Studies of TS1 upgrade to > 1 MW

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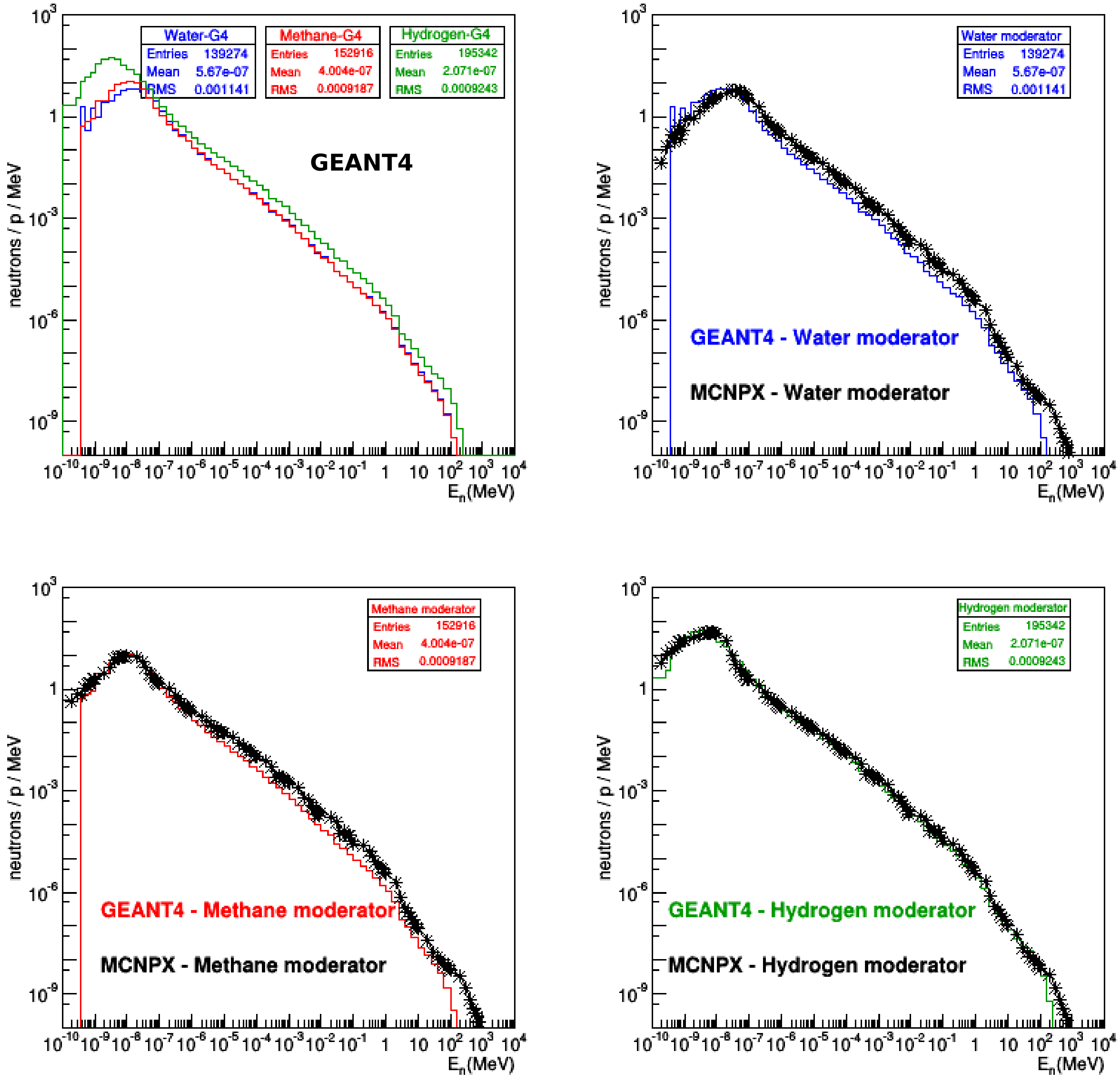
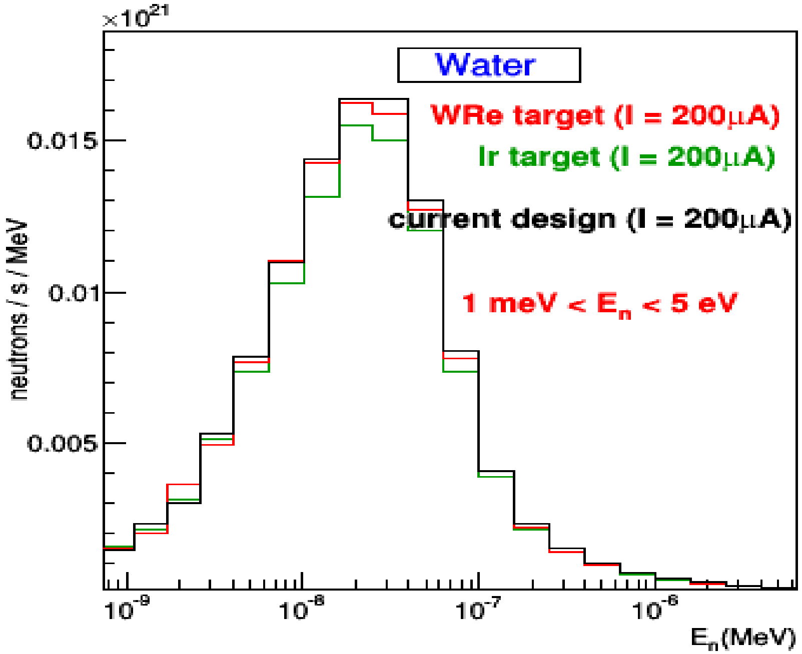
9 September 2014

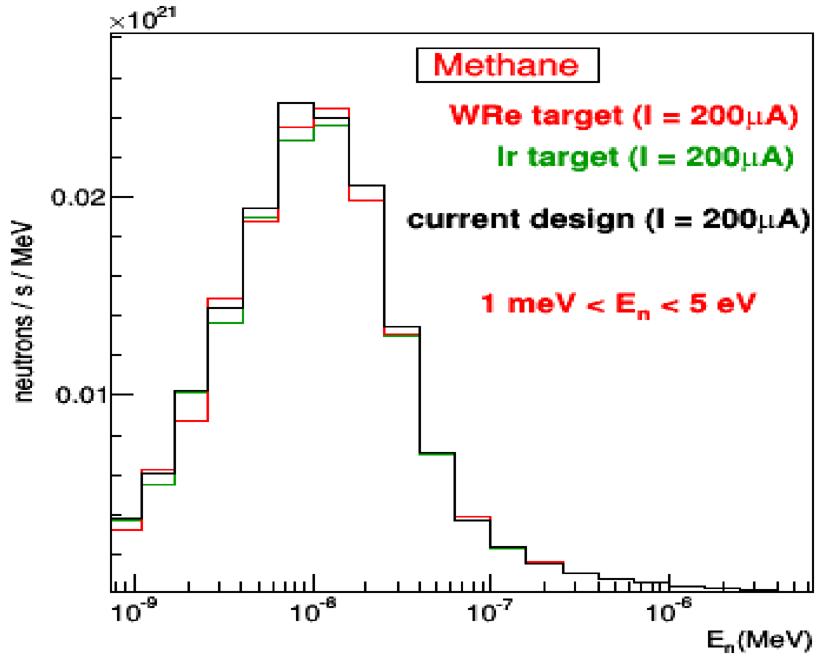
GEANT4 vs MCNPX neutron yields

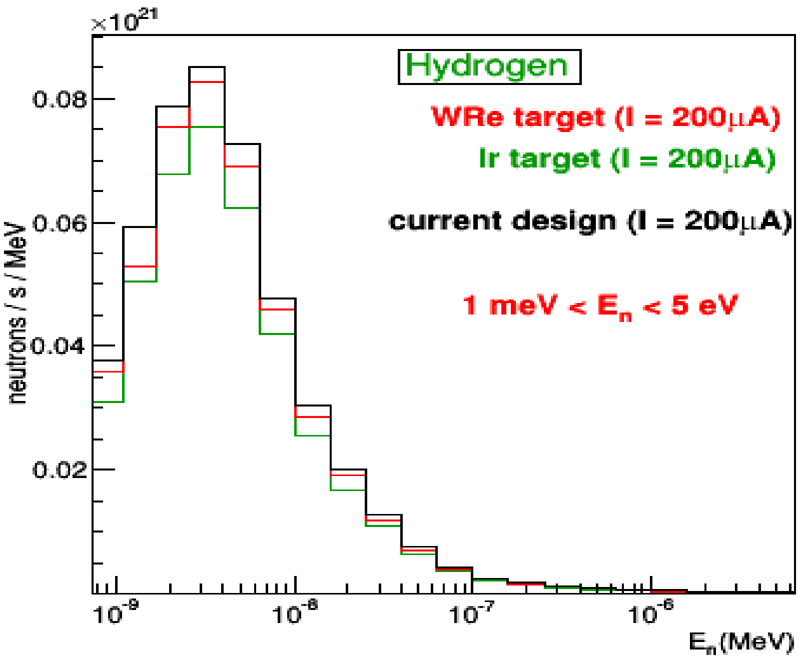


W, WRe and Ir targets

- Since various studies for the NLC/SLC positron target showed that WRe (27% Re) has better structural properties than pure W and Ir turned out to survive very big thermal shocks at the AD target (CERN), I did a comparison at 200 μA between the three materials;
- However, while for W exist both experimental n yields data (p ENDF), for Re and Ir there are no data, the best we have are TALYS calculations for the n yields;
- Therefore in all simulations I used the TALYS calculations, even for W (for consistency), even though for W there are not-negligible differences between the ENDF (experimental data) and TALYS (calculations) predictions for the n yields;







Since for all three materials I used the TALYS theoretical calculations, and due to the similarity between the three elements, there are no significant differences in the predicted neutron yields.

Increasing the proton beam power

- For a 5 MW beam footprint of ~ 100 cm^2 and a parabolic intensity distribution wit a peak value I_{peak} ~ 100μA/cm^2 of 800 MeV protons → peak power density ~ 2.5 kW/cm^3;
- The resulting temperature increase in a heavy metal target (W) is about 20 K in 20 ms (i.e. per pulse at 50 Hz operation);
- Removing this heat in a solid target requires:
  - very thin target plates → high coolant fraction;

    OR
  - a rotating target;

Thinner plates design

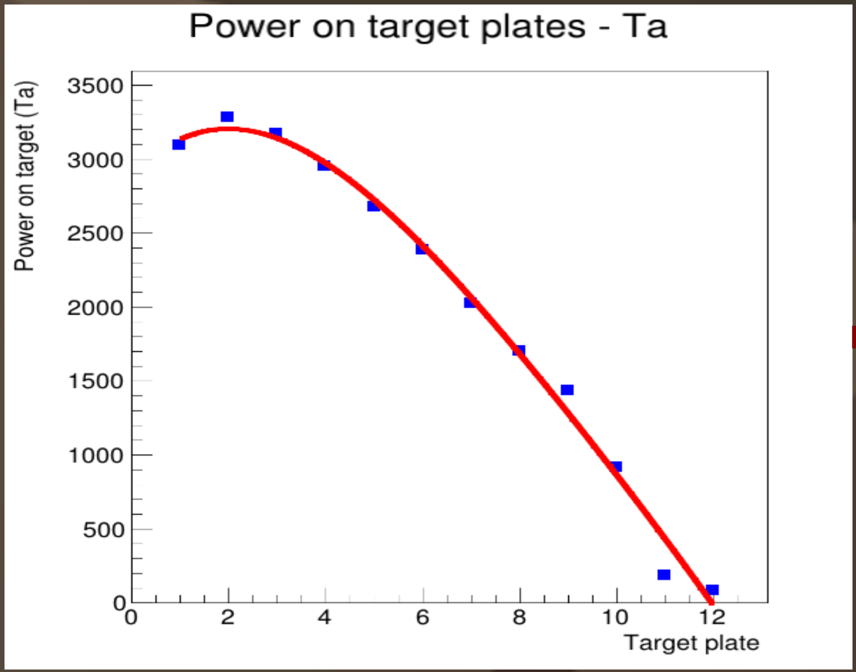
- Before moving to molten metal target designs → study how many useful neutrons vs proton power we can get in a static target of varying geometry of plates;

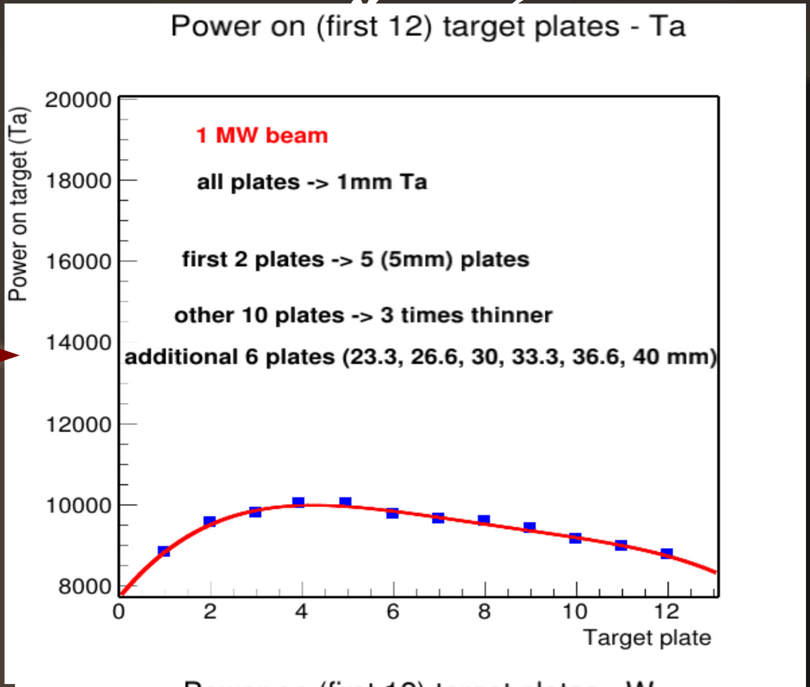
  Firstly:

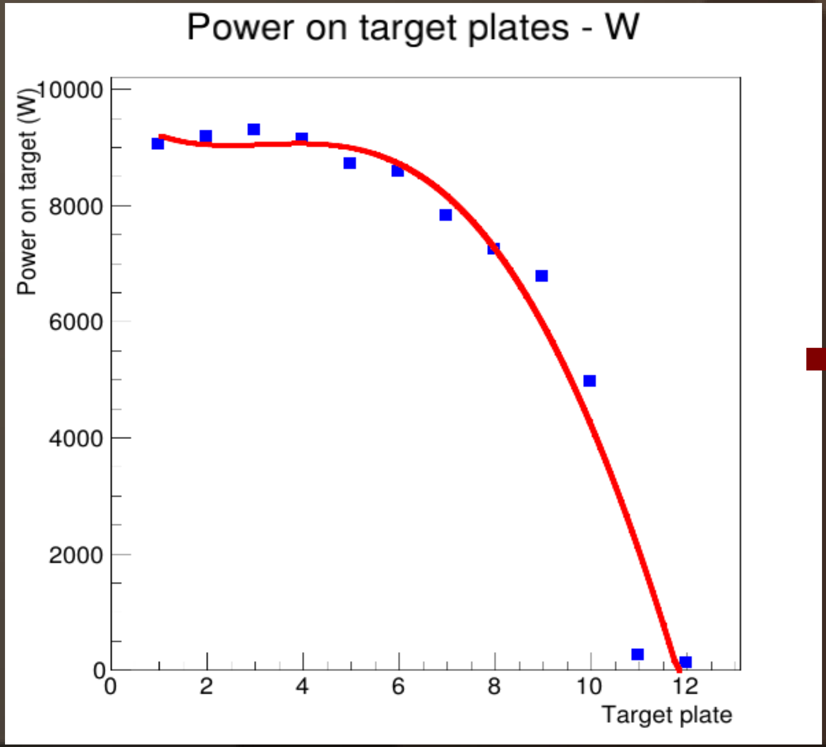
- Reduce the Ta thickness to 1 mm;
- Keep 2 mm water thickness between all plates;
- First 2 (15 mm) plates → 5 (5 mm) plates;
- The remaining 10 plates → 3 times thinner each;
- Add 6 more plates to fill in the end gap created;

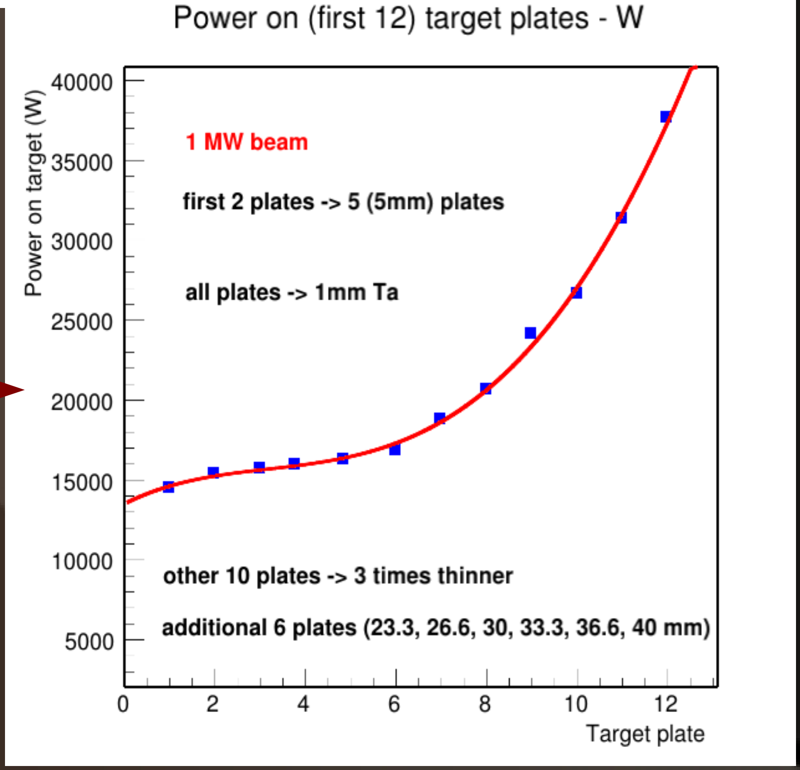
Power on plates (before and after)

Power deposition on outer Ta







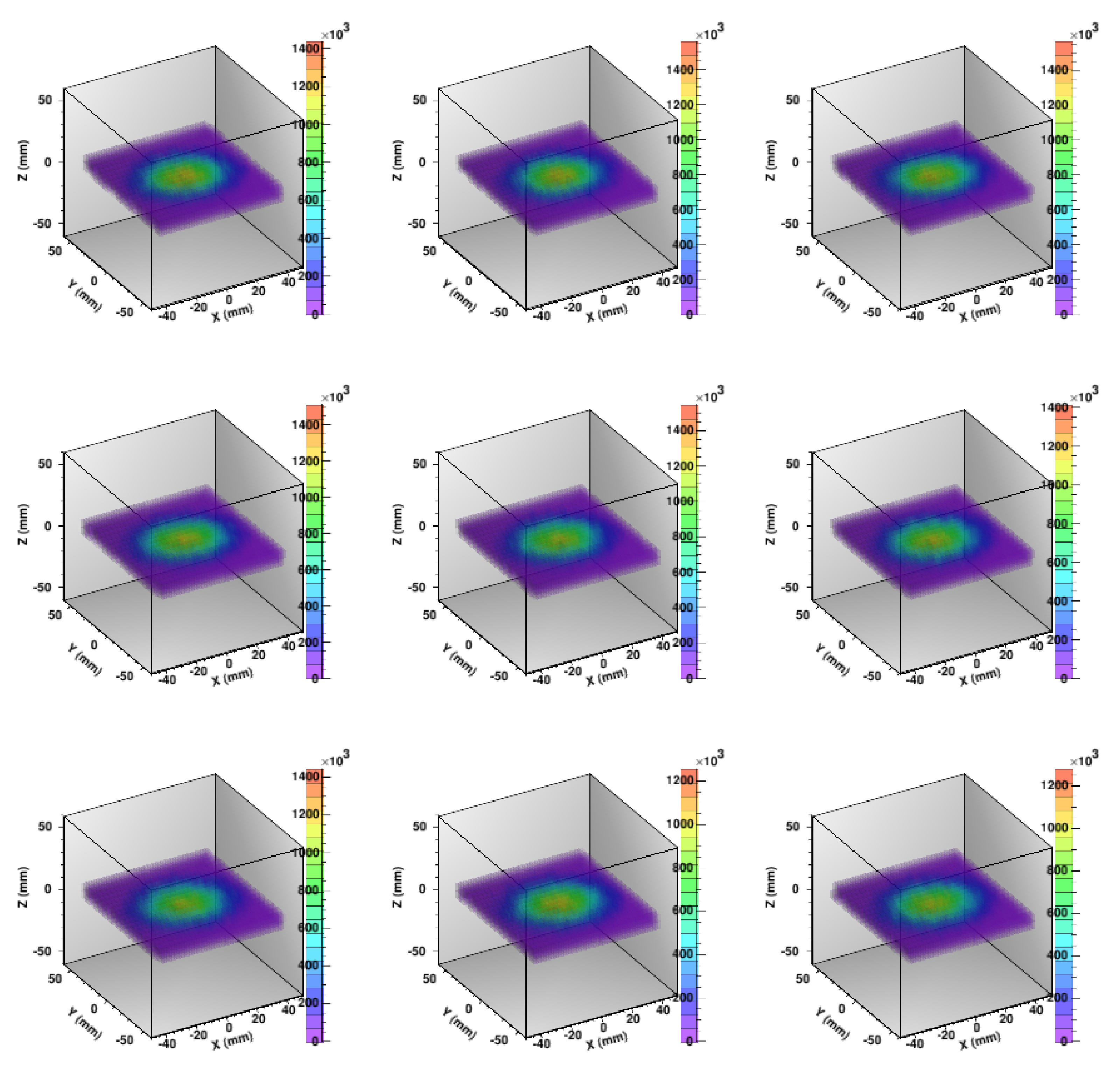


3 times thinner plates do not cope with 1 MW beam power

Alternative plates arrangement

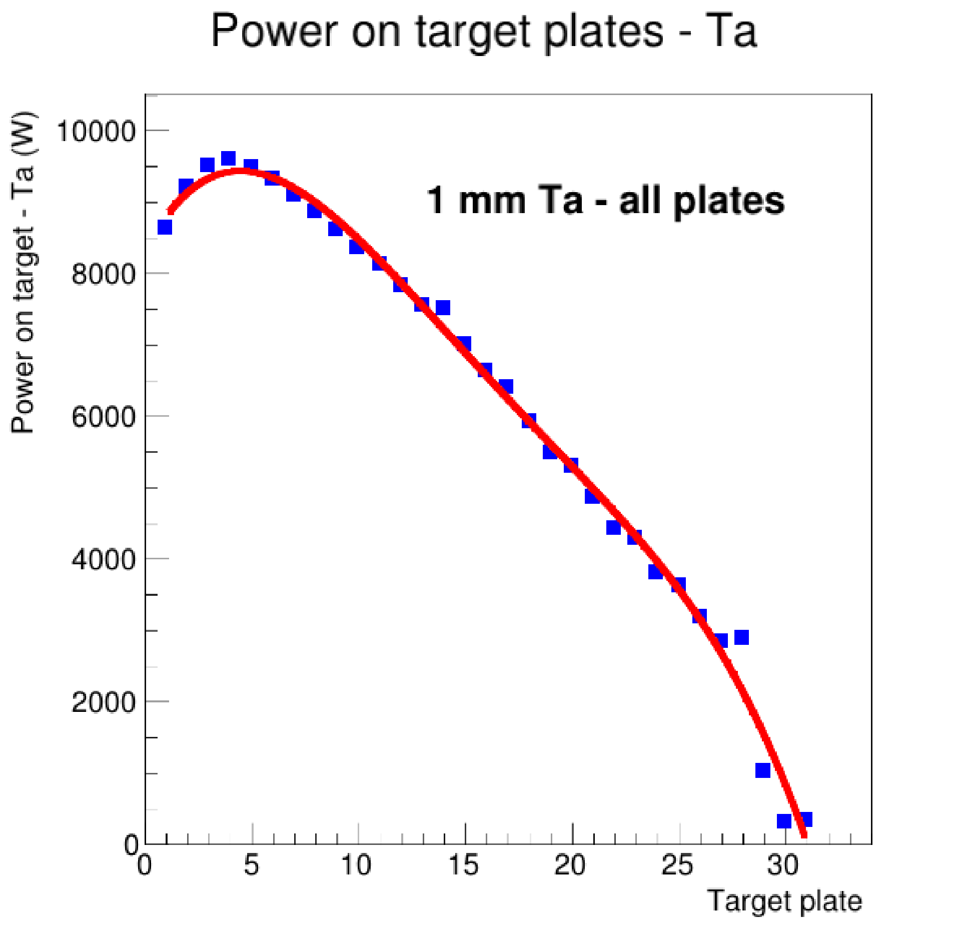
- Having tried various configurations, I came up with this set up of 31 (instead of 12) plates (which can be further refined if we decide to stick with it);
- 1 mm Ta on each plate & 2 mm water in between all plates; all dimensions below will include the 1 mm Ta;
- 13 plates each 5 mm thick followed by: 3 (7 mm) plates, 3 (8 mm) plates, 3 (10 mm) plates, 2 (13 mm) pates, 3 (15 mm) plates, 2 (17 mm) plates, 1 (20 mm) plate, and finally 1 (39.5 mm) plate;

Energy deposited distribution inside the first 9 (5 mm) target plates

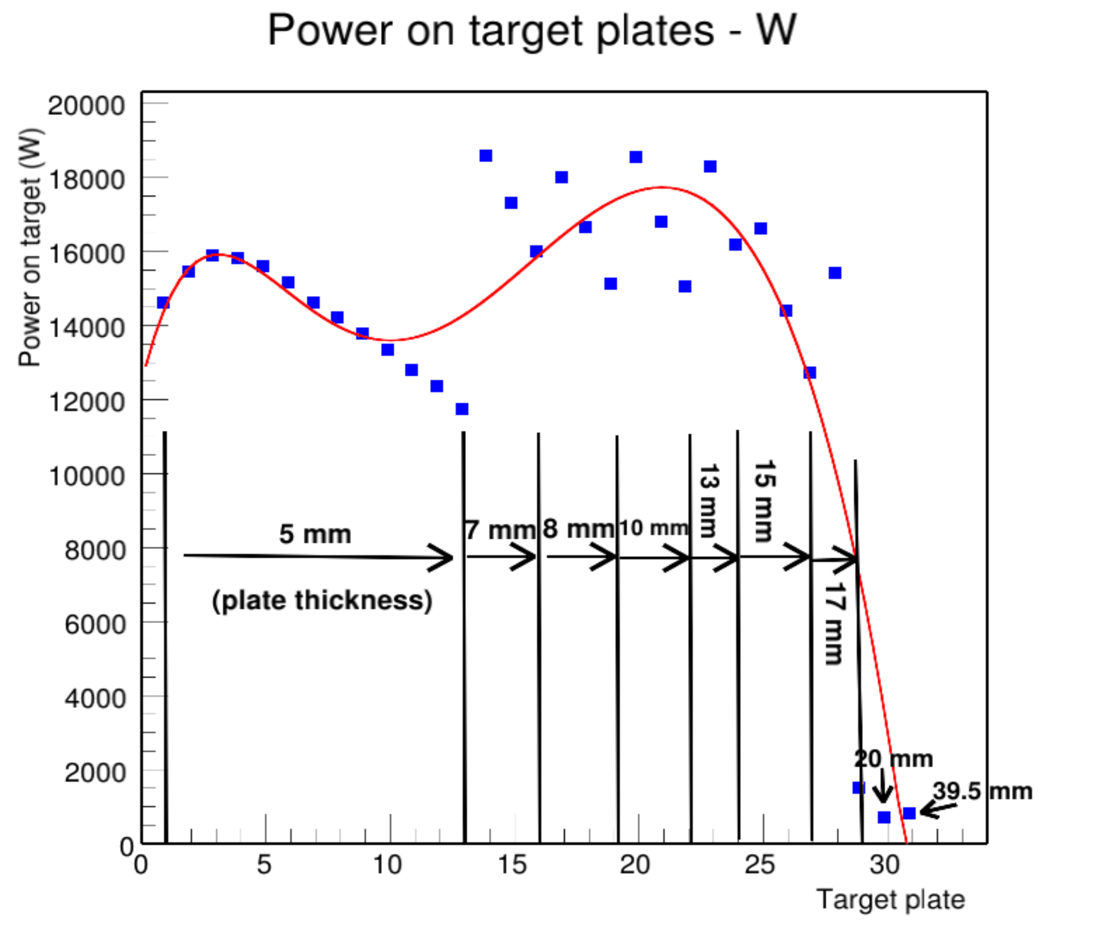


Power on the new 31 plates @ 1MW

Power deposition on outer (1 mm) Ta

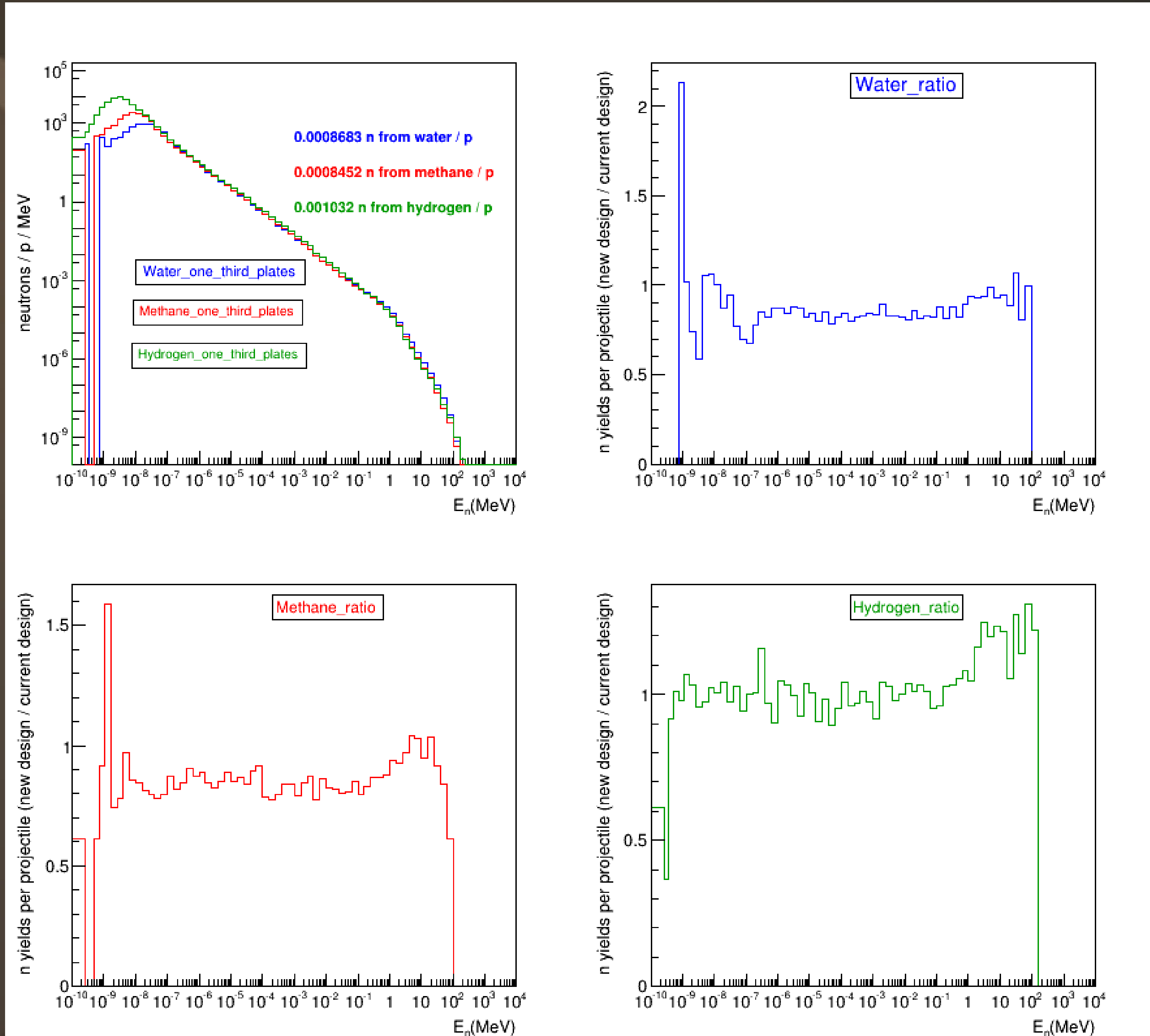


Power deposition on inner W



- The maximum power on plates with the existing design is ~ 12,000 W;
- With the new thinner plates, the maximum power is ~ 26,000 W;
- The fist 13 plates are already very thin (5 mm → 2 mm Ta + 3 mm W) – it is NOT possible to go any thinner...

Neutron yields ratio (new design / current design)

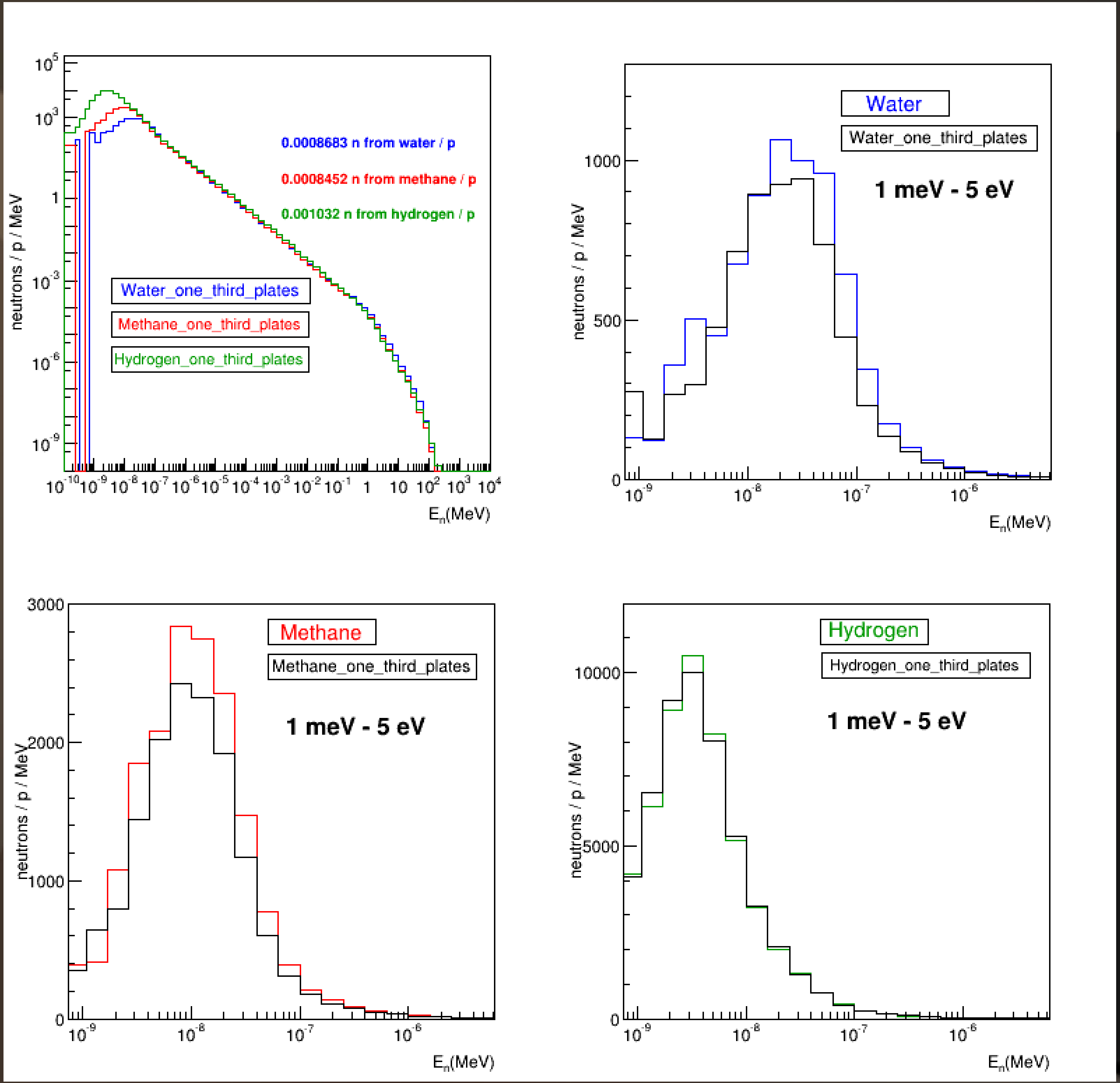


Advantages:

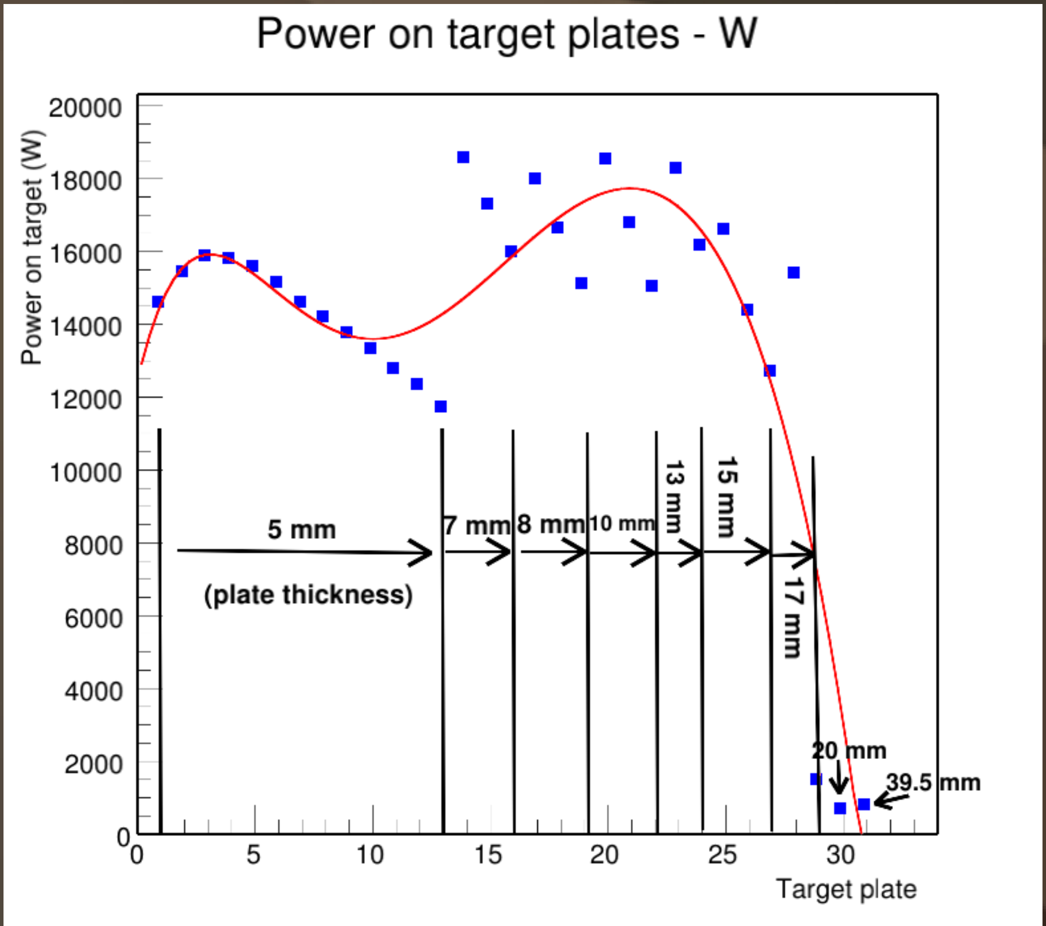
- 6 times more neutrons due to 6 times more power;

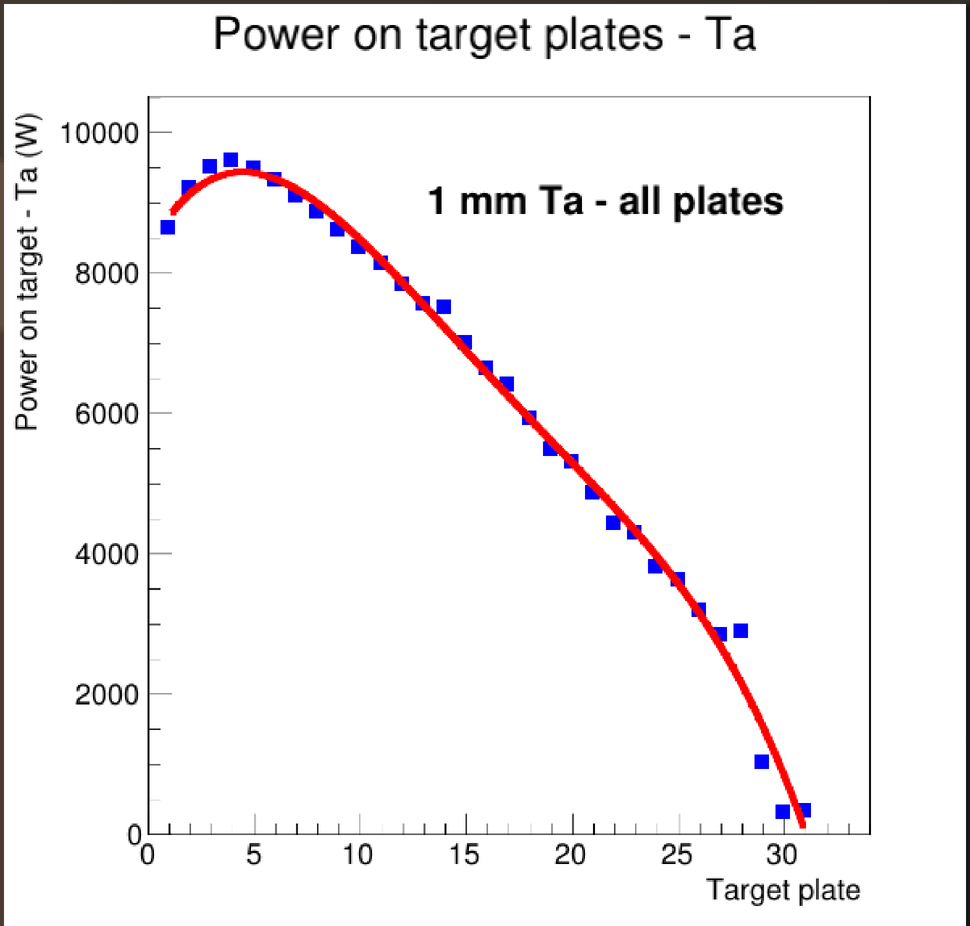
Disadvantages:

- Cope with 2 x more power on the new plates;
- Since the plates are much thinner, the power *density* will be much higher;



At 1 MW



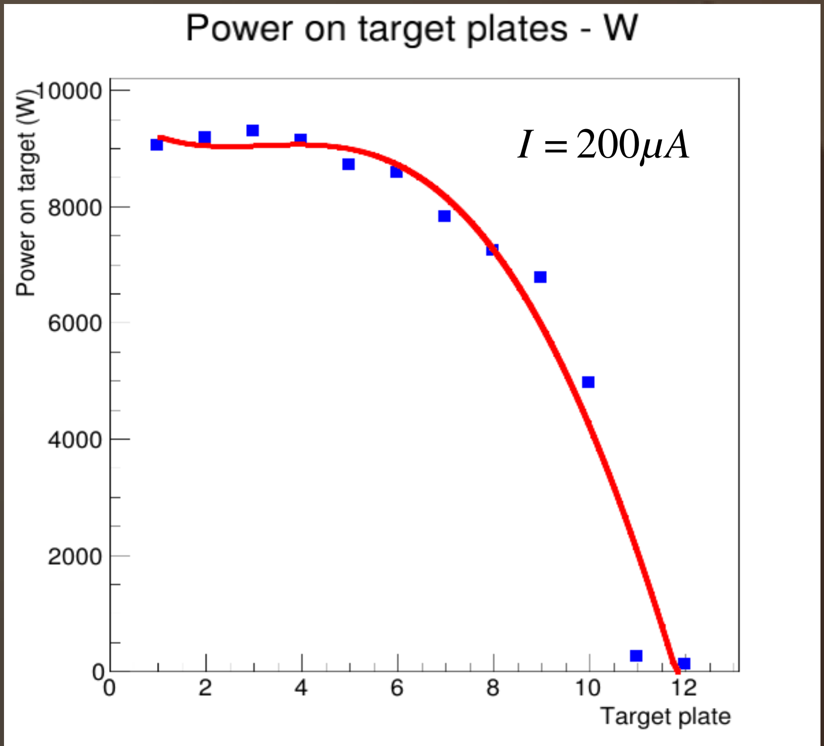


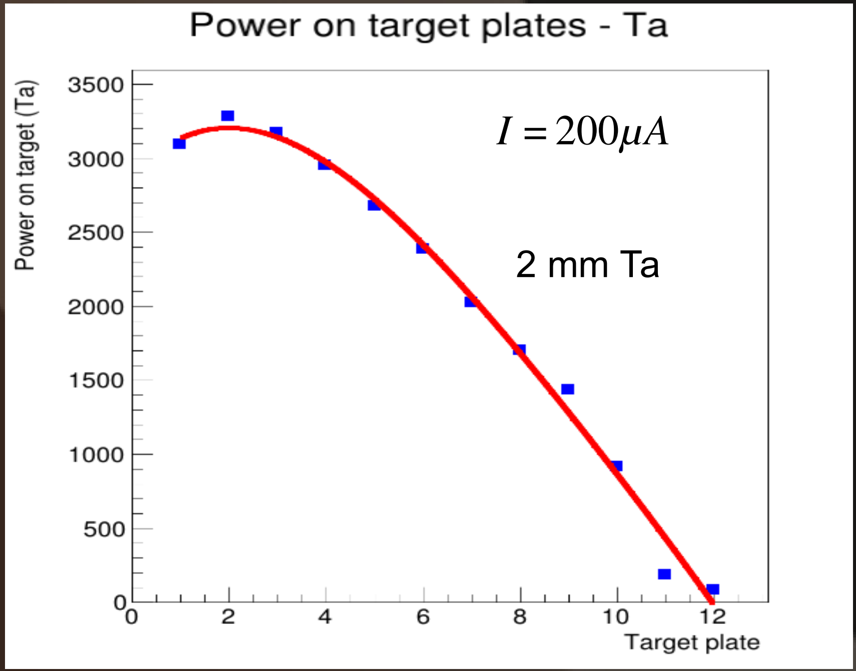
• Although by adjusting the plates dimensions, the (average) power inside the inner W could be kept at values not much higher than they are currently (i.e. up to 12,000 W), inside the outer Ta the power increase is too high (currently this is below 3,000 W).

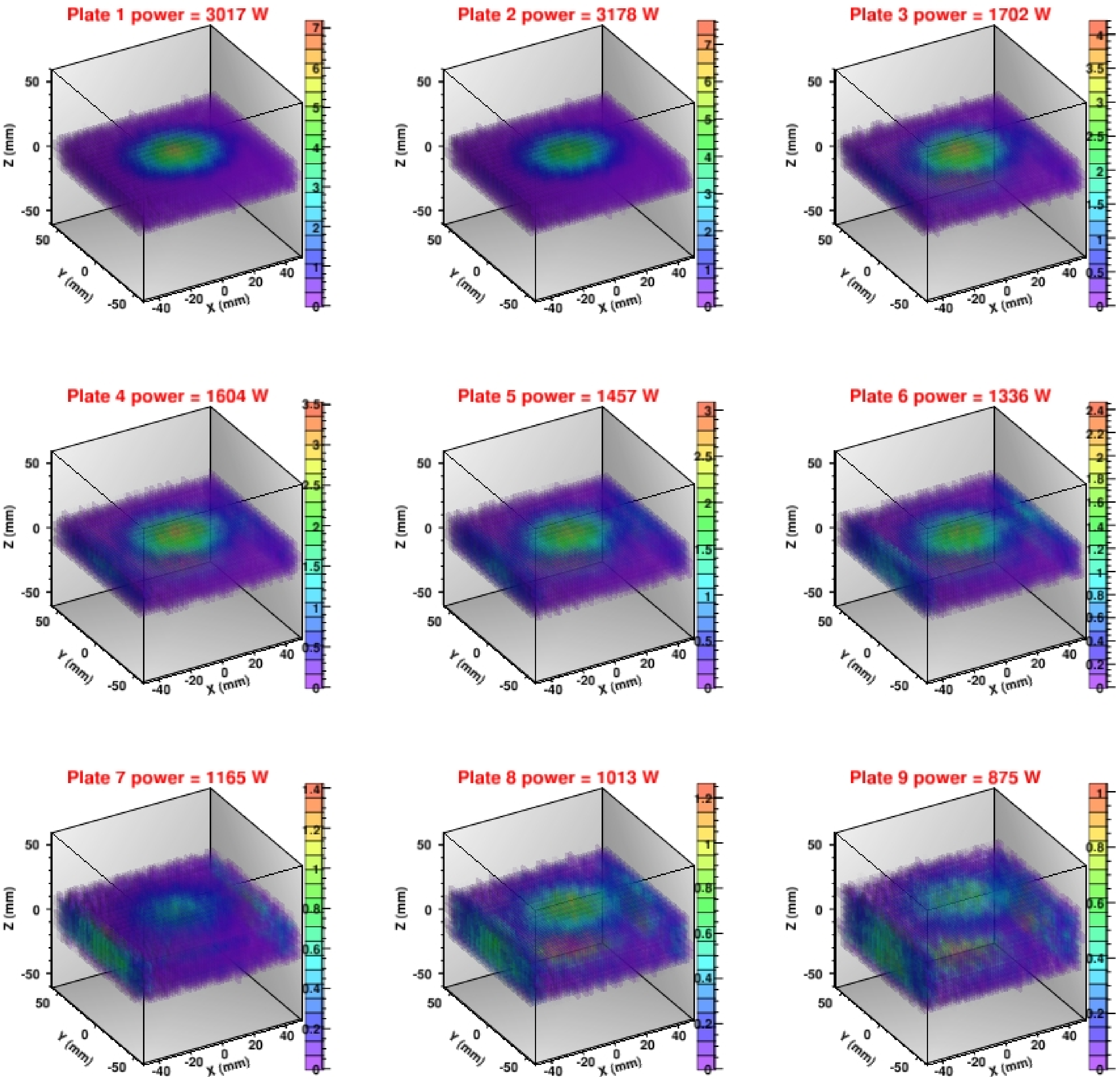
• This suggests that, since we cannot get a Ta layer thinner than 1 mm, these plates will not work at 1 MW, even with the new optimized dimensions.

Sow what is the maximum power for these new plates?

- Rather than looking at the average power, I looked at the power distribution to find the maximum peak value, and used the upper limit as up to twice - in other talks people mentioned an increase to (1.8 x current values) as a maximum factor;
- Since the W volume is fine, I'll focus on the outer Ta layer;

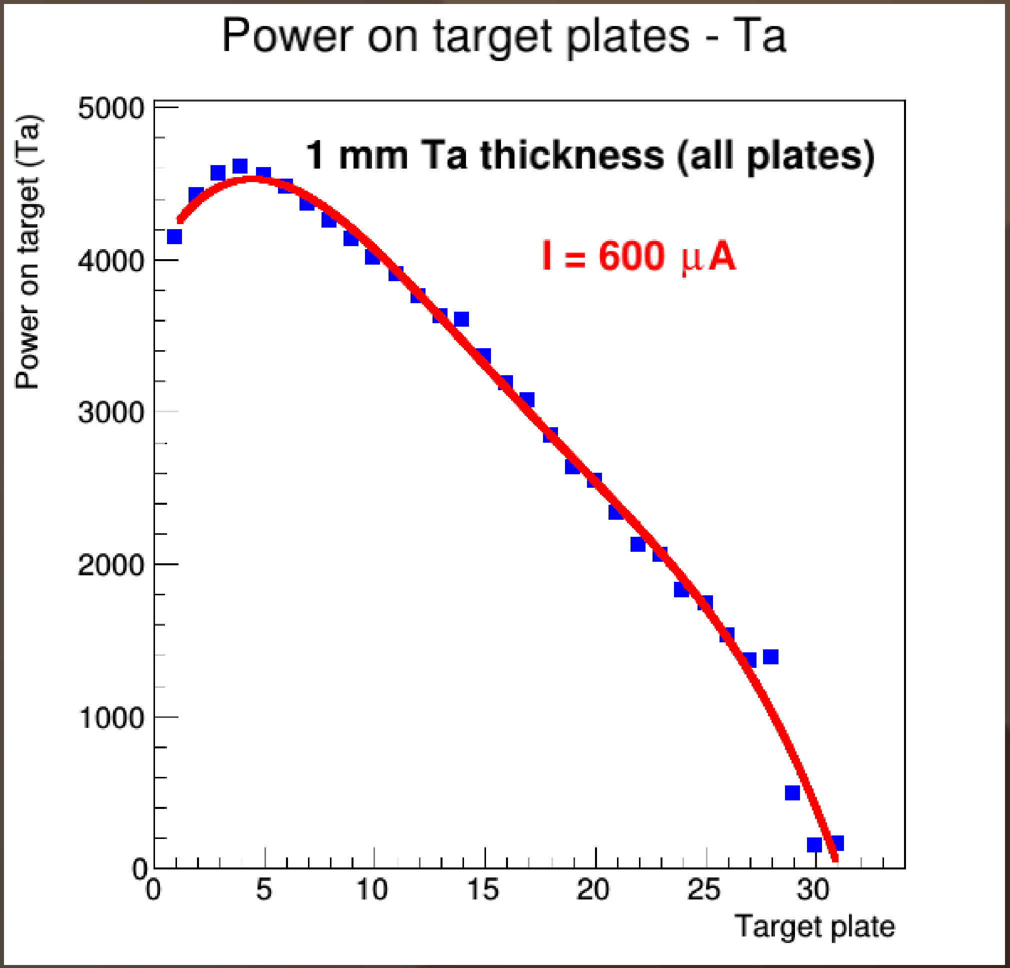


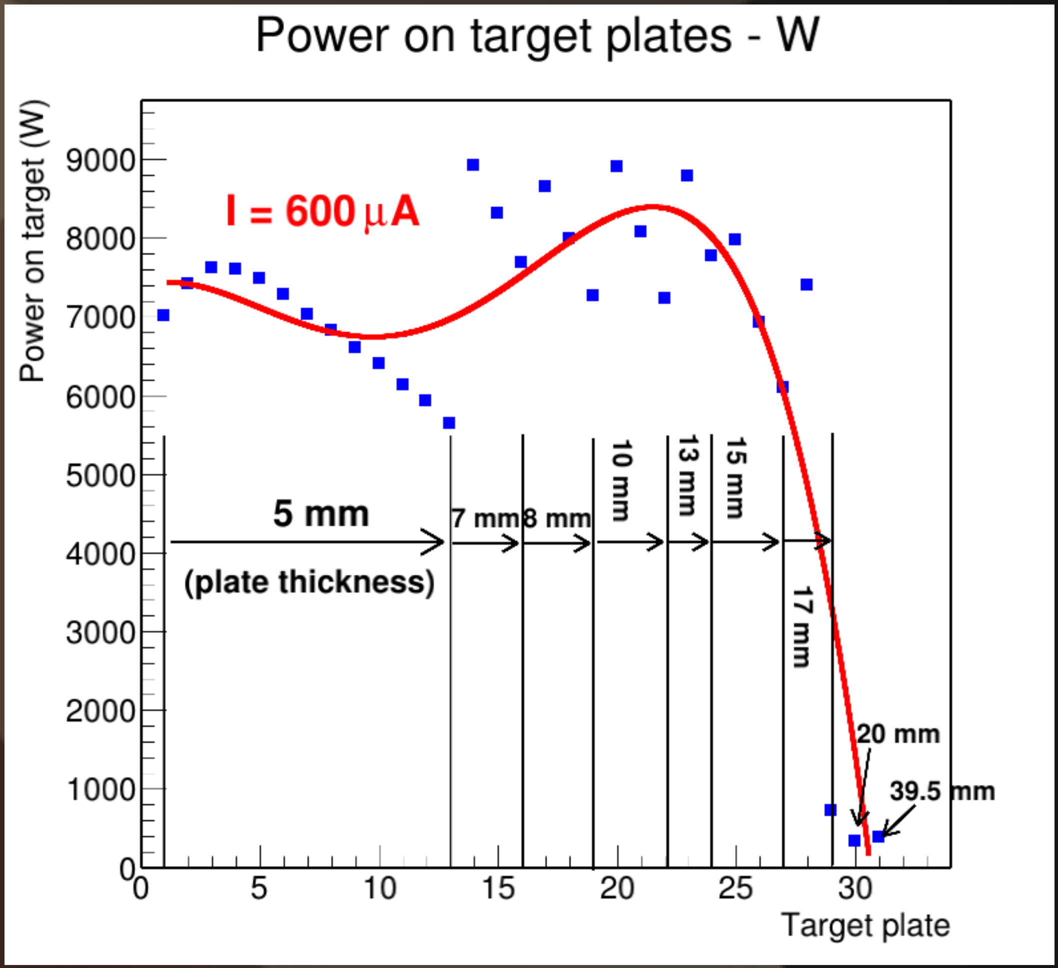


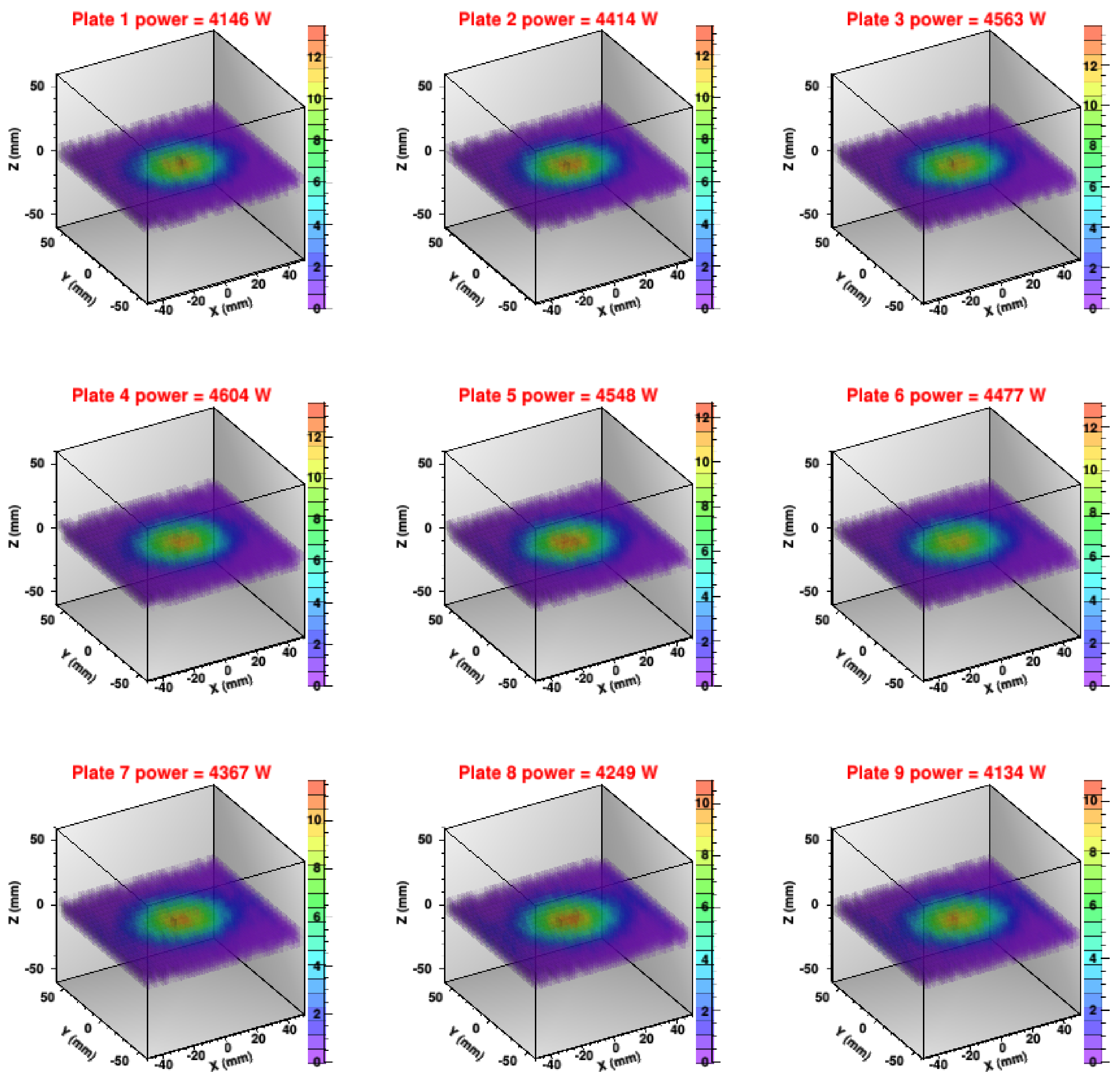


Peak power density = 7 W / (1.6x6x6) mm^3

Even for the new plates, due to the Ta minimum thickness of 1 mm, the power can be increased only up to about 0.5 MW, for which we have:



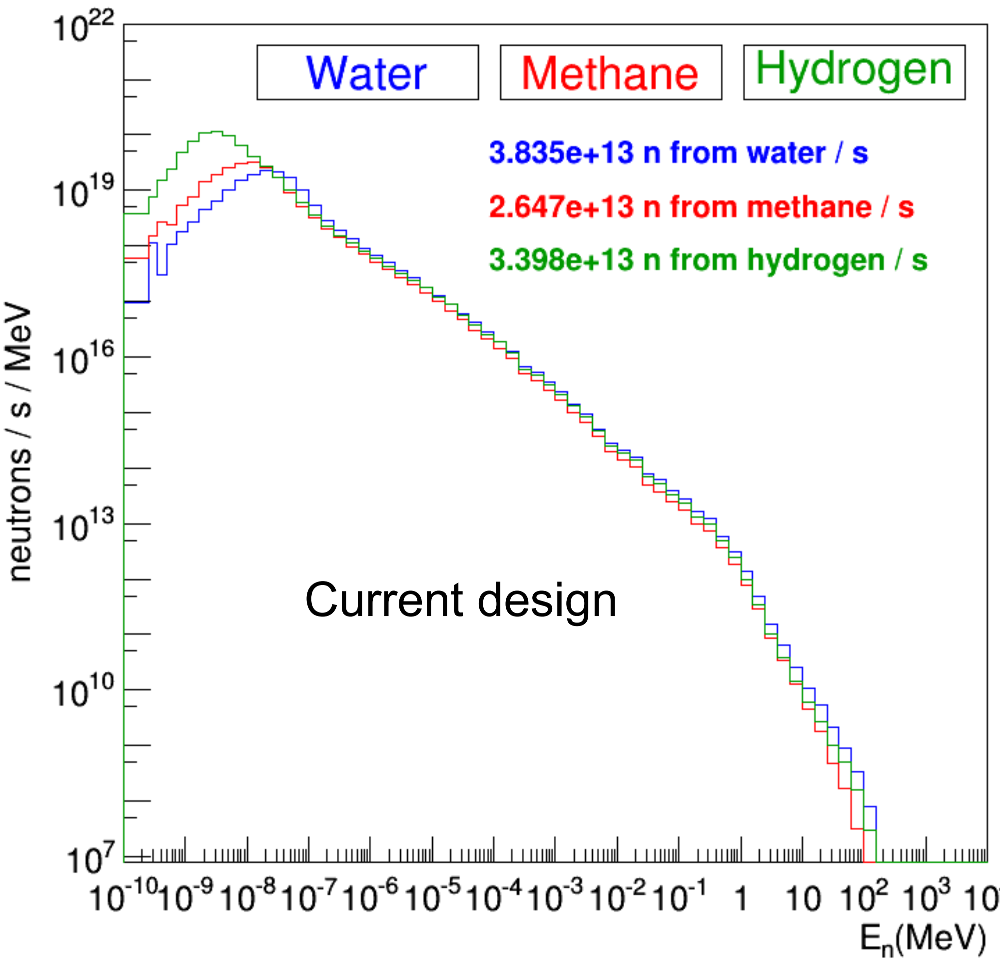


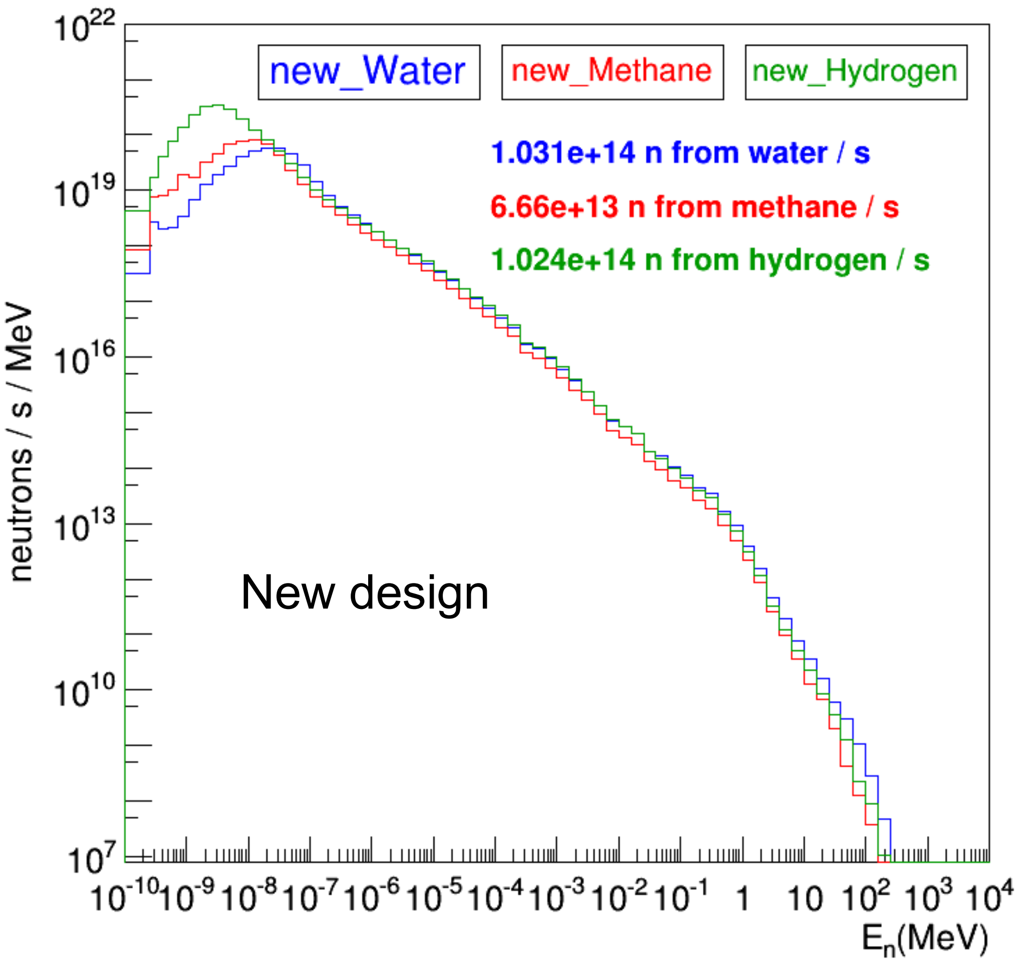


$I = 600\mu A$

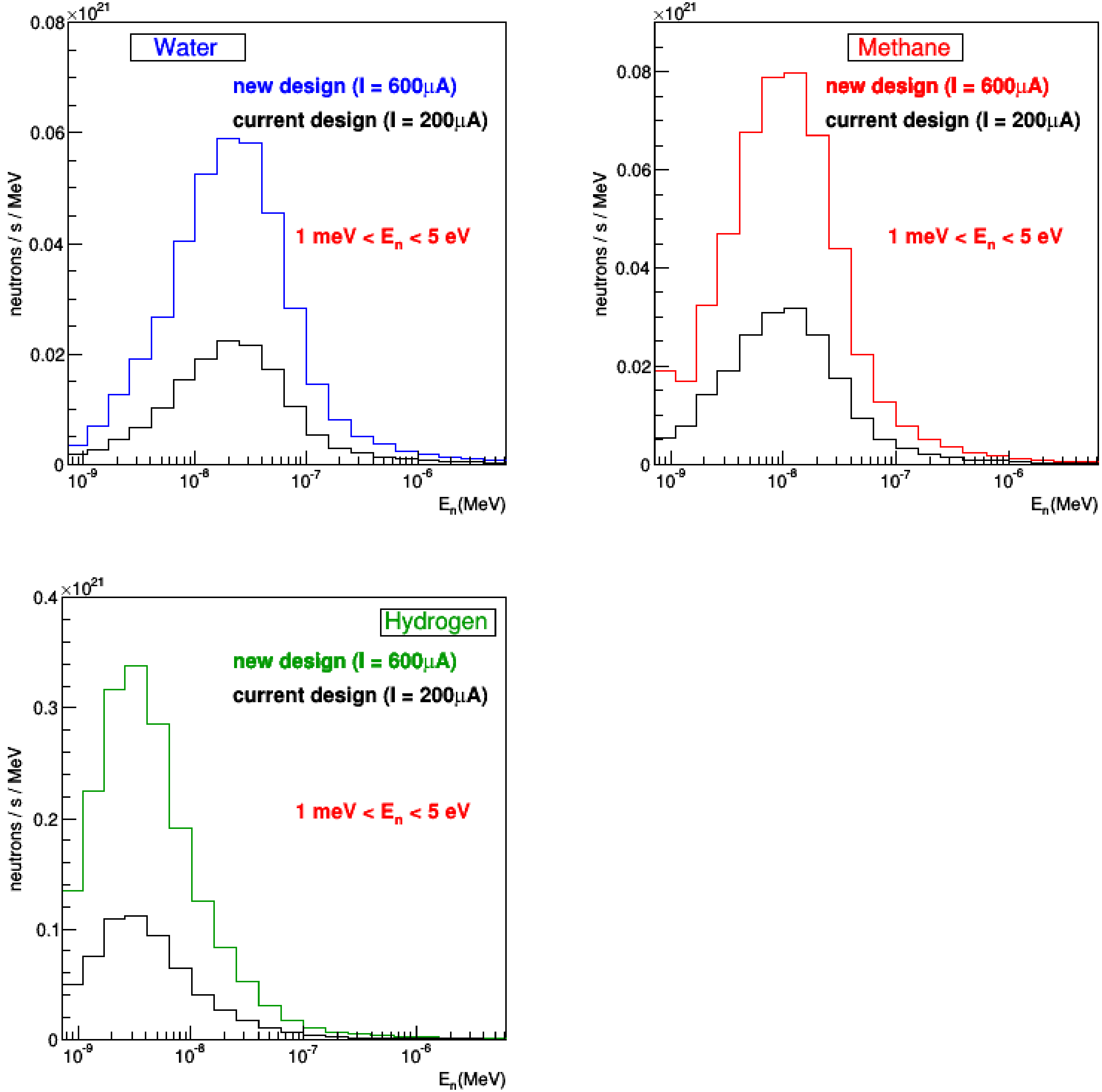
Peak power density = 13 W / (1.6x6x6) mm^3

Neutron yield increase





n spectra overlapped for direct comparison in the next slide…


Water
new design (I = 600μA)
current design (I = 200μA)
1 meV < E_n < 5 eV
neutrons / s / MeV
×10^21
E_n(MeV)
Methane
new design (I = 600μA)
current design (I = 200μA)
1 meV < E_n < 5 eV
neutrons / s / MeV
×10^21
E_n(MeV)
Hydrogen
new design (I = 600μA)
current design (I = 200μA)
1 meV < E_n < 5 eV
neutrons / s / MeV
×10^21
E_n(MeV)

Molten metal target materials

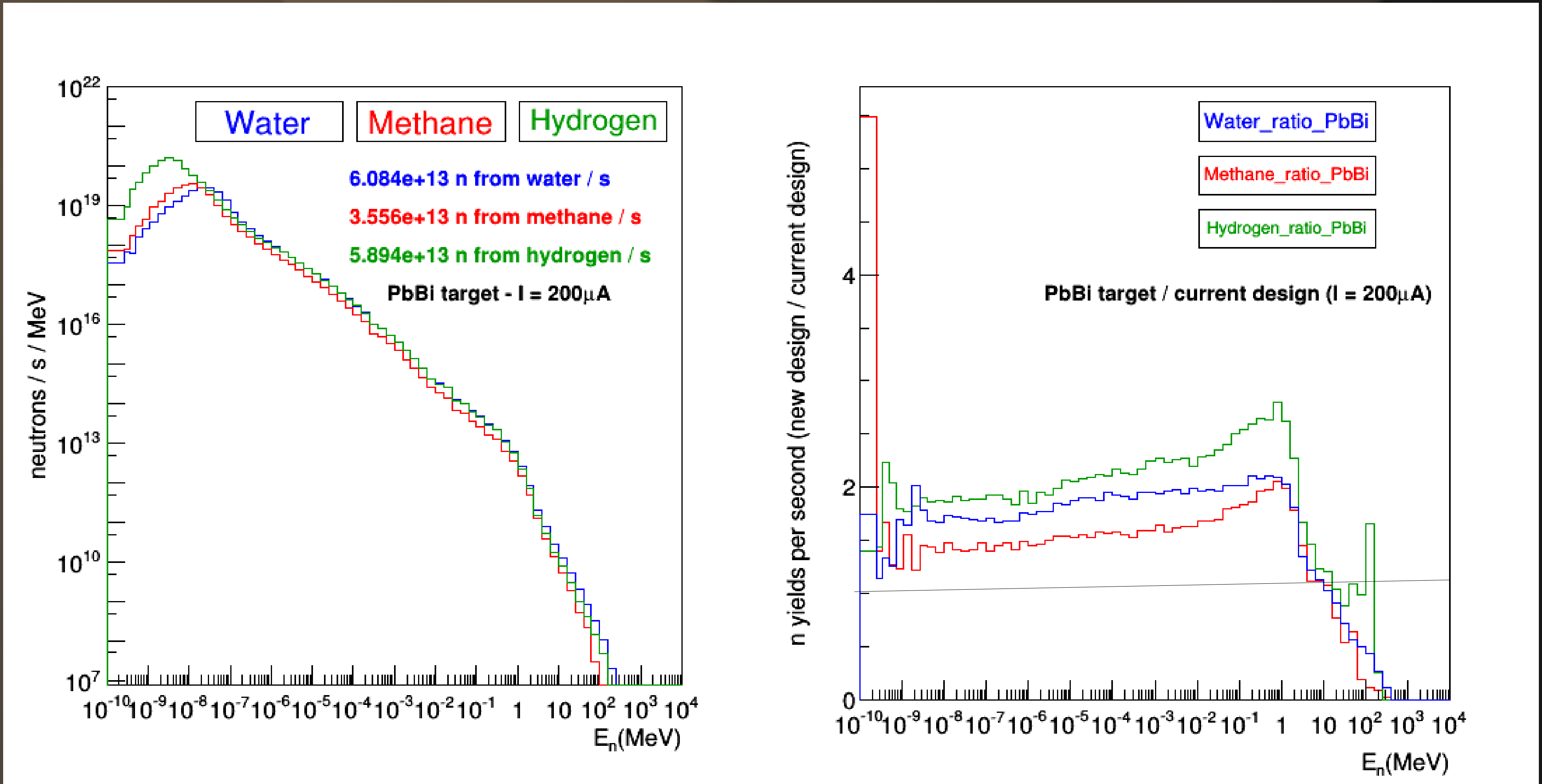
- Many studies already done for molten PbBi targets for ADS applications. These studies include:
  - neutron yields;
  - spallation products;
  - gas production;
  - thermal-hydraulic studies;
  - etc;
- Such studies include a preliminary design of the 750 MW_{th} fast-thermal ADS system in India and the MYRRHA project studies in Belgium on R&D in PbBi technology;

Advantages of a heavy liquid metal target

- high heat removal capacity by convective flow;
- high average density of the target material in the beam interaction zone;
- no neutron moderation inside the target
- no water in the beam interaction zone;
- no structural damage in the target material;
- any hazardous volatiles could be continuously extracted to reduce the potential hazard;

- For the MEGAPIE target (PSI) it was decided it was safe to use PbBi. It has major advantages, including a very low melting point of 125 C, relatively high density and low thermal neutron cross-section. The release of Po proved to be quite slow below 700 C, which was far above the operating temperature of MEGAPIE.
- Furthermore, the neutron yield was first simulated to be 40% higher than a solid target would provide (at identical current of course). But the later experimental measurements showed an increase of 90%;
- after changing their MCNP codes to model in more detail the target and moderators, the simulations reproduced the 90% n yield gain.
- during the MEGAPIE operation there were no serious issues with PbBi, while getting an increase in neutron yields greatly exceeding expectations.

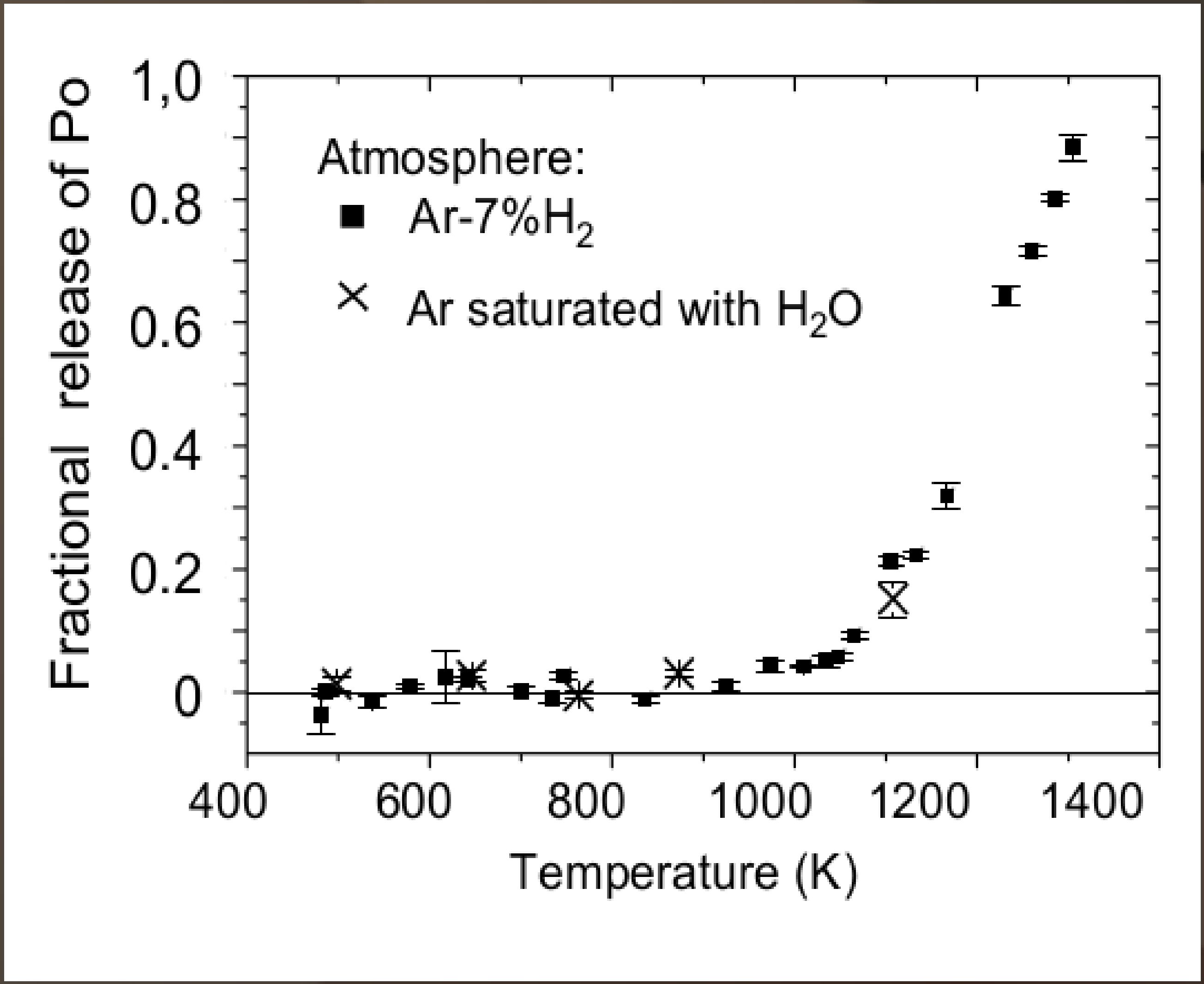
Pb eutectics targets – PbBi



Weight of alloy component: 17%;

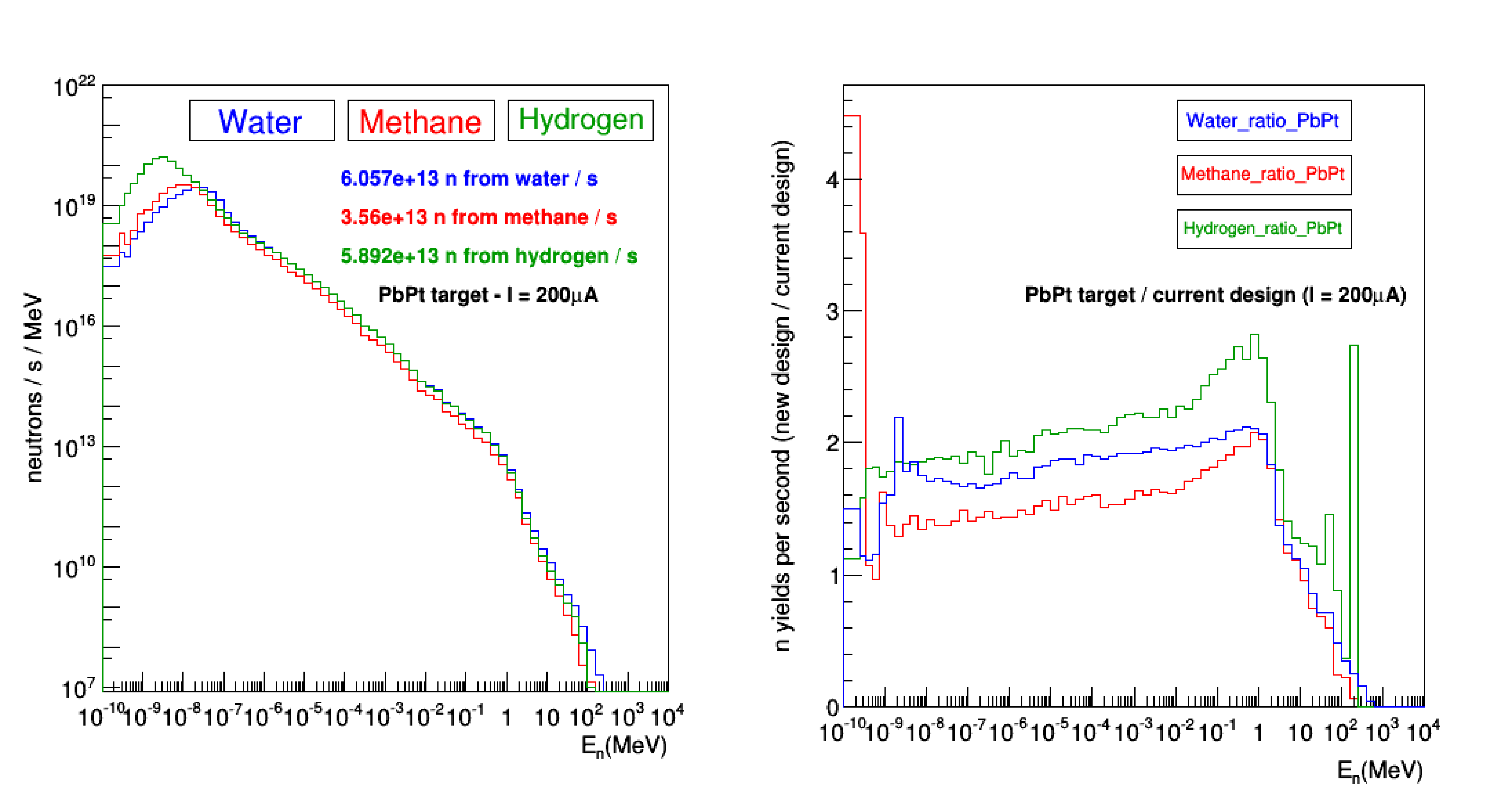
Melting point: 398 K; for direct comparison – used the same p current;

Release of Po from PbBi



J. Neuhausen, U. Köster, B. Eichler: “Investigation of evaporation characteristics of polonium and its lighter homologues selenium and tellurium from liquid PbBi eutecticum” published in Radiochimica Acta

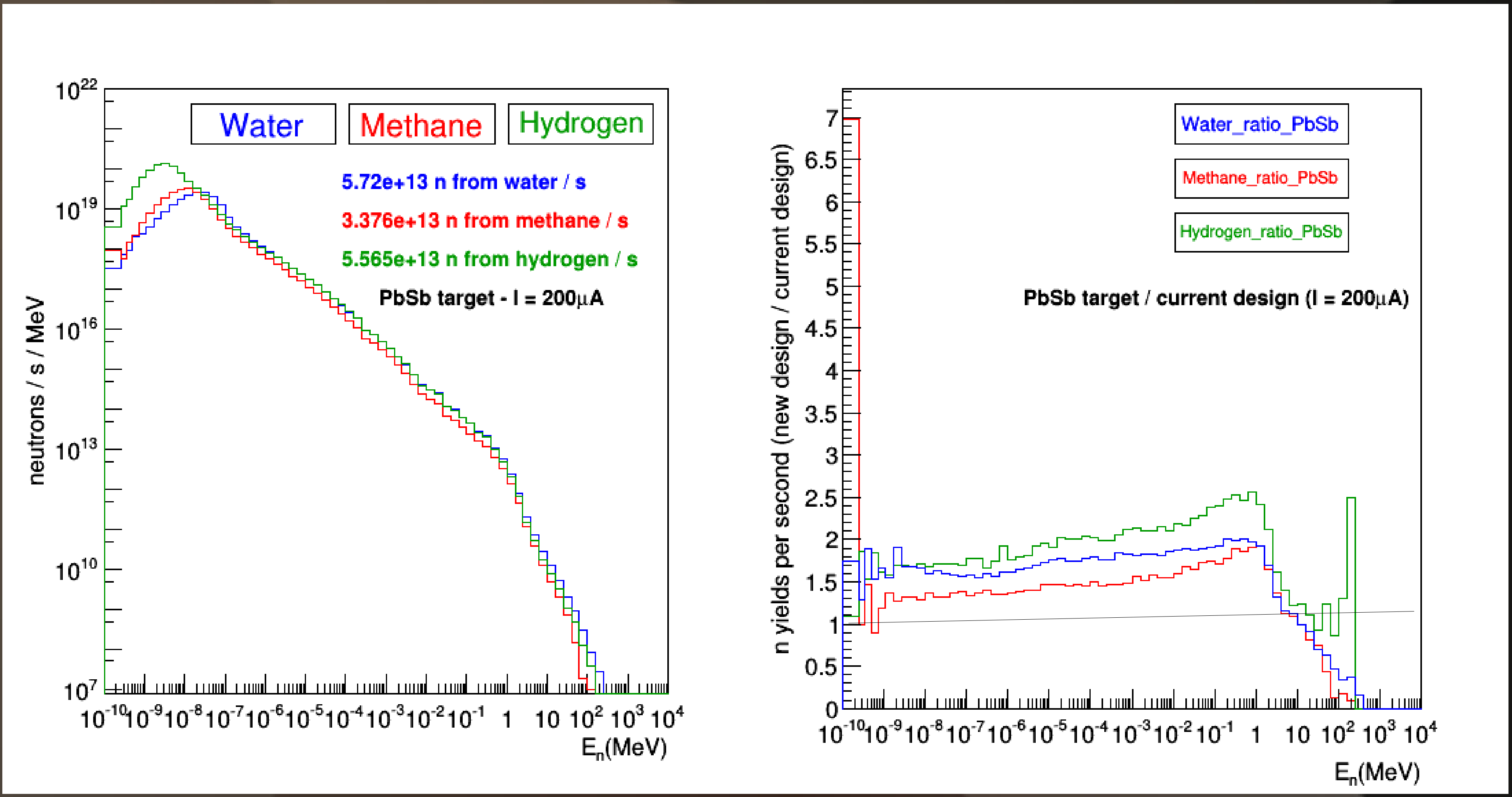
Pb eutectics targets – PbPt



Weight of alloy component: 5%;

Melting point: 563 K; for direct comparison – used the same p current;

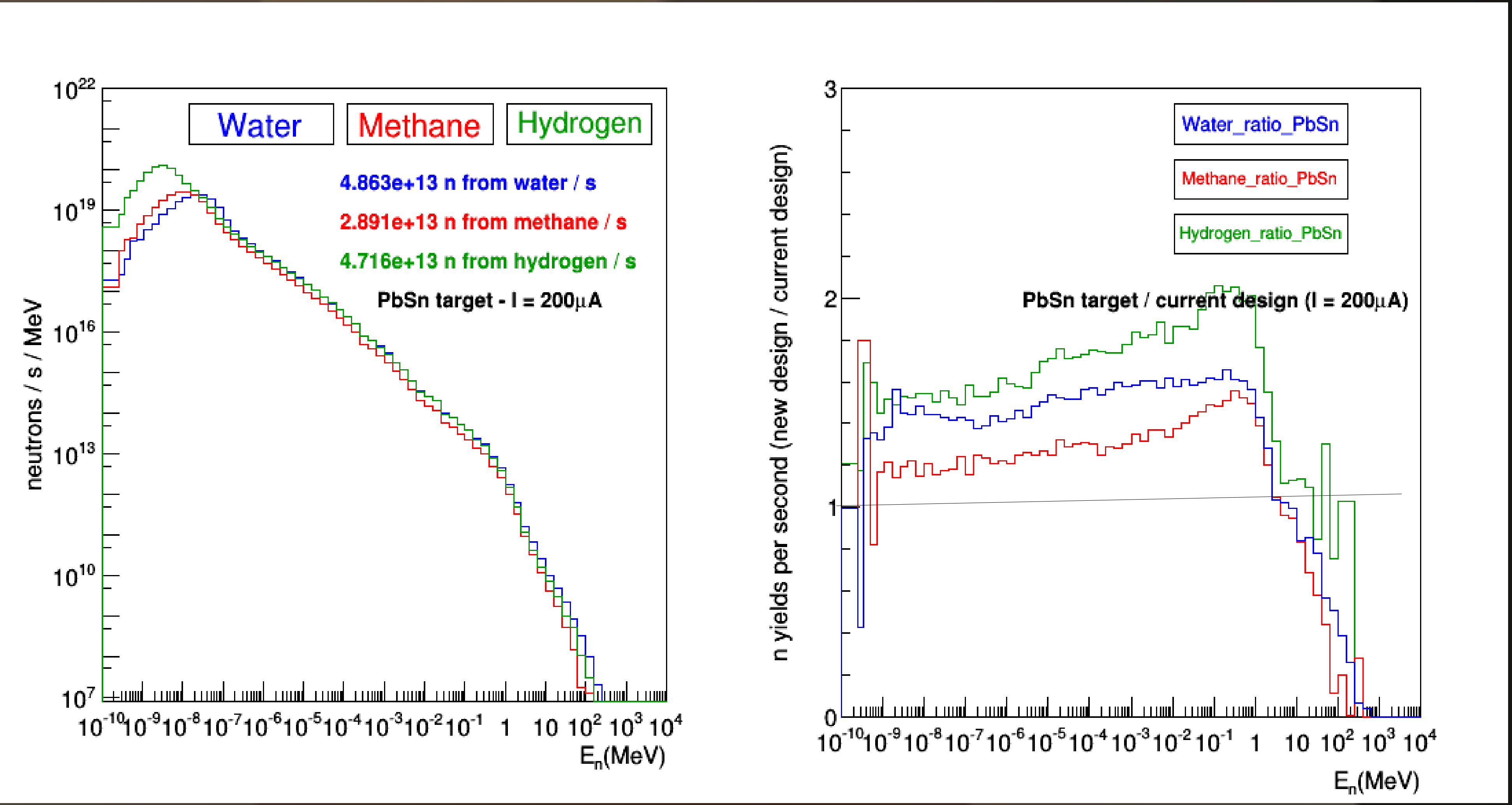
Pb eutectics targets – PbSb



Weight of alloy component: 11%;

Melting point: 520 K;

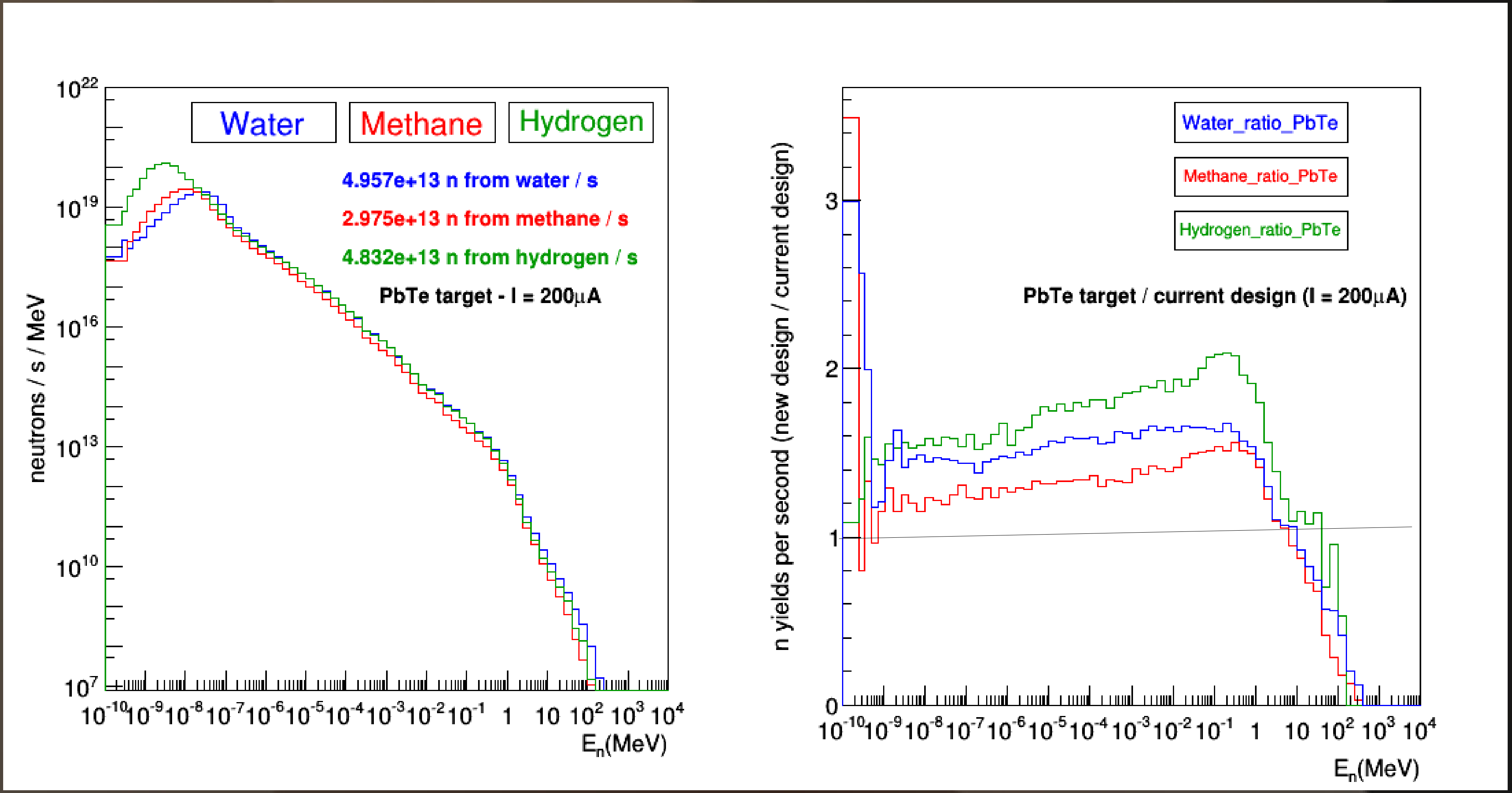
Pb eutectics targets – PbSn



Weight of alloy component: 61%;

Melting point: 460 K;

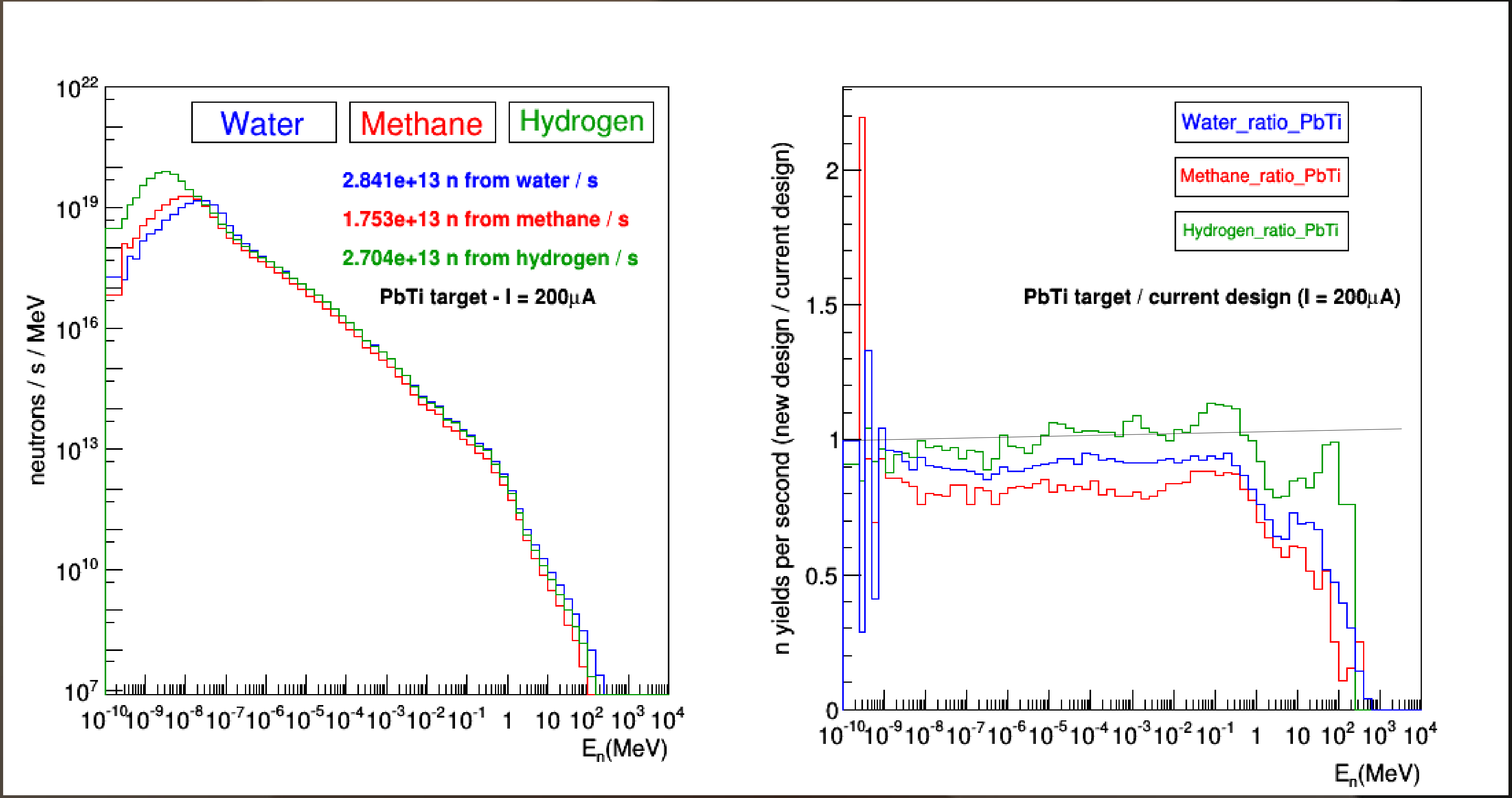
Pb eutectics targets – PbTe



Weight of alloy component: 78%;

Melting point: 680 K;

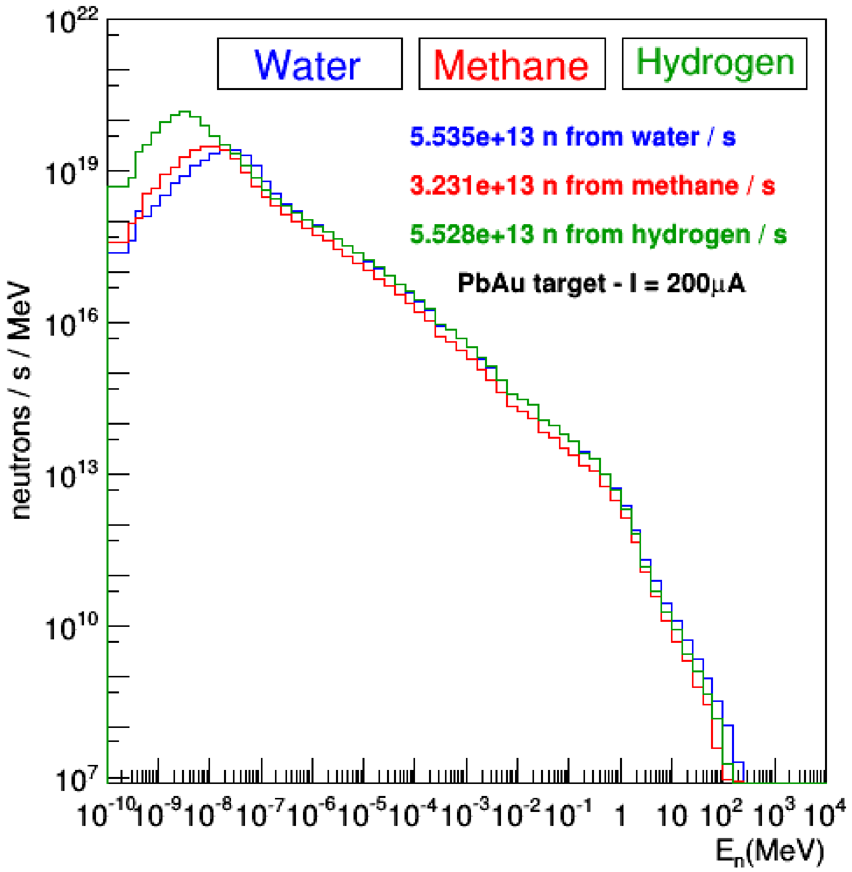
Pb eutectics targets – PbTi

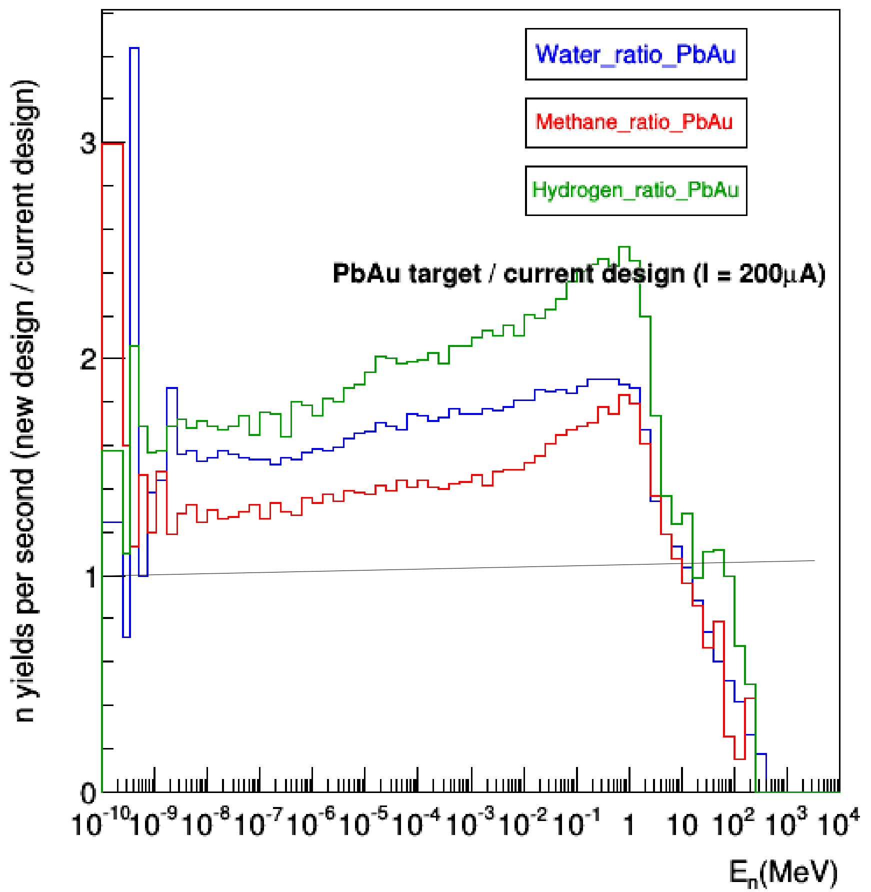


Weight of alloy component: 74%;

Melting point: 998 K;

Pb eutectics targets – PbAu

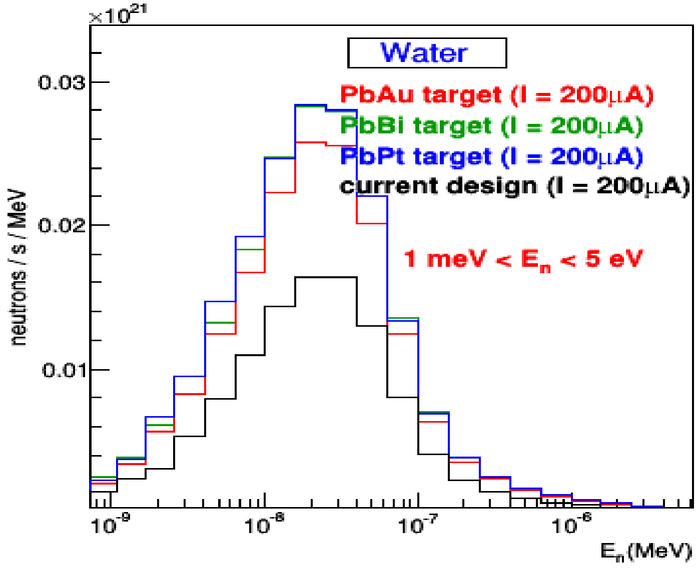


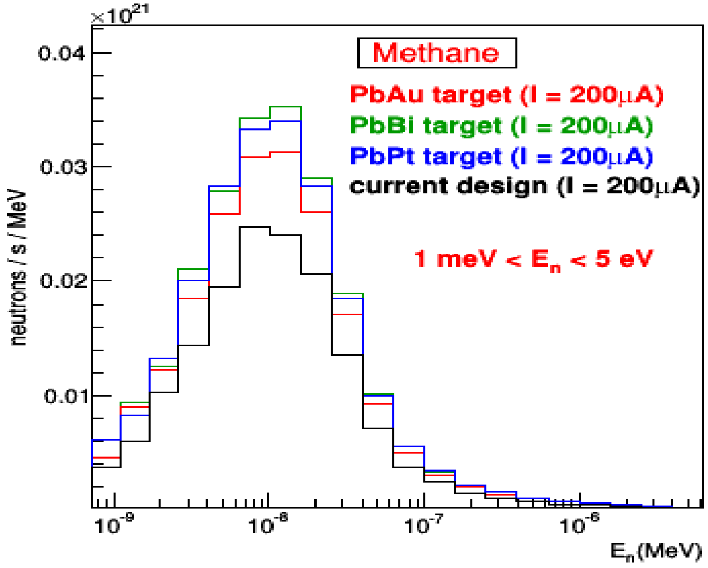


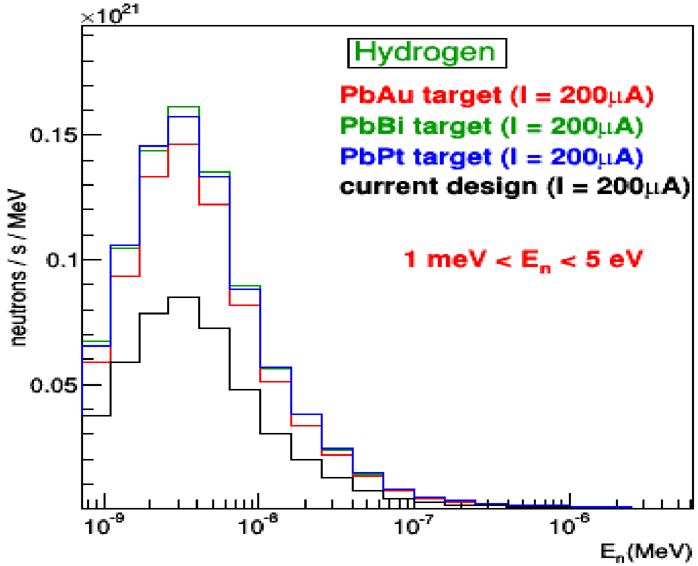
Weight of alloy component: 17%;

Melting point: 485 K;

Comparison between W and Pb eutectics at 200 μA (1)



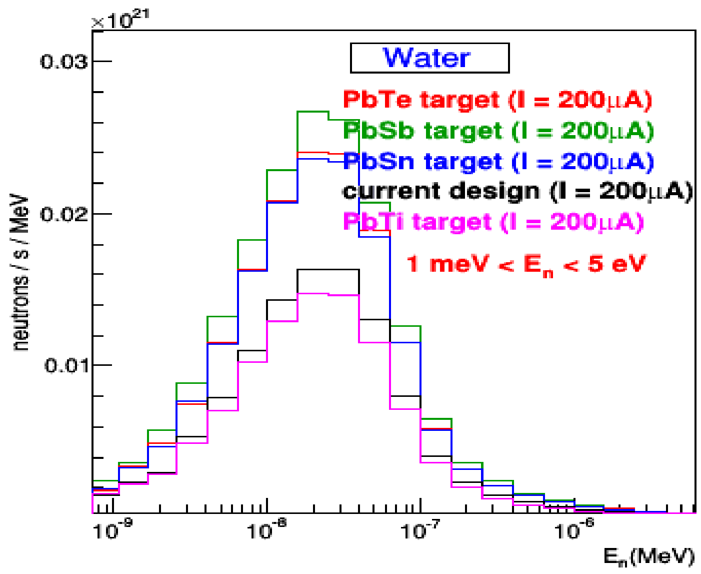


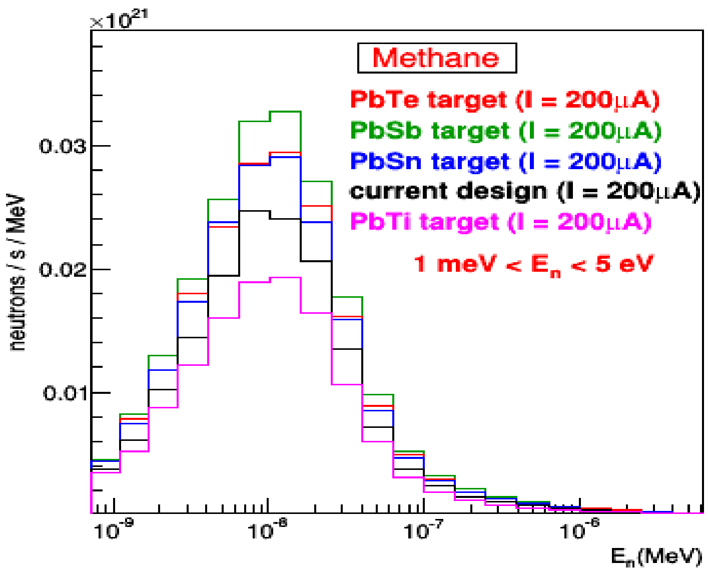


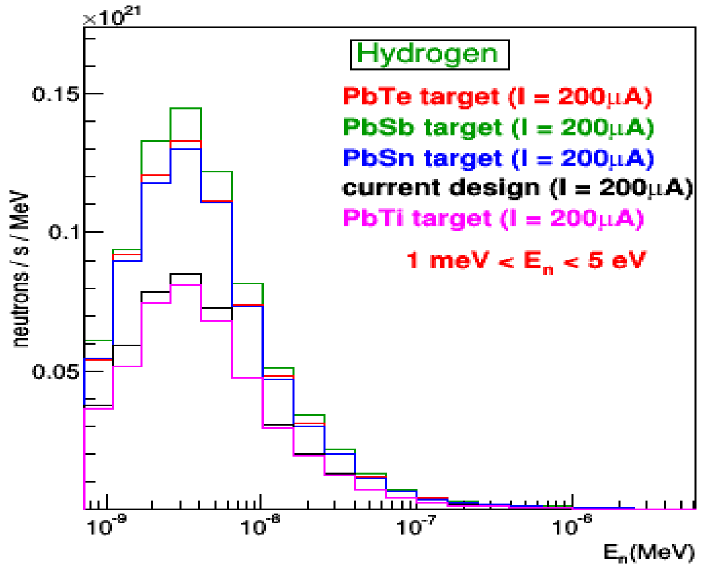
Even at such low proton currents of 200 μA, the Pb eutectics are superior to the W target.

The Pb eutectics molten targets can easily operate at proton currents of up to 10 mA, resulting in much higher neutron yields.

Comparison between W and Pb eutectics at 200 μA (2)

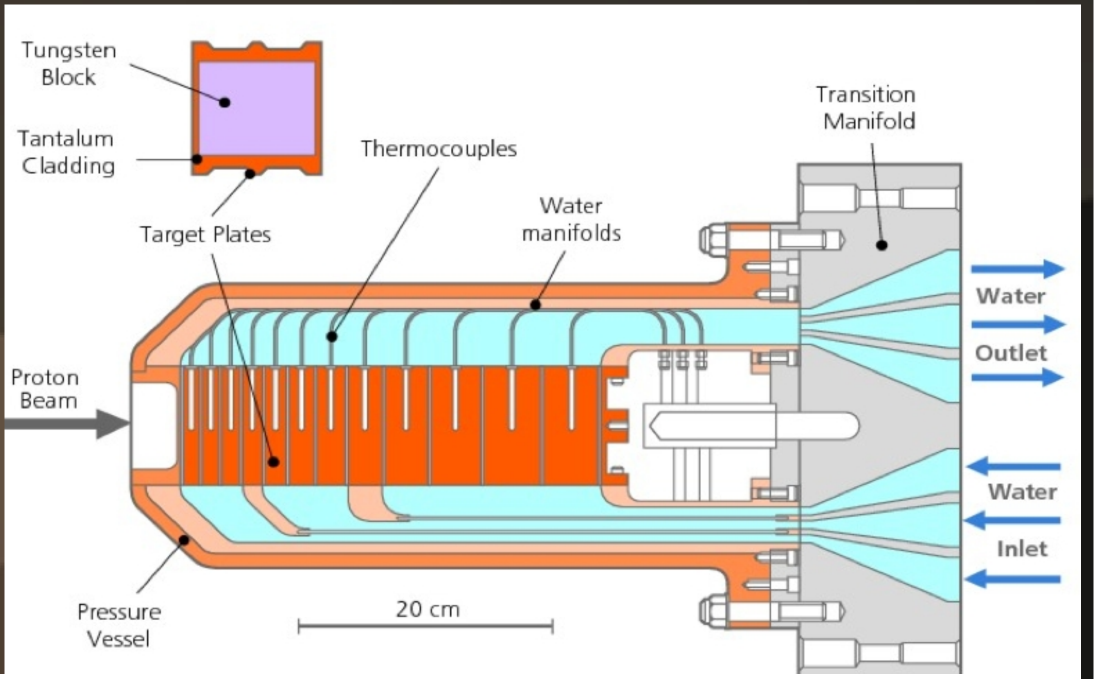


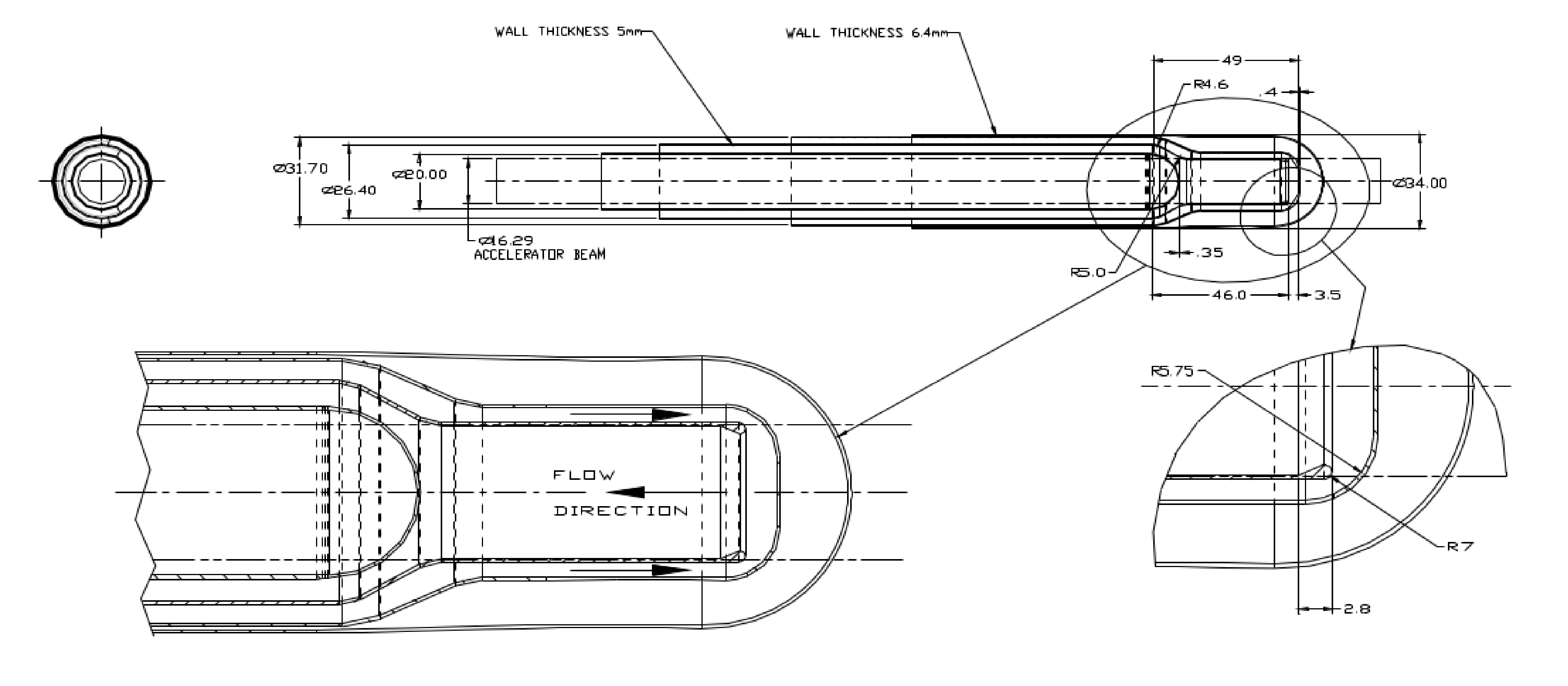


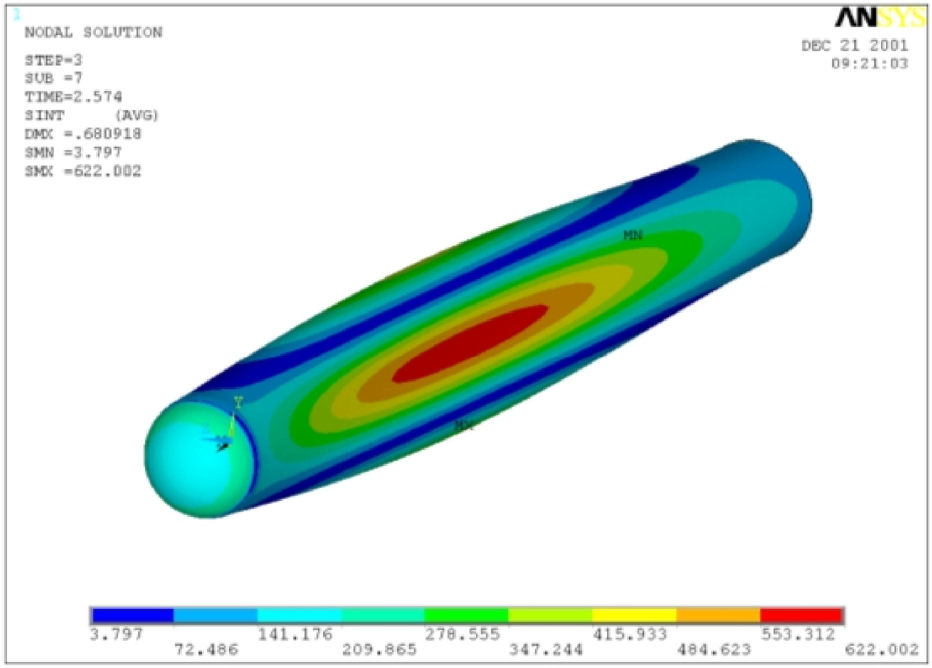


As in the previous slide, all the Pb eutectics results (except PbTi) show higher n yields than the W target, for the same proton current for direct comparison.

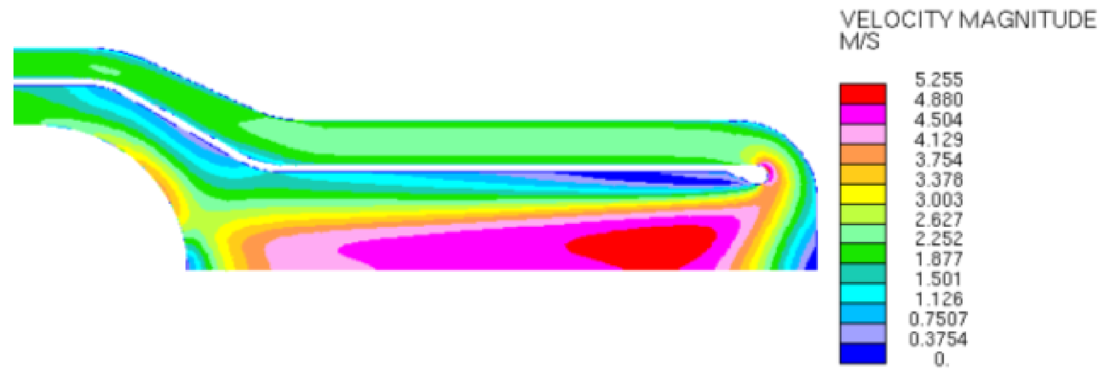
ISIS TS1 target



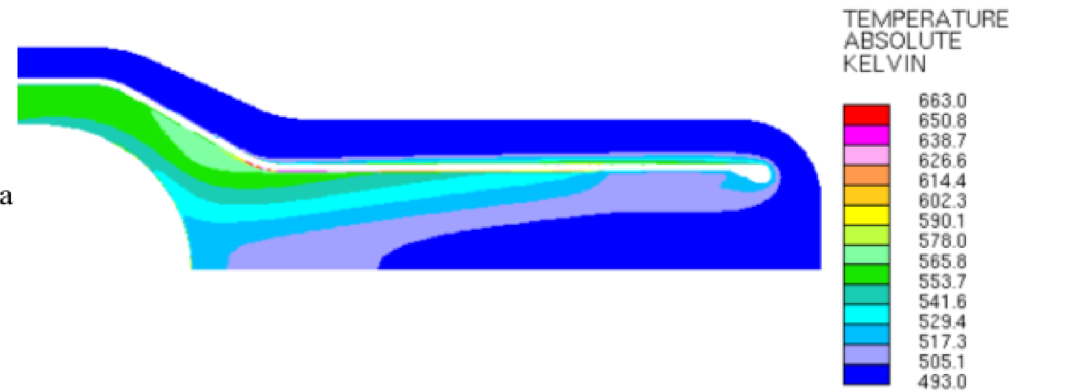


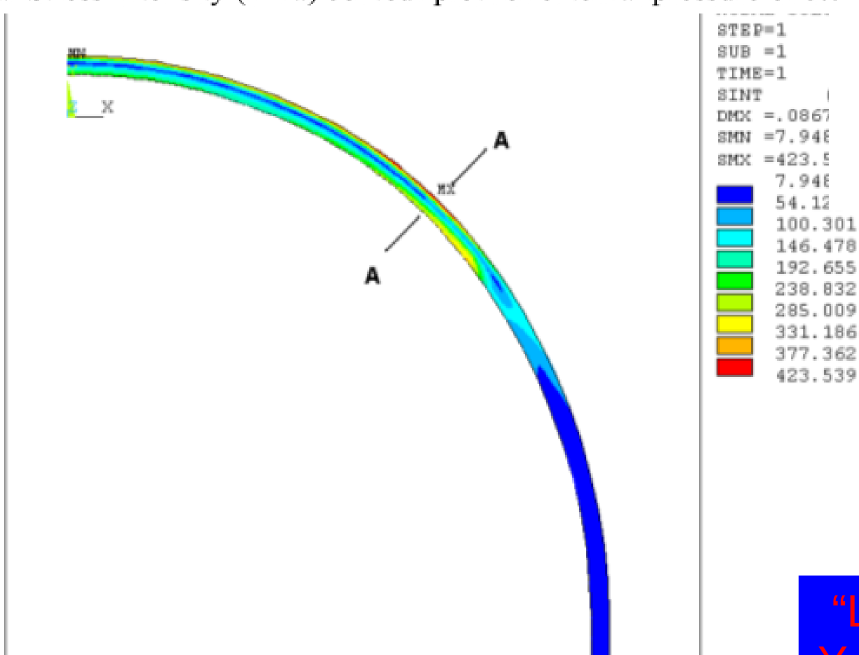


. Total Stress Intensity (MPa) contour plot for external pressure of 5.74 MPa



(a)





Stress intensity (Pa) in the 3.5-mm hemi-spherical beam window during the normal operating conditions

An LBE target design has been successfully developed. Physics, heat-transfer, hydraulics, structure, activation, and safety analyses were iterated to develop the current target design.

"Lead-Bismuth Target Design for Transmutation Reactors", Y. Gohar et al, PHYSOR 2002, Seoul, Korea, October, 2002

Conclusion

- Due to the limitation imposed by the minimum Ta thickness, the plates do not cope with more than 500 kW power. For this power, new plates can be used and the neutron yield increase has been calculated for this new configuration.
- The inner W volume for these new plates could cope with up to 1 MW power on target, but not the 1 mm outer Ta;
- Several Pb eutectics alternatives for the target material have been investigated and they all (except PbTi) show higher n yields than the W target, for the same proton current for direct comparison.