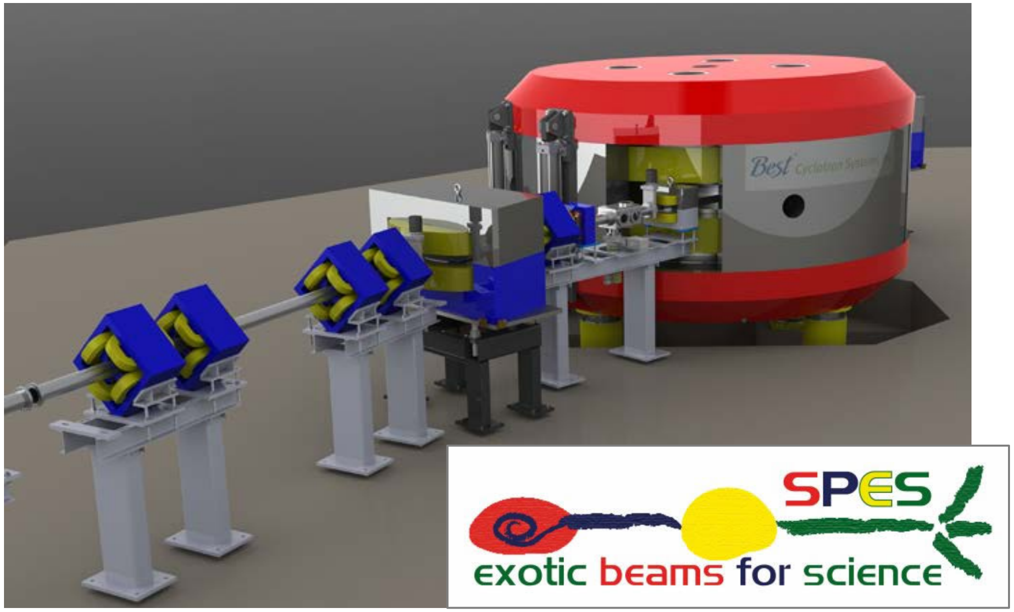
ANEM:
a rotating composite neutron production target for Single Event Effects Studies

Luca Silvestrin luca.silvestrin@pd.infn.it

SPES



The SPES proton Cyclotron at LNL

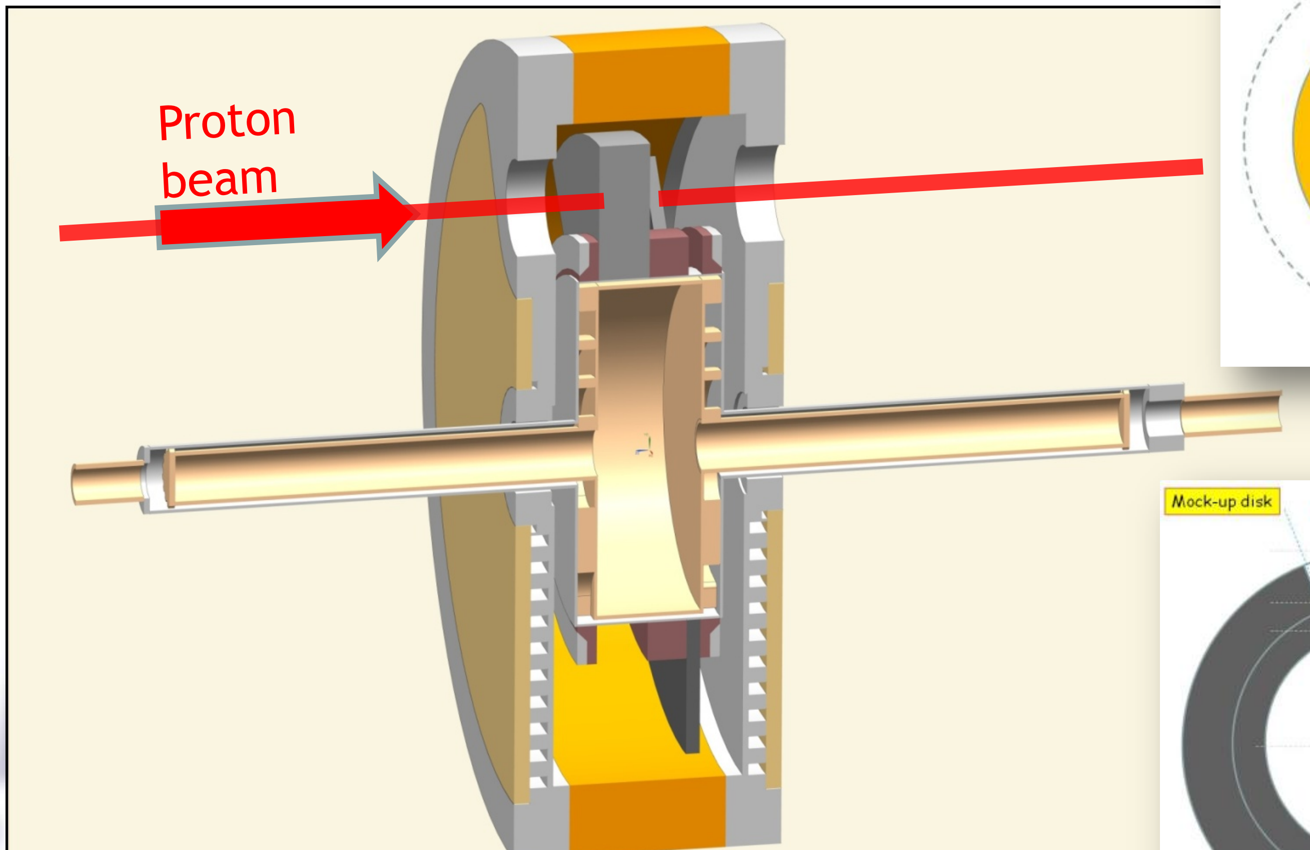
The SPES laboratory building

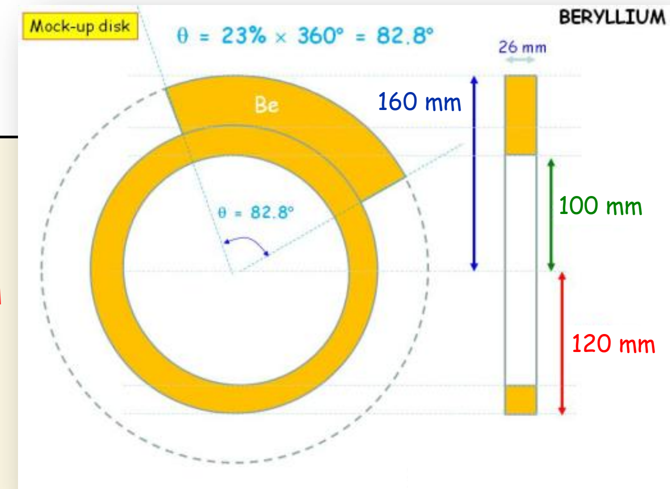
A variable energy (35-70 MeV) high current proton cyclotron (I_{max} = 500-1000 μA) is being install in the SPES laboratory.

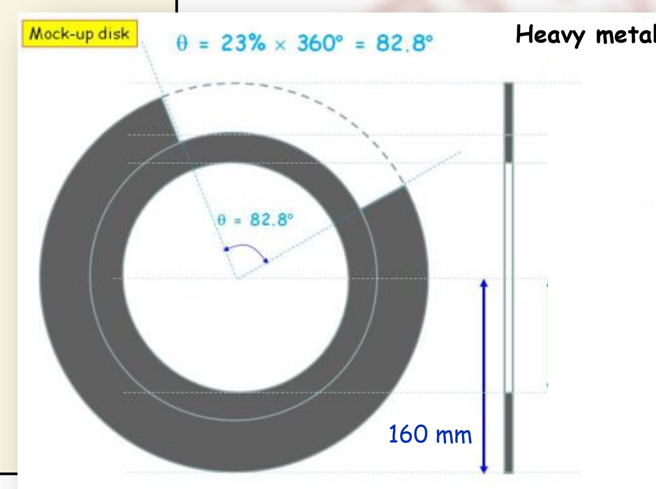
It opens the prospect of high flux neutron facility in Italy

ANEM (Atmospheric Neutron EMulator)

ANEM composite target made of Be and a heavy element (W) to produce an effective atmospheric-like neutron spectrum in the 1-60 MeV range, without the use of moderators.



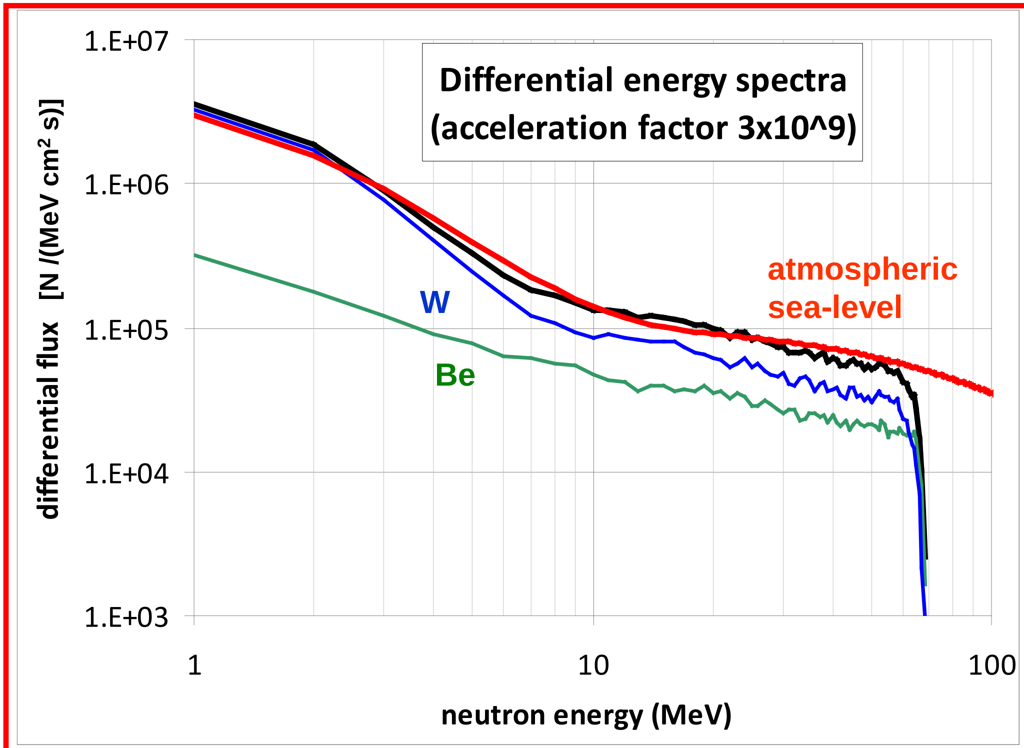




ANSYS simulations under way.
Thermal tests with Al disk foreseen in the next months.

Luca Silvestrin luca.silvestrin@pd.infn.it

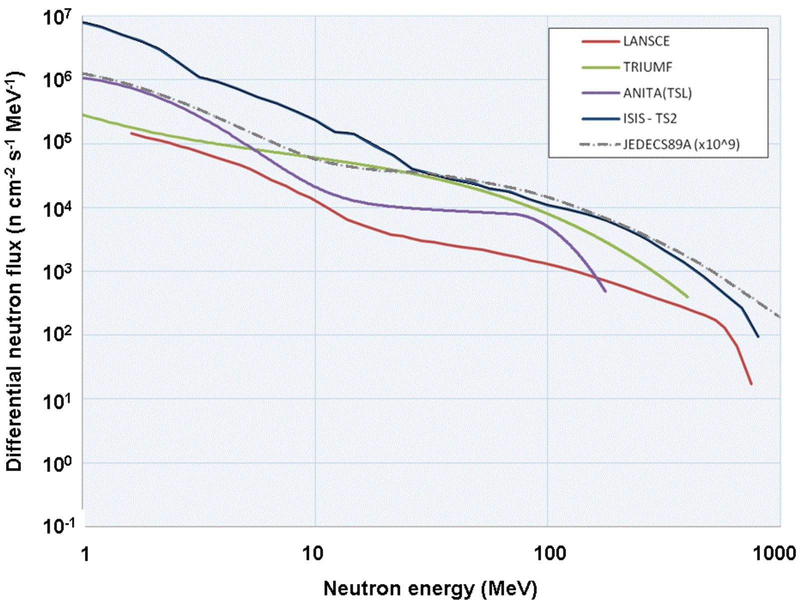
Spectra combination



70 MeV proton beam **current: 33 μA** (power 2.31 kW)

Composition: **Be 18%** , **W 82%**

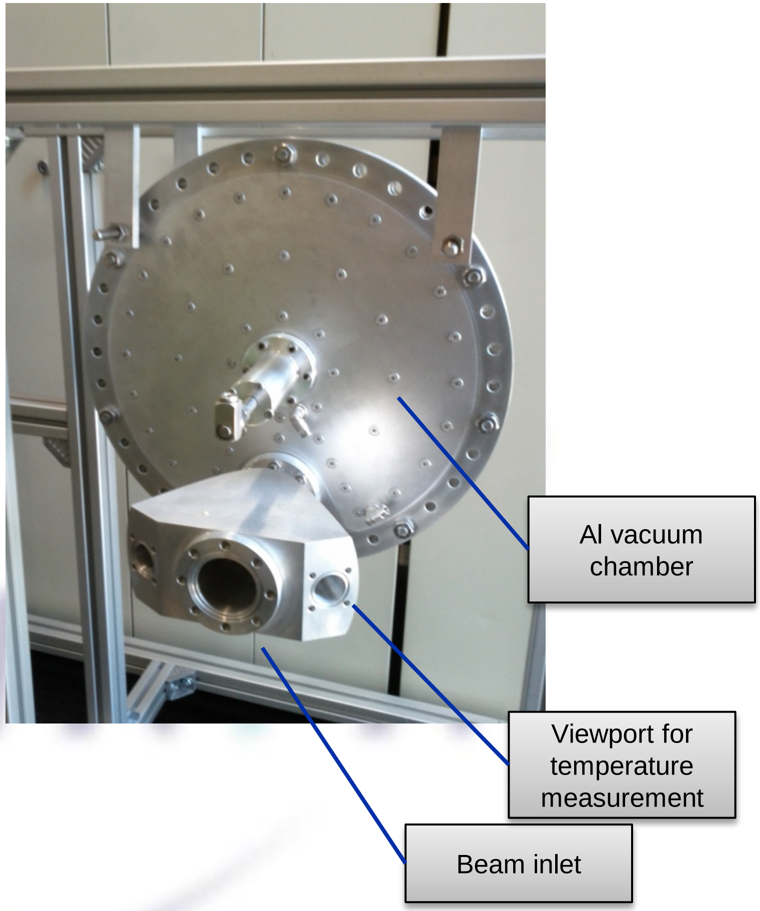
Distance from target: **6 m**

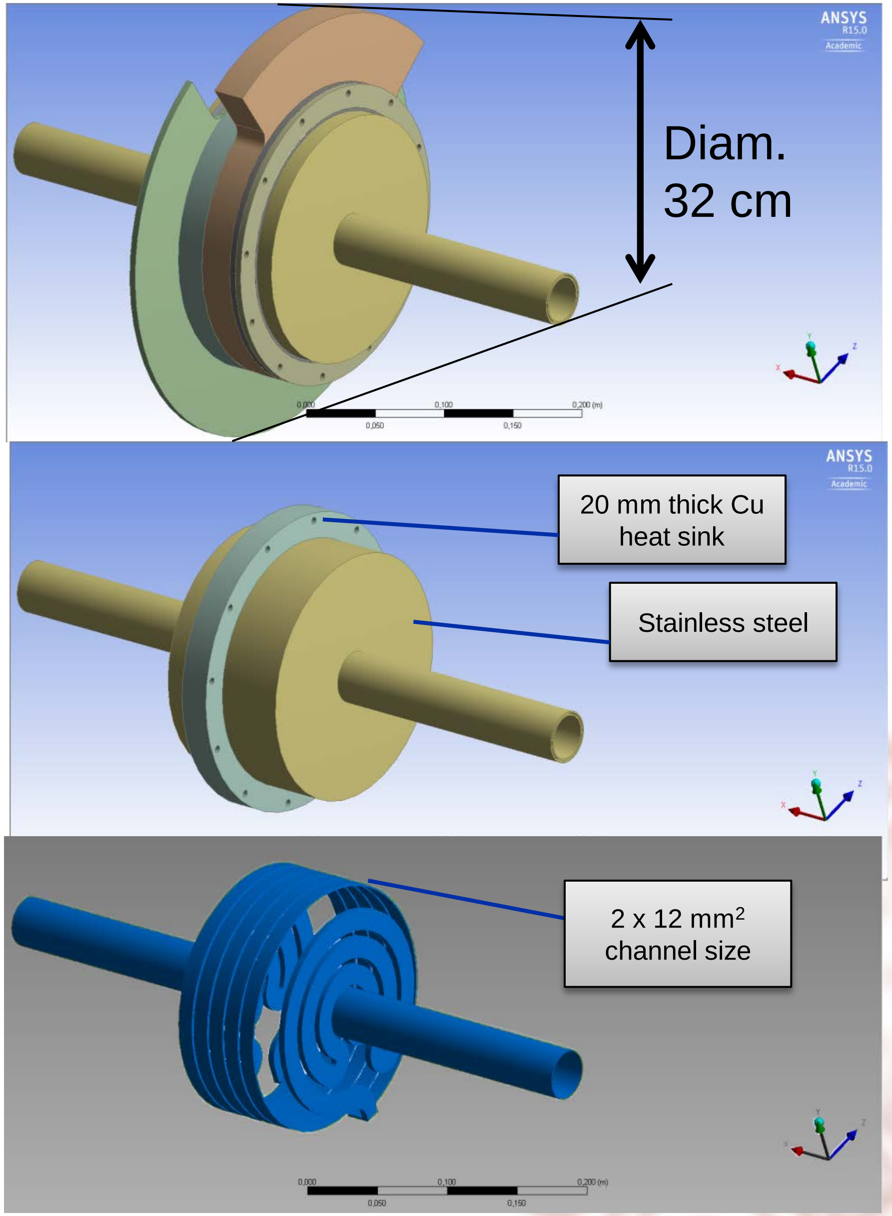


The differential energy spectra of neutrons at irradiation facilities. The dashed curve is the JEDEC reference spectrum multiplied by F = 10^9. The **Chip-IR** facility, located at the ISIS Target Station 2 (TS2), is design with an **acceleration factor F = 3 × 10^9**.

Target geometry

The ANEM target design is derived from the target designed for the LENOS experiment: is uses the same chamber, but with modified innards to house Be and heavy element "disks" and a water flow cooling system.

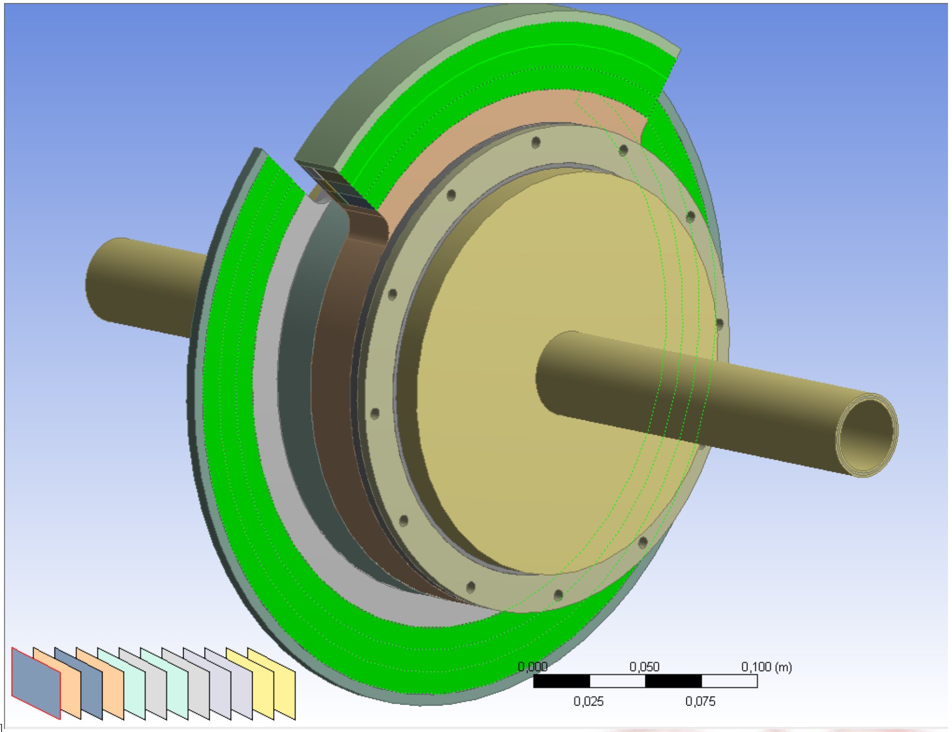


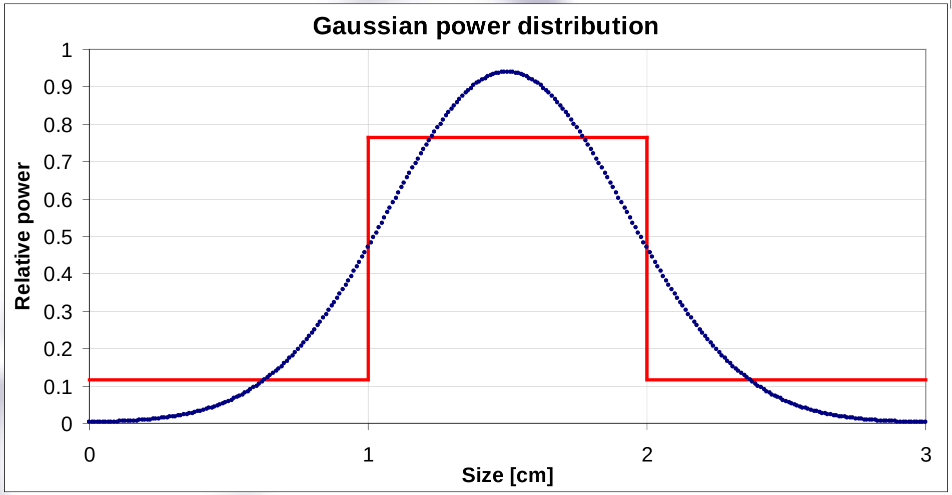


Power deposition

The power deposited by the beam both in Be and W target elements is simulated as power released in a ring at the periphery of the sectors. The gaussian (FWHM = 1 cm) beam energy release is roughly approximated in the radial direction, using a three steps function.

To be more conservative we simulated the worst case scenario in which the heat doesn't propagate directly from Be (or W) to stainess steel, but the whole heat flux is forced to pass through the Cu heat sink to leave the irradiated sectors.





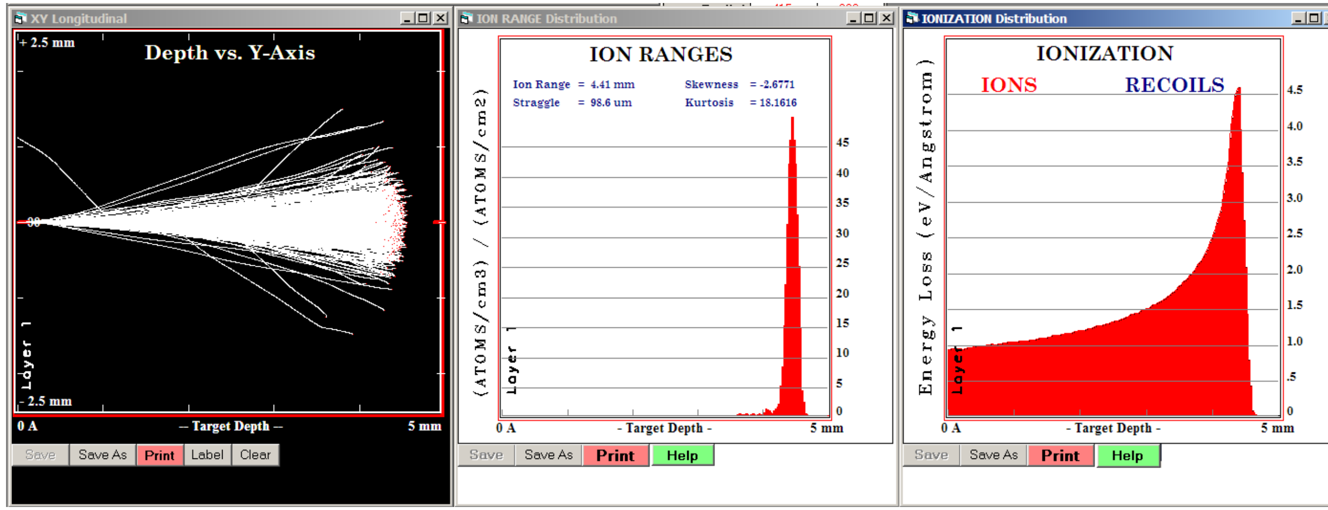
Gaussian radial energy deposition approximation

Luca Silvestrin luca.silvestrin@pd.infn.it

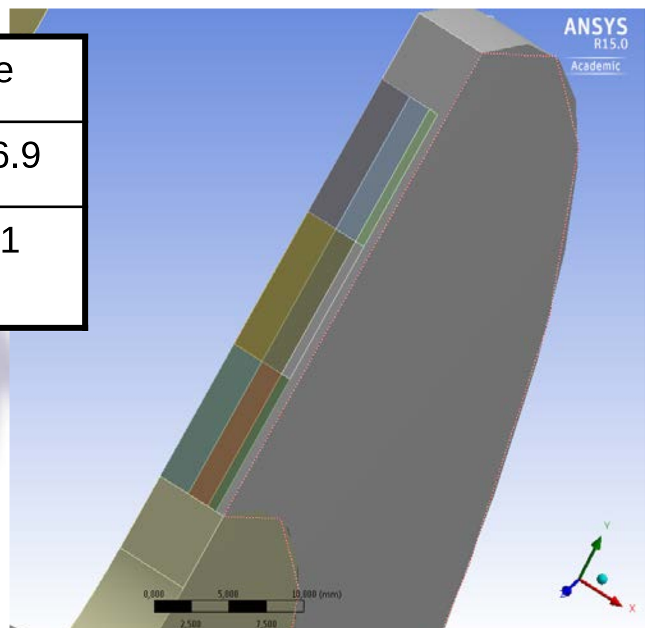
Beam propagation in W

The Tungsten sector thickness was chosen to be 5 mm. Since this element well tolerates Hydrogen implantation, it was designed as a beam-stopping target

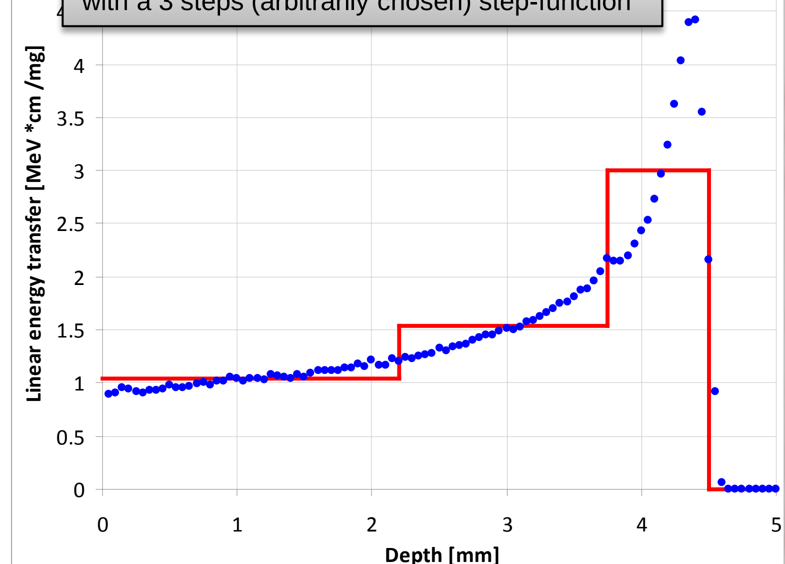
Srim simulation of a 70 MeV proton beam in W



	W	Be
Range [mm]	4.37	26.9
Struggling (*<Var>*$^{0.5}$) [mm]	0.235	1.1



The Bragg peak in Be was also approximated with a 3 steps (arbitrarily chosen) step-function



Beam propagation in Be

The Beryllium sector thickness must be carefully determined. This element doesn't tolerates Hydrogen implantation (it undergoes blistering). For this reason it must be designed as a **NON beam-stopping** target.

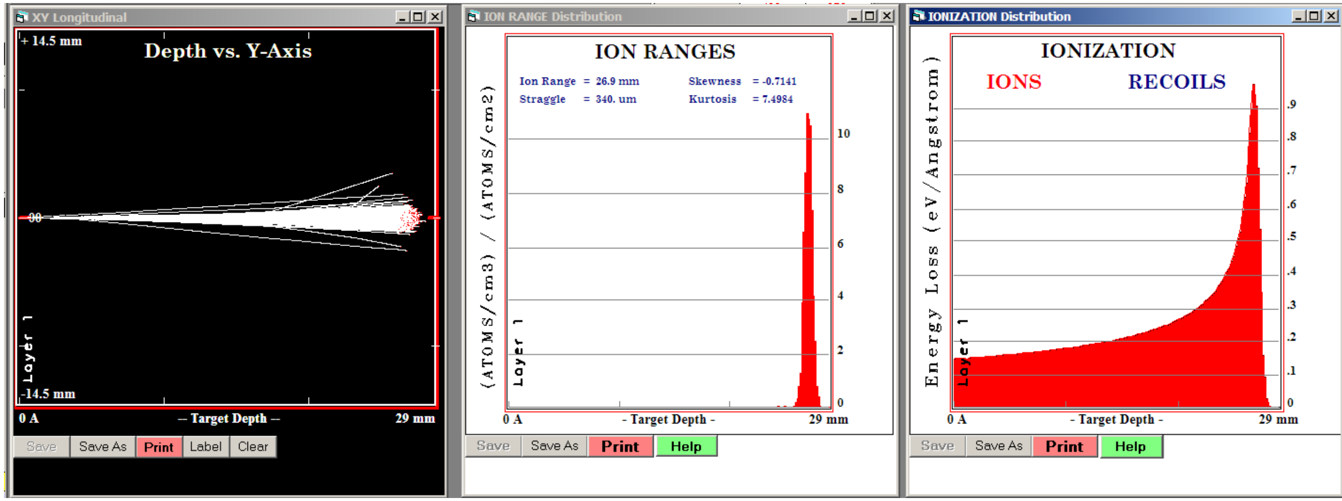
The exiting protons must be deflected in a beam dump.

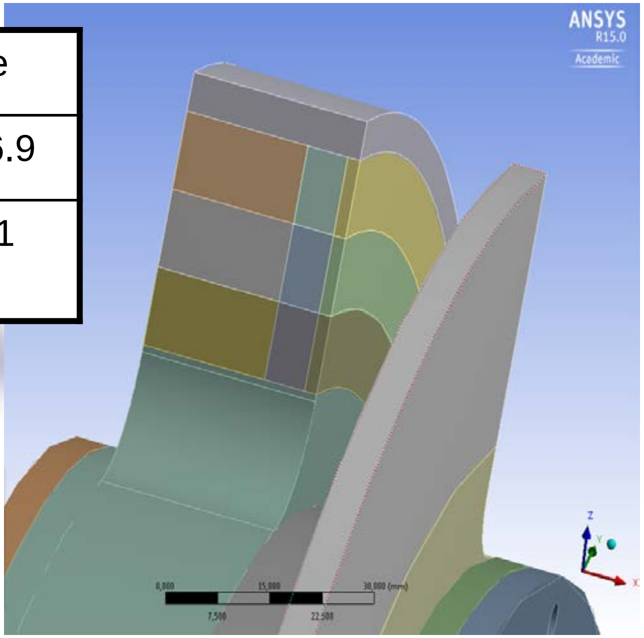
The energy deposited by the beam in the 26 mm thick target, calculated using SRIM, was found to be 85%.

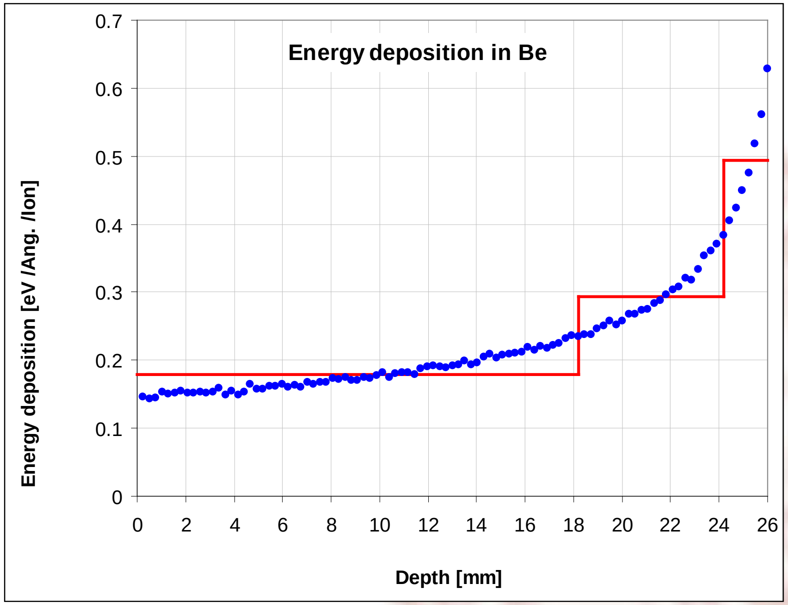
	W	Be
Range [mm]	4.37	26.9
Struggling $(<Var>^{0.5})$ [mm]	0.23 5	1.1

To avoid stopping protons, the Be sector thickness should be no more than 24 mm.

Srim simulation of a 70 MeV proton beam in Be



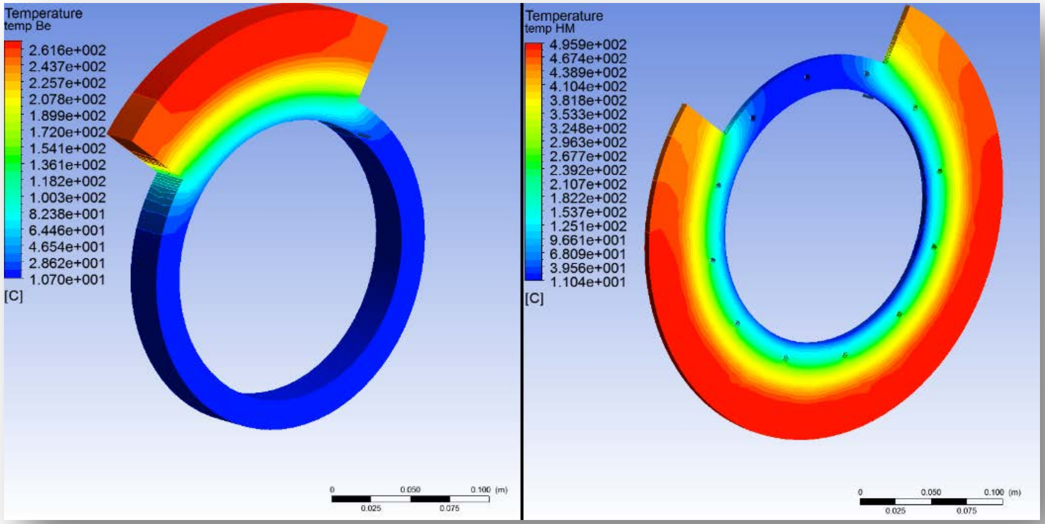




Thermal power dissipation

Impinging proton beam
- power 5 kW
- Gaussian beam spot (FWHM 1 cm)

Results
- Be max temp 216 C (melting point 1287 C),
- W max temp 495 C (melting point 3422 C).



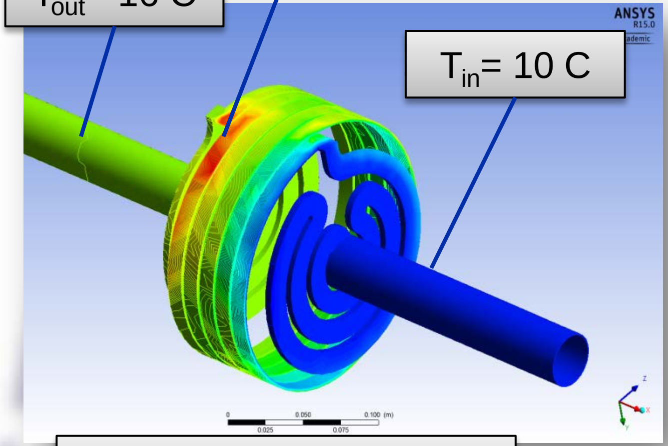
Thermal map of Be and W

<u>Temperature is not a problem</u>
in our target

T_{max}= 34 C

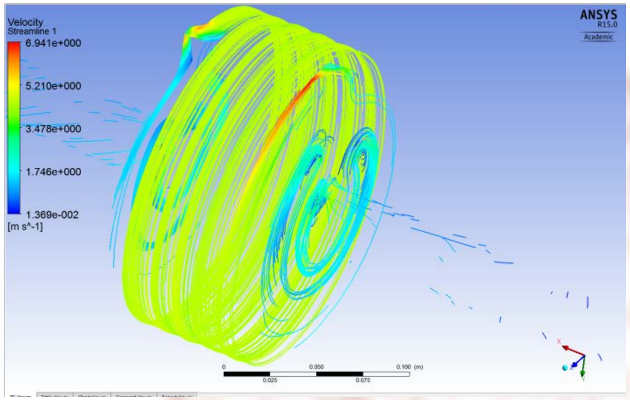
T_{out}= 16 C

T_{in}= 10 C



Temperature map of the cooling circuit

Temperature distribution in cooling circuit is everywhere well below the boiling point. The flux is 0.2 l/s, the water speed 4 m/s in the coil.



Water speed in the cooling circuit

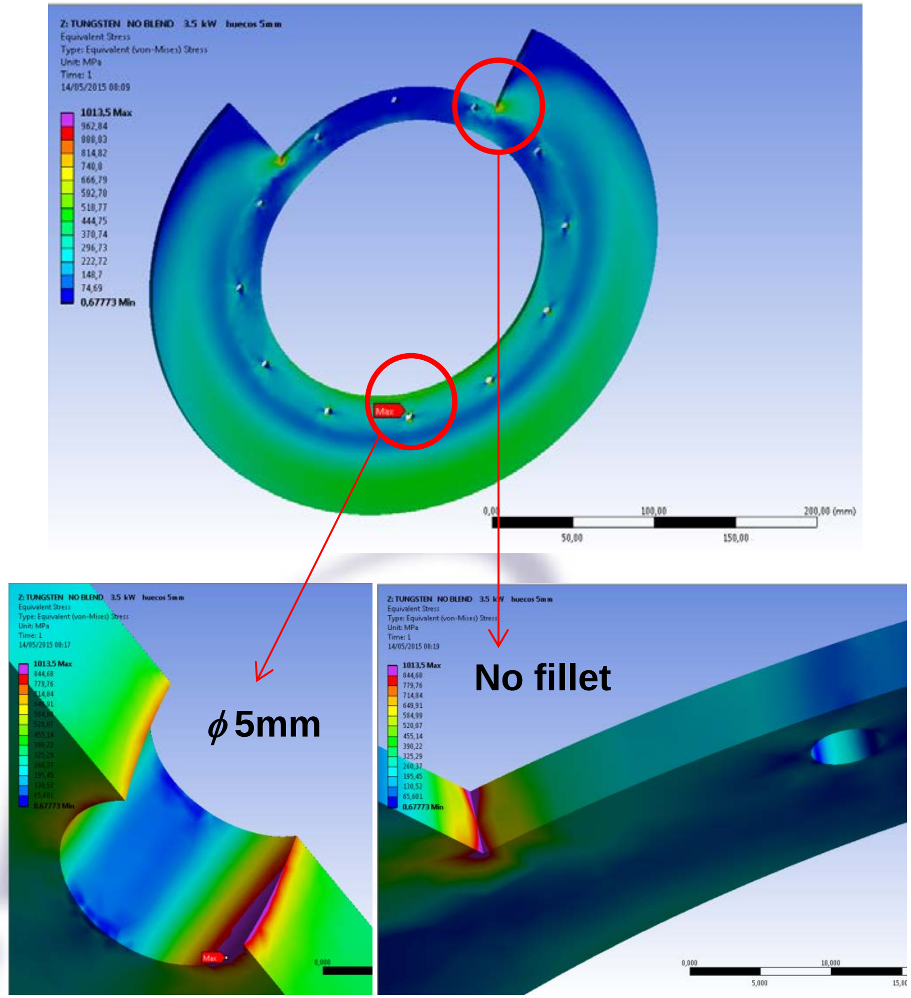
Ansys CFX module was used to perform thermal simulation

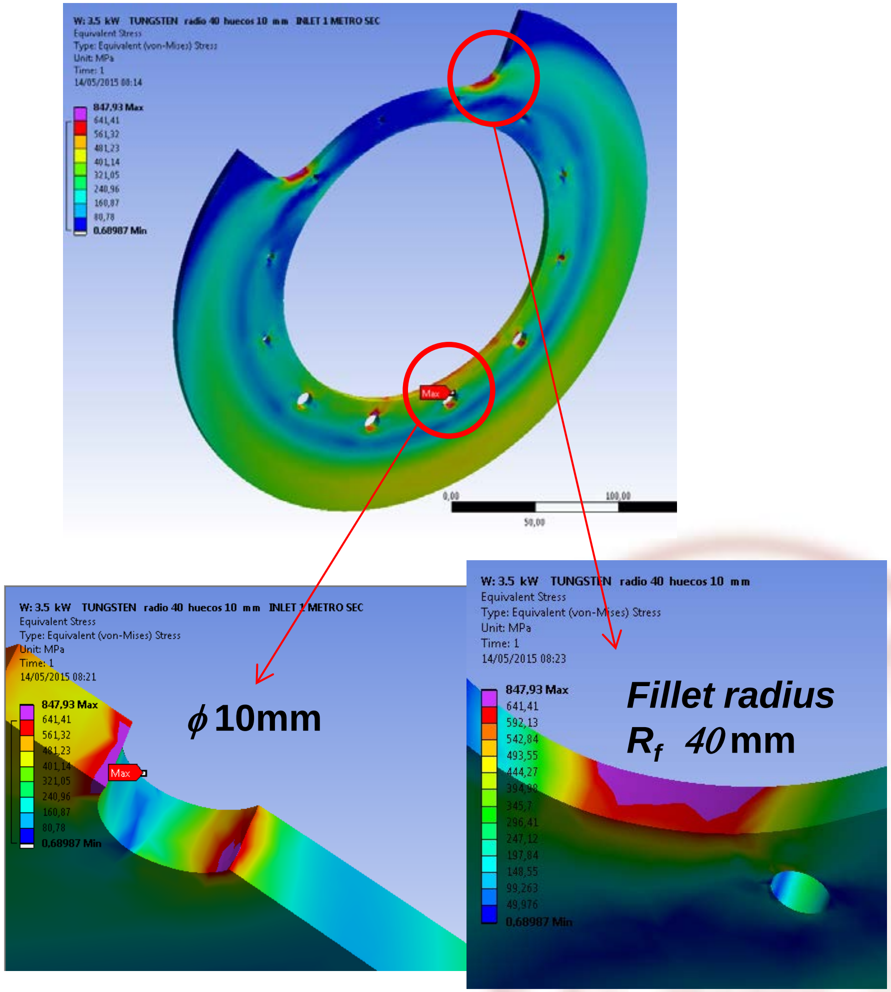
Luca Silvestrin luca.silvestrin@pd.infn.it

Stress

We performed variations to the initial design looking for more robust configuration with a minimum impact on the manufacturng cost (non negligible for the Be sector).

We concentrated on the areas where the maximum stress was localized

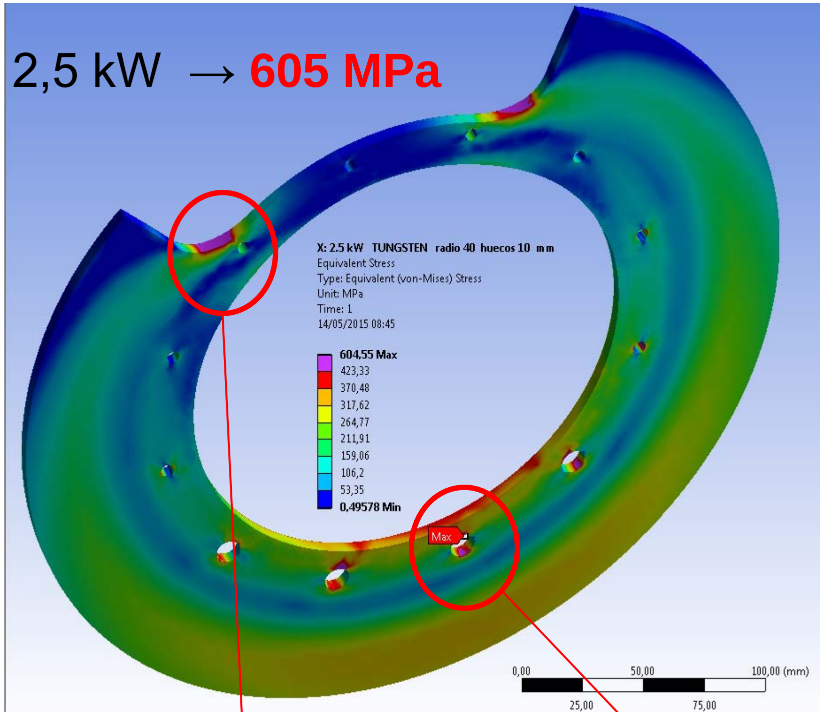


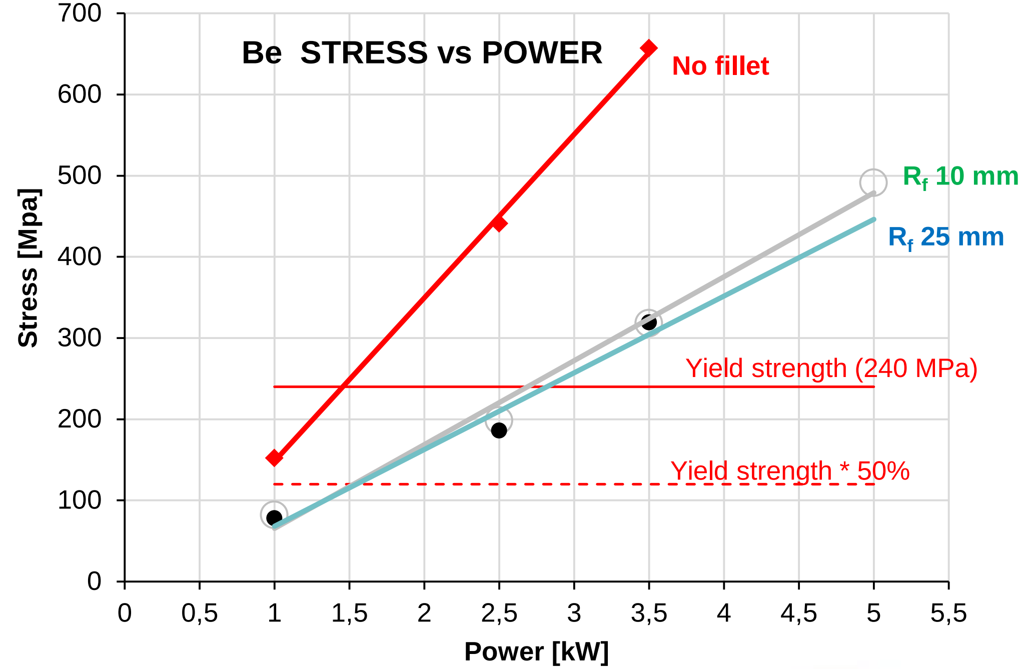


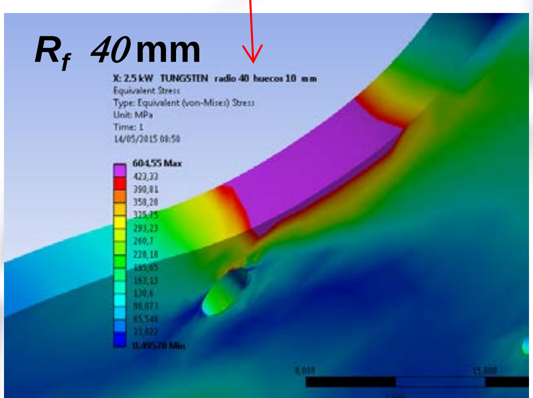
3,5 kW → **1013 MPa**

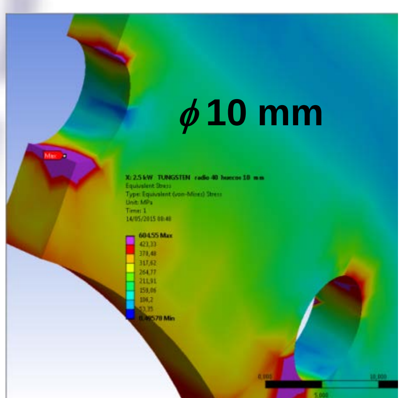
3,5 kW → **847 MPa**

Design variations









Stress in Be target as a function of power for different fillet radius values.
The Be yeld strenght is shown by the horizontal red line, the horizontal dashed green line is 50% (conservative safety margin).

Tungsten (in extra slides) is a very robust element: it tolerates a power deposition which exceeds 5 kW.

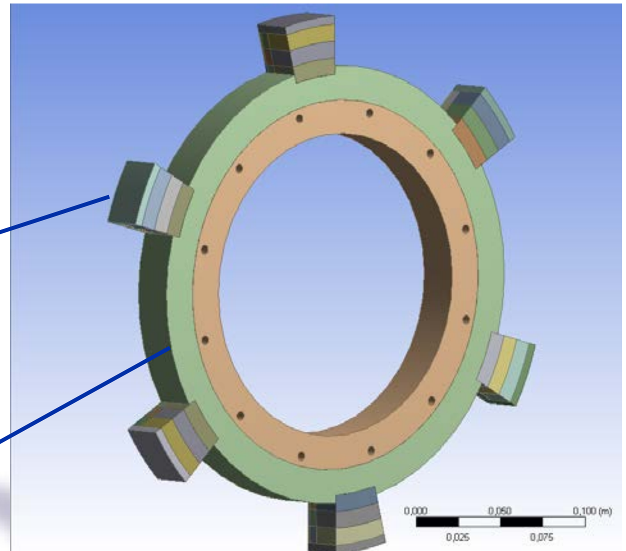
Alternative design

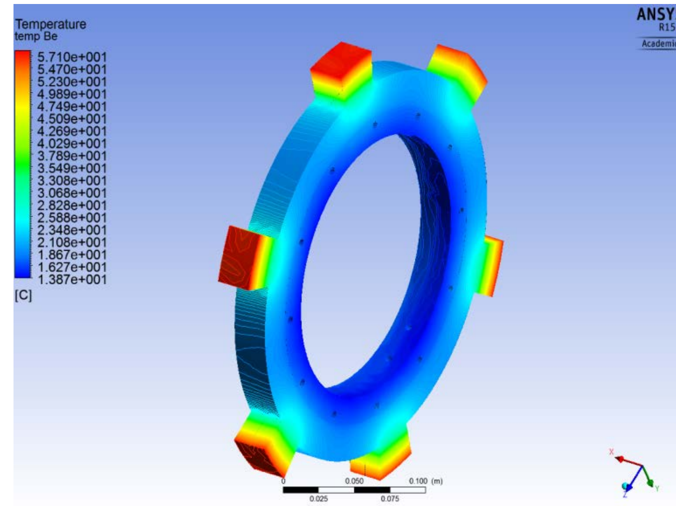
We are considering alternative solutions to the initial design of the target, looking for a more modular, more robust, less expensive (less Be) design.

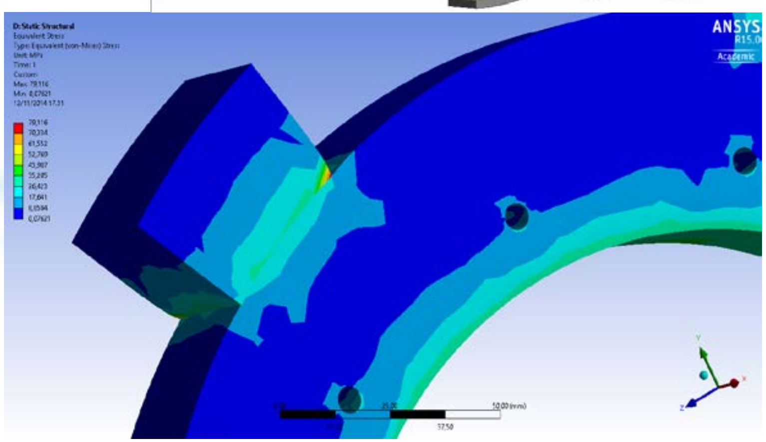
A solution under study is to realize in Be only the irradiated elements, and in Cu the "collar".

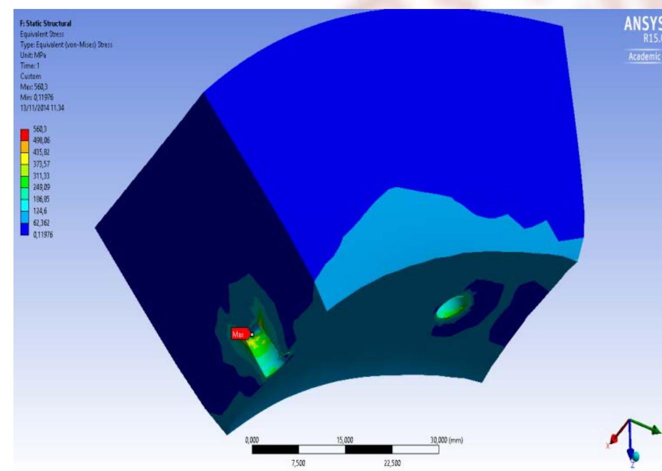
Be irradiated elements

Cu "collar"









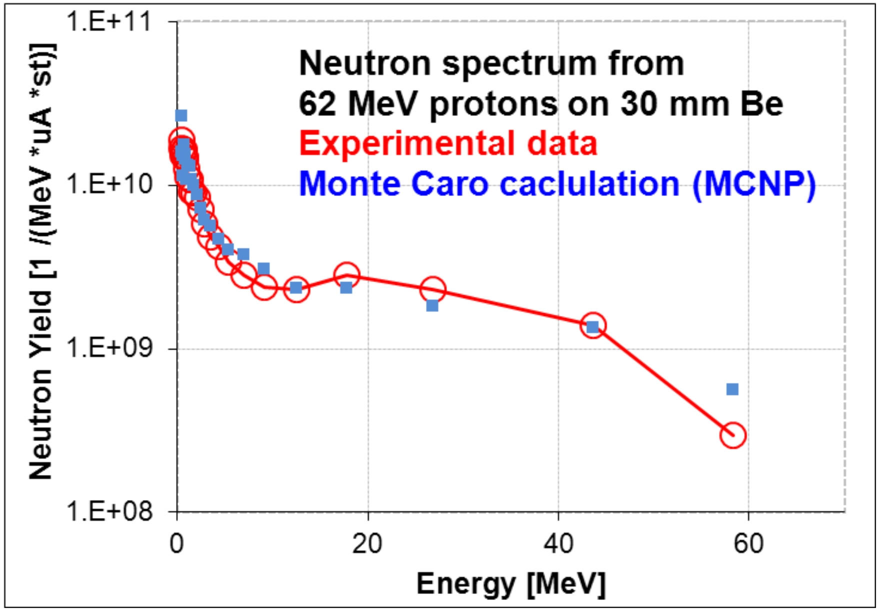
Luca Silvestrin luca.silvestrin@pd.infn.it

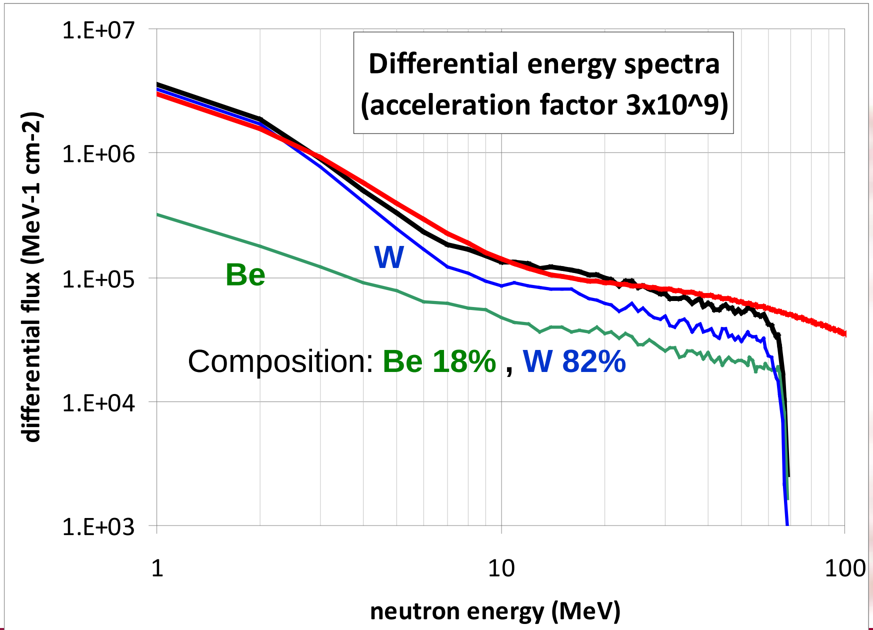
Monte Carlo calculations

Monte Carlo calculations were performed to obtain both the shape and the yield of the neutron spectrum generated by the Be and the W targets.

We feel satisfied of the calculated neutron yield obtained by the W sector, but we are worried by the ureliability of the results obtained with Be.

We ***successfully*** reproduced the experimental results obtained by a 62 MeV proton beam on a thick (30 mm) Be target using MCNP with Bertini model. But the same Monte Carlo ***completely*** fails in the reproduction of the neutron spectrum generated by 70 MeV protons on a 4 mm thick Be target.



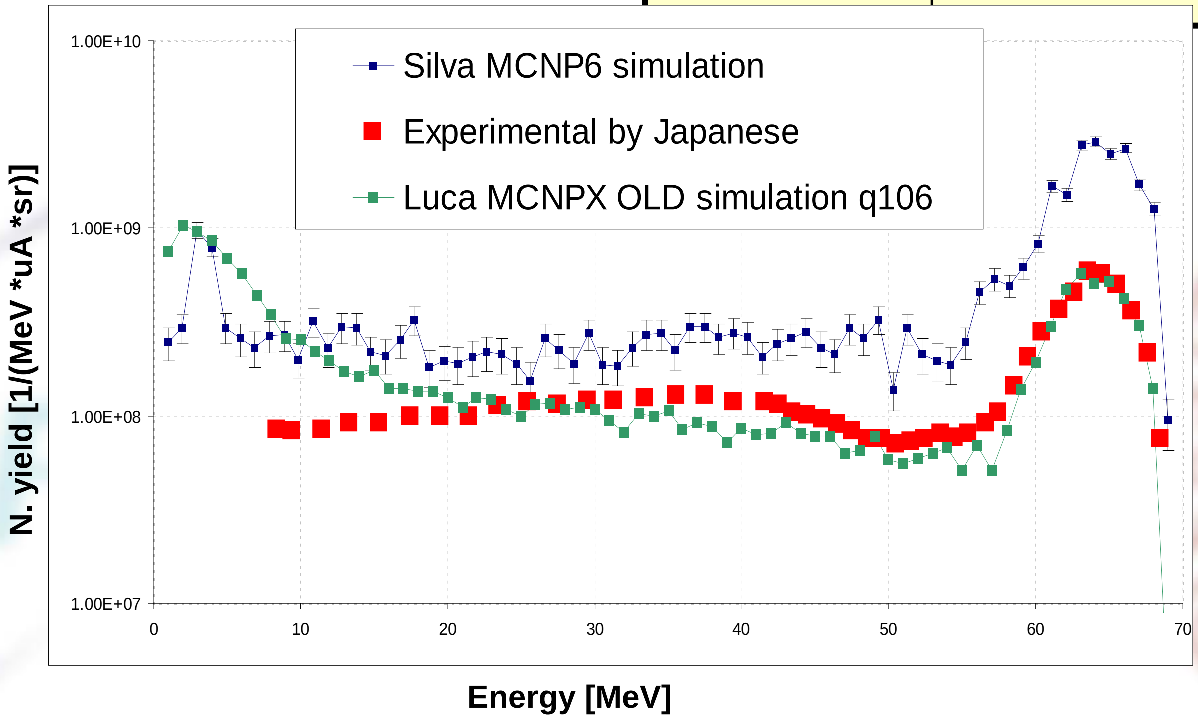


The optimal weighted composition of the spectra generated by Be and W varies strongly with the shape of the calculated spectra.

Be MC calculation summary

Benchmark simulation of the neutron spectrum from 70 MeV protons on a thin (4 mm thick) Be slab.
MCNP6 and MCNPX (older) were used with different models and libraries. Here we report the best results obtained.
MCNP6 tends to overestimate the neutron production, but the spectrum shape is quet similar to the experimental one.
MCNPX well reproduces the high energy peak, but fails below 20 MeV.

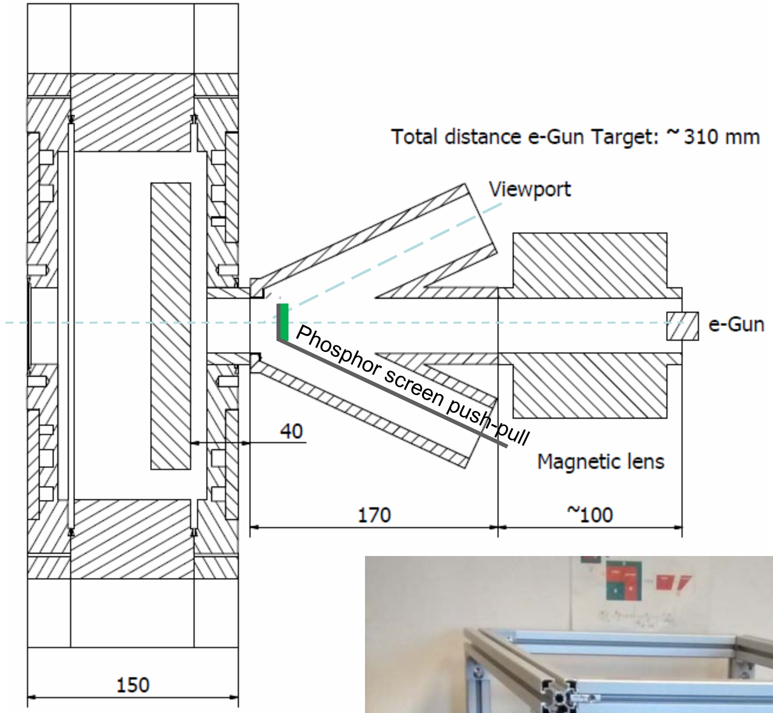
	Low energy tail	Medium energy tail	Peak
MCNPX (Bertini model)		Ok	Very good agreement
MCNPX (libraries)	ABSENT		
MCNP6 lib. (Mix and match)	Overestim. ~250%, (at least it's flat)	Overestim ~250%,	Overestim
MCNP6 Bertini model	Overestim. ~250%, (at least it's flat)	Ok	Overestim. and not so good agreement

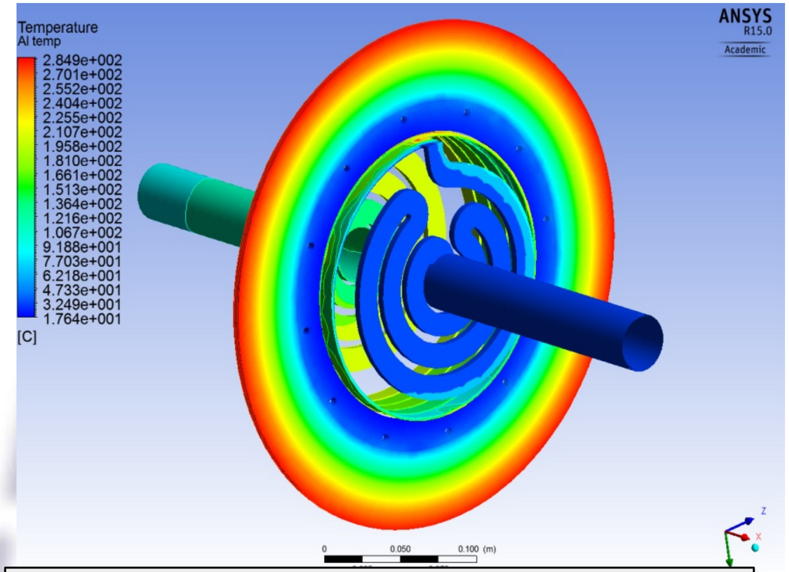


Thermal test setup

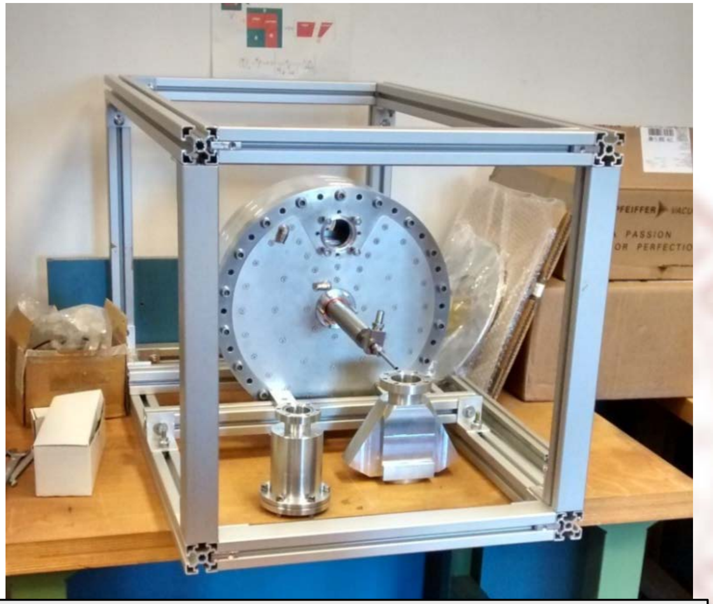
To validate the Ansys simulation, a comparison with experimental data is necessary.
A thermal test is foreseen in summer/autumn using a high power electron gun to deposit energy on the target (Power >1 kW).
The irradiated material is a disc made of alluminun alloy (Ergal, yield strength 700 MPa).

The power deposition due to an electron beam is much different from the one due to protons, which are much more penetrating. Simulations show that, due to the high thermal conductivity of Al, the temperature difference between the two faces of the target is minimal





Temperature map of the Al alloy test disk.
E-beam power 5 kW , T_{max} 285 C

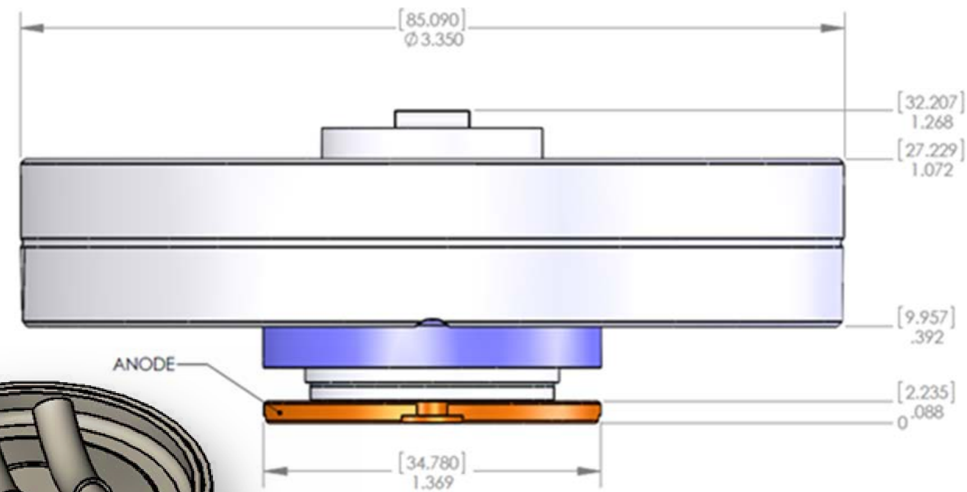


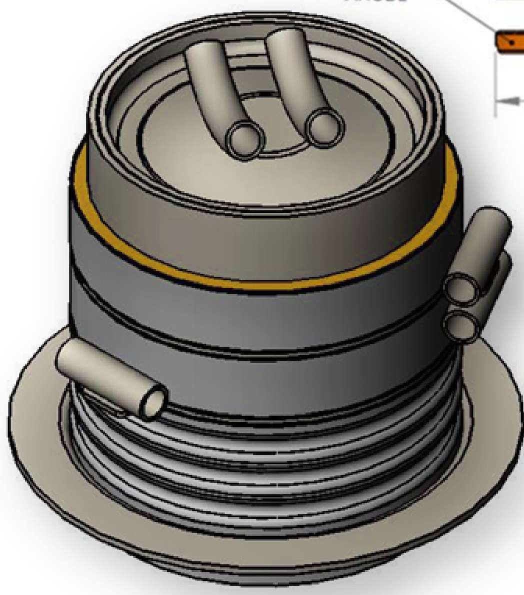
Setup for the thermal test will be assembled next week in Padova physics dept.

Electron Gun

The final requirements are listed here:

- Nominal voltage 10 kV;
- Max extracted current 1 A;
- Beam current controlled by varying cathode voltage;
- Electron source equipped with a focusing electrode
- Flange mounted (CF 3 3/8) gun assembly;
- Minimum focusing required (with INFN supplied electromagnet) 1 cm^2 spot (Gaussian);
- Cathode supplyied by Altair Technologies





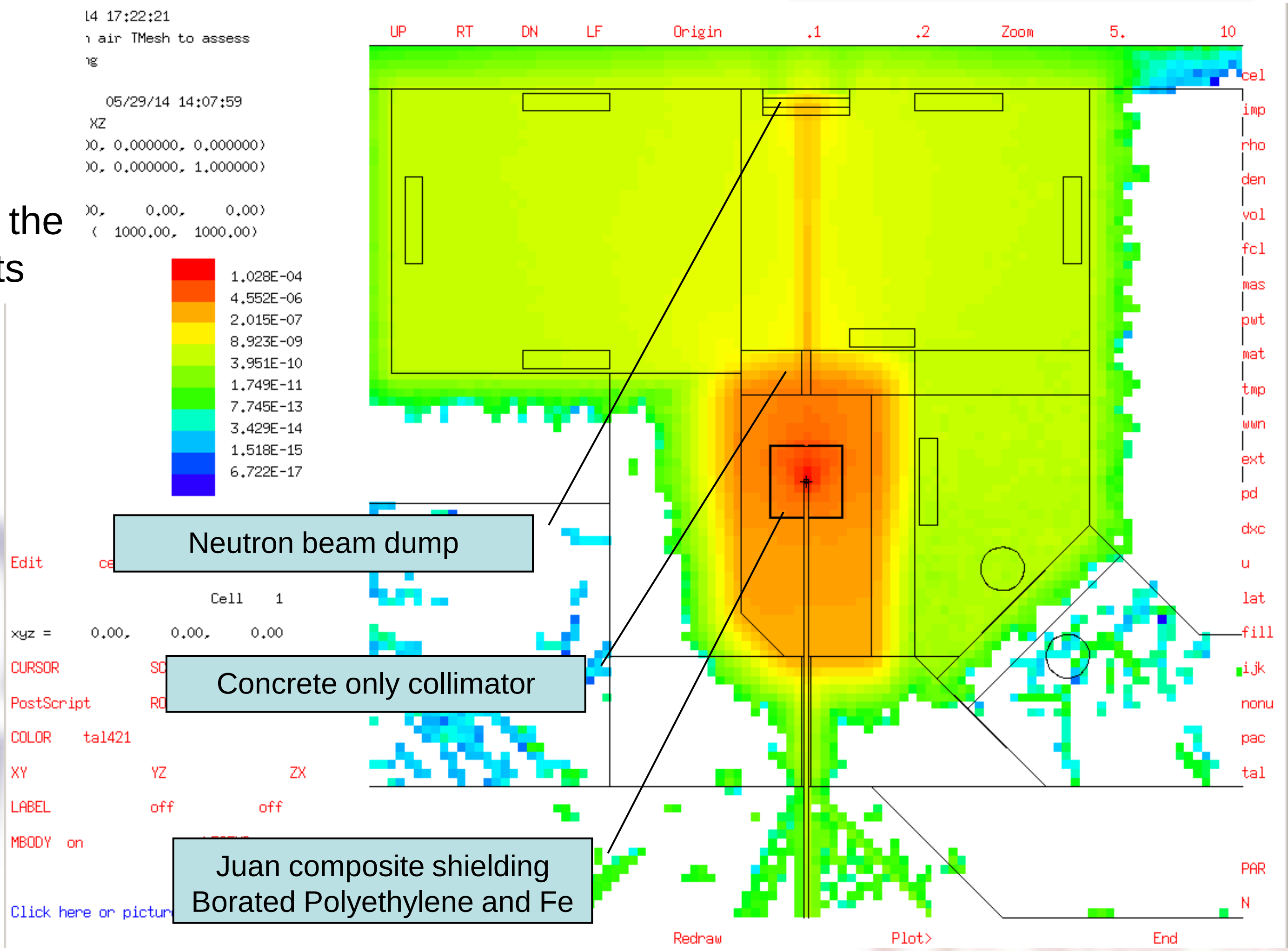
Electron gun for thermal test

Luca Silvestrin luca.silvestrin@pd.infn.it

What's next...

- Neutron beam collimator
- Neutron beam dump
- Target shielding
- Verify the satisfaction of the radioprotection requirements

Neutron field in (and outside) the NEPIR experimental hall

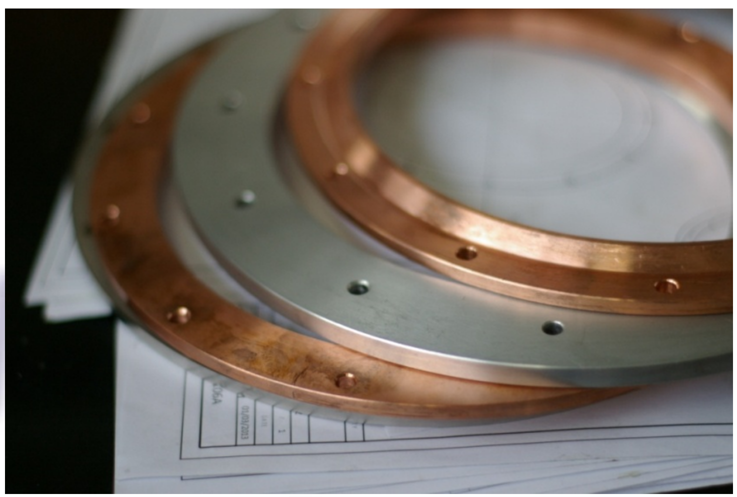


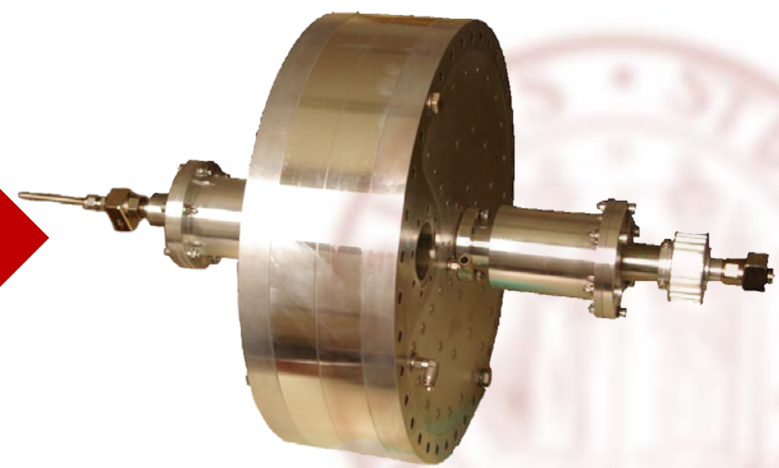
Conclusion

We are developing a high power (2.5 kW) target for the production of a neutron beam with an energy spectrum (in the 1-65 MeV range) similar to the one of the neutrons naturally present in the atmosphere, to perform neutron-induced SEE test in micorelectronic circuits.

A prototype of the target was manufactured and will undergo thermal power tests in the next monts. The results of the test will be used to validate/tune the Ansys simulation that will drive the final design of the target.

The design process is still work in progress, we learned a lot of things, but many more we have to learn before a working target will be ready.





Luca Silvestrin luca.silvestrin@pd.infn.it

THE END
Thank you for your attention

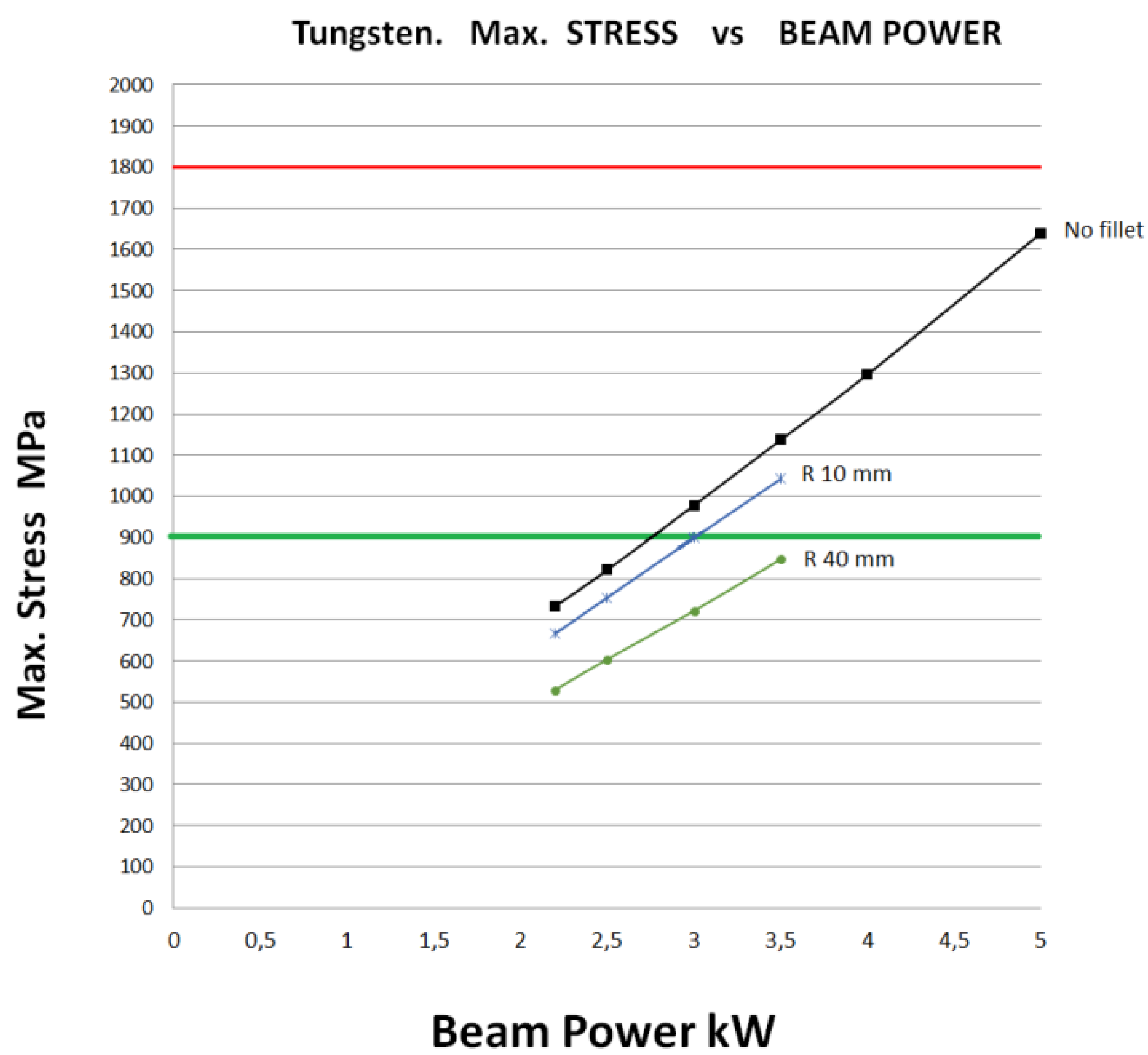
Backup slides follow…

Thanks also to:
prof. Dario Bisello
prof. Jeffery Wyss
dr. Gabriela Acosta

Mechanical properties for target materials for room temperature.

	Thermal Conductivity.	Melting point	Yield Strenght	Density	Specific heat	Thermal expansion
	W/mK	°C	MPa	kg/m3	J/kgK	μ/μK
Pb	35,3	326	5	11340	160	28,9
Ta	57	3017	705	16650	140	6,3
W	174	3422	1920	19250	133	4,5
Be	190	1287	240	1850	1825	11,3
Al	237	660	170	2698	900	22,2
Cu	400	1084	70	8933	385	16,5

Tugnsten sector mechanical performace



Color test slide

Cerulean blue

Klein b.

Dark azure RGB: 0, 56, 168

Notte b.

Notte b. scuro

Prussian b.

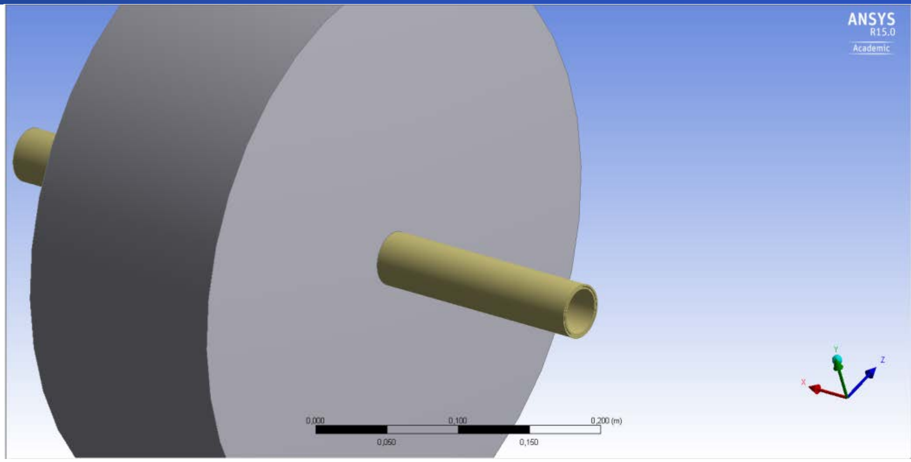
Transient simulation

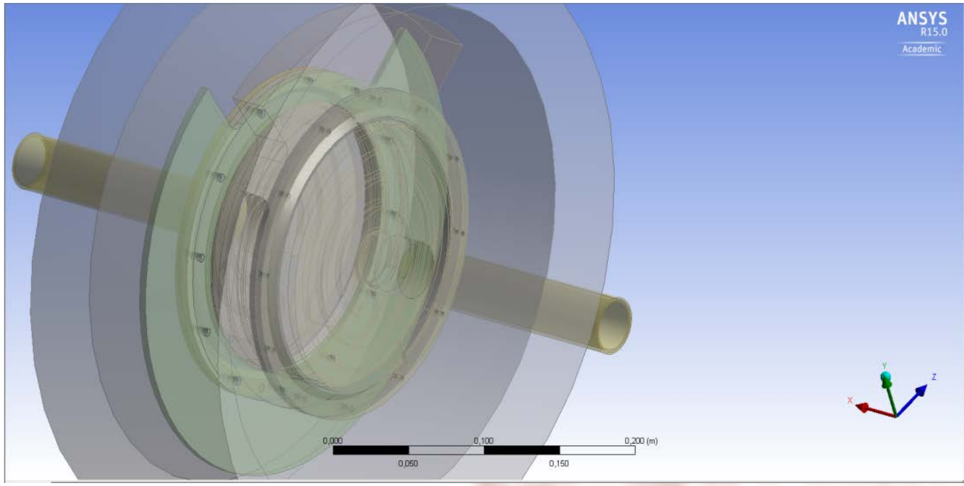
The rotation speed of the target was determined by calculating the relaxation time (cool down) of the target, heated by a 5 kW proton beam.

The rotation period was chosen as a fraction of the relaxation time.

This is to be considered a starting value which will be finely tuned only in the termal test phase.

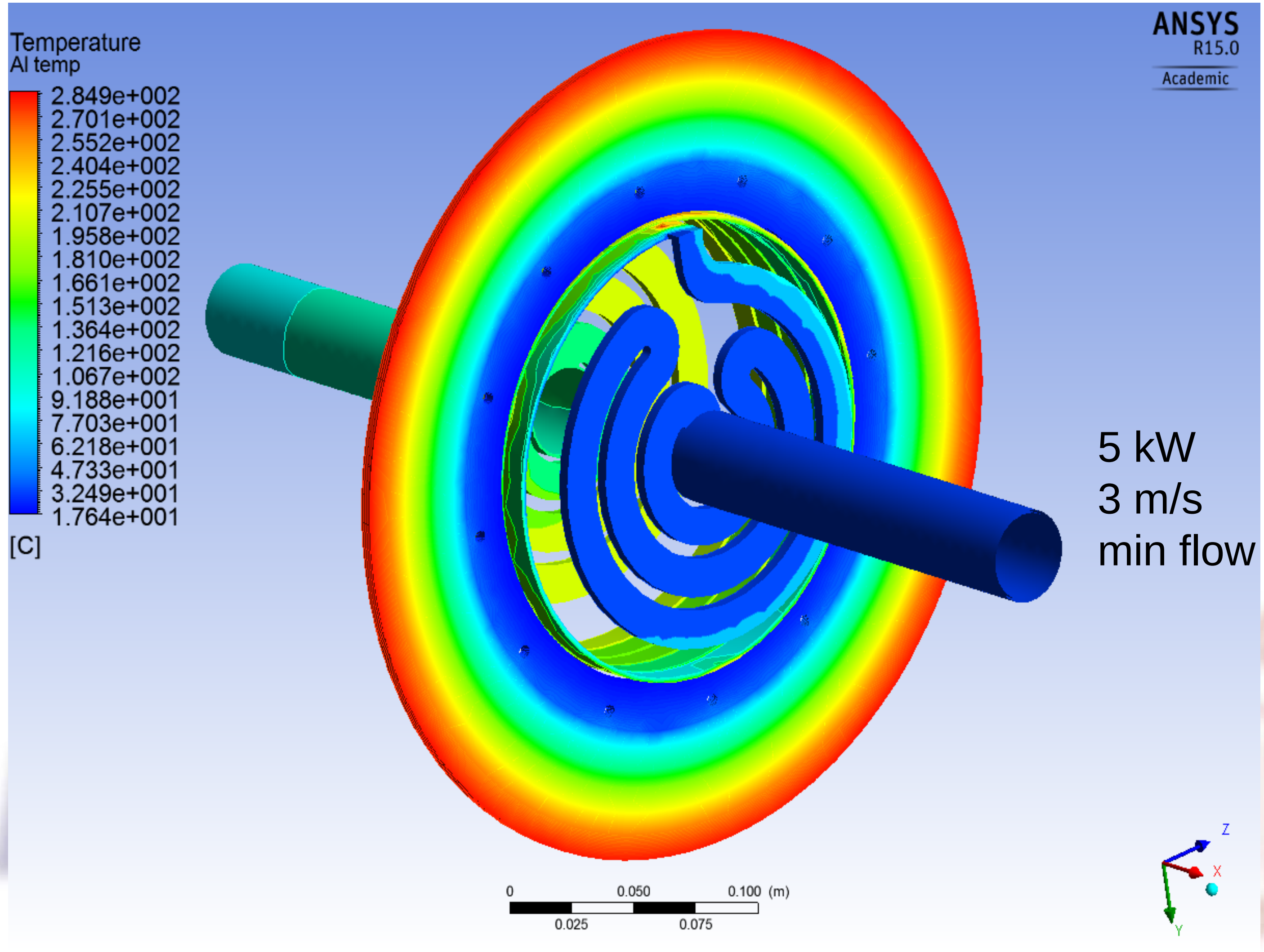
The ANEM target design is derived from the target designed for the LENOS experiment: is uses the same chamber, but with modified innards to house Be and heavy element “disks” and a water flow cooling system.





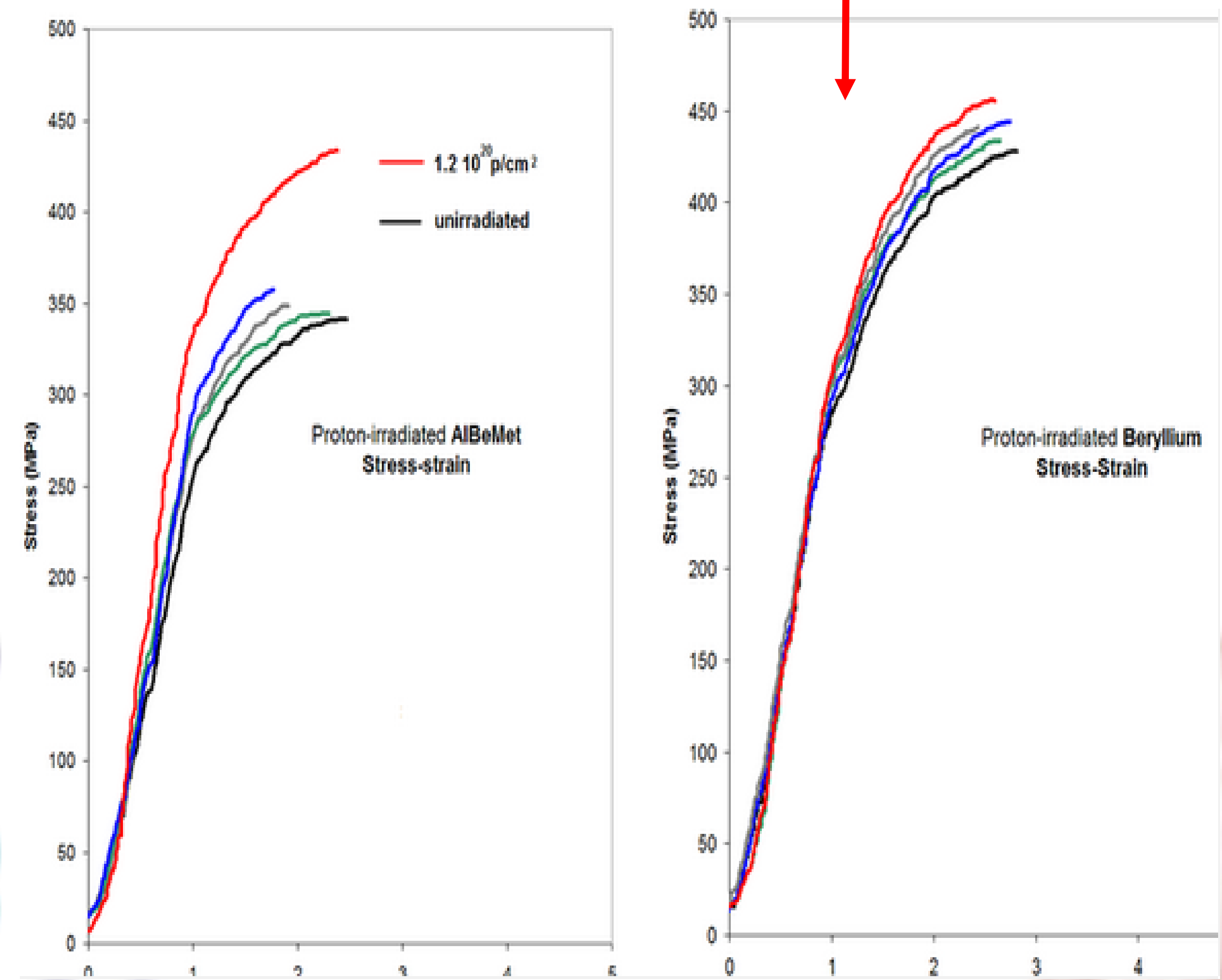
- ANEM target requirements
- Target working principle
- ANEM geometry
- Simulations of neutron beam
- energy deposition
- Thermo mechanical simulations
- Heat dissipation
- Stress in heated sectors
- Electron gun test setup

Luca Silvestrin



5 kW
3 m/s
min flow 0,12 m/s

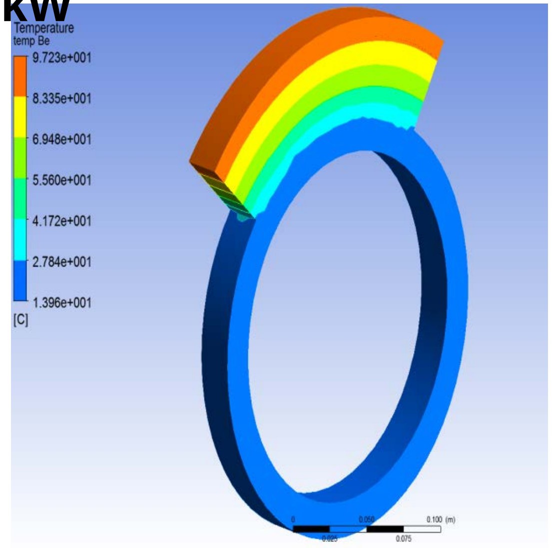
Be Stress-Strain

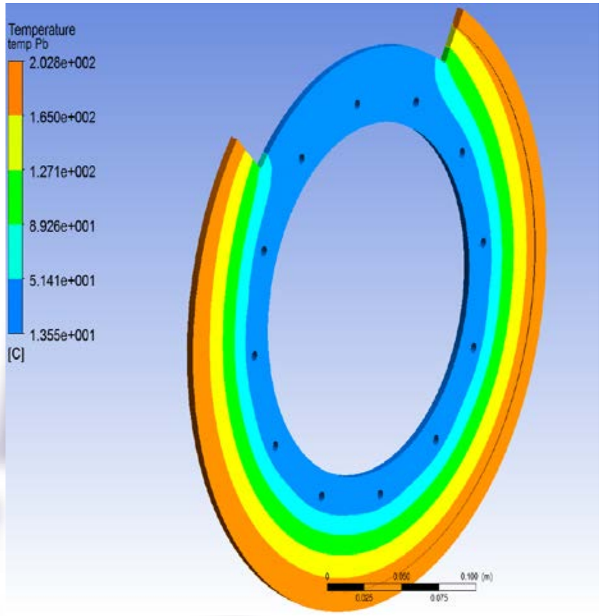


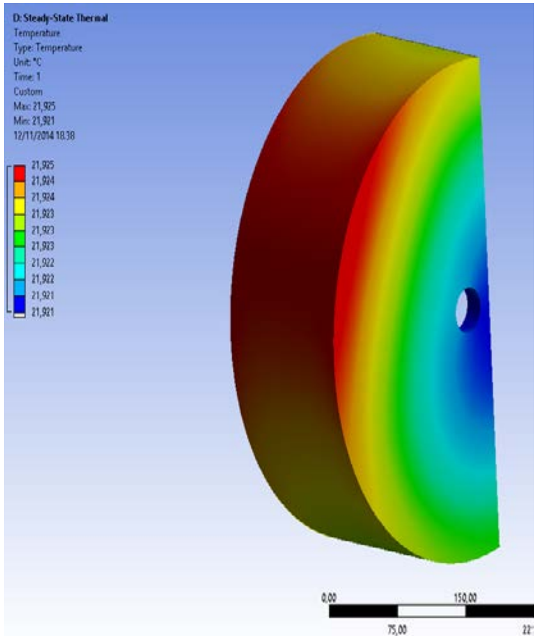
Effects of 140 MeV proton irradiation on AlBeMet (left) and beryllium (right) on the stress-strain relations (range of fluence of irradiated samples 0.4 - 1.2 1020 p/cm2)

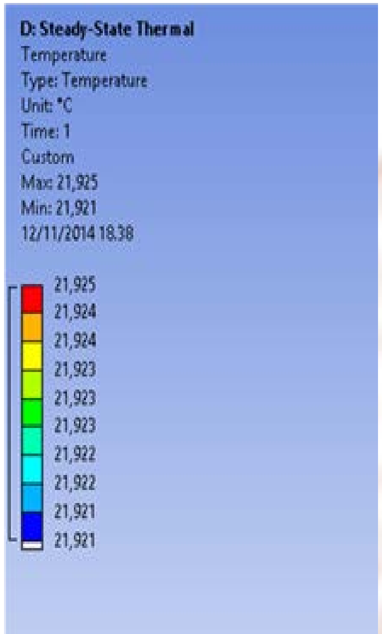
http://www.intechopen.com/books/metal-ceramic-and-polymeric-composites-for-various-uses/composite-materials-under-extreme-radiation-and-temperature-environments-of-the-next-generation-nucl

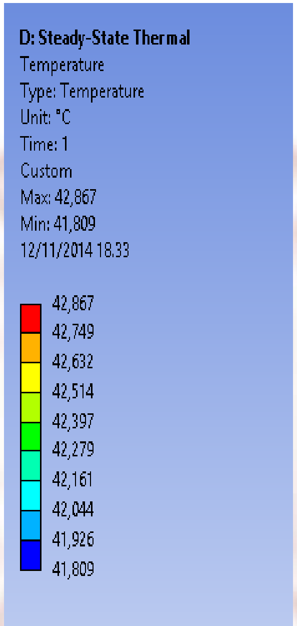
Target Be @ 5 kW





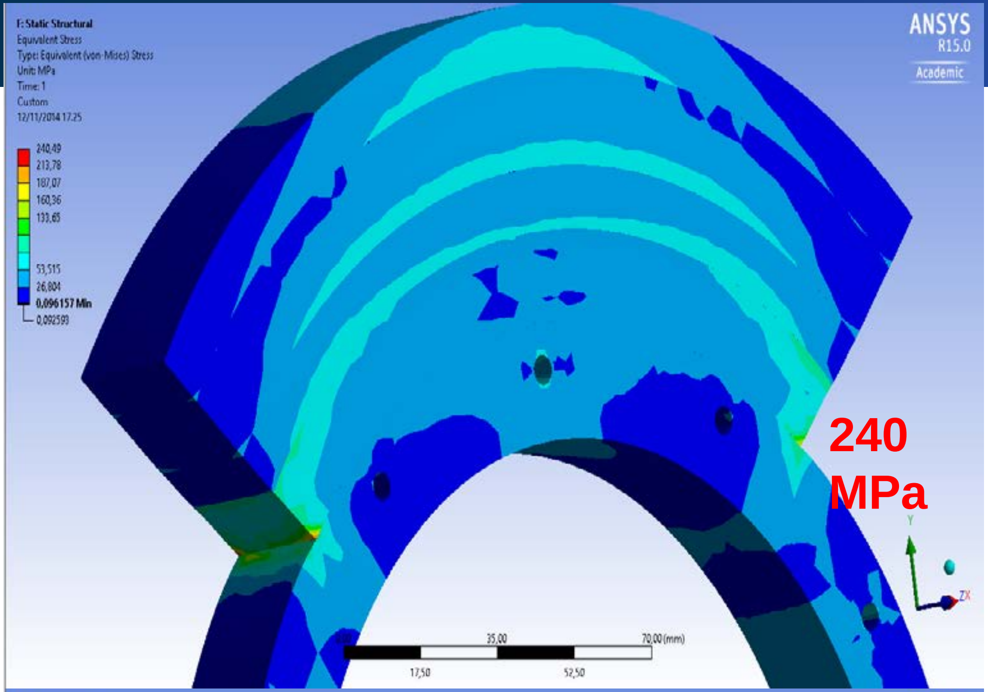


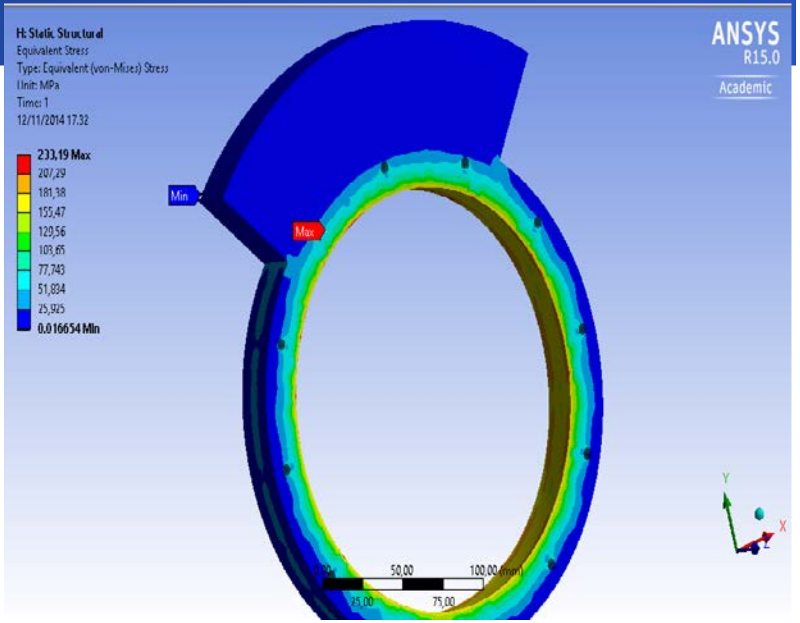


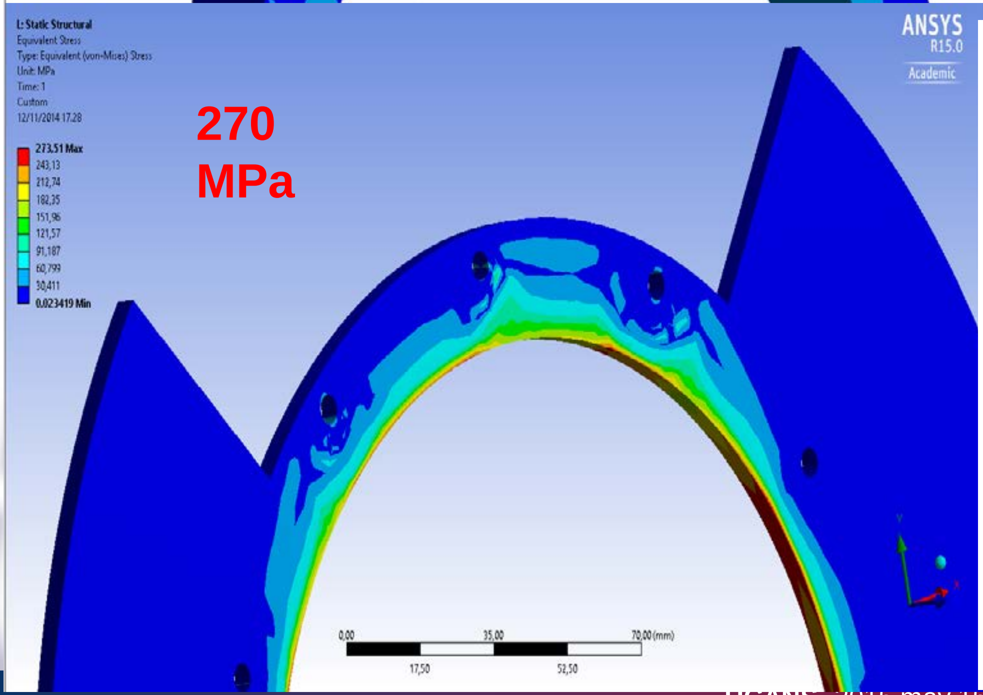


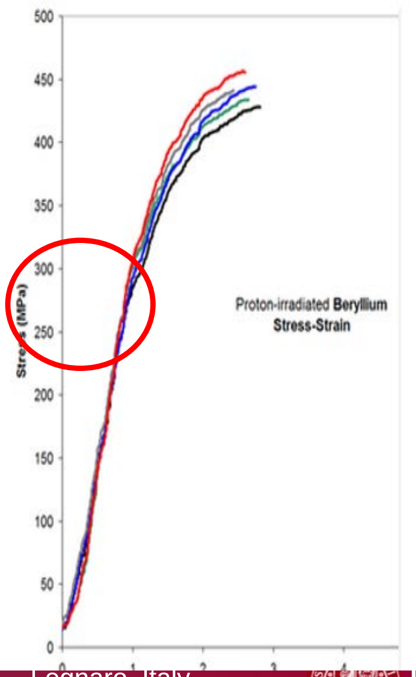
Shiny surface

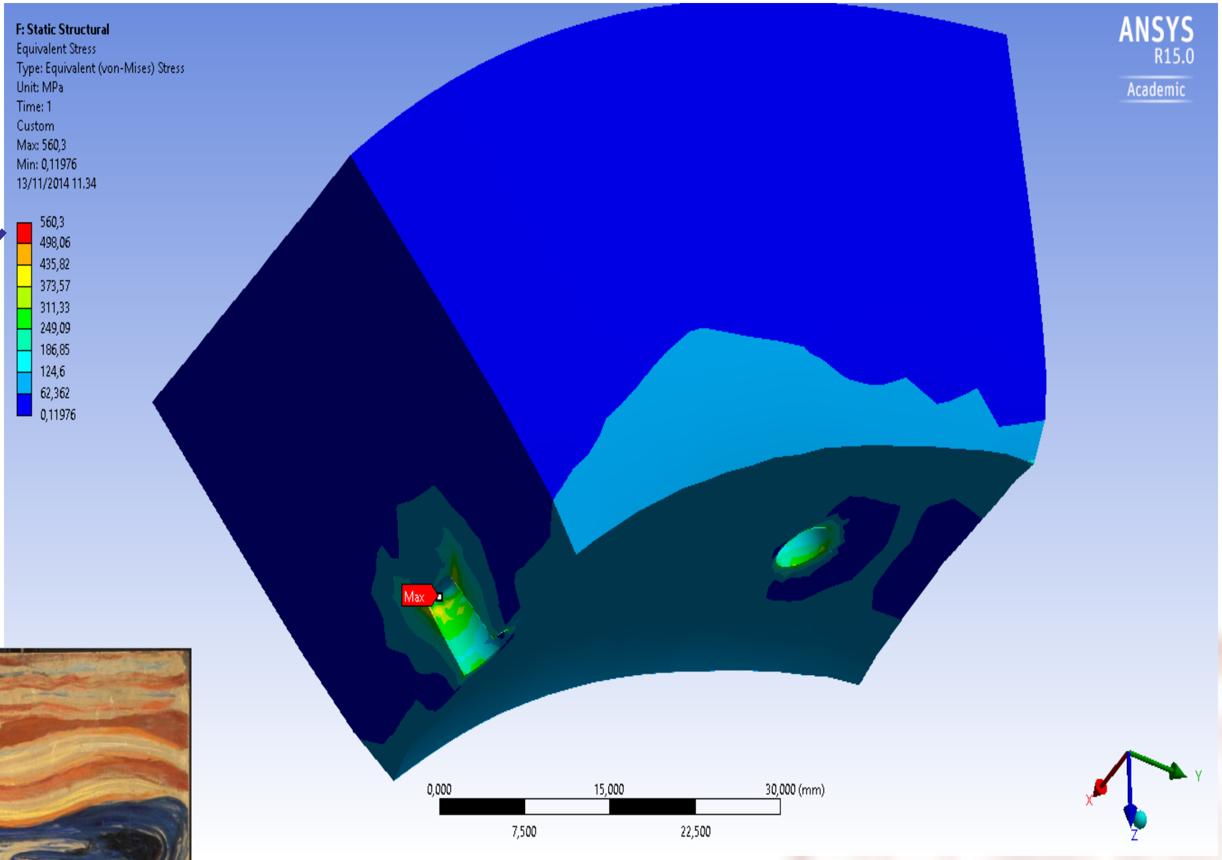
Black body

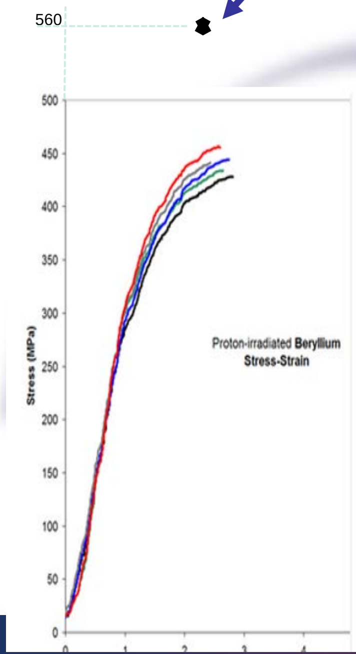

F: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
Custom
12/11/2014 17.25
240,49
213,78
187,07
160,36
133,65
53,515
26,804
0,096157 Min
0,092593
ANSYS
R15.0
Academic
240
MPa
0,00
35,00
70,00 (mm)
17,50
52,50

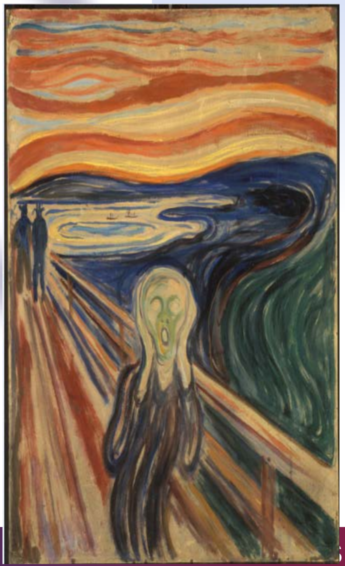

H: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/11/2014 17.32
233,19 Max
207,29
181,38
155,47
129,56
103,65
77,743
51,834
25,925
0,016654 Min
Min
Max
ANSYS
R15.0
Academic
50,00
100,00 (mm)
25,00
75,00

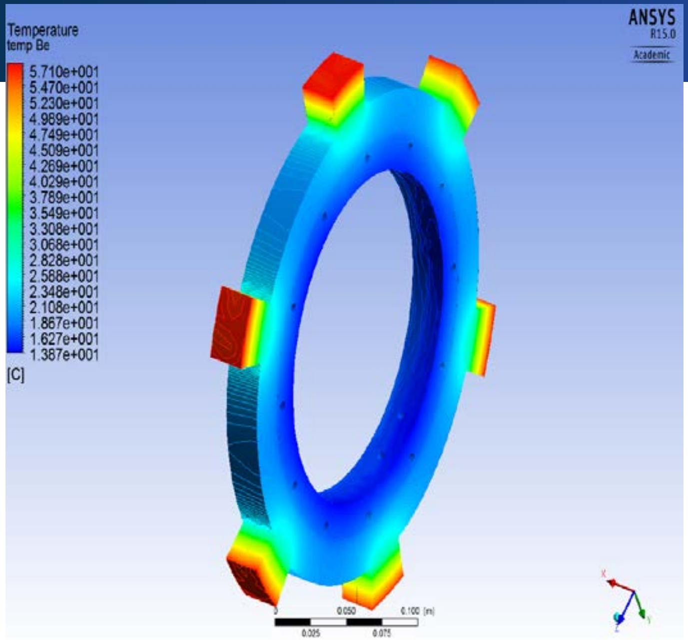

L: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
Custom
12/11/2014 17.28
273,51 Max
243,13
212,74
182,35
151,96
121,57
91,187
60,799
30,411
0,023419 Min
270
MPa
ANSYS
R15.0
Academic
0,00
35,00
70,00 (mm)
17,50
52,50

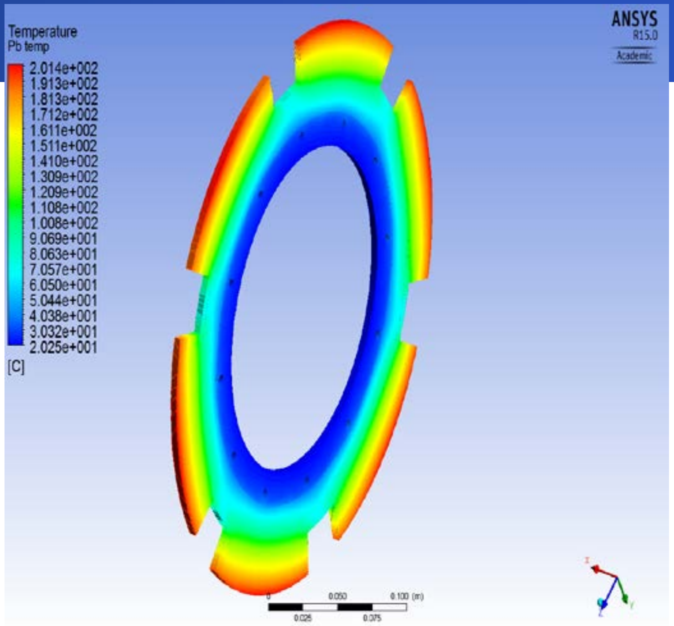

Proton-irradiated Beryllium
Stress-Strain
Stress (MPa)
500
450
400
350
300
250
200
150
100
50
0

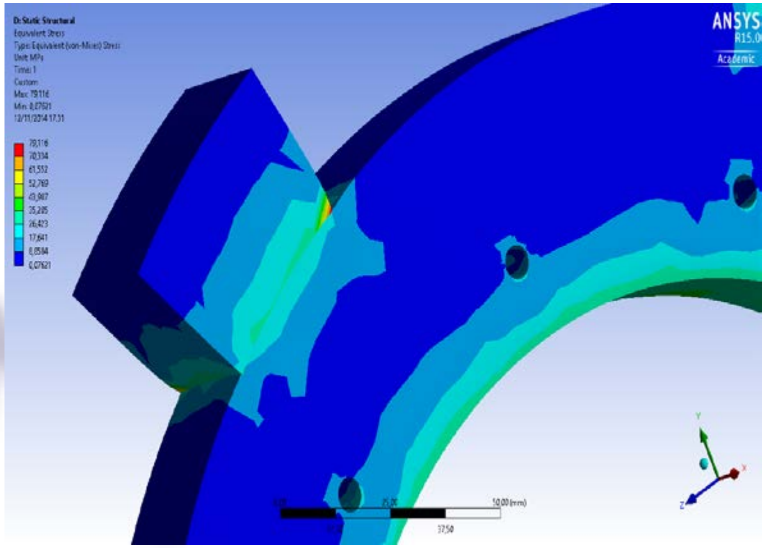

F: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
Custom
Max: 560,3
Min: 0,11976
13/11/2014 11.34
560,3
498,06
435,82
373,57
311,33
249,09
186,85
124,6
62,362
0,11976
ANSYS
R15.0
Academic
Max
0,000
15,000
30,000 (mm)
7,500
22,500
X
Y
Z

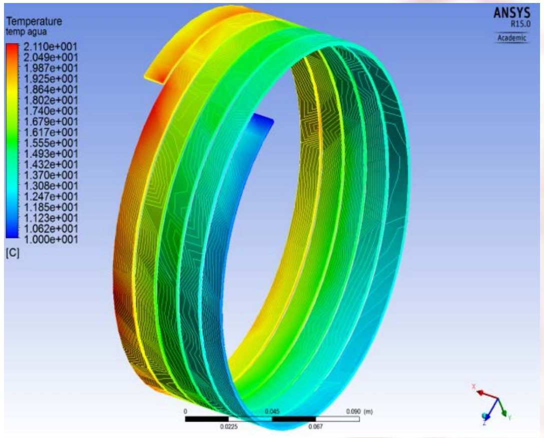

560
Stress (MPa)
500
450
400
350
300
250
200
150
100
50
0
Proton-irradiated Beryllium
Stress-Strain




Temperature
temp Be
5.710e+001
5.470e+001
5.230e+001
4.989e+001
4.749e+001
4.509e+001
4.269e+001
4.029e+001
3.789e+001
3.549e+001
3.308e+001
3.068e+001
2.828e+001
2.588e+001
2.348e+001
2.108e+001
1.867e+001
1.627e+001
1.387e+001
[C]
ANSYS
R15.0
Academic


Temperature
Pb temp
2.014e+002
1.913e+002
1.813e+002
1.712e+002
1.611e+002
1.511e+002
1.410e+002
1.309e+002
1.209e+002
1.108e+002
1.008e+002
9.069e+001
8.063e+001
7.057e+001
6.050e+001
5.044e+001
4.038e+001
3.032e+001
2.025e+001
[C]
ANSYS
R15.0
Academic


ANSYS
R15.0
Academic


Temperature
temp agua
2.110e+001
2.049e+001
1.987e+001
1.925e+001
1.864e+001
1.802e+001
1.740e+001
1.679e+001
1.617e+001
1.555e+001
1.493e+001
1.432e+001
1.370e+001
1.308e+001
1.247e+001
1.185e+001
1.123e+001
1.062e+001
1.000e+001
[C]
ANSYS
R15.0
Academic

ΔT=10 °C

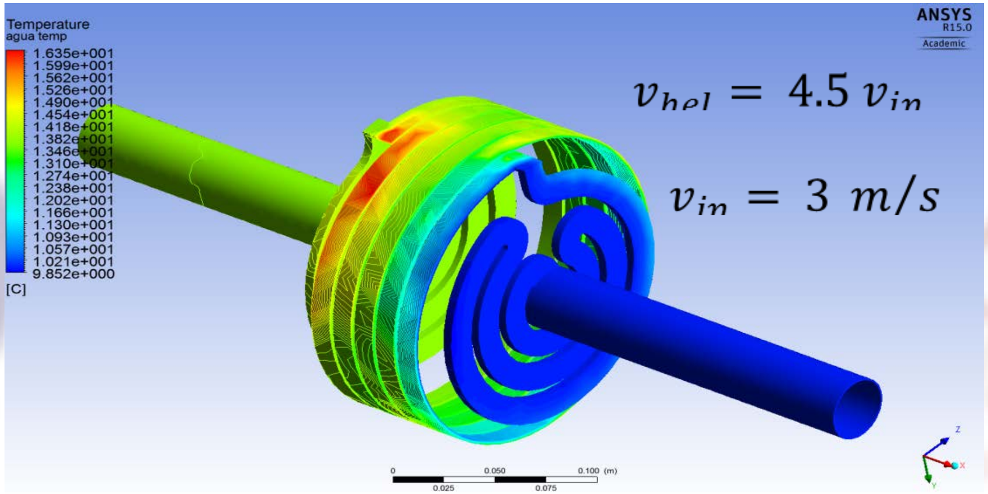
Water flux

diam in	0,034									
diam out	0,036		Q flow (area tubo)							
area espira	area tubo	Vel	m^3/s	lt/s or kg/s	q.	m.	Cp	ΔT	area espiral	h conv.
0,000024	1,10E-04	0,12	1,32E-05	0,0132	4750	0,0132	4187	86,022431	0,033905	1628,61
4,579166667	1,10E-04	0,2	2,20E-05	0,0220	4750	0,0220	4187	51,613458	0,033905	2714,36
	1,10E-04	0,4	4,40E-05	0,0440	4750	0,0440	4187	25,806729	0,033905	5428,71
	1,10E-04	0,6	6,59E-05	0,0659	4750	0,0659	4187	17,204486	0,033905	8143,07
	1,10E-04	0,8	8,79E-05	0,0879	4750	0,0879	4187	12,903365	0,033905	10857,4
	1,10E-04	1	1,10E-04	0,1099	5000	0,1099	4187	10,865991	0,033905	13571,8
	1,10E-04	1,2	1,32E-04	0,1319	4750	0,1319	4187	8,6022431	0,033905	16286,1
	1,10E-04	1,4	1,54E-04	0,1539	4750	0,1539	4187	7,3733512	0,033905	19000,5
	1,10E-04	1,6	1,76E-04	0,1758	4750	0,1758	4187	6,4516823	0,033905	21714,9
	1,10E-04	1,8	1,98E-04	0,1978	4750	0,1978	4187	5,7348287	0,033905	24429,2
0,5495	1,10E-04	2	2,20E-04	0,2198	4750	0,2198	4187	5,1613458	0,033905	27143,6
	1,10E-04	2,2	2,42E-04	0,2418	4750	0,2418	4187	4,6921326	0,033905	29857,9
	1,10E-04	2,4	2,64E-04	0,2638	4750	0,2638	4187	4,3011215	0,033905	32572,3
	1,10E-04	2,6	2,86E-04	0,2857	4750	0,2857	4187	3,970266	0,033905	35286,6
	1,10E-04	2,8	3,08E-04	0,3077	4750	0,3077	4187	3,6866756	0,033905	38001
	1,10E-04	3	3,30E-04	0,3297	4750	0,3297	4187	3,4408972	0,033905	40715,3

$Q = \dot{m} Cp \Delta T$

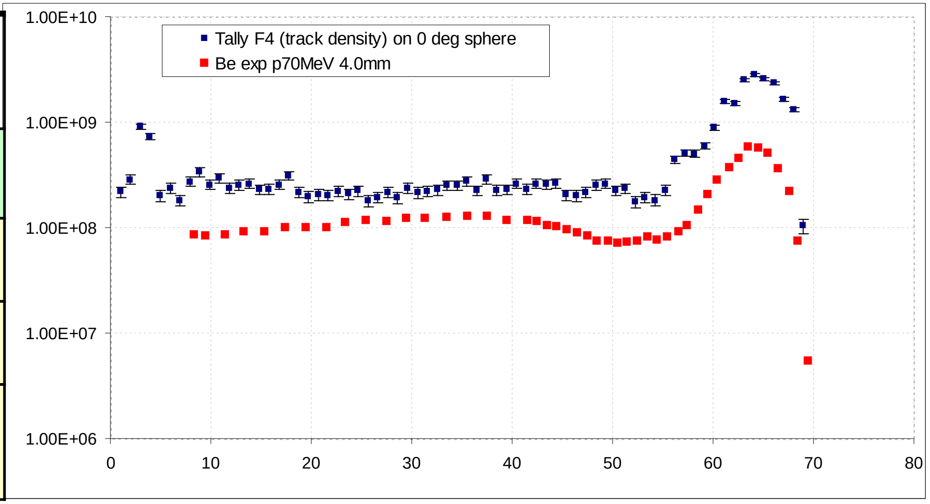
q''=$Ah\Delta T$

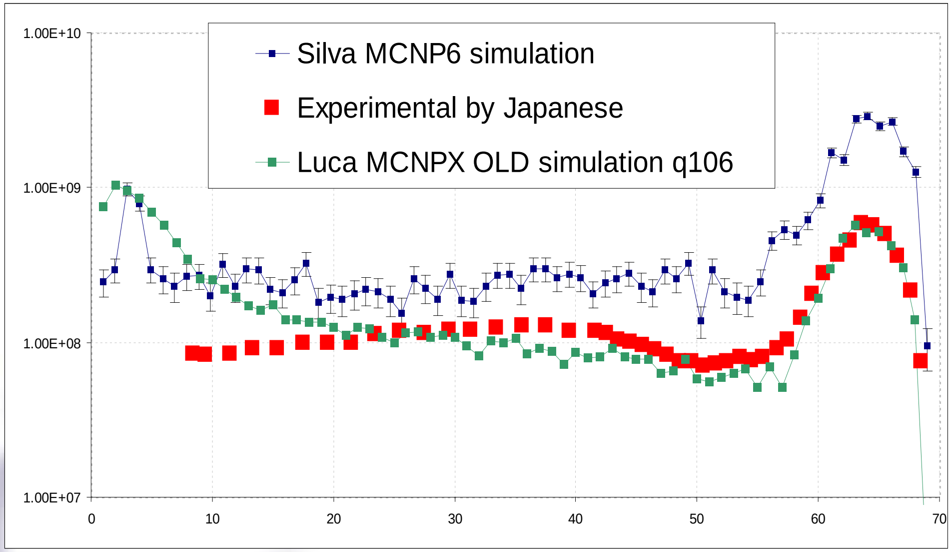
$$h = \frac{\dot{q}''}{A\Delta T}$$

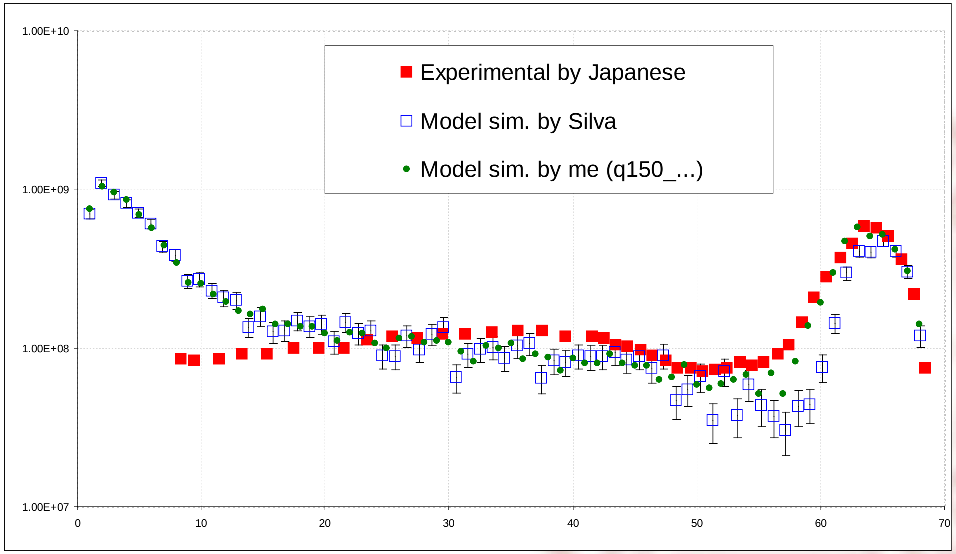

Temperature
agua temp
1.635e+001
1.599e+001
1.562e+001
1.526e+001
1.490e+001
1.454e+001
1.418e+001
1.382e+001
1.346e+001
1.310e+001
1.274e+001
1.238e+001
1.202e+001
1.166e+001
1.130e+001
1.093e+001
1.057e+001
1.021e+001
9.852e+000
[C]
ANSYS
R15.0
Academic
$v_{hel} = 4.5\, v_{in}$
$v_{in} = 3\ m/s$
0
0.050
0.100 (m)
0.025
0.075

MCNP6 model and library comparison

	Coda bassa nrg	Coda media energia	Picco
MCNPX (modello)		Ok	Ottimo
MCNPX (libraries)	ABSENT		
MCNP6 lib. (Mix and Match)	Sovrastima ~250%, ma almeno e' piatta	Sovrastima ~250%,	Sovrastima
MCNP6 solo modello	Sovrastima ~250%, ma almeno e' piatta	Ok	Sovrastimato e non cosi' buono

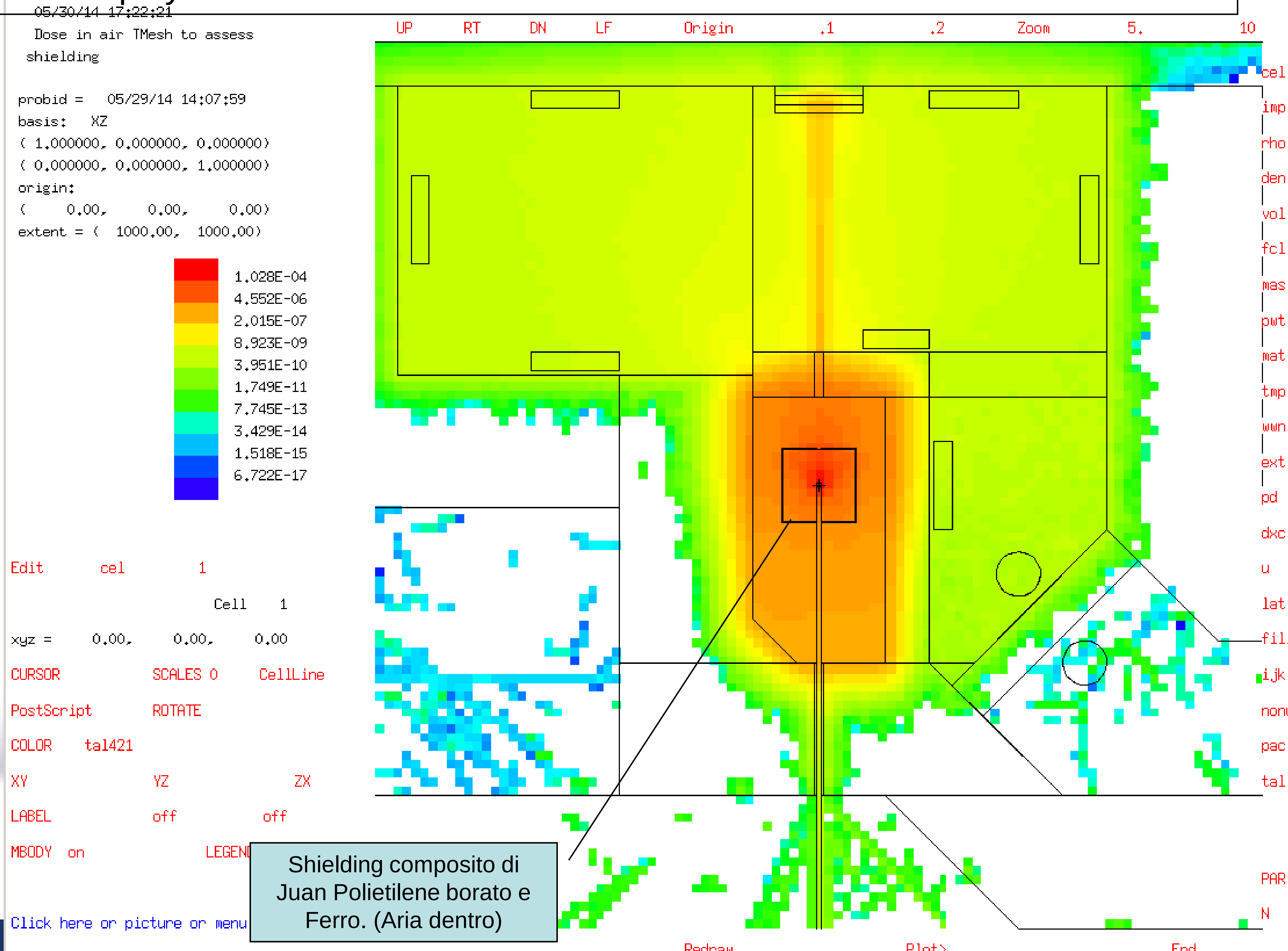


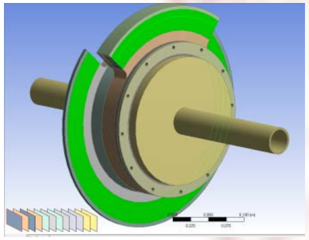


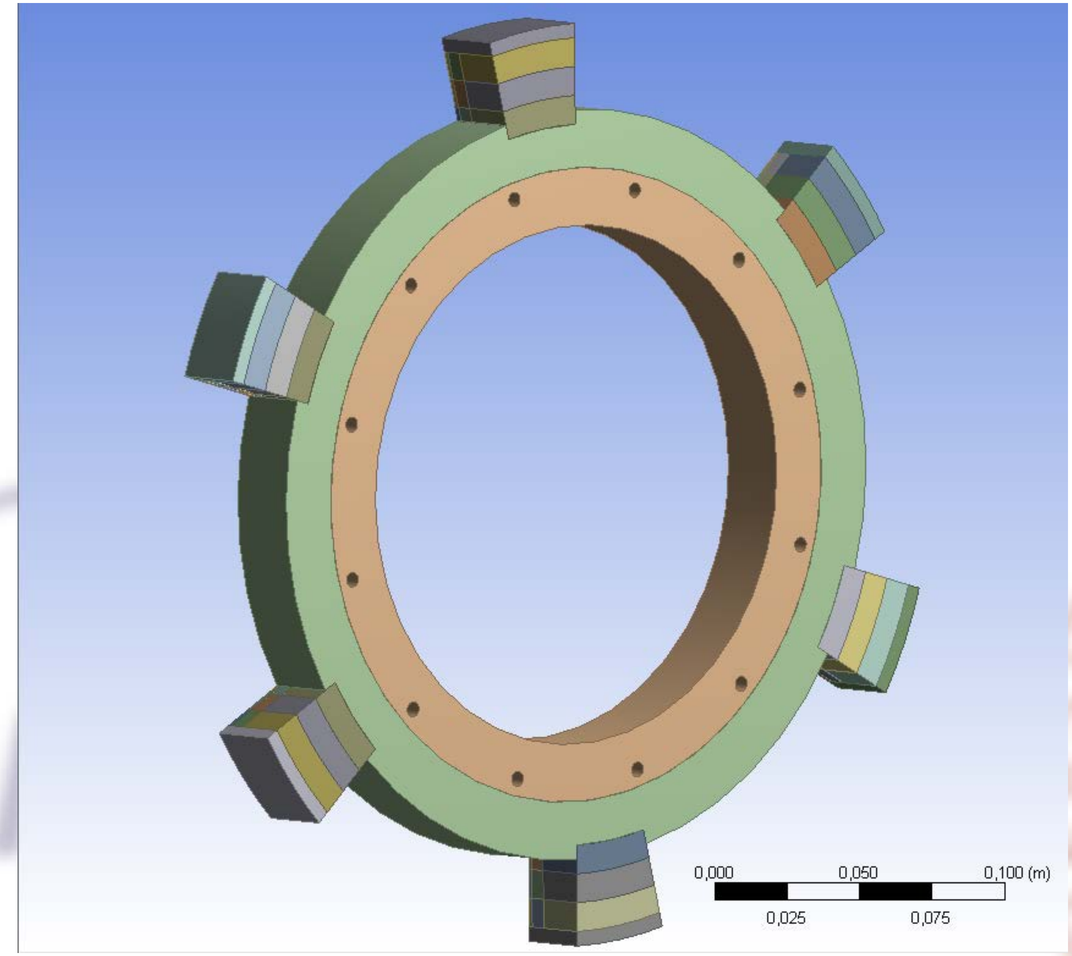


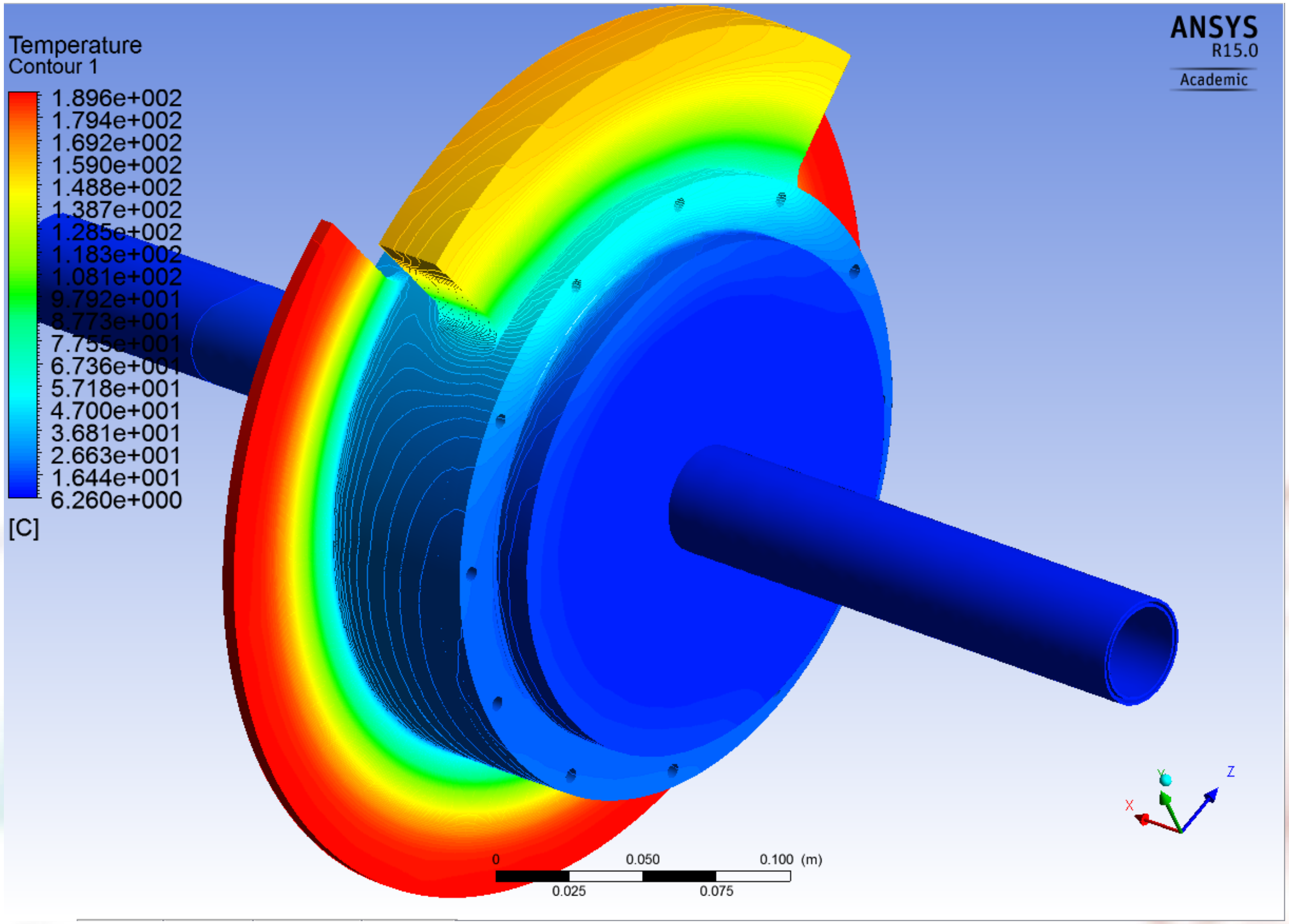
Luca Silvestrin luca.silvestrin@pd.infn.it

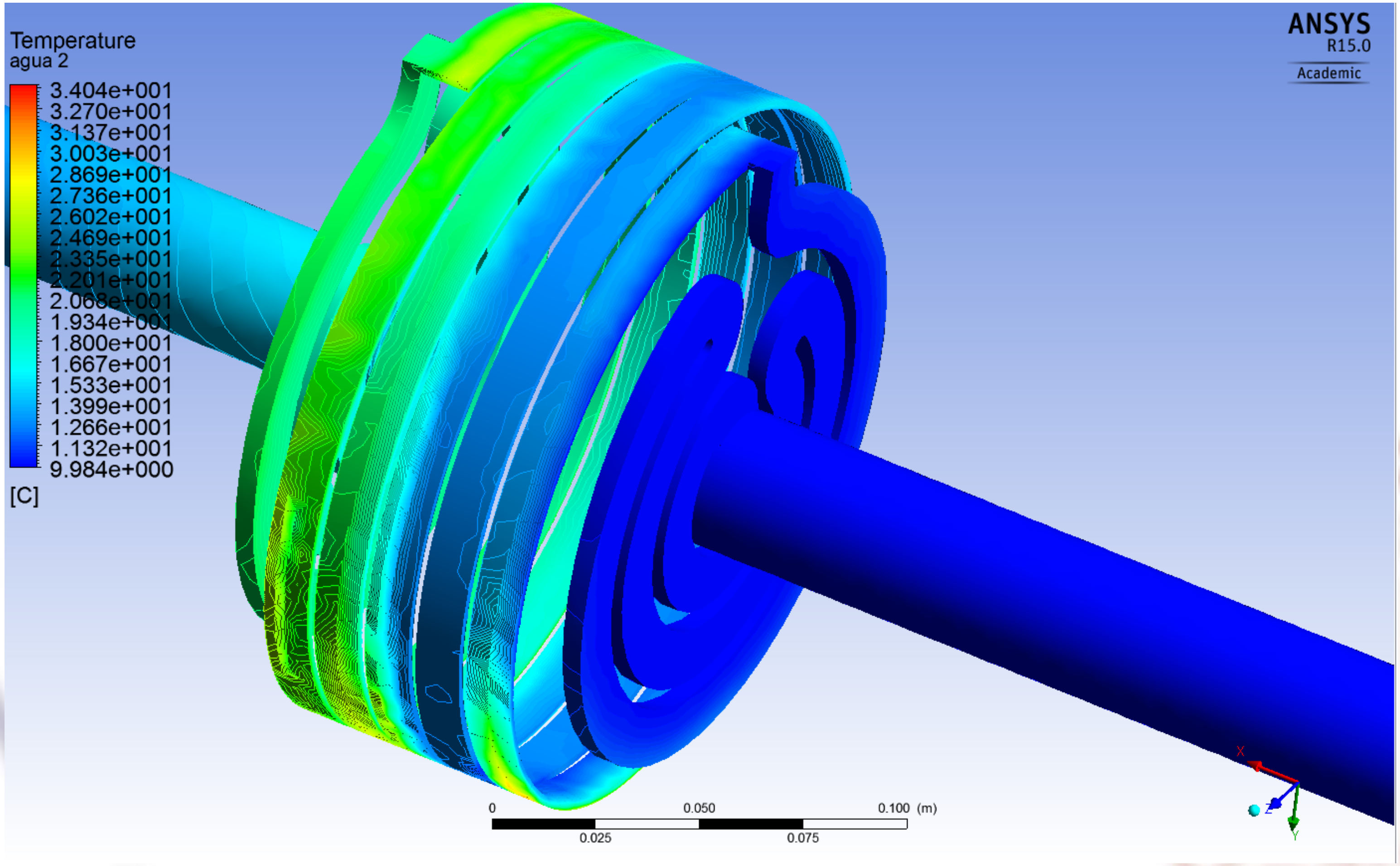
Neutron field in experimental hall, shielding suggested by Juan: a box with 2 layers: 1’ Fe and 1’ polyethilene enriched with Boron

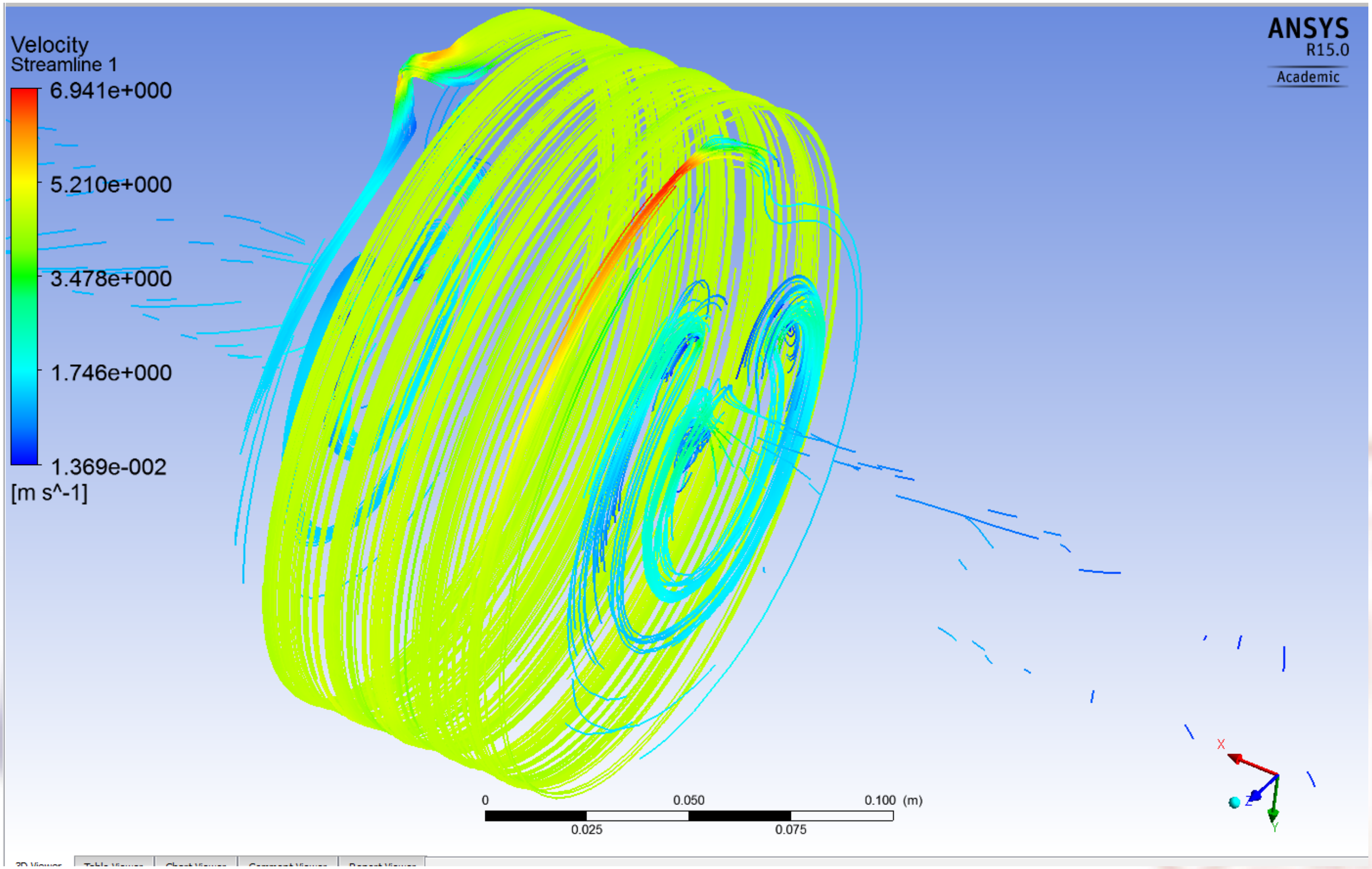





0,000
0,050
0,100 (m)
0,025
0,075


Temperature
Contour 1
1.896e+002
1.794e+002
1.692e+002
1.590e+002
1.488e+002
1.387e+002
1.285e+002
1.183e+002
1.081e+002
9.792e+001
8.773e+001
7.755e+001
6.736e+001
5.718e+001
4.700e+001
3.681e+001
2.663e+001
1.644e+001
6.260e+000
[C]
ANSYS
R15.0
Academic
0
0.050
0.100 (m)
0.025
0.075
X
Y
Z


Temperature
agua 2
3.404e+001
3.270e+001
3.137e+001
3.003e+001
2.869e+001
2.736e+001
2.602e+001
2.469e+001
2.335e+001
2.201e+001
2.068e+001
1.934e+001
1.800e+001
1.667e+001
1.533e+001
1.399e+001
1.266e+001
1.132e+001
9.984e+000
[C]
ANSYS
R15.0
Academic
0
0.050
0.100 (m)
0.025
0.075


Velocity
Streamline 1
6.941e+000
5.210e+000
3.478e+000
1.746e+000
1.369e-002
[m s^-1]
ANSYS
R15.0
Academic
0
0.050
0.100 (m)
0.025
0.075