Sapienza Università di Roma
Dipartimento di Fisica
PhD school in accelerator physics XXXI cycle
AA 2017/2018

Study and Design of Magnet System for Linacs

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Outline

Beam Test Facility2 Project

- Overview and Machine Layout
- Design of New Magnets for the BTF-2 (Electromagnetic and mechanical design)
  - Fast Ramped Dipole
  - DC Magnets (Dipoles and Quadrupoles)
- New Power supply for the BTF-2

ELI-NP Gamma Beam Source Project

- Overview and Machine Layout
- Magnet and Power Supplies of the ELI-NP Linac
- Magnet and Power Supplies FAT
- Electromagnetic Finite Elements Analysis of a Beam Current Monitor and Steerer
- Insertion of 3D Field Map in Beam Dynamics Simulation Software for ELI-NP GBS

Future works

BTF2 – Overview and Machine Layout

Transfer line optimized for selection, attenuation and manipulation of electrons and positrons extracted from the DAΦNE LINAC

- **Upgrade of the LINAC energy to 920 MeV (actual 750 MeV)** → Increase the facility capability
- **Consolidation of the LINAC infrastructure** → Guarantee a stable operation in the longer term
- **Doubling of the BTF beam-line** → Cope with the increase of users due to the much wider range of applications.

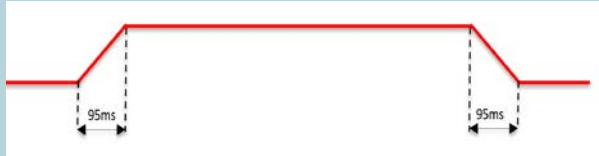
BTF2 – Magnet overview

10 New Magnets

- 1 Fast ramped dipole (DP01)
- 2 H-shape identical sector dipoles (DH01, DH02)
- 1 C-shape sector dipole (DC01)
- 6 quadrupoles (QUAD) (+ 1 SPARE)

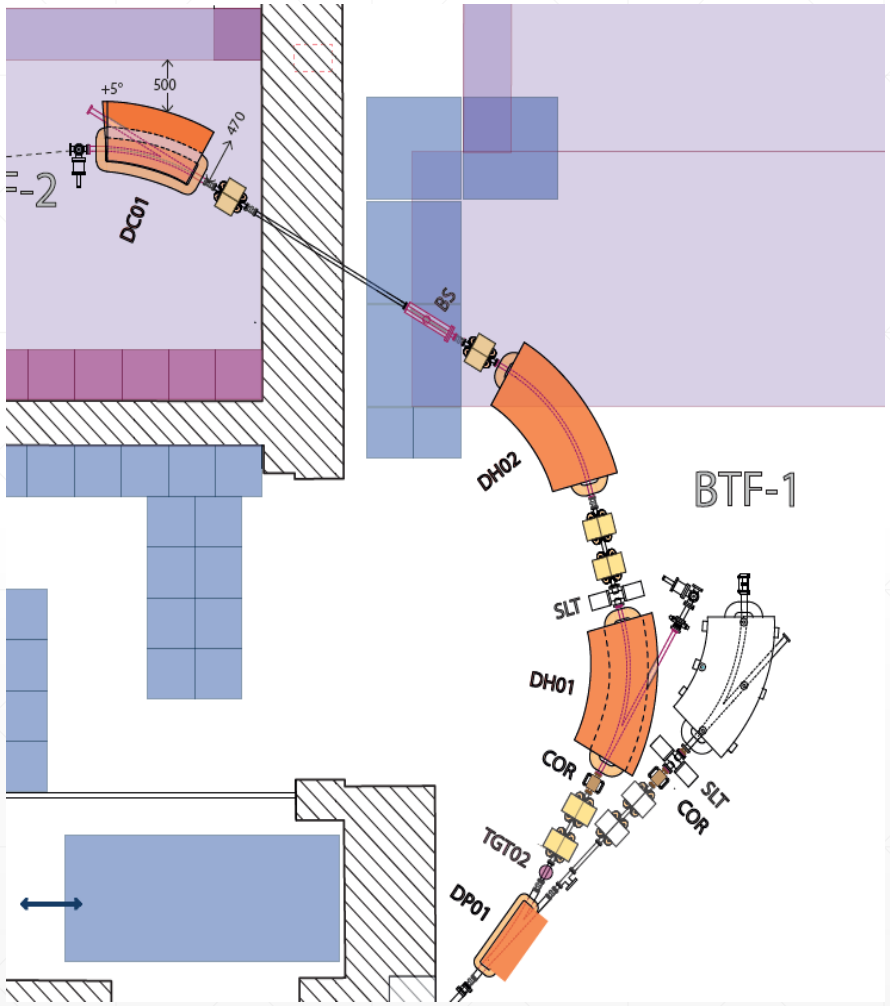
- All the magnets operate in DC except DP01 (raising time 95 ms)
- All the magnets have a full iron yoke except DP01 (laminated iron yoke)
- Dipoles bending angle:
  - DP 01 → 15°
  - DH01, DH02 → 45°
  - DC01 → 35°

TOTAL BEAM DEFLECTION ANGLE 140°

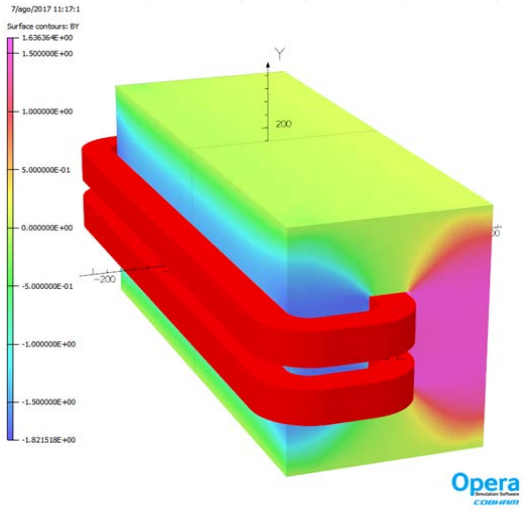


PHASES OF THE PROJECT

- Magnetic Design
- Mechanical Drawings (Mechanical Engigneering Service of LNF A.D.)
- Technical Specification
- Manufacturing
- F.A.T. (Coils Test)
- Magnet Measuremetns at LNF Magnet Laboratories

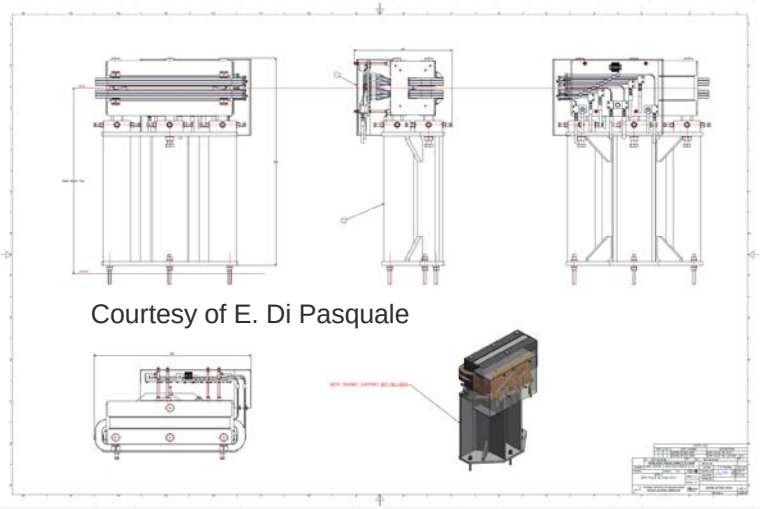


BTF2 – DP01 Magnet Design



- Magnetic design completed
- All mechanical drawings are completed
- The DP01 manufacturing has been started by O.R.M.E.T. s.r.l. company
- Check of iron sheets samples dimensions and tolerances required is ongoing.

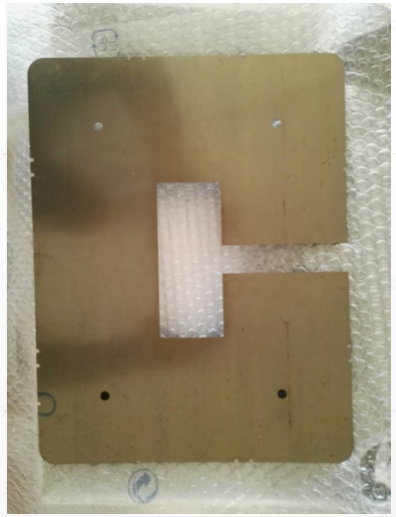
	Unit	Value
MAIN SPECIFICATION		
Beam energy	GeV	1
Nominal Magnetic Field	T	1,11
Bending angle	°	15
Pole iron gap	mm	25
Pole base width	mm	110
Magnetic length	mm	786
Yoke material		M270-35A
Integrated field quality (over ±25mm)		$1.8\ 10^{-3}$
Iron Weight	kg	60
Coils Weight	kg	570
COIL DATA		
Conductor dimensions	mm x mm	7x7 / bore φ 4mm
Number of turns per pole		36
Cooling water pressure drop	bar	3
INTERFACE DATA		
Nominal Current	A	316
Magnet Resistance	mΩ	78
Magnet Inductance	mH	29
Nominal Voltage	V	122
Power	KW	7.8



Courtesy of E. Di Pasquale

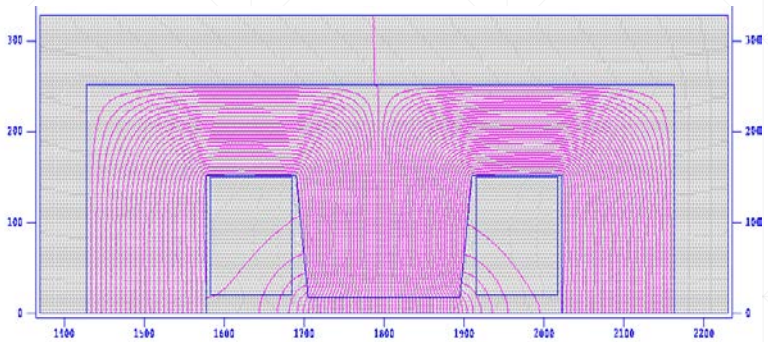
Mechanical Drawing of DP01

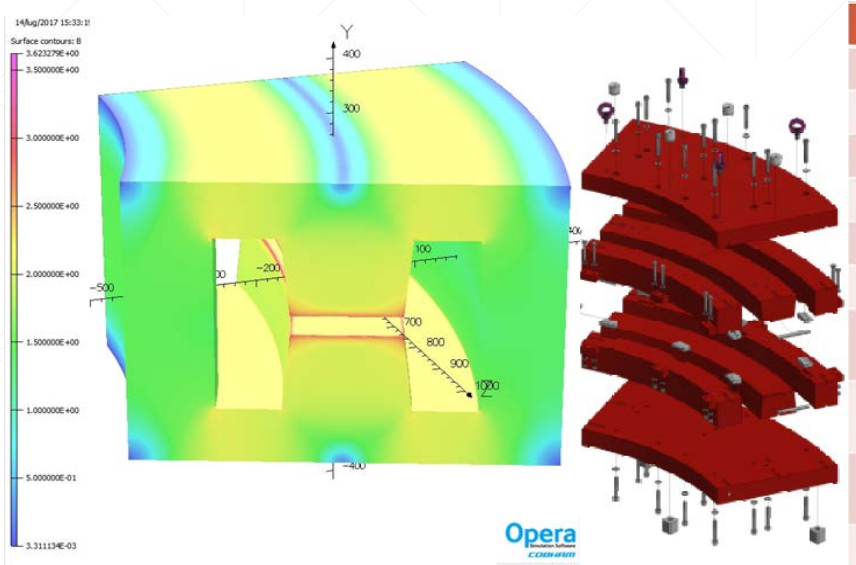
Laser cut sample

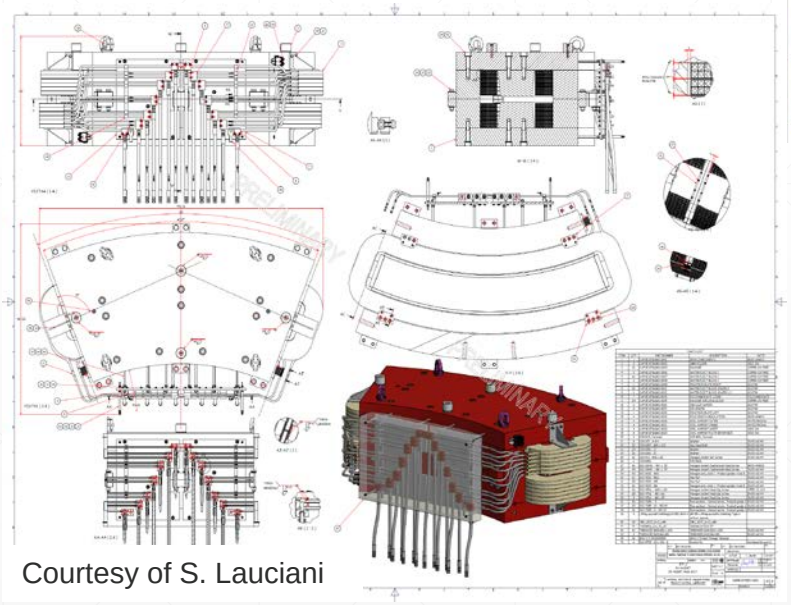


Electrical Discharge Machining sample

BTF2 – DH01 DH02 Magnet Design







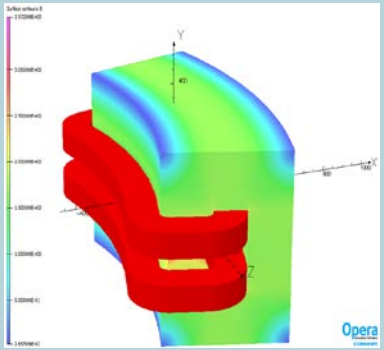
Courtesy of S. Lauciani

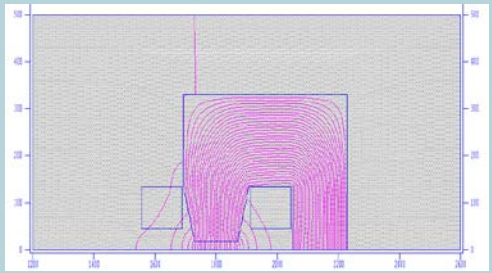
- 2D and 3D electromagnetics FEA simulations performed respectively with Poisson superfish and Opera 3D
- Mechanical drawings Completed
- Technical specification is completed
- A magnet yoke assembly was proposed in collaboration with CECOM
- The DH01 call for tender is ongoing

	Unit	Value
Beam Energy	MeV	920
Maximum Field	T	1,7
Bending Radius	mm	1800
Magnet Lenght	mm	1413
Bending Angle	deg	45
Pole Iron Gap	mm	35
Yoke Material		AME Pure Iron
Integrated Field Homogeneity		$5*10^{-4}$ over ±15mm
Number of turns per coil		120
Conductor dimensions	mm	9,5x9x5/ bore 5,5
Nominal Current	A	263
Nominal Voltage	V	85
Coil resistance @60°C	mΩ	280
Inductance	mH	422
Power Complete Magnet	kW	19
Pressure Drop	bar	3
Water Flow	l/min	18
Iron Weight	kg	3140
Coils Weight	kg	506

BTF2 – DC01 and QUAD Magnet Design

DC01

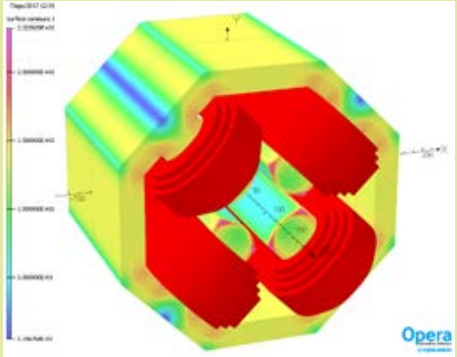


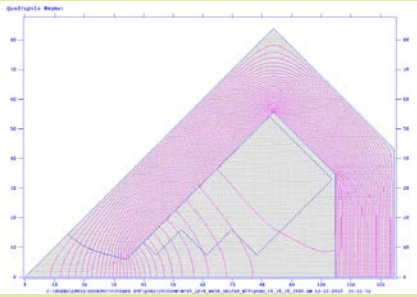


- Only magnetic design has been completed

	Unit	Value
Beam Energy	MeV	920
Maximum Field	T	1,7
Bending Radius	mm	1800
Magnet Lenght	mm	1100
Bending Angle	deg	35
Pole Iron Gap	mm	35
Yoke Material		AME Pure Iron
Integrated Field Homogeneity		$5{,}6 \cdot 10^{-4}$ over ±15mm
Number of turns per coil		104
Conductor dimensions	mm	9,5x9x5/ bore 5,5
Nominal Current	A	255
Nominal Voltage	V	58
Coil resistance @60°C	mΩ	195
Inductance	mH	348
Power Complete Magnet	kW	13
Pressure Drop	bar	3,15
Water Flow	l/min	12

Quadrupoles





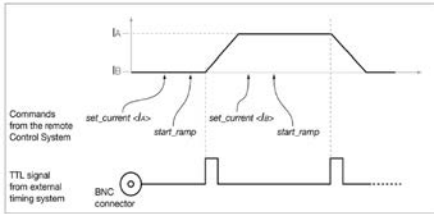
- Magnetic design completed
- Mechanical drawings ongoing
- Technial Specifications ongoing

	Unit	Value
MAIN SPECIFICATION		
Nominal Gradient	T/m	20
Bore	mm	45
Pole Width	mm	45
Magnetic length	mm	200
Integrated quality (r=15mm)		1E-3
Iron Weight	kg	45
Coils Weight	kg	17
COIL DATA		
Conductor dimensions	mm x mm	5x5 / bore φ 3mm
Number of turns per pole		46
Cooling water pressure drop	bar	3,5
INTERFACE DATA		
Nominal Current	A	88
Magnet Resistance	mΩ	110
Magnet Inductance	mH	22
Nominal Voltage	V	11
Power	KW	1

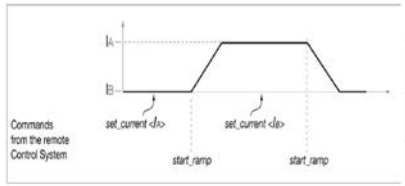
BTF2 – Power Supplies

	DP01 Power Supply	DH01 DH02 Power supply	DC 01 Power supply	Quadrupoles Power supply
Operating Mode	Fast Ramped	DC	DC	DC
Maximum output Voltage DC (V)	135	95	95	20
Maximum output Current (A)	330	285	285	100
POWER (kW)	44550	27075	27075	2000
QTY	1	2	1	6
Input Voltage (V)	400 ± 10%	400 ± 10%	400 ± 10%	400 ± 10%
Nominal current ramp (A/s)	3475	10	10	10
Steady State Output Current Resolution (ppm)	±20	±20	±20	±20
Steady State Output Current Ripple (ppm)	±100	±100	±100	±100
Output Current stability (8h @Nominal current)	±100	±100	±100	±100

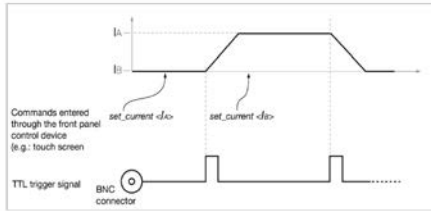
- Two power supply technical specifications have been completed:
  - Power Supply DP01
  - DC Power Supplies
- The specifications include also the control specification, FAT and terms between LNF and tenderer
- For DP01 a special care has been taken for implementation with the DAΦNE timing system



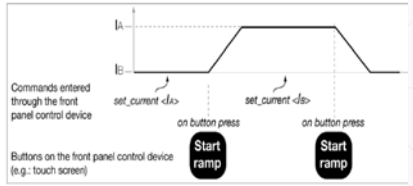
REMOTE control *trigger* mode



REMOTE control *software* mode



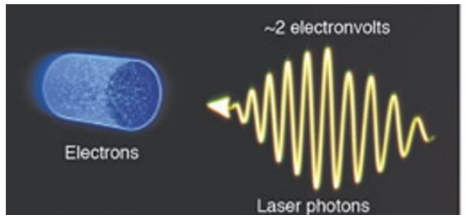
LOCAL control *trigger* mode

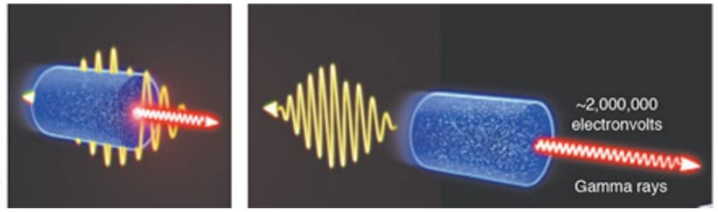


LOCAL control *software* mode

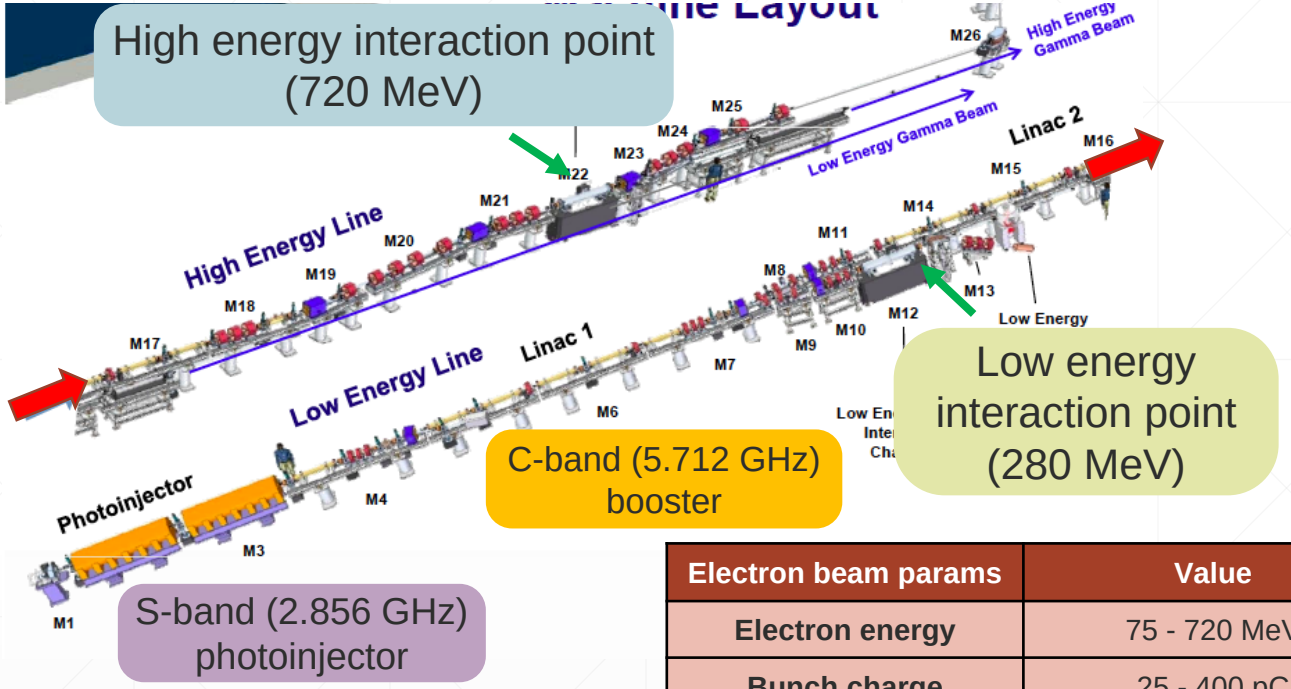
ELI-NP Gamma Beam Source

- **Source of Gamma-ray photons** under construction in Magurele (RO)
- ɣ-rays generated by **Inverse Compton scattering** in the collision between a high quality **e⁻** beam and a high power **laser pulse**



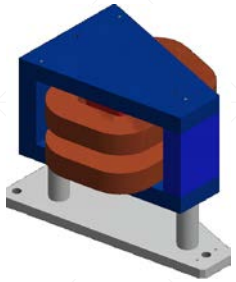


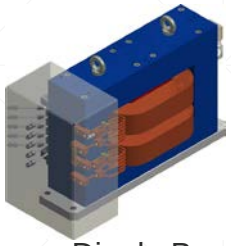
Gamma beam params	Value
Energy	0.2-19.5 MeV
Spectral density	0.8 – 4 • 10^4 ph/(s•eV)
RMS bandwidth	< 0.5%
Peak brilliance	> 10^{20} ph/(s•mm^2•mrad^2•0.1%)
Spot size	10-30 µm

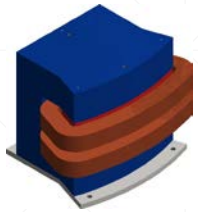


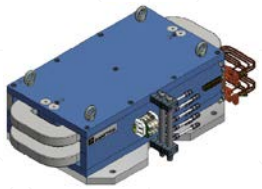
Electron beam params	Value
Electron energy	75 - 720 MeV
Bunch charge	25 - 400 pC
N. of bunches / pulse	32
Bunch distance	16 ns
Bunch length	100 - 400 µm
Energy spread (RMS)	0.04 - 0.1%
Norm. emittance	< 0.5 mm • mrad
RF Rep. rate	100 Hz

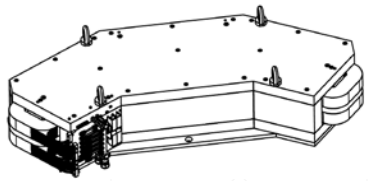
ELI-NP GBS – Magnets Overview

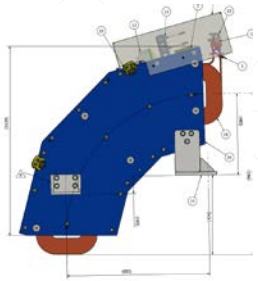

Dipole A

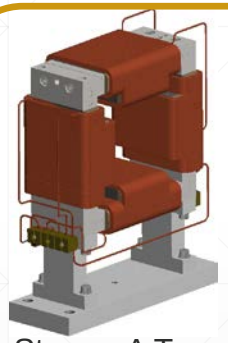

Dipole B

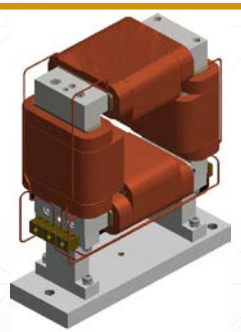

Dipole C

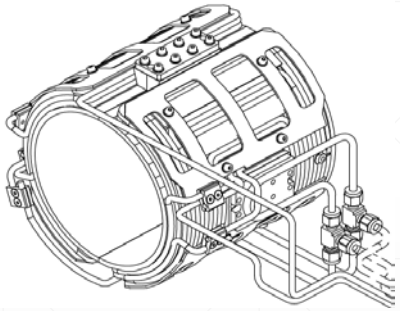

Dipole D

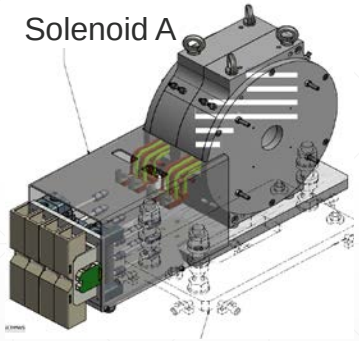

Dipole F

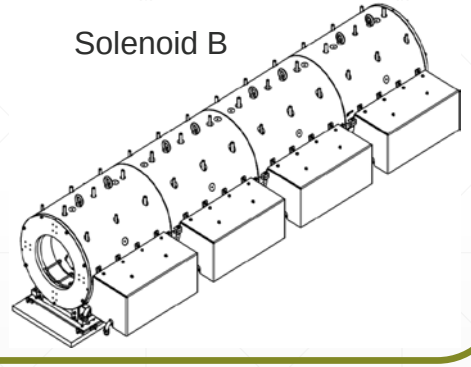

Dipole G


Steerer A Type

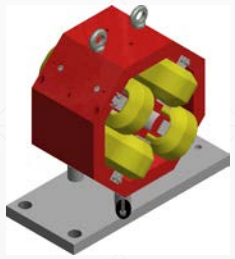

Steerer C, D, E, F

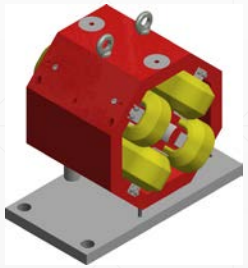

Steerer B1, B2 Type

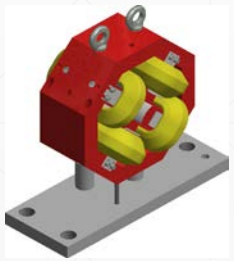

Solenoid A

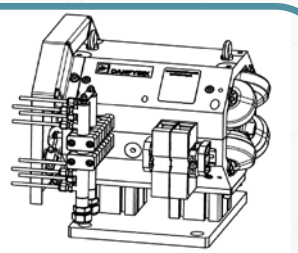

Solenoid B

Magnet	QTY
Solenoids	2
Dipoles	9
Quads	37
Steerers	30
TOTAL	**78**


Quadrupole B


Quadrupole C


Quadrupole D

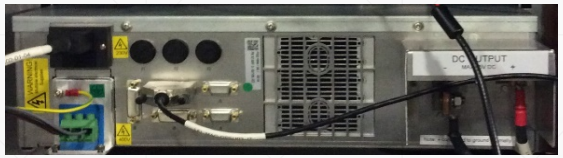

Quadrupoles E, F*

- All the magnets provided by Danfysik
- All the magnes operate in DC and have a full iron yoke
- All the magnets are water cooled except for the steerers
- The magnet flux density goes from 33 G (steererA) to 1,6 T (Dipole B)
- The quadrupole gradients are 18T/m for B,E types and 30 T/m for the others
- All the dipole and quadrupole aperture gap are 30 mm

ELI-NP GBS – Power Supply Overview

Sigmaphi START 11

Sigmaphi START 2

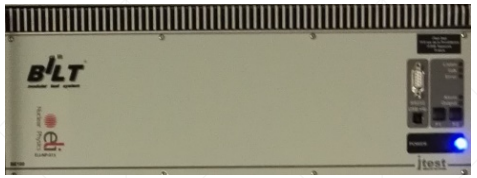


PERFORMANCE		POWER SUPPLY	REQUESTED
Output nominal voltage		55 V (START11) 15V (START 2)	
Output nominal current		200 A (START 11) 135 A (START 2)	
Operation mode		DC constant	DC constant
Output current ripple	1 Hz --> 1 kHz	< 20 ppm	150 ppm
Output current resolution		5 ppm	120 ppm
Output stability at Nom current	100s --> 8h	±100 ppm	±150 ppm
Reproductibility		±50 ppm	±200 ppm
Cos Φ	for P > 50% Pmax	>0.9	0,92
Efficency	@30% P @ full power	>80% >90 %	>85% @ nominal voltage input

Magnet	Quantity
START 11 (Dipoles and Solenoid coils)	16
START 2 (Quadrupoles)	37

ELI-NP GBS – Power Supply Overview

iTest Bilt BN 100



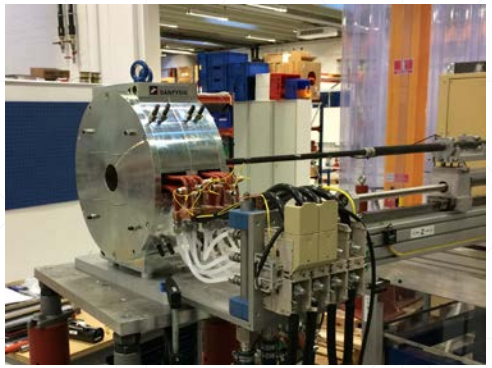
PERFORMANCE		BE2811	BE2812	REQUESTED
Output nominal voltage		18V	8V	
Output nominal current		5A	15A	
Operation mode		DC constant	DC constant	DC constant
Output current ripple	1 Hz --> 1 kHz	7 ppm	7 ppm	150 ppm
Output current resolution		14 ppm	8 ppm	120 ppm
Output stability at Nom current	100s --> 8h	24 ppm	24 ppm	±150 ppm
Reproductibility		±60 ppm	±60 ppm	±200 ppm
Cos Φ	for P > 50% Pmax	>0.9	0,9	0,92
Efficency	@30% P @ full power	>80% >90 %	>80% >90%	>85%

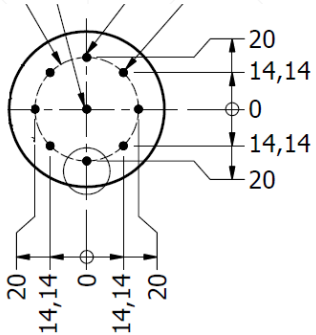
iTest BE 2811

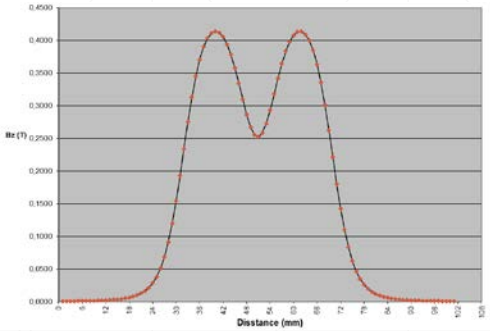
iTest BE 2812

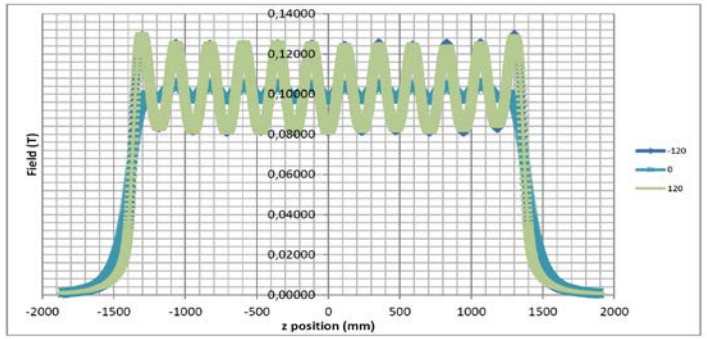
Magnet	Quantity
START 11 (Dipoles and Solenoid coils)	16
START 2 (Quadrupoles)	37
iTest	50
TOTAL	**103**

ELI-NP GBS – DANFYSIK SOLENOIDS FAT







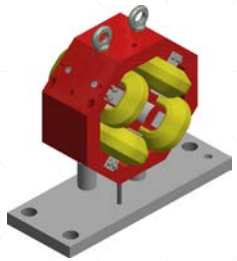


MAGNETIC MEASUREMENTS				
Magnet	Good Field Radius	Parameter	Desired	Measured
Solenoid A	20 mm	Integrated Field Homogeneity	1E-3	2,42E-4
Solenoid B	120 mm	Integrated Field Homogeneity	1E-3	6,50E-04

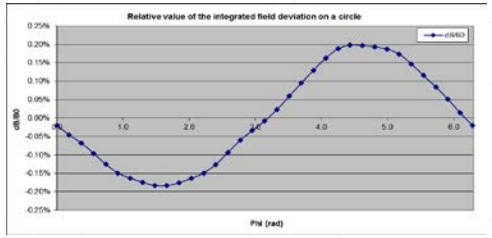
- Longitudinal field component has been measured in ++ and +- configuration
- Excitation curve
- Coils test:
  - Inter-turn insulation
  - Ground insulation
  - Electric parameters measurements
  - Hydraulic tests
  - Thermo-switch test

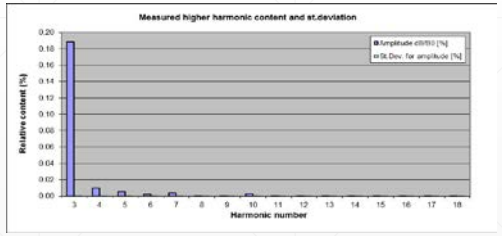
The solenoids fulfills the requirements on all accounts.

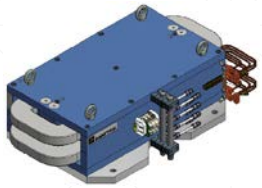
ELI-NP GBS – DANFYSIK OTHER FAT



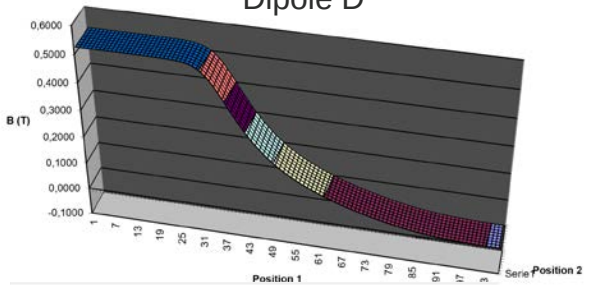
Quadrupole D

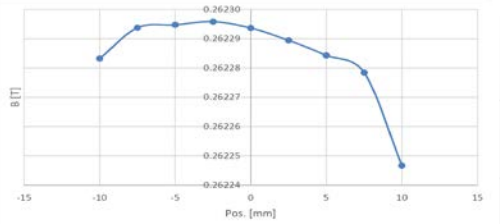


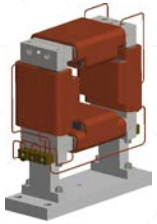




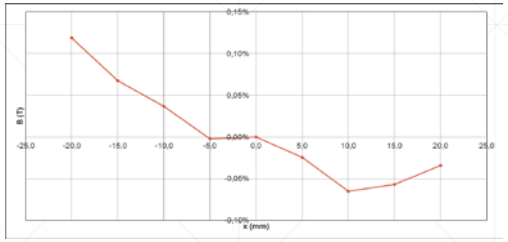
Dipole D

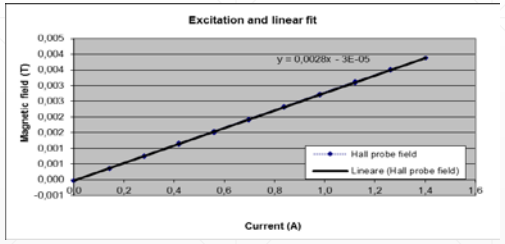






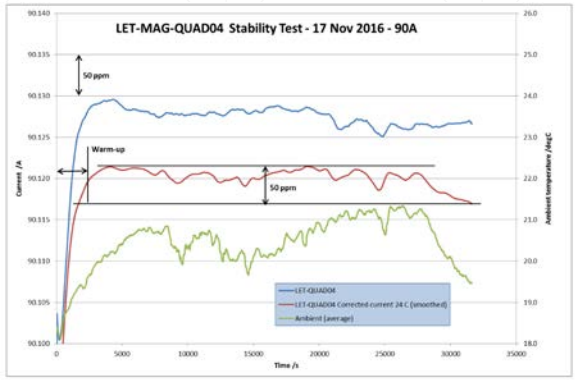
Steerer A Type

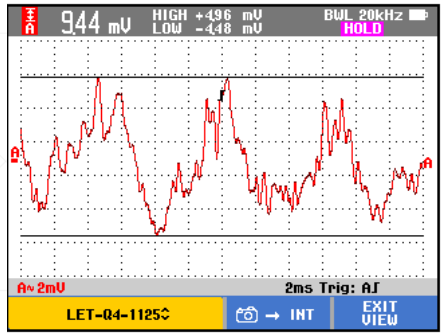




- Check Danfysik measurements for LNF approval
- All the magnets have been accepted by LNF except a last quadrupole type D
- These FAT include also coil test

Magnets and Power supply tests at STFC Lab.





Ext Filter 1,1 kHz; Vpk-pk =9,4 mV

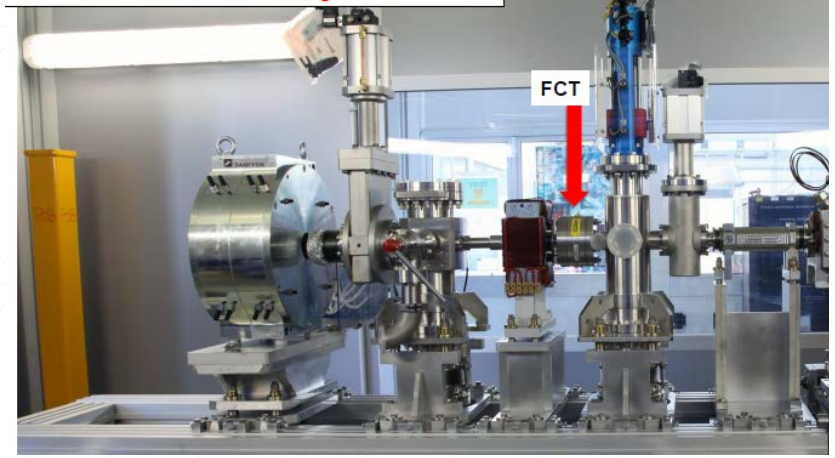
Module 8

Test Type	Desired	START 11 Meas.	START 2 Meas.
Ripple	150 ppm	10 ppm	7 ppm
Resolution	120 ppm	27 ppm	38 ppm
Earth leakage	-	20 mA	100 mA
Efficency	85 % (full rated load)	77% (@51% rated load)	86% (@48% rated load)
1PHASE LINE VOLTAGE VARIATION		Voltage dip 100% Duration 0.2 s	Voltage dip 100% Duration 0.2 s
3 PHASE LINE VOLTAGE VARIATION		Voltage variation 45% Duration: few seconds NO output variation	Voltage variation 45% Duration: few seconds NO output variation
Reproducibility	±200 ppm	100 ppm	120 ppm
Long Term Stability	±150 ppm	50 ppm peak to peak	110 ppm peak to peak

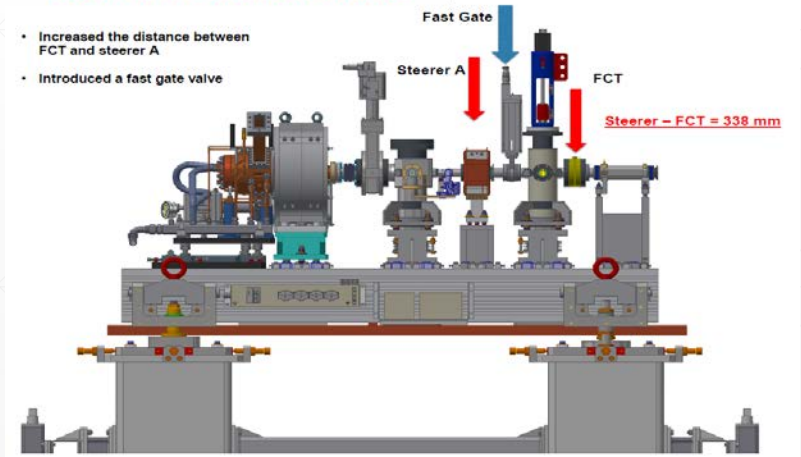
- Modules M4 and M8 tests witnessed by LNF staff
- All power supplies types have been tested
- All the magnets and power supply tested up to now, show a fulfillment with the requests

Simulations – BCM + Steerer

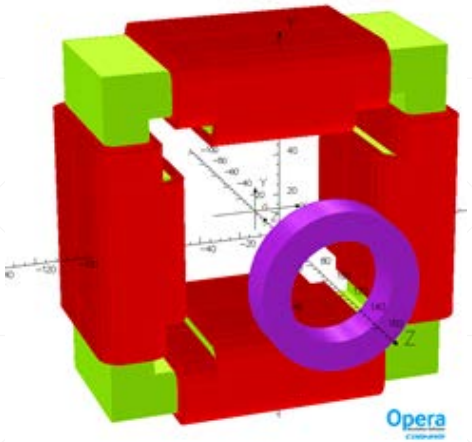
Module M1: old layout

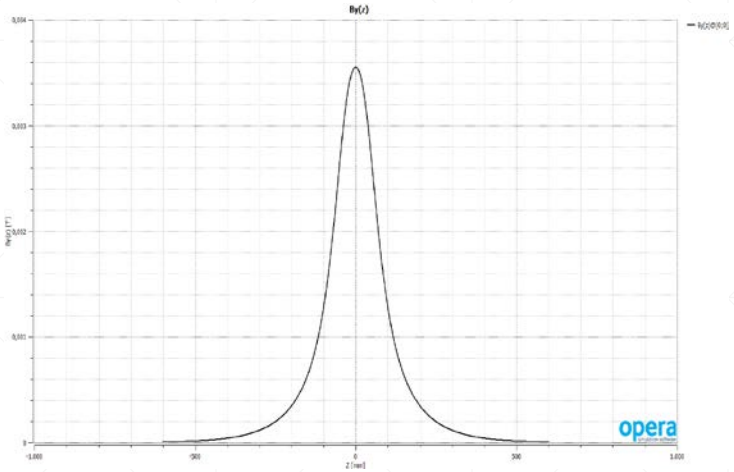


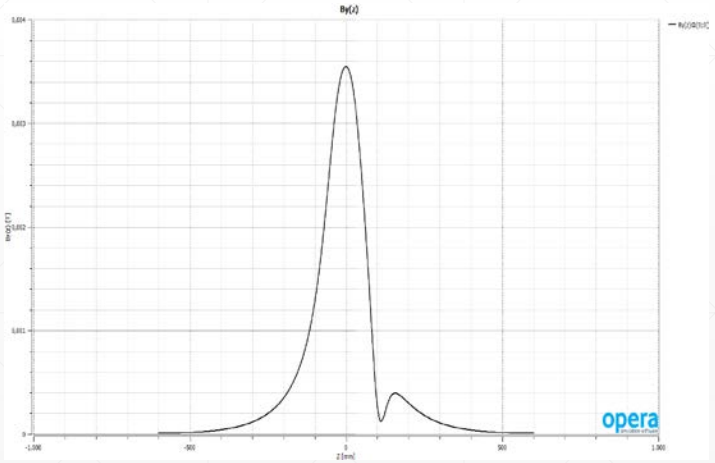
Module M1: present layout



- Increased the distance between FCT and steerer A
- Introduced a fast gate valve







- FCT magnetic toroid affects steerer type A fringe field
- Steerer type A is the Gun energy spectrometer →High performances
- No maximum variation (33G)
- No integral field quality variation (1E-3)
- Field integral variation of about 10%

FCT MOVED DOWNSTREAM

3D Field Maps in *elegant* code

The goal is to achieve as much as possible a realistic model for ELI-NP machine.
3D field maps from Opera 3D files based on company design and fitted with measurements perormed during the FAT.
Two evaluation:

- Fringe-fields evaluation inserting field integral according to K.Brown models [1]
- 3D field maps insertion in tracking code *elegant*

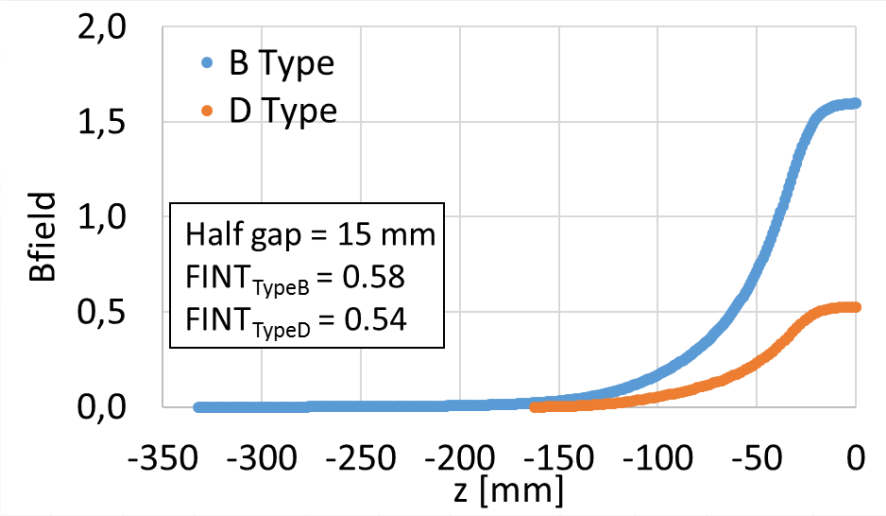
Dipole Fringe Field Evaluation (i)

The Model

- Fringe fields of type B and type D dipoles Fringe field contributions evaluated with Elegant simulations
- Fringe field is characterized by the Fringe-field INTegral (*FINT*) based on the «K. Brown's Model» (*)

$$k_1 = FINT = \int_{-\infty}^{+\infty} \frac{B_y(s)(B_0 - B_y(s))}{g \cdot B_0^2} ds$$

Where $g = 2 \cdot HGAP$ is the dipole gap diameter.



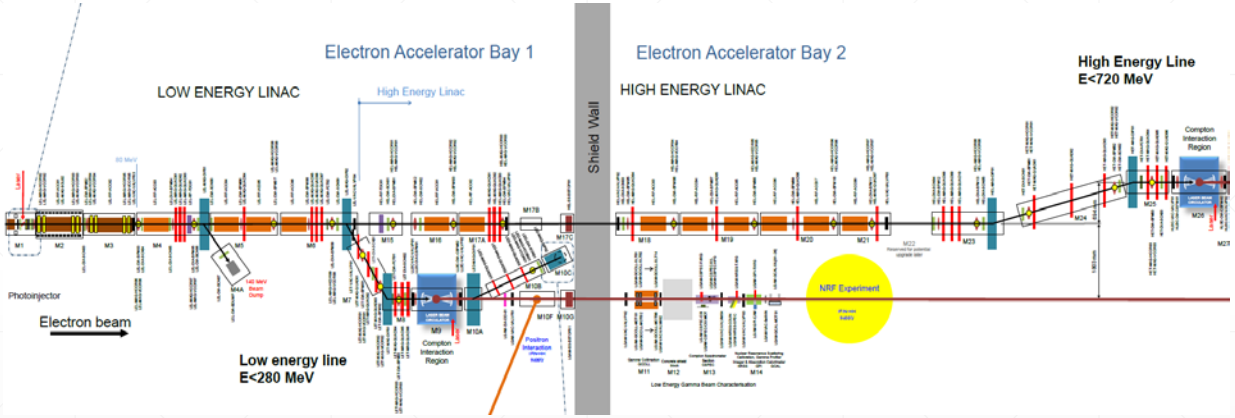
Default FINT value in *elegant* code is 0.5

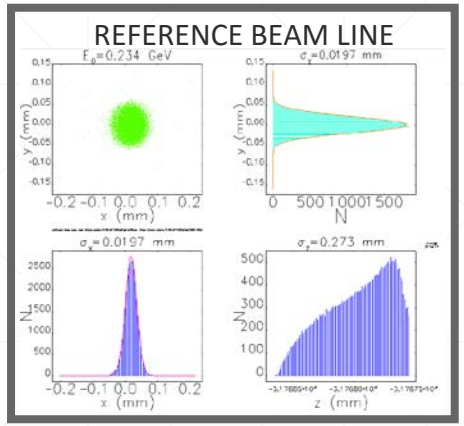
[1] K. Brown, "A First and Second Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers," in *SLAC 75, Revision 3*, SLAC, 1972.

3D Field Maps in *elegant* code

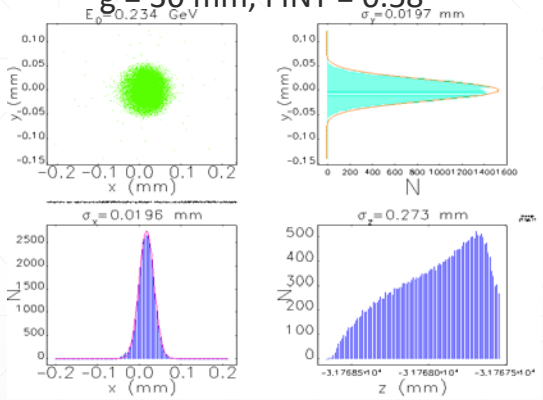
Dipole Fringe Field Evaluation (ii)

Low Energy Beamline nominal working point: 2.0 MeV
The beamline has been newly matched to obtain the nominal parameters.





g = 30 mm, FINT = 0.58

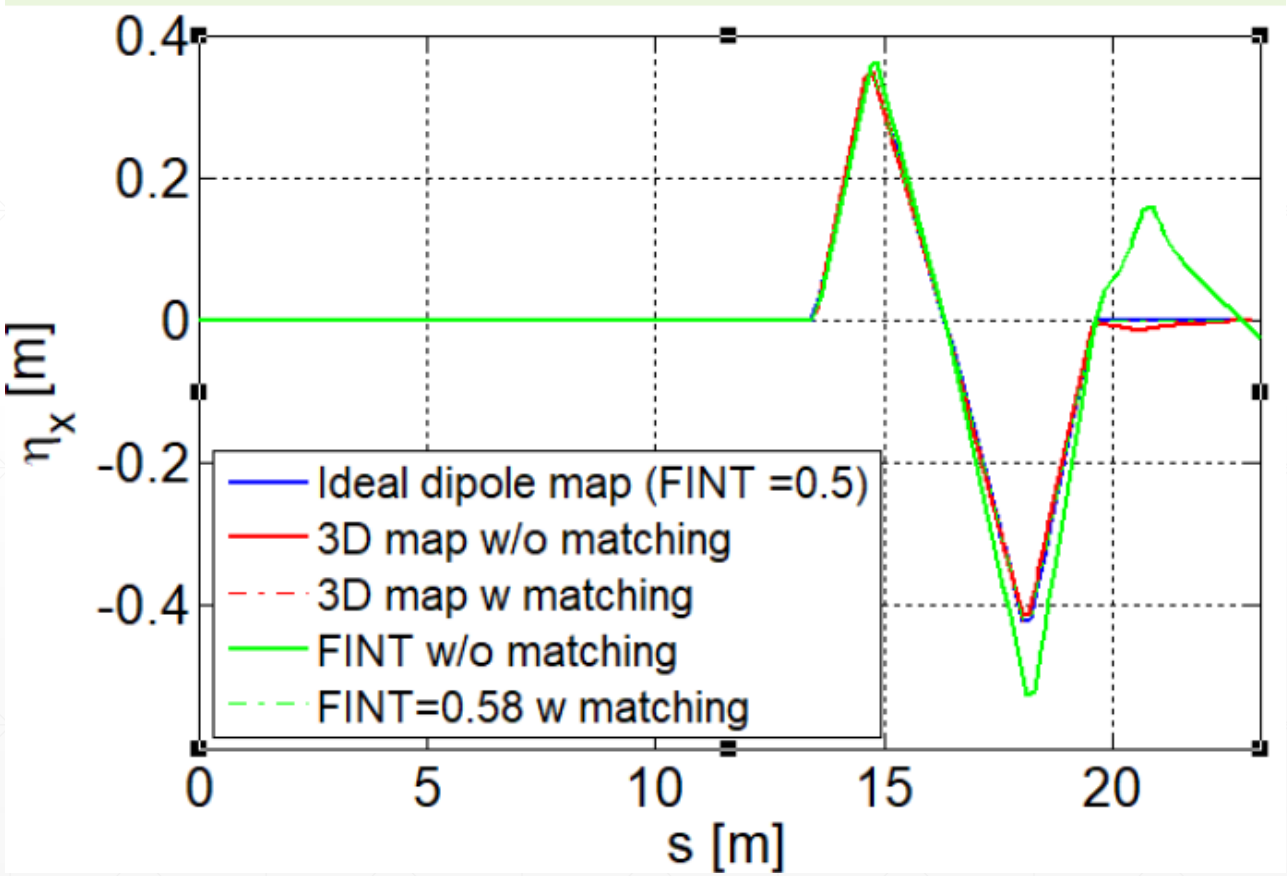


Horizontal local dispersion <2,5 mm

- Matching at interaction point with dogleg quads (nullify dispersion)
- Last triplet before the dump used to adjust the transverse distribution at interaction point
- Manually matching → *elegant* has tools to optimize the distribution

3D Field Maps in *elegant* code

3D field maps insertion in tracking code *elegant*



Future Works

Beam Test Facility2 Project

- DC01 technical specification completition
- Follow magnet production (starting from DP01)
- Witness to FAT
- Magnetic Measurements to perform at LNF
- Installation of the magnets

ELI-NP Gamma Beam Source Project

- Check of last quadrupole magnetic measruments
- Installation of the machine (next year)
- Test on magnets and power supply after the installation
- Continue the insertion of 3D Field Map in *elegant* code of all the magnets of both low and high energy line

Thank you for the attention