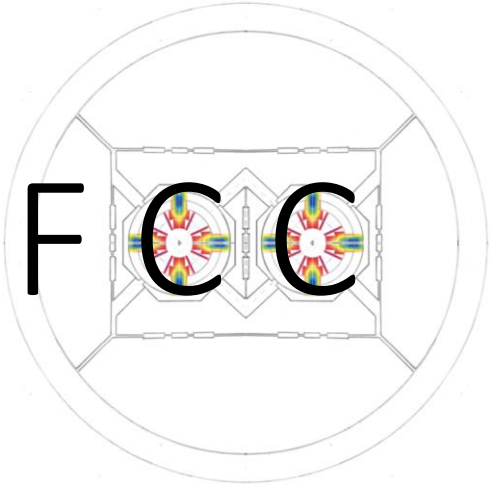


FCC Main Quadrupoles

Clément Lorin - CEA
Ezio Todesco - CERN
Tiina Salmi - TUT

Roma, 14 april 2016

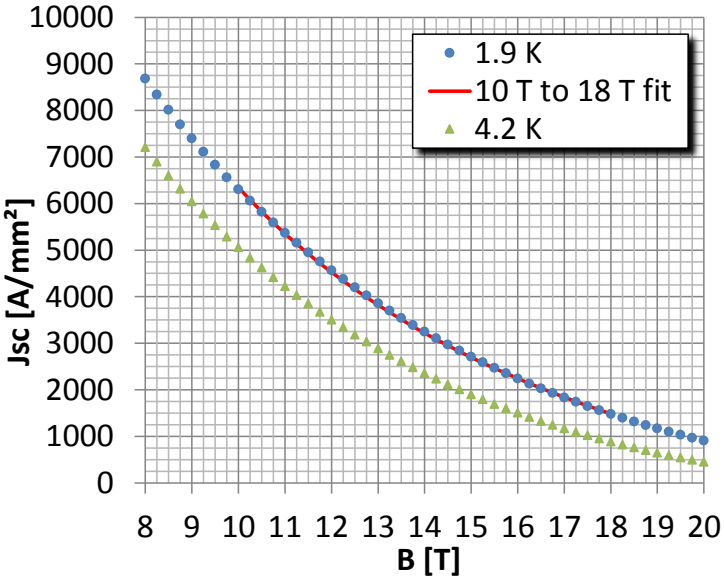
FCC 2015 targets

	G (T/m)	B_{peak} (T)	Bore (mm)	Length (units x m)
MQ FCC	420	12	50	800 x 6.5
MQ LHC	223	6.5	56	392 x 3.2

Number of apertures	(-)	2	2
Inter-aperture spacing	(mm)	250	194
Operating temperature	(K)	1.9	1.9
Margin along the loadline	(%)	20	20
Yoke OD max	(mm)	800	

SC density / cable features

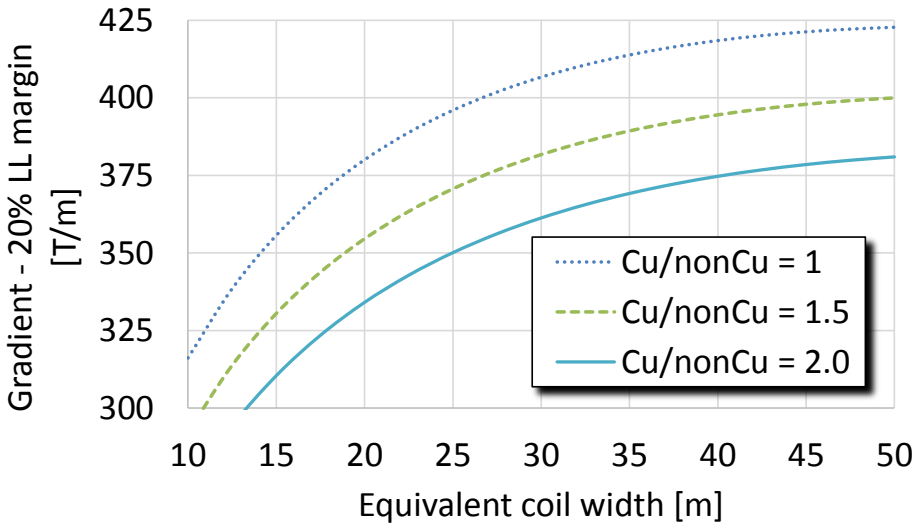
- Specifications close to EuroCirCol project (16 T Nb_3Sn dipole)
  - Cable specifications
    - Strand diameter max: 1.1 mm
    - Number of strands max: 40
    - Cu/non-Cu ratio min: 1/1
  - SC current density
    - 1500 A/mm² @ 16 T and 4.2 K
    - 2250 A/mm² @ 16 T and 1.9 K
    - Hyperbolic fit for scaling law



$$J_{sc}(B) = a\left(\frac{b}{B} - 1\right)$$ with a = 4600 A/mm², b = 23.8 T

Equivalent coil width vs gradient

- What the scaling law* provides:
  - no gain in [T/m] beyond 45 mm eq. coil width
  - protection drives the design: Cu/nonCu vs amount of conductor
  - at first glance, can go beyond 380 T/m

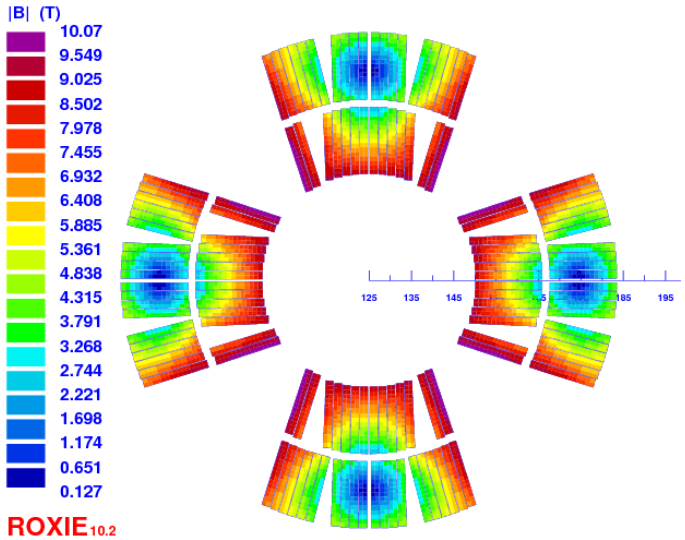


*Todesco et al, Semi-analyticl approaches to magnet design, Wamsdo 2013
Rossi L., Todesco E. Electromagnetic design of superconducting quadrupoles, PRSTAB, 2006

2 Nb_3Sn layers – version 1

- Protection $T_{hotspot}$ < 350 K @ 105% of $I_{nominal}$
- Triggering time (15 ms) + QH delay (25 ms)
  - Cu/nonCu = 2.2
  - I_n = 24100 A
  - G = 364 T/m
  - $J_{overall}$ = 716 A/mm²
  - Bare cable width = 15.75 mm

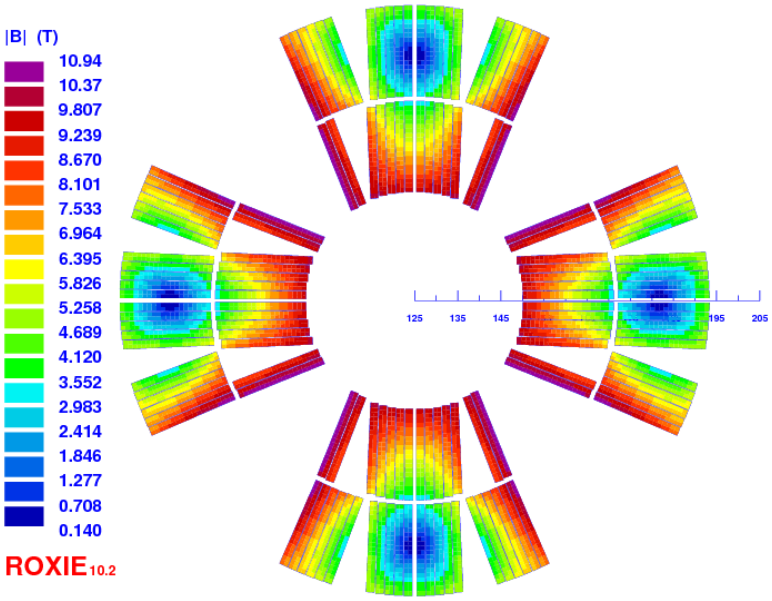
-> 2 layer designs lead to
high Cu/nonCu ratio for protection



[based on Mikko Karppinen's design]

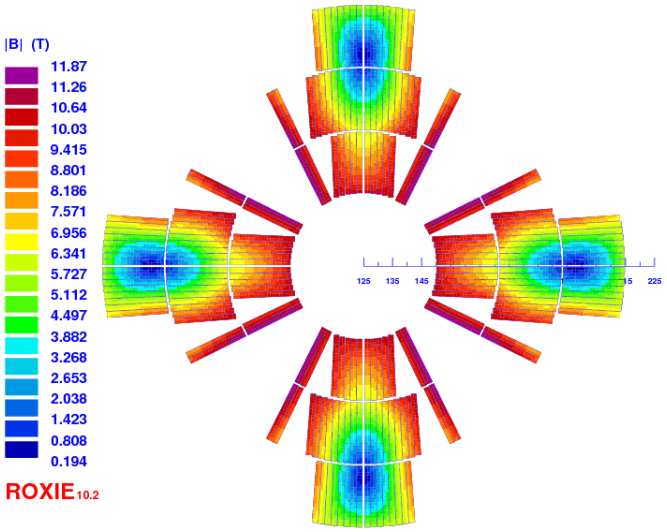
2 Nb_3Sn layers – version 2

- Protection $T_{hotspot}$ < 350 K @ 105% of $I_{nominal}$
- Triggering time (15 ms) + QH delay (25 ms)
  - Cu/nonCu = 1.8
  - I_n = 29900 A
  - G = 390 T/m
  - $J_{overall}$ = 680 A/mm²
  - Bare cable width:
    - 21.0 mm (Fresca2-like cable)



3 Nb_3Sn layers – version 3

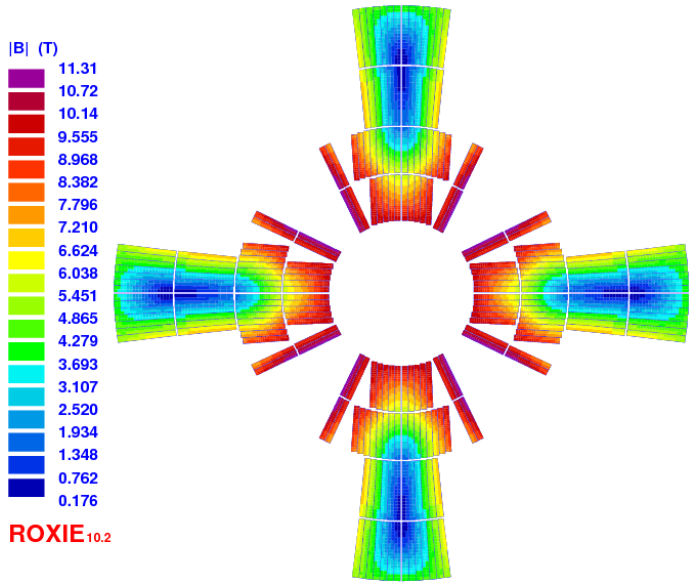
- Protection $T_{hotspot}$ < 350 K @ 105% of $I_{nominal}$
- Triggering time (15 ms) + QH delay (25 ms)
  - Cu/nonCu = 1.55
  - I_n = 27260 A
  - G = 413 T/m
  - $J_{overall}$ = 610 A/mm²
  - Bare cable width:
    - 21.0 mm (Fresca2-like cable)



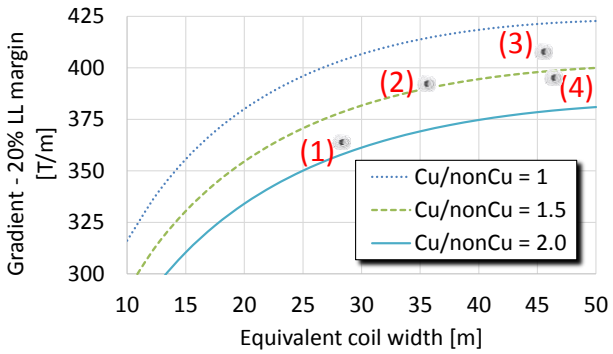
[Ezio Todesco's design]

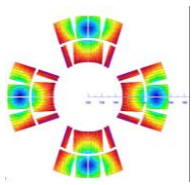
2 Nb_3Sn layers + 2 Nb-Ti layers – v4

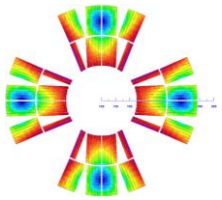
- Protection $T_{hotspot}$ < 350 K @ 105% of $I_{nominal}$
- Triggering time (15 ms) + QH delay (25 ms)
  - Cu/nonCu = 1.95_{Nb_3Sn} – $1.05_{Nb\text{-}Ti}$
  - I_n = 21200 A
  - G = 392 T/m
  - J_{copper} = 630_{Nb_3Sn} – $450_{Nb\text{-}Ti}$ A/mm²
  - Bare cable width:
    - 15.75_{Nb_3Sn} – $20.2_{Nb\text{-}Ti}$ mm

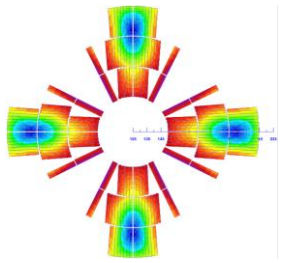


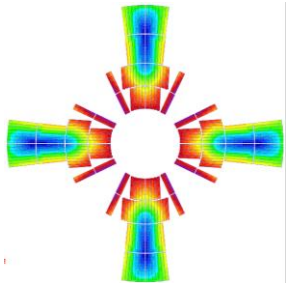
Summary design options







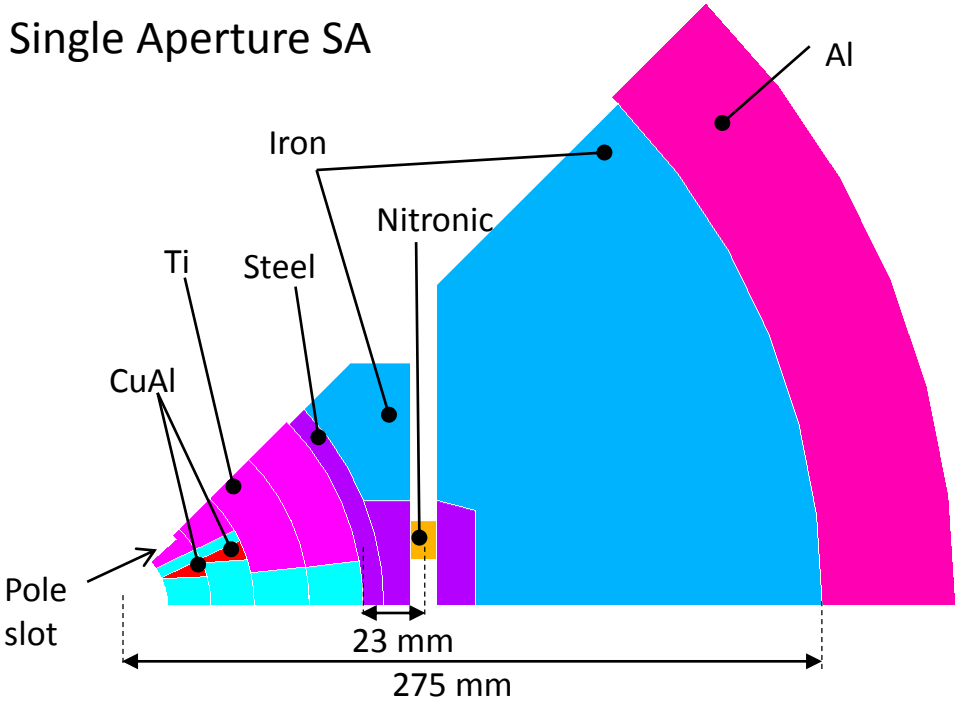


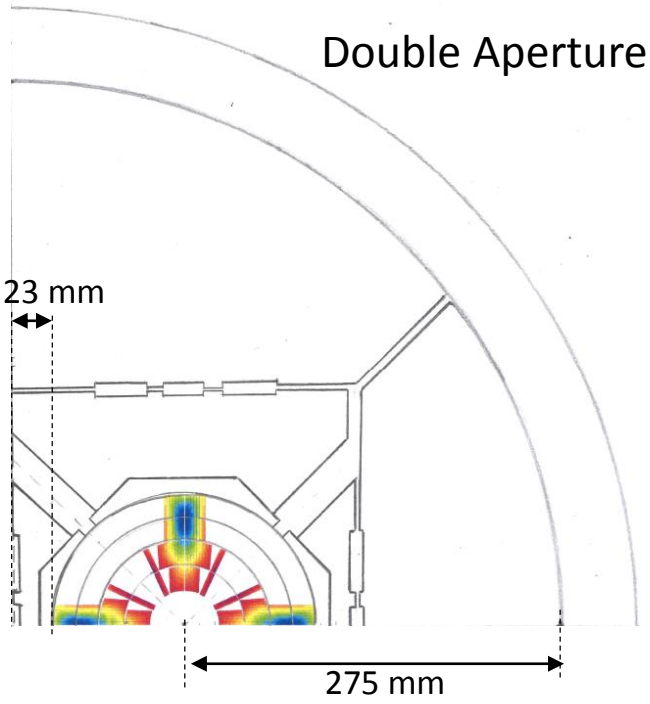


	Units	v1 Nb_3Sn	v2 Nb_3Sn	v3 Nb_3Sn	v4 Nb_3Sn Nb-Ti
Gnom	T/m	365	390	413	392
Inom	A	24100	29900	27260	21200
Bpeak	T	10.07	10.94	11.87	11.31
Ind. diff (2 ap)	mH/m	1.77	1.87	4.08	5.26
Stored energy (2 ap)	kJ/m	617	843	1533	1216
Φ x nb strands	mm x adim	1.0 x 30	1.0 x 40	1.0 x 40	1.0 x 30 1.065 x 38
Cu/nonCu		2.2	1.8	1.55	1.95 1.05
Est. length	m	7.4	6.9	6.5	6.9
Est. quantity of cond.	tons	330	435	590	330 + 318

1 m shorter quad -> 1% more filling factor for dipoles -> 1 % more margin on dipoles -> ~300-500 tons saved on dipoles

Single aperture model – v4 (1/4)



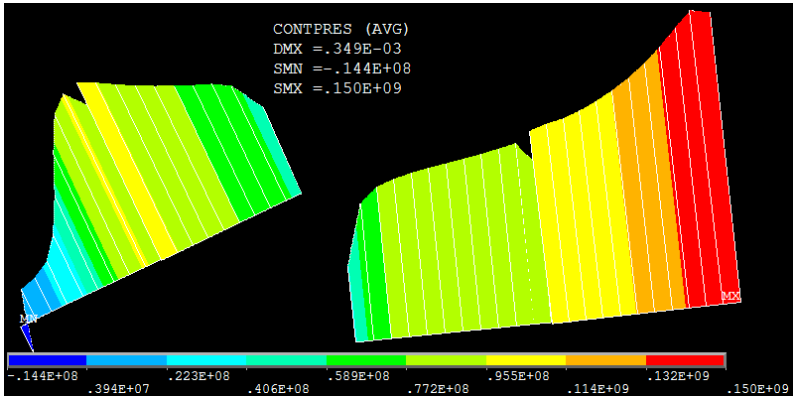


- SA yoke radius = 275 mm
  - distance between aperture center and shell in the DA configuration
- SA distance outer coil to middle of the key = 23 mm
  - distance between outer coil and center of the DA configuration

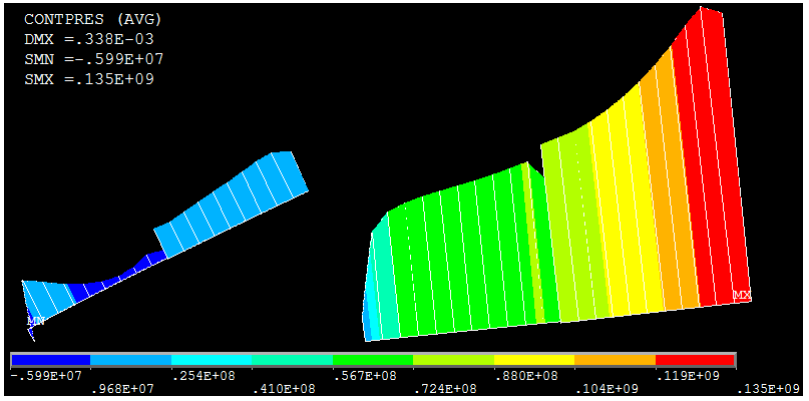
Single aperture model – v4 (2/4)

- Mechanical properties similar for Nb_3Sn and Nb-Ti coils
- Key: 400 µm extra size
- Shell: 51 mm
- Contact coil-pole at 105 % of $I_{nominal}$ =21200 A (22260 A)

Cool-down



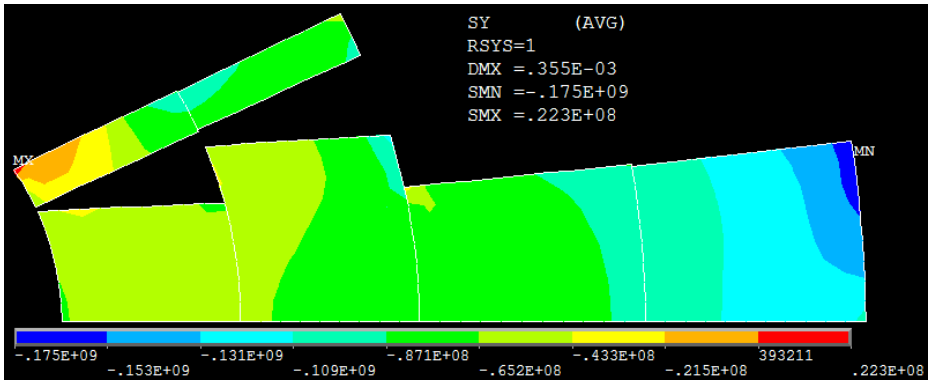
Powering at 105 %



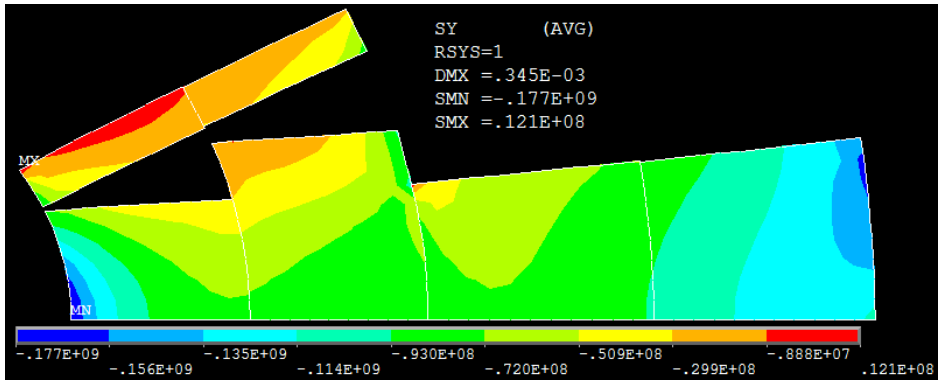
Single aperture model – v4 (3/4)

- Azimuthal stress in the coil: 180 MPa
  - ~70 MPa at warm (not shown)
- Radial stress in the coil: 110 MPa at cold (not shown)

Azimuthal stress: cool-down



Azimuthal stress: powering at 105 %

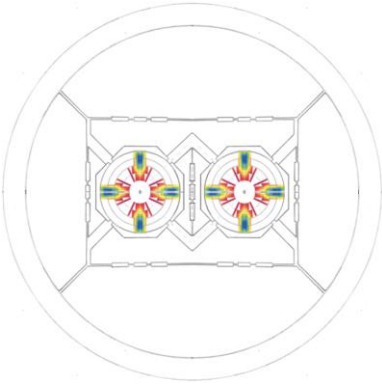


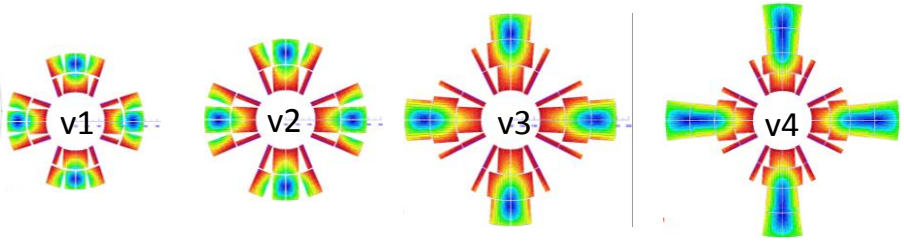
Single aperture model – v4 (4/4)

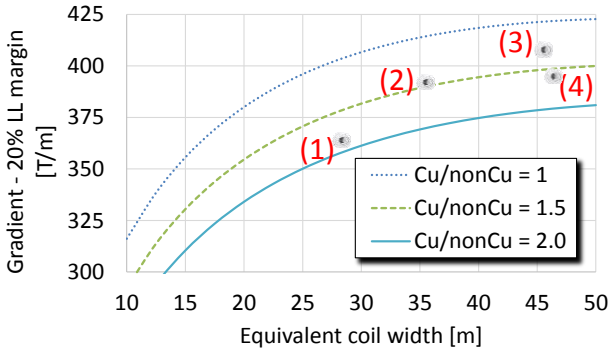
Von mises [MPa]	Material	Key insertion	Cool-down	Powering 105%
Pole	Ti6Al4V	184	324	278
Collar	316LN	131	355	378
Pad	Iron	42	205	203
Yoke	Iron	74	188	190
Key support	316LN	193	635	641
Key	Nitronic40®	404	1280	1300
Shell	AL 7075	124	251	260

- Peak stress values in the key corners can be reduced

Conclusion







- Quadrupole magnets with gradients from 365 to 415 T/m
- Quantity of conductor between 300 to 600 tons of Nb_3Sn (~5% of dipoles)
- Preliminary single aperture mechanics promising (double ap. tbc)
- Double aperture central part: shims or bladder&key?
- Magnet end windability (15.75 mm or 21 mm cable) ⟶
- Development phase ideas:
  - Starting with v1 and v2 which are somehow the cores of v4 and v3
  - Then, if needed, go for v4 or v3 which are more complex design