Free Surface and Splashing simulation of a windowless target concept for ESS

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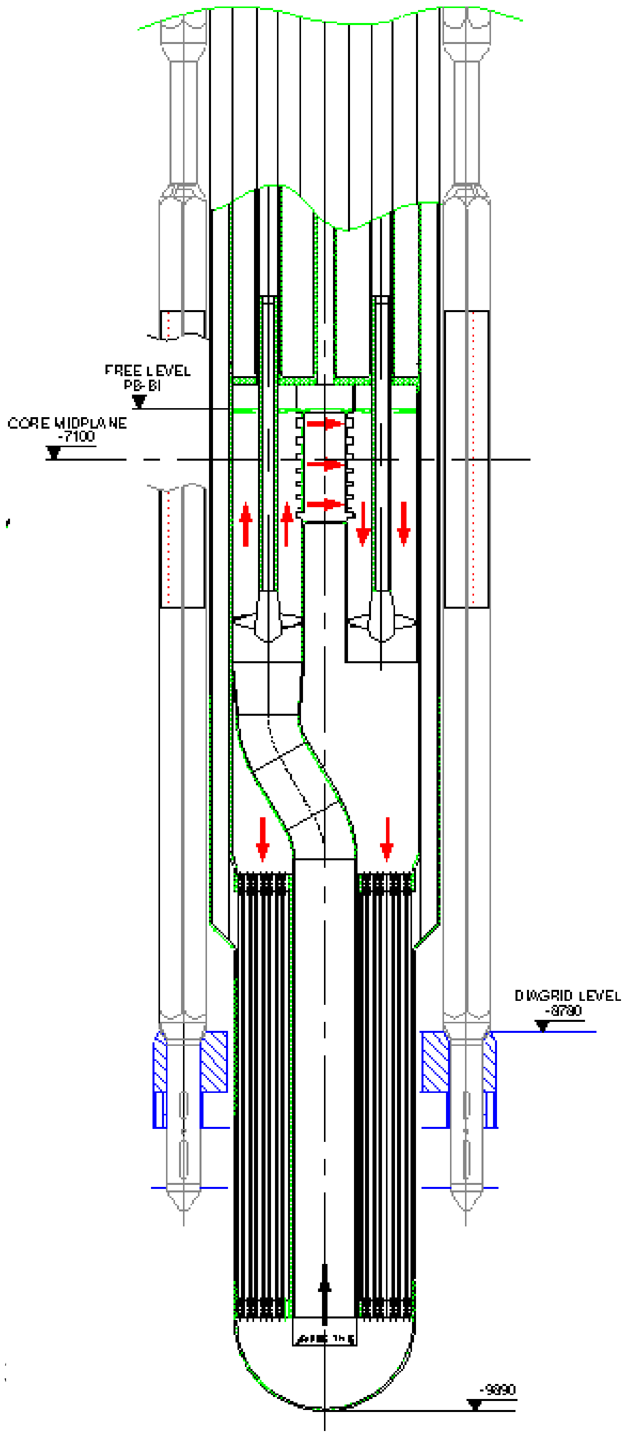
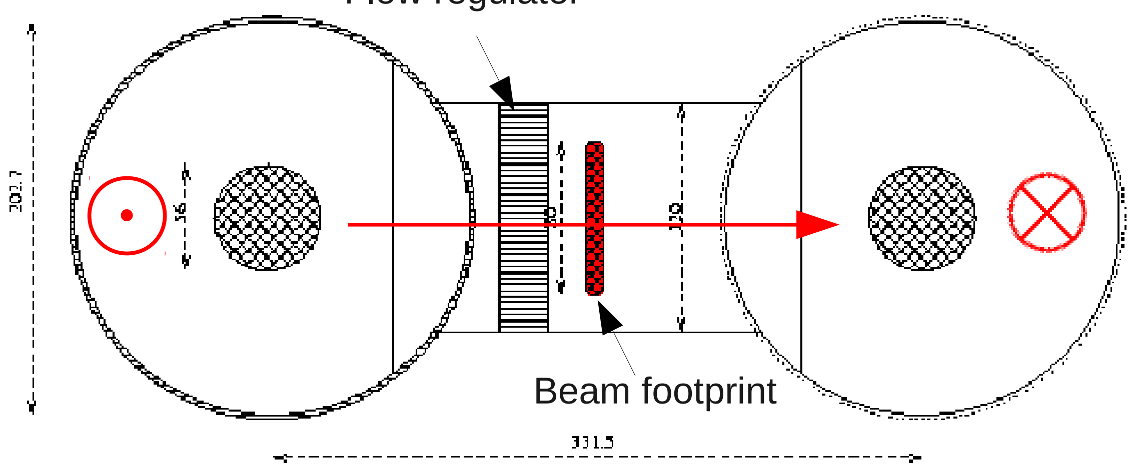
A bit of history of PDS-XADS

- The windowless channel spallation target was proposed first by Ansaldo as a back-up option for the PDS-XADS (FP5). Main motivation was:
  - Solid windows may result short lived
  - Myrrha-like targets, while quite compact, seem very complex to organize/stabilize.
- Starting from the Ansaldo concept, CRS4 and ENEA have developed the design in the context of PDS-XADS. Thermal and structural coupling have been performed, including incidental transients.
- The design was considered sufficiently advanced to be “frozen” and directly extrapolated for EFIT (FP6) without additional development (to let the other options reach the same level).

PDS-XADS Design

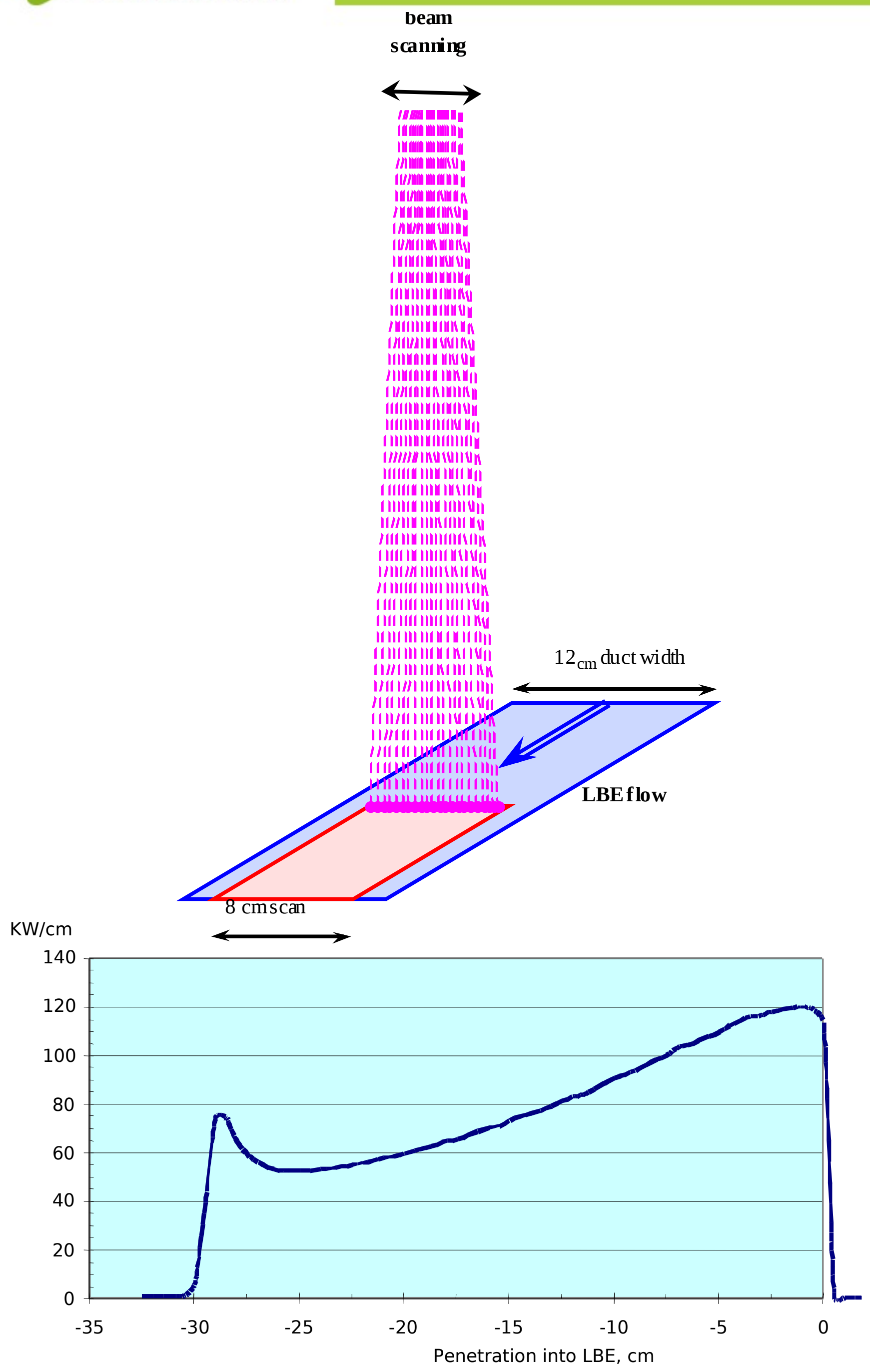


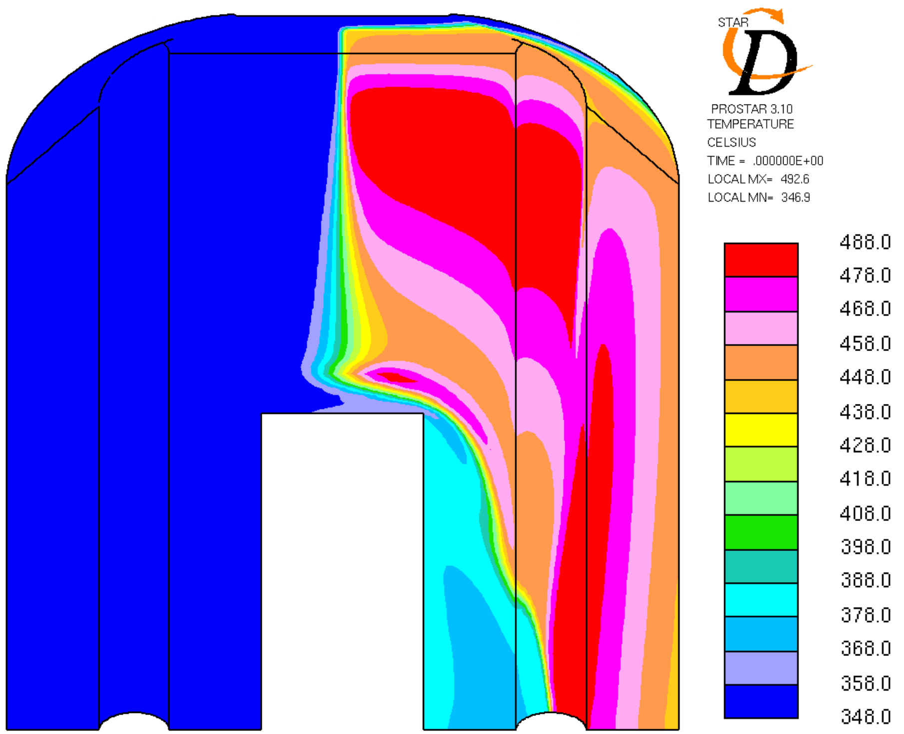


- PDS-XADS target module sketch with flow direction and transverse section with beam deposition area

*Flow regulator: simulated as an anisotrope localized resistance

PDS-XADS Design





- The beam is scanned on the top surface to distribute the power deposition on a channel 12cm and 30cm deep

Some numbers for PDS-XADS and EFIT

	PDS-XADS	EFIT
Proton beam	600MeV, 6mA, 3MWe, 2.6MWth	800MeV, 20mA, 16WMe, 11MWth
Beam penetration length	30cm (LBE)	44cm (lead)
Beam footprint	8cm x 1cm	14cm x 1cm
Flowrate	20l/s	76l/s
Max dT	140K	
Mean dT	78K	104K
Slot diameter	56cm	78cm

An extension to ESS

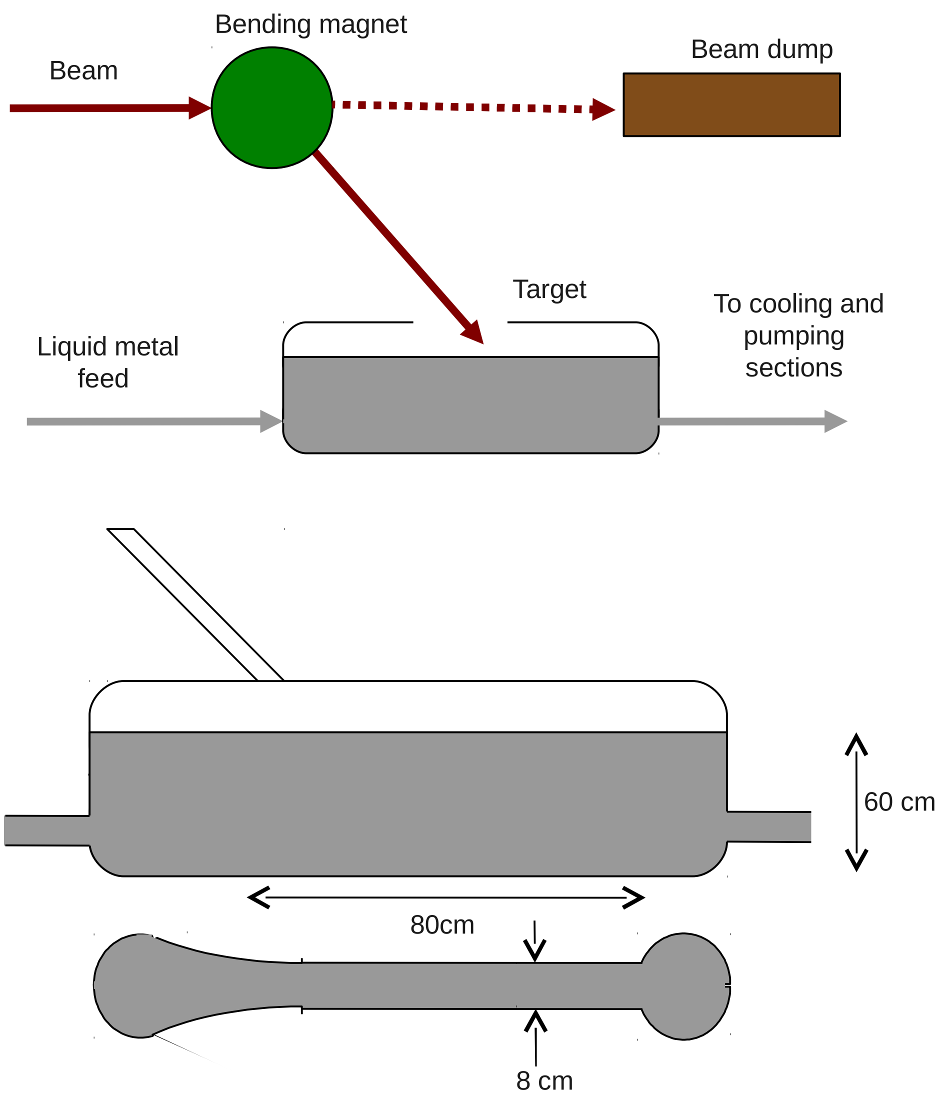
- We tried to apply the channel windowless concept to the ESS target design.
- Technical difficulty for the PDS-XADS project where linked to the very small available space. This constraint can be greatly relaxed for ESS.
- From PDS-XADS experience, we know that we can keep the ratio between maximum and mean dT below 2 with a simple flow tailoring.
- For a 5MWth 20cm wide beam footprint, a channel section 30cm wide, 1m high with 150l/s keeping max velocity below 1m/s would give mean dT about 20K if the beam is vertical.

An extension to ESS

- The main difference is the beam orientation, vertical in PDS-XADS and horizontal for ESS. But it appeared that it would have been possible to modify this parameter bending the beam
- Beam can be inclined 30deg, obtaining half-depth, half-flowrate, double dT. The same dT is obtained doubling the footprint
- Even in windowless configuration, as a safety measure, it is better to isolate the beam line vacuum from the target vacuum.
- The window should only resist a very low pressure difference, this way the target and beam line isolation problems are decoupled. Similar solutions have been tested in PSI and CERN

A rough scheme of the target loop

- The target is a bath of liquid metal with a forced cooling loop
- It is windowless, with the beam entering the vessel angled at 45deg with respect to the vertical
- It requires an additional beam dump and magnet
- The channel size (80x60x8 cm^3) is determined by the beam deposition profile on the target.



Liquid metal selection

Property @ atmosferic and melting temperature	Hg	Pb	LBE
Density [kg/m3]	13534	10673	**10551**
Standard weight [g/mol]	200.6	207.2	**208.2**
Melting point [K]	234.3	600.6	**397.7**
Boiling point [K]	630	2022	**1943**
Heat capacity [J/molK]	28	30.7	**30.8**
Vapour pressure [Pa]	10 @ 350K	1E-4 @ 700K	**1E-4 @ 700K**
Sound speed [m/s]	1451.4	1791	**1774**
Thermal exp. Coeff. [10-6/K]	60.4	120	**123**

- Lead Bismuth Eutectic was selected.
- It has a relatively low boiling point and is characterized by an extremely low value of the vapor pressure

Demonstration of feasibility through CFD analysis

- The channel design similar to PDS-XADS has been tested in the ESS operating conditions to verify the thermal and fluid dynamica feasibility of the concept
- The beam hits the free surface of the channel at an angle of 45deg
- The ESS beam has an energy of 2.5 GeV, and mean current intensity of 2mA, the beam power is deposited with long pulses, each pulse is 1ms long and the pulse frequency is 20Hz
- The peak current is therefore 50 times higher than the average
- The total average power on the target is 2.3 MW

Demonstration of feasibility through CFD analysis

- The energy distribution per proton inside the material is approximated with an analytical formula interpolating montecarlo simulations (courtesy of E. Noah)

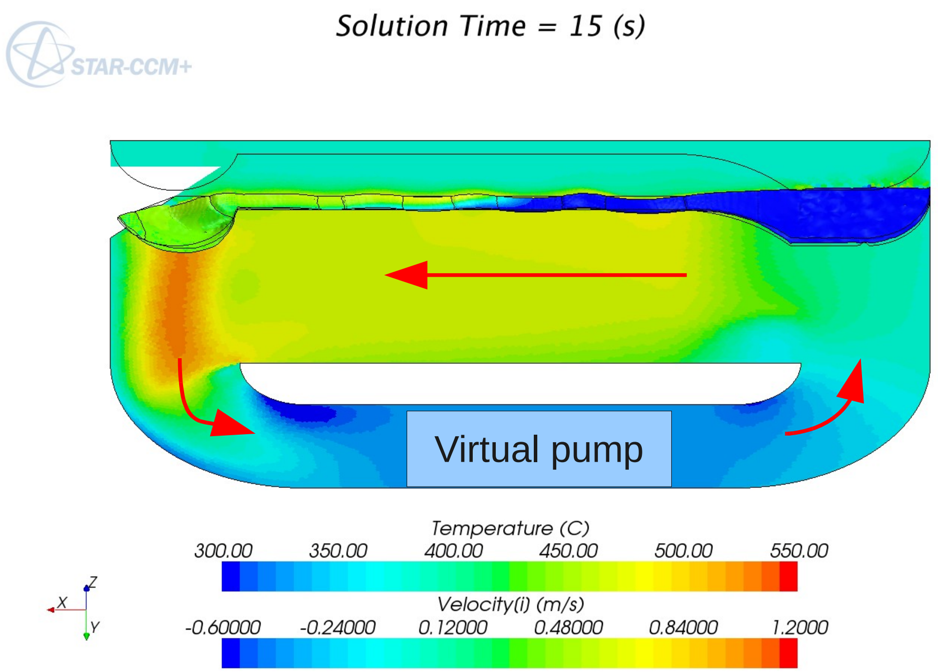
$$e_p(x_1, x_2, x_3) = f(x_1, x_2)\, g(x_3)$$

$$f(x_1, x_2) = \exp\left(-\frac{1}{2}\left(\left(\frac{x_1}{\sigma_1}\right)^2 + \left(\frac{x_2}{\sigma_2}\right)^2\right)\right) \qquad g(x_3) = \alpha \exp\left(\frac{-x_3}{\beta}\right)\left(1 - \exp\left(-\gamma - \frac{x_3}{\delta}\right)\right)$$

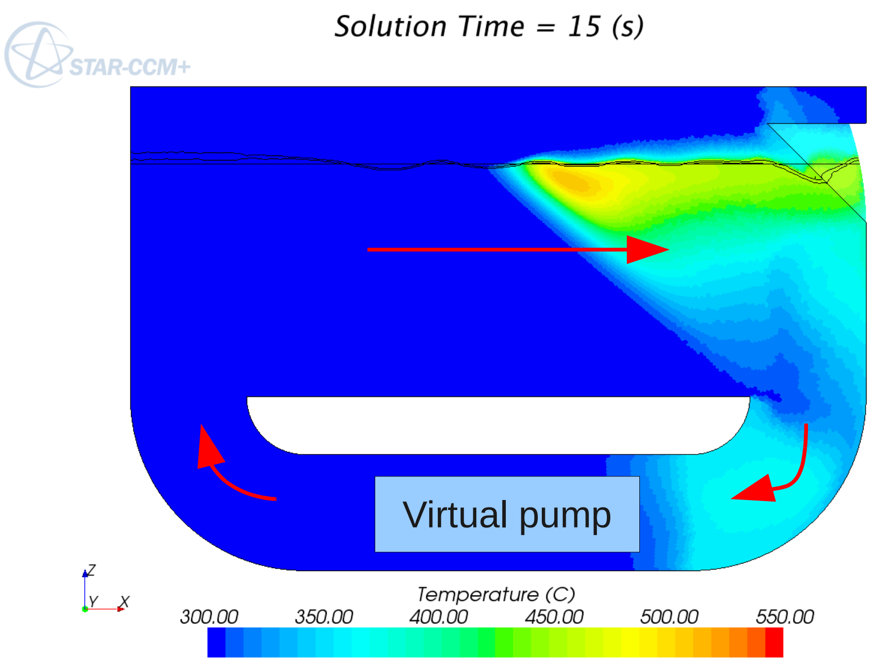
- Peak thermal power: 2.23 kW/cm3
- Flow rate: 28.2 l/s
- Velocity in the spallation zone: ~0.6 m/s
- Incoming flow temperature: 300 C
- Maximum temperature: surface 489 C, bulk 510 C (vapour pressure ~10^{-3}Pa)

Flow analysis and temperature distribution

- The free surface is stable with a flow rate of 28.2l/s

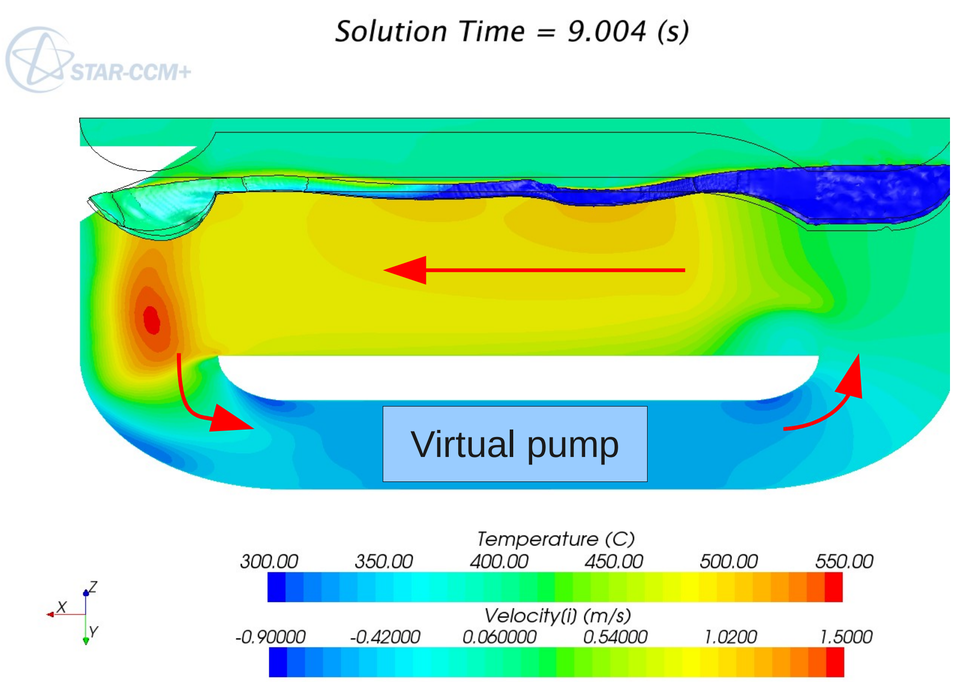


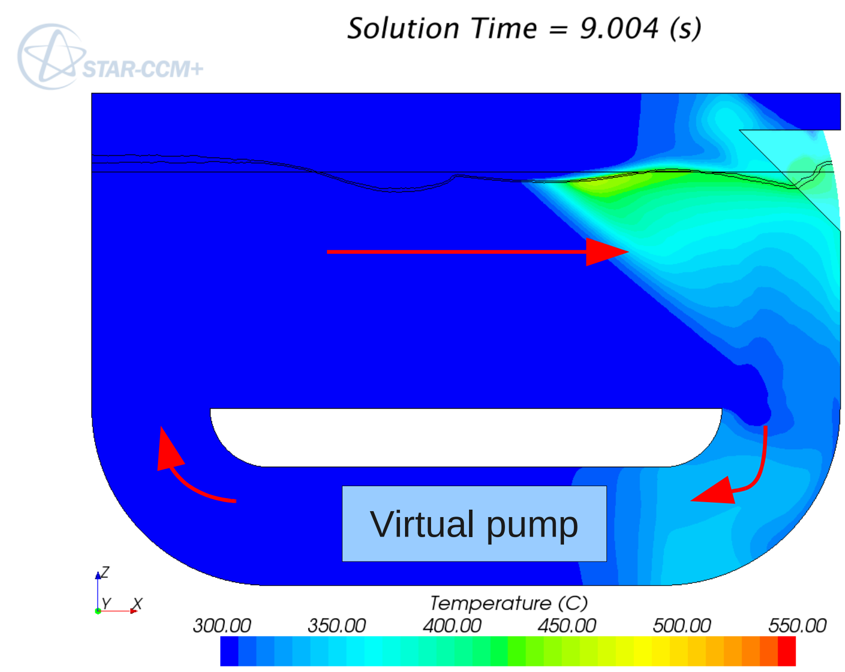
- Temperature on the free surf. and velocity magnitude on simmetry plane



- Temperature field on the simmetry plane

Flow analysis and temperature distribution





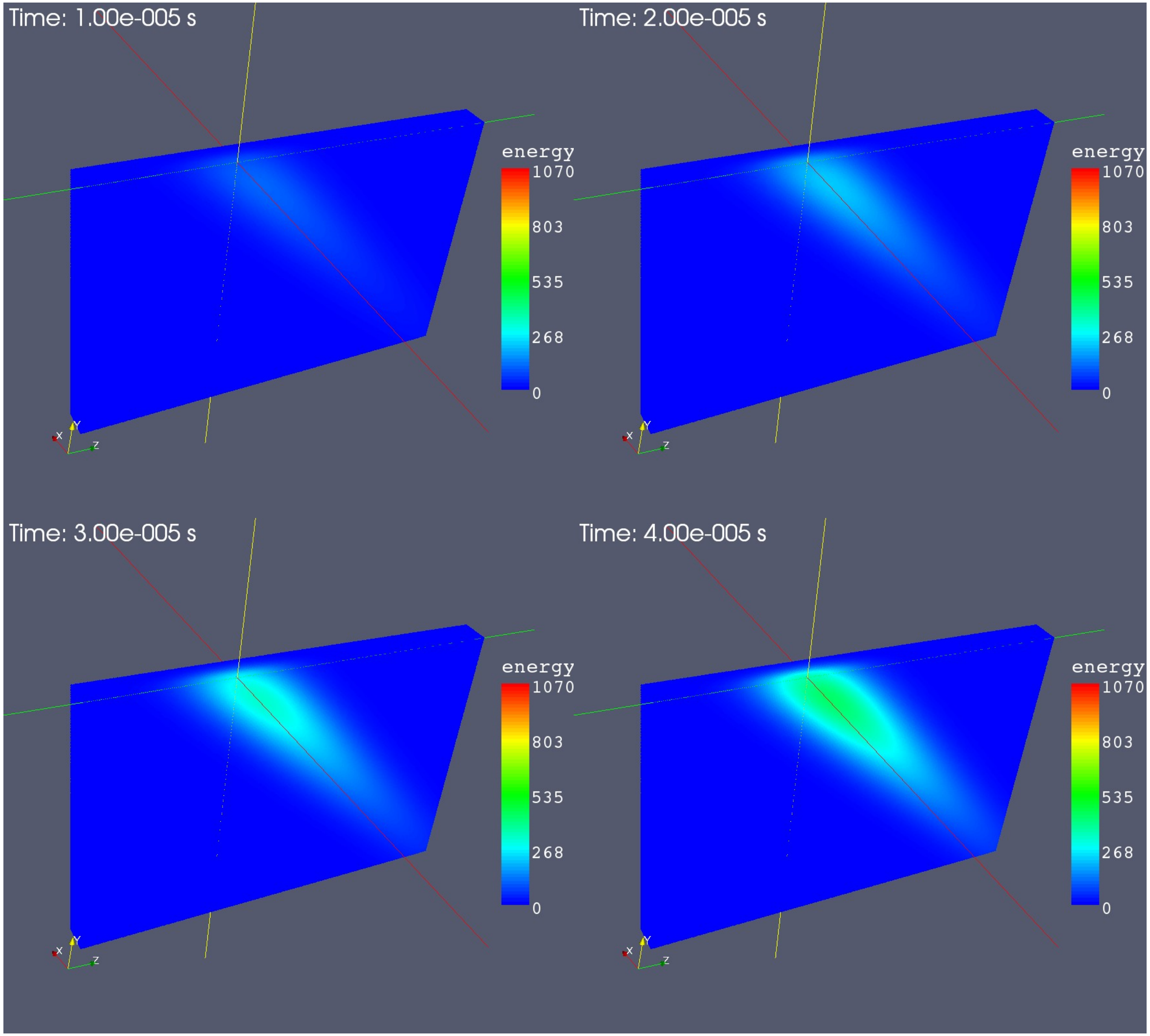
- Increasing the flow rate to 39.0l/s, the velocity in the spallation zone reaches ~0.8m/s, the max. temperature is 451 C but the free surface becomes slightly unstable

Splashing: an SPH analysis

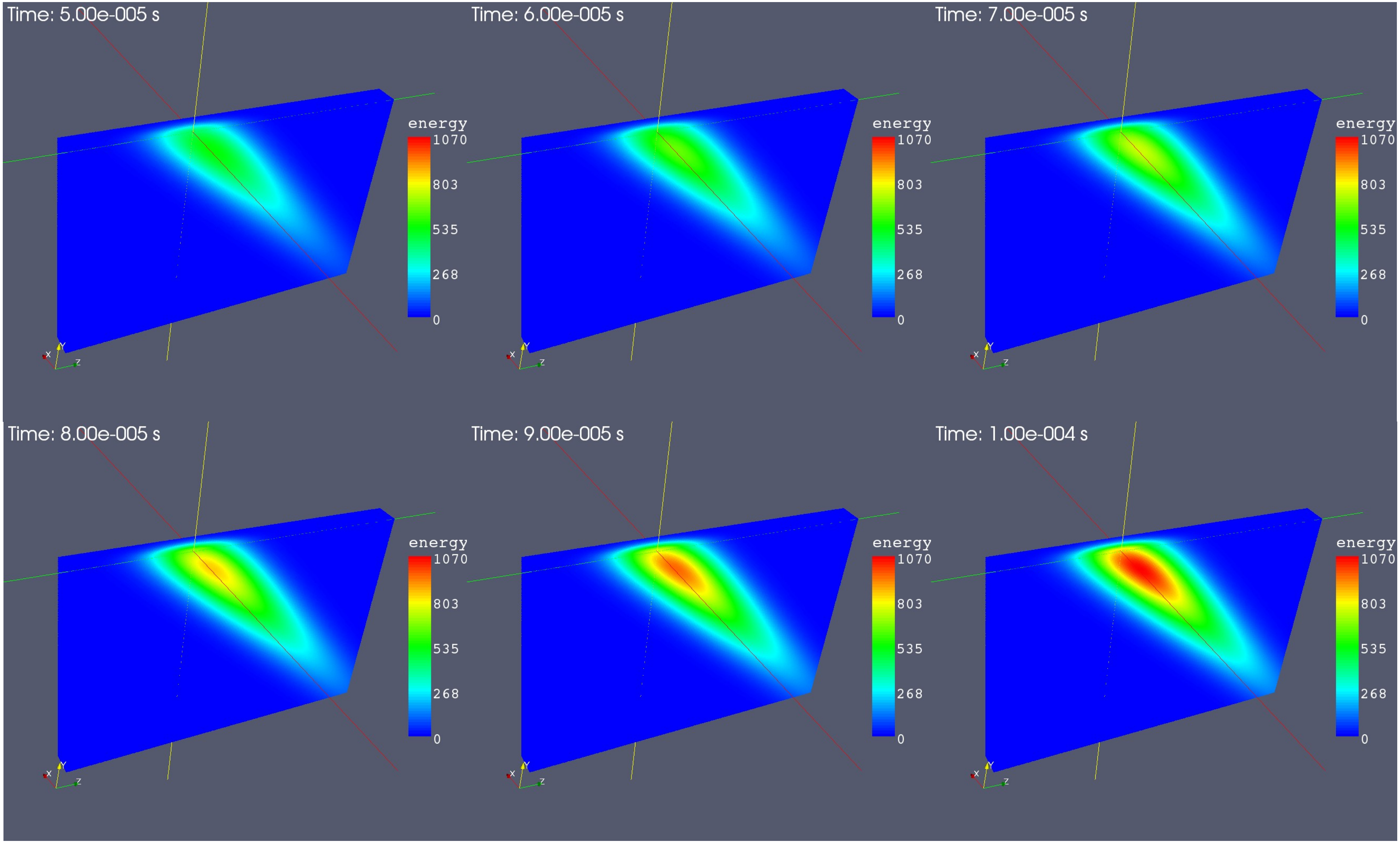
- A concern for windowless target concept is the splashing phenomenon from the free surface.
- Targets with short pulse design have experienced splashing velocities up to 10m/s, corresponding to an height of the drop jet of 5m ($h = 0.5\ v^2/g$).
- To verify this an Smoothed Particle Hydrodynamics analysis was run, capable of capturing the acoustic wave propagation.
- The SPH model takes advantage of the symmetry and uses over a million particles with a spacing of 2.5mm
- The transient simulations are run for 0.1ms at first to capture the development of the pressure wave and then for 2ms. We show the effects of the first pulse.

SPH results: energy density

- The plots show the thermal energy distribution in one half of the model
- The first 0.1ms of beam deposition is shown
- Most of the phenomena happen in this period

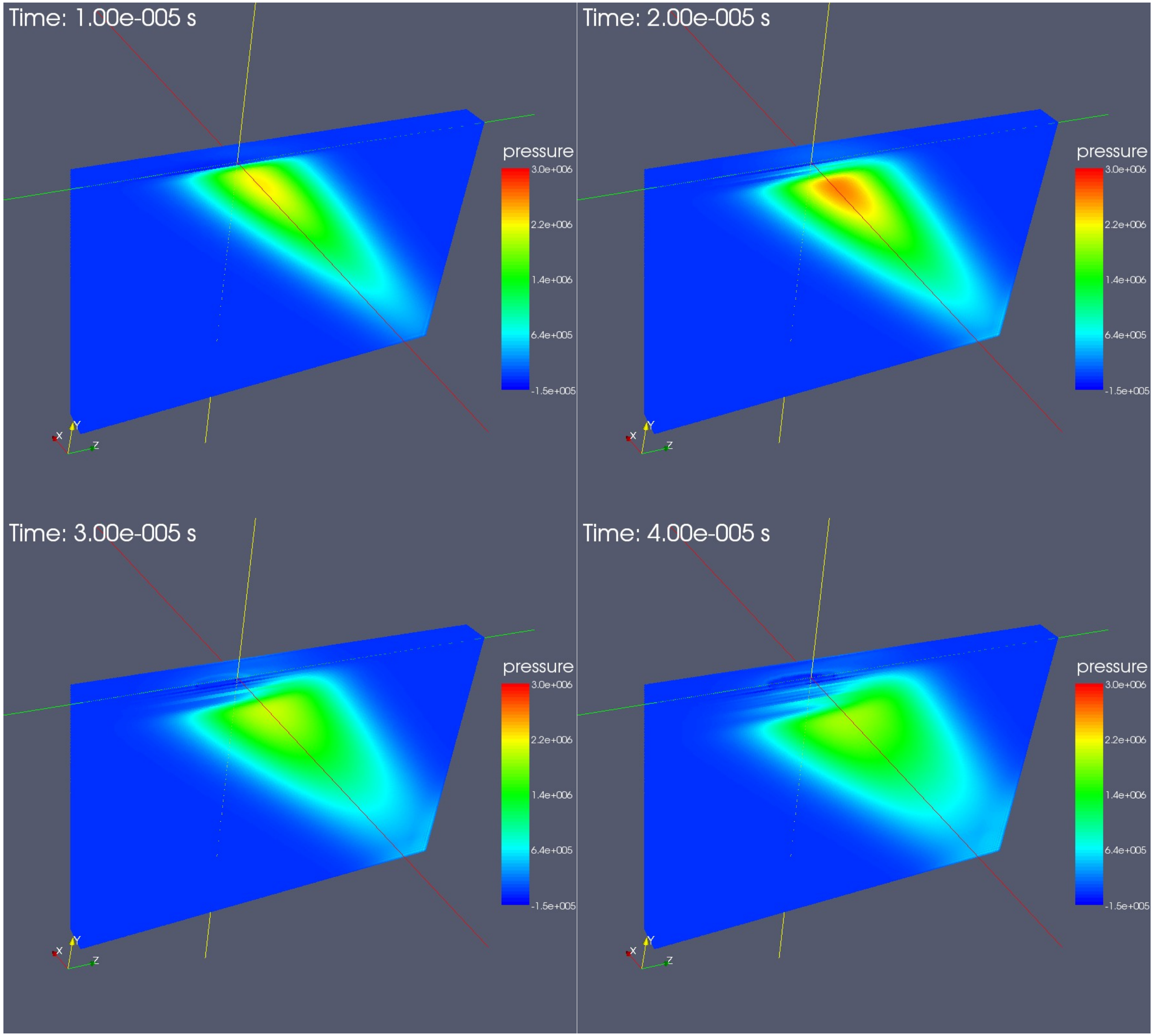


SPH results: energy density

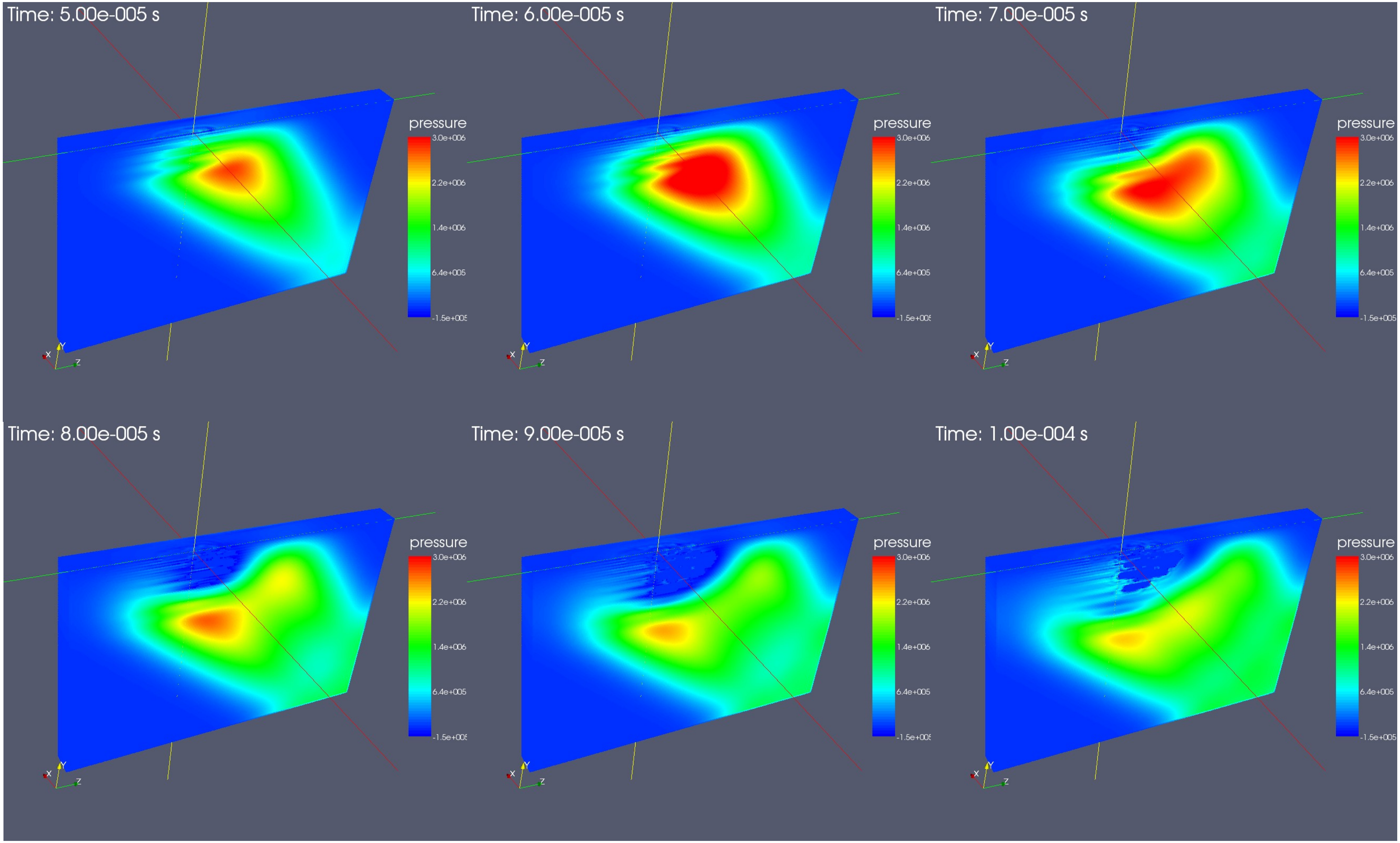


SPH results pressure

- The plots show the propagation of a pressure wave in the model
- The maximum pressure is recorded in the center of the model
- The free surface induces a cavitation at the beam entrance

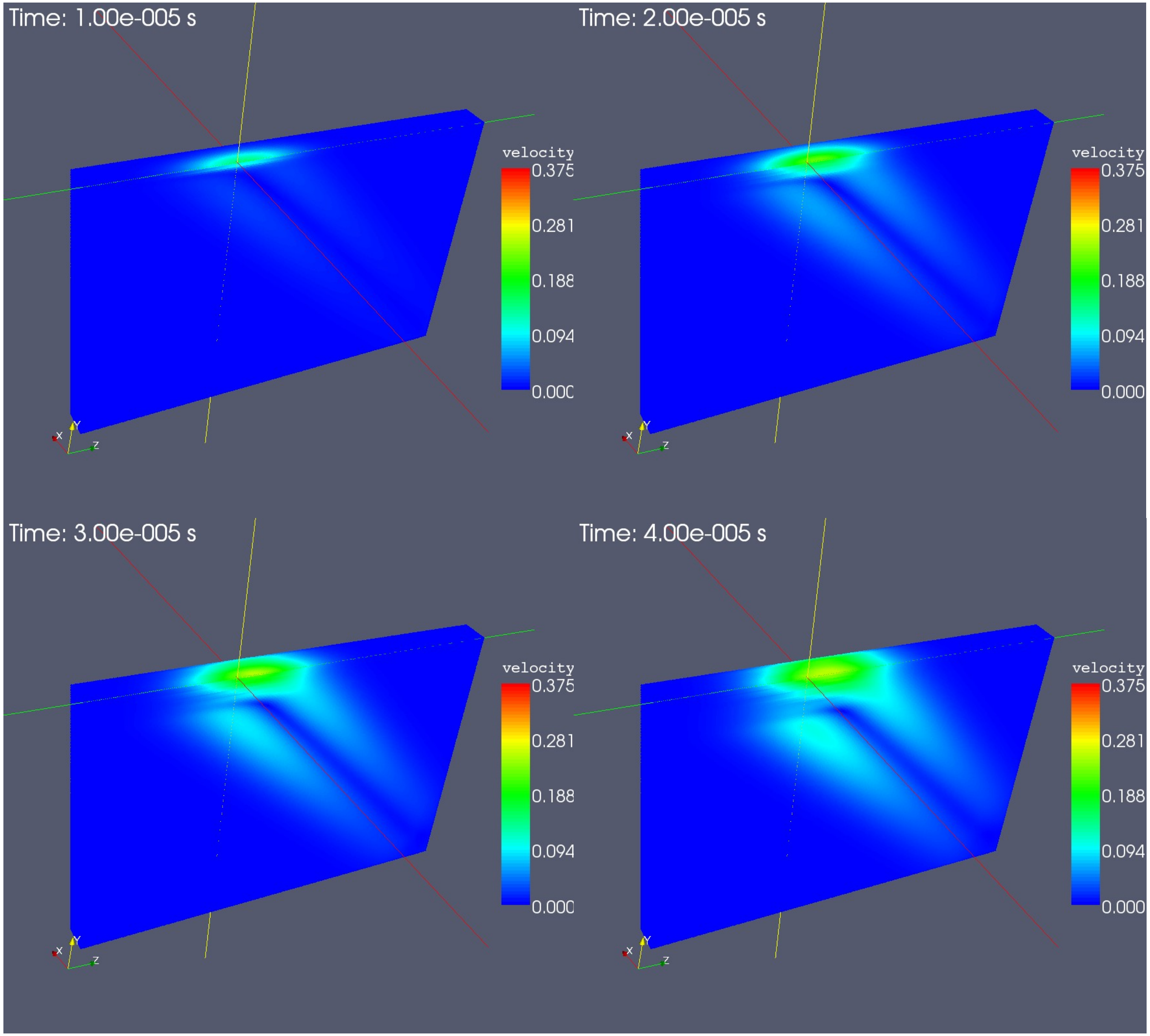


SPH results: pressure

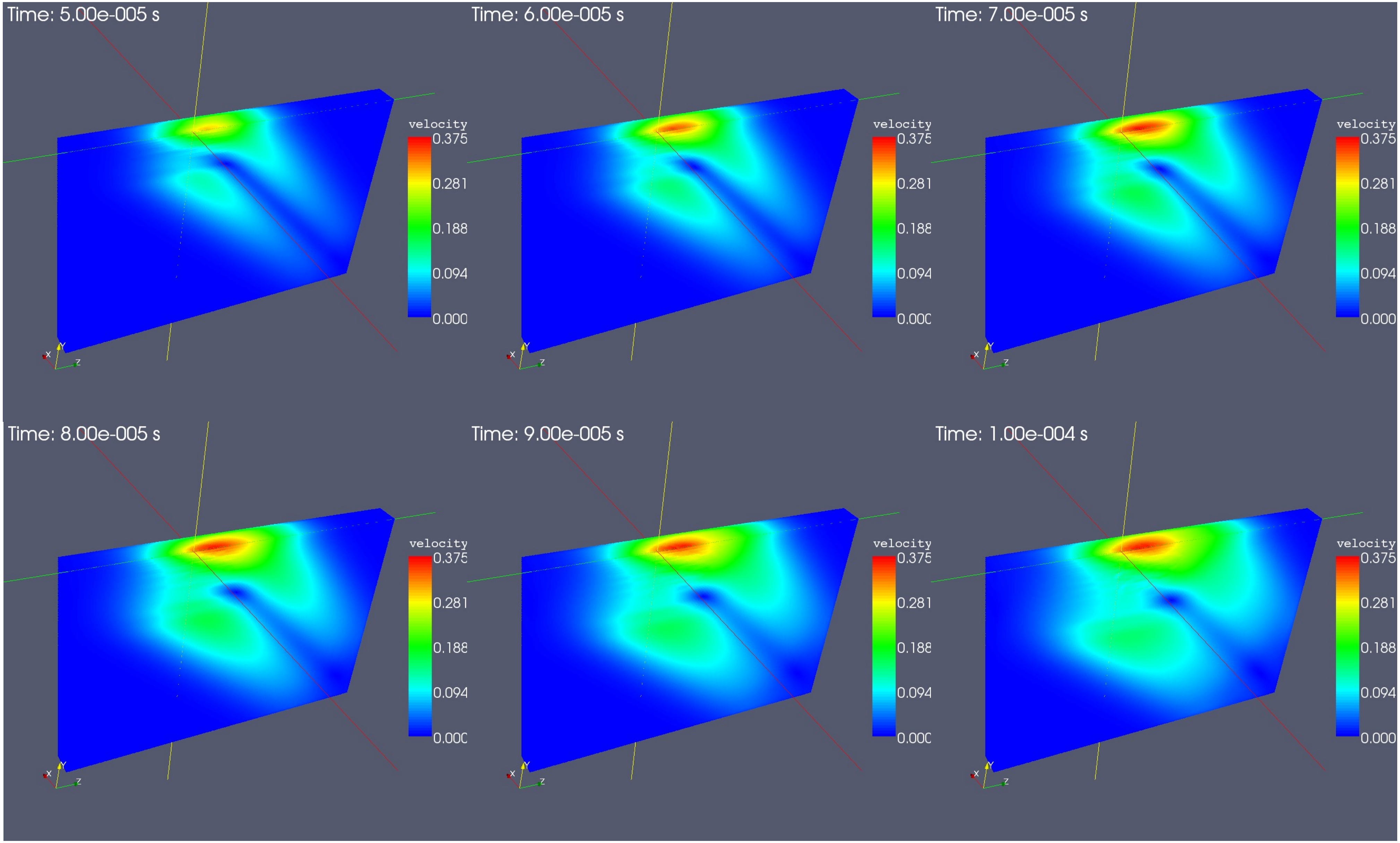


SPH results: velocity magnitude

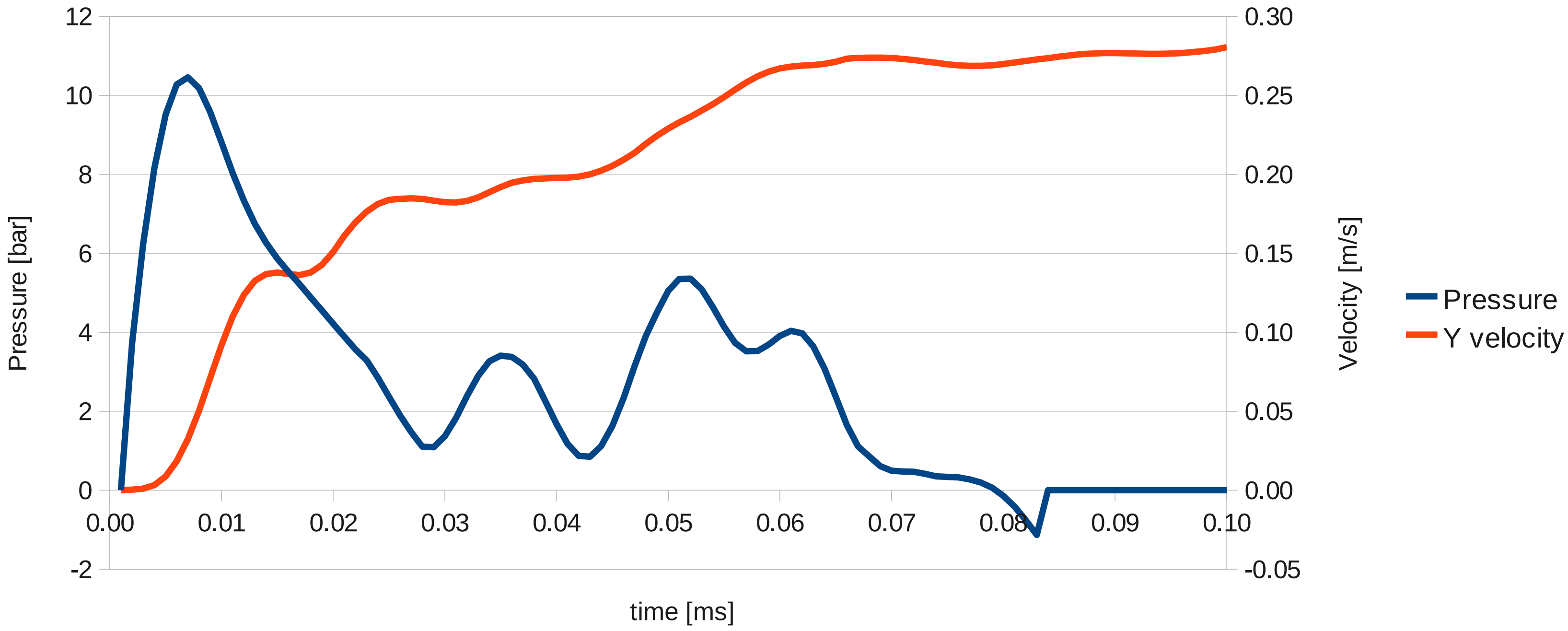
- The plots show the velocity magnitude inside the model and the propagation of the acoustic wave
- The velocity at the free surface becomes constant due to the loss of continuity



SPH results: velocity magnitude

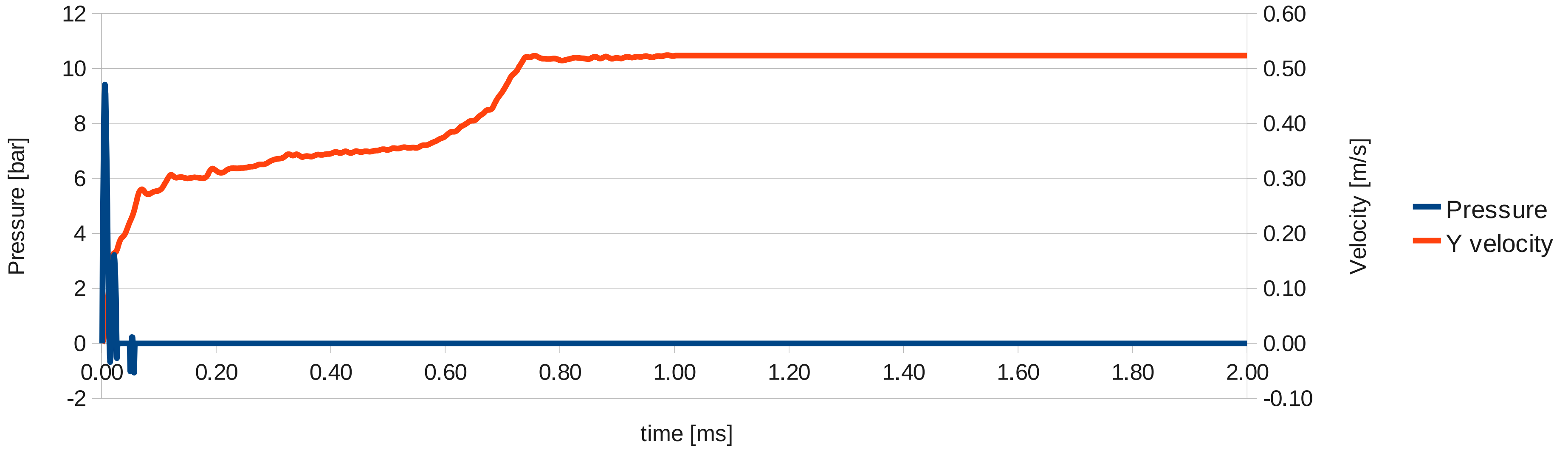


SPH results: splashing velocity



- The graph shows pressure and vertical velocity for a point located on the beam axis, 5mm below the free surface
- The vertical velocity reaches a plateau due to cavitation
- Due to the rate of power deposition compared to the speed of sound in LBE and the beam footprint, less than 1/10 of pulse energy contributes to splashing velocity

SPH results: splashing velocity



- In the 2ms long simulation we see the first plateau due to the direct wave and a second increase in velocity after 0.6ms due to the reflected wave coming from the bottom and the sides of the vessel
- The maximum velocity is constant after a time lower than the deposition time of the first pulse
- After 1ms, the continuity is temporarily lost and only gravity acts on the droplets

SPH results: discussion

- The peak value of the fluid velocity calculated is 0.6m/s. This value is obtained with a tensile strength of the liquid of 1.5bar an estimation based on experiments on mercury loops.
- The tensile limit is hard to measure, depends on the purity of the material and on the surface tension, several factors let us think that this limit for LBE in experiment conditions may be much lower; the splashing velocity would therefore be even lower if present.
- The peak value of 0.6m/s is much lower than the estimated value of 10m/s of the 2003 report, based on short pulse experiments and simulations
- The droplet jet in these conditions would have a maximum height of less than 2cm

Conclusions

- The loop can be operated with LBE or Lead keeping the vapor pressure below 0.01Pa.
- Splashing, if ever, is expected to be very low (few centimeters).
- There is large room for optimization and upgrading: avoid second reflection, make flow temperature more uniform, organize better the flow velocity profile and the beam profile.
- The main issues are in the bending of the particle beam and in the difficult positioning of the moderators.
- These issues have been solved by KIT in the development of the WITA concept