High-gradient proton accelerating structure developments at CERN

Alexej Grudiev

3/06/2013

HG2013, ICTP Trieste, Italy

Acknowledgements

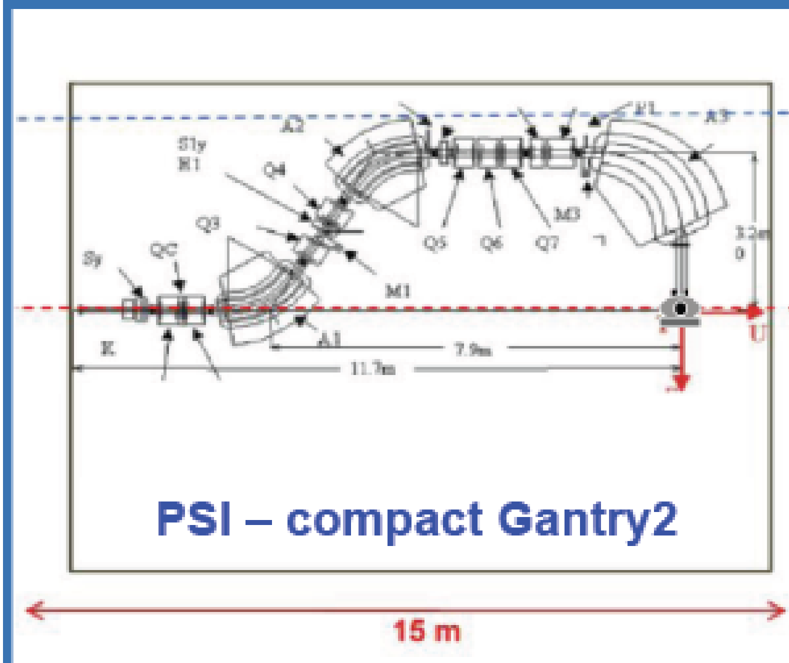
- This work is done in close collaboration between CERN (M. Garlasche, A. Grudiev, I. Syratchev, W. Wuensch) and TERA foundation (U. Amaldi, A. Degiovanni, P. Magagnin) in the frame work of the CERN Knowledge Transfer (KT) Fund project: “High-gradient Accelerating Structure for Proton Therapy Linacs”
- Special thanks to A. Degiovanni and P. Magagnin for preparing the slides

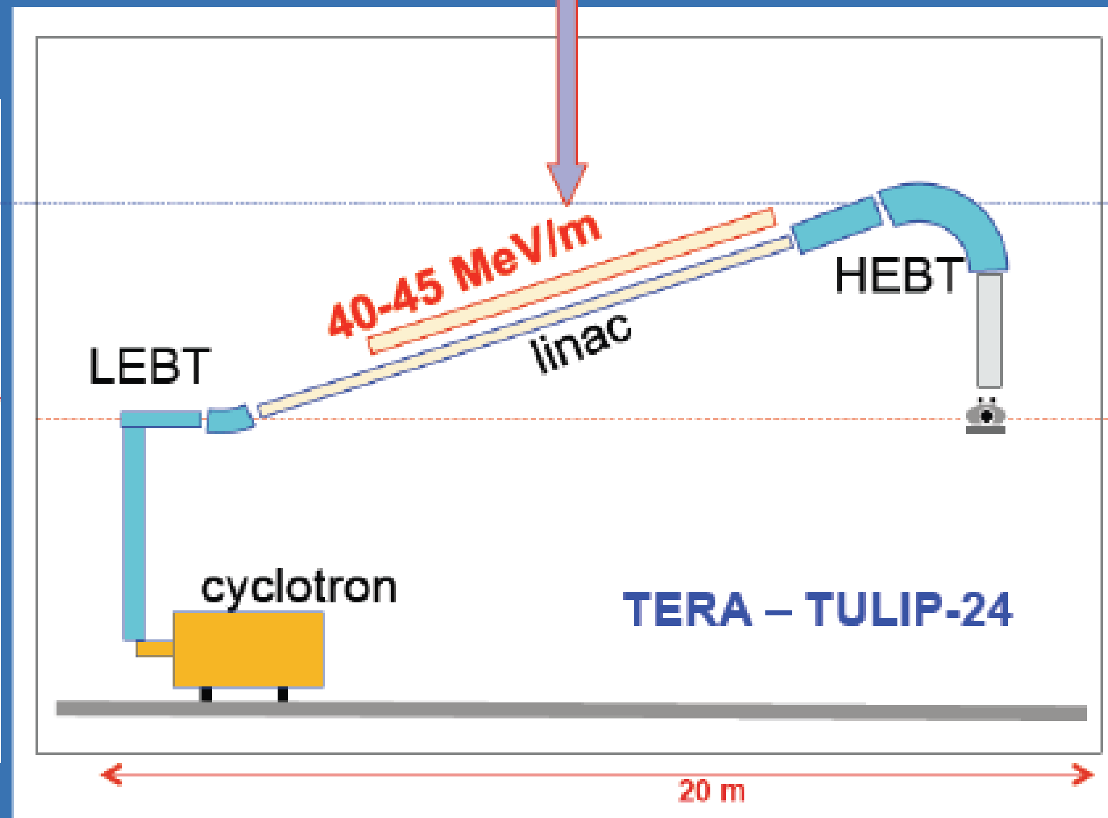
Outline

- *Introduction*
  - *RF cavities constraints for hadrontherapy*
- *Backward travelling wave **cell design** and **optimization** for high gradient operations*
  - *Nose cone study*
  - *Tapering*
- ***Comparison** of different structure designs*
  - *SW SCL design*
  - *backward TW*
- *Preliminary studies for **Engenearing design***
- *Conclusions*

Next step: from 30 MV/m to 50 MV/m

A new Travelling Wave structure is being prototyped with CLIC (CERN): length from 11 m to 8 m





Linac layout and BDR requirements

- Quasi-periodic **PMQ FODO lattice** sets a limit to the length of each structure and determines the group velocity range.

- The cells in each structure (**tank**) have the same length, while from one tank to the next, the cell length increases:

β tapering in the range 0.22-0.60

- Trade-off between transverse acceptance and RF efficiency:

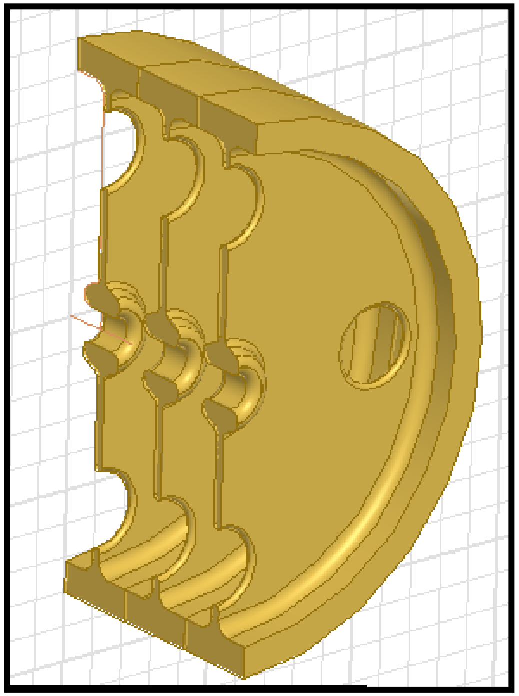
bore aperture = 5 mm

- **Max BDR:** 1 BD per treatment session (~ 5 min) on the whole linac length (~ 10 m).

→ BDR ~ 10^{-6} bpp/m

NOVEL DESIGN FOR HIGH GRADIENT OPERATION

Proposal for bTW design for hadrontherapy



Proposed by A. Grudiev

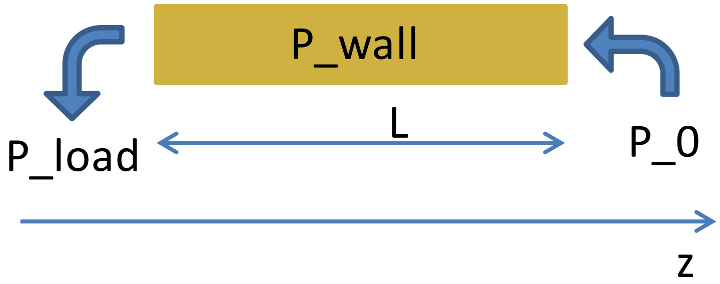
<u>DESIGN GOAL and CONSTRAINTS</u>

$$E_a := E_0 T \geq 50\ \text{MV/m}$$

$$S_c/E_a^2 < 7\ 10^{-4}\ \text{A/V}$$

$$\frac{S_c^{15} \cdot t_{pulse}^5}{BDR} = const.$$

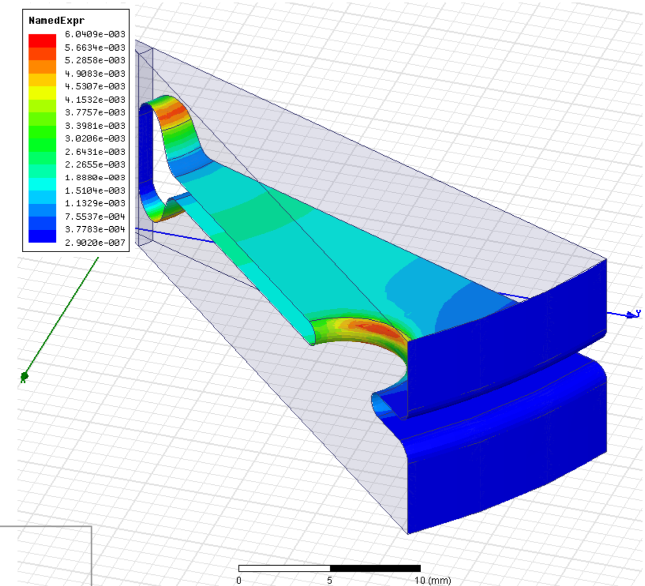
with: $S_c < 4\ \text{MW/mm}^2$
$t_{TERA} = 2500$ ns
$t_{CLIC} = 200$ ns
$BDR_{TERA} = BDR_{CLIC} = 10^{-6}$ bpp/m

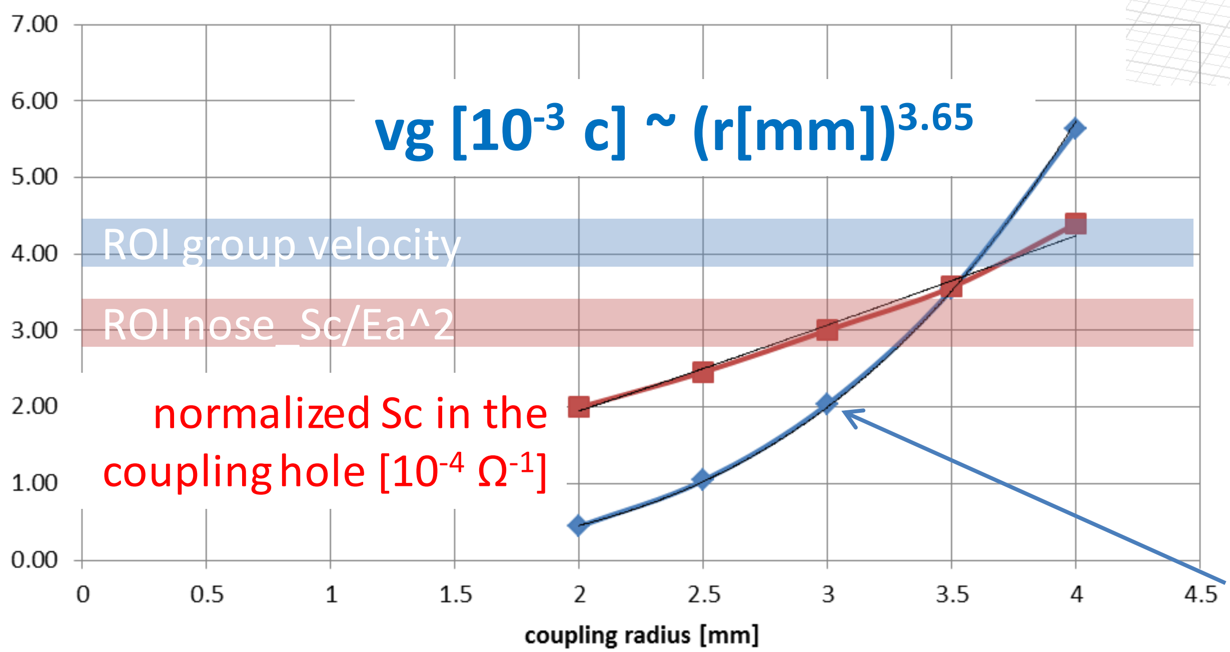


vg_in ~ 0.4% c
vg_out ~ 0.2% c
filling time ~ 0.3 µs

From 8 coupling holes to 16

cone A	gap	Rc	cs_h	ac_Diam	vg	R'/Q	Sc/Ea^2_slot
deg	mm	mm	mm	mm	‰	Ohm/m	10-4 V/A
25	5.2	2	28	72.331	0.45	8111	2.00
25	5.2	2.5	28	72.172	1.04	8127	2.46
25	5.2	3	28	71.927	2.04	8147	3.01
25	5.2	3.5	28	71.564	3.54	8177	3.57
25	5.2	4	28	71.093	5.63	8215	4.40

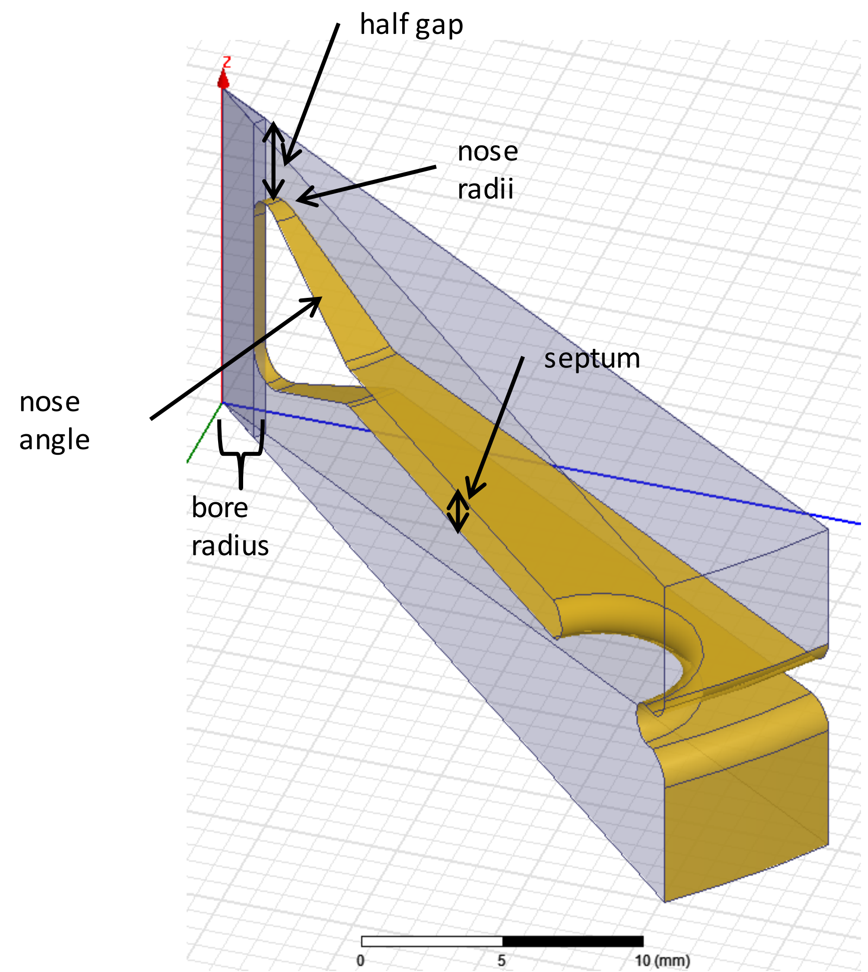




doubling the number of holes will double vg while keeping Sc_hole almost constant

Nose geometry optimization

- Scan on:
  - Nose cone angle
  - Gap
  - Nose cone radius(*)
  - Phase advance (120°-150°)
  - coupling hole radius
    (vg = 4 ‰ and 2 ‰)

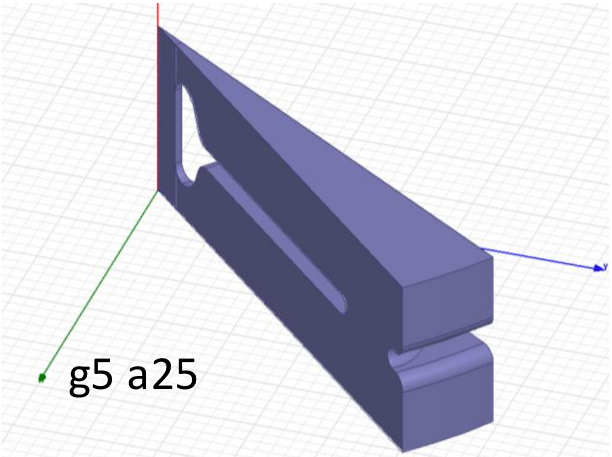


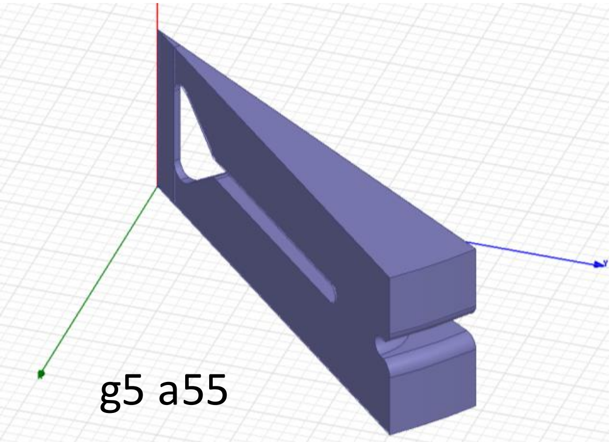
- **Optima:**
  - **Minimum of the quantity:**

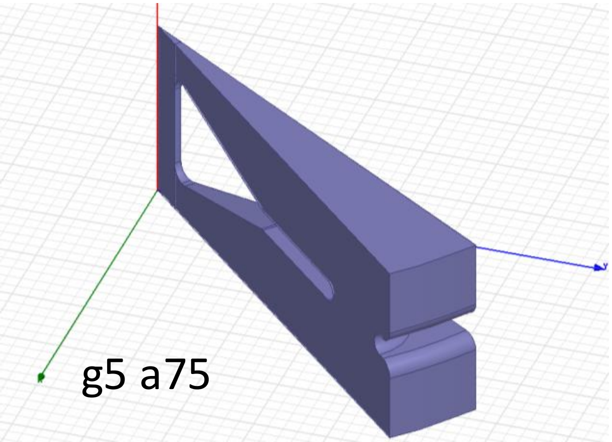
$$\boxed{\frac{P}{E_a^2}\cdot\frac{S_c}{E_a^2}} = \frac{v_g}{\omega}\cdot\frac{S_c / E_a^2}{R' / Q}$$

* based also on results of the SCL optimization

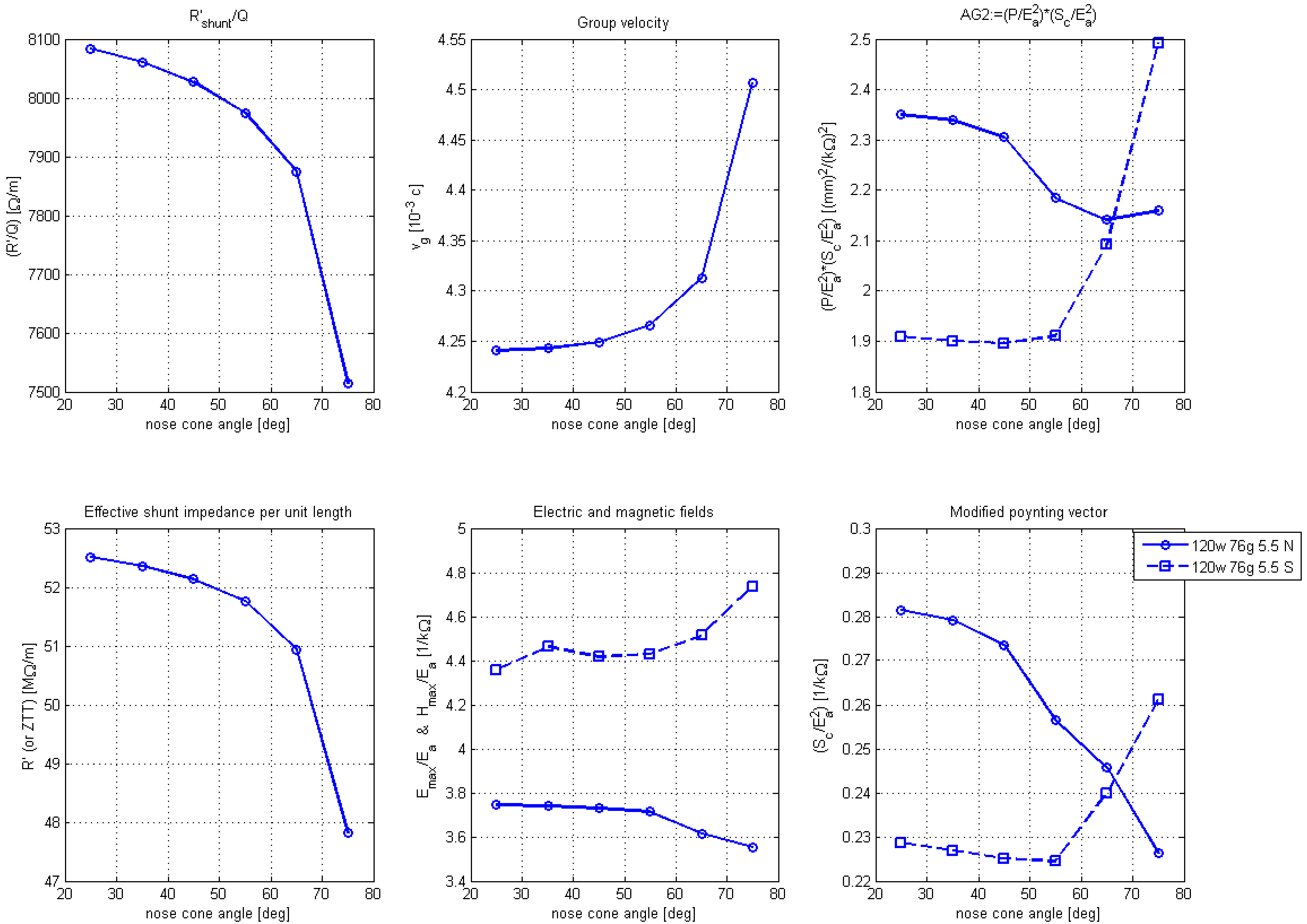
angle scan – 120 deg



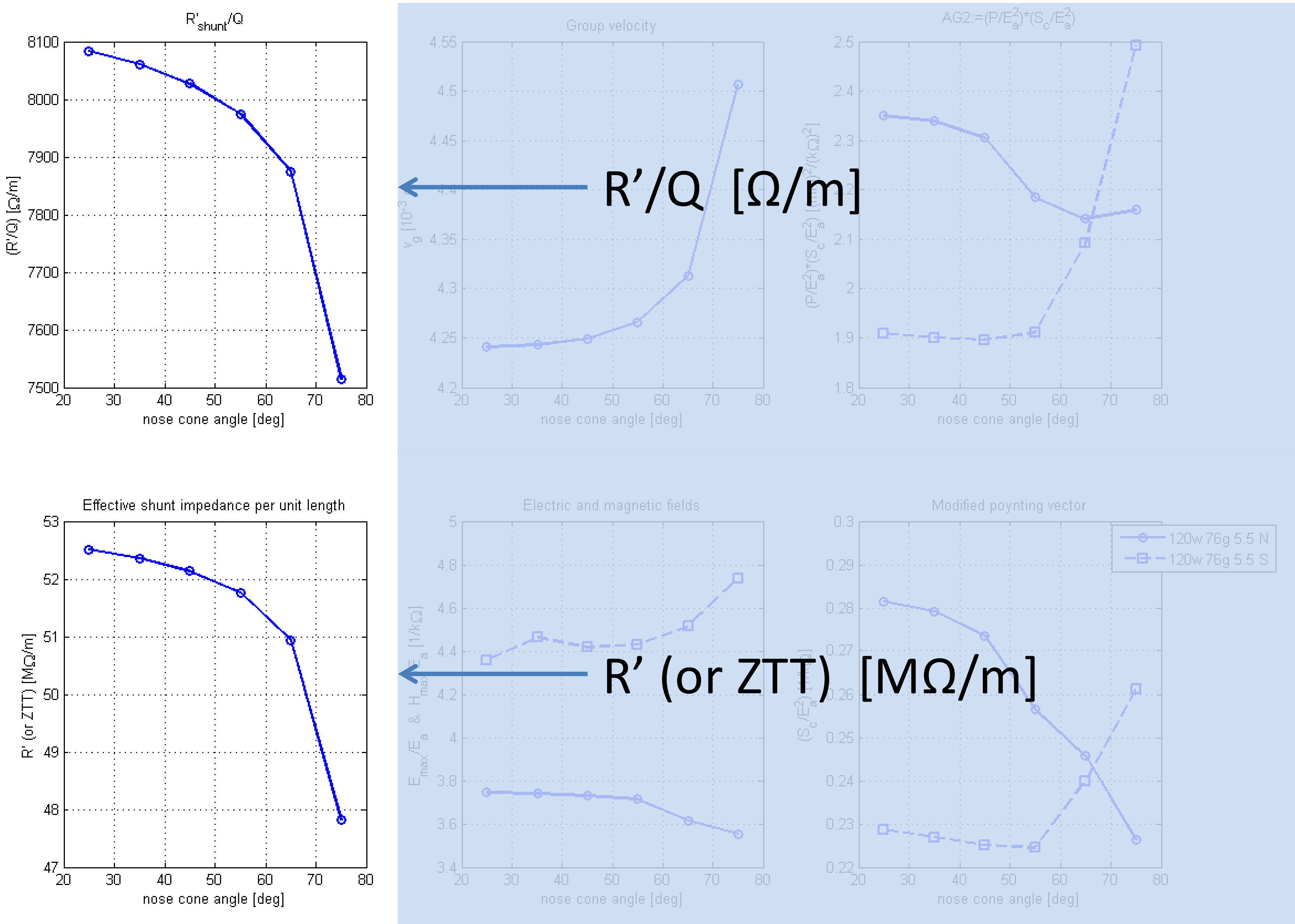




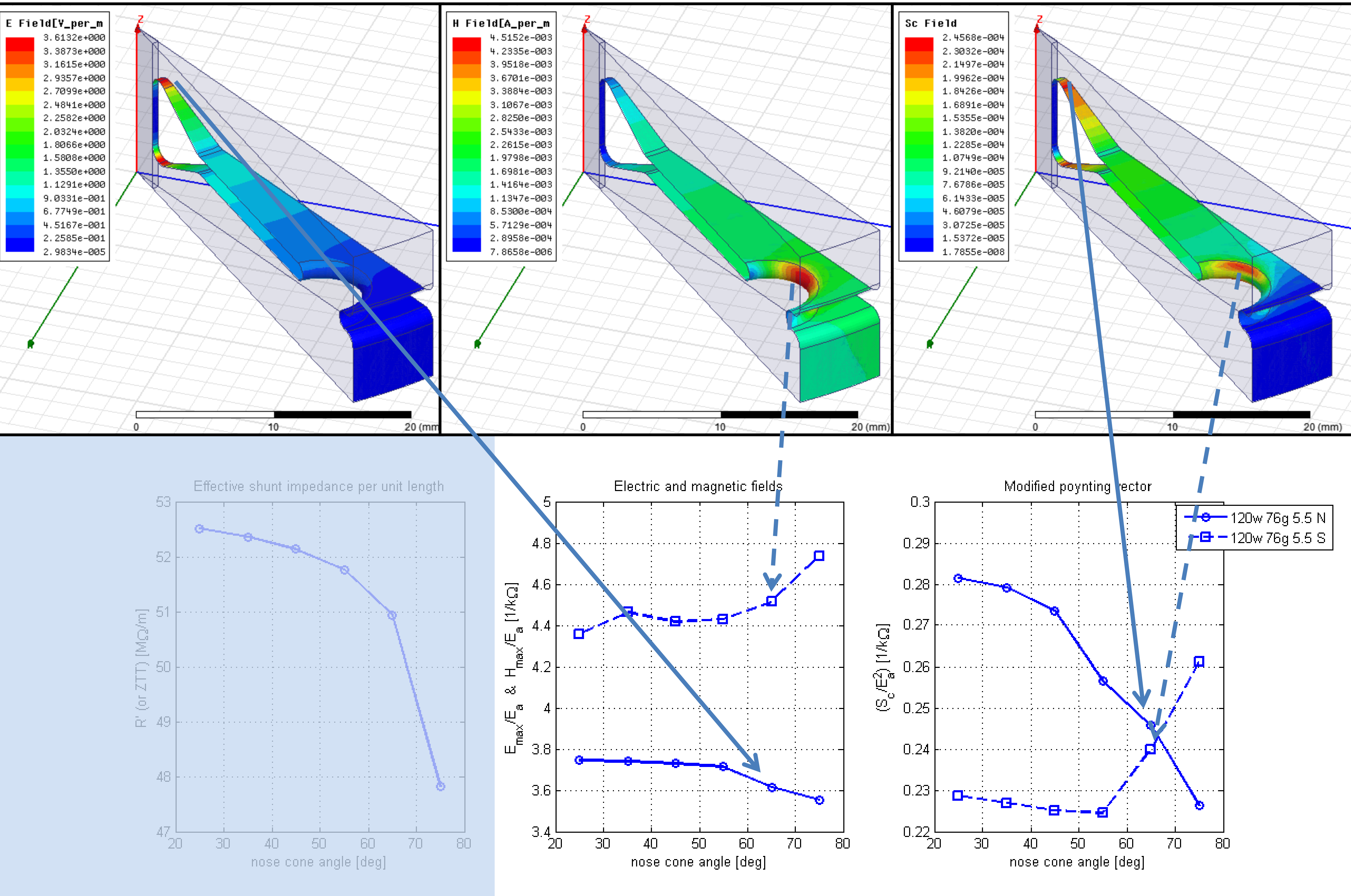
Optimization plots



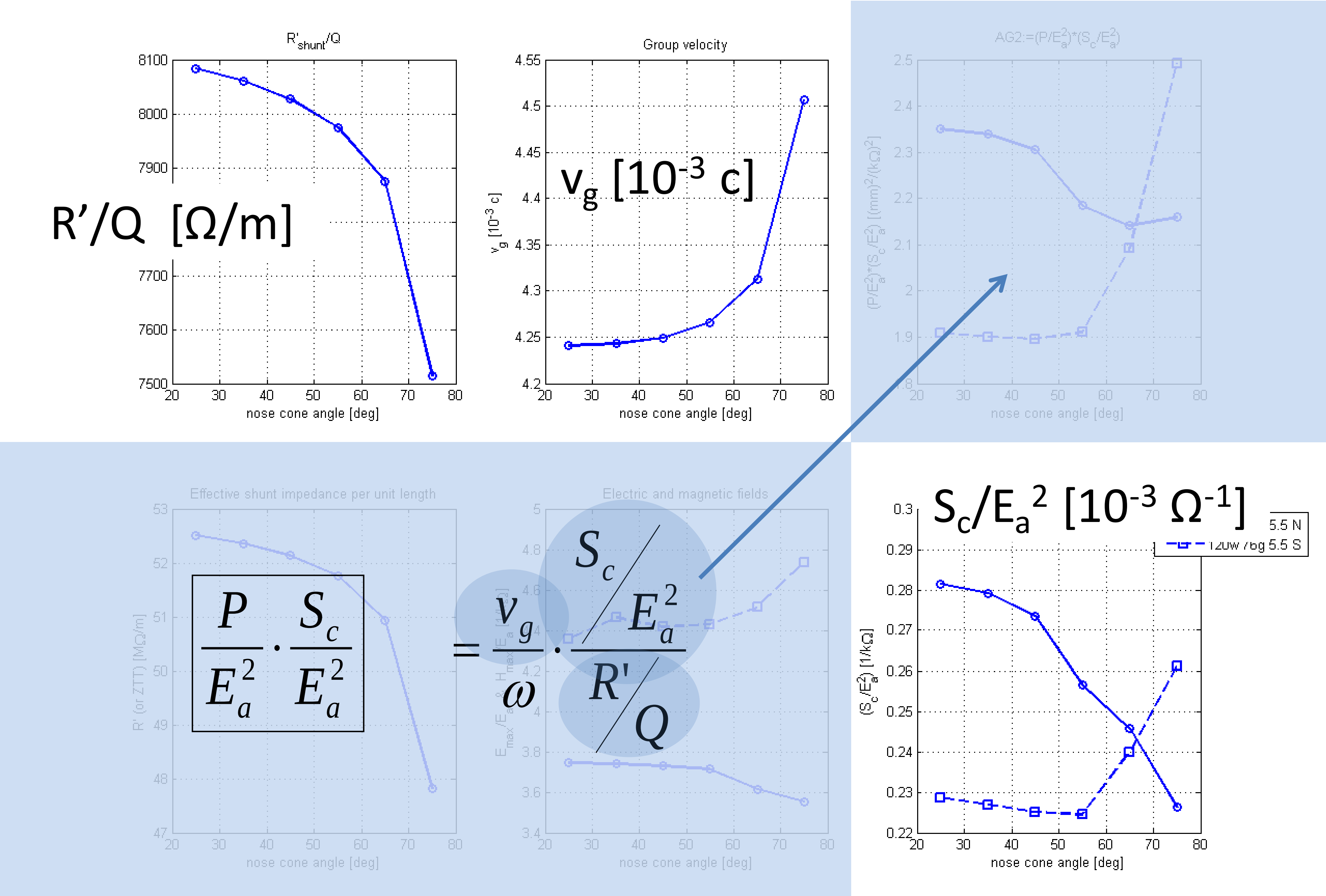
Optimization plots



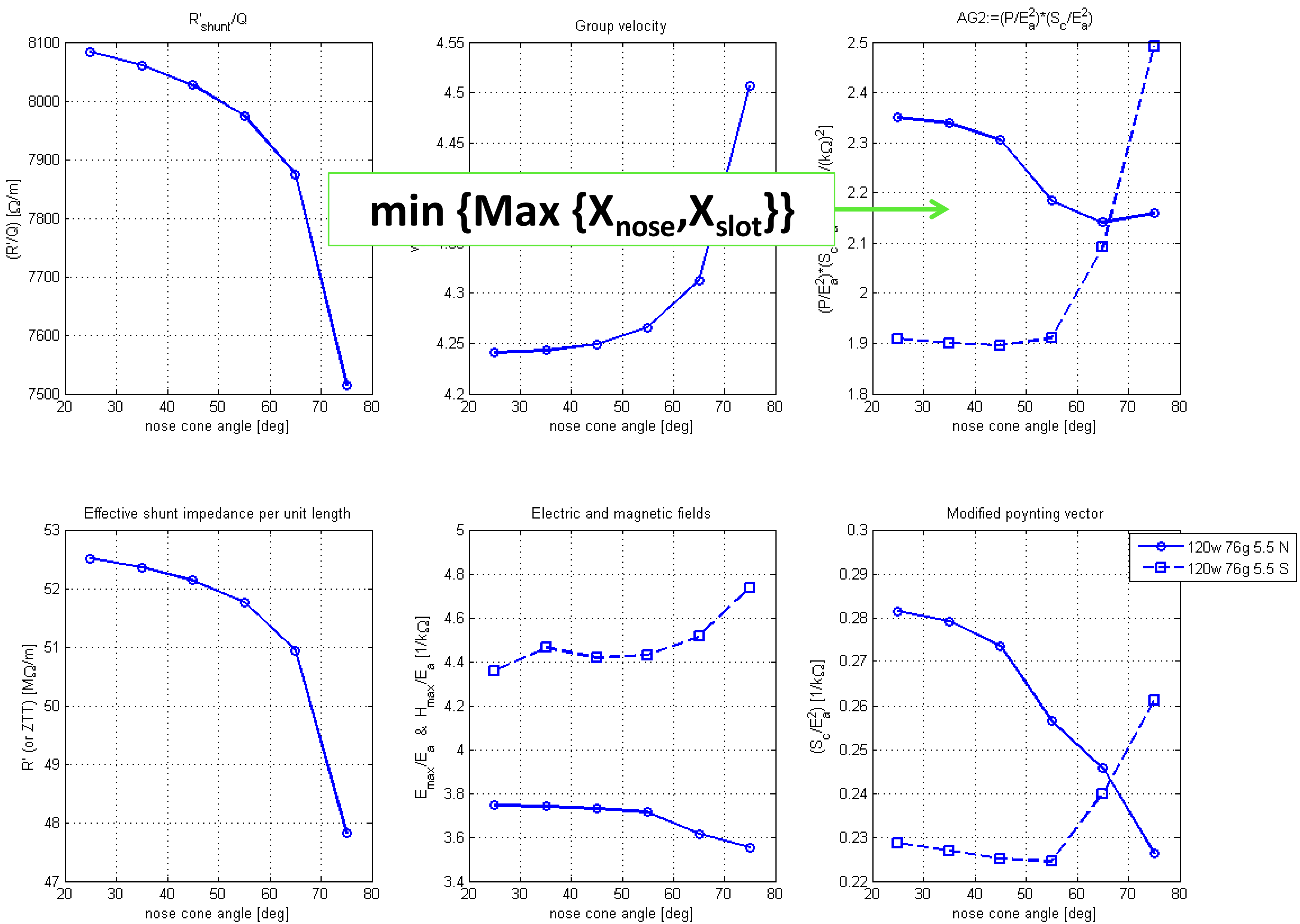
Optimization plots - fields



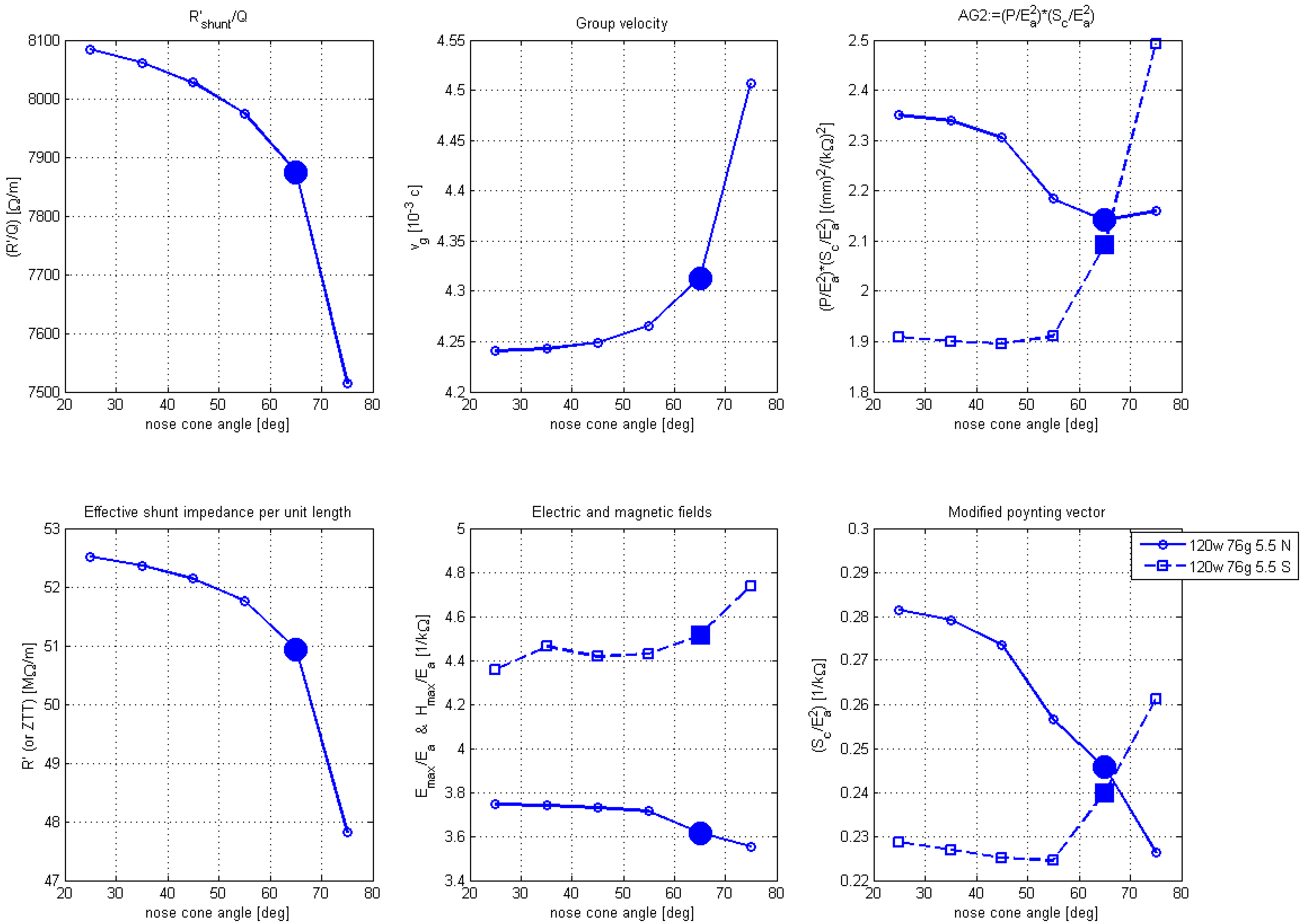
Optimization plots



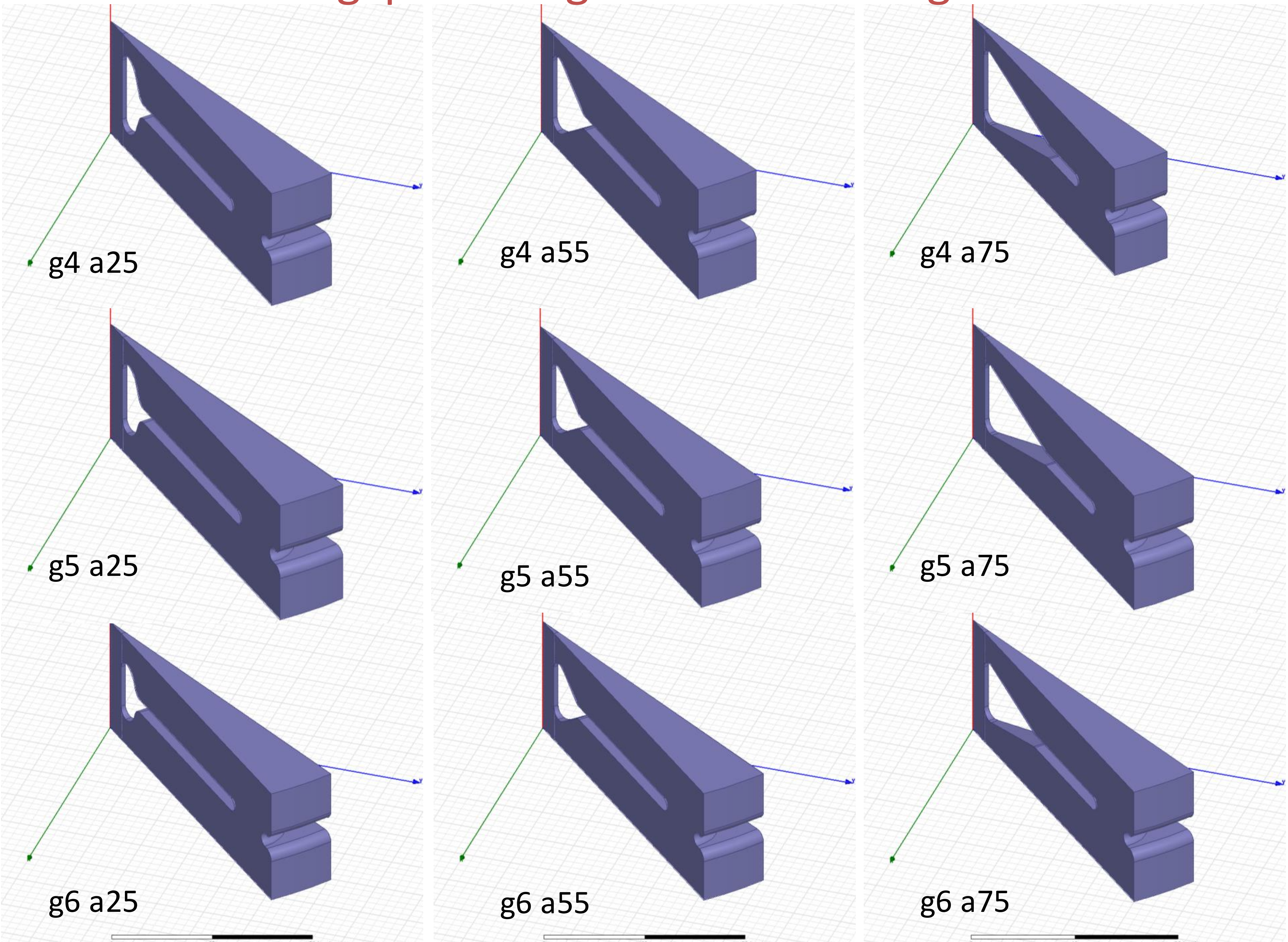
Optimization plot – 120 deg – gap = 5.5 mm



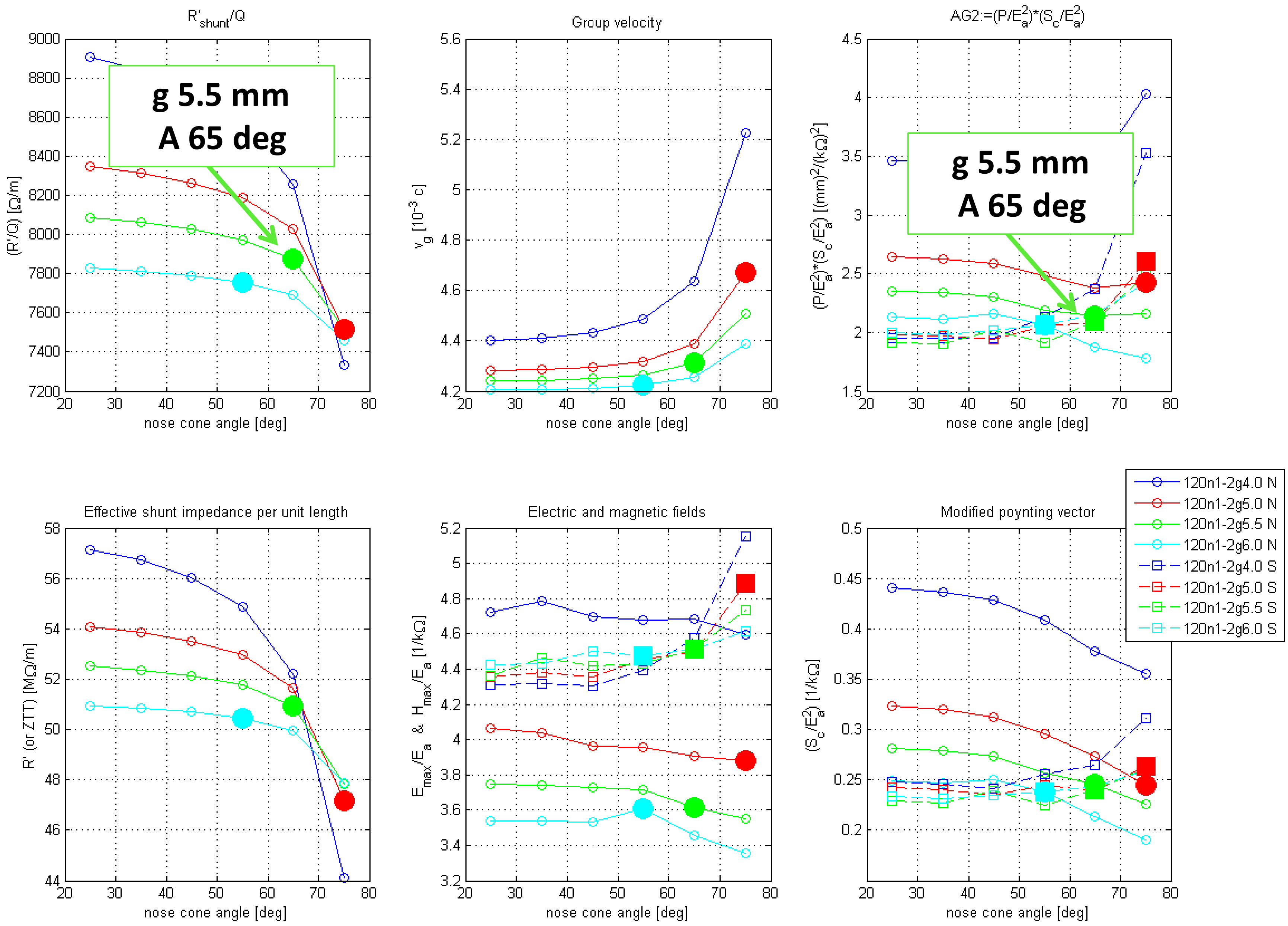
Optimization plot – 120 deg – gap = 5.5 mm



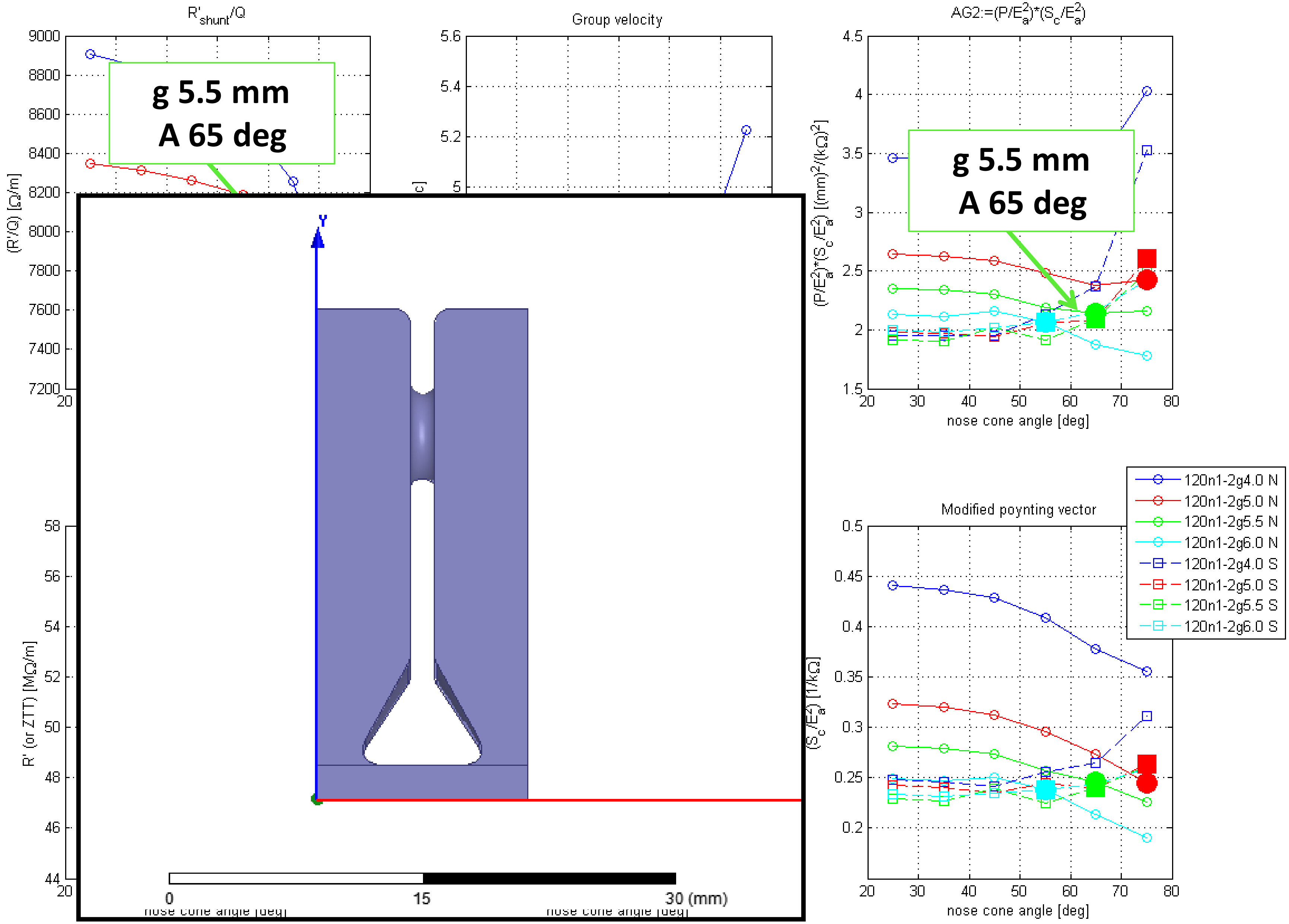
gap and angle scan – 120 deg



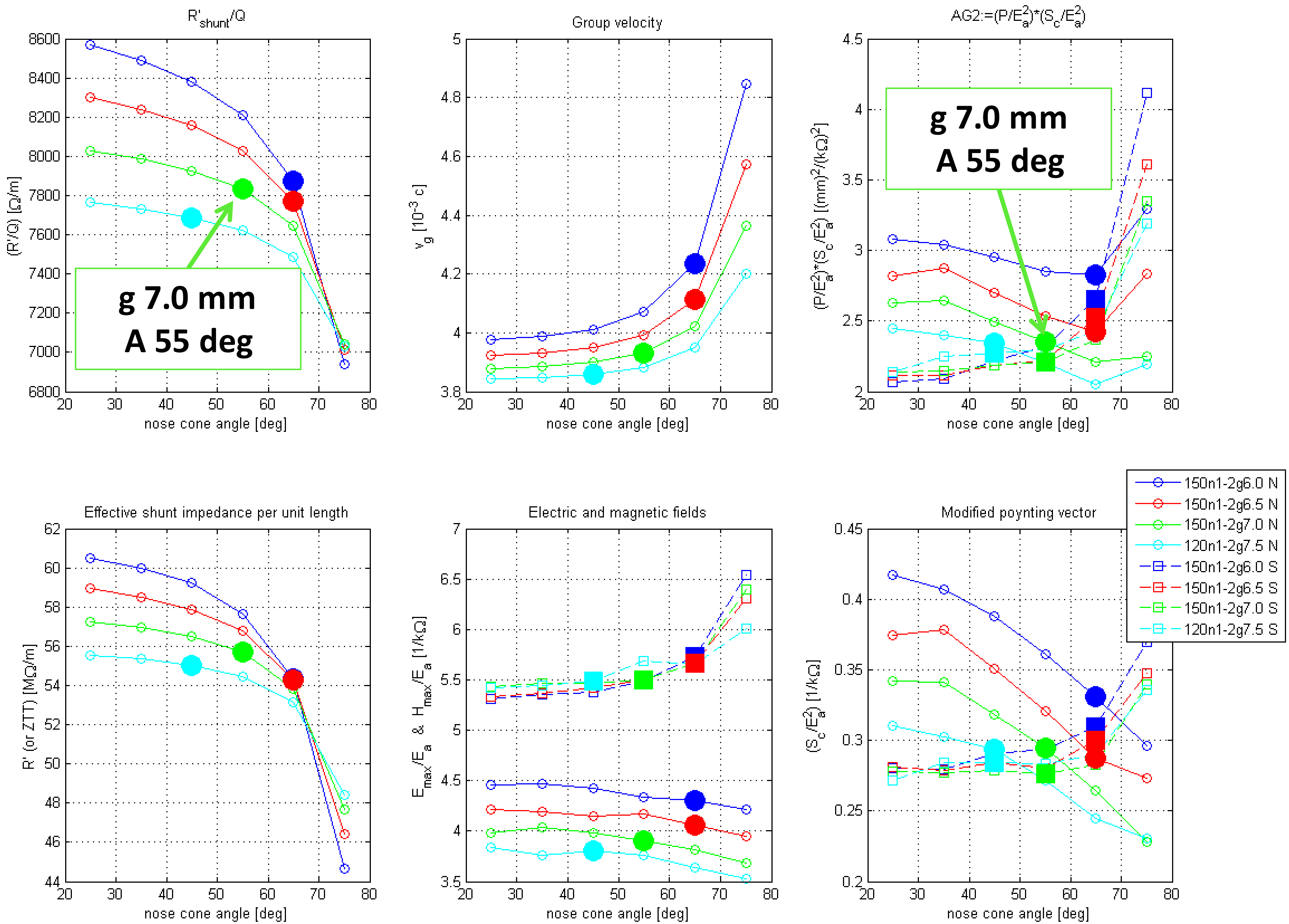
120° - 16 holes – nose 1 -2 mm – gap and angle scan



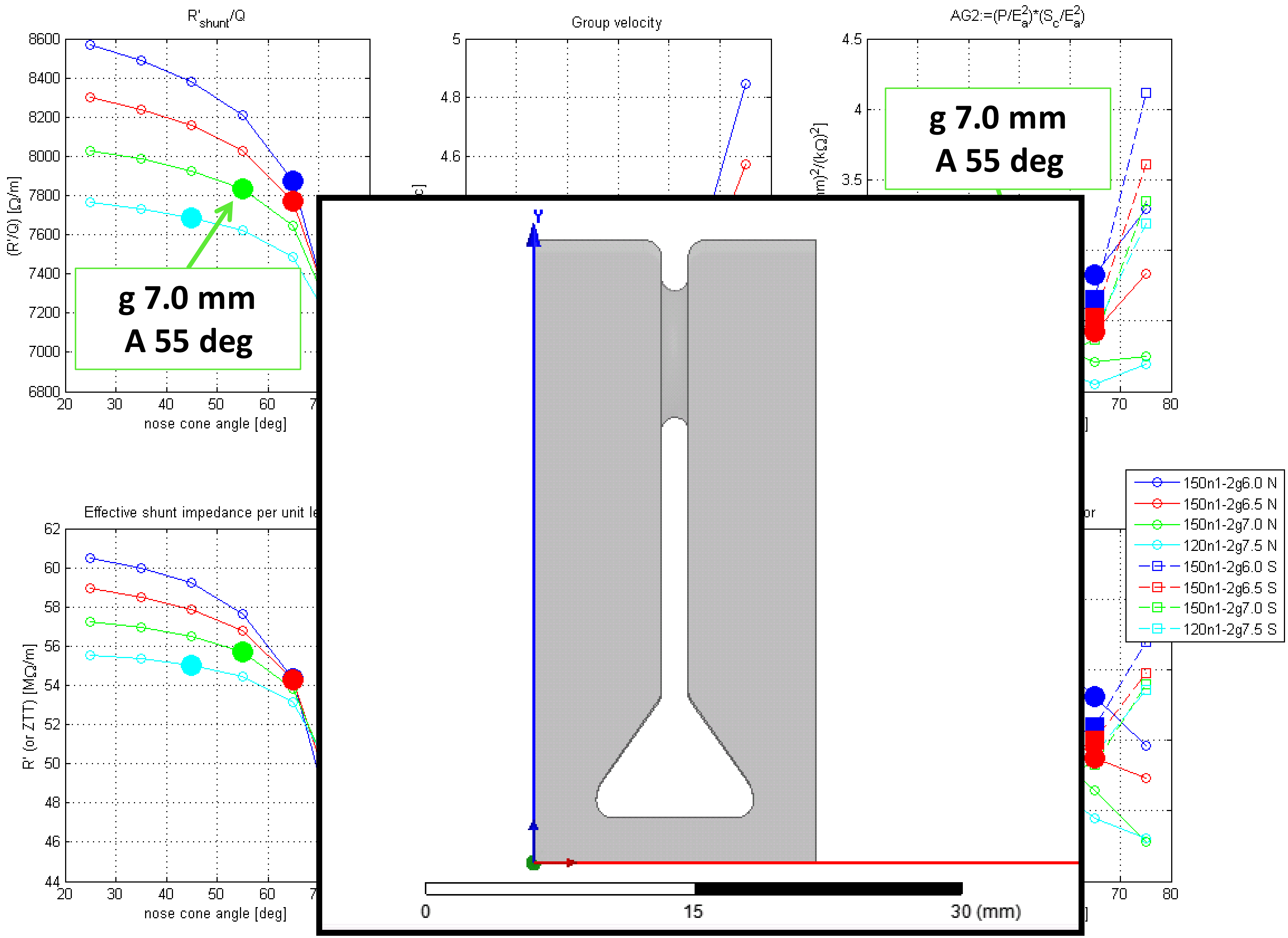
120° - 16 holes – nose 1 -2 mm – gap and angle scan



150° - 16 holes – nose 1 -2 mm – gap and angle scan



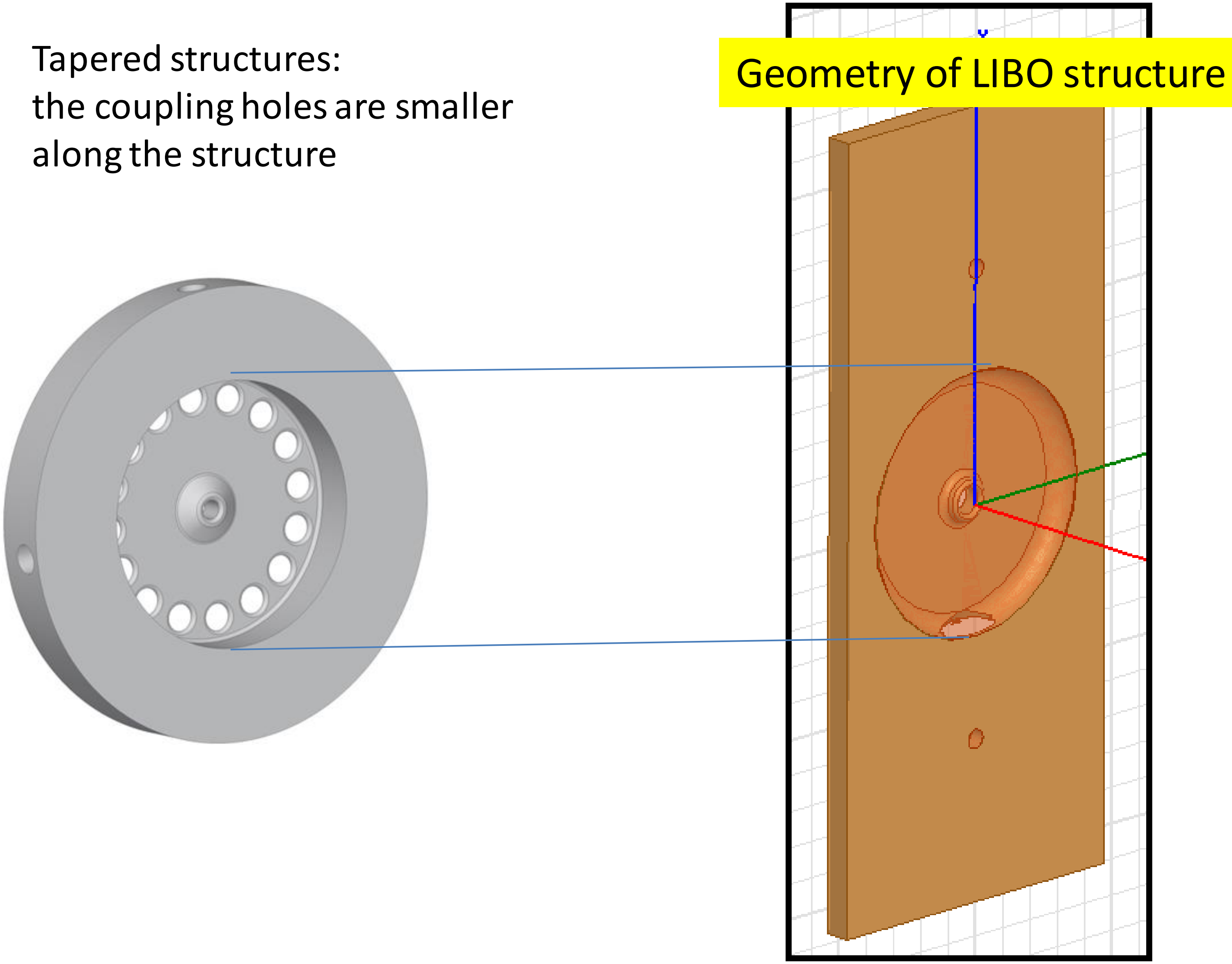
150° - 16 holes – nose 1 -2 mm – gap and angle scan



COMPARISON BETWEEN TW AND SW STRUCTURES

Comparison between TW structure and SCL

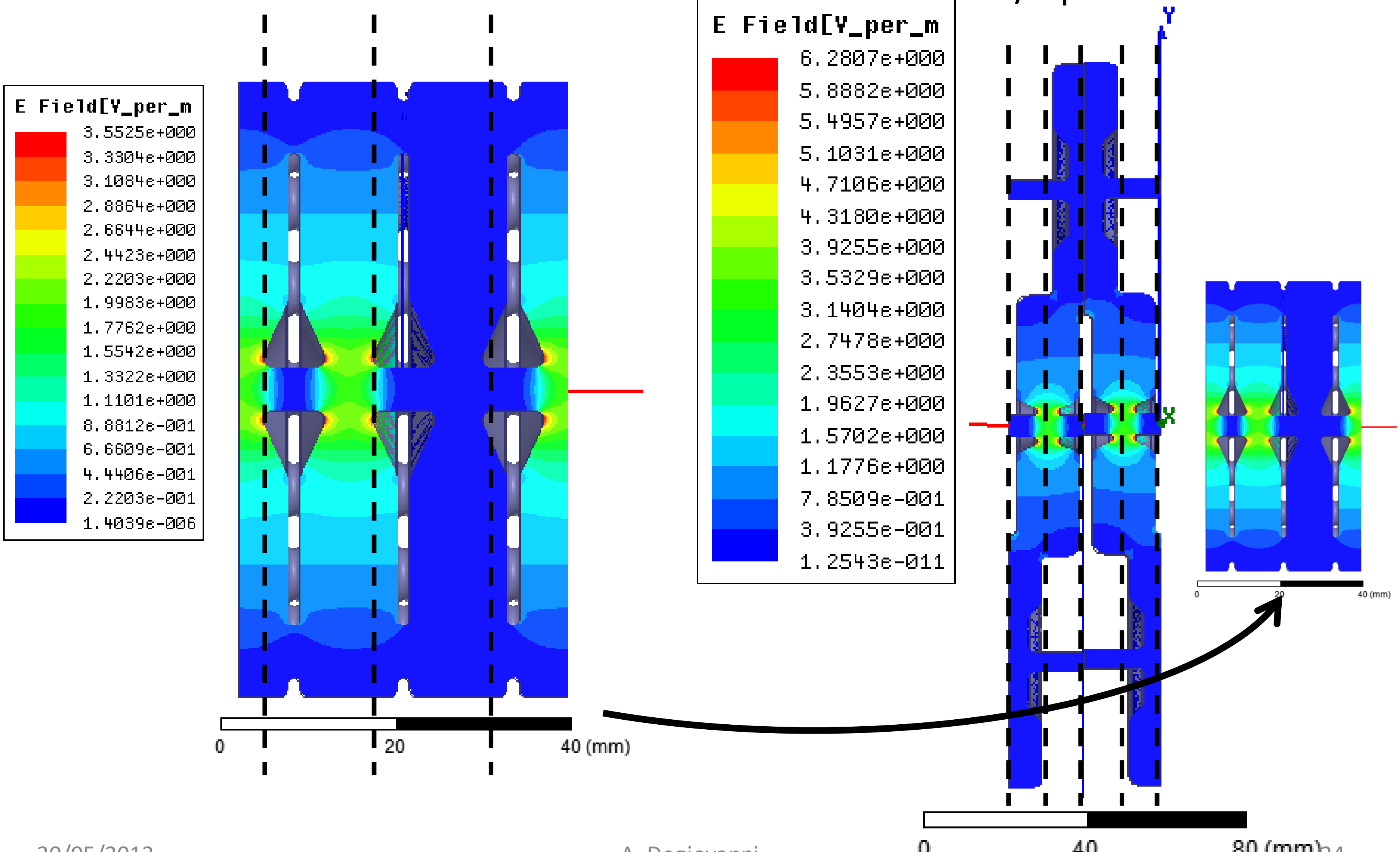
Tapered structures:
the coupling holes are smaller along the structure



Comparison of E-field in TW and SW

2/3 π phase advance

π/2 phase advance



PROs and CONs of bTW compared to standard SCL design

+ simpler mechanically

+ less material and brazing needed (lower number of cells)

+ tuning is easier for TW

+ shorter filling time

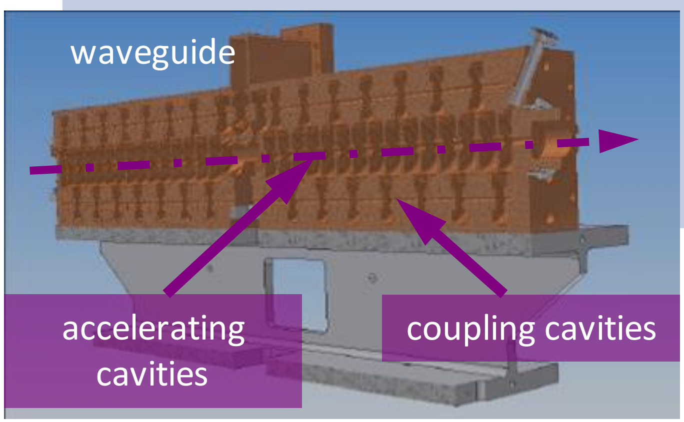
+ no bridge couplers

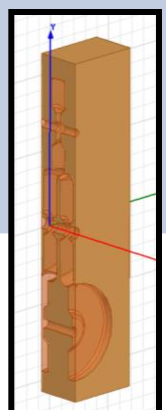
- small wall thickness

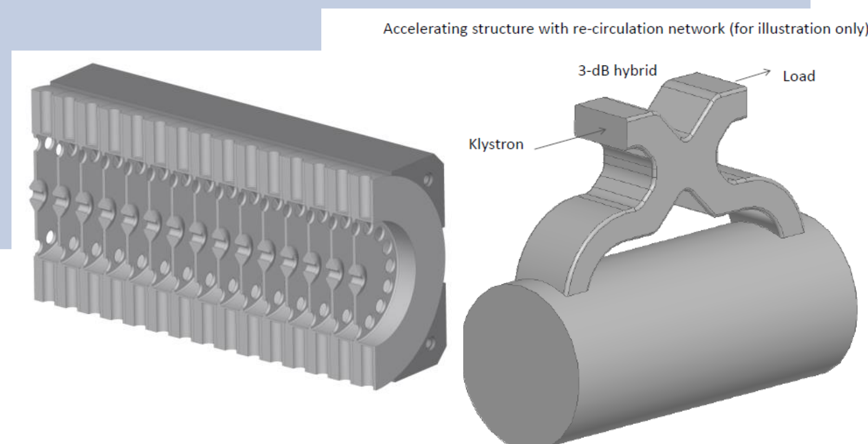
- material properties change during brazing

- Dissipated power is higher (half power goes to the load)

→ **Recirculation loop** (power for TW 10-20% higher than SW)



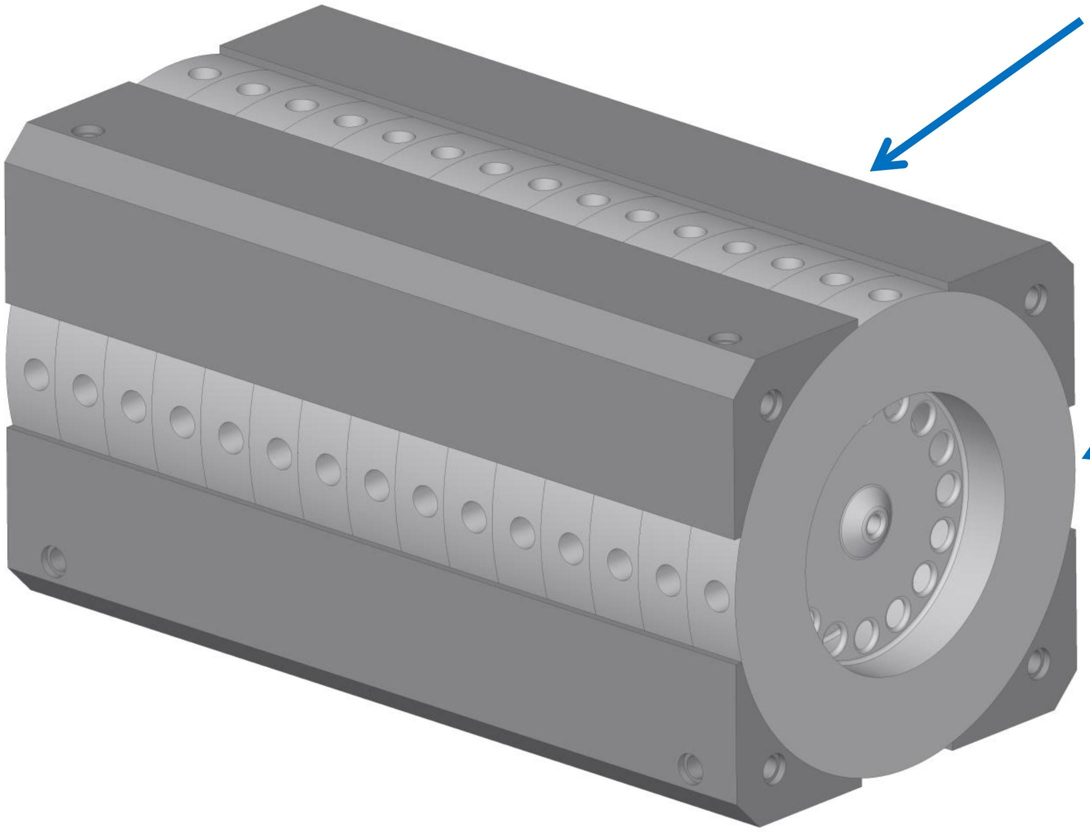




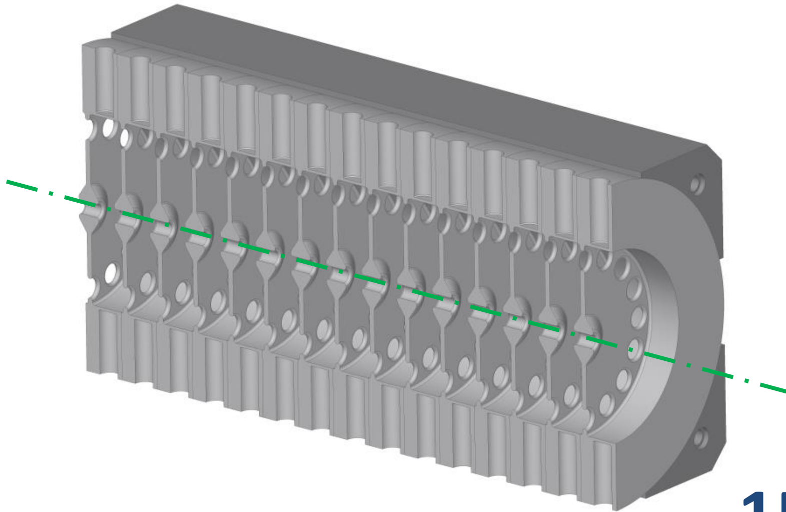
I. Syratchev

PRELIMINARY STUDIES FOR ENGENERING DESIGN

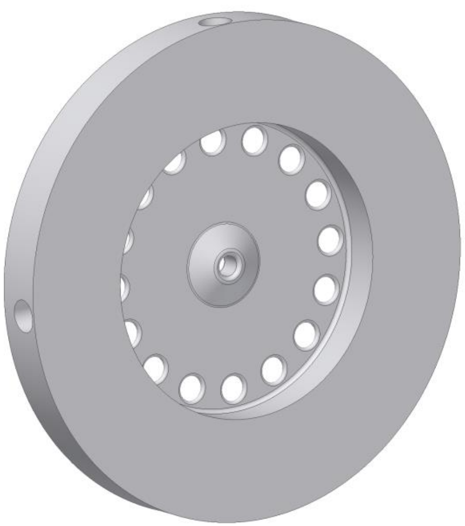
Backward travelling wave accelerating structure



Accelerating elements

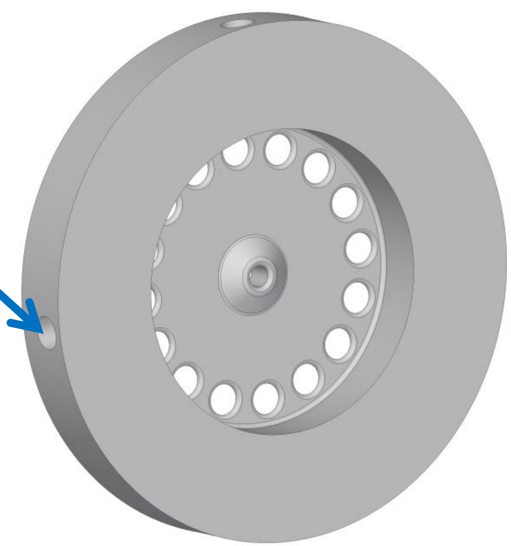


120° of phase advance

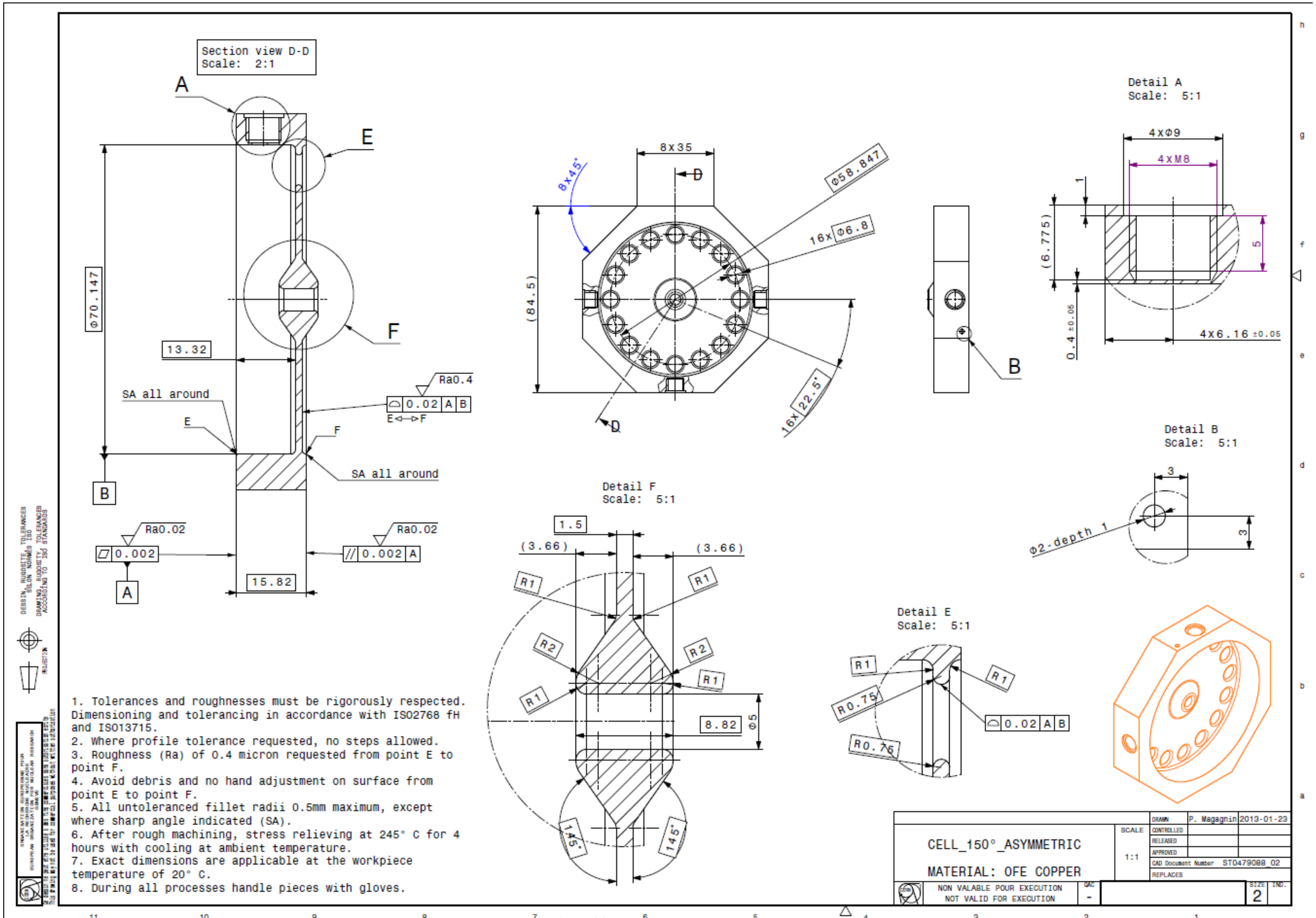


150° of phase advance

4 holes for dimpler tuners

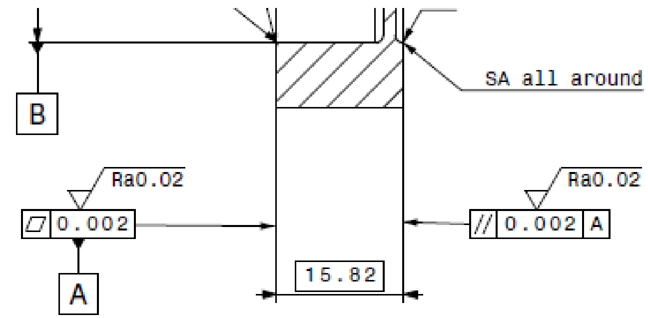


Feasibility of requested tolerances



Feasibility of requested tolerances

- Bonding surfaces

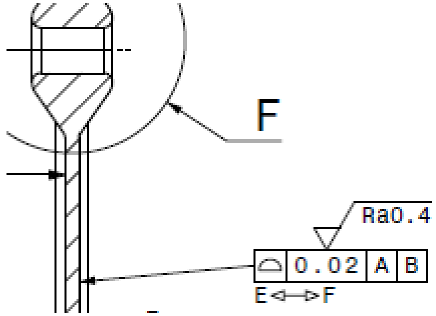


Planarity

Requested: 2 microns, reachable in fixed state, with the application of a pressure of 0.05 MPa
Reachable in free state: 4 microns

Roughness: 20 nanometers, reachable

- RF surfaces

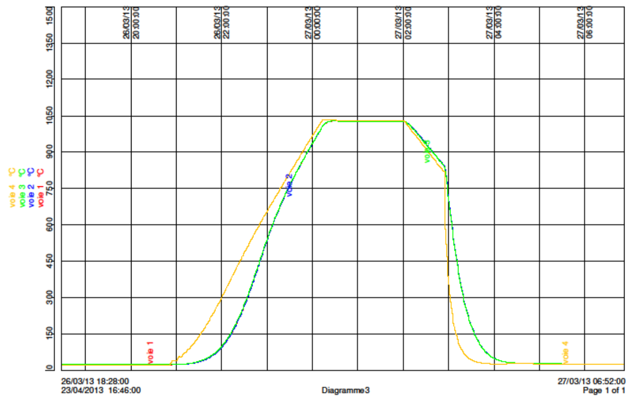


Profile tolerance

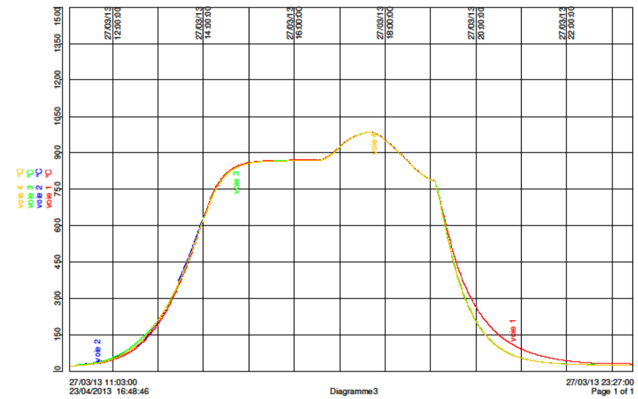
Requested: 20 microns
Reachable: 10 microns, but more expensive (even in the case of wall thickness 1.5 mm)

Joining procedures

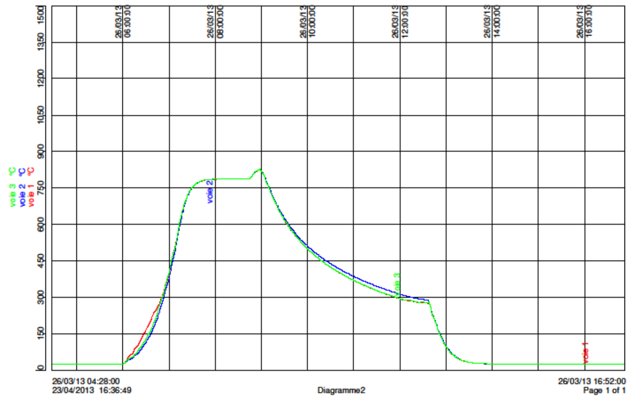
Hydrogen Bonding: T_{HB}=1050 °C



Gold Brazing: T_{GB}=950 °C



Silver Brazing: T_{SB}=820 °C



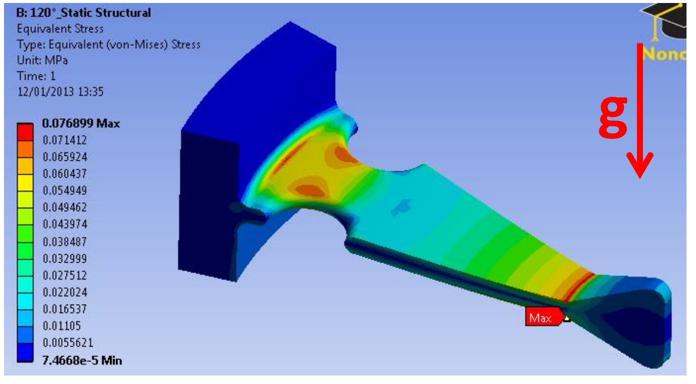
OFE Copper melting point

1083 °C

CREEP?

Evaluation of different cells structural performance

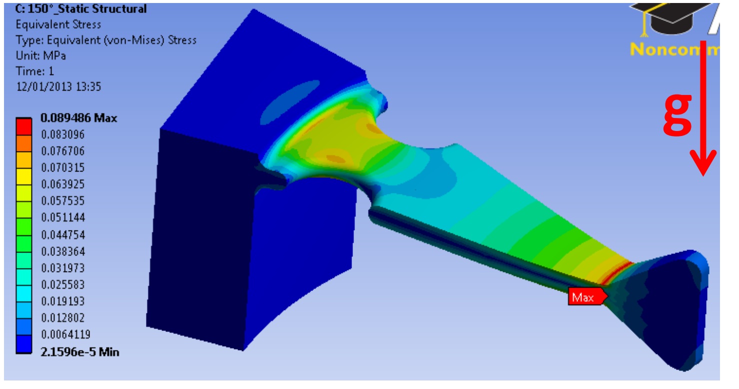
120° of phase advance



$$\sigma_{max} = 0.077\ [MPa]$$
$$f_{max} = 8.9 \cdot 10^{-5}\ [mm]$$

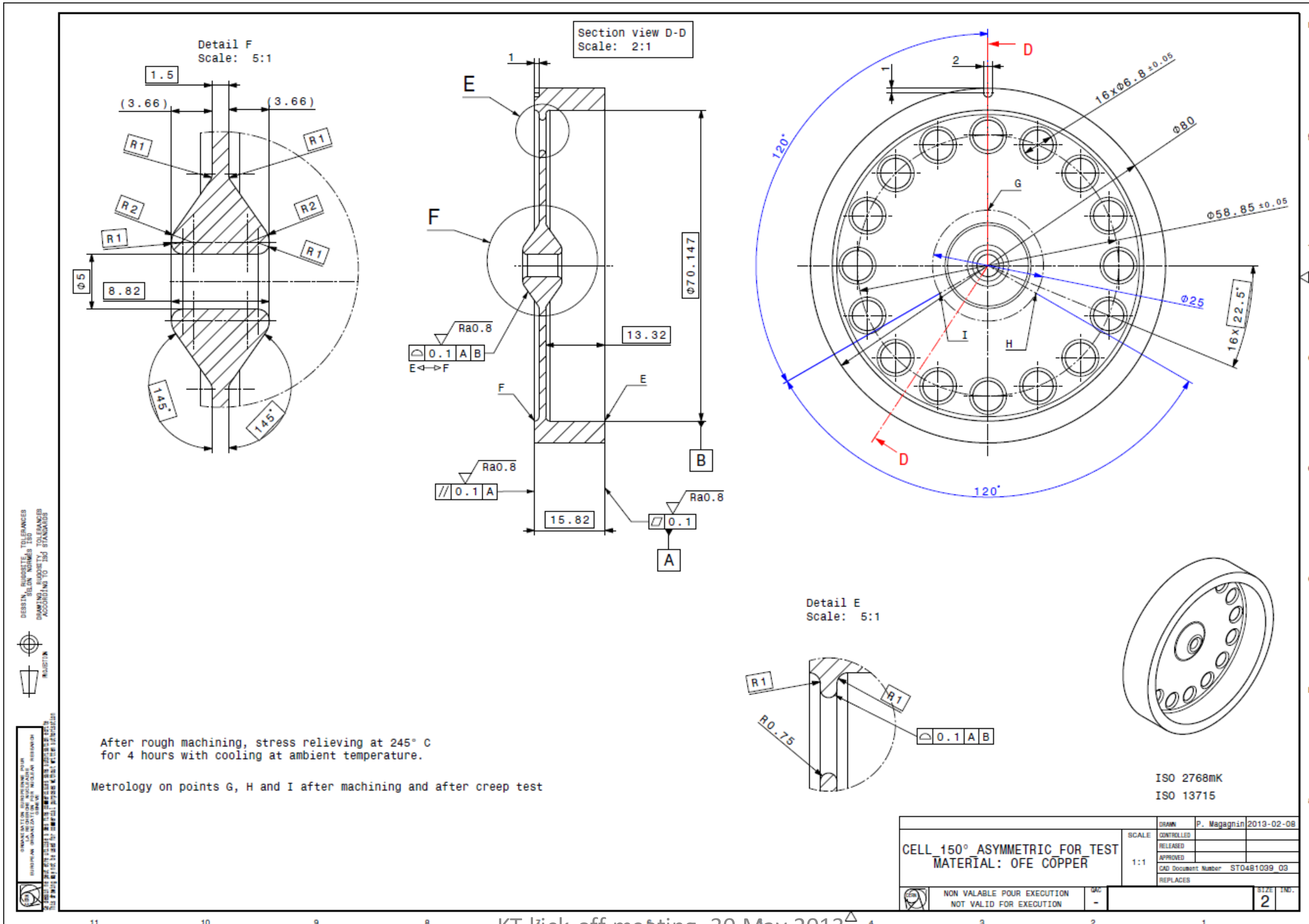
Load: gravitational force

150° of phase advance



$$\sigma_{max} = 0.090\ [MPa]$$
$$f_{max} = 9.1 \cdot 10^{-5}\ [mm]$$

Creep test

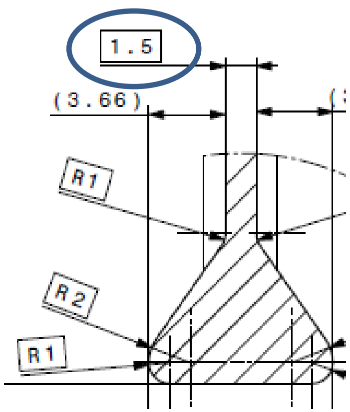


Detail F
Scale: 5:1
Section view D-D
Scale: 2:1
Detail E
Scale: 5:1
After rough machining, stress relieving at 245° C
for 4 hours with cooling at ambient temperature.
Metrology on points G, H and I after machining and after creep test
ISO 2768mK
ISO 13715
CELL_150°_ASYMMETRIC_FOR_TEST
MATERIAL: OFE COPPER
P. Magagnin 2013-02-08
ST0481039_03
NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

Creep test

150° of phase advance

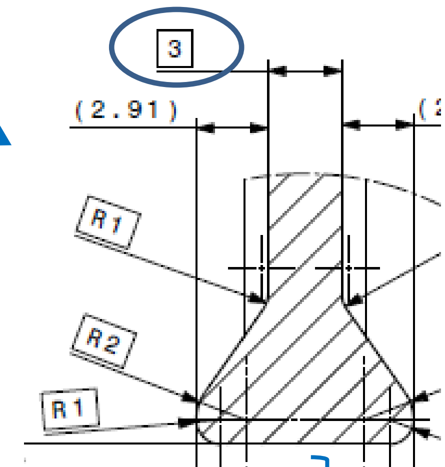
S = 1.5 mm



Hydrogen Bonding: T_{HB}=1050 °C
Silver Brazing: T_{SB}=820 °C
Gold Brazing: T_{GB}=950 °C

X 2 → **6 cells**

S = 3 mm



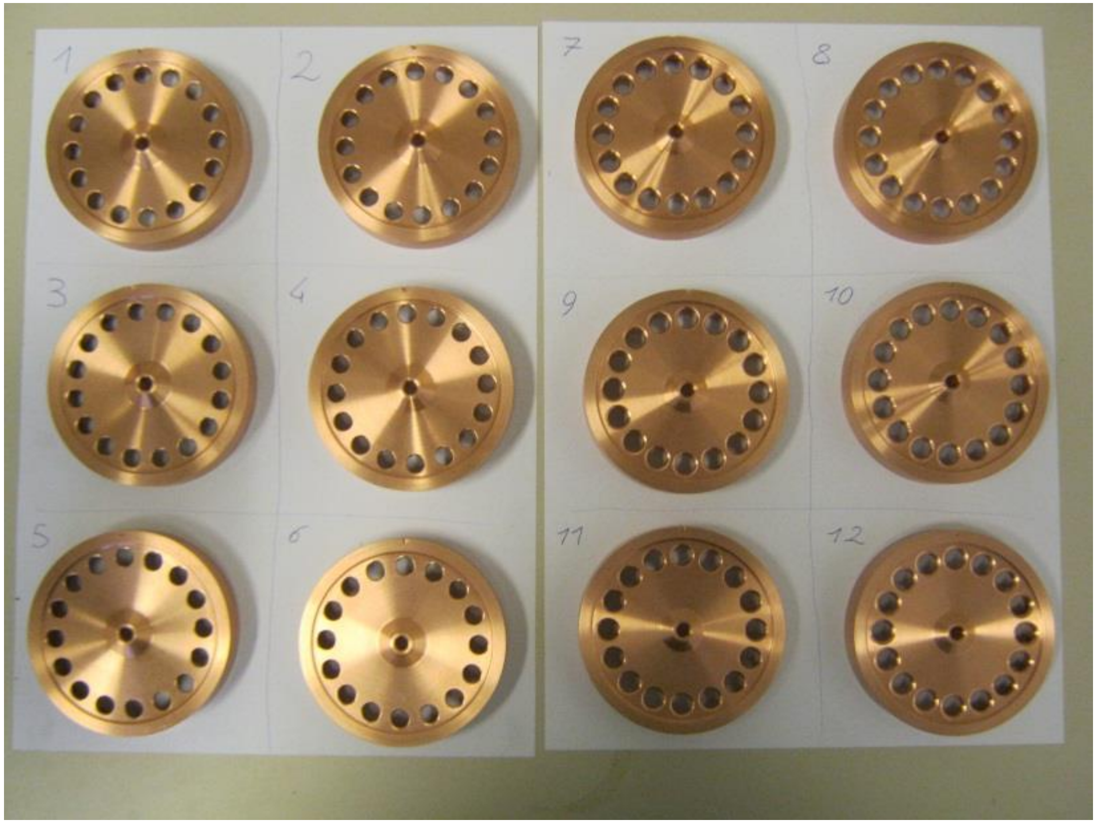
Hydrogen Bonding: T_{HB}=1050 °C
Silver Brazing: T_{SB}=820 °C
Gold Brazing: T_{GB}=950 °C

X 2 → **6 cells**

Creep test

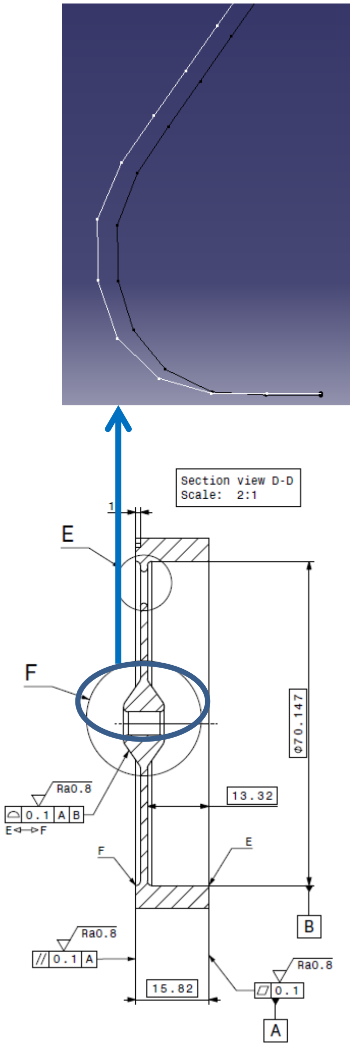
Machining steps used by VDL and adopted also for the creep test:

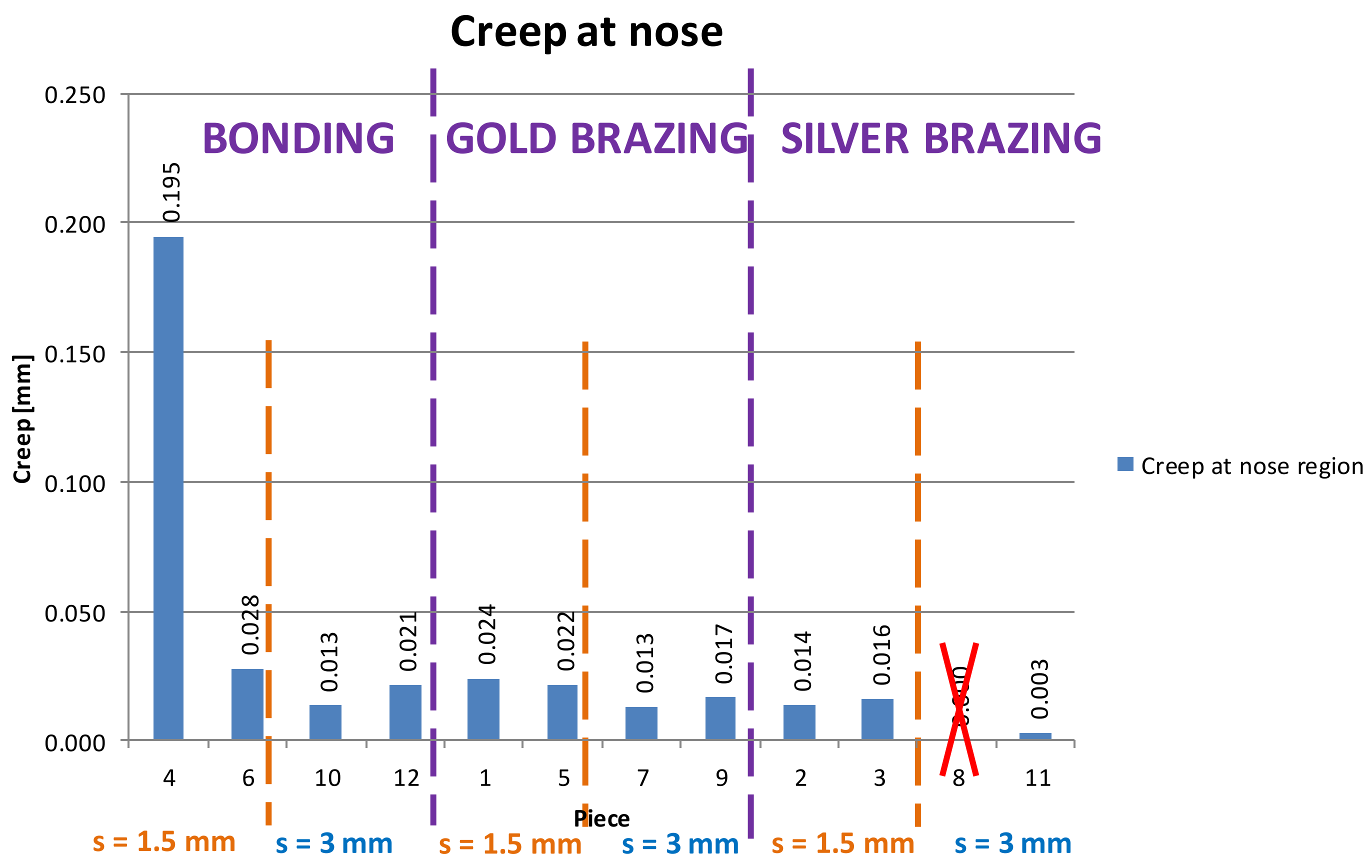
- Premachining
- Annealing: 245 °C for 4 hours
- Final machining



Creep test results

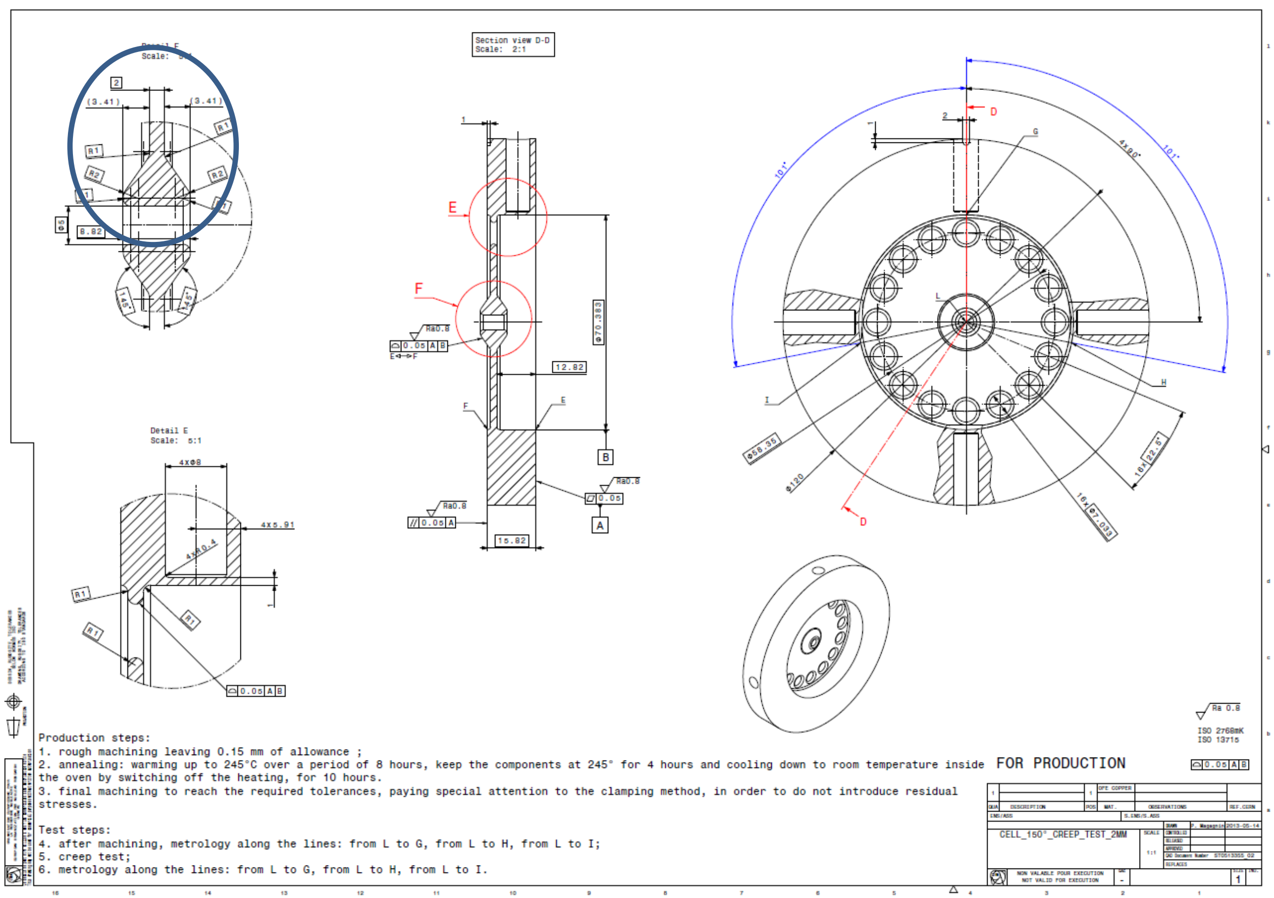
Creep values along the cell's axis direction



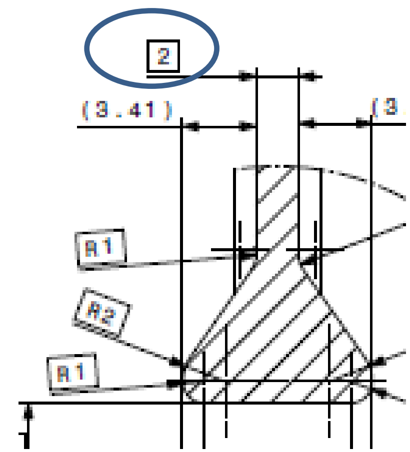


Second creep test

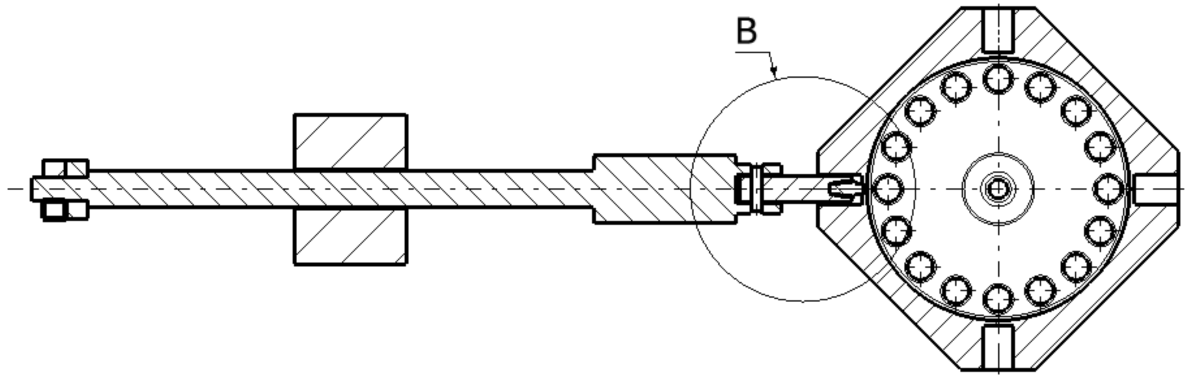
20 discs, to be tested at the 3 temperatures, in order to simulate vertical and horizontal bonding/brazing.

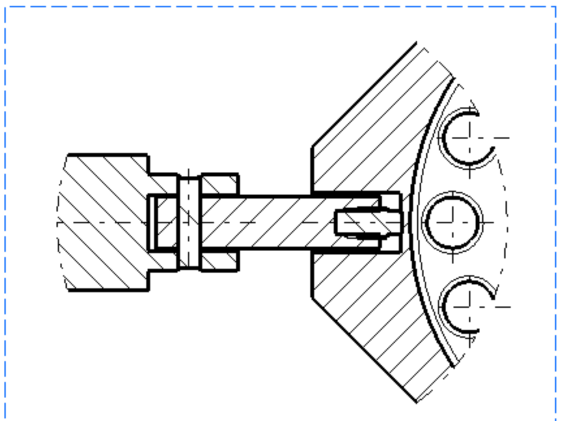


S = 2 mm

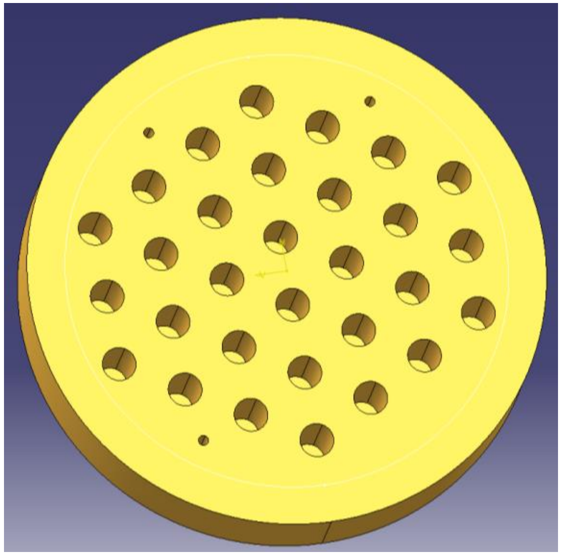


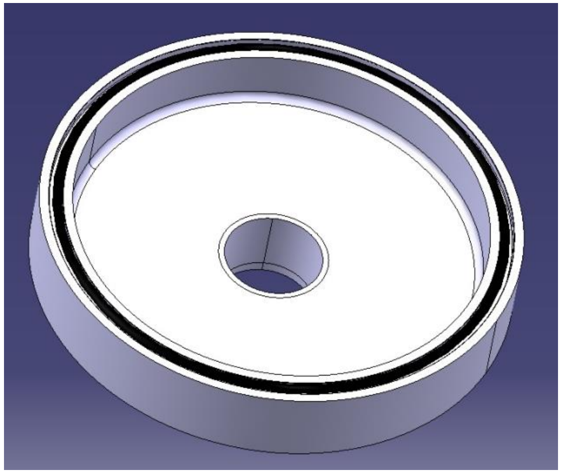
Tuning features

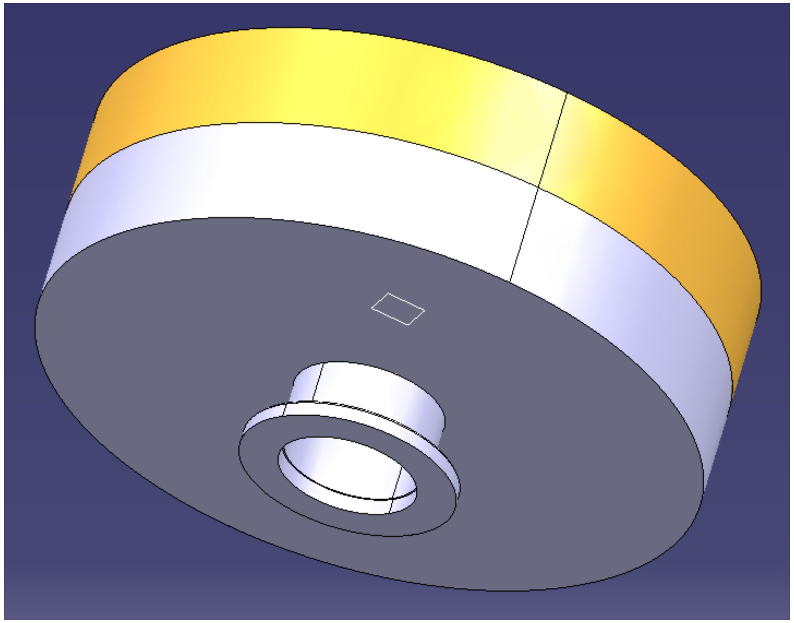




Test of tuning capability

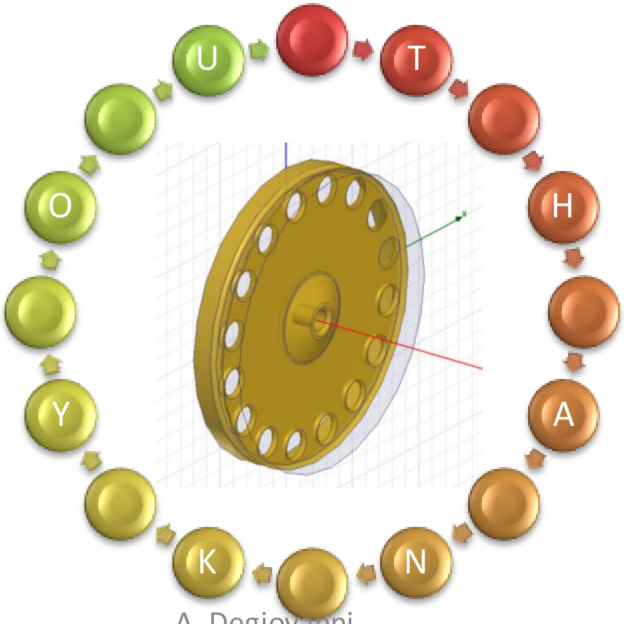






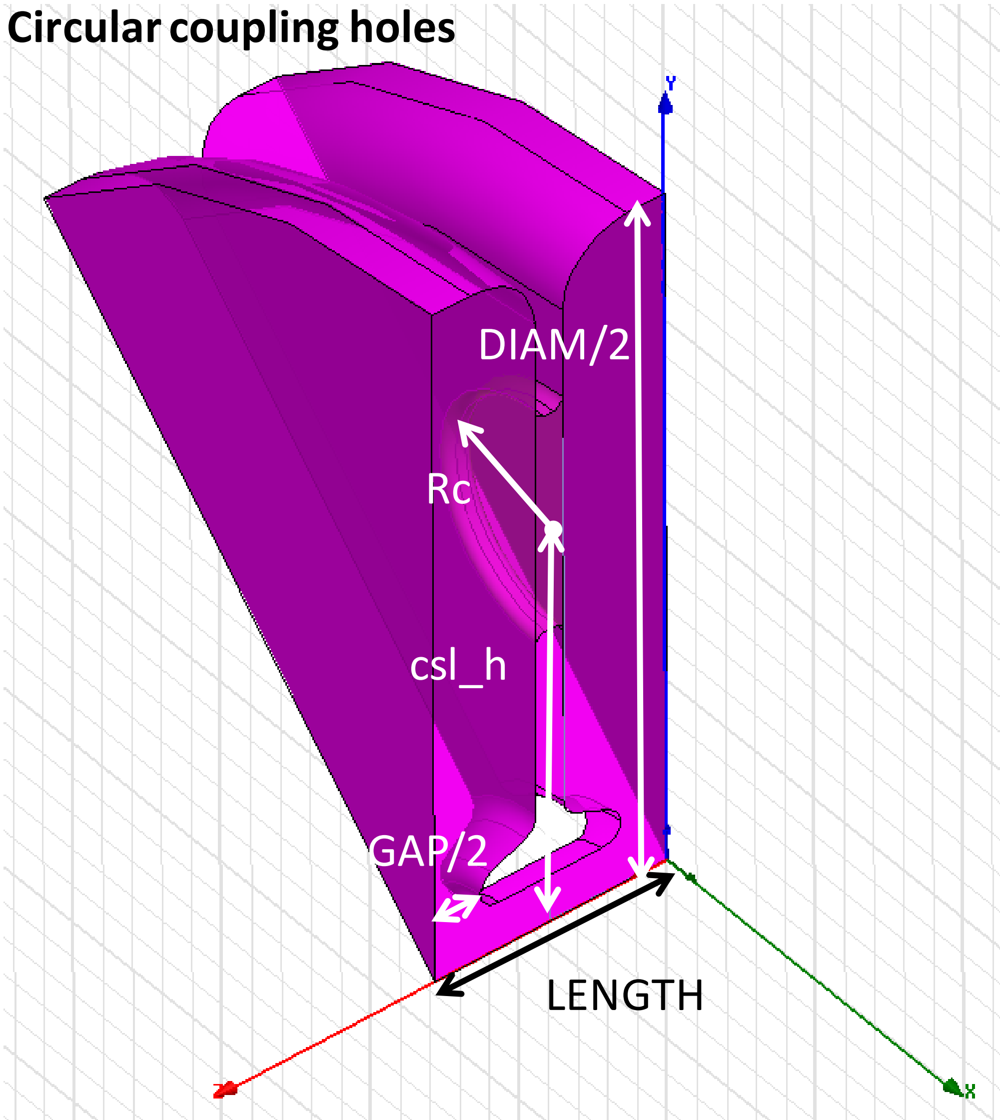
Summary

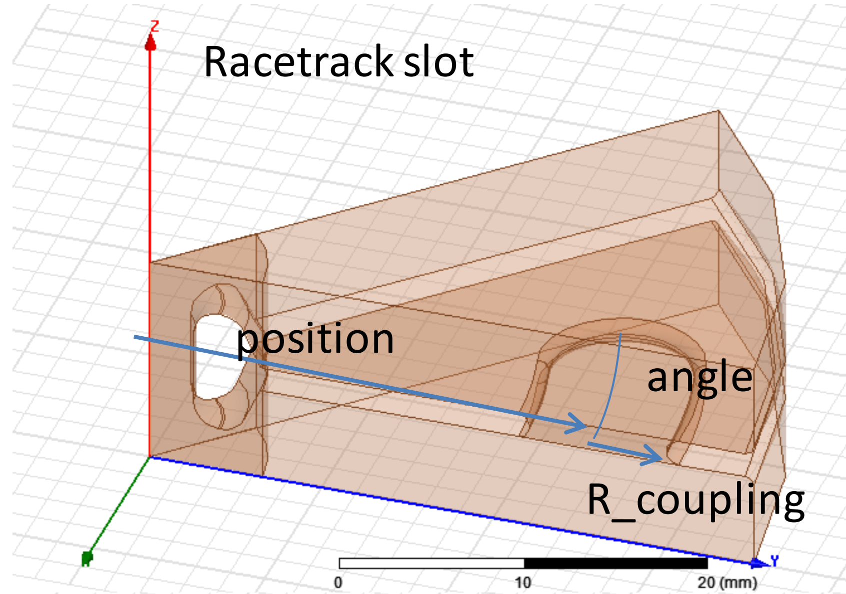
- **Optimization** of TW structures for high gradient operations has been performed **for 120° and 150° phase advance**.
- The **RF design of the input and output coupler** is now ongoing.
- The **Engenering design including thermo-mechnical simulation and Creep tests** is progressing well
- **The design and test of the novel bTW structures is boosting the TULIP project!**

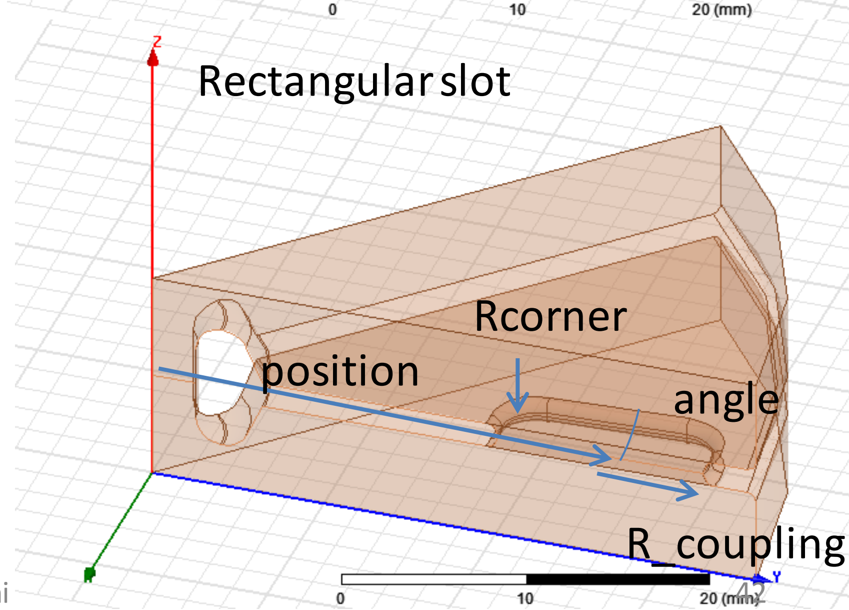


BACK-UP slides

TULIP-CLIC-bTW – beta=0.3798 (W=76 MeV)







SUMMARY	120 deg		150 deg		SCL base	SCL – HG
wall thickness (mm)	1.5		1.5		3.0	3.0
gap (mm)	5.5		7.0		5.1	9.5
nose cone angle (deg)	65		55		25	55
length (mm)	189.9		189.9		189.9	189.9
ncell	15		12		10	10
Ea_avg (MV/m)	25		25		25	25
Sc_nose (MW/mm2)	0.149		0.185		0.486	0.188
t_pulse (ns) flat	2500		2500		2500	2500
expected BDR (at given Ea and t_pulse) (bpp/m) based on Sc limit	1.1 E-22		2.9 E-21		5.7 E-15	3.7 E-21
max Ea (for BDR of 10^{-6} bpp/m) (MV/m)	85.2		76.3		47.1	75.7
Pin (MW) (w/o recirculation)	2.70	5.19	2.49	5.10	1.75	2.26
Pout (MW) (w/o recirculation)	-	2.90	-	3.02	-	-
Q0 (first/last)	6482/6721		7088/7545		8291	8250
vg (first/last) [%c]	0.421/0.226		0.404/0.236		-	-
R'/Q (first/last) [Ohm/m]	7872/7847		7835/7794		8406	6355
time constant (ns)	320		340		440	440
field rise time (time to reach 99% field) (ns) (w/o recirculation)	750	204	800	204	1050	1050