

# Warm magnets for LHeC

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14 Jun. 2012



- Ring-Ring magnets
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  - quadrupoles
- Linac-Ring magnets
  - dipoles
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- Conclusion and discussion

Many thanks to Davide Tommasini, Miriam Fitterer and Alex Bogacz for the optics, the colleagues of TE-MSU and BINP that built and measured the dipole models, and Neil Marks.

# RR dipoles: requirements and challenges



number of magnets	3080
free aperture	90×40 mm <sup>2</sup>
flux density	0.0127 T (10 GeV) to 0.0763 T (60 GeV)
magnetic length	5.35 m
field quality	$2 \cdot 10^{-4}$ in GFR of $\pm 10 \times 6$ mm <sup>2</sup>
field reproducibility at inj.	better than $\pm 0.1 \cdot 10^{-5}$ T

## LEP main dipoles:

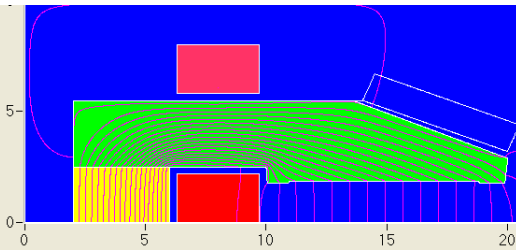
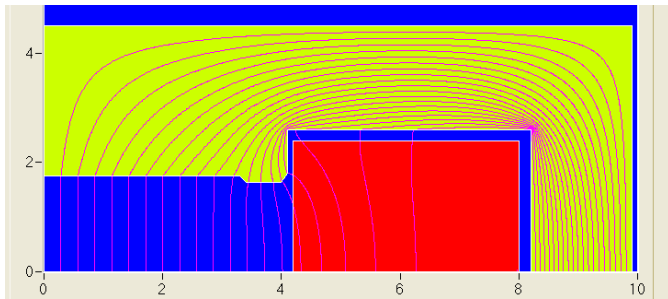
5.75 m per core × 3280 cores (steel/concrete length 27%)

gap 100 mm, flux density 0.0220 T (20 GeV) to 0.1100 T (100 GeV)

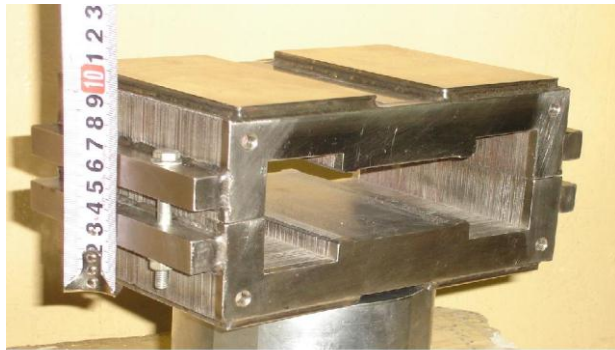
## Challenges

- compact and light magnets, to fit in the existing LHC tunnel
- sufficient mechanical stability in a light structure
- compatible with emitted synchrotron radiation
- satisfactory field homogeneity from injection to collision energy
- satisfactory field reproducibility from cycle to cycle

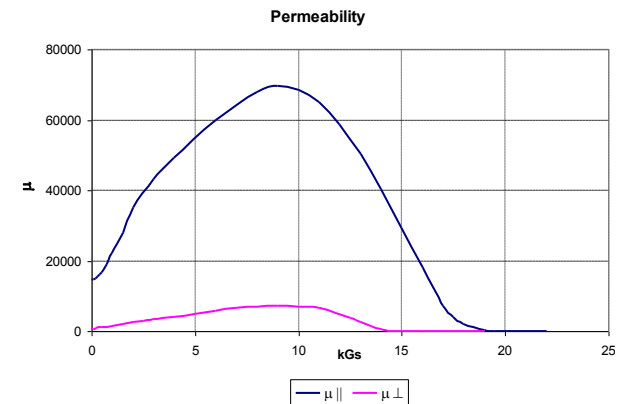
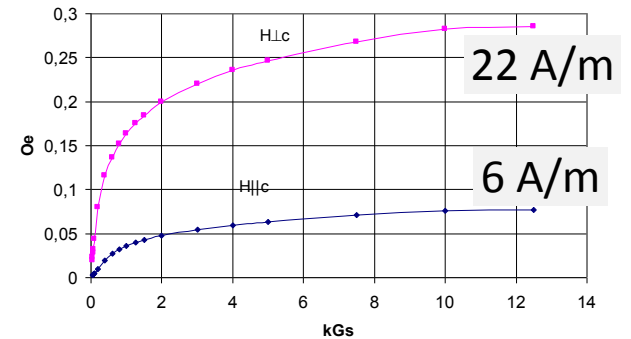
# RR dipoles: BINP models



3408 grain oriented steel  
0.35 mm thick laminations



The coercive force depending on the magnetizations field.



After cycles of different amplitude, the remanent field is of about 1 Gauss in all cases. The measured reproducibility of the injection field is about  $\pm 0.075$  Gauss.

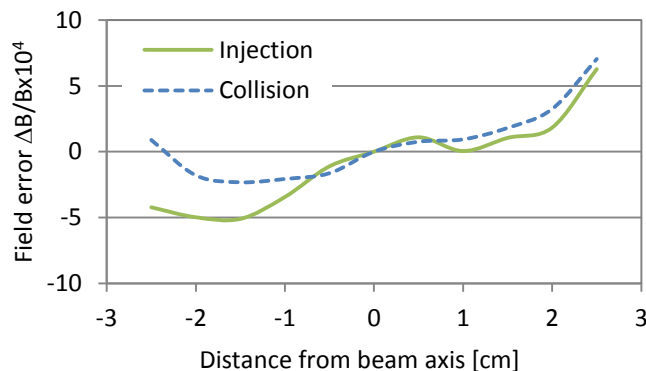
# RR dipoles: CERN models



- one-turn conductor, air cooled
- interleaved laminations (1 mm iron, 2 mm plastic)

Three 400 mm long models with different types of iron:

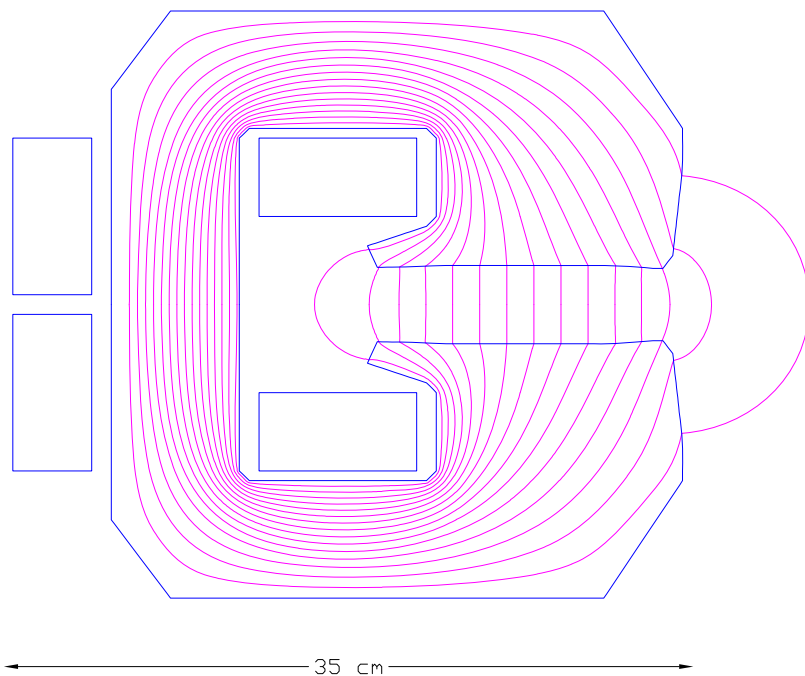
1. NiFe,  $H_c < 6$  A/m
2. low C,  $H_c \approx 70$  A/m
3. grain oriented,  $H_c \approx 7-22$  A/m



Model	Low field	High field
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5 \cdot 10^{-5}$	$4 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$6 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2 \cdot 10^{-5}$	$4 \cdot 10^{-5}$

Within this range of field levels the value of  $H_c$  does not seem to play a major role in the cycle to cycle reproducibility and all three models meet the LHeC specifications.

# RR dipoles: design



beam energy	10 to 60 GeV
flux density in the centre	0.0127 to 0.0763 T
magnetic length	5.35 m
vertical aperture	40 mm
pole width	150 mm
mass	1400 kg
number of magnets	3080
current @ 0.0763 T	1300 A
number of turns per pole	1
current density @ 0.0763 T	0.4 A/mm <sup>2</sup>
conductor material	Aluminium
inductance	0.13 mH
resistance	0.18 mΩ
power @ 60 GeV	300 W
total power @ 60 GeV	0.92 MW
cooling	Air

# RR quadrupoles: requirements

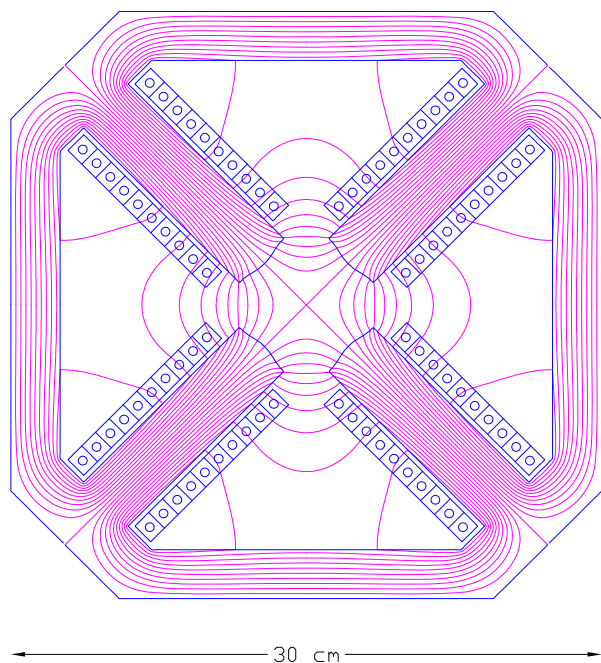


Arc	QF	QD
number of magnets	336	336
aperture radius	> 20 mm	> 20 mm
maximum gradient	10.28 T/m	8.40 T/m
magnetic length	1.0 m	1.0 m

Insertion / by-pass	QF	QD
number of magnets	148	148
aperture radius	> 20 mm	> 20 mm
maximum gradient	18 T/m	18 T/m
magnetic length	1.0 m	0.7 m

Compactness is needed in particular for the arc quadrupoles.

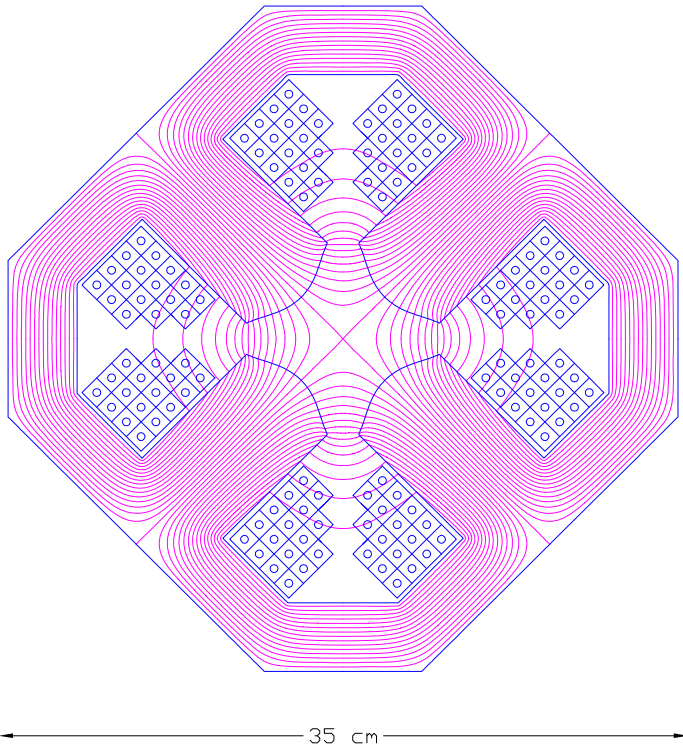
# RR quadrupoles: design (arc)



beam energy	10 to 60 GeV
field gradient @ 60 GeV (QF/QD)	10.28 / 8.40 T/m
magnetic length	1.0 m
aperture radius	30 mm
pole width	32 mm
mass	400 kg
number of magnets (QF/QD)	336 / 336
current @ 60 GeV	380 / 310 A
number of turns per pole	10
current density @ 60 GeV (QF/QD)	4.0 / 3.3 A/mm <sup>2</sup>
conductor material	copper
inductance	4 mH
resistance	16 mΩ
power @ 60 GeV (QF/QD)	2.3 / 1.5 kW
total power @ 60 GeV (QF/QD)	0.77 / 0.52 MW
cooling	water



# RR quadrupoles: design (insert. & by-pass)



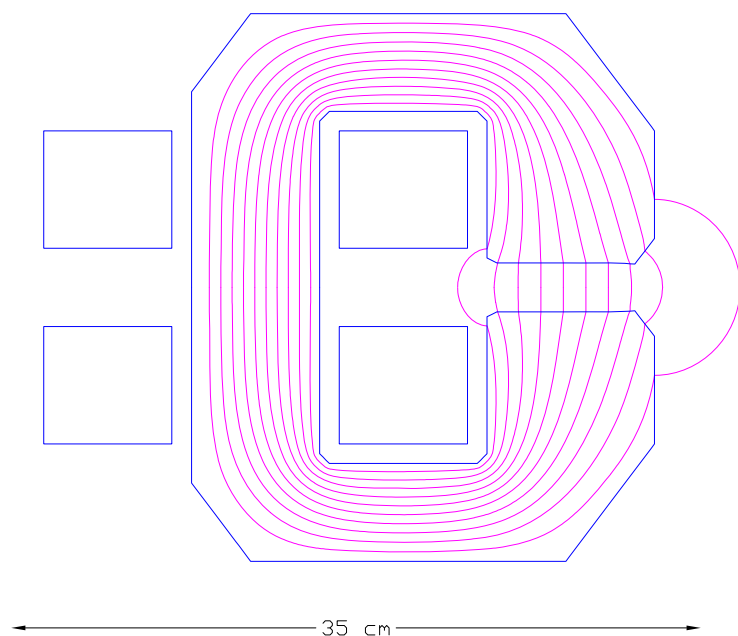
beam energy	10 to 60 GeV
field gradient @ 60 GeV	19 T/m
magnetic length (QD/QF)	1.0 / 0.7 m
aperture radius	30 mm
pole root width	58 mm
mass (QD/QF)	560 / 390 kg
number of magnets (QD/QF)	148 / 148
current @ 19 T/m	420 A
number of turns per pole	17
current density @ 19 T/m	4.6 A/mm <sup>2</sup>
conductor material	copper
inductance (QD/QF)	15 / 10 mH
resistance (QD/QF)	30 / 23 mΩ
power @ 19 T/m (QD/QF)	5.3 / 3.9 kW
total power @ 19 T/m (QD/QF)	0.78 / 0.58 MW
cooling	water

	#	flux density [T]	length [m]
Arc 1 (10.5 GeV)	584	0.046	4.0
Arc 2 (20.5 GeV)	584	0.089	4.0
Arc 3 (30.5 GeV)	584	0.133	4.0
Arc 4 (40.5 GeV)	584	0.177	4.0
Arc 5 (50.5 GeV)	584	0.221	4.0
Arc 6 (60.5 GeV)	584	0.264	4.0

## Proposed solution

- one type of bending magnets for the six arcs, possibly with different conductors

# LR dipoles: design (recirculator)



beam energy	10.5 to 60.5 GeV
flux density in the centre	0.046 to 0.264 T
magnetic length	4.0 m
vertical aperture	25 mm
pole width	80 mm
mass	2000 kg
number of magnets	$6 \times 584 = 3504$
current @ 60.5 GeV	2700 A
number of turns per pole	1
current density @ 0.264 T	$0.7 \text{ A/mm}^2$
conductor material	copper
inductance	0.08 mH
resistance	0.08 m $\Omega$
power @ 60.5 GeV	585 W
total power 6 arcs (10.5 to 60.5 GeV)	0.87 MW
cooling	air

# LR quadrupoles: requirements



Linacs FODO Arcs FMC	Q0			Q1			Q2			Q3		
	#	G [T/m]	L [m]	#	G [T/m]	L [m]	#	G [T/m]	L [m]	#	G [T/m]	L [m]
LINAC 1	18	2.2	1.0				18	2.2	1.0			
LINAC 2	18	2.2	1.0				18	2.2	1.0			
Arc 1 (10.5 GeV)	60	3.2	1.0	60	10.5	1.0	60	11.1	1.0	60	10.5	1.0
Arc 2 (20.5 GeV)	60	6.2	1.0	60	20.5	1.0	60	21.6	1.0	60	20.6	1.0
Arc 3 (30.5 GeV)	60	12.4	1.0	60	17.5	1.0	60	24.6	1.0	60	17.9	1.0
Arc 4 (40.5 GeV)	60	16.5	1.0	60	23.2	1.0	60	32.6	1.0	60	23.8	1.0
Arc 5 (50.5 GeV)	60	29.2	1.0	60	28.9	1.0	60	40.8	1.0	60	29.7	1.0
Arc 6 (60.5 GeV)	60	35.0	1.0	60	34.6	1.0	60	48.9	1.0	60	35.5	1.0

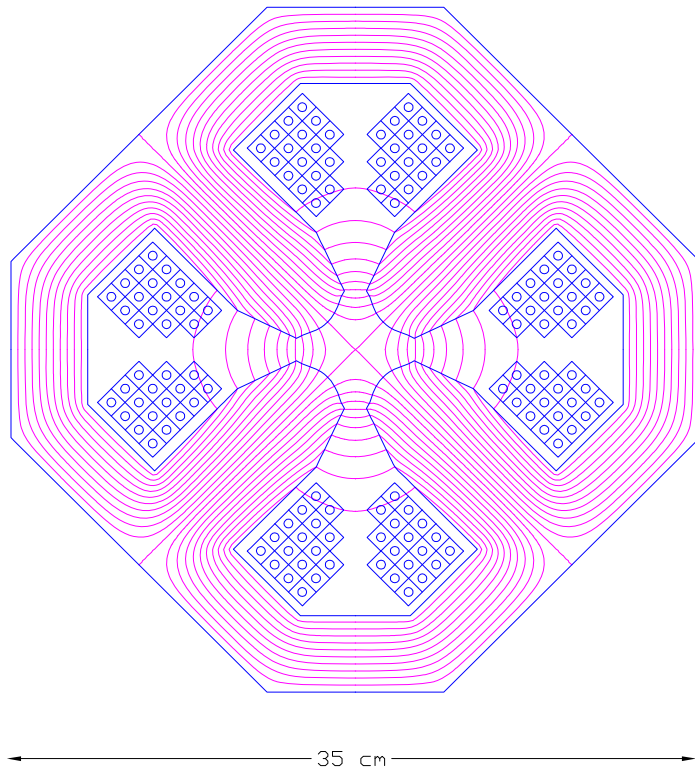
## Proposed solution

- one type of quadrupoles for the Linacs
- one type of quadrupoles for the arcs in two different lengths

Q2                      1.2 m

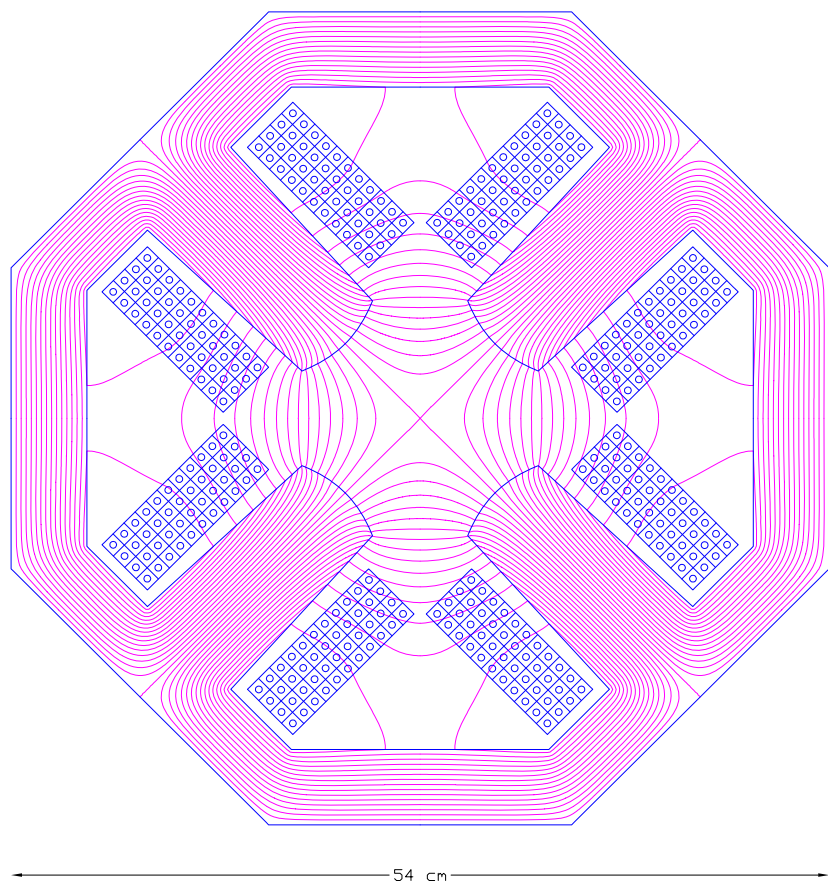
Q0, Q1 and Q3      0.9 m

# LR quadrupoles: design (recirculator)



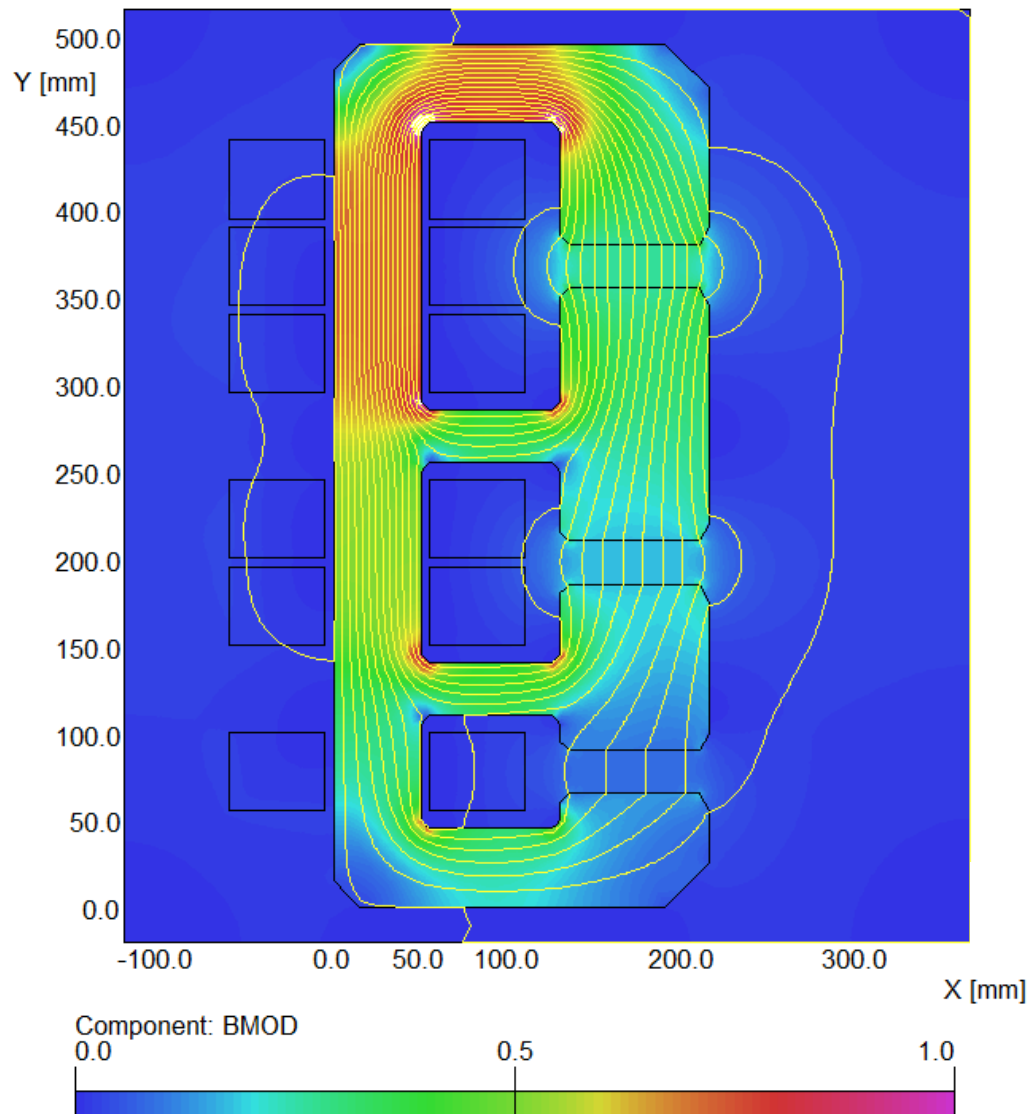
beam energy	10.5 to 60.5 GeV
field gradient	41 T/m
magnetic length (short/long)	0.9 / 1.2 m
aperture radius	20 mm
pole root width	57 mm
mass (short/long)	750 / 980 kg
number of magnets (Q0+Q1+Q2+Q3)	$6 \times 240 = 1440$
current @ 41 T/m	400 A
number of turns per pole	17
current density @ 41 T/m	$4.8 \text{ A/mm}^2$
conductor material	copper
inductance (short/long)	17 / 22 mH
resistance (short/long)	30 / 40 m $\Omega$
power @ 60.5 GeV (short/long)	4.8 / 6.4 kW
total power 6 arcs (10.5 to 60.5 GeV)	3.17 MW
cooling	water

# LR quadrupoles: design (linac)



field gradient	10 T/m
magnetic length	0.250 m
aperture radius	70 mm
pole root width	78 mm
mass	440 kg
number of magnets	$37 + 37 = 74$
current @ 10 T/m	460 A
number of turns per pole	44
current density @ 10 T/m	$5.0 \text{ A/mm}^2$
conductor material	copper
Inductance	24 mH
resistance	25 m $\Omega$
power @ 10 T/m	5.3 kW
cooling	water

# LR dipoles: three apertures (not in the CdR)



## First conceptual cross-section

flux density in the gaps	0.264 T 0.176 T 0.088 T
magnetic length	4.0 m
vertical aperture	25 mm
pole width	85 mm
number of magnets	584
current	1750 A
number of turns per aperture	1 / 2 / 3
current density	0.7 A/mm <sup>2</sup>
conductor material	copper
resistance	0.36 mΩ
power	1.1 kW
total power 20 / 40 / 60 GeV	642 kW
cooling	air

## RR magnets

For the dipoles, several short models have been built at BINP and at CERN. The reproducibility of the (low) injection field has been met. The CERN design is light and compact, but an optimization of its support (considering structural, logistic and economic constraints) would be important.

## LR recirculator magnets

These magnets are operated in DC and, at this stage, do not represent an issue. Other solutions (for example involving multiple apertures or permanent magnets) can be investigated.



# Discussion / next steps

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## LR recirculator dipoles and quadrupoles

New requirements (aperture, field)?

Use of permanent magnets?

Combined apertures?

Combined functions (for example, dipole + quad)?

## LR linac quadrupoles and correctors

New requirements (aperture, field)?

More compact magnets, maybe with at least two families for quadrupoles?

Permanent magnets / superconducting for quads?

## Magnets for ERL test stand?

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Thank you.