ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB366

DESIGN AND REALIZATION OF NEW SOLENOIDS FOR HIGH BRIGHTNESS ELECTRON BEAM INJECTORS

A. Vannozzi*, D. Alesini, A. Giribono, C. Vaccarezza
INFN –LNF, Rome, Italy

Abstract

High-brightness, high-current electron beams are the main requirements for fourth generation light sources such as free-electron lasers (FELs) [1], energy recovery Linacs (ERLs) [2] and high-energy linear colliders [3]. The most successful device for producing such beams is the Radio-Frequency photo-injector where a key element is the gun solenoid. Its main task is to limit the beam emittance growth in the first acceleration stages by imposing a spiraling motion to the beam.

This paper is focused on two magnets: the first one is the solenoid gun for the new photo-injector at INFN-LNF SPARC_LAB test facility [4,5]. The design, the realization, and all the measurements performed at the factory and at LNF are shown. Moreover, the design of a solenoid for a novel C-band gun for CompactLight project is presented.

Both magnets have been designed with the goal to reach the same integrated field of the gun solenoid currently installed at SPARC_LAB, with an integrated field quality of 5E-4 in a good field radius of 30 mm and 10 mm radius respectively for SPARC_LAB and CompactLight solenoid. This one is equipped with a bucking coil to limit the field on cathode that could led to an undesired emittance growth.

INTRODUCTION

This work is focused on two solenoids both devoted to the focus of electron beams accelerated by two different RF guns operating respectively in S-band and C-band frequency ranges. The first one will be installed in the photo injector of LNF test facility, SPARC_LAB. This is a linac, where potentialities of the SPARC_LAB high power high intensity laser system, named FLAME [6], and the high brightness electron beam are merged to perform several R&D activities on ultra-brilliant electron beam photo injector, plasma based acceleration experiments and on FELs physics. Moreover a crucial role of this facility is to explore the performances of a FEL driven by a plasma based accelerator for the EuPRAXIA project [7], since LNF will host the beam driven plasma acceleration pillar of this new facility.

In this framework the installation of a new photo-injector is ongoing including the new gun surrounded by a focusing solenoid. The new photo injector, will allow to achieve several improvements such as a breakdown rate decrease with respect to the old gun, more space available for a future installation of a X-band linearizer and a better characterization of the new solenoid. The design, the production and the characterization of this solenoid have been completed, while its installation in the machine is ongoing. Regarding the solenoid for the C-band gun, it have been designed for the CompactLight Project [8]. The goal of this project is a Conceptual Design Report (CDR) of a X-band Hard X-ray facility. The INFN role is to design [9] and to optimize [10] the photo-injector including the RF gun and the gun solenoid design. A C-band electron gun will allow to reach higher field on the cathode (so a higher beam brilliance), to increase the RF gun repetition rate up to 1 kHz with electric field in the range of 150 MV/m.

The C-band gun and the solenoid actually are only designed for the CompactLight CDR, they have never been realized before, but they could be built thanks to TOUAREG project [11]. All these achievements led to a more compact photo-injector and they are extremely important for all facilities requiring high brightness electron beams.

In this context, a good design and realization of gun solenoids play a crucial role for the beam properties in the first acceleration stages since from the solenoid design goodness it depends the beam focalization and in general its emittance that could grow also for a high magnetic field on cathode.

In this proceeding 2D, 3D simulations and the measurements of the S-band gun solenoid measurements will be show while the design will be presented for the C-band gun solenoid.

S-BAND GUN SOLENOID

Magnetic Design

The magnetic design of this solenoid is based on the achievement of the following main goals:

- Reach the same integrated field and focus strength of the gun solenoid currently installed in the SPARC _LAB photo injector.
- Minimize the field on cathode aiming to avoid undesired emittance growth.

Moreover, the inner diameter have been sized in order to guarantee an easier access to the mirror for the laser beam transport on the cathode putting him out of vacuum. From the mechanical point of view, the magnet is equipped with a remote controlled motorized support aiming to have a fine adjustment of its transverse position by means of beam based alignment.

The solenoid have been composed by two coils surrounded by an iron shield that ensure a limitation of stray field over the magnet ends and it reduce the power current for a given peak field. The choice of two coils allows to have a better compensation of the possible misalignment between the two coils powering each coil with an opposite current polarity (+- configuration).

* alessandro.vannozzi@lnf.infn.it

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB366

Several 2D and 3D simulations have been performed with Poisson Superfish and Opera3D software respectively. Regarding the Poisson Superfish simulations these had been run with axial symmetry conditions. Figures 1 and 2 show the 2D and 3D model of the solenoid simulated with the softwares above mentioned.

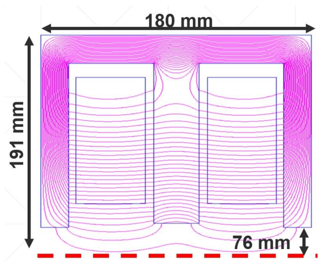

Figure 1: S-band Gun Solenoid Poisson Superfish 2D model with its most relevant dimensions.

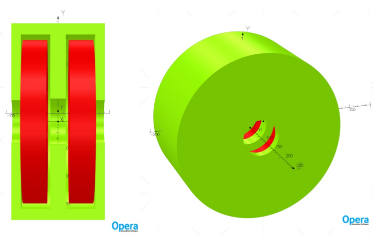

Figure 2: S-band Gun Solenoid Opera 3D model. Longitudinal cross section and an axonometry of the solenoid are illustrated on the left and right respectively.

Table 1 shows the final specifications of the solenoid design compared with the main requirements. The ++ and +- configurations refer to same and opposite current polarity in the two coils respectively. IB is the integral of longitudinal component of magnetic field (B_z) in the longitudinal direction (z), while FS is the focusing strength corresponding to the field integral of B_z^2 along z direction. The Integrated Field Quality parameter (IFQ) in Table 1 is defined by Eq. (1) where the numerator and denominator terms are the IB along a general trajectory and IB on axis respectively. IFQ have been evaluated within a good field radius of 30 mm.

$$IFQ = 1 - \frac{\int B_z(x,y)\,dz}{\int B_z(0,0)\,dz}. \qquad (1)$$

Manufacturing and Magnetic Measurements

The solenoid have been produced by Danfysik company [12] according to the design provided by INFN. Several Factory Acceptance Tests (FAT) have been done including: 3D mapping of B_z on several trajectories, excitation curve, dimensional check and coil tests (electric and hydraulic). Regarding the magnetic measurements, the FS and the IB have been evaluated on several trajectories within the 30 mm good field radius, calculating the IFQ according to the simulations.

Table 1: S Band Gun Solenoid Specifications

	Simulated	**Required**
Bmax in ++ Config.	3 943 G	
Bmax in +- Config.	3 629 G	
Yoke Material	St.37	
IB on Axis	0.062 6 Tm	≥0.062 0 Tm
IFQ	4E-5	≤5E-4
Good Field Radius	30 mm	30 mm
FS on Axis in +- Conf.	0.015 5 T^{2m}	≥0.015 0 T^{2m}
Bmax on Cathode	8.5 G	≤15 G
Number of Turns per Coil	136	
Cooling	Water cool	
Conductor Dim.	5x5/bore 3 mm	
Water Pressure Drop	3 bar	
Water Flow Rate	4.2 l/min	
Water ΔT	25 °C	≤30 °C
Nominal Current in ++/+- Config.	182/192 A	
Nominal Voltage	35 V	
Inductance	35 mH	
Resistance	191 mΩ	

It resulted by the FAT, that the IB and FS on axis were respectively 0.0621 and 0.0150, while the IFQ is 2.01E-4, lower than the requested 5E-4.The performances of the magnet are fully compliant with the requirements.

After the FAT, magnetic measurements at LNF have been also performed to check if any misalignment occurred during the shipping. In detail, a 3D mapping on few trajectories measured in the FAT have been done by means of a the hall probe measurement bench shown in Fig. 3. No relevant differences between the two measurements have been seen. In Fig. 4 the B_z scan on the axis in ++ and +- configuration measured at Danfysik and at LNF is compared with the Opera 3D simulations.

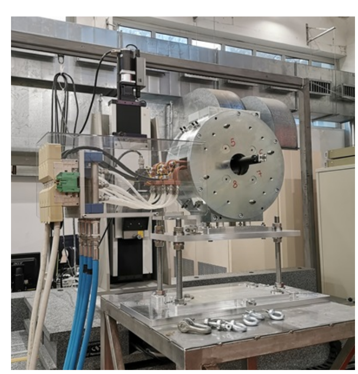

Figure 3: Solenoid on the hall probe measurement bench at LNF.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB366

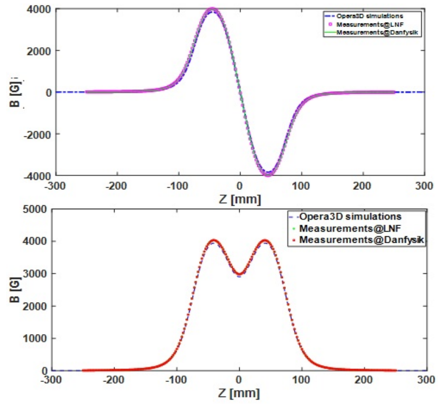

Figure 4: Comparison between the B_z on axis measured at Danfysik, at LNF with the Opera 3D simulations in +- (top) and ++ configuration (bottom).

C-BAND GUN SOLENOID

This solenoid have been tailored on the CompactLight one cell and half RF gun design [9]. The main goal of the magnetic design, was to reach an integrated field in the order of 0.06 Tm (almost the same one of the current SPARC_LAB gun solenoid) in a reduced longitudinal length of 120 mm with respect to the current 200 mm. This led to an increasing of radial dimension and to very high stray field outside the iron.

Thus the solution of one water cooled coil surrounded by an iron shield and equipped with a bucking coil was necessary to reach the desired field integral and to minimize the field on cathode avoiding undesired beam emittance growth. The bucking coil is composed by an enamelled copper air cooled conductor.

Several 2D axial symmetry simulations with Poisson Superfish code have been performed; Figure 5 illustrates the 2D model of the solenoid. In Table 5 all the main magnet parameters are listed including integrated field (IB) and the IFQ defined by Eq. (1).

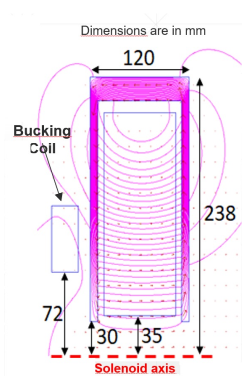

Figure 5: C-band Gun Solenoid Poisson Superfish 2D model with the most relevant magnet dimensions.

Figure 6 show the B_z longitudinal field profile with the bucking coil switched ON and OFF. It is possible to see how the field on cathode is reduced from almost 350 G to 1 G.

Table 2: C-band Gun Solenoid Specifications. Bucking Coils Parameters are Indicated with the BC Acronym

Parameter	Value
Bmax	5 285 G
Yoke Material	Low Carbon Steel
IB	0.059 4 Tm
Good Field Radius	10 mm
IFQ	3E-5
Number of Turns	336
Cond. Dimens.	5.6x5.6/bore 3.6 mm
Nominal Current	164 A
Nominal Voltage	40 V
Inductance	3 mH
Resistance	242 mΩ
Water Flow Rate	3.72 l/min
Water ΔT	25 °C
Water ΔP	2.72 bar
BC Conductor Diam.	1.6 mm(ins.)
BC Number of Turns	700
BC Nominal Current	7.5 A

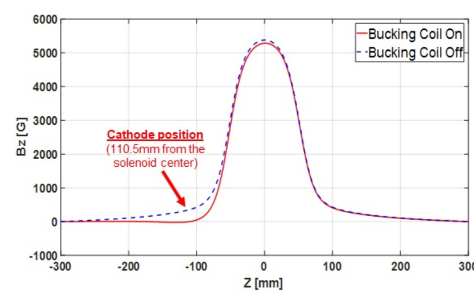

Figure 6: B_z longitudinal profile with bucking coil switched ON (dashed blue line) and OFF (solid red line).

CONCLUSIONS

The design of two solenoids for a S-band and C-band RF gun have been realized. On the basis of the S-band gun solenoid design, Danfysik company realized the magnet and performed several FAT showing a good agreement with the simulations. Moreover no evidence of coils misalignment due to shipping have been seen by means of a new set of magnetic measurements at LNF. Regarding the C-band gun solenoid, it has been designed and it was equipped with a bucking coil to cancel the field on cathode. All the solenoid parameters are fully achievable with the current technologies, so this work demonstrate that this magnet could be installed around an C-band RF gun, that has not yet been realized.

ACKNOWLEDGEMENTS

This work has received funding from the INFN Commission V TUAREG proposal [11], from the European Union's Horizon 2020 Research and Innovation program under GA No 101004730 and BEATS H2020 European Project.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB366

REFERENCES

[1] W. B. Colson, "Theory of a free electron laser", *Physics Letters A*, vol. 59, no. 3, pp. 187-190, 1976.

[2] S. M. Gruner *et al.*, "Energy recovery linacs as synchrotron radiation sources", *Review of Scientific Instruments*, vol. 73, no. 3, pp. 1402-1406, 2002. doi:10.1063/1.1420754

[3] E. Accomando *et al.*, "Physics at the CLIC multi-TeV linear collider", CERN, Geneva, Switzerland, Rep. CERN-2004-005, 2004.

[4] R. Pompili *et al.*, "2018 Recent results at SPARC_LAB", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 909, pp. 139-144, 2018. doi:10.1016/j.nima.2018.01.071

[5] M. Ferrario *et al.*, "SPARC LAB present and future", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 309, pp. 183–188, 2013. doi:10.1016/j.nimb.2013.03.049

[6] L. A. Gizzi *et al.*, "2009 An integrated approach to ultraintense laser sciences: The PLASMON-X project", *Eur. Phys. J. Spec. Top.*, vol. 175, pp. 3-10, 2009. doi:10.1140/epjst/e2009-01109-4

[7] P. A. Walker *et al.*, "2017 Horizon 2020 EuPRAXIA design study" *J. Phys.: Conf. Series*, vol. 874, p. 012029, 2017. doi:10.1088/1742-6596/874/1/012029

[8] CompactLight, http://www.compactlight.eu/Main/HomePage

[9] D. Alesini *et al.*, "Design of a Full C-Band Injector for Ultra-High Brightness Electron Beam", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1979-1982. doi:10.18429/JACoW-IPAC2019-TUPTS024

[10] M. Croia *et al.*, "High gradient ultra-high brightness C-band photo injector optimization", *Journal of Physics: Conference Series*, *J. Phys.: Conf. Series*, vol. 1596, p. 012031, Jul. 2020. doi:10.1088/1742-6596/1596/1/012031

[11] TUAREG, http://w3.lnf.infn.it/technological-research-lab/tuareg/?lang=en

[12] DANFYSIK, https://www.danfysik.com/.