Pulsed magnet and powering system design and optimization

MuCol Mini-Workshop on Rapid Cycled Synchrotrons, pulsed magnets and powering

CERN, 15/05/2024

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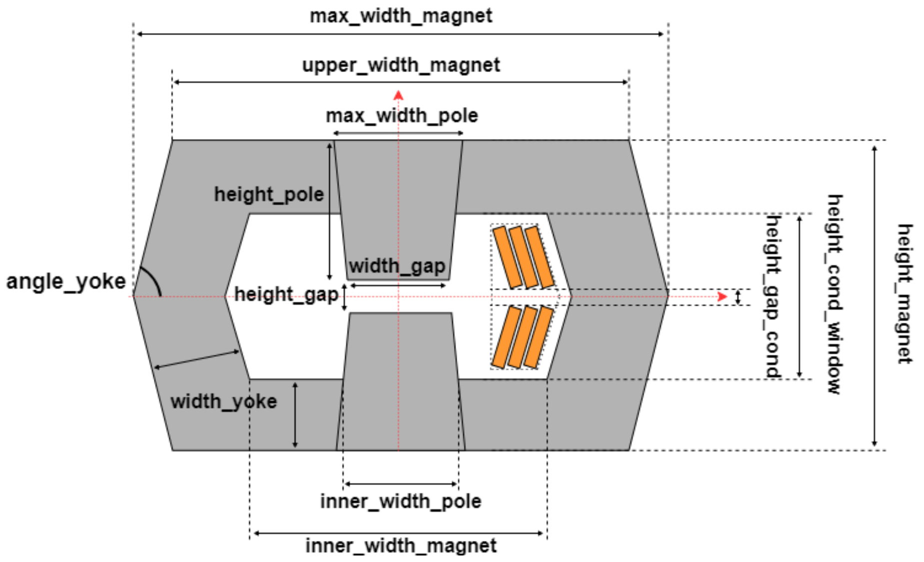
Outline of the presentation

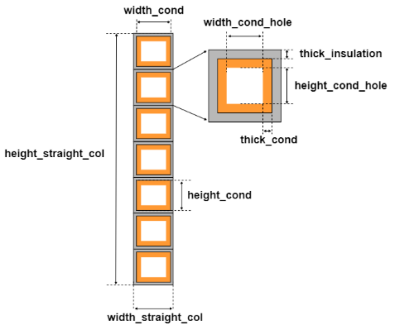
- Presentation of the Python classes and the new cost model;
- New optimizations and cost computation (pu values)
- Conclusions

Introduction – Dipole class

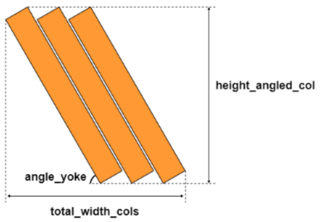
Unified dipole class to treat both “Hourglass” and “H-type” magnets with hollow or flat conductors



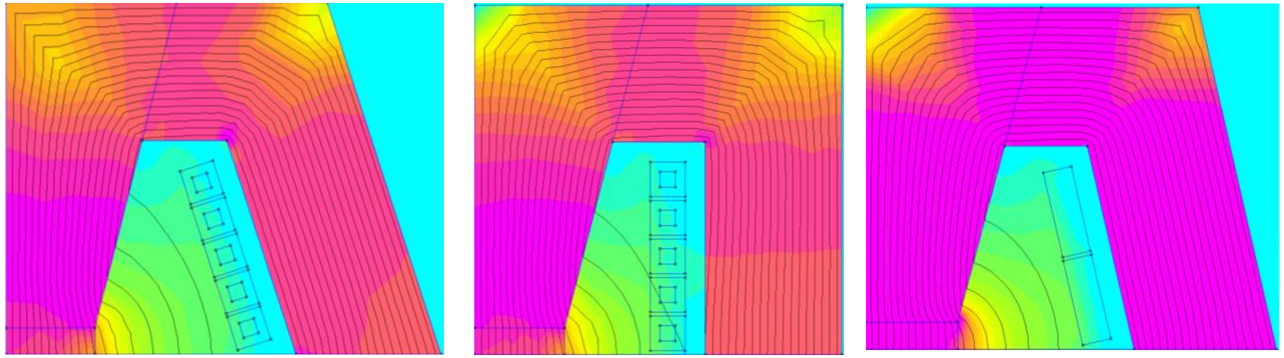
- Hourglass and H-type magnet
- Hollow Water-cooled and flat coils
- Magnet joke and pole made of possibly different steel M235-35A
- Each parallel coil is connected to a separate parallel power electronics circuit to keep the maximum current of each power electronic cell low



(a) Straight conductor column consisting of 7 conductors

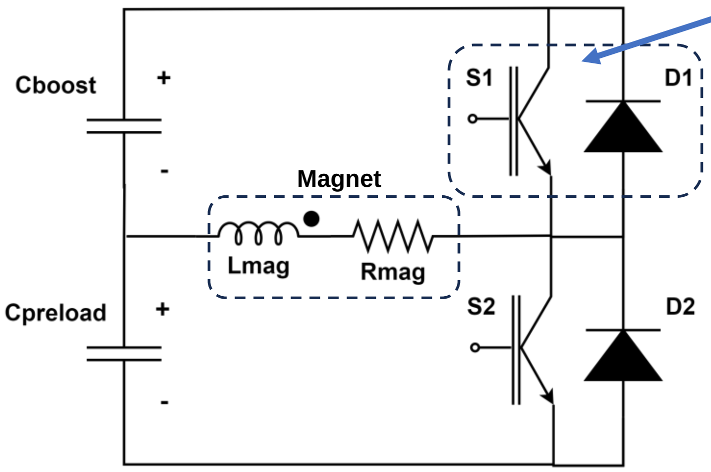


(b) Bunched, angled conductor columns



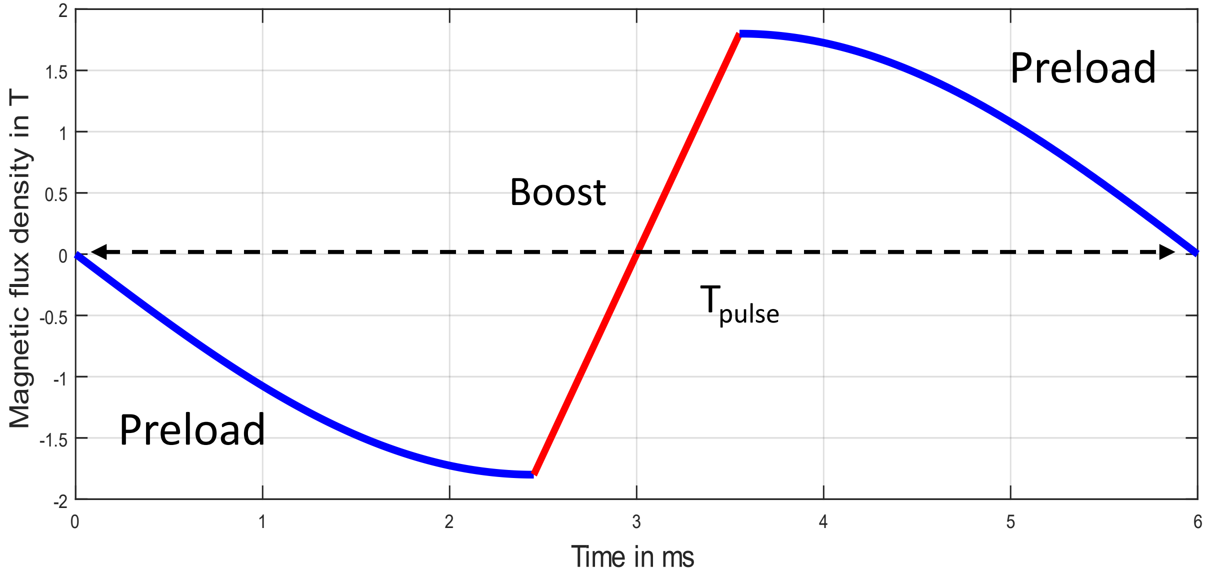
Introduction – Power Converters Class

Power converter cell

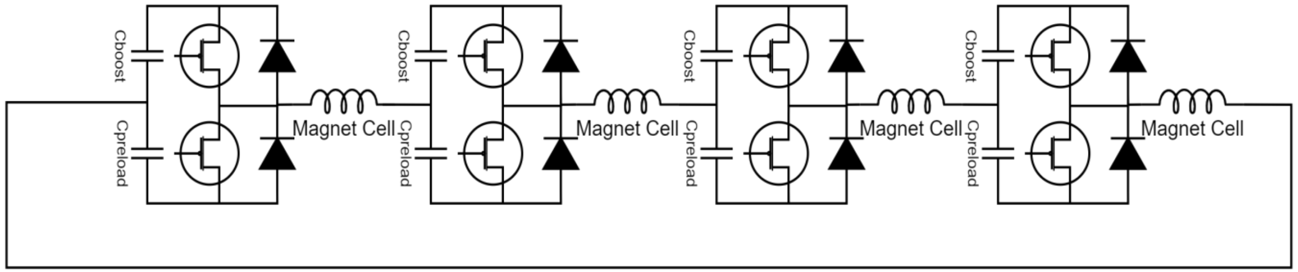


"One" IGBT/diode shown in the circuit diagram can hold several IGBTs/diodes connected in parallel and series.

Magnetic field reference

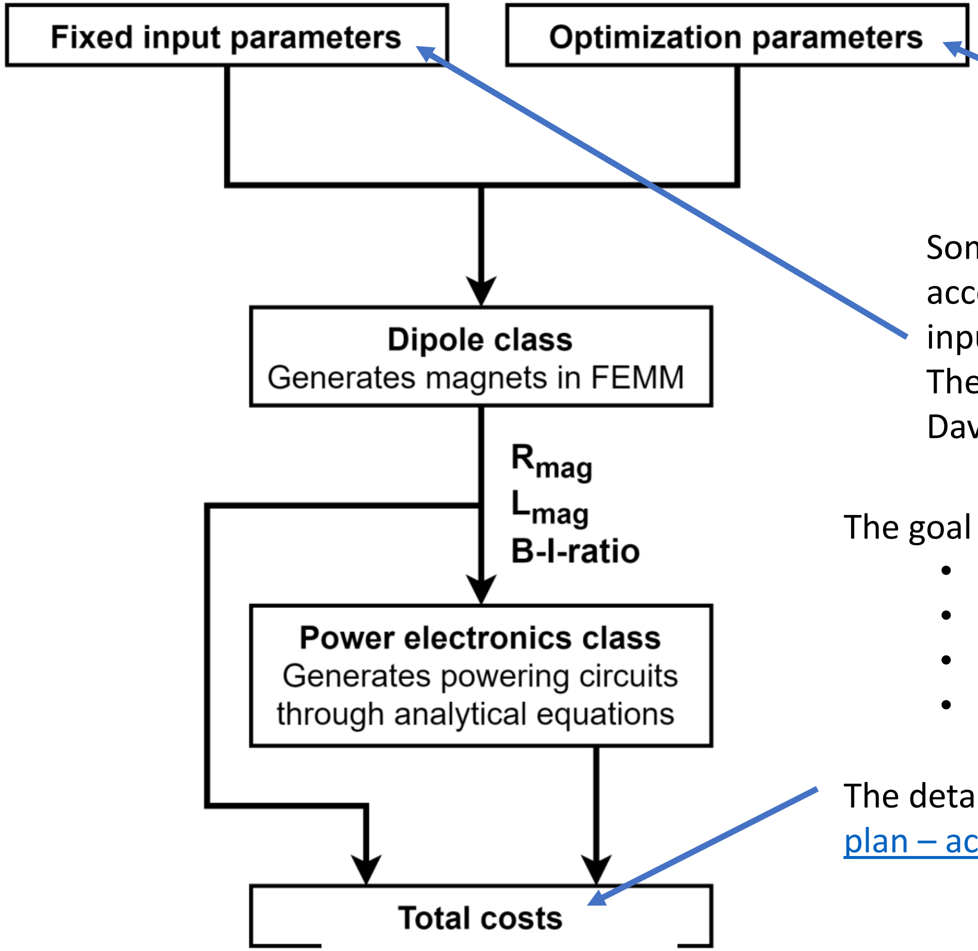


Connection of the magnets and the power cells



- The preload capacitor pre-charges the magnet to the injection field Binj.
- The boost capacitor generates the desired magnetic field ramp for the muons.
- Splitting the cell into two circuits allows more degrees of freedom, so that, for example, the pulse time Tpulse and the maximum magnetic field gradient Bdot,max can be varied.

Optimization Process in Python



COST MODEL

Some inputs of the Dipole and power converter classes are used as optimization variables. EX: B_max_yoke, B_ratio, pulse_time, height_gap_cond, angle_yoke, sigma_RMS_cycle

Some input parameters are fixed because they come from different systems or the overall accelerator design. To ensure a flexible optimization for varying accelerator designs, these input parameters come from the Python classes of the other systems.
The detailed explanation of the setup can be found in the presentation "Software tools" by David Amorim.

The goal of the optimization is minimizing the overall costs. The following costs are included:

- Magnet costs (material + manufacturing)
- Capacitor costs including containers
- Power electronics costs
- Operational costs (Losses in magnets and IGBTs, and energy needed for cooling of the coils) for 20 years of operation with 6000h per year

The detailed overview of the cost models is described in the presentation "Magnet and power systems plan – accelerators" by Fulvio Boattini.

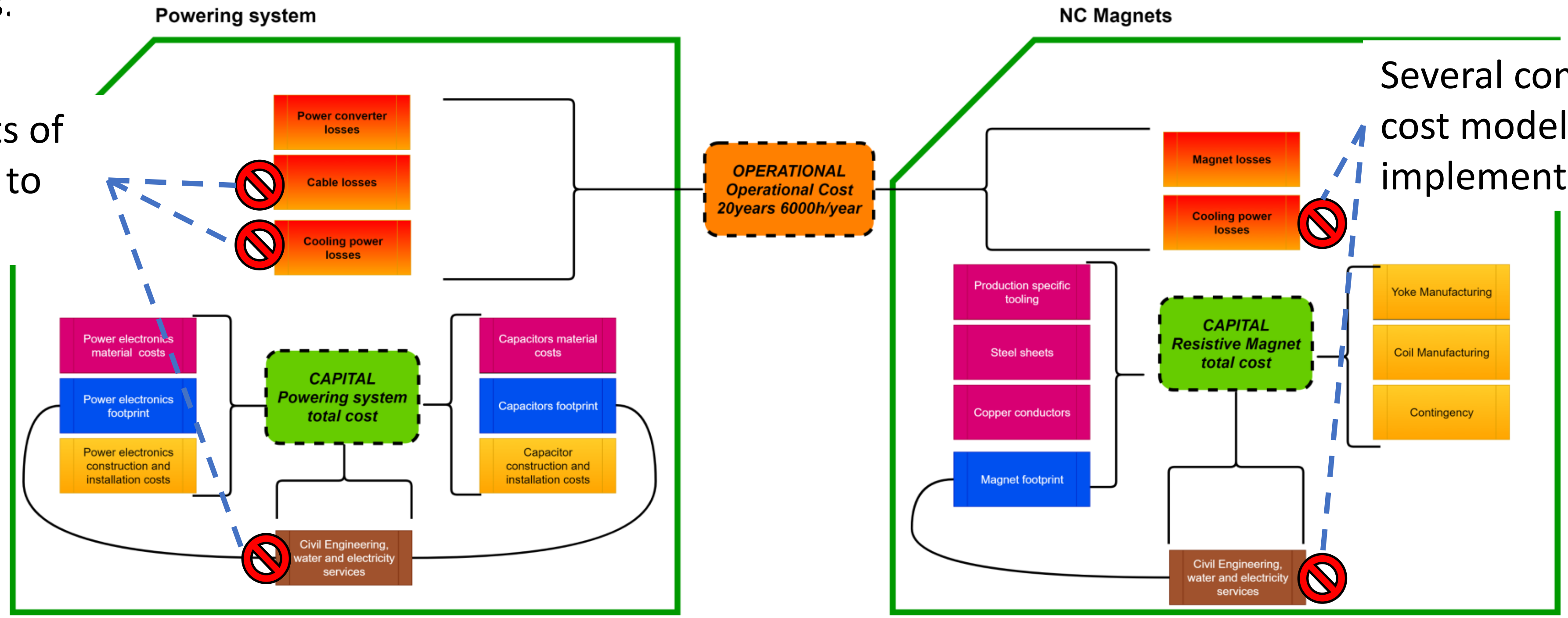
Cost model layout – Both classes

The cost model is based on the computation of capital and operational cost.
Capital costs includes:

- Material
- Construction
- Infrastructures.

Infrastructure costs are strongly dependent upon the location of the power converters (surface or tunnel). In the following computations we will consider installation on surface

Several components of the cost model still to be implemented



Several components of the cost model still to be implemented

Cost Models: NC Magnets. Bottom-up model
Capital costs

Much simpler model because of lack of expertise in magnet construction. Briefly discussed with magnet expert but requires verification.

The simplified cost approach is taken from "Basic design and engineering of normal-conducting, iron-dominated electromagnets" by Th. Zickler.

Cost figures are adapted for 3% of inflation over the last 14 years and the highest value of the range is taken.

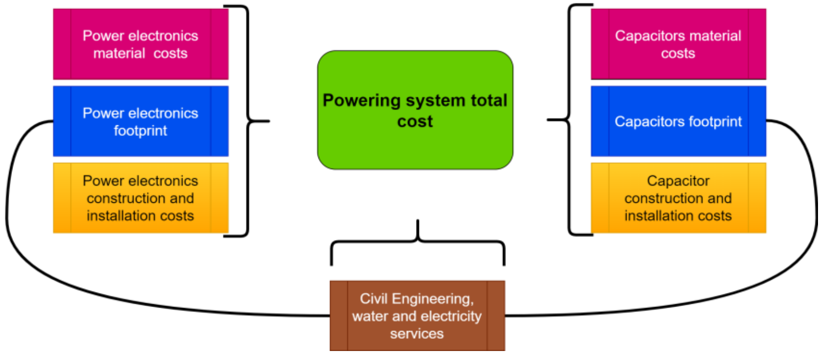
The material costs for Vacoflux 48 are estimated values in consultation with magnet experts.

Table 4: Cost indication for standard magnets (valid for 2010)

Item	Cost indication
Production-specific tooling	5000 – 15 000 €/tooling
Steel sheets	1.0 – 1.5 €/kg
Copper conductor	10 – 15 €/kg
Yoke manufacture:	
Dipoles (> 1000 kg)	6 – 10 €/kg
Quadrupoles, sextupoles (> 200 kg)	50 – 80 €/kg
Small magnets	up to 300 €/kg
Coil manufacture:	
Dipoles (> 200 kg)	30 – 50 €/kg
Quadrupoles, sextupoles (> 30 kg)	65 – 80 €/kg
Small magnets	up to 300 €/kg
Contingency	10 – 20%

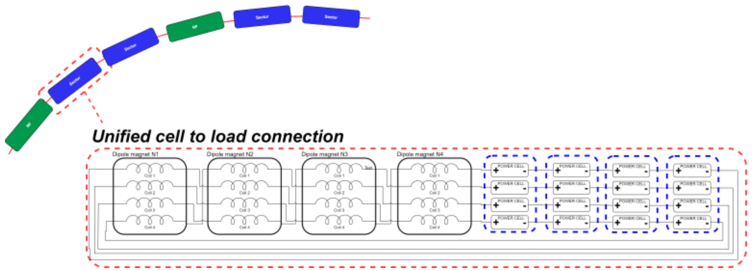
	Cost material [U/kg]	Cost manufacturing [U/kg]
Steel yoke	2.27	15.13
Vacoflux-48 yoke	50.00	15.13
Copper conductors	22.69	75.63

Cost Models: Power converters. Bottom-up model
Capital costs

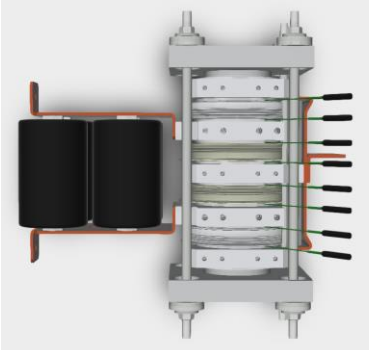


1 HP: installation on surface. *Unified cell to load connection*. One powering system per sector.

Identify Nseries/Nparallel power cells.

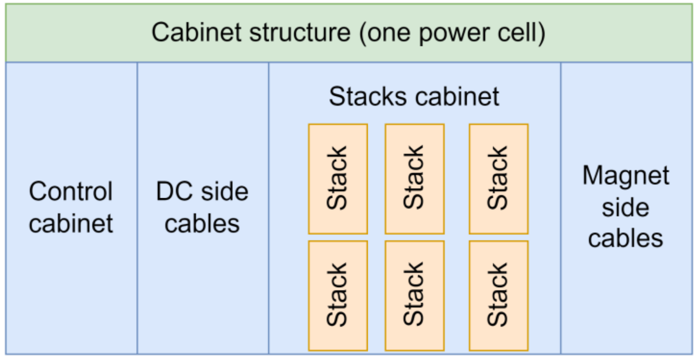


2 Compute the size and cost of IGBTs/Diodes and stacks.

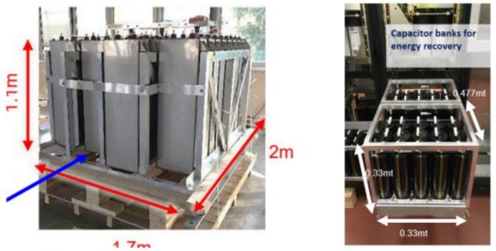


5 Identify size and cost of the technical building and capacitor containers

4 Identify size and cost of the power cell cabinet. Included fabrication costs



3 Compute the size and cost of Boost (left) and preload(right) capacitors.



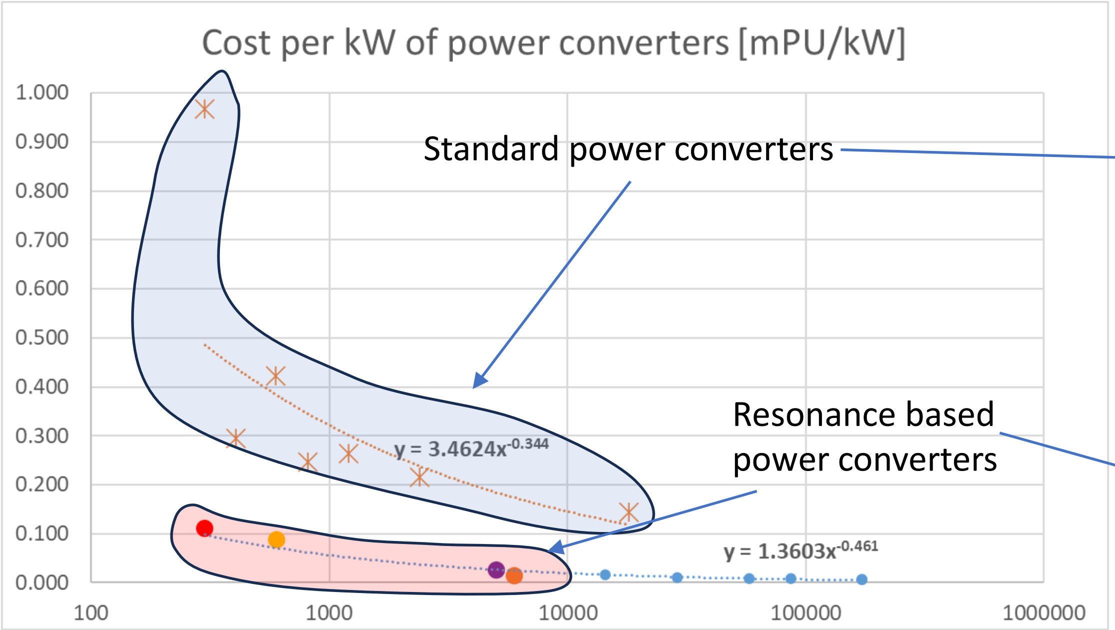
NRG: 900 kJ
Volume: 3700 lt → 4 lt/kJ
Weight: 3500 kg → 3.9 kg/kJ
Cost: 80'000 CHF → 89 CHF/kJ
Vmax ≈ 25kV

NRG: 35 kJ
Volume: 52 lt → 1.5 lt/kJ
Weight: 43 kg → 1.2 kg/kJ
Cost: 2'600 CHF → 74 CHF/kJ
Vmax ≈ 500V

Cost Models: Power converters. Bottom-up model

Capital costs… let's check them

Cost per kW seems quite low with respect to existing fast pulse converters→ let's compare with existing power converters of different power



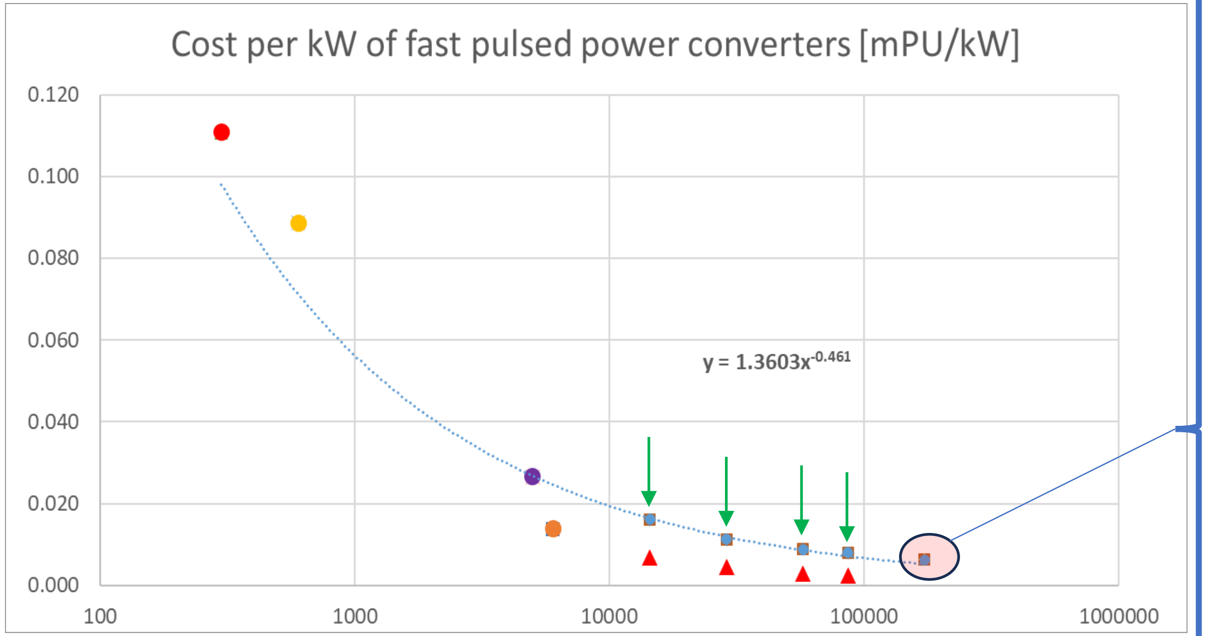
	V [V]	I [A]	P [kW]	Cost [mPU/kW]
Cycled Polaris 4P	188	1600	300.8	0.967
Cycled Sirius 2S	900	450	405	0.295
Cycled Saturn 2P	350	1700	595	0.422
Cycled Sirius 4P	450	1800	810	0.246
Cycled Boreal 2P	400	3000	1200	0.263
Cycled Boreal 2S2P	800	3000	2400	0.215

	V [V]	I [A]	P [kW]	Cost [nPU/kW]
Pulsed Maxiplus Single	600	500	300	0.111
Pulsed Maxiplus Double	600	1000	600	0.089
MegaDiscap	2500	2000	5000	0.027
FP 2P2S	2000	3000	6000	0.014

Cost computed with cost model is low but two effects are active:

1. Peak power: the higher the peak power the lower is the cost per kW (must consider same power converter category)
2. High numbers: Mucol will require high number of power cells

Cost Models: Power converters. Bottom-up model
Capital costs… let's check them

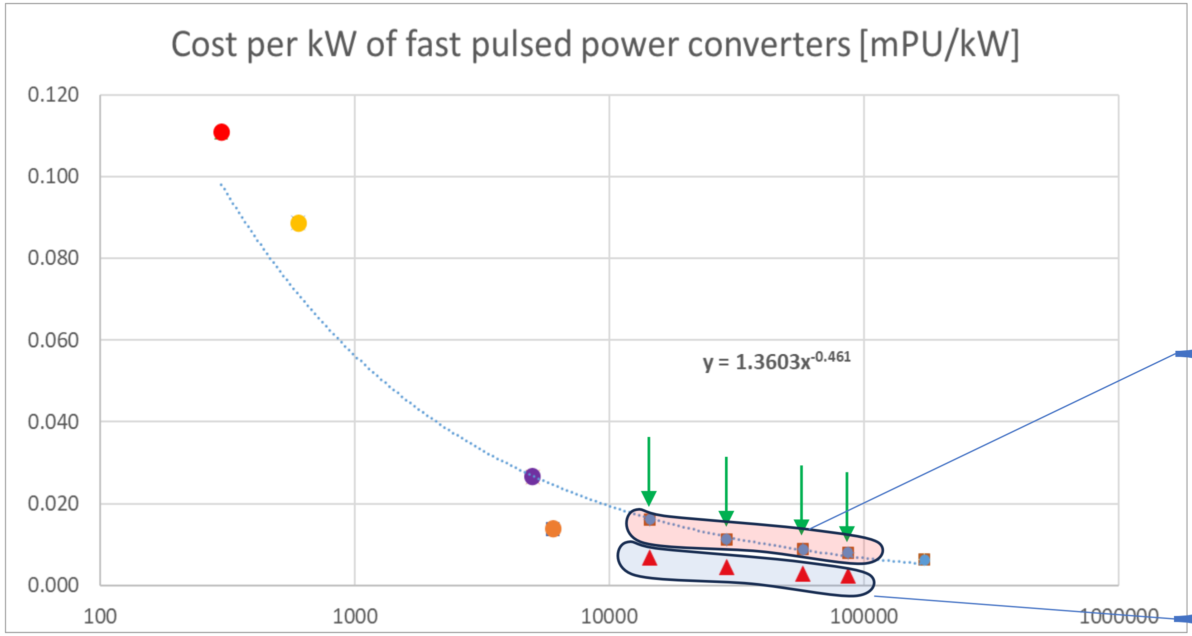


Consider the DCDC part of POPS as a set of power stacks with an equivalent LC discharge power.

	Standard POPS	low duty cycle LC discharge POPS
Peak Power	**18 MW**	**172 MW**
	Cost [pu]	Cost [pu]
Total	2.1971	1.0543
Cabinets POPSplus	0.2932	0.146587073
Copper busbars	0.0251	0.012564606
DC filtering capacitors	0.0439	0
DC commutation caps	0.0209	0.013960674
Precharge transformer	0.0249	0
Precharge resistors	0.0083	0
Precharge contactors LV	0.0033	0
Precharge Contactors MV	0.0083	0
Precharge lems	0.0017	0
Afe Line inductor	0.0299	0
RC snubber	0.0083	0
AFE/DCDC line LEMs	0.0108	0.007179775
IGBTstacks	0.5983	0.418820208
Diode stacks	0.2493	0.161544937
DCDC inductance	0.1496	0
AFE DC output switch (Motor)	0.0166	0
AFE DC output Switch (Manual)	0.0100	0
Ground Switch 3 poles (Manual)	0.0133	0.01329588
Hydraulic pipes, cable ladders…	0.0758	0.038697658
Assembly activities FSU	0.1609	0.102378273
Testing activities FSU	0.0293	0.014625468
Control	0.2493	0.124648871
Cooling unit	0.1662	0

Cost Models: Power converters. Bottom-up model
Capital costs… let's check them

From POPS estimation, we derive a new set of cost figures.



	V [V]	I [A]	P [kW]	Cost [mPU/kW]
Pulsed Maxiplus Single	600	500	300	0.111
Pulsed Maxiplus Double	600	1000	600	0.089
MegaDiscap	2500	2000	5000	0.027
FP 2P2S	2000	3000	6000	0.014
MUcol new Model Ex1	3000	4800	14400	0.016
MUcol new Model Ex2	3000	9600	28800	0.011
MUcol new Model Ex3	6000	9600	57600	0.009
MUcol new Model Ex4	6000	14400	86400	0.008
POPS as LC discharge	6000	28800	172800	0.006
MUcol old Model Ex1	3000	4800	14400	0.007
MUcol old Model Ex2	3000	9600	28800	0.004
MUcol old Model Ex3	6000	9600	57600	0.003
MUcol old Model Ex4	6000	14400	86400	0.003

A nice power curve seems to fit almost all real and computed vales.

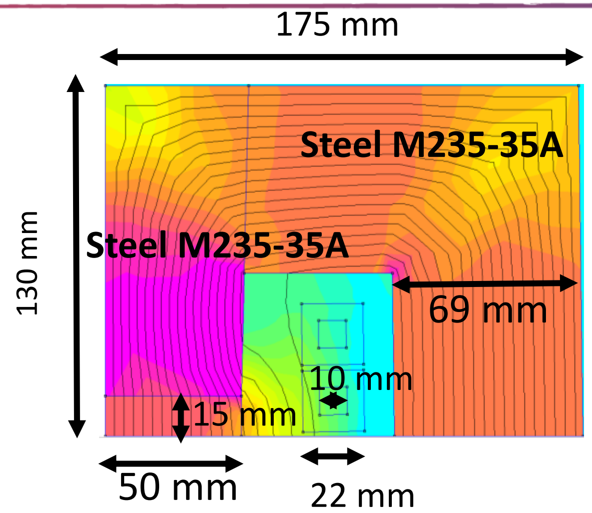
Cost estimation increased by a factor of 2-3.

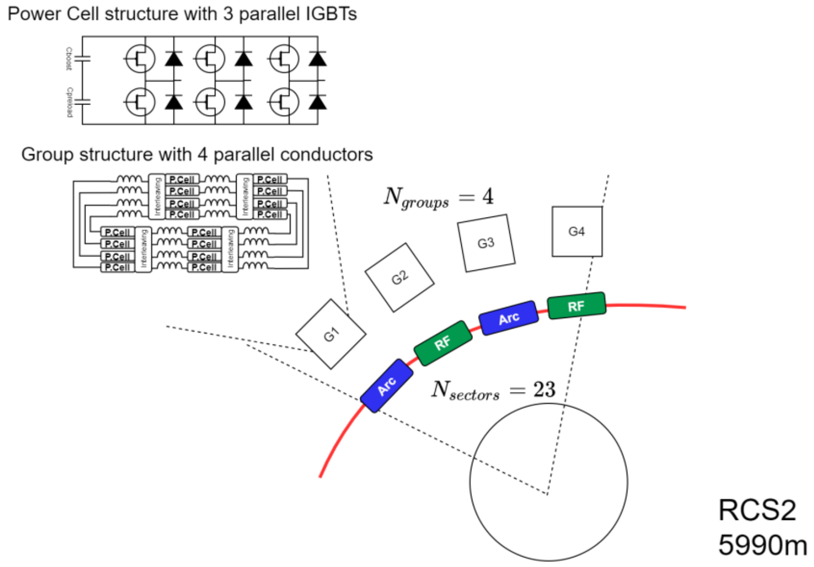
OPTIMIZATION RESULTS: RCS2

Optimization with the new cost model and dipole class

T_{pulse}= 6.6 ms
σ_{rms}= 4.4 A/mm2
mmf = 55860 At

$E_{lossIron}$= 55 J/m/pulse
E_{losscu}= 762 J/m/pulse
NRG_{stored}= 5687 J/m



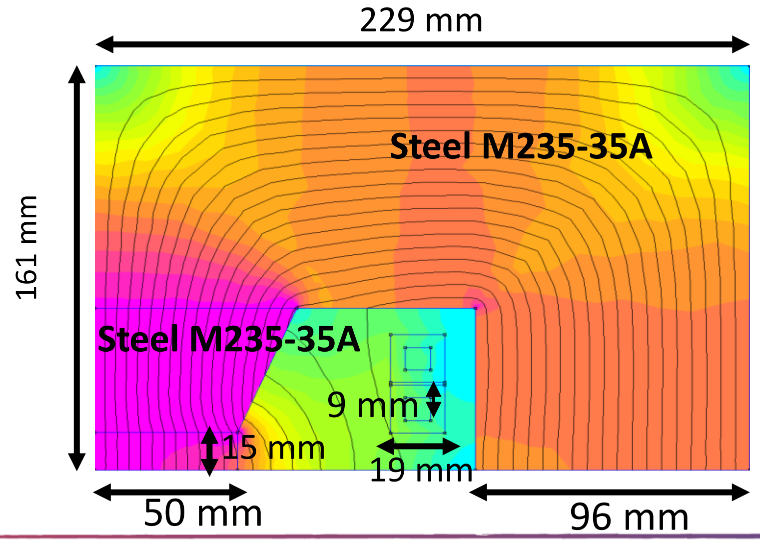


Optimization with the old cost model and class

T_{pulse}= 4.5 ms
σ_{rms}= 4.6 A/mm2
mmf= 48374 At

$E_{lossIron}$= 56.2 J/m/pulse
E_{losscu}= 424.9 J/m/pulse
NRG_{stored}= 6263 J/m

Presented here: IMCC Annual 2024



The Power Cell are more expensive with the new cost model; therefore the optimizer tries to reduce the energy in the magnet at the cost of higher losses

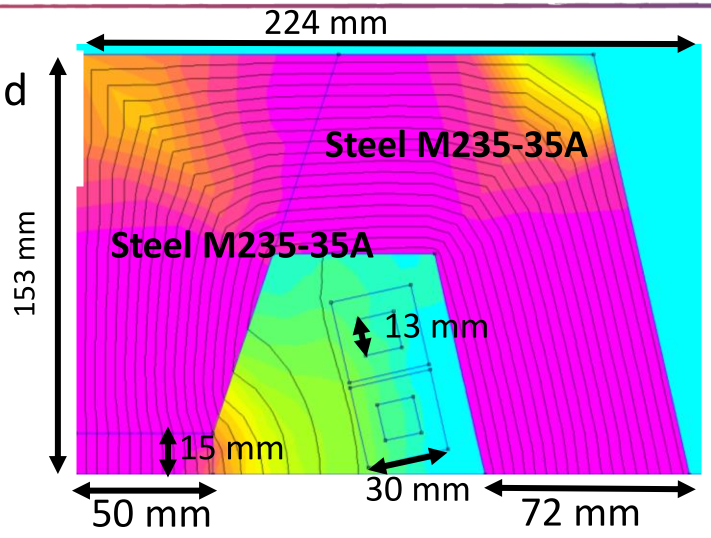
OPTIMIZATION RESULTS: RCS4

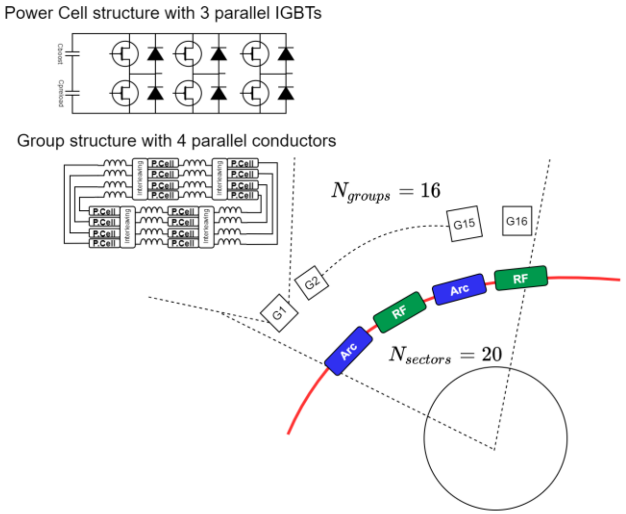
Optimization with the new cost model and dipole class

T_{pulse}= 11.0 ms
σ_{rms}= 3.3 A/mm2
mmf = 56562 At

$E_{lossIron}$= 69 J/m/pulse
E_{losscu}= 588 J/m/pulse
NRG_{stored}= 6393 J/m

$E_{lossMag}$= 2615 J/cell/pulse
$E_{lossIGBTs}$= 233 J/cell/pulse
N_{cells}=5120 → $E_{lossTot}$=14'581'760 J/pulse





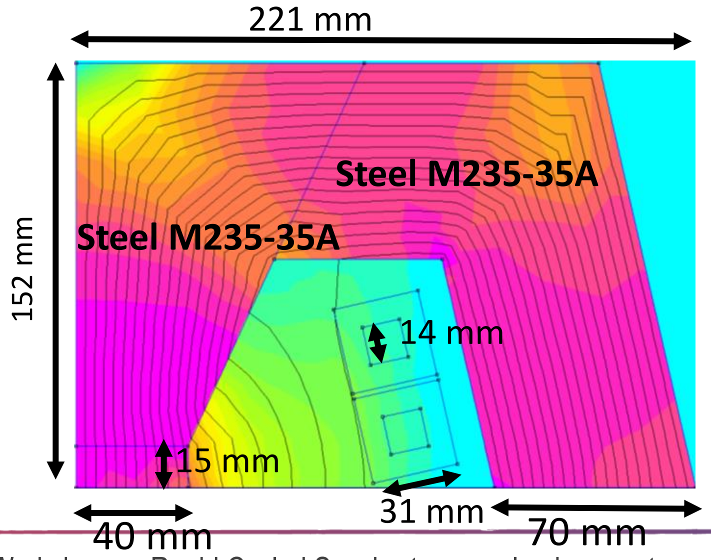
RCS4
20376m

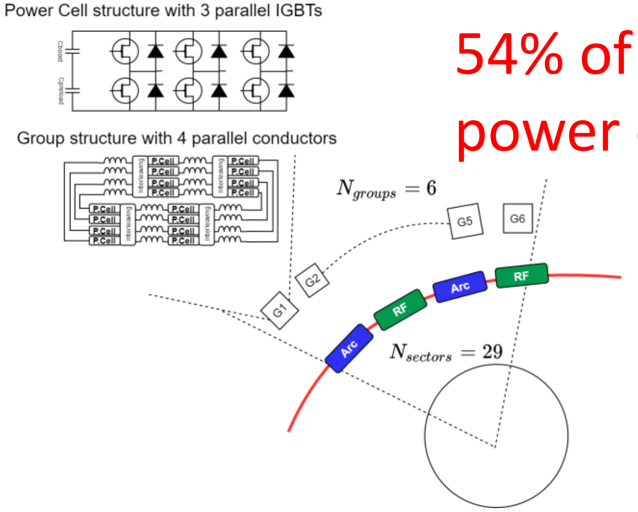
Optimization with the new cost model and class. Shorter gap 80mm x 30mm

T_{pulse}= 20.4 ms
σ_{rms}= 3.9 A/mm2
mmf= 52687 At

$E_{lossIron}$= 56.6 J/m/pulse
E_{losscu}= 736 J/m/pulse
NRG_{stored}= 5738 J/m

$E_{lossMag}$= 5903 J/cell/pulse
$E_{lossIGBTs}$= 347 J/cell/pulse
N_{cells}=2784 → $E_{lossTot}$=17'400'000 J/pulse





54% of the power cells

RCS4
20376m

Cost Computation

	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
NC mags Lm [km]	3.65	2.54	4.37	20.38
SC mags Lm [km]	0	1.11	2.36	4.26
Binj in gap [T]	0.36	−1.8	−1.8	−1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	100	100
Dipoles Gap h [mm]	30	30	30	30
Dipoles Egap@Bext [MJ]	14.1	9.8	16.9	78.8
Dipoles Etot@Bext [MJ]	21.2	14.7	25.3	118.2
Dipoles Pmax [GW]	121	54	43	74

Using the new cost model for the Power Converters, a new sets of simulations was re-run only for RCS2 and RCS4

	RCS2(new)	RCS2 (***)	RCS4(new)	RCS4 (***)	RCS4(smaller gap)
NC Magnets cost (*) [pu]	0.3%	0.4%	2.9%	4.2%	2.9%
SC Magnets cost [MEu]	4.0%	4.0%	15.5%	15.5%	< 15.5% (to be updated)
PC cost: power cells [MEu]	2.5%	1.3%	8.8%	7.4%	4.8%
PC cost: capacitors [MEu]	0.1%	0.1%	0.8%	1.3%	1.0%
Operation cost (losses NC+PC+Cool) (**) [MEu]	0.8%	0.5%	5.3%	3.4%	6.3%
Totals	***7.8%***	***6.3%***	***33.3%***	***31.9%***	***<30.5%***

Courtesy of Siara Fabbri and Luca Bottura

With the new cost model, values don't change much if we can accept more losses

(*) to be verified by magnets' experts

(**) 20years 6000h/year. Cable losses are not included

(***) Old cost model. Presented here: IMCC Annual 2024

Cost Computation

	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
NC mags Lm [km]	3.65	2.54	4.37	20.38
SC mags Lm [km]	0	1.11	2.36	4.26
Binj in gap [T]	0.36	−1.8	−1.8	−1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	100	100
Dipoles Gap h [mm]	30	30	30	30
Dipoles Egap@Bext [MJ]	14.1	9.8	16.9	78.8
Dipoles Etot@Bext [MJ]	21.2	14.7	25.3	118.2
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PC cost: power cells [MEu]	2.5%	1.3%	8.8%	7.4%	4.8%
PC cost: capacitors [MEu]	0.1%	0.1%	0.8%	1.3%	1.0%
Operation cost (losses NC+PC+Cool) (**) [MEu]	0.8%	0.5%	5.3%	3.4%	6.3%
Totals	***7.8%***	***6.3%***	***33.3%*** ***(Ncmag+PC 17.8%)***	***31.9%***	***<30.5%*** ***(Ncmag+PC 15%)***

Courtesy of Siara Fabbri and Luca Bottura

The effect of reducing gap width by 20% brings a reduction in cost of about 16% of the Ncmag + PC costs.

The reduction of SC magnets' cost is not included here.

(*) to be verified by magnets' experts

(**) 20years 6000h/year. Cable losses are not included

(***) Old cost model. Presented here: IMCC Annual 2024

Conclusions

- A more generic Dipole Class has been presented. With this we can extend the optimization to different shapes of magnets.
- The NC magnets cost model is a first test based on existing literature. No experts' eye verified it (carefully).
- A new more consolidate cost model for the power converters has been presented. A comprehensive cost comparison with several existing power converters, suggests that we should not use lower figures than the ones highlighted during this new analysis.
- We should not focus too much on magnets' losses. Other components like cables may change the perspective when included in the model.
- We shall include the full resonance mode power converter in the power converter class and have a correspondent cost model for this.
- A big chunk of the cost of the PE comes from the IGBT and stacks. We have so far considered only Press-pack type. We should probably enrich the cost model with module IGBTs power stacks that are cheaper (but also less reliable).
- Civil/ electric/ cooling engineering costs should be included, both for the capital part and for the losses operation costs (cables)
- A lot of uncertainty still exist on the "cahier de charge" of the Power Converters, particularly concerning the accuracy that is required to the control. This can greatly influence the topology and cost of the pc. More precise data should be provided.

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