International
MUON Collider
Collaboration

Magnets Cycling Considerations

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12.October.22

Values from excel sheet
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Power and Energy: a general frame

	RCS2
Total Accelerator length [km]	6
Injection Energy [GeV]	330
Extraction Energy [GeV]	750
Ramping field in NC magnets [T]	-1.8 ÷ 1.8
Ramp time Tramp [ms]	1.12
Repetition time Trep [ms]	100
dB/dt [T/s]	3200
NC magnet length [m]	2438
SC magnets length [m]	1416
NC dipole gap (hxw) [mmxmm]	30x90

$$E_{\text{gap } B_{max}} = \frac{B_{max}^2}{2\,\mu_0}\,.\,L_{NCmags}.\,h_{gap}.\,w_{gap} = 8.5\text{ MJ}$$

…but: the total NRG of the dipole magnets is higher. Depending upon the layout of the magnet and the requested field quality, there could be a factor of two or even higher

$$E_{mag} \approx 2 \cdot E_{\text{gap } B_{max}} = 16.9\text{ MJ}$$

Not so big in value but must be delivered very quickly

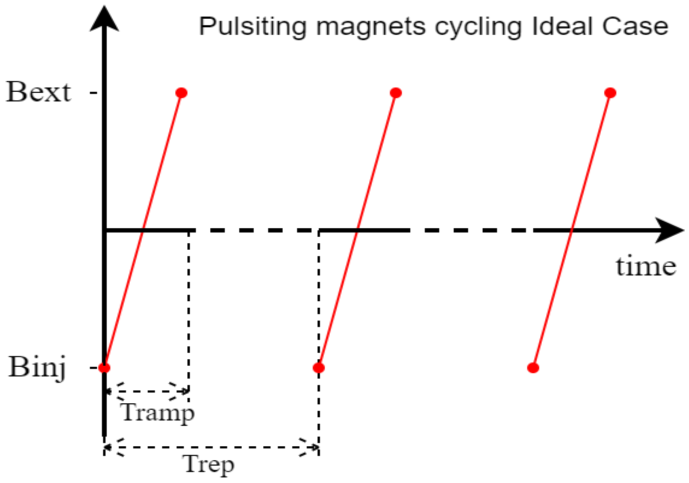
To be minimized in magnet design.

$$P(t) = \frac{2 \cdot E_{mag}}{T_{ramp}/2} = 52GW$$

Big and repetitive.

To be minimized with choice of a different Bref

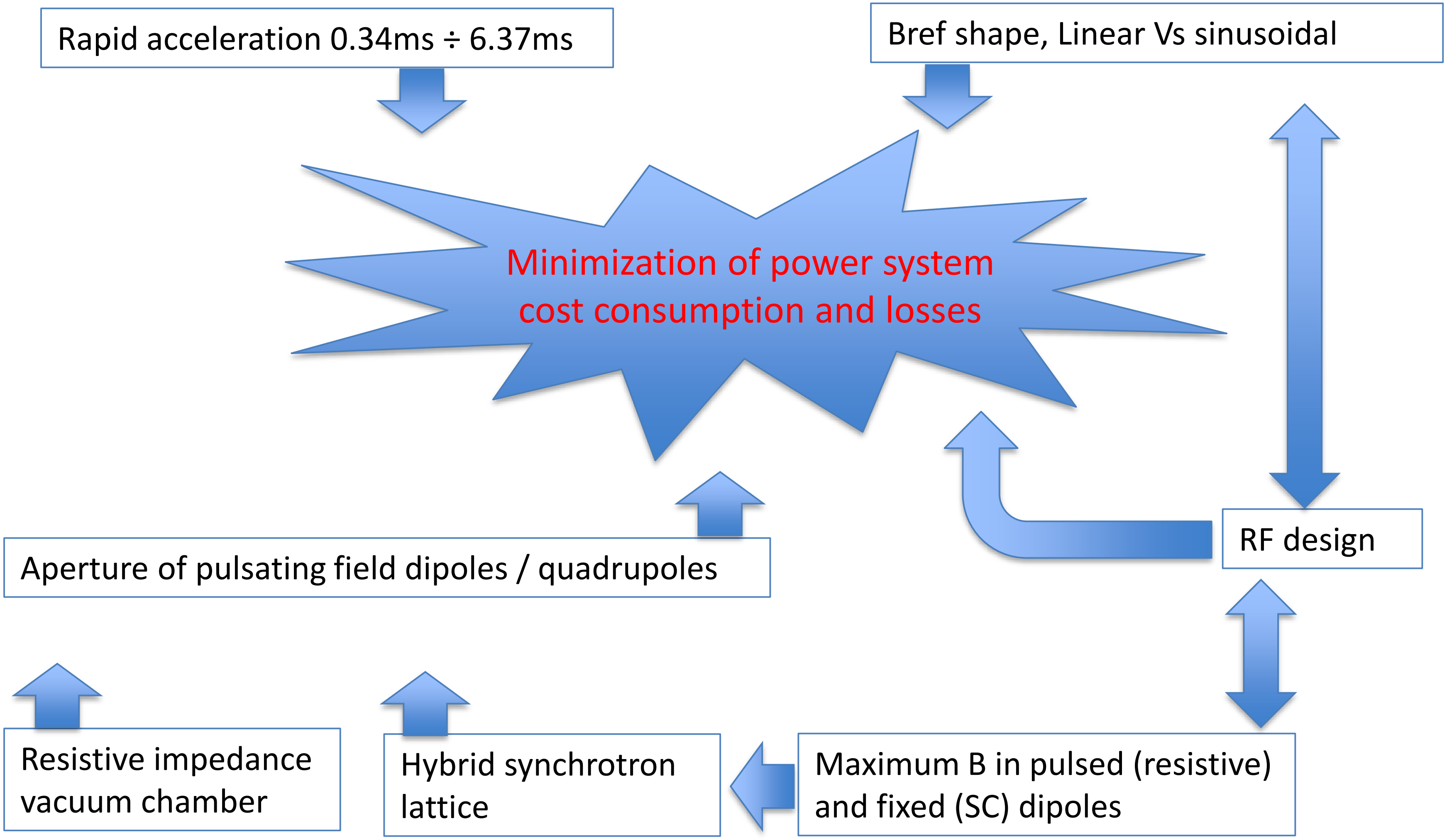
For the linear ramp case



Task 3: Accelerator magnets and powering system

Numbers: $\mathrm{NRG} \approx 10 \div 100MJ; PW_{pk} \approx 10 \div 50GW;$ Optimization required

$T_{ramp} \approx 0.5 \div 10ms; f_{rep} \approx 10Hz$



Rapid acceleration 0.34ms ÷ 6.37ms

Bref shape, Linear Vs sinusoidal

Minimization of power system cost consumption and losses

RF design

Aperture of pulsating field dipoles / quadrupoles

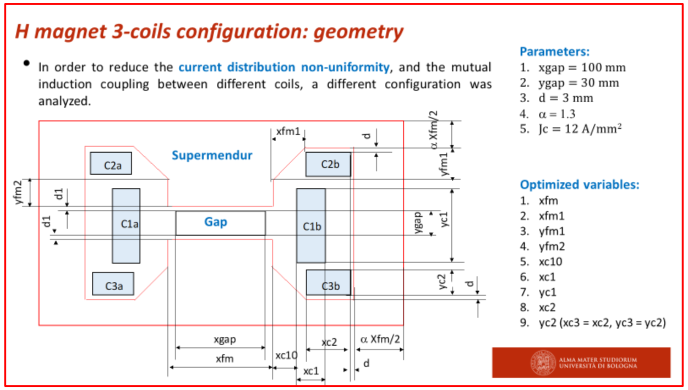
Resistive impedance vacuum chamber

Hybrid synchrotron lattice

Maximum B in pulsed (resistive) and fixed (SC) dipoles

Resistive magnets. Looking at optimization

Courtesy of Marco Breschi University of Bologna



H magnet 3-coils configuration: geometry

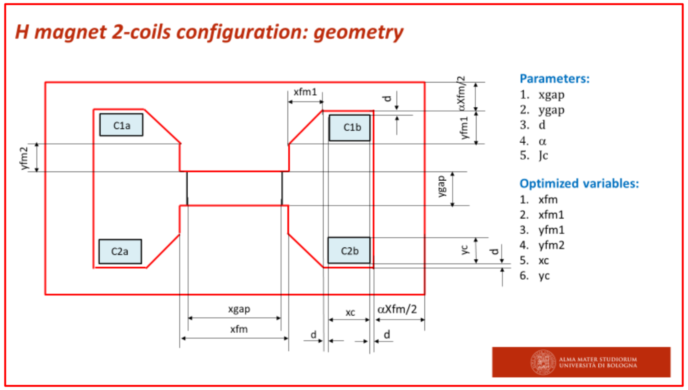
- In order to reduce the **current distribution non-uniformity**, and the mutual induction coupling between different coils, a different configuration was analyzed.

Parameters:

1. xgap = 100 mm
2. ygap = 30 mm
3. d = 3 mm
4. $\alpha = 1.3$
5. Jc = 12 A/mm^2

Optimized variables:

1. xfm
2. xfm1
3. yfm1
4. yfm2
5. xc10
6. xc1
7. yc1
8. xc2
9. yc2 (xc3 = xc2, yc3 = yc2)



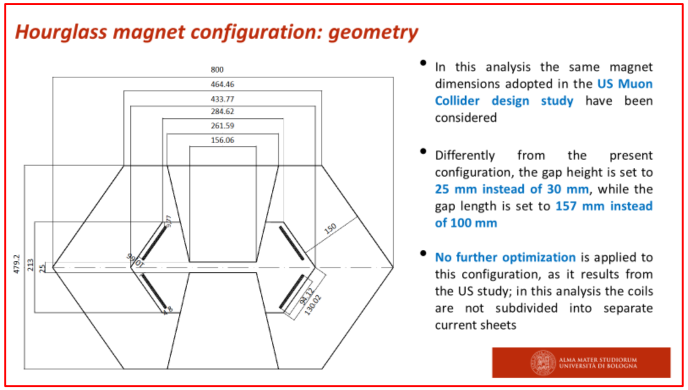
H magnet 2-coils configuration: geometry

Parameters:

1. xgap
2. ygap
3. d
4. α
5. Jc

Optimized variables:

1. xfm
2. xfm1
3. yfm1
4. yfm2
5. xc
6. yc



Hourglass magnet configuration: geometry

- In this analysis the same magnet dimensions adopted in the **US Muon Collider design study** have been considered
- Differently from the present configuration, the gap height is set to **25 mm instead of 30 mm**, while the gap length is set to **157 mm instead of 100 mm**
- **No further optimization** is applied to this configuration, as it results from the US study; in this analysis the coils are not subdivided into separate current sheets

Minimization of total magnet energy.
Winding window should be small?

Comparison of the three analyzed configurations

- The **'hourglass' magnet** from the US study exhibits the **lowest real power (losses) and low reactive power**
- The windowframe magnet exhibits the **lowest reactive power**
- The H-magnets exhibit **lower copper losses** than the windowframe magnet

	Active power [kW/m]	Reactive power [MVar/m]	Gap energy [J/m]	Energy in air (no gap) [J/m]	Energy in coils [J/m]	Losses in iron [kW/m]
Windowframe magnet	1236	14.0	3697	668	1485	18
H magnet - 3 coils	356	16.3	3814	1305	552	26
H magnet - 2 coils	182	19.9	3875	3140	142	111
Hourglass magnet	149	15.7	3821	1165	7	122

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Preliminary beta results. Optimization tool still in work

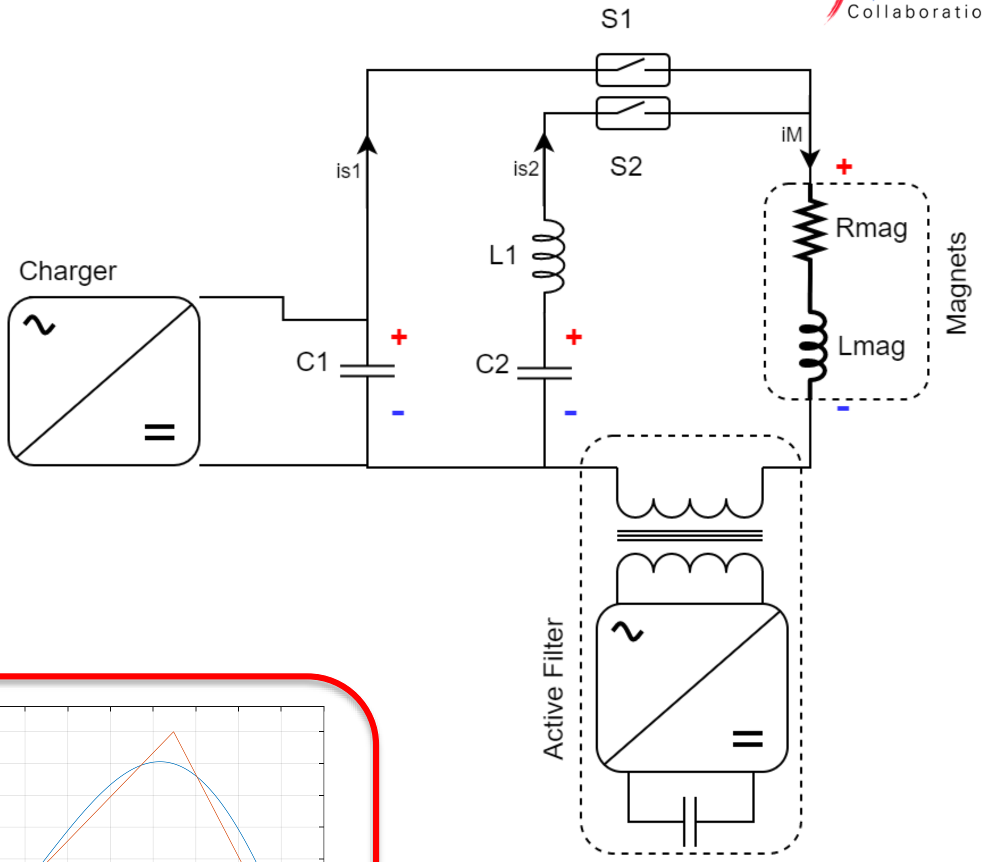
Question:
Can we use cobalt-iron soft ferromagnetic alloys?

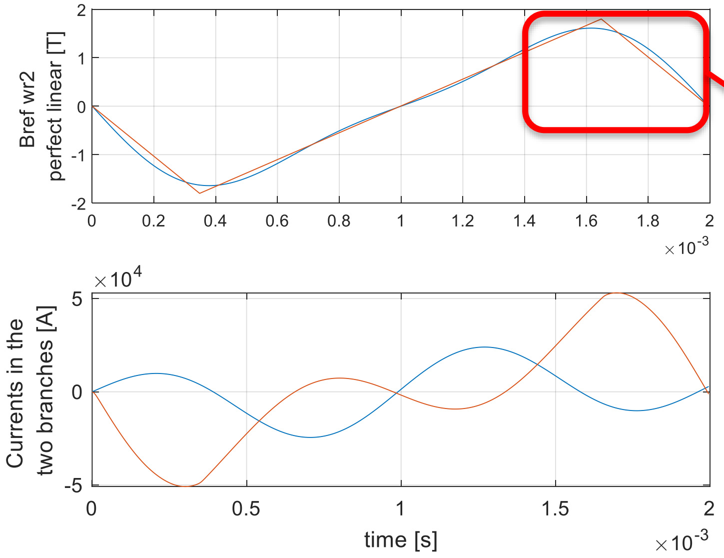
Some calculations of the Powering system for RC(Q)S2

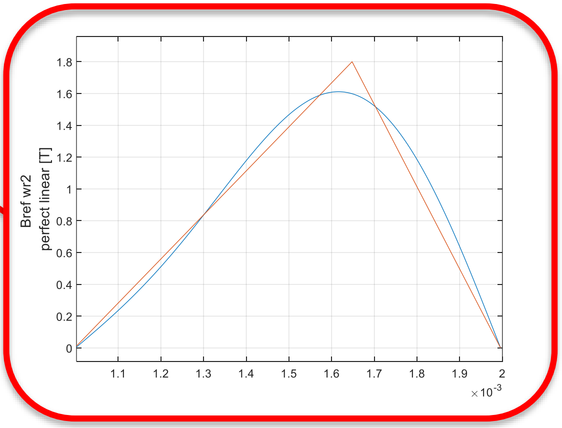
Muon Accelerator Power Supply System. Two harmonics circuit

Simple and generic circuit with double harmonics and active filter.
Two capacitor banks tuned to two different resonating frequencies

Two close-only switches that can be activated synchronously or asynchronously. Possibly based on semiconductor tech.







Two branches contribute to the total magnet current

Non linear magnet model for circuit analysis

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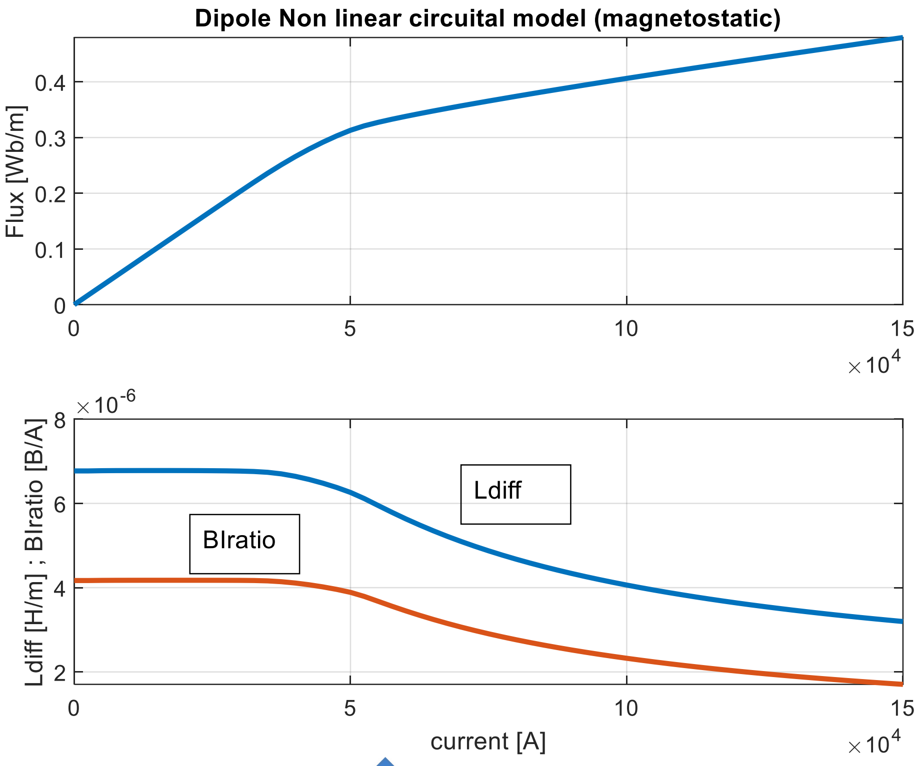
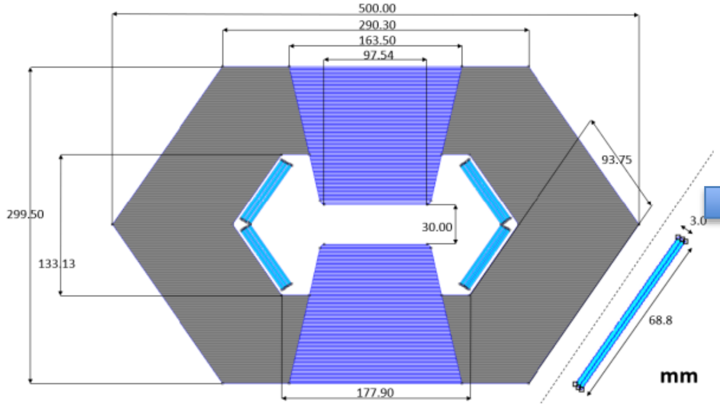


Magnet linear model (unsaturated)

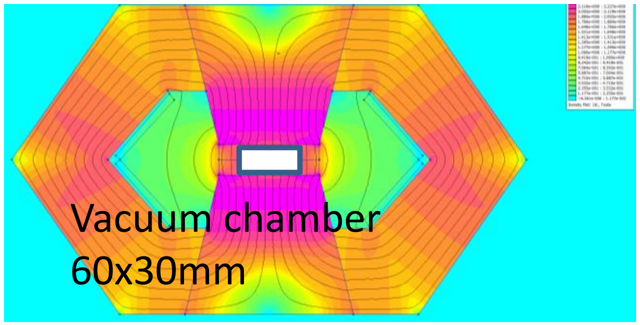
$$L_m = 6.3 \frac{\mu H}{m\,.\,turn}$$

$$\frac{B}{I} = 41.0 \frac{\mu T}{A}$$

MAP design for pulsed dipoles



Femm non linear magnetostatic



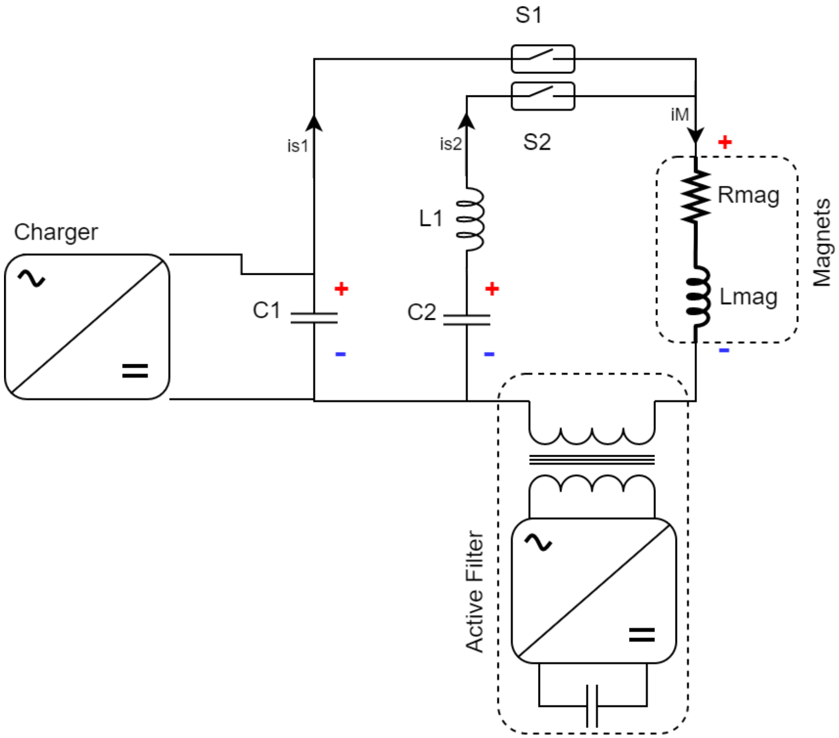
One of the outcomes of Task3. Here a preliminary result to run the calculations of the power circuit

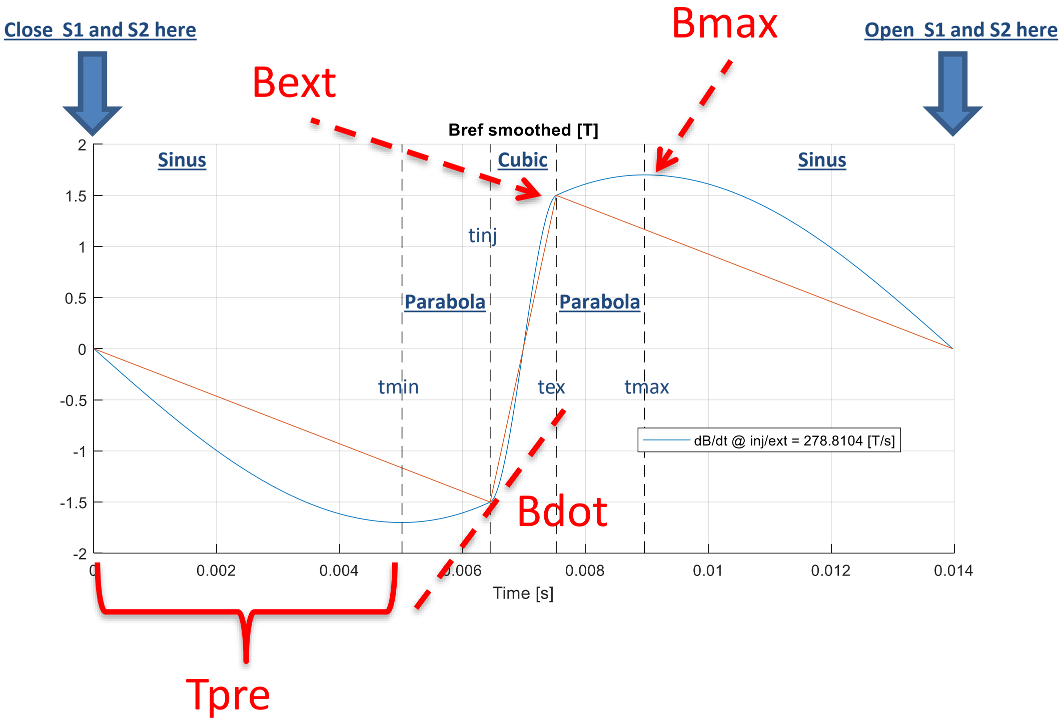
First step: Bref calculation

Select the paramenters: Bdot, Bmax, Binj/ext, Tpre
The reference is generated automatically

Piecewise reference Brefsmooth:

$$B_{gapavg}(t) = \begin{cases} Sinus & 0 < t \leq t_{min} \\ Parabola & t_{min} < t \leq t_{inj} \\ Cubic & t_{inj} < t \leq t_{ext} \\ Parabola & t_{ext} < t \leq t_{max} \\ Sinus & t_{max} < t \leq t_{end} \end{cases}$$




Close S1 and S2 here

Open S1 and S2 here

Bext

Bmax

Bdot

Tpre

We need a non linear model of the magnet

Second step: Circuit parameters

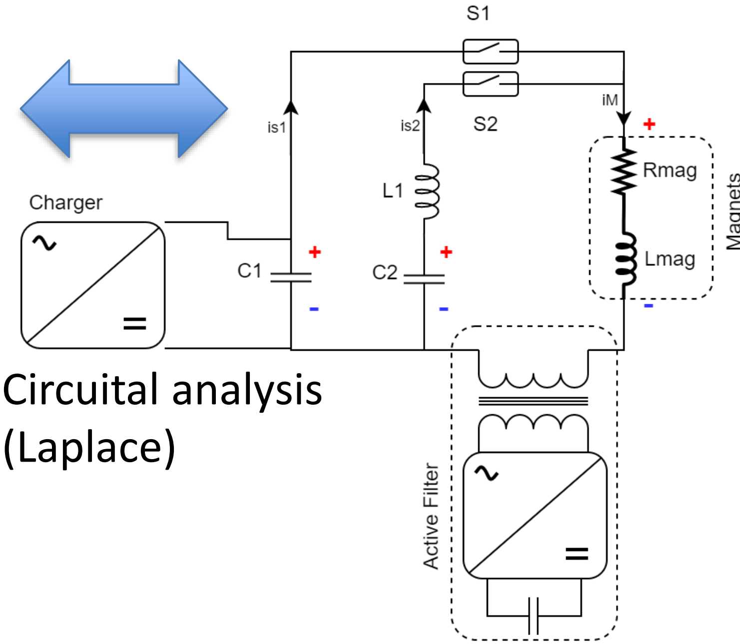
$$I_{MAG_h}(t) = I_{K1}\,\sin(\omega_1 t) + I_{Kn}\,\sin(\omega_n t)$$

What we want (from Fourier series of Brefsmooth)

$$I_{MAG_h}(s) = I_{K1}\,\frac{\omega_f}{s^2+\omega_f^2} + I_{Kn}\,\frac{n\,\omega_f}{s^2+n^2\,\omega_f^2}$$

Laplace(What we want)

$$I_{MAG_h}(s) = \frac{(C_1 C_2 L_2 s^2 + C_1)\,V_{C1}(0) + C_2 V_{C2}(0)}{(C_1 C_2 L_2 \mathrm{Lmag})\,s^4 + (C_2 L_2 + C_1 \mathrm{Lmag} + C_2 \mathrm{Lmag})\,s^2 + 1}$$



Circuital analysis (Laplace)

$$C_1 = \frac{1}{\mathrm{Lmag}\,n^2\omega_f^2 + \mathrm{Lmag}\,\omega_f^2 - \mathrm{Lmag}\,\omega_p^2}$$

$$C_2 = -\frac{n^2\omega_f{}^4 - n^2\omega_f{}^2\omega_p{}^2 - \omega_f{}^2\omega_p{}^2 + \omega_p{}^4}{n^2\omega_f{}^4\,(\mathrm{Lmag}\,n^2\omega_f{}^2 + \mathrm{Lmag}\,\omega_f{}^2 - \mathrm{Lmag}\,\omega_p{}^2)}$$

$$L_2 = -\frac{(n^2\omega_f{}^2 + \omega_f{}^2 - \omega_p{}^2)\,(\mathrm{Lmag}\,n^2\omega_f{}^2 + \mathrm{Lmag}\,\omega_f{}^2 - \mathrm{Lmag}\,\omega_p{}^2)}{n^2\omega_f{}^4 - n^2\omega_f{}^2\omega_p{}^2 - \omega_f{}^2\omega_p{}^2 + \omega_p{}^4}$$

$$V_{C1}(0) = \mathrm{Lmag}\,\omega_f\,(\mathrm{Ik}_1 + \mathrm{Ik}_n n)$$

$$V_{C2}(0) = -\frac{\mathrm{Lmag}\,n\,\omega_f{}^3\,(\mathrm{Ik}_1 n^3\omega_f{}^2 + \mathrm{Ik}_n n^2\omega_f{}^2 - \mathrm{Ik}_n n\,\omega_f{}^2 - \mathrm{Ik}_1 n\,\omega_p{}^2 + \mathrm{Ik}_n\omega_f{}^2 - \mathrm{Ik}_n\omega_p{}^2)}{n^2\omega_f{}^4 - n^2\omega_f{}^2\omega_p{}^2 - \omega_f{}^2\omega_p{}^2 + \omega_p{}^4}$$

Third step: optimization of free oscillation

In case of non linearity (magnet saturation), the equations are not working well. An optimization is needed to find a better set

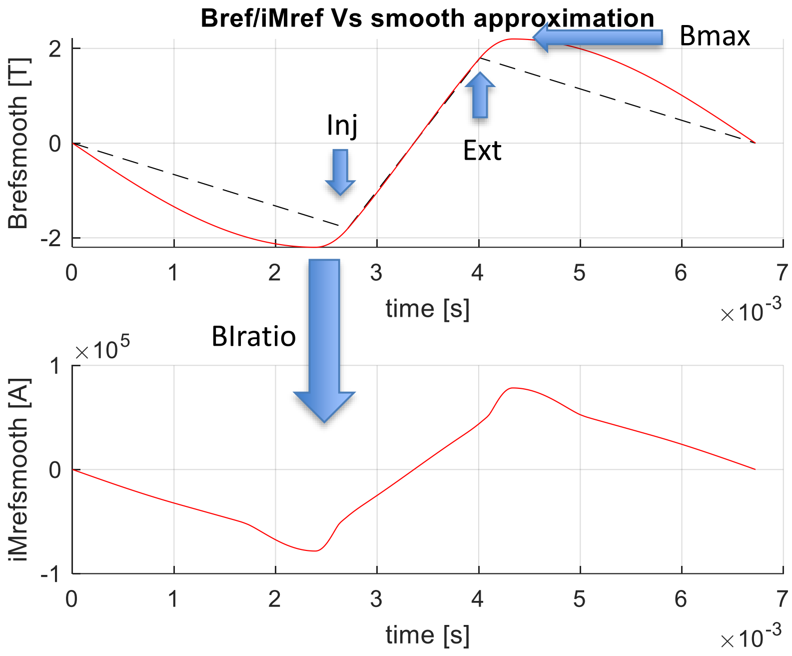
$$C_1 = \frac{1}{\mathrm{Lmag}\, n^2 \omega_f^2 + \mathrm{Lmag}\, \omega_f^2 - \mathrm{Lmag}\, \omega_p^2}$$

$$C_2 = -\frac{n^2 {\omega_f}^4 - n^2 {\omega_f}^2 {\omega_p}^2 - {\omega_f}^2 {\omega_p}^2 + {\omega_p}^4}{n^2 {\omega_f}^4 \left(\mathrm{Lmag}\, n^2 {\omega_f}^2 + \mathrm{Lmag}\, {\omega_f}^2 - \mathrm{Lmag}\, {\omega_p}^2\right)}$$

$$L_2 = -\frac{\left(n^2 {\omega_f}^2 + {\omega_f}^2 - {\omega_p}^2\right)\left(\mathrm{Lmag}\, n^2 {\omega_f}^2 + \mathrm{Lmag}\, {\omega_f}^2 - \mathrm{Lmag}\, {\omega_p}^2\right)}{n^2 {\omega_f}^4 - n^2 {\omega_f}^2 {\omega_p}^2 - {\omega_f}^2 {\omega_p}^2 + {\omega_p}^4}$$

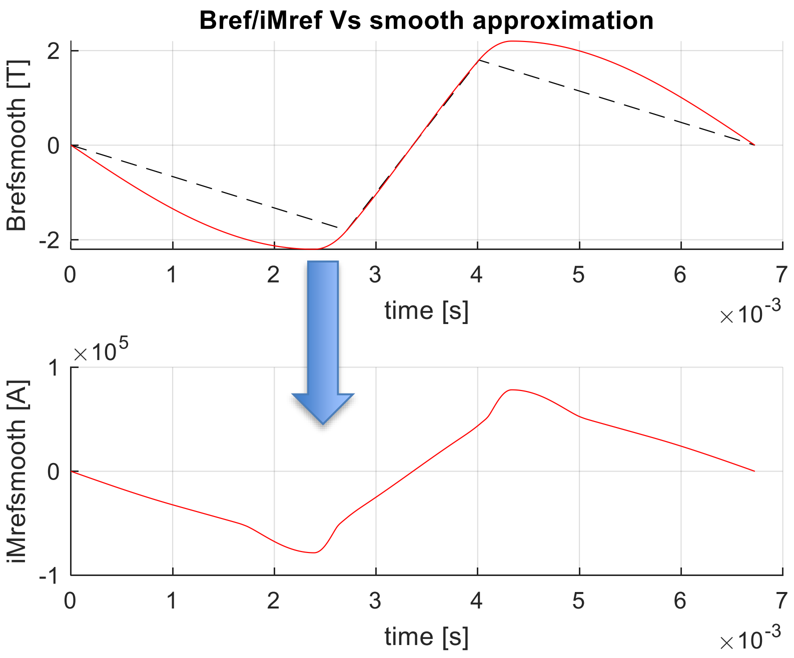
$$V_{C1}(0) = \mathrm{Lmag}\, \omega_f \left(\mathrm{Ik}_1 + \mathrm{Ik}_n n\right)$$

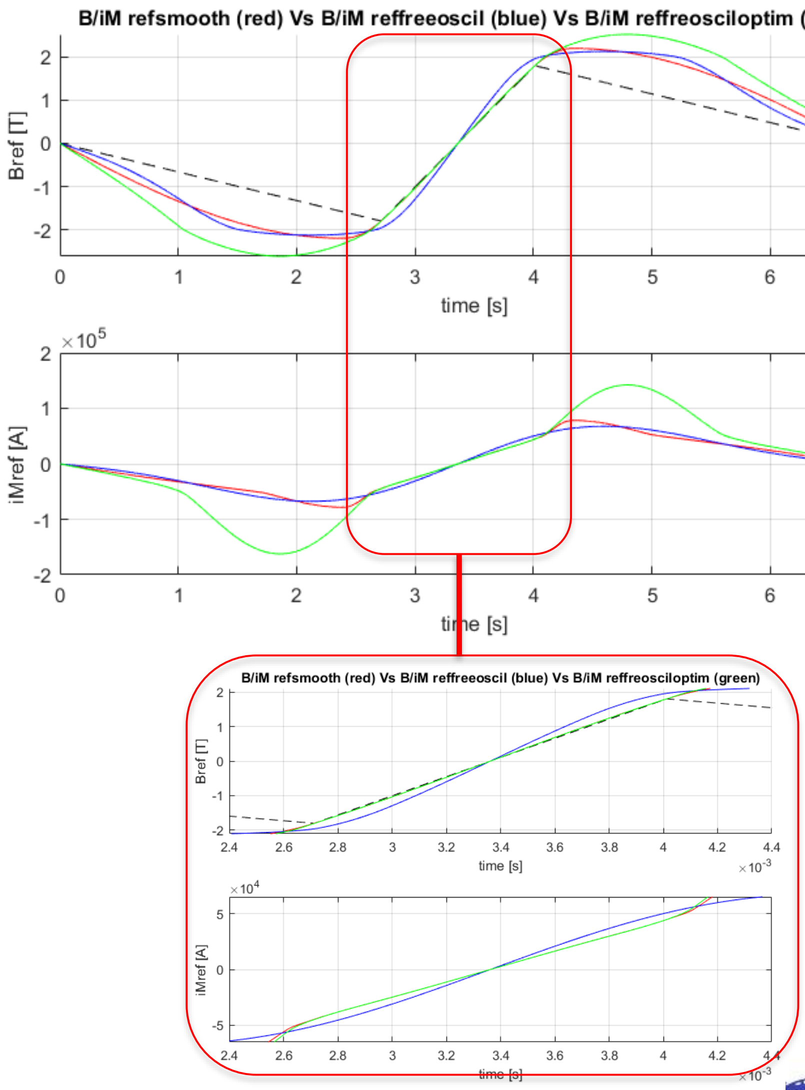
$$V_{C2}(0) = -\frac{\mathrm{Lmag}\, n\, {\omega_f}^3 \left(\mathrm{Ik}_1 n^3 {\omega_f}^2 + \mathrm{Ik}_n n^2 {\omega_f}^2 - \mathrm{Ik}_n n\, {\omega_f}^2 - \mathrm{Ik}_1 n\, {\omega_p}^2 + \mathrm{Ik}_n {\omega_f}^2 - \mathrm{Ik}_n {\omega_p}^2\right)}{n^2 {\omega_f}^4 - n^2 {\omega_f}^2 {\omega_p}^2 - {\omega_f}^2 {\omega_p}^2 + {\omega_p}^4}$$



Third step: optimization of free oscillation

In case of non linearity (magnet saturation), the equations are not working well. An optimization is needed to find a better set

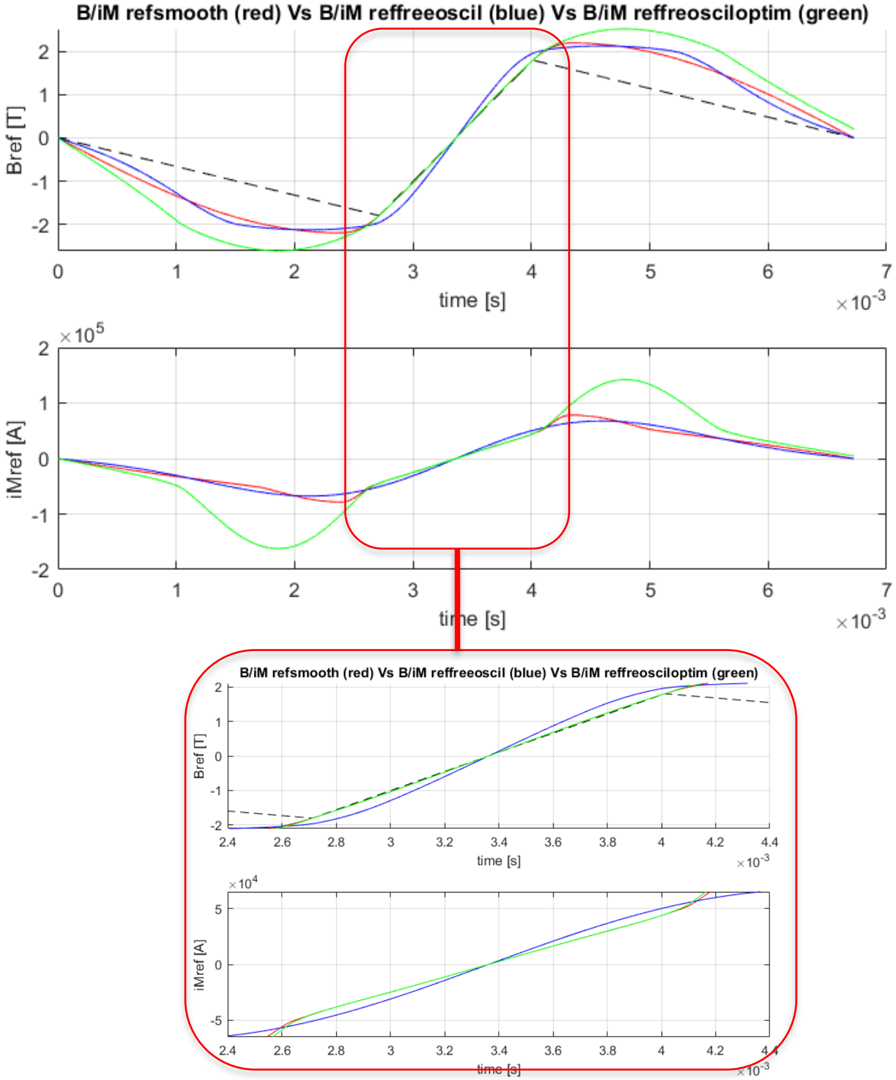




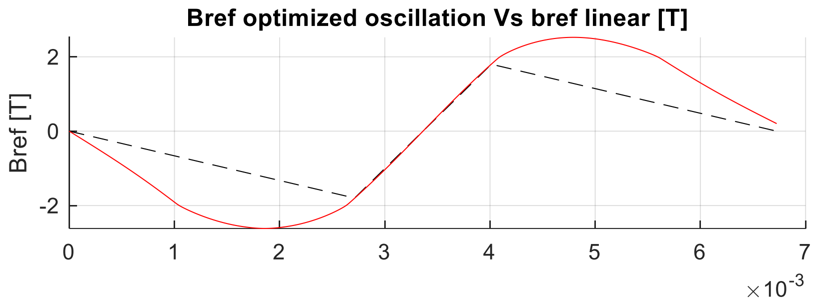
Optimization is focused in the area between injection and extraction.
Bmax is higher that what we asked for in the Brefsmooth.

Third step: optimization of free oscillation

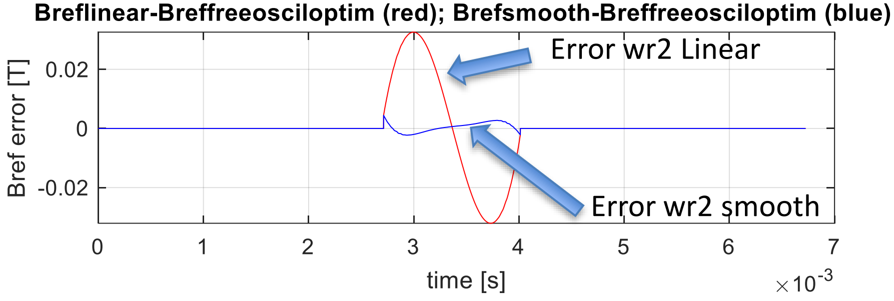
In case of non linearity (magnet saturation), the equations are not working well. An optimization is needed to find a better set



B/iM refsmooth (red) Vs B/iM reffreeoscil (blue) Vs B/iM reffreosciloptim (green)



Bref optimized oscillation Vs bref linear [T]



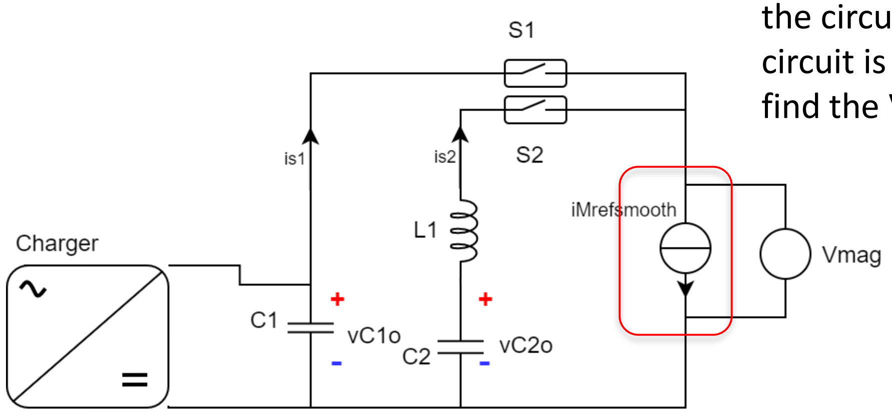
Breflinear-Breffreeosciloptim (red); Brefsmooth-Breffreeosciloptim (blue)

At this point we have the free oscillation that best approximates the Brefsmooth generated at Step1 (correspondent to a given set of Bdot, Bmax, Binj/ext, Tpre)

If we want to go closer to the Brefsmooth, we need the active filter and we proceed to step4

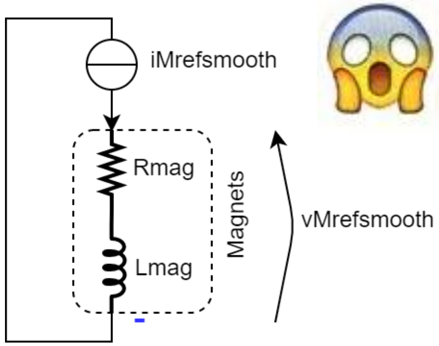
Fourth step: calculation of the Active Filter contribution

Solve the circuit equations below:



iMrefsmooth is imposed in the circuit and the electric circuit is solved in order to find the Vmag

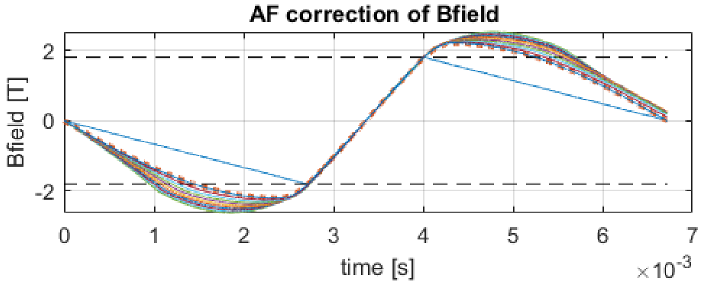
Don’t do this at home!!

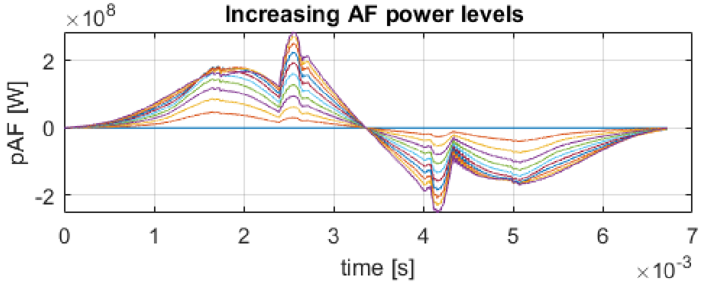


Desired response with imposed current shape. Calculate Vmag

$$v_{AF} = v_{mag} - v_{refsmooth}$$

$$P_{AF} = v_{AF} \cdot iM_{refsmooth}$$



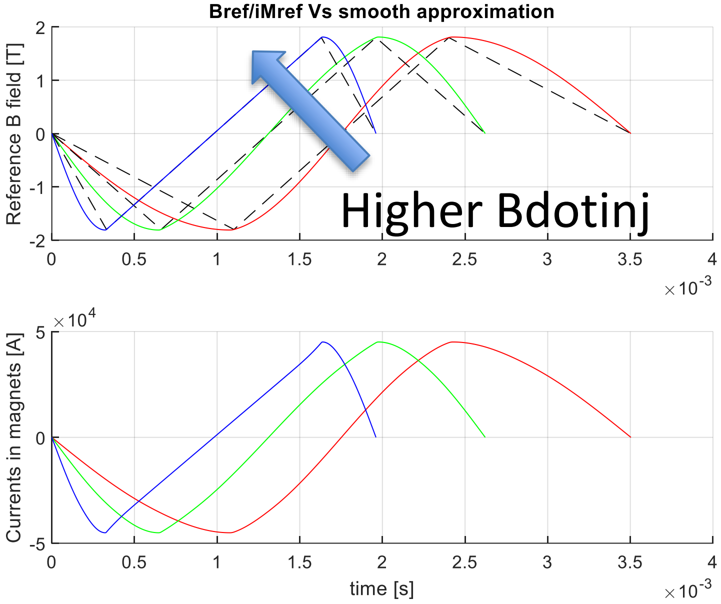


The higher the contribution of the AF the closer you get to the desired Brefsmooth (dotted line)

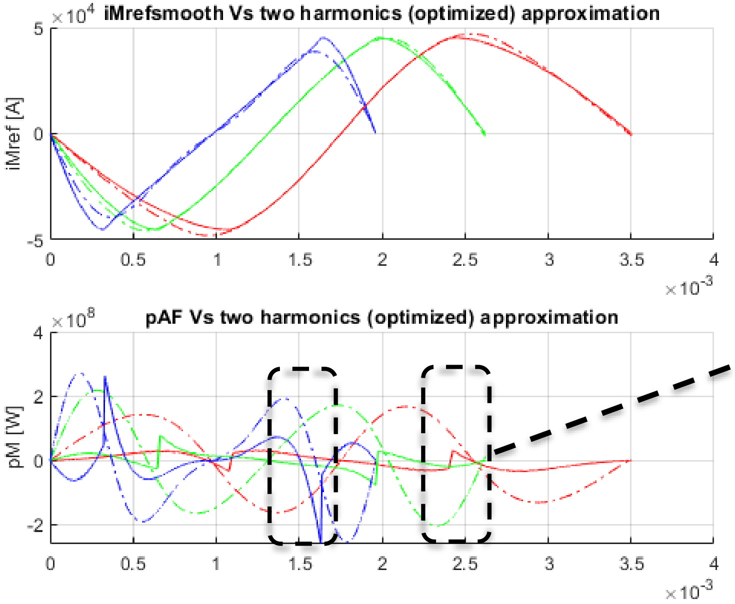
We can play some trends

Change the Bdot at Inj/Ext

Changing the Inj-Ext derivative with Bmax=Bext=1.8T

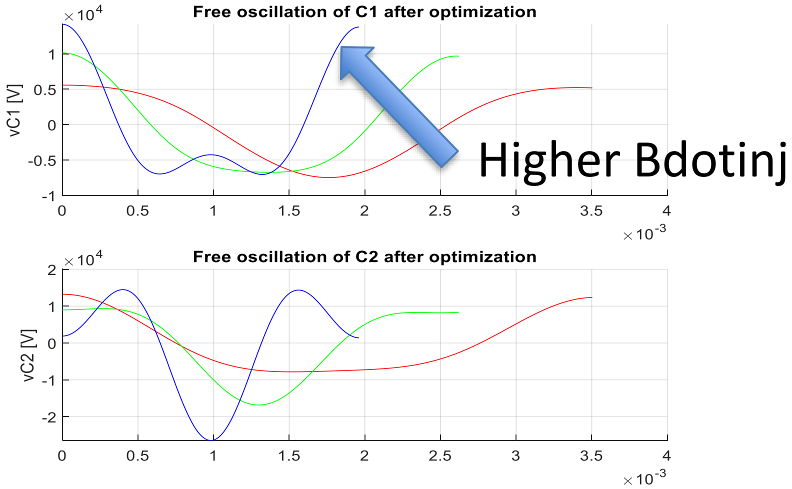

Bref/iMref Vs smooth approximation

Higher Bdotinj


iMrefsmooth Vs two harmonics (optimized) approximation

pAF Vs two harmonics (optimized) approximation

Higher dBdt in inj/ext requires higher pAF


Free oscillation of C1 after optimization

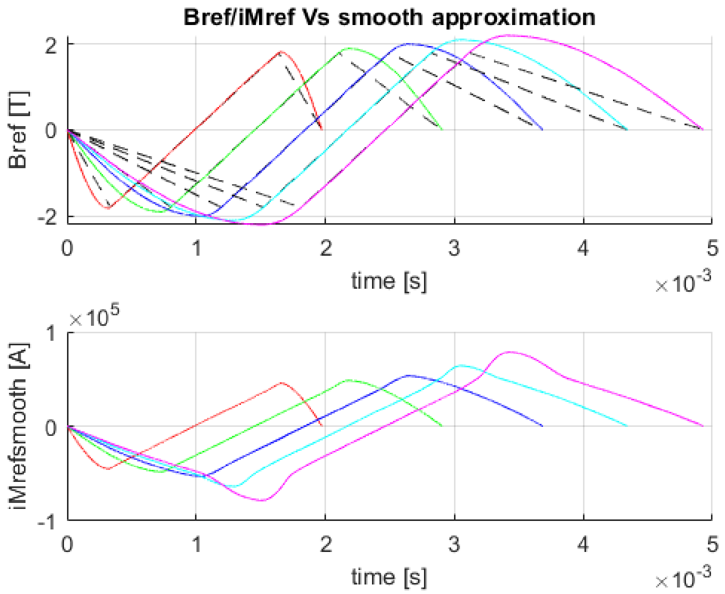
Free oscillation of C2 after optimization

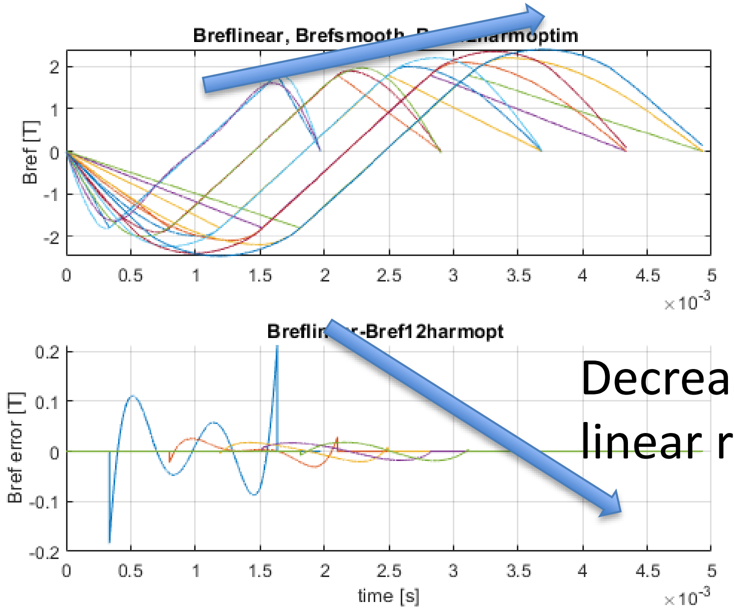
Higher Bdotinj

Releasing the requirements of the Bdotinj will help also in terms of voltage across the capacitors

Change the Bmax (no AF here)

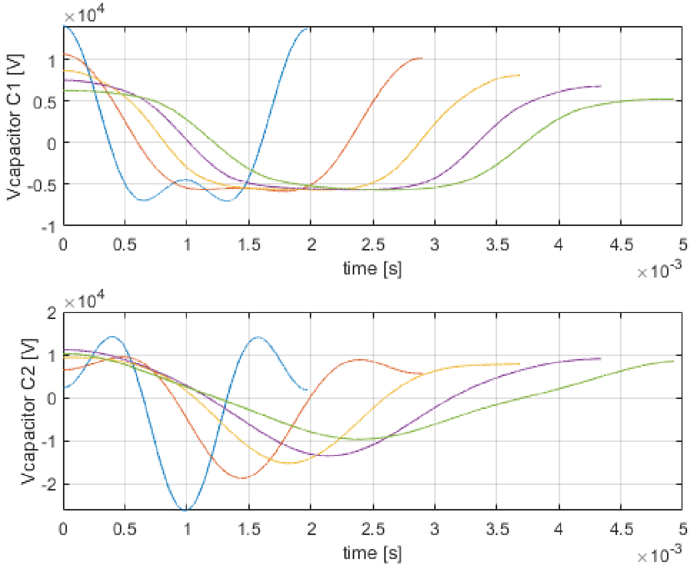
Increased saturation





Decreased Berror wr2 linear ramp

Is it OK for the magnet?



Decreased voltage across capacitors

CONCLUSIONS

- The design of resistive magnets has commenced. The MAP results are taken as starting/tuning point and alternative designs are considered with the goal of reducing the overall NRG content (UNIBO and TU Darmstadt)
- ENERGY:A correct dimensioning of the gap is fundamental and should benefit from results of the lattice decisions, the RF design and the vacuum chamber dimensioning. We should make sure these three aspects are included as soon as possible
- POWER: shaping correctly the Bref is essential to optimize the maximum power to be delivered. Optimization with RF has started already.
- Magnets models are required with consistent losses calculation in saturated regime. Hysteresis model?