Thoughts about the main FCC-ee warm magnets

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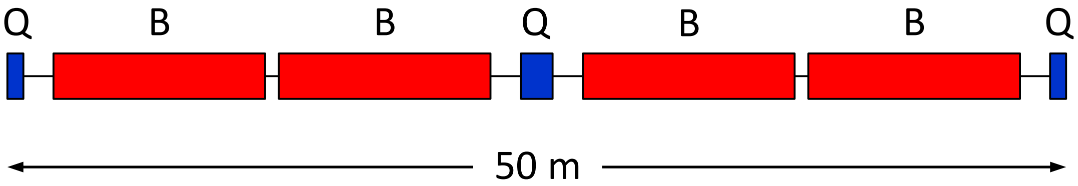
13 Apr. 2016

The two (tentative) lattices for FCC-ee have similar ∫B though different ∫B’

@ 175 GeV per ring

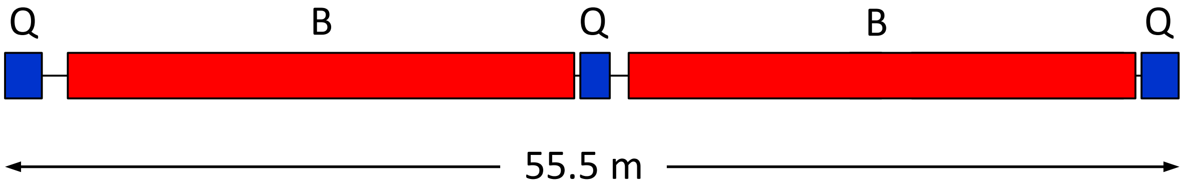


B: $6528 \times 60\ \text{mT} \times 10\ \text{m} = 3917\ \text{Tm}$

QF: $2000 \times 21.4\ \text{T/m} \times 1.5\ \text{m} = 64200\ \text{T}$

QD: $2002 \times 17.5\ \text{T/m} \times 1.5\ \text{m} = 52552\ \text{T}$

Bastian Härer



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B: $2928 \times 52\ \text{mT} \times 23.93\ \text{m} = 3643\ \text{Tm}$

QF: $1460 \times 8.8\ \text{T/m} \times 3.5\ \text{m} = 44968\ \text{T}$

QD: $1460 \times 21.8\ \text{T/m} \times 1.4\ \text{m} = 44560\ \text{T}$

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the main dipoles

This conceptual design is based on a tentative aperture

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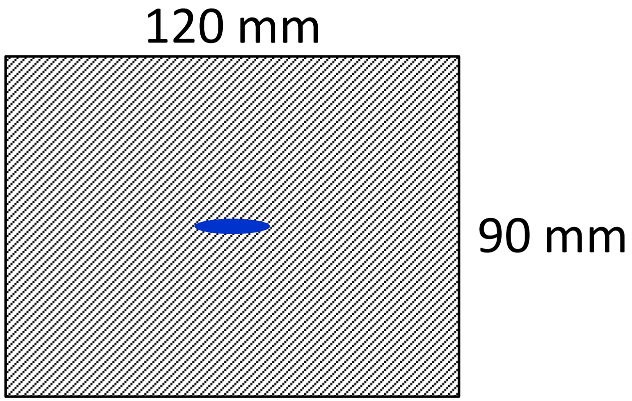
10^{-4} field homogeneity in ±10 mm horiz. (not counting quad term)

$e_x/e_y \approx 2000$

Roberto Kersevan and others

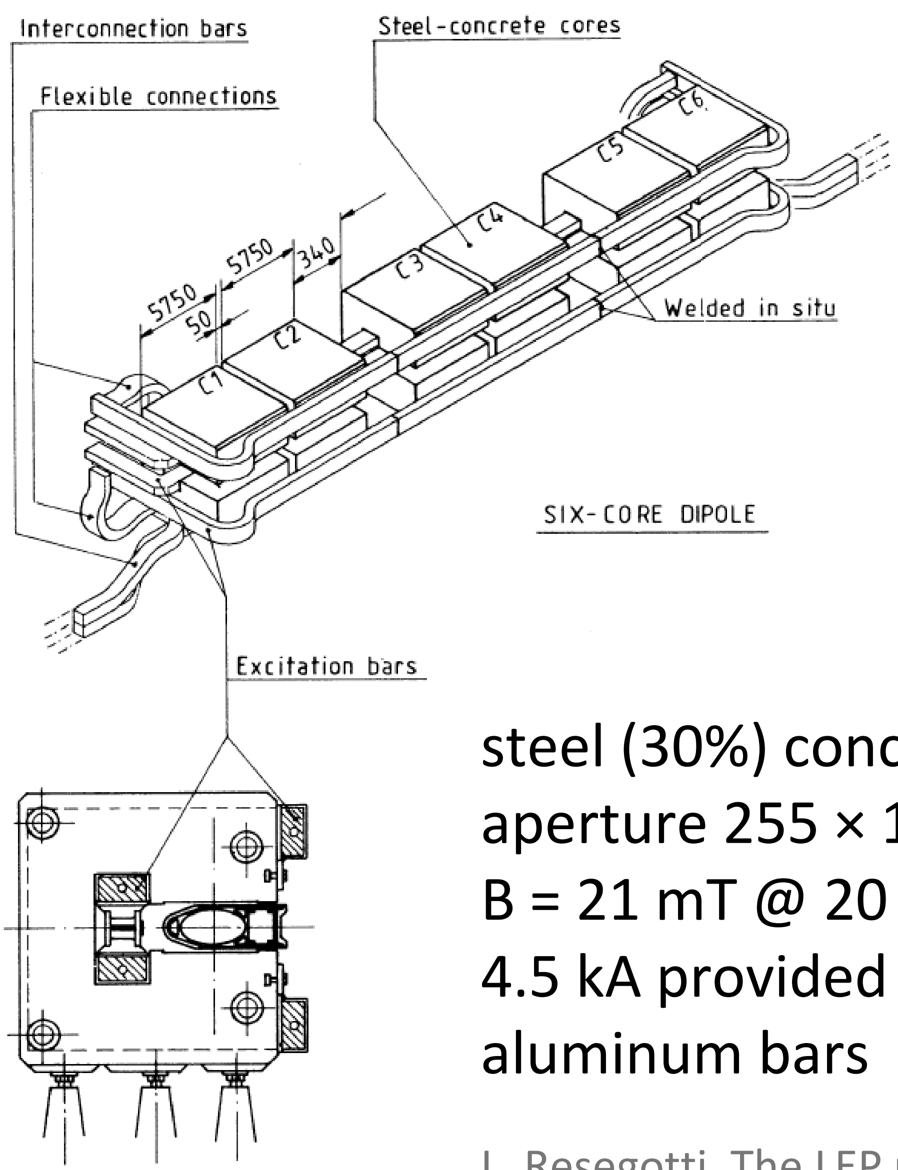
vertical aperture 90 mm

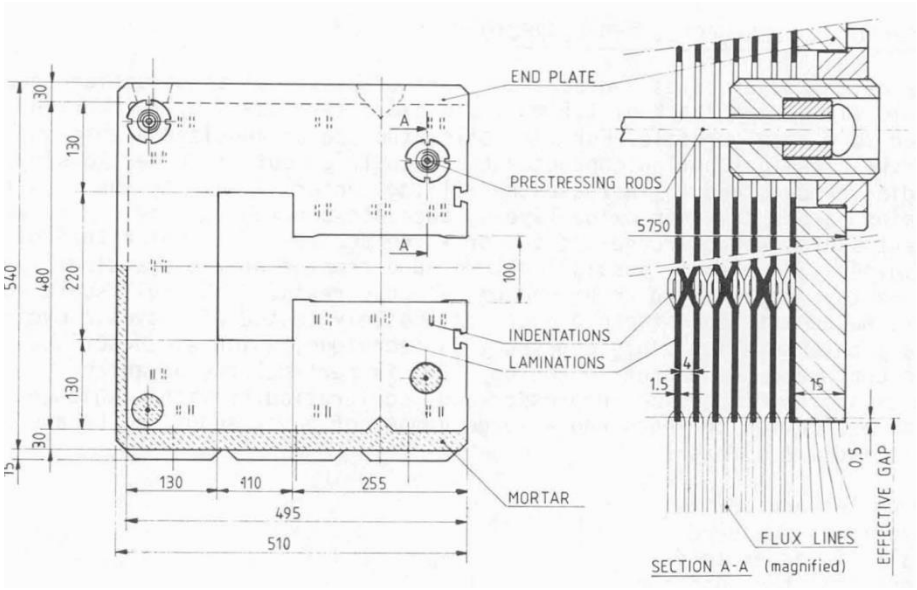
horizontal aperture 120 mm (recently changed to ≈200 mm)



dictated by impedance / vacuum considerations

The closest case of many low field dipoles is LEP





steel (30%) concrete (70%) cores, 5.75 m long

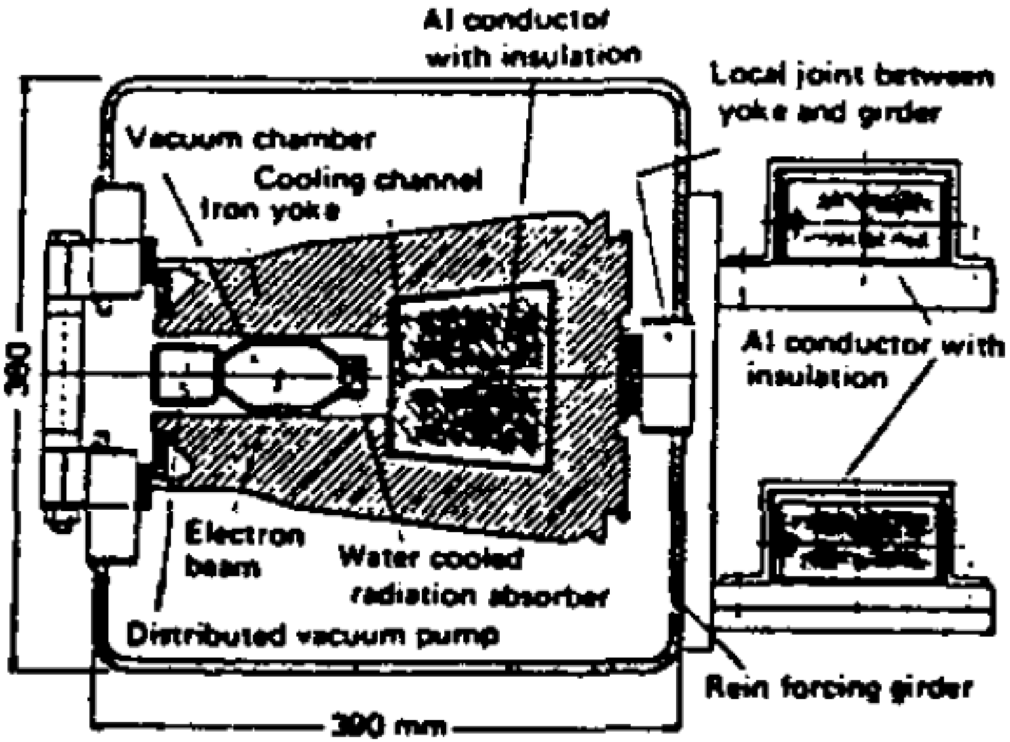
aperture 255 × 100 mm

B = 21 mT @ 20 GeV, 110 mT @ 100 GeV

4.5 kA provided by 4 water cooled 90 × 44 mm^2 aluminum bars

L. Resegotti. The LEP magnet system. Journal de Physique, 1984, 45

Another example is HERA



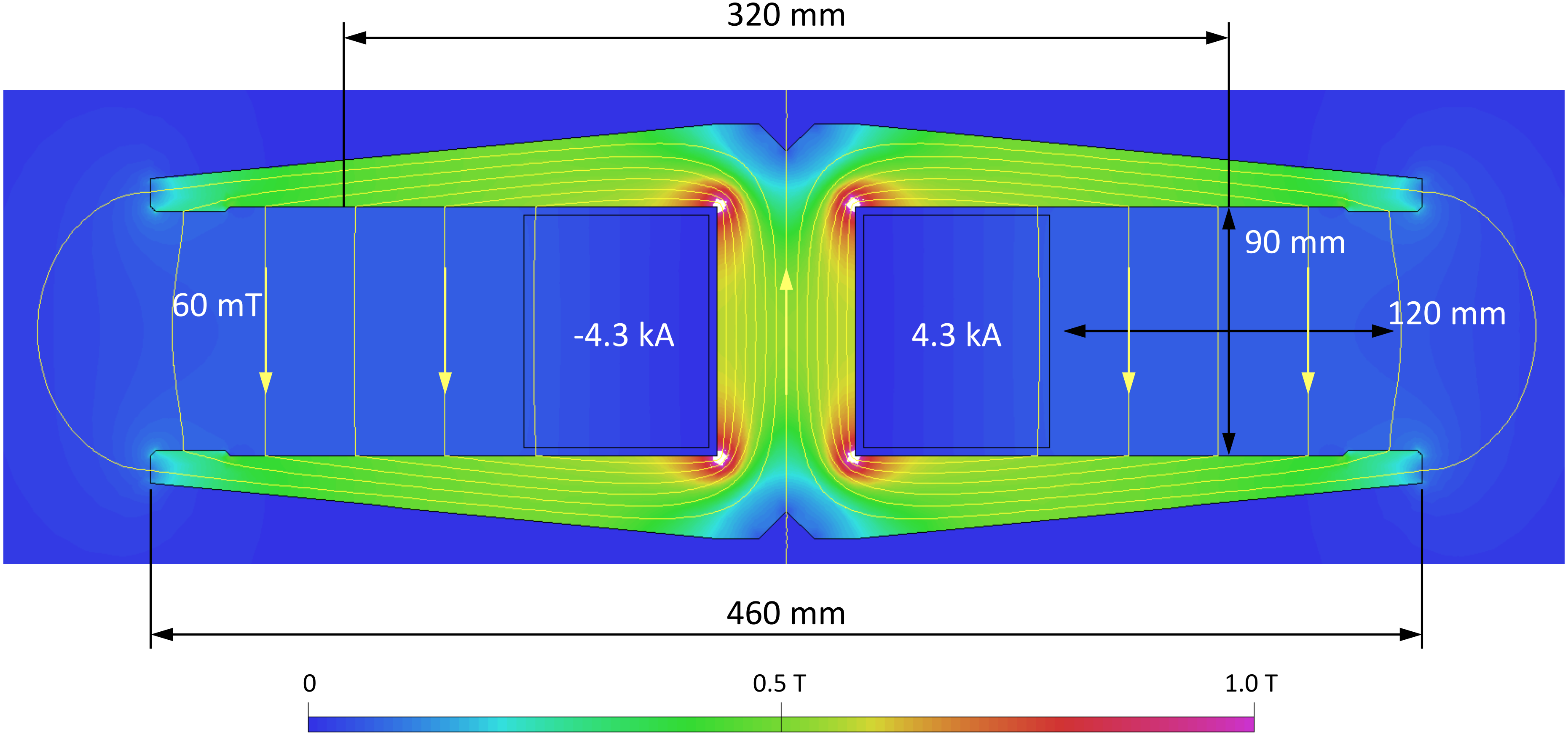
TECHNICAL DATA at 30 GeV

Field strength	0.1638 T
Bending radius	610.4 m
Gapheight	51.5 mm
Good field cross section	40x80 mm^2
Conductor (aluminum)	100 cm^2
Number of turns in coil	1
Current	6767 A
Power	2.57 kW

5 mm thick laminations, 9 m length
aperture 160 × 51.5 mm

R. Brinkmann. HERA. CAS - CERN Accelerator School, 1987

The proposed concept for the FCC-ee dipoles is a X layout, with a twin aperture yoke and single busbars as coils



This concept for the bending magnets has several features

twin 2-in-1

the Ampere-turns are recycled, with 50% power consumption

less units to manufacture, transport, install, align, remove

yoke

compact: 190 kg/m × 6528 magnets × 10 m ≈ 12400 t

punched thick laminations (5-6 mm, like HERA and LHC)

no dilution (like LEP), with easier recycling of raw material

excitation circuit

1-turn conductor busbar, 67×84 mm^2: 30.4 kg/m of Al, 100.2 kg/m of Cu

no cost for coil manufacturing

no inter-turn insulation (reliability even with radiation)

easier recycling of raw material

individual trims on left / right aperture are possible

The aspect ratio of the yoke still provides a reasonable field homogeneity

energy	[GeV]	45	175
B_1	[mT]	15	60
b_2	[10^{-4}]	-6.0	-4.2
b_3	[10^{-4}]	-0.3	-0.4
b_4	[10^{-4}]	-0.5	-0.5
b_5	[10^{-4}]	-0.1	-0.1
b_6	[10^{-4}]	0.0	0.0

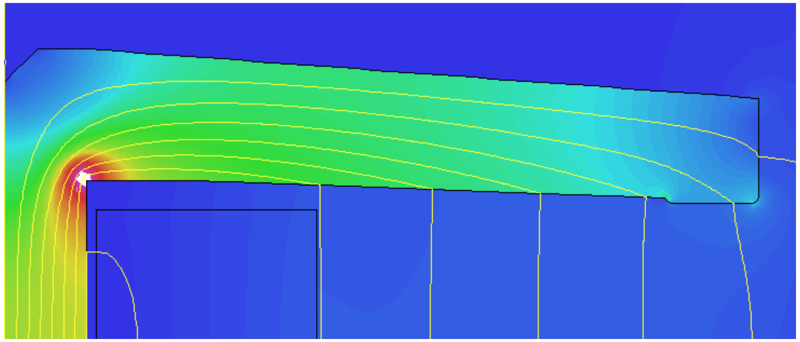
allowed multipoles
at 10 mm radius

a (systematic) b_2 – quadrupole component – is not critical, and it can be adjusted if necessary in the design

a change in iron permeability impacts only b_2

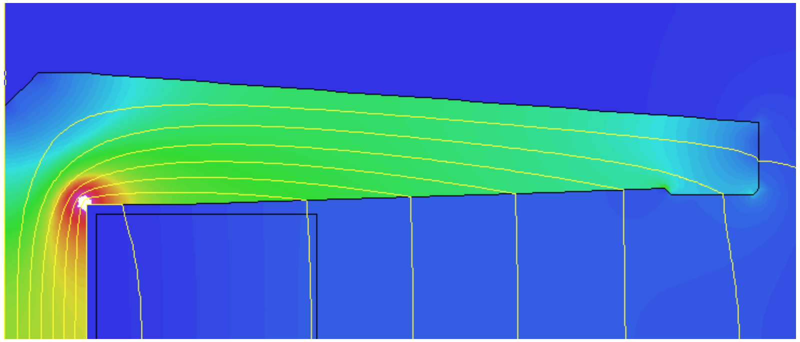
shuffling of yoke instead of shuffling of laminations, for such a large machine?

Conceptually, there is no problem in making it more *combined function*, using an inclined circular arc at the pole



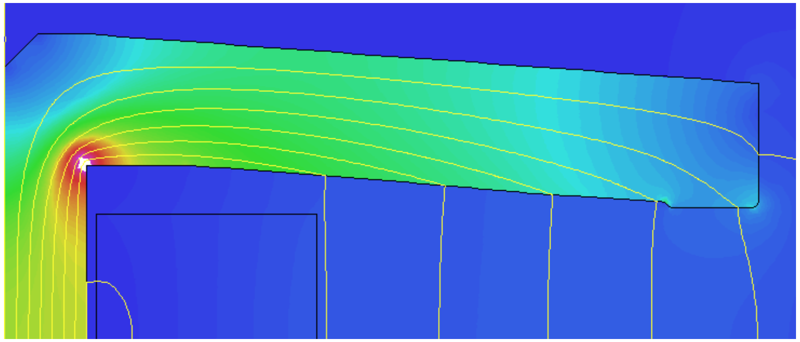
$\alpha_{\text{pole}} = -2$ deg

60 mT & 43 mT/m



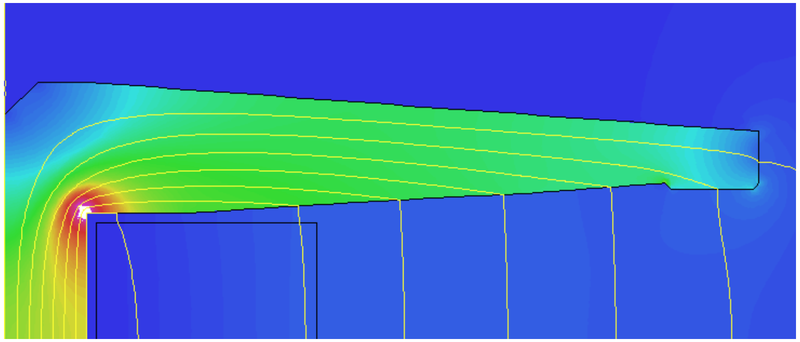
$\alpha_{\text{pole}} = 2$ deg

60 mT & -46 mT/m



$\alpha_{\text{pole}} = -4$ deg

60 mT & 90 mT/m



$\alpha_{\text{pole}} = 4$ deg

60 mT & -86 mT/m

PS main units: $\alpha_{\text{pole,eq}} \approx 12$ deg (ISR had a combined quad and sext as well)

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the main quadrupoles

The proposal for the quadrupoles is to make QF = QD

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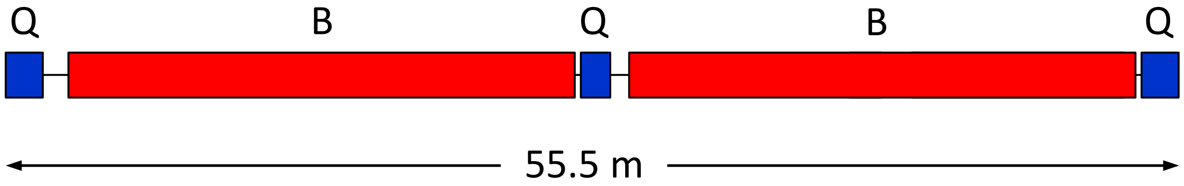
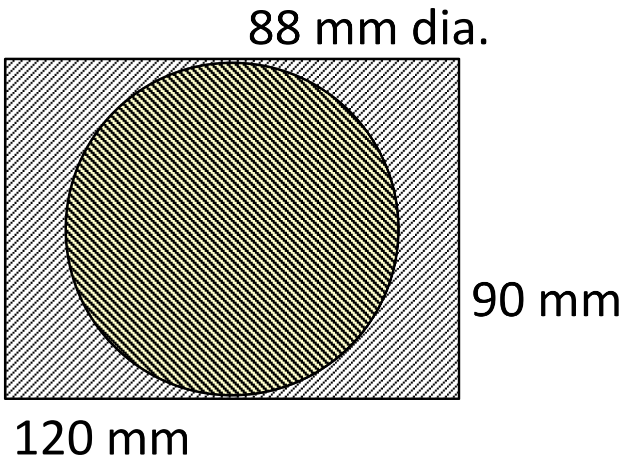


QF: 8.8 T/m × 3.5 m = 30.8 T

⇒ QF ≈ QD ≈ 8.8 T/m × 3.5 m

QD: 21.8 T/m × 1.4 m = 30.5 T

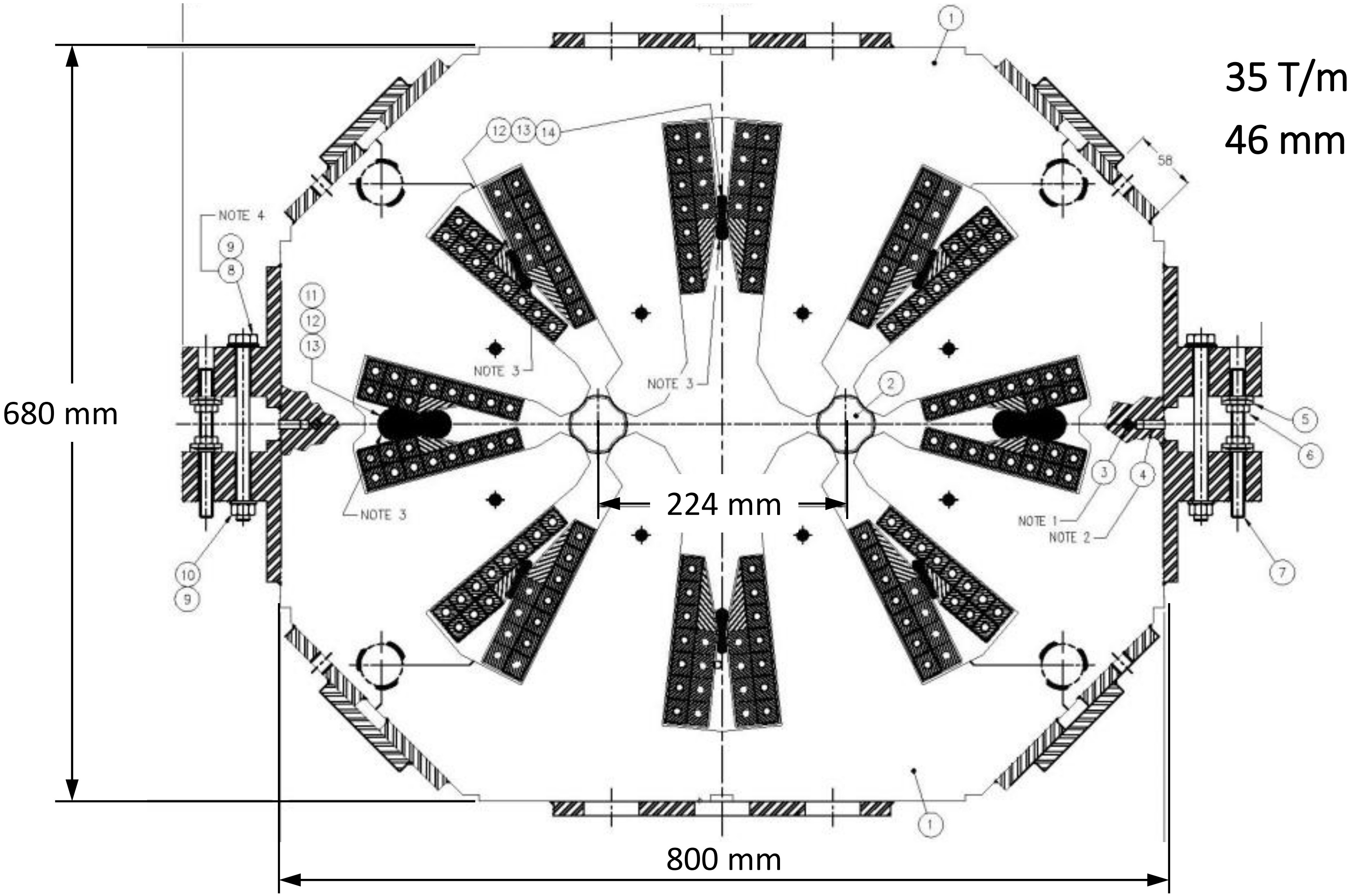


circular aperture discussed with Frank Zimmermann

[for comparison: 125 mm in LEP, 88 mm in SPS]

intrabeam distance 320 mm as in the dipoles

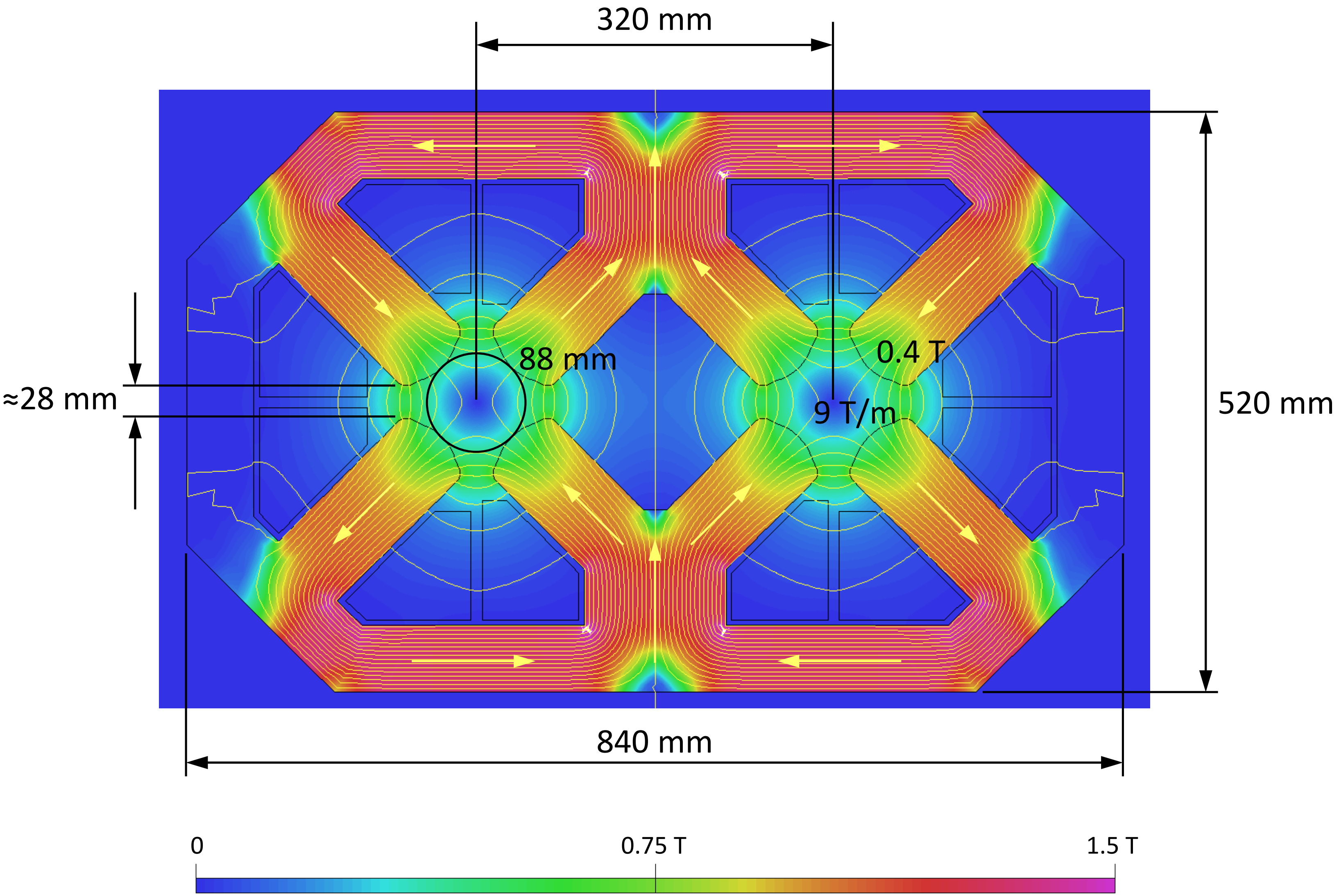
A *conventional* twin quadrupole design can be like the MQW of the LHC – aperture and intrabeam distance would fit



35 T/m

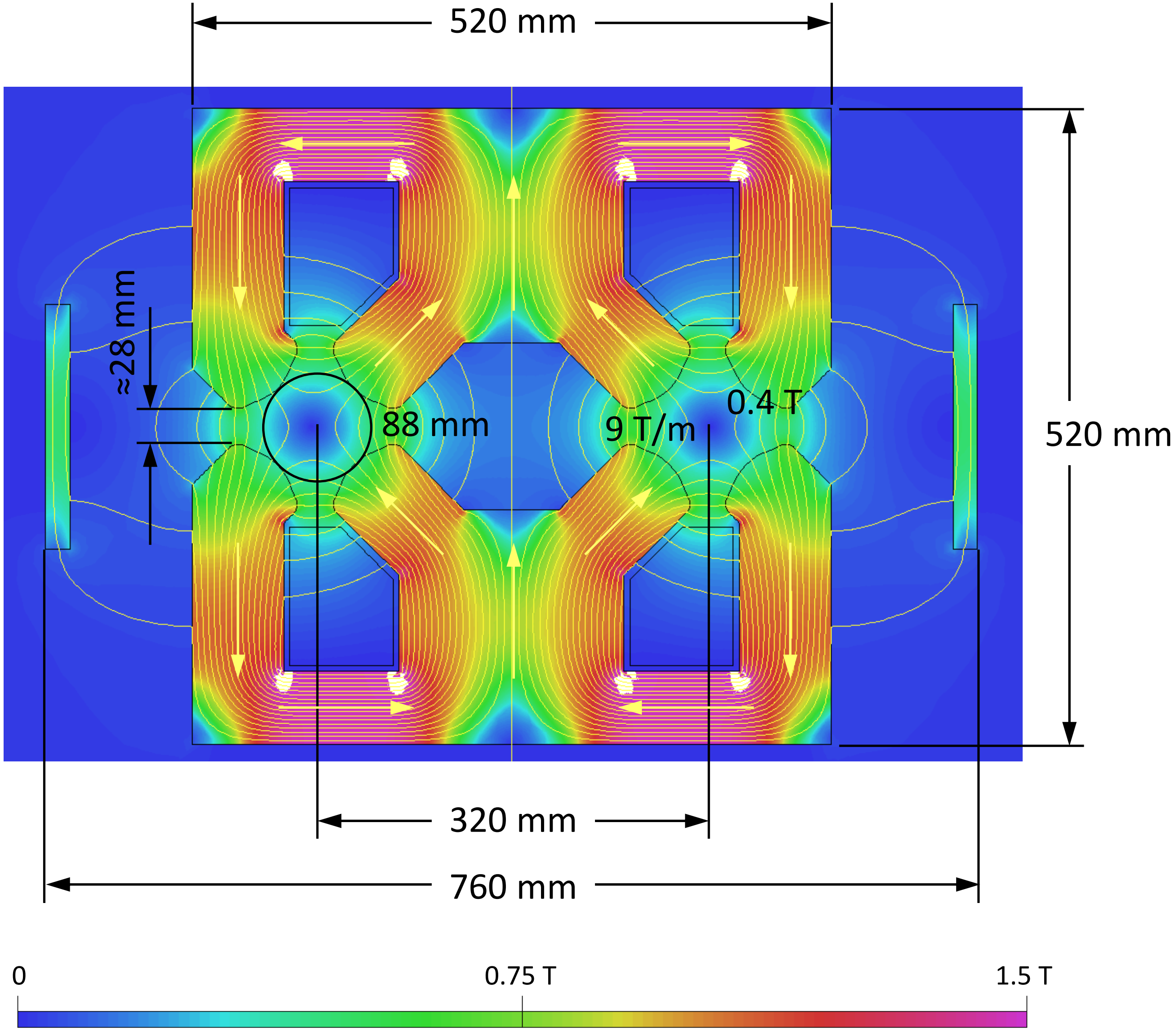
46 mm dia.

This design saves 25% in power (for the same current density) – with a constrained F/D polarity



While this design saves 50% in power (for the same current density) with respect to a 4 quadrant MQW like magnet

midplane shield for stray field



These concepts for the quadrupoles have several features

twin 2-in-1

novel arrangements of the magnetic circuit allow for considerable savings in Ampere-turns and power consumption

less units to manufacture, transport, install, align, remove

F/D polarity

the design is compatible with individual trims on the apertures

the main quadrupoles of LHC are also F/D, and the (independent) powering circuits are run typically with 5% difference

yoke

punched laminations + plates and non magnetic spacers (for open midplane option)

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power estimates
&
conclusions

Running the (twin) main dipoles at 175 GeV

$B = 60$ mT

$I = 4320$ A per busbar

$j = 0.8\ \mathrm{A/mm^2}$

dissipated power (for 2 apertures)

per m	Al: 175 W/m	Cu: 115 W/m
total (70 km)	Al: 12 MW	Cu: 8 MW

losses in interconnects / cables to be considered, likely 20-30%

depending on arc filling factor and location of power converter(s)

[cooling of busbars with demineralized water not shown]

Running the (twin) main quadrupoles at 175 GeV

B’ = 8.8 T/m

NI = 13700 A per coil (2 coils, open midplane design)

j = 2.1 A/mm^2 75% filling factor for insulation & cooling

total dissipated power for 2 apertures, ∫B’ = 2 × 45000 T

open midplane layout

total (10.2 km) Al: 35 MW Cu: 23 MW

+ a few % of cable losses

50% more for the twin F/D closed midplane

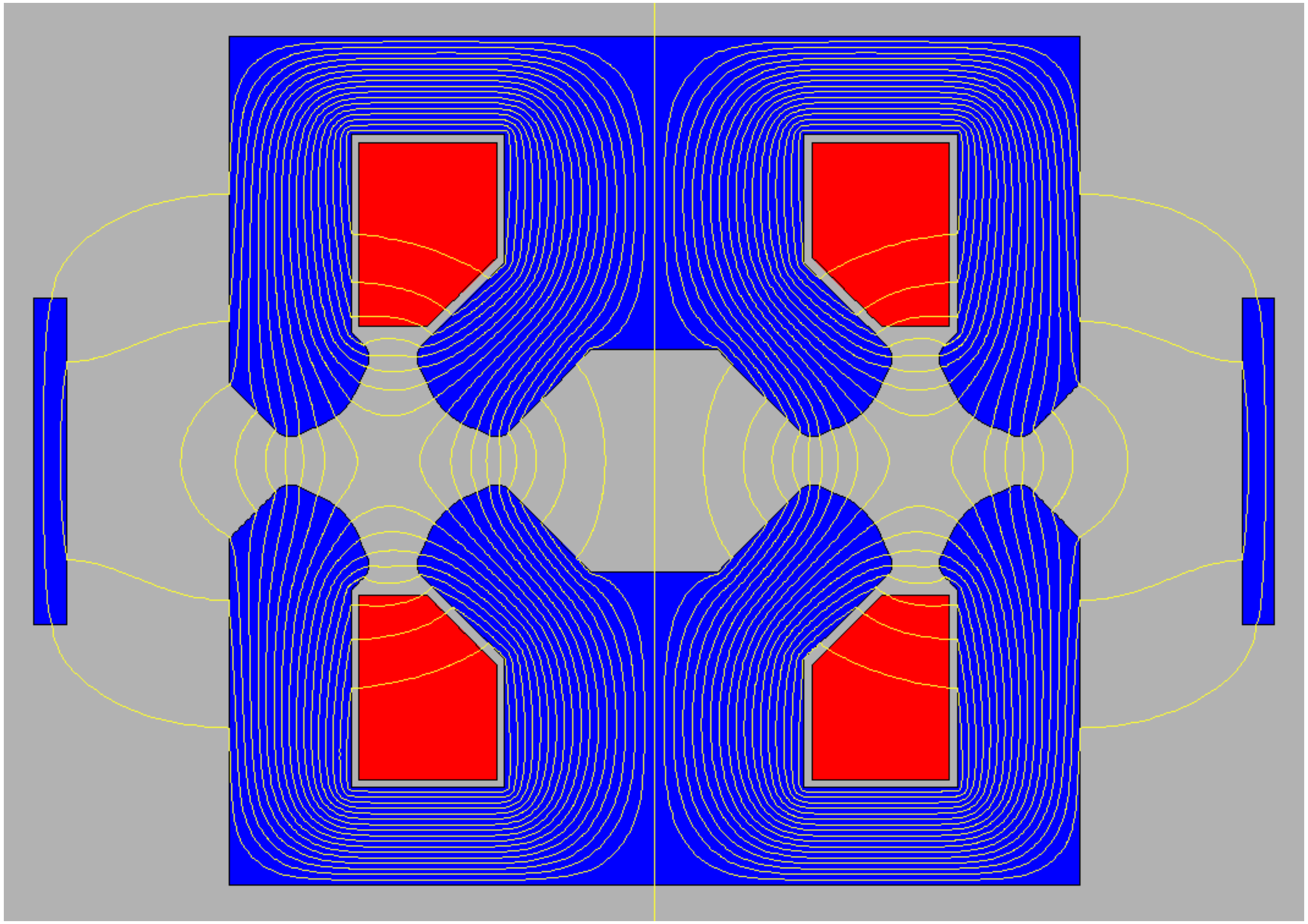
100% more for a classical more symmetric MQW design

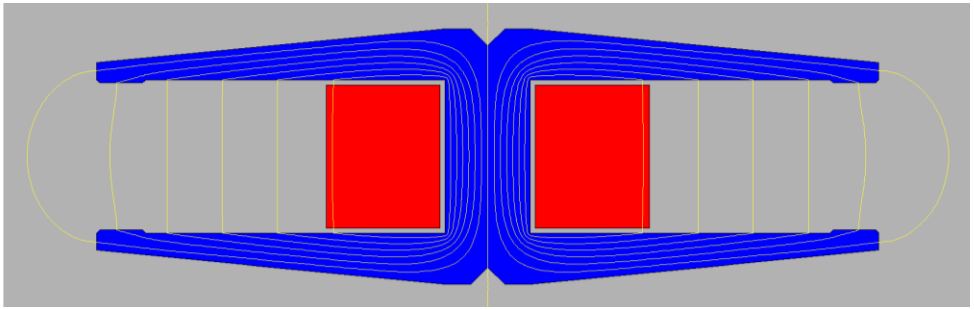
Conclusions

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

2. The design of the dipoles allows exploring a combined function bending magnet for the lattice design

3. Tuning the strengths in the two apertures can be further developed, if needed
   - dipoles: for synchrotron radiation sawtooth
   - quadrupoles: separate trim on F/D polarities





thank you