NEW MATERIALS AND DESIGNS FOR SUPERCONDUCTIVE INSERTION DEVICES

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Abstract

NbTi wires are relatively easy to handle and are therefore up to now the preferred material for superconductive insertion devices. Yet other materials, like Nb_3Sn, MgB_2 or high temperature superconductors, are less sensitive to beam heat load and/or are able to produce higher magnetic fields. In this paper the different superconducting materials and their advantages and challenges are discussed. Additionally this paper describes new designs for special insertion devices like damping wigglers and undulators for laser wakefield accelerators.

WHY NEW MATERIALS?

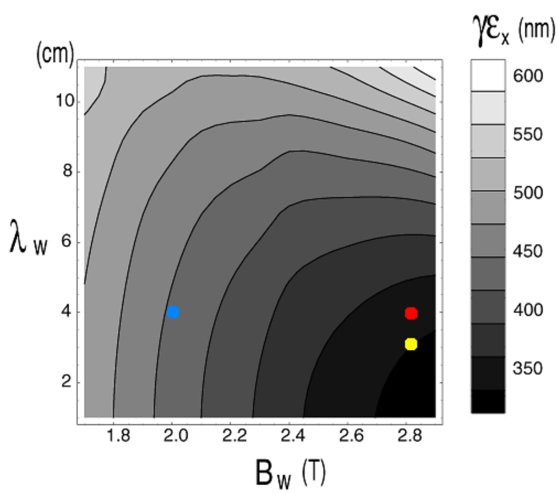

Figure 1: Wiggler dominated equilibrium normalised emittance for the CLIC damping rings, depending on period length λ_W and maximal field strength B_W. The blue dot marks the performance of a NbTi based wiggler, red is the required performance for CLIC, yellow is the calculated maximum performance for Nb_3Sn [1, 2].

State of the art superconductive insertion devices use NbTi as conductor material. Its handling is comparatively easy, but it has the drawback of being sensitive to heat load. Its critical temperature of ca. 9 K is not far from the operating temperature of superconductive devices (about 4.2 K, depending on cooling method). For devices with a high heat load like damping wigglers or cold-bore undulators [3, 4] the use of a material with a higher critical temperature is desirable.

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Damping wigglers reduce the emittance of stored beams through the emission of synchrotron radiation. The minimal emittance achievable by this method decreases with smaller period length and increasing field strength as shown in Fig. 1. To reach the target emittance in the CLIC damping rings, especially under the influence of strong intrabeam scattering, the damping wigglers require a higher field strength than achievable with NbTi at the given period length.

A similar requirements is valid for undulators for low-energy beams, like those of Laser Wakefield Accelerators (LWFA). Here very short period lengths and high fields are necessary to achieve the emission of X-ray photons from the low-energy electrons ($\mathcal{O}$(1 GeV)). Table 1 lists some of the possible conductor materials.

Table 1: Comparison of some currently available conductor materials. I_C=critical current density, T_C=critical temperature ($\widehat{=}$ sensitivity to heat load). The abatement of the disadvantages is a focus of current research.

Material	Advantages	Disadvantages
NbTi	Easy to handle	Heat sensitive (T_C ca. 9 K)
Nb_3Sn [5, 6]	Very high I_C, higher T_C (18 K)	Difficult production and handling, low-field instabilities
YBCO tape	I_C comparable to NbTi at 4 K, very high T_C (> 90 K)	sensitive to external fields
MgB_2 [7]	Easy handling, high T_C (> 30 K)	Lower I_C than NbTi

DAMPING WIGGLER DESIGN FOR CLIC

The Compact Linear Collider (CLIC) is designed to be an electron-positron collider at CERN with beam energies in the TeV range. For the R&D necessary for this project the CTF3 collaboration has been founded. Since the CLIC damping rings design foresees the use of damping wigglers with performance parameters beyond the capabilities of NbTi, one of the topics within the CTF3 collaboration is the development of wiggler prototypes based on new conductor materials.

Apart from material science, also various design options are tested. Figure 2 shows such a new wiggler layout. The idea is, not to use two coils facing each other, but to use only one coil with the beam pipe leading through the coil

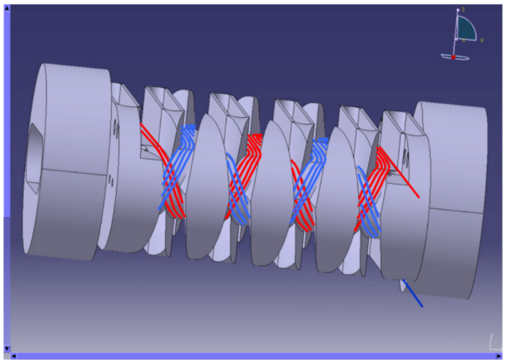

Figure 2: Double-helical wiggler design for CLIC [2].

along the main axis. Two helical windings cross each other in a way, that the current direction in opposing groves is identical, like it would be in the standard two-coil design. The poles are inserted between the groves.

This design has several advantages: first, it uses only half the conductor material. Secondly the winding body can be mounted as part of the beam pipe, which simplifies assembly, cooling and vacuum system. Third, the position of the poles can be easily corrected even after mounting, which facilitates the correction of field errors. Fourth, since the poles only make up a small fraction of the body mass, it might be financially possible to use a material with a higher magnetic saturation point than iron, like holmium. This would allow to reach even higher fields. However, there is also the disadvantage that the gap width is constrained by the minimal bending radius of the superconductive wire. This design is currently in the prototype phase.

NEW UNDULATOR DESIGNS FOR LASER WAKEFIELD ACCELERATORS

As stated above, the possibility to attain higher fields at short period lengths is also necessary for LWFA based X-ray sources. The combination of LWFA and short period undulators is the topic of a R&D collaboration between the LMU Munich and the University Karlsruhe. The eventual goal of this research is the design of a table-top synchrotron light source. An additional challenge is, that the energy spread of LWFA based particle beams ($\sim$10% $\Delta E/E$) is yet too large for monochromatic emission. To overcome this problem either the LWFA has to be improved or the energy spread has to be compensated. A possibility is an internal compensation of the effect of the energy spread. The beam is spectrally dispersed by two consecutive magnetic deflections. Electrons with different energy end up in different lateral positions x. If the magnetic field also depends on x, the emitted wavelength in forward direction is given by the undulator formula:

$$\lambda_{em}(x) = \frac{\lambda_u(x)}{2(\gamma(x))^2}\left(1+\frac{(K(x))^2}{2}\right) \qquad (1)$$

where $\lambda_{em}(x)$ is the wavelength of the emitted radiation, $\gamma(x)$ is the beam energy, $\lambda_u(x)$ is the period length of the undulator and $K(x) = 0.943 \cdot \lambda_u(x)[\mathrm{cm}] \cdot B(x)[\mathrm{T}]$ is the undulator parameter.

By matching $\gamma(x)$ and either $\lambda_u(x)$ or $B(x)$ it can be achieved that the emitted wavelength is constant for all lateral positions x. The lateral variation of the field strength $B(x)$ by a non-planar undulator turns out to be technically easier than a variation of the period length.

Various designs were calculated and as the best compromise between field matching and technical feasibility an undulator with cylindrical cross-section as shown in Fig. 3 was chosen. The lateral energy distribution in the beam after dispersion is shown in Fig. 4, compared to the ideal energy distribution for the monochromatic emission of photons in the cylindrical undulator. The match is very good in the region of interest. In this simulation the beam has a width of less than 1 mm and the emitted radiation has a remaining energy spread of 1%. This means, that the energy spread has been reduced by more than one order of magnitude.

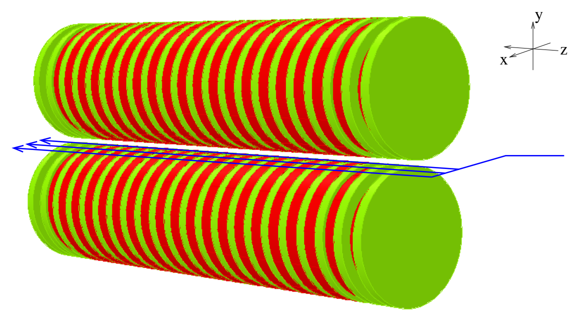

Figure 3: Cylindrical undulator for laterally varying magnetic field. Green: iron body, red: conductor coils and blue: dispersed electron beam.

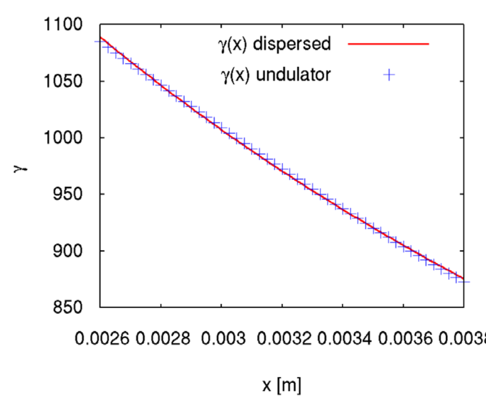

Figure 4: The lateral energy distribution in an electron beam after dispersion (red) compared to the energy distribution required to produce monochromatic radiation using a cylindrical undulator (blue). Plotted is the relativistic γ factor over lateral position x in m.

However, in the laterally varying—i. e. inhomogeneous—field the electrons experience a different deflecting force at the opposite extrema of their undulator trajectory. This results in a net deflection of the beam. This leads to a deviation between observation angle and the direction of forward emission and to an effective change of the local period length. It also reduces the possibility of coherent constructive interference of the emitted photons. This net deflection has to be compensated.

A second effect of the inhomogeneous field is a chromatic error. High energetic electrons experience a higher net field and therefore also a higher net deflection. This leads to a defocusing of the beam. Figure 5 shows the trajectories of a 0.45 GeV (blue) and a 0.55 GeV electron (red). The net deflection is stronger for the red line. But calculations show, that both errors can be compensated by a combination of a dipole and a sextupole field. Figure 5 shows the corrected trajectories. The field strengths required are ∼0.1 mT for the dipole and ∼16 T/m^2 for the sextupole, which is easily achievable and is low enough as not to disturb the monochromatising effect of the laterally varying undulator field, which has a maximal field strength of 4 T. The unidirectional emission of photons is therefore possible from such a beam. The remaining chromatic error is within the numerical precision of the simulation.

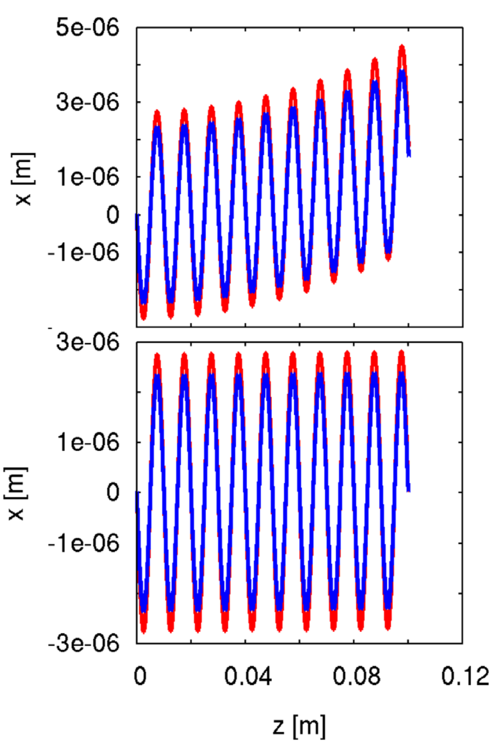

Figure 5: The trajectories of a 0.45 GeV (blue) and a 0.55 GeV electron (red) through the laterally varying 'cylindrical undulator' field. Top: uncompensated, bottom: compensated by a dipole and a sextupole field.

While the results for the cylindrical undulator shape are encouraging, it has the drawback, that the dispersion necessary for the compensation of the effect of the energy spread leads to an increased beam size. For current technologies the lateral beam size for the cylindrical undulator is just below 1 mm. With new conductor materials that allow a higher current density (higher fields) or a smaller bending radius (higher gradient) than NbTi, as well as for an improved initial energy spread, the beam size can be further reduced. It is also possible to reduce energy spread and beam size by a factor two by using another pole shape. For poles that are shaped as a narrow parabola the match between the field and the energy distribution in the beam is even better than in the cylindrical case. But it is not possible to wind current superconductors around such a tight bending radius. However, a non-magnetic winding body combined with slots for the poles, similar to the design in Fig. 2, might allow to use such shaped poles.

SUMMARY

The R&D for the CLIC damping wigglers is making progress and a promising new winding design has been developed and will be tested in the near future. The preferred conductor material is Nb_3Sn due to its high critical current density, but other materials are also investigated.

For Laser Wakefield Accelerator sources: in principle undulators that generate quasi-monochromatic radiation from non-monochromatic electron beams are possible. A mockup device for field measurements and experiments will be built soon. Whether the benefits of this concept outweigh the loss of brilliance due to the increased beam size and if it allows spontaneous monochromatic emission remains to be shown.

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