Muon magnet working group meeting

Recent progress on the models of power converters and resistive magnets

CERN, 15/02/2024

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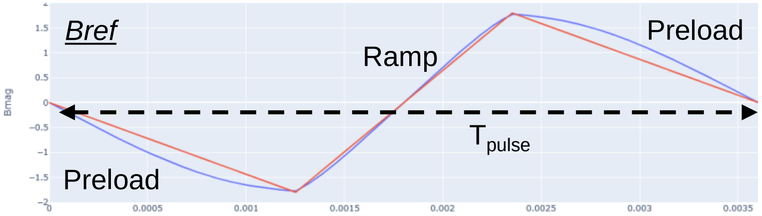
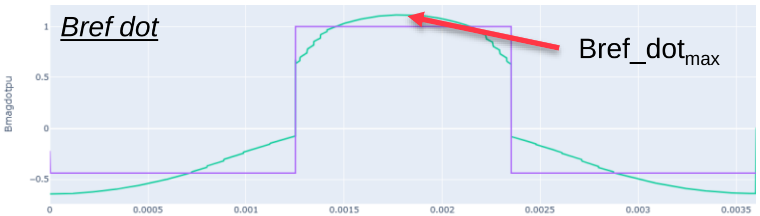
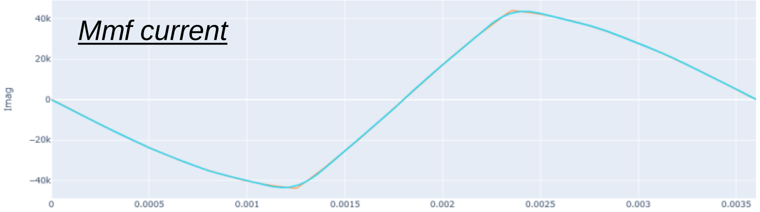
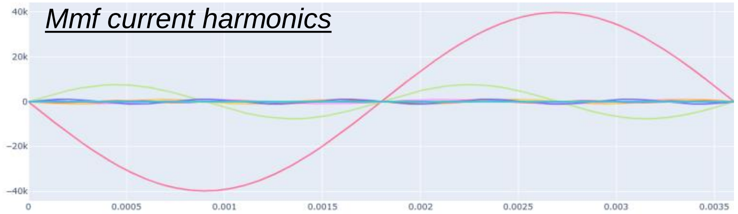
Funded by the European Union under
Grant Agreement n.101094300

Setting the stage: some important definitions









The Bref is created by the connection of two different sinusoids named here Preload and Ramp. The power electronic does that.

- Playing with the Preload circuit Tpulse can be varied;
- Playing with the Boost circuit, Bref_dot max can be changed;

Short T_{pulse} requires high power in the converter

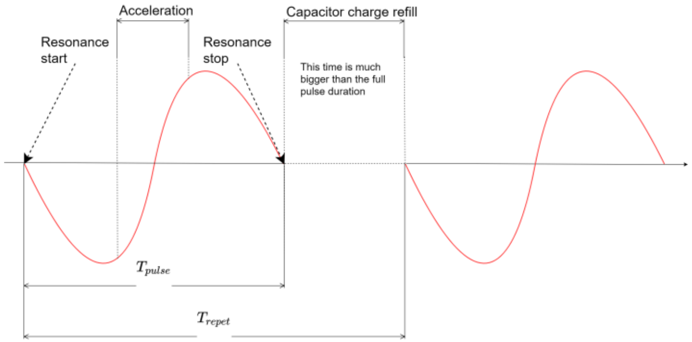
The first harmonic of the magnet current has a frequency of $1/T_{pulse}$
The next most important harmonic is the second.

The magnet losses reported in this presentation are computed with AC simulation with the first harmonic only

Transient simulation necessary to simulate proper losses

Setting the stage: some important definitions

Losses are calculated by considering the energy lost per cycle and per meter or the average power losses



$$E_{loss} = P_{ac} \cdot T_{pulse}$$

$$P_{loss} = P_{ac} \cdot \frac{T_{pulse}}{T_{repet}}$$

Copper conductors:

P_{ac} decreases less than linearly with T_{pulse}

E_{loss} increases linearly with T_{pulse}

Iron:

P_{ac} decreases more than linearly with T_{pulse}

E_{loss} increases linearly with T_{pulse}

Magnetic dimension of the magnet

Conductor current density used for magnet design is defined as σ_{pulse} this relates to the σ_{rms}:

$$\sigma_{pulse} = \sigma_{rms} \cdot \sqrt{\frac{T_{repet}}{T_{pulse}}}$$

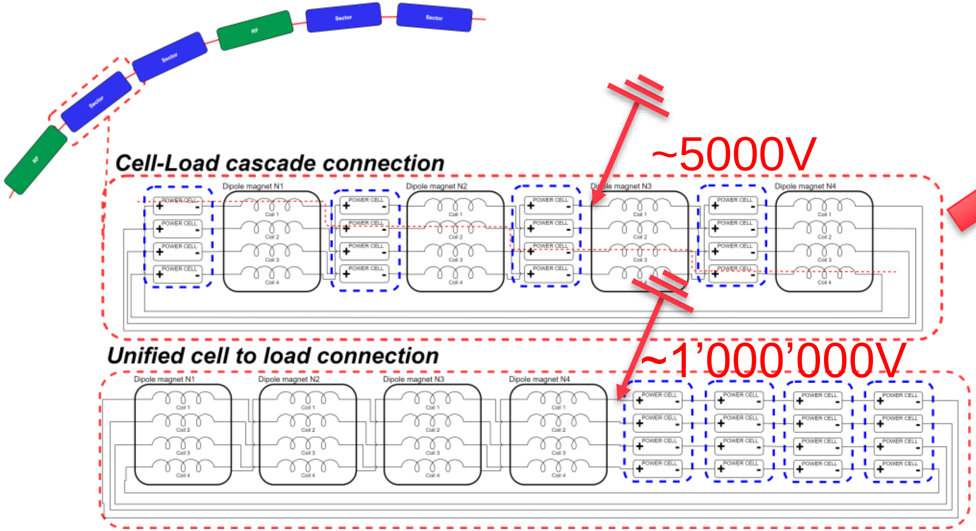
Water cooled conductors: $\sigma_{rms} = 5\,{}^{A}/_{mm^2}$; T_{pulse} = 5ms and T_{repet} = 200ms → $\sigma_{pulse} = 31.6\,{}^{A}/_{mm^2}$

Air cooled conductors: $\sigma_{rms} = 2\,{}^{A}/_{mm^2}$; T_{pulse} = 5ms and T_{repet} = 200ms → $\sigma_{pulse} = 12.6\,{}^{A}/_{mm^2}$

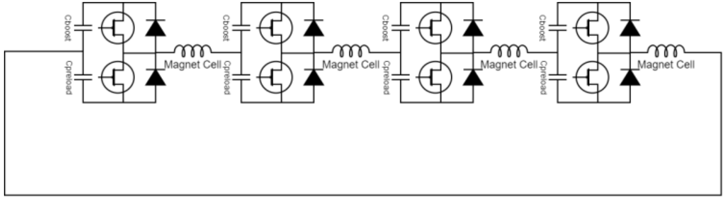
Setting the stage: Power Converters – magnets connection

Cell-load connection (SPS): the voltage to ground is limited by the PC voltage → can connect all mags of the accelerator in one single sector → current will be the same everywhere

Unified cell connection (LHC): the voltage to ground is the sum of series connected PC → must divide in several sectors → current will not be the same everywhere (control problem is harder)



Should be distributed into the tunnel to minimize cabling (and cable losses)

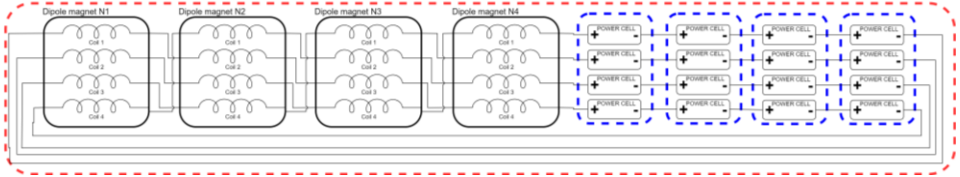


…an MMC but at much higher frequency!

Interleaving connection makes the impedances of each circuit the same. We can treat the single circuit as if the same current was flowing and the same voltage applied (ideal case). We could treat FEM computation as current controlled in each circuit.

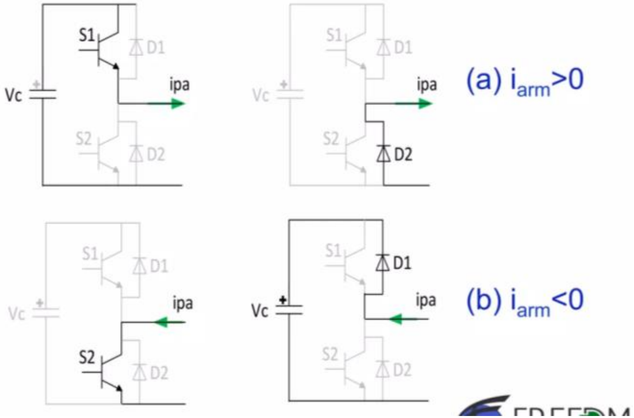
MMC: a similar topology for a different application

Unified cell to load connection



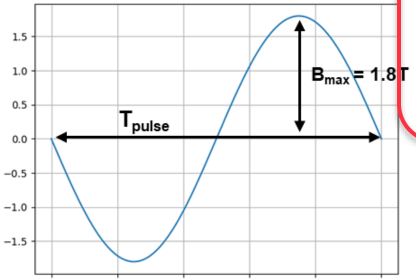
640 kVdc
2 GW
Hundreds of connected cells

Basic cell:

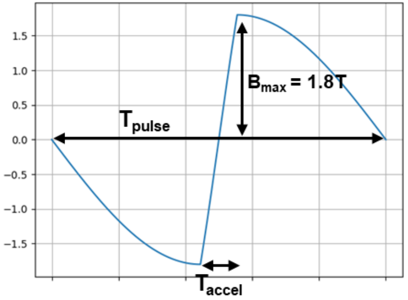


Optimization of power converters and dipole magnets

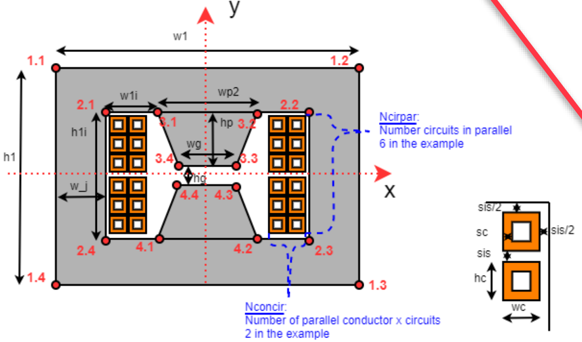
Magnetic field in magnet



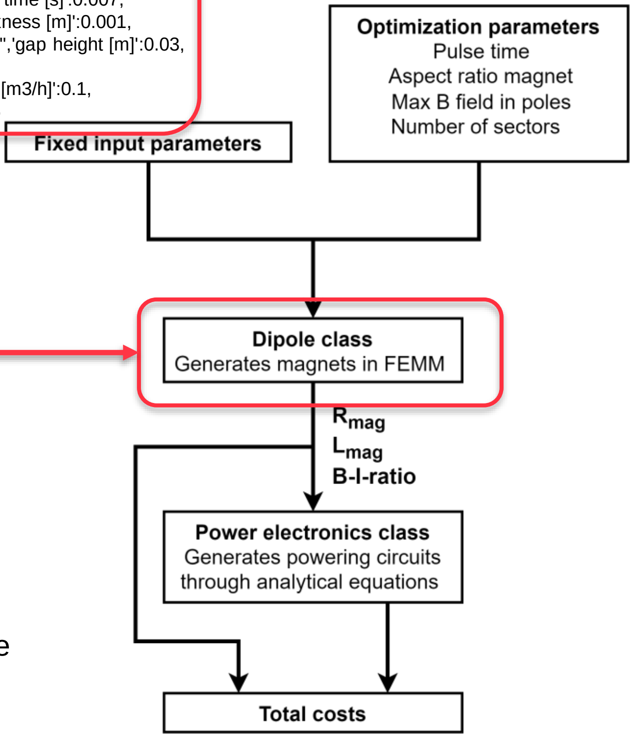
Magnetic field produced by PE



```
base_input_parameters={'Maximum B field in air[T]': 1.8,'Maximum B field in joke[T]': 1.4,
                       'B field ratio in poles[Bp/Bg]':0.6 ,'Total length of normal conducting dipoles [m]':2540,
                       'Number of sectors for powering': 48,'Number of parallel circuits': 8,
                       'Acceleration ramping time [s]':0.0011, 'Pulse cycling time [s]':0.2,'Pulse duration time [s]':0.007,
                       'RMS current density [A/mm2]':5,'Conductor thickness [m]':0.003,'Insulation thickness [m]':0.001,
                       'Joke steel type':"steel_M235_35A.json",'Poles steel type':"steel_M235_35A.json",'gap height [m]':0.03,
                       'gap width [m]':0.1,'Aspect ratio of conductor hc/wc':1,
                       'Aspect ratio of the conductor window h1i/w1i':3,'Cooling water flow in conductor [m3/h]':0.1,
                       'Cooling water speed in conductor [m/s]':3,'Filling factor of conductor window':0.5
```



All based on FEMM computing…very slow



Optimization parameters
Pulse time
Aspect ratio magnet
Max B field in poles
Number of sectors

Fixed input parameters

Dipole class
Generates magnets in FEMM

R_{mag}
L_{mag}
B-I-ratio

Power electronics class
Generates powering circuits through analytical equations

Total costs

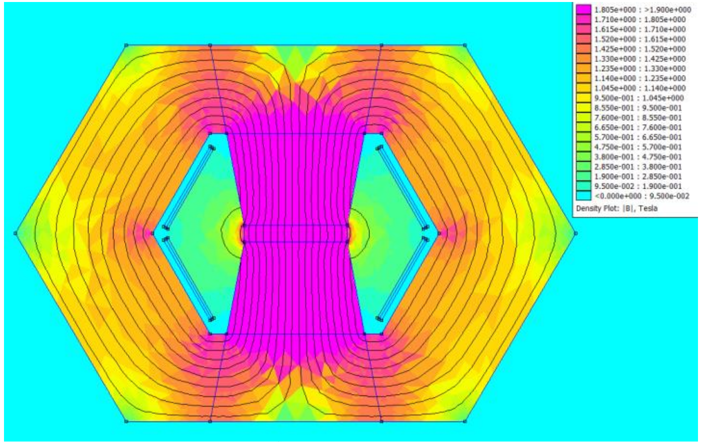
The ultimate goal of the optimization is minimizing the overall costs. The following costs are included:

- Magnet costs (material + manufacturing)
- Capacitor costs including containers
- Power electronics cost including peripherals and building (no cables)
- Operational costs (Losses in magnets and IGBTs) for 20 years of operation with 6000h per year

Optimization: minimize the losses of magnets only

Benchmark: Hourglass type with 30x100mm gap

Here T_{pulse} = 2 ms



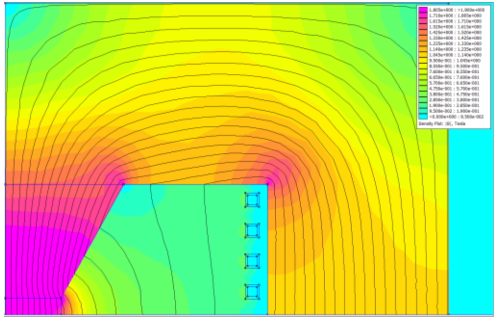
h1=570 mm
w1=850 mm
wj= 163mm
hc=140 mm
sc= 2x3.5 mm
sis=10 mm
T_{pulse}= 2 ms
σ_{rms}= 2.7 A
mmf= 53000 At
$E_{lossIron}$= 153 J/m/pulse
E_{losscu}= 91 J/m/pulse
NRG_{stored}= 7084 J/m

We can have two dipole topologies:

1) Air cooled with flat conductors
2) Water cooled with hollow conductors

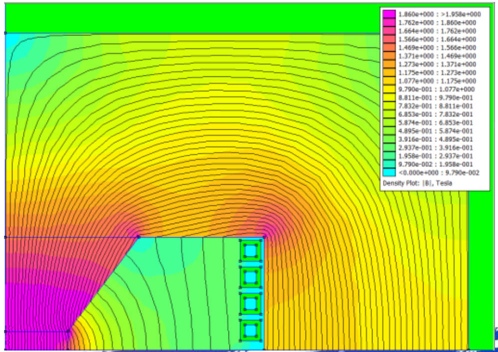
Optimization Losses only: Bratio_pole, AsRatwdw

h1=560 mm
w1=800 mm
wj= 163mm
hc=12.5 mm
sc= 2 mm
sis=15 mm
T_{pulse}= 2 ms
σ_{rms}= 7 A
mmf= 47270 At
$E_{lossIron}$= 160 J/m/pulse
E_{losscu}= 196 J/m/pulse
NRG_{stored}= 7654 J/m



Optimization Losses only: sc, sis, water cooling section

h1=500 mm
w1=738 mm
wj= 163mm
hc=16.5 mm
sc= 3.8 mm
sis=4.8 mm
T_{pulse}= 2 ms
σ_{rms}= 3 A
mmf= 46115 At
$E_{lossIron}$= 136 J/m/pulse
E_{losscu}= 161 J/m/pulse
NRG_{stored}= 7577 J/m

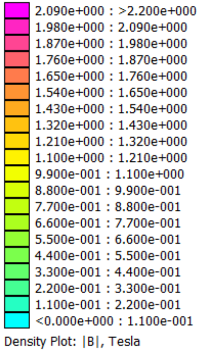


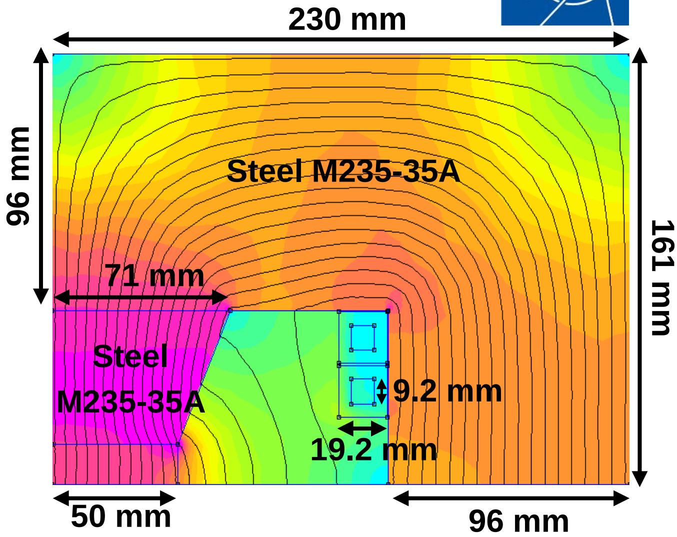
Optimization: minimize the total cost of Magnets and power converters

MUON Collider Collaboration MuCol

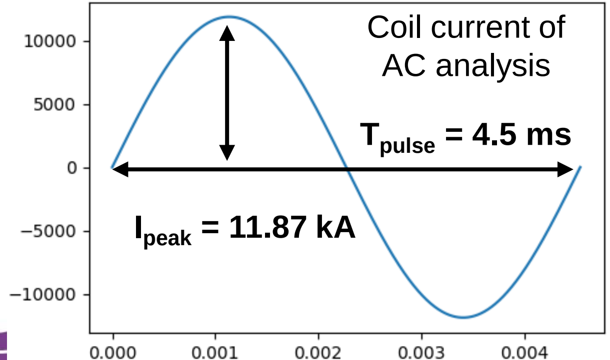
Steel: M235-35A everywhere

External dimensions [mm x mm]	460 x 322
Joke cross section [dm^2]	11.35
Pole cross section [dm^2]	1.21
Coil cross section [mm^2]	285.39
Number of parallel coils	4
Bgap [T]	1.80
Gap size [mm x mm]	100 x 30
MMF [kAt]	47.49
Sigma_RMS (pulse) [A / mm^2]	29.41
Sigma_RMS (cycle) [A / mm^2]	4.41
Iron losses (joke) [J / (cycle * m)]	48.29
Iron losses (pole) [J / (cycle * m)]	10.22
Coil losses [J / (cycle * m)]	447.47
Total losses [J / (cycle * m)]	505.98
Energy (total) [J / m]	6386.12
Energy (gap) [J / m]	3830.48





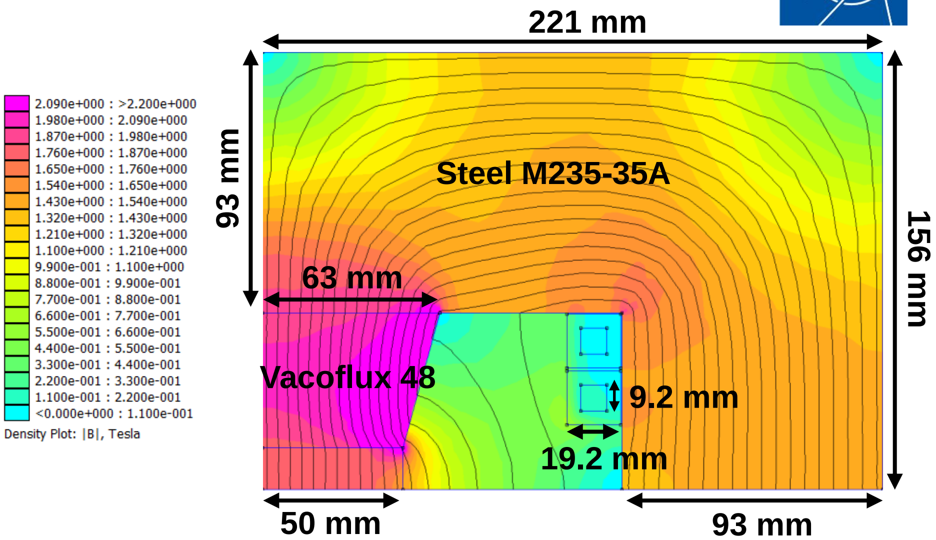
Here T_{pulse} = 4.5 ms



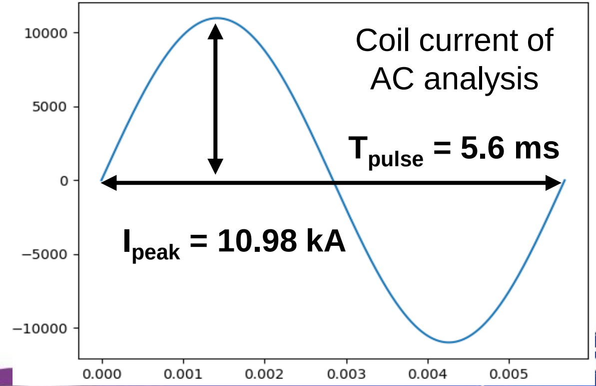
Optimization: minimize the total cost of Magnets and power converters

Steel: M235-35A for the joke, Vacoflux 48 for the Poles

External dimensions [mm x mm]	442 x 312
Joke cross section [dm^2]	10.55
Pole cross section [dm^2]	1.09
Coil cross section [mm^2]	285.39
Number of parallel coils	4
Bgap [T]	1.78
Gap size [mm x mm]	100 x 30
MMF [kAt]	43.92
Sigma_RMS (pulse) [A / mm^2]	27.20
Sigma_RMS (cycle) [A / mm^2]	4.59
Iron losses (joke) [J / (cycle * m)]	38.12
Iron losses (pole) [J / (cycle * m)]	8.70
Coil losses [J / (cycle * m)]	434.89
Total losses [J / (cycle * m)]	481.71
Energy (total) [J / m]	5773.80
Energy (gap) [J / m]	3702.65



Here T_{pulse} = 5.6 ms



Comparisons

Recomputed to T_{pulse}=5 ms

	Hollow conductors water cooled		**Flat conductors air cooled**
	Optimization for loss in magnets	Optimization for overall cost in Power Converters + Magnets	Flat conductors Hourglass. Not optimized
Total losses [J/m/pulse]	381	506	230
Total NRG [J/m] (DC equivalent)	7577	6386	7084
Outer Dimensions wxh [mm]	738 x 500	442 x 312	850 x 163
T_{pulse} [ms]	5	~ 5	5

Lower losses and higher NRG and dimensions

Higher losses and lower NRG and dimensions

A good compromise?

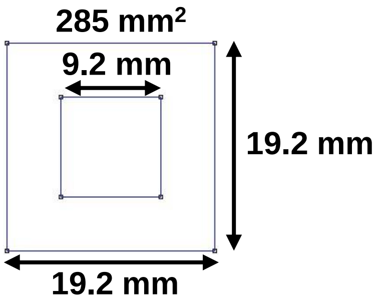
Source: http://dx.doi.org/10.1051/e3sconf/20171302008

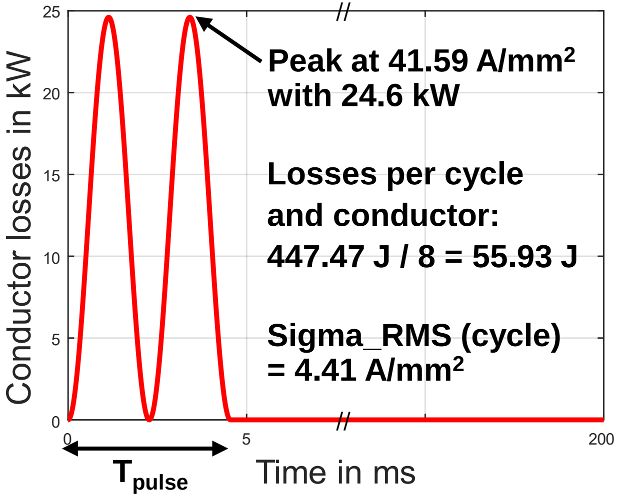
Cooling of hollow conductors

One meter of a single conductor of the full steel H-type magnet is considered

Assumptions:

- Coil losses are equally distributed.
- Flow speed of water is 3 m/s.
- Only heat transfer from copper to water is considered.
- Cooling water stays at a steady temperature. Therefore, the temperature of the conductor doesn’t change along its length.



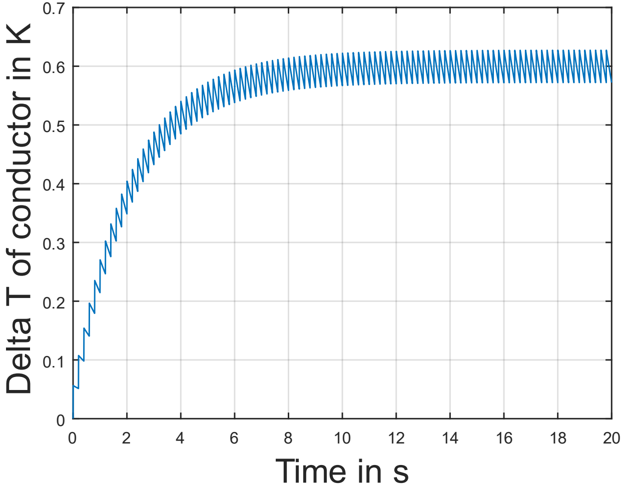


Peak at 41.59 A/mm^2 with 24.6 kW

Losses per cycle and conductor: 447.47 J / 8 = 55.93 J

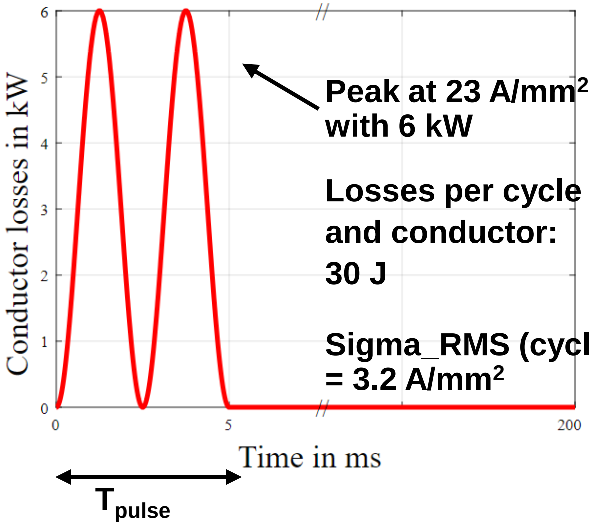
Sigma_RMS (cycle) = 4.41 A/mm^2

100 powering cycles simulated



Cooling of bulk conductors

Values taken from Fulvio’s simulation of bulk conductors for 20kA peak per conductor and a frequency of 200 Hz. Pulse time is comparable to hollow conductor optimization.



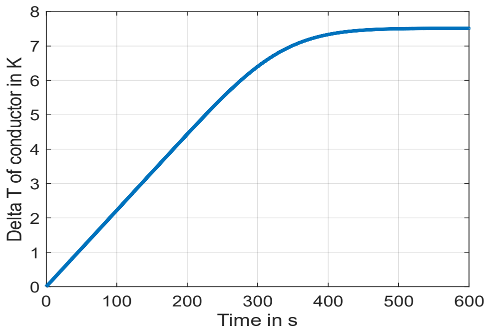
Peak at 23 A/mm^2 with 6 kW

Losses per cycle and conductor: 30 J

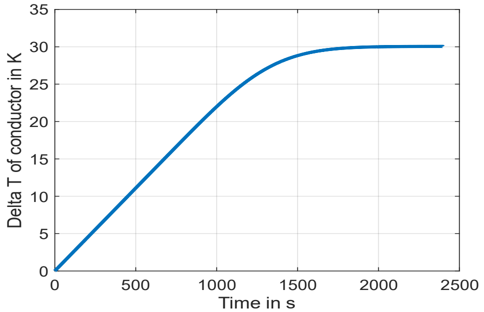
Sigma_RMS (cycle) = 3.2 A/mm^2

What is the accepted Max T?

Conductor length of 2m

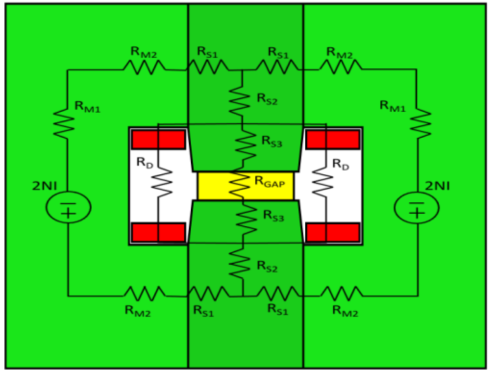


Conductor length of 4m

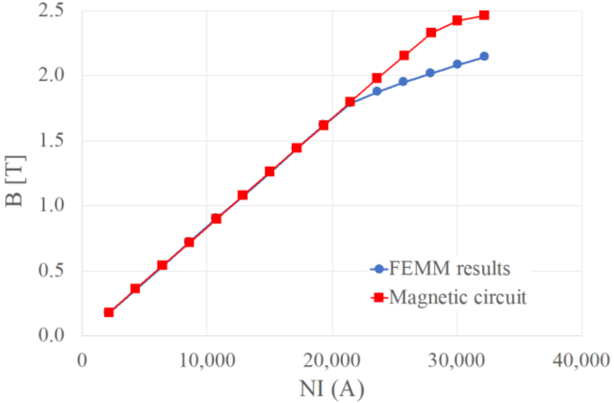


Analytical model for optimization speed-up

Combined optimizations required about 12 hours to converge. With UNIBO, we are developing analytical models to replace lengthy FEM computation in the optimization process



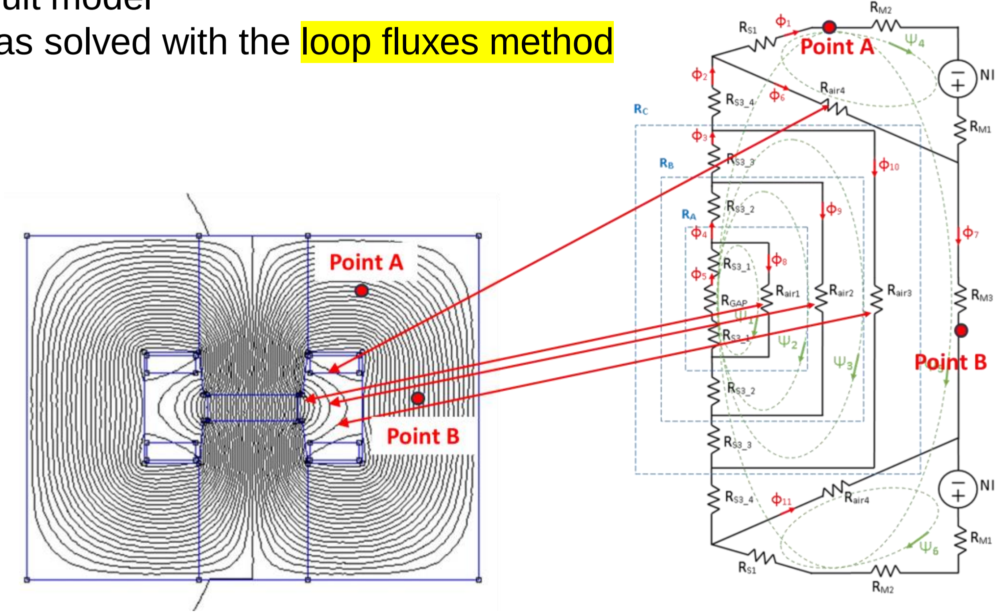
- The model includes lumped reluctances which describe the various parts of the magnet
- The non-linear reluctances depend on the value of the magnetic flux density: R (B) = l / m (B) S

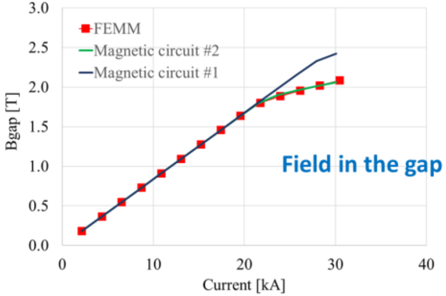


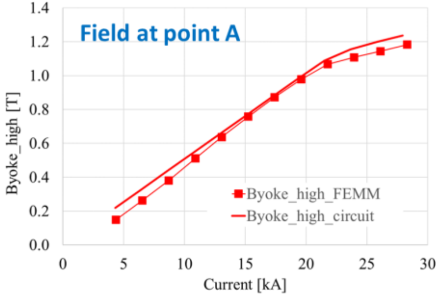
- The results of the FEMM model and of the equivalent non-linear magnetic circuit are in very good agreement before saturation
- A discrepancy between the two models is observed above saturation
- Improvements of the magnetic circuit were implemented to reduce this discrepancy

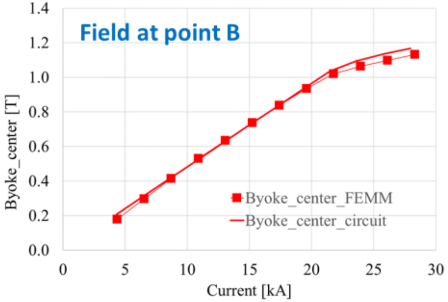
Analytical model for optimization speed-up

- The possibility for flux lines to pass through the air outside the gap was considered with 4 additional reluctances in a more complex non-linear magnetic circuit model
- The model was solved with the loop fluxes method





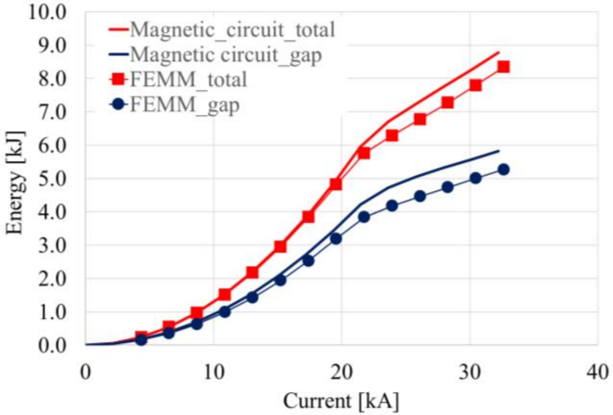




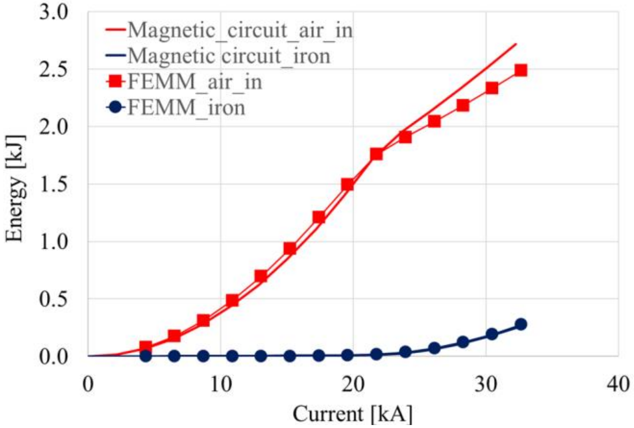
- The novel circuit allows one to correctly compute the field in the gap at saturation
- The field in other locations of the magnetic circuit is also computed with acceptable accuracy

Analytical model for optimization speed-up

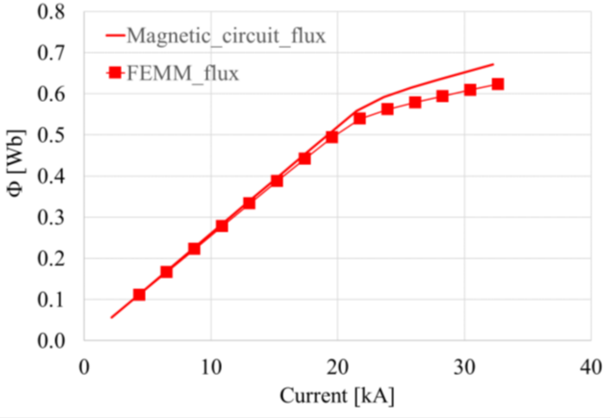
Total energy and gap energy: FEMM vs magnetic circuit



Energy in the air outside the gap and energy in the iron



Linked flux: FEMM vs magnetic circuit



The development of a magnetic circuit model of the resistive magnet is proceeding, with significant improvements in the calculation of magnetic field, magnetic energy and flux linked to the circuit

Further developments are foreseen to include in the model the analytical formulae for the iron and copper losses and for a simplified description of the cooling system

Now… Fasten your seat-belts We try with a cost model.

Please consider:

1) This is a first attempt. Future trials could lead to different values as the model progresses and include additional costs (like the cabling and the installation / testing FTE for example that are presently not included)
2) For the magnet, we discussed with an expert and applied the model that he suggested from this paper:[“Basic design and engineering of normal-conducting, iron-dominated electromagnets”] by Th. Zickler. The reliability of the calculations presented below, is quite low, because they have not been verified by a magnet expert.
3) The Power Converter cost model is a bottom up approach based on experience with power converters for large systems (POPS-POPSB). We intend to verify it with similar ones developed for the FCC.

Dipole magnet cost model

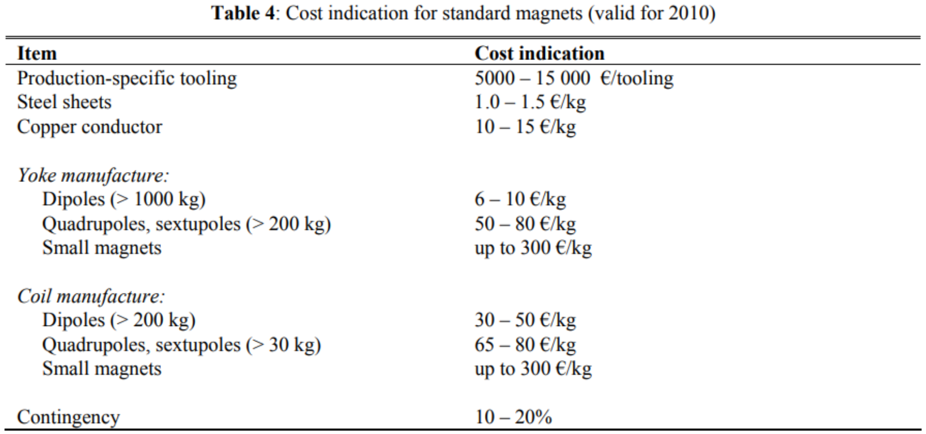


Table 4: Cost indication for standard magnets (valid for 2010)

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%

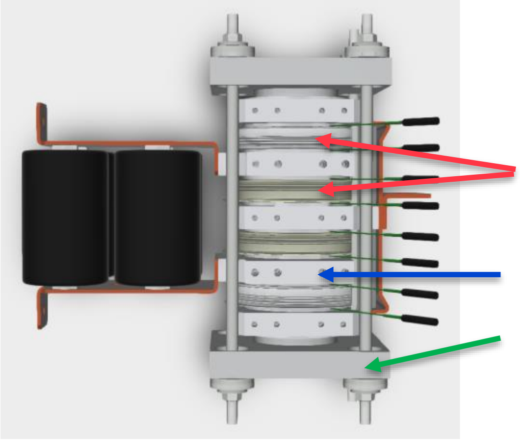
The simplified cost approach is taken from “Basic design and engineering of normal-conducting, iron-dominated electromagnets” by Th. Zickler.

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.

	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

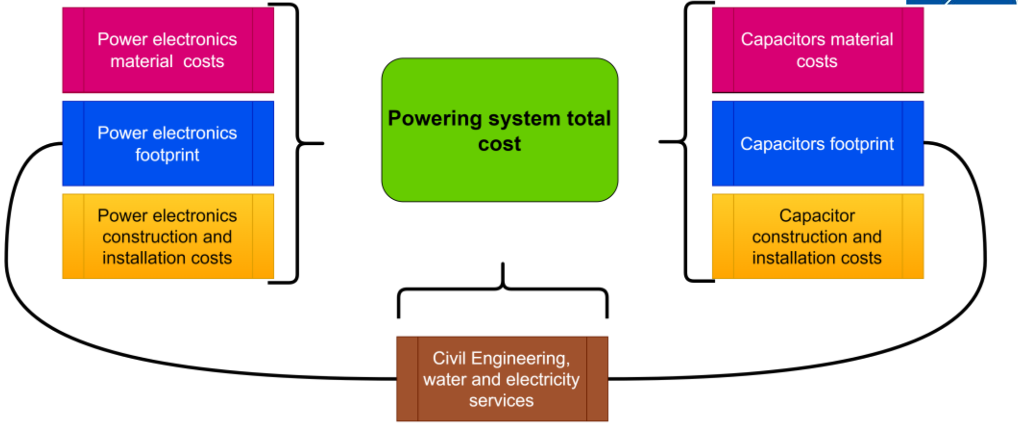
PE cost model



IGBTs\diodes

Cooling plates

Stack mechanics



Power electronics material costs

Power electronics footprint

Power electronics construction and installation costs

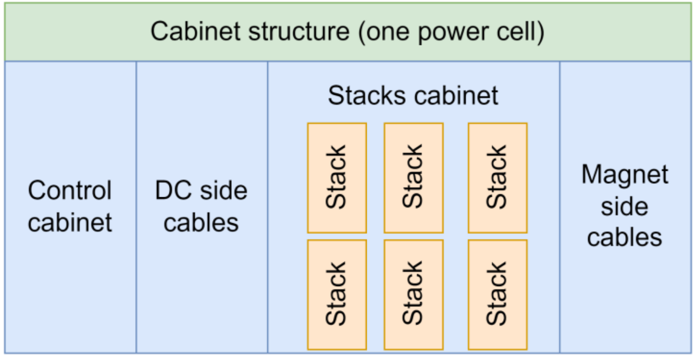
Powering system total cost

Capacitors material costs

Capacitors footprint

Capacitor construction and installation costs

Civil Engineering, water and electricity services



Cabinet structure (one power cell)

Control cabinet

DC side cables

Stacks cabinet

Stack

Stack

Stack

Stack

Stack

Stack

Magnet side cables

PE cost model consists of:

- Capacitors + storing containers
- IGBTs\diodes + cooling plates + mechanics for stack
- Cabinets (space for cables, stacks and control)
- Control
- Buildings
- No cables included yet

PE cost model is a bottom-up model including discrete modelling of the IGBTs\diodes and the stacks. (A dictionary with different press-pack IGBTs is used as an input)

Results cost optimization

Costs are calculated for RCS2 which consists of 2540m of normal conducting dipole magnets.

	H-type (full steel)	H-type (Vacoflux + steel)
Costs pole [pu]	0.012	0.042
Costs joke [pu]	0.111	0.103
Costs conductors [pu]	0.019	0.019
Total magnet costs [pu]	0.142	0.164
Costs capacitors [pu]	0.050	0.047
Costs power electronics[1] [pu]	0.611	0.567
Cost losses magnets[2] [pu]	0.151	0.150
Cost losses PE[2] [pu]	0.041	0.043
Total costs [pu]	0.995	0.971

[1] Due to the discrete IGBT model in the overall cost model the costs are slightly overestimated and probably can be reduced by 30% to 40%.

[2] Operational costs are considered only for the losses in the IGBTs and the magnet (no cables). The assumption is 20 years of operation with 6000h per year and costs of 90 U/MWh.

Conclusions

- Optimal dipole: we have just scratched the surface. More optimization exercises are required. Dipole class is too slow. Analytical models from UNIBO will help speeding it up; A quick computation of conductor losses could come from integral of the energy in the conductor (UNILAVAL). Can we implement this analytically?

- Resistance and Inductance modeling: We assumed sinusoidal excitation. It is an approximation. We need transient approach to input the real current shape;

- Cost model: Basic implementation is done. Cables should be included but how? Is installation in tunnels possible? Also, validation of the magnet model by a magnet expert is required;

END

Questions?

We can have two dipole topologies:

1) Air cooled with flat conductors
2) Water cooled with hollow conductors

Flat air-cooled conductors

TABLE 2. Approximate resistivities and dipole fields achievable with a pole made from a number of different materials [5, 6, 7, 8]. Field values are based on first-pass magnet designs that have not been fully optimized.

Material	Resistivity $\mu\Omega$ cm	Dipole field T	Material	Resistivity $\mu\Omega$ cm	Dipole field T
Pure iron	10	1.75	6.5% Si steel	82	1.4
3.5% Si steel, non-oriented	40	1.75	Fe-Co (49% Fe, 49% Co, 2% V)	44	2.0
3.5% Si steel, grain oriented	50	1.8			

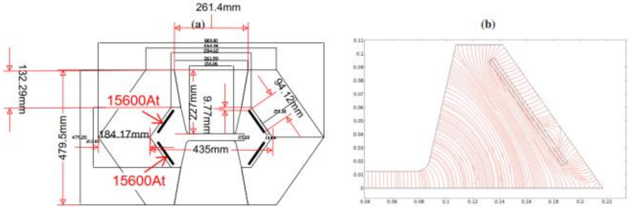
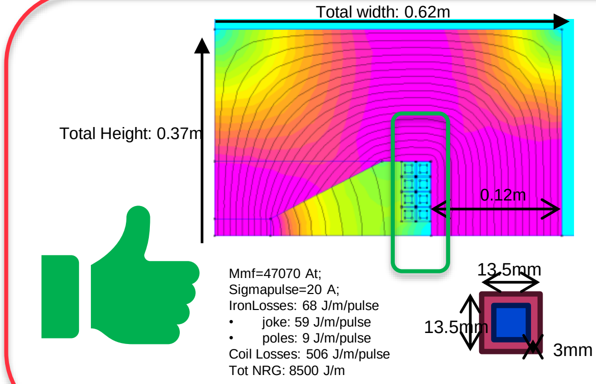


FIGURE 2. (a) Geometry of the magnet (dimensions in mm). (b) Field lines near the excitation coil at peak field.

The dipole class cannot generate flat conductor configurations. I'd like to implement this feature

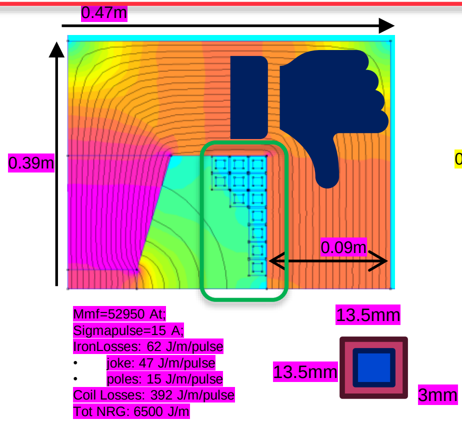
The dipole class can generate all sort of configuration with hollow conductors as shown here. The strong asymmetrical ones shall be removed. A modification of the Dipole class is required

Hollow water-cooled conductors



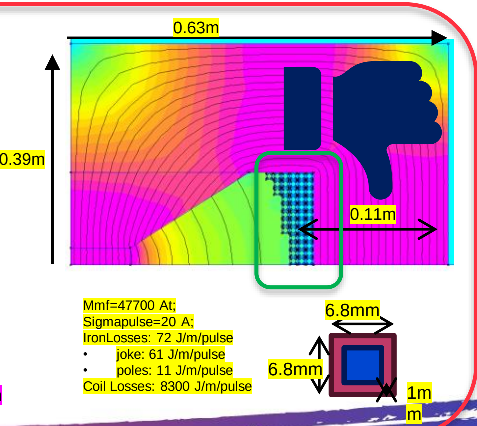
Mmf=47070 At;
Sigmapulse=20 A;
IronLosses: 68 J/m/pulse
- joke: 59 J/m/pulse
- poles: 9 J/m/pulse

Coil Losses: 506 J/m/pulse
Tot NRG: 8500 J/m



Mmf=52950 At;
Sigmapulse=15 A;
IronLosses: 62 J/m/pulse
- joke: 47 J/m/pulse
- poles: 15 J/m/pulse

Coil Losses: 392 J/m/pulse
Tot NRG: 6500 J/m



Mmf=47700 At;
Sigmapulse=20 A;
IronLosses: 72 J/m/pulse
- joke: 61 J/m/pulse
- poles: 11 J/m/pulse

Coil Losses: 8300 J/m/pulse