Compact permanent magnet spectrometer for CILEX/APOLLON

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- Introduction
- Design and construction of a permanent dipole magnet
- Measurement and characterization of the magnet as a spectrometer at CILEX
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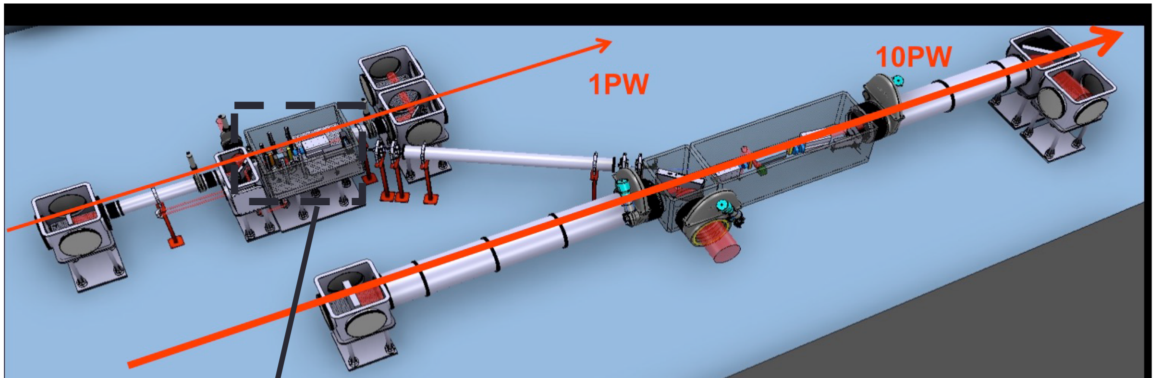
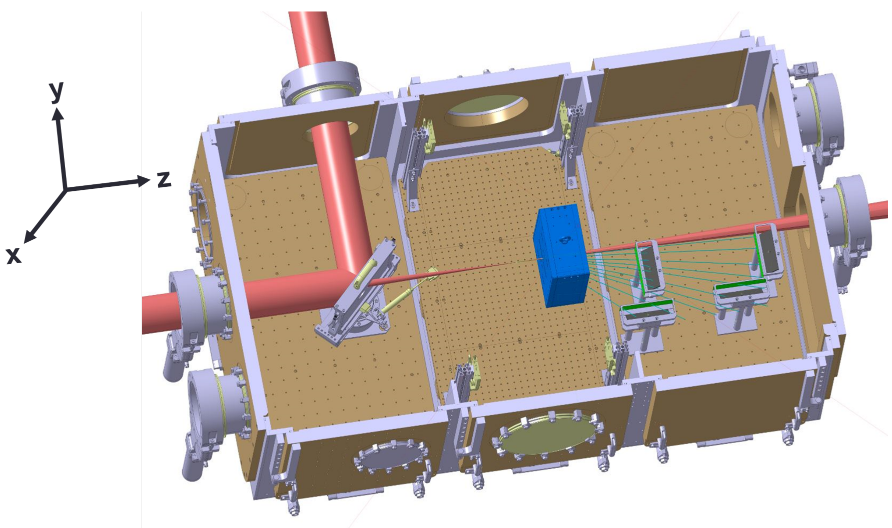
CILEX project

GALOP: Groupe d'Acceleration Par Laser et Ondes Plasma





Electron acceleration
using PW lasers

Electron transfer line for
multi-stage acceleration

LLR (A. Specka) coordinates first
experiments and is responsible for
electron spectrometer design

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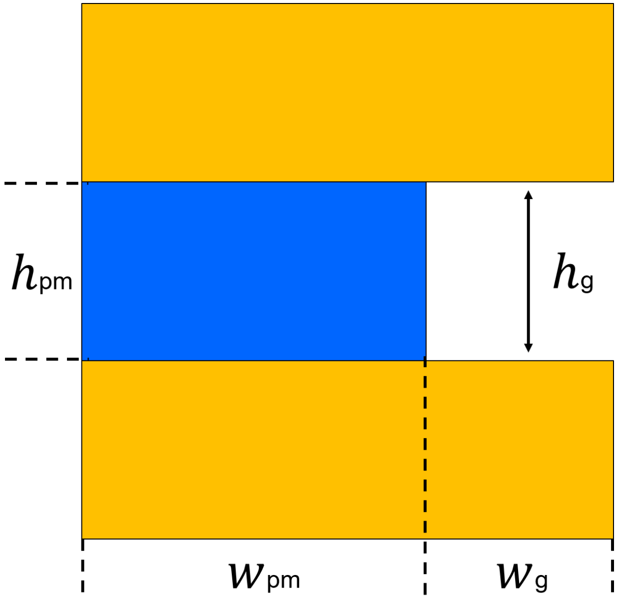
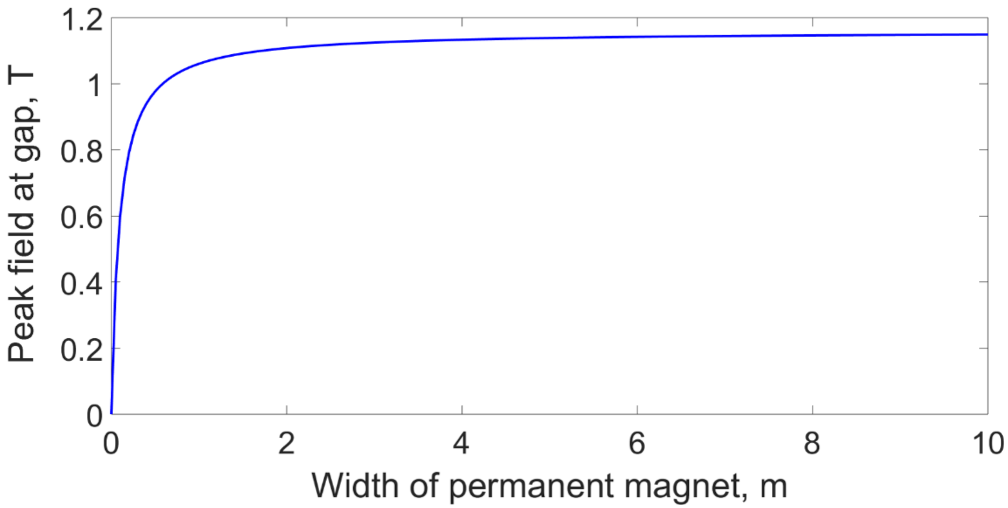
Magnet design: Introduction



2D view of a C shaped dipole with a permanent magnet shown in blue and steel/iron in yellow colors.

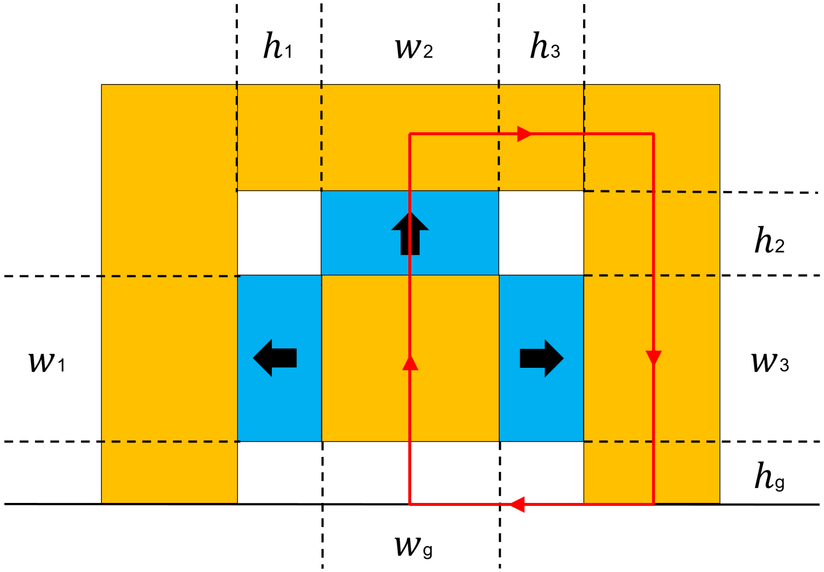
$$B_g = -\frac{B_r w_{pm}}{w_g + \frac{\mu_r h_g w_{pm}}{h_{pm}}}$$



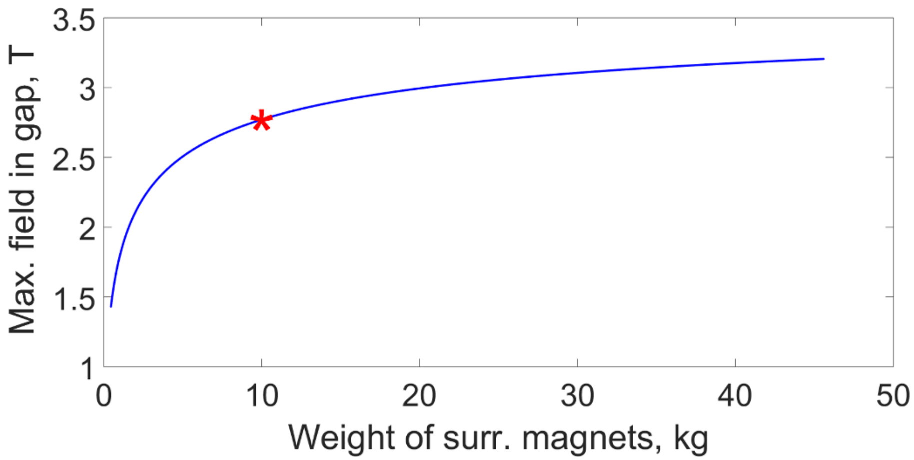
Peak field in the gap as function of permanent magnet width for the gap height of 0.1 mm.

Peak field in the gap cannot exceed remnant induction field of the magnet !

Design of PM dipole: Analytic estimation



Schematic view of top half of H shaped magnet. Iron parts are shown in yellow, and surrounding magnets blue colors.



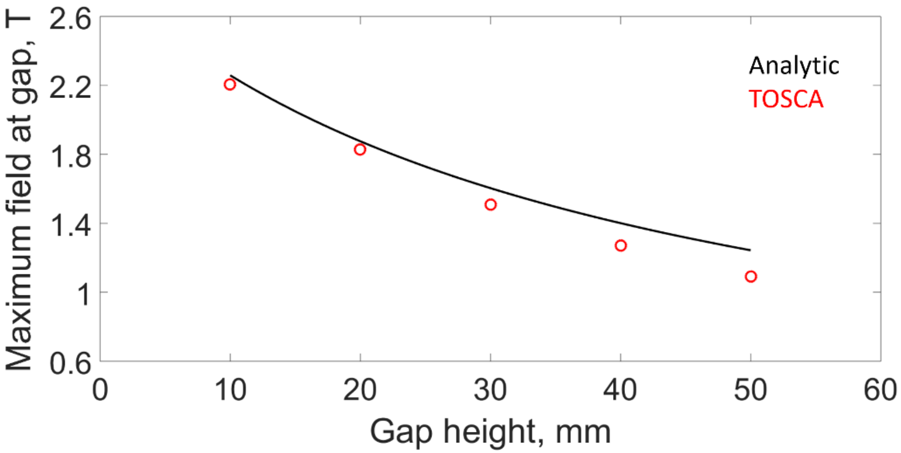
Peak magnetic field vs. total weight of the surrounding magnets. Red asterisk represents the values assuming 51 mm square pole sizes ($w_{pole}=w_2$) for 10 mm gap height ($2h_g$).

$$B_g^* = \frac{1}{h_g} \frac{(w_1 + w_2 + w_3)B_r}{\left(\frac{w_g}{h_g} + \frac{\mu_r w_1}{h_1} + \frac{\mu_r w_2}{h_2} + \frac{\mu_r w_3}{h_3} \right)}$$

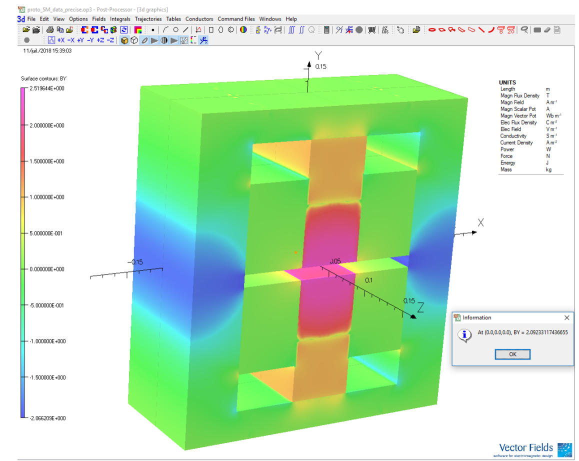
** Bruce C. Brown, Fermilab/Conf-96/273, 1996.*

Design of PM dipole: Numerical calculation

$$h_1 = h_3 = 5.08cm \quad w_1 = w_3 = 7.08cm \quad h_2 = w_2 = 5.08cm$$



Magnetic induction in the gap for various gap sizes. Red dots: TOSCA calculations. Black curve: analytical estimation applying a factor 2.26/2.96.



TOSCA model of magnet with 2.09 T in gap (2.18 T pole saturation field).

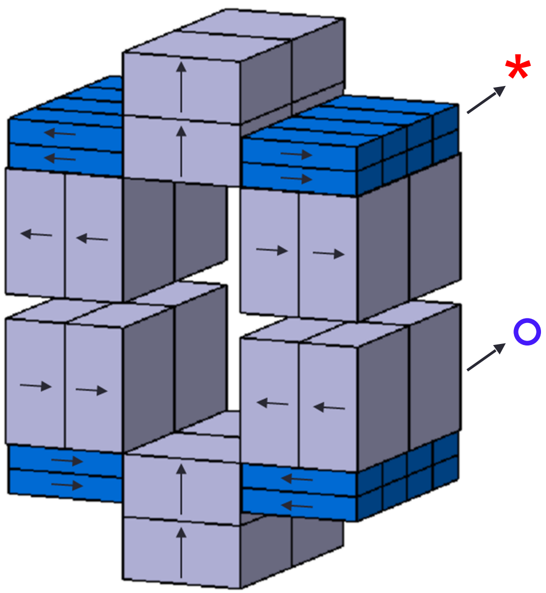
- **Details**

The pole pieces are made of iron (~2.26 T saturation field)
NdFeB 40 magnets are used to construct the dipole (Br ~ 1.24 T)
A fixed ratio (20) of magnet length to gap height in TOSCA

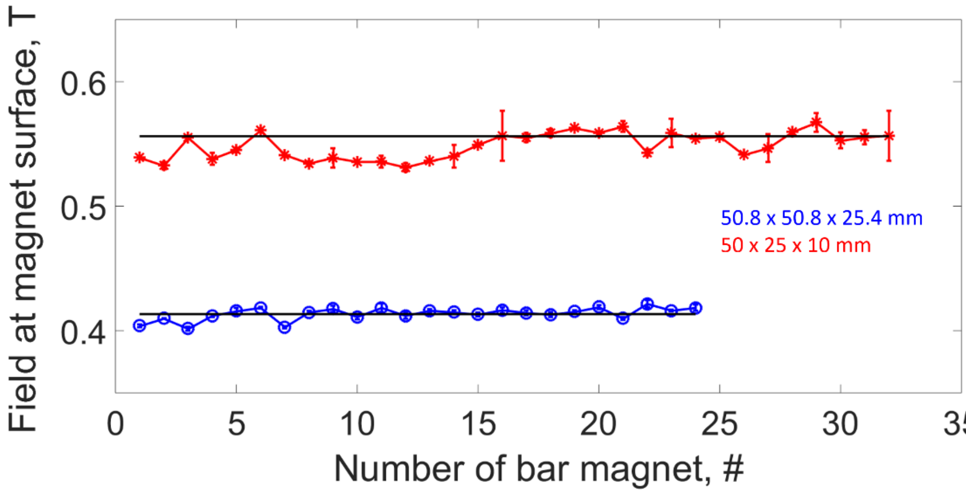
Summary of magnet characteristics .

Parameter	Value
Gap height, mm	10
Peak field at gap center, T	2.092
Horizontal GFR / FGR, mm	50 / 150
Length x height x width , mm	100 x 260 x 240
Weight, kg	~ 50

PM dipole: Construction



Overview of different block magnets used to assembly the dipole. Arrows on the blocks illustrate directions of magnetization.



Measured magnetic induction at the surface of two types of neodymium magnets. For each case, black lines represent analytically estimated field value assuming 0.5 mm offset of Hall probe sensor from the magnet surface.

Geometry of iron poles will smoothen field inhomogeneities once the pole material is saturated !

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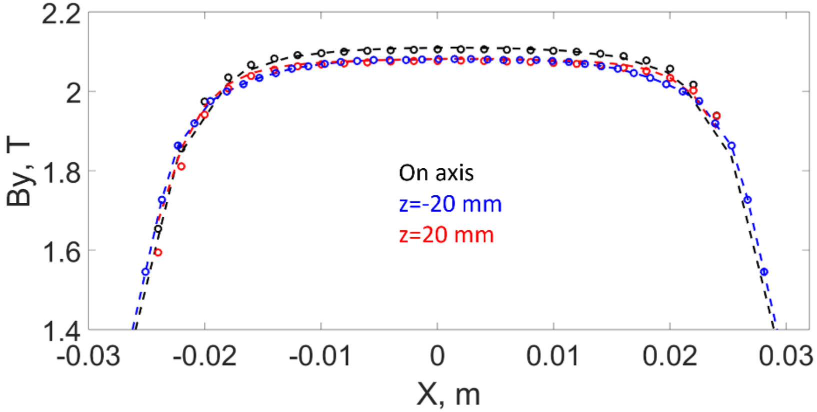
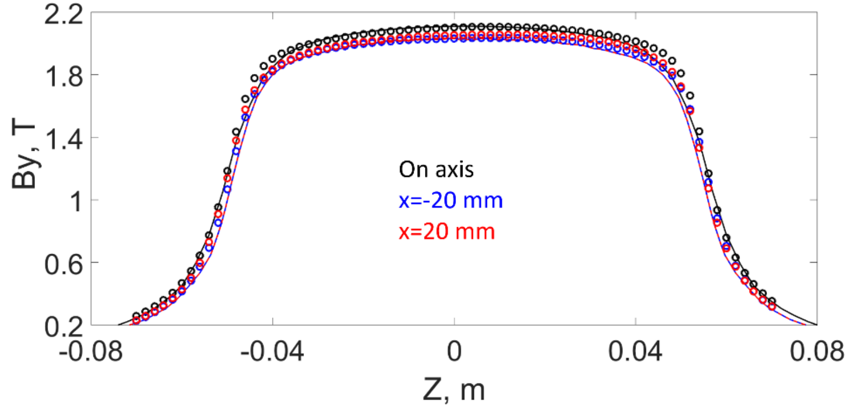
PM dipole: Measurements I

Measurement bench at LLR.

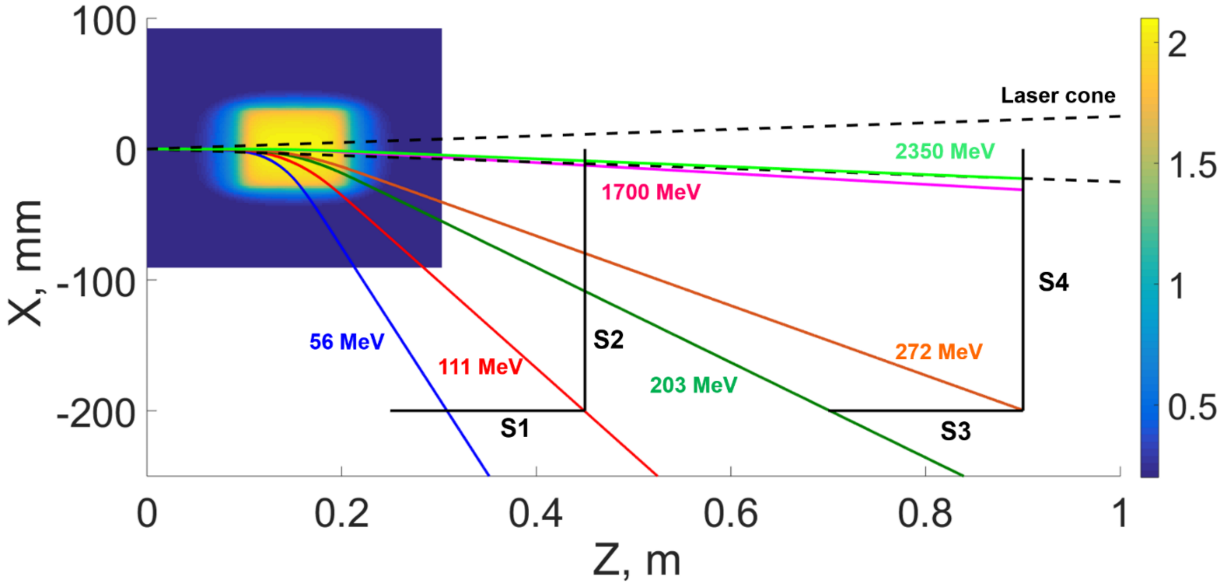
~ 1 % scaling factor applied to match the measured and simulated field values !





On and off-axis main component field profiles along horizontal and longitudinal directions. For each case dots correspond to the measured and curves to the simulated field values.

PM dipole as a spectrometer II



Reference electron trajectories and corresponding screen positions/ orientations for energy measurement inside the interaction chamber of CILEX.

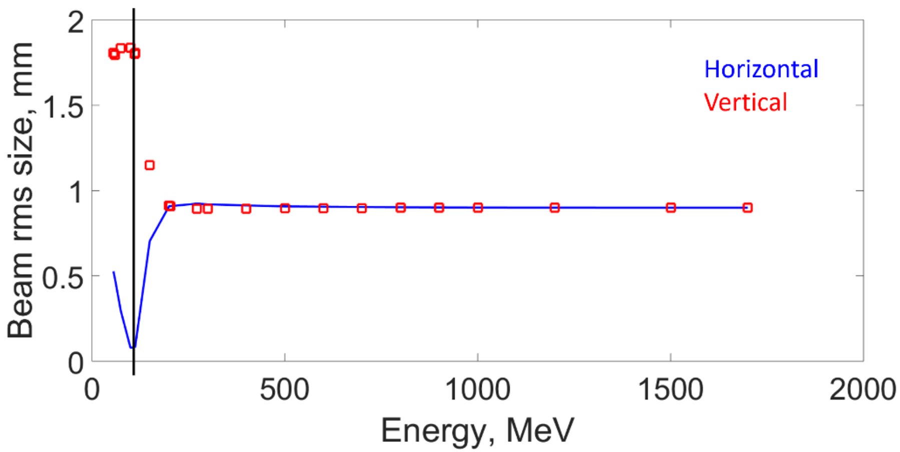
E-beam parameters used in ASTRA

Parameter	Value
Charge, pC	10
Peak current, kA	1.2
Energy, MeV	56 - 2350
Transverse rms size , μm	2.5
Rms divergence, mrad	2

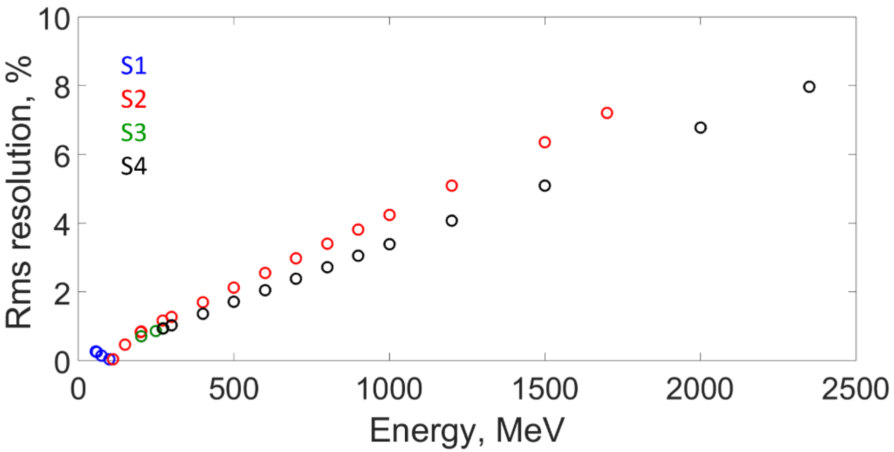
56 MeV → the lowest energy exiting magnet from side

2350 MeV → the highest energy measurable out of 50 mrad divergent laser cone

Beam size and resolution



Beam rms transverse sizes at screen positions of S1 and S2. Blue line: horizontal, red rectangles: vertical.



Rms energy resolution estimated at different screens for 2 milliradians electron beam divergence.

- ❑ Electrons of energies below 200 MeV are strongly affected by the fringe field (FF) effects
- ❑ The FF effects may be modified by adjusting the magnet laterally

≤ 8 % resolution over the whole energy range !

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Summary

- 2.1 Tesla PM dipole was designed measured and characterized as a spectrometer for CILEX
- Very good agreement (~ 1 %) between predicted and realized field values
- The magnet will cover energy range of ~ [0.06-2.35] GeV with less than 10 % resolution (without additional focusing)

Thank you !