ESS
NEUTRINO
SUPER BEAM

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

The HiRadMat capabilities for ESSνSB future target tests

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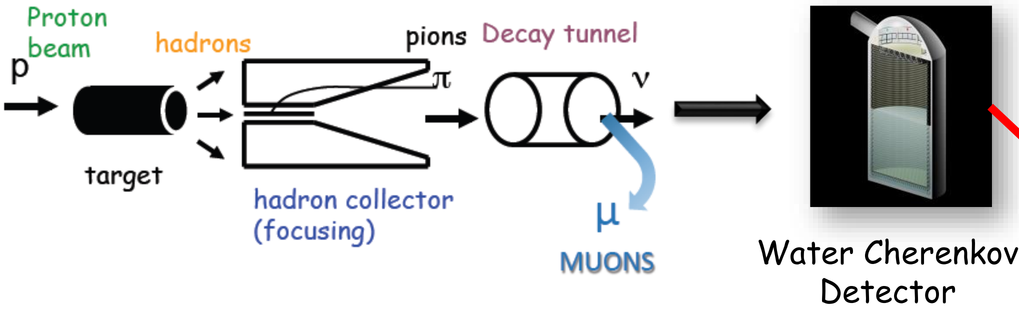
Outline

- Overview of the ESSνSB (European Spallation Source Neutrino Super Beam) project
- Design of the target station
- Possible HiRadMat future tests
- Summary

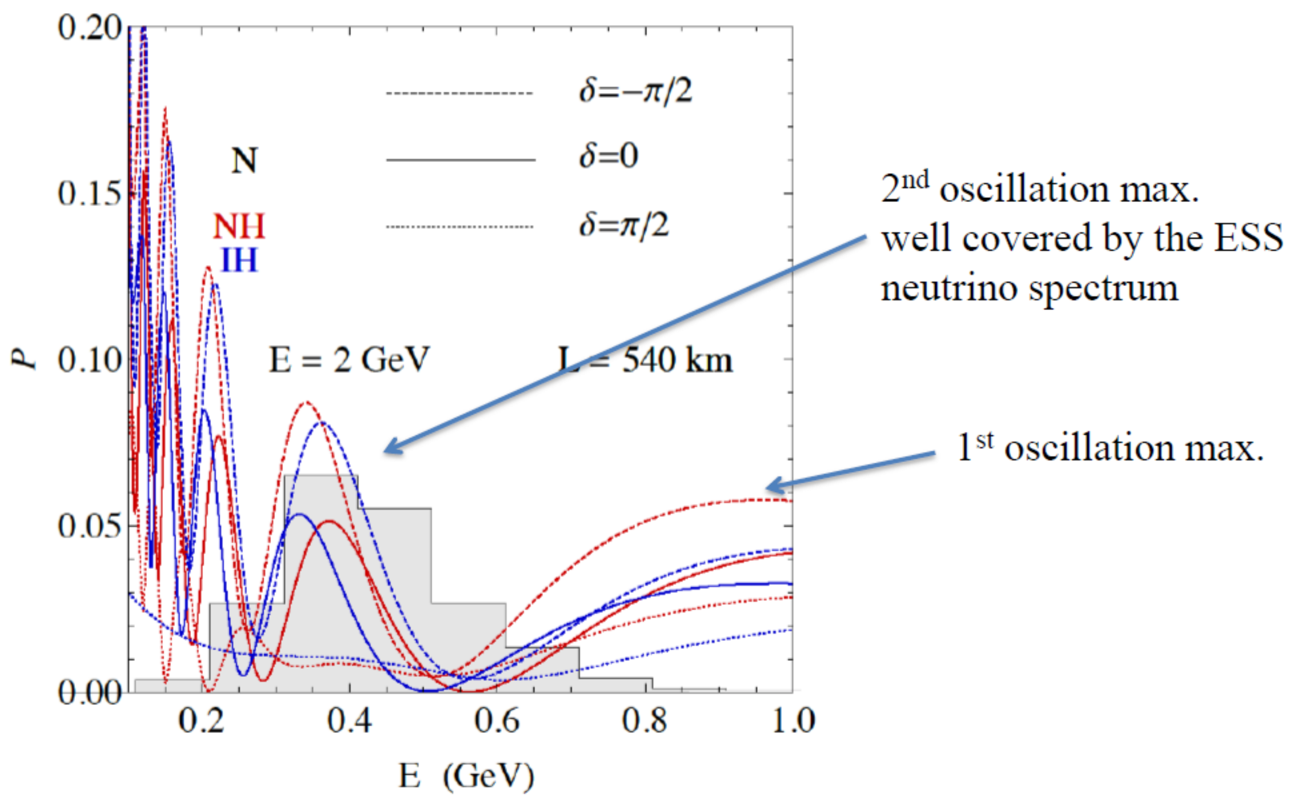
ESSνSB experiment



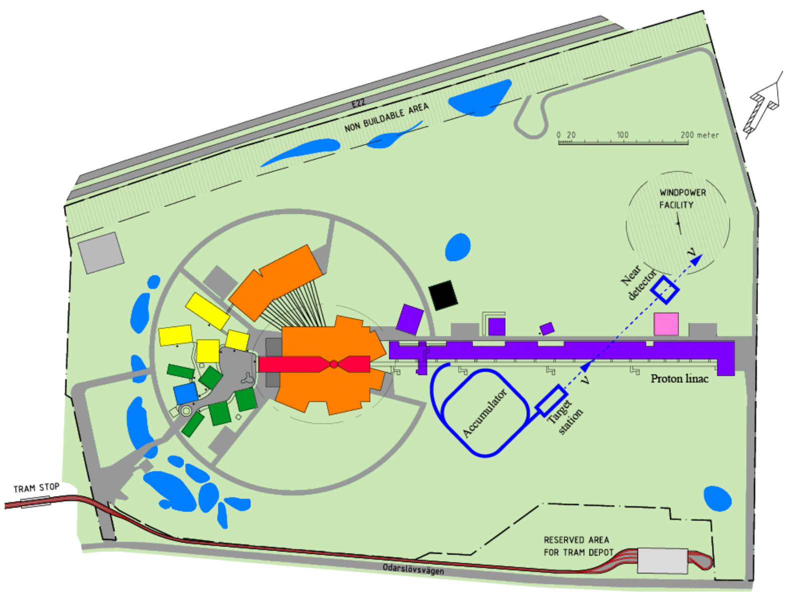
The far water Cherenkov detector will be placed at the second oscillation maximum, at the Garpenberg mine, 540 km from Lund

Given sufficient statistics, as obtainable with the ESS 5MW linac the sensitivity to CP violation is 3 times higher at the second oscillation maximum, as compared to the first

Second oscillation max. coverage



How to add a neutrino facility to ESS?



« This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777419 »

- Increase the ESS linac average power from 5 MW to 10 MW by increasing the linac pulse rate from 14 Hz to 28 Hz, implying that the linac duty cycle increases from 4% to 8%.
- Inject into an accumulator ring circumference ca 400 m) to compress the 3 ms proton pulse length to 1.2 μs, which is required by the operation of the neutrino horn (fed with 350 kA current pulses). The injection in the ring requires H^- pulses to be accelerated in the linac.
- Add a neutrino target station (studied in EUROν)
- Build near and far neutrino detectors (studied in LAGUNA)

<u>Duration</u>: 1 January 2018 – 31 December 2021

<u>Main aim:</u>

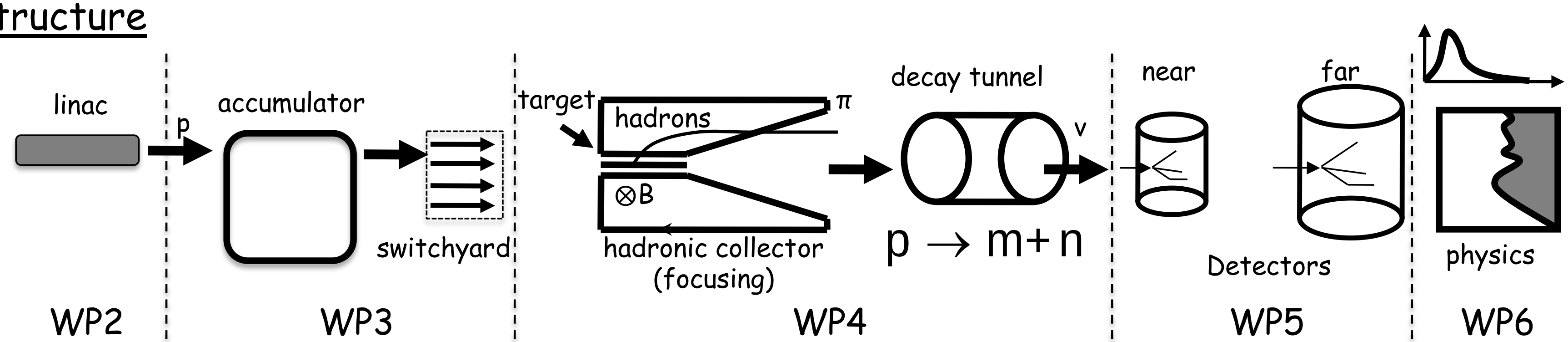
The primary aim of the ESSνSB initiative is to measure the parameters of the neutrino oscillations, in particular the leptonic CP-violating phase angle δ_{CP}. This requires the production of a very intense neutrino beam possible with the ESS proton linac.

<u>Organization:</u>

15 participating institutes, with CNRS (France) acting as coordinating institute

Several collaborating institutes from outside the EU.

<u>Structure</u>



<u>Web page:</u> http://essnusb.eu/site/

Neutrino Beam Production

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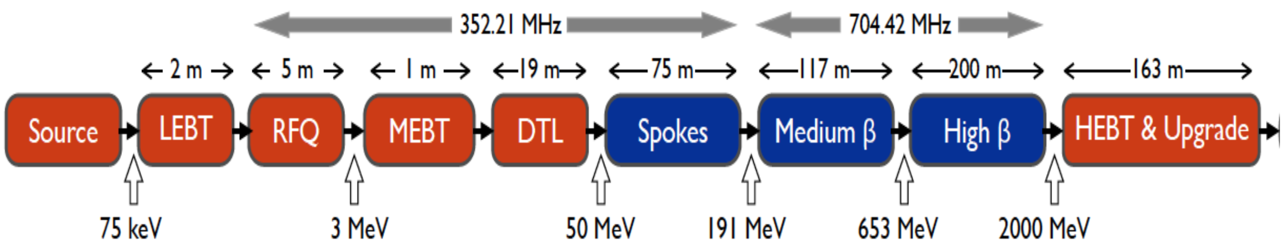
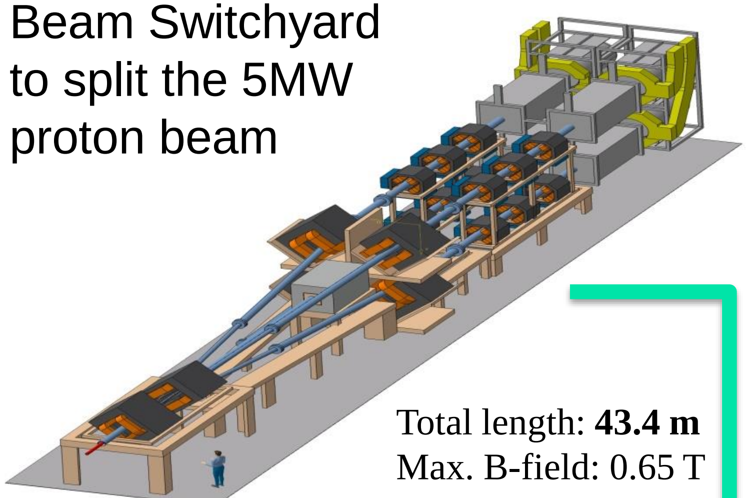
ESS Proton Beam LINAC



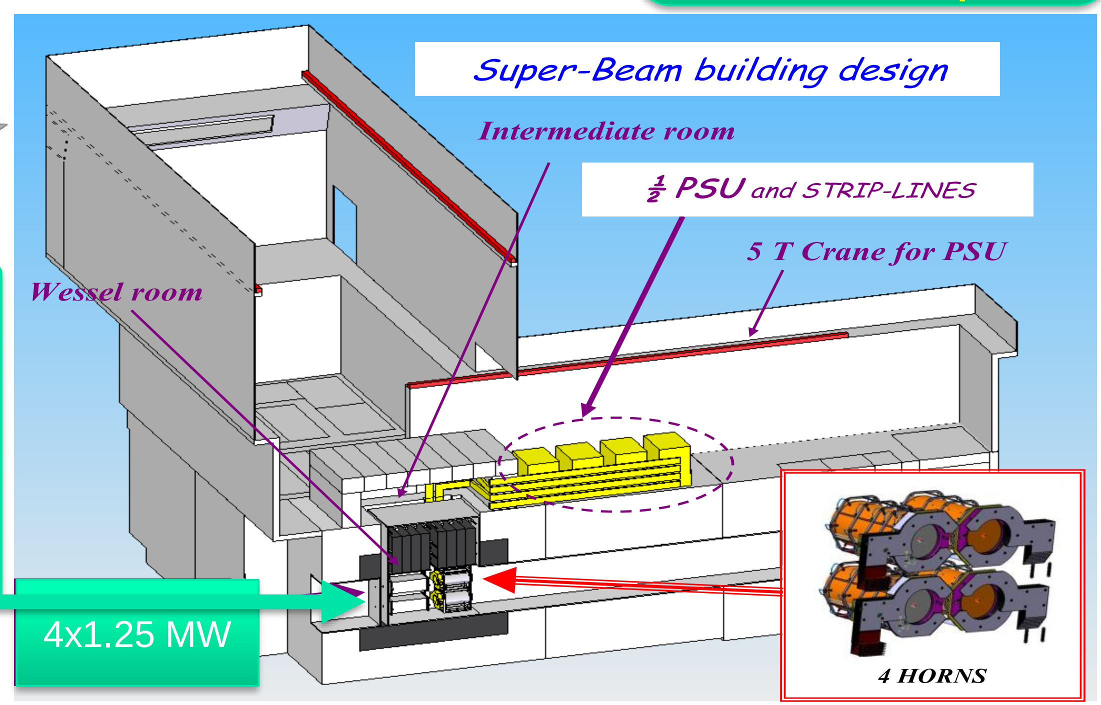
5 MW proton beam for neutron users (2.86 ms pulse width)

5 MW proton beam for neutrino users
1 μs pulse width =>
Accumulator requested

Beam Switchyard to split the 5MW proton beam



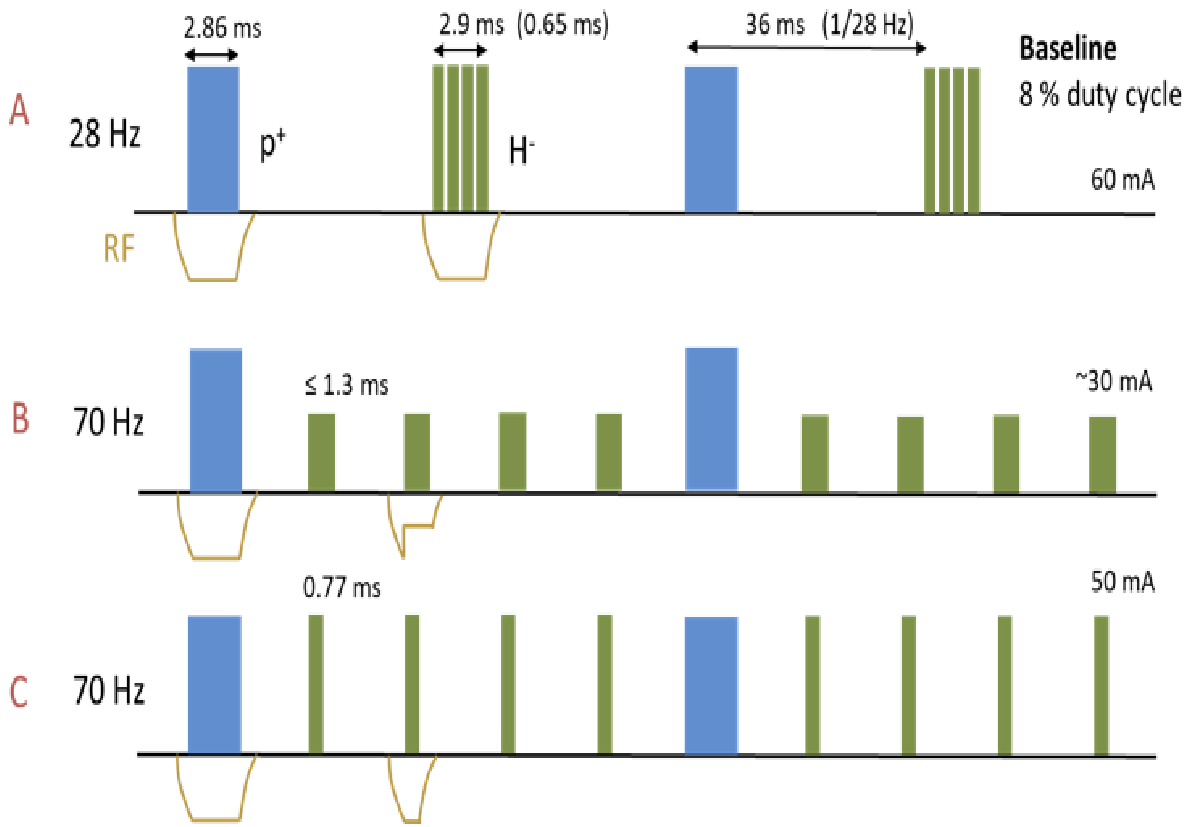
Total length: **43.4 m**
Max. B-field: 0.65 T
(25 kA turns / pole)
Dipole length: 2 m



Basic parameters

Parameters	Value
Power (MW)	5
Proton Energy (GeV)	2.5
Target length (cm)	78
Target radius (cm)	1.5
Horn current (kA)	350
Current pulse repetition rate (Hz)	14
Tunnel length (m)	15-25
Tunnel radius (m)	2
Exposure (years)	2 ν+ 8 anti-ν

Different beam scenarios at the entrance to the accumulator ring



The pulses will then be compressed to about 1.2 μs

P. Sievers's proposal of a granular target at CERN (2001)

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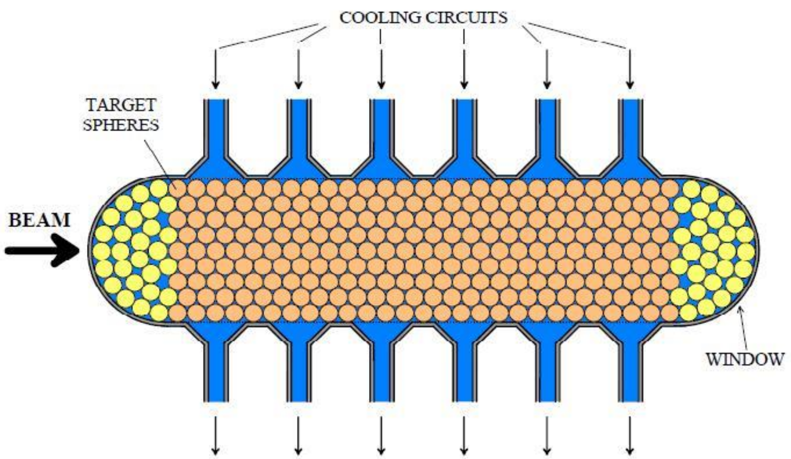
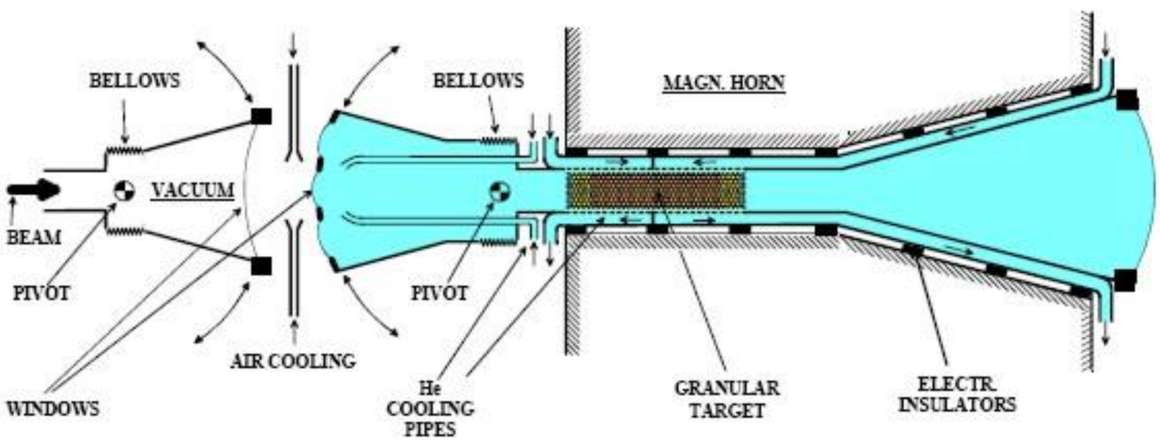


Cooling medium: water or gas helium



Concept of target integration inside a magnetic horn

P. Sievers's proposal of a granular target at CERN (2001)

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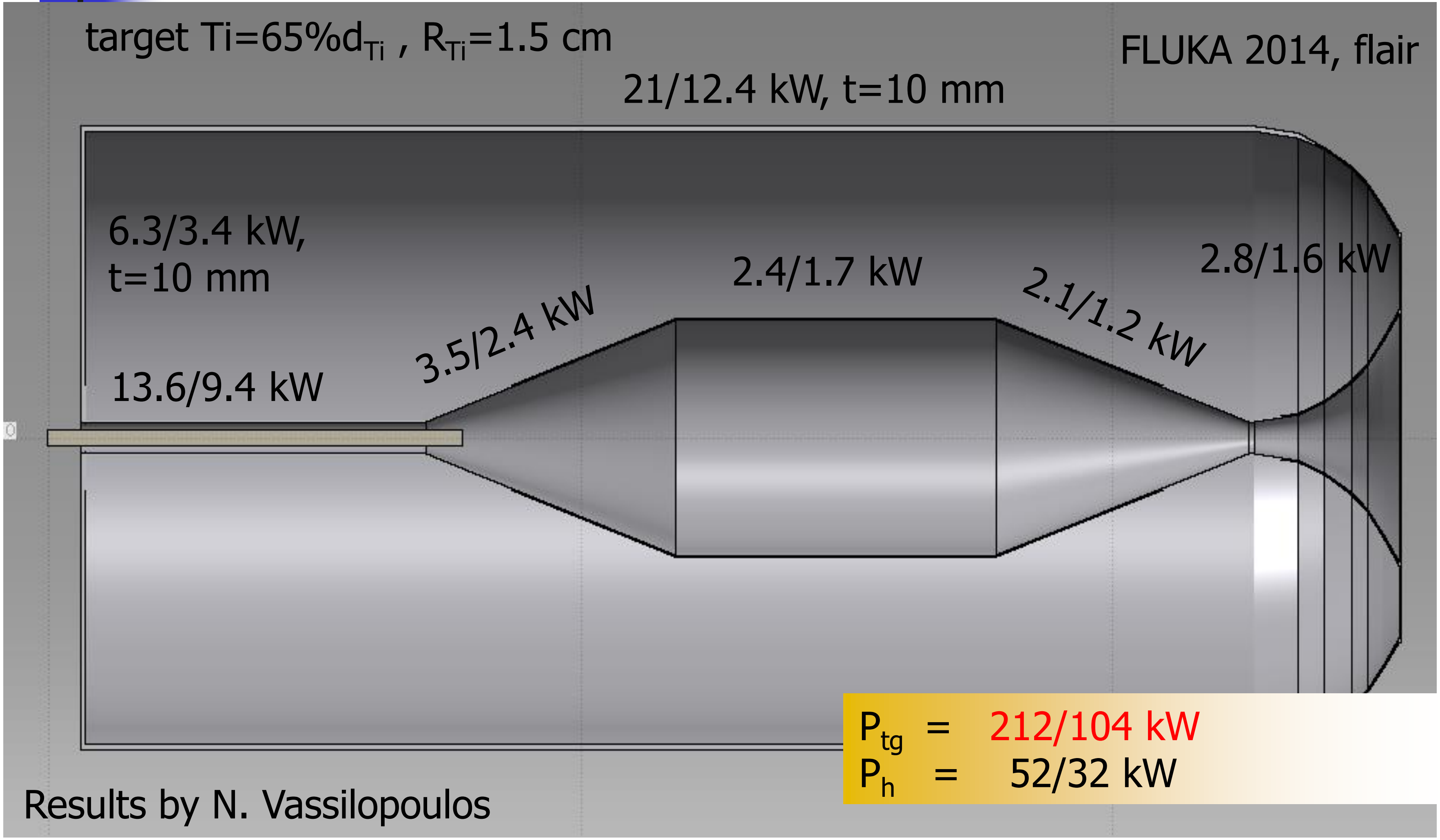
Main conclusions (P. Sievers „A Stationary Target for the CERN-Neutrino-Factory", CERN-NuFact-Note 065):

- Efficient heat removal and low dynamic stresses and pressures are achieved, mainly due to the small size in millimetre range of the target constituents in combination with relatively long proton bursts of several micro-second duration
- Further computational and experimental studies of the performance limits must be investigated
- These studies must include detailed considerations of the lifetime, due to the fatigue induced by the very high rate of the cycles per day, of the target spheres and, in particular, the entrance and exit windows
- Dedicated laboratory tests without the need of a proton beam should be devised to elucidate these problems

Energy deposition, three operating horns (one horn suffers a failure), the higher values shown are for the ESSνSB conditions (1.66 MW/target)



P_{tg} = 212/104 kW
P_h = 52/32 kW

Target cooling studies

The estimated energy density deposited in target spheres:

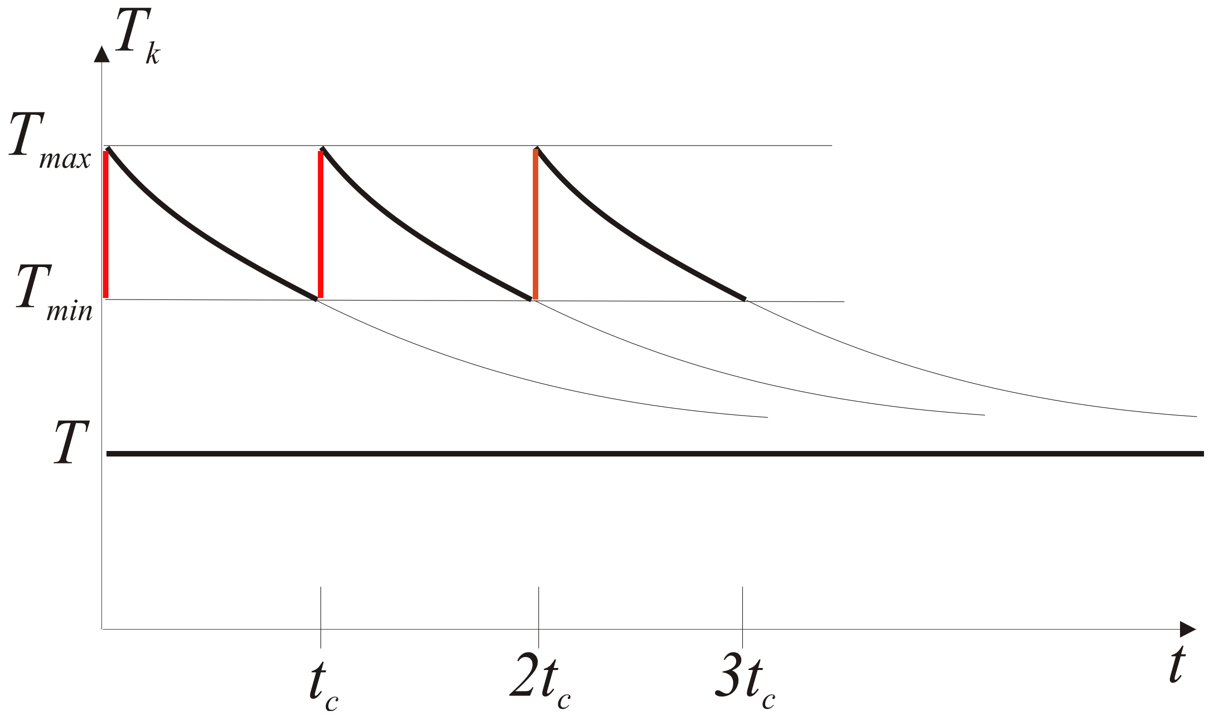
$$Q=9.4*10^3 \text{ J/kg/cycle}$$

Three analysis approaches are being used:

- Analytical method based on energy balance
- Finite element modeling of the spheres inside the target
- The use of prorous media theory (homogenisation method)

Target cooling

Character of temperature change of the spheres at some distance from the target beam-incoming end, during cycles of heat exchange (in red – heating, in black- cooling)



T – steady-state temperature of the cooling medium (avaraged over a cycle)

Analytical model

Main assumptions:

- Heat exchange takes place only on the interface of the spheres and the flowing helium
- The heat flux from the spheres to the cooling medium is proportional to the temperature difference between the sphere surface and that of the cooling medium
- Helium is modelled as a compressible ideal gas
- Steady-state condition is considered

The analysis is based on: heat balance for spheres; balance of mass, momentum and enthalpy for the flowing helium; ideal gas equation of state, the steady-state condition of operation of heat exchanger

Main result:

Both the axial (simpler) and the transverse (more difficult) helium flow cases have been studied. Higher mass flow rate is easier to achieve with the transverse flow. One technical realization including transverse flow was proposed by RAL during the EUROnu project.

Example results for axial flow

Data used:

Target length=78 cm, target radius=1,5 cm; volume packing fraction=0.66%, effective area=0.3*nominal target cross-section; sphere radius=1.5 mm, sphere material – titanium (ρ_k=4500 kg/m^3, c_k=600 J/(kg K), index *k* stands for spheres); helium (gas constant for helium R=2709 J/(kg K), specific heat of helium at constant pressure c_p=5193 J/(kg K), $\kappa = c_p/c_v = 5/3$)

Pulse repetition frequency=14 Hz (cycle period=0.07143 s), energy deposition per cycle=9400 J/kg/cycle

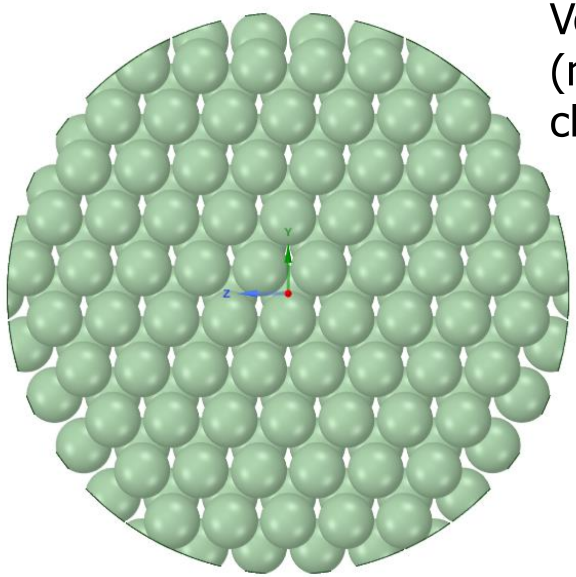
Heat transfer coefficient on the interface between the spheres and helium=1100 W/(K m^2)

Parameters of helium entering the target: p_1=10 bar, T_1=273 K, v_1=200 m/s (Mach number=0.2); mass flow rate = 0.07 kg/s

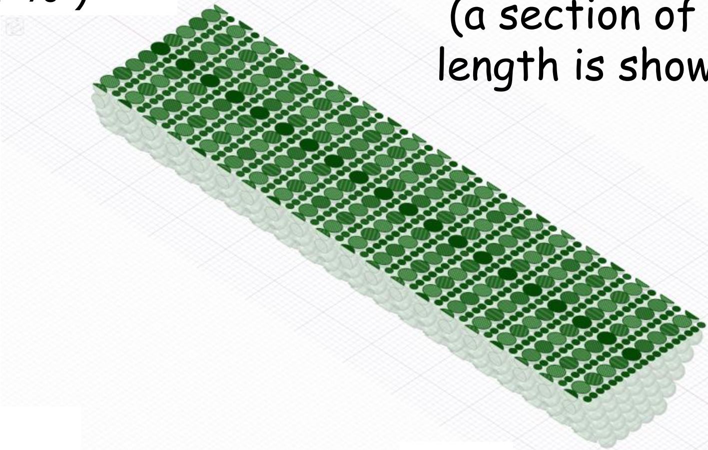
Results: helium outlet temperature T_2=847 K, helium outlet pressure 8.4 bar, helium outlet velocity v_2=689 m/s (Mach number=0.4)

For helium inlet velocity v_1=60 m/s (mass flow rate=0.02 kg/s), the helium outlet temperature would be 2258 *K*

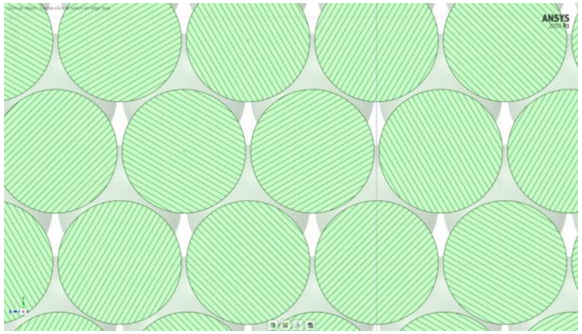
Finite element target modelling



Volume packing is about 66% (maximum value for the hexagonal close packing is 74 %)



Cut through a target (a section of target length is shown)



3D modelling of a complete target is computationally demanding. An alternative is to use the porous media approach (homogenization method). The two models are now being studied on a simpler 2D model of an array of infinite cylinders placed between two parallel plates

Apart from the cooling issues, the vibration and wave phenomena studies have begun

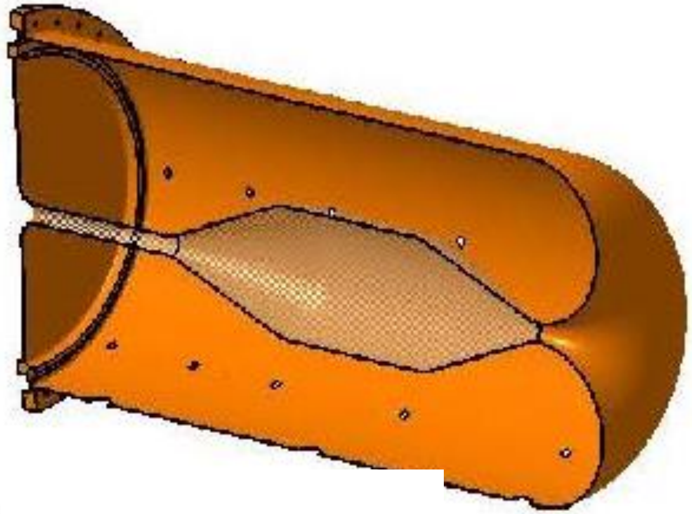
Several issues

- Material properties of irradiated titanium operated as a He-cooled target need more consideration
- The cyclic thermal load and the use of He at a high pressure as a coolant call for better understanding. Surface imperfections can be sites of crack initiation, leading eventually to fracture
- Fatigue life of the spheres under high intensity proton pulses is not well defined
- Surface erosion can result in the activated titanium dust being carried away in the He stream

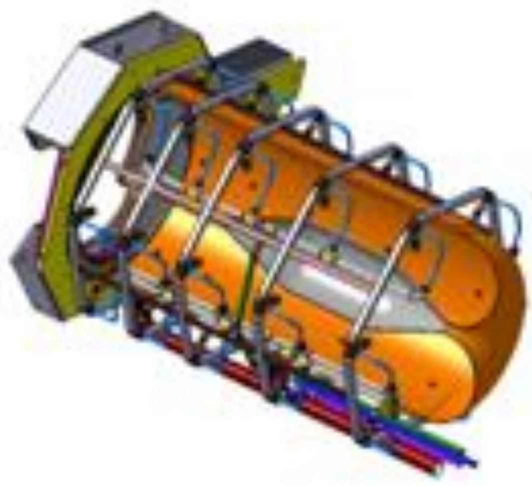
Horn design

Material : Aluminum Al T 6061 – T6
Geometry : Length 2.4 m, diameter 1.2 m
Inner/Outer conductor thickness : 3 mm /10 mm
Peak Current : 350 kA

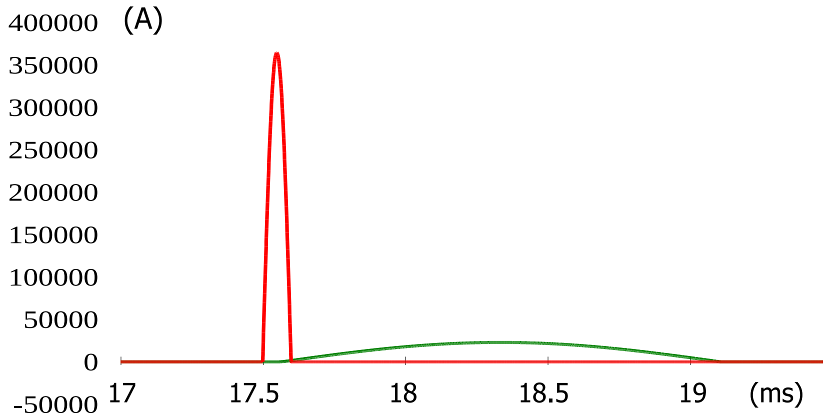
=> Horn shape evolves as a result of the iterative optimization process

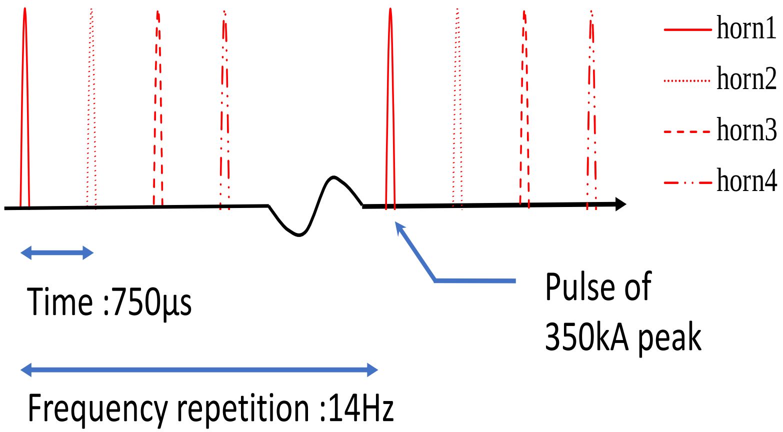


Horn cooling by water spray



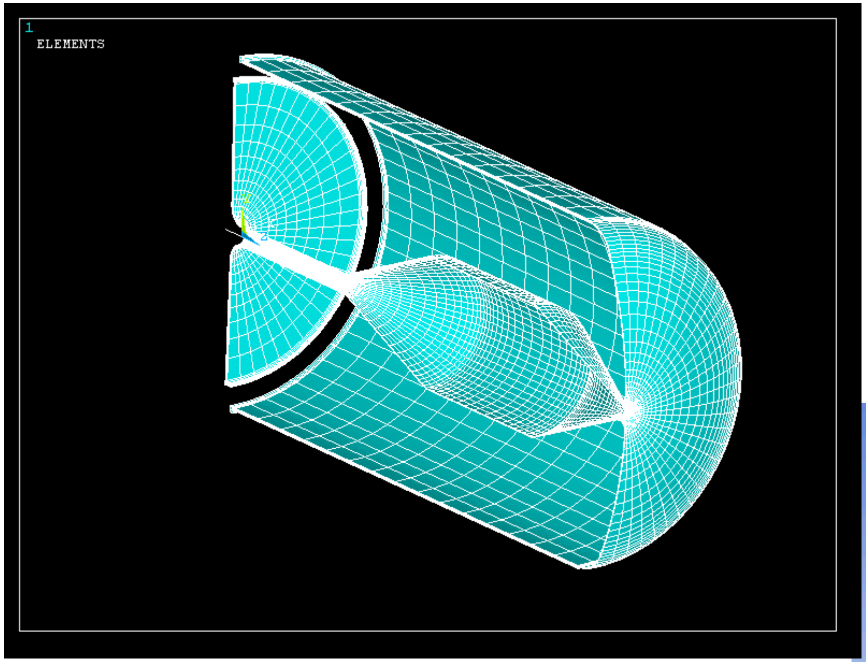
Horn pulsing structure





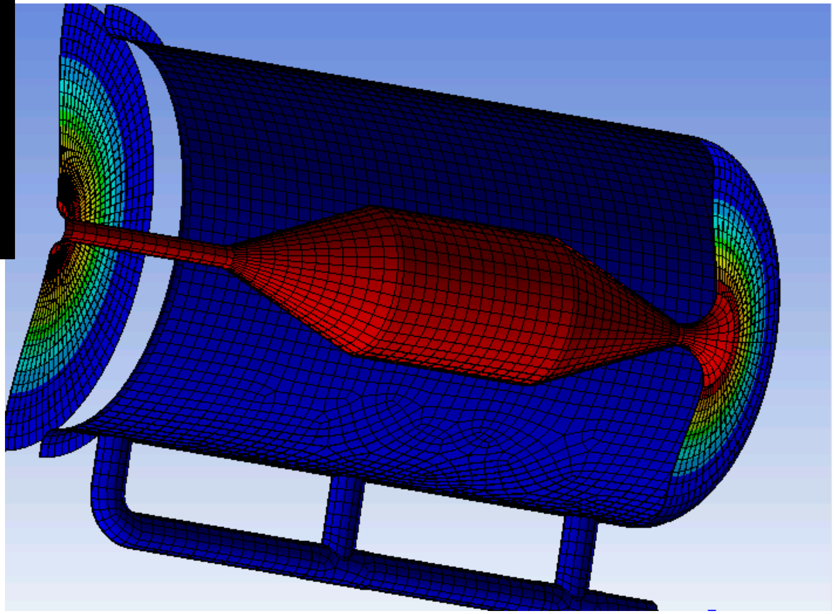
The design of the horn power supply is being worked out at CNRS in Strasbourg

Finite element horn studies



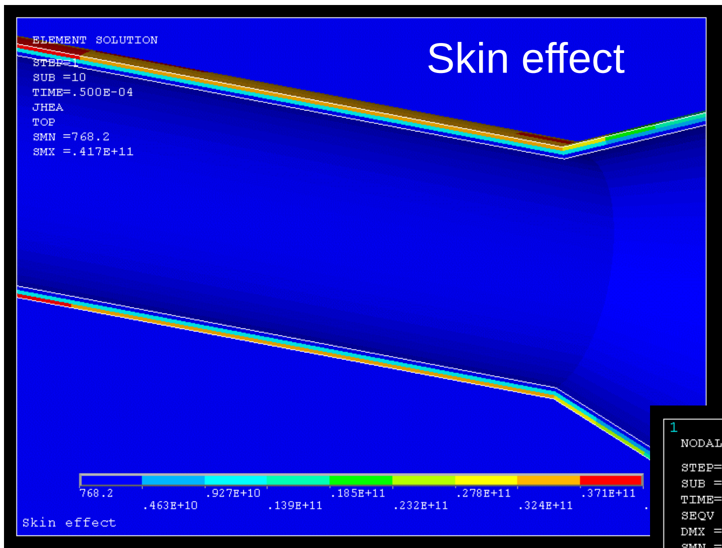
Types of analyses:

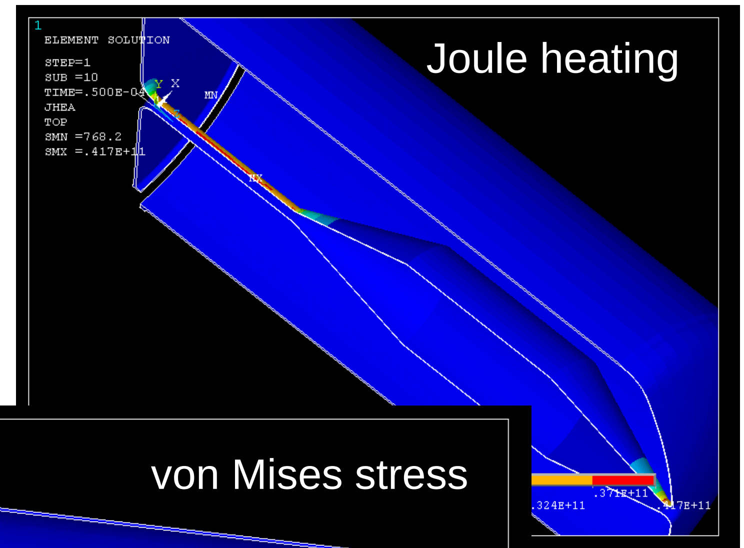
- Electromagnetic analyses including the skin effect and Joule heating
- Coupled transient thermo-mechanical analyses

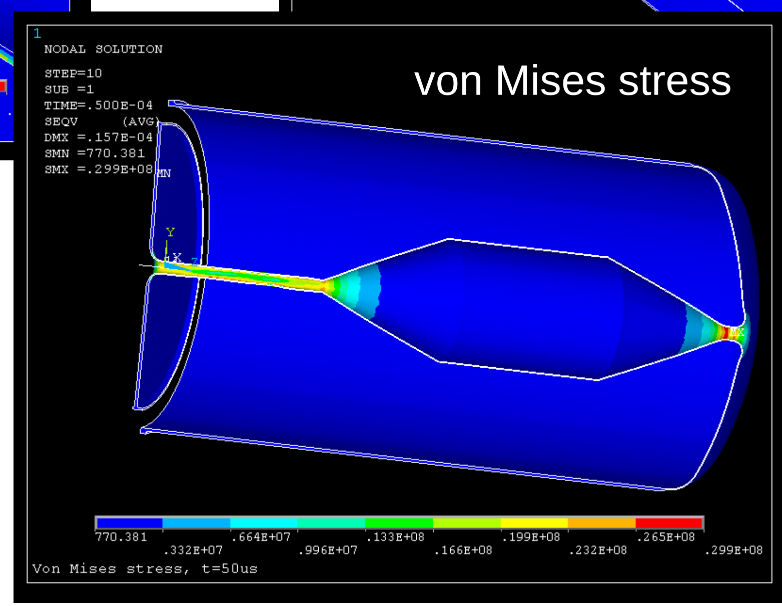


Some results at t=50 μs

Half-sine current, 100 μs long of amplitude 350 kA







Maksimum von Mises stress is about 30 MPa. Stress is higher under a sequence of current pulses.

Possible future HiRadMat tests

- The testing of shock phenomena taking place within granular targets hit by a sequence of proton pulses. As a result of the spheres undergoing repeated impacts, these phenomena are difficult to model. Some numerical modelling has been attempted though, and simulation studies in this direction are being done within the ESSnuSB project. The dynamic phenomena including impacts between spheres of a granular target and shock wave propagation in this kind of structured material require more experimental study. The aspects covered by the tests performed so far at HiRadMat on the powder jet target, have focused on different phenomena

- The study of the material issues of a prototype ESSnuSB target and elements of magnetic horns in the irradiated environment, created by high-intensity beam pulses

Possible future HiRadMat tests

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- The testing of some electronic components may be of interest, reflecting some studies considered within the ESSnuSB project, relying on the use of such components in the radiation zone

Tests at different pulse energies, therefore with different number of bunches in a pulse are being considered. Other dedicated laboratory tests without a need for a proton beam are also considered, with the principal aim of testing the fatigue life of the target spheres

We predict that the tests could begin in 2022, with the necessary documents submitted in 2021 (a letter of interest has been submitted to the Workshop organizers)

Summary

- The ESSνSB Design Study is now into its second realization year
- The project draws on the previous experience: on the EUROν project for the target station, and LAGUNA for detectors
- Work is now underway on all aspects that are pertinent to this design study (only a small part of the activities has been reviewed)
- The HighRadMat facility could offer unique possibilities of testing target components when the project enters the R&D phase

THANK YOU FOR YOUR ATTENTION

BACK-UP SLIDES

(ANALYTICAL MODEL TO CALCULATE THE HORN COOLING - THE CASE OF AXIAL FLOW)

Analytical model: assumptions and description

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Equation that describes the temperature of the spheres:

$$\tau_0 \frac{dT_k}{dt} + T_k = T \qquad \tau_0 = \frac{\rho_k c_k r}{3\alpha}$$

T_k – temperature of a sphere

T – temperature of the cooling medium

α - heat transfer coefficient between the spheres and helium

Temperature of the cooling medium under the steady-state condition (ideal compressible gas model)

Balance of mass for target upstream and downstream ends:

$$\rho_1 A_{efek} u_1 = \rho_2 A_{efek} u_2$$

Balance of momentum:

$$\rho A_{efek} u dx \frac{du}{dx} = -A_{efek} dp$$

Analytical model: assumptions and description

State equations for ideal gass:

$$p_1 = \rho_1 R T_1$$

$$p_2 = \rho_2 R T_2$$

R – gas constant of helium

Balance of enthalpy:

$$c_p\left(T_{02} - T_{01}\right) = \frac{\dot{Q}}{\dot{m}} \qquad T_0 = T\left(1 + \frac{\kappa - 1}{2} M^2\right) \qquad M = \frac{u}{\sqrt{\kappa R T}}$$

T_0 - stagnation temperature, *M* – Mach number
$\dot{Q}$- rate of heat deposited by the beam in all spheres (power deposited in target)

Steady-state condition of the heat exchanger:

$$T_{\max} - T_k(t_c) = \Delta T_k \qquad \Delta T_k = \frac{Q}{c_k}$$