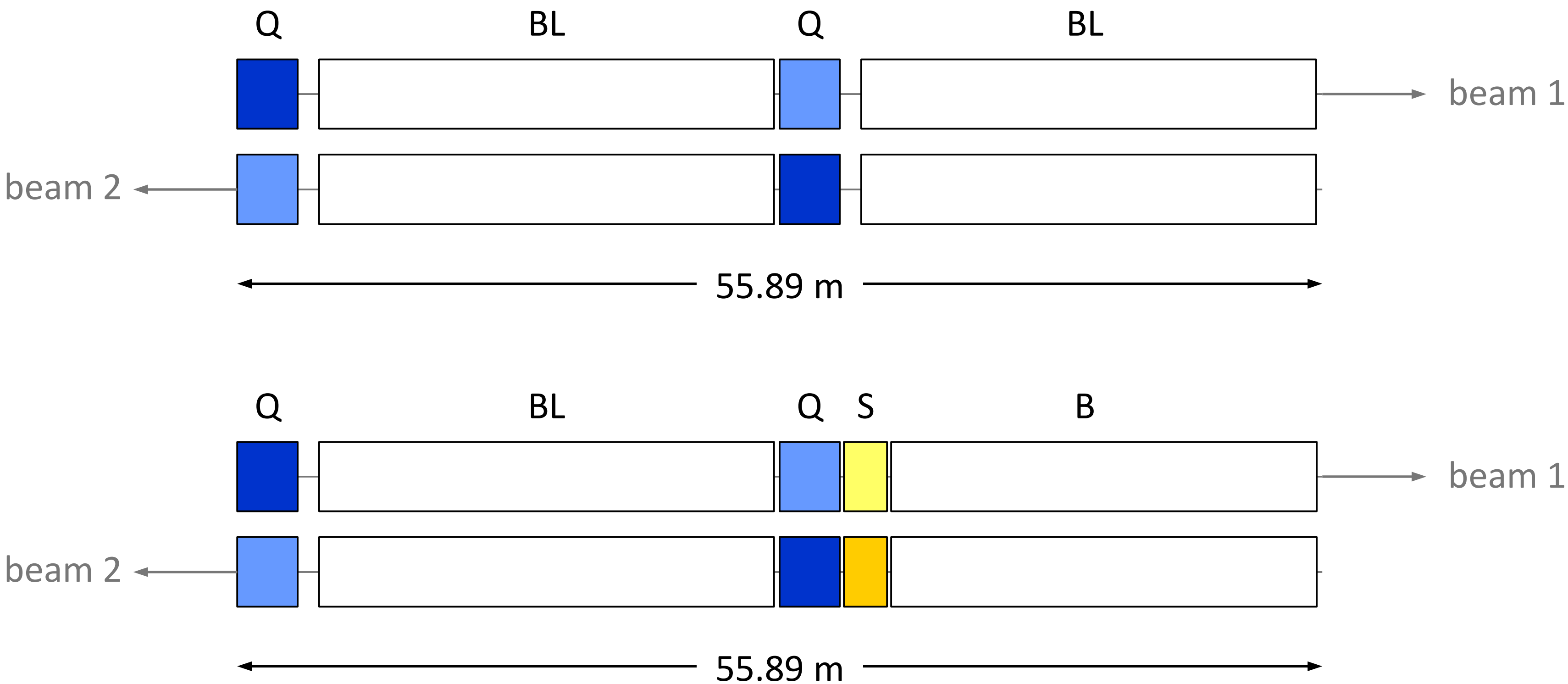
Progress with the design of the main FCC-ee warm magnets

Attilio Milanese

1 Jun. 2017

The current lattice for FCC-ee incorporates twin dipoles and quadrupoles, thanks to Katsunobu Oide



bending: 1740 × 23.94 m (BL) + 1160 × 21.94 m (B) = 67 106 m

quadrupoles: 2 × 1450 × 3.1 m = 8 990 m

no combined function bending magnets

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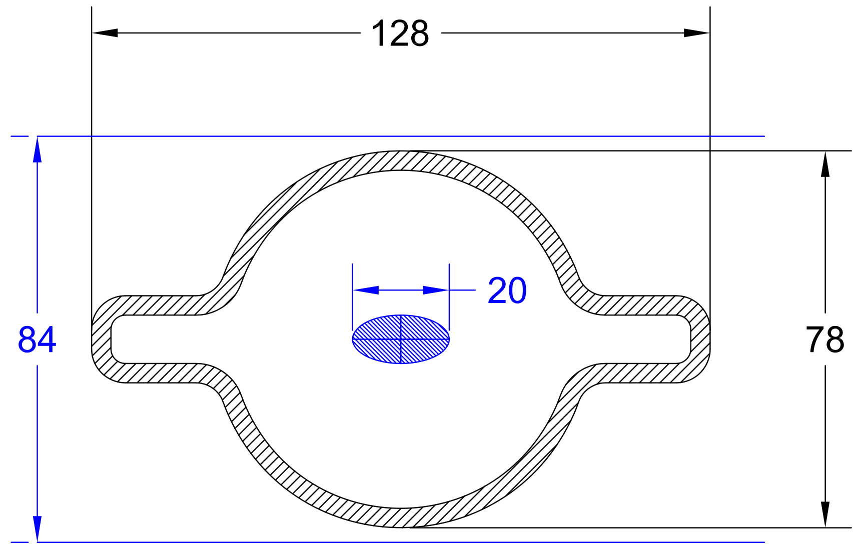
main dipoles

The input parameters have been updated with respect to last year, in particular for the aperture

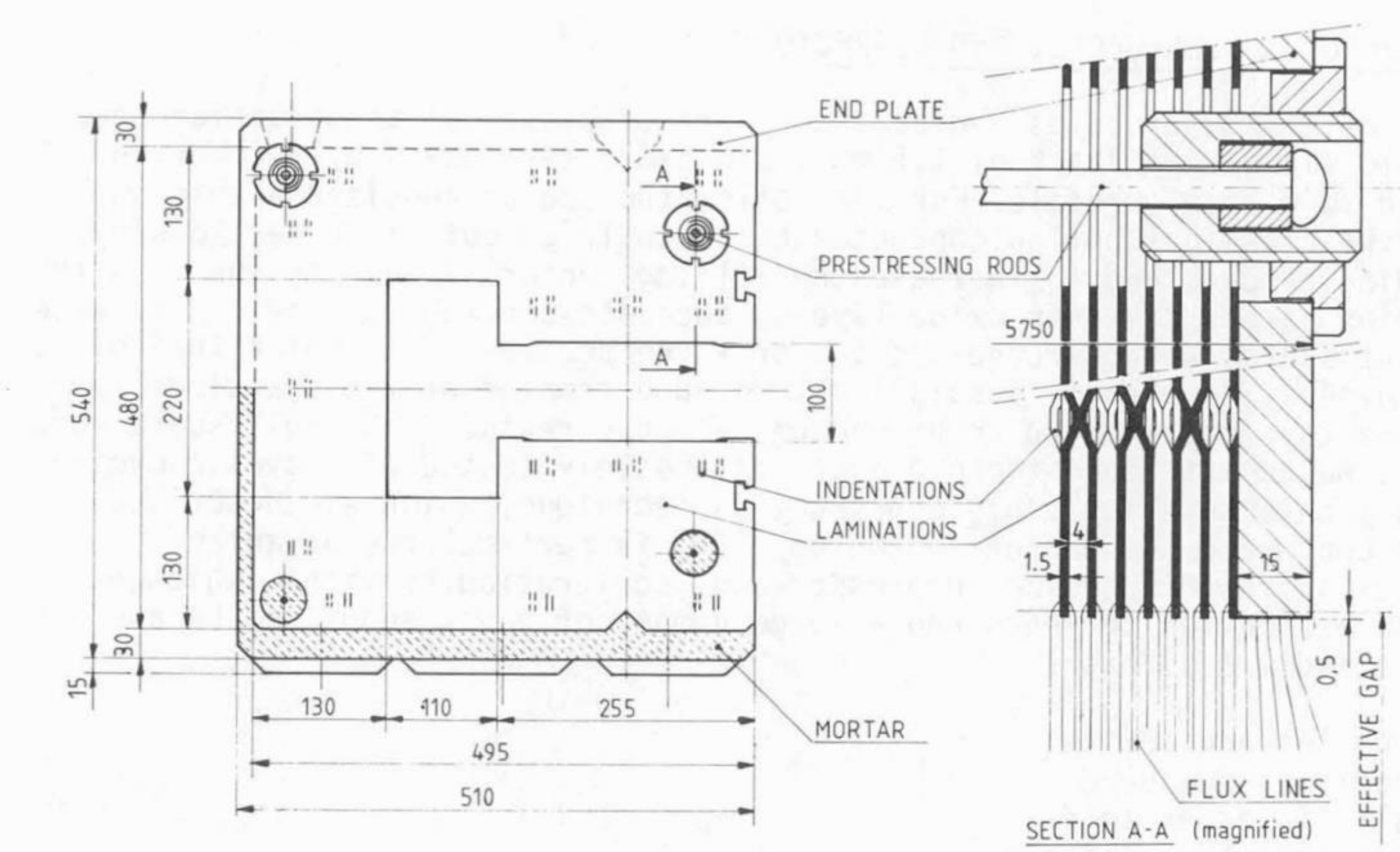


aperture: compatible with vacuum chamber with winglets

field: 14.1 mT (45.6 GeV) to 54.3 mT (175 GeV)

good field region: 10^{-4} in ±10 mm horizontally, not counting systematic quadrupole term

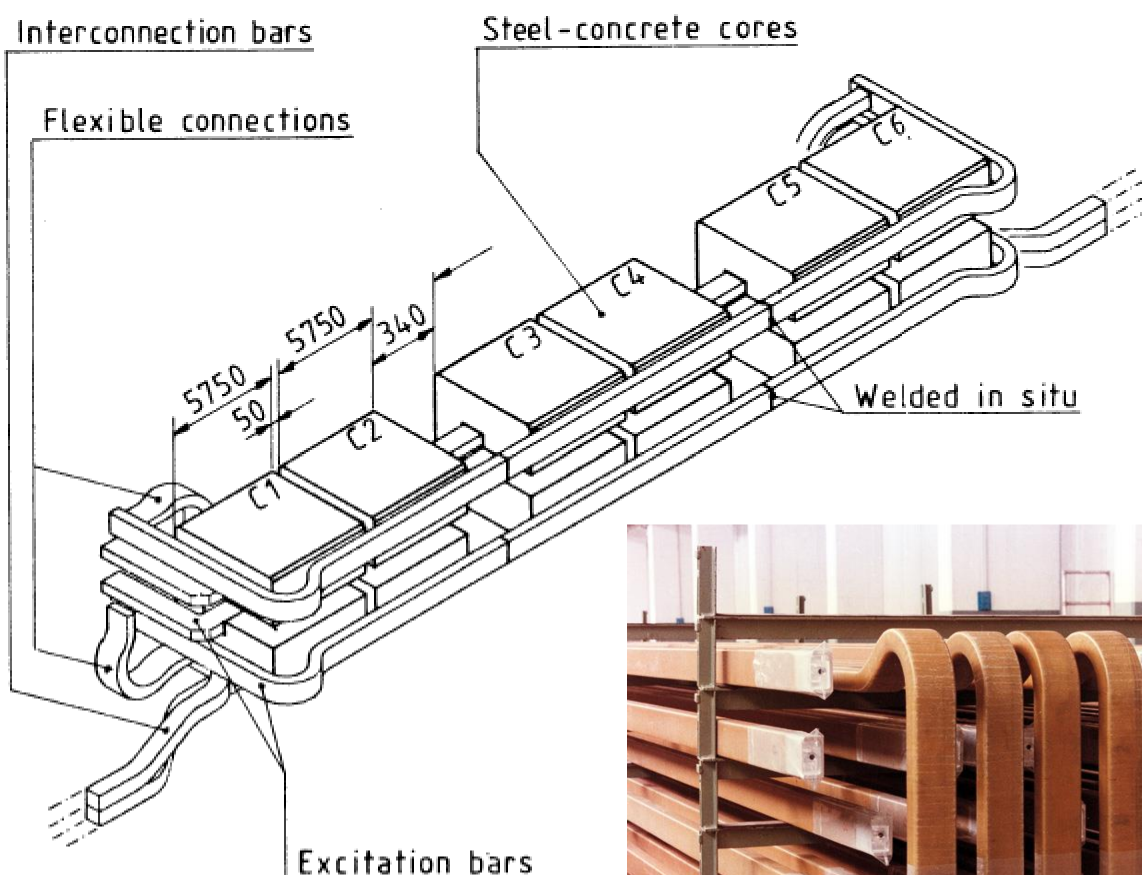
As a reference, we recall the LEP dipoles, with their steel (30%) / concrete (70%) cores

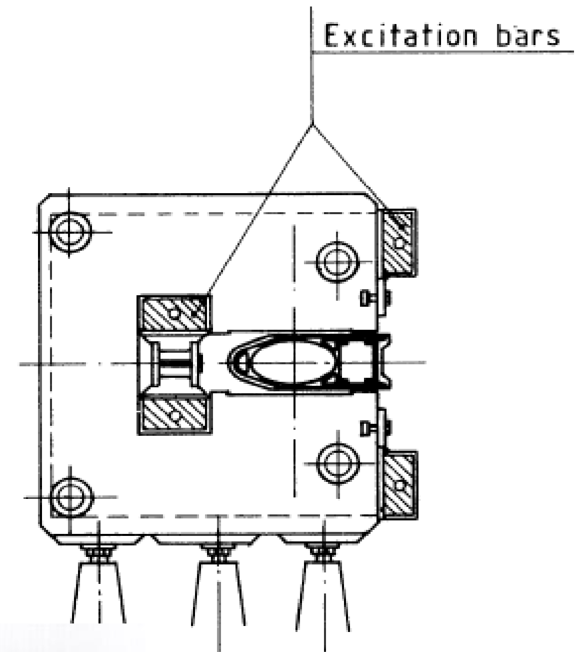


aperture: 255 × 100 mm

field: 22 mT (20 GeV injection) to 108 mT (100 GeV)

The (main) LEP dipoles had 5.75 m long cores and four water cooled aluminium excitation bars, carrying 4.5 kA each





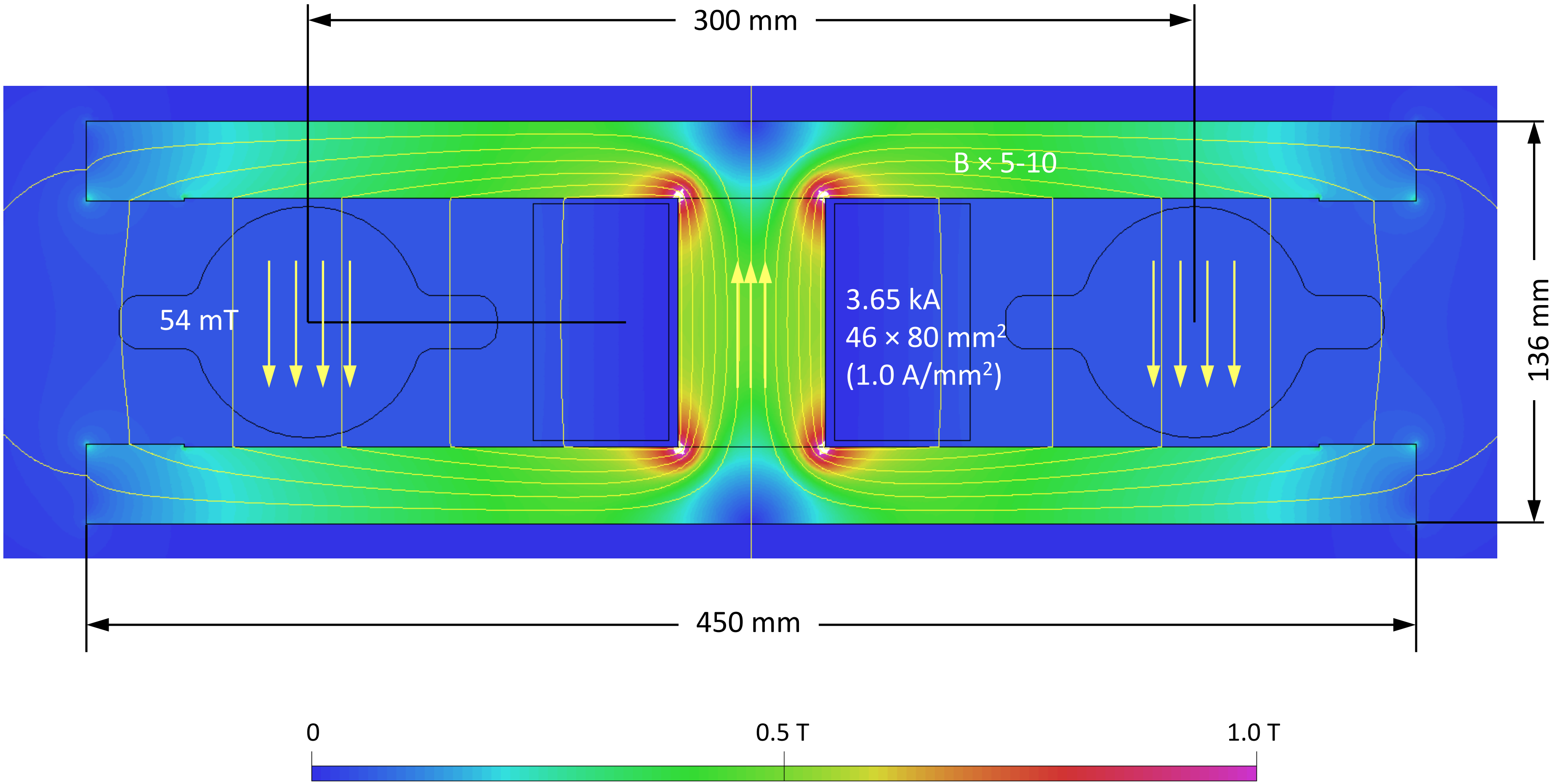
insulated LEP dipole bars

courtesy of ASG

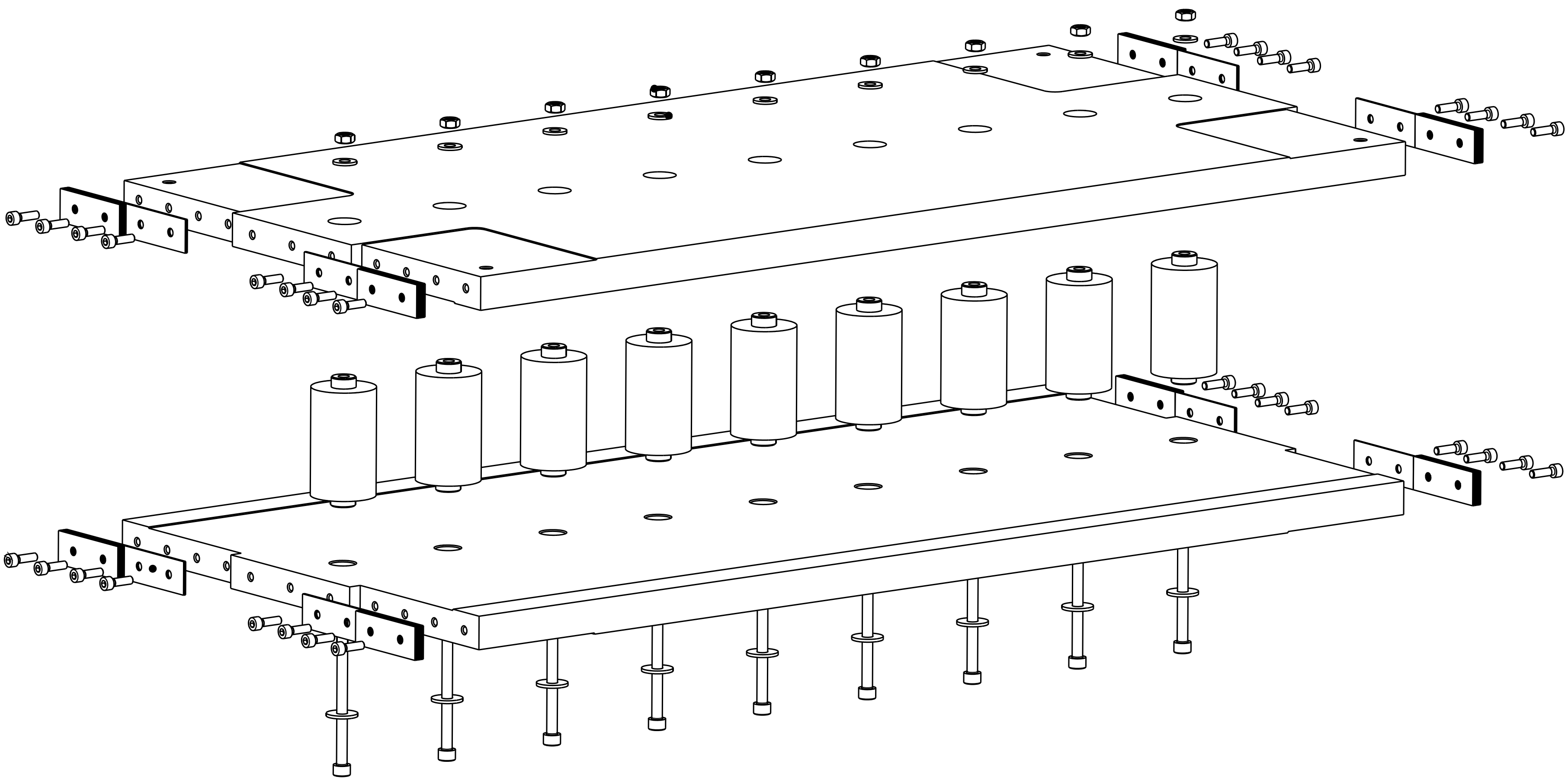
LEP dipoles: *sic transit gloria mundi*... though a better destiny than some of the ISR dipole cores (LHC dump)

LEP cores in 2017

We propose for FCC-ee twin dipoles with an I layout, with two aluminium excitation bars



We are designing a 1 m long prototype, with cylinders as spacers, to further increasing the flux density in the return leg



The pole width is compatible with the target field quality, which benefits also from the flux concentration in the plates

energy	[GeV]	45	175
B_1	[mT]	14.1	54.3
b_2	[10^{-4}]	-3.3	-2.6
b_3	[10^{-4}]	0.2	0.1
b_4	[10^{-4}]	-0.2	-0.2
b_5	[10^{-4}]	-0.1	-0.1
b_6	[10^{-4}]	-0.0	-0.0

allowed multipoles at 10 mm radius

The twin design for the dipoles strives to be simple, compact and to save energy, "recycling" the Ampere-turns

simple

few components

no cost for coil manufacturing

no inter-turn insulation, more naturally radiation hard

compact

aluminium	20 kg/m	1650 tons total, with connections
(low carbon) iron	200 kg/m	13500 tons total
		(≈10000 tons for LEP dipoles)

energy saving

50% power consumption with respect to separate magnets

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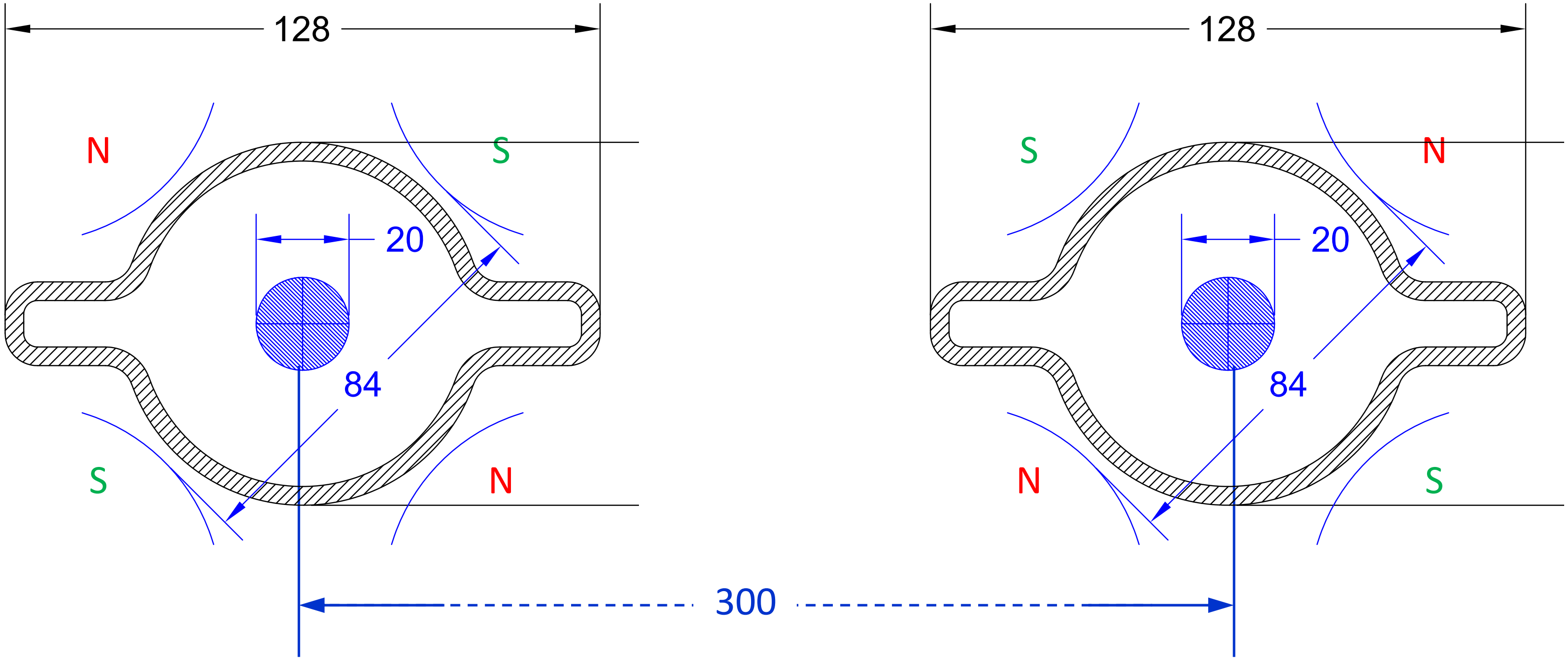
main quadrupoles

The main assumption is to have an FD polarity, to exploit a (magnetically coupled) twin layout

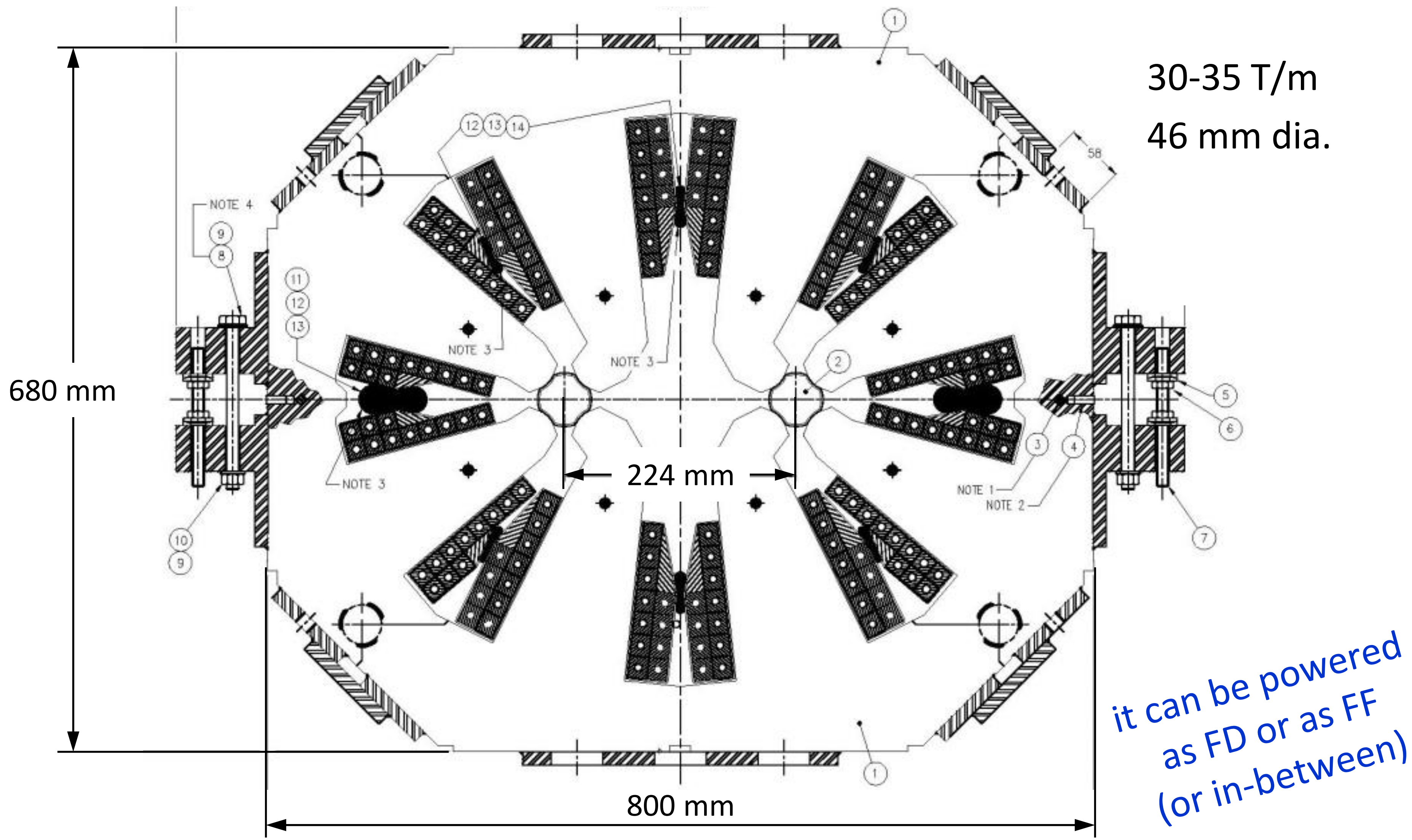


aperture and intra-beam distance: as for bending magnets

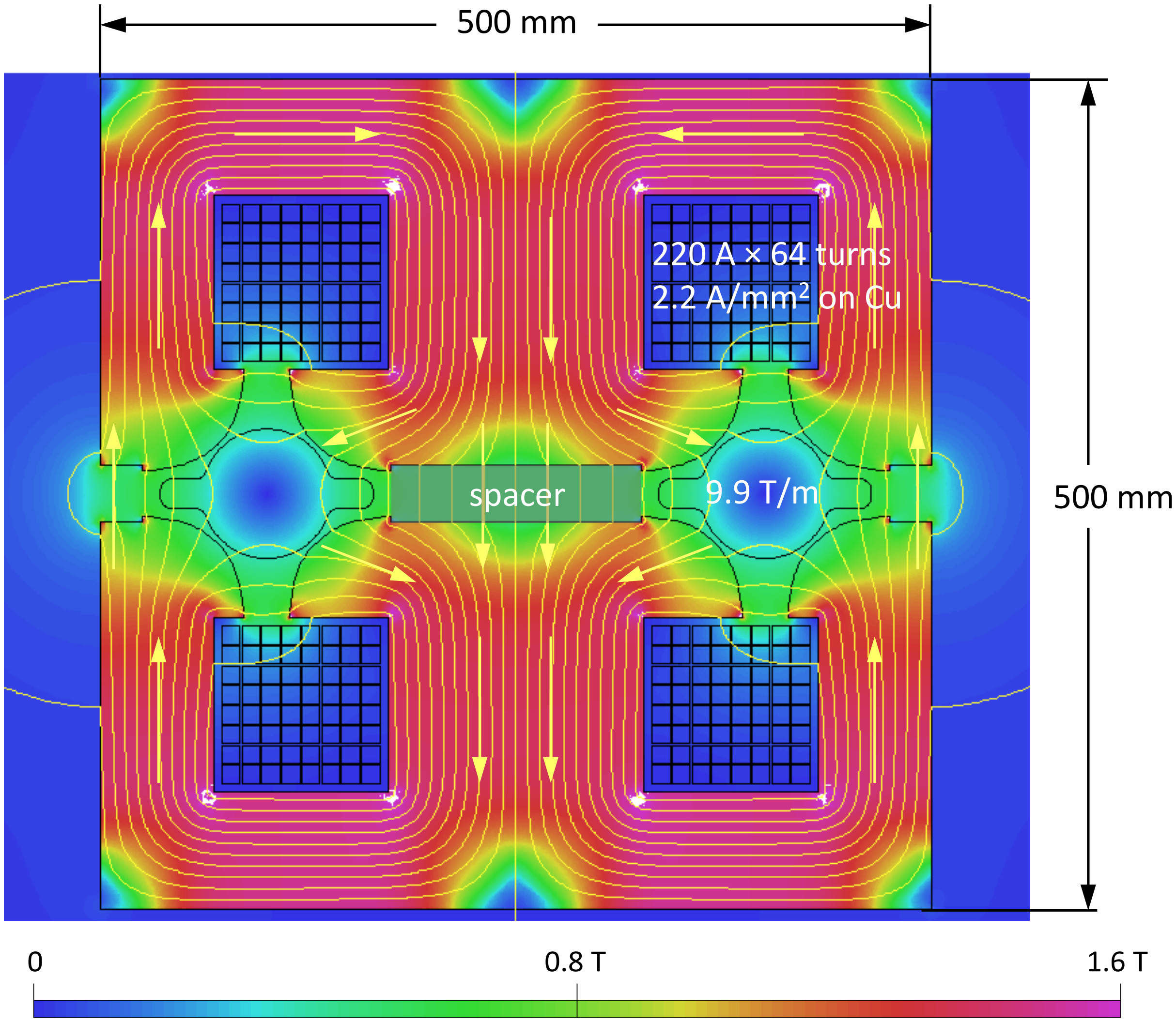
field gradient: max 9.9 T/m, for 90°/90° FODO at 175 GeV

good field region: 10^{-4} at 10 mm radius

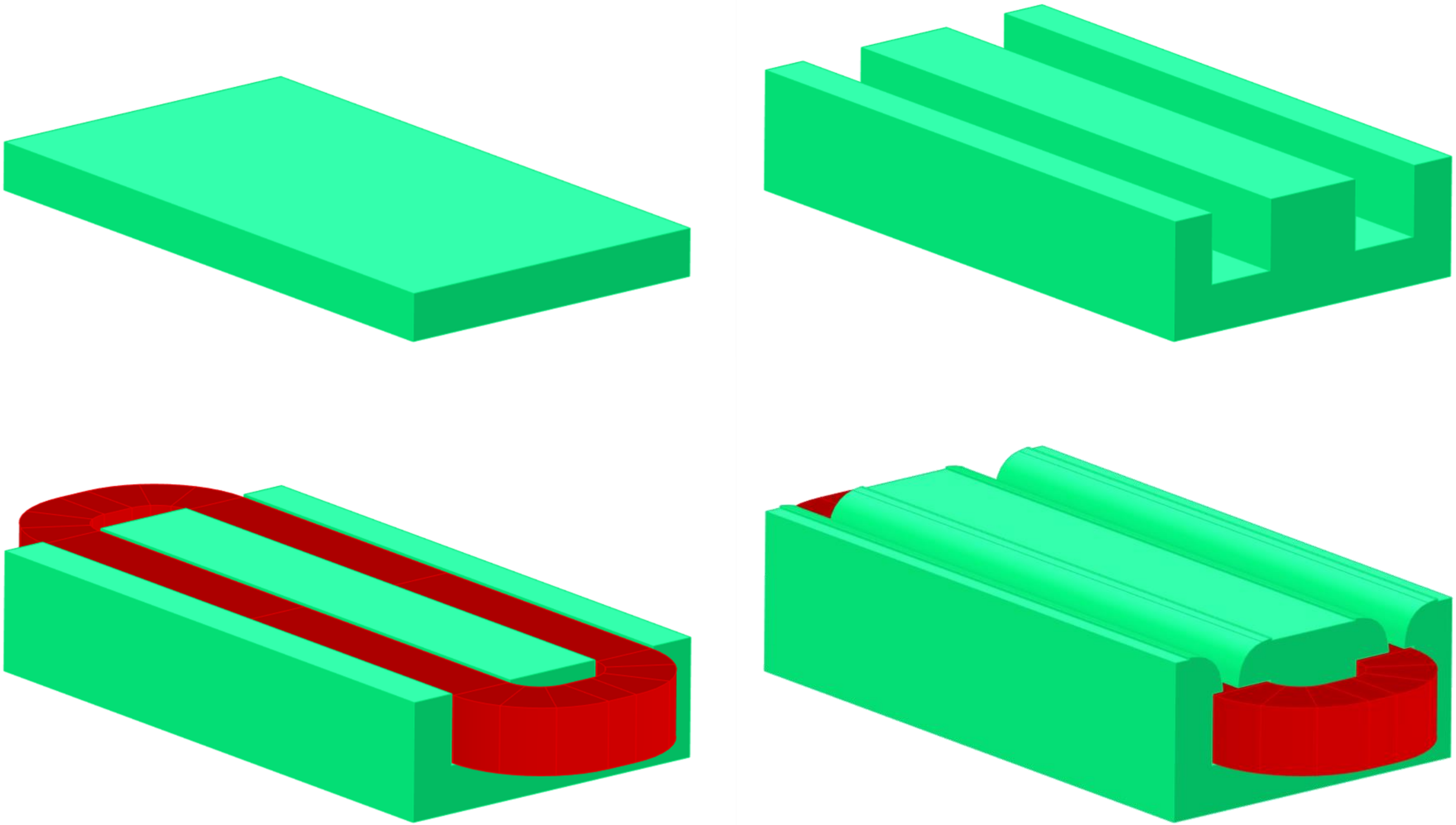
Conventional twin quadrupoles exist, for example the MQW of the LHC – aperture and intrabeam distance would fit



We propose a (coupled) twin quadrupole, saving 50% power (at equal A/mm^2) with respect to a traditional design, at the same time putting the coil far from the midplane radiation

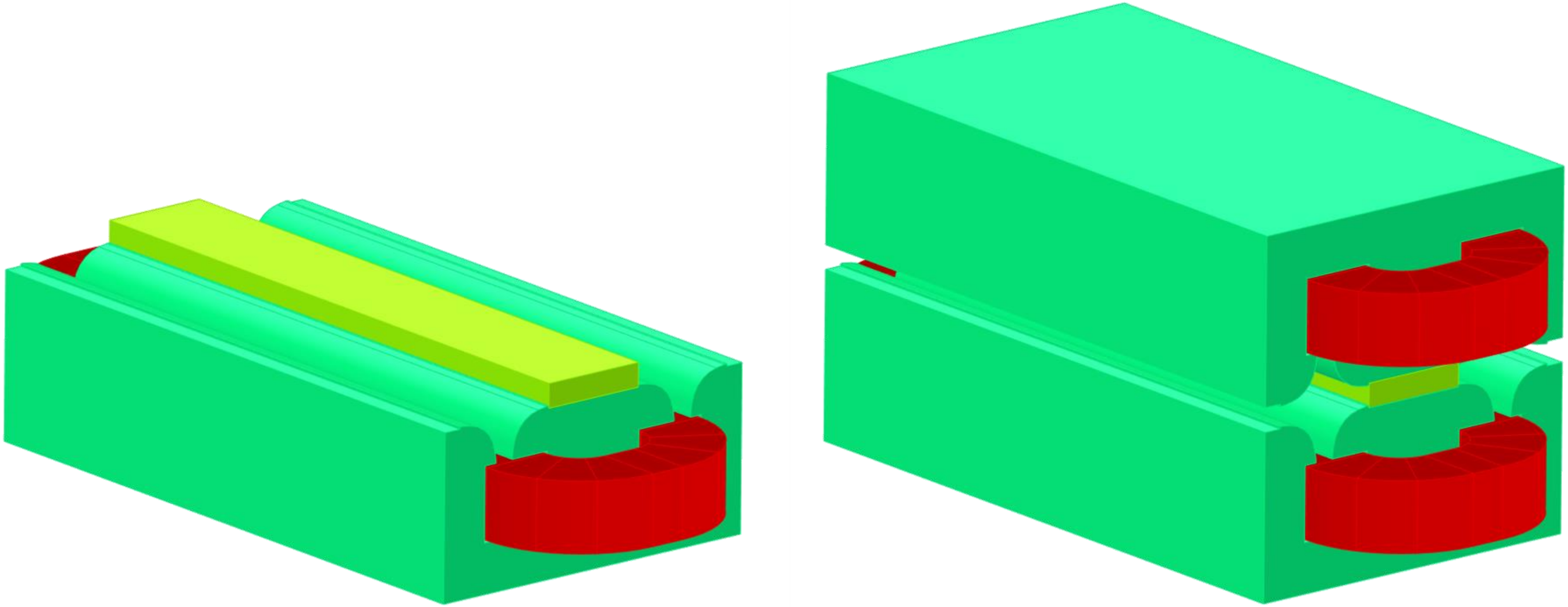


The assembly is unusual for a quadrupole, with an increased number of yoke pieces, but less coils



1 m long prototype

For the moment, a single central non-magnetic spacer is considered, to position the two halves



1 m long prototype

The left / right asymmetry and the open midplane make the field quality optimization tricky: the pole (and the overall yoke) might be slimmed after the tests on the prototype

B’	[T/m]	9.9
$B_{pole\ tip}$	[T]	0.42
b_3	$[10^{-4}]$	-0.7 / -2.0
b_4	$[10^{-4}]$	0.0
b_5	$[10^{-4}]$	0.1
b_6	$[10^{-4}]$	0.2
b_{10}	$[10^{-4}]$	0.0

$B_{pole\ tip}$: 8× dipole field

b_3 to b_{10}: allowed multipoles at 10 mm radius

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power estimates & conclusions

This is the estimated power consumption for the twin main dipoles at 175 GeV

field	54.3 mT	at 175 GeV
vertical full gap	84 mm	
current density	1.0 A/mm^2	on aluminium
power per m	192 W/m	
total power (81 km)	16 MW	includes connections

[cooling of busbars with demineralized water not shown]

At the moment the quadrupoles – even considering copper as conductor – consume more than the dipoles

field gradient	9.9 T/m	at 175 GeV, 90°/90° FODO
aperture diameter	84 mm	
current density	2.2 A/mm^2	on copper
power per magnet	7.3 kW	3.1 m long

[was 20.3 kW for a MQA of LEP at 9.9 T/m, 2.0 m long, 125 mm aperture, in Al]

total power	22 MW	with 5% for cable losses

[44 MW for a more classical symmetric MQW-like design]

Conclusions

1. The main warm magnets for FCC-ee can run with reasonable power consumption, provided innovative schemes are used for both dipoles and quadrupoles

2. The proposed design for the dipole aims at compactness and simplicity – 67.1 km of bending magnets are needed; for the quadrupoles, we focus more on low consumption

3. 1 m long prototypes have been funded and they are being designed, to prove experimentally the twin configuration
   - low field and very elongated pole (for the dipole)
   - unconventional asymmetries (for the quadrupole)

4. These are proofs of concept and starting points for further optimizations, needed for a series production of thousands of units

thank you