The high power target for LENOS Project at Laboratori Nazionali di Legnaro of INFN-LNL

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LEgnaro NeutrOn Source

- **Neutron Irradiation Facility**. RFQ/Cyclotron.
- **Time-of-Flight Facility**. CN accelerator

Main characteristic:

Based on a method for the production of different neutron spectra which avoid the use of moderators.

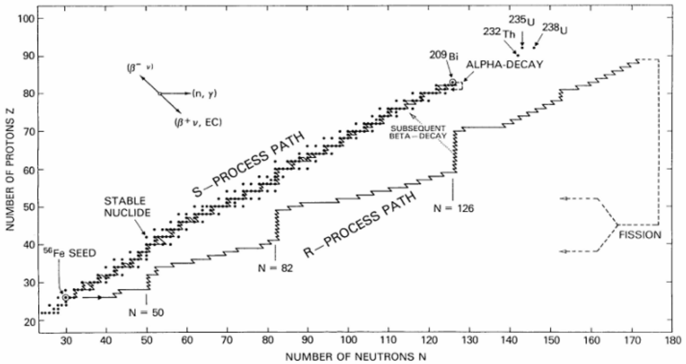
Applications:

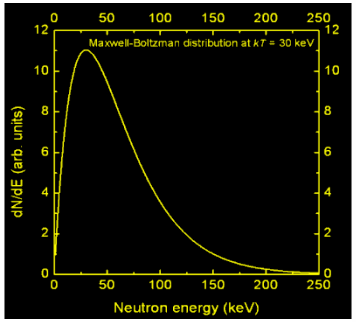
- Nuclear Astrophysics.
- Validation of Evaluated Data.
- Nuclear data.
- Medical physics applications.
- Radiation damage tests (SEE).
- Material science physics (neutron imaging).

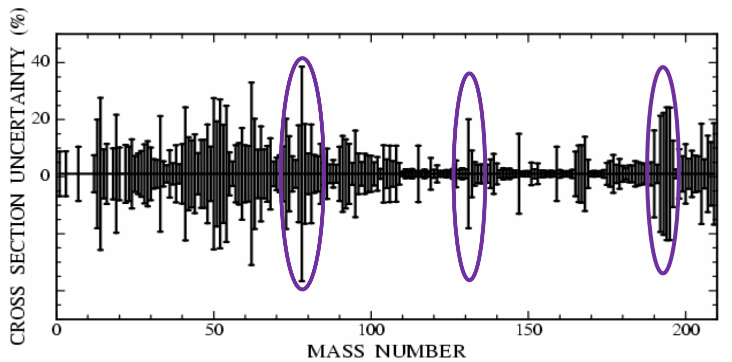
Our main motivation: Astrophysics

Nucleosynthesis of elements beyond Fe (B=8.8 MeV/A) are produced in stars by successive (n,γ) and β-decays.

The stellar velocity neutron spectrum is a Maxwell-Boltzmann distribution. Depending on the stellar site and the evolutionary stage of the star the most important kT are 8, 30 or 90keV, being 30 keV the standard temperature of reference. (*)







$$\frac{dN_A(t)}{dt} = N_{A-1}(t)\cdot n_n(t)\langle\sigma\cdot v\rangle_{A-1} - N_A(t)\cdot n_n(t)\langle\sigma\cdot v\rangle_A - \lambda_\beta(t)N_A(t)$$

$$MACS \equiv \langle\sigma\rangle = \frac{\langle\sigma\cdot v\rangle_A}{v_T} \longrightarrow$$

MACS (Maxwellian Averaged Cross Section)

[*] Z. Y. Bao *et al.* , ADNDT 76, 70 (2000).

Neutron Activation: validation of nuclear data.

Neutron integral experiments play a central role in validation of evaluated nuclear data [1][2][3].

Evaluated spectrum averaged cross-section in Maxwellian spectrum are being used for the validation of evaluated reactor dosimetry files [4].

[1] M.B. Chadwick *et al.* Nuclear Data Sheets 102, 2887 (2012).
[2] U. Fischer *et al.*, Fusion Engineering and Design 663,51 (2000)
[3] R.A. Forrest *et al.*, UKAEA FUS 467, 2001.
[4] International Reactor Dosimetry and Fusion File, IAEA, 2012.

International Atomic Energy Agency
Nuclear Data Services
Секция Ядерных Данных МАГАТЭ

For instance, experimental MACS can be used for the validation of nuclear data libraries in the 10-120 keV range that is important in the description of fast neutron systems (e.g. Gen-IV nuclear reactors).

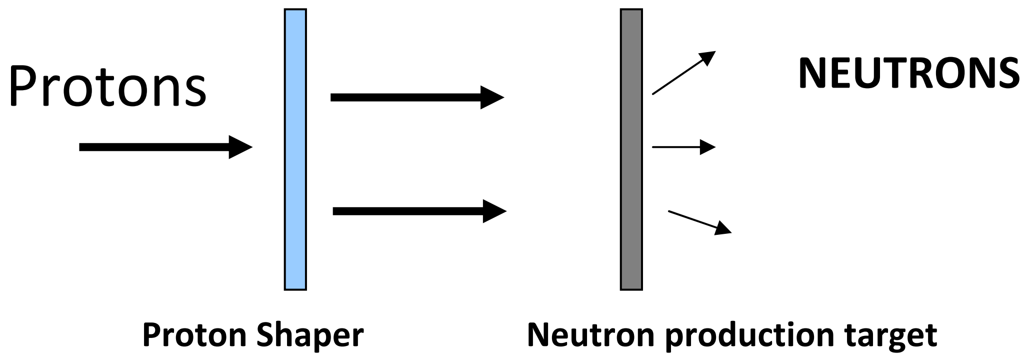
The integral measurements with our method at CNA (and LNL) are of interest for the IAEA and it has been mentioned as one of the Actions in few IAEA Reports:

INDC (NDS)-0583. International Neutron Cross-Sections Standards: extending and updating. 2010.
INDC (NDS)-0639. Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF). 2013.
INDC (NDS)-0641. Toward a New Evaluation of Neutron Standards. 2013.

LENOS' method concept

In order to produce a MB neutron energy spectra or other desired spectra, we developed a new method:

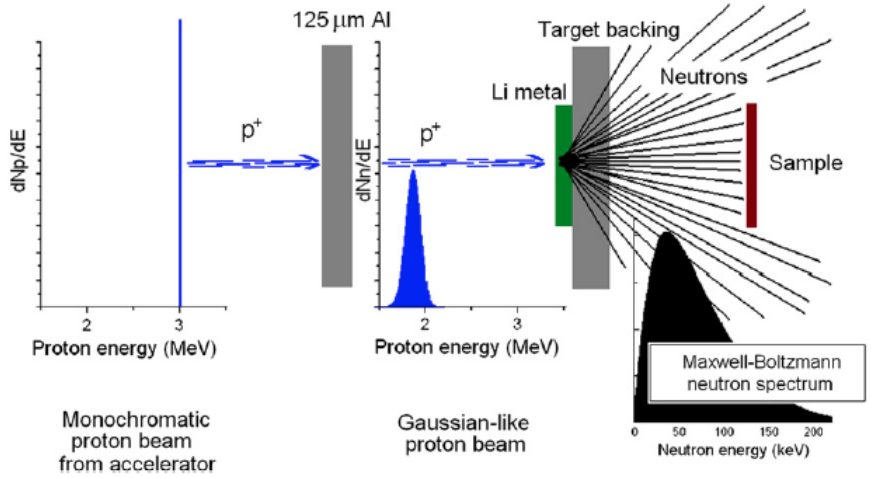
Shaping the proton beam to shape the neutron beam energy spectra to a desired distribution

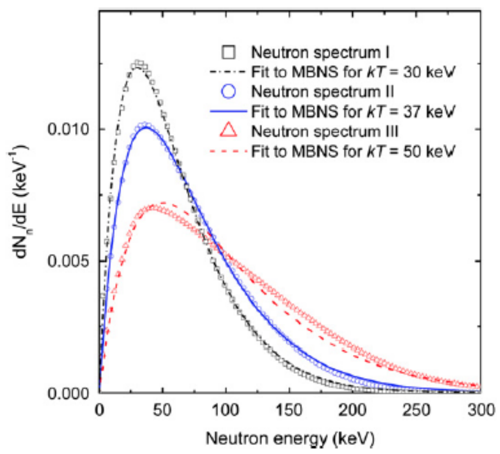


This method avoid the use of moderators and improve the neutron flux at sample position. (*)

[*] P.F. Mastinu *et al.,* NIM A, 601 (2009) 333-338

Example of production of stellar or maxwellian neutron spectra. Low power accelerator.





Tunable stellar temperature kT=25 to 60 keV.

G. Martin-Hernandez *et al.*, App. Rad. Iso. 70 (2012).

Setup for low power, CN at LNL-INFN. (7 MV Van Der Graaf accelerator)

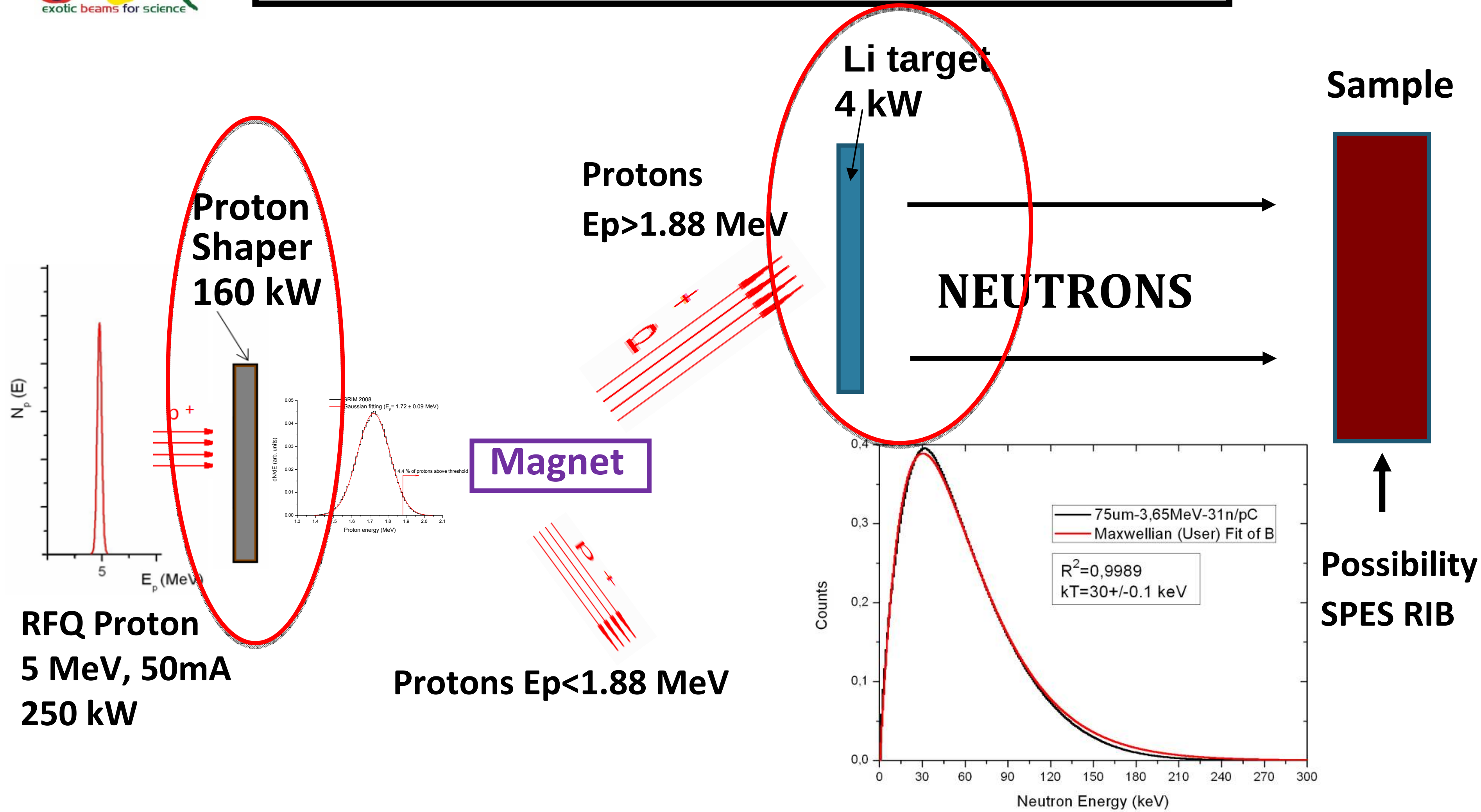
- Proton energy shaper: Al or Pb foil (70-125 um)
- Li metal target
- Low mass water cooled target

- Tunable proton energy
- Tunable viewing angle

Since minor corrections are needed, MACS can be directly measured by neutron activation. Our first measurement was the MACS of ^{181}Ta(n,γ) at kT=30 keV. (*)

J. Praena, P.F. Mastinu *et al.*, NIM A , 727, 1-6 (2013).

Sketch of SPES/LENOS Layout



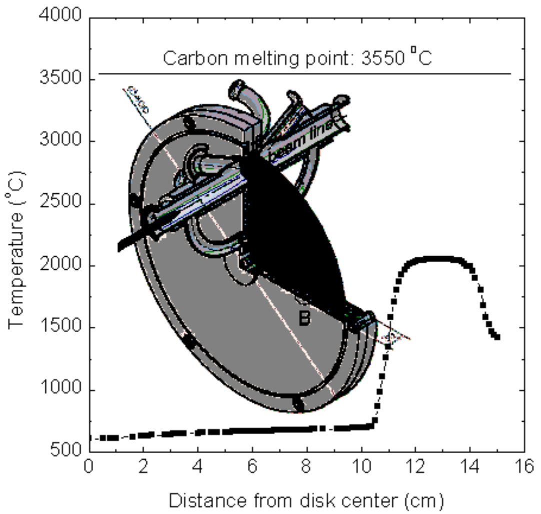
Expected Neutron Flux = $5{\cdot}10^{10}$ n/s·cm^2

[*] J. Praena, P.F. Mastinu *et al.* , P. Ast. Soc. Aust., 26, 225 (2009).

SPES/LENOS Layout: Energy Shaper (1/3)

We decide to shape the proton beam by using the energy straggling and stopping power of charge particles when interact with a thin foil of material. General method: **multilayer energy shaper.**

LENOS foil material requirements :
Low atomic number and low density, high melting point, high emissivity, high thermal conductivity, high tensile strength.



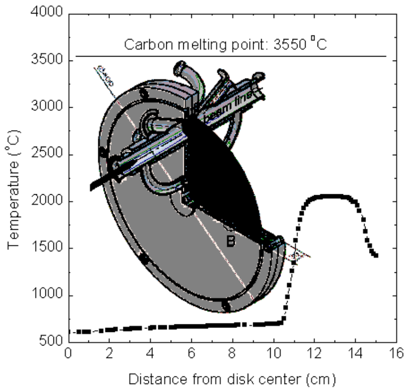
P=2x80 kW for 50mA *ANSYS, Inc*

→ GRAPHITE foil

For lower power we can use a monolayer Aluminium foil.

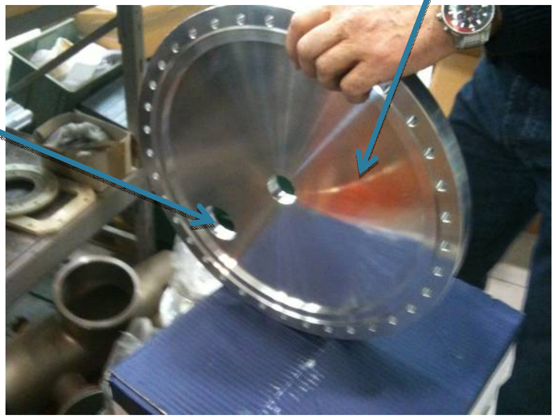
SPES/LENOS Layout: Energy Shaper (2/3)

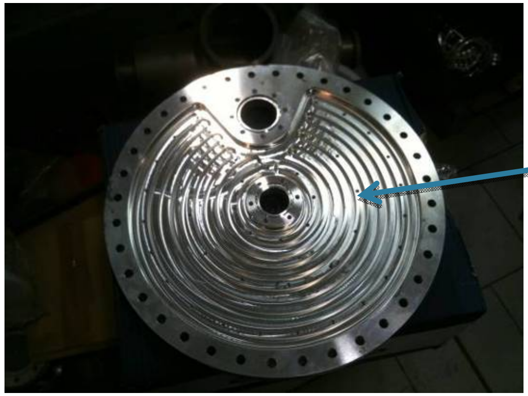
Graphite disk 70 μm thickness. Power to be dissipated about 50 kW, Mainly by radiation. Working temperature <2000°C
Construction material Al Ergal alloy



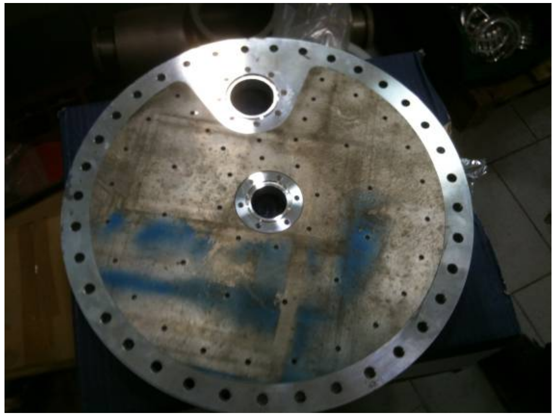
Beam entrance

Internal part

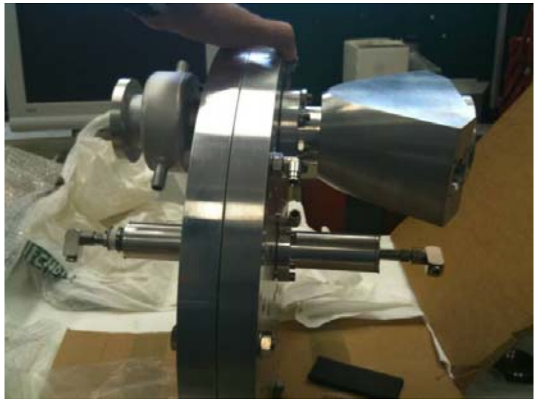


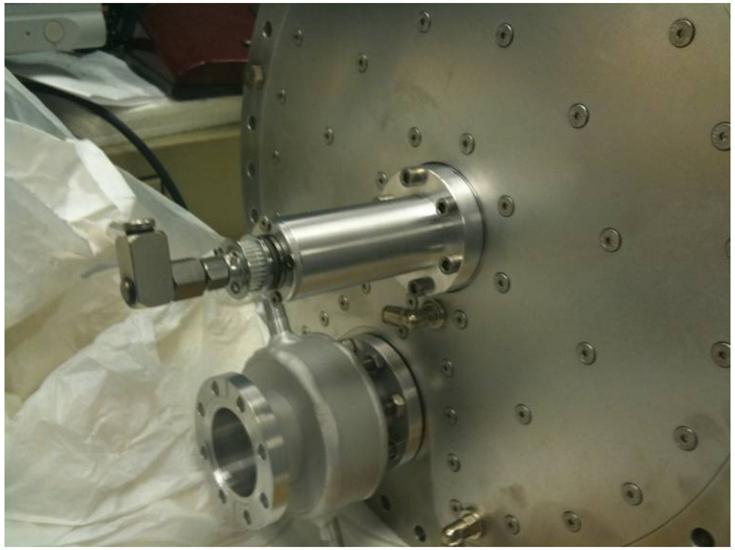


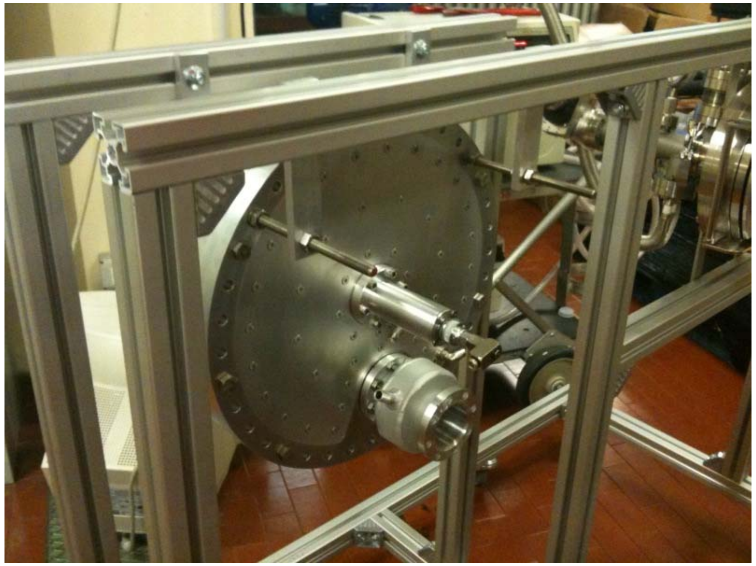
Water cooled serpentine



LENOS Layout: Energy Shaper (3/3)







Prototype almost completed

LENOS Layout: Lithium target (1/7)

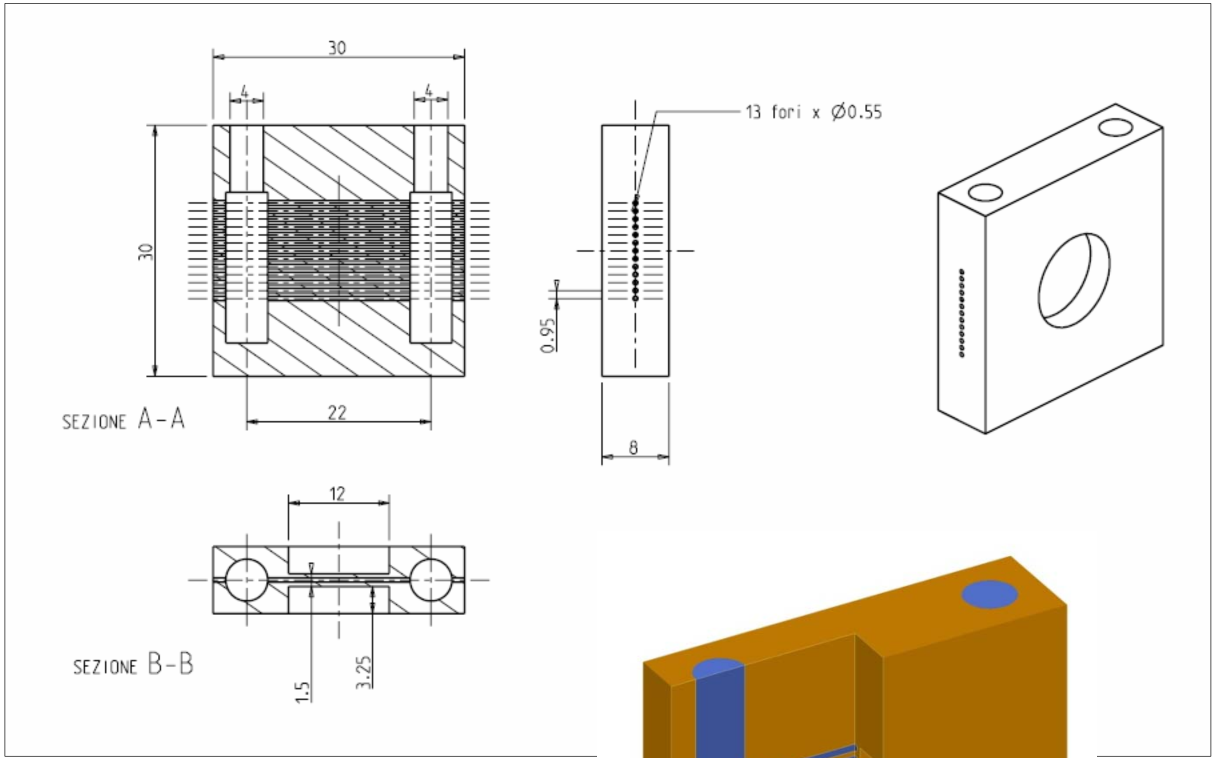
In order to dissipate so high specific power (about 3 kW/cm^2) a new generation of heat cooling device have to be implemented and developed.

The target must satisfy some constrains:

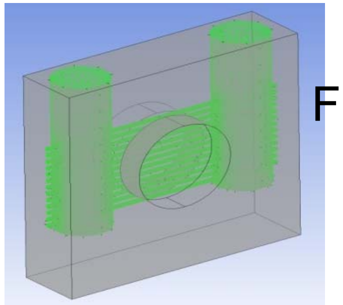
- Low mass (to avoid neutron backscattering and reduce radioactivity)
- Small thickness, in order to maximize the neutron flux (keeping the measuring sample in touch with the neutron producing surface) and reduce neutron spectra perturbation
- Low cost and easy to fabricate procedure, in order to replace the target often even during a measurements

Microchannels + liquid metal cooling medium

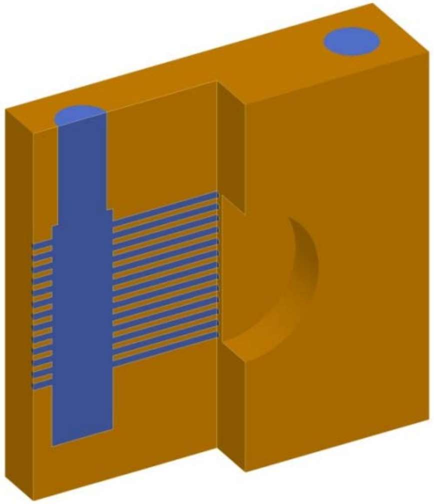
LENOS: Lithium target. Design. (2/7)



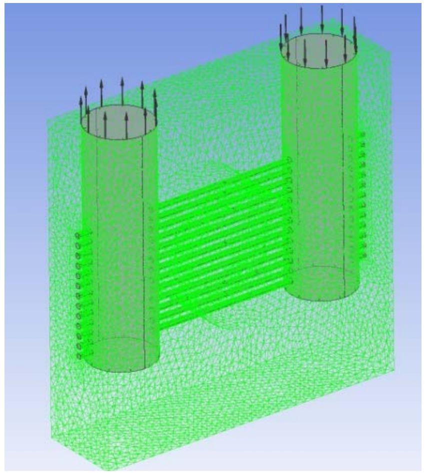
Cu Backing:
13 micro channels
14 mm long
0.45 mm diameter
0.95 mm spacing
0.5 wall thickness
6.4 mm in-out diam tube



Fluid domain



Solid domain



LENOS: Lithium target. Analytical results (3/7)

WATER		
parameters	description	value
c_p [J/kg K]	fluid specific heat	4181,7
λ_{Fl} [W/m K]	fluid thermal conductivity	0,6069
λ_{Cu} [W/m K]	target thermal conductivity	401
v [Pa s]	fluid viscosity dinamic	0,0008899
ρ [kg/m^3]	fluid density	997
d [m]	diameter of the microchannels	0,00055
Pr	Prandtl number	6,131644142
v [m/s]	velocity in the microchannels	15
Re	Reynolds number	9242,89246
Nu	Nusselt number	73,77145321
α [W/m^2 K]	convection coefficient	81403,44537
$T_{av,fl}$ [ºC]	fluid average temperature	23
n	number of microchannels	13
q [W/m^2]	beam specific thermal power	4420970,641
q [W/cm^2]	beam specific thermal power	884,1941283
q [W]	beam thermal power on target	1000
T_s [ºC]		77,30937992
T_{beam} [ºC]	temperature on beam surface	124,6909261
T_{in} [ºC]	fluid inlet temperature	20
Q [m^3/s]	fluid volumetric flow	4,63287E-05
T_{us} [ºC]	fluid outlet temperature	25,17728529
	lithium thickness [m]	0,00004
$T_{s(Li)}$ [ºC]		126,7787516
λ_{Li} [W/m K]	gold thermal conductivity	84,7

GALINSTAN		
parameters	description	value
c_p [J/kg K]	fluid specific heat	365
λ_{Fl} [W/m K]	fluid thermal conductivity	36
λ_{Cu} [W/m K]	target thermal conductivity	401
v [Pa s]	fluid viscosity dinamic	0,00221
ρ [kg/m^3]	fluid density	6363
d [m]	diameter of the microchannels	0,00055
Pr	Prandtl number	0,022406944
v [m/s]	velocity in the microchannels	15
Re	Reynolds number	23753,28054
Nu	Nusselt number	8,85821701
α [W/m^2 K]	convection coefficient	579810,5679
$T_{av,fl}$ [ºC]	fluid average temperature	50
n	number of microchannels	13
q [W/m^2]	beam specific thermal power	19231222,29
q [W/cm^2]	beam specific thermal power	3846,244458
q [W/]	beam thermal power on target	4350
T_s [ºC]		83,16811275
T_{beam} [ºC]	temperature on beam surface	117,338302
T_{in} [ºC]	fluid inlet temperature	20
Q [m^3/s]	fluid volumetric flow	4,63287E-05
T_{us} [ºC]	fluid outlet temperature	60,42821788
	lithium thickness [m]	0,00004
$T_{s(Li)}$ [ºC]		126,4203432
λ_{Li} [W/m K]	gold thermal conductivity	84,7

Different GaInSn eutectic alloys are commercially available with different thermophysical propierties

TABLE I. Summary of the thermophysical properties of liquid metals used in heat transfer applications and water for comparison. Experiments conducted as part of this study utilized a commercially available $Ga^{61}In^{25}Sn^{13}Zn^{1}$ alloy. The limited thermophysical property data for this alloy available to the authors includes a melting point of 8 °C and a density of 6500 kg/m³ (Ref. 15).

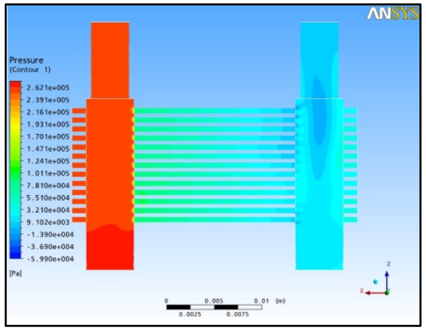
	Hg[a]	$Ga^{68}In^{20}Sn^{12}$[a]	$Na^{22}K^{78}$[a]	SnPbInBi[a]	Water[a]
Density (kg/m³)	13 564.0[f]	6363.2[f]	868.2[f]	9230[e]	998.0[g]
Melting point (°C)	−38.87	10.5	−11	58	0
Heat capacity (J/kg/K)	139.068[c]	365.813[c]	982.1[c]	209[e]	4181[g]
Kinematic viscosity (10^{-6} m²/s)	0.114 8[c]	0.348 09[c]	1.05[c]	4.04[e]	0.960[g]
Electrical conductivity (S/μm)	1.044 52[c]	3.307 37[c]	2.878[c]	1.28[e]	5.5×10^{-12}
Thermal conductivity (W/m/K)	8.716 9[f]	39[d]	21.8[c]	10[d]	0.606[g]
Prandtl Number ()[f]	0.024 8	0.020 8	0.0411	0.7793	6.62

- Conservative calculations shows that ~3.5 kW/cm² could be dissipated. T_{Li}<152 °C. Melting point of Lithium is 182°C.
- Li (30μm) on a backing of Cu (1.5mm). g
- Microchannels, GALINSTAN (**gal**lium**, in**dium **e stan**num $Ga_{68}In_{21}Sn_{11}$), alloy at T=15 °C

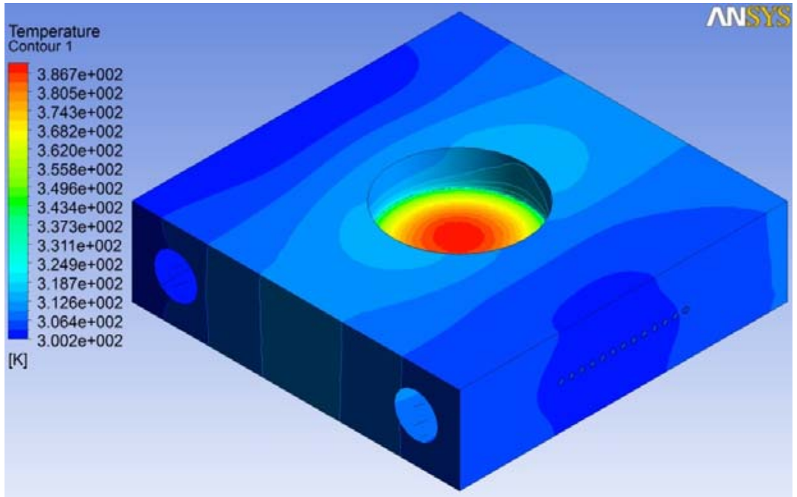
LENOS: Lithium target. ANSYS results (4/7)

Water cooled

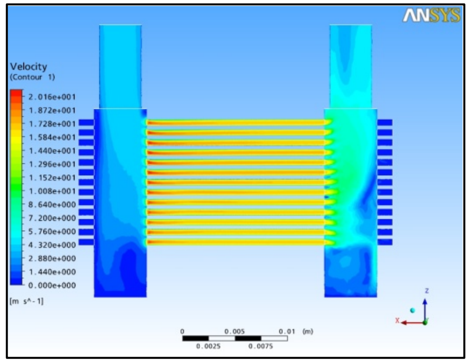
Pressure



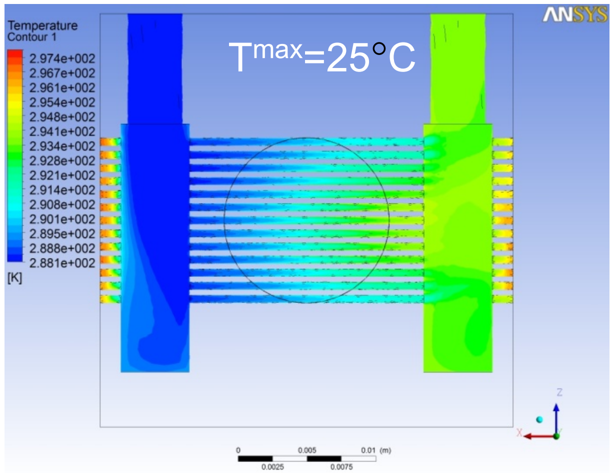
P^{in}=2.7 bar
ΔP=2.7 bar



Velocity



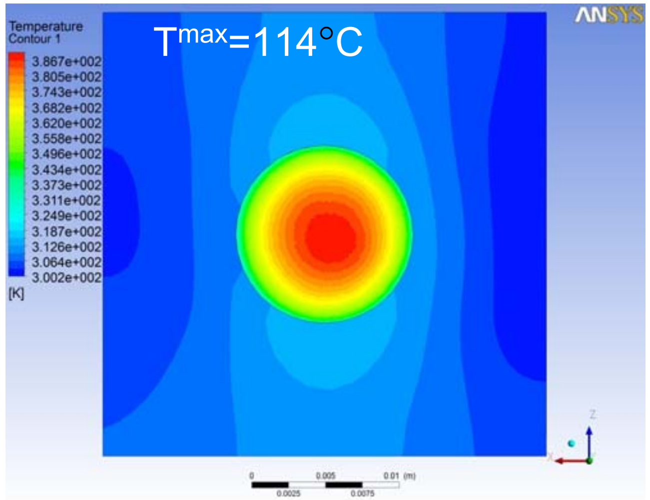
μ-channel fluid velocity =15m/s



Temperature

Li 40 μm
Mass flow=160l/h
Inlet fluid temperature=15°C
Beam Power=1000W
Flat beam profile

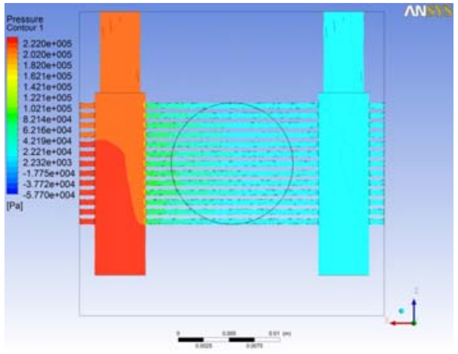
Melting point Li = 182°C



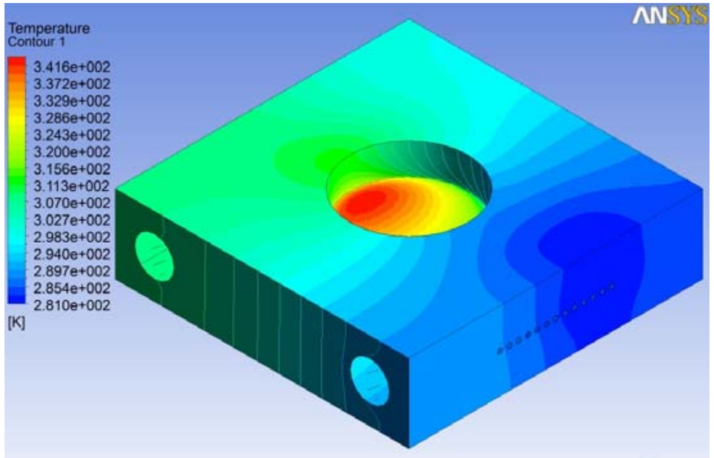
LENOS: Lithium target. ANSYS results (5/7)

SnInGa alloy cooled

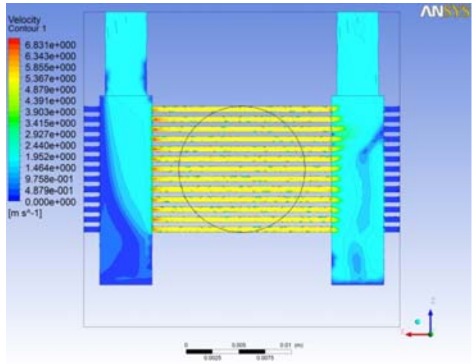
Pressure



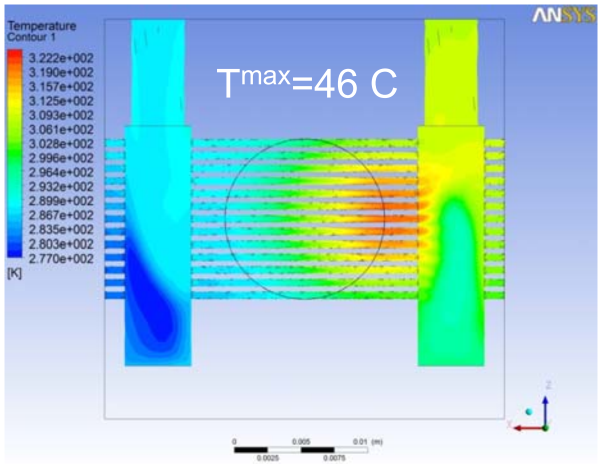
P^{in}=2.5bar
ΔP=2.5 bar



Velocity



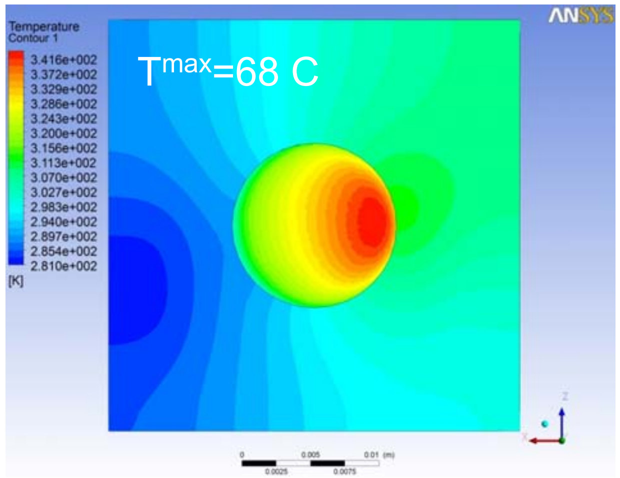
μ-channel fluid velocity =5 m/s



Temperature

Li 40 μm
Mass flow=55 l/h
Inlet fluid temperature=15°C
beam Power=1000W
Flat beam profile

Melting point Li = 182°C



LENOS: Lithium target. Comparison (6/7)

Analytical

WATER		
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v [Pa s]	fluid viscosity dinamic	0,0008899
ρ [kg/m^3]	fluid density	997
d [m]	diameter of the microchannels	0,00055
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v [m/s]	velocity in the microchannels	15
Re	Reynolds number	9242,89246
Nu	Nusselt number	73,77145321
α [W/m^2 K]	convection coefficient	81403,44537
$T_{av,fl}$ [ºC]	fluid average temperature	23
n	number of microchannels	13
q [W/m^2]	beam specific thermal power	4420970,641
q [W/cm^2]	beam specific thermal power	884,1941283
q [W]	beam thermal power on target	1000
T_s [ºC]		77,30937992
T_{beam} [ºC]	temperature on beam surface	124,6909261
T_{in} [ºC]	fluid inlet temperature	20
Q [m^3/s]	fluid volumetric flow	4,63287E-05
T_{us} [ºC]	fluid outlet temperature	25,17728529
	lithium thickness [m]	0,00004
$T_{s(Li)}$ [ºC]		126,7787516
λ_{Li} [W/m K]	gold thermal conductivity	84,7

GALINSTAN		
parameters	description	value
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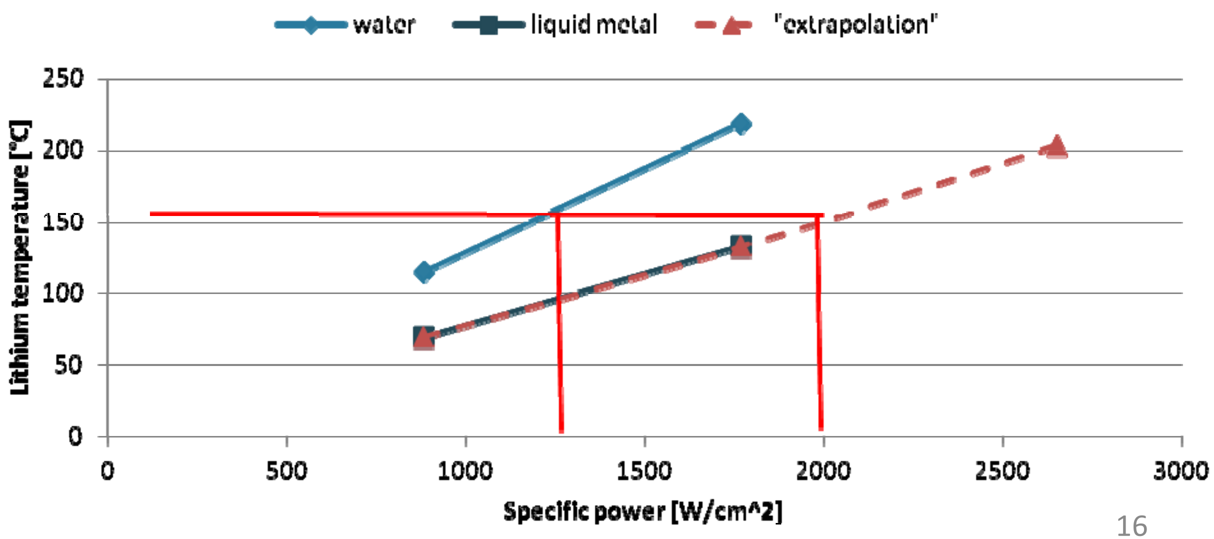
λ_{Fl} [W/m K]	fluid thermal conductivity	36
λ_{Cu} [W/m K]	target thermal conductivity	401
v [Pa s]	fluid viscosity dinamic	0,00221
ρ [kg/m^3]	fluid density	6363
d [m]	diameter of the microchannels	0,00055
Pr	Prandtl number	0,022406944
v [m/s]	velocity in the microchannels	5
Re	Reynolds number	7917,760181
Nu	Nusselt number	7,305505188
α [W/m^2 K]	convection coefficient	478178,5214
$T_{av,fl}$ [ºC]	fluid average temperature	80
n	number of microchannels	13
q [W/m^2]	beam specific thermal power	11052426,6
q [W/cm^2]	beam specific thermal power	2210,485321
q [W/]	beam thermal power on target	2500
T_s [ºC]		103,113599
T_{beam} [ºC]	temperature on beam surface	122,7516388
T_{in} [ºC]	fluid inlet temperature	20
Q [m^3/s]	fluid volumetric flow	1,54429E-05
T_{us} [ºC]	fluid outlet temperature	89,70382393
	lithium thickness [m]	0,00004
$T_{s(Li)}$ [ºC]		127,9712027
λ_{Li} [W/m K]	gold thermal conductivity	84,7

Good agreement for water, less for liquid metal

ANSYS



But…

- Micro-channels are not small «tubes»
- CFX package has problems also to reproduce the fluidoDynamics inside the microchannels, even the velocity-pressure drop relation
- Internal characteristics of the channels hard to measure
- So we (triyed) moved fast to hardware tests
- We have continuosly developed our target in order to improve the performances: the new developments are PATENT PENDING by INFN and will be ready soon.

LENOS: Lithium target. Tests (7/7)

Many targets has been successfully manufactured at LNL

<u>Indium has been used as a threshold thermometer</u>

TIG test:
Measured power transfer: 3.4 kW
Not reached the Indium melting point

Preliminary Tests done depositing a thin Indium layer instead of Lithium.
Melting point of Indium 157°C.
Thermal conductivity of Indium is 81.6 W/(m·K).
Thermal conductivity of Lithium is 84.7 W/(m·K).

Heat spot

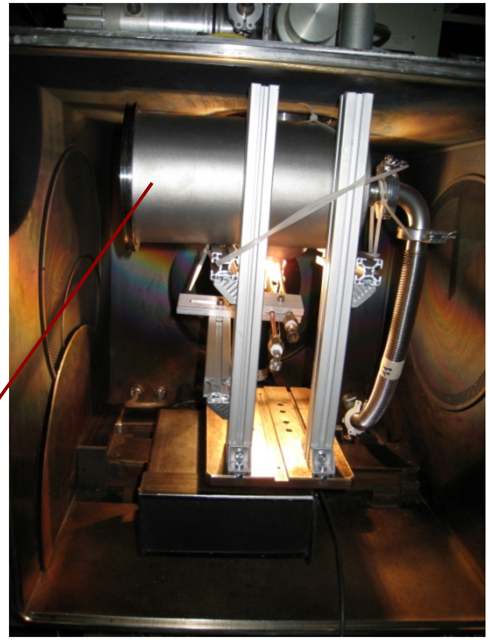
Oxyd-acethilene test:
Measured power transfer =1.5 kW
Not reached the Indium melting point

Lithium target testing: e-Beam

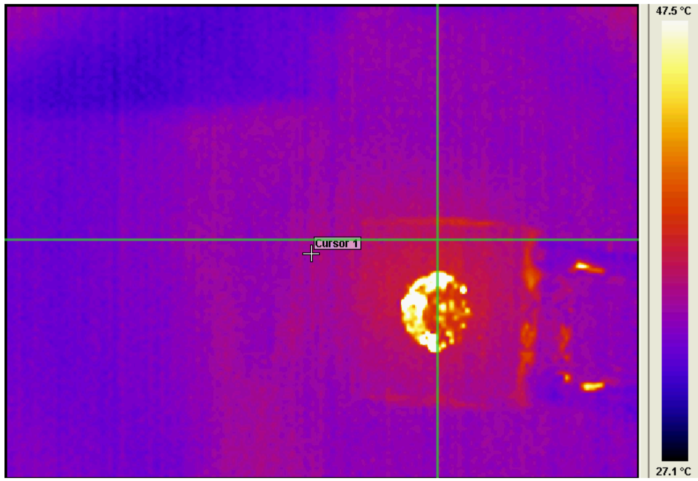
Target (copper backing) was irradiated by electron beam in 10^{-4} mbar

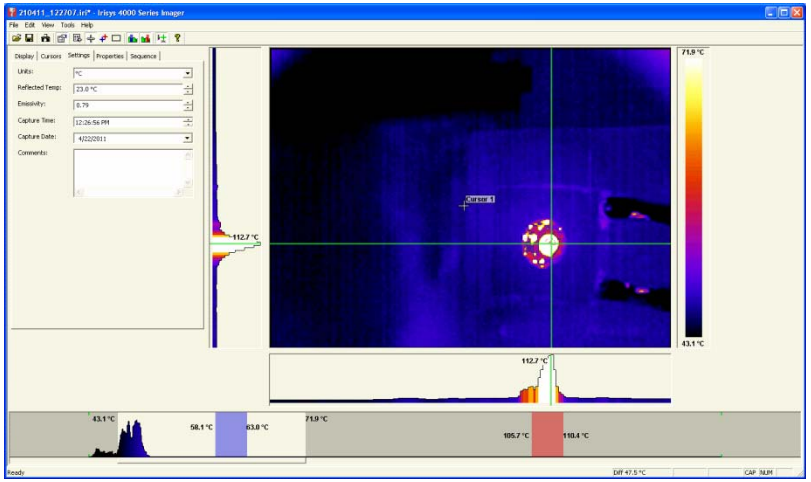
I=0-74 A V=60 kV
P=ηV·I =0-4.4 kW

Maximum transfered Power 13 kW/cm²



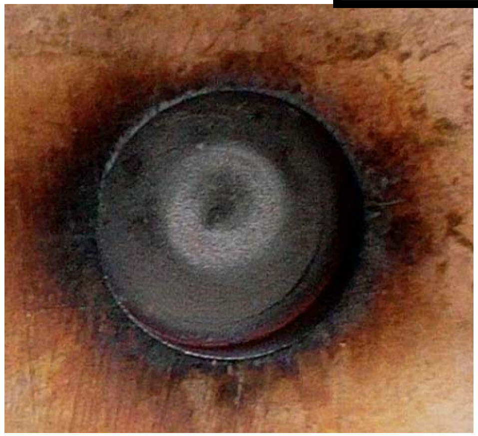
Temperature mapped with thermocamera.Transfered power measured by the water temperature and mass flow. Beam spot 0.5 and 1.2 cm diameter



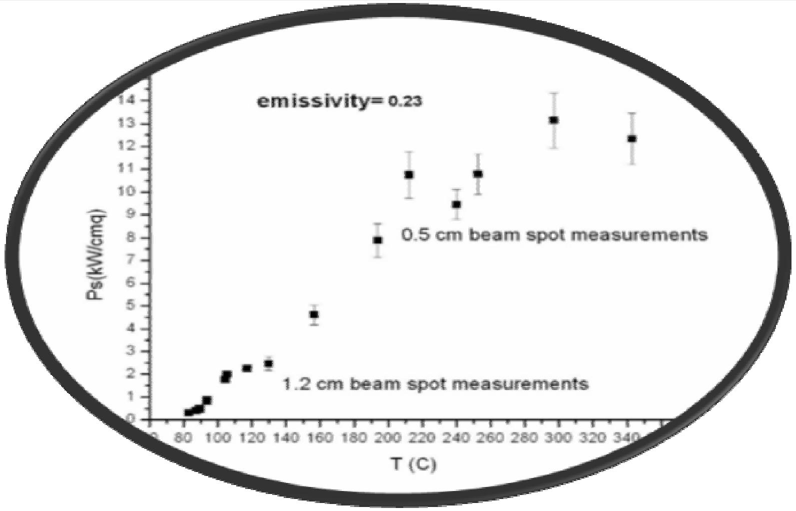


[*] P.F. Mastinu *et al.,* Physics Procedia 26 (2012) 261-273

Lithium target testing- E-Beam



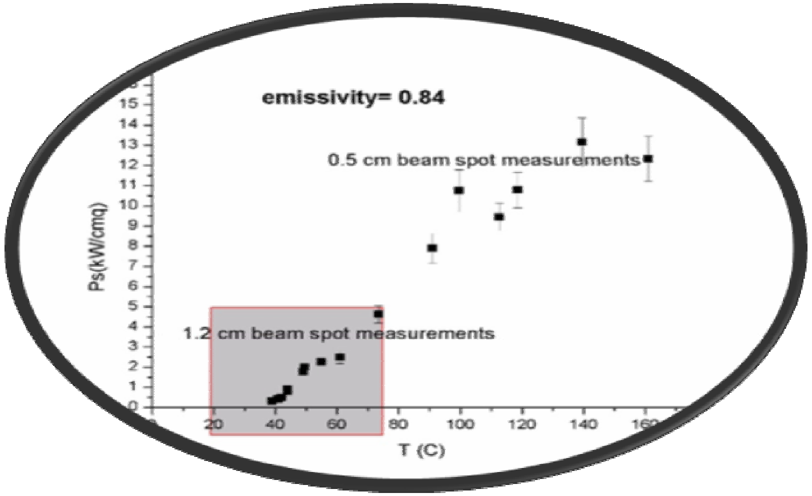
After irradiation



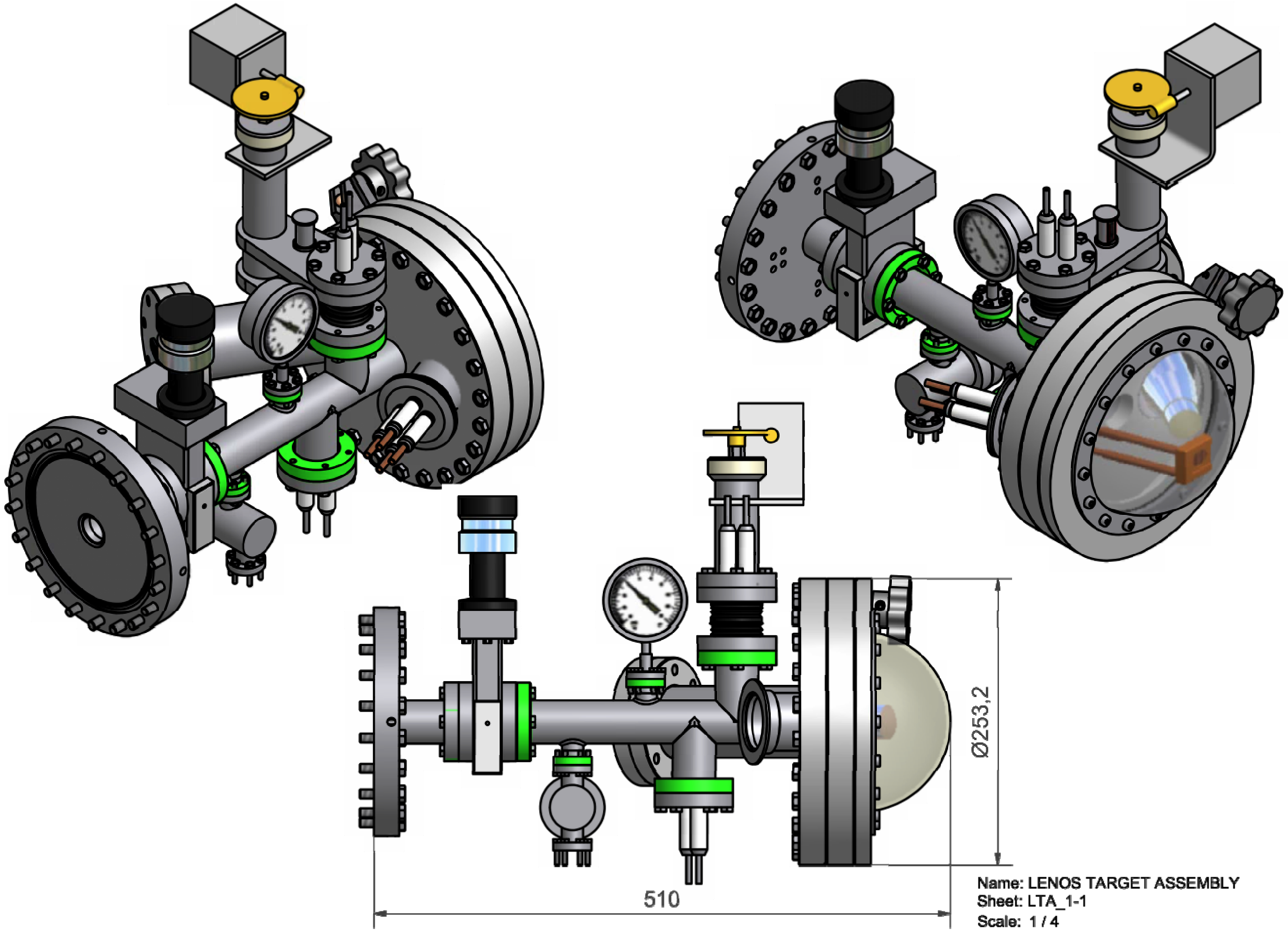
Linear rise. At least one point for normalization is needed

Large uncertainty in surface temperature determination due to uncertaincy in the emissivity. Estimated value 0.23<ε<0.84

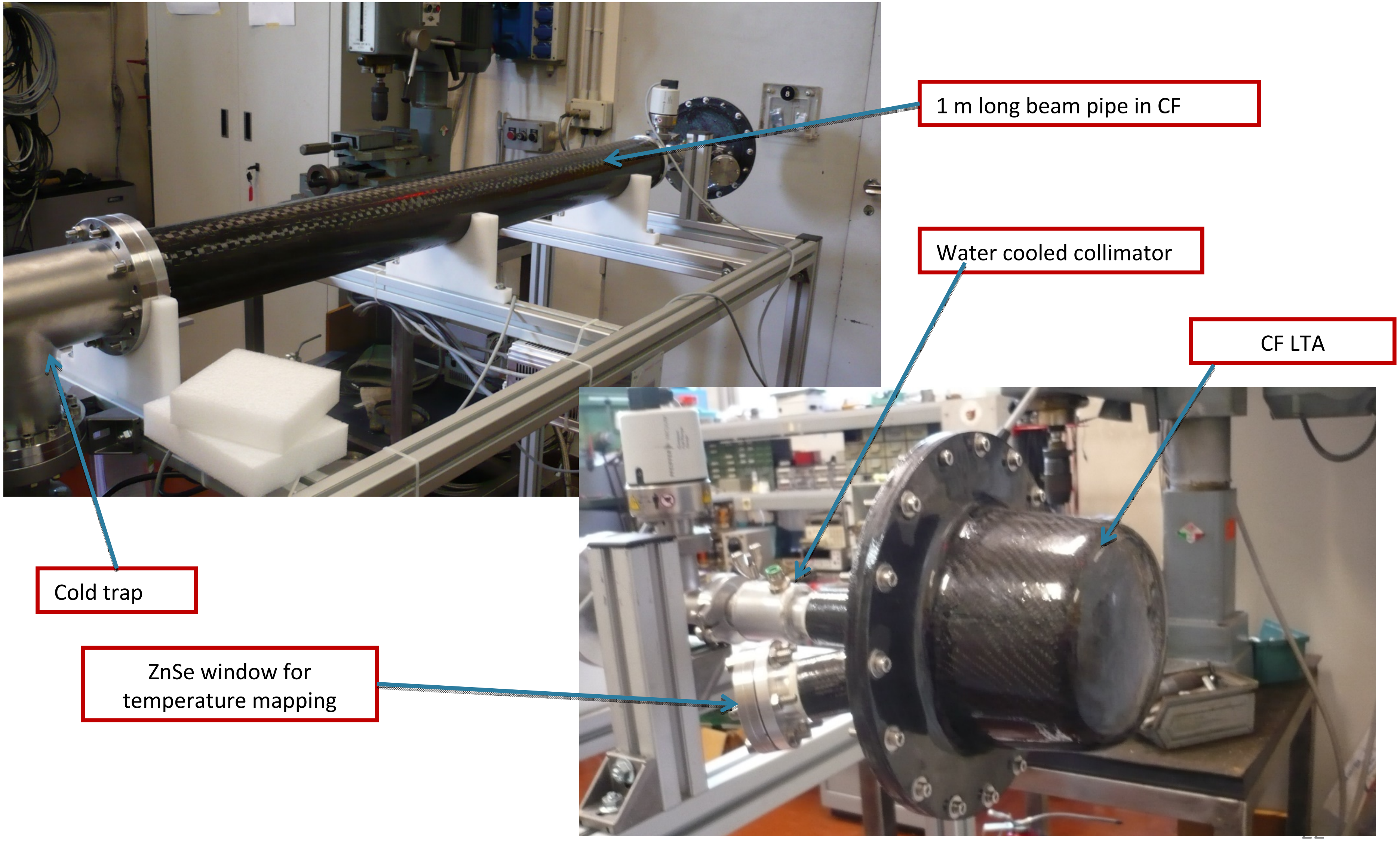
At home



Lenos Target Assembly



Lithium Target Assembly final version in CF

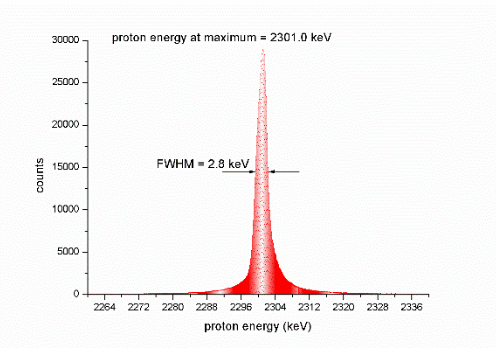


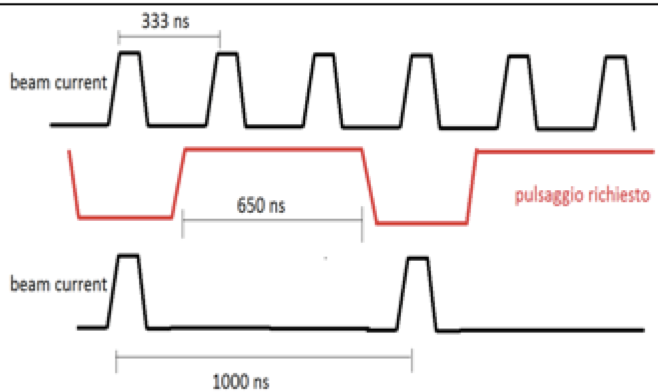
LENOS facility TOF: CN 7 MV Van der Graaf.

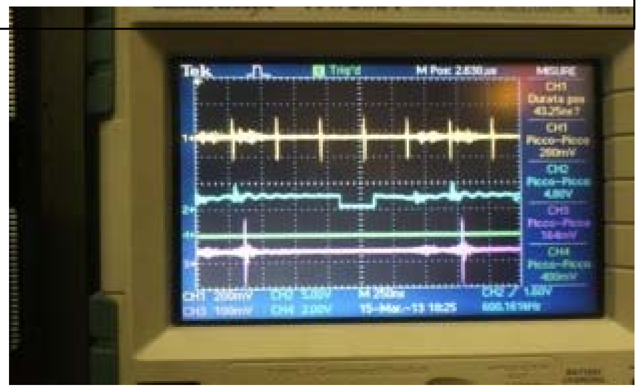
Pulsed beam:

- 3 MHz rf pulsing system on the high voltage terminal.
- 1 ns pulse width.
- Only 3 MHz operating: no adequate for neutron TOF measurement in the energy range of interest.

We have developed, installed and testing a switching system able to provide 1 ns pulse at 1 MHz, 625 kHz…. (*) low Rep rate available now for TOF measurements at CN accelerator of LNL







[*] P. Mastinu *et al.*, TALES Report (2013).

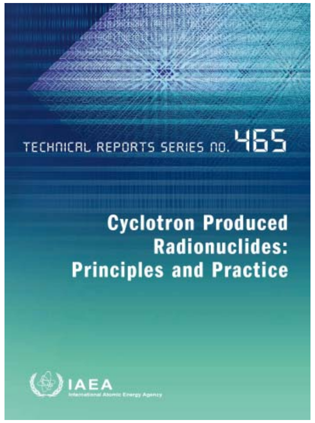
LENOS TARGET APPLICATION: LARAMED, THE MEDICAL RADIOISOTOPE PRODUCTION FACILITY@LNL

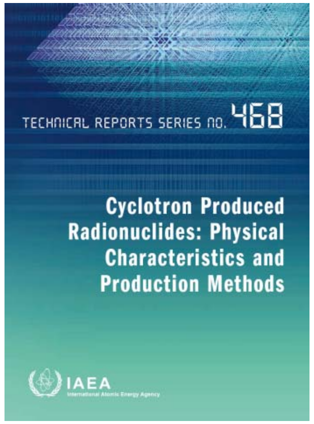
Among the several radionuclides of copper, ^{64}Cu is the most commonly used for basic science investigations and clinical PET, and its production and use have now been reported in the United States, Europe, and Japan. Several companies, including MDSNordion (Canada), ACOM(Italy), Trace Life Sciences (United States), IBA Molecular (United States and Europe), and IsoTrace (United States) are supplying ^{64}Cu for use in preparation of radiopharmaceuticals.

- PET
- CANCER RADIOTHERAPY

$^{62}Zn/^{62}Cu$ generator can be used instead of the more common ^{18}F for PET. Problems related to the time distribution of the short lived (109.8 min) ^{18}F can be reduced. It can also be used instead of ^{99m}Tc.

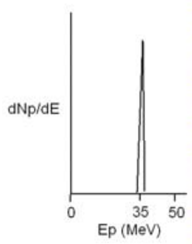
- PET

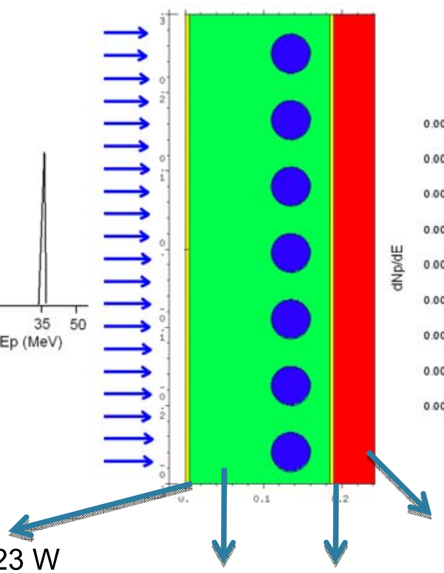


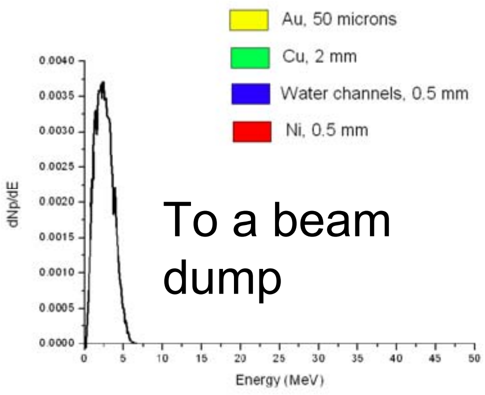


LARAMED: $^{64}Cu/^{62}Zn$ tandem production, single target

E_p=35 MeV, 300 uA







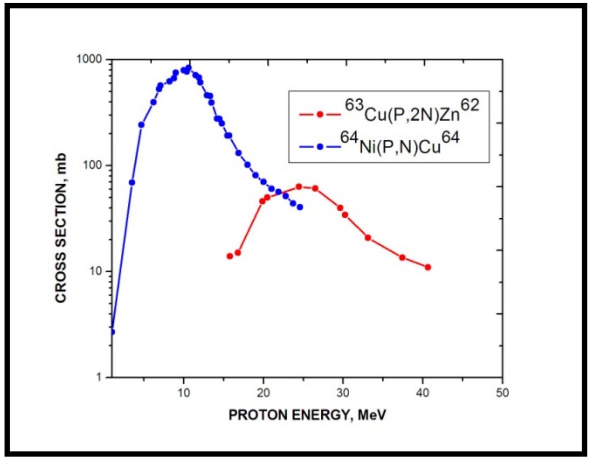
To a beam dump

P 223 W
T 700

P 6 kW
2 Ci

P 463 W
T 650

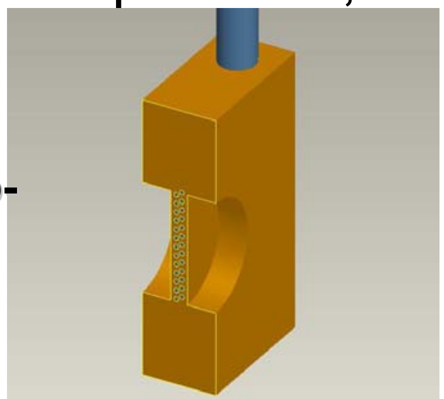
P 3.3 kW
T 850
5 Ci



Sublimation effects not taken into account

Beam spot size 1.2 cm
Total power to be dissipated 10,2 kW

When an high heat removal performance are needed, more than one row of micro-channels can be implemented



$^{nat}Cu(p,x)^{62}Zn$:
T_{irr}=10 h , m=0.3 g T_{cool}=36 h

$^{64}Ni(p,n)^{64}Cu$:
T_{irr}= 10 h T_{cool}=36 h m=300 mg

I=300 uA

Proton energy distribution impinging on Ni

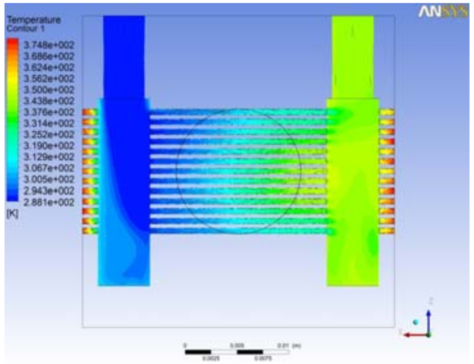
LARAMED: $^{64}Cu/^{62}Zn$ tandem production, single target

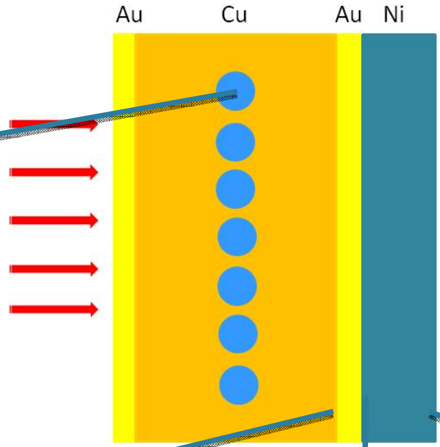
With water

Mass flow=160l/h → fluid velocity on pipes=15m/s water inlet temperature=15°C

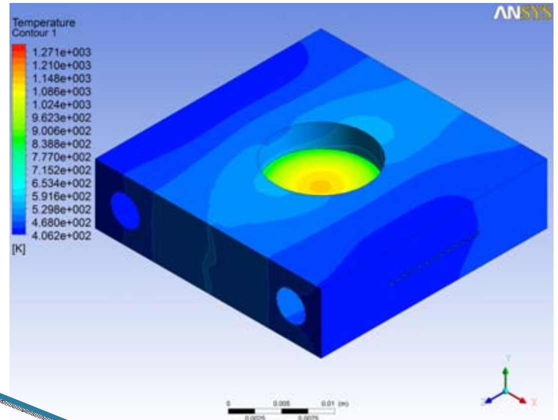
Total dissipated power=105kW

On fluid

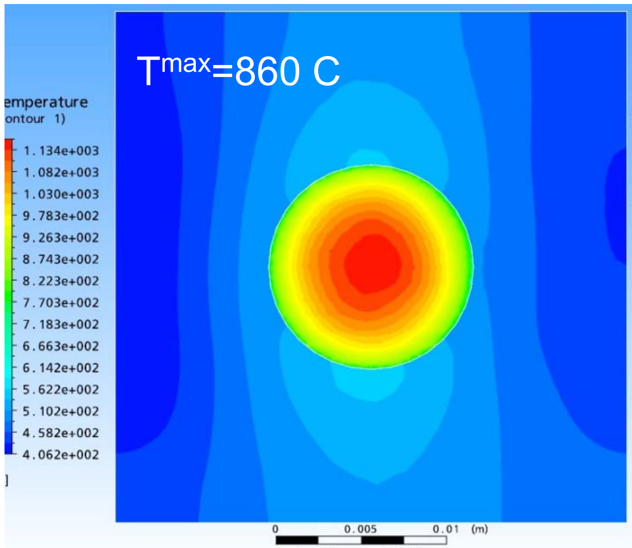




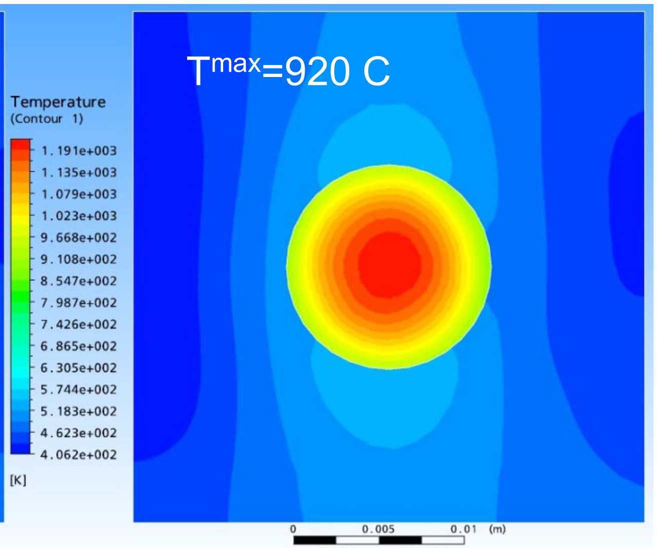
On target



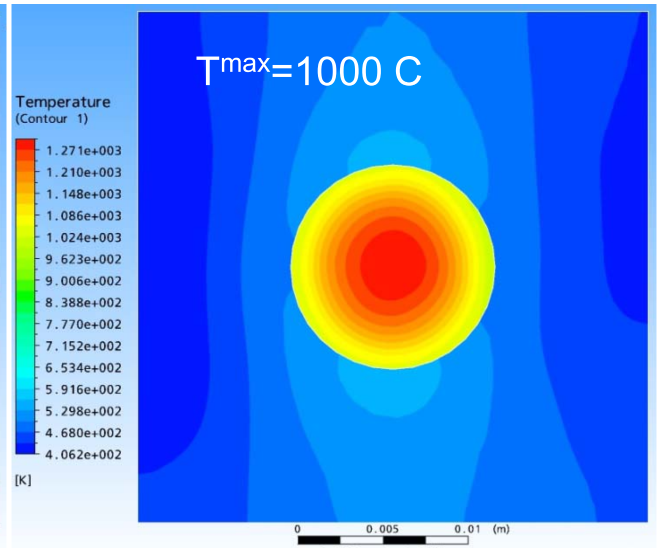
On Cu surface



On Au surface

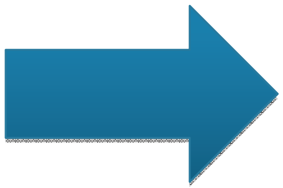


On Ni surface



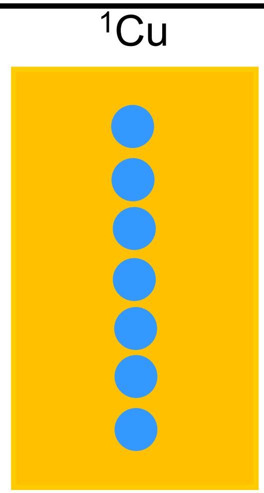
LARAMED: $^{64}Cu/^{62}Zn$ tandem production, two targets

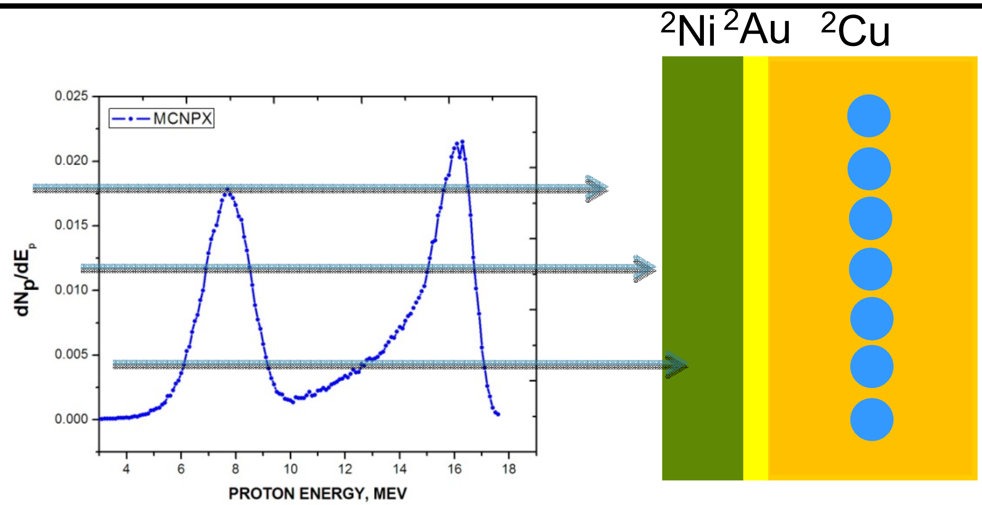
E_p=35 MeV, 300 uA



Fluid: water

Mass flow=160l/h





^{1}Cu 2 mm

P = 6042 W

^{2}Ni 0,52 mm

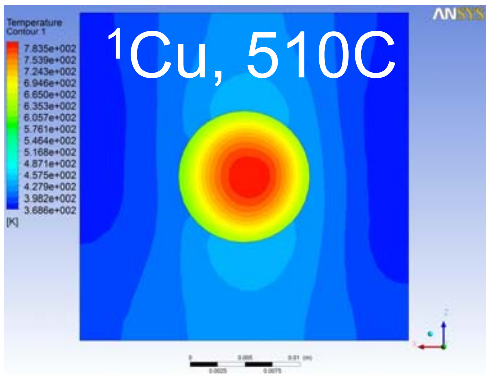
P = 3258 W

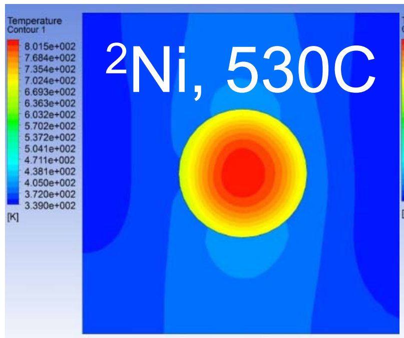
^{2}Au 1,5 mm

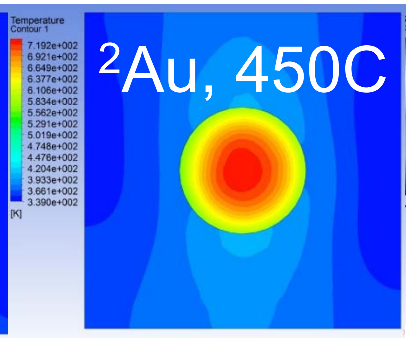
P = 650 W

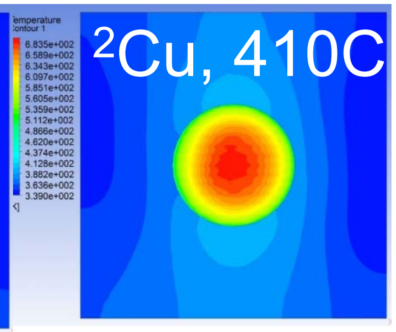
^{2}Cu 1,5 mm

P = 550 W

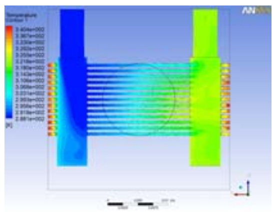


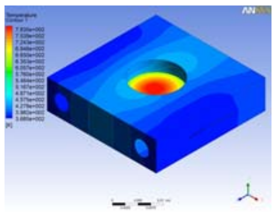


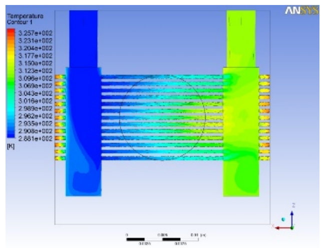


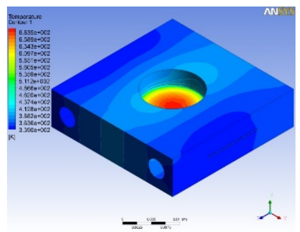


T^{max}(Fluido)=45 C









THANK YOU FOR YOUR ATTENTION !
And see you in Legnaro

UCANS V

INFN Istituto Nazionale di Fisica Nucleare

Union of Compact Accelerator driven Neutron Source

Laboratori Nazionali di Legnaro
13-15 May 2015

What would be LENOS?

- Neutron facility (irradiation, ? TOF ?)
- Based on a method for the production of different neutron spectra which avoid the use of moderators
  - Nuclear Astrophysics.
  - Validation of Evaluated Data for energy and non-energy applications.
  - Medical physics applications.
  - Radiation damage tests (SEE)
  - Material science physics (neutron imaging)