two wires per groove.

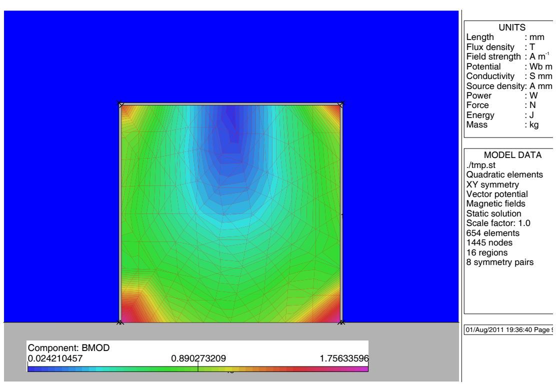

Figure 6: A plot of the magnetic flux density across the wire bundle cross-section in a short period undulator. Maximal field at conductor 1.76 T.

the poles. With rounded poles instead of a rectangular pole shape (Fig. 7), the achievable field is increased by 10-20%, regardless of pole material.

CONCLUSION

With currently available technology, Nb-Ti remains the best conductor material for superconductive undulators with a period length of ∼5 mm or below. But achieving a K-value of one remains difficult. One possibility to increase the achievable fields with Nb-Ti is an optimization of the pole shape. But the increase is only 10-20%. Cooling the undulator down to 1,9 K also increases the critical current density in Nb-Ti (see Fig. 1) and the achievable field values. However, using superfluid helium increases the effort that is necessary for the cryogenic system and thereby increases the cost significantly.

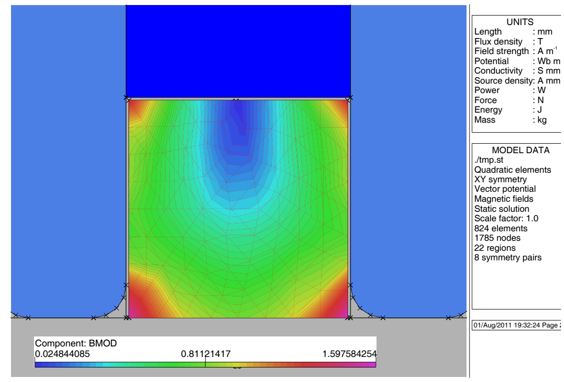

Figure 7: A plot of the magnetic flux density across the wire bundle cross-section in a short period undulator with rounded poles. The general field distribution stays the same, but the maximal field at the conductor is reduced to 1.60 T.

But research into improvements of the available Nb_3Sn wires is ongoing. Both in terms of thin, heat- and scratch-resistant insulations in the U.S. [6] and in terms of improved wires. With these two developments, a K$\geq$1 undulator with a period length $\lambda_U \leq$5 mm will be possible in the near future.

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