Elettra Sincrotrone Trieste

On ESS LWU quadrupoles QC6 and QC7: DC and pulsed mode evaluation, magnet design and power supplies

Davide Castronovo, Roberto Visintini
Elettra Sincrotrone Trieste

Outline

- ✓ ***Introduction***
- ✓ ***Basic parameters and specifications***
- ✓ ***Pre-design***
- ✓ ***Design***
- ✓ ***All models***
- ✓ ***Magnetic simulation***
- ✓ ***Power Supplies Considerations***
- ✓ ***Conclusions***

Introduction

Based on the ESS report “*On the feasibility of pulsing the ESS LWU Quadrupoles*” (ESS-0019925), with the most updated requirements on the magnets, this presentation shows a comparison among potential magnet designs for the LWU QC6 and QC7 quadrupoles operated either with DC or pulsed excitation.

The goal is to obtain some information about the:

1. ***Feasibility***
2. ***Performance***
3. ***Power consumption***
4. ***Overall dimensions***
5. ***Cost considerations***

Basic parameters and specifications

Real basic requirements

Parameters		QC6	QC7	unit
Number of required quads	n	**95**	**12**	#
Maximum integrated gradient	$IntG_{Max}$	**2.3**	**2.9**	T
Range of integrated gradient	$IntG_{range}$	**1.20 - 2.20**	**0.85 - 2.70**	T
Minimum magnetic length	L_{eff}	275	275	mm
Minimum bore diameter	Ø	112	112	mm
Maximum overall length	$L_{Overall}$	350	350	mm

QC6 and QC7 have the same dimension but different nominal ranges

QC7 have a wider range of use (lower and upper values), but…

…there are many more QC6 than QC7 (95 vs. 12)

How to merge the two quadrupole families into one?

Pre Design ●○○○○

In the pre-design we decided to **fix** common parameters **for all** the possible models:

1. The maximum current (DC) equal to the maximum RMS current (pulsed)
2. The max current density (DC) and the max RMS current density (pulsed)
3. The bore diameter and pole width (the poles geometry)
4. The yoke length and the overall length (the maximum thickness of the coils)

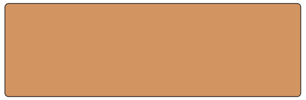
The values are:

- Maximum Power Supply (PS) current, DC or RMS = **150 A**
- Maximum **water** cooled current density = **4 A/mm²** *(at max PS Current, DC or RMS)*
- Maximum **air** cooled current density = **1.1 A/mm²** *(at max PC Current, DC or RMS)*
- Bore diameter = **112 mm** *(equal to the min requested in order to reduce the ampereturns)*
- Poles width = **70 mm** *(equal to the GFR in order to reduce the frame dimensions)*
- Yoke length = **240 mm**
- Overall Length = **350 mm** *(equal to the max value requested)*

Pre Design ●●○○○

The desired current densities are achieved with the following copper conductors:

- Air cooled:

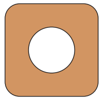


OD = **6.30** x 20 mm^2 (125.1 mm^2)

If I_{RMS} = **150** A → ρ_{RMS} = **1.19** A/mm^2

else if ρ_{RMS} < 1.10 A/mm^2 → I_{RMS} < **137.6** A

- Water cooled



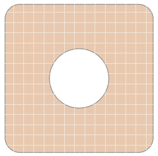
OD = **6.35** x 6.35 mm^2 (32.3 mm^2), ID = 3.15 mm

If I_{DC} = **150** A → ρ_{DC} = **4.6** A/mm^2

else if ρ_{DC} < 4.0 A/mm^2 → I_{DC} < **129.2** A

If we want to reduce the DC power, we must increase the conductor section, example:

- Water cooled



OD = 10.0 x 10.0 mm^2 (86.6 mm^2), ID = 4.0 mm

If I_{DC} = **150** A → ρ_{DC} = **1.7** A/mm^2

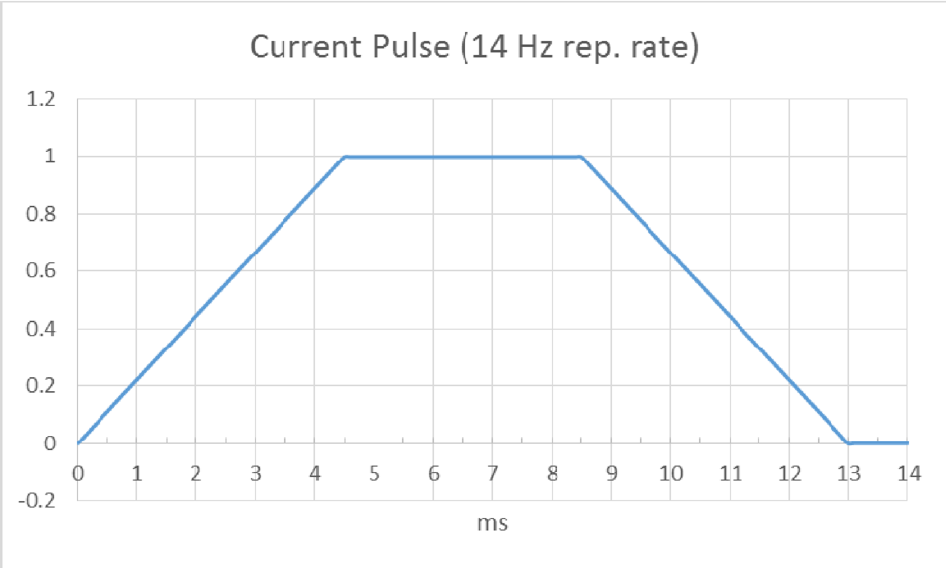
if I_{DC} = **129.2** → ρ_{DC} = **1.5** A/mm^2

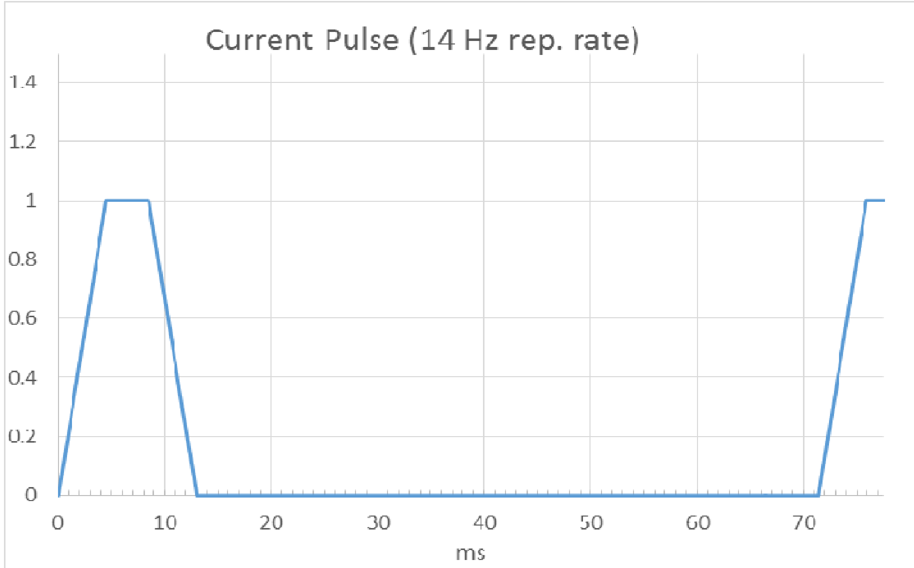
All the other parameters are calculated in the following excel sheets

Pre Design ●●●○○

For the pulsed excitation, two waveforms have been considered:

- Trapezoidal, 4.5 ms rise/fall, 4 ms flat-top, 14 Hz repetition rate (71.4 ms period)
- Trapezoidal, 8 ms rise/fall, 4 ms flat-top, 14 Hz repetition rate (71.4 ms period)





Current Pulse [4.5 – 4 – 4.5] ms

Pre Design ●●●●○

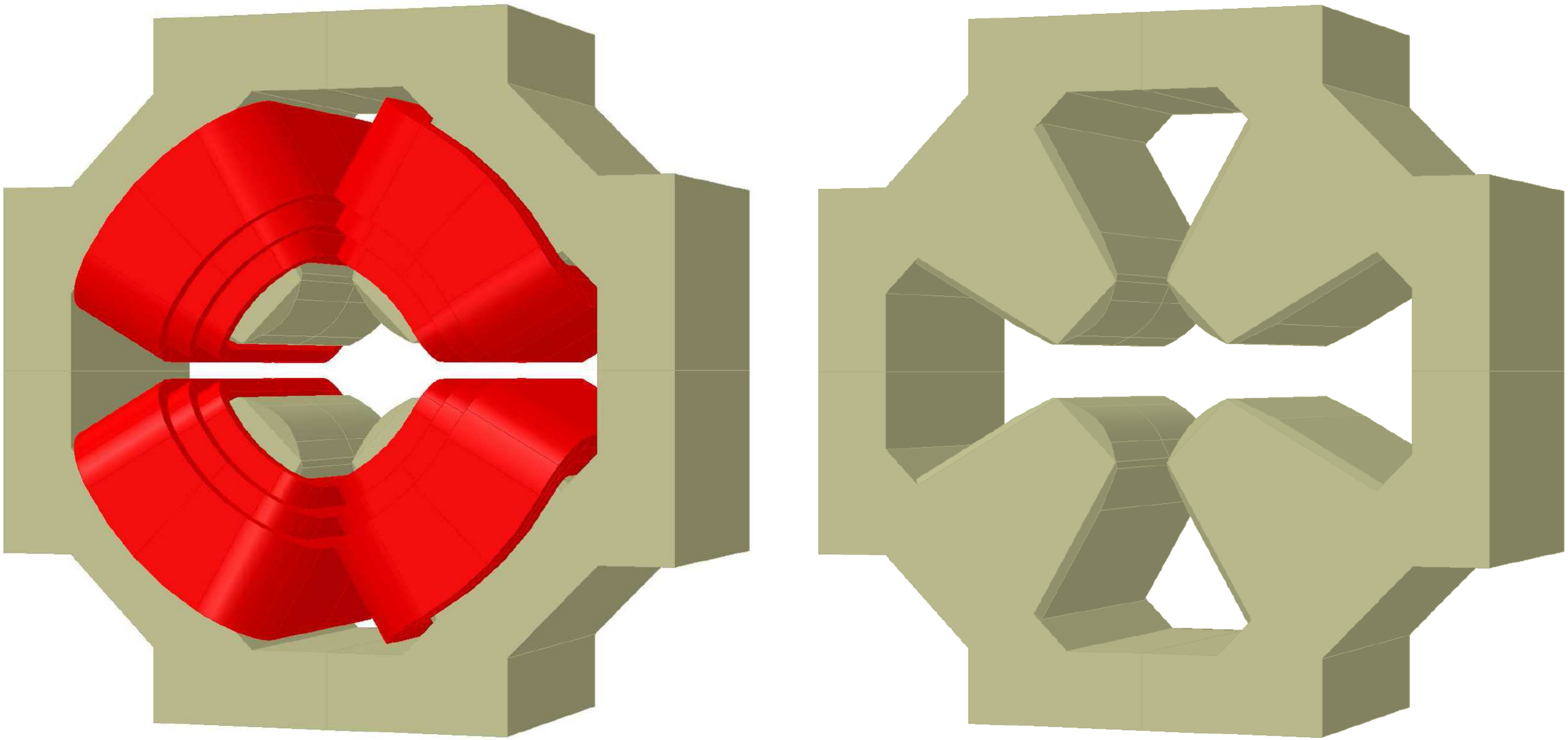
		Pulsed	Pulsed	DC	DC	Pulsed	Pulsed	DC	DC	
		QC6	QC6 air	QC6	QC6 air	QC7	QC7 air	QC7	QC7 air	unit
# of Quads	N	95	95	95	95	12	12	12	12	
Expected total length	Z_{Tot}	350	350	350	350	350	350	350	350	mm
Maximum Integrated Gradient	G_{Int}	2,30	2,30	2,30	2,30	2,90	2,90	2,90	2,90	T
Maximum Nominal Integrated Gradient	G_{nom}	2,20	2,20	2,20	2,20	2,70	2,70	2,70	2,70	T
Minimum Nominal Integrated Gradient	G_{NOM}	1,20	1,20	1,20	1,20	0,80	0,80	0,80	0,80	T
Bore diameter	Ø	112	112	112	112	112	112	112	112	mm
Pulse Frequency	Fr	14,0	14,0	14,0	14,0	14,0	14,0	14,0	14,0	Hz
Pulse RiseTime	T_{up}	4,5	4,5	0,0	0,0	4,5	4,5	0,0	0,0	msec
Pulse Flat TopTime	T_{flat}	4,0	4,0	71,4	71,4	4,0	4,0	71,4	71,4	msec
Pulse Fall Time	T_{down}	4,5	4,5	0,0	0,0	4,5	4,5	0,0	0,0	msec
Pulse RMS	I_{cRMS}	31,3	31,3	100,0	100,0	31,3	31,3	100,0	100,0	%
Pole ampere-turns density		0,36	0,36	0,36	0,36	0,46	0,46	0,46	0,46	$N \cdot I/mm^2$
Magnetic Lenght	L_{Mag}	275	275	275	275	275	275	275	275	mm
Maximum Gradient	G_{Max}	8,364	8,364	8,364	8,364	10,545	10,545	10,545	10,545	T/m
Field at pole tip radius	B_{Pole}	0,468	0,468	0,468	0,468	0,591	0,591	0,591	0,591	T
Current·Turns (per Pole) + 0 %	$N_{Tot} \cdot I_{Coil}$	10436	10436	10436	10436	13159	13159	13159	13159	A·Turns
Turns per pole	N_{Tot}	24	24	78	78	30	30	96	96	Turns
Number of turns for each layer	NL_1	10	5	18	14	12	6	21	17	#
	NL_2	8	5	16	14	10	6	19	17	#
	NL_3	6	4	14	13	8	5	17	16	#
	NL_4	0	4	12	13	0	5	15	16	#
	NL_5	0	3	10	12	0	4	13	15	#
	NL_6	0	3	8	12	0	4	11	15	#
Coils current at Max Int. Grad.	I_c	434,9	434,9	133,8	133,8	438,7	438,7	137,1	137,1	A
RMS Coils current at Max Int. Grad.	$I_{c\ RMS}$	137	137	134	134	138	138	138	138	A

Pre Design ●●●●●

		Pulsed	Pulsed	DC	DC	Pulsed	Pulsed	DC	DC	
		QC6	$QC6_{air}$	QC6	$QC6_{air}$	QC7	$QC7_{air}$	QC7	$QC7_{air}$	unit
Conductor cross section width	W_{Cu}	6,35	6,30	6,35	6,30	6,35	6,30	6,35	6,30	mm
Conductor cross section heigth	H_{Cu}	6,35	20,00	6,35	20,00	6,35	20,00	6,35	20,00	mm
Conductor cross section dia bore	$Ø_{Cu}$	3,15	0,00	3,15	0,00	3,15	0,00	3,15	0,00	mm
Conductor cross section smooth	r_{Cu}	0,500	0,500	0,500	0,500	0,500	0,500	0,500	0,500	mm
Conductor cross section area	A_{Cu}	32,315	125,785	32,315	125,785	32,315	125,785	32,315	125,785	mm^2
RMS current density = I_c / A_{Cu}	ρ_{Cu}	4,24	1,09	4,15	1,07	4,27	1,10	4,27	1,10	A/mm^2
Conductor insulation thickness	T_{Cu}	1,00	1,00	0,20	0,20	1,00	1,00	0,20	0,20	mm
Conductor cross section overall width	TW_{Cu}	7,35	7,30	6,55	6,50	7,35	7,30	6,55	6,50	mm
Conductor cross section overall heigth	TH_{Cu}	7,35	21,00	6,55	20,20	7,35	21,00	6,55	20,20	mm
Coil Heigth	H_{Coil}	73,5	504,0	117,9	282,8	88,2	126,0	137,6	343,4	mm
Pole length	L_{Yoke}	240	240	240	240	240	240	240	240	mm
Pole width (avg)	W_{Pole}	120	120	120	120	120	120	120	120	mm
Coil inner straight length	L_{Ci}	220	220	220	220	220	220	220	220	mm
Coil inner width	W_{Ci}	130	130	130	130	130	130	130	130	mm
Single Coil conductor length	L_{Coil}	19,3	20,8	66,2	67,2	24,2	26,1	81,8	82,8	m
Single Coil electric resistance at T_{ave}	R_{Coil}	10,30	2,88	36,52	9,30	12,95	3,61	45,77	11,46	mΩ
Single Coil voltage drop at T_{ave} & I_c	V_{Coil}	4,48	1,25	4,89	1,24	5,68	1,58	6,27	1,57	V
Magnet Inductance	L_H	8,2	8,2	0,0	0,0	10,3	10,3	0,0	0,0	mH
Max Over Voltage L*dI/dt	V_{Rip}	792	792	0	0	1.004	1.004	0	0	V
Overall Length	L_{Tot}	301,2	344,4	336,5	335,6	301,2	344,4	336,5	335,6	mm
RMS Max PC current = I_c + 0 %	I_{PS}	136,1	136,1	133,8	133,8	137,3	137,3	137,1	137,1	A
Magnet Power at I_{PS} and T_{ave}	P_{Mag}	0,76	0,21	2,62	0,67	0,98	0,27	3,44	0,86	kW

Design ●○○

As the Good Field Region (GFR) is lower than the bore diameter, the idea is to use, for all the models, only one geometry of the pole profile, the width of the termination equals the diameter of the GFR. The coils are very close to the vacuum chamber and the frame is more compact.

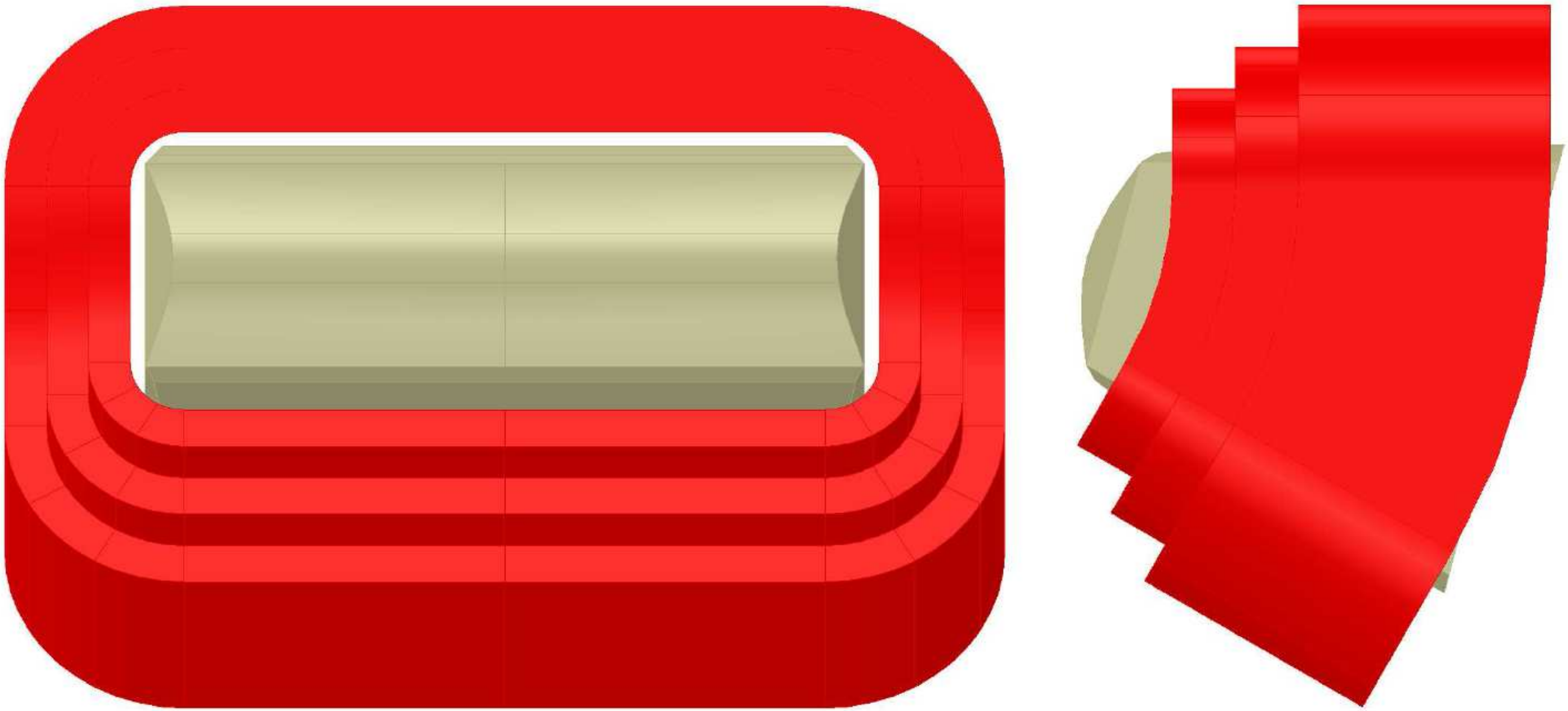


Design ●●○

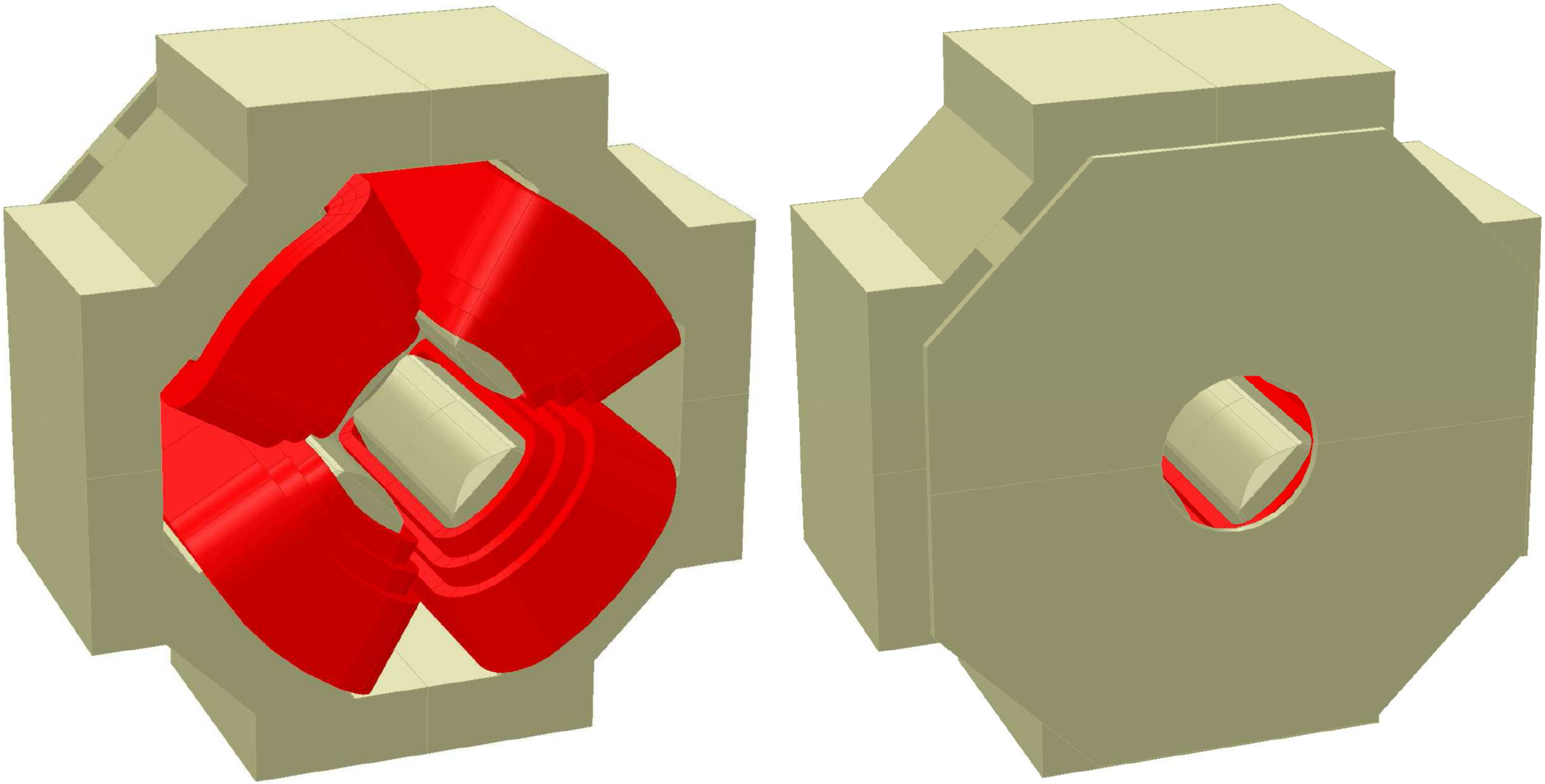
The poles edges are vertically chamfered to allow rounding the coils close to the pole itself…

The pole transversal section is trapezoidal to reduce the saturation…

The coils are not simple racetrack, they are defined in Opera by straight and arc conductors



QC7 with 30 turns and coils made by solid copper… (shield shown on one side only)



All models ●○○○○

(*) Pulsed | **DC**

Turns per pole = 24

I@G_{Max} = 435A

I_{RMS}@G_{Max} = 137A

P_{Mag} = 0.21kW

L_{Mag} = 8.2 mH

V_{PK} = 0.79 kV

Turns per pole = 78

I@G_{Max} = 134 A

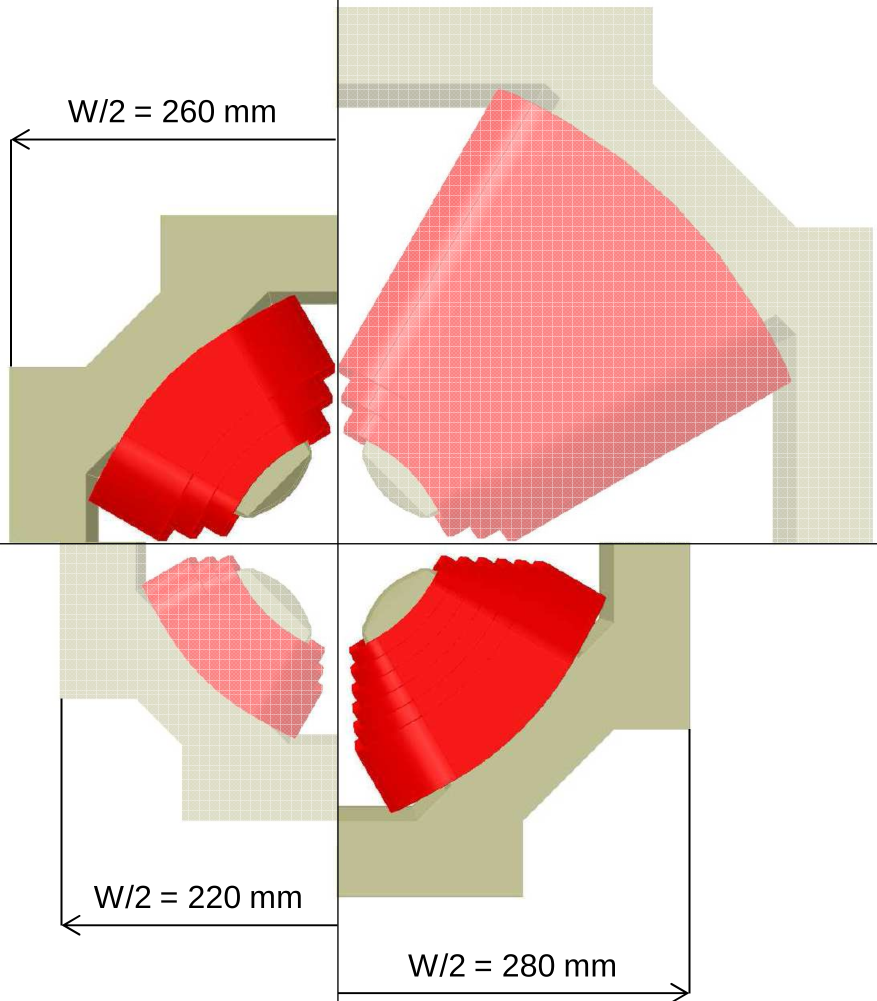
I_{RMS}@G_{Max} = 134 A

P_{Mag} = 0.67 kW

Air

QC6

H_2O



Turns per pole = 24

I@G_{Max} = 435A

I_{RMS}@G_{Max} = 137A

P_{Mag} = 0.76 kW

Turns per pole = 78

I@G_{Max} = 134 A

I_{RMS}@G_{Max} = 134 A

P_{Mag} = 2.62 kW

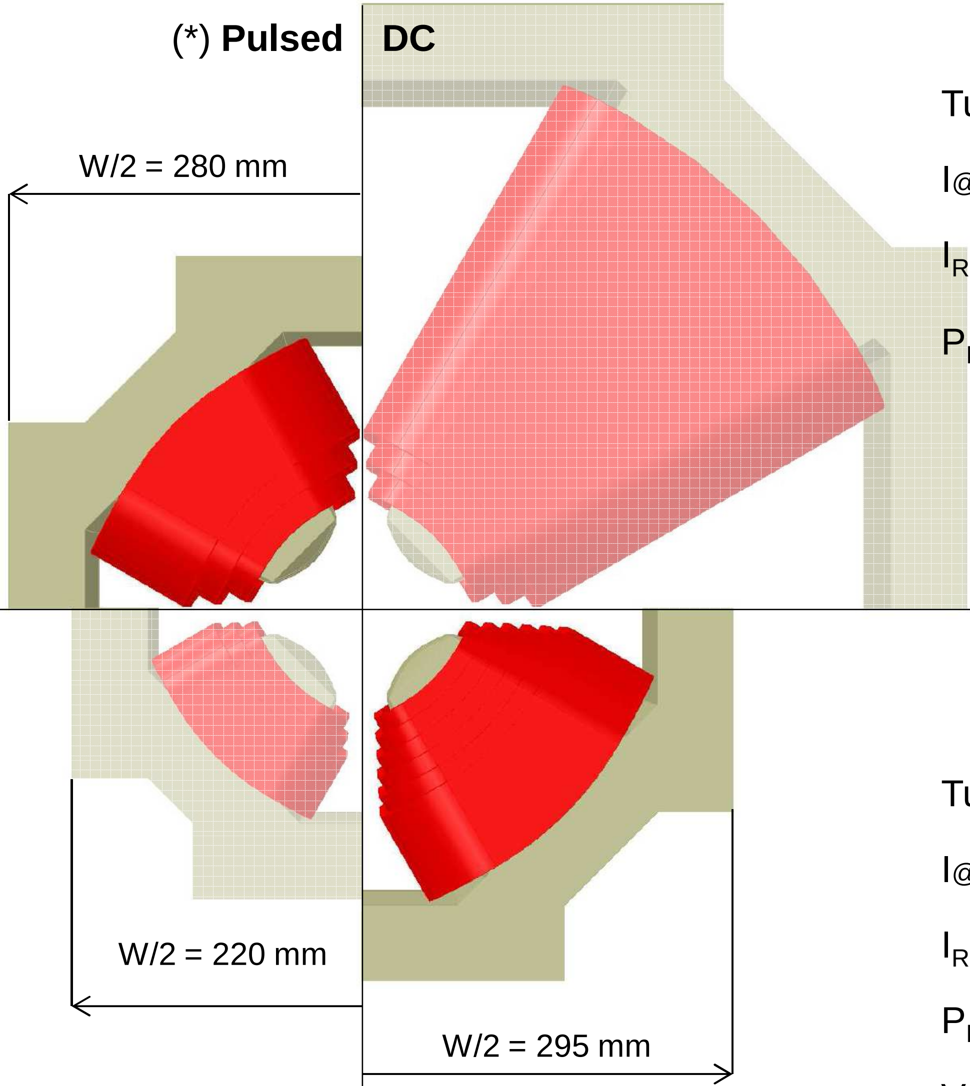
V_{MAX} = 20 V

(*) Rise time 4.5 ms, flat top time 4 ms and fall time 4.5 ms

All models ●●○○○

QC7

Air / H_2O



(*) Pulsed, Air

Turns per pole = 30

$I@G_{Max}$ = 439A

$I_{RMS}@G_{Max}$ = 138A

P_{Mag} = 0.27kW

L_{Mag} = 10.3 mH

V_{PK} = 1kV

DC, Air

Turns per pole = 96

$I@G_{Max}$ = 137 A

$I_{RMS}@G_{Max}$ = 137 A

P_{Mag} = 0.86 kW

(*) Pulsed, H_2O

Turns per pole = 30

$I@G_{Max}$ = 439A

$I_{RMS}@G_{Max}$ = 138A

P_{Mag} = 0.98 kW

DC, H_2O

Turns per pole = 96

$I@G_{Max}$ = 137 A

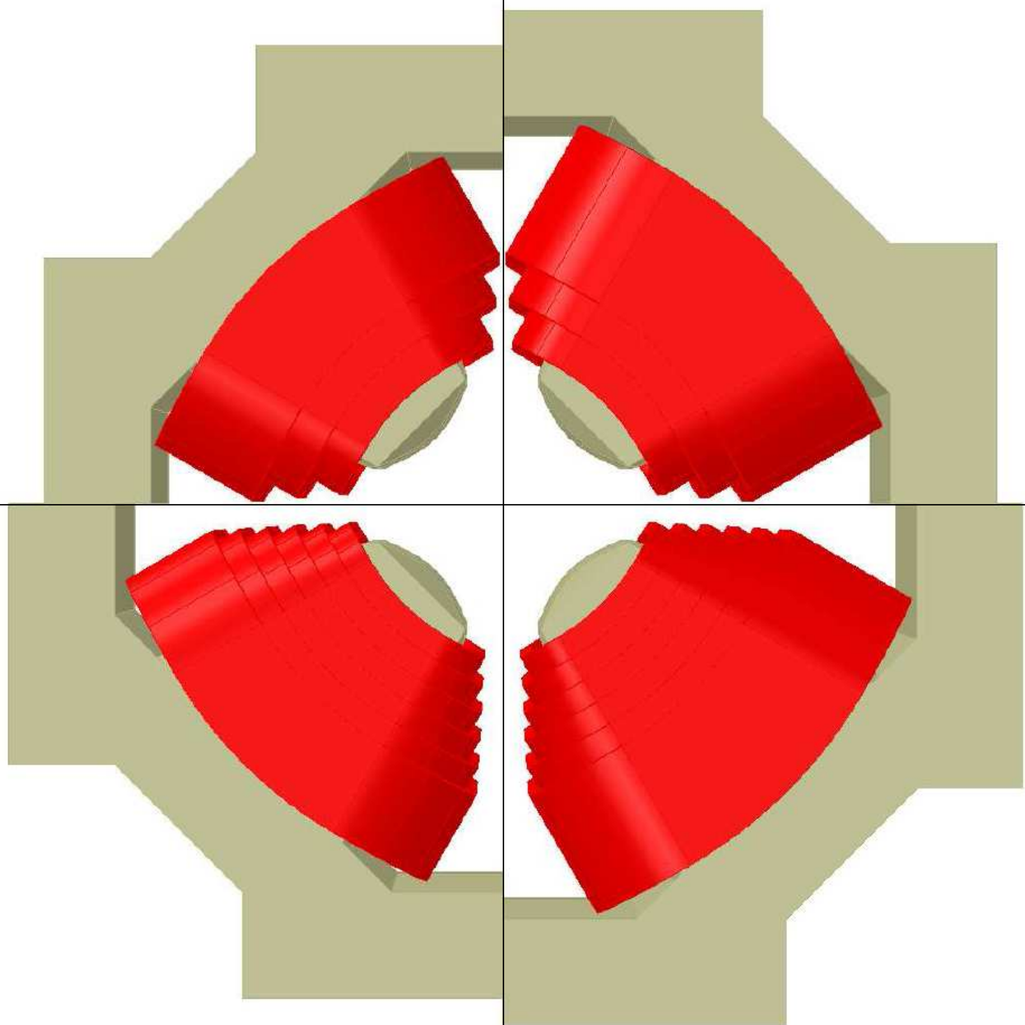
$I_{RMS}@G_{Max}$ = 137 A

P_{Mag} = 3.44 kW

V_{MAX} = 25 V

(*) Rise time 4.5 ms, flat top time 4 ms and fall time 4.5 ms

All models ●●●○○



QC6 – Pulsed (*)

Turns per pole = 24

$I@G_{Max}$ = 435A

$I_{RMS}@G_{Max}$ = 137A

P_{Mag} = 0.21kW

L_{Mag} = 8.2 mH

V_{PK} = 0.79 kV

QC7 – Pulsed (*)

Turns per pole = 30

$I@G_{Max}$ = 439 A

$I_{RMS}@G_{Max}$ = 138 A

P_{Mag} = 0.27 kW

L_{Mag} = 10.3 mH

V_{PK} = 1kV

QC6 – DC

Turns per pole = 78

$I@G_{Max}$ = 134 A

$I_{RMS}@G_{Max}$ = 134 A

P_{Mag} = 2.62 kW

V_{MAX} = 20 V

QC7 – DC

Turns per pole = 96

$I@G_{Max}$ = 137 A

$I_{RMS}@G_{Max}$ = 137 A

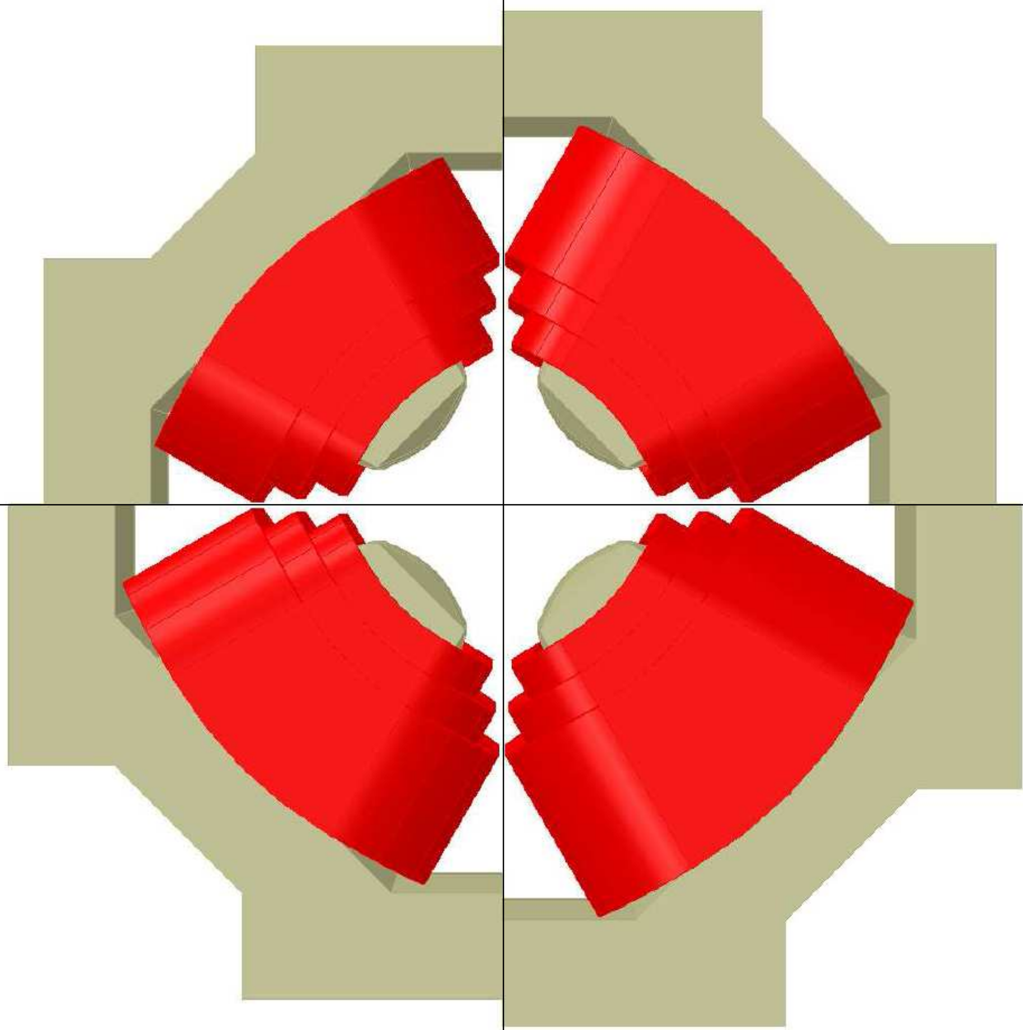
P_{Mag} = 3.44 kW

V_{MAX} = 25 V

(*) Rise time 4.5 ms, flat top time 4 ms and fall time 4.5 ms

All models ●●●●○

QC6 | QC7



Rise/Fall 4.5 ms

QC6:

Turns per pole = 24

$I@G_{Max}$ = 435A

$I_{RMS}@G_{Max}$ = 137A

P_{Mag} = 0.21kW

L_{Mag} = 8.2 mH

V_{PK} = 0.79 kV

QC7:

Turns per pole = 30

$I@G_{Max}$ = 439 A

$I_{RMS}@G_{Max}$ = 138 A

PMag = 0.27 kW

L_{Mag} = 10.3 mH

V_{PK} = 1kV

Rise/Fall 8.0 ms

QC6:

Turns per pole = 30

$I@G_{Max}$ = 126 A

$I_{RMS}@G_{Max}$ = 348 A

P_{Mag} = 0.23 kW

L_{Mag} = 10.3 mH

V_{PK} = 0.45 kV

QC7:

Turns per pole = 36

$I@G_{Max}$ = 133 A

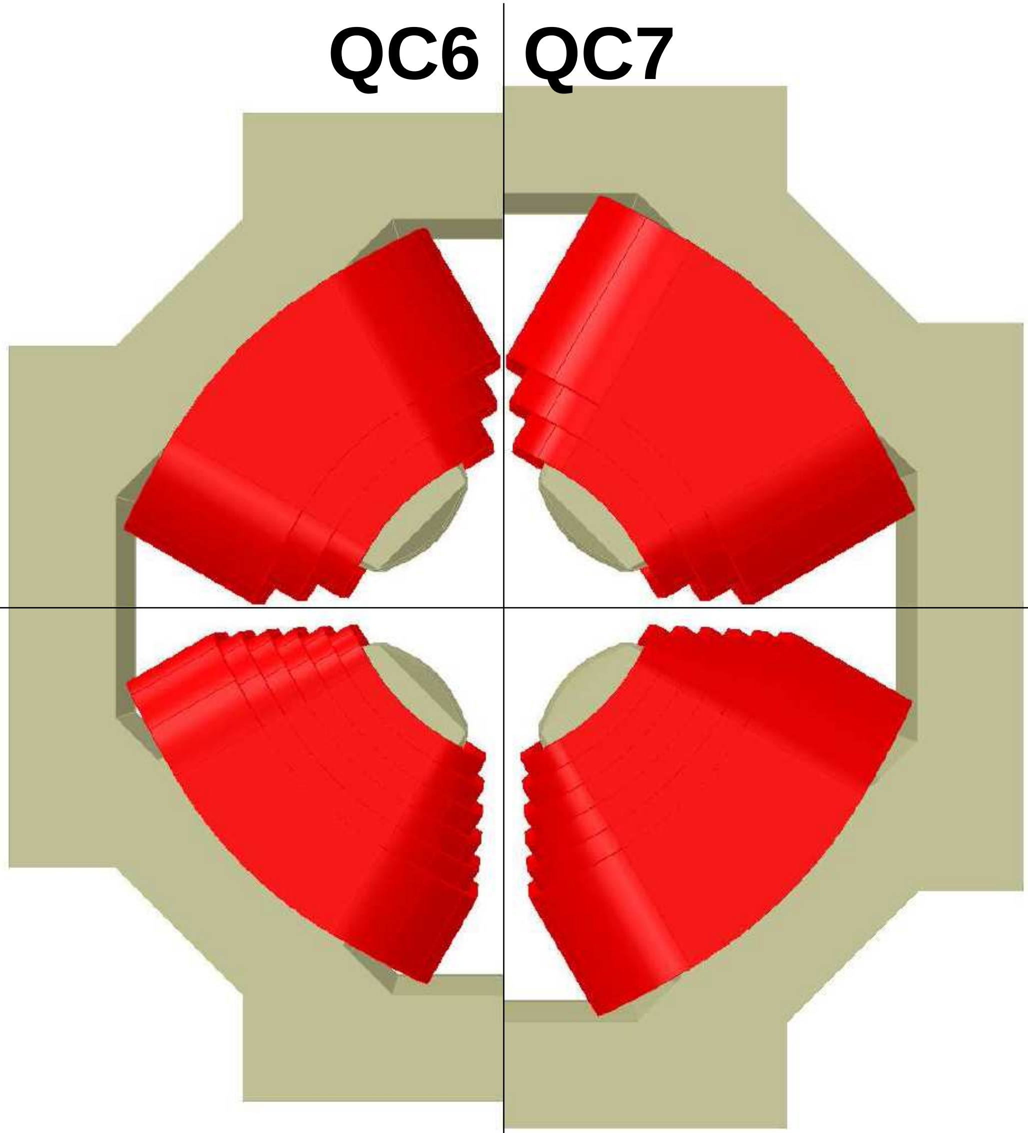
$I_{RMS}@G_{Max}$ = 366 A

P_{Mag} = 0.30 kW

L_{Mag} = 14.0 mH

V_{PK} = 0.64 kV

All models ●●●●●



Rise 8 ms (*)

QC6:

Turns per pole = 30

$I@G_{Max}$ = 348 A

$I_{RMS}@G_{Max}$ = 126 A

P_{Mag} = 0.23 kW

L_{Mag} = 10.3 mH

V_{PK} = 0.45 kV

QC7:

Turns per pole = 36

$I@G_{Max}$ = 366 A

$I_{RMS}@G_{Max}$ = 133 A

P_{Mag} = 0.30 kW

L_{Mag} = 14.0 mH

V_{PK} = 0.64 kV

DC

QC6:

Turns per pole = 78

$I@G_{Max}$ = 134 A

$I_{RMS}@G_{Max}$ = 134 A

P_{Mag} = 2.62 kW

V_{MAX} = 20 V

QC7:

Turns per pole = 96

$I@G_{Max}$ = 137 A

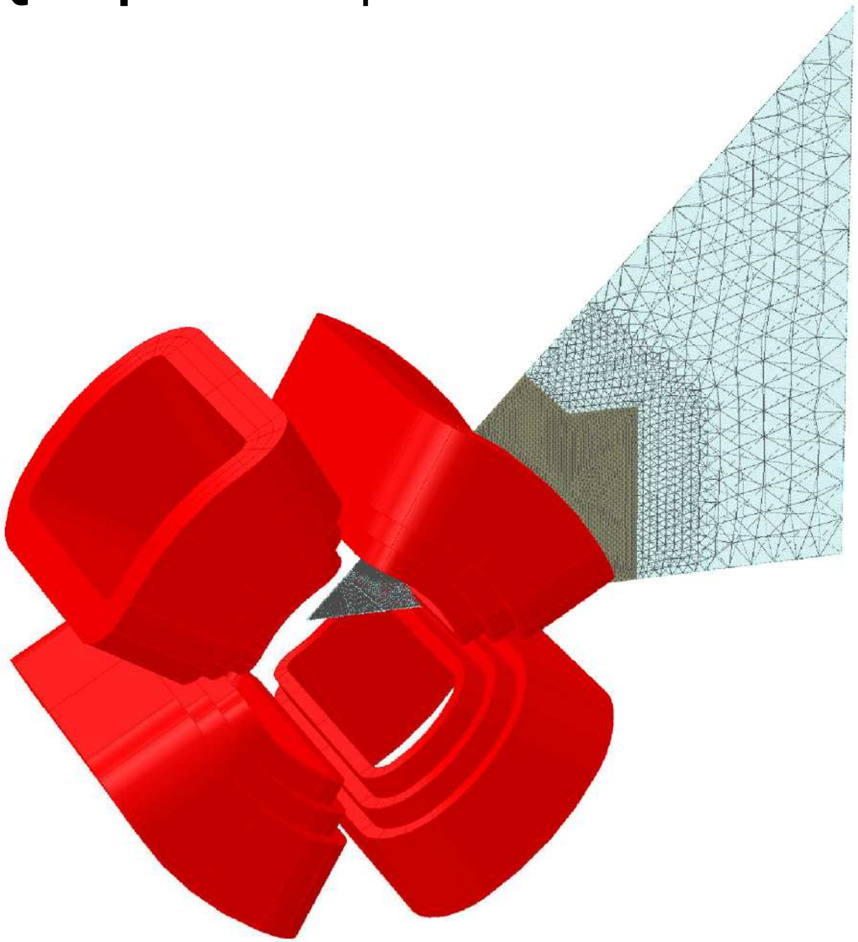
$I_{RMS}@G_{Max}$ = 137 A

P_{Mag} = 3.44 kW

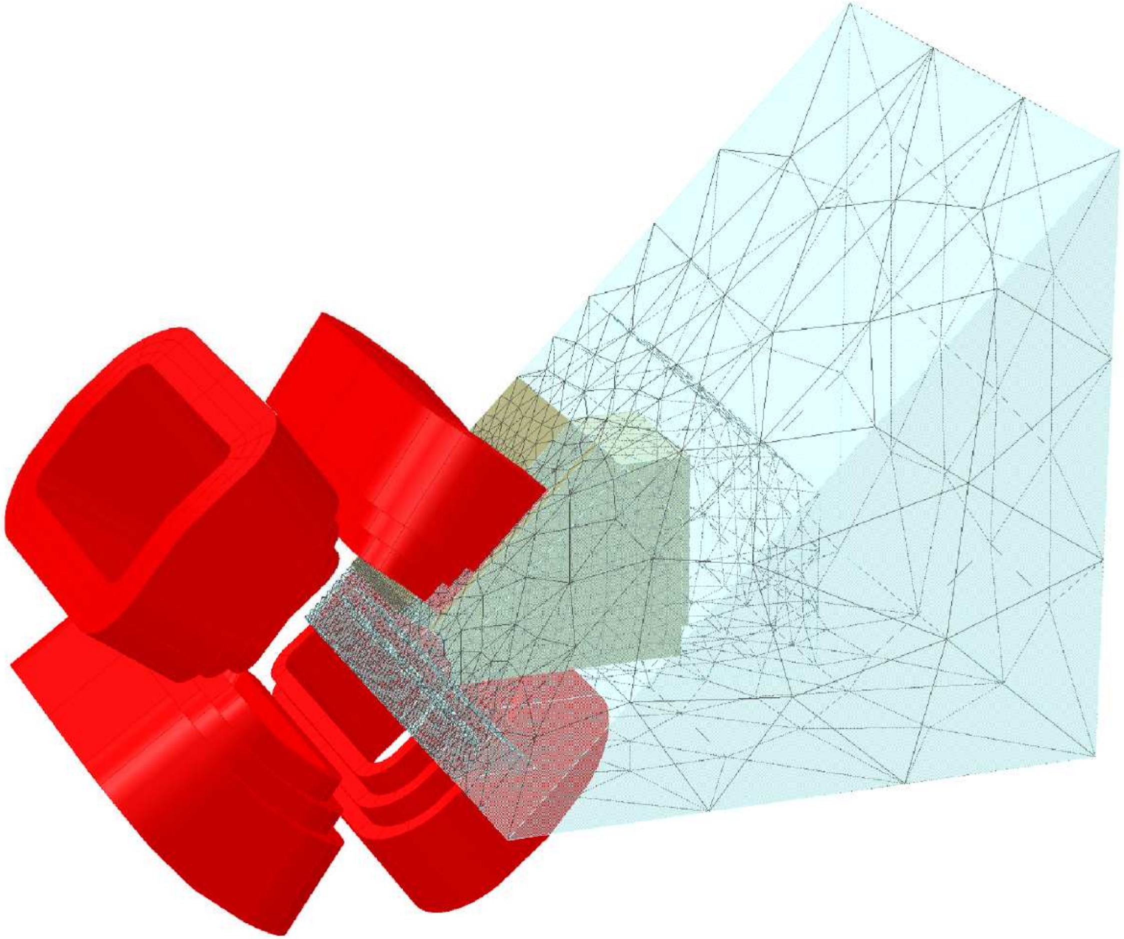
V_{MAX} = 25 V

(*) Rise time 8.0 ms, flat top time 4 ms and fall time 8.0 ms

QC7 pulsed: Opera models

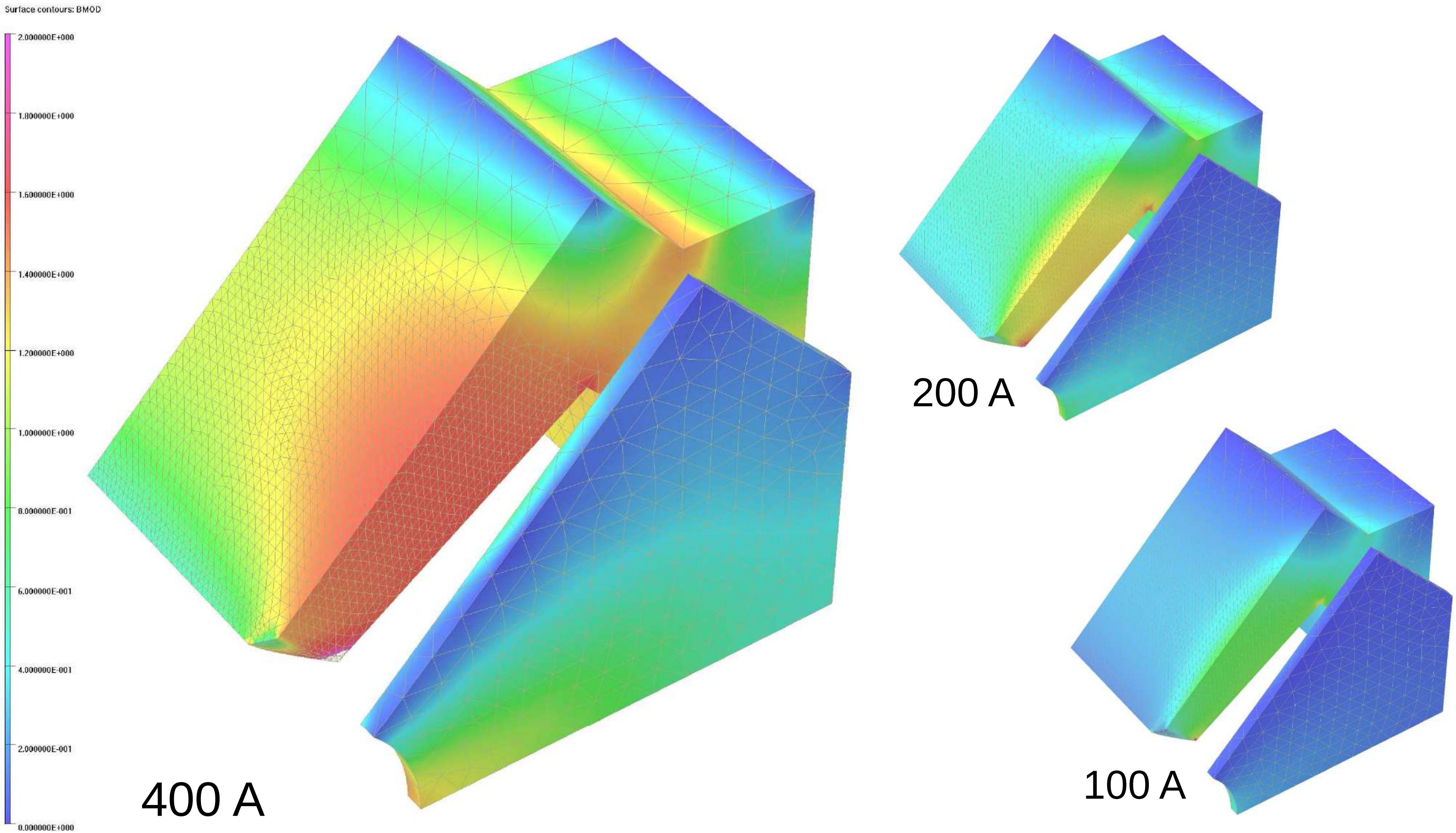


Single lamination model (2.5D)

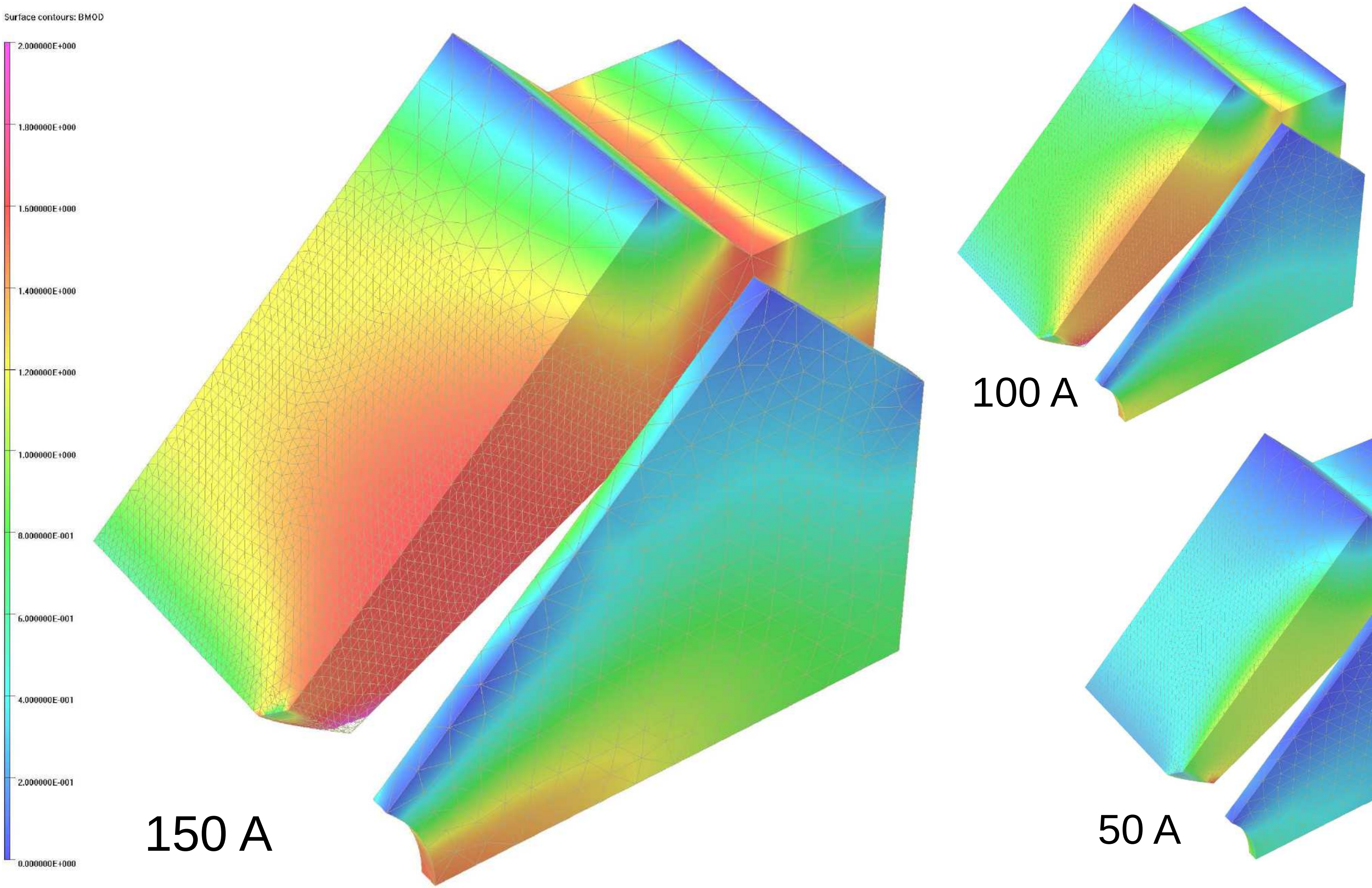


3D model

QC7 pulsed: Tosca simulations at:



QC7 DC: Tosca simulations at:

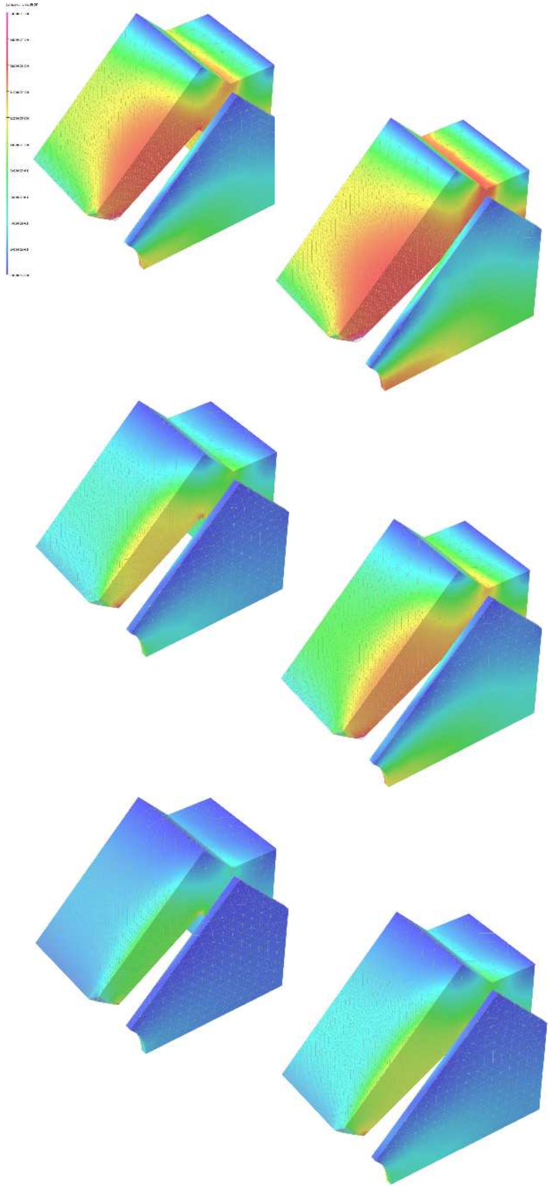


QC7 pulsed - *Tosca results:*

*Int.Gradient (at x = 35mm) at **400A; $G2_{sat}$ = -0.99%***		
GN	|G|	G/G2 [%]
G2 [T/m]	**2.5671**	100.00
G4 [T/m^4]	0.0001	0.0020
G6 [T/m^6]	0.0013	**0.0510**
G8 [T/m^8]	0.0001	0.0042
G10 [T/m^{10}]	0.0004	**0.0141**

*Int.Gradient (at x = 35mm) at **200A; $G2_{sat}$ = -0.06%***		
GN	|G|	G/G2 [%]
G2 [T/m]	**1.2956**	100.00
G4 [T/m^4]	0.0000	0.0021
G6 [T/m^6]	0.0006	**0.0456**
G8 [T/m^8]	0.0001	0.0042
G10 [T/m^{10}]	0.0002	**0.0141**

*Int.Gradient (at x = 35mm) at **100A; $G2_{sat}$ = ref(0%)***		
GN	|G|	G/G2 [%]
G2 [T/m]	**0.6482**	100.00
G4 [T/m^4]	0.0000	0.0021
G6 [T/m^6]	0.0003	**0.0451**
G8 [T/m^8]	0.0000	0.0042
G10 [T/m^{10}]	0.0001	**0.0142**



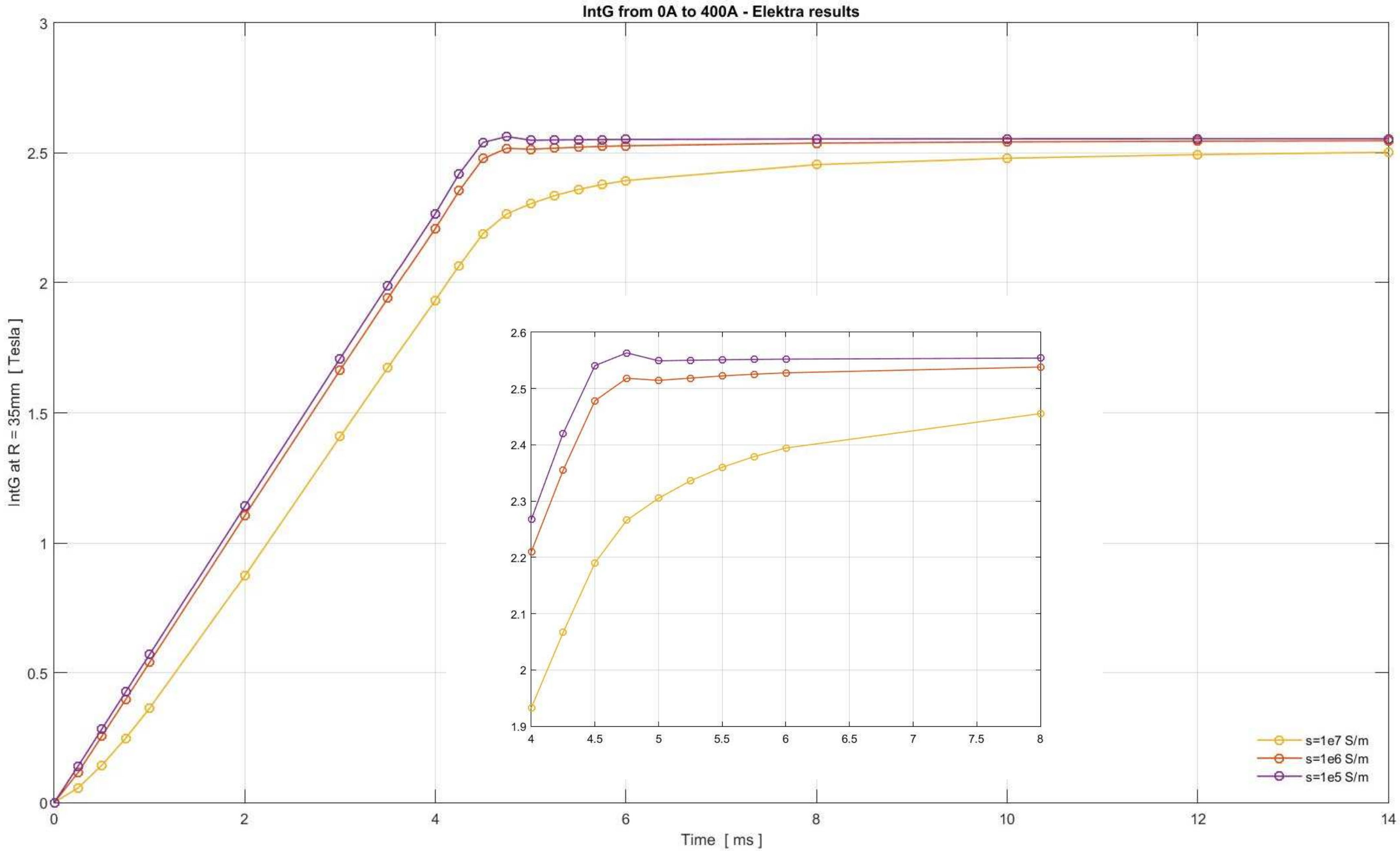
QC7 DC - *Tosca results:*

*Int.Gradient (at x = 35mm) at **150A; $G2_{sat}$ = -3.72%***		
GN	|G|	G/G2 [%]
G2 [T/m]	**2.9937**	100.00
G4 [T/m^4]	0.0001	0.0015
G6 [T/m^6]	0.0014	**0.0461**
G8 [T/m^8]	0.0001	0.0045
G10 [T/m^{10}]	0.0004	**0.0141**

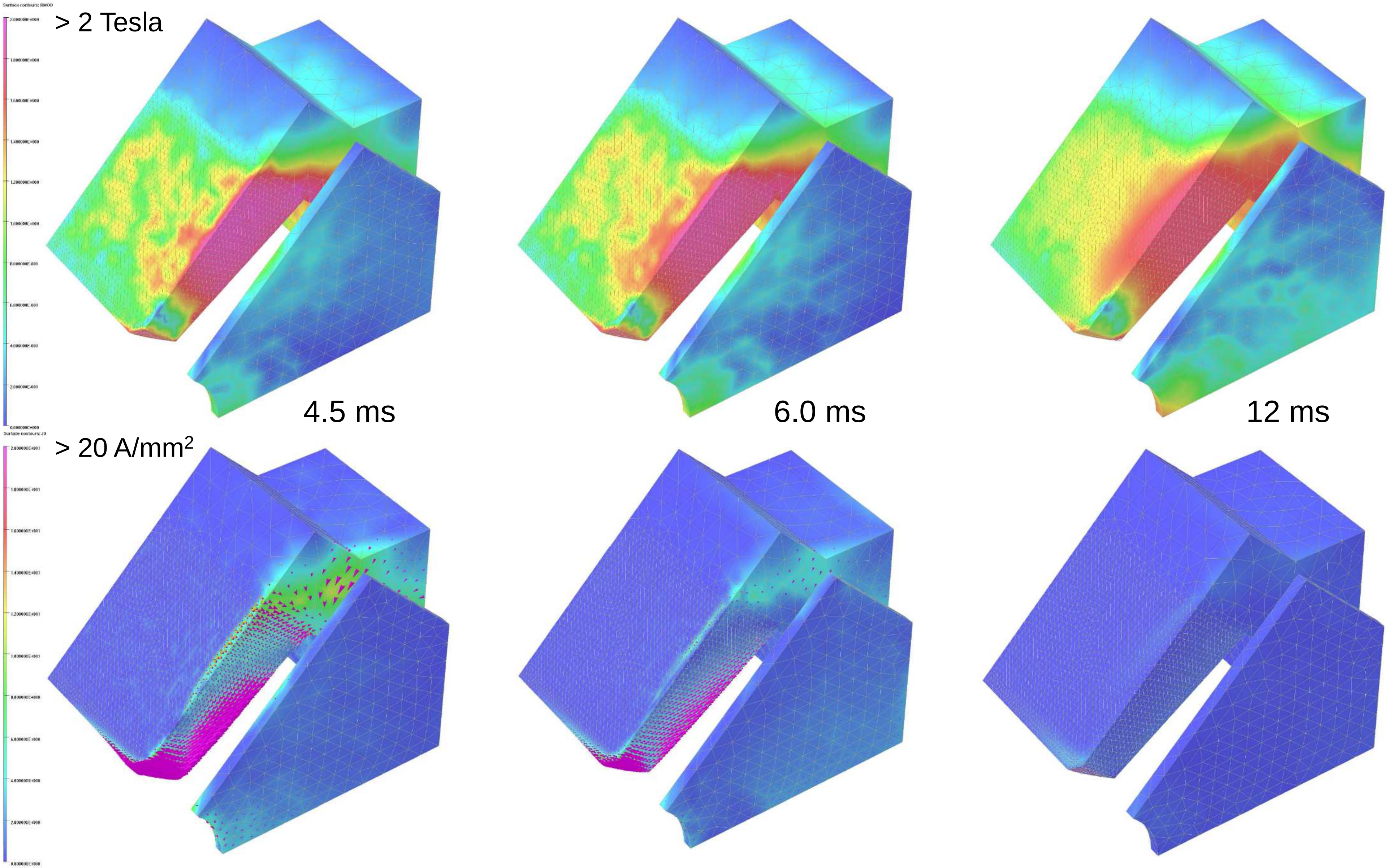
*Int.Gradient (at x = 35mm) at **100A; $G2_{sat}$ = -0.43%***		
GN	|G|	G/G2 [%]
G2 [T/m]	**2.0639**	100.00
G4 [T/m^4]	0.0000	0.0016
G6 [T/m^6]	0.0008	**0.0389**
G8 [T/m^8]	0.0001	0.0045
G10 [T/m^{10}]	0.0003	**0.0141**

*Int.Gradient (at x = 35mm) at **50A; $G2_{sat}$ = ref(0%)***		
GN	|G|	G/G2 [%]
G2 [T/m]	**1.0365**	100.00
G4 [T/m^4]	0.0000	0.0017
G6 [T/m^6]	0.0004	**0.0368**
G8 [T/m^8]	0.0000	0.0045
G10 [T/m^{10}]	0.0001	**0.0141**

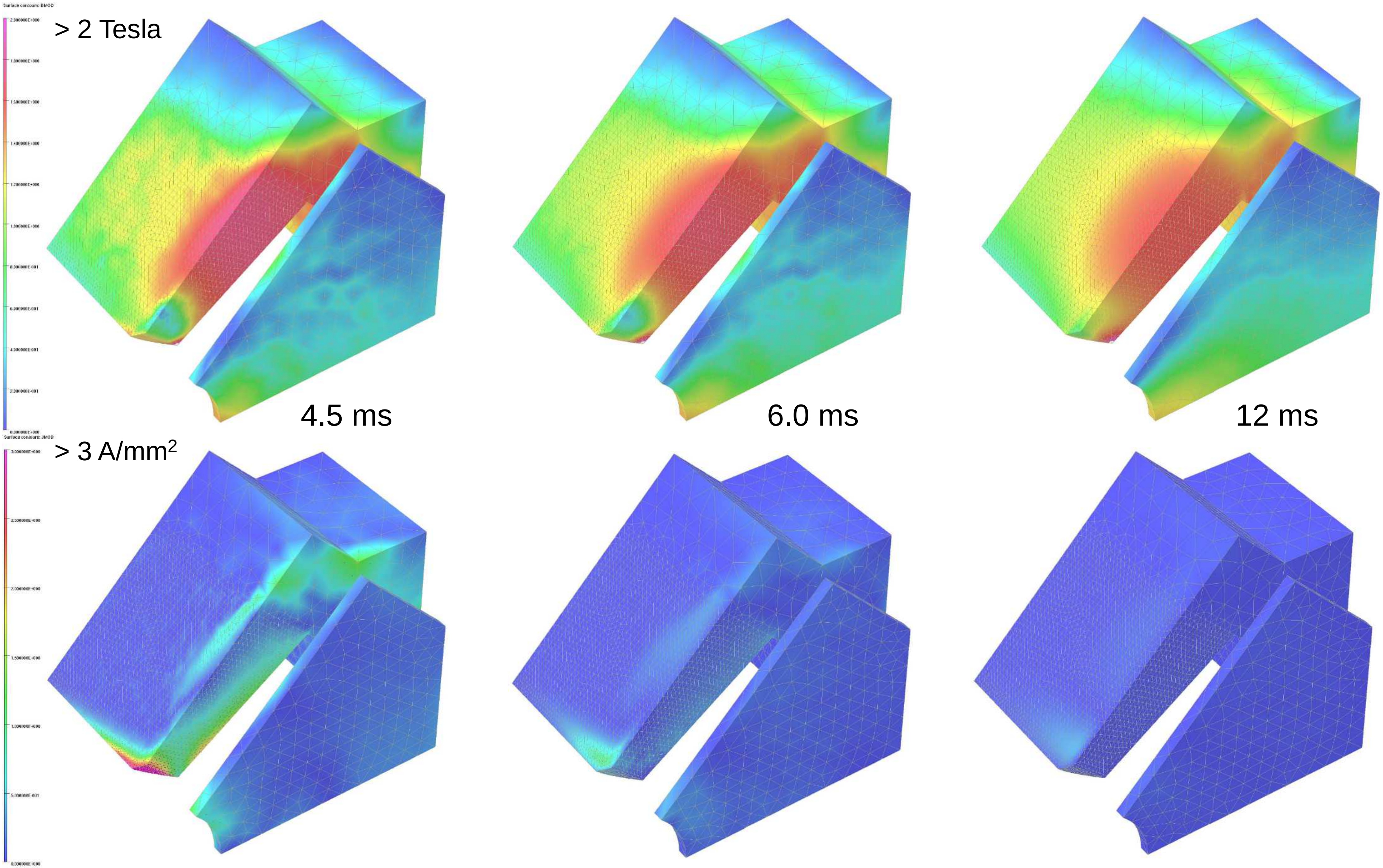
QC7 pulsed - *Elektra results:*



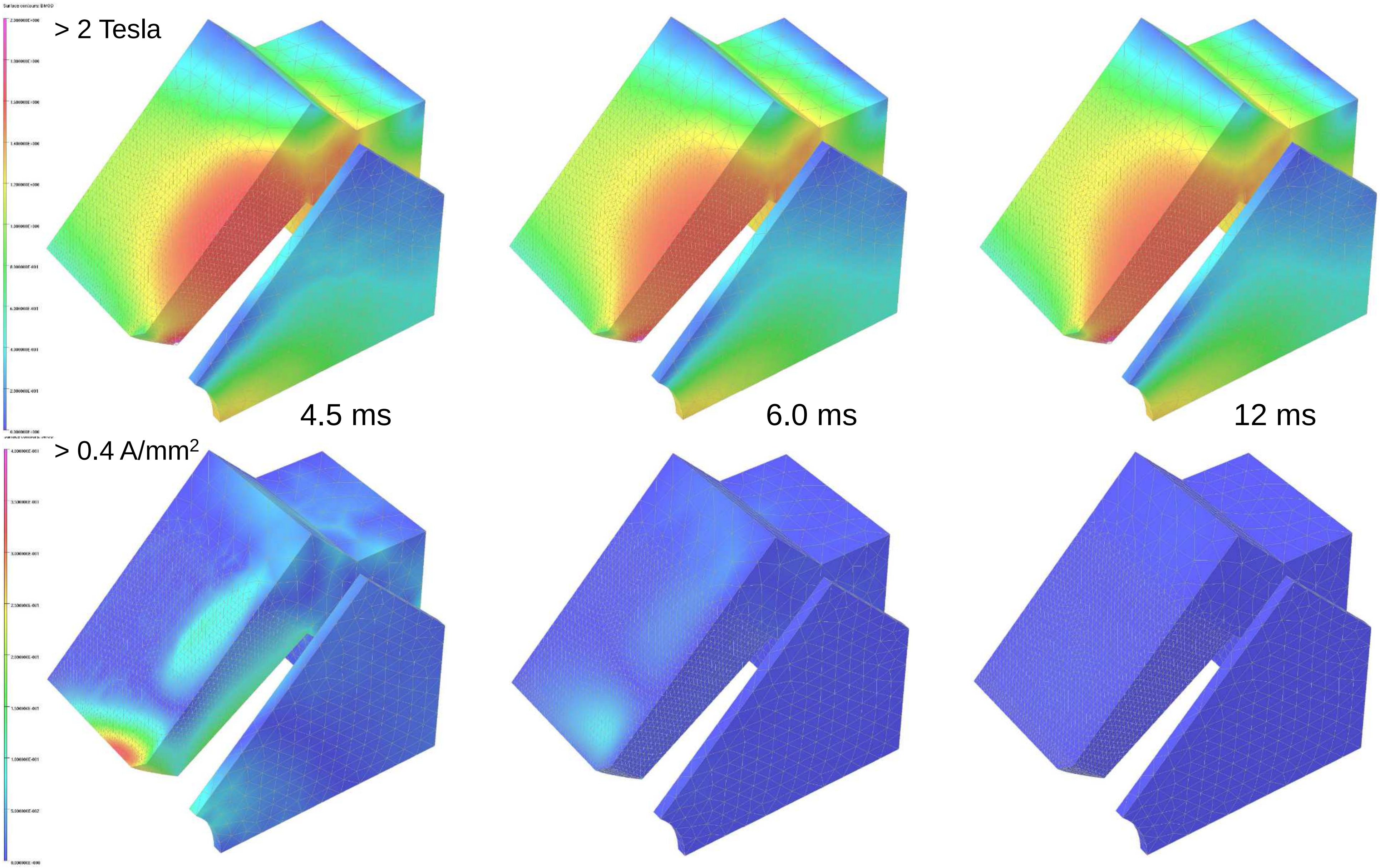
QC7 pulsed - *Elektra simulation (iron* σ = 1e**7** S/m)



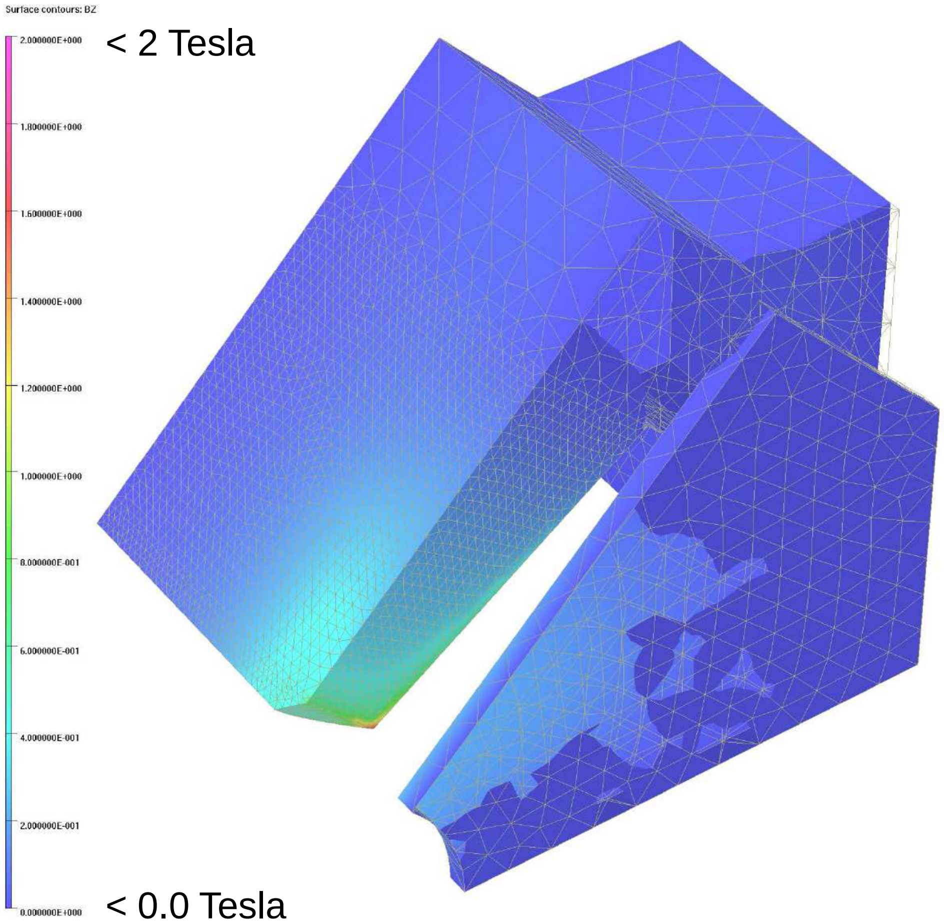
QC7 pulsed - *Elektra simulation (iron* σ = 1e**6** S/m)

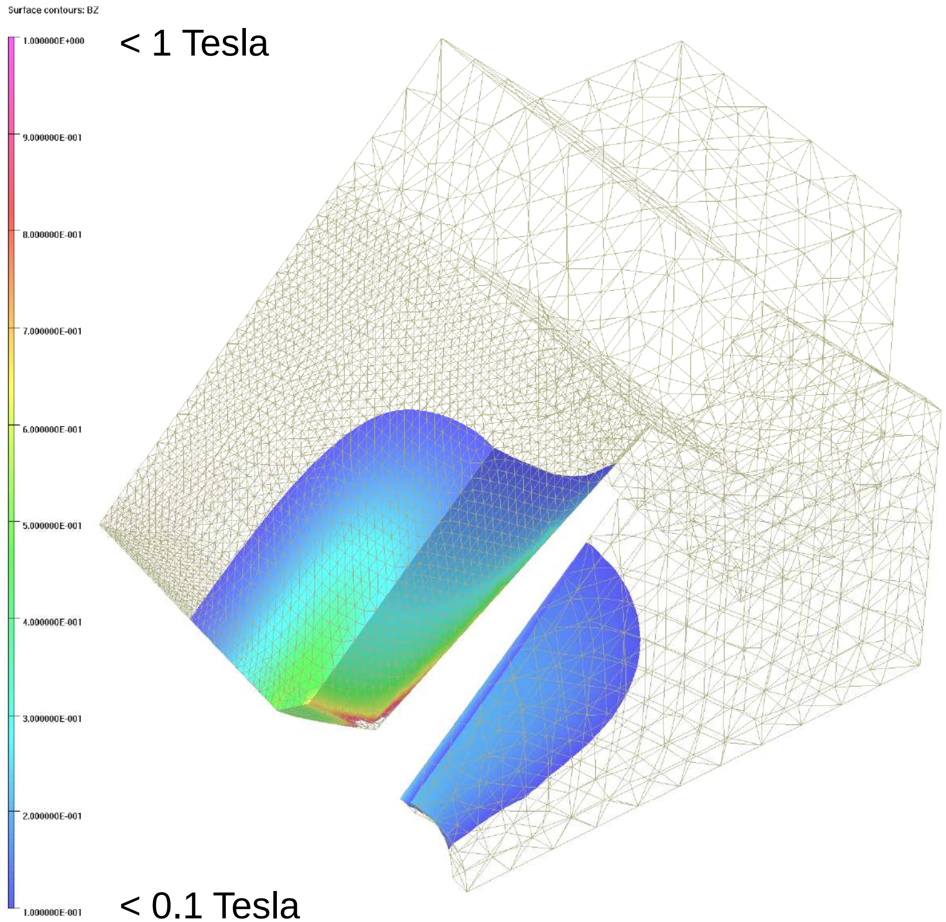


QC7 pulsed - *Elektra simulation (iron* σ = 1e**5** S/m)



Big aperture magnets → B_z distribution





> The Yoke must be realized by 0.35 mm lamination of Fe-Si 3-3.5%

QC7 pulsed **with shields**

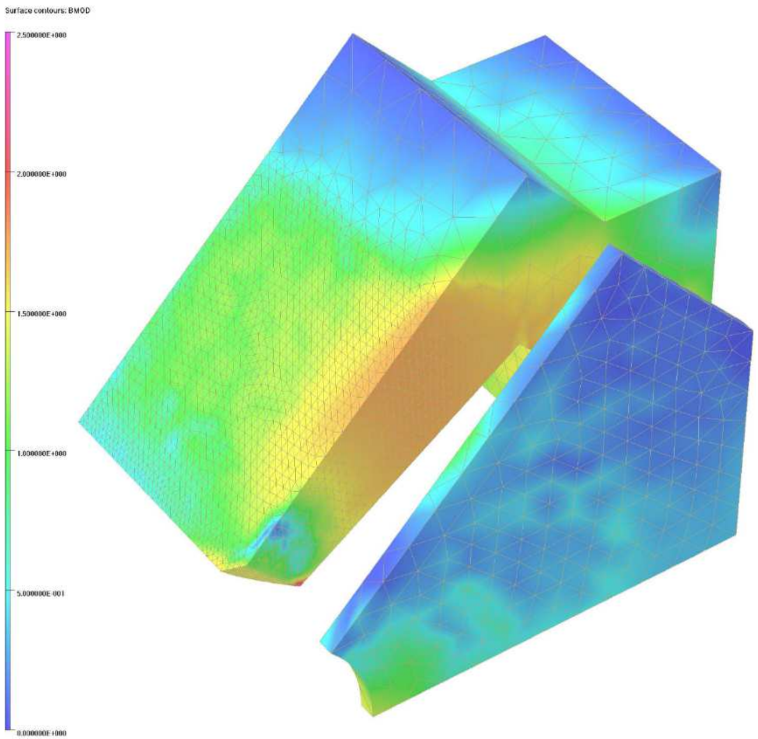
*Int.Gradient (at x = 35 mm) at **400 A** (T = 12 ms)**;***		
GN	|G|	G/G2 [%]
G2 [T/m]	**2.4981**	100.00
G4 [T/m^4]	0.0002	0.0075
G6 [T/m^6]	0.0032	**0.1278**
G8 [T/m^8]	0.0031	0.1230
G10 [T/m^{10}]	0.0005	**0.0190**

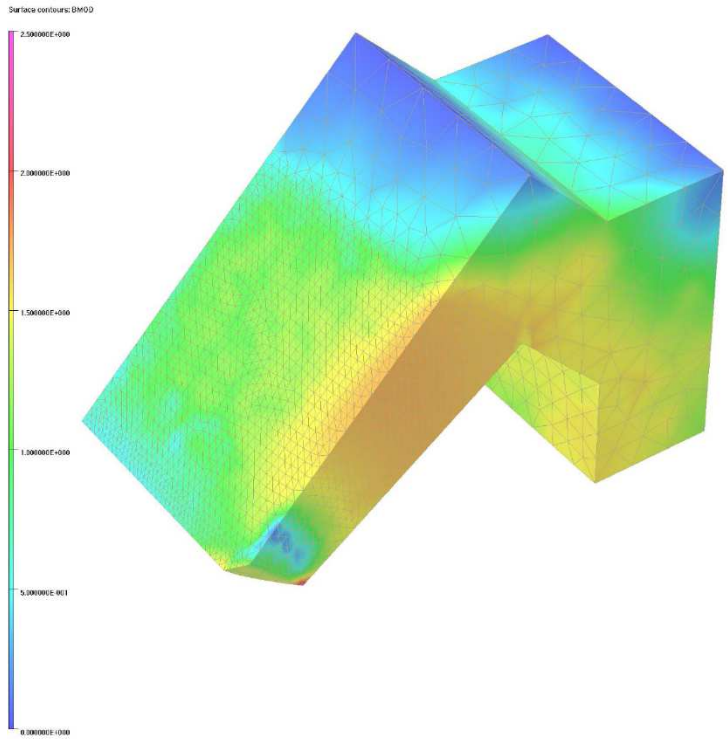
2.50 T/m Vs **2.65** T/m

$\Rightarrow$ **+6%**

QC7 pulsed **without shields**

*Int.Gradient (at x = 35 mm) at **400 A** (T = 12 ms);*		
GN	|G|	G/G2 [%]
G2 [T/m]	**2.6486**	100.00
G4 [T/m^4]	0.0002	0.0057
G6 [T/m^6]	0.0028	**0.1071**
G8 [T/m^8]	0.0034	0.1276
G10 [T/m^{10}]	0.0006	**0.0214**





Power Supplies Considerations ●○○

Required stability: ±**100 ppm vs. nominal** DC (i.e. ±**15 mA**)

1. DC

- Estimated max voltage drop on cable (@ 150 A) = **5 V**
- Unify the PS type for both QC6 & QC7: **35 V / 150 A**
- Unify the remote control interface **FOR ALL PS** (not only QC6 & QC7)
- Large number of PS for QC6 & QC7: **120 PS** (incl. 10% spare)
- Stability higher than "average commercial"

Custom-made solution could be economically comparable to "Commercial"

AND

tailored to actual needs

Power Supplies Considerations ●●○

Required stability: ±**100 ppm vs. nominal** on Flat-Top of the pulse (i.e. ±**45 mA**)

Additional requirement: Output voltage and internal DC-Link voltage **<1 kV**

2. *Pulsed "4.5" – peak current 450 A_{PK}, rms current 140 A_{RMS}*

- Estimated max **resistive** voltage drop on cable (@ 450 A) = **11 V**
- Different PS types for QC6 & QC7: **850 V_{PK} / 450 A_{PK}** (QC6) & **1050 V_{PK} / 450 A_{PK}** (QC7)
- Unify the remote control interface **FOR ALL PS** (not only QC6 & QC7)
- Large number of PS for QC6: **105 PS** (incl. 10% spare)
- Small number of PS for QC7: **14 PS** (incl. 15% spare)
- Various topologies are possible and available, to be further investigated

Custom-made solution is needed to meet the actual needs

Power Supplies Considerations ●●●

Required stability: ±**100 ppm vs. nominal** on Flat-Top of the pulse (i.e. ±**40 mA**)

Additional requirement: Output voltage and internal DC-Link voltage **<1 kV**

3. *Pulsed "8.0" – peak current 400 A_{PK}, rms current 130 A_{RMS}*
   - Estimated max **resistive** voltage drop on cable (@ 400 A) = **11 V**
   - Similar PS types for QC6 & QC7: **500 V_{PK} / 400 A_{PK}** (QC6) & **700 V_{PK} / 400 A_{PK}** (QC7)
   - Unify the PS for both QC6 & QC7: **700 V_{PK} / 400 A_{PK}**
   - Unify the remote control interface **FOR ALL PS** (not only QC6 & QC7)
   - Large number of PS for QC6 & QC7: **120 PS** (incl. 10% spare)
   - Various topologies are possible and available, to be further investigated

Custom-made solution is needed to meet the actual needs

Additional Considerations

From our experience on Elettra and FERMI:

1. Power is always paid twice: for generating it, and removing it
2. Keep the peak voltage on PS and magnets <1 kV $\Rightarrow$ avoid MV-rated components, cables, rules,…
3. Minimize the number of different types of PS (operation, maintenance, spares,…)
4. Unify interfaces PS-RCS and PS-PSS+MPS[(+)] among PS types/families
5. Minimize use of water cooling both on magnets and PS
   - Plant $\Rightarrow$ de-ionized water, radiation resistant rubber pipes for magnets,…
   - Operation $\Rightarrow$ integration into MPS,…
   - Reliability $\Rightarrow$ risk of leakages, clogging of coils,…
   - Maintenance $\Rightarrow$ operate close or over delicate equipment,…

[(+)]*RCS = Remote Control System; PSS = Personnel Safety System; MSS = Machine Protection System*

Conclusions ●○

Compared several design for magnets QC6 and QC7, both in DC and Pulsed

1. DC is a standard, well-known solution:
   - x Power consumption ⇒ 2.4 kW for each QC6; 3.5 kW for each QC7
   - x Water cooling of magnets ⇒ de-ionized water plant,…
   - ✓ "Low Power" but stable power supplies (~5 kW)
2. Pulsed excitation is a less common solution:
   - ✓ Power consumption ⇒ significantly more efficient than DC
   - ✓ Air cooling of magnets ⇒ no piping, etc. but heat to environment
   - \- High peak output voltage ⇒ <u>risk</u> of exceeding 1 kV (design & operations)
   - \- Shape of the pulse is important (e.g. rise time: 8.0 ms vs. 4.5 ms)

Conclusions ●●

3. Costs considerations for magnets:
   - QC6 and QC7 could be the same model with and without the shields
   - Both DC and Pulsed could have the same yoke geometry
   - ❖ Pulsed mode yoke must be realized with Fe-Si 3-3.5%, lamination 0.35 mm
   - Both DC and Pulsed have the same coils dimension
   - ❖ DC coils are water-cooled
   - ⇒ **The total costs could be comparable for both types**
4. Costs considerations for power supplies:
   - Custom PS (either DC or Pulsed)
   - Pulsed PS are more powerful (peak) than DC, more expensive
5. Potential savings with Pulsed Solution:
   - No need of de-ionized water (plant installation and running)
   - Reduced electrical power consumption (mains and dissipation)
   - Reliability of operations and reduced maintenance

Thank You!