International MUON Collider Collaboration

Cost and Power

C. Rossi – 14th May 2025

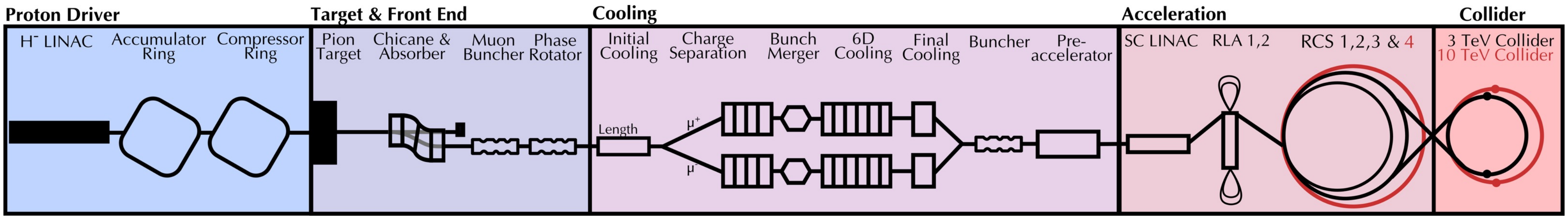
OUTLINE

- General approach to the costing of the Muon Collider Facility
- What is included and what is not
- Cost analysis
- Indications and limits from the first exercise
- Possible way to the next step

General Approach

- The estimate is presented in the form of a **cost range**
- The **CERN scenario** is first considered, to exploit the existing infrastructure: boundary conditions to the facility configurations.
  - The environmental impact is reduced;
  - A staging approach is still possible.
- The estimate is based on **main cost drivers only**, provided by experts and based on existing designs and on expected developments:
  - Magnets
  - RF
  - Cryogenics
  - Power converters
  - Civil engineering + extrapolated infrastructure

General Approach



Starting from the facility layout, a Project Breakdown Structure (PBS) was built

PBS				Class	Description
1st lvl	2nd lvl	3rd lvl	4th lvl	uncertainty	
1.0.0					Proton Driver
	1.1.0			4	SC Linac
	1.2.0				Accumulator
	1.3.0				Compressor

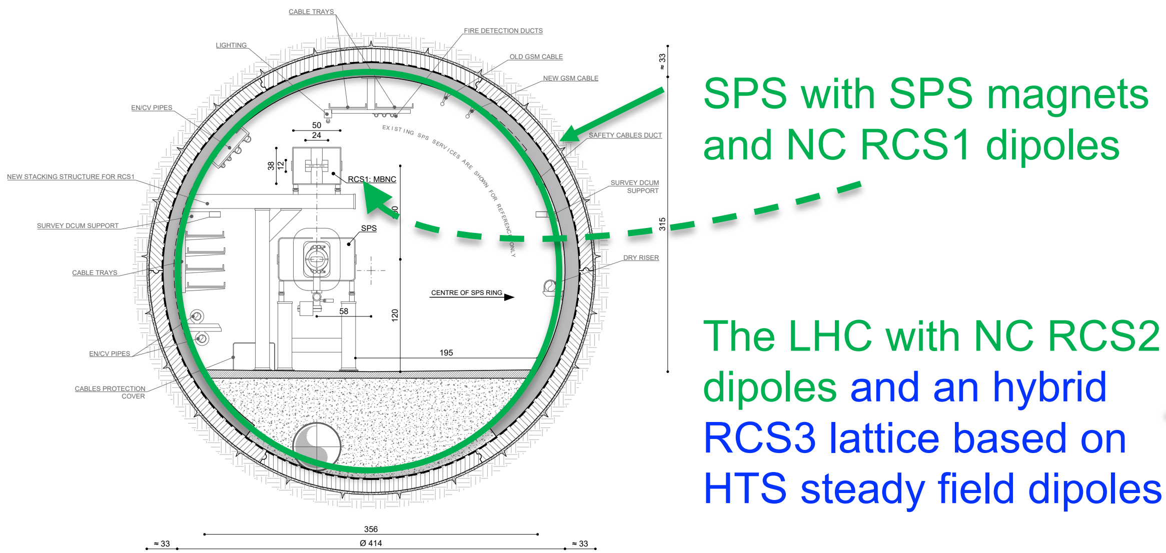
Combines Class IV and Class V for overall uncertainty.

Configurations

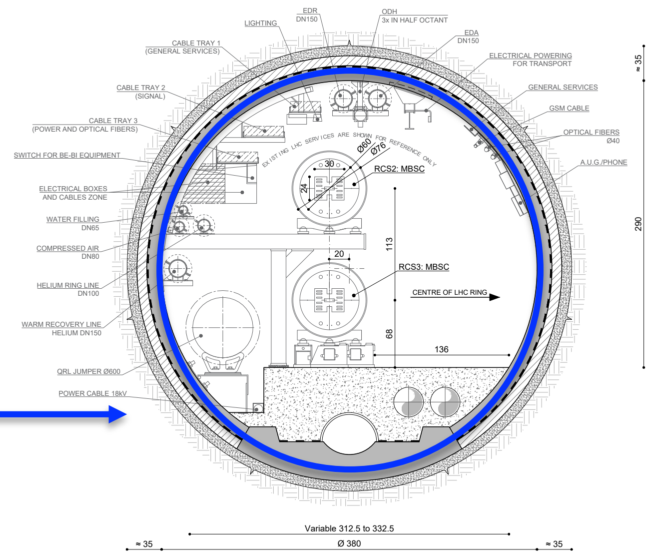
Parameter	Symbol	unit	Site independent		CERN	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	17.5	0.9	7.9
Collider circumference	C_{coll}	km	4.5	11.4	11	11
Collider arc peak field	B_{arc}	T	11	14	4.8	11
Collider dipole technology			Nb_3Sn	HTS	NbTi	Nb_3Sn or HTS

Configurations

- The CERN installation has considered two stages at collision energies of 3.2 TeV and 7.6 TeV, with a possible ramp up to 10 TeV as soon as HTS dipoles would become available with 15 T field.

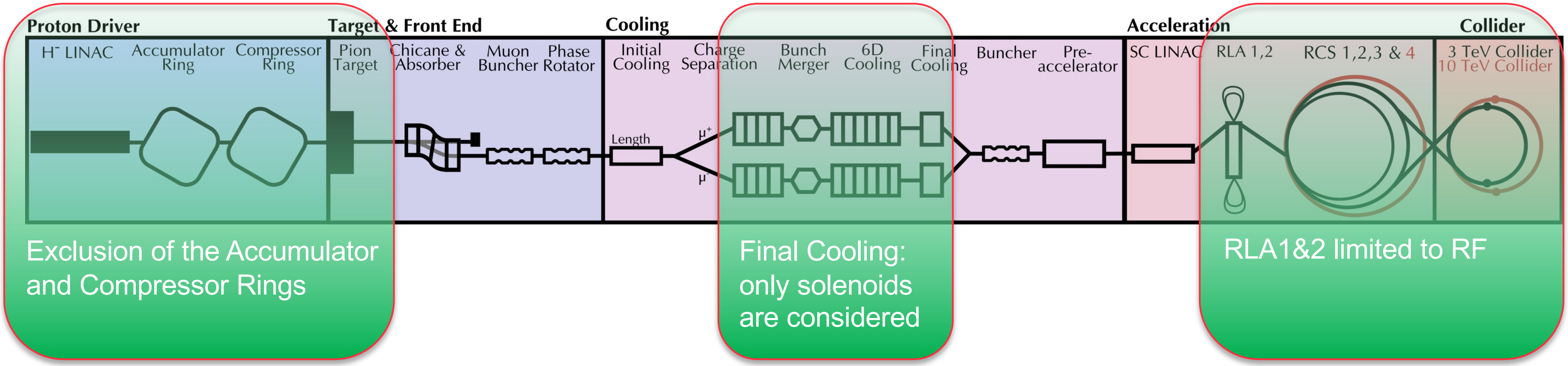


TYPICAL CROSS SECTION
ACCELERATOR IN THE SPS TUNNEL
RCS1: MBNC
SPS



TYPICAL CROSS SECTION
ACCELERATOR IN THE LHC TUNNEL
RCS2: MBSC
RCS3: MBSC

What is included and what is not



- **Areas in green are included**. Some other areas are not sufficiently specified yet for a cost estimate.
- Avaiable cost models were used, like for the cooling channel RF system, however R&D may introduce new requirements.
- On the other hand, beam dynamics design should not ignore cost implications of design choices and explore trade-offs with equipment experts.

RF Systems Estimate

- Multi-cell RF cavities, normal and super conducting technology. Same **tool** used for CLIC and FCC

RF frequencies and gradients			
Proton driver - Linac			
RF frequencies	MHz	352	704
Muon cooling complex - 6D cooling			
RF frequencies	MHz	352	704
Maximum accelerating field	MV/m	22	30
Maximum accelerating field	MV/m	35	50
Muon cooling complex - Final cooling			
design in progress			
Acceleration complex - Low Energy Acceleration			
RF frequencies	MHz	352	1056
Maximum accelerating field	MV/m	16	30
Maximum accelerating field	MV/m	25	45
Acceleration complex - RCS			
RF frequency	MHz	1300	
Maximum accelerating field	MV/m	30	
Maximum accelerating field	MV/m	45	

NC and SC Cavity production

	Technology
raw material	Cost raw material in CHF/m² in kCHF (Cu or Nb sheet) - year 2017
raw material	Surface area per cell in m²
raw material	Surface beam tube in m²
raw material	Cell length in m
raw material	Beam tube length per cell in m (total)
raw material	# of cells per cavity
raw material	Total length per cooling cell m
raw material	Surface per cavity in m²
raw material	Cost cavity raw material
assembly	Cost of half-cell fabrication (per pair)
assembly	Cost of cut-off fabrication (per pair)
assembly	Cost per cavity assembly (extras)
assembly	Additional workshop costs par cavity (e.g. metrology)
assembly	*Total cost cavity fabrication*
surface prep.	Cost of cavity surface treatment (15 kCHF/m²)
surface prep.	Cost of heat treatment per cavity (10 kCHF)
surface prep.	Cost of Nb coating per cavity (5 kCHF)
surface prep.	Cost of HP rinsing per cavity (5 kCHF)
surface prep.	***Total cost of cavity SRF surface preparation***
	Total cost of a bare cavity
components	Cost of tuning system
components	Cost per HOM coupler
components	# of HOM coupler per cavity
components	Cost per FPC (fixed LP = 70 kCHF, movable/HP = 150 kCHF)
components	Cost of helium vessel/distribution per cavity
	Total cost of a dressed cavity
cryomodule	# cavities
cryomodule	Cost of cavities
cryomodule	**Optimized cost of cavities**
cryomodule	Cost of cryomodule frame (2kCHF/m)
cryomodule	Cost of vacuum vessel
cryomodule	Cost magnetic shielding (4 kCHF/m)
cryomodule	Cost thermal shielding (4 kCHF/m)
cryomodule	Cost for the assembly of a cryomodule
cryomodule	Cost for cryo system (valves, exchangers, rupture discs...)
cryomodule	Cost for vacuum system
cryomodule	Cost for instrumentation
cryomodule	Cost for HOM coaxial lines
	Total cost of a cryomodule
	Overhead for running & operation costs
	Total cost of a cryomodule
	number of cavities per stage

RF Power production

Technology
Cost of the WG system per klystron
Cost of the WG support system per power source
Cost of the RF circulators (400MHz - 2x, 800 MHz - 1x)
Cost of the RF loads
Cost of the RF circulator & RF load chassis per klystron
Cost of arc detection system per klystron/SSA
Cost of the RF dir. Couplers per klystron/SSA
Cost of RF monitoring system (safety)
Total cost of a RF power distribution system per klystron/SSA
Cost of a HV distribution (surface-tunnel)
Cost of a HV bunker (fraction per klystron/SSA -> 8 per bunker)
Cost of the HV bunker equipment per klystron/SSA
Cost of a HV cable set per klystron/SSA
Cost of a crowbar system per klystron/SSA
Total cost of a HV RF system per klystron/SSA
Cost of the water cooling system per klystron/SSA
Cost of the air cooling system per klystron/SSA
Total cost of a cooling system per klystron/SSA
Cost per klystron/SSA
Cost of ionic pumps power supples per klystron
Cost of focus power supplies per klystron
Cost of heating system per klystron
Cost of RF driver per klystron/SSA
Cost of DC power distribution per SSA (in bunkers)
Cost controls racks per klystron/SSA
Total cost of auxillaries per klystron/SSA
Total cost of a RF power system
Overhead for running & operation costs
Total cost of a RF power system

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RF Systems Estimate

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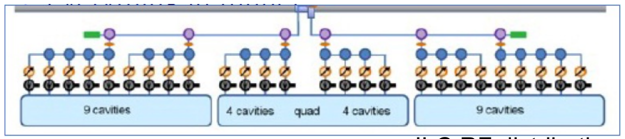
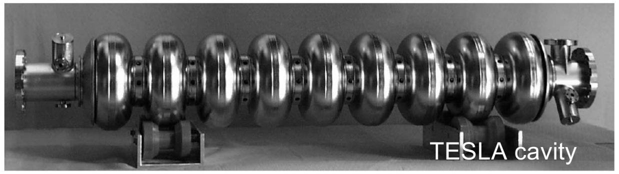
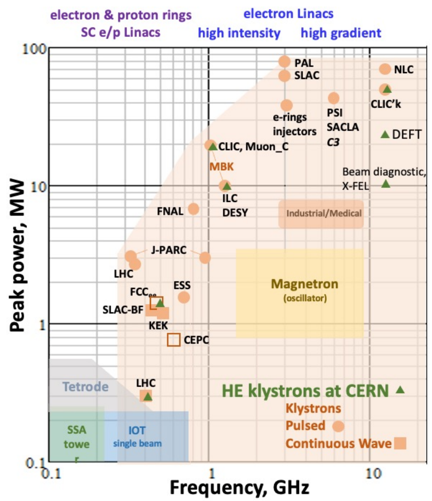
- Multi-cell RF cavities, normal and super conducting technology.
  - For **RCS top-down model** was scaled from ILC, based on TESLA – like cavity.



ILC RF distribution

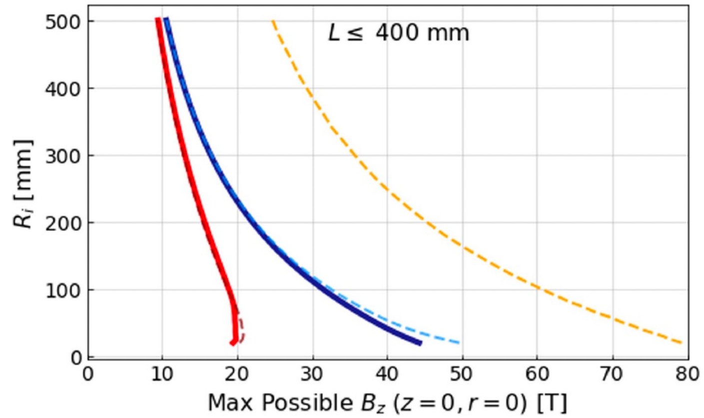




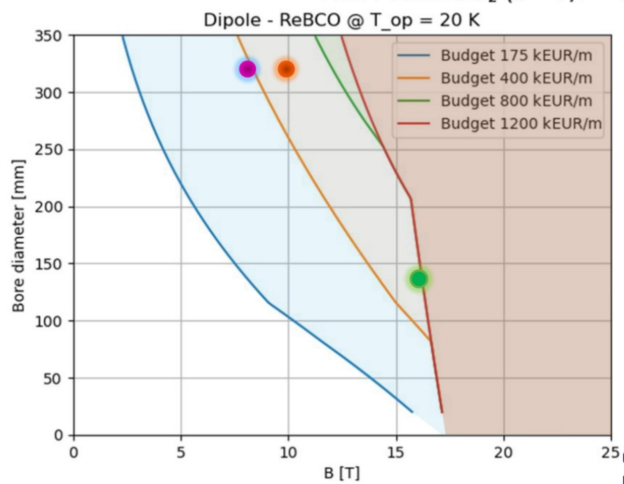
- For all other systems cost was scaled from cost models developed from LHC, CLIC, FCC cavities and associated RF equipment.

Magnets and Power Converters

- Very challenging developments in the field of NC and SC magnets
  - SC solenoids for the target, for the decay and cooling channels
  - NC magnets with fast cycling power converters for the RCSs
  - SC magnets for RCS and collider ring, with combined-function SC magnets in the collider ring.



Magnet development targets					
Complex	Magnet	No. of Magnets	Aperture [mm]	Length [m]	Field [T] / Gradient [T/m]
Target, decay and capture	Solenoid	23	1380	~0.4 - 0.8	2 to 20
6D cooling	Solenoid	~6000	90-1500	0.08 - 0.5	2 to 17
Final cooling	Solenoid	14	50	0.5	>40
RCS	NC dipole	~1500	30x100	5	-1.8 to +1.8
	SC dipole	~2500	30x100	1.5	10
Collider ring	SC dipole	~1050	100 - 140	5	*16
	Combined Function (Dip. + Quad.)	~628	100 - 280	5. - 10.	4 to 8 T / ~100 T/m to *320 T/m
	IR Quadrupoles	~20	100 - 280	5.-10.	110 T/m to *330 T/m



- Development of a cost model, with benchmarking to existing projects.
  - **ABG plots with defined cost target and state-of-the-art power converter technology** were used to orient the estimate

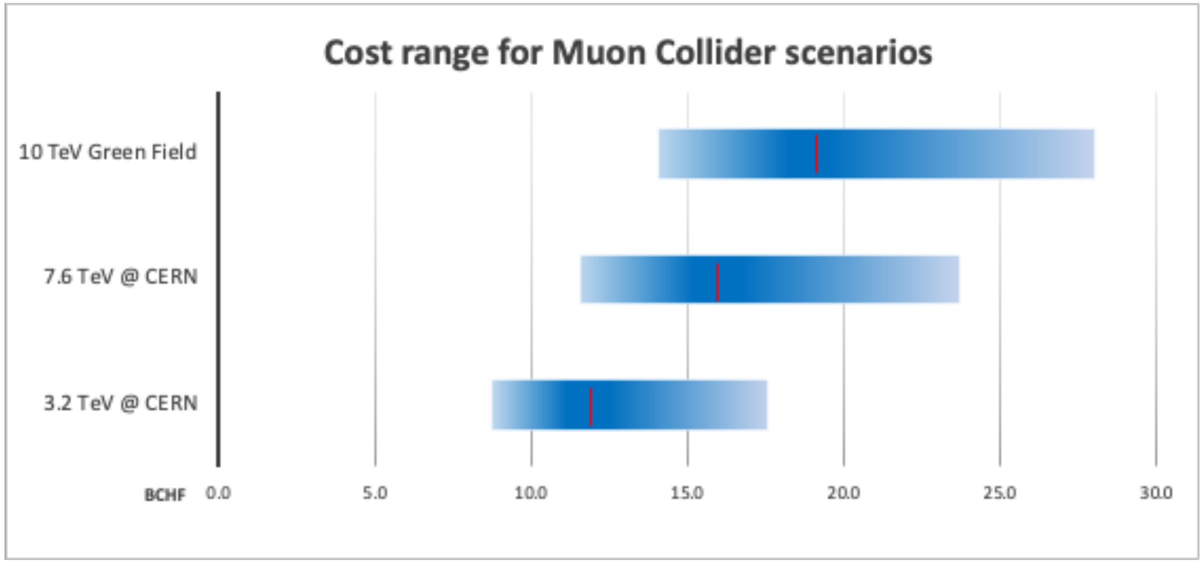
Magnets and Power Converters

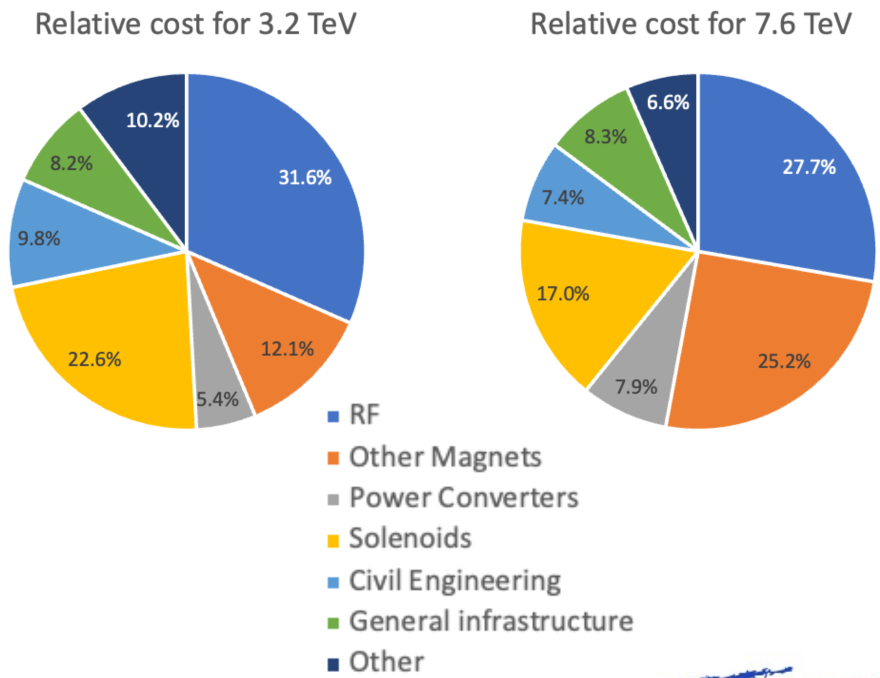
- Development of a **cost model**, with benchmarking to existing projects.

		Nb-Ti	Nb_3Sn (present)	Nb_3Sn (aspirational)	REBCO (present)	REBCO (aspirational)	BSCCO (present)	BSCCO (aspirational)
c_{Strand}	(EUR/kg)	159	2274	758	8013	2671	17700	5900
d_{Strand}	(kg/m^3)	8000	8000	8000	7800	7800	9000	9000
f_{Cable}	(-)	0.1	0.1	0.1	0	0	0.1	0.1
$C_{CoilManufacturing}$	(kEUR/m)	9.9	11.9	11.9	9.9	9.9	15	15
$C_{ColdMassMaterials}^{Ref}$	(kEUR/m)	26.4						
B^{Ref}	(T)	8.33						
$C_{ColdMassManufacturing}$	(kEUR/m)	26.4	31.7	31.7	26.4	26.4	31.7	31.7
$C_{CryoMagnet}$	(kEUR/m)	8.0						

Summary of cost

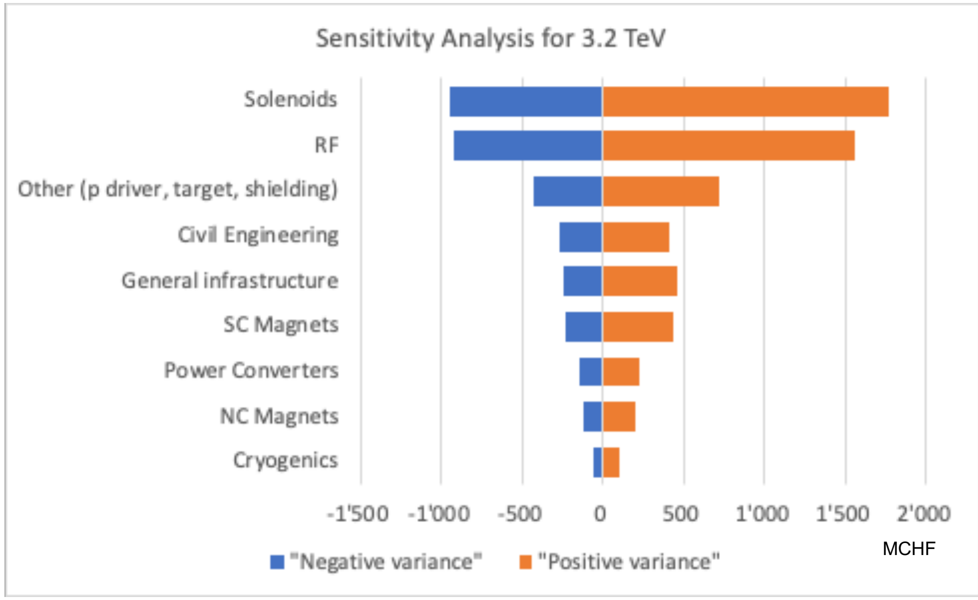
- The cost range for the different configurations was evaluated and compared to the Green Field scenario, where a cost for Civil Engineering of 50kCHF/m was assumed in the absence of a detailed study.

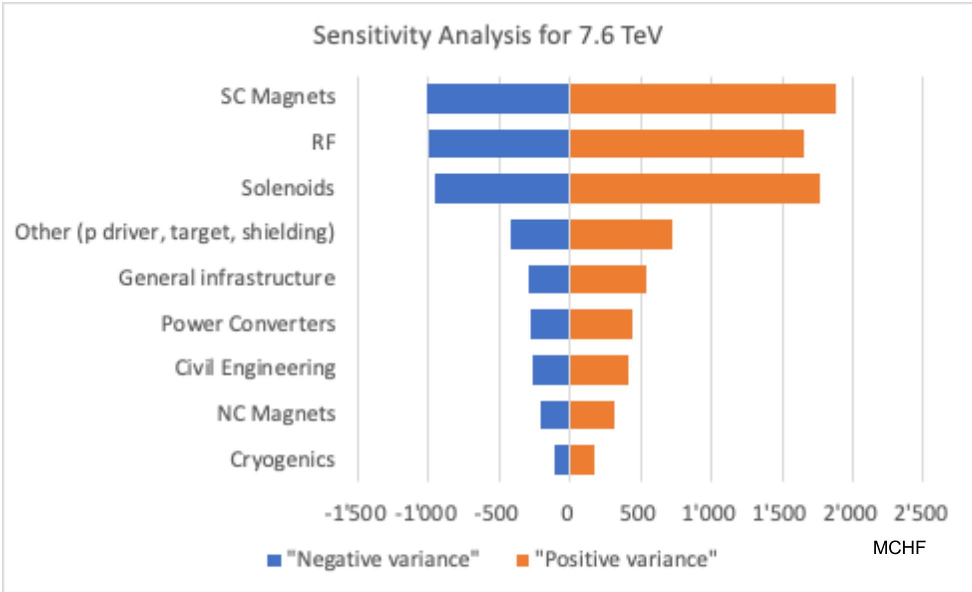




Cost sensitivity

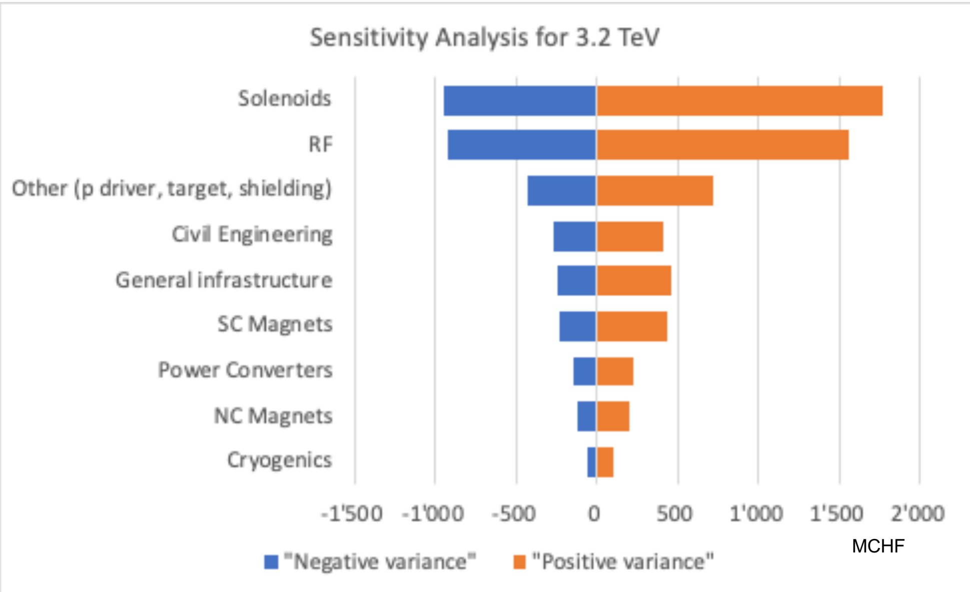
- In the two configurations, the same technologies weigh differently in the cost uncertainty, showing the path for some risk mitigation.

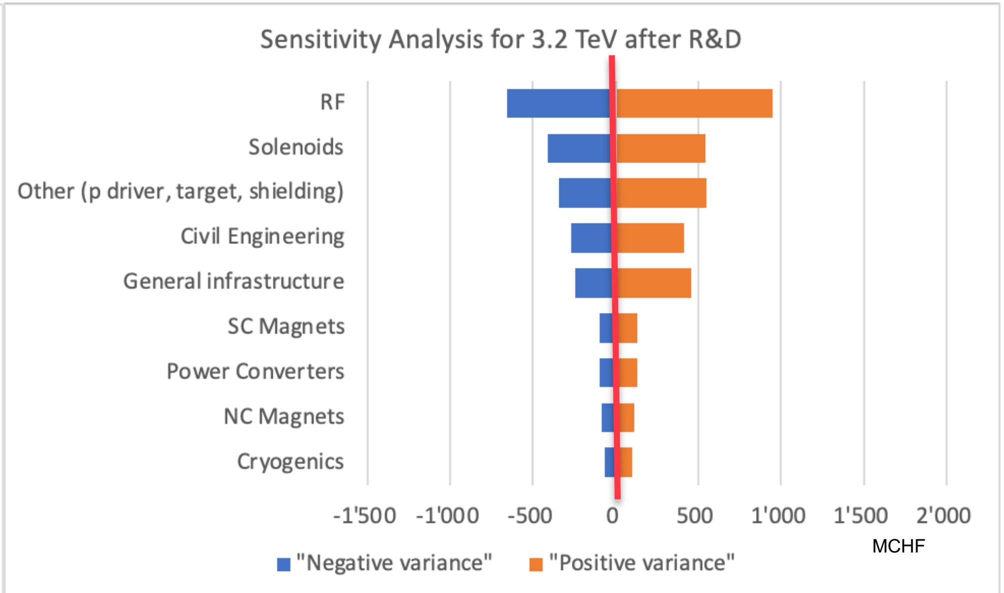




Risk mitigation

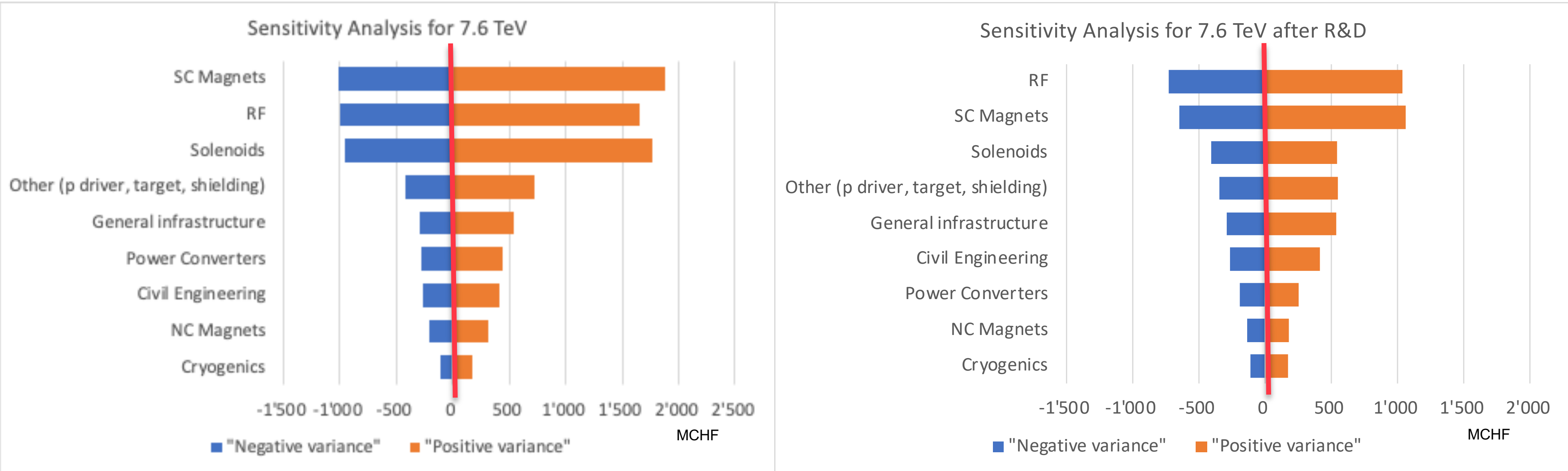
- Investments in a substantial **R&D activity that can bring the relevant technologies to a TRL6 level** represent an effective strategy for **risk mitigation**.





Cost sensitivity

- Investments in a substantial **R&D activity** represent an effective strategy for **risk mitigation**.



Power Calculation

- Power needs were derived from **p Driver**, **RF systems, power converters and cryogenics**.

		RCS1	RCS2	RCS3
RF peak/cav	MW	0.987	0.228	0.195
N cavities	-	686	1958	2017
RF peak	MW	905	569	529
RF average	MW	2.91	10.3	14.3
RF plug	MW	4.48	15.8	22
NC magnets	m	4103	18650	12940
SC magnets	m	-	-	5680
P magnets	MW	1.93	12.8	26.6
P cryo RF	MW	1.5	7.7	11.6
P cryo mag	MW	-	-	4.5

		RLA2 acc	RLA2 lin
RF peak/cav	MW	3.425	2.965
N cavities	-	600	80
RF peak	MW	2055	237.2
RF average	kW	5.16	0.16
RF plug	kW	7.94	0.24

	6D Cooling channel													
		A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
RF peak	MW	5.094	5.21	2.468	2.655	3.336	3.883	4.882	4.701	1.419	2.809	2.531	2.304	2.573	1.806
N cavities	-	348	356	405	496	144	170	216	183	275	220	204	276	212	196
RF peak	MW	1773	1855	999.4	1317	480.4	660.1	1055	860.3	390.1	617.9	516.4	635.8	545.4	354.1
RF average	kW	277.1	297.9	56.7	75.41	96.11	120.1	169.9	158.5	22.37	35.35	29.55	36.39	31.15	20.26
RF plug	kW	439.8	472.8	90	119.7	152.6	190.6	269.7	251.7	35.51	56.11	46.9	57.77	49.45	32.16

Power and Energy Calculation

- Power needs were focused on RF systems, power converters and cryogenics. **Operation scenario** similar to what was used for CLIC and LCF.

Summary TABLE full power			
	3.2 TeV	**7.6 TeV**	**10 TeV**
	MW	MW	MW
P driver	16.700	16.700	16.700
6D Cooling	11.765	11.765	11.765
RLA2	10.770	10.770	10.770
RCS	44.190	108.930	124.680
Collider	10.000	4.100	4.100
General CV	20.000	20.000	20.000
TOTAL	113.425	172.265	188.015

	DAYS		
Operation	165	hours op.	4509
Luminosity	115.5	hours std-by	1251
Technical stops	15	hours off	3000
MD	20		
Commissioning	40		
YETS	125		
sum	365		8760

	3.2 TeV			**7.6 TeV**			**10 TeV Green Field**		
	ON	*STD-BY*	*OFF*	*ON*	*STD-BY*	*OFF*	*ON*	*STD-BY*	*OFF*
	MW	**MW**	**MW**	**MW**	**MW**	**MW**	**MW**	**MW**	**MW**
P driver	16.70	4.83	4.83	16.70	4.83	4.83	16.70	4.83	4.83
6D Cooling	11.76	9.50	9.50	11.76	9.50	9.50	11.76	9.50	9.50
RLA2	10.77	2.59	2.59	10.77	2.59	2.59	10.77	2.59	2.59
RCS	44.19	25.71	11.00	108.93	69.75	28.40	124.68	85.79	48.80
Collider	10.00	10.00	10.00	4.10	4.10	4.10	4.10	4.10	4.10
General CV	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
TOTAL	113.42	72.63	57.92	172.26	110.77	69.42	188.01	126.81	89.82
hours	*4509*	*1251*	*3000*	*4509*	*1251*	*3000*	*4509*	*1251*	*3000*
Energy cons. TWh	0.511	0.091	0.174	0.777	0.139	0.208	0.848	0.159	0.269
Energy TOTAL TWh		0.776			1.124			1.276	

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Indications and Limits from the first exercise

- The early stage of the study does not allow to adopt a complete **bottom-up approach**.
- Cost drivers in the sensitivity analysis provide indications for a risk mitigation related to cost uncertainty.
- Only a substantial R&D can produce a reduction of that cost uncertainty.

- The present estimate remains a partial exercise, due to the not yet mature technical advancement in some areas. However it provides a frame to further develop our model and improve its accuracy.

Indications for the next iteration

- Few technical points are worth investigating in the light of **cost optimization**, like :
  - Review technical choices related to the cooling channel in the perspective of a cost optimization;
  - Explore the impact of transition energy from RLAs to RCS1;
  - Consider other acceleration techniques that may positively impact the final cost of the complex, like FFAG;
  - Consider the right trade-off between beam transmission efficiency and cost, after that all other aspects have been optimized.
- Permanently include cost considerations into the facility design for an early optimization of technical options.

Thanks to all colleagues in the Collaboration who provided their contribution to this estimate

Thank you

International MUON Collider Collaboration

CERN

Additional Slides

The ITF Estimate

- A previous estimate was done in the frame of the Snowmass exercise in 2022, by using a multi-parameter cost model and starting from estimates provided by project proponents (B$ in the scale below).

Project Cost *(no esc., no cont.)*	4	7	12	18	30	50
MC-3						
MC-10						

Estimate Classes

International MUON Collider Collaboration

Recommended Practice No. 18R-97

Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries

aace International — The Association for the Advancement of Cost Engineering through Total Cost Management

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Use an internationally recognized approach for the estimate of accuracy

Classes of estimate used for most areas of the MC facility.

Class of estimate that was used for established equipment like the RCS RF system, based on ILC technology.