International
MUON Collider
Collaboration

Powering Schemes and Optimization

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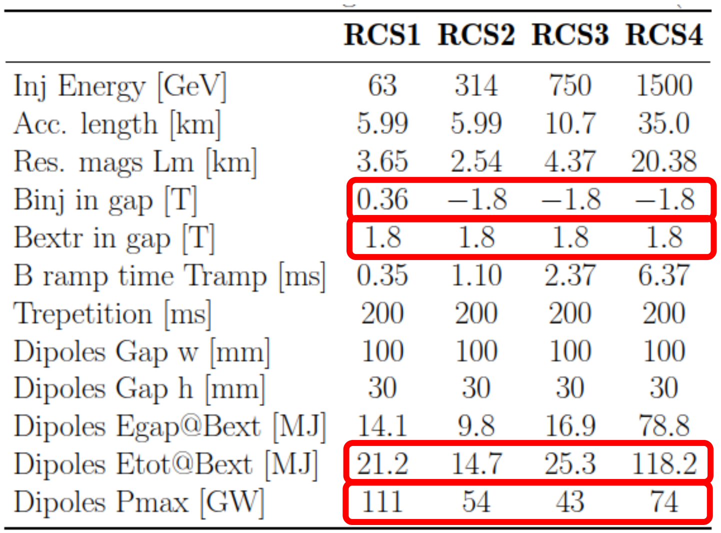
Organization of the presentation

- Muon acceleration with RCS: Power and Energy frame
- Power circuit considerations
- Powering Schemes
- The Control problem description
- Technologies
- Working plan
- Conclusions

Accelerator Power and Energy: a general frame

RCS values from excel sheet
F. Batsch, H. Daimerau.

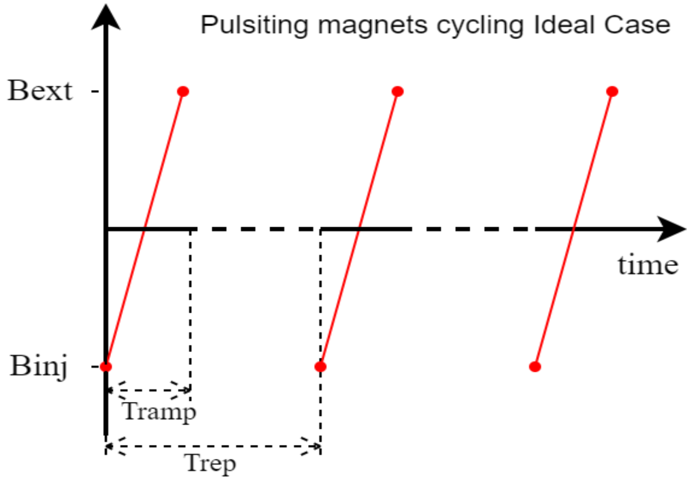


	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
Res. mags Lm [km]	3.65	2.54	4.37	20.38
Binj in gap [T]	0.36	−1.8	−1.8	−1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	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]	111	54	43	74

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

$$E_{mag} \approx 1.5 \cdot E_{\text{gap }B_{max}}$$

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



Approximate calculations for the magnetic circuit, show that the total mmf is about 40 ÷ 50 kAturns with an inductance of about 4.5 ÷ 6.5 uH/m with a single series conductor.

The correspondent inductive voltage for the four RCS would be:

	RCS1	RCS2	RCS3	RCS4
Inductive Voltage of the power supply with a single turn	670 [V/m]	420 [V/m]	200 [V/m]	70 [V/m]
Total magnet voltage	2.4 [MV]	1.07 [MV]	0.9 [MV]	1.5 [MV]

High voltage and power must be divided into several sectors

Power Circuit Considerations: sectors in the accelerators

Independent power circuit sectors:

The ground can be placed on each circuit. Lower voltage to ground

Much easier operation of power converters

What accuracy is required intra-sector?

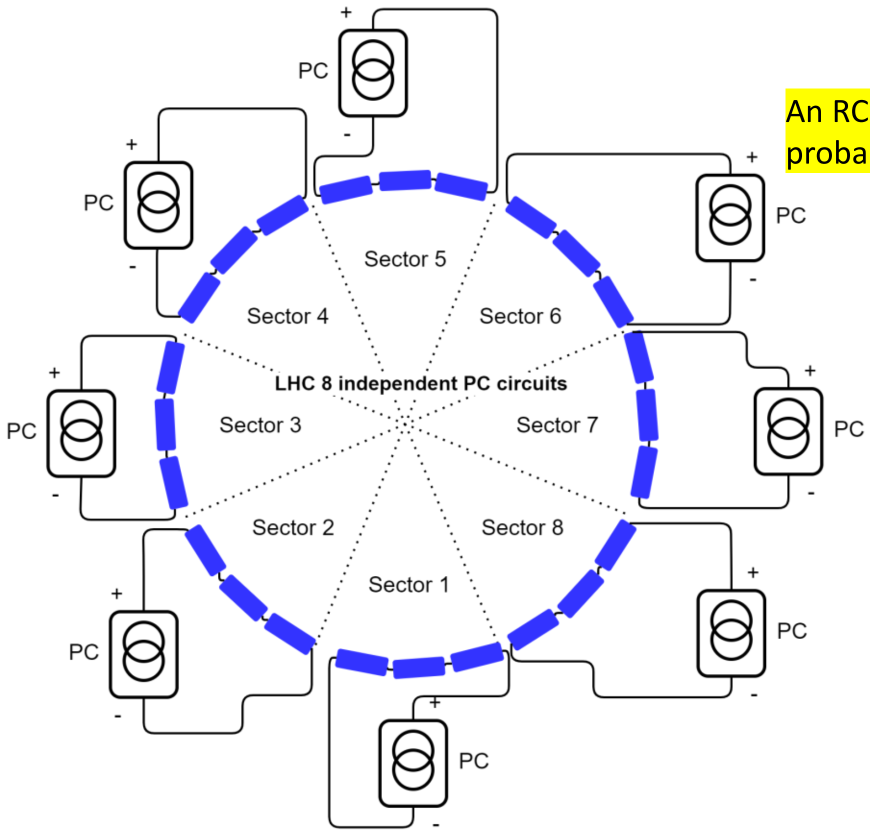
Pulse to pulse reproducibility stem from the intra-sector accuracy

Quasi-Series connection of all power circuit sectors:

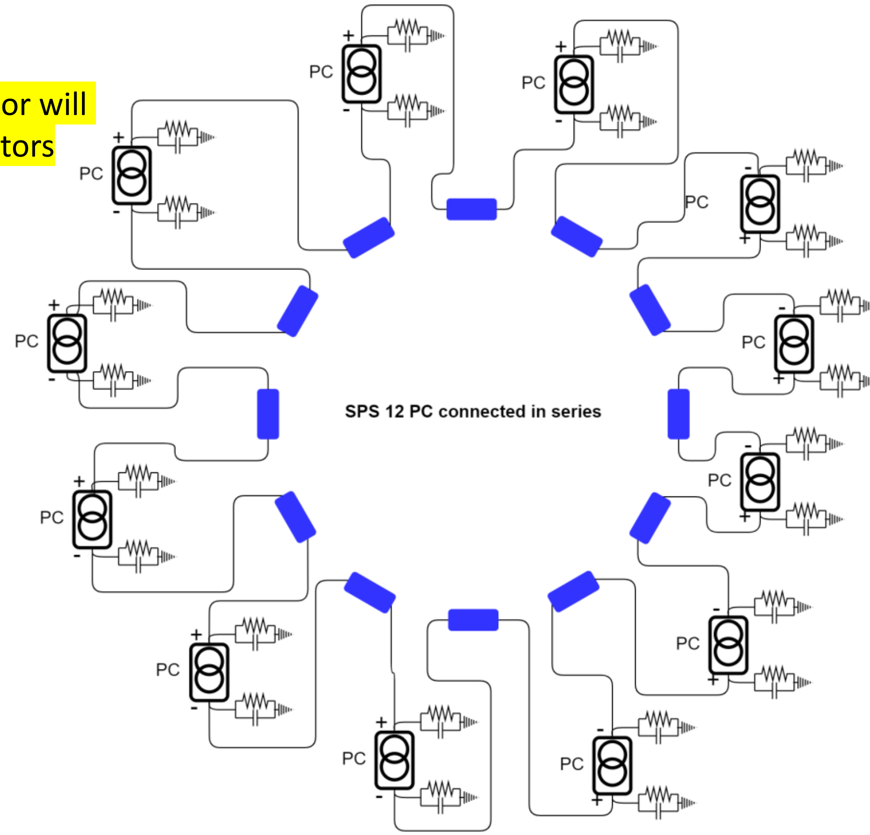
Current is the same in all circuits.

Complicated tuning of ground RCs particularly with high dV/dt.

Pulse to pulse reproducibility still to be specified



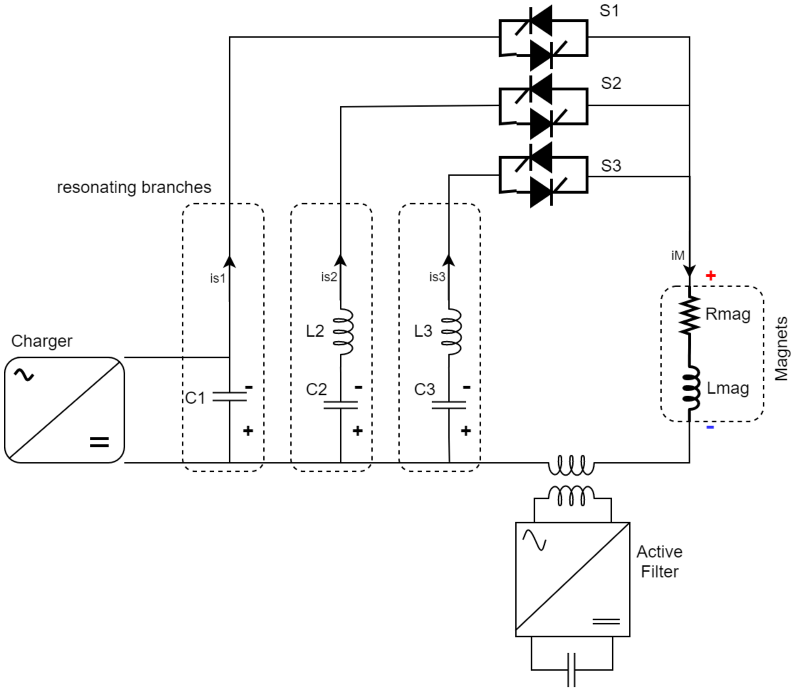
An RCS for the muon accelerator will probably need around 200 sectors



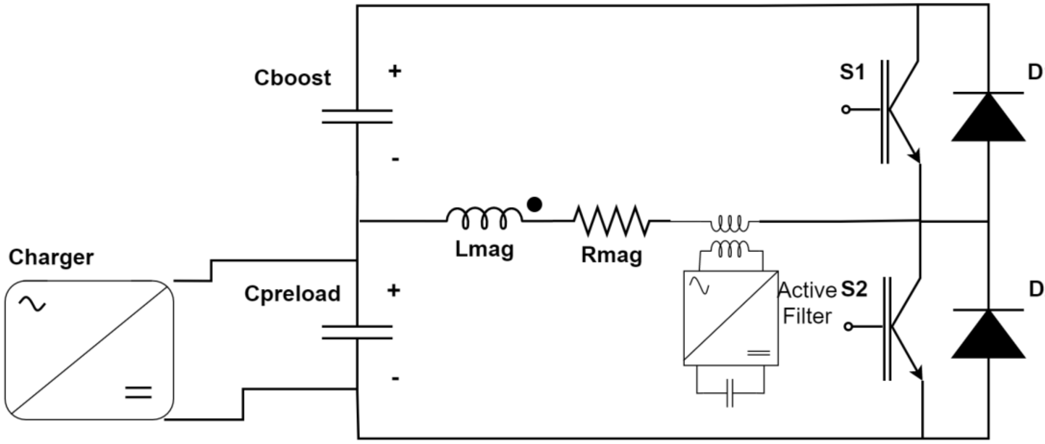
Powering Schemes

Two macro concepts identified. Both based on resonance. Several possible realization circuits.

Concept 1: full wave resonance



Concept 2: commutated resonance



2-3 Harmonics add to shape the current / magnetic field in the magnets.

- Multi-resonance evolves until current is zero again
- Limited flexibility to change working conditions
- Simpler power electronics

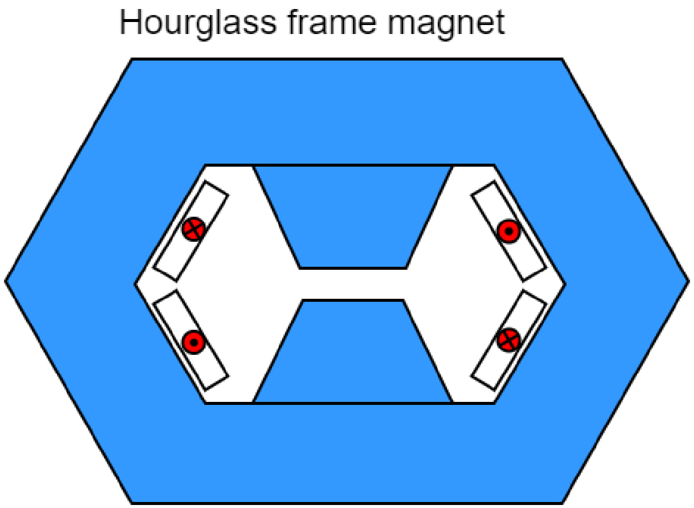
The discharge evolves in two phases:

- Magnets are preloaded to the injection Bfield, and quickly switched onto field rapid step up.
- Increased flexibility to change working conditions
- Power electronics more complicated

Powering scheme: magnet model for calculations

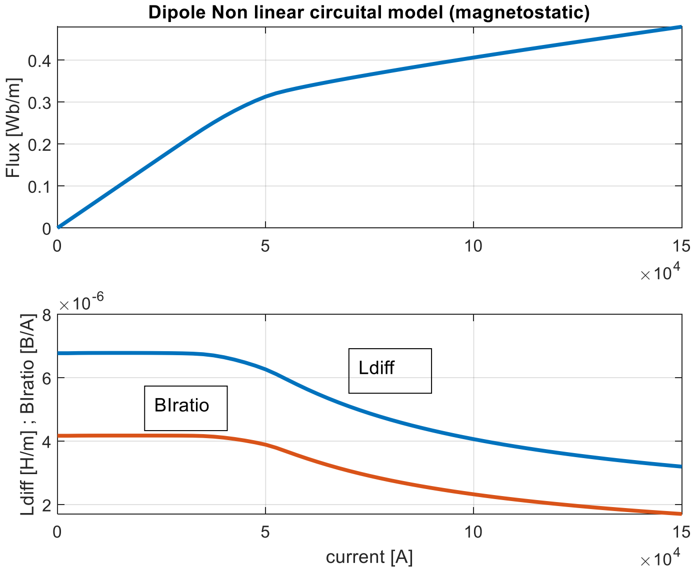
Worst case model: Highest stored energy and highest losses

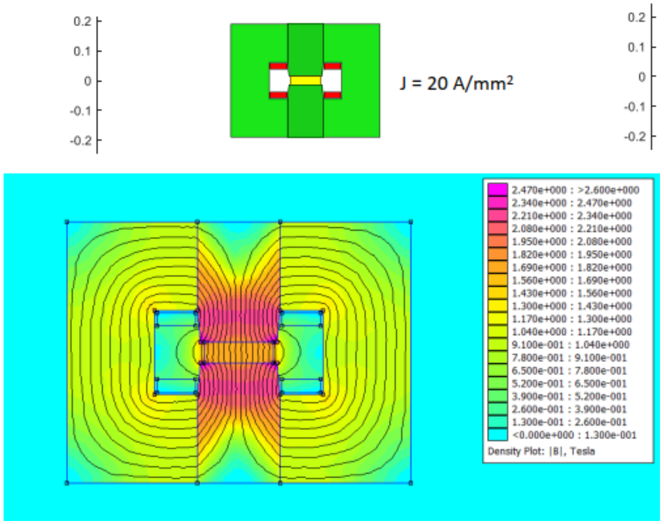
Model from early work in JAI "A Design for a 3 TeV Rapid Cycling Synchrotron for Muon Acceleration in the SPS Tunnel"
https://cds.cern.ch/record/2723310/files/JAI%20Muon_RCS.pdf
Inspired to MAP Hourglass design: "Pulsed Synchrotrons for very rapid acceleration"
https://doi.org/10.1063/1.4965683



Losses values taken by the work from UNIBO "Resistive Magnet Design Studies"

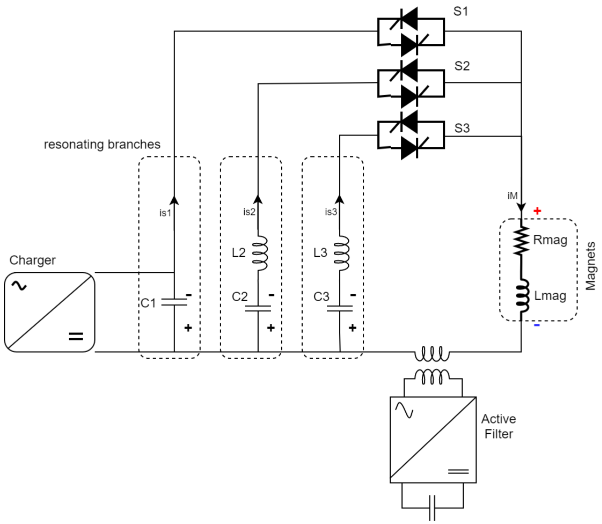
Lmag (differential-unsaturated) = 6.6uH/m
Rmag = 0.2mOhm/m
mmF (@1.8T) = 46 kA





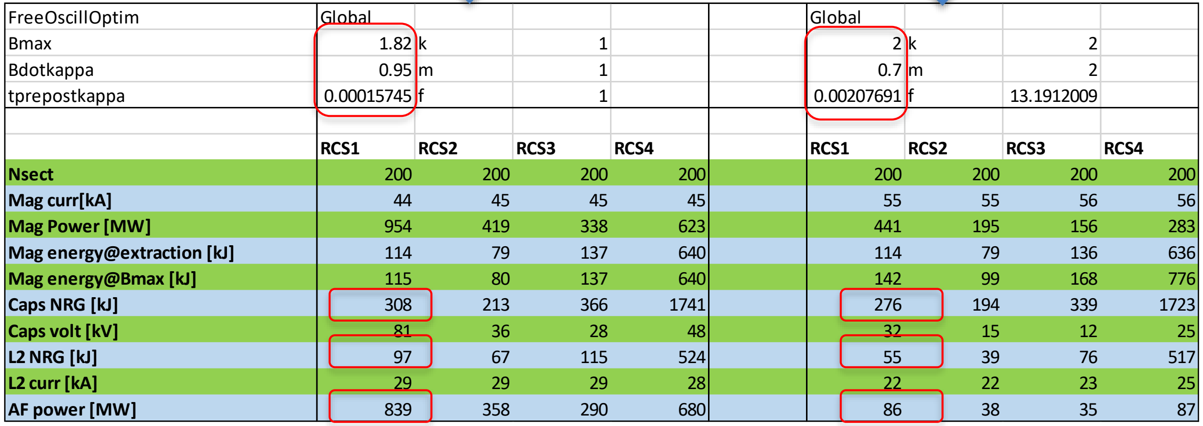
Powering Schemes: Full wave resonance analysis

Full wave resonance: comparison of two extreme situations

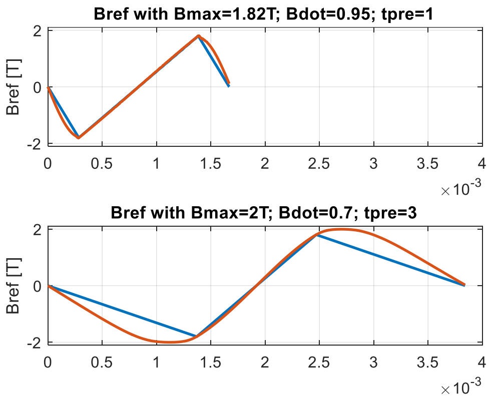


Linear (almost) Bref

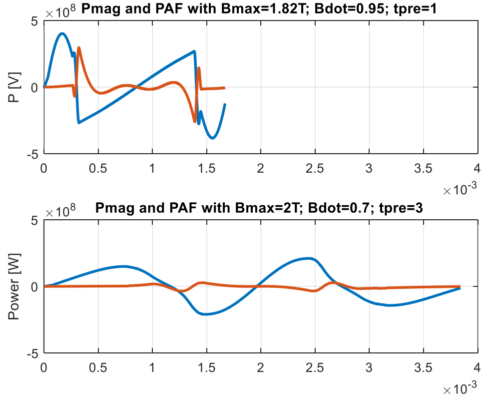
“cheaper” Bref



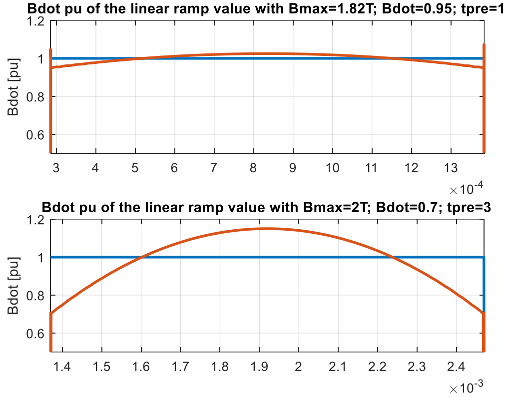
FreeOscillOptim	Global					Global			
Bmax	1.82	k	1			2	k	2	
Bdotkappa	0.95	m	1			0.7	m	2	
tprepostkappa	0.00015745	f	1			0.00207691	f	13.1912009	
	RCS1	**RCS2**	**RCS3**	**RCS4**		**RCS1**	**RCS2**	**RCS3**	**RCS4**
Nsect	200	200	200	200		200	200	200	200
Mag curr[kA]	44	45	45	45		55	55	56	56
Mag Power [MW]	954	419	338	623		441	195	156	283
Mag energy@extraction [kJ]	114	79	137	640		114	79	136	636
Mag energy@Bmax [kJ]	115	80	137	640		142	99	168	776
Caps NRG [kJ]	308	213	366	1741		276	194	339	1723
Caps volt [kV]	81	36	28	48		32	15	12	25
L2 NRG [kJ]	97	67	115	524		55	39	76	517
L2 curr [kA]	29	29	29	28		22	22	23	25
AF power [MW]	839	358	290	680		86	38	35	87



AF helps following the “cheaper” Bref



The cheaper solution comes at the cost of increased Bdot

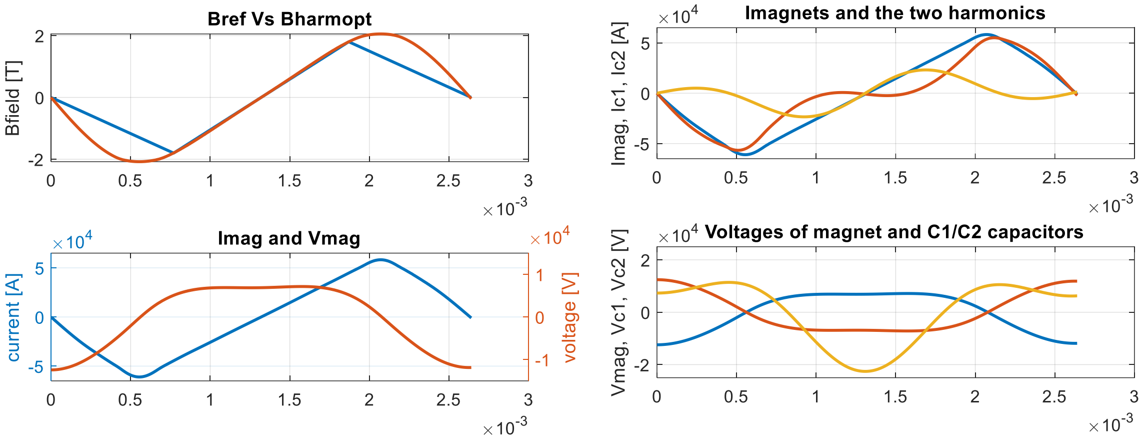


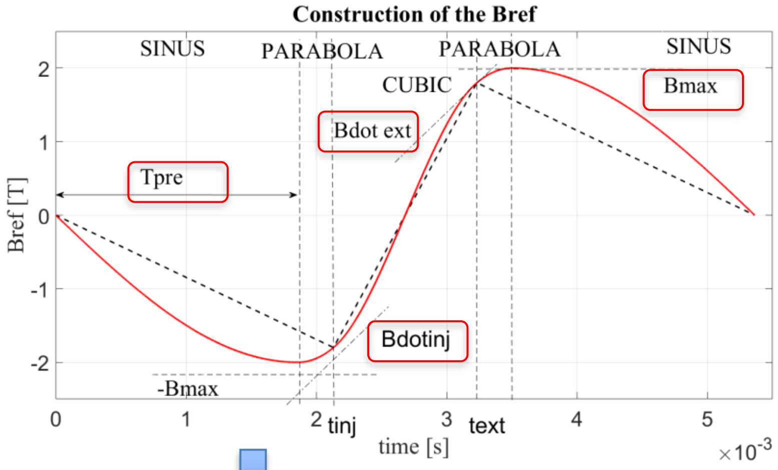
Optimizations are possible, however in preliminary evaluations, the Active filter showed to be a very expensive element.

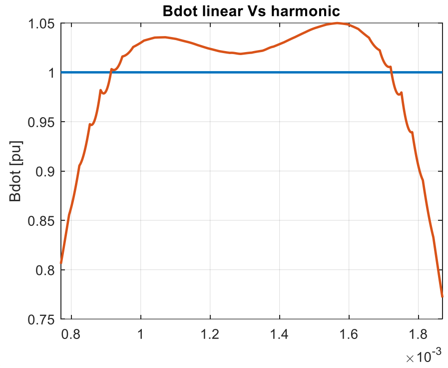
It seems very difficult to reduce its power to an acceptable level, there it will not be considered it in the following of this presentation

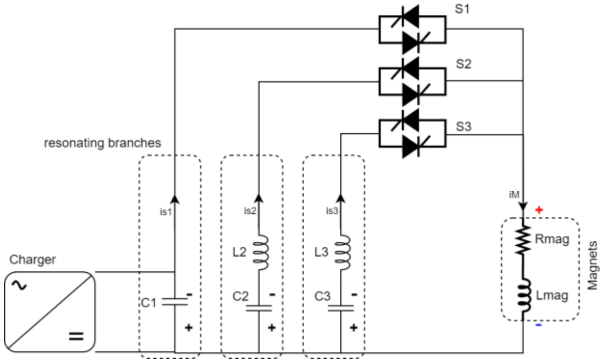
Powering Schemes: full wave resonance

Each harmonics allows better approximation to the linear Bref profile. Case RCS2









$$C_1 = \frac{1}{L_{mag}\omega_f^2(1+n^2) - L_{mag}\omega_p^2};$$

$$C_2 = \frac{n^2\omega_f^4 - n^2\omega_f^2\omega_p^2 -^2 \omega_p^2 + \omega_p^4}{n^2\omega_f^4 L_{mag}(n^2\omega_f^2 + \omega_f^2 - \omega_p^2)};$$

$$L_2 = \frac{2L_{mag}(n^2\omega_f^2 + \omega_f^2 - \omega_p^2)}{(\omega_f^2 - \omega_p^2)(n^2\omega_f^2 - \omega_p^2)};$$

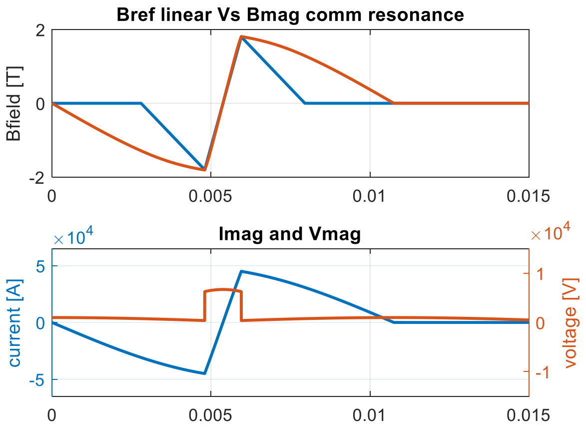
$$\boxed{V_{C1}(0) = L_{mag}\omega_f(I_{k_1} + I_{k_n}n);}$$

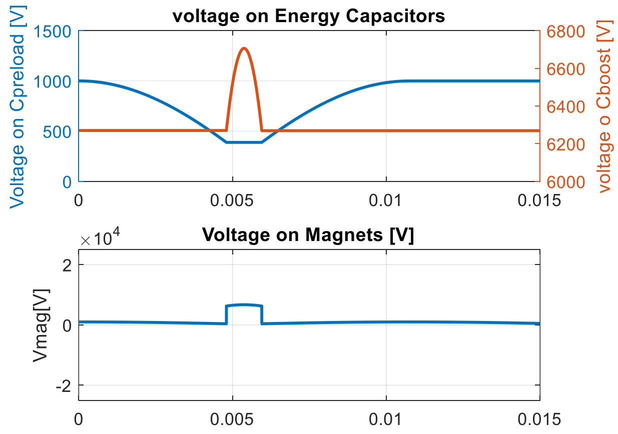
$$\boxed{V_{C2}(0) = \frac{L_{mag}n\omega_f^3(I_{k_1}(n^3\omega_f^2 - n\omega_p^2) + I_{k_n}(n^2\omega_f^2 - n\omega_f^2 + \omega_f^2 - \omega_p^2))}{(\omega_f^2 - \omega_p^2)(n^2\omega_f^2 - \omega_p^2)};}$$

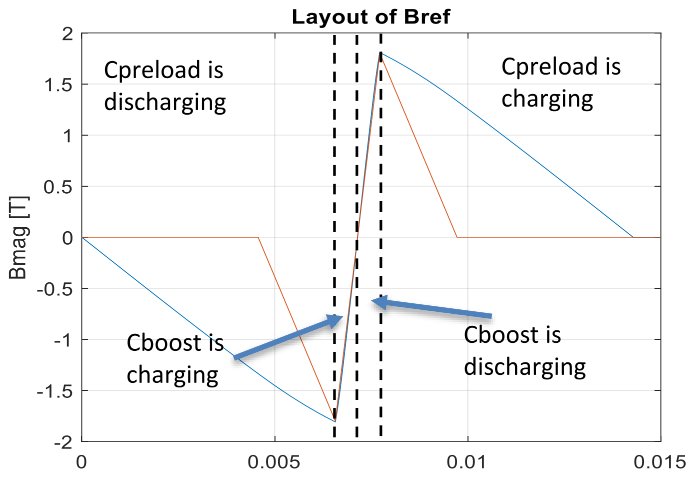
L_{mag}	Magnets inductance
ω_f	main resonating frequency
ω_p	Pole frequency: additional dof
n	Order of the additional harmonic. Assumed n=2
I_{k_1}	Required current first harmonic value
I_{k_n}	Required current nth harmonic value

Resonating parameters are very interlinked. Uncertainties in the circuit parameters cannot be corrected. Additional bulky hardware is required.

Powering Schemes: commutated resonance





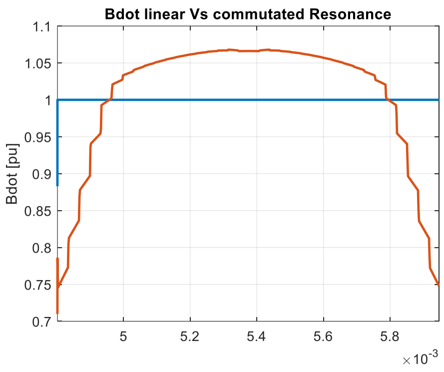


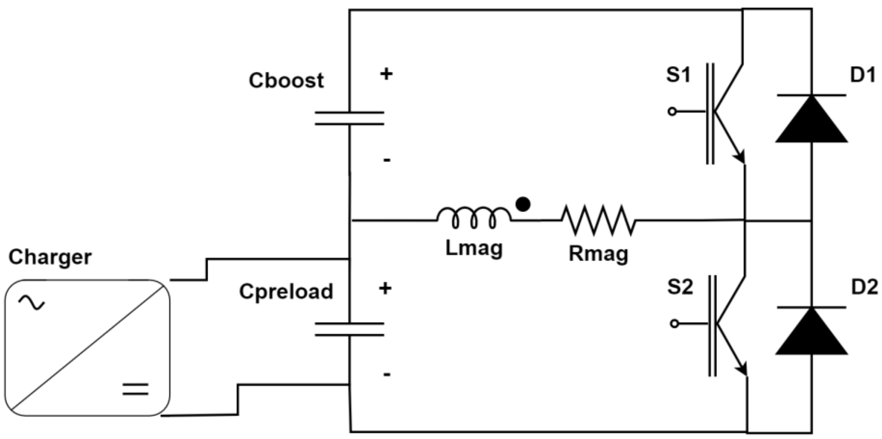
Cpreload is discharging

Cpreload is charging

Cboost is charging

Cboost is discharging





Simpler resonance principle. Voltages of Cboost and Cpreload can be used for regulation (pulse to pulse).

Powering Schemes: comparison

Full wave resonance	RCS2
C1 capacitor bank (per sector)	130 [kJ]
C1 peak positive and negative voltage	+12.5 -7.2 [kV]
C2 capacitor bank (per sector)	90 [kJ]
C2 peak positive and negative voltage	+11.4 -22.6 [kV]
L2 inductor bank (per sector)	45 [kJ]
Total installed energy (RCS2)	53 [MJ]
Total magnet energy @ extraction (RCS2)	17 [MJ]
Total magnet energy @ peak (RCS2)	22 [MJ]
RMS current in the magnet (RCS2)	4.2 [kA]
Magnet losses x m	3.6 [kW/m]
PK current in the magnet (RCS2)	58 [kA]
Field derivative [pu]	1.06

- The capacitors have double polarity excitation and are very high voltage. Much less energy density.
- Inductors for second harmonic are bulky and costly elements.
- The peak current can be high in order to be more linear. High saturation.
- The rms current in the magnet is close to the minimum possible.
- The power electronics is the simplest possible (thyristors)

Commutated resonance	RCS2
Cpreload capacitor bank (per sector)	100 [kJ]
Cpreload peak positive and negative voltage	+1 +0.4 [kV]
Cboost capacitor bank (per sector)	670 [kJ]
Cboost peak positive and negative voltage	+6.9 +6.0 [kV]
L2 inductor bank (per sector)	0 [kJ]
Total installed energy (RCS2)	150 [MJ]
Total magnet energy @ extraction (RCS2)	17 [MJ]
Total magnet energy @ peak (RCS2)	17 [MJ]
RMS current in the magnet (RCS2)	6.6 [kA] (*)
Magnet losses x m	8.7 [kW/m] (*)
PK current in the magnet (RCS2)	45 [kA]
Field derivative [pu]	1.06

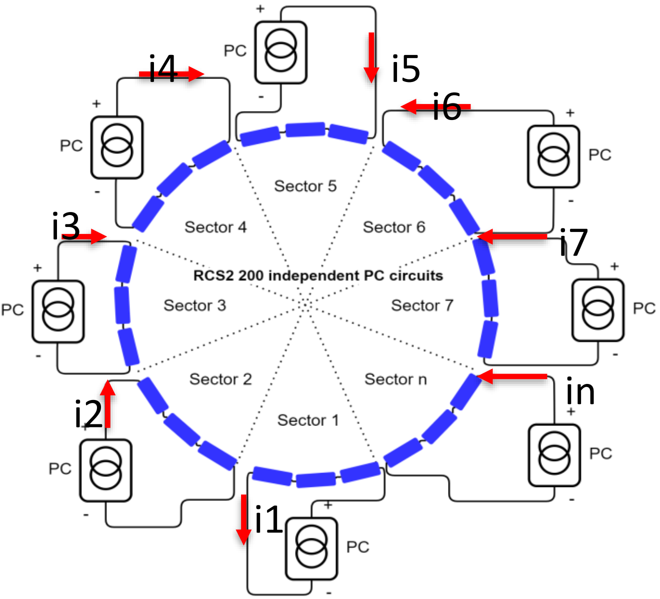
- The installed capacitor energy is ~ 4 times that of the full wave resonance, but there is no voltage polarity reversal, therefore the quantity of material will probably be the same or lower and so the cost.
- No additional inductors are required.
- Peak current is smaller. No or limited saturation
- The rms current is considerably higher than the full wave resonance. (*)
- The power electronics is more complex.

(*) Can be decreased if Higher preload voltage is considered.
As a reference, the PS accelerator (@CERN) has about 4.8kW/m of losses

The control problem description

Independent sectors:

How small must the tracking error among sectors be?



Control performance requirements

During acceleration

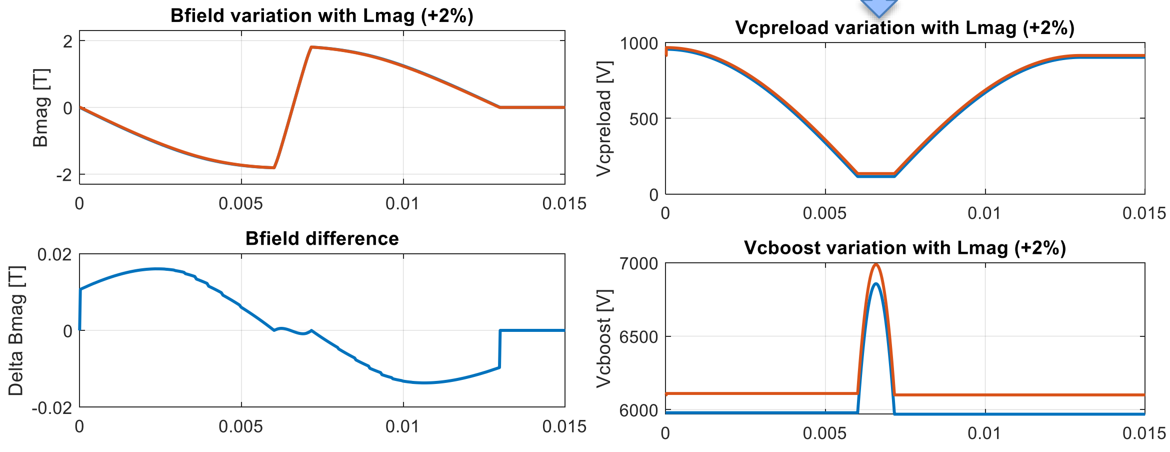
😟 Very hard as acceleration is quick

From pulse to pulse

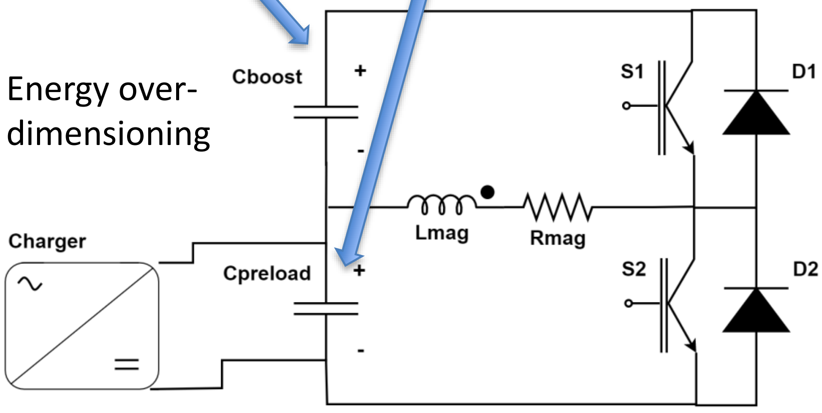
🤔 With a good model of the system we can recover the error in each sector

It means there can be pulses where the tracking error among sectors is out of the limits but then a sort of *"Iterative Learning Control"* recovers the error.

Cpreload and Cboost voltage adjusted



Energy over-dimensioning



Technologies: Capacitors

Ageing Factors: self healing

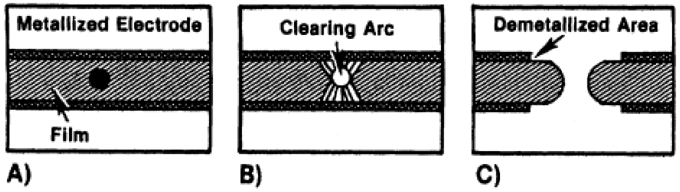


Fig. 2: Schematic diagram of the clearing sequence. A) Metallized film with a defect. B) Voltage applied between electrodes causes breakdown at the defect site and high fault current flows and C) heat from fault current vaporizes electrode and isolates the defect site.

Polypropylene metalized film capacitors are capable to self heal. Self heal comes with a loss of capacitance and it is therefore an ageing factor. The lower the Electric field, the lower the self-healing loss of C.

It is accepted to have short circuits in the design. Ex LMJ capacitors experience a large number of self healings but it’s OK because they only have to make 25’000 pulses in their lifetime.

First discussions with supplier:

Comparing the application to POPS (CERN Main Power Converter for PS)

Full wave resonance
$$NRG_{DensityMUco} = NRG_{DensityMUco} \cdot \left[\frac{E_{fullWave}}{E_{POPS}}\right]^2 = 274\,{}^{J}/_{l} \cdot \left[\frac{65\,{}^{V}/_{\mu m}}{250\,{}^{V}/_{\mu m}}\right]^2 = 274\,{}^{J}/_{l} \cdot \frac{1}{15}$$

Commutated resonance
$$NRG_{DensityMUco} = NRG_{DensityMUco} \cdot \left[\frac{E_{comm}}{E_{POPS}}\right]^2 = 274\,{}^{J}/_{l} \cdot \left[\frac{250\,{}^{V}/_{\mu m}}{250\,{}^{V}/_{\mu m}}\right]^2 = 274\,{}^{J}/_{l}$$

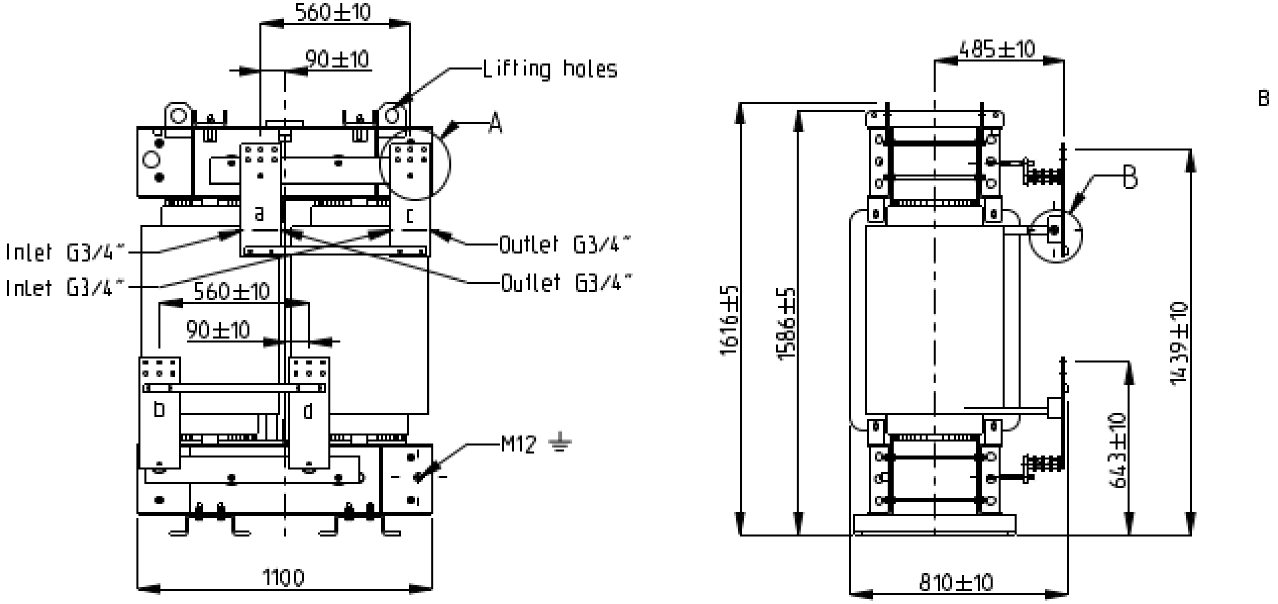
POPS container 12mx2.5mx2.5m; 26tons; 0.5MCHF;
Full wave resonance → 0.22MJ
Commutated resonance → 3.3MJ

Technologies: Inductors

Still to be analysed but for the order of magnitude:

POPS AC inductor:

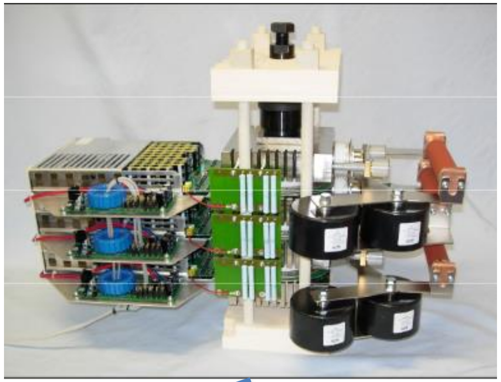
- Energy 18 kJ
- Current 6kA
- Weight 3 tonnes
- Cost 40 kEur



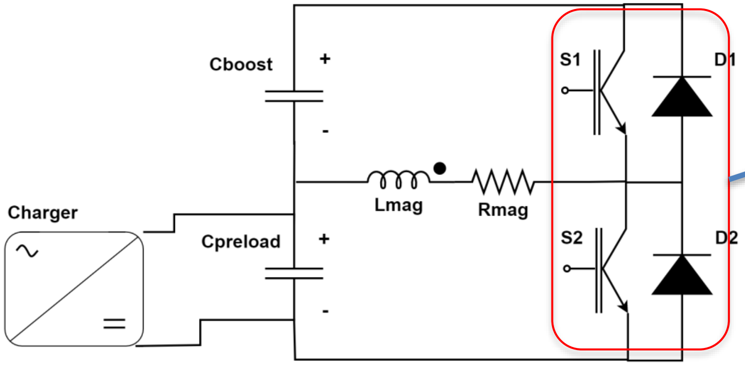
Technologies: Thyristors and IGBTs/IGCTs

IGCT

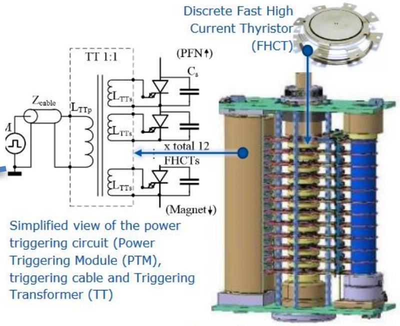
Voltage: up to 6kV
Turn-on/off current: up to 6kA
Several series/parallel required



IGBT



50 kA turn off current;
10 kV blocking voltage;
6 kA rms current;
100A/us dI/dt;

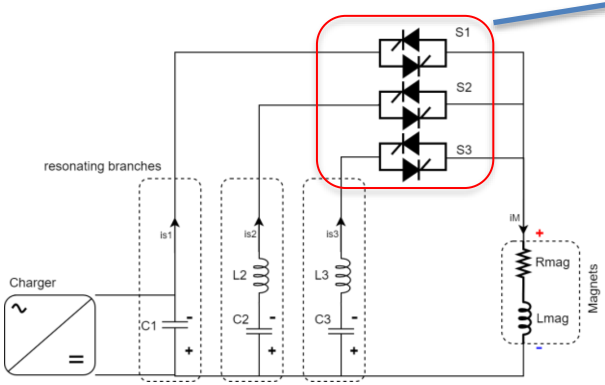


Discrete Fast High Current Thyristor (FHCT)

Simplified view of the power triggering circuit (Power Triggering Module (PTM), triggering cable and Triggering Transformer (TT)

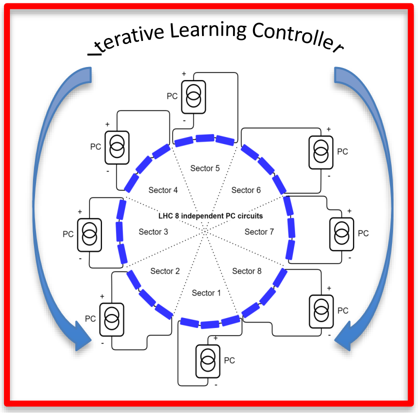
Main switch of future SPS Beam Dumping System, 3D Model

Pulsed power thyristors
To be completed

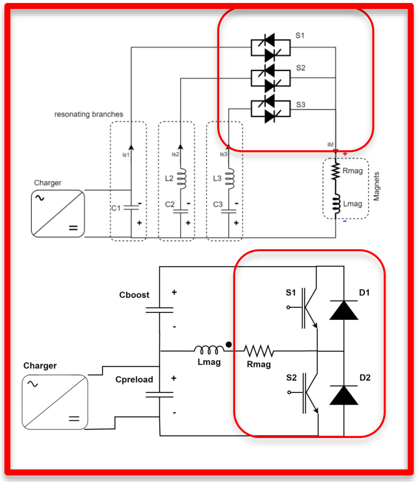


50 kA peak current;
20 kV blocking voltage;
100A/us dI/dt
Several series/parallel required

Working plan



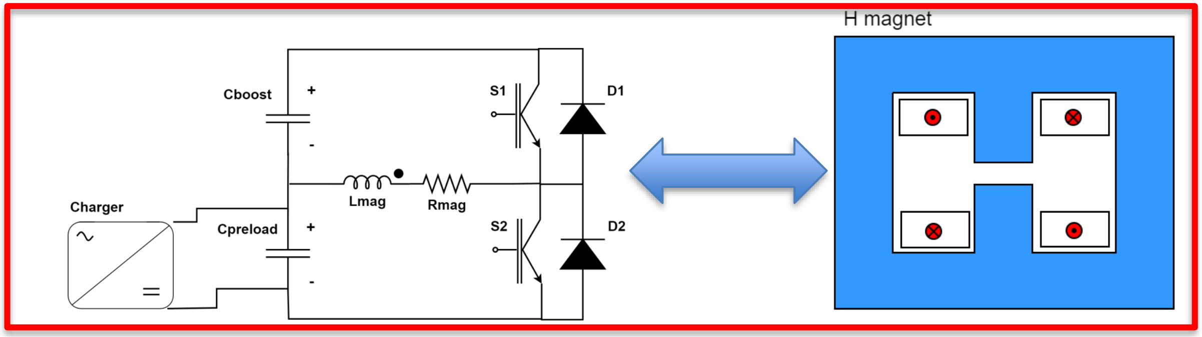
1) Circuital studies of a reduced scale model to prove the possibility of controlling the field in pulse-to-pulse mode
2) Identification of circuital parameters variation: Magnet, Capacitors, IGBT jitter etc…



3) Design rules of the power electronics elements

4) Design rules of the capacitors and inductors

5) Coupled Power converter – magnet optimization with cost estimation



Conclusions

- The extremely high peak power requires division into several sector. These can be connected either in series or be independent;
- Two resonance mode powering schemes have been presented. The commutated resonance is potentially more flexible but requires a more complicated power electronics development. R&D will be required for it;
- The different resonating scheme have an impact on the design of the energy storage elements;
- Tracking control accuracy very difficult to achieve → pulse to pulse control → Input required: control accuracy;
- Design rules for the main components of the powering system needs to be checked with suppliers;
- Eventually an optimization of the powering scheme Vs the magnet design must be performed to find lowest cost solution.