STATUS OF THE NEW LINAC4 MAGNETS AT CERN

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Abstract

Linac4 is a new H- linear accelerator at CERN replacing Linac2 as injector to the PS Booster. Almost 100 electro-magnets of different types are needed for the Linac4 project. Following a detailed analysis of the requirements and constraints, several magnet designs have been studied and are well advanced. This paper presents the design considerations, main parameters and characteristics of the new Linac4 magnets and summarizes the present status.

LINAC4

As the first step of a long-term programme aiming at an increase in the LHC luminosity, CERN is building a new 160 MeV H^- linear accelerator, Linac4, to replace the ageing Linac2 as injector to the PS Booster. Linac4 is an 86-m long normal-conducting linac made of an H^- source, a Radio Frequency Quadrupole, a chopping line and a sequence of three accelerating structures: a Drift-Tube Linac (DTL), a Cell-Coupled DTL (CCDTL) and a Pi-Mode Structure (PIMS). A new transfer line will connect Linac4 to the PS Booster. The civil engineering has been recently completed, and construction of the main accelerator components has started with the support of a network of international collaborations [1].

Both, the accelerating section and the new transfer-line require a number of different electro-magnets:

The 3-MeV front-end will be equipped with four low-energy correctors and two new solenoids in addition to several quadrupole families, which have been recuperated from the present Linac2.

Table 1: New Magnets for The Linac4 Project

Position	Magnet type	Number
3-MeV Front-End	Solenoid	2
	Low-Energy Corrector	4
DTL	Low-Energy Corrector	1
	Linac Corrector type 1	1
	Linac Corrector type 2	1
	Inter-tank Quadrupoles	2
CCDTL	Linac Corrector type 2	4
	Inter-tank Quadrupoles	7
PIMS	Linac Corrector type 2	6
	Inter-tank Quadrupoles	12
Transfer-Line	Horizontal Bending	3
	Vertical Bending	2
	TL Quadrupoles	17
	Linac Corrector type 2	11

The linac itself will comprise 21 inter-tank quadrupoles and 11 corrector magnets in total. The first part of the linac requires special attention: due to the limited available space, a low-energy corrector and a short version of a standard linac corrector will be used in the DTL inter-tank regions.

For the new transfer-line, 17 transfer-line quadrupoles, five bending magnets, and 11 two-plane corrector magnets will be built. A detailed overview of the required new magnets is shown in Table 1.

The electro-magnetic design work for these magnets has been recently completed. All simulations and field computations have been performed using the finite element program OPERA 2D or OPERA 3D/TOSCA from Vectorfields/Cobham. The outcome of the design study and the present production status of the electro-magnets will be summarized in the following sections.

3-MEV FRONT-END

Low-Energy Correctors

The low-energy correctors needed for the Low-Energy Beam Transfer Line (LEBT) and the chopper line are combined horizontal/vertical corrector magnets. They have a magnetic length of 170 mm and a mechanical aperture of 108 mm, providing an integrated field of 1.28×10^{-3} Tm. The yokes are made of 0.5 mm thick laminated electrical steel and the coils are wound from solid copper wire and are air cooled by natural convection. The main constraints were the limited space and the magnetic interference with the adjacent equipment. A preliminary integration layout of the LEBT is shown in Figure 1.

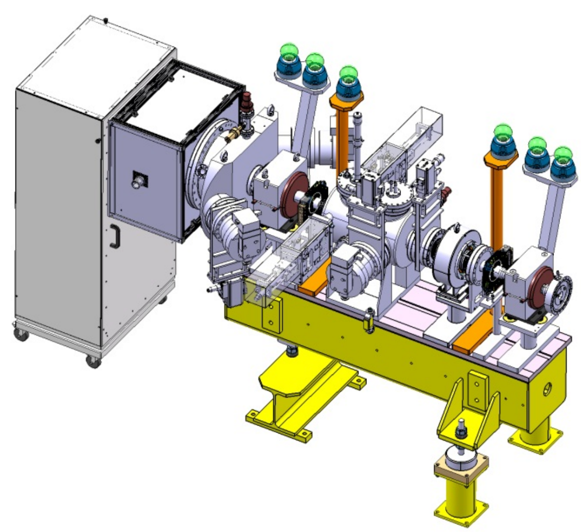

Figure 1: LEBT layout.

The magnet fabrication is finished and measurements of the integrated field strength have been performed on three out of six magnets with a rotating coil setup. The manufacturing of the magnets is reasonably conforming to the specification, as the dipole transfer function in both planes is within 0.2% with respect to each other and to the nominal value. The transfer function shows that the iron yoke operates in the linear range far from saturation.

The measurement results are in good coherence with the outcome of the 3D simulations. As expected, the field quality is affected by very large allowed multi-poles due to the low aspect ratio (length to aperture).

Solenoids

New solenoids are indispensable to be compatible with the large aperture of the rest of the LEBT. Low energy solenoids with an aperture radius of 75 mm have been specified for the MedAustron accelerator, in collaboration with CERN. These DC-operated solenoids entirely fulfil the Linac4 requirements and feature an effective length of 309 mm and an integrated axial field of 8×10^{-2} Tm. The design work included a comprehensive study on the impact of the conductor configuration onto the field homogeneity. The complete conductor geometry including layer transitions and connection leads have been modelled in OPERA 3D and several layouts have been tested leading to the final design. The four coils are mounted into a magnetic steel barrel to confine the fringe fields. The field quality has been intensively cross-checked using the ray-tracing feature of OPERA 3D. A dedicated simulation could provide certainty that the close-by corrector magnet does not distort the solenoid field quality in a significant way and the magnetic coupling remains negligible.

LINAC INTER-TANK SECTIONS

Quadrupoles

Beam focusing in the linac is provided by Electro-Magnetic Quadrupoles (EMQ) and Permanent Magnet Quadrupoles (PMQ). A common EMQ type will be used for the inter-tank sections of the entire Linac4. The quadrupoles have an aperture radius of 27 mm and provide a maximum integrated gradient of 2.4 T. They are designed to operate with a repetition rate of up to 2 Hz and a flat top length of 2 ms keeping the r.m.s. current and the power consumption low enough to allow air cooling by natural convection, which consequently cuts the installation and operation costs. In addition, an air-cooled magnet design permits a reduction of the overall magnet dimensions, helping to meet the stringent geometric boundary conditions in the inter-tank regions. The yokes are made of 0.5-mm-thick laminated electrical steel glued together, cut by Electro Discharge Machining (EDM) and pressed into a stainless-steel ring; the coils are wound from solid copper cast in resin after the final magnet assembly.

Apart from a very compact design (overall length less than 106 mm), this layout brings the advantage to keep the mechanical tolerance on the poles and in the magnet assembly narrow and to assure a gradient homogeneity of $\Delta\int G/\int G_0 = \pm\ 0.05\%$ inside the good field region (GFR).

OPERA 2D was used to design the pole profile and the yoke cross-section. The integrated harmonics amplitude values were obtained from the 3D simulations by Fourier analysis of the radial field component B_r integrated on a cylindrical surface. The integrated field quality was fine-tuned by trimming the pole ends (chamfering). The quadrupoles are presently under fabrication.

Field errors due to eddy currents in the magnet and in the vacuum chamber have been computed and compared with measurements on a prototype of similar design. The time constant of the 1.5-mm-thick vacuum chamber (50 µs) was found to be small compared to the time constant of the magnet itself (200 µs) and can therefore be ignored.

Corrector Magnets

Several types of combined horizontal/vertical correctors with different mechanical apertures and field strengths are needed for the inter-tank regions and the new transfer-line. In order to reduce the costs and the number of spare magnets, a common window-frame design with a free aperture of 100 mm × 100 mm and a maximum integrated field strength of 3.5×10^{-3} Tm will be used for all subsystems. Like the quadrupoles, these magnets will be operated in pulsed mode with the repetition frequency of 2 Hz.

Since the magnets are short and have a large aperture, the fringe field in the direction of the beam axis is significant. In such a case, 2D field calculations give imprecise results and need to be verified by 3D simulations. Thus, 3D models were used to optimize the conductor distribution in the coils. It was found that the required field quality can be achieved by introducing 10 additional turns on each side of the coil, as shown in Figure 2.

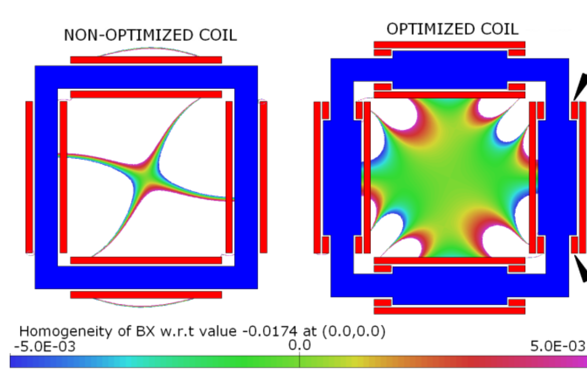

Figure 2: Non-optimized vs. optimized coils.

The integrated horizontal and vertical field errors stay below ±0.5% for a GFR radius of 35 mm (transfer line correctors) and below ±0.1% for a GFR radius of 20 mm (inter-tank correctors).

The mechanical layout is similar to the above mentioned low-energy correctors. Two prototypes with different lamination thickness (0.5 mm and 0.35 mm) have been manufactured and will be measured to study their dynamic behaviour when operated in pulsed mode.

Magnetic Coupling

The short distance between the linac tanks and the fact that different equipment has to share this limited space leads to the situation that individual elements have to be placed very close to each other, which consequently can create interferences amongst them. The most critical position is the inter-tank region between the DTL and the CCDTL, where the distance between the edge of quadrupole and the edge of the corrector is 30 mm only. To investigate possible cross-talk and magnetic coupling, 3D simulation were performed. Because the fringe field of the corrector penetrates the yoke of the quadrupole and vice versa, it is not sufficient to study the fringe fields of the individual elements separately and quantify the interference effect by a simple superposition. Hence it was necessary to represent the quadrupole and the corrector in one common model. The results show that for the quadrupole the effects on the higher multi-pole components and on the integrated gradient are negligible. On the other side, significant effects on the corrector field have been observed: the integrated field level was reduced from 3.5×10^{-3} Tm to 2.86×10^{-3} Tm due to the sole presence of the quadrupole yoke, i.e. without powering the quadrupole coils (see Figure 3).

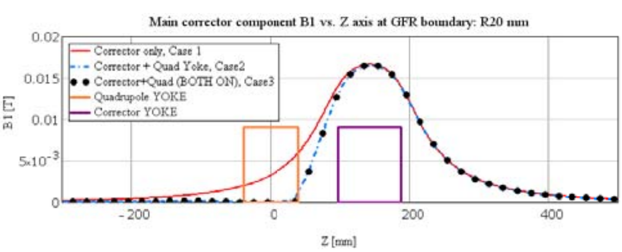

Figure 3: Influence of the adjacent quadrupole on the field distribution on the corrector.

However, this field reduction can be compensated by increasing the excitation current in the corrector coils. The field quality became worse but still remains acceptable inside the specified good field region.

TRANSFER-LINE

Quadrupoles

While the first part of the new transfer-line will make use of two linac-type quadrupoles, the remaining part involves quadrupoles with larger aperture. A series of 15 quadrupoles with an aperture radius of 50 mm providing an integrated gradient of 1.8 T will be built. The propose design is a classical 4-quadrant quadrupole with hyperbolic pole profile. The magnets are operated in pulsed mode at 1.1 Hz to reduce power consumption and avoid water cooling. One of the main challenges in the design was to match the magnet inductance and resistance to an existing power converter design. To approach this issue in a systematic way, a scaling law has been derived which relates the stored energy E of an electromagnet with its aperture radius r and with its magnetic length L_{eff}:

$$E \propto c_1 \frac{1}{L_{eff}} r^4 + c_2 \frac{1}{L_{eff}^2} r^5$$

with c_1 and c_2 being constant values. The correctness of the formula has been cross-checked by a series of numerical 2D calculation. Since neither the aperture nor the effective length could be reduced significantly, the beam optics had to be modified instead to lower the field gradient. In parallel it was necessary to increase the stored energy delivered by the capacitor-discharge power converter to converge to a satisfactory solution.

Bending Magnets

In order to direct the beam from Linac4 towards the PS Booster, several bending magnets will be required. The horizontal 70 degrees turn right after the linac will be achieved by three bending magnets connected in series, each deflecting the beam by 23.3 degrees. Since Linac4 and the PS Booster are not on the same underground level two vertical bending magnets are needed. They provide a beam deflection of 14.5 degrees each. For economic reasons it was decided to aim for a common design. The pulsed magnets will provide a maximum integrated field strength of 0.78 Tm in an aperture gap of 56 mm at a repetition frequency of 1.1 Hz. The proposed design is a classical laminated H-type magnet with water cooled coils as shown in Fig. 4. Since the beam will travel through the transfer-line with a constant energy, the required field homogeneity of $\pm5\times10^{-4}$ has to be achieved only for two given field levels.

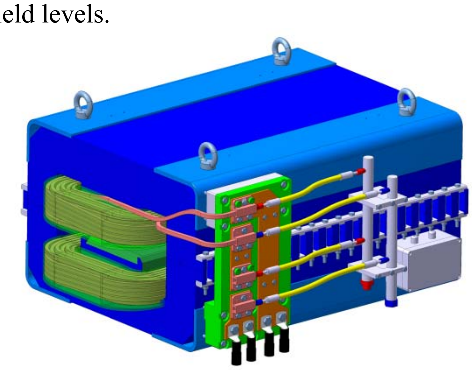

Figure 4: Transfer-line bending magnet.

CONCLUSION

Most of the design work has been completed and the production in industry according to CERN's specifications has started. Beginning with the inter-tank quadrupoles and correctors, the magnets will be progressively delivered, tested and measured. The first elements have to be ready for installation by June 2012. The delivery of the magnets for the transfer-line shall be completed before June 2013.

REFERENCES

[1] M. Vretenar et al., "The Linac4 Project at CERN", this Conference.