CHARACTERIZATION AND ALIGNMENT OF LINAC MAGNETS FOR ELI-GBS FACILITY*

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Abstract

This paper presents an overview of the magnet system used in the ELI-GBS linear accelerator (LINAC), including the configuration of quadrupole and dipole magnets, their placement along the accelerator, and the results of magnetic field characterization performed at factory and in laboratory conditions. The alignment methodology used to position the magnetic centers relative to the mechanical axes is also summarized. The results confirm that the Q2041i quadrupoles and D2018i dipoles meet the required field specifications and that the alignment procedures ensure the tolerances necessary for stable beam transport.

INTRODUCTION

The Extreme Light – Gamma Beam System (ELI-GBS) LINAC incorporates 23 quadrupole magnets (Q2041i) and 2 dipole magnets (D2018i), distributed along six accelerating modules [1] and are presented in Fig. 1. Quadrupoles provide transverse focusing and beam steering through main and trimming coils, while dipoles deflect the beam toward diagnostic lines. All magnets were characterized at factory and in specialized laboratory conditions to verify compliance with the design requirements. This paper summarizes the magnet layout, the main results of magnetic measurements, and the alignment procedures applied to ensure proper beam transport.

MAGNET TYPES AND FUNCTIONS

Quadrupoles are arranged in groups of two to four units. Each quadrupole includes a main focusing coil and a trimming coil for horizontal (H) or vertical (V) steering. The last two quadrupoles in each group are equipped with trimming coils to provide fine steering corrections. Dipoles are installed at the end of modules 2 and 6, providing an 18° deflection toward diagnostic stations.

Main Magnets Characteristics

D2018i Dipole:

- 2 pc, 20 mm gap, 18° bend, $l_{\text{eff}} = 0.524$ m.
- Field: −1.60 T; Coils: 2 × 132 turns.
- $I = 103$ A; $R = 0.364\ \Omega$.

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Q2041i Quadrupole:

- 23 pcs, 20 mm gap, $l_{\text{eff}} = 0.052$ m.
- Gradient: −50 T/m (±0.02 T).
- Coils: 4 focus + 4 trim; Turns: 170 (focus), 15 (trim).
- $I = 13$ A (±12 A trim); $R = 0.939\ \Omega$ (0.105 Ω trim).

Quadrupole and dipole models are shown in Fig. 1.

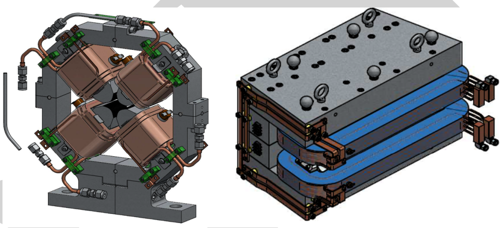

Figure 1: Views of the LINAC quadrupole and dipole.

MAGNET LAYOUT

The magnet layout follows the design of the ELI-GBS LINAC shown in Fig. 2. Quadrupoles alternate between focusing (QF) and defocusing (QD) configurations, while trimming coils provide local steering corrections. The dipoles provide an 18° deflection toward diagnostic lines. Electrical polarity determines whether a quadrupole acts as QF or QD. Trim coils are wired so that:

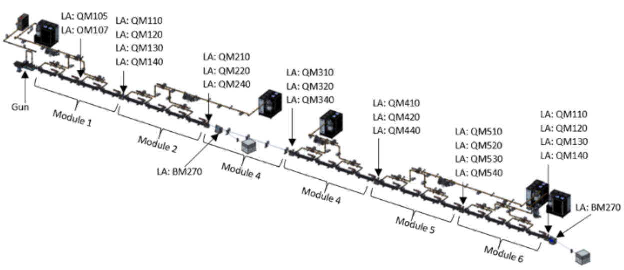

Figure 2: Placement of magnets along the ELI-GBS LINAC.

- Positive current → $+x$ steering (horizontal corrector).
- Positive current → $+y$ steering (vertical corrector).

This ensures consistent steering behavior across all modules.

MAGNETIC MEASUREMENTS OVERVIEW

Magnetic characterization was performed in two stages: 1) Factory measurements using a rotating coil system; 2) Laboratory measurements using a 3D Hall-probe mapping system.

Both campaigns aimed to verify field strength, linearity, harmonic content, and magnetic axis position.

QUADRUPOLE FACTORY MEASUREMENTS

The rotating-coil method, shown in Fig. 3, provided the integrated gradient and harmonic content of the Q2041i quadrupoles [2]. Conditioning cycles were applied prior to measurement to stabilize the magnetic properties. At 15 A, the measured integrated field reached 2.93 T, exceeding the design requirement of 2.6 T. Field uniformity was excellent:

$$\left|\frac{\int \Delta B_y dz}{\int B_y dz}\right| = 2.4 \times 10^{-4}$$

$$\left|\frac{\int \Delta B_x dz}{\int B_x dz}\right| = 9.7 \times 10^{-5}$$

These results confirm that the quadrupoles meet the required focusing performance.

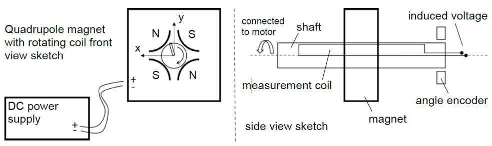

Figure 3: Rotating-coil measurement setup.

Additional factory measurement results: 1) Harmonic analysis confirmed negligible sextupole and octupole components; 2) The field quality satisfies the design tolerance of 10^{-2} across the good-field region; 3) The quadrupole field distribution was symmetric with respect to both transverse axes.

These results validate the manufacturing quality and magnetic symmetry of the Q2041i series.

QUADRUPOLE LABORATORY MEASUREMENTS

The measurements were performed at the National Institute for R&D in Electrical Engineering (ICPE-CA) [3]. A 3D Hall probe was used to map the magnetic field at multiple transverse positions. Measurements were automated and post-processed using MATLAB. The excitation characteristic remained linear up to approximately 12 A, beyond which magnetic saturation was observed, according to the plot in Fig. 4.

These deviations presented in Table 1 indicate that the magnetic center is offset from the geometric center and requires mechanical correction during alignment.

Table 1: Magnetic Axis Deviations (Quadrupole 1)

Translation		Tilt	
X [µm]	Y [µm]	ρ [°]	θ [°]
+182.77	+207.17	−0.1602	+73.7578

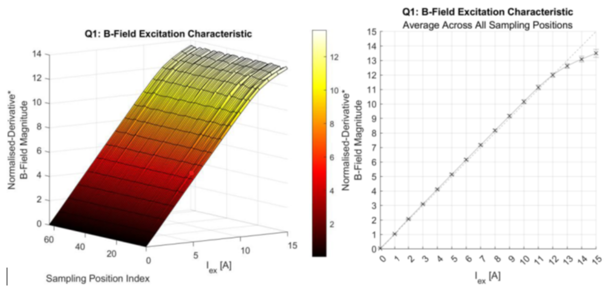

Figure 4: Non-linearity of the excitation characteristic. Magnetic axis deviations were determined using multi-polar expansion and least-squares fitting.

QUADRUPOLES ALIGNMENT

Quadrupole alignment was performed on a precision support table equipped with micrometric screws and optional actuators. The alignment procedure consists of:

1) Mount the magnet on the alignment table; 2) Apply tilt corrections; 3) Apply translation corrections; 4) Lock the mechanical supports; 5) Verify alignment through magnetic re-measurement.

The calculation states that the magnetic axis is described by linear equations of the form:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \alpha_x & \beta_x \\ \alpha_y & \beta_y \end{bmatrix} \begin{bmatrix} z \\ 1 \end{bmatrix}$$

Where:

- $X = -\beta_x = 182.77$ µm, $Y = -\beta_y = +207.17$ µm are the measured offsets of the magnetic axis.
- $\rho = -(1 + j\sqrt{\alpha_x^2 + \alpha_y^2})$ is angular deviation and reduces to $\rho = \sqrt{\alpha_x^2 + \alpha_y^2} = -0.1602°$.
- $\theta = -(\alpha_x + j\alpha_y) = \text{atan2}(\alpha_y, \alpha_x) = +73.7578°$ is the azimuthal angle of the tilt direction, defined in the XY plane, measured around the Z axis.

The system provides eight degrees of freedom, presented in Fig. 5, and enables correction of:

1) Horizontal translation (X); 2) Vertical translation (Y); 3) Tilt in XZ plane; 4) Tilt in YZ plane.

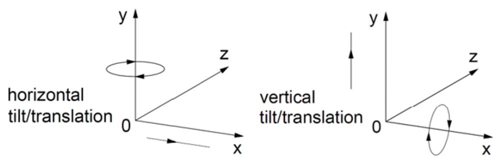

Figure 5: Horizontal and vertical tilt/translation.

The corrections presented in Table 2 and Table 3 ensure that the magnetic axis coincides with the geometric axis within the required tolerances, as presented in Fig. 6.

Table 2: Example of Horizontal Screw Corrections (Quadrupole 1)

Screw Position	Tilt X [µm]	Trans X [µm]	Total [µm]
Upstream left	−174	−182.77	−356.77
Upstream right	+174	−182.77	−8.77
Downstream left	+174	+182.77	+356.77
Downstream right	−174	+182.77	+8.77

Table 3: Example of Vertical Screw Corrections (Quadrupole 1)

Screw Position	Tilt Y [µm]	Trans Y [µm]	Total [µm]
Upstream left	−53.5	+207.17	+153.67
Upstream right	−53.5	+207.17	+153.67
Downstream left	+53.5	+207.17	+260.67
Downstream right	+53.5	+207.17	+260.67

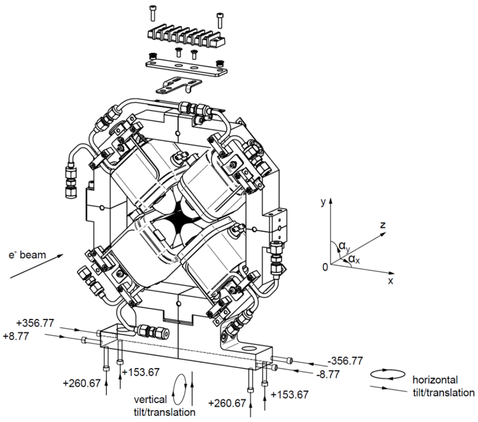

Figure 6: Alignment screw configuration.

DIPOLE FACTORY MEASUREMENTS

Factory characterization of the D2018i dipole was performed using a rotating-coil and Hall-probe hybrid system similar to the quadrupole procedure. The magnet was cycled between 0 A and its nominal current to stabilize hysteresis before measurement.

The main results confirmed:

- Nominal field: −1.60 T at 103 A.
- Field uniformity: within the specified tolerance across the 20 mm gap.
- Harmonic content: negligible higher-order multipoles, indicating excellent field symmetry.

These results validate the manufacturing quality and confirm that the dipole meets the required bending-field specification for the 18° deflection toward the diagnostic line.

DIPOLE LABORATORY MEASUREMENTS

A complementary 3D Hall-probe mapping was performed to verify the dipole field under controlled laboratory conditions, at the same ICPE-CA laboratory. Measurements were taken along the beam trajectory and across the transverse aperture.

Key observations include:

- Field vs. current curve matched factory data within 1.5%, as presented in Fig. 7.
- Linearity maintained up to the nominal operating current.
- Good-field region confirmed over the central: ±5 mm.

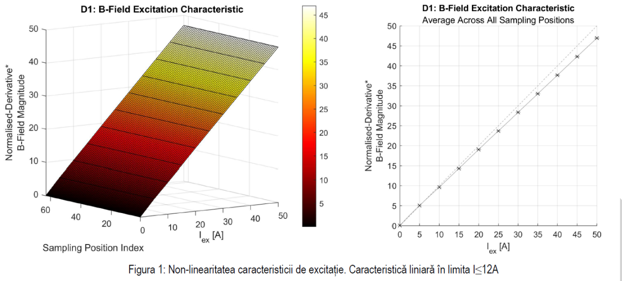

Figure 7: Excitation curve from laboratory measurements.

The agreement between factory and laboratory results demonstrates the stability and reproducibility of the D2018i magnetic performance.

CONCLUSION

A complete characterization and alignment campaign was performed for the Q2041i quadrupoles and D2018i dipoles of the ELI-GBS LINAC. Factory and laboratory measurements confirmed that the magnets meet the required field specifications, with excellent linearity and field uniformity. The quadrupoles alignment procedures successfully minimized magnetic axis deviations, ensuring reliable beam transport and compliance with the accelerator design. The results validate the readiness of the magnet system for installation and operation in the ELI-GBS LINAC.

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