International MUON Collider Collaboration

Collider Magnet Systems Cost Estimate

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MAGNET REQUIREMENTS

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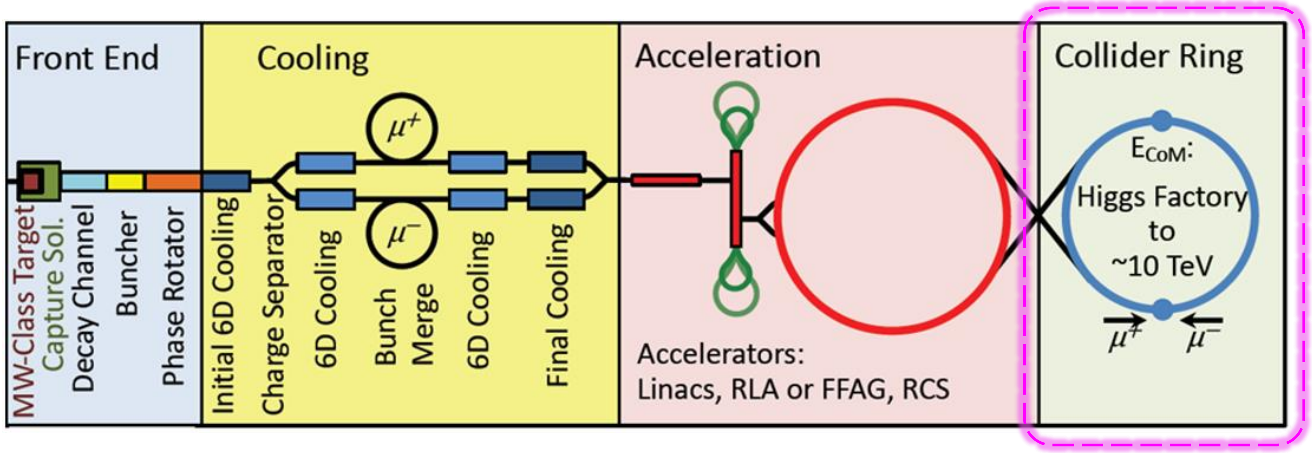
Task 7.4 Collider Ring Magnets (INFN)

10 TeV collider
10 km ring



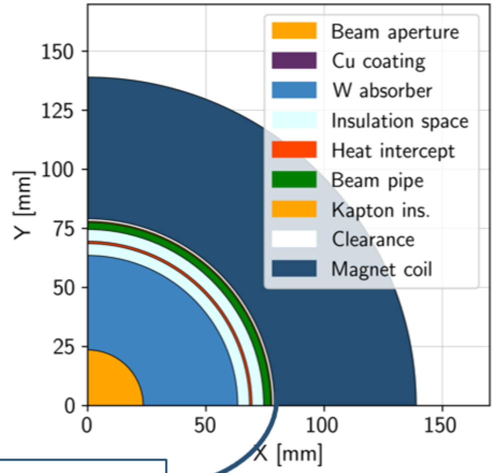
	2 cm	3 cm	4 cm
Beam aperture (radius)	23.5 mm	23.5 mm	23.5 mm
Outer shielding radius	43.5 mm	53.5 mm	63.5 mm
Inner coil aperture (radius)	59 mm	69 mm	79 mm
Power penetrating tungsten absorber	19.1 W/m (3.8%)	8.2 W/m (1.6%)	4.1 W/m (0.8%)
Peak power density in coils	6.5 mW/cm^3	2.1 mW/cm^3	0.7 mW/cm^3
Peak dose in Kapton (5/10 years)	56/112 MGy	18/36 MGy	7/14 MGy
Peak dose in coils (5/10 years)	45/90 MGy	15/30 MGy	5/10 MGy
Peak DPA in coils (5/10 years)	8/16$\times 10^{-5}$ DPA	6/12$\times 10^{-5}$ DPA	5/10$\times 10^{-5}$ DPA

Courtesy of Anton Lechner

Radial Build

• Beam aperture (5σ)	23.5 mm radius
• Cu layer beam screen	0.01 mm thick
• Tungsten absorber	40 mm thick
• Insulation space	5 mm thick
• Heat intercept	1 mm thick
• Insulation space	5 mm thick
• Beam pipe	3 mm thick
• Kapton insulation	0.5 mm thick
• Clearance	1 mm thick
• Coil pack*	(60 mm thick)

*thickness TBD, placeholder



Coil aperture 158 mm

138 mm

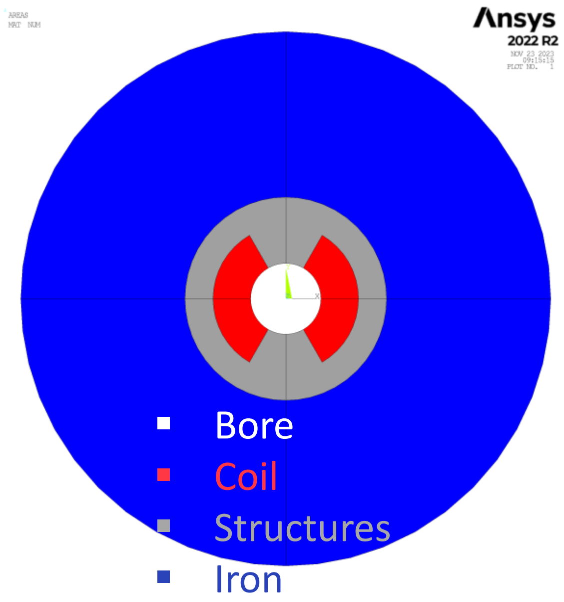
Courtesy of Patricia Borges de Sousa

https://indico.cern.ch/event/1250075/contributions/5357594/

4 cm W_{abs} @ T<10K (LTS) (P<5 W/m)
→ 158 mm magnet aperture
3 cm W_{abs} @ T=20K (HTS) (P<10 W/m)
→ 138 mm magnet aperture

Cost Model

- Optimization of the cross section still ongoing.
- Cost estimate performed on a simplified geometry with a **sector coil** dipole, iron and steel structure modelled as circular crowns.
- R_{bore}, w_{coil}, w_{iron} and w_{struct} optimized to fulfill beam optics requirements, margin on the load line, acceptable stress on the conductor and effectiveness of the quench protection [ref])



$\boldsymbol{C_{tot}} = 400\ \text{kEUR/m}$ *(FCC-hh 175 kEUR/m [ref])*

$\boldsymbol{C_{assembly}} = 20\ \text{kEUR/m}$ *(as LHC)*

$\boldsymbol{C_{mat}} = \sum_i C_i \rho_i A_i$ where $i = \text{coil, structures, iron}$

$$\begin{cases} \rho_{Strucutres} = \rho_{iron} = 7800\ kg/m^3 \\ C_{Structures} = 10\ EUR/kg \quad \textit{(D2 HL-LHC as benchmark)} \\ C_{iron} = 8\ EUR/kg \quad \textit{(D2 HL-LHC as benchmark)} \\ \rho_{coil} = 8000\ kg/m^3 \end{cases}$$

Material	C_{SC}	
NbTi	330 EUR/kg	*Escalated price in 2016*
Nb_3Sn	2000 EUR/kg	*The right value in 2016*
aspirational value	700 EUR/kg	*Corresponds to the ITER target*
ReBCO	8000 EUR/kg	*The value of today (2023)*
aspirational value	2500 EUR/kg	*A realistic projection for the next years*

Cost Estimate 10 TeV

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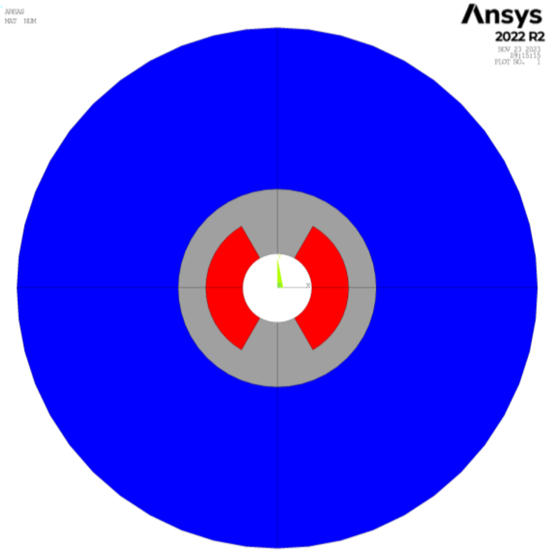
14T /140 mm (REBCO)



Template geometrical parameter taken for cost estimate

R_{bore} = 70 mm

w_{coil} = 60 mm

w_{struct} = 30 mm

w_{iron} = 300 mm

Dipoles of the arc for the series production
(quadrupoles and IR not included)

€/kg iron	€/kg struct	€/kg conductor *
8	10	2500

*50 €/kAm: 1/3 of today prize (150€/kAm)
Also based on projection of ref
A. Molodyk and C. Larbalestier, Science, 2023

Iron [Kg/m]	Structure [kg/m]	Coil [kg/m]
4560	213	130
Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
36	2.1	322

Tot. Material k€/m	56	14%
Tot. Assembly k€/m	20	5%
Tot. Conductor k€/m	322	81%
Tot. Cost k€/m	**400**	

Tot. Material = $(C_{iron} + C_{struct}) * f_{struct}$

$f_{struct} = 1.5$

100 k€/magnet (~2FTE)

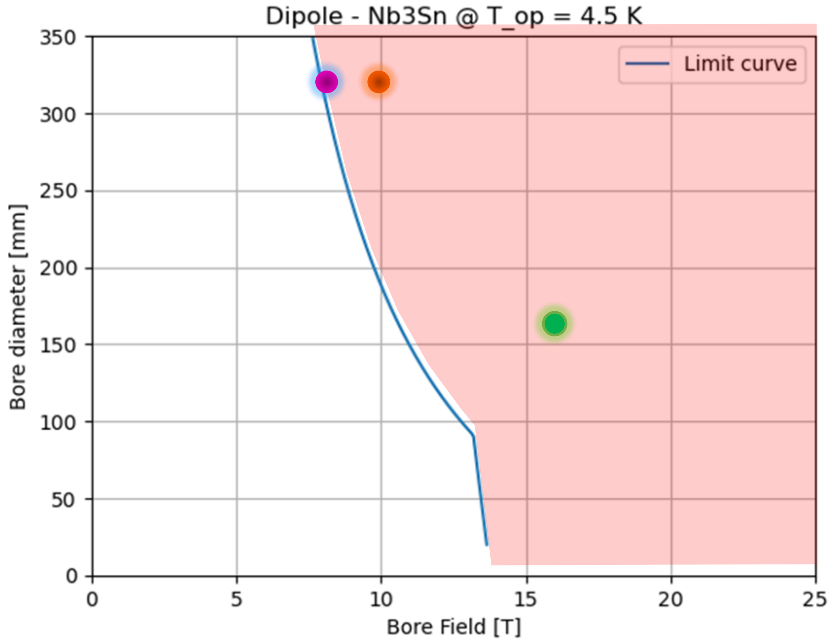
N units=1200, Length= 5m

Coordination, design and follow-up: 4 FTE x 4 years= 16 FTE-years (1.6 MEur)

TOTAL COST: 2.4 GEur (19.0% overall magnets budget)

Disclaimer: cryostat, specific tooling, W absorber not taken into account

A-B plots for Nb_3Sn



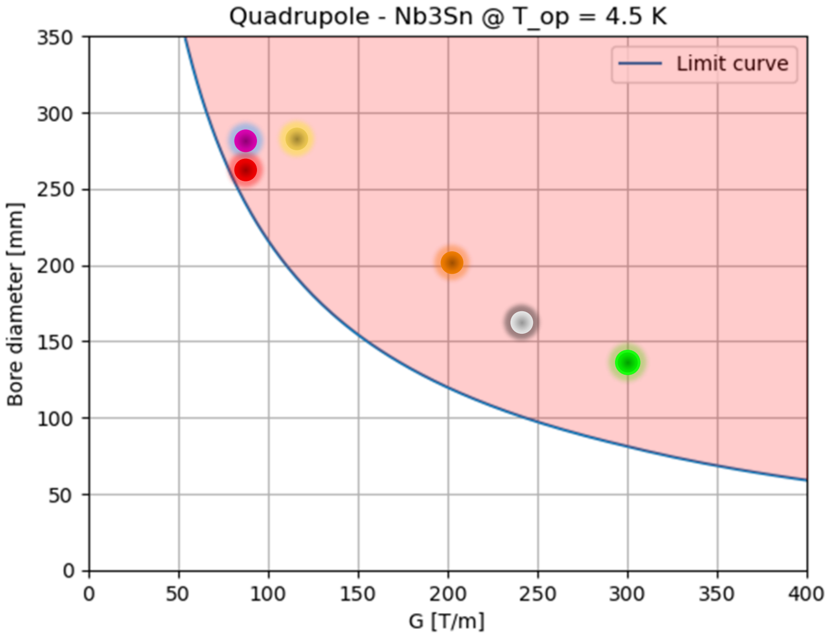
DIPOLES

Final Focusing: (v 0.8)
- 8.1 T, 320 mm
- 9.7 T, 320 mm

Arc: (v 0.7)
- 16 T, 160 mm (140mm @ 20K)

QUADRUPOLES

Final Focusing: (v 0.8)
- 85 T/m, 280 mm
- 85 T/m, 266 mm
- 115 T/m, 290 mm
- 205 T/m, 204 mm
- 242 T/m, 172 mm
- 300 T/m, 140 mm



Summary of magnet assumptions:

- Single sector coil quadrupole
- Maximum stress: 150 MPa
- FCC design target cable for the J_c fit
- Filling factor SC of 0.3
- Protection with quench heater
- Maximum coil width: 80 mm

Summary of cost assumptions:

- We use the Nb3Sn aspirational cost 700 EUR/kg (from FCC)
  - Today's price is around 2500 EUR/kg
- The starting budget of 400 kEUR/m is roughly double the estimate given by the FCC cost model for each magnet.
  - In principle, we can assume a higher budget for each magnet than FCC because we have a smaller circumference and less magnets.
- Cryogenic, protection and shielding costs are not taken into account.

- The **white area** is the allowed design space where all constraints of the magnet are satisfied.
- The **limit curve** is an ensemble of the many technological limitations taken into consideration to make the magnet design realistic [ref].
- For the 10 TeV and 10 km collider, Nb_3Sn falls short of required performance.

Nb3Sn not suitable technology for the 10 TeV collider

A-B PLOTS FOR HTS DIPOLE

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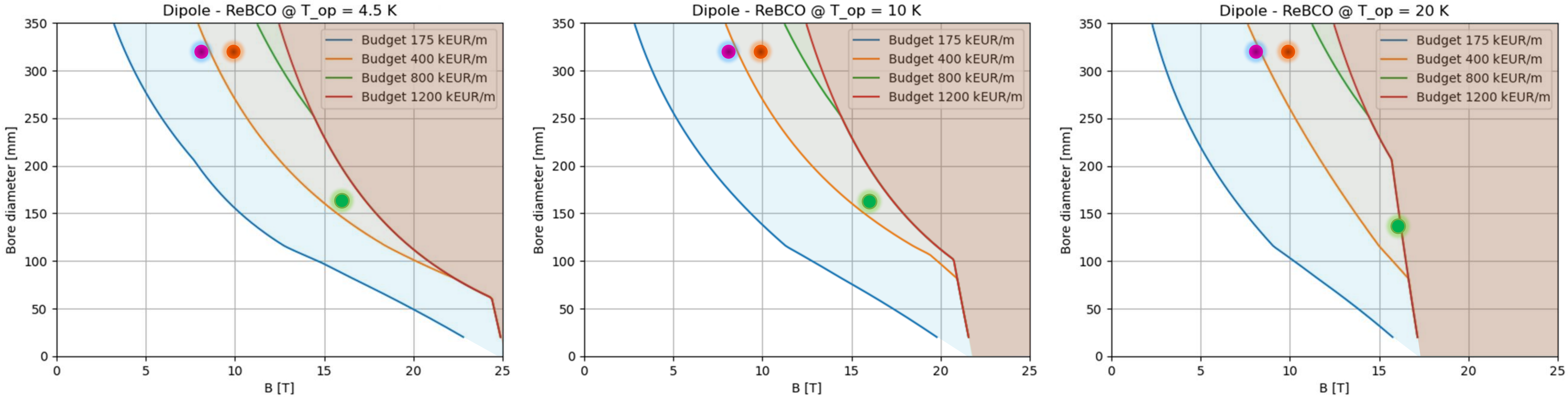


Summary of cost assumptions:

- We use the ReBCO's aspirational cost 2500 EUR/kg
  - Today's price is around 8000 EUR/kg
- The starting budget of 175 kEUR/m for each magnet is taken from the FCC cost model
  - We can assume a higher budget than FCC because we have a smaller circumference and less magnets.
- Cryogenic, protection and shielding costs are not taken into account.

Summary of assumptions:

- Single sector coil dipole
- Maximum stress: 400 MPa
- Fujikura Tape for the J_c fit
- Filling factor SC of 0.011
- Non-insulated or Metal-insulated cable
- Maximum coil width: 80 mm

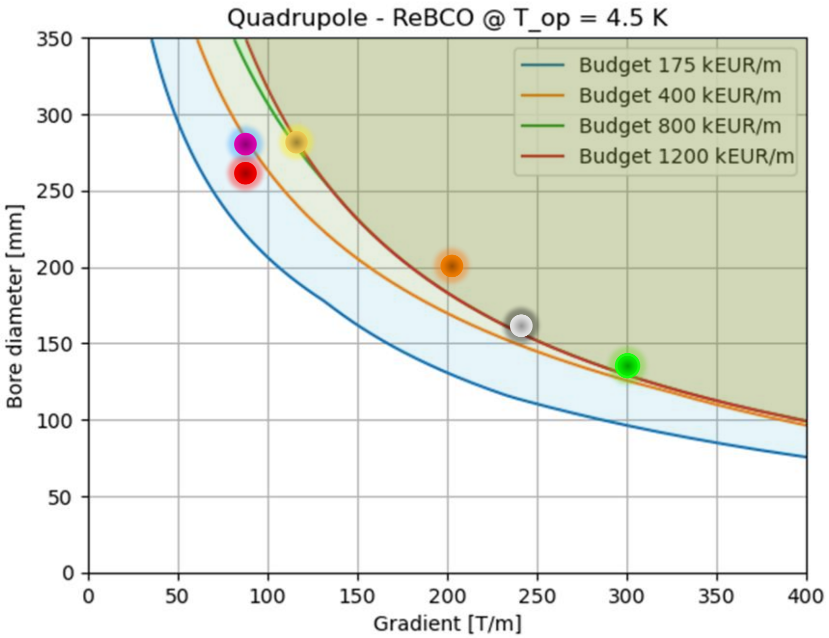
Final Focusing: (v 0.8)

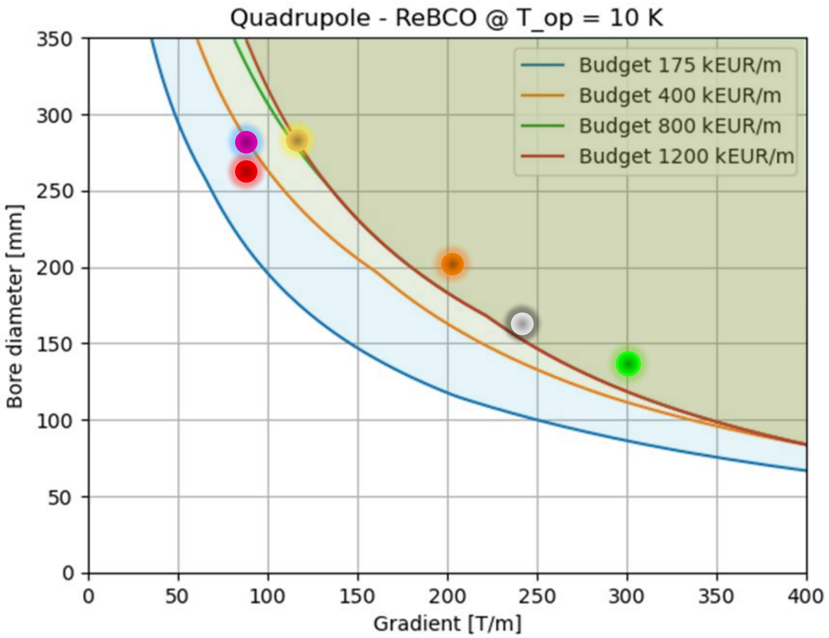
- 8.1 T, 320 mm
- 9.7 T, 320 mm

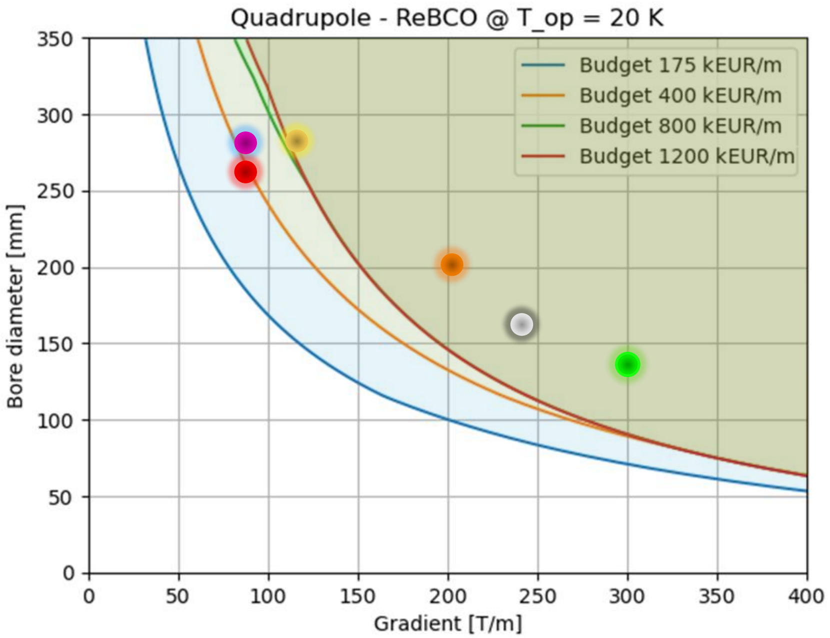
Arc: (v 0.7)

- 16 T, 160 mm (140mm @ 20K)

A-B PLOTS FOR HTS QUADRUPOLE







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Final Focusing: (v 0.8)

- 85 T/m, 280 mm
- 85 T/m, 266 mm
- 115 T/m, 290 mm
- 205 T/m, 204 mm
- 242 T/m, 172 mm
- 300 T/m, 140 mm

FINAL CONSIDERATION

- With a proper revision of the optics **, 400 kEur/m** can be considered a credible maximum budget for the **ARC dipoles and quadrupoles** (assuming as baseline HTS @ 20 K).

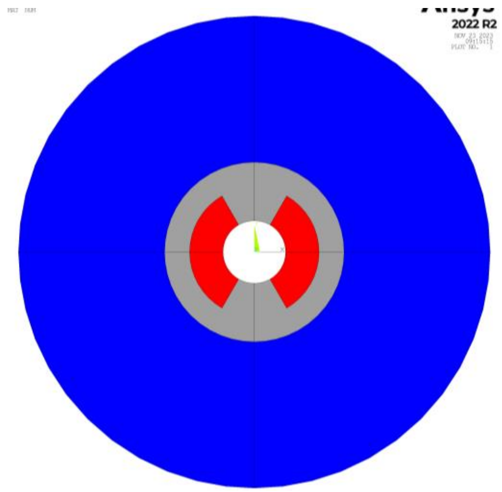
- For the **IR magnets**, a budget of **800 kEur/m** must be taken into account, together with a lower working temperature (T<10 K), which can be estimated more accurately only when the revised optics will be available.

Thank you for your attention

Cost Estimate (3TeV)

Dipoles of the arc for the series production
(quadrupoles and IR not included)

11T /158 mm (Nb_3Sn)



R_{bore}= 79 mm
w_{coil}= 80 mm
w_{struct}= 50 mm
w_{iron}=350 mm

€/kg iron	€/kg struct	€/kg conductor *
8	10	700

* 7€/kAm, FCC target 5€/kAm

Iron [Kg/m]	Structure [kg/m]	Coil [kg/m]
6587	450	223
Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
53	4.5	156

Tot. Material k€/m	84	30%
Tot. Assembly k€/m	40	14%
Tot. Conductor k€/m	156	56%
Tot. Cost k€/m	**280**	

Tot. Material = $(C_{iron}+ C_{struct})*f_{struct}$
$f_{struct} = 1.5$

200 k€/magnet (~2FTE)

Coordination, design and follow-up: 4 FTE x 4 years= 16 FTE-years (1.6 MEur)

TOTAL COST: 6.7% O.M.B. (overall magnets budget)

Disclaimer: cryostat, specific tooling (e.g. oven for thermal treatment of Nb3Sn) W absorber not taken into account

Magnet requirements for Lattice

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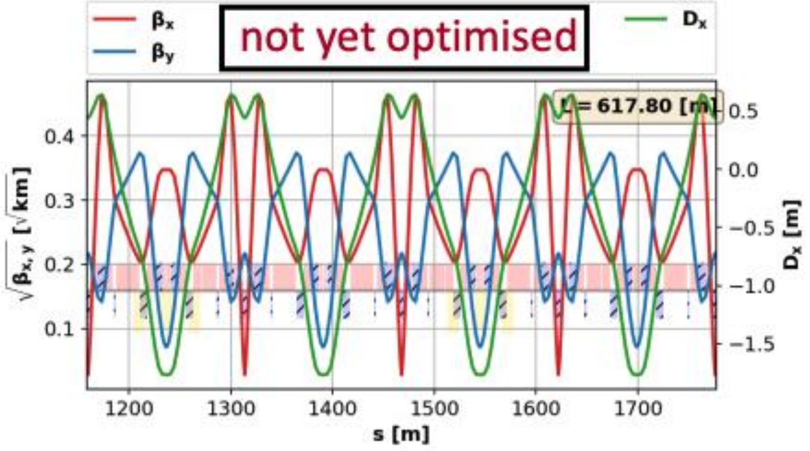
10TeV collider[ref] - preliminary

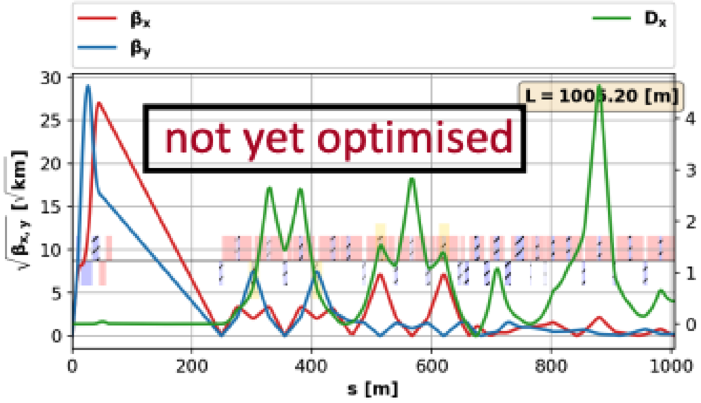
ARC

- Dipole-sextupoles with B_d~14T G_2~±7100T/m² with radius~50mm
- Dipole-quads with B_d~8T G_1~±320T/m with radius~50mm
- Dipoles B_d~16T



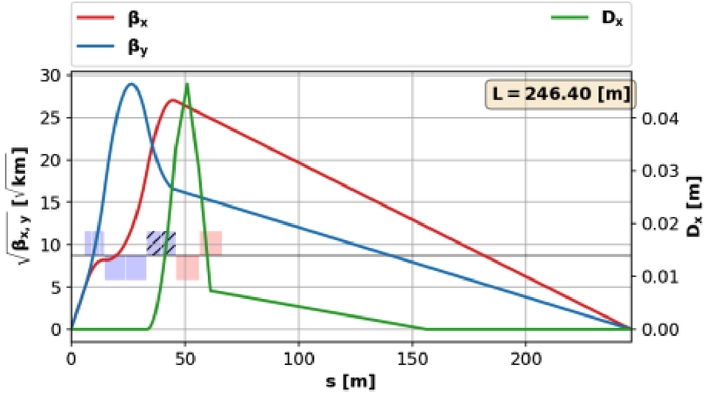
Chromatic correction

- Dipole-sextupoles with B_d~4T G_2~±11555T/m² with radius~70mm
- Dipole-quads with B_d~4T G_1~±240T/m with radius~70mm
- Dipole-quads with B_d~4T G_1~±330T/m with radius~50mm
- Dipoles B_d~16T



Final Focusing

- Quads with G_1~±300T/m with radius~60mm
- Quads with G_1~±110T/m with radius~150mm
- Dipole-quads with B_d~8T G_1~±100T/m with radius~140mm
- Dipoles B_d~±16T



Courtesy of Kyriakos Skoufaris

Several magnet typology needed (dip, quad, combined, etc) , but optimization & definition of requirements still on going

Cost reduction learning curve

How to rescale for the other steps (pre-series, prototypes, short models, demonstrators)?

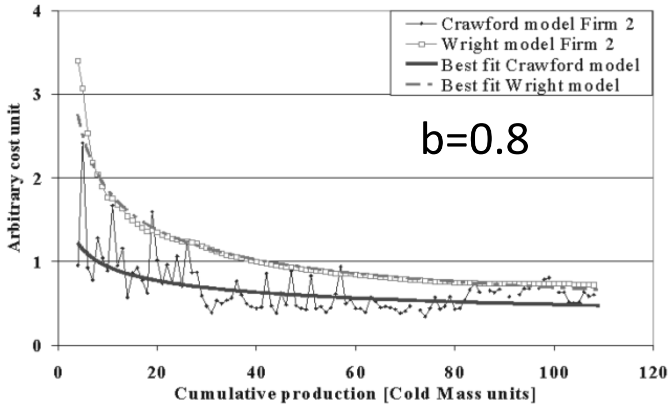
Learning curve

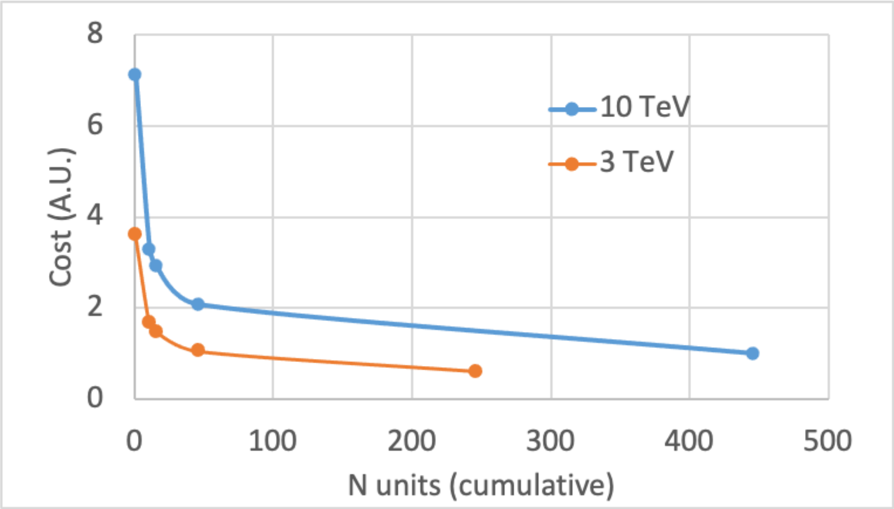
Wright's law

$$C_x = C_1 x^{\log_2(b)}$$

b: learning percentage

Applied to LHC magnets works perfectly! [ref]





	3 TeV		10 TeV	
	N units (cumulative)	cost (A.U.*)	N units (cumulative)	cost (A.U.*)
demostrator	1	3.36	1	7.13
short model	11	1.55	11	3.29
proto	16	1.38	16	2.92
pre series	46	0.98	46	2.08
series	246	0.57	446	1.00

*w.r.t. cost of 10 TeV series magnet

COST ESTIMATE (3TEV)

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Pre-series

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
91	8	269
Tot. Material k€/m	144	30%
Tot. Assembly k€/m	69	14%
Tot. Conductor k€/m	269	56%
Tot. Cost k€/m	**481**	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
90	5	4	1600	1.70%

Prototypes

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
127	11	377
Tot. Material k€/m	201	30%
Tot. Assembly k€/m	96	14%
Tot. Conductor k€/m	377	56%
Tot. Cost k€/m	**674**	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
5	5	5	2000	0.15%

Short Models

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
143	12	425
Tot. Material k€/m	227	30%
Tot. Assembly k€/m	109	14%
Tot. Conductor k€/m	425	56%
Tot. Cost k€/m	**761**	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
10	1.5	6	3000	0.11%

Demonstrators

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
310	27	919
Tot. Material k€/m	491	30%
Tot. Assembly k€/m	235	14%
Tot. Conductor k€/m	919	56%
Tot. Cost k€/m	**1645**	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
1	1.5	4	12000	0.03%

*overall magnets bugdet

COST ESTIMATE (10TEV)

Pre-series

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
75	4.3	633
Tot. Material k€/m	116	15%
Tot. Assembly k€/m	42	5%
Tot. Conductor k€/m	632	80%
Tot. Cost k€/m	790	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
90	5	4	1600	2.80%

Prototypes

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
105	6.1	888
Tot. Material k€/m	163	15%
Tot. Assembly k€/m	58	5%
Tot. Conductor k€/m	888	80%
Tot. Cost k€/m	1109	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
5	5	5	2000	0.24%

Short Models

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
119	7	1000
Tot. Material k€/m	183	15%
Tot. Assembly k€/m	66	5%
Tot. Conductor k€/m	1000	80%
Tot. Cost k€/m	1250	

N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
10	1.5	8	4000	0.18%

Demonstrators

Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
257	15	2168
Tot. Material k€/m	397	15%
Tot. Assembly k€/m	143	5%
Tot. Conductor k€/m	2168	80%
Tot. Cost k€/m	2708	

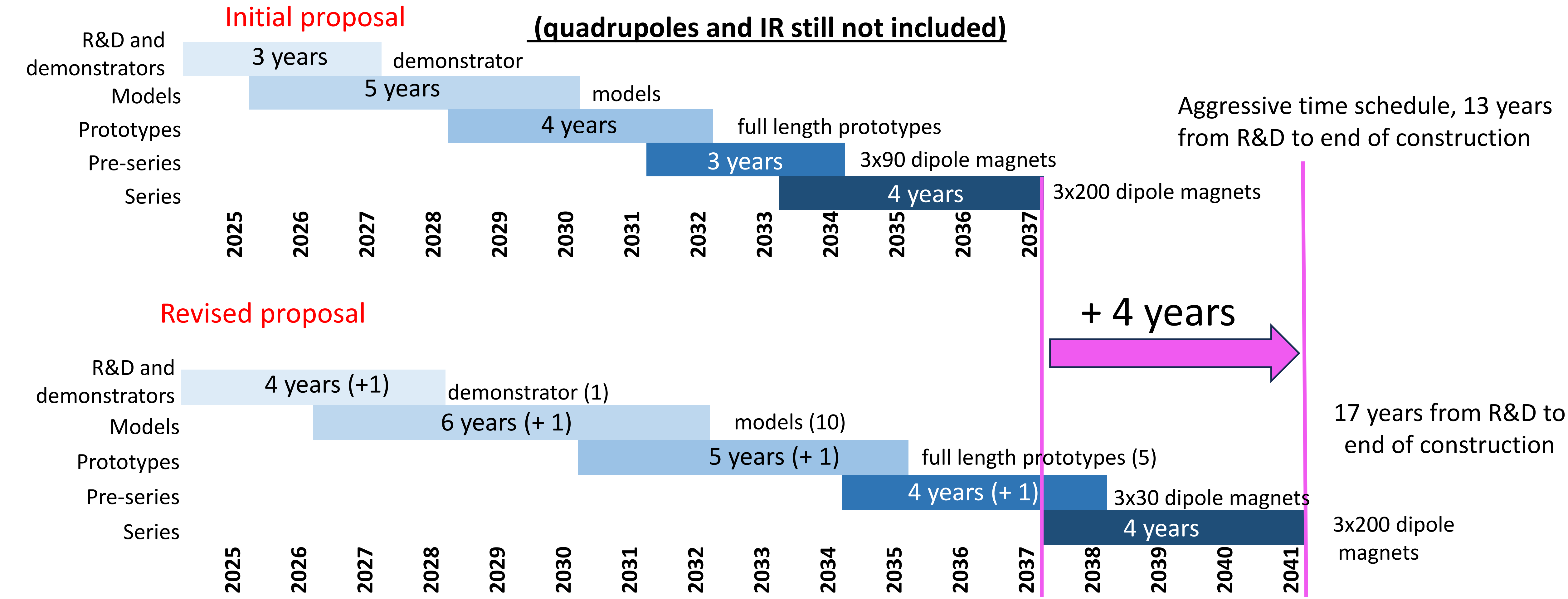
N units	length [m]	N years	cost FTE-y [k€]	Total cost [o.m.b*]
1	1.5	6	24000	0.05%

*overall magnets bugdet

TENTATIVE SCHEDULE (3 TEV COLLIDER)

ARC DIPOLES 11T/158mm

(quadrupoles and IR still not included)

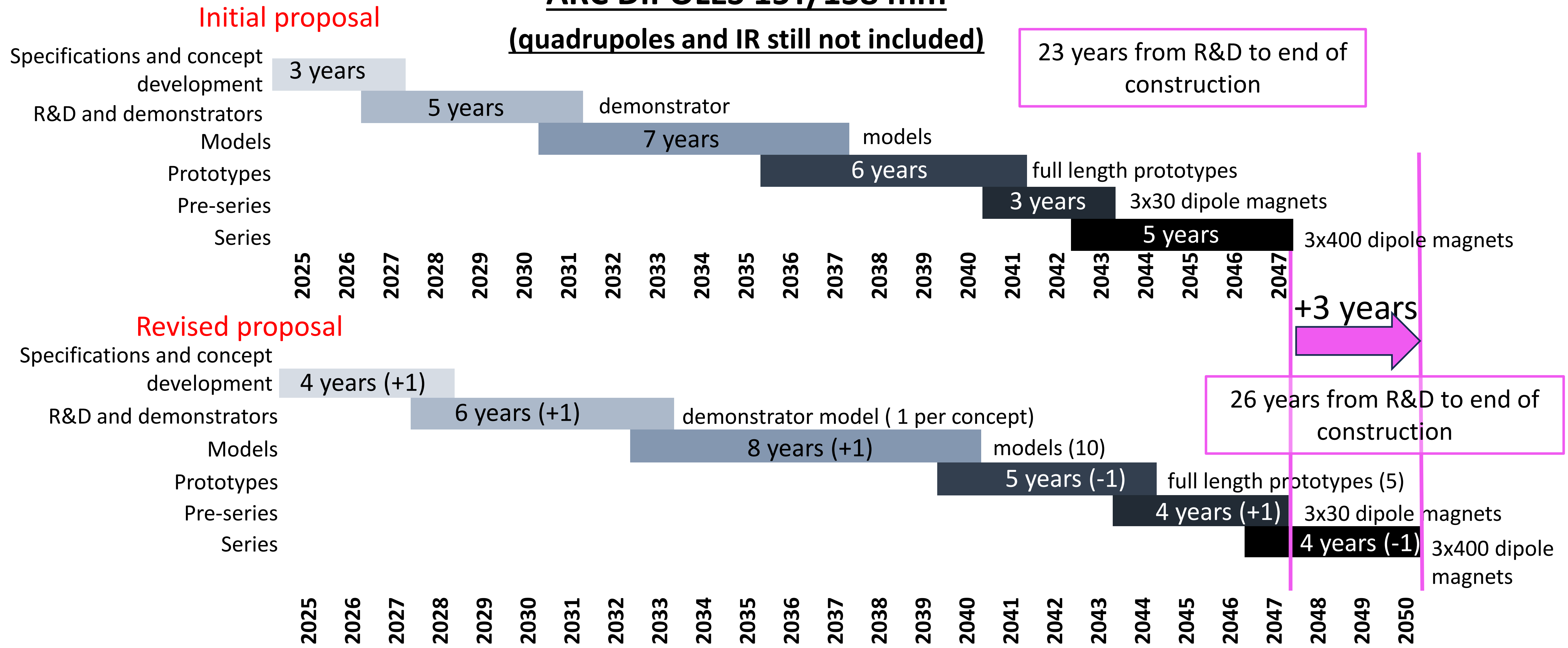


- Nb3Sn demonstrator program ~ 6 years
- LHC: 13 short models in 11 years, 6 prototypes in 4 years, pre-series 4 years, series 4 years

TENTATIVE SCHEDULE (10 TEV COLLIDER)

ARC DIPOLES 15T/138 mm

(quadrupoles and IR still not included)

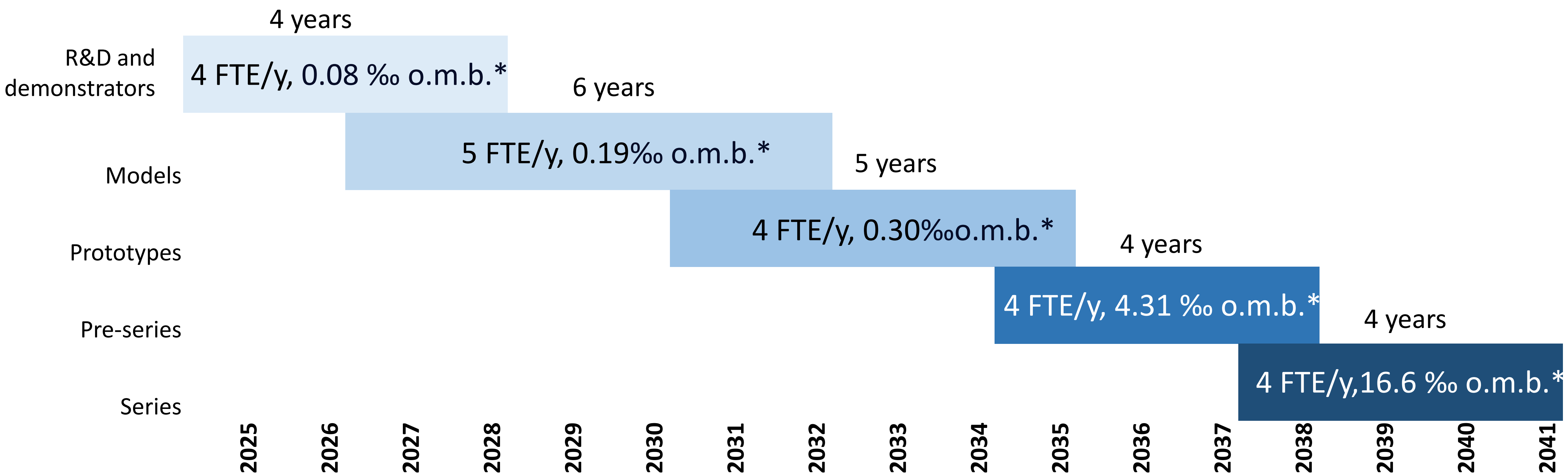


More emphasis on demonstrator and short model phase (REBCO or hybrid solutions still to be studied)

TENTATIVE SCHEDULE (3 TEV COLLIDER)

ARC DIPOLES 11T/150mm

(quadrupoles and IR still not included)



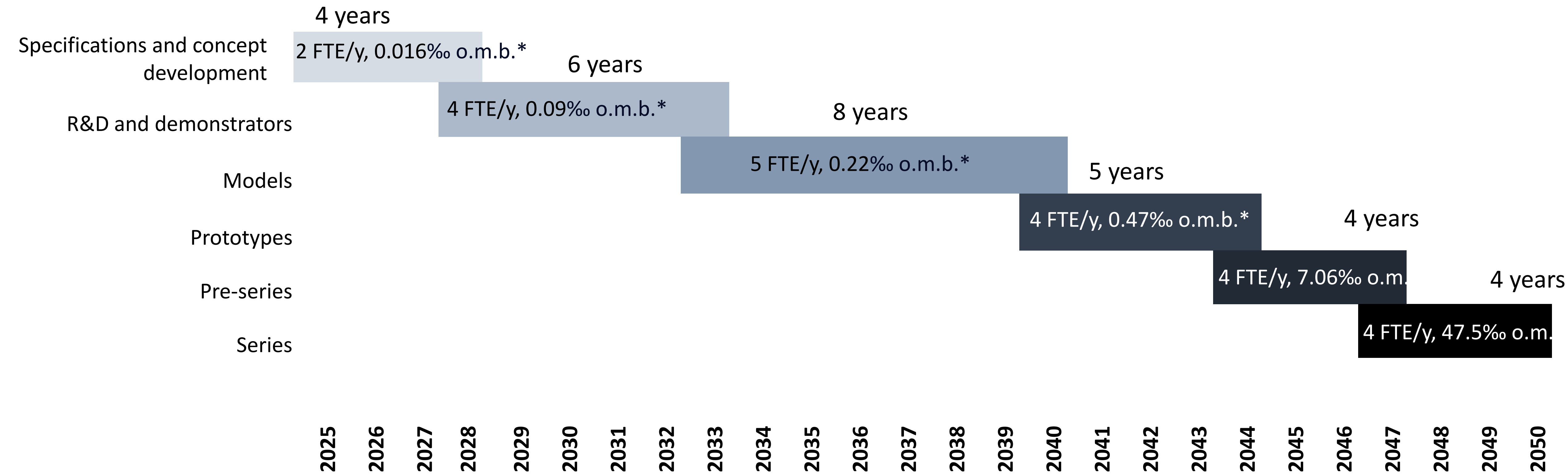
TOTAL: 8.67% o.m.b.*

*overall magnets bugdet

TENTATIVE SCHEDULE (10 TEV COLLIDER)

ARC DIPOLES 15T/150 mm

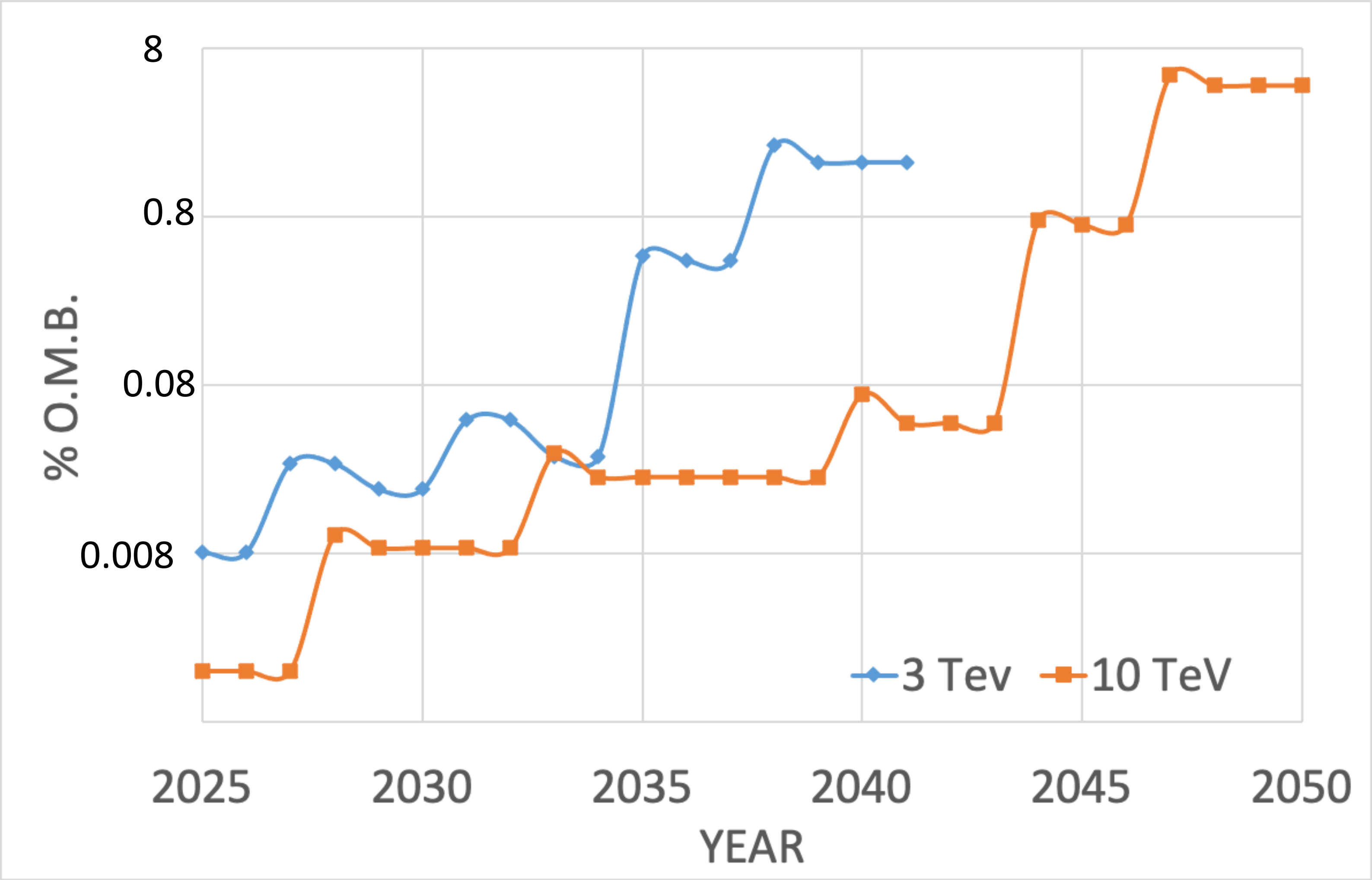
(quadrupoles and IR still not included)



TOTAL: 22.3% o.m.b.*

*overall magnets bugdet

Cost Profile



*overall magnets bugdet