ECFA
European Committee for Future Accelerators

EUROnu Target and Horn Studies

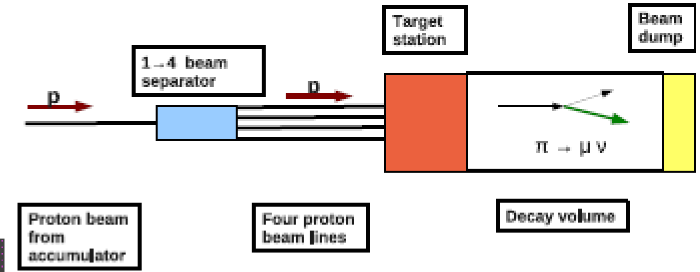
Nikolaos Vassilopoulos/IPHC-CNRS
on behalf of WP2

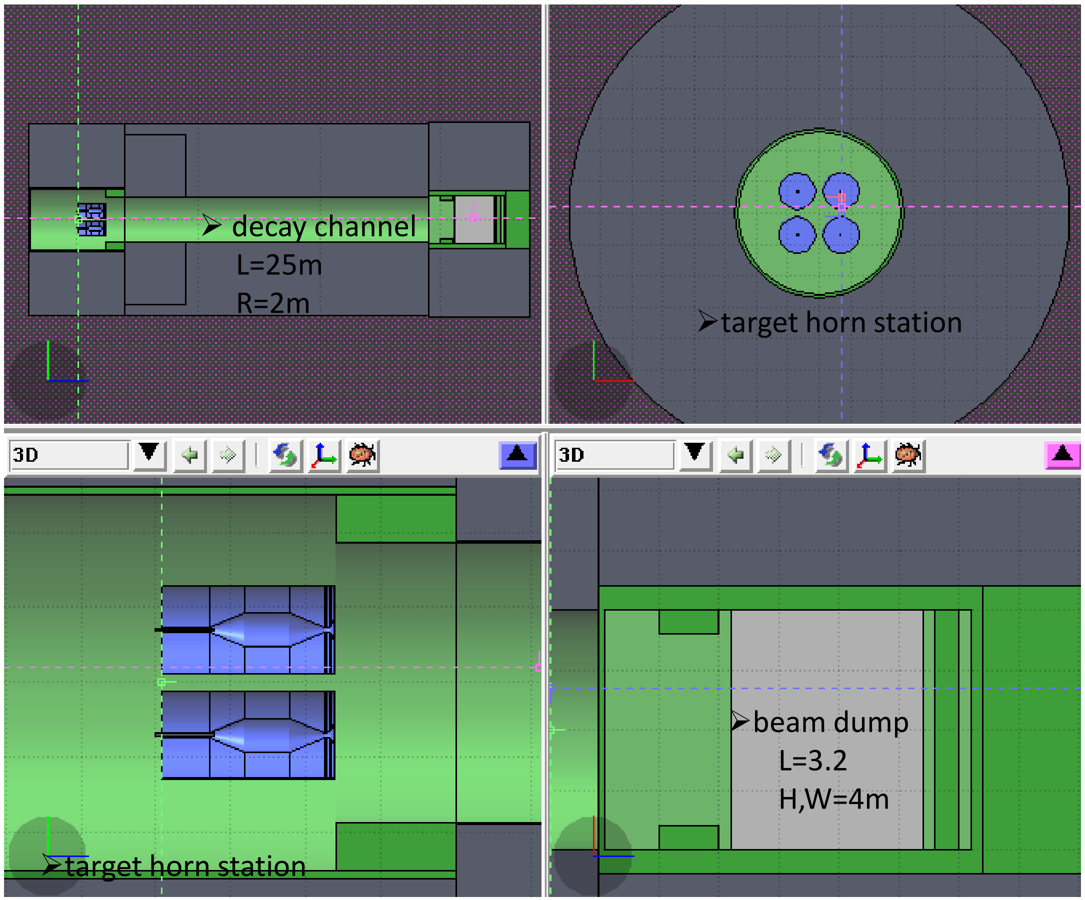
Institut Pluridisciplinaire Hubert Curien STRASBOURG

Talk layout

- Horn/Physics performance optimization
- Target Studies
- Energy Deposition Studies for different elements of the Super Beam $\Rightarrow$ cooling
- Horn Studies
- Preliminary Radiation Studies

SuperBeam Layout





Parameters	unit	SPL
Energy	[GeV]	4.5
Beam power	[MW]	4.0
Repetition rate	[Hz]	50
Average pulse current	[mA]	40
Peak pulse current	[mA]	64
Chopping ratio	[%]	62
Beam Pulse length	[ms]	0.6
Protons per pulse for PS2	[10^{14}]	1.5
Beam duty cycle	[%]	2.0
Number of klystrons (LEP)		14
Number of klystrons (704 MHz)		57
Peak RF power	[MW]	219
Average power consumption	[MW]	38.5
Cryogenics av. power consumption	[MW]	4.5
Cryogenic temperature	[K]	2.0
Length	[m]	534

use 4 horn system

split the 4MW beam power

increase reliability for the target and horn

achieve an adequate cooling

Horn optimization

details in WP2 notes @ http://www.euronu.org/

evolution of the horn shape after many studies:

- triangle shape (van der Meer) with target inside the horn : in general best configuration for low energy beam

⇓

- triangle with target integrated to the inner conductor : very good physics results due to high energy deposition and stresses on the conductors

⇓

- miniboone shape with target integrated to the inner conductor : best physics results, best rejection of wrong sign mesons but high energy deposition and stresses

⇓

- miniboone shape with target around the horn: best compromise between physics and reliability

Horn's Shape Optimization I

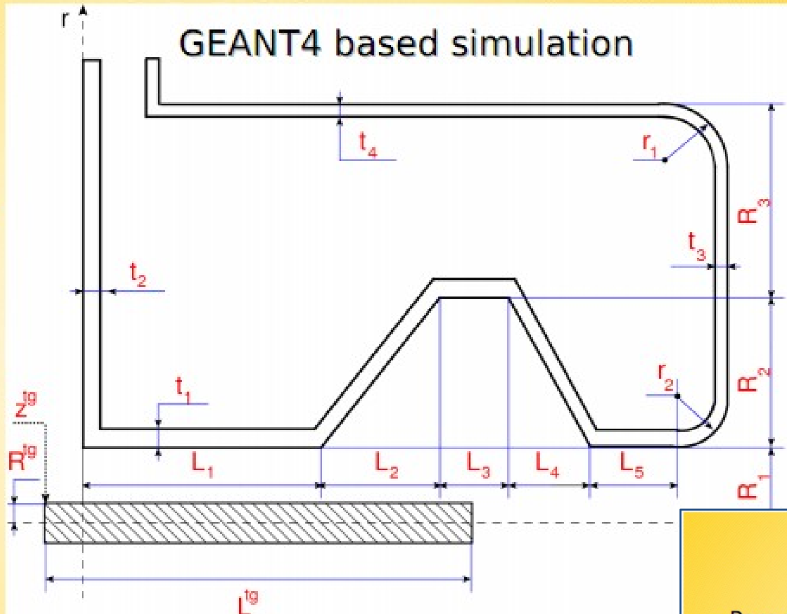
Horn geometrical model

4

à la MiniBoone
("forward closed")

large acceptance for
forward produced particles

This shape is well suited
for long targets



Good suppression of wrong charge pion
dangerous in "-" focusing mode due to
ν_e from $\pi^+ \rightarrow \mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$ and $K^+ \rightarrow \pi^0 e^+ \nu_e$ ← EURONu-WP2 note 0

A. Longhin — Third EUROnu annual meeting, RA

Optimization strategy

5

- Parametric model of magnetic horns
- Random sampling of parameters
- Ranking of configurations based on achievable θ_{13} limits

Figure of merit: $\lambda \equiv$
θ_{13} sensitivity limit at 99% C.L. averaged over the δ_{CP} phase

$$\lambda = \frac{10^3}{2\pi} \int_0^{2\pi} \lambda_{99}(\delta_{CP})\, d\delta_{CP}$$

We want as low as possible λ

- Broad sampling of the (many) parameters to identify the most relevant variables. Then restrict the ranges of variation and iterate.

→

A. Longhin — Third EUROnu annual meeting, RAL 19 Jan 2011

Horn's Shape Optimization II

6

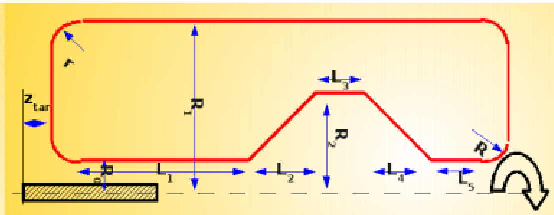
Broad scan

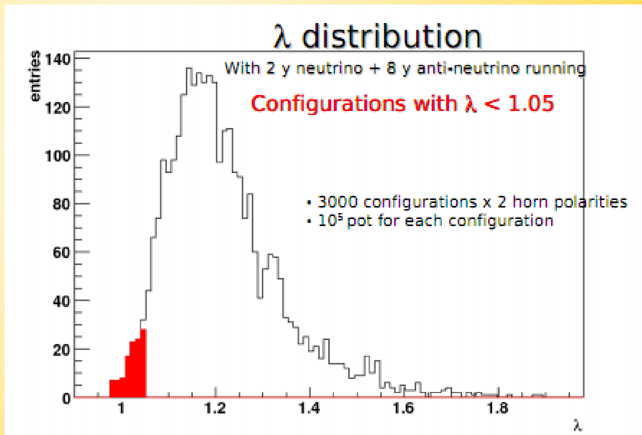
Allow parameters to vary independently

Limit	value
L_{max}	250 cm
R_{max}	80 cm
R_{min}	1.2 cm

Parameter	Interval
L_1	[50, L_{max}] cm
L_2, L_3, L_4	[1, L_{max}] cm
L_5	[1, 15] cm
R, R_1, R_2	[R_{min},R_{max}]
R_0	[R_{min}, 4] cm
z_{tar}	[-30, 0] cm
L_{tun}	[35, 45] m
r_{tun}	[1.8, 2.2] m

Parameter	Value
L_{tar}	0.78 m
r_{tar}	1.5 cm
i	300 kA
s	3 mm
r	5.08 cm





L_{max} and R_{max}: keep the horns small to allow for the 4-horns in parallel to fit

A. Longhin

Third EUROnu annual meeting, RAL 19 Jan 2011

restrict & re-iterate for best horn parameters

Parameters	value [mm]
L_1, L_2, L_3, L_4, L_5	589, 468, 603, 475, 10.8
t_1, t_2 , t_3, t_4	3, 3, 3, 3
r_1, r_2	108
r_3	50.8
R^{tg}	12
L^{tg}	780
z^{tg}	68
R_2, R_3	191, 359
R_1 combined	12
R_1 separate	30

similar logic for Decay Tunnel dimensions

from Liquid Targets to Static Packed one

Summary of target options

Mercury jet
- high-Z (too many neutrons & heat load on horn)
- not chemically compatible with horn

Graphite rod
- thermal conductivity degrades with radiation damage
- mechanical stress depends on dT
- hence short life time

Beryllium rod
- thermal stress is significant
- alternative geometries could overcome the problem (still under investigation)

Integrated Be target and horn
- extra heat load makes it even more challenging
- combined failure modes could reduce the life time

Fluidised powder target
- potential solution for higher heat load

Static pebble bed
- reduced stresses. Favourable transversal cooling. Good yield

goal: to achieve reliable target operation with 4 MW beam

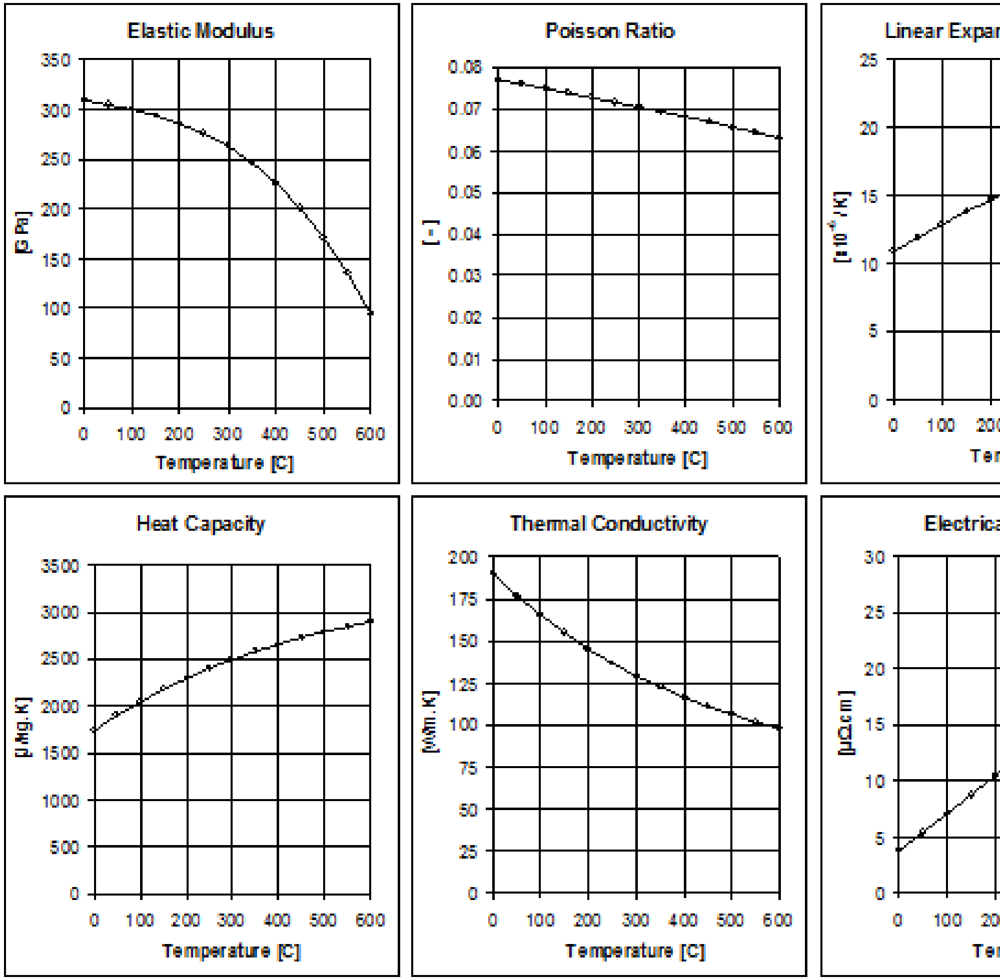
favourable baseline for WP2

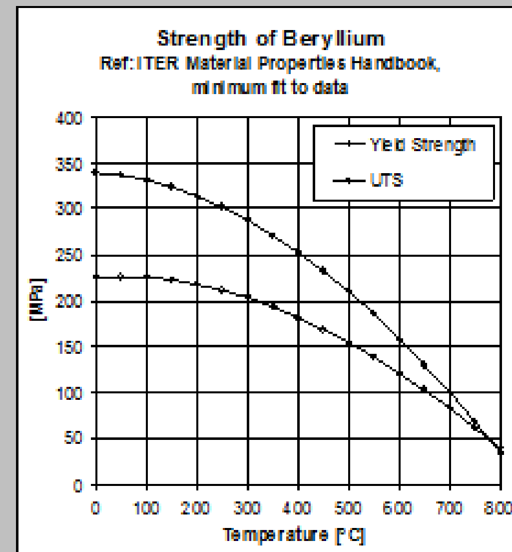
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Ottone Caretta, RAL, January 2011

High Power Targets

Beryllium Material Properties





Note degradation in strength at elevated temperature

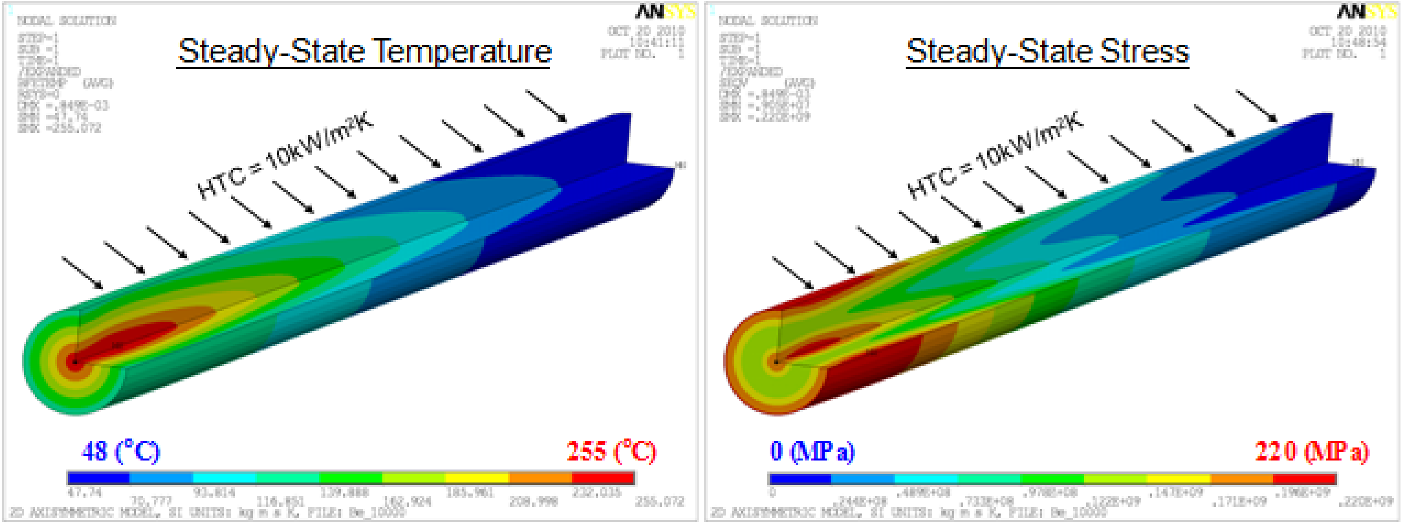
Suggest to limit T_{max} to, say ~300°C ?

Need to define a design stress limit as some fraction of σy say, ~160 MPa ?

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Cylindrical Solid Target

- Initial baseline was a solid cylindrical beryllium target. This has since been ruled out
  - At thermal equilibrium (after a few hundred beam pulses) large temperature variations develop within the target
  - The large ΔT between the target surface and core leads to an excessive steady-state thermal stress
  - This ΔT depends on the material thermal conductivity and cannot be overcome by more aggressive surface cooling



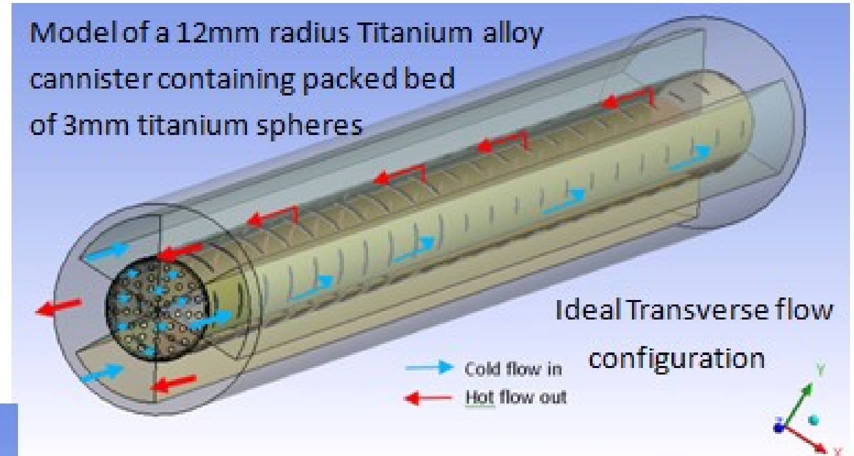
Temperature (left) and and Von-Mises thermal stress (right) corresponding to steady state operation of a peripherally cooled cylindrical beryllium target

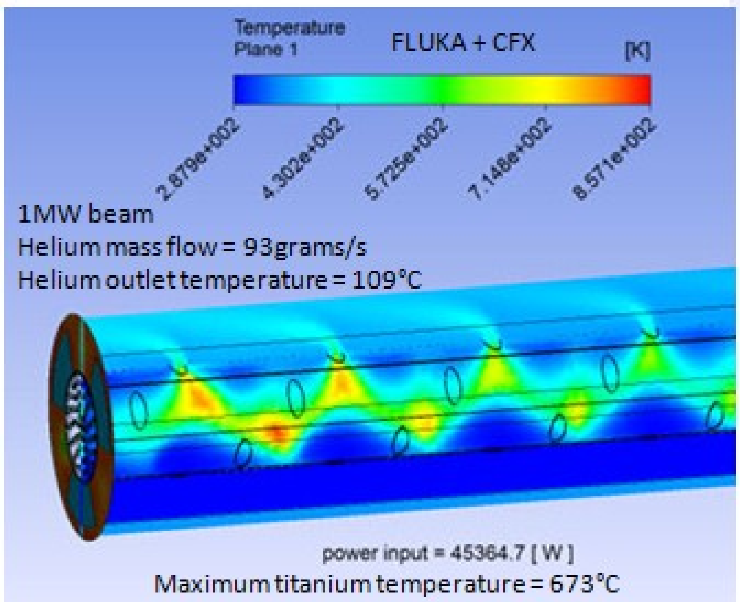
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Packed bed Target Concept for EUROnu

Tristan Davenne

- Offers high surface to volume ratio for good heat transfer throughout target
- Possible to remove dissipated energy without concerning temperatures and stress
- Insensitive to off-centre beam
- Need pressurised gas for high power deposition
- Bulk density lower than solid density (use titanium instead of beryllium)

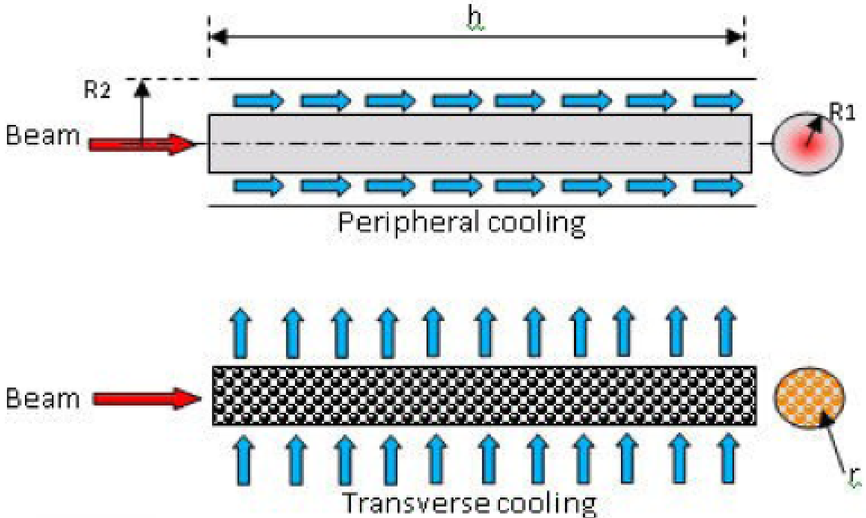




Physics performance for titanium spheres looks reasonable

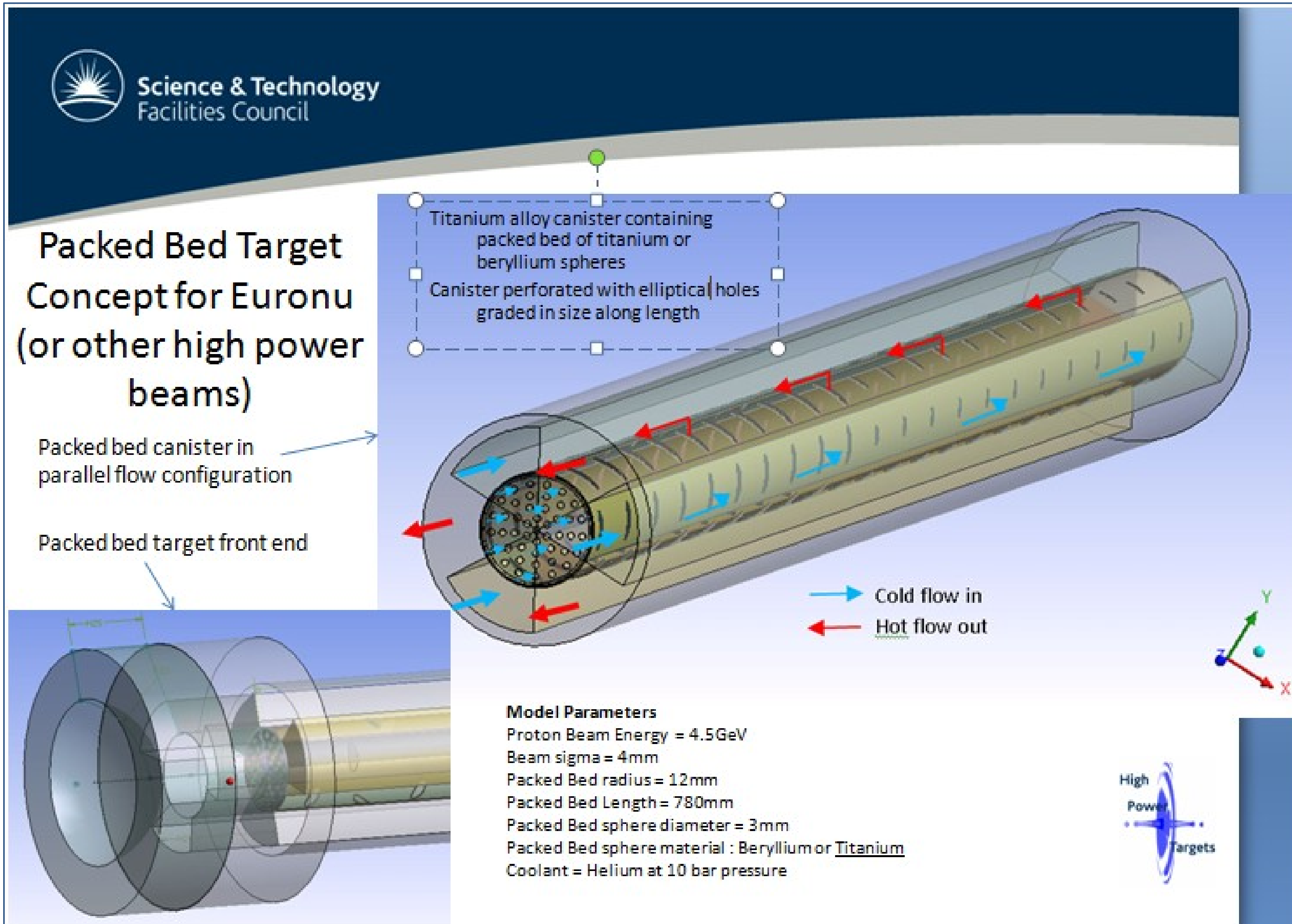
Induction heating may provide an interesting way to test a packed bed

Solid target vs. Ideal Packed Bed Configuration

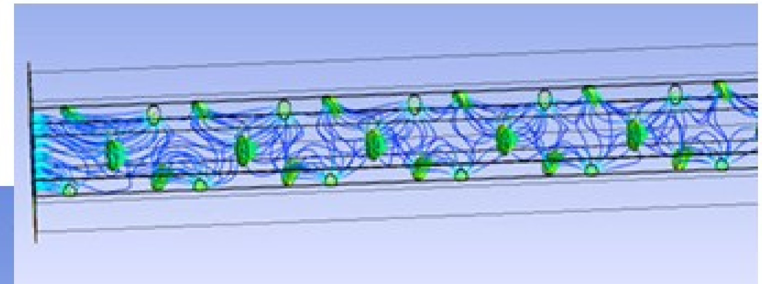


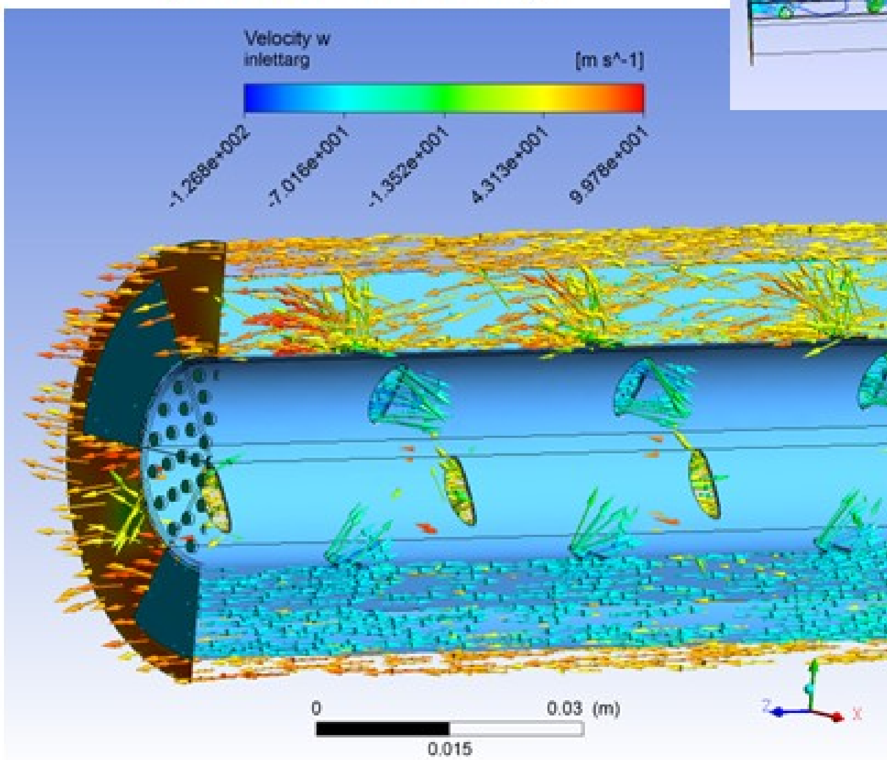
Example Comparison (h=0.78m, R_1=12mm, R_2=25mm, r=1.5mm, Q=1.5e9W/m^3, k=200W/mK)

Target→	Solid Target	Packed Bed Sphere
Radial temperature difference (Thermal stress)	$3R_1^2Q/16k$ =202.5K	$QR_1^2/6k$ =3K
Inertial Stress	Significant (stress waves due to rapid heating and stress oscillation due to off centre beam)	Small (stress waves small due to fast expansion time, off centre beam not a problem due to segmentation)
Surface area for heat exchange	$2\pi R_1h$=0.058m^2	$\pi R_1^2h/(4/3\ \pi r^3)$* $4\pi r^2$=0.71m^2
Flow area	$\pi(R_2^2-R_1^2)$ = 1.5e-3m^2	$R_1h/2$ =4.68e-3m^2


Science & Technology Facilities Council
Packed Bed Target Concept for Euronu (or other high power beams)
Packed bed canister in parallel flow configuration
Packed bed target front end
Titanium alloy canister containing packed bed of titanium or beryllium spheres
Canister perforated with elliptical holes graded in size along length
Cold flow in
Hot flow out
Y
X
Z
Model Parameters
Proton Beam Energy = 4.5GeV
Beam sigma = 4mm
Packed Bed radius = 12mm
Packed Bed Length = 780mm
Packed Bed sphere diameter = 3mm
Packed Bed sphere material : Beryllium or Titanium
Coolant = Helium at 10 bar pressure
High Power Targets

Packed Bed Model
(FLUKA + CFX v13)





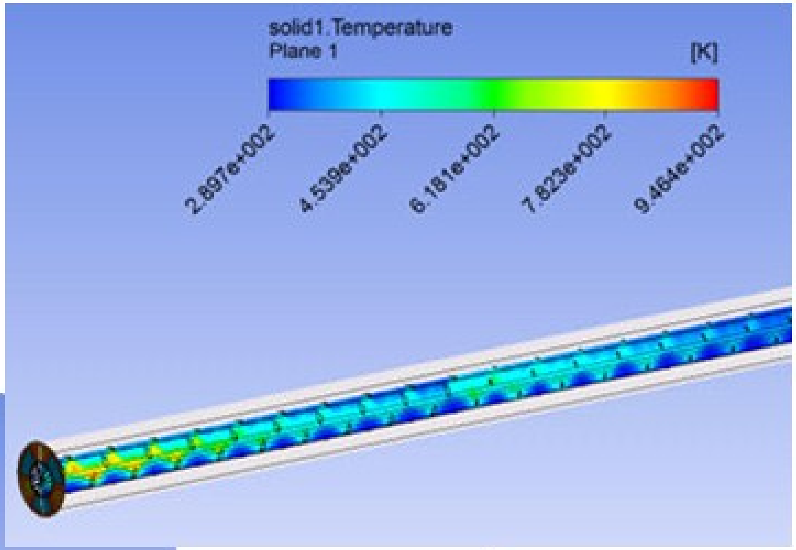
Streamlines in packed bed

- Packed bed modelled as a porous domain
- Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)
- Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium
- Interfacial surface area depends on sphere size
- Acts as a natural diffuser flow spreads through target easily

Velocity vectors showing inlet and outlet channels and entry and exit from packed bed

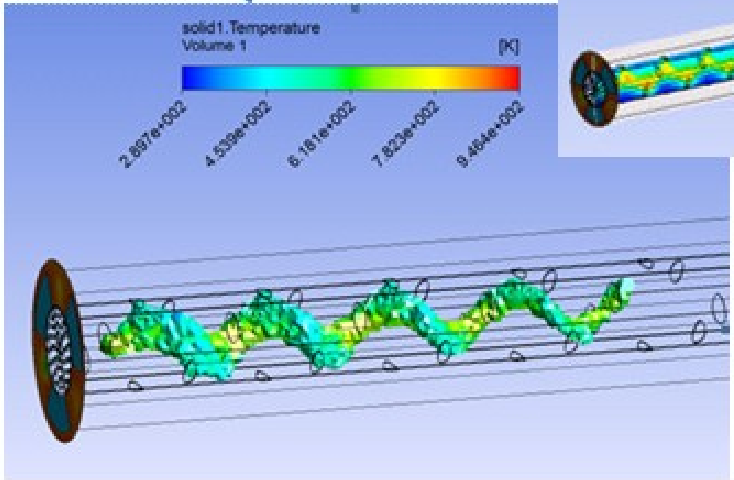
Science & Technology
Facilities Council

Packed Bed



<u>High Temperature region</u>

Highest temperature Spheres occur near outlet holes due to the gas leaving the canister being at its hottest

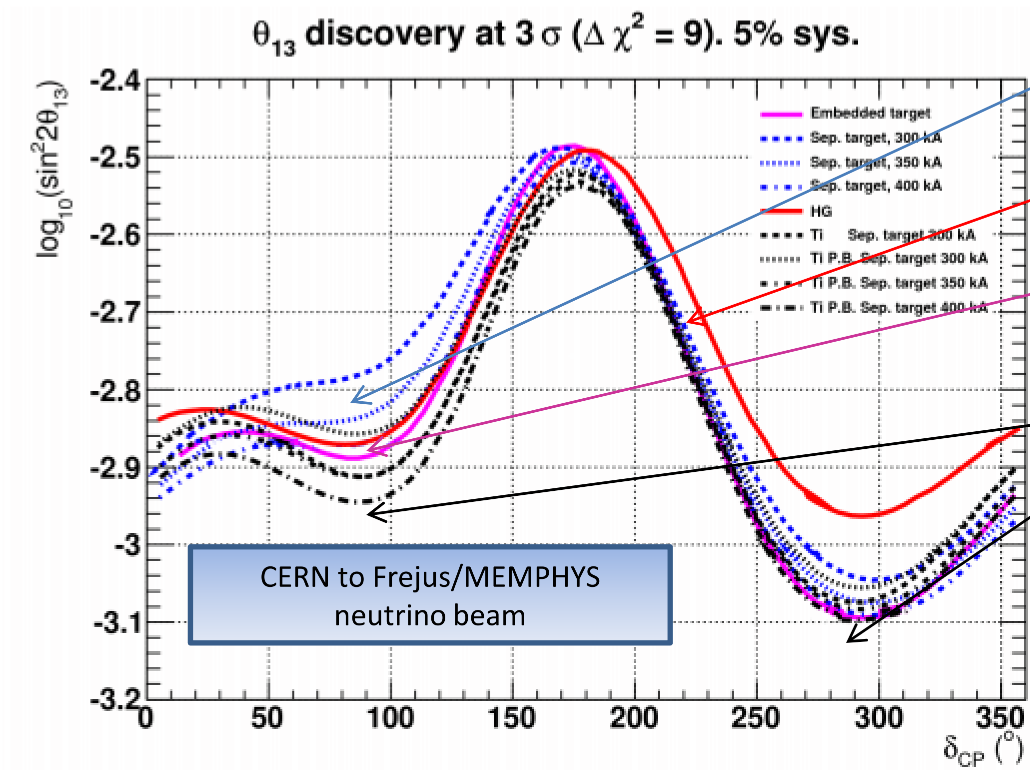


<u>Titanium temperature contours</u>

Maximum titanium temperature = 946K =673°C (N.B. Melting temp =1668°C)

High Power Targets

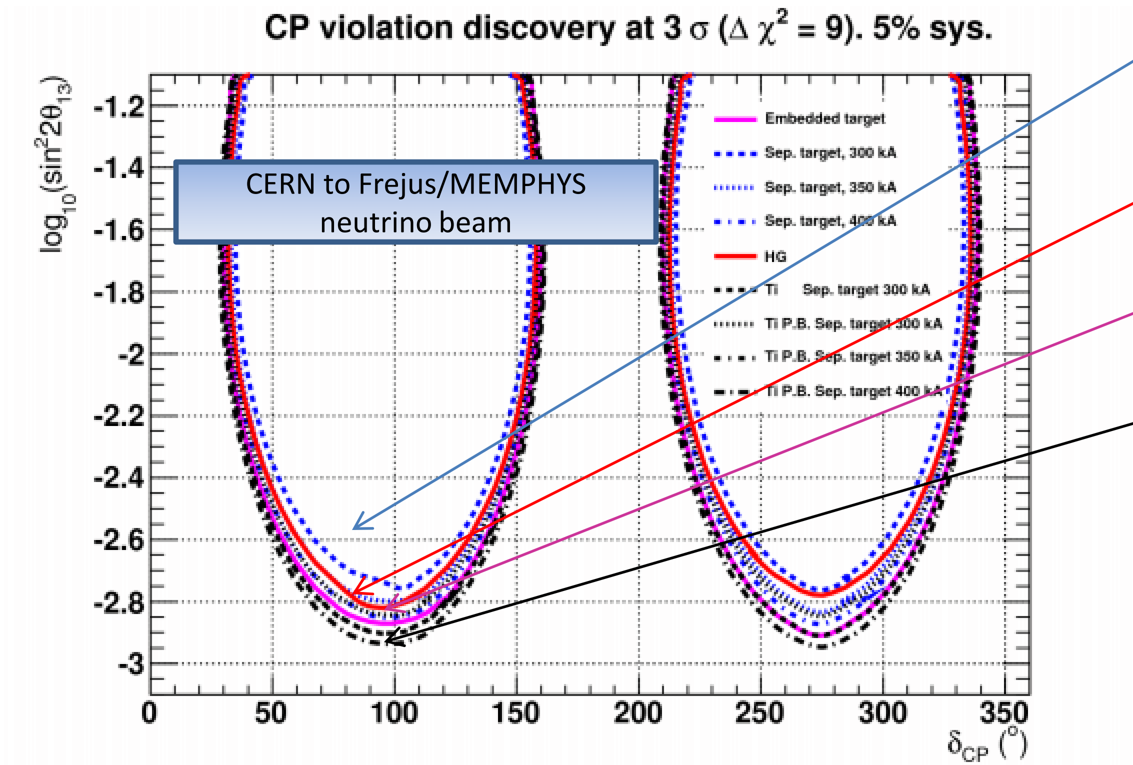
Physics Performance for different Targets I



- Graphite Solid target, $2\lambda_I$
- Hg, $2\lambda_I$
- Integrated target, $2\lambda_I$
- excellent performance of packed bed Ti, d= 74%d_{Ti}

any density reduction of packed could be recuperated increasing the horn current by 50, 100 kA

Physics Performance for different Targets II



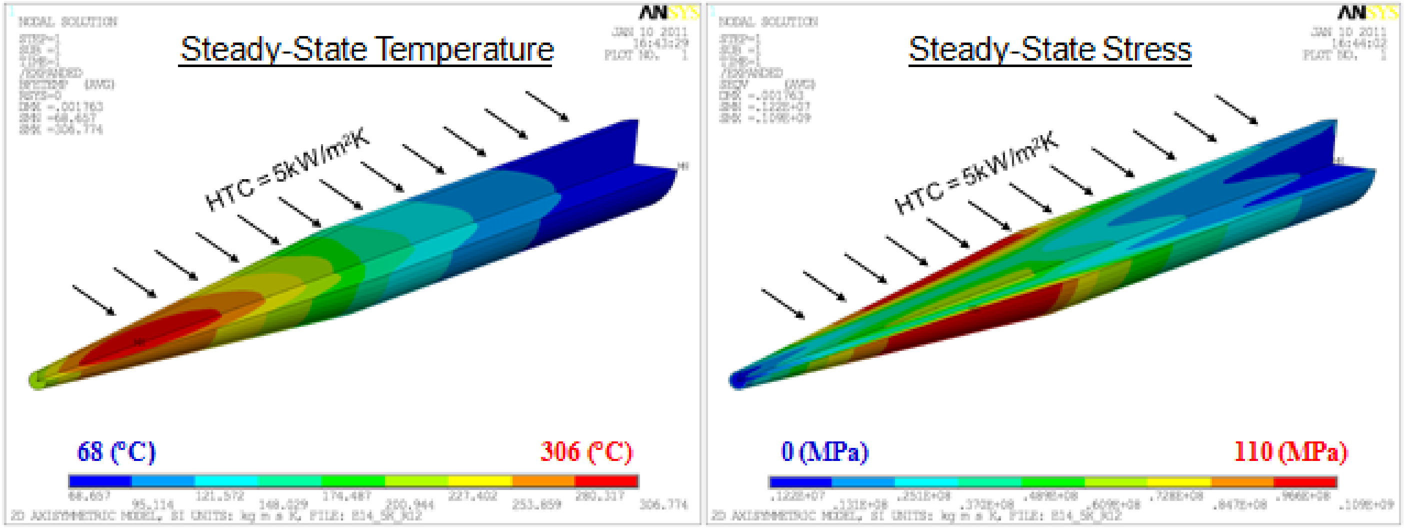
- Graphite Solid target, $2\lambda_I$
- Hg, $2\lambda_I$
- Integrated target, $2\lambda_I$
- excellent performance of packed bed Ti, d= 77%d_{Ti}

any density reduction of packed could be recuperated increasing the horn current by 50, 100 kA

alternative target solution:

"Pencil Shaped" Solid Target

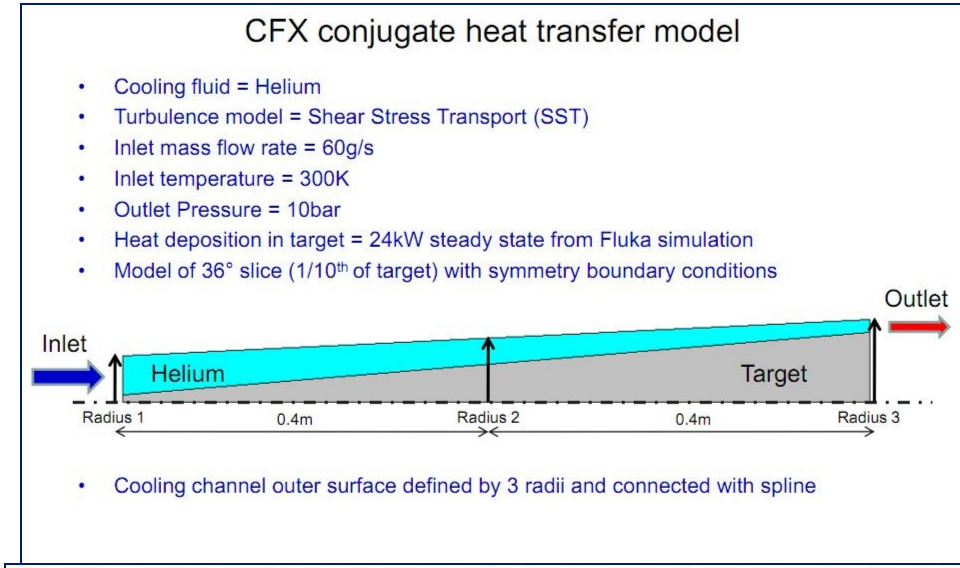
- A potential solution may be found by shaping the upstream end of the target such that the cooling fluid is in close proximity to the region of peak energy deposition
  - Shorter conduction path to coolant
  - Reduced ΔT between surface and location of Tmax
  - Thermal stress is reduced to an acceptable level
  - Able to operate with a factor 2 x less aggressive surface cooling
  - Pressurised helium gas cooling appears feasible

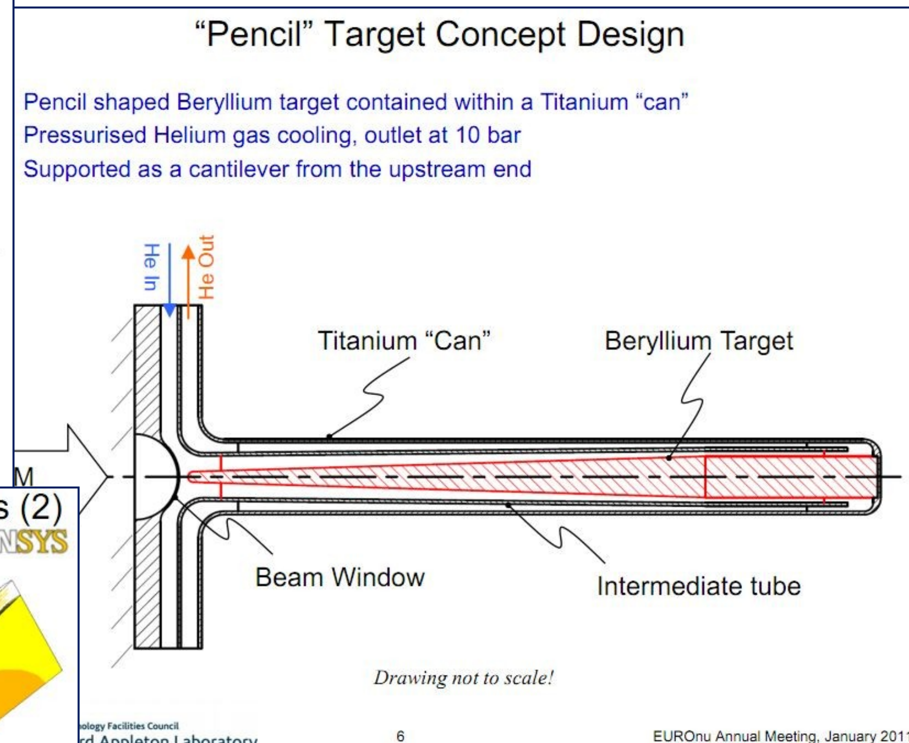


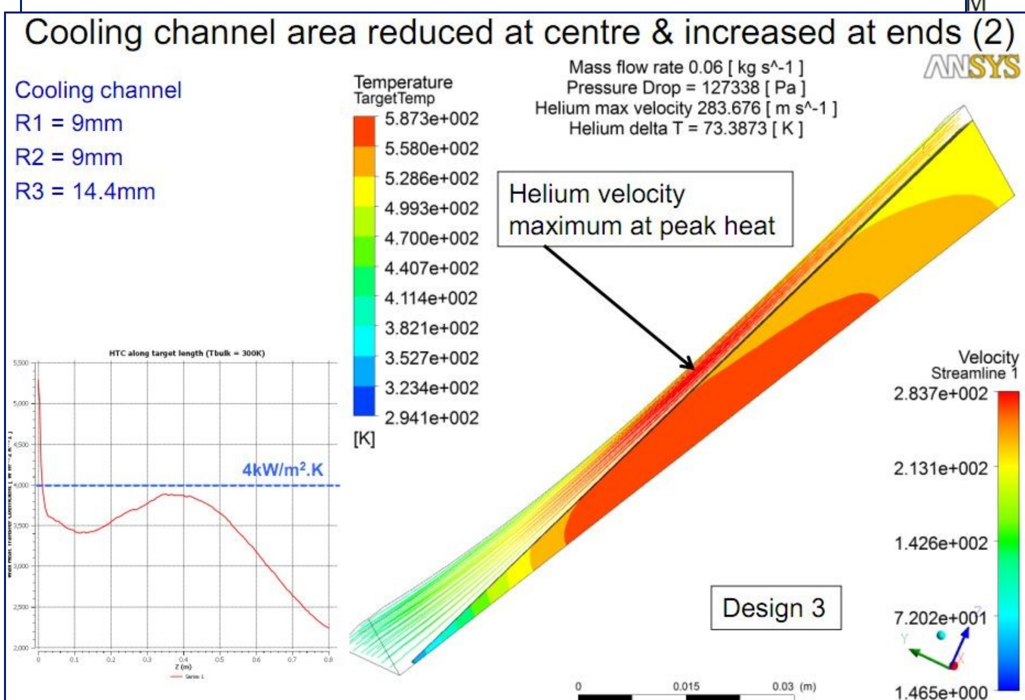
Temperature (left) and Von-Mises thermal stress (right) corresponding to steady state operation of a peripherally cooled "pencil shaped" beryllium target

Science & Technology Facilities Council
Rutherford Appleton Laboratory

pen like target: cooling





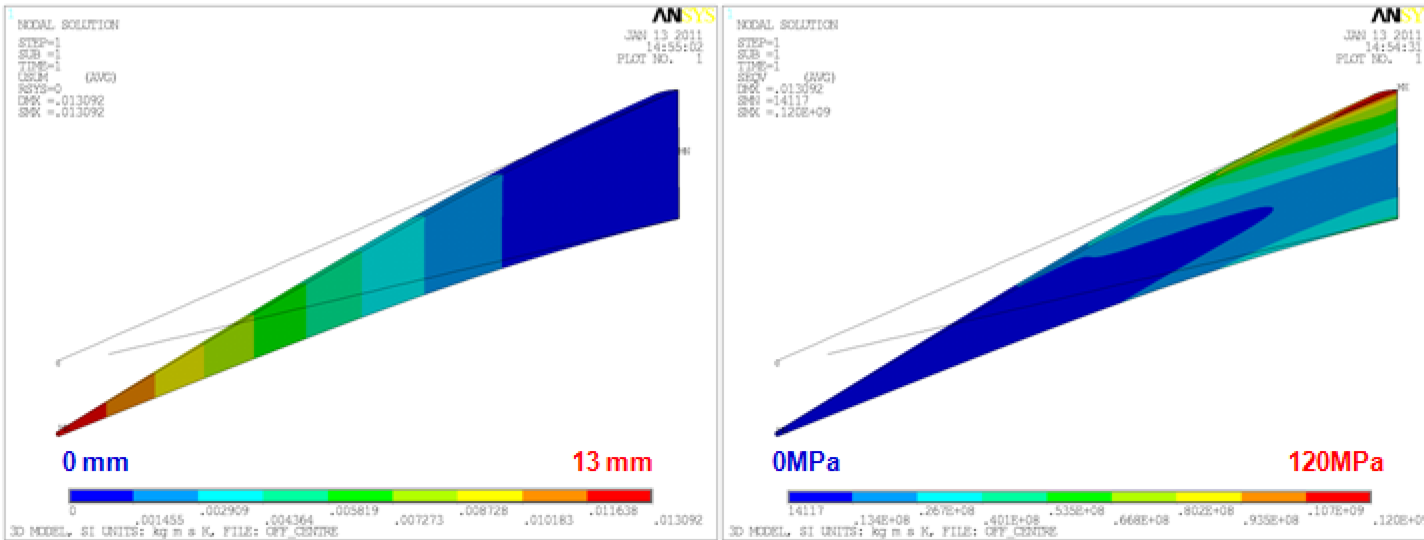


looks feasible

considerations:

Off Centre Beam (Accident Case)

- Lateral deflection due to steady-state off-centre heating:
  - 13 mm lateral deflection if cantilevered from downstream end
  - Max stress increased to 120 MPa (recall 83 MPa in well centred beam case)



Deflection (left) and Von-Mises thermal stress (right) corresponding to a laterally mis-steered beam

Comments on Packed-bed & Pencil like Target

- Pencil like Geometry merits further investigation
  - ✓ Steady-state thermal stress within acceptable range
  - ✓ Pressurized helium cooling appears feasible
  - ✓ Off centre beam effects could be problematic?
  - ✓ Needs further thermo-mechanical studies

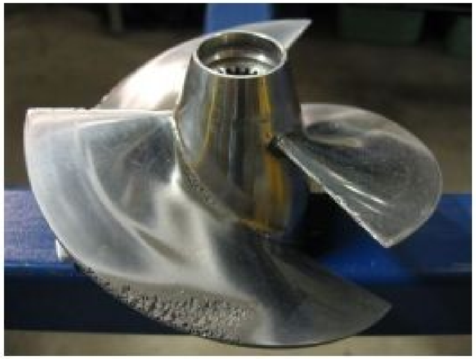
- Packed-bed target:
  - ✓ Large surface area for heat transfer
  - ✓ Coolant able to access areas with highest energy deposition
  - ✓ Minimal stresses
  - ✓ Potential heat removal rates at the hundreds of kiloWatt level
  - ✓ Pressurised cooling gas required at high power levels
  - ✓ Bulk density lower than solid density
  - ✓ From a thermal and engineering point of view seems a reasonable concept where stress levels in a traditional solid target design look concerningly high

Cooling layout & medium

Water

avoid enclosed water in proximity of the beam:
1K of (instantaneous) beam induced heating generates approximately 5bar of pressure rise which may result in **water hammer** and/or **cavitation**

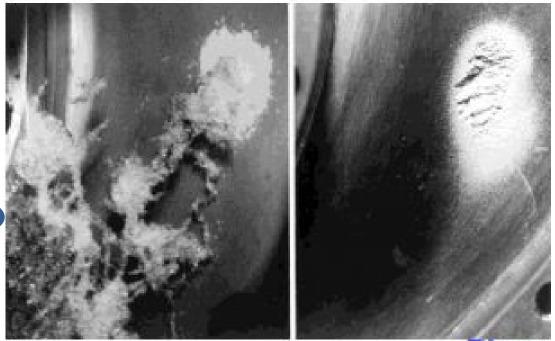
Helium



favourable method

almost beam "neutral" is good also for transversal flow cooling (across the beam footprint)
although pressure has to be kept higher (10bar) to obtain a high cooling efficiency.
No generation of stress waves in coolant.
Low activation of coolant. No corrosion problems

Peripheral vs transversal cooling



peripheral cooling does not appear sufficient to maintain a low dT within the target material.
A transversal cooling arrangement may be necessary to provide cooling at the core of the target.

Science & Technology Facilities Council
Rutherford Appleton Laboratory

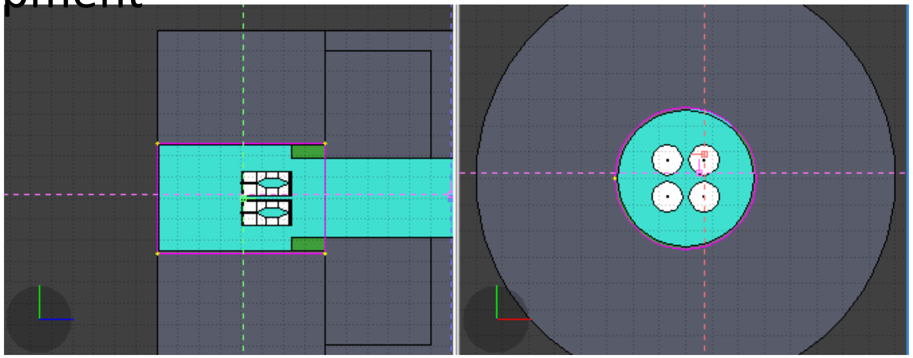
Targets

Ottone Caretta, RAL, January 2011

Energy Deposition Studies in different elements of SuperBeam

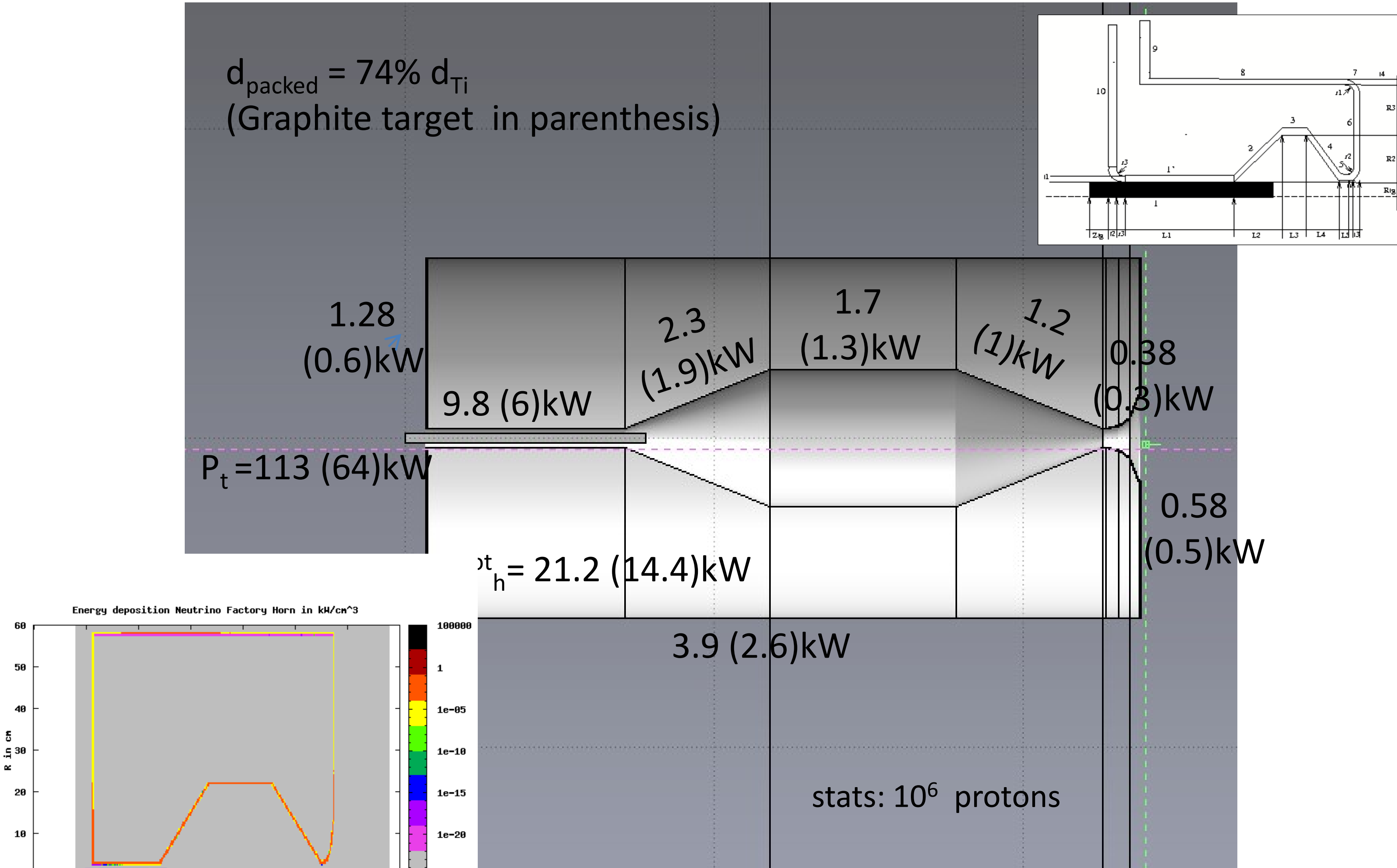
aim safety:

- use T2K as guideline as shielding designed for 4MW
- design the shielding of the layout to confine all the energy
- calculate the energy deposition on Horn, Target , ..., Decay Tunnel Vessel, ..., Beam Dump
- define
  - ✓ any shielding to protect the equipment
  - ✓ the cooling methods



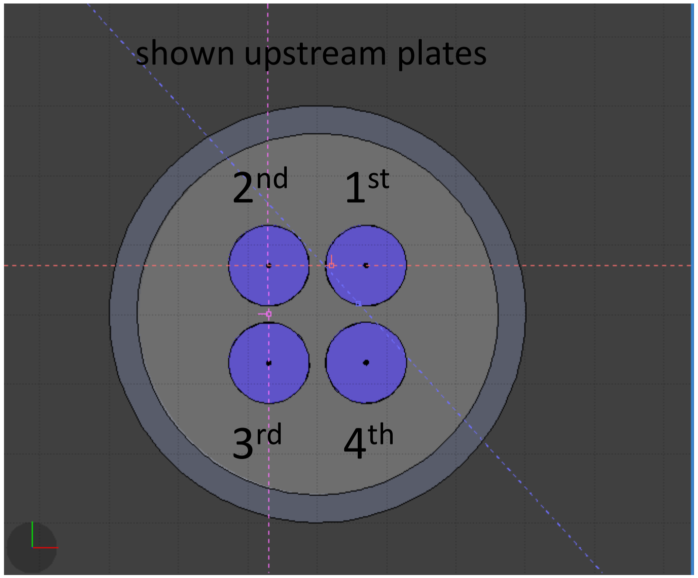
Power distribution for 4horn System, 350kA, 1.3MW, Ti packed bed target

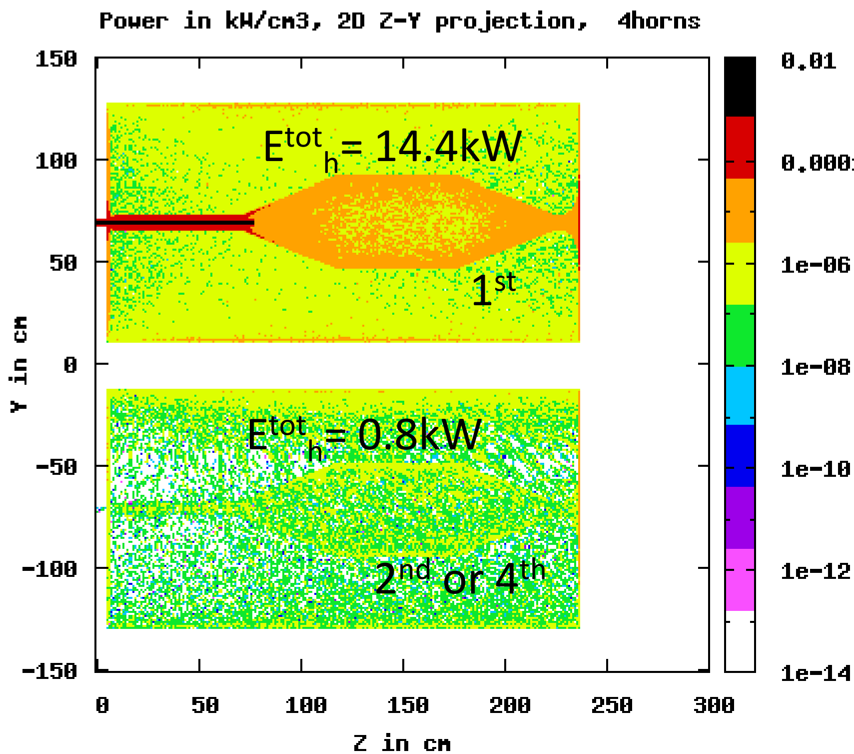
studies done with flair 0.9.1 with geoviewer 0.9, fluka 2008.3d



Power on horn # 2,4 (next to the active one)

- active horn is # 1, 1.3MW beam, 350kA, Gr target

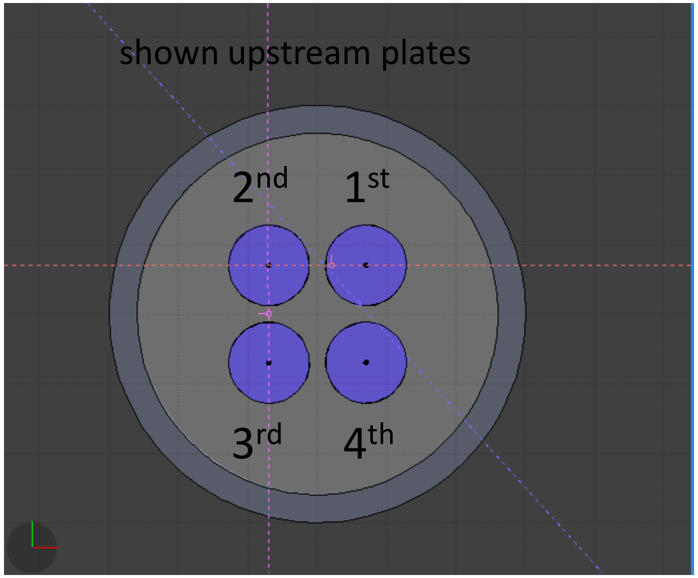


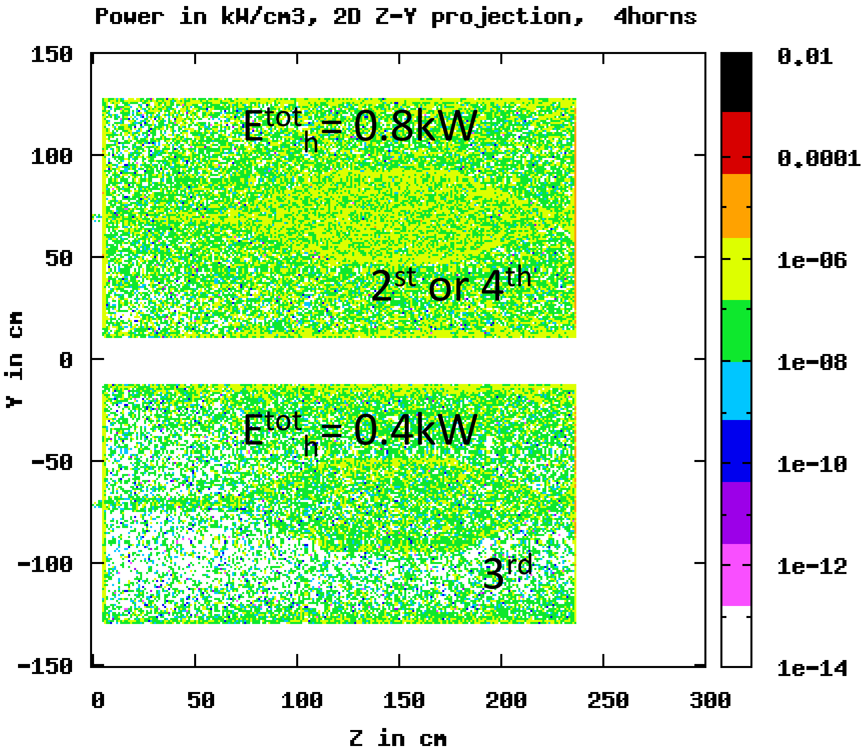


Power in kW for the horn next to the active one			
total	inner	outer	plates
0.8 (5.5% of active horn)	0.1	0.6 (50% of outer next to 1^{st})	0.1

Power on horn # 3 (diagonal to the active one)

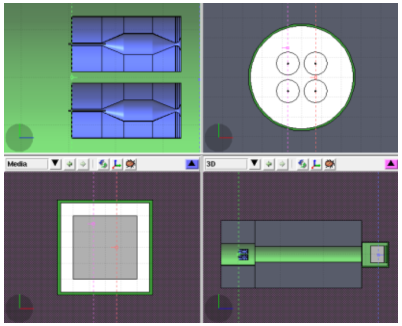
- active horn is # 1, 1.3MW beam, 350kA, Gr target



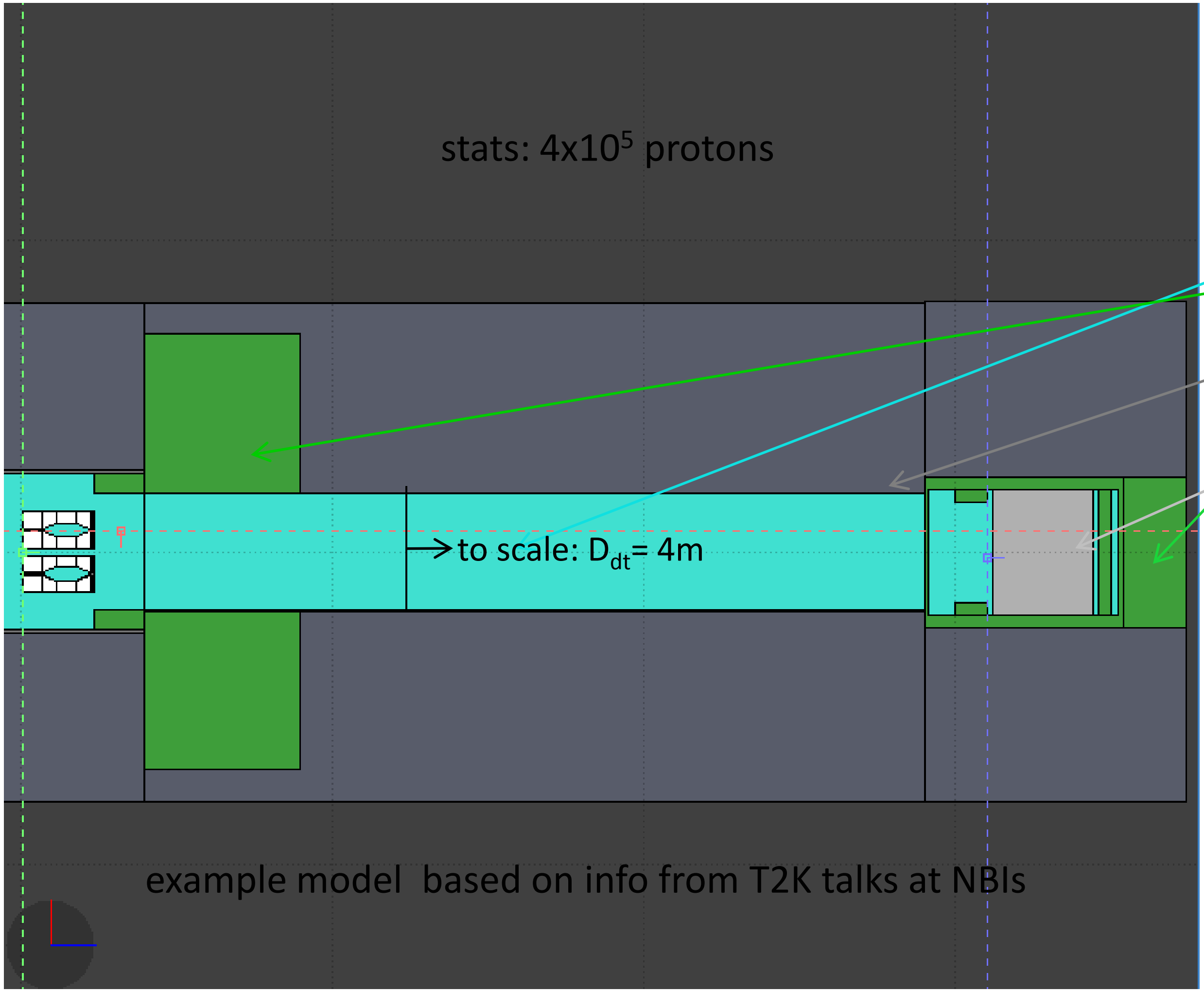


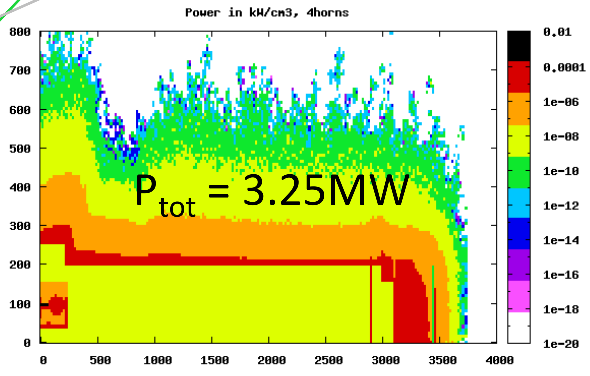
Power in kW for the horn diagonal to the active one			
total	inner	outer	plates
0.4 (2.8% of active horn)	0.06	0.28 (50% next to 1st)	0.06

Power for SB Layout, 4MW

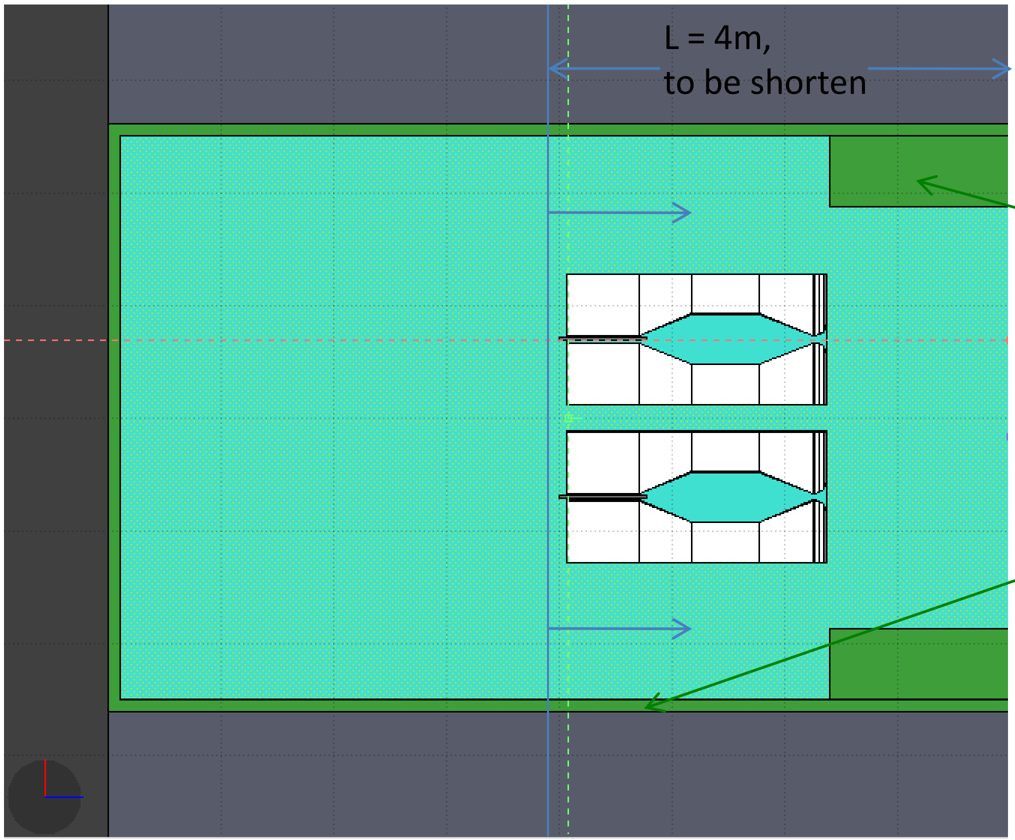


- FLUKA schematics for SB layout, service gallery not studied yet





Power in Target Horn Station, 4MW



Power scoring parameters:

concrete:

t = 5.7m

L = 4m

P = 128kW

collimator, water cooled (in T2K):

t_{Fe} = 60cm

L_{Fe} =160cm

P_{Fe} = 420kW

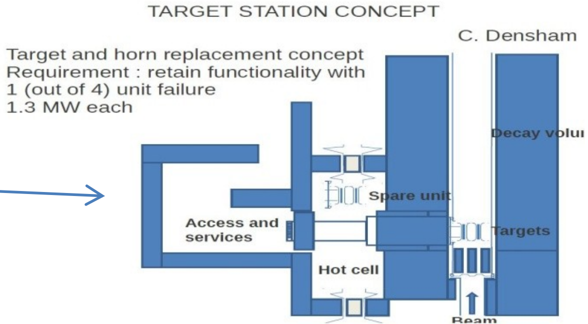
He vessel, water cooled:

t_{Fe} = 10cm

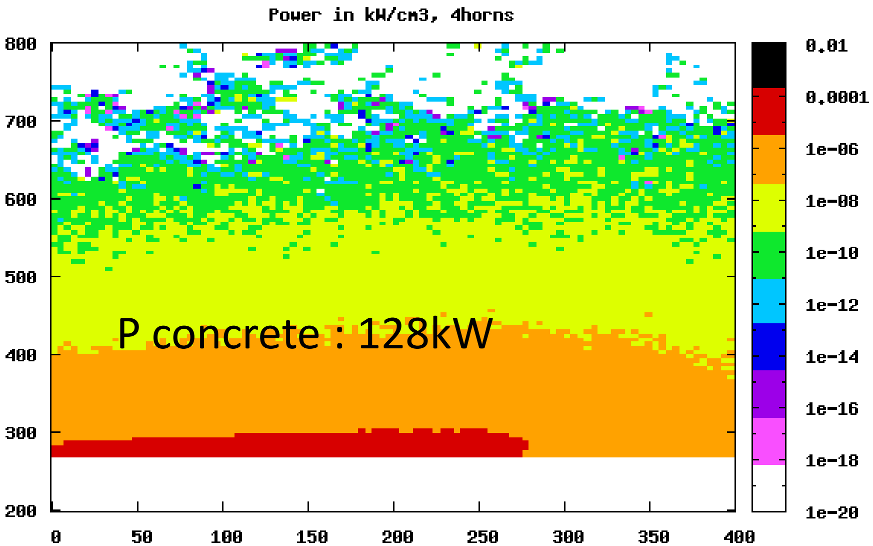
L_{Fe}= 4m

P_{Fe} = 243kW

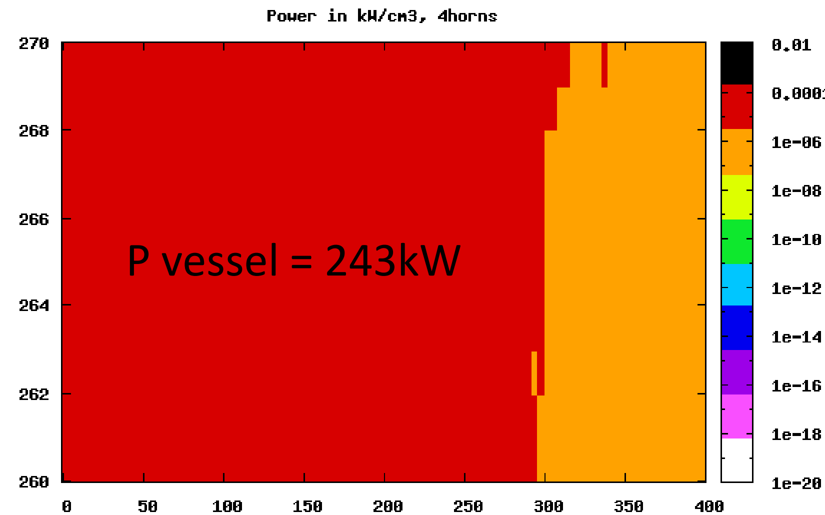
- shielding will be re-defined for the protection of the service gallery and equipment

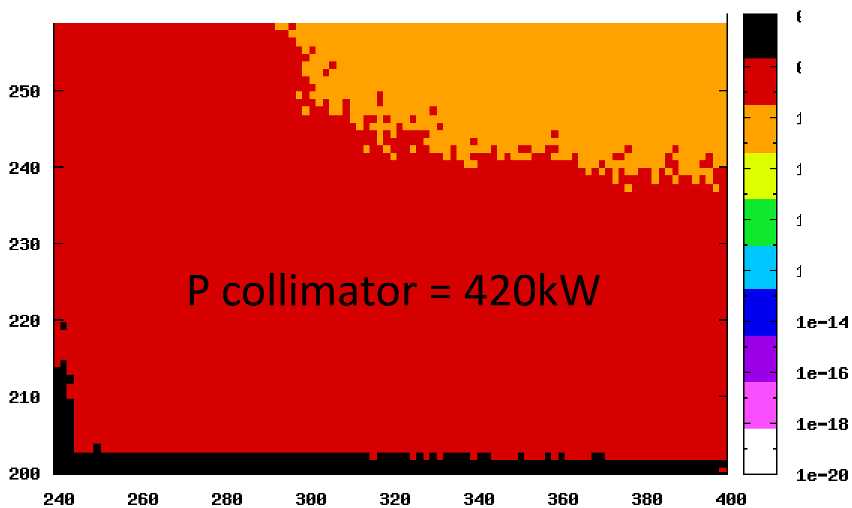


Power in Target Horn Station, 4MW

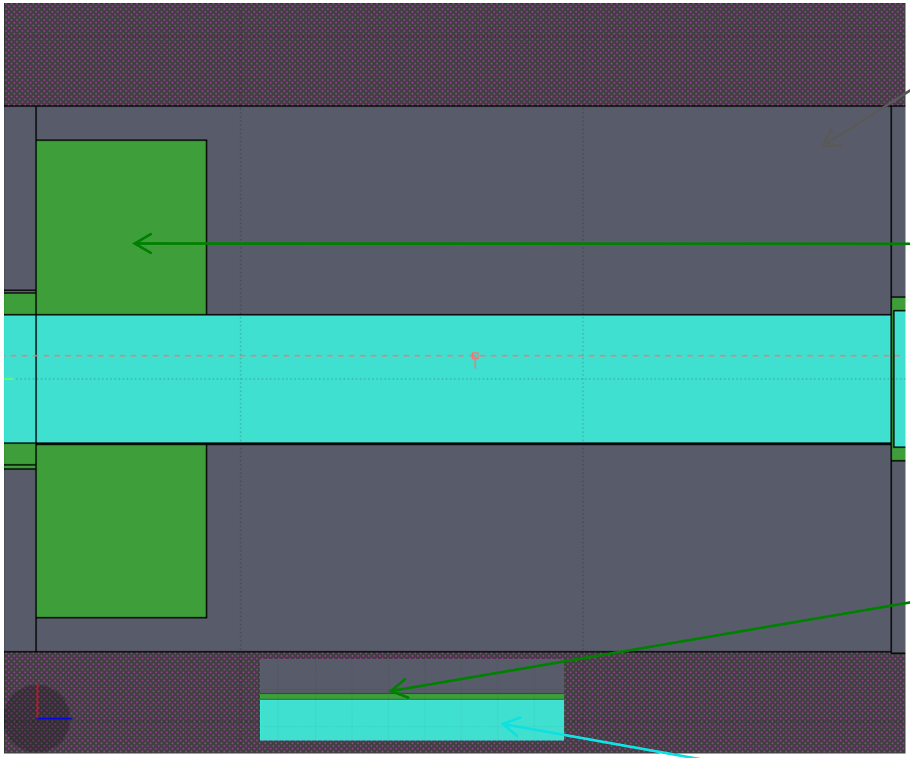


R-Z
Power density distribution in kW/cm^3





Power in Decay tunnel



Power scoring parameters:

concrete:

t = 6m

L = 20m

P = 452kW

upstream collimator *(will be re-defined accordingly)* :

t_{Fe} = 5m

L_{Fe} = 5m

P_{Fe} = 420kW

He vessel, water cooled

t_{Fe} = 1.6cm

L_{Fe} = 25m

P_{Fe} = 362kW

He decay tunnel:

R = 2m

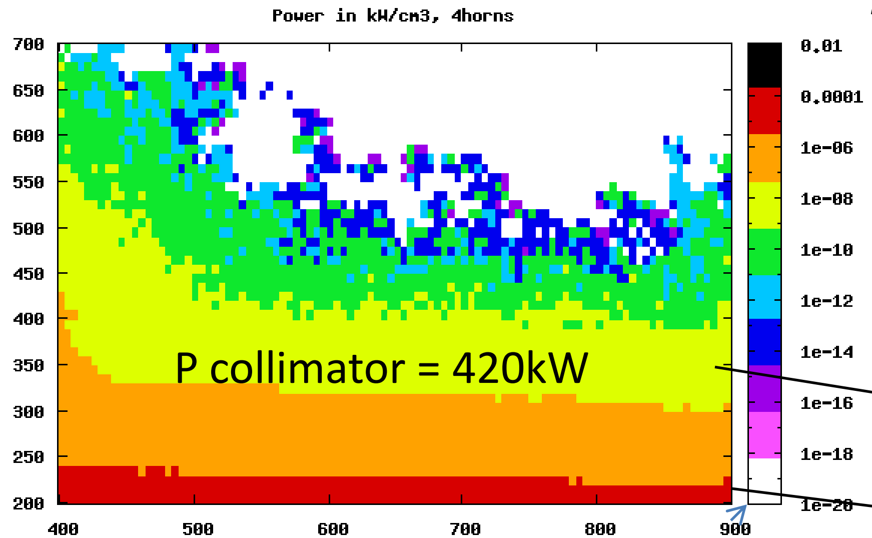
L = 25m

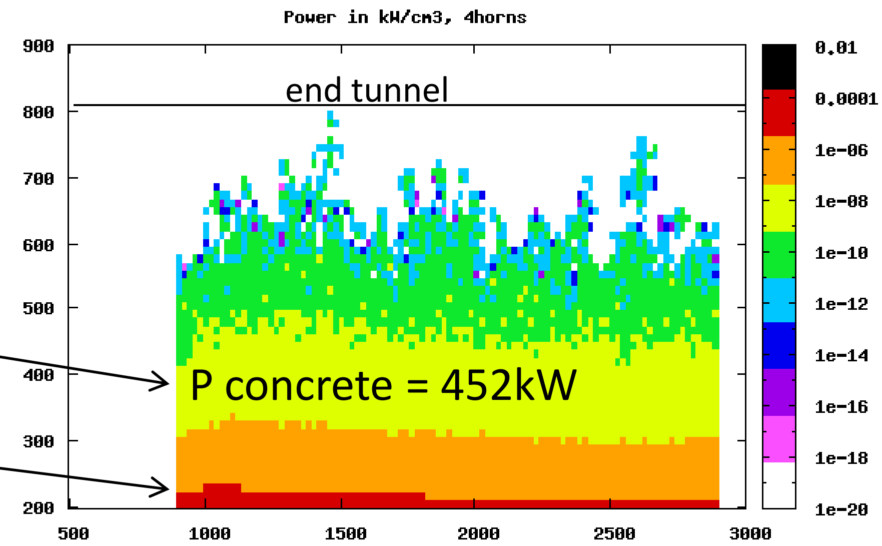
P_{He} = 1.5kW

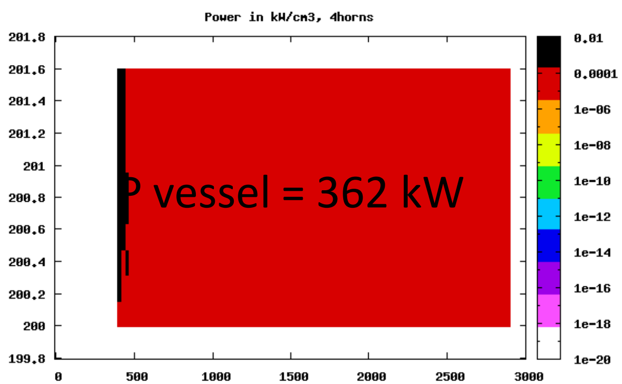
Power in Decay Tunnel Elements

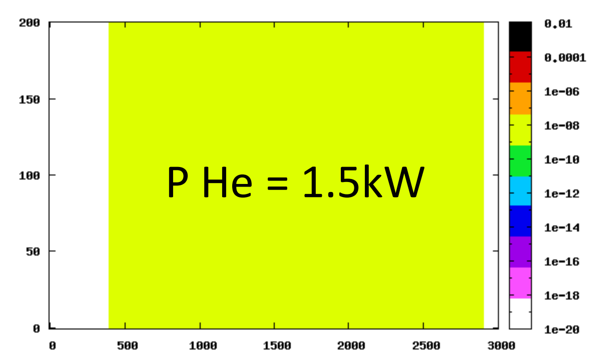
R-Z

Power density distribution in kW/cm³

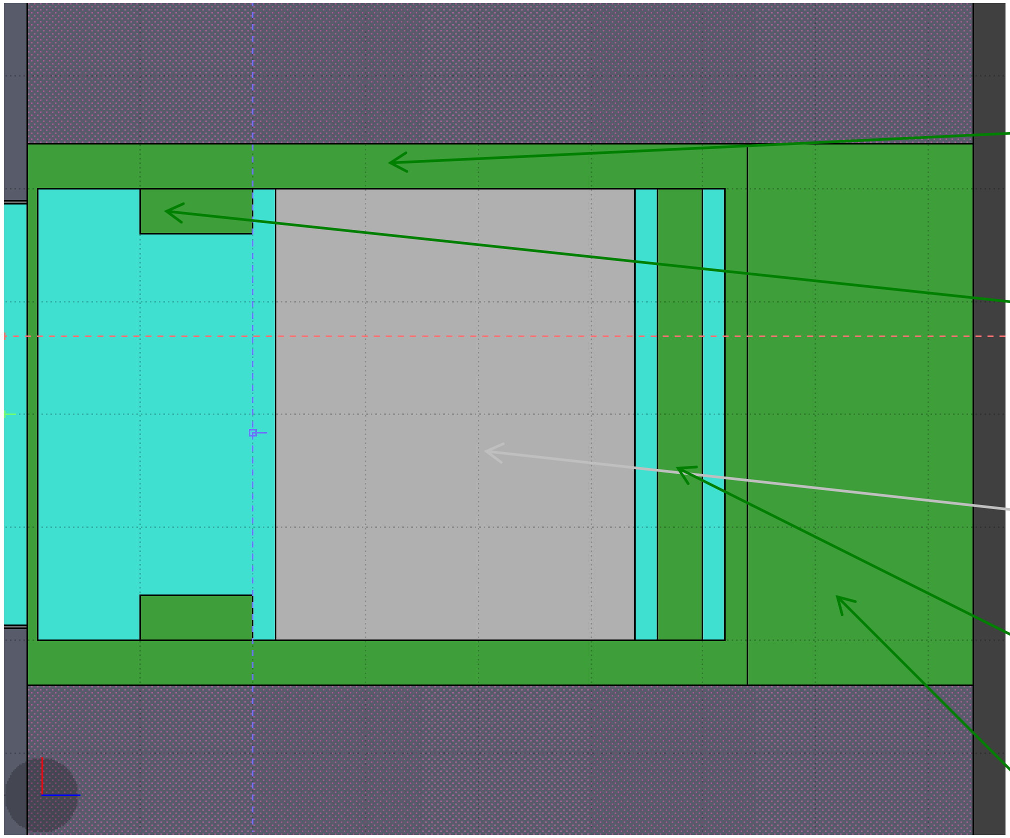








Power in Beam Dump



Power scoring parameters:

concrete:

$t = 5.6$m
$L = 8.4$m

He vessel + iron plates, water cooled

$t_{Fe} = 10\text{-}40$cm
$L_{Fe} = 4$m

upstream shield (iron plates), water cooled

$t_{Fe} = 40$cm
$L_{Fe} = 1$m

Graphite beam dump:

L = 3.2m, W = 4m, H = 4m
P= 473kW

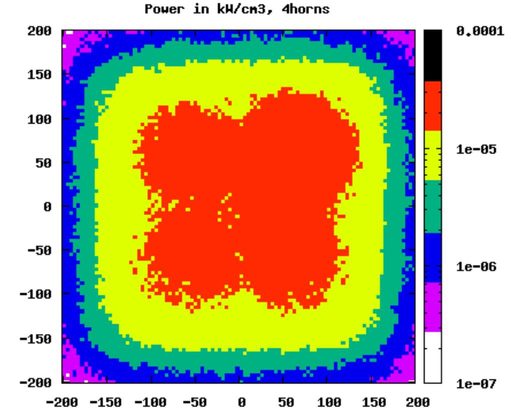
downstream iron shield (iron plates), water cooled:

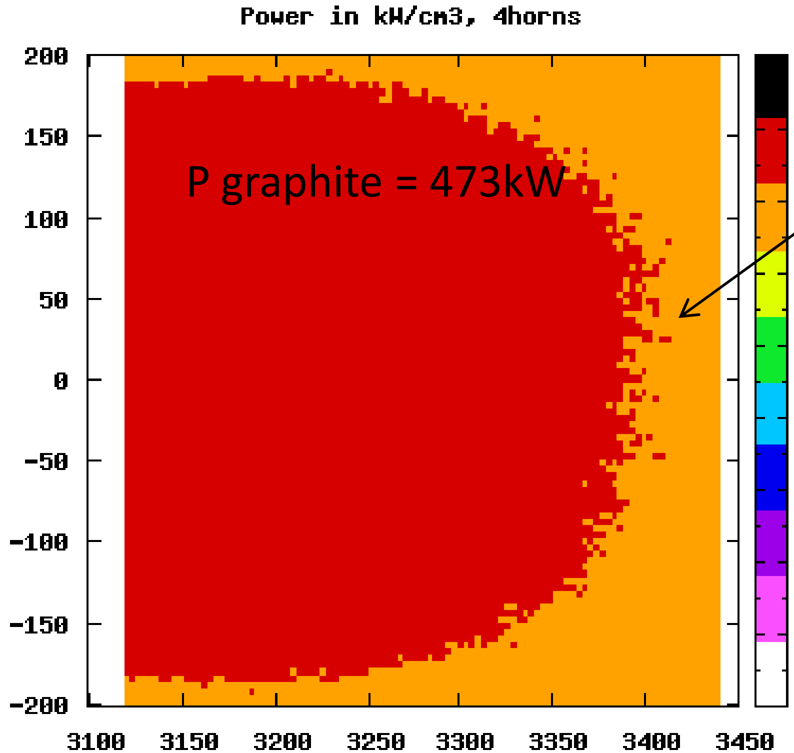
$L_{Fe} = 40$cm, $W_{Fe} = 4$m, $H_{Fe} = 4$m
$P_{Fe} = 9.2$kW

outer iron shields (iron plates), water cooled

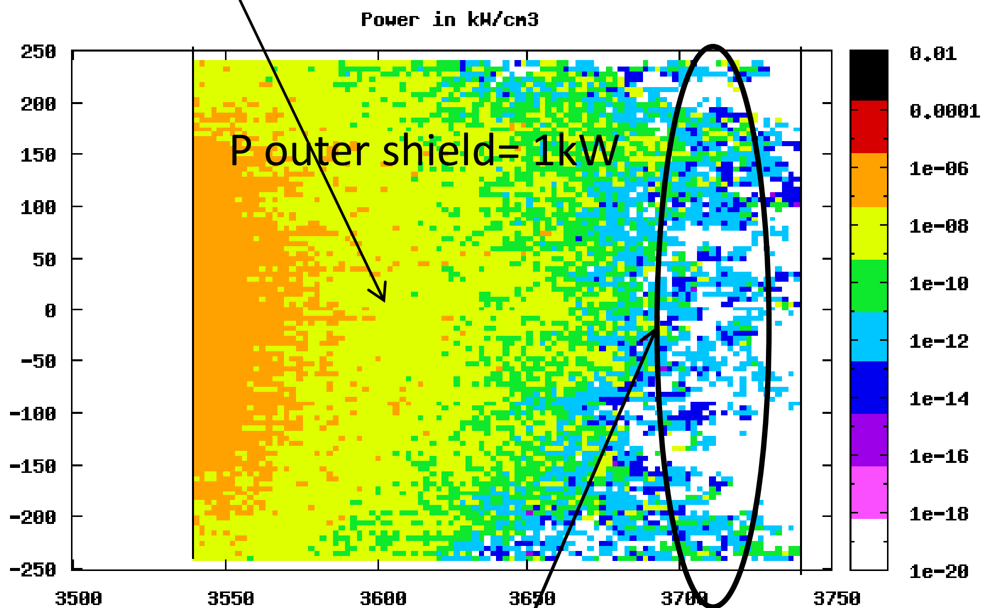
$L_{Fe} = 2$m, $W_{Fe} = 4.8$m, $H_{Fe} = 4.8$m
$P_{Fe} = 1$kW

Power in Beam Dump





R-Z
Power density distribution in kW/cm^3



end of beam dump structure: Power Density minimum along the direction of secondary beam

Horn: Dynamic Stress Analyses due to Thermal and Magnetic pulses

Dynamic stresses are due to

- Transient Joule heating due to the current passing through the horn’s skin
- Secondary Particles
- Magnetic Pulses/forces

stress vs time in the horn, 25pulses

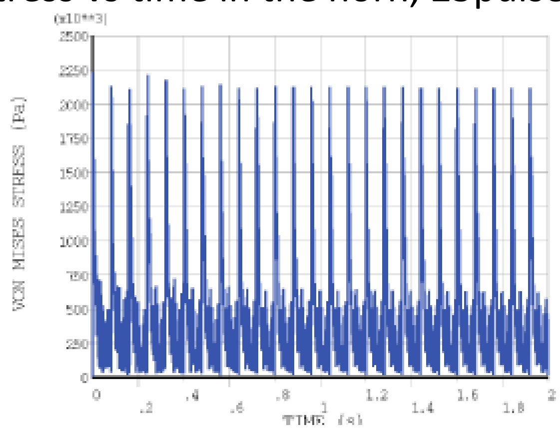
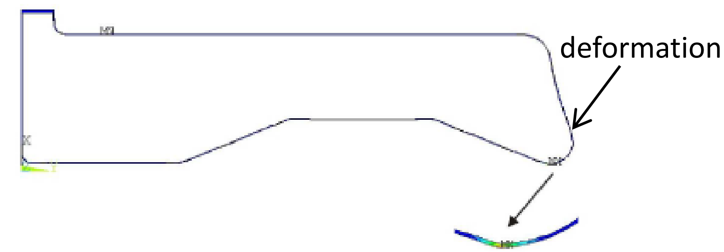


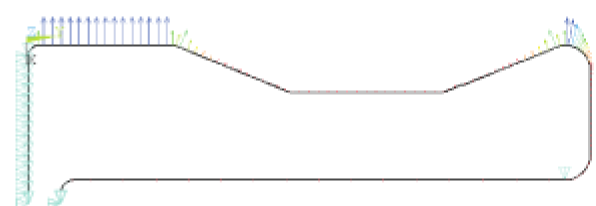
Table 15: Summary of the dynamic stresses

Stress due to Joule heating	3.7 MPa (at 350 kA) 2.7 MPa (at 300 kA)
Stress due to secondary particle heating	3.1 MPa
Stress due to magnetic forces	41 MPa (at 350 kA) 30 MPa (at 300 kA)



von Mises stresses due to thermal loads

Pulse: 100µs
T=1/50/4s=0.08s



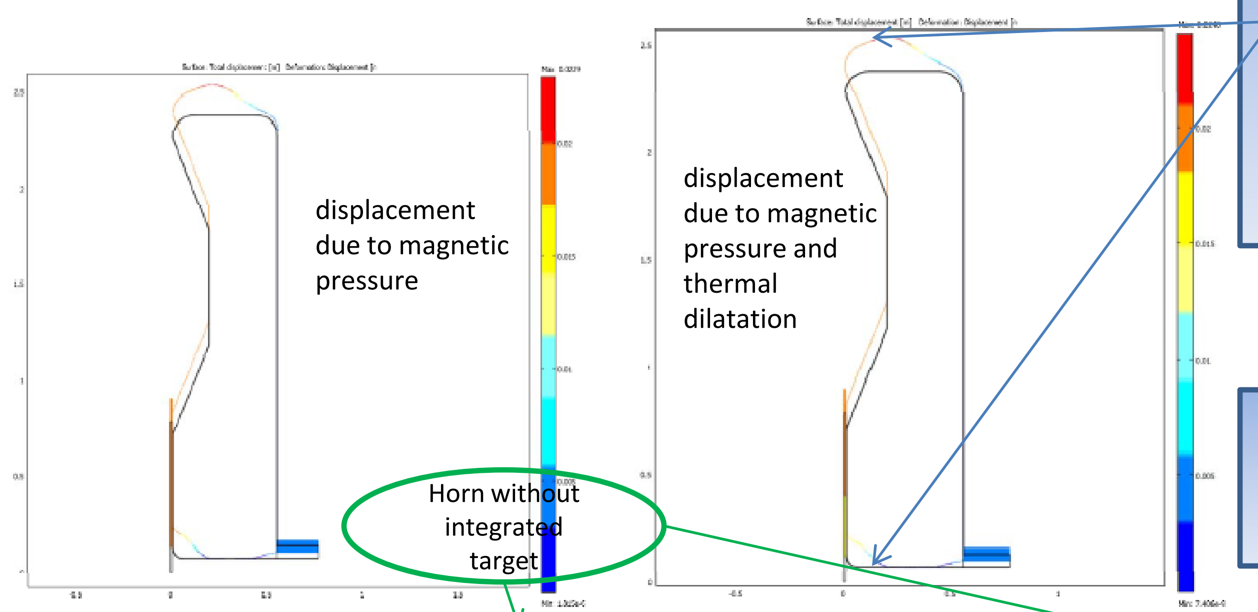
magnetic pressure on the horn

static stress

Horn: Static stress, deformation

- in order to assess the horn deformation and horn life time, the calculation of the stress inside the horn is necessary. The stress level in the structure should be low enough in comparison with the fatigue limit of the materials. Loads coming from the magnetic pressure and the thermal dilatation of the material

- dynamic stress superimposed on the quasi-static stress are the basis of the fatigue life time estimate of the horn – work ongoing

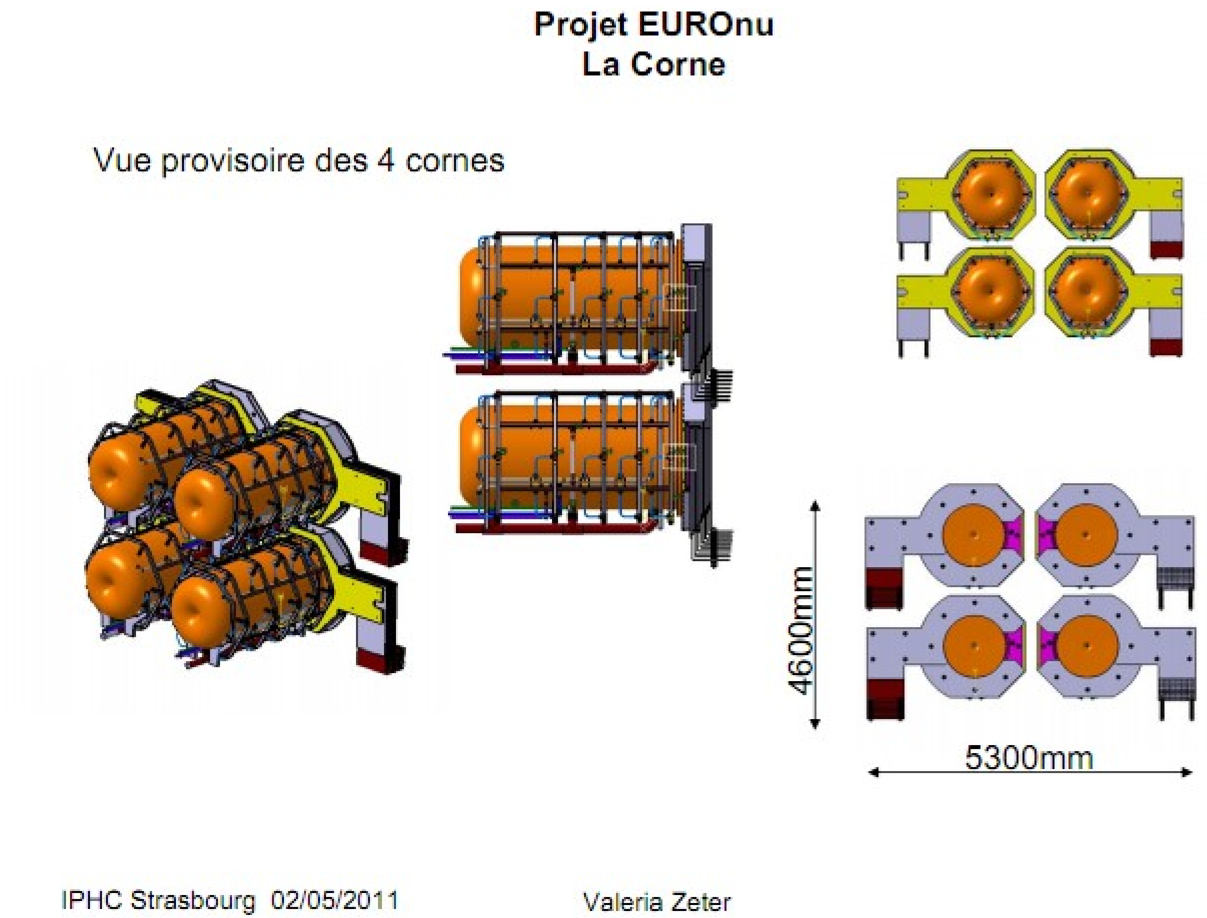


a) $t = 3$ mm, $u_{max} = 22$ mm 9.9mm b) $t = 3$ mm, $u_{max} = 24$ mm 10.5mm

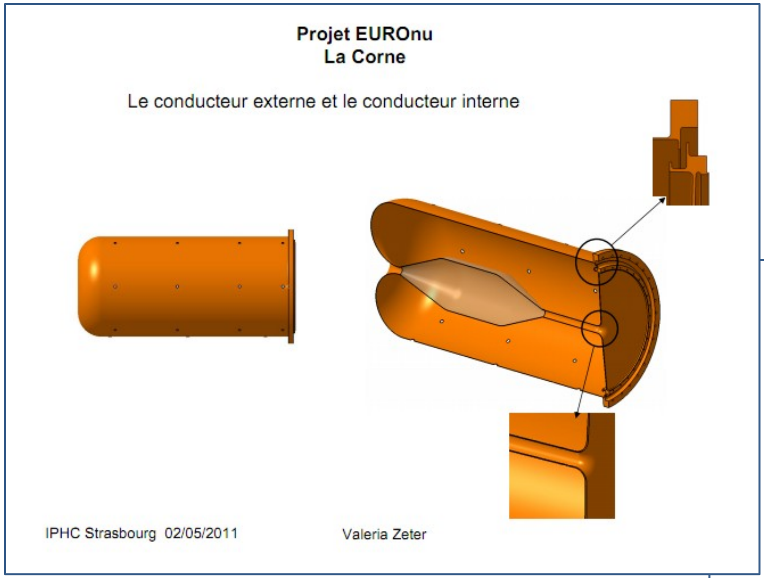
horn with integrated target: highly stress domain exists on the inner conductor and in the right angles connection domains + high energy deposition on the inner conductor

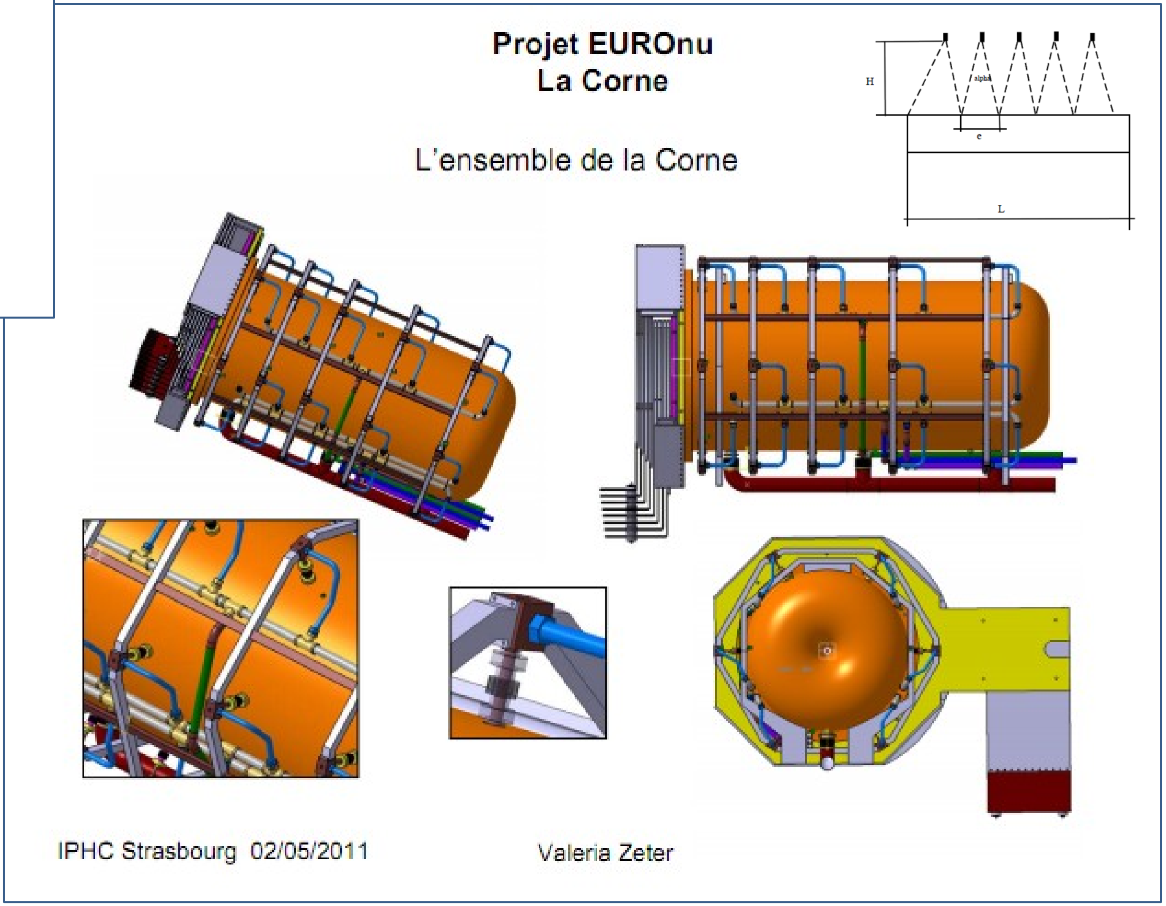
Horn with separated target and rounded back-plate, corners

baseline horn shape for EUROnu



Horn Drawings & cooling scenario

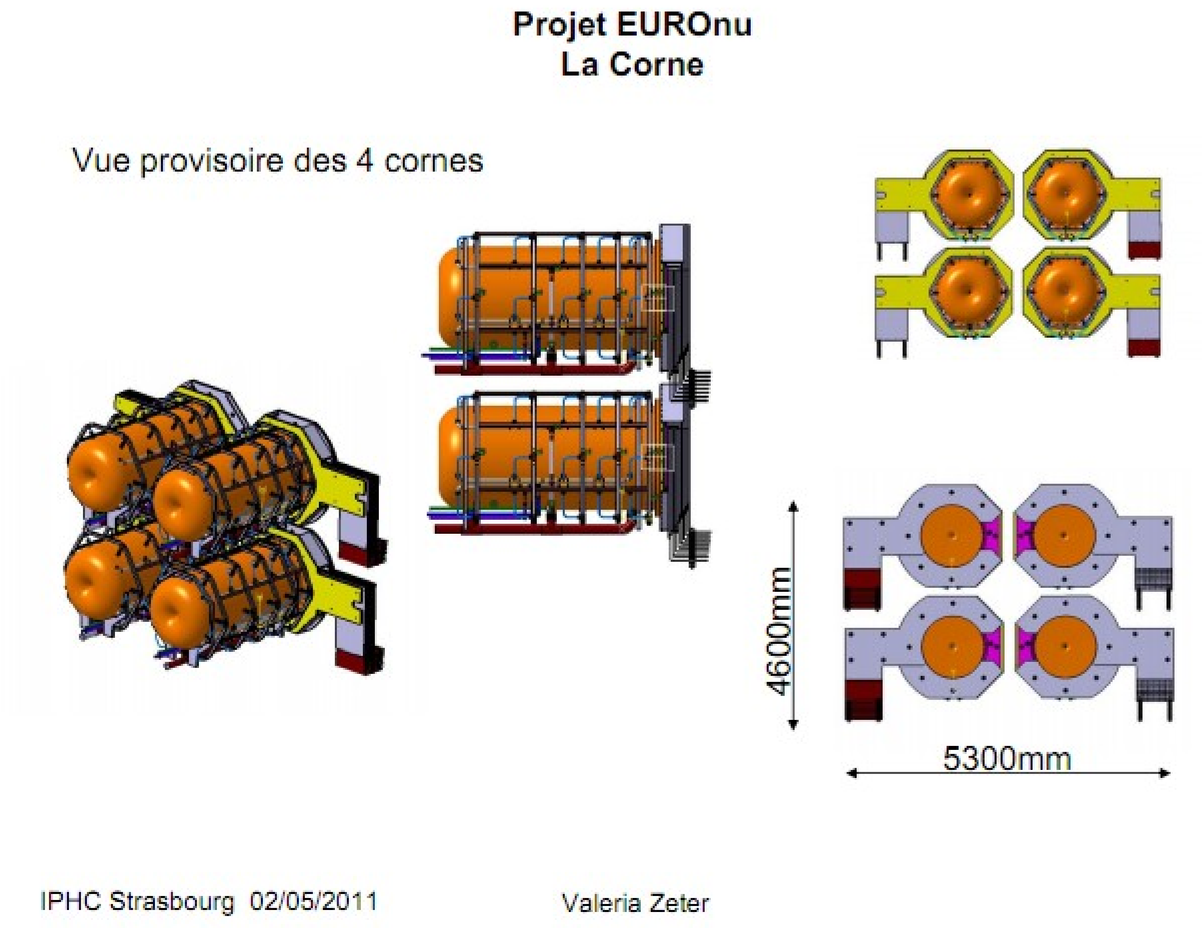




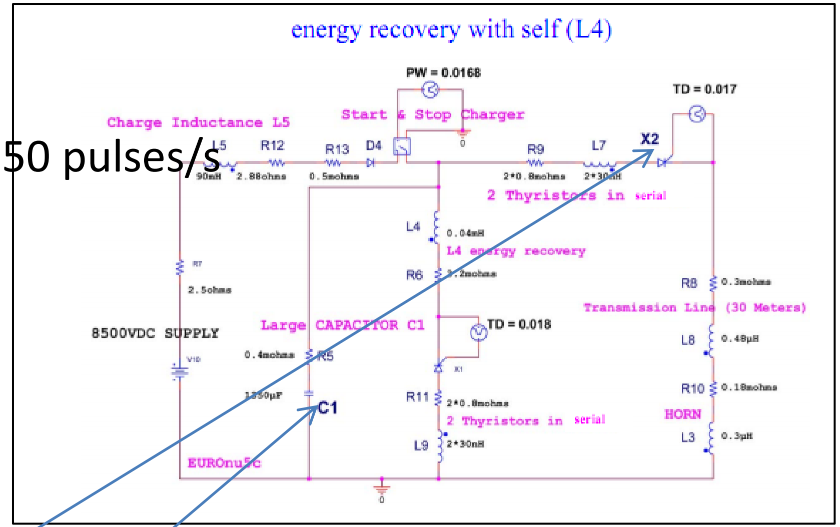
cooling (EUROnu WP2 Note 10-06)

- power distribution due to Joule losses & secondary particles
- energy balance, to maintain working temperature
- flow rate
- jet distribution along the outer conductor
- h correlation for jets' geometry

4-Horn System Drawings with strip Lines



Horn: Power Supply Studies



Requirements: 350kA, ½ sinusoid, 100μs length, 50 pulses/s

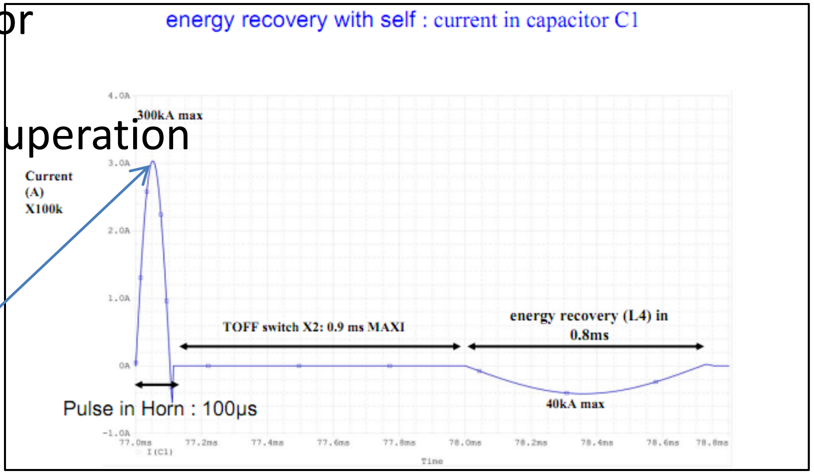
- ➢ critical lifetime 13x10^{9} pulses, 200d
- ➢ modularity

Studied two solutions:

- ➢ Energy recovery with a self (L4): good energy recuperation 60% but needs to further investigate the large constraints on the switch X2 and capacitor
- ➢ Energy recovery with diode and resistor: less constraints on the capacitor but less energy recuperation

needs to estimate the cost for both cases

horn focusing plateau

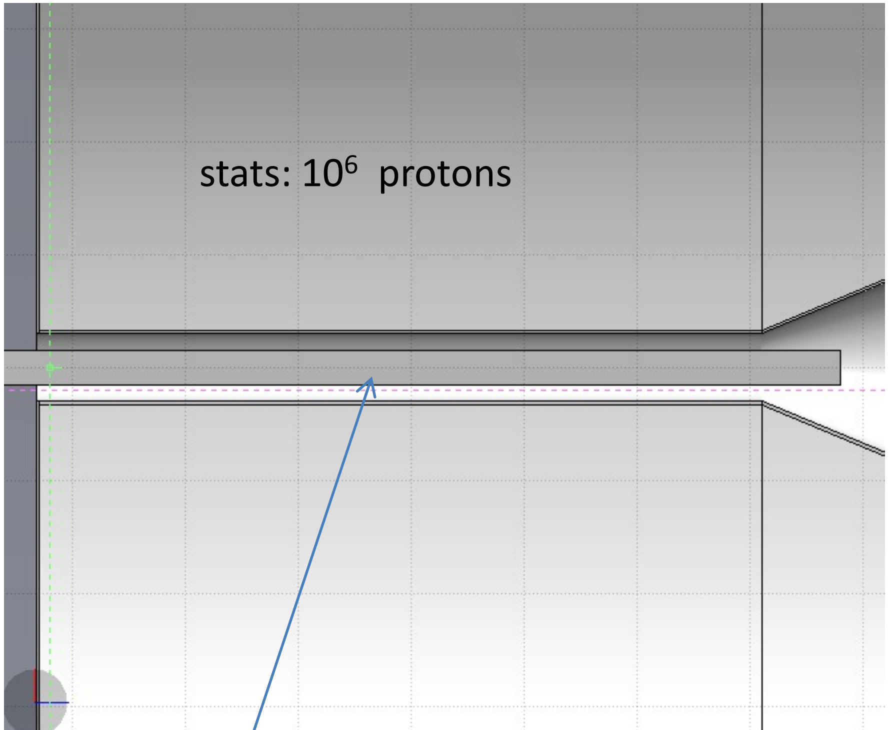


Radiation Studies

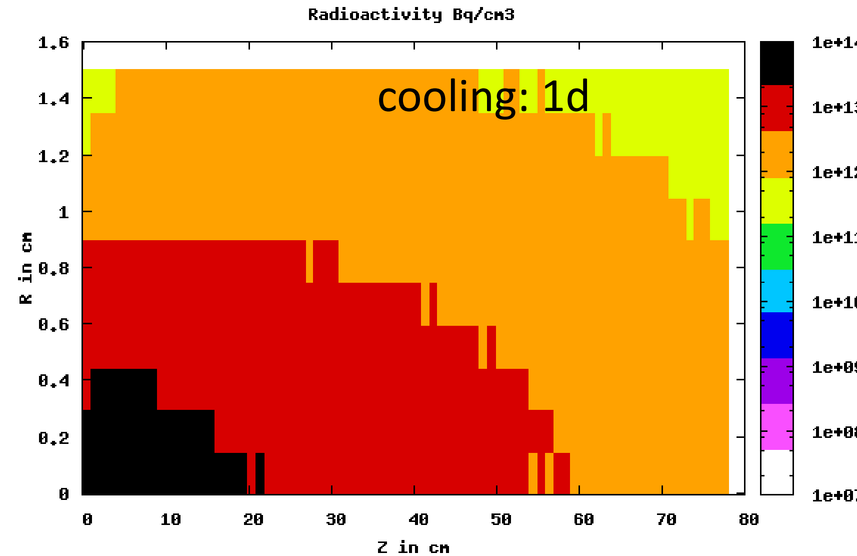
for a given part of the SB layout e.g. target, horn, cable, tunnel ...

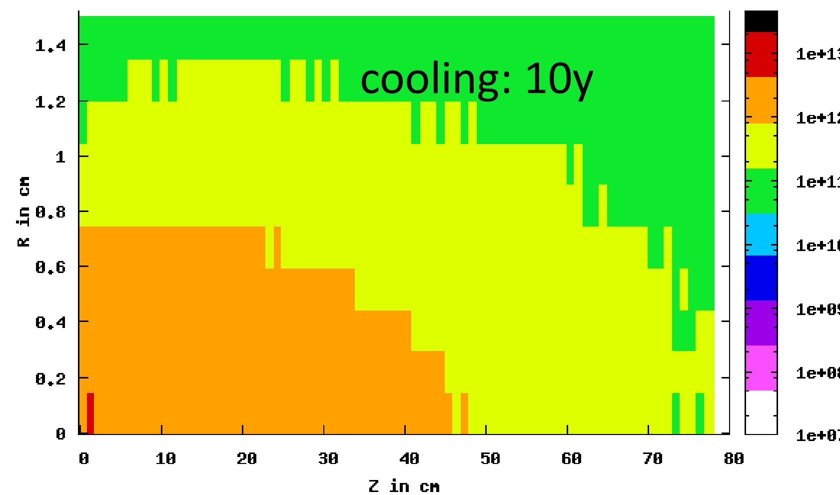
- specify the level radioactivity and its synthesis after irradiation of 200days and different cooling times ...
- calculate effective doses at the different distances from the radiated material
- benchmark the results with CNGS studies:
  - CNGS http://proj-cngs.web.cern.ch/proj-cngs/
- Safety

Ti packed target's radioactivity, 4MW : irradiation=200days, cooling times= 1d, 10y

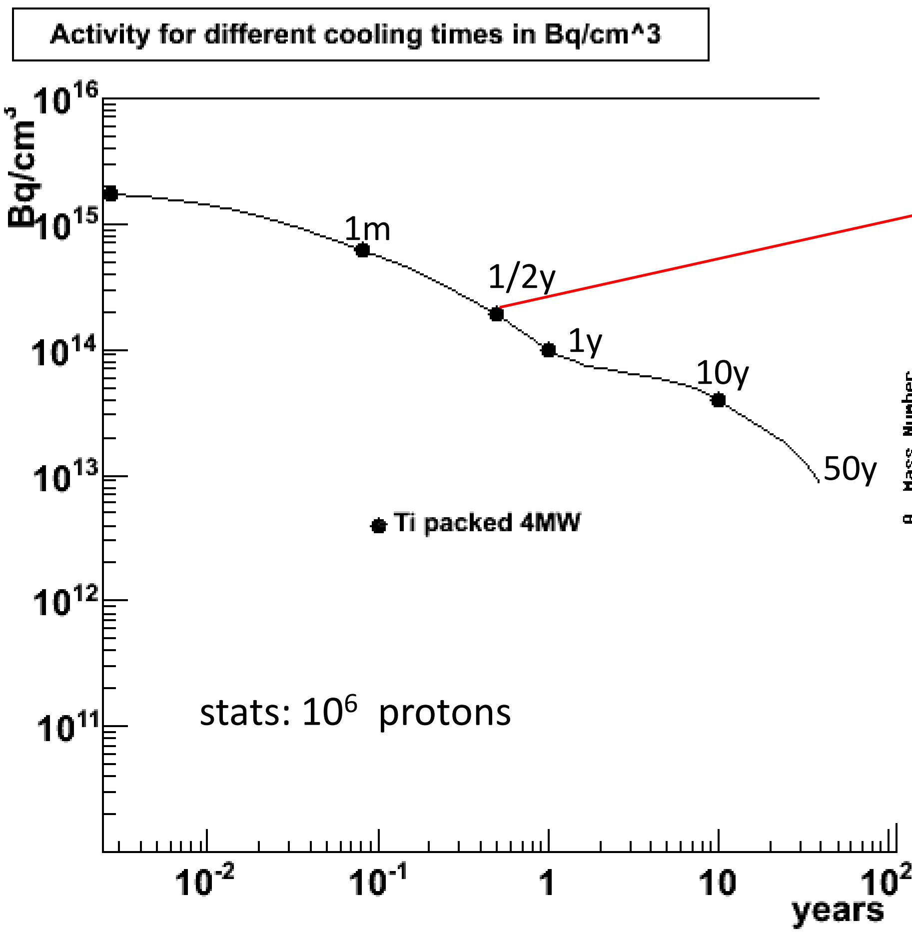


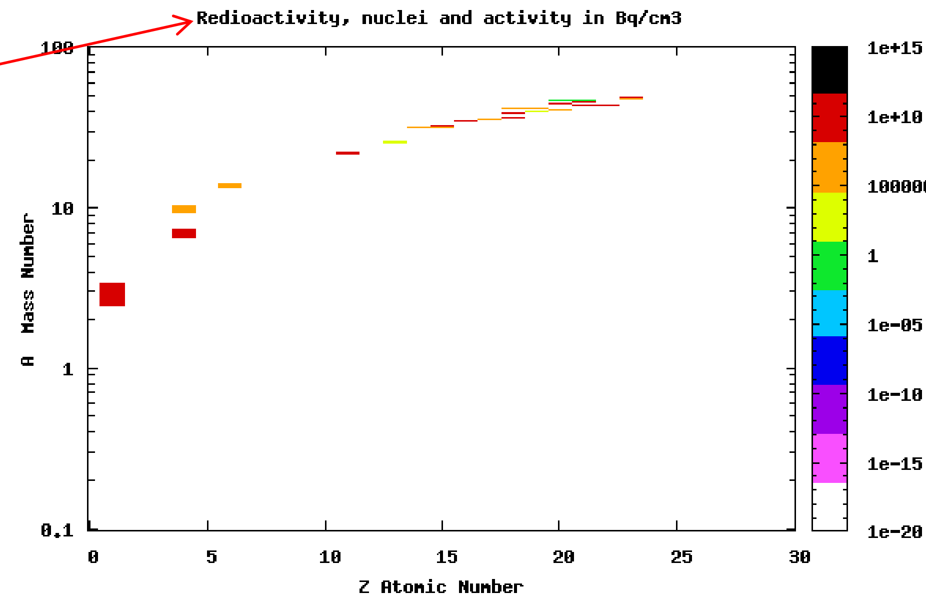
target activity in Bq	
1d	10y
1.7E15	3.9E13





Ti packed target's radioactivity, 4MW : irradiation=200days cooling times= 1d, 1m, 1/2y, 1y, 10y, 50y, 100y





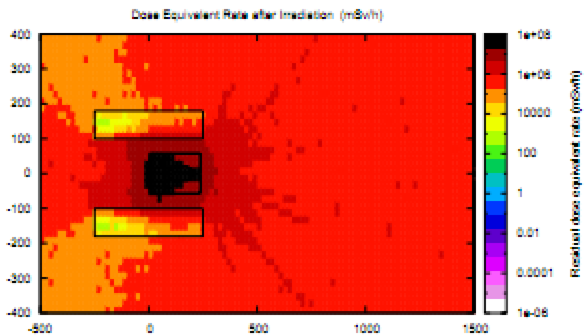
from those calculations:

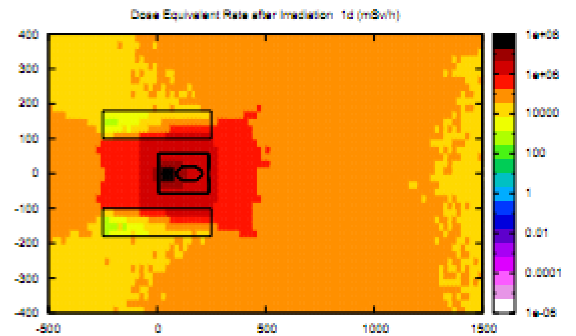
- dose rates for different locations and cooling times to define accessibility time-table

work ongoing

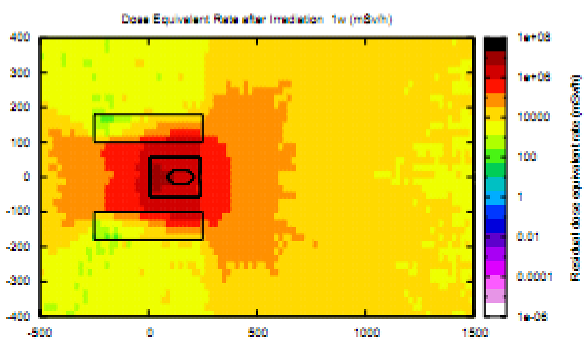
Towards the benchmarking:

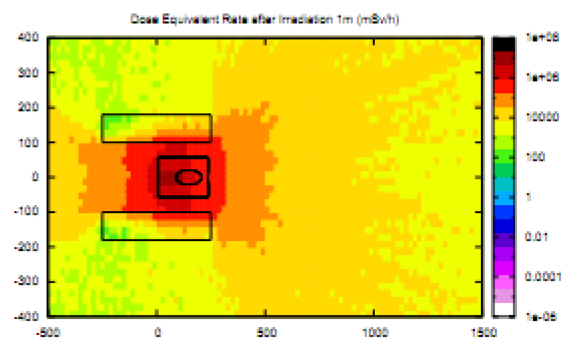
Dose Equivalent Rate with Iron Shielding





effective dose rates in mS/h for different cooling times



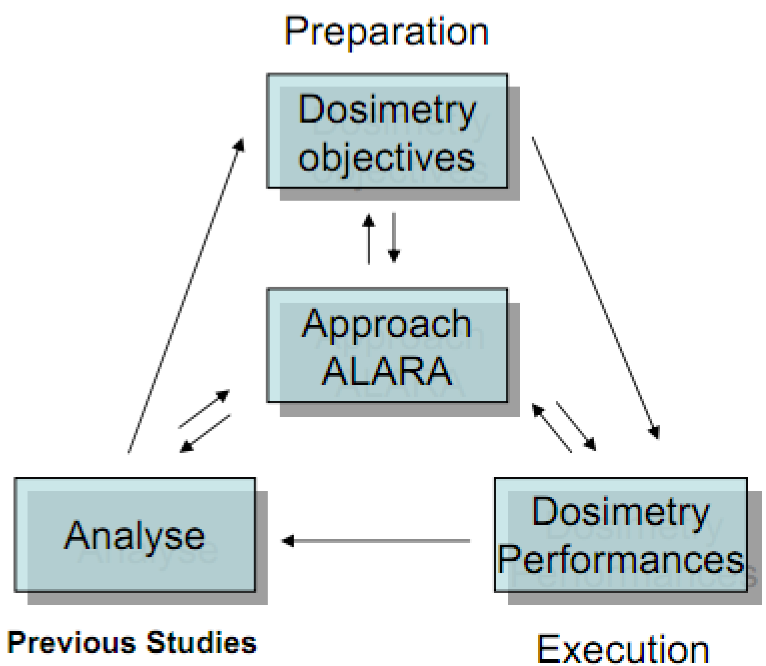


Safety : Toward a Safety Roadmap

- **ALARA approach :**

⇒ **Anticipate and reduce individual and collective exposition to radiation**

- **Iterative processes :**
  - Préparation
    - Building Structure lists of materials
    - Dose Equivalent Rate Estimation
    - Optimize procedure during operation and maintenance phases
    - Evaluate residual activity of wastes ….
  - Execution
  - Safety Analyse from previous facilities (WANF, CNGS, NuMi, J-PARC…)

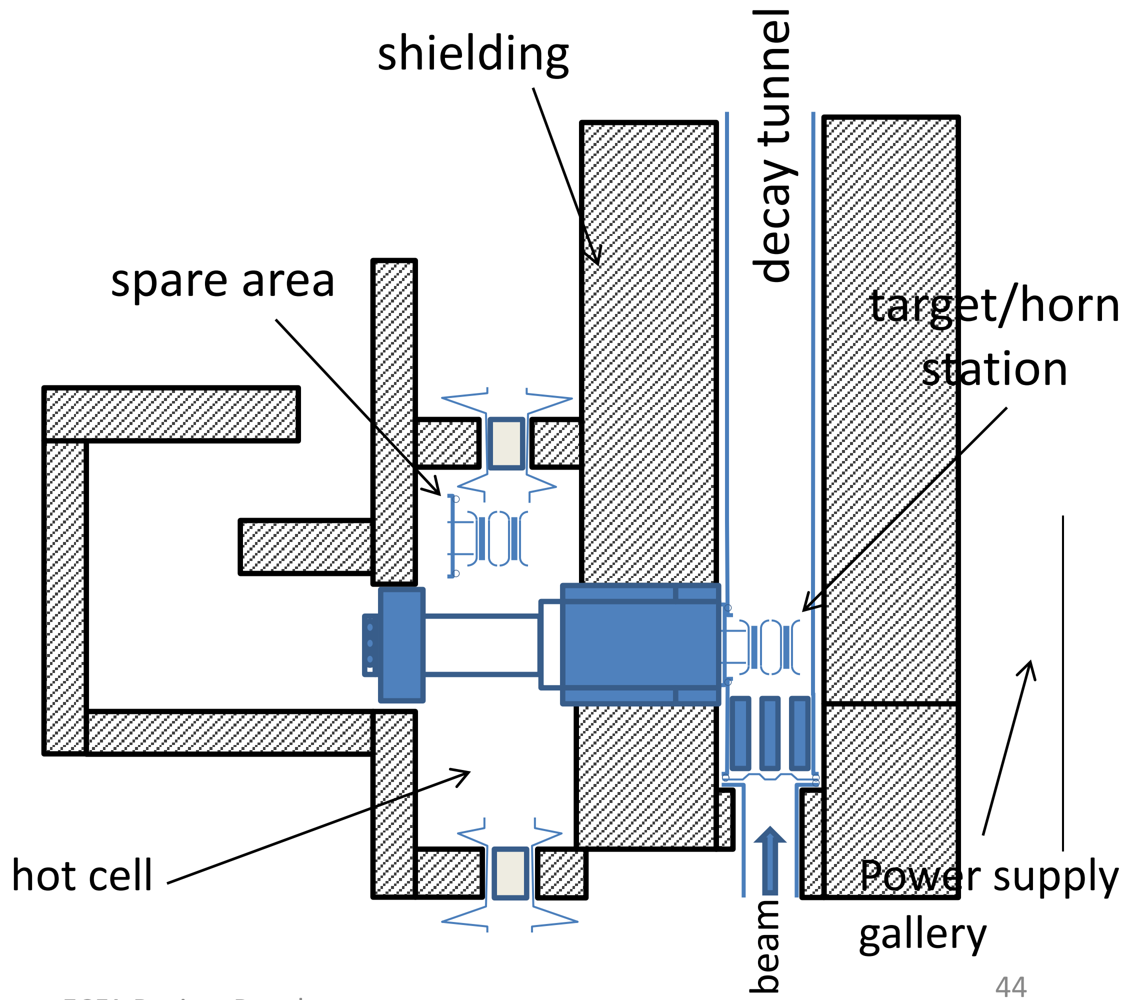


As Low As Reasonably Achievable

for Experimental Hall (Target/Horns, DT, Beam Dump), Safety Gallery, Maintenance Room, Waste Area

Safety II

- Proton driver
  - to be done by CERN
  - beam lines by WP2
- Target/horn station
  - Shielding around
  - Air recycling
  - Cooling system
  - Tritium production
  - Lifetime
    - target
    - horn (+pulser)
- Decay tunnel
  - Shielding
  - Cooling
- System repairing/exchange
- Retreatment



Conclusions

- Horn with separated target baseline as result of dynamic and static stress analyses

- 4-horn system to reduce the 4MW power effects

- Horn shape defined as miniboone-like due to best physics results and reliability issues

- Horn cooling/power supply studies ongoing

- Packed-bed Target is preferable in multi-Watt beam environment due to minimum stresses and high heat rate removal due to transverse cooling among others

- Safety Studies ongoing for the design of the layout and radiation

Thanks