

International

JON Collider

laboration



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NC magnet configuration (dipoles and quadrupoles)

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Dipole magnet design

- Dipole Topologies
- Design Specs & Objectives of H-Type Dipoles
- H-Type Dipole Dimensioning Model
- H-Type Dipole Optimal Design environment
- Optimal Design Scenarios, Objectives & Constraints
- Results

Quadrupole magnet design

- Analyzed configurations
- Electromagnetic design optimization
- Comparison of the different configurations



Outline



Dipole magnet design

- Dipole Topologies
- Design Specs & Objectives of Dipoles Unipolar supply
- Dipole Dimensioning Model
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Dipole topologies

CERN





- From initial magnet optimization with specifications:
 - Magnetic field in the aperture 1.8 T
 - Good field region (30 mm * 100 mm)
 - 1 ms ramp from -1.8 to + 1.8 T (Bipolar)
- Identification of 2 magnet topologies minimizing the total magnetic energy



Pole material:



Yoke material: M235-35A

Hourglass Topology



Design Specs & Objectives of Dipoles





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Unipolar Supply Converter Topology



-) Physics-based specifications Air gap Dimensions
- Extraction & Injection Inductions
- Spatial distribution of air gap induction
 - $t_r \& T_{cycle}$
 - $\frac{dB}{dt}$ constant during t_r
- Vacuum chamber dimensions & Ti coating



Optimal Design Objectives: Cost & Losses

- Magnet:
 - Minimize Mass Copper & Magnetic Material
 - Minimize Copper& Magnetic losses
- Power converter:
 - Minimize Apparent Power V x I (kVA)
 - Best V vs I switch technology
- Minimizing magnet inductance (total stored energy) ensures minimization of Converter apparent power
- For fixed required energy, magnet coil turns ensure V vs I adaptation

Dipole Dimensioning Model





• Model structured as an inverse problem \rightarrow well suited for optimization-driven sizing.

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- Electromagnetic model based on combined 2D FEA: magnetostatic (saturated or linear) & timeharmonic simulations.
- Thermal cooling model based on FEA loss input + analytical water-cooling model for hollow conductors

Dipole Dimensioning Model









Dipole Optimal Design Environment





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Optimal Design Scenarios, Objectives & Constraints



- Different magnet optimization scenarios can be evaluated within this versatile design environment, using multiple decision input & performance output variables to compute the objective & constraint functions of the optimization problem.
 - Performance objectives can include: Minimization of magnet inductance Minimization of the total mass of active components – Minimization of total losses – etc.
 - Possible design constraints include:- Thermal cooling capacity- Geometry-related limitations- Material or fabrication constraints - etc.

Optimization example:

 Objective: 	 Subject to constraints: 	$B_{airgap} = B_{spec}$ $B_{yoke} \le 1.2 \text{ T}$ $B_{pole} \le 1.7 \text{ T}$
Minimize the total mass of a	ctive components:	$\Delta \theta_{\text{water}} \leq 2.5 \degree \text{C}$
min <i>M</i> _{total}		$\tau_{\rm th} \le \frac{1}{5} (T_{\rm cycle} - T_{\rm p})$ Re ≥ 5000

• 6 Decision variables:

```
\theta, e_{pcul}, h_{ctotin}
w_{ctotin}, k_{jg}, e_{pcond}
With
J = 18A/mm^2
```



Optimal Design Results Airgap width = 60, 80,100 mm







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Analyzed quadrupole configurations







- Main requirements for the quadrupole magnets design
 - Field gradient about 30 T/m, but higher gradients would also be desirable
 - **Magnetic field homogeneity** within 10 x 10⁻⁴ in the good field region
 - **Fast Ramps** in the order of 1 ms (values depend on the considered RCS).

Main objectives of the design

- Limit the magnetic stored energy (crucial design specification for the supplied power)
- Limit the total losses (iron + copper)





Conductors parallel to the yoke for Cu loss reduction (8 bars) Conductor 6.0 Magnetic poles Ferromagnetic Quadrupole magnet for a rapid cycling yoke National Laboratory, Upton, NY, USA

- **Conductors** parallel to the poles, with reduction of the leakage flux (8 bars)
- Yoke with shaved corners to reduce Fe losses

synchrotron, H. Witte⁺, J. S. Berg, Brookhaven Proceedings of IPAC2015, Richmond, VA, USA

MAP Configuration #1





 Conductors parallel to the poles, with reduction of the leakage flux (4 bars only)



Conductors with trapezoidal shape to fill the empty spaces between poles



Poles shaping tangential to the air gap region to reduce the magnetic energy





Design methodology









Optimization procedure

• An optimization procedure was applied to minimize the following objective function:

 $\min F(\boldsymbol{a})$ $\boldsymbol{a}_{\min} \leq \boldsymbol{a} \leq \boldsymbol{a}_{\max}$ $G(\boldsymbol{a}) \leq 0$

 $G(\boldsymbol{a}) = 1 - \frac{|gradB|}{gradB_{ref}}$ with gradBref set to 30 T/m

 α = vector of the adimensional geometric parameters describing the magnet

ErrB = field error indicator

 $F(a) = c_1 Em + c_2 G(a)^2 + c_3 ErrB$

Em = total stored magnetic energy

- The results presented here correspond to the choice of c1 = 1, c2 = 0, c3 = 0
- Two different optimization methodologies were adopted, namely a deterministic method and a genetic algorithm



Design methodology





Gradient and field error calculation





 The field computations were performed in FEMM. The optimization is performed in DC, while the AC loss computation at 500 Hz.



Design parameters: *Lgap, d, Jc, gradB_ref* pole shape

Design variables:

 $\alpha_b=bp1/Lgap (\alpha_b \ge 1)$ $\beta_b=bp2/bp1 (\beta_b \le 1)$ $\alpha_c=wc/Lgap$ $\beta_c=hc/wc (\beta_c \le 1)$ $\alpha_y=wy/Lgap$

Lgap [mm]	gradB [T/m]	errB	Mag. Energy [J/m]	wc [mm]	hc [mm]	wy [m1m]
40	30.0	0.012	443	39.8	6.1	17.6
60	30.0	0.016	2416	63.2	10.1	31.9
80	30.1	0.005	26053	104.3	30.1	92.1





Results of Configurations #2, #3, #4



Field gradient set to 30 T/m, Lgap set to 60 mm

Em = 1052 J/m



Bx on x axis calculated 1.0 desired 0.8 0.6 Bx [T] 0.4 0.2 0.0 0.010 0.015 0.020 0.025 0.000 0.005 0.030 v coordinato [m]



Em = 831 J/m



Comparison of the different configurations



- Field gradient set to 30 T/m
- Configuration #1 is the best in terms of total losses, due to the conductor placement
- Configuration #4 exhibits the lowest magnetic energy, due to the small air region outside of the good field area
- Configuration #3 exhibits a good tradeoff between losses, magnetic energy and field error and was selected for further studies

Lgap [mm]	Layout	Mag. Energy [J/m]	errB	total loss [J/(m*cycle)]
	1	443	0.012	42
40	2	210	0.051	121
40	3	228	0.015	122
	4	163	0.041	98
	1	2416	0.016	212
60	2	1052	0.046	432
00	3	1110	0.015	408
	4	831	0.035	352
	1	26053	0.005	2772
80	2	3665	0.042	1544
00	3	3454	0.015	990
	4	2789	0.031	1125





Lgap set to 60 mm, Jc set to 20 A/mm²

gradB [T/m]	errB	Mag. Energy [J/m]	total Loss [J/m/cycle]
30	0.015	1108	407
35	0.016	1637	554
40	0.015	2318	731

gradB = 35 T/m



- The magnetic energy of the 40 T/m quadrupole seems too high, but 35 T/m seems feasible
- For comparison, the magnetic energy of the dipoles is about 5 kJ/m



Conclusions for the quadrupole studies



- Four different configurations of resistive quadrupole magnets were optimized for three values of the air gap diameter.
- All the optimized configurations achieve the specified field gradient of 30 T/m. Even a higher gradient, up to 35 T/m is attainable without exceedingly high energy and losses.
- The most suitable configuration in terms of losses is #1 (MAP), in terms of magnetic energy #4 and a tradeoff of loss, magnetic energy and field quality is found for #3.
- Further investigations are required to reduce the field error.













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Design methodology





Deterministic algorithm

COBYLA, based on linear approximations

COBYLA is an implementation of Powell's nonlinear derivative-free constrained optimization that uses a linear approximation approach. With this algorithm we found difficulties in respecting the constraint on the gradient, that was therefore added to the objective function.

Python + FEMM **Genetic algorithm** Random generation of the initial population Vector of variables characterizing (a_c, a_y) each individual $\delta_c = 0$ Cycle of iterations 2 Evolution process up to 60 generations. Probability of mutation 0.5. Probability of crossover 0.7. Fitness evaluation for each individual 3