Twin aperture bending magnets and quadrupoles for FCC-ee

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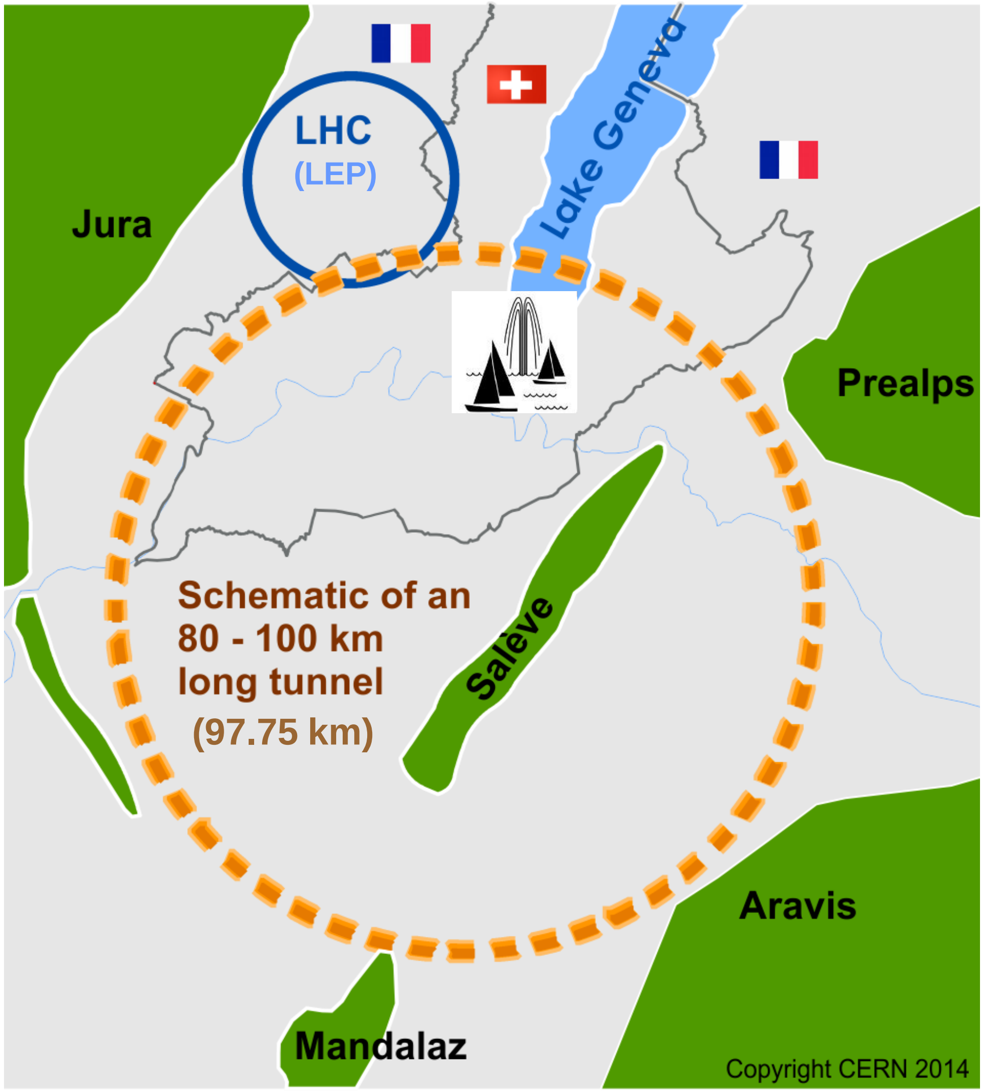
30 Aug. 2017

FCC-ee (Future Circular Collider) is a study for a large lepton collider, hosted around CERN



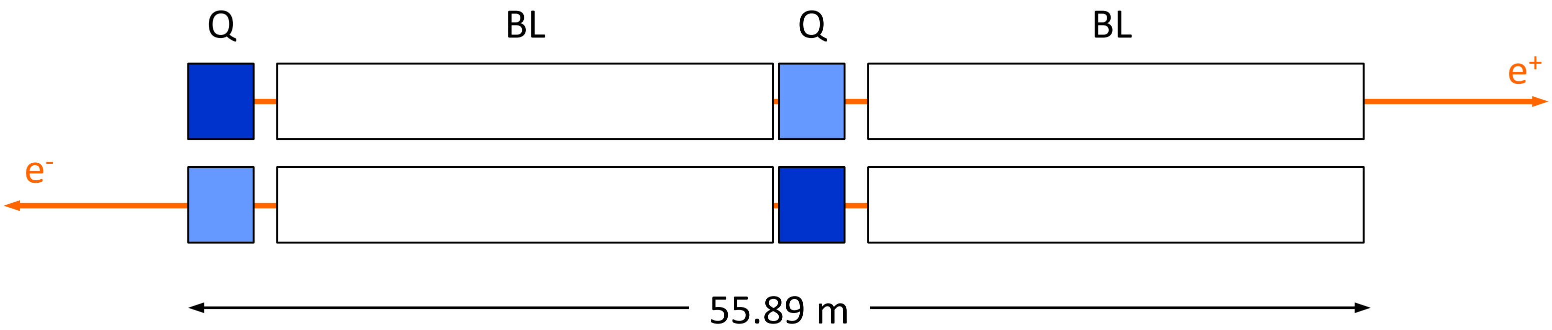
mode	cm collision energy [GeV]
Z	91
W	160
H (ZH)	240
ttbar	350

dc operation
with top-up injection

double collider
counter-rotating e^+ / e^- beams

courtesy of Michael Benedikt

The FCC-ee magnet system involves thousands of resistive (low field) dipoles and quadrupoles



bending magnets

2900 per ring × magnetic length 23.94 / 21.94 m = 67.1 km

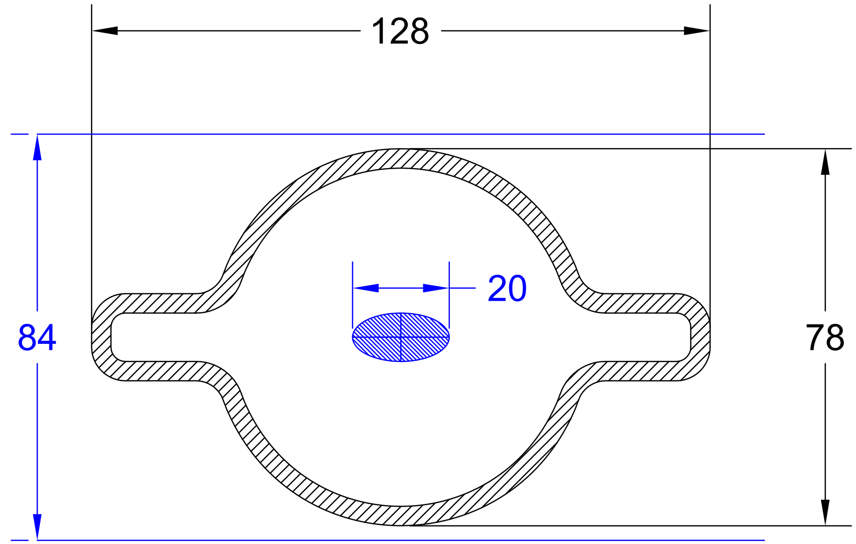
B field 14.1 mT to 54.3 mT (dc)

quadrupoles

1450 units (per ring) × magnetic length 3.1 m = 9.0 km

main (twin) dipoles

These are the main requirements for the FCC-ee dipoles

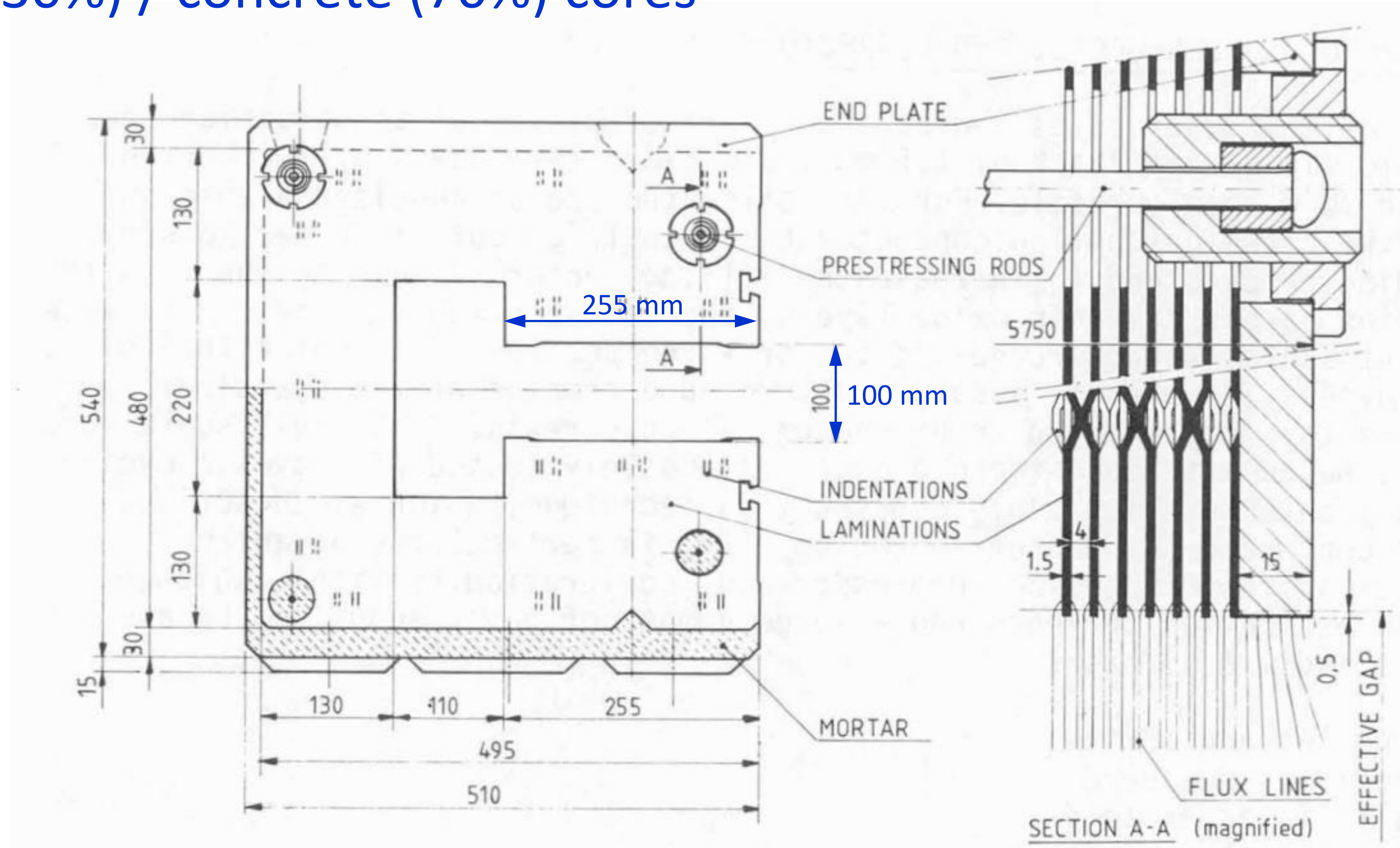


aperture: compatible with vacuum chamber with winglets

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

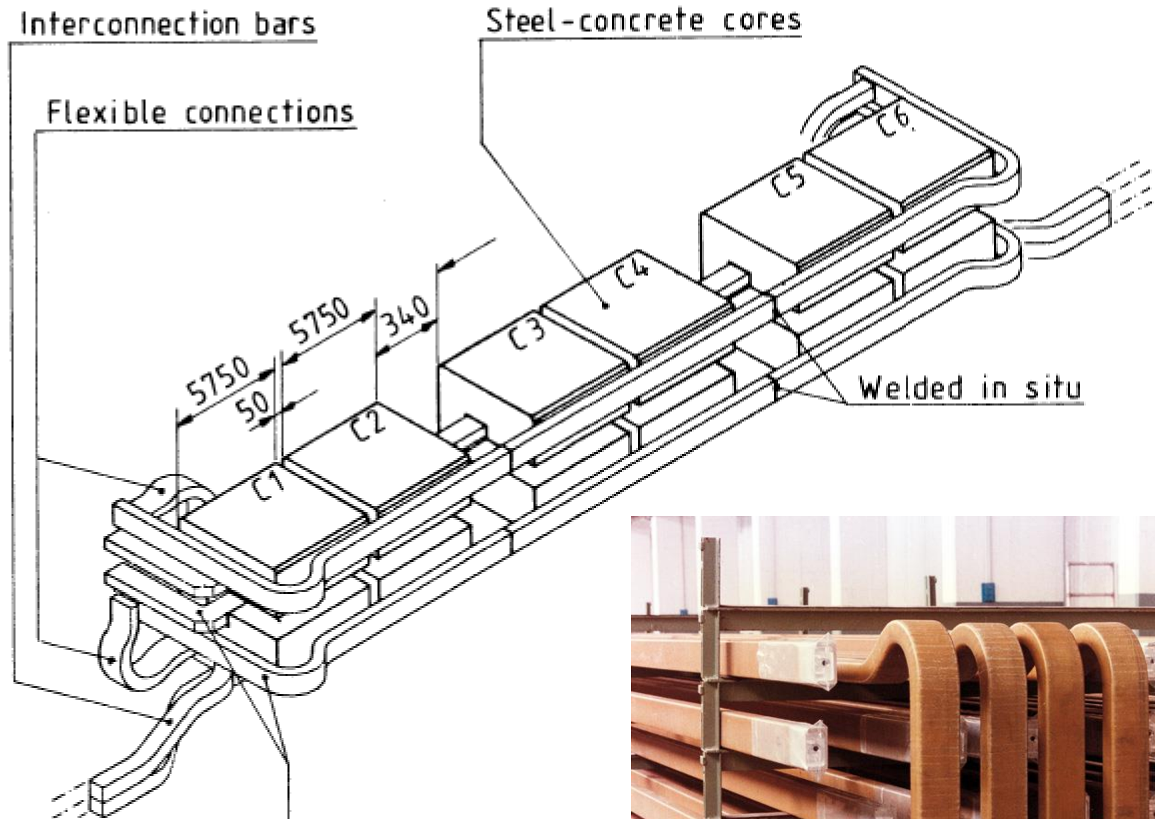
good field region: $\approx 10^{-4}$ in ±10 mm horizontally
(without counting a systematic quadrupole term)

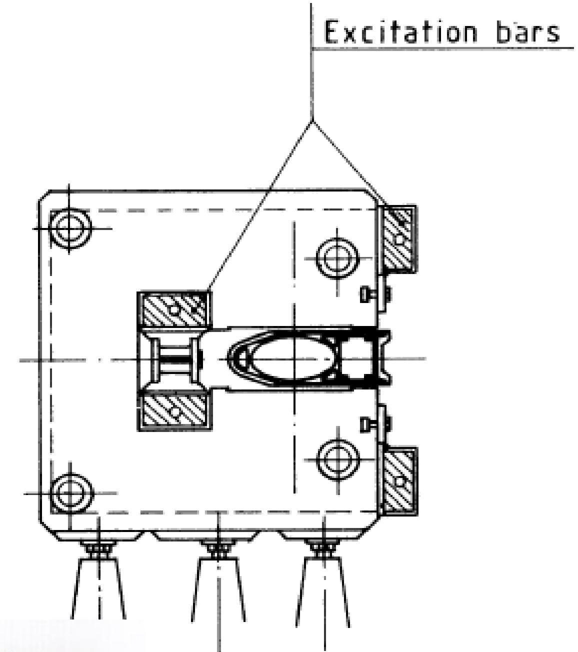
As a reference, we recall the LEP dipoles, with their steel (30%) / concrete (70%) cores

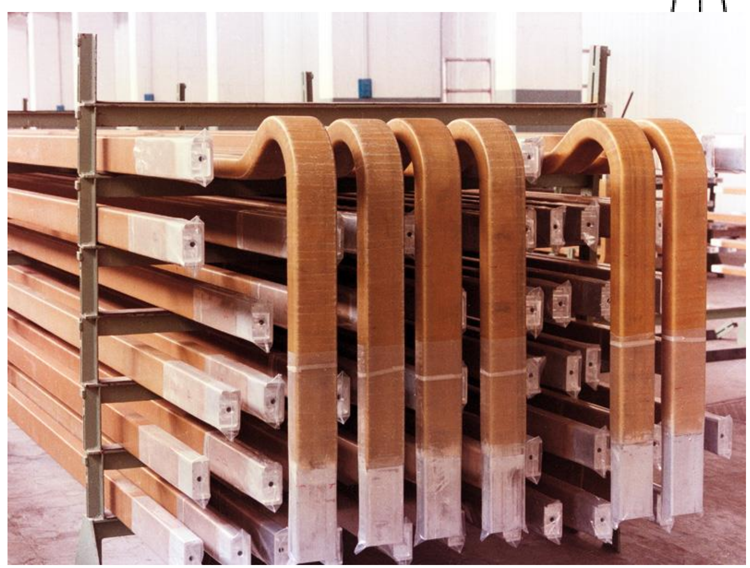


field: 22 mT (20 GeV injection) to 108 mT (100 GeV), not dc

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



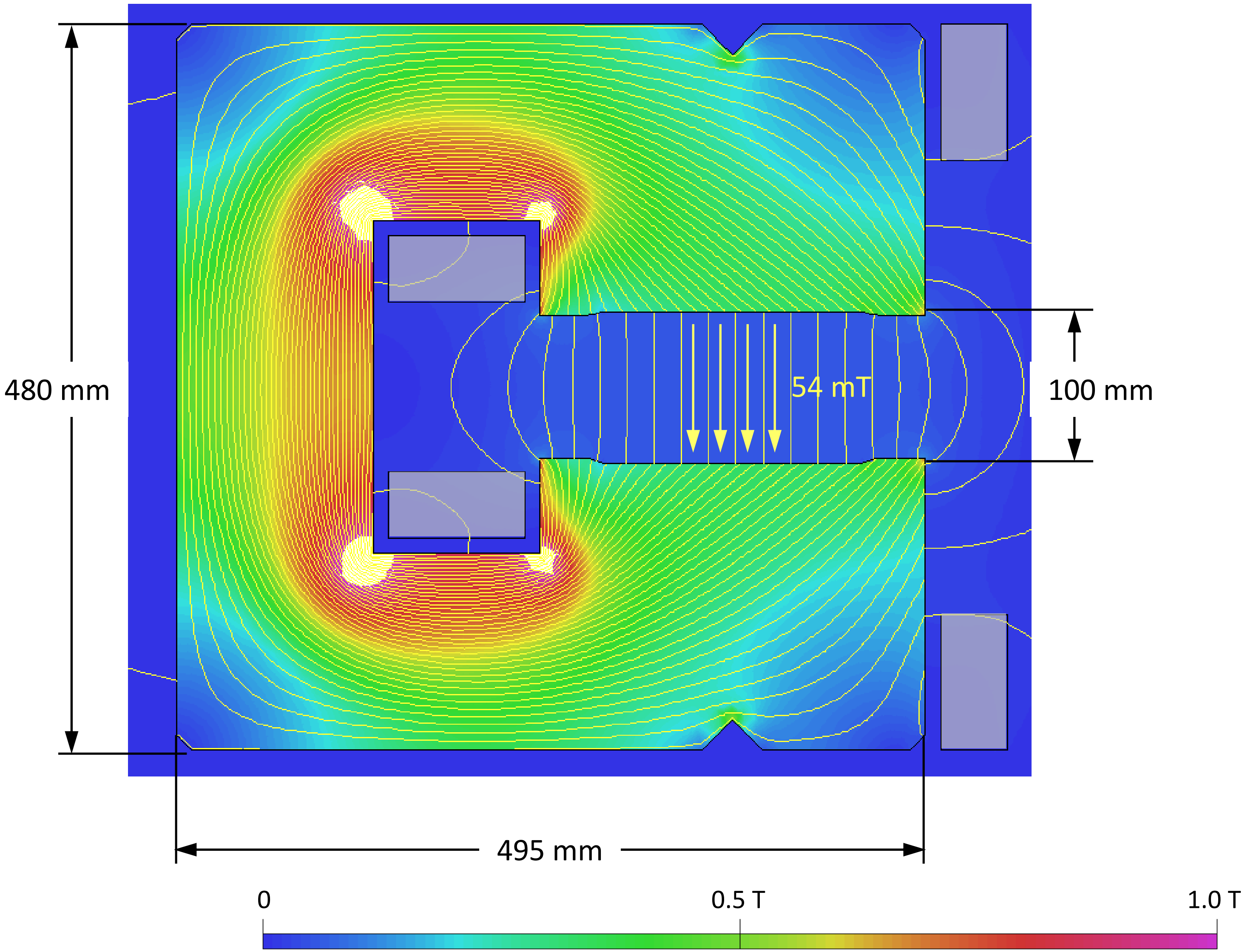




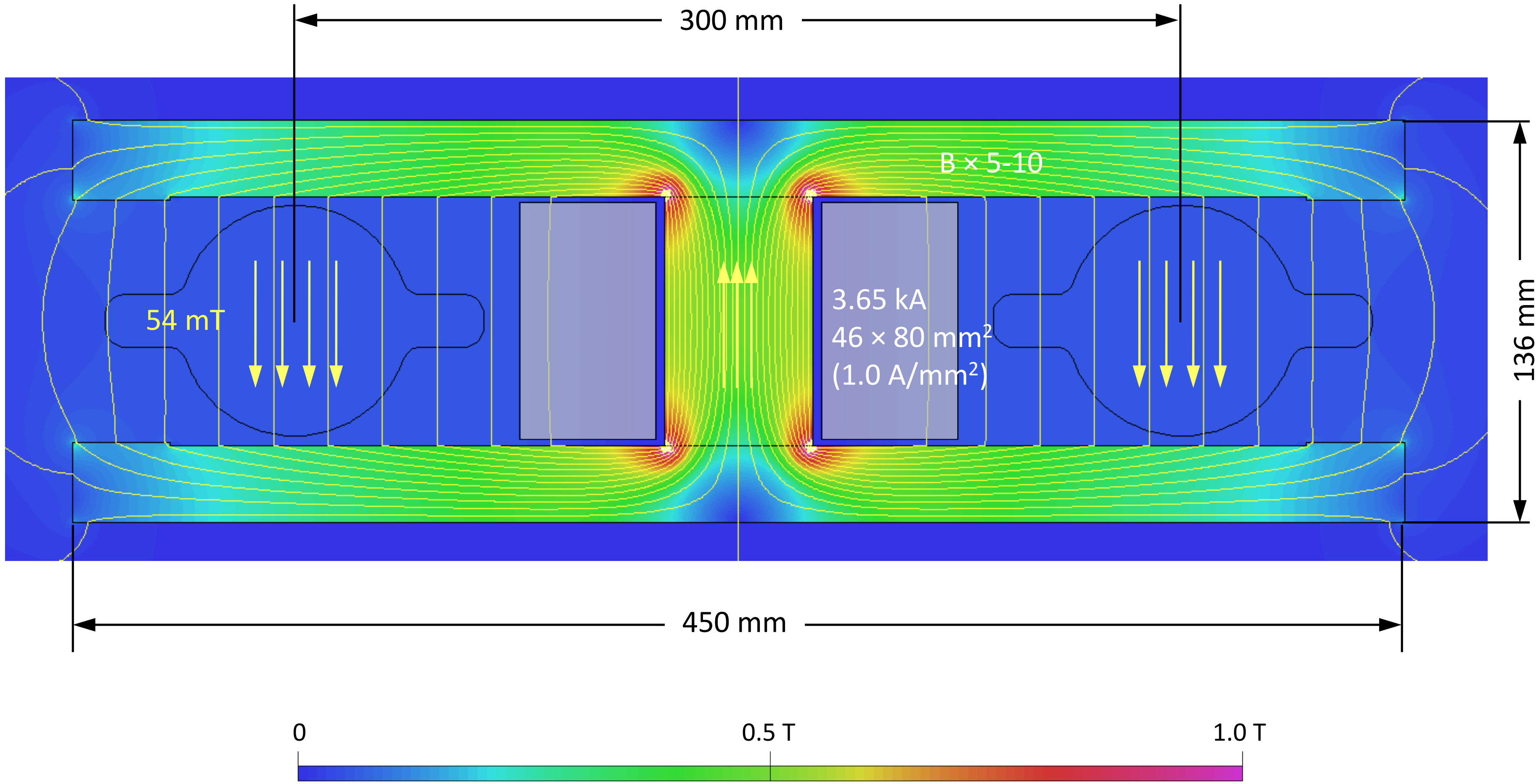
insulated LEP dipole bars

courtesy of ASG

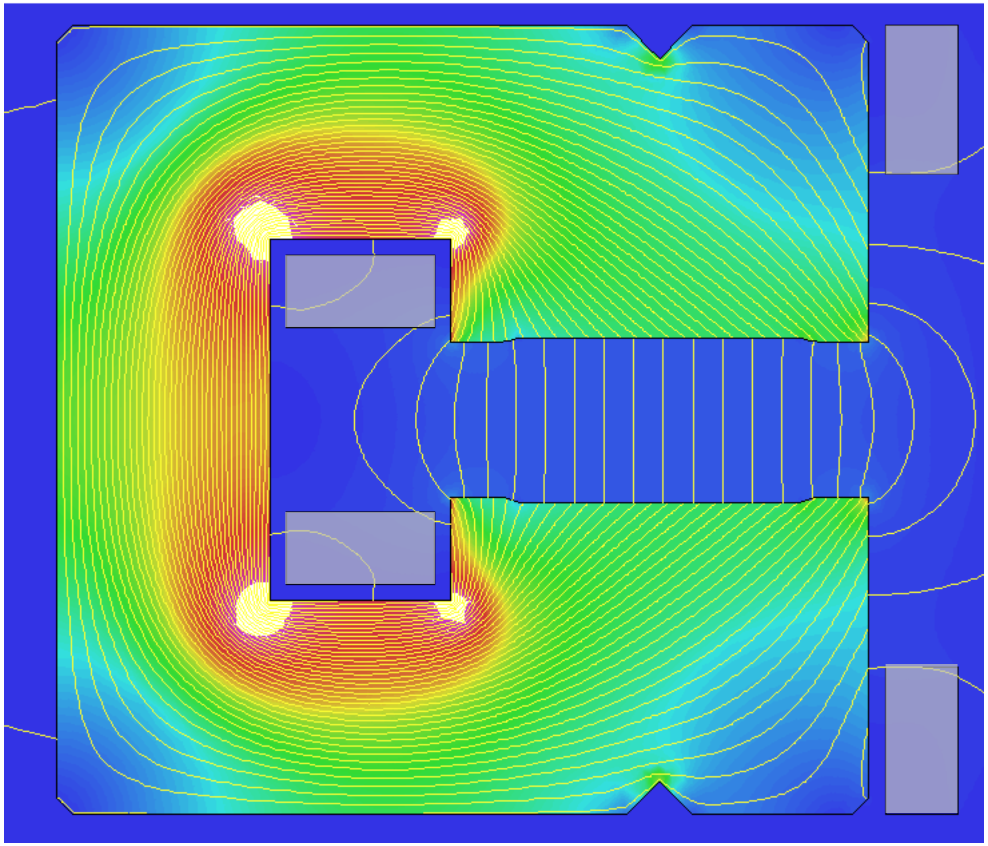
This is the flux density (for the max field of FCC-ee) if we were to use the LEP dipoles, exploiting the 30% dilution of the iron



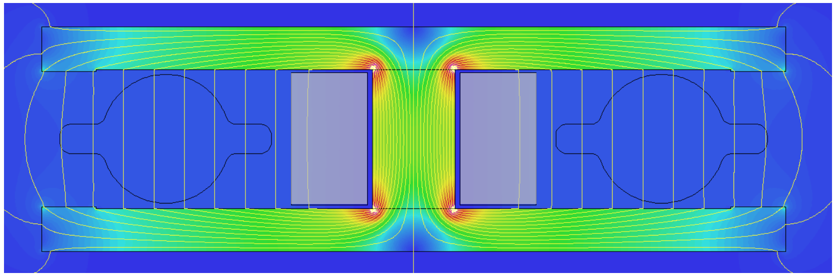
For FCC-ee we propose a twin dipole (I layout), with two aluminium excitation bars: simple, compact and energy saving



These are the cross-sections of the LEP and FCC-ee main dipoles, to scale (54 mT in the bore)

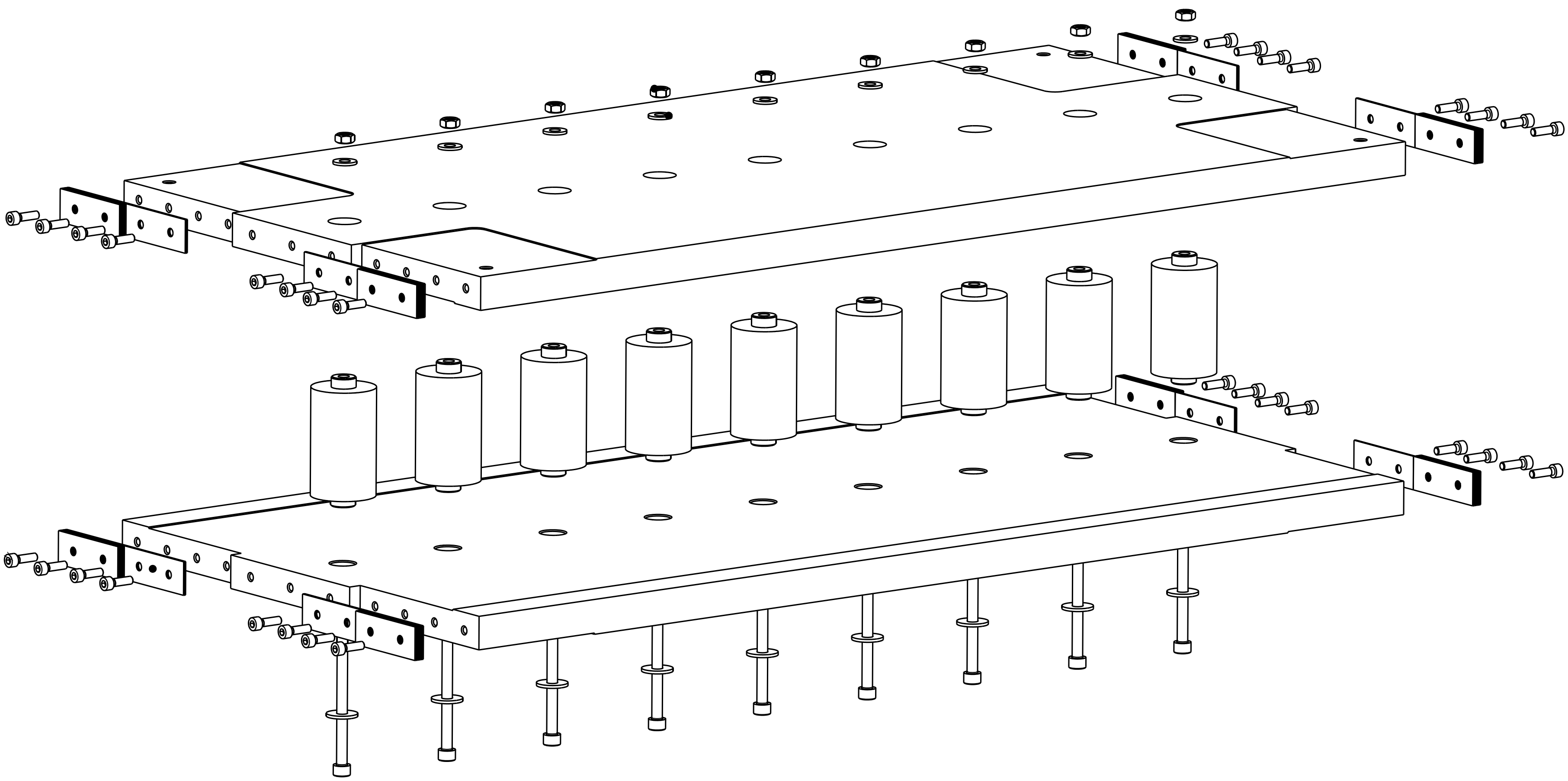


LEP
(built)

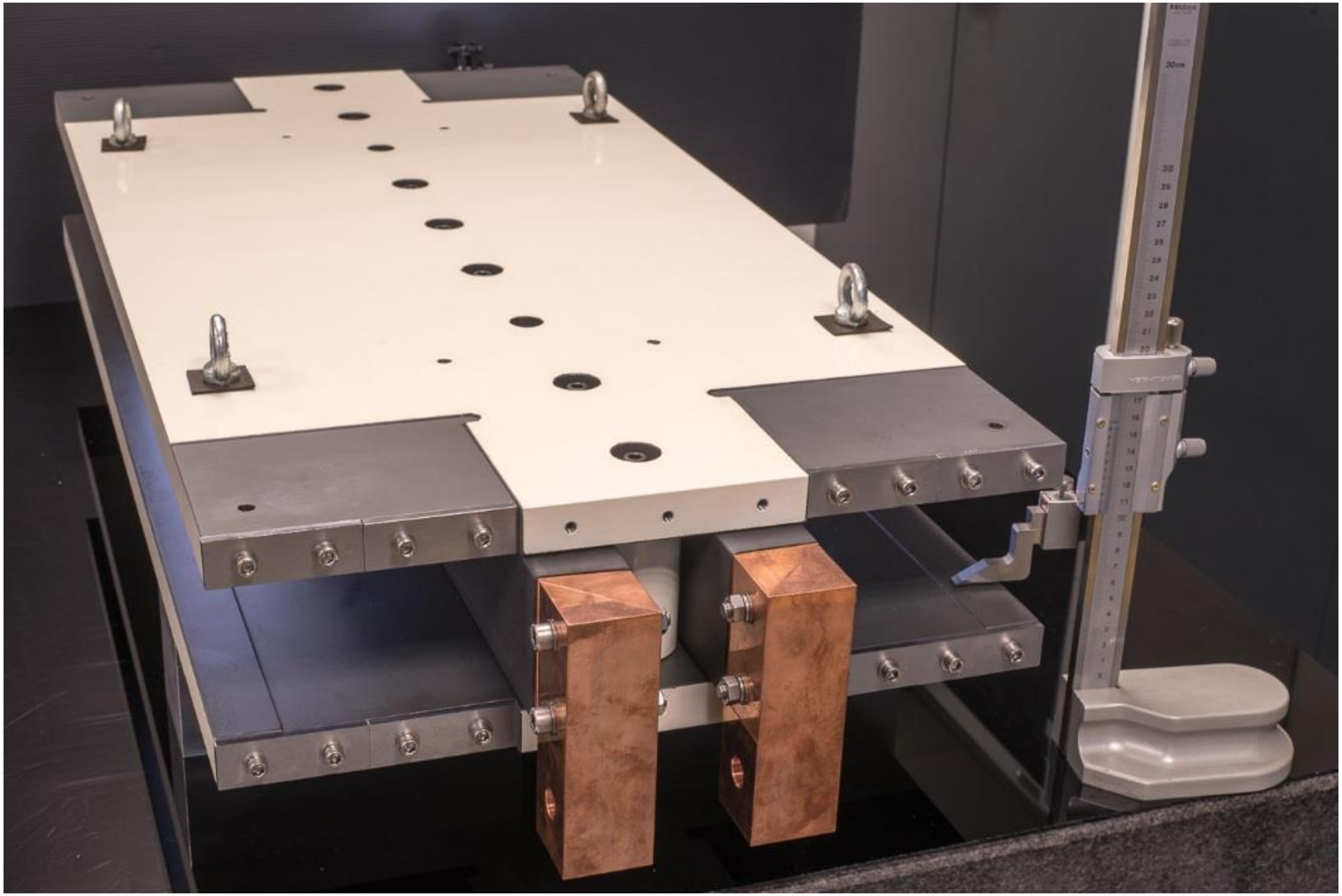


FCC-ee
(prototype)

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



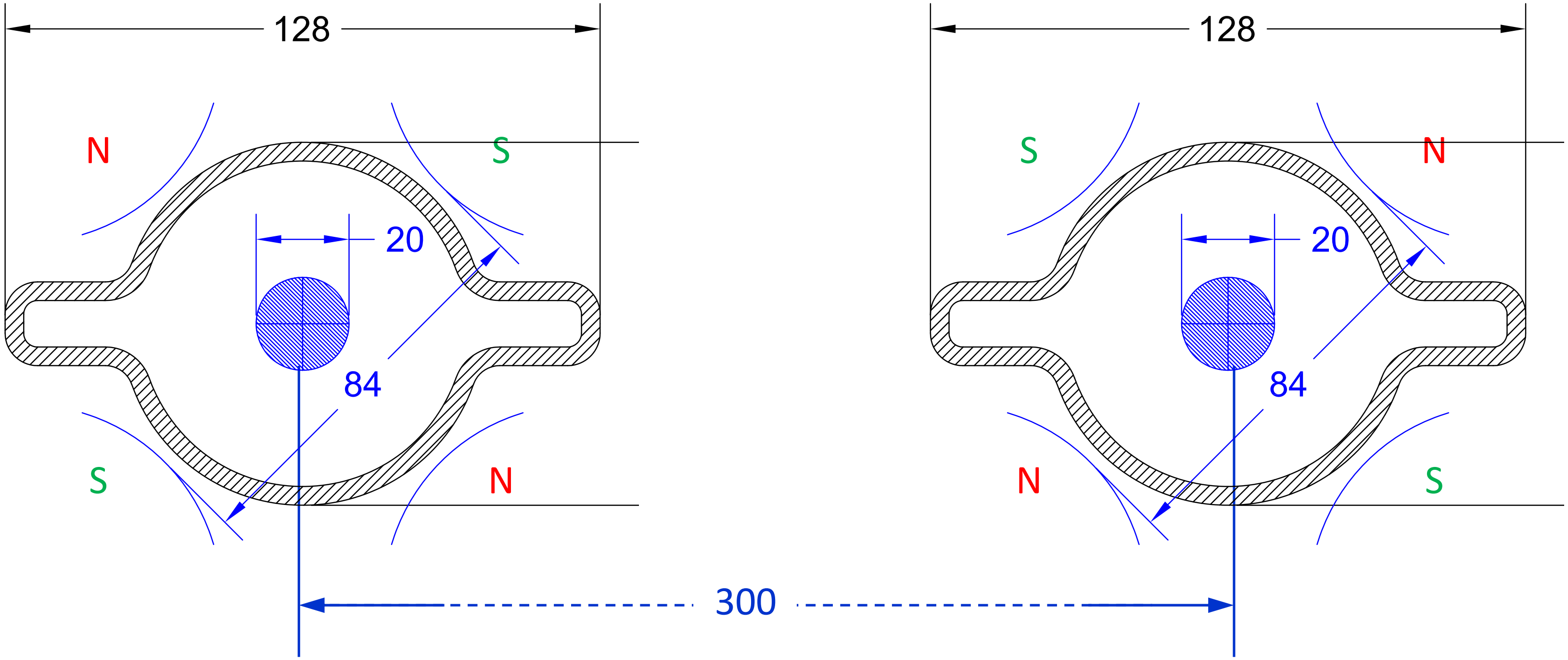
This was assembled at CERN last week, with copper busbars (instead of aluminium) for the prototype



picture by Mike Struik

main (twin) quadrupoles

To exploit a magnetically coupled twin layout, we use an FD polarity in the two apertures

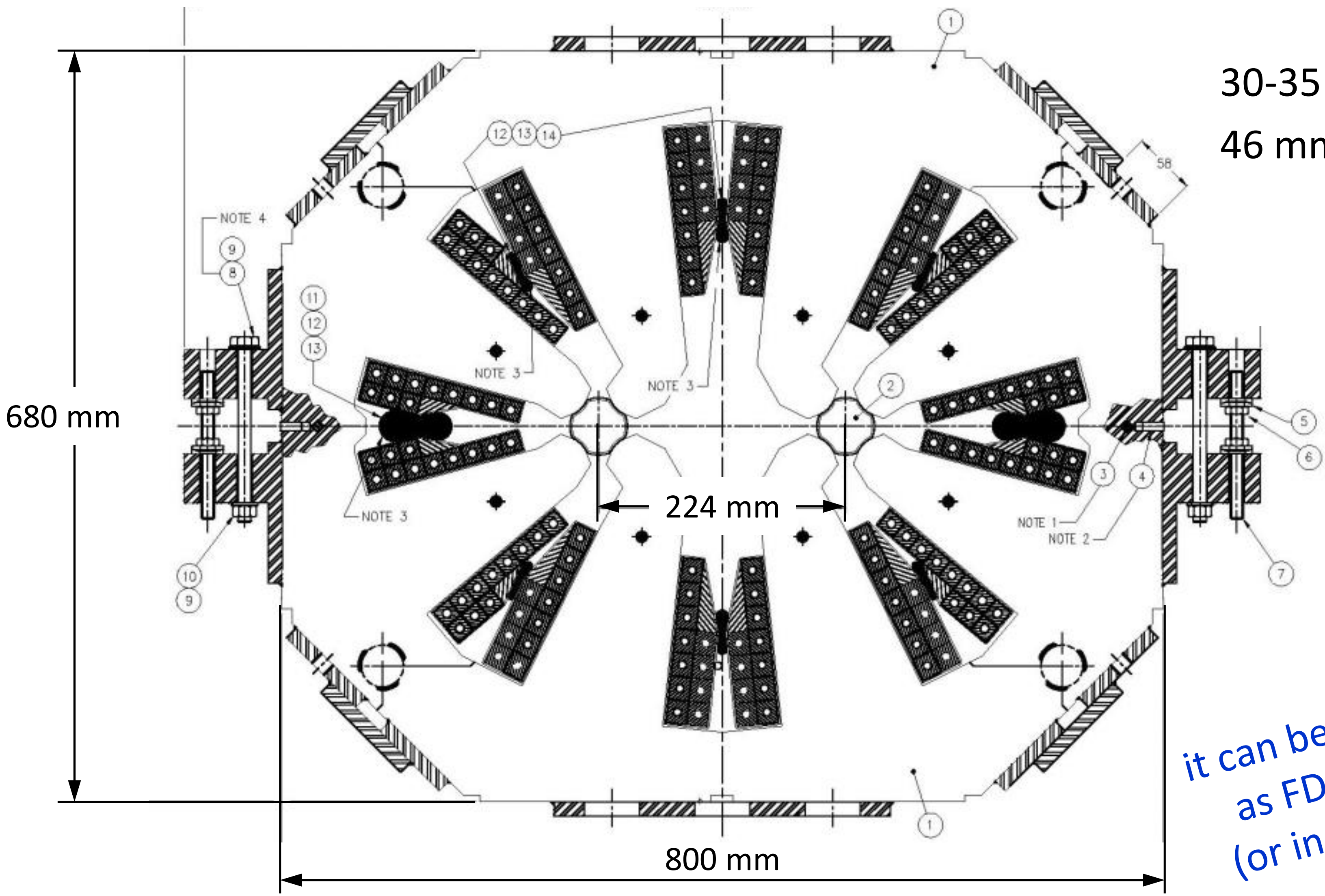


aperture and intra-beam distance: as for bending magnets

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

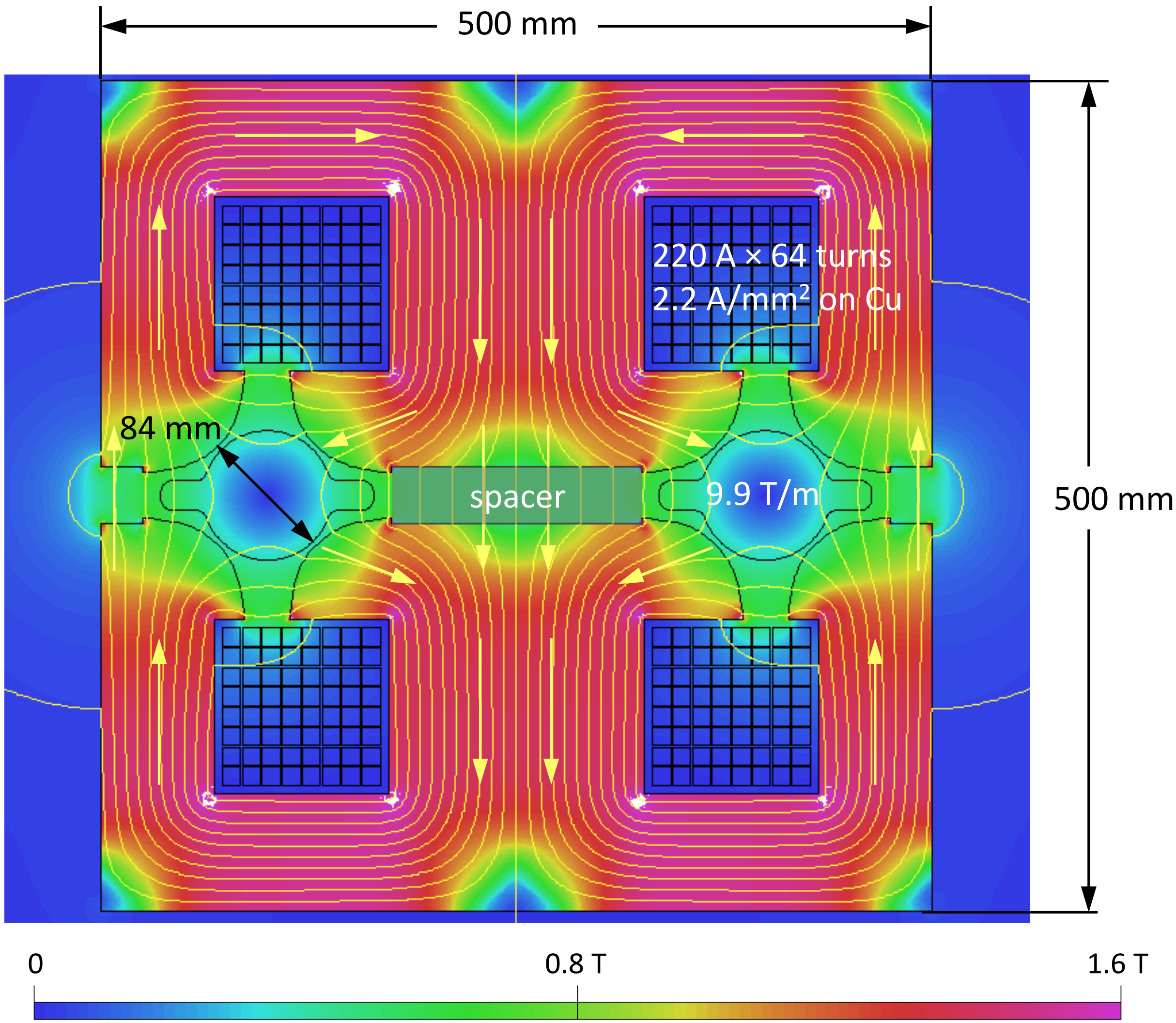


30-35 T/m

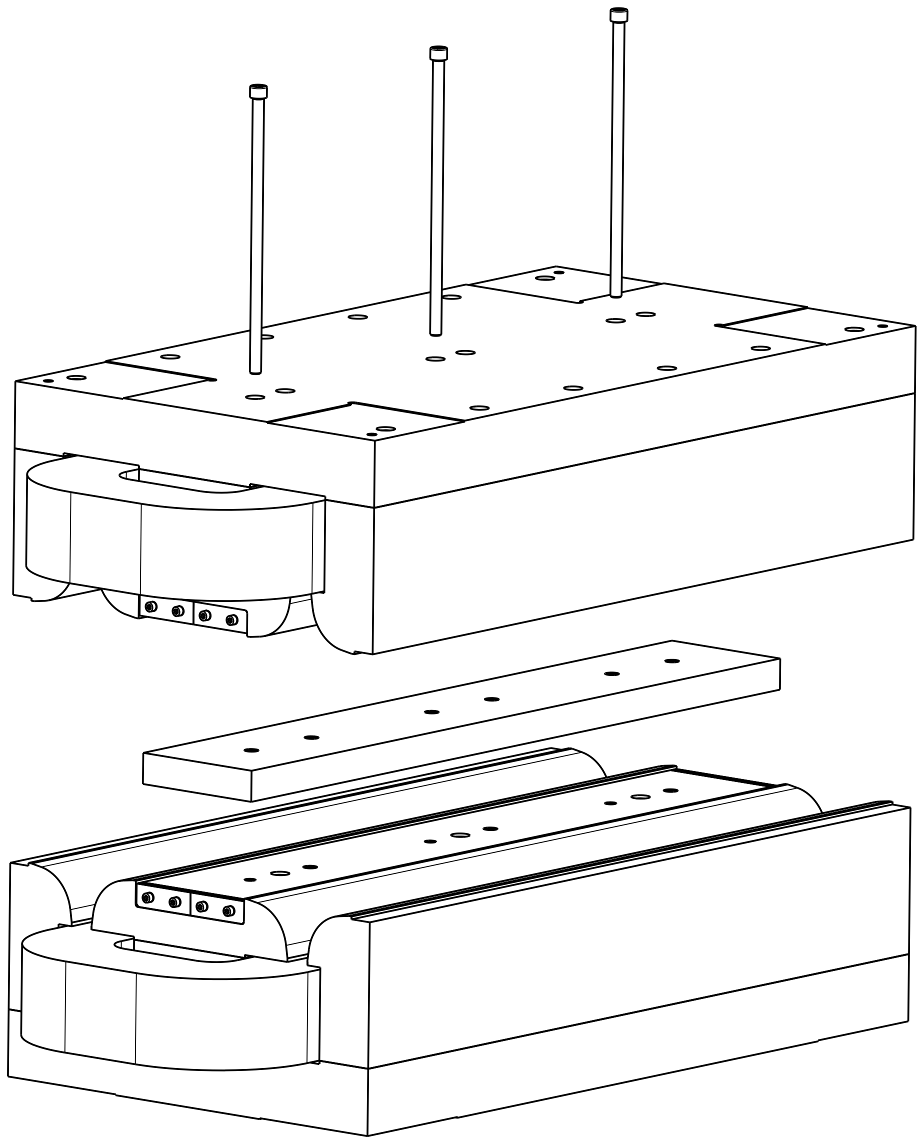
46 mm dia.

it can be powered as FD or as FF (or in between)

We propose a (coupled) twin quadrupole, saving 50% power (at equal A/mm²) with respect to a traditional design; moreover, the coils are far from the midplane radiation



We are manufacturing a 1 m long prototype, with a central non-magnetic spacer to position the two halves



conclusions

Conclusions

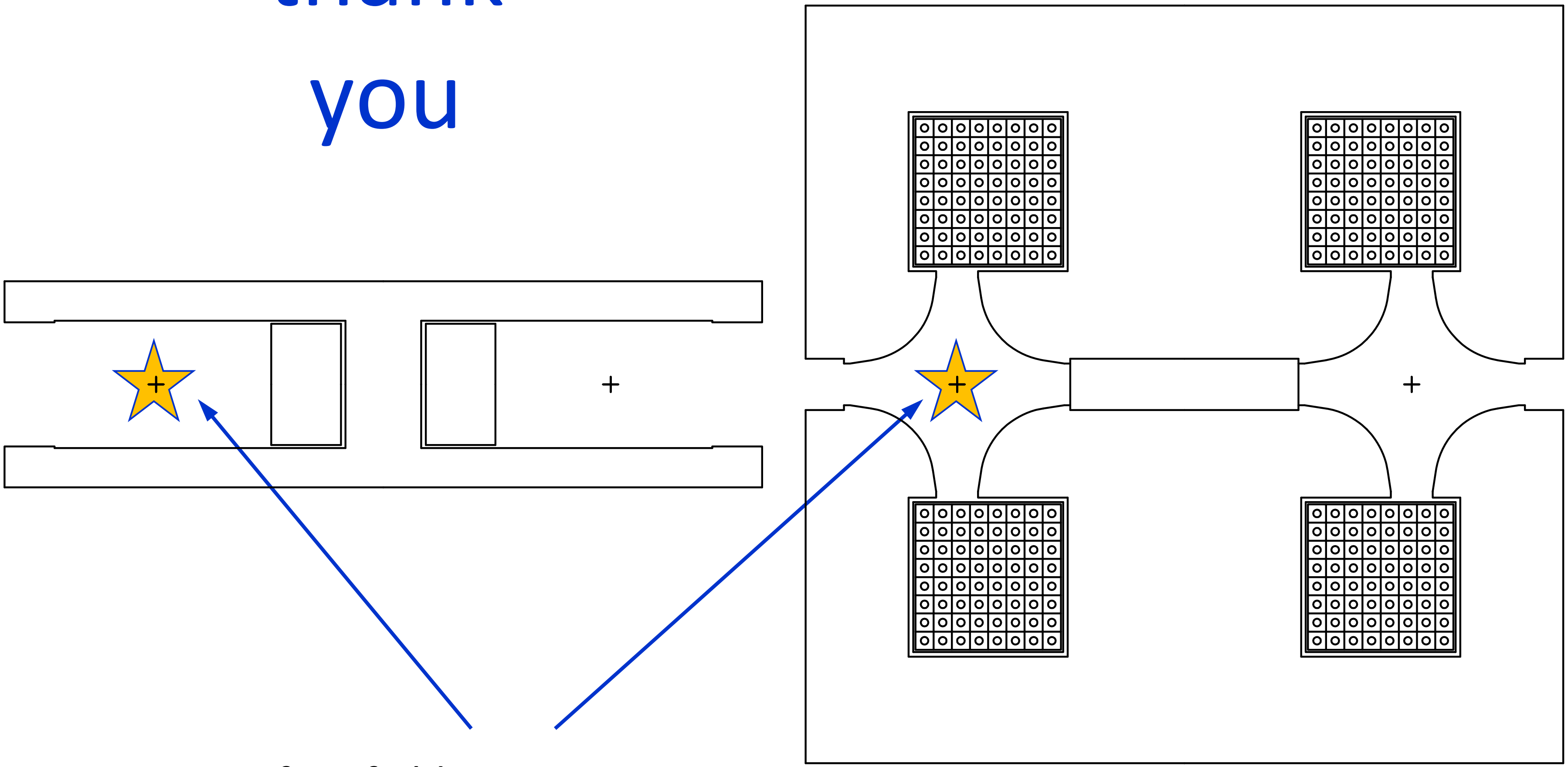
1. The main magnets for FCC-ee can run with reasonable power consumption (16 MW for main dipoles, 25 MW for main quadrupoles) if innovative designs are used

2. The proposed cross-sections aim at compactness and simplicity, as 67 km of (main) dipoles and 9 km of (main) quadrupoles are needed

3. 1 m long prototypes are being designed, to prove experimentally the twin configuration
   - low field and unusual aspect ratio (for the dipole)
   - unconventional asymmetries (for the quadrupole)

4. These are proofs of concept and starting points for further optimizations, which will be needed in the future for a series production of thousands of units in the industry

thank you



free field in one aperture

For the twin dipole, the pole width is compatible with the target field quality, according to simulations

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 (b_2–b_6)

For the twin quadrupole, the left / right asymmetry and the open midplane make the field quality tricky: the prototype can then guide further simulations

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 – b_{10}: allowed multipoles at 10 mm radius