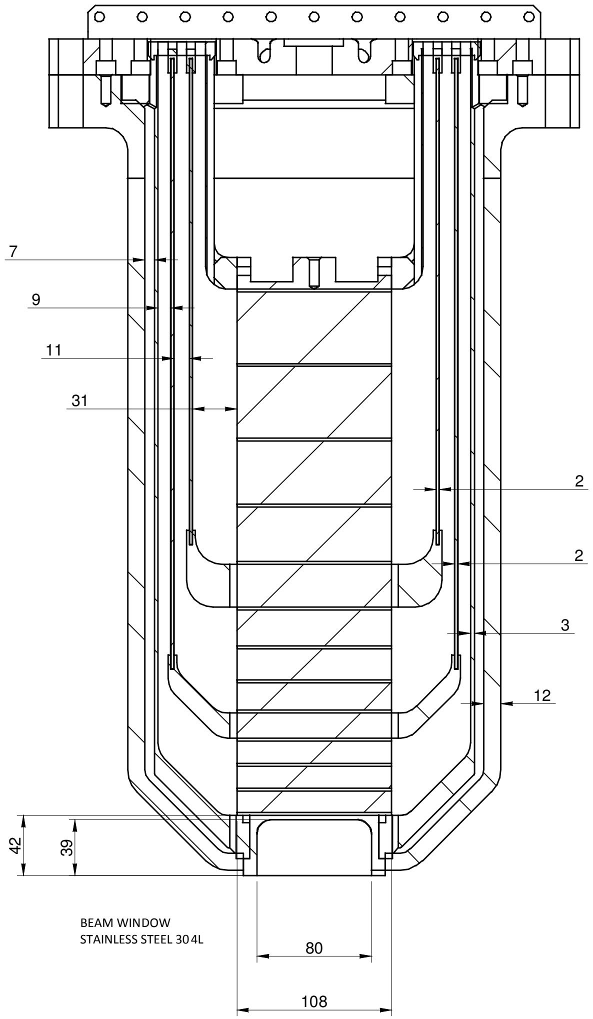
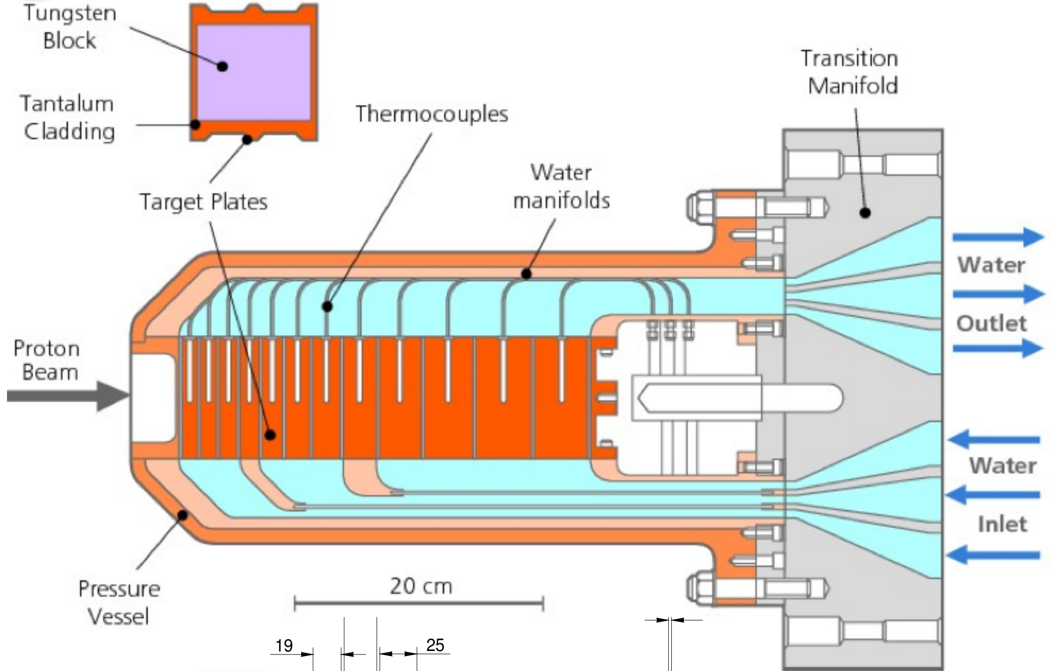
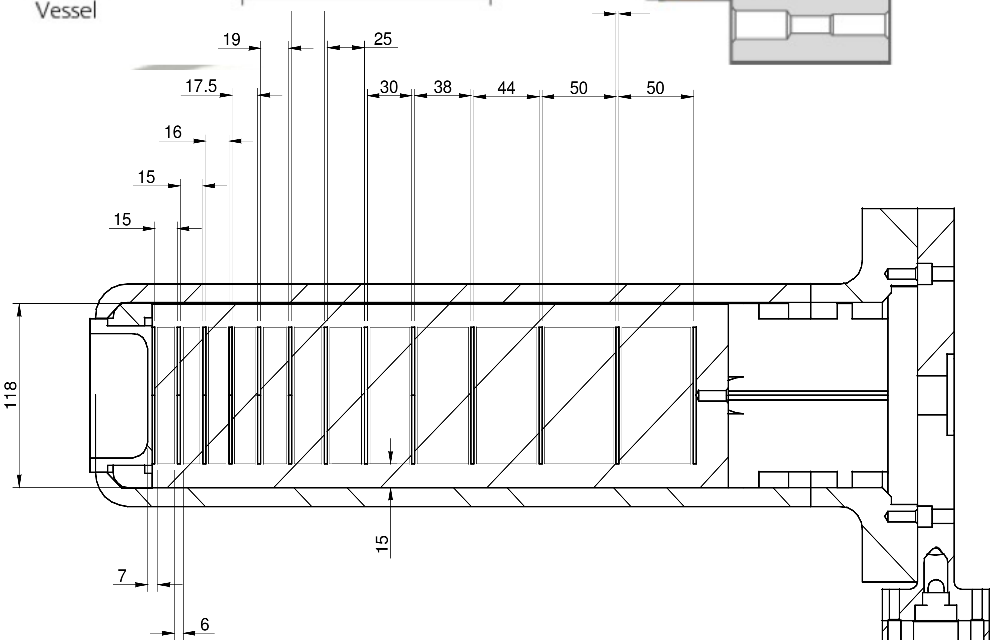
ISIS-TS1 simulations and power upgrade plans and ESS activation studies

Cristian Bungau
University of Huddersfield

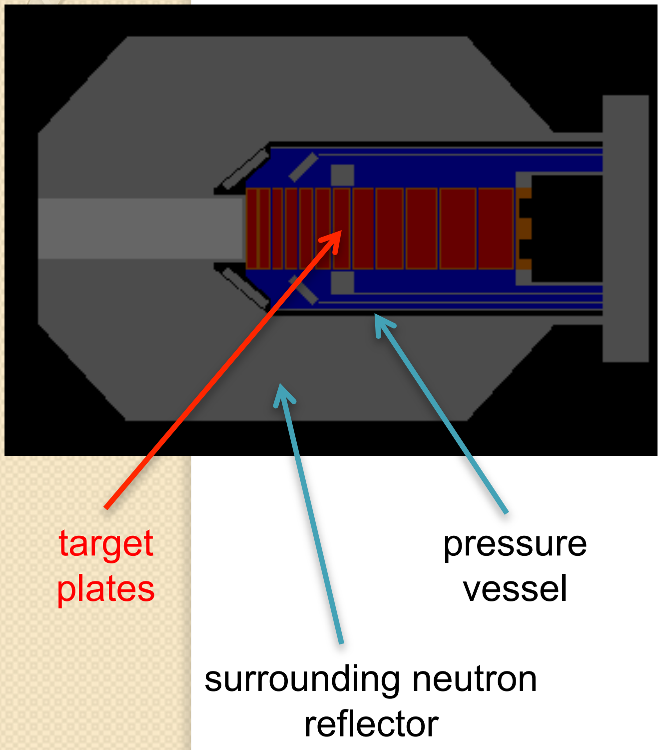
ISIS TS1 target

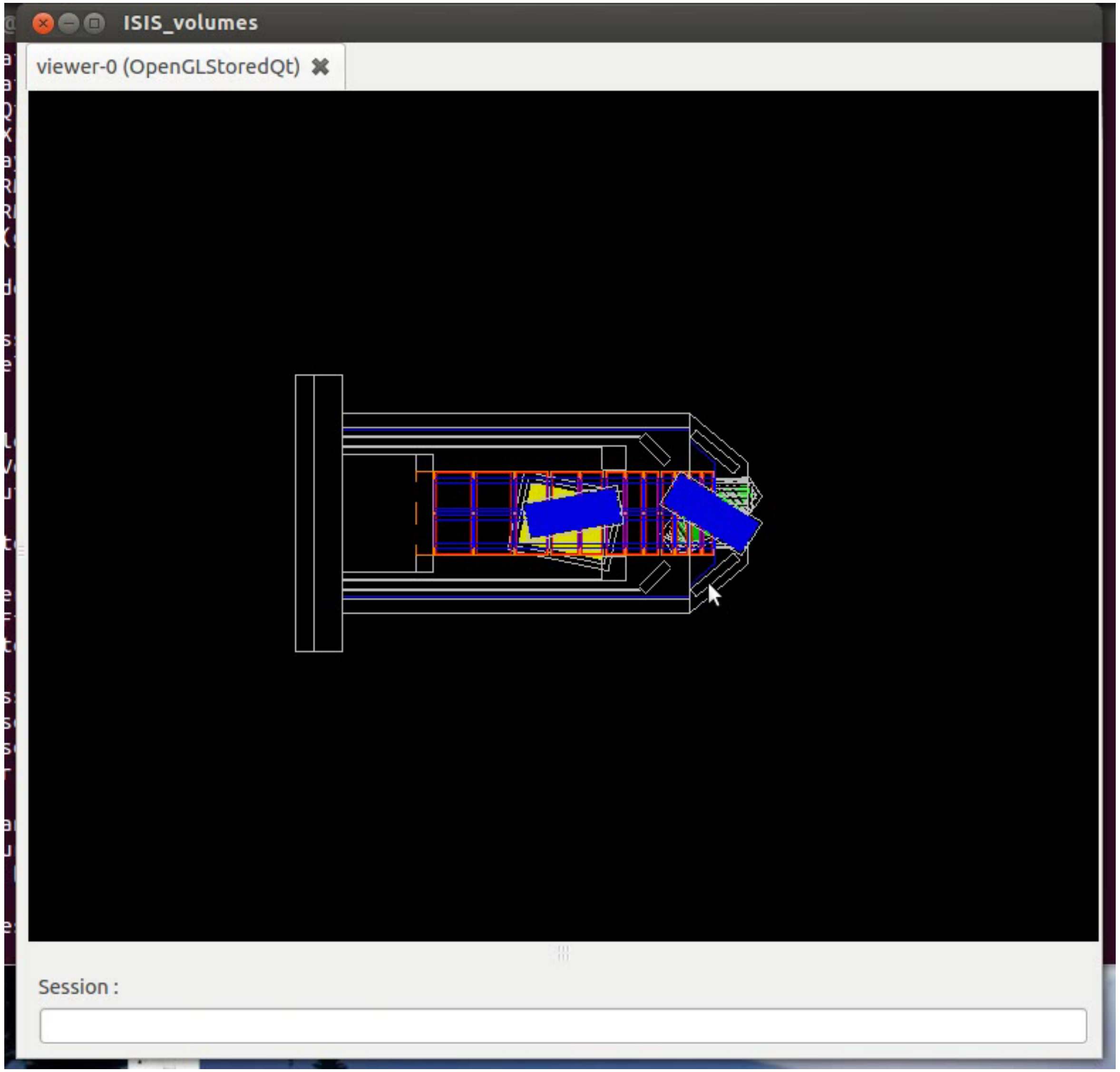




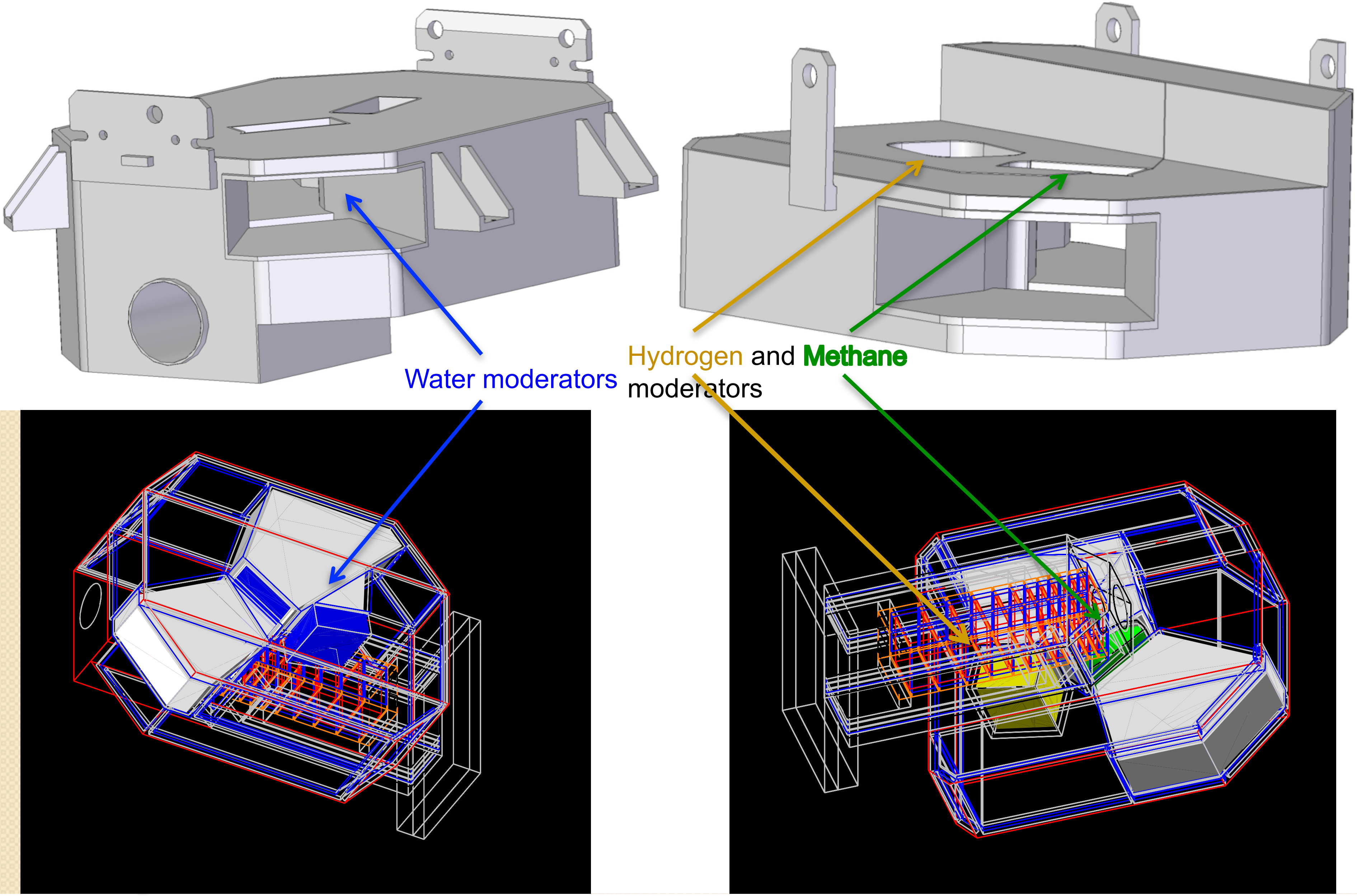


Implementing the TS1 target geometry into GEANT4

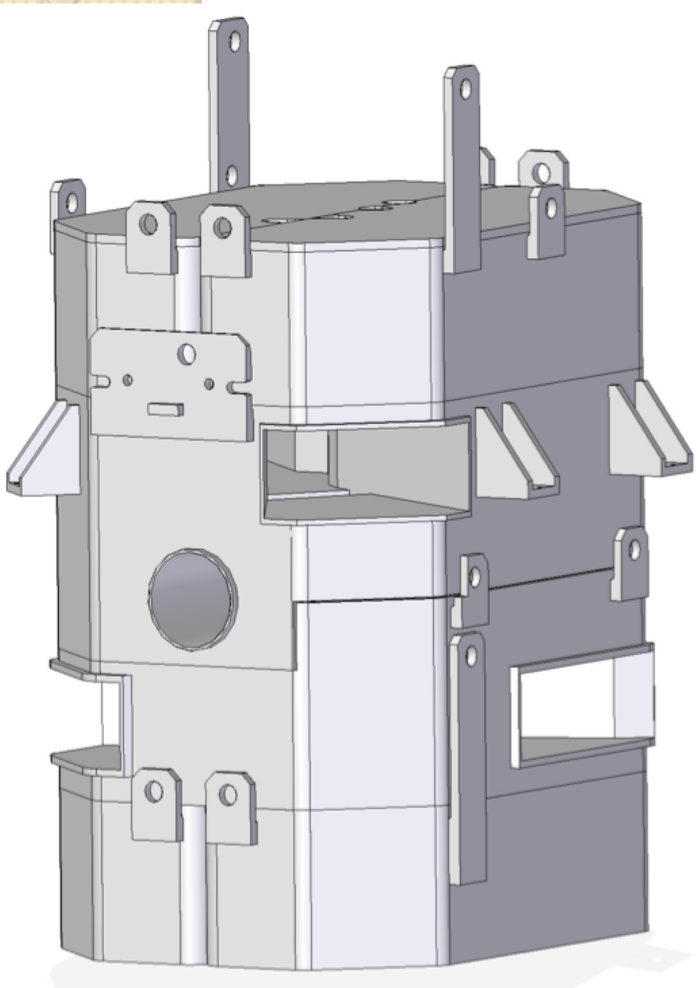


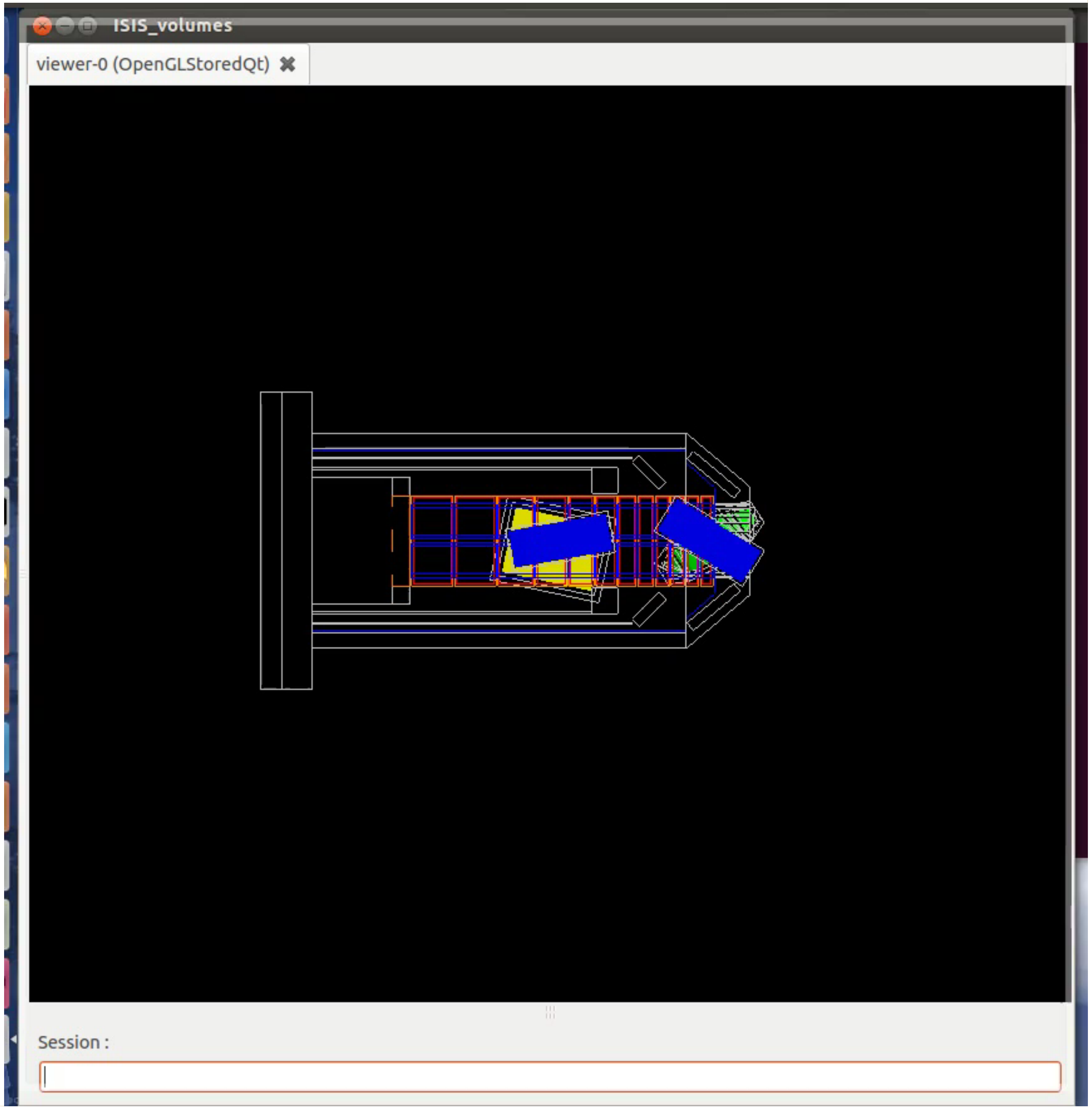


The Neutron Moderators



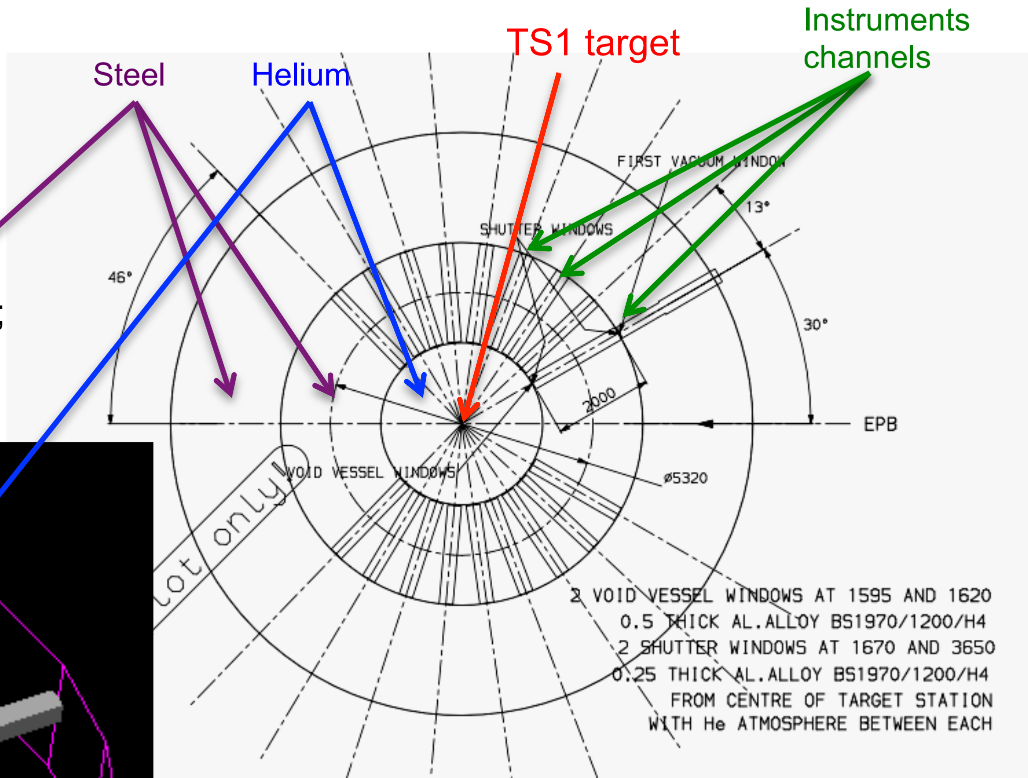
The Neutron Reflector

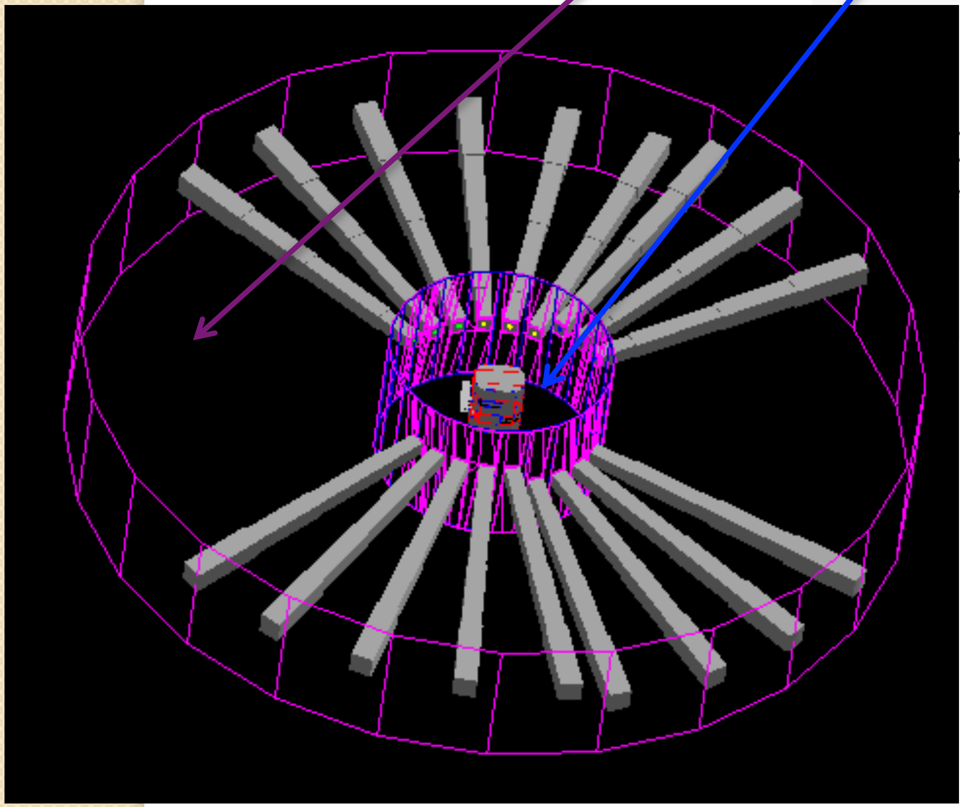




Neutron Shielding and Beamlines to the Instruments

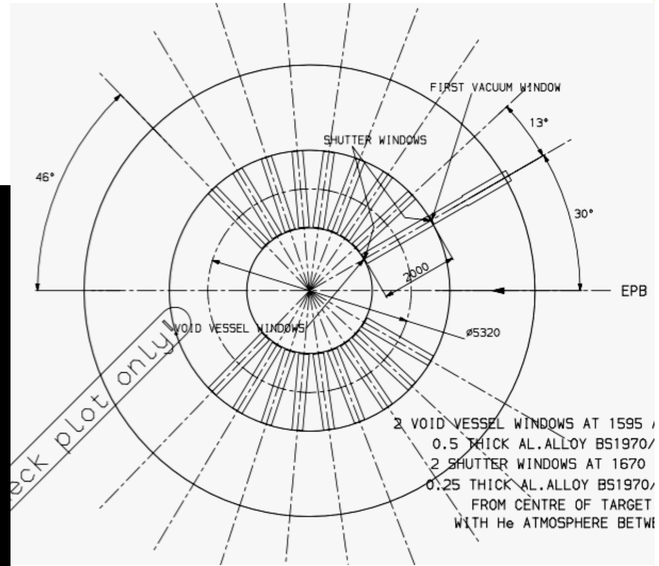
-18 neutron beamlines implemented at various angles;
- vertical offsets allowing different beamlines to point to different moderators;
- the space between the instruments channels was filled with steel shielding;



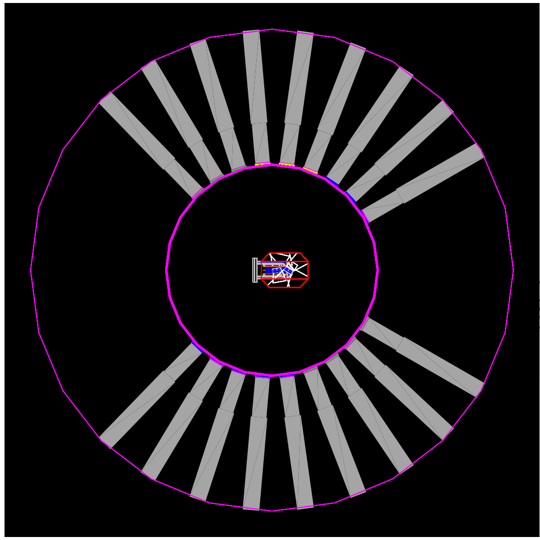


Issues encountered…

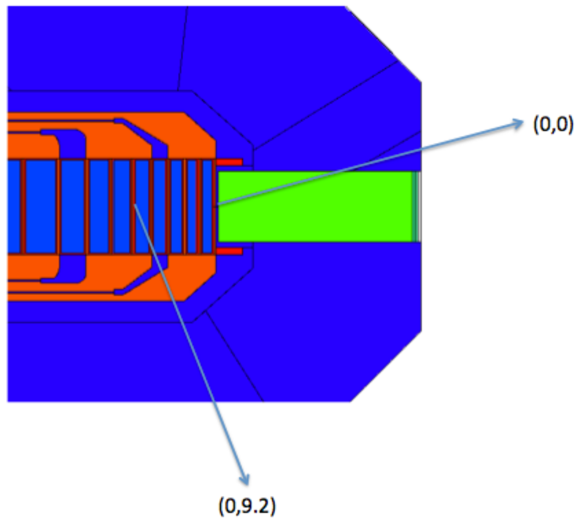
- As in the engineering drawing, I pointed the neutron beamlines to the (0,0) point;



- Then I checked by how much to shift the reflector in order to have the beamlines see the corresponding moderators;



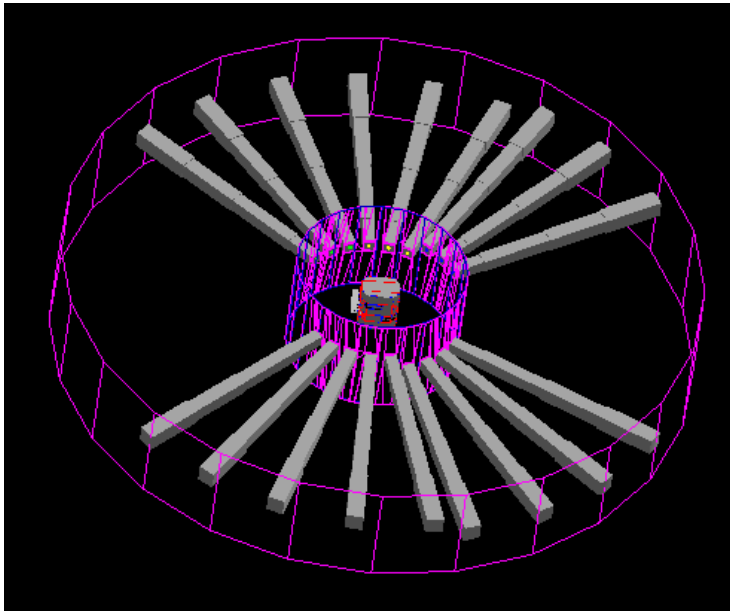
- I asked Ali to check this for me by looking into the ISIS MCNPX model which contained the neutron instruments' channels;
- Reflector position adjusted – beamlines started to "see" the moderators, but only parts…



This is the centre of the shielding cylinders
i.e where the beamlines are pointing

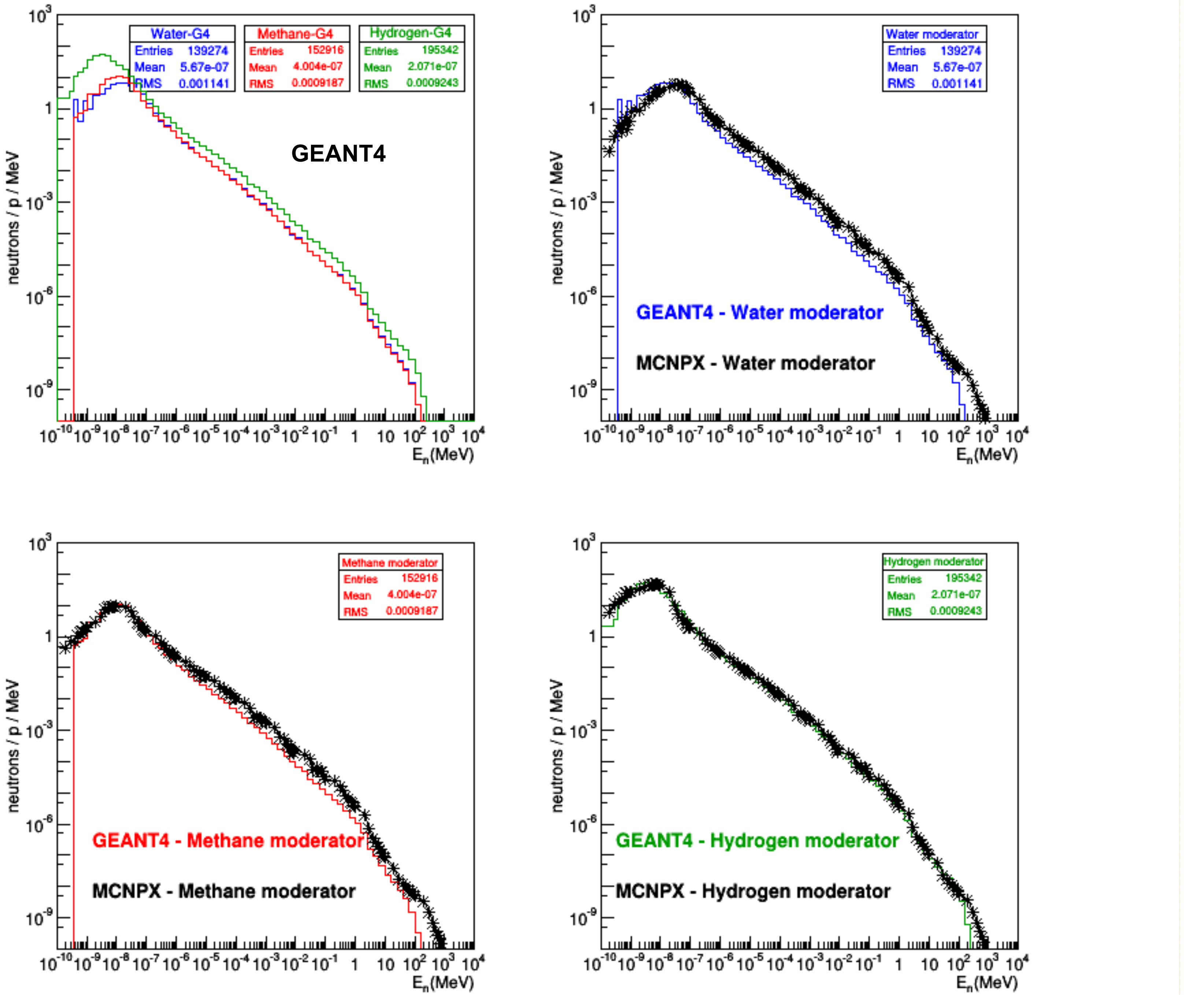
Issues encountered (continued)

- Solution: each instrument beamline channel should have a different angle in order to fully face the moderators, so the beamlines should no longer be focused in the same point in horizontal plane;
- Small (different) rotations applied to each beamline:
  - Each beamline faced its corresponding moderator;
  - But several volumes overlaps;
  - Add additional logical volume operations (such as intersection) to avoid the overlaps;



- Finally … all the beamlines in place, having correct angles in order to face the moderators, and no overlapping volumes whatsoever.

Comparison between the GEANT4 code prediction and the MCNPX code predictions for neutron spectra for each moderator type


Water-G4
Entries 139274
Mean 5.67e-07
RMS 0.001141
Methane-G4
Entries 152916
Mean 4.004e-07
RMS 0.0009187
Hydrogen-G4
Entries 195342
Mean 2.071e-07
RMS 0.0009243
GEANT4
neutrons / p / MeV
E_n(MeV)
Water moderator
Entries 139274
Mean 5.67e-07
RMS 0.001141
GEANT4 - Water moderator
MCNPX - Water moderator
Methane moderator
Entries 152916
Mean 4.004e-07
RMS 0.0009187
GEANT4 - Methane moderator
MCNPX - Methane moderator
Hydrogen moderator
Entries 195342
Mean 2.071e-07
RMS 0.0009243
GEANT4 - Hydrogen moderator
MCNPX - Hydrogen moderator

Future plans for TS1 power upgrade studies

- Increase the proton beam current to increase the power to 1 MW and beyond;
- As a figure of merit use the flux of useful neutrons reaching the instruments;
- Monitor the increase in heat deposition and reduce the target plates thickness as needed;
- Determine at what point during the power increase the target has to be changed to a liquid target;
- Consider also a rotating solid target and continue to monitor the temperature rise;
- At every step, consider the neutron pulse width, which should be kept at the present value;

Timescale

- Monitor the increase in heat deposition and reduce the target plates thickness as needed;
- For each new power on target configuration run an optimization study of moderators + reflector configuration;
- Determine at what point during the power increase the target has to be changed to a liquid target;

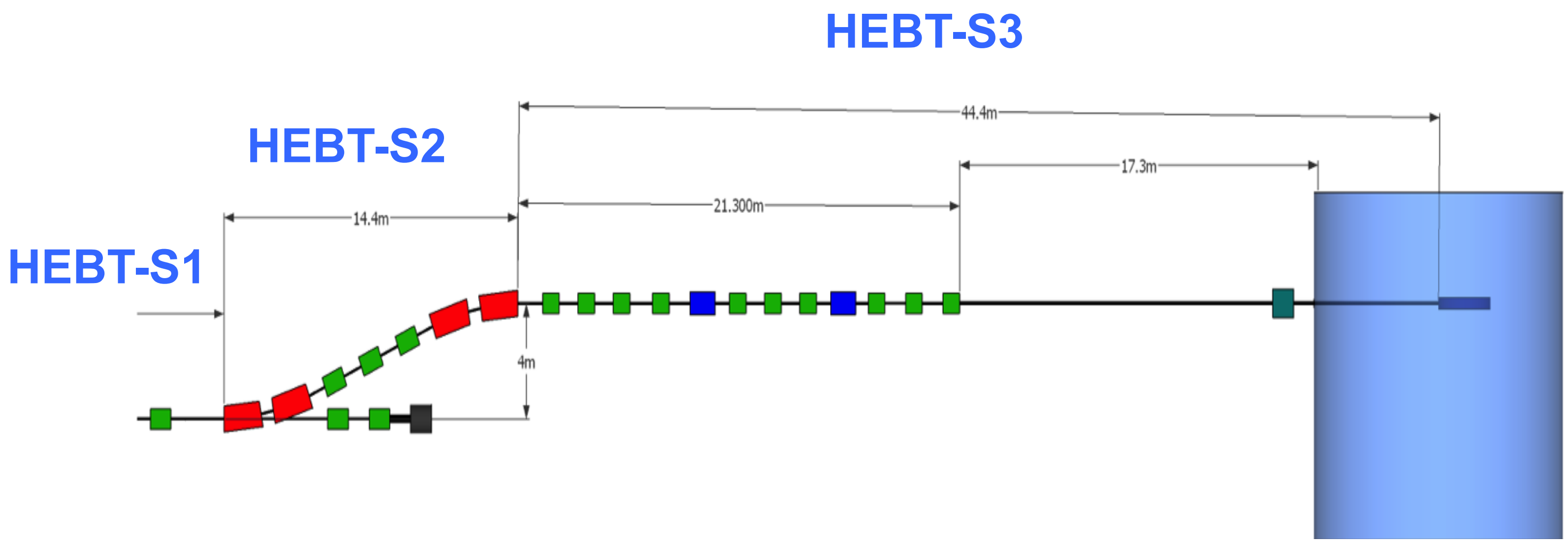
➢ 0.5 MW – 5 MW in 10 steps
➢ Approx 4 weeks / new optimization study (!!) ~ 40 weeks starting Jan'14

- Consider also a rotating solid target;
- For each new power on target configuration run an optimization study of moderators + reflector configuration;

➢ 1.5 MW (?) – 4.5 MW in 4 steps
➢ Approx 4 weeks / new optimization study ~ additional 16 weeks

ESS Activation Studies using GEANT4

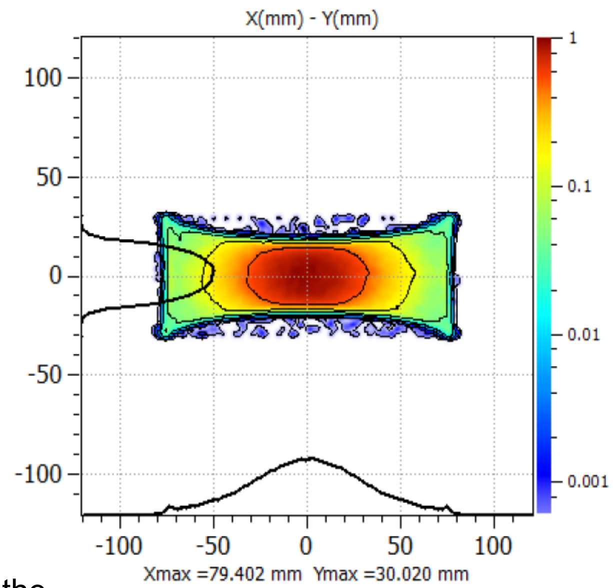
The HEBT line



HEBT-S1: 100 m long (collimation system + space for additional cryo-modules)

HEBT-S2: brings the beam from underground (1.6 m above the ground)

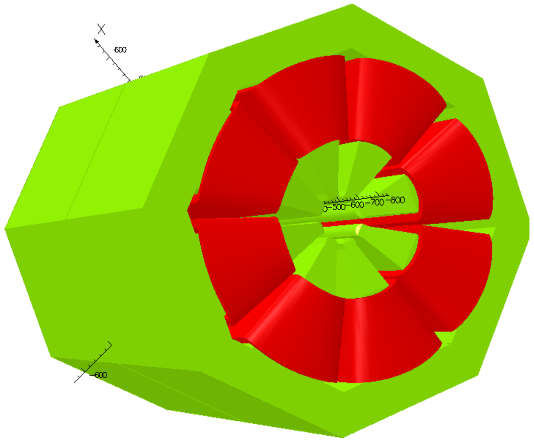
HEBT-S3: - includes the expansion system to provide the beam footprint at the target
- peak current density is minimal

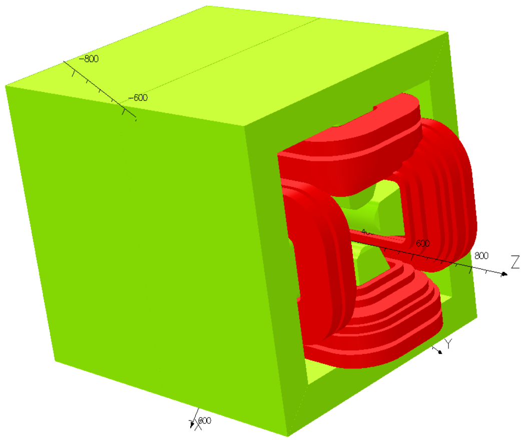


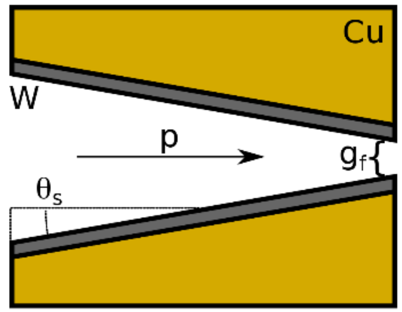
Beam profile at the target surface

The HEBT-S3 magnets and collimator

- includes a large number of magnets with associated power supplies
- both normal conducting and superconducting magnets considered







Element	Length (mm)	Aperture (mm)	Strength (T)
Dipoles	1570	40x80 (gap)	1.47
Quadrupoles	400 or 800	40 (radius)	0.48
Octupoles	800	25 (radius)	0.35

These magnets and the collimator are exposed to a high radiation level from back streaming neutrons !

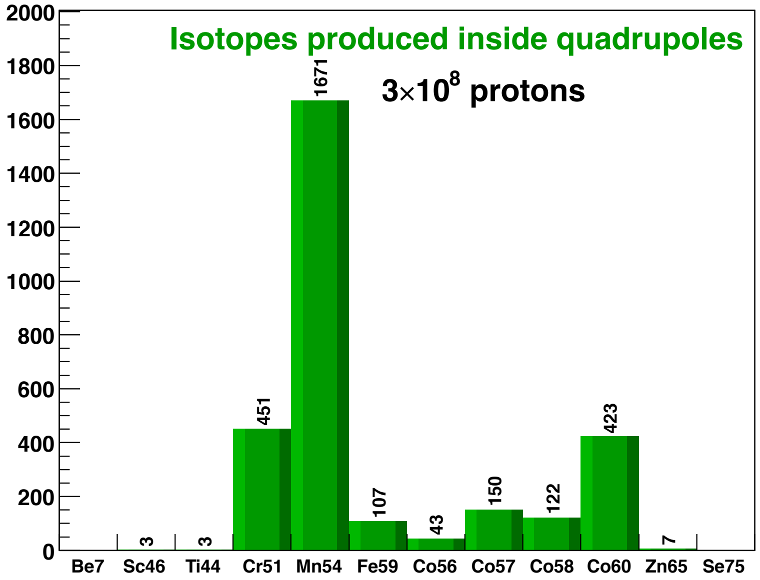
Radioactive inventory

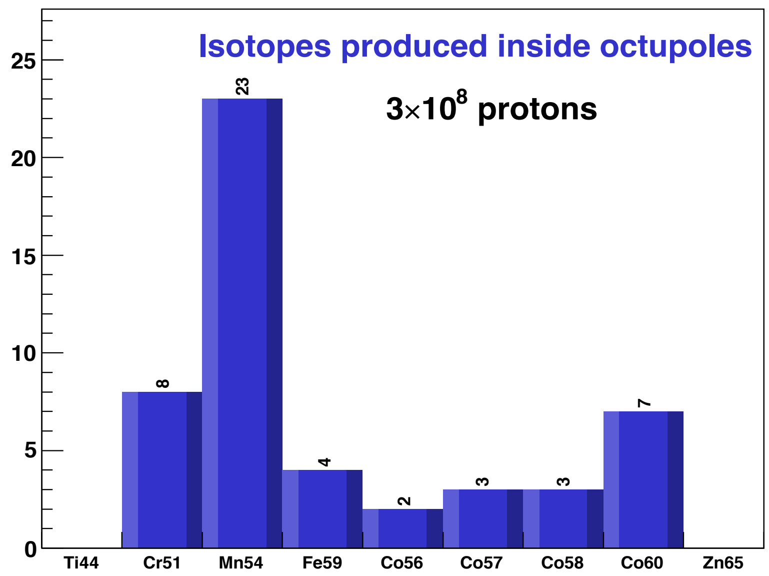
Experience with radionuclide inventory from accelerator components have shown that the gamma-emitting isotopes are dominant along with relatively short-lived beta isotopes !

^{7}Be	^{46}Sc	^{44}Ti	^{51}Cr	^{54}Mn	^{59}Fe	^{56}Co
^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{75}Se	^{84}Rb	^{85}Sr
^{88}Y	^{95}Zr	^{94}Nb	^{95}Nb	^{106}Ru	^{109}Cd	^{111}In
^{113}Sn	^{125}Sn	^{124}Sb	^{125}Sb	^{125}I	^{132}Cs	^{134}Cs
^{137}Cs	^{133}Ba	^{139}Ce	^{141}Ce	^{144}Ce	^{152}Eu	^{154}Eu
^{153}Gd	^{160}Tb	^{161}Tb	^{169}Yb	^{172}Hf	^{182}Ta	^{185}Os
^{192}Ir	^{198}Au	^{199}Au	^{203}Hg	^{210}Pb	^{207}Bi	^{228}Th
^{239}Np	^{241}Am	^{243}Am	^{170}Tm			

Isotopes produced inside the magnets

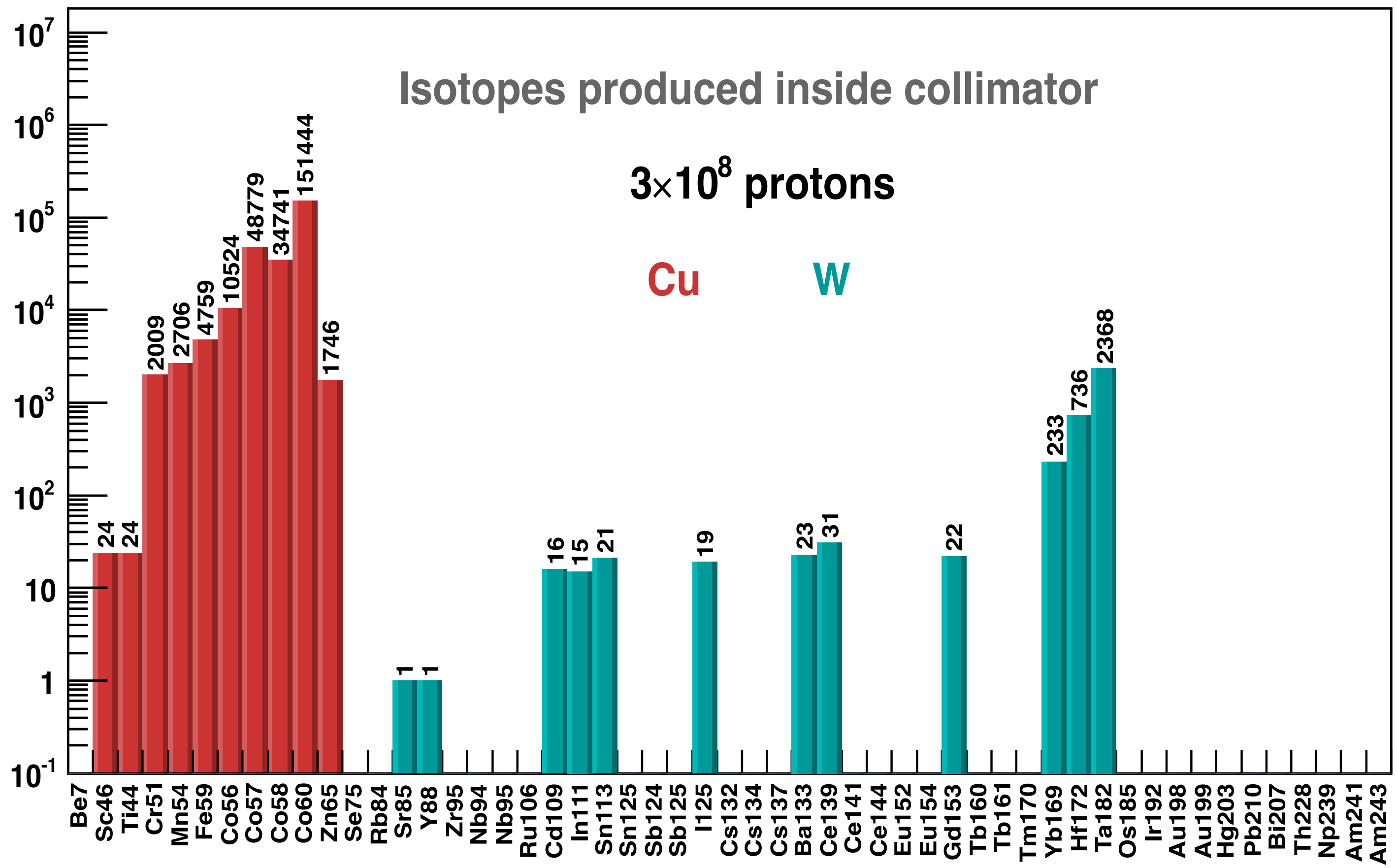
- isotope yield was calculated for each magnet separately
- plots show the total amount of each isotope in all quadrupoles and octupoles
- results are for $3x10^8$ POT
- ^{51}Cr, ^{54}Mn, ^{59}Fe and ^{60}Co are predominant in the magnets





Isotopes produced inside the collimator

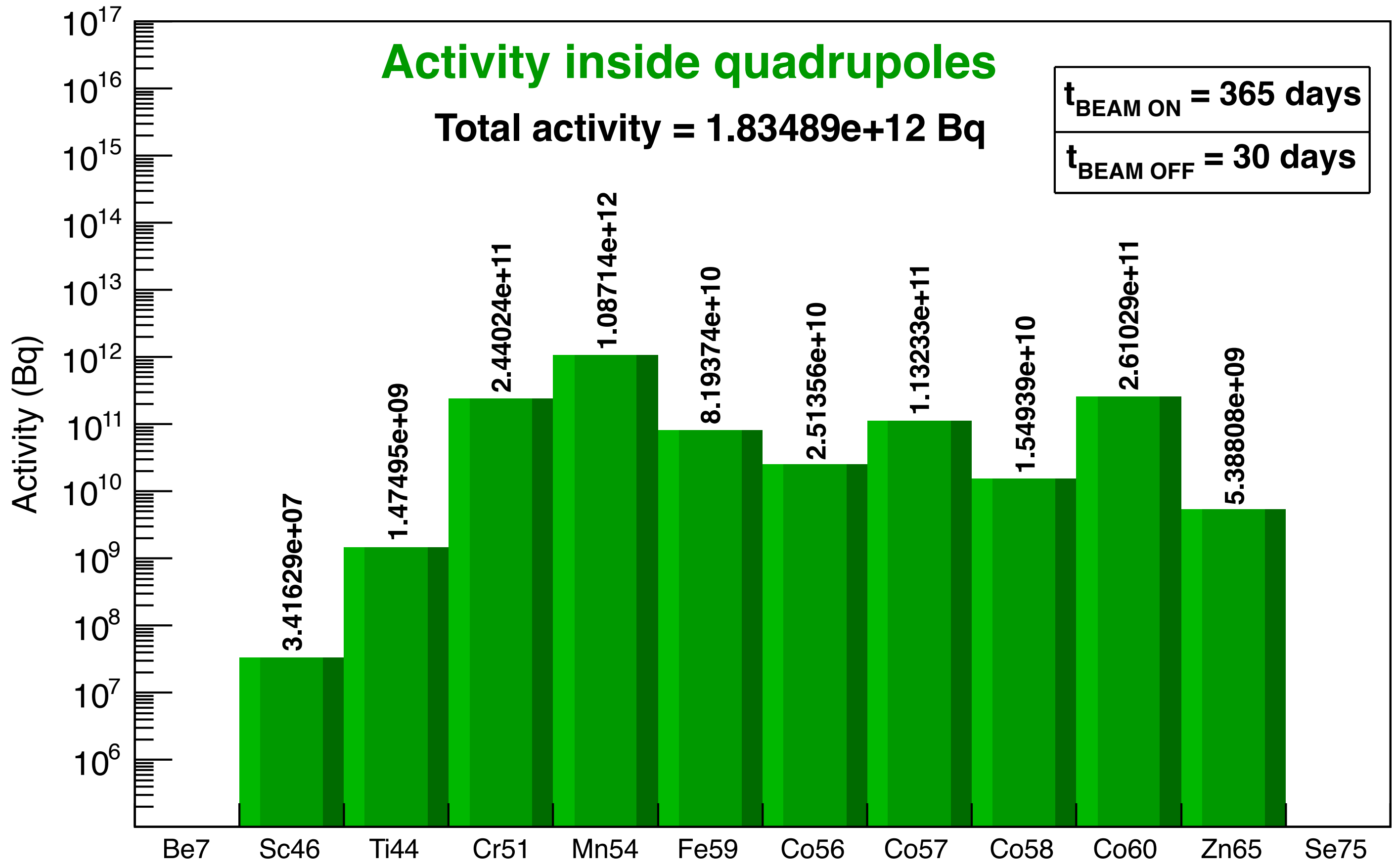
- high isotope rates found in the Cu parts: ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{65}Zn
- isotopes found in the tungsten coating: ^{169}Yb, ^{172}Hf, ^{182}Ta



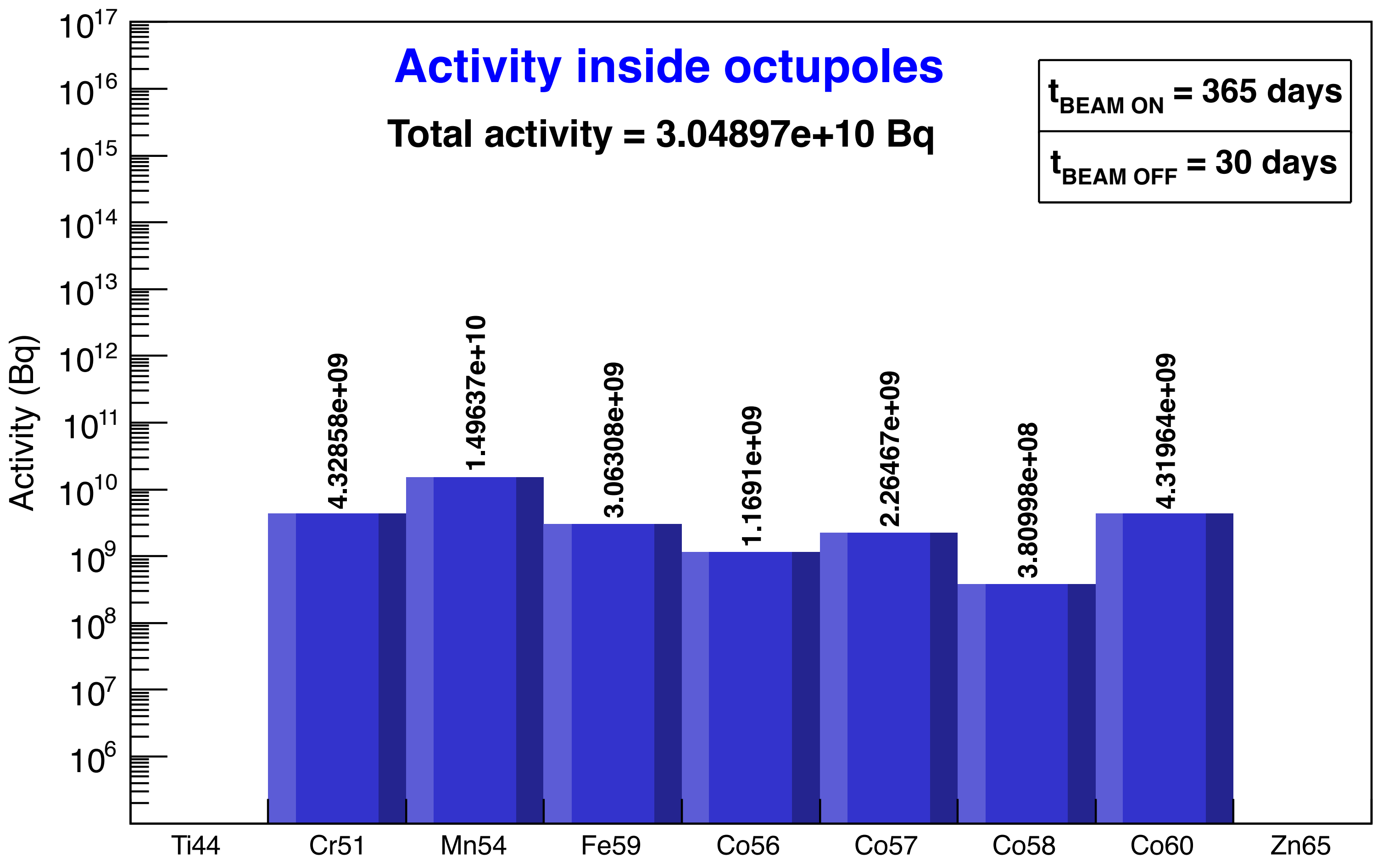
Half life of isotopes produced in the Cu parts of magnets and the collimator

Isotope	Half life	Decay mode	fSv h^{-1} Bq^{-1}
^{46}Sc	84 d	β^-	283
^{44}Ti	63 y	EC	-
^{51}Cr	28 d	EC	4.3
^{54}Mn	312 d	EC, β^+	114
^{59}Fe	44 d	β^-	147
^{56}Co	77 d	β^+	350
^{57}Co	272 d	EC	17.5
^{58}Co	70 d	β^+	131
^{60}Co	5.3 y	β^-	340
^{65}Zn	245 d	EC, β^+	76

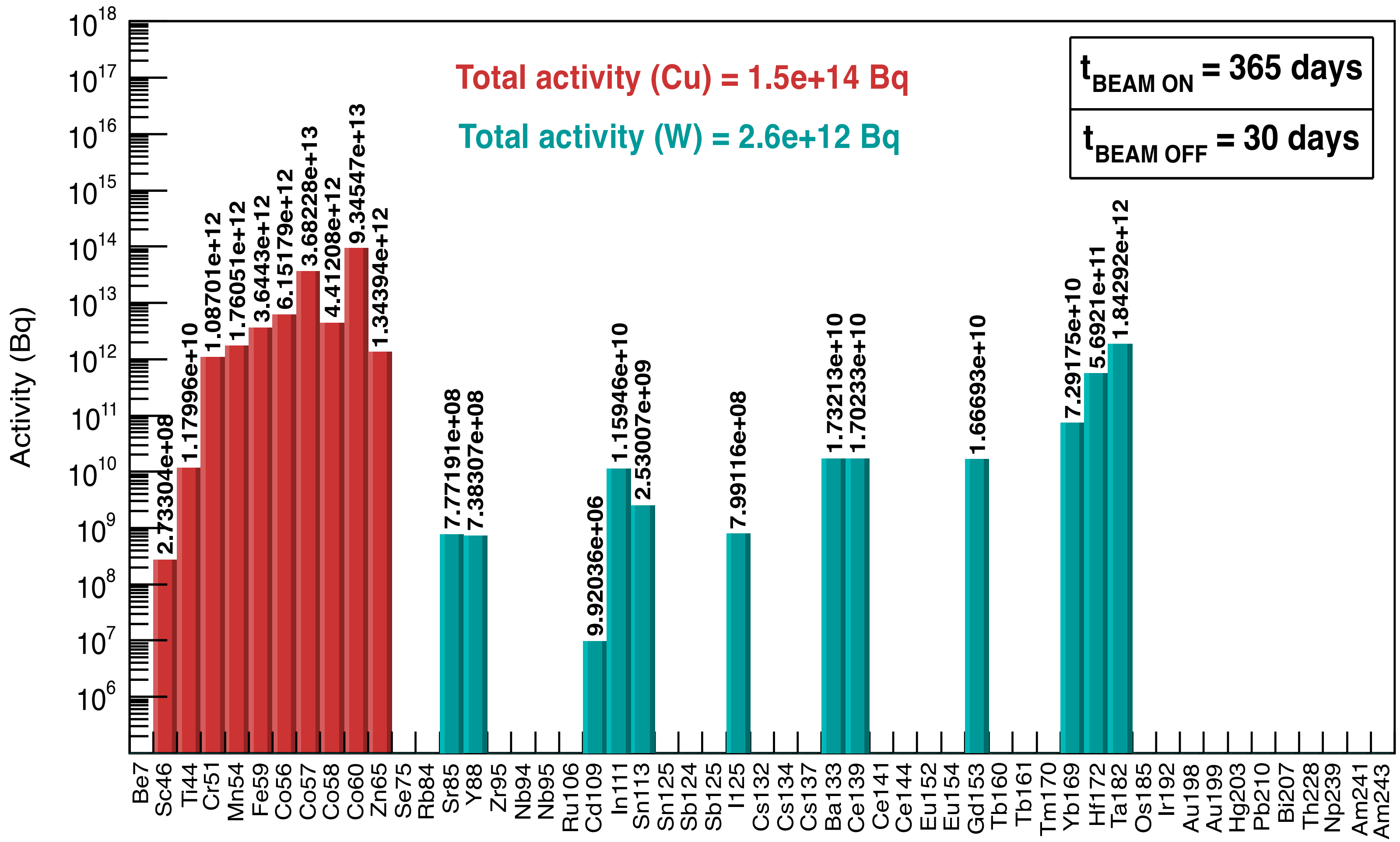
Isotope	Half life	Decay mode
^{85}Sr	65 d	EC
^{88}Y	107 d	EC, β^+
^{109}Cd	463 d	EC
^{111}In	3 d	EC
^{113}Sn	115 d	EC, β^+
^{125}I	59 d	EC
^{133}Ba	10.51 y	EC
^{139}Ce	138 d	EC
^{153}Gd	240 d	EC
^{169}Yb	32 d	EC
^{172}Hf	1.8 y	EC
^{182}Ta	114 d	β^-

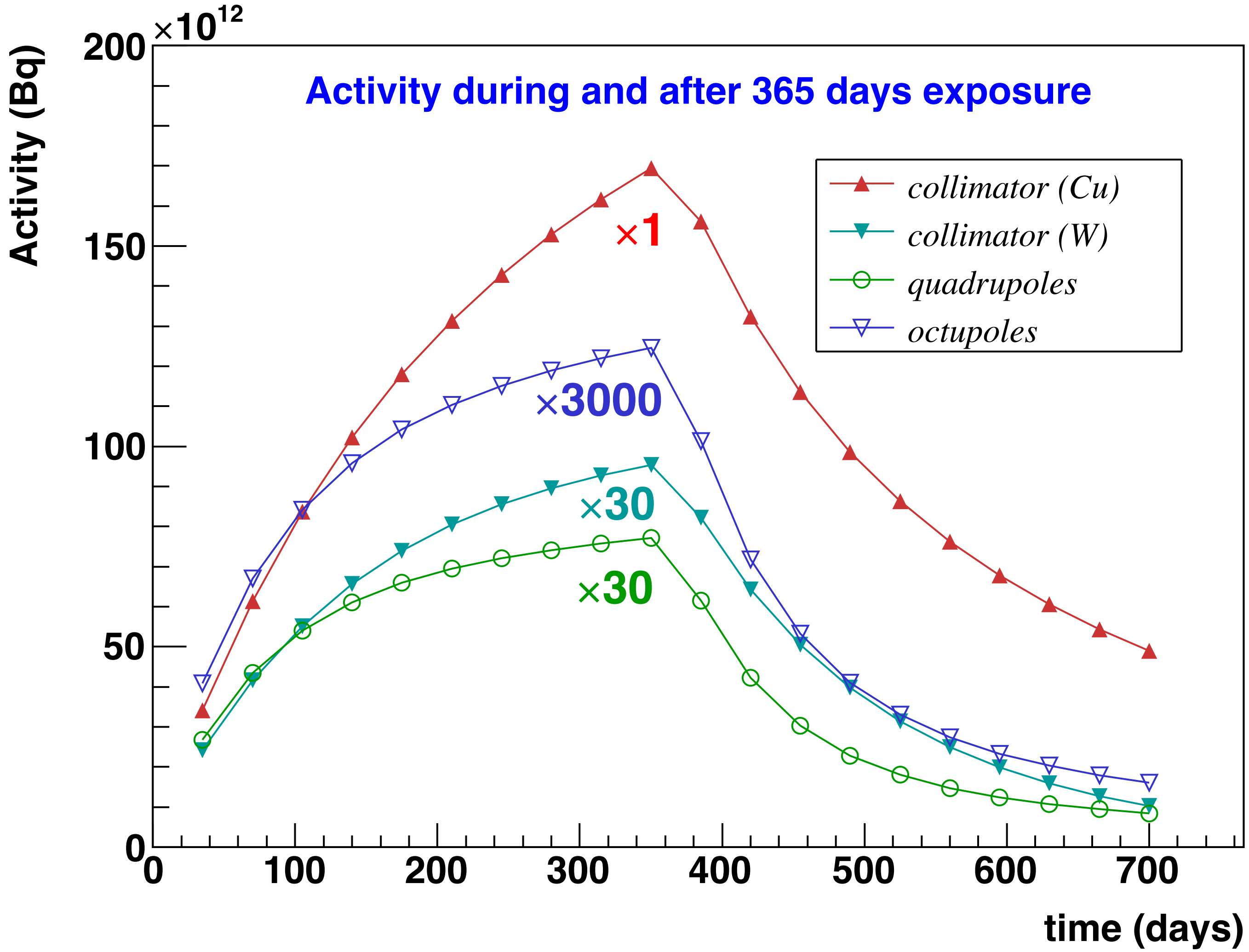


Activity inside quadrupoles
Total activity = 1.83489e+12 Bq
$t_{BEAM\ ON}$ = 365 days
$t_{BEAM\ OFF}$ = 30 days
Activity (Bq)
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
3.41629e+07
1.47495e+09
2.44024e+11
1.08714e+12
8.19374e+10
2.51356e+10
1.13233e+11
1.54939e+10
2.61029e+11
5.38808e+09
Be7
Sc46
Ti44
Cr51
Mn54
Fe59
Co56
Co57
Co58
Co60
Zn65
Se75



Activity inside octupoles
Total activity = 3.04897e+10 Bq
t BEAM ON = 365 days
t BEAM OFF = 30 days
Activity (Bq)
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
4.32858e+09
1.49637e+10
3.06308e+09
1.1691e+09
2.26467e+09
3.80998e+08
4.31964e+09
Ti44
Cr51
Mn54
Fe59
Co56
Co57
Co58
Co60
Zn65


Total activity (Cu) = 1.5e+14 Bq
Total activity (W) = 2.6e+12 Bq
$t_{BEAM\ ON}$ = 365 days
$t_{BEAM\ OFF}$ = 30 days
Activity (Bq)
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
2.73304e+08
1.17996e+10
1.08701e+12
1.76051e+12
3.6443e+12
6.15179e+12
3.68228e+13
4.41208e+12
9.34547e+13
1.34394e+12
7.77191e+08
7.38307e+08
9.92036e+06
1.15946e+10
2.53007e+09
7.99116e+08
1.73213e+10
1.70233e+10
1.66693e+10
7.29175e+10
5.6921e+11
1.84292e+12
Be7
Sc46
Ti44
Cr51
Mn54
Fe59
Co56
Co57
Co58
Co60
Zn65
Se75
Rb84
Sr85
Y88
Zr95
Nb94
Nb95
Ru106
Cd109
In111
Sn113
Sn125
Sb124
Sb125
I125
Cs132
Cs134
Cs137
Ba133
Ce139
Ce141
Ce144
Eu152
Eu154
Gd153
Tb160
Tb161
Tm170
Yb169
Hf172
Ta182
Os185
Ir192
Au198
Au199
Hg203
Pb210
Bi207
Th228
Np239
Am241
Am243



Activity during and after 365 days exposure
Activity (Bq)
×10^12
200
150
100
50
0
0
100
200
300
400
500
600
700
time (days)
collimator (Cu)
collimator (W)
quadrupoles
octupoles
×1
×3000
×30
×30

- paper submitted to PRST-AB;
- received minor corrections from referees
- done

Induced Activation in Accelerator Components

Cristian Bungau,* Adriana Bungau, Robert Cywinski, Roger Barlow, and Thomas Robert Edgecock
University of Huddersfield, School of Applied Sciences, Huddersfield, HD1 3DH, United Kingdom

Patrick Carlsson, Hakan Danared, and Ferenc Mezei
European Spallation Source, Lund, Sweden

Anne Ivalu Sander Holm, Søren Pape Møller, and Heine Dølrath Thomsen
ISA, Aarhus University, 8000 Aarhus C, Denmark

(Dated: September 12, 2013)

The residual activity induced in particle accelerators by high-energy neutrons is a serious issue from the point of view of radiation safety as the long-lived radionuclides produced by fast or moderated neutrons cause problems of radiation exposure for staff involved in the maintenance of accelerators. The long-lived radionuclides also contribute to the radioactive waste at the decommissioning of the accelerator facility as beam components that becomes radioactive are certain candidates for failure as a result of radiation damage. This paper presents activation studies of the magnets and collimators in the High Energy Beam Transport line of the European Spallation Source due to mainly the back-scattered neutrons from the target and also to the direct proton interactions and their secondaries. An estimate of the radionuclide inventory and induced activation are predicted using the GEANT4 code.

I. INTRODUCTION

Activation induced by particle nuclear interactions in beamline components represents one of the main radiation hazards of high-energy accelerators. Elements such as target, collimators, magnets and beam dumps are the first candidates for failure as a result of induced activation. Induced radioactivity is due either to direct interactions of the incoming beam or indirect interactions of secondary particles in the accelerator components leading to radionuclides production. This activation causes remnant ambient dose rates inside accelerator tunnels and target areas but also means that when components are being replaced at the end of their operational lifetime, they must be treated as radioactive waste. Big quantities of activated material arises when the whole accelerator is decommissioned as dismantling it will pose a major challenge for radiation protection. Exposure to radiation from induced activation can occur in connection with handling, transport, machining, welding, chemical treatment and storage of irradiated items. These procedures can be extremely difficult because the personnel accumulate dose and if they exceed the permitted limits, remote handling becomes necessary. In the field of radioactive materials and waste there are no internationally agreed recommendations like in radiation protection. Both the International and European Basic Safety Standards [1] only contain tables with radionuclide specific exemption limits [2] and do not make recommendations with respect to the clearance of radioactive material. In countries like France or Switzerland for example, the accelerator waste is not accepted contrary to waste coming from nuclear industry with the argument that its radionuclide inventory as a result of high energy spallation reactions is not well known [3].

Because the accelerator components reveal high induced activation during normal operations and after accelerator shutdown, it is of primary importance to predict correctly their radionuclide inventory and residual activity before any handling and maintenance procedures. The technical challenge is firstly to ensure that the beam losses are small as residual activity depends greatly not only on material properties but also on the amount of beam loss. The main causes of beam loss in high current accelerators are:

- space charge effects that arise due to Coulomb repulsion between particles; the Coulomb repulsion becomes more important as the beam current is increased and causes an increased emittance leading to beam losses
- beam halo surrounding the beam core, caused by space charge induced emittance growth
- emittance increase which could be due to several reasons like space charge effects, non-linear resonances, chromatic aberrations in lenses
- back-streaming neutrons coming from the target on the beam pipe
- mismatch of the beam across accelerator elements transitions
- low aperture to rms beam size ratio; this should be kept reasonably high to prevent the beam from hitting elements and getting lost

The high energy protons lost along the beamline generate secondary neutrons by spallation and these in turn

* C.Bungau@hud.ac.uk