DIPOLES FOR HIGH ENERGY LHC

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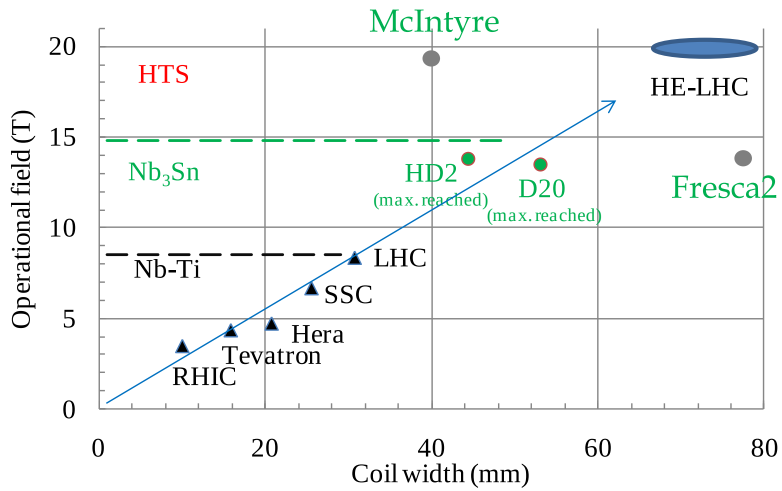
CONTENTS

- Recall of Malta design
- Where are we with current density requirements?
- Possible simplifications and associated costs
- Optimization of cell length

Recall of design

- Field ~ current density j × coil width w
  - Current density is the main choice of the magnet designer
  - Pioneering work of McIntyre
  - With 380 A/mm^2, one makes ~ 2.5 T each 10 mm of coil, so we need 80 mm
    - Most accelerator magnets not far from this j value

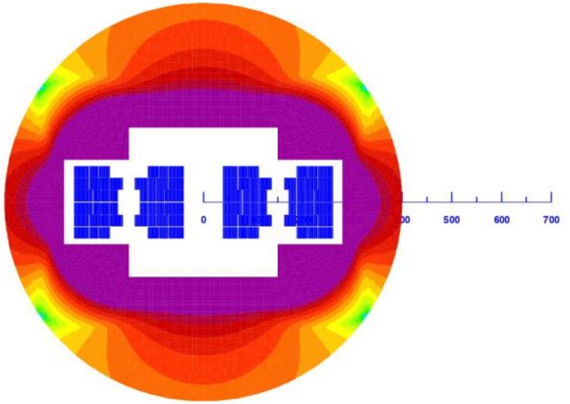


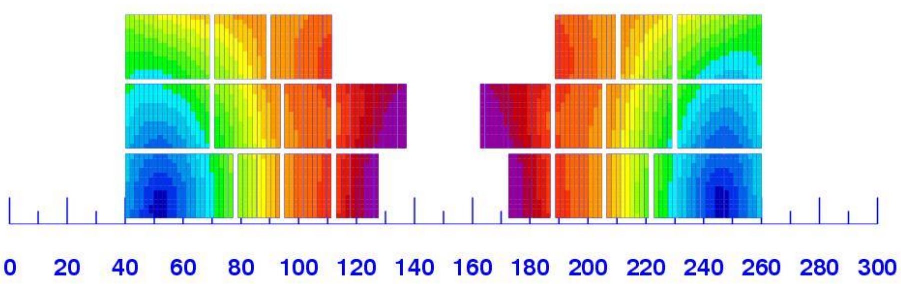
Field versus coil width

- Low current density brings two advantages
  - More margin for protection
  - Lower stress
- Other main choice: have a 20% margin on the loadline
  - So we must have a coil reaching 25 T at short sample!

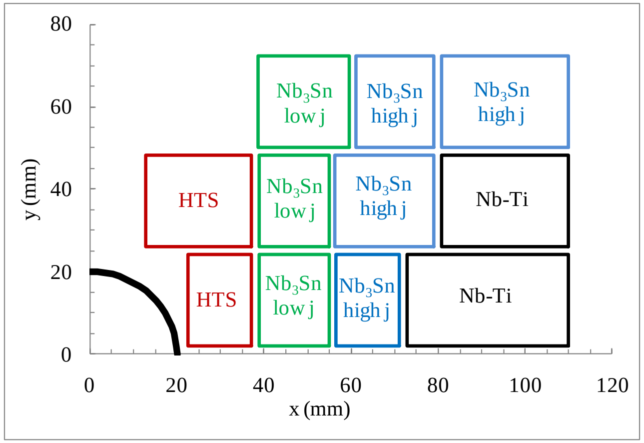
RECALL OF DESIGN

- Malta layout highly optimized to minimize conductor cost
  - Hypothesis: cost Nb-Ti is one, Nb_3Sn is 4 times, HTS is 16 times
  - Use Nb-Ti up to 8 T, Nb_3Sn up to 13 T, HTS up to 20 T
  - We also use Nb_3Sn with half current density to have 2 more Tesla and reach 15 T, saving on HTS (see next section)
    - Lower cost, at the price of complexity





20 T hybrid magnet: the Malta design [E. Todesco, L. Rossi]



One quarter of a coil

CONTENTS

- Recall of Malta design
- Where are we with the current density requirements?
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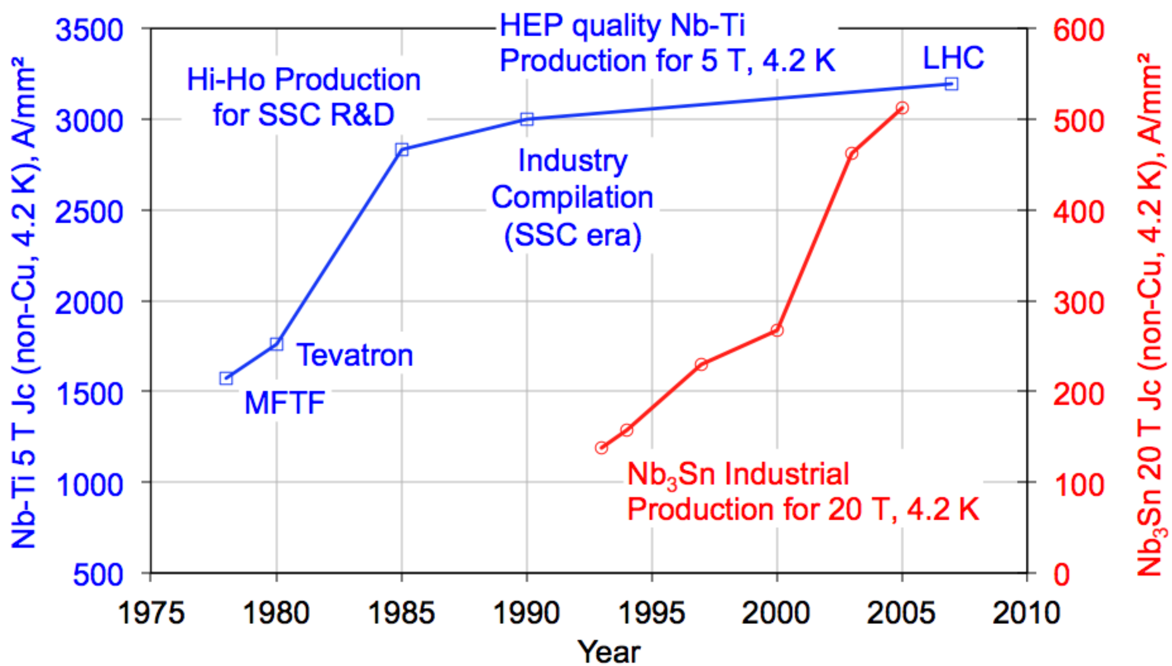
Where are we with Nb_3Sn?

- Project is in mid term future so some optimism is allowed to account for progress in technology
  - Nb_3Sn performance has greatly improved (doubled in ten years), so no space is assumed for further optimization



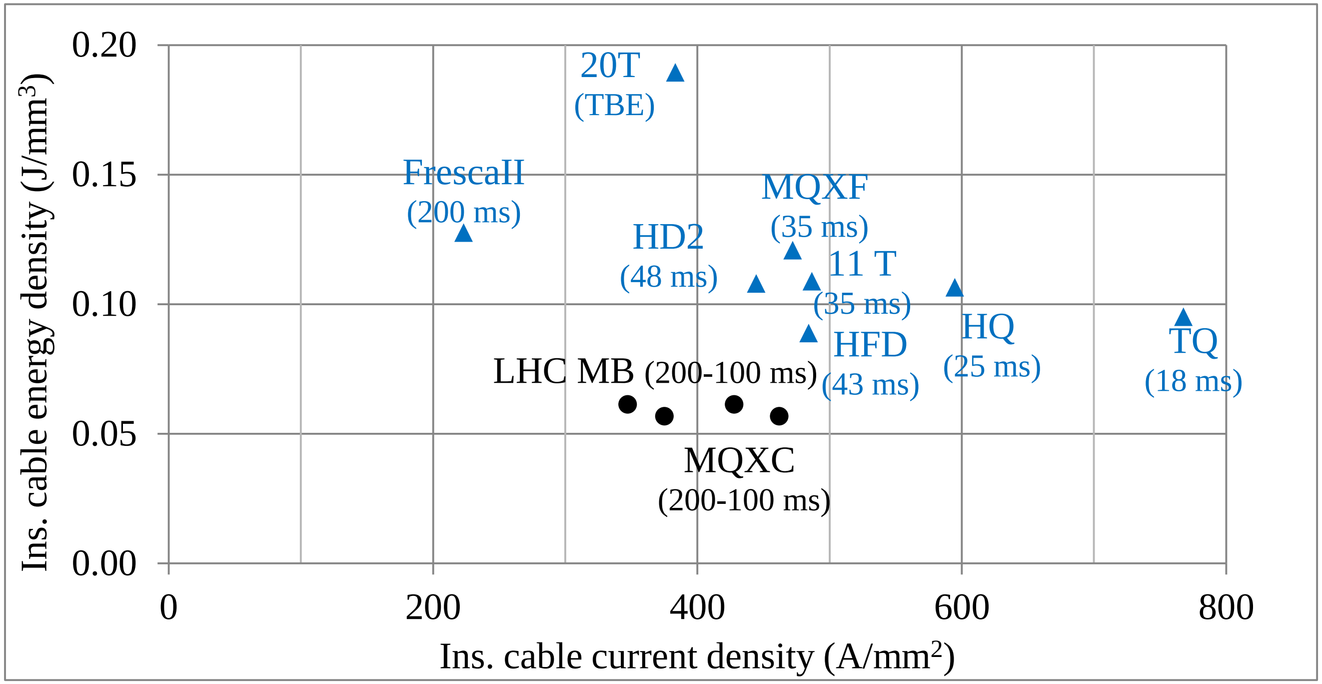
An historical view on the improvement of Nb-Ti and Nb_3Sn performance [L. Bottura, ASC 2012]

Where are we with Nb_3Sn?

- Hypothesis
  - Copper to superconductor of 1.1 (as in recent LARP and 11 T magnets)
  - Insulation, voids (impregnation) bring dilution factor to 0.33
  - So we aim at
    - 13/0.8=16.25 T we want 380*3/0.8=1400 A/mm^2
    - 15/0.8=18.75 T we want 190*3/0.8=700 A/mm^2
  - Today best conductor (2500 A/mm^2 at 12 T, 4.2 K) provides these values, with 10% cable degradation [B. Bordini, based on PIT and RRP data]
    - But this is extrapolation of data at lower fields, so measurements in the 15-18 T range would be warmly welcome

WHERE ARE WE WITH NB$_3$SN?

- Protection
  - For protection, we are at a level of energy density in the coil of about 0.2 J/mm^3 – this is ~50% more what we have in Nb$_3$Sn magnets
    - More copper could be needed, so further increase of current density in the superconductor could be useful



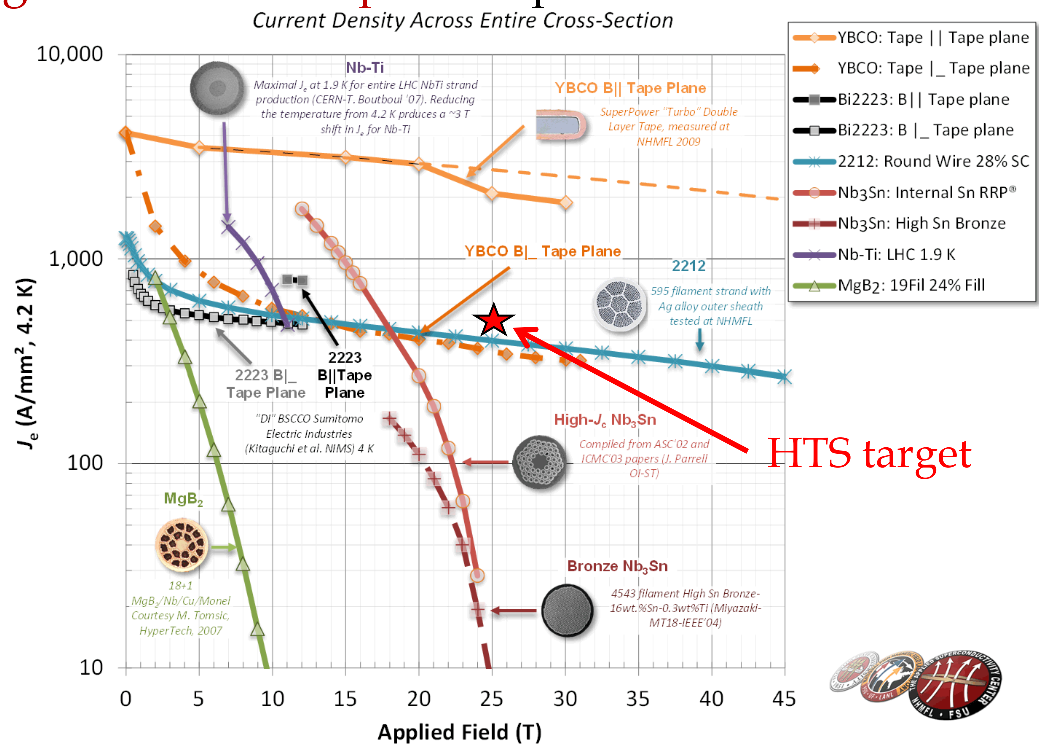
Energy density in the coil versus current density in the coil, with protection time margin
[E. Todesco, ASC 2012]

WHERE ARE WE WITH HTS?

- Two options: YBCO and Bi-2212
- YBCO
  - Tape ☹
  - Very good current density in parallel direction ☺ but strong anisotropy ☹
  - Stress resistant ☺
- Bi-2212
  - Cable ☺
  - No anisotropy ☺
  - No stress resistant (reinforemcent in strand needed) ☹
- Several activities ongoing in different labs [G. De Rijk, S. Prestemon, this workshop], wide experience with solenoids

WHERE ARE WE WITH HTS?

- Both YBCO and Bi-2122 are ~400 A/mm², vs 480 A/mm² required
  - YBCO: Preliminary analysis of field direction in Malta coil: in HTS coil angle between field and conductor is up to 30°, so I think we have to forget about YBCO parallel performance



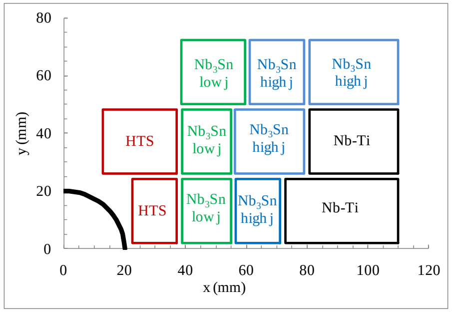
Engineering current density of YBCO and of Bi-2212 [P. Lee]

Large improvement w.r.t. Malta workshop 2.5 years ago !
(we had ~200 A/mm²)

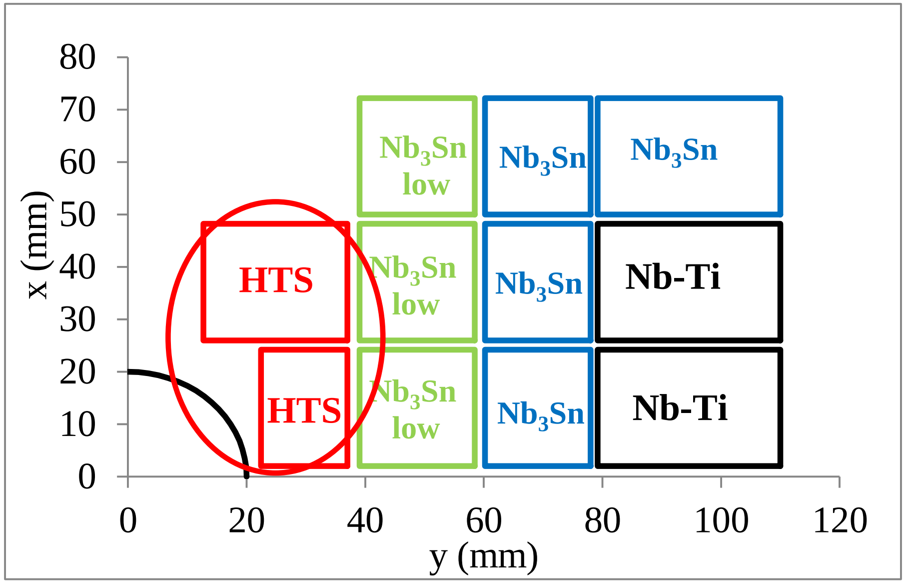
CONTENTS

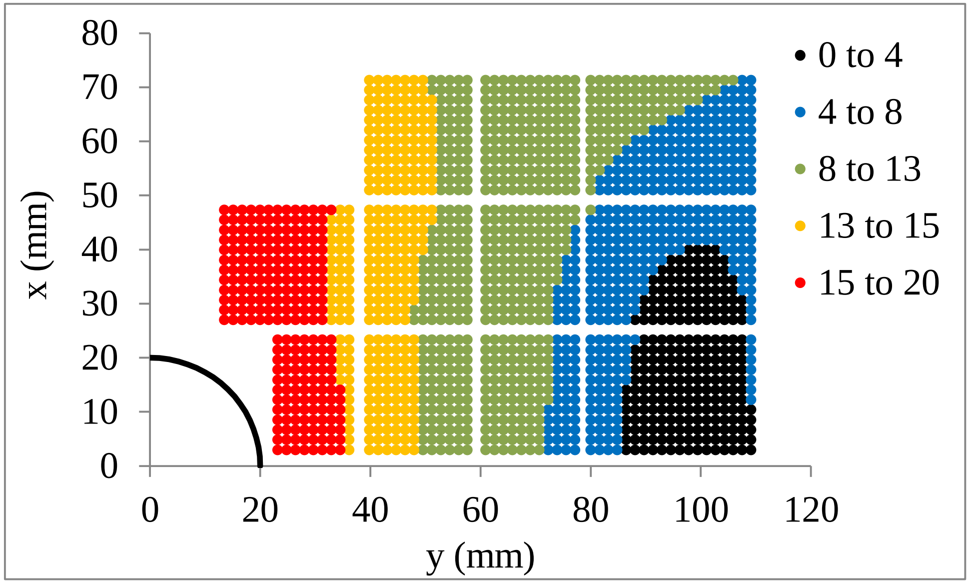
- Recall of Malta design
- Where are we with HTS requirements?
- Possible simplifications and associated costs
- Optimization of cell length

- Malta design (slightly simplified)
  - Guideline: follow HD2 and Fresca2 mechanical structure, i.e. no supporting elements in the coil – preliminary analysis shows stress<200 MPa



  - One double pancake of HTS

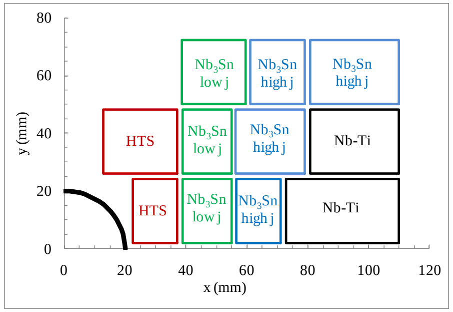


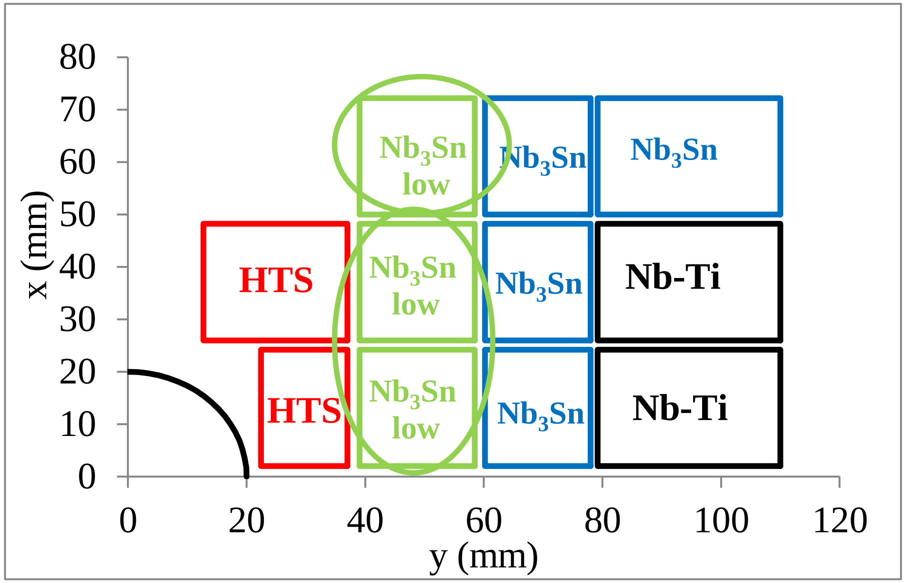


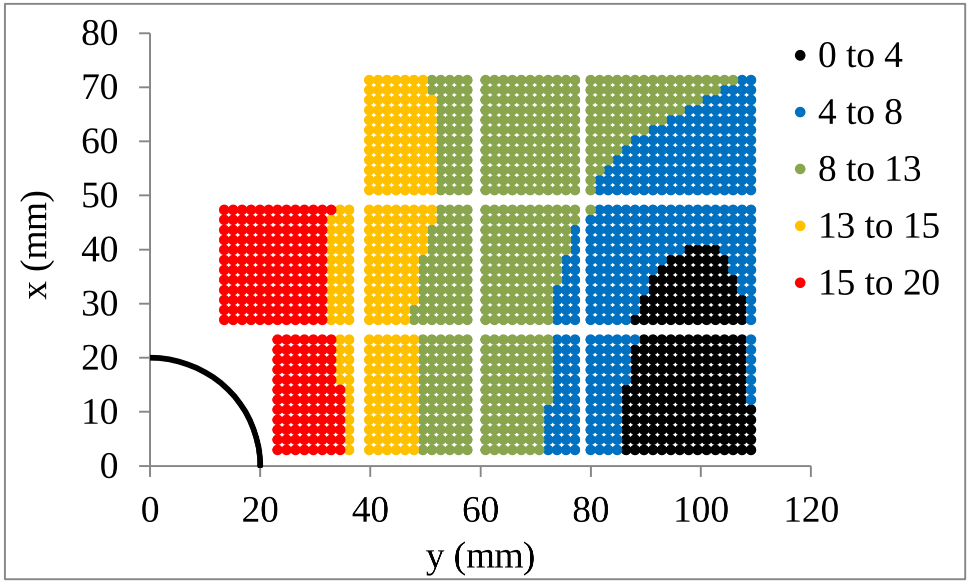
Revised Malta design for 20 T magnet, one quarter of coil shown

Making it simpler?

- Malta design (slightly simplified)
  - One double pancake of HTS
  - One double + one single pancake of low j Nb_3Sn







Revised Malta design for 20 T magnet, one quarter of coil shown

MAKING IT SIMPLER?

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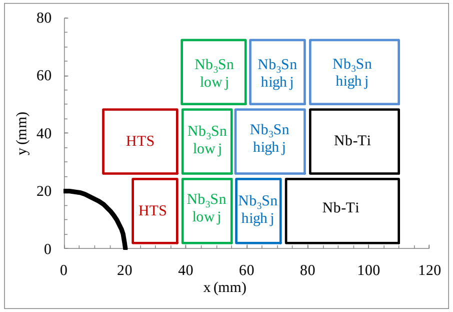
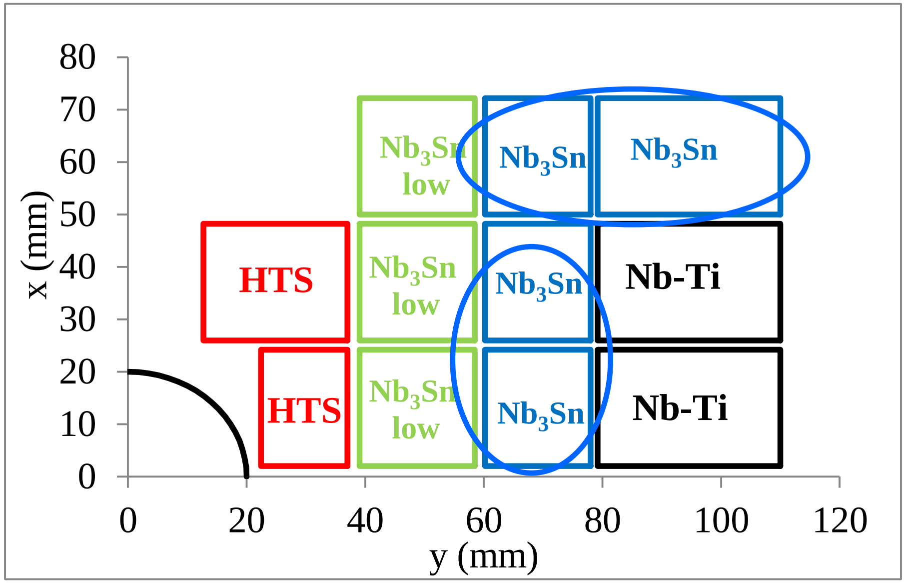
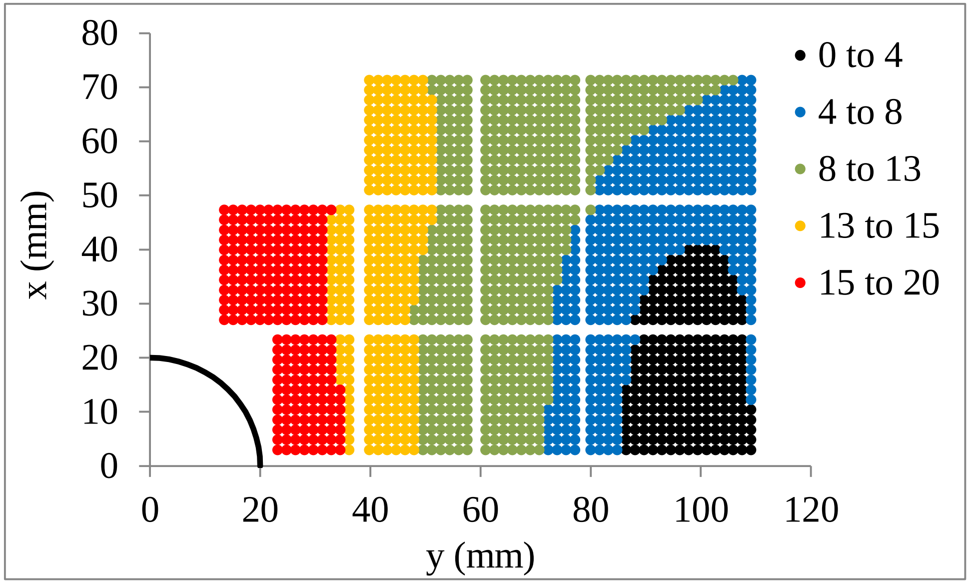
  - One double pancake of HTS
  - One double + one single pancake of low j Nb_3Sn
  - One double + one single pancake of Nb_3Sn



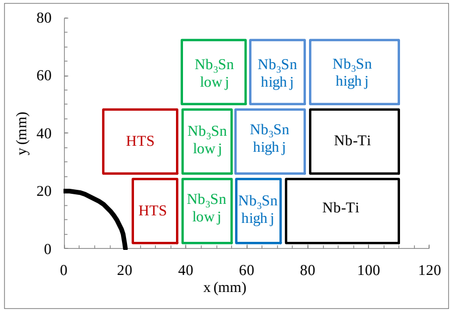


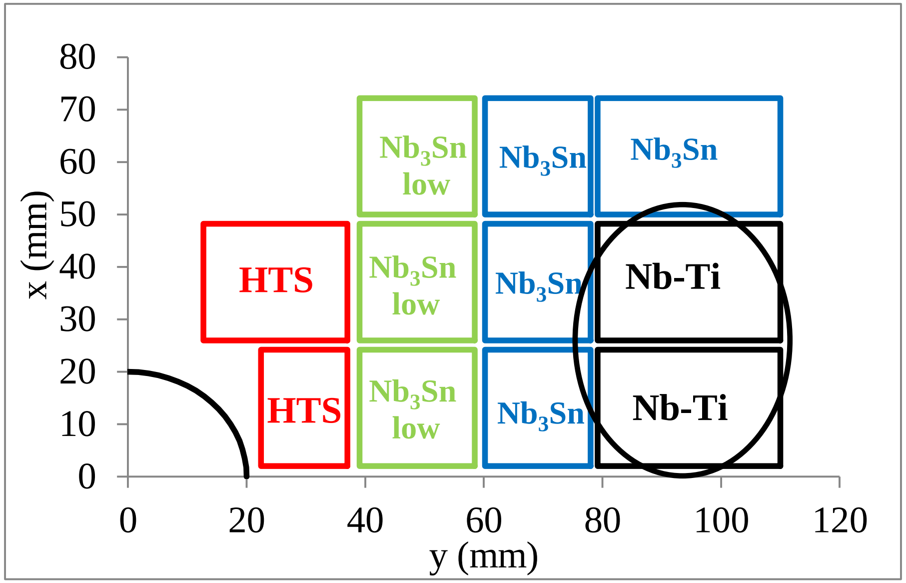


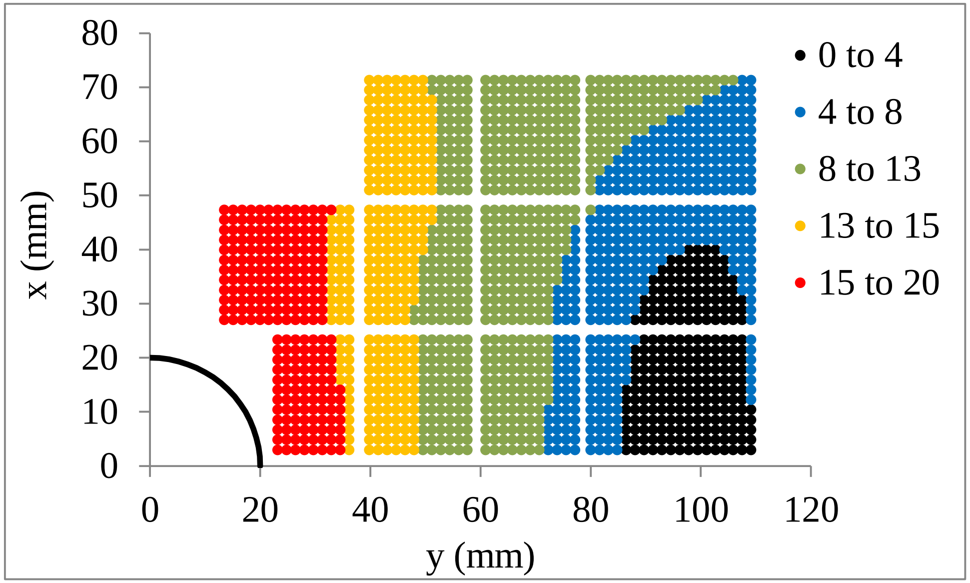
Revised Malta design for 20 T magnet, one quarter of coil shown

MAKING IT SIMPLER?

- Malta design (slightly simplified)
  - One double pancake of HTS
  - One double + one single pancake of low j Nb_3Sn
  - One double + one single pancake of Nb_3Sn
  - One double pancake of Nb-Ti
    - Six coils to be assembled per pole, four with flared ends, two flat



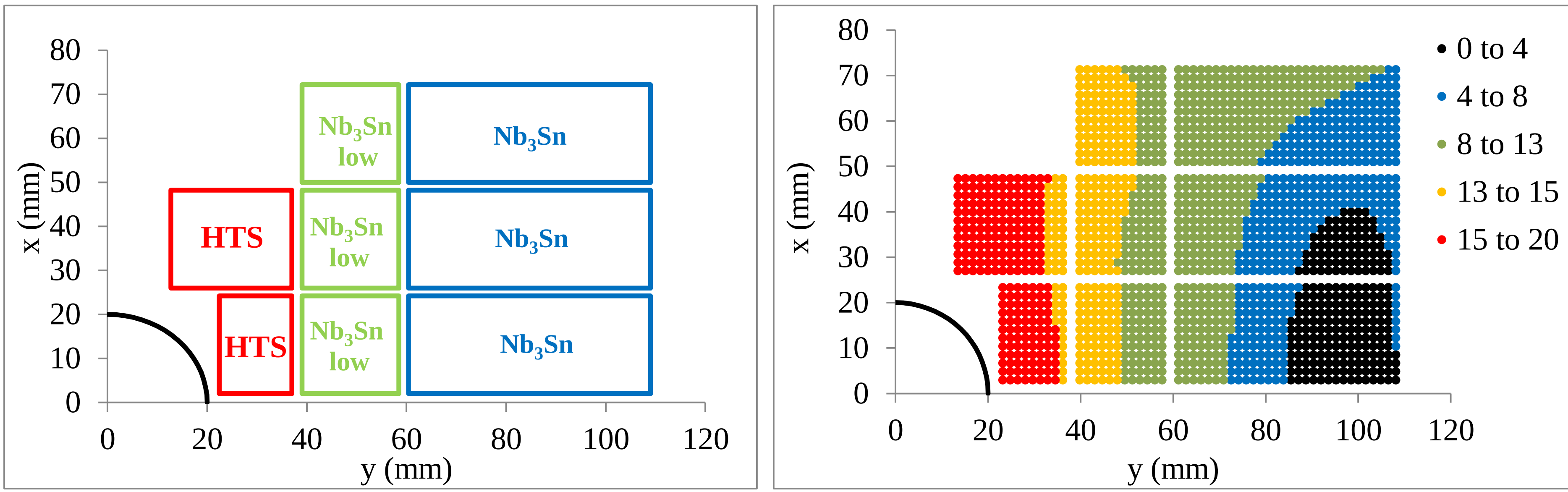




Revised Malta design for 20 T magnet, one quarter of coil shown

MAKING IT SIMPLER?

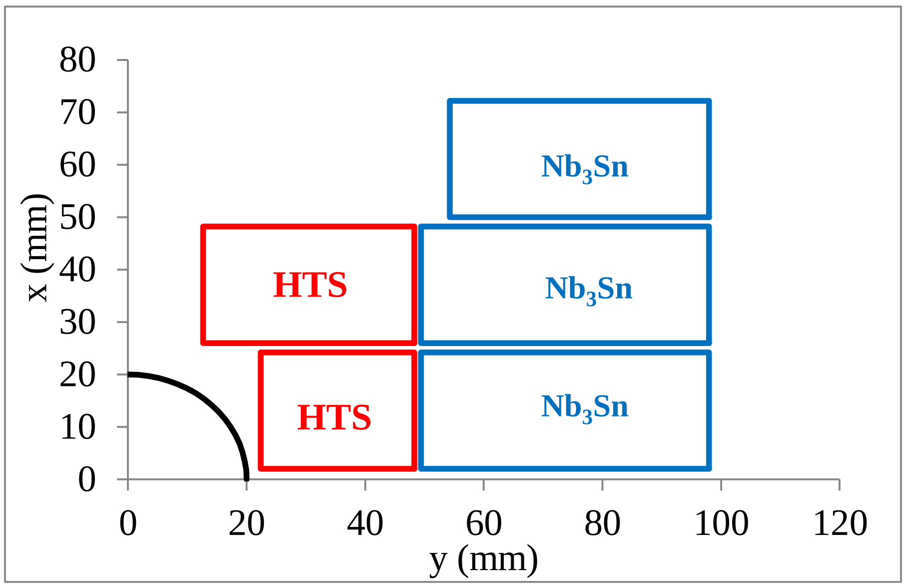
- Malta design, without Nb-Ti
  - One double pancake of HTS
  - One double + one single pancake of low j Nb_3Sn
  - One double + one single pancake of Nb_3Sn
    - Five coils to be assembled per pole
  - Cost: +15%

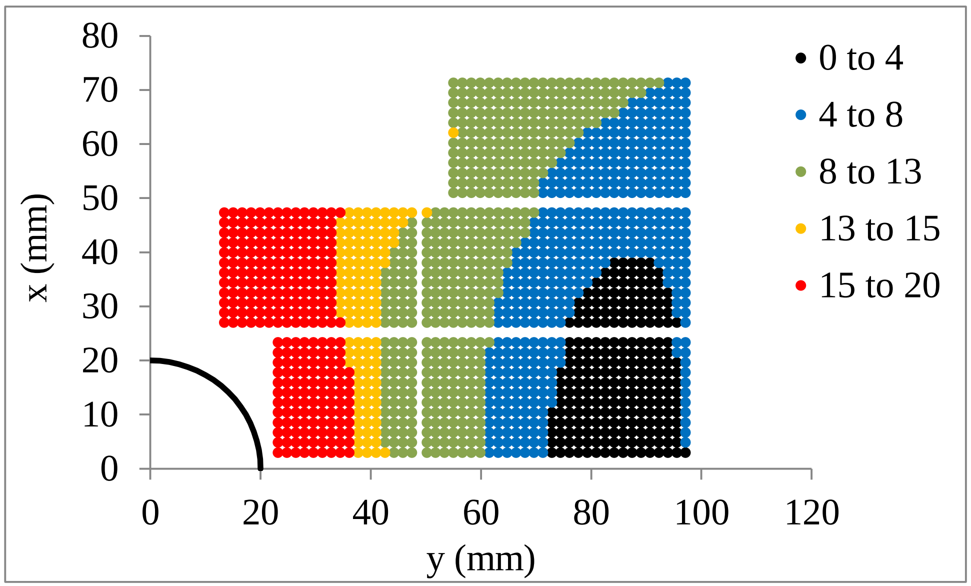


Revised Malta design for 20 T magnet (no Nb-Ti), one quarter of coil shown

Making it simpler?

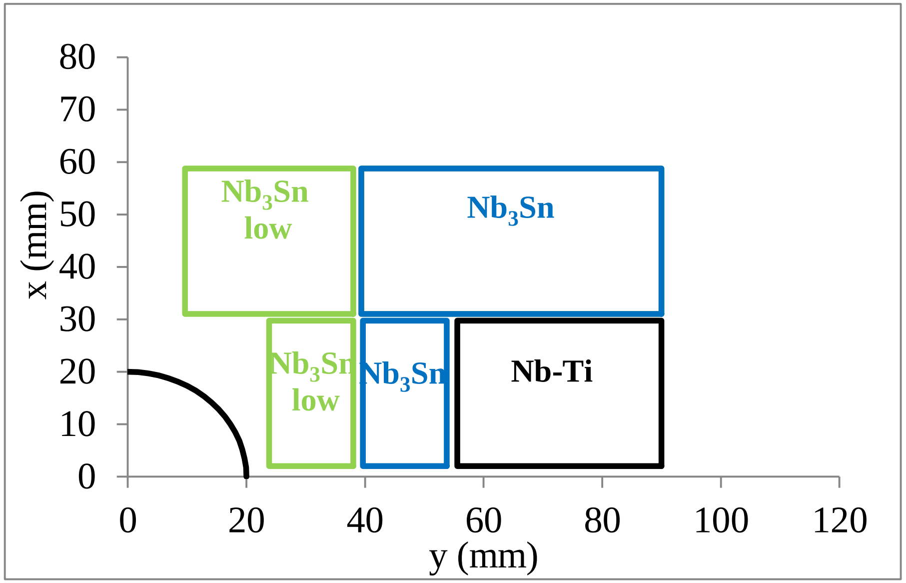
- Malta design without graded Nb_3Sn
  - One double pancake of HTS
  - One double + one single pancake of Nb_3Sn
    - Three coils to be assembled per pole
  - Cost: +50% (1.5 times the Malta design)

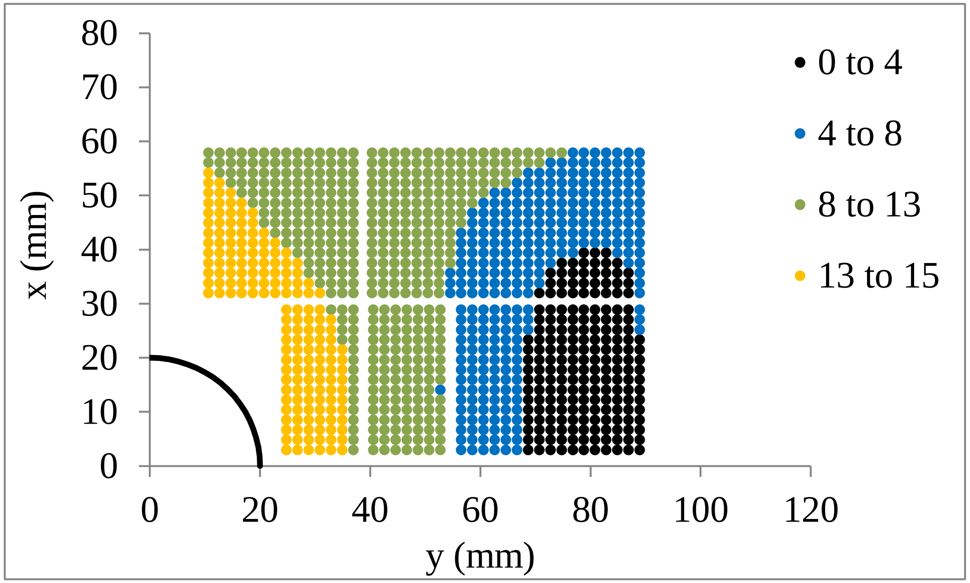




Revised Malta design for 20 T magnet (no Nb_3Sn grading, no Nb-Ti), one quarter of coil shown

- The 15 T case, without Nb-Ti
  - I passed to 1 mm strand to avoid three layers – HD2-like layout
- One double pancake of Nb_3Sn used at low j_e = 190 A/mm^2
- One double pancake of Nb_3Sn, two coils to be assembled per pole
- Cost: 45% of Malta
  - 20% more (i.e. 55% of Malta) if no Nb-Ti grading

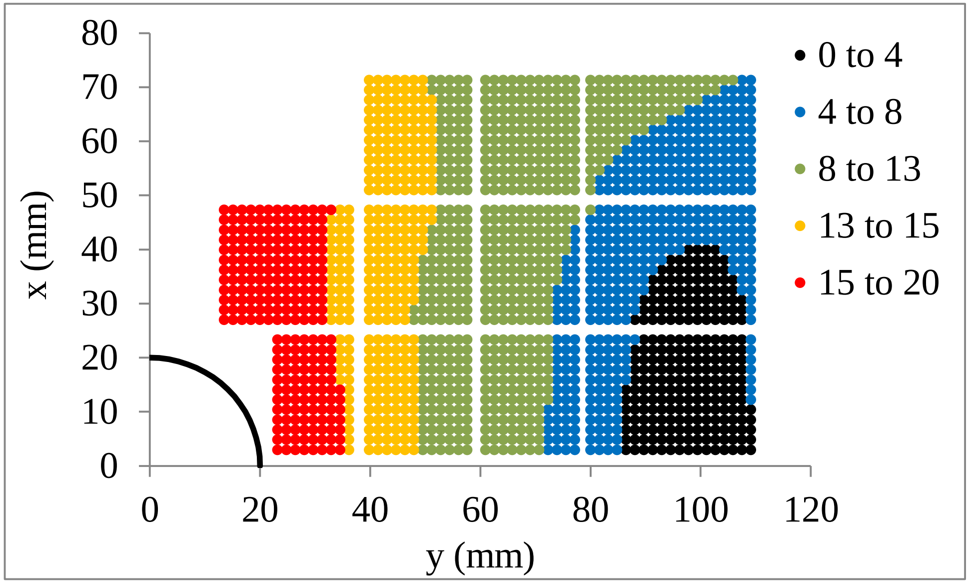




Snowmass design for 15 T magnet, one quarter of coil shown

Block versus cos theta

- Block design advantages
  - Fits the shape of the field allowing grading for very large coils
    - Natural position of quench heaters (midplane and between double pancakes
  - Pursuing studies on this design is important (Fresca2, HD2, HD3)



Bologna city centre: block (left) vs cos theta (right)

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Optimizazion of cell length

- LHC has a semi-cell length (distance between quadrupoles) of L=50 m
- Main scaling
  - Beta function $\propto L$
  - Beam size $\propto\sqrt{L}$ so longer spacing requires larger aperture ☹
  - Longer spacing requires less quadrupoles ☺
  - Integrated gradient $Gl\propto 1/L$ so longer spacing requires lower integrated gradient ☺
- Example
  - HE-LHC needs 1600 T, 40 mm aperture so with Nb_3Sn we need 3.5 m quads

Energy E (TeV)	Aperture ϕ (mm)	Cell lenght L (m)	Int. gradient $G l_q$ (T)	Gradient G (T/m)	Length l_q (m)
7.0	56	50	693	220	3.15
16.5	40	50	1636	462	3.54

Optimizazion of cell length

- If we get longer cell length, we will have less force needed and less quadrupoles but larger aperture
  - Hypothesis: 20 m max length of dipoles
  - Either 20 T fixed and larger energy, or energy fixed and lower field

FIRST CASE: FIXED FIELD OF 20T

Energy E (TeV)	Aperture ϕ (mm)	Cell lenght L (m)	Int. gradient $G l_q$ (T)	Gradient G (T/m)	Length l_q (m)	Field B (T)	Length l_d (m)	Number n_d (adim)	Filling f (adim)
7.0	56	50	693	220	3.15	8.3	14.3	3	0.858
16.5	40	50	1636	462	3.54	20.0	14.0	3	0.841
17.4	45	66	1303	411	3.17	20.0	19.5	3	0.885
17.7	50	83	1054	370	2.85	20.0	18.6	4	0.898
17.8	55	100	883	336	2.63	20.0	18.1	5	0.906

  - Keeping a 20 T magnet, and making it larger we can gain 0.9-1.3 TeV out of 16.5 TeV

OPTIMIZAZION OF CELL LENGTH

- If we get longer cell length, we will have less force needed and less quadrupoles but larger aperture

  - Either 20 T fixed and larger energy, or energy fixed and lower field

SECOND CASE: FIXED ENERGY OF 16.5 TeV

Energy E (TeV)	Aperture ϕ (mm)	Cell lenght L (m)	Int. gradient $G\,l_q$ (T)	Gradient G (T/m)	Length l_q (m)	Field B (T)	Length l_d (m)	Number n_d (adim)	Filling f (adim)
7.0	56	50	693	220	3.15	8.3	14.3	3	0.858
16.5	40	50	1636	462	3.54	20.0	14.0	3	0.841
16.5	45	66	1235	411	3.01	18.9	19.5	3	0.887
16.5	50	83	983	370	2.66	18.6	18.7	4	0.901
16.5	55	100	818	336	2.44	18.5	18.2	5	0.908

  - Keeping a 16.5 TeV energy, we can lower the field of 1-1.5 T

OPTIMIZAZION OF CELL LENGTH

- Whats the price? Rough estimate based on sector coil
  - For a fixed energy, a 66 m long cell allows go to 45 mm aperture with 19 T, saving 20% of HTS (10% of conductor cost in the cross-section, 5% on global cost accouting for higher filling)
  - Looks marginal – and longer cell does not help

Aperture	Field	Cable quantity ratio w.r.t. 20 T, 40 mm			
ϕ	B	HTS	Nb_3Sn l	Nb_3Sn h	Nb-Ti
(mm)	(T)	(mm)	(mm)	(mm)	(mm)
40	20.0	1.00	1.00	1.00	1.00
45	18.9	0.79	0.97	0.98	0.96
50	18.6	0.78	1.00	1.00	0.97
55	18.5	0.81	1.03	1.02	1.00

  - For a fixed field, 1 additional TeV costs ~10%
    - Then it rapidly diverges

Aperture	Field	Cable quantity ratio w.r.t. 20 T, 40 mm			
ϕ	B	HTS	Nb_3Sn l	Nb_3Sn h	Nb-Ti
(mm)	(T)	(mm)	(mm)	(mm)	(mm)
40	20.0	1.00	1.00	1.00	1.00
45	20.0	1.09	1.05	1.03	1.04
50	20.0	1.17	1.09	1.06	1.08
55	20.0	1.26	1.14	1.09	1.12

Further developments

- Superconductors
  - Push (and measure) performance of Nb_3Sn in the range 15-18 T
    - We are at Malta design values, but improvement could considerably reduce costs
  - Get a 20% more on j_e in HTS, to reach 500 A/mm^2 at 25 T
    - Today we are not so far !
- Magnet technology
  - Fresca2 and HD block designs are an essential step towards the 20 T dipoles
    - Block design has the advantage of allowing a natural way of grading the material, and saving money
  - Removable pole technology for Nb_3Sn needed
  - Splice technology to be widely studied
  - Flared ends are still a problem today for block design

CONCLUSION

- Simplifications
  - We presented successive simplification of Malta design, each one with price tag
    - Seen from end to beginning, it can indicate a roadmap towards 20 T
  - The Nb-Ti allows saving about 15%
  - Without grading of Nb_3Sn, price doubles
  - Stopping at 15 T, with graded Nb_3Sn price is 55%

- Optimizing cell length
  - One could explore an option with longer cell length to have less quadrupoles are larger filling factor
    - Saving is not significant in this phase of the project