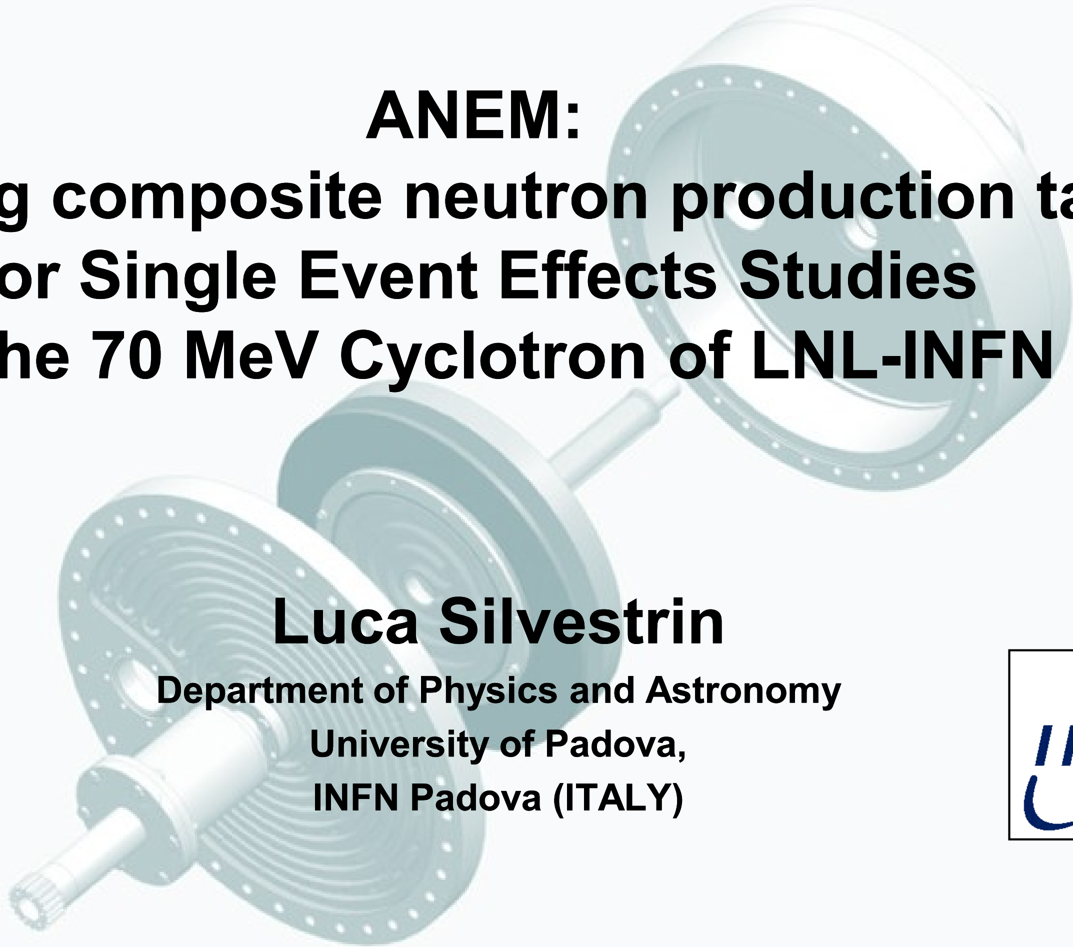
ABNP 2014
Workshop on Accelerator based Neutron Production
April 14th-15th, 2014
Laboratori Nazionali di Legnaro (Padova), Italy

ANEM:
a rotating composite neutron production target for Single Event Effects Studies at the 70 MeV Cyclotron of LNL-INFN



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NEutron and Proton IRradiation Facility at SPES

NEPIR

A SPES delta-phase project involving:

Project coordinator

NEUTARGS Padova collaboration

INFN / Padova:	D. Bisello, L. Silvestrin, *J. Wyss*
INFN / LNL:	J. Esposito, A. Lombardi, M. Maggiore, P. Mastinu, G. Prete,D. Zafiropoulos, L. Sarchiapone
INFN / Milano:	G. Gorini
CNR:	C. Andreani

"Core business": **radiation damage effects in electronics**

- **Atmospheric neutrons** (avionics and ground-based electronics)
- **Solar protons** (space applications)

Versatile ⇒ other applications too

Neutrons are a widening problem for Industry

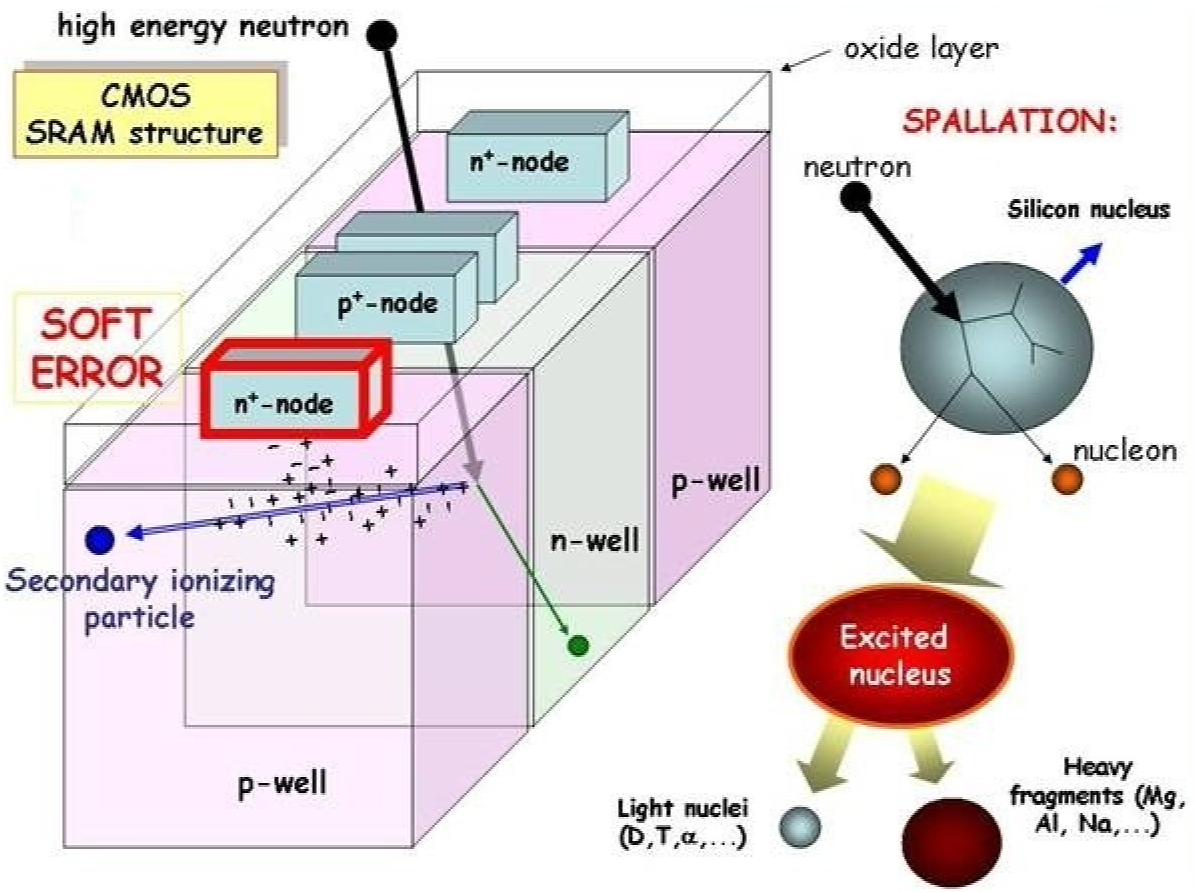
Automotive

"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."
Paul Dodd, Sandia National Laboratories

Physics of neutron-induced SEE

(1) Primary neutron
(accelerator, cosmic-rays,...)

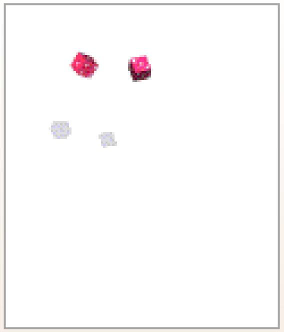
(2) neutron-nucleus reactions with production of ionizing secondaries
(Nuclear Physics)



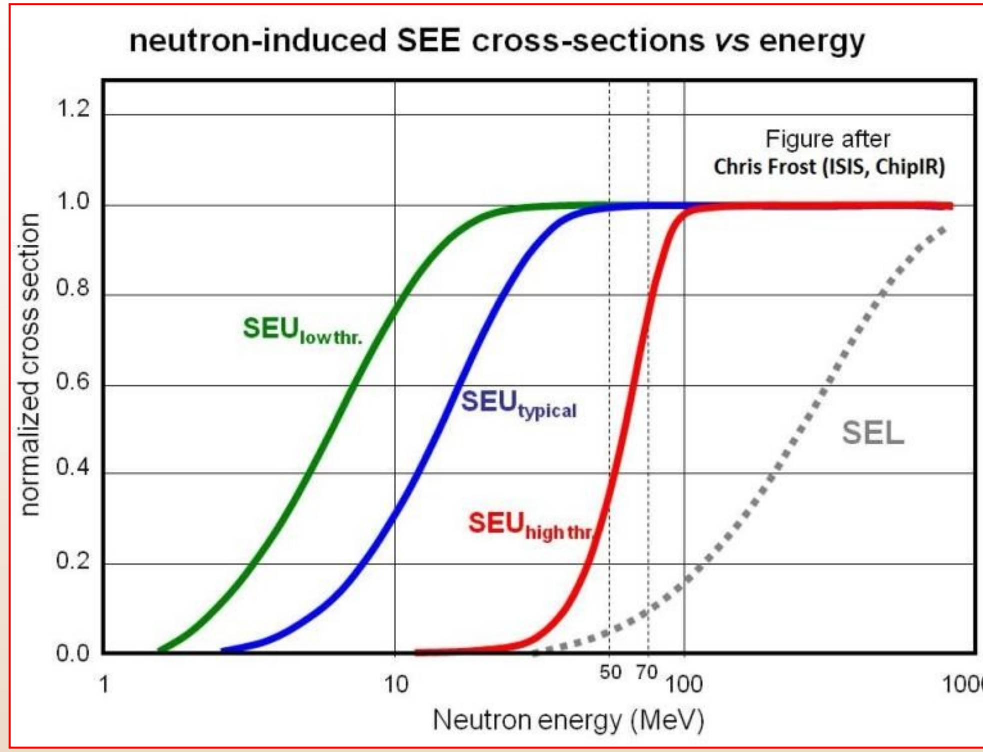
(3) Generation of electron-hole pairs
(radiation physics and solid-state physics)

(4) Charge transport in device
(device physics)

If neutron is fast enough a SEE may occur



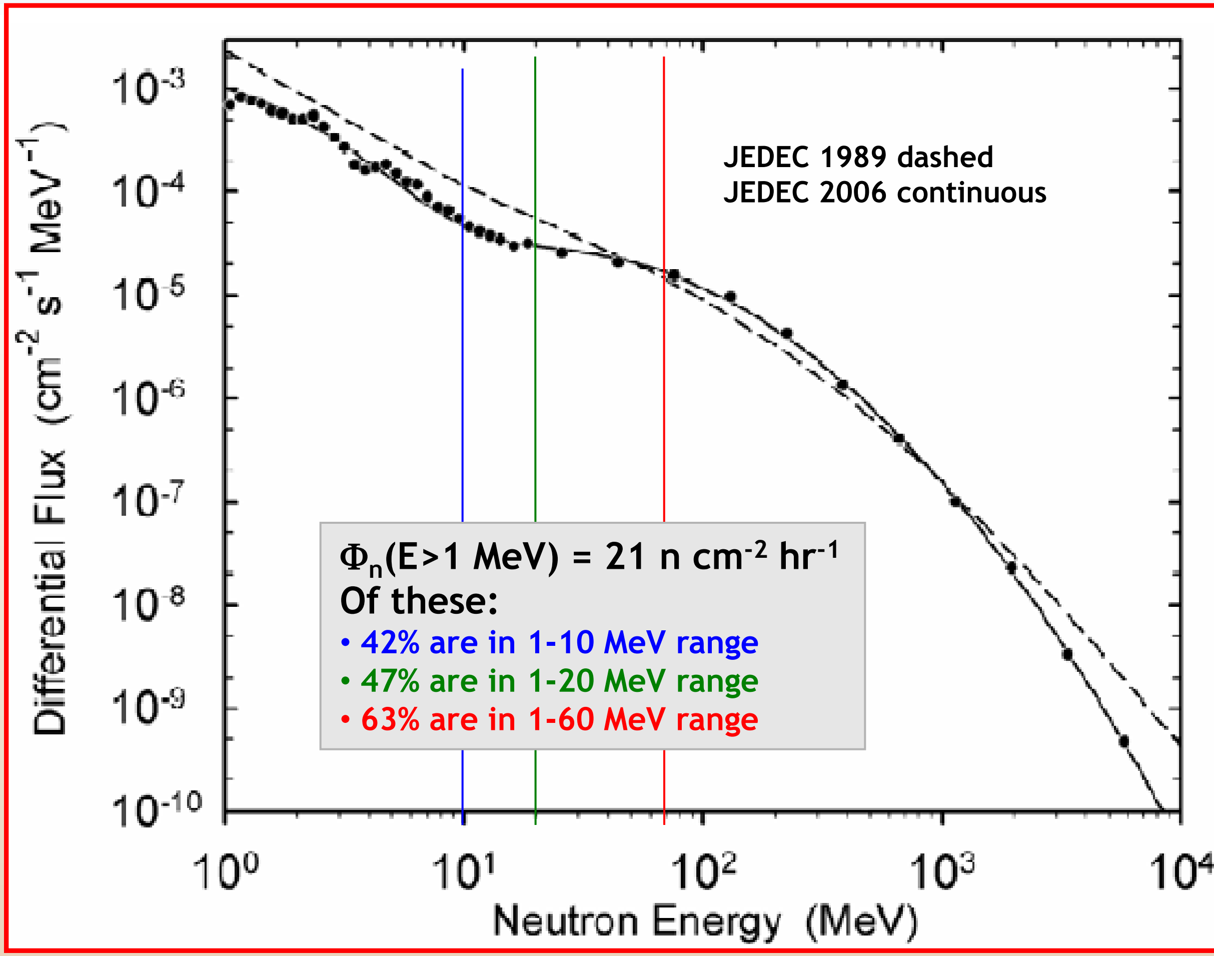
Typically, neutron-induced SEE occur when the energy of the impinging neutron is above some minimum **threshold value**; the probability of a SEE occurring, usually expressed as a **cross-section**, **increases with neutron energy,** until a **plateau value** is reached.



Weibull fit function for a typical cross section curve

$$\sigma(E) = \sigma_P \left(1 - e^{-\left[\frac{E - E_{thres}}{W} \right]^S} \right)$$

Spectrum $\varphi_{atm}(E)$ of fast (E>1MeV) atmospheric neutrons



JEDEC 2006 reference curve is fit to data (Gordon)

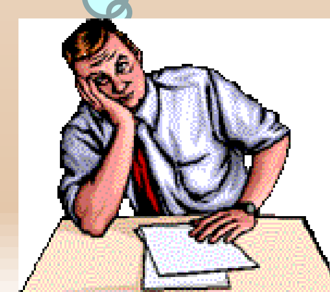
- sea level
- New York City
- mid-level Solar activity
- outdoors

Typical value for SEU
$\sigma_{Plateau}$ = 10^{-14} cm^2/bit
gives
4 SEU / (month · 8 GByte)

(yawn)
I need to speed things up…
I want an accelerator!

And the rate of neutron-induced Single Event Upsets (SEU) in a device located at New York City (NYC) is…

$$R_{SEU}^{NYC} = \int_{E_{th}}^{\infty} \sigma_{device}(E)\varphi_{atm}(E)dE = N_{bits} \times \int_{E_{th}}^{\infty} \sigma_{bit}(E)\varphi_{atm}(E)dE$$



Neutron SEE tests: field and accelerated

Type	Experimental Method	Merit/demerit
Neutron Field Tests	Keep a large number of device under test (DUT) at a certain location for a long time.	• costly, time consuming • realistic ad reliable • few corrections necessary (related to altitude and location)
Monoenergetic Neutrons *Thin light targets*	Irradiate DUT with mono-energetic neutrons. Vary energy of the neutrons to study energy dependent effects	• facilities limited • versatile • actually neutrons are quasi-mono-energetic (QMN), hence corrections are necessary to account for significant fraction of neutrons with wrong energy.
Evaporation and Spallation Neutrons *Thick targets*	Irradiate DUT with neutrons of a broad energy range similar to atmospheric neutron spectrum.	• high fluxes • facilities limited • continuous (white) spectrum needs to be similar to atmospheric one • uncertain in selection of energy range
Thermal Neutrons	Irradiate DUT with thermal neutrons at experimental reactors or using targets with moderators	• facilities limited • using reactors the estimation of SEE rate in field is difficult due to great difference in neutron spectra
Proxy mono-energetic protons	*Irradiate DUT with mono-energetic protons. Vary the energy of the protons to study energy dependent effects.*	• *many facilities available* • *pseudo-equality with neutron nuclear cross-sections* • *ionization dose effects in DUT*

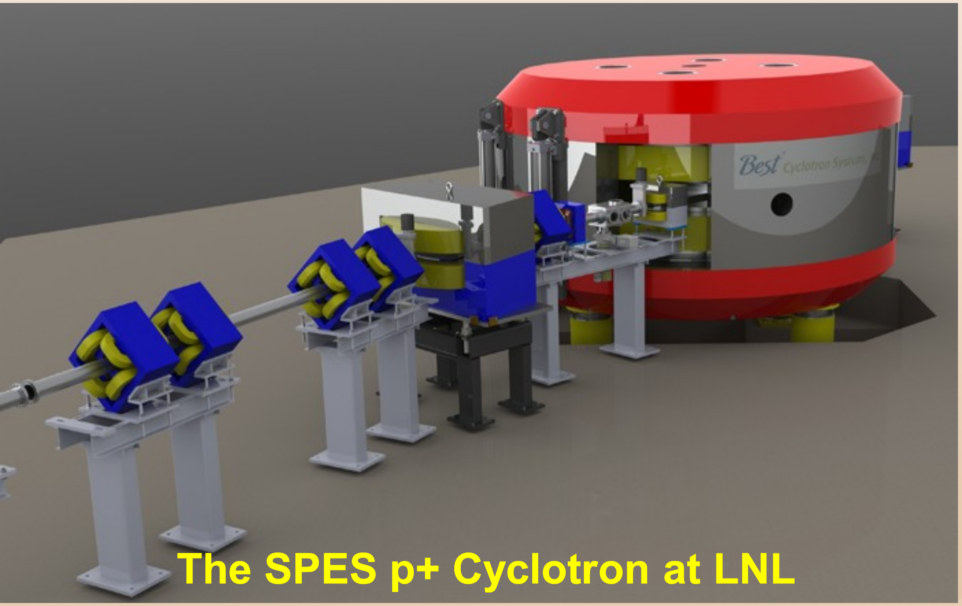
Accelerated SEE studies and tests

Useful probes:

- **(quasi) Mono-energetic neutrons**
  to study energy dependence effects
- **Continuous energy neutrons**
  to emulate atmospheric neutrons

$$R_{SEE}^{test} = F \times \int_{E_{th}}^{cutoff} \sigma_{device}(E)\varphi_{atm}(E)dE$$

F is the *"acceleration factor"*



The SPES p+ Cyclotron at LNL

At the INFN National Labs of Legnaro (LNL), a variable energy (35-70 MeV) high current proton cyclotron (I_{max} = 750 μA) will soon come into operation.

It will open up the **prospect of high flux neutron facilities in Italy** that could perform various research activities.

Tools at the proposed neutron facility (NEPIR)

Fast Quasi Mono-energetic Neutrons (QMN) from 35-70 MeV protons

- multi-angle collimator for "tail correction"
- assortment of thin (2-4 mm) Li and Be targets

COMPLEMENTARY TOOLS

Continuous energy (*white*) *atmospheric-like* **neutrons** from intense 70 MeV protons

Two high power targets:

a) Slow neutrons: a "conventional" ***thick (stopping)*** W-based target and moderator system (49 kW) (SLOWNE)

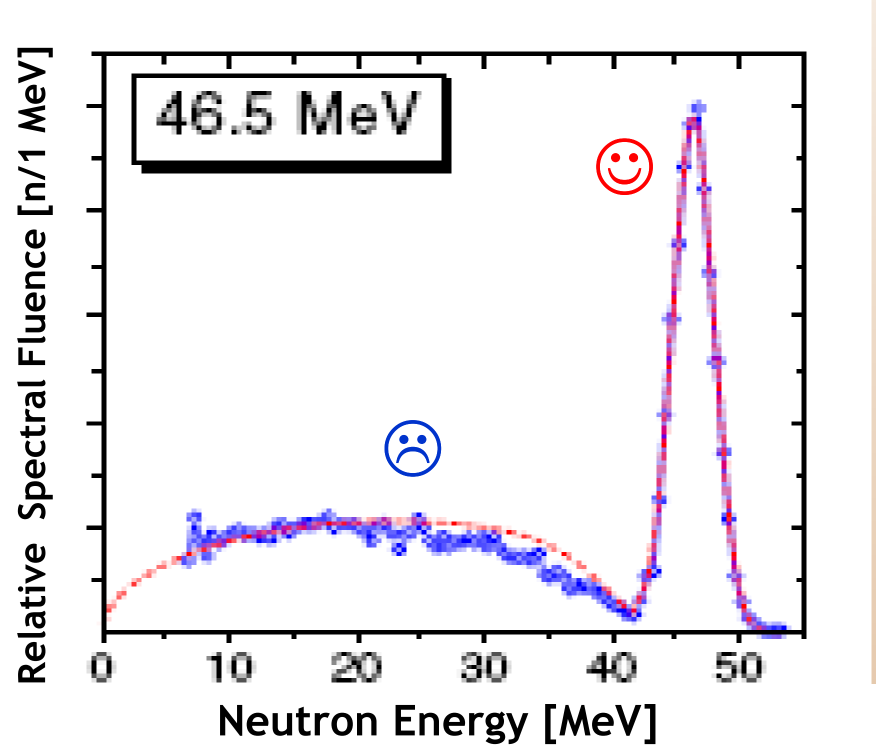
b) Fast neutrons: a "novel" rotating BePb (or BeTa) composite target system, ***relatively thick*** (non-stopping), without moderator (ANEM)

Direct protons (35-70 MeV, low current)

1) Monoenergetic Neutrons … almost (QMN)

Well defined energy neutrons are produced in **^{7}Li(p,n)** and **^{9}Be(p,n)** reactions. However the experimental neutron spectrum is not purely mono-energetic because neutrons released during nuclear break-up can assume a continuous range of energy values.

In the **forward direction (θ= 0°)** only about half of the neutrons form a peak with a well defined energy (☺), while the rest have lower energies distributed over a broad range of values (☹).



Typical **forward** QMN spectrum at **Zvedberg (TSL)** for

E_{proton} = 49.5 ± 0.2 MeV

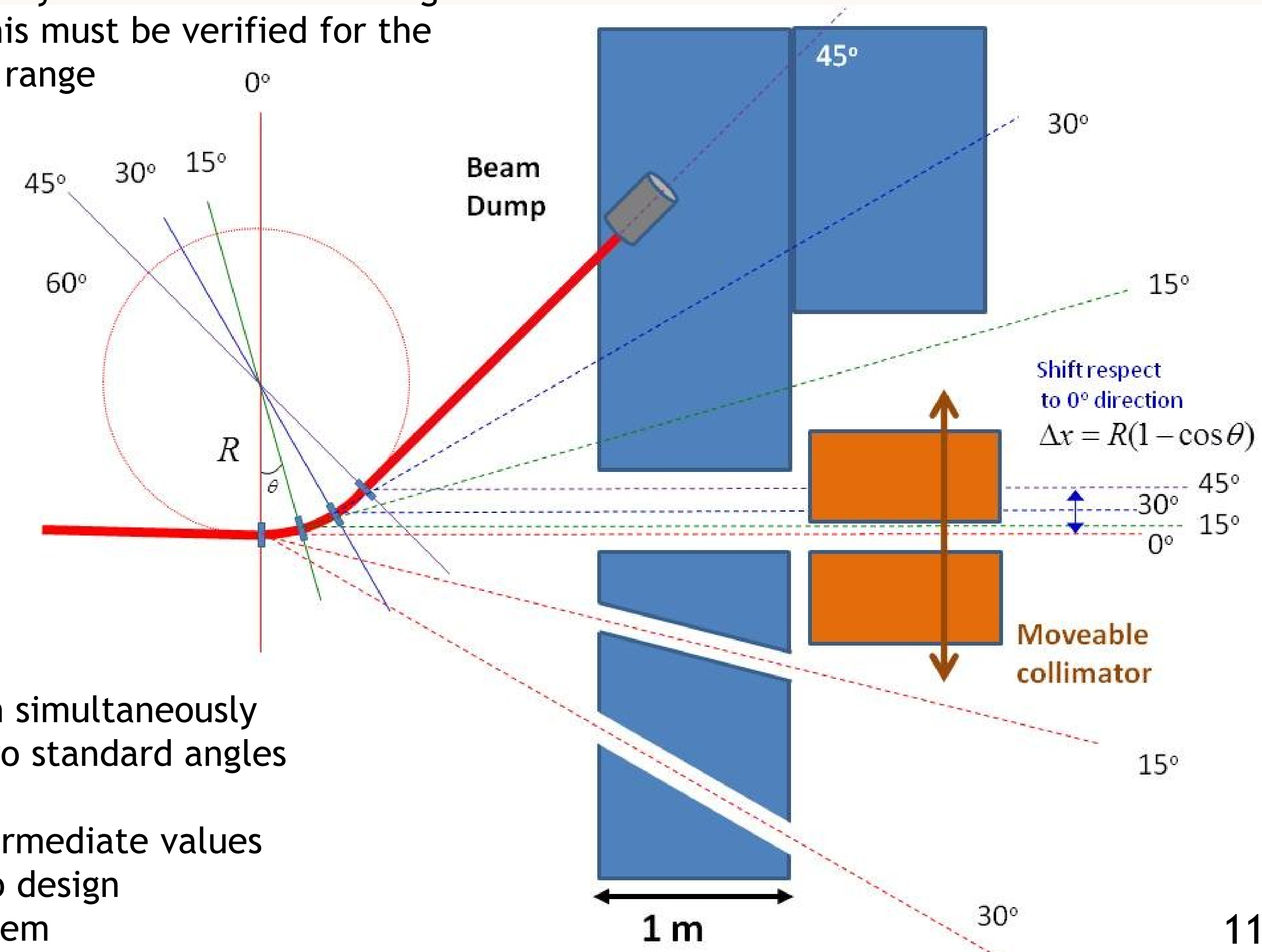
on **thin** (4 mm) Lithium slab.

- Thin ⇒ must pay price of lowered neutron yield/current
- The protons that do not undergo nuclear reactions (~99%) are magnetically defected towards a beam dump.

QMN tail subtraction

<u>PERFORMANCE</u> for 1mm and 2mm Be slabs: n flux at test point $> 3\times10^{5}$ n cm^{-2} s^{-1}
Limited neutron yield => high current: *50μA max*

A 30° collimator is likely to be the standard angle for correction, but this must be verified for the 20-35-70 MeV energy range



- data can be taken simultaneously at 0° and one or two standard angles (say 15° and 30°)
- flexibility for intermediate values
- but challenging to design magnet/target system

Forecast of EURADOS report

EURADOS

European Radiation Dosimetry Group e. V.

EURADOS Report 2013-02

Braunschweig, May 2013

The Report concludes that, out of the worldwide six QMN facilities currently in existence, all operate in sub-optimal conditions for dosimetry. Of the three facilities in Japan, one is at least temporarily out of action, and the only currently available QMN facility in Europe capable of operating at energies above 40 MeV, TSL in Uppsala Sweden, is threatened with shutdown in the immediate future. In Europe, a facility, NFS at GANIL, France, is currently under construction. NFS could deliver QMN beams up to about 30 MeV. It is, however, so far not clear if and when NFS will be able to offer QMN beams or operate with only so-called white neutron beams. It is likely that in about five years, QMN beams with energies above 40 MeV will be available only in South Africa and Japan, with none in Europe.

The QMN beam line of NEPIR would close the gap. It is of the highest priority, as it would be a precious multidisciplinary tool making NEPIR an important reference point for Italian and European research, applied and basic.

The risk of shut-down of the TSL radiation damage facilities is because the accelerator beam is increasingly used for proton therapy.

SLOWNE: a conventional continuum spectrum target

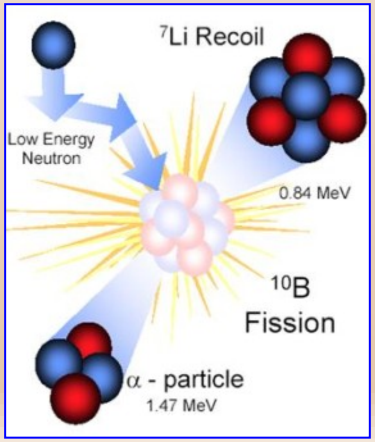
It is *conventional* in that

1. it produces the largest amount of neutrons possible…
2. …and then the neutron spectra is *shaped* using moderators

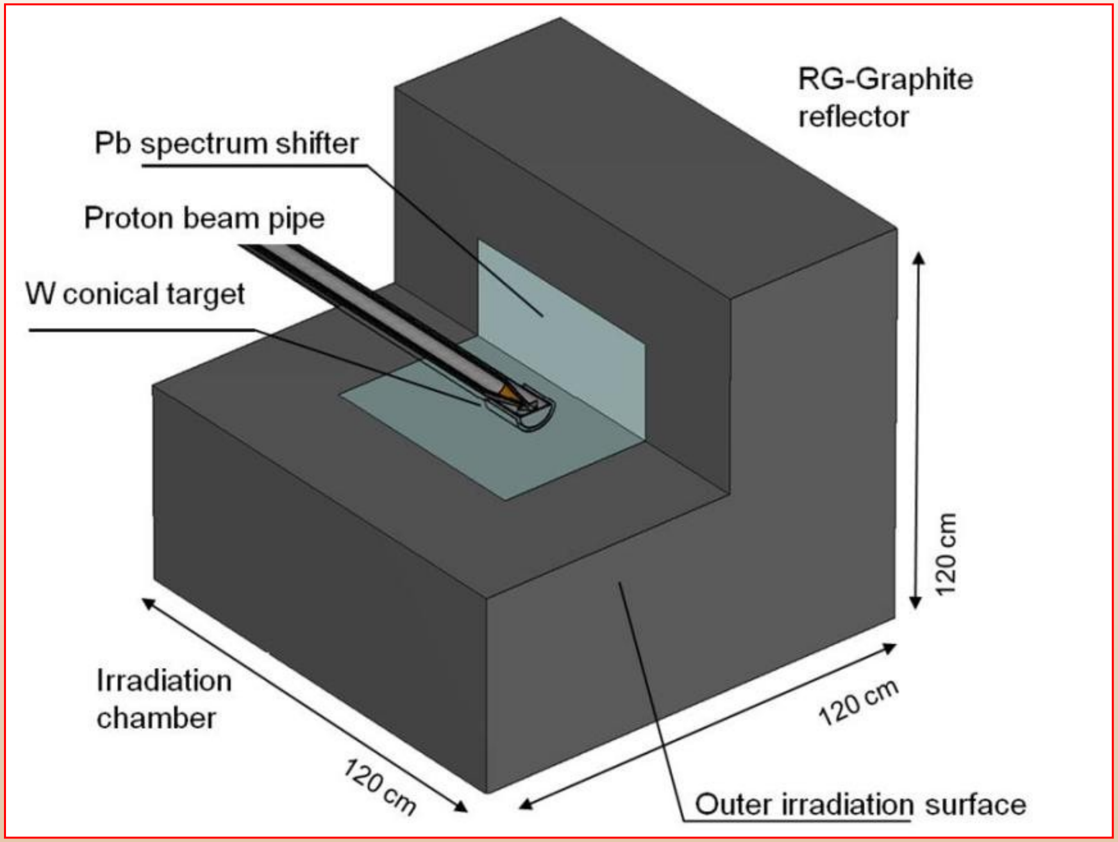
The target for the high neutron flux beam line is a **thick** W-based self-shielding production target that **completely stops the proton beam**.

Moderators and reflectors are then used to SLOW the neutrons and shape the energy spectrum to resemble the desired one, namely the atmospheric spectrum

also down to epithermal and thermal energies. Thermal neutrons may cause SEE if ^{10}B is present in device under test (same used for BNCT) .



Thick target W-based target (FARETRA*-like)

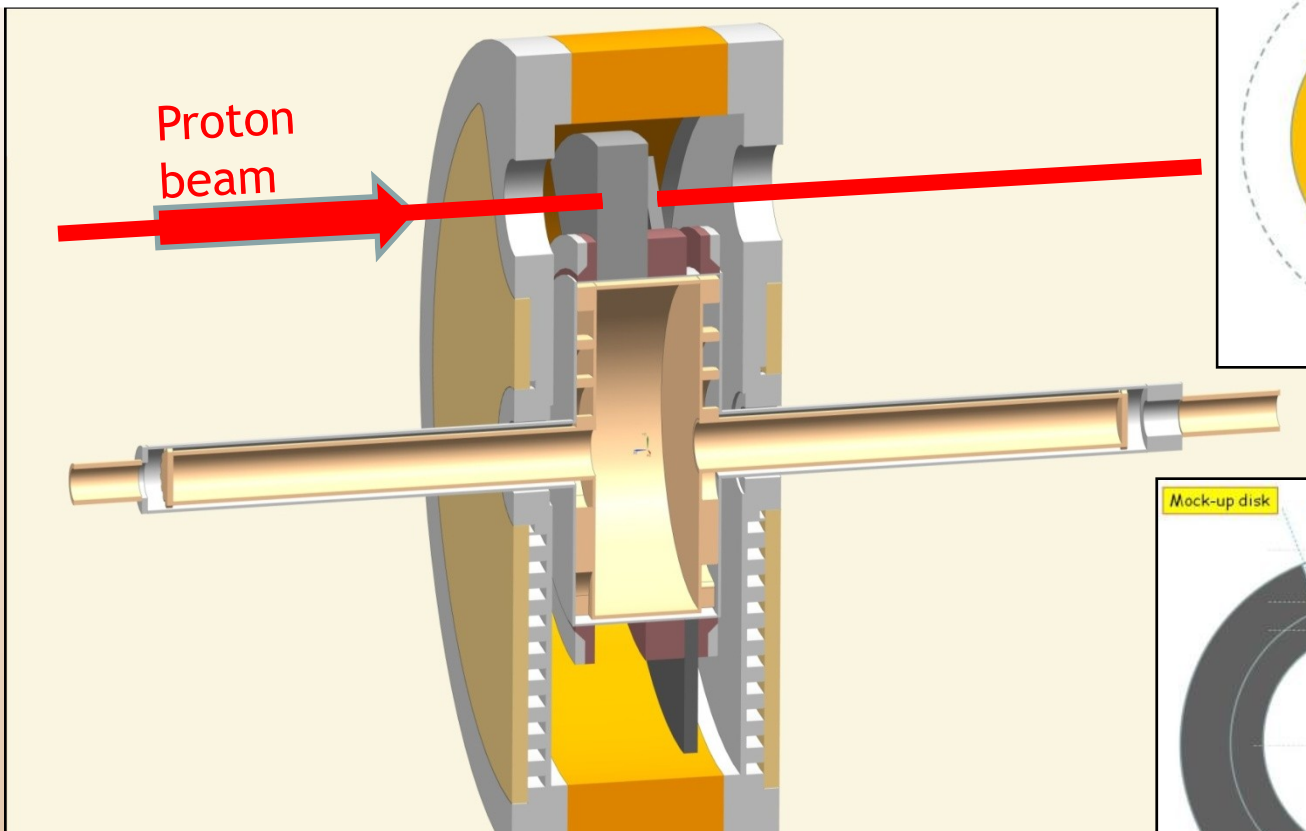


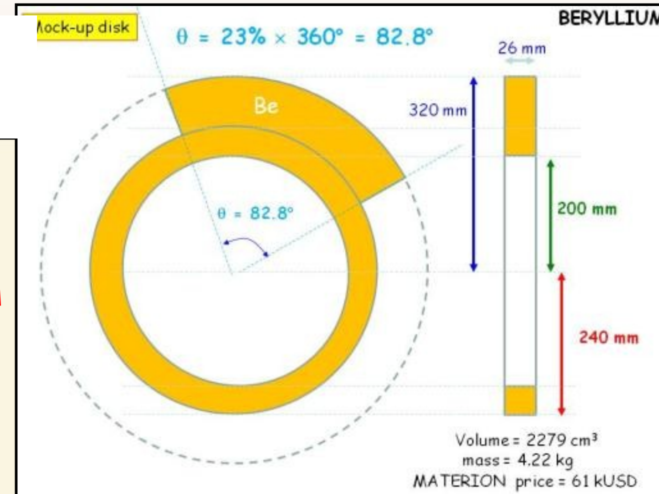
* FARETRA = FAst REactor simulator for TRAnsmutaion studies

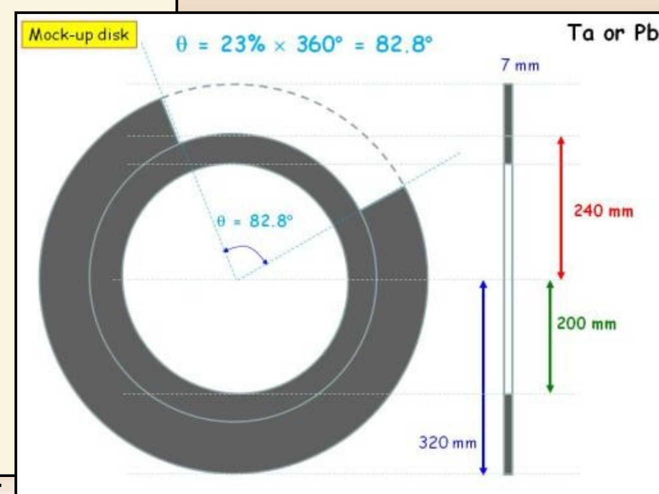
Atmospheric-Neutron Emulator (ANEM) for SEE studies

Composite Be-Pb system: Two complementary disks, rotating on a common hub, alternatively intercept the off axis proton beam; the beam is **NOT stopped by Be** (to avoid damaging due to blistering), the spent protons are the magnetically defected towards a beam dump (shared with QMN).

The LENOS chamber with modified innards to house Be and Pb (or Ta) "disks" and water flow system.

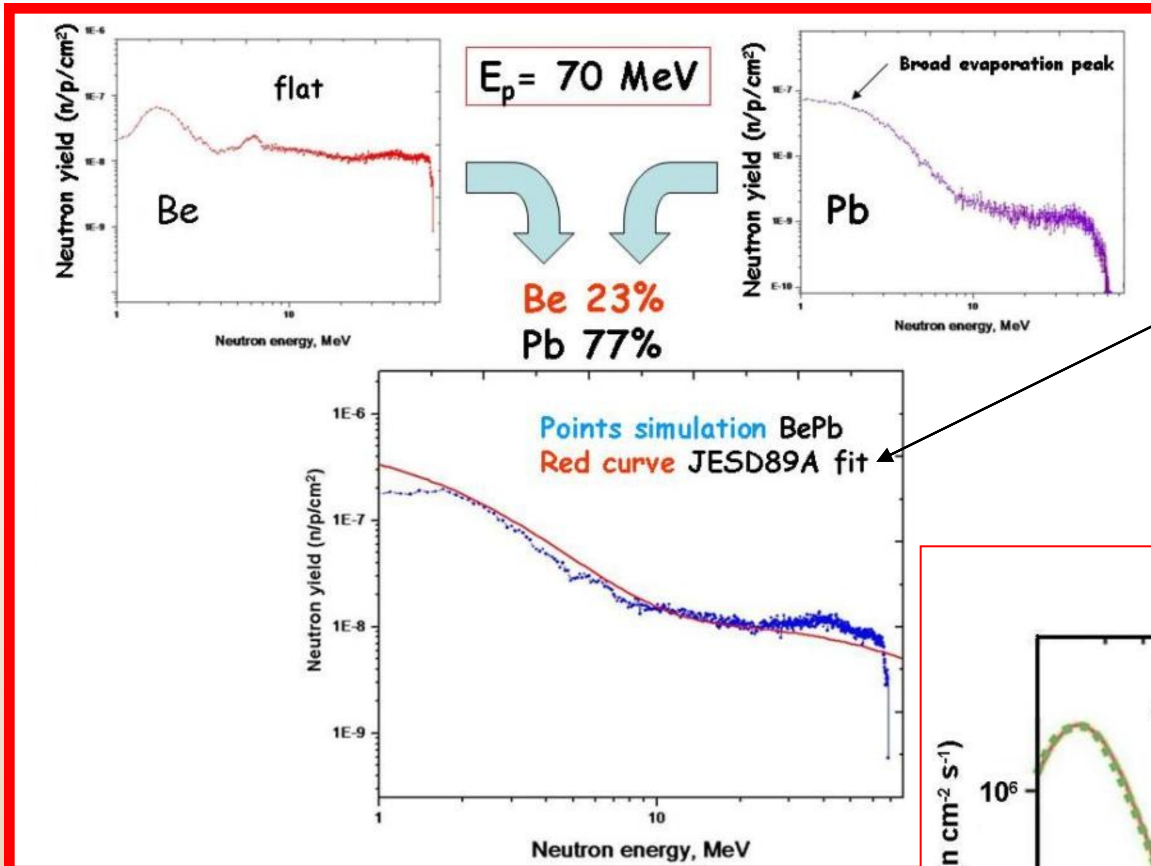




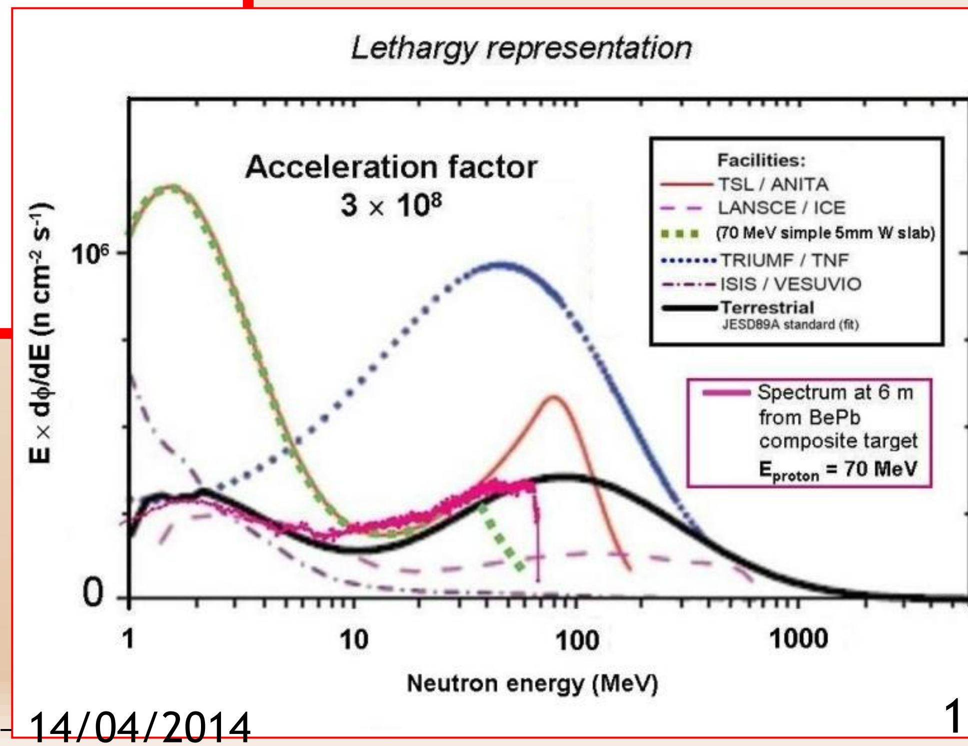


ANSYS simulations under way.
Thermal tests with Al disk foreseen in the next months.

Fast neutron energy spectrum of ANEM (BePb variant)



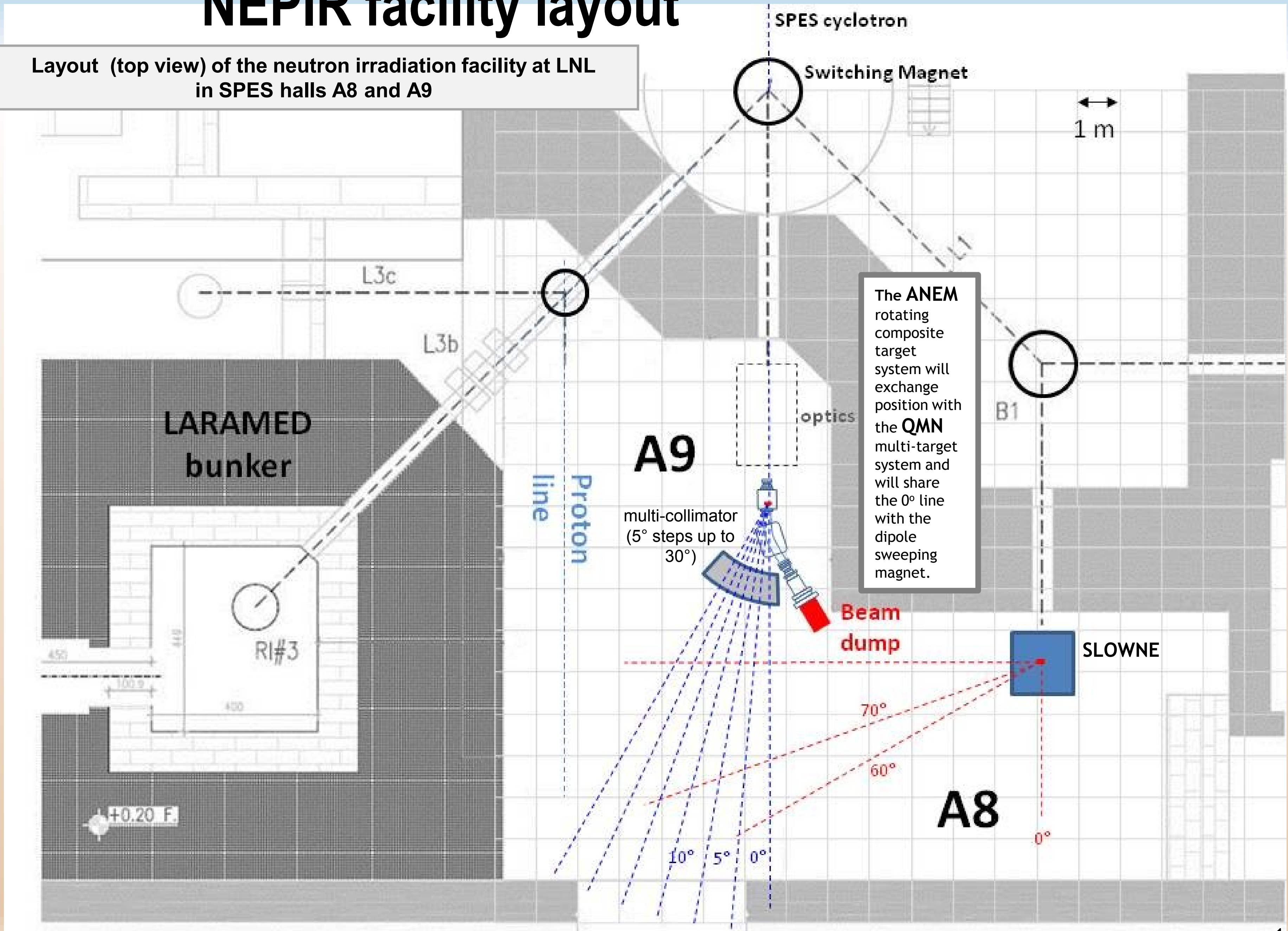
Atmospheric neutrons at sea level at New York
integrated flux E > 1 MeV
ϕ_n (E > 1 MeV) = 21 cm^{-2} hr^{-1}



Neutron FLUX at 6 m from the target: 20-30×10^9 n cm^{-2} s^{-1}
(current: 50-100 μA)
An "acceleration factors" of few 10^9 can be achieved with few tens of μA.

NEPIR facility layout

Layout (top view) of the neutron irradiation facility at LNL
in SPES halls A8 and A9



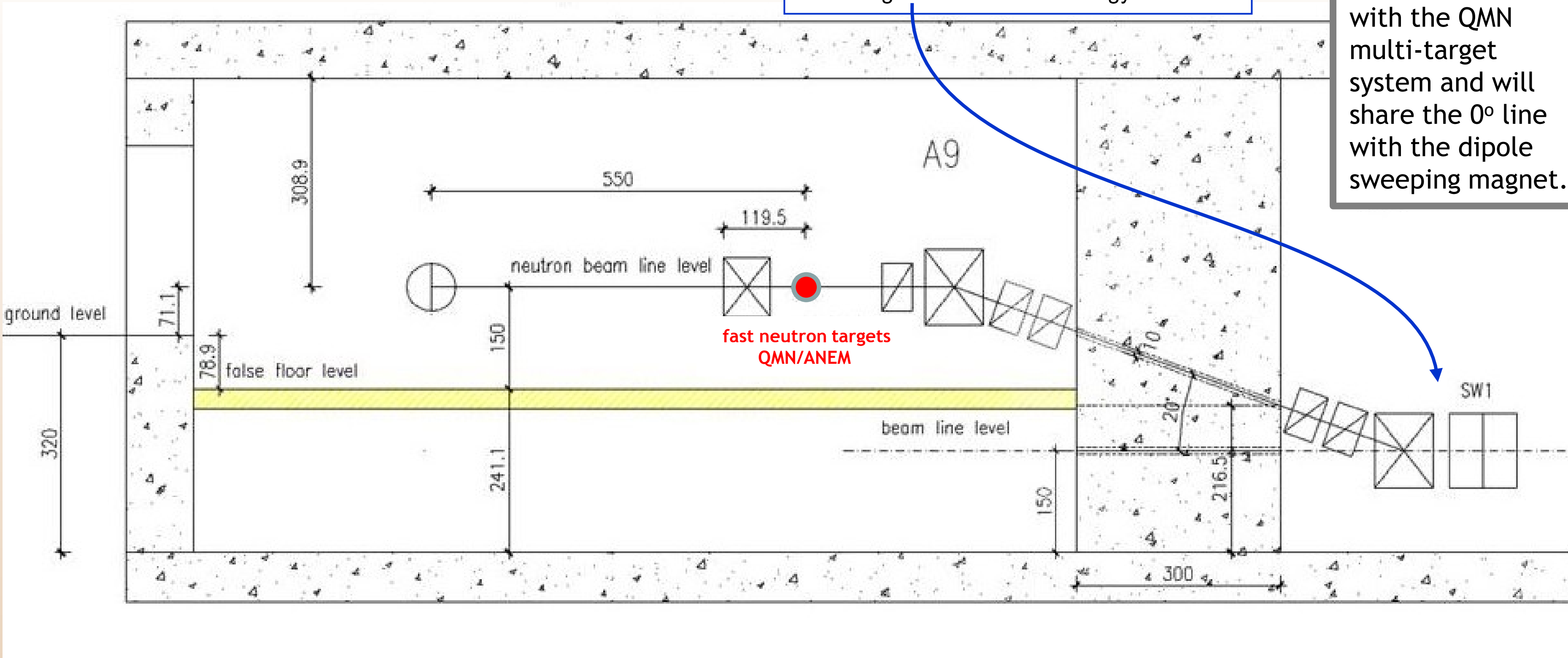
NEPIR fast neutron line (QMN/ANEM)

SPES hall A9, side view

Chicane to:

- avoid neutrons towards cyclotron
- have test point at same distance from floor and ceiling (minimize albedo)
- use degradator for lower energy neutrons

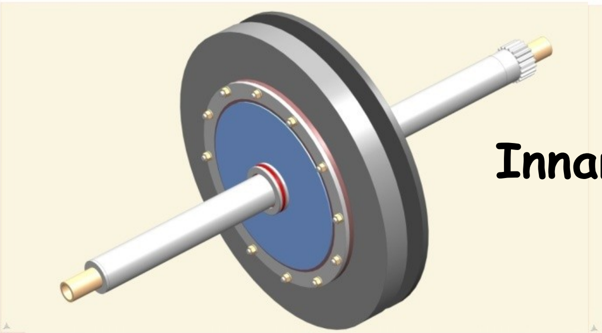
The rotating composite BePb target system will exchange position with the QMN multi-target system and will share the 0º line with the dipole sweeping magnet.



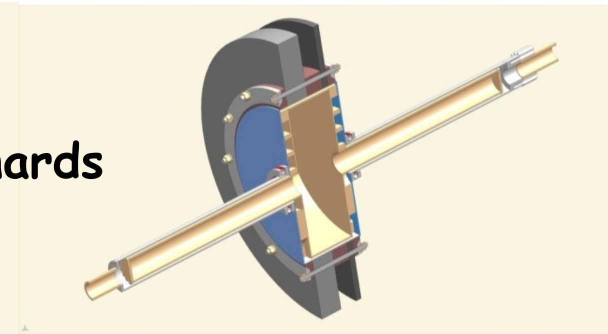
Optics of halls A1 and A9 of the fast neutron NEPIR neutron lines (QMN and ANEM).
At the test point, the neutron beam is 1.50 m from the false floor (3.91 m from the bottom cement floor). The optics consists of two dipole magnets, two quadrupole doublets and a single one, and a bending magnet for the spent proton beam. The supplementary shielding is not shown.

The ANEM prototype (mock-up) system

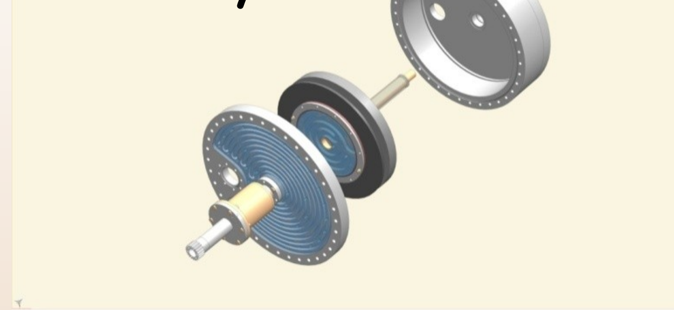
A mock up of the target was manufactured to perform the measurements of power dissipation necessary to tune the ANSYS simulations, to test the rotation system and tune the cooling system.



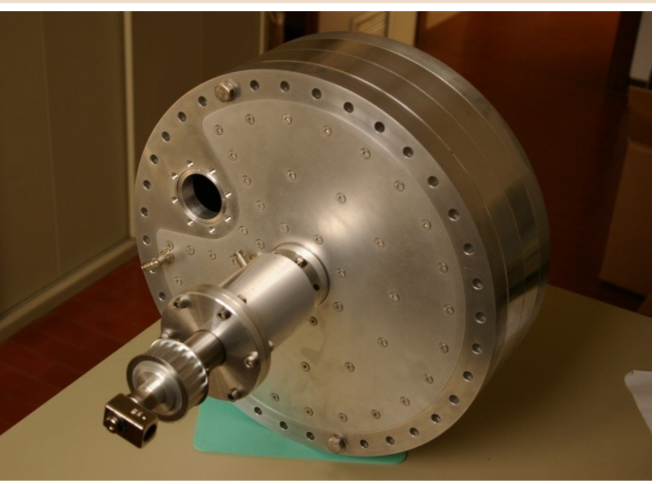
Innards

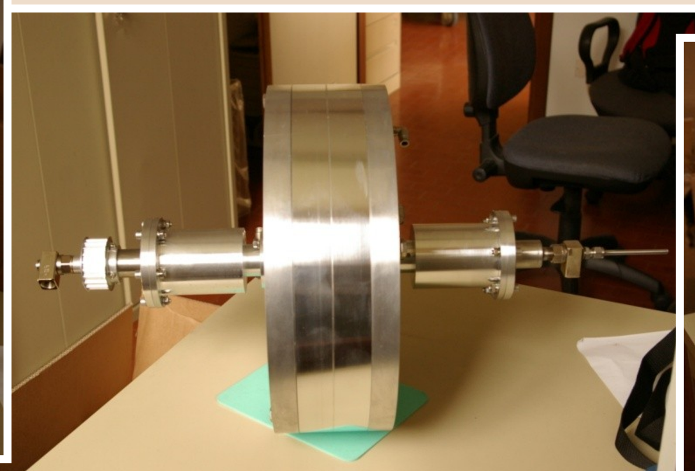


assembly



The mock up employes the existing vacuum chamber of the Lenos project while new innards were manufactured. The element exposed to the beam is a 7mm thick Al (99%) ring.

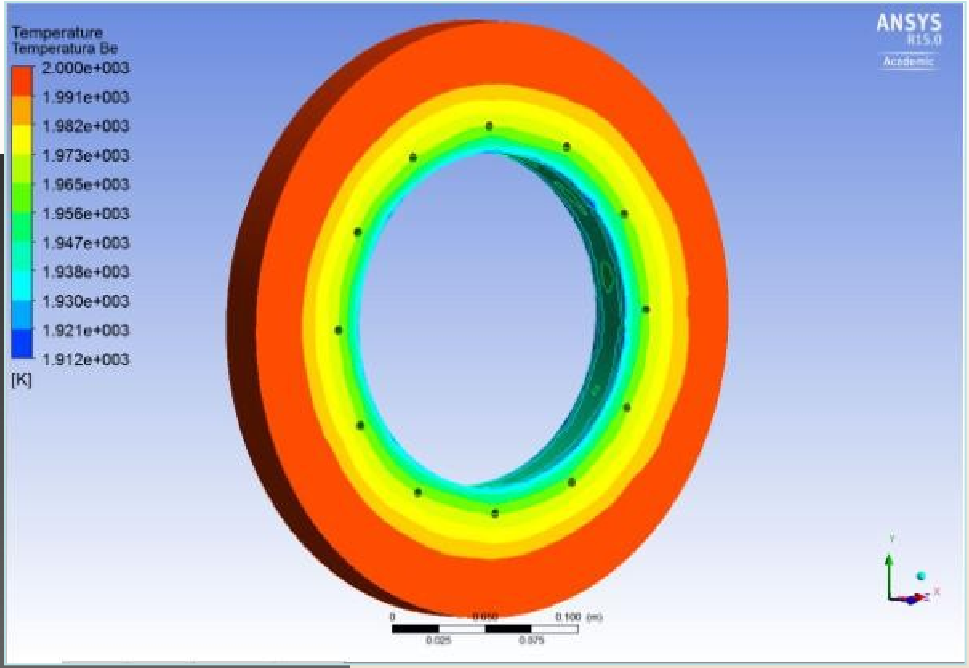




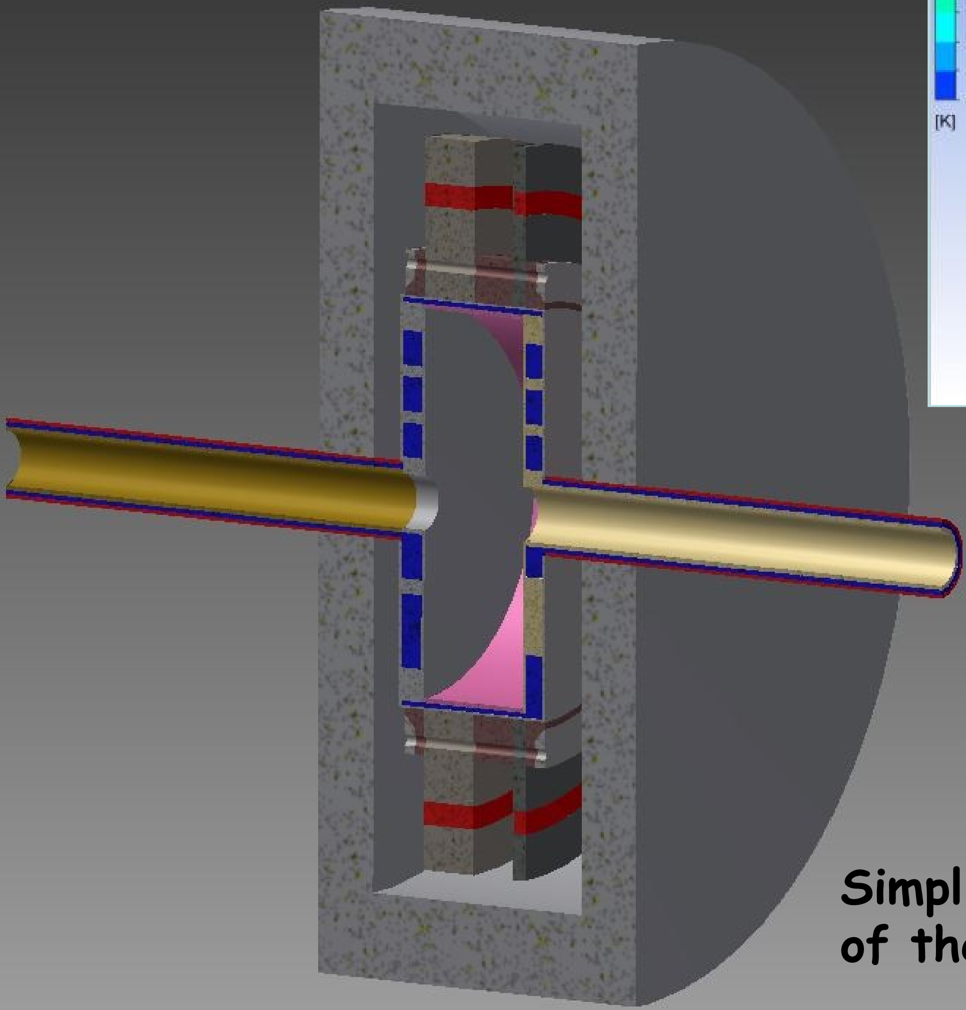
Vacuum chamber and cooling system

ANSYS thermal simulations

26 mm thick Be element
thermal map

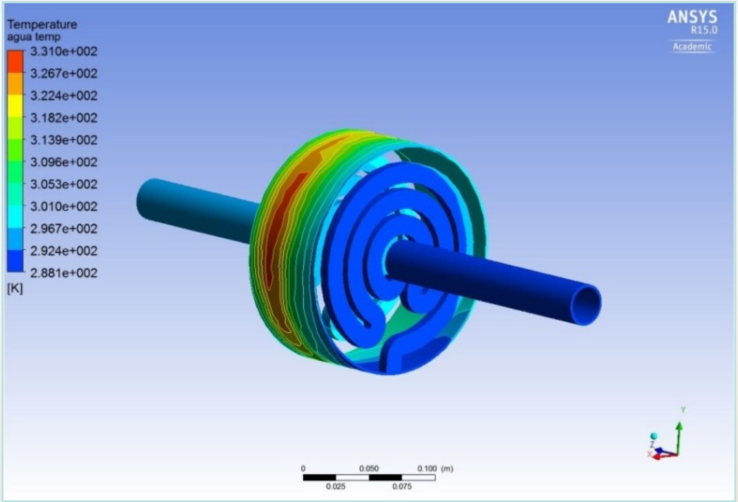


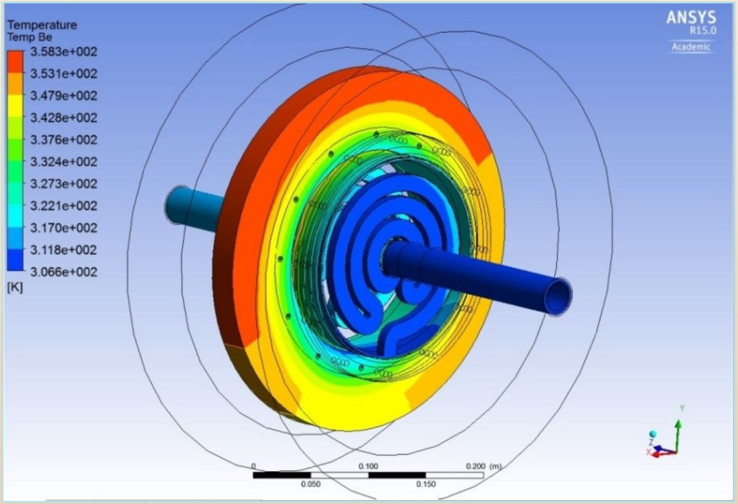
Sim. 008SS.wbpj
Steady State Analysis
Power = 5kW
No water cooling
$T_{be\ min}$ = 1639 °C
$T_{be\ max}$ = 1727 °C

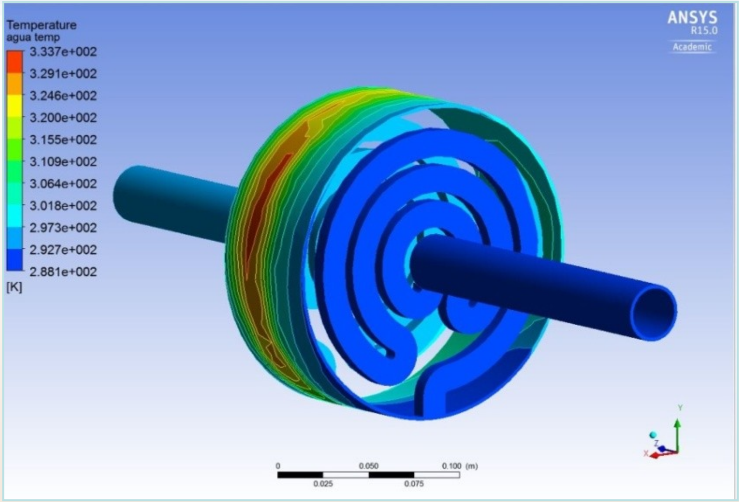


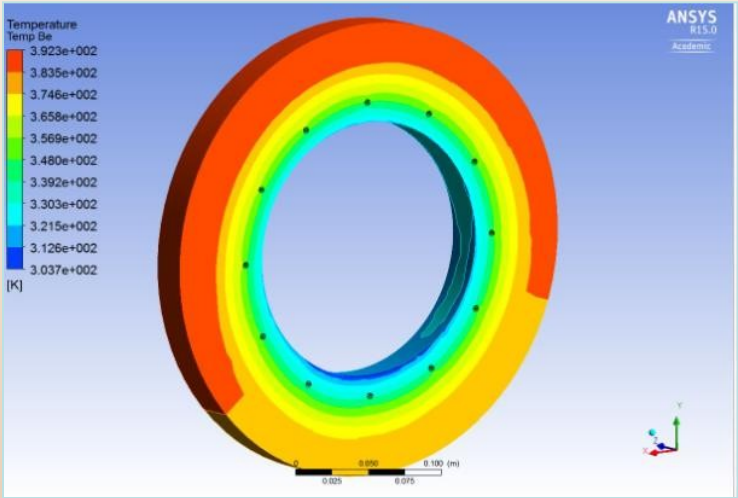
Simplified structure
of the simulated target.

ANSYS thermal simulations









021.wbpj

T_{Bemin} = 33 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 85 °C $T_{agua-max}$ = 58 °C

m. = 0,18 l/s 1m/s **2,5 kW**

Heat Transfer Model: conservative interflux

024.wbpj

T_{Bemin} = 31 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 113 °C $T_{agua-max}$ = 61 °C

m. = 0,283 l/s (1,5m/s) **5 kW**

Heat Transfer Model: conservative interflux

Thermal simulation results

Sim. #		H_2O s.	Be [°C]		H_2O [°C]	
.wbpj	*l/s*	*m/s*	*Tmin*	*Tmax*	*Tmin*	*Tmax*
008SS	0	0	1639	1727	---	---
020	0,09	0,5	53	159	15	103
023	0,18	1	36	130	15	73
024	0,283	1,5	31	113	15	61
025	0,377	2	27	112	15	53
026	0,471	2,5	25	108	15	48

Steady State Analysis varying water speed (Power = 5kW)

020.03	60 s	5 bar	3	12	80	4	29
020.04	10 min	5 bar	3	16	111	4	42
020.05	10 hr	5 bar	3	16	111	4	46

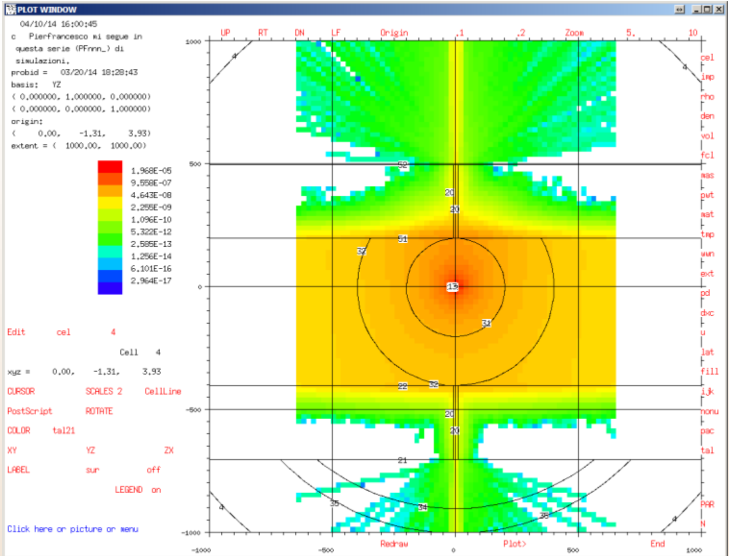
Transient Analysis
Regime condition reached in less than 10 minutes with 5 kW

Sim. #	**Power**		Be [°C]		H_2O [°C]	
.wbpj			*Tmin*	*Tmax*	*Tmin*	*Tmax*
026.03	6		27	126	-	55
026.04	7		29	144	15	61
026.06	8	Running PF			15	
026.07	9	Running GA			15	
025.03	10		35	200	15	81
026.05	12		39	237	15	**94**

Steady State Analysis varying proton beam power
(Water speed = 2.5 m/s, input pressure = 3 bar).
Maximum power tolerated by Be element: 10 kW

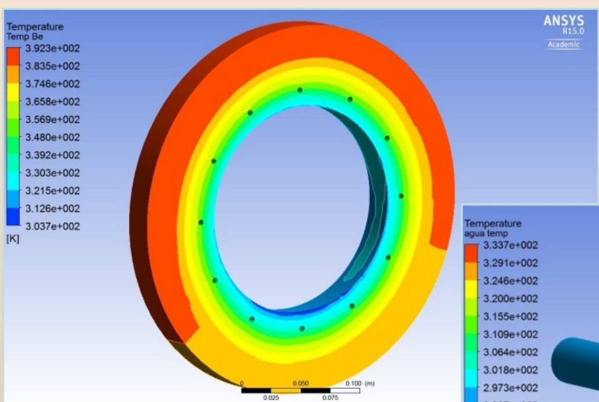
ANSIS Heat Transfer Model used: "conservative interface flux"

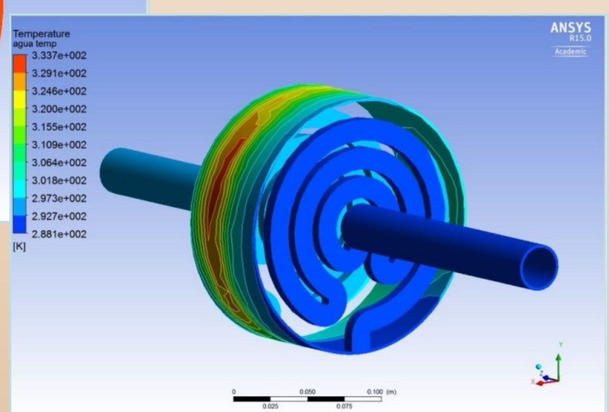
What’s next



MCNPX/Fluka simulations to **assess target shielding and collimator** system are ongoing. The design of beam dump will limit the maximum neutron flux.

To **experimentally define key heat transfer parameters,** thermal tests will be performed with the mock up target in the next months, using a hign power electron gun.





New ANSYS simulations will be performed using the experimentally defined paramenters. These will be used to **validate the final design** of the target, or to suggest modifications.

NEPIR

Particle and spectrum	Energy	Max flux at test point *(SPES current)*
neutron (discrete)	Adjustable QMN peak in 35-70 MeV energy range	Few 10^6 n cm^{-2} s^{-1} *(50μA max)*
neutron (continuous)	Atmospheric-like over 1<E<70 MeV energy range	20-30$\times 10^9$ n cm^{-2} s^{-1} *(50-100 μA)*
neutron (continuous)	Slow (moderated) neutrons depending on special applications	Flux depends on moderator system *(up to 500 μA)*
proton (discrete)	Adjustable in 35-70 MeV peak; using absorbers down to ~10 MeV	*(< 50 nA for pencil, < 250 nA for broad)*

(*) **F = 10^9** corresponds to an integral neutron flux of $\Phi_{E > 1MeV}$ **~ 6×10^6 n $cm^{-2} \cdot s^{-1}$**

THE END

Thank you for your attention,
extra slides follow

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13.1.2.2. Heat Transfer

Determines whether or not heat transfer models are applied between the sides of the interface.

The options are:

- **Conservative Interface Flux**

  This option enables you to define the **Thermal Contact Resistance** or **Thin Material**, which are two ways of defining the same charact
  That is, if you do not know the contact resistance, you can define the thin material and its thickness and have the solver derive the resistanc

- **Side Dependent**

13.1.2.2.1. Conservative Interface Flux: Interface Model

13.1.2.2.1.1. None

No models are provided for any additional heat transfer between side 1 and side 2 of the interface.

13.1.2.2.1.2. Interface Model Option: Thermal Contact Resistance

Enter a numerical quantity or CEL expression that specifies the value of the thermal contact resistance from side 1 to side 2 of the interface.

13.1.2.2.1.3. Interface Model Option: Thin Material

Select a material and enter a numerical quantity or CEL expression that specifies the value of the thickness of the material spanning from side 1 to sid
interface.

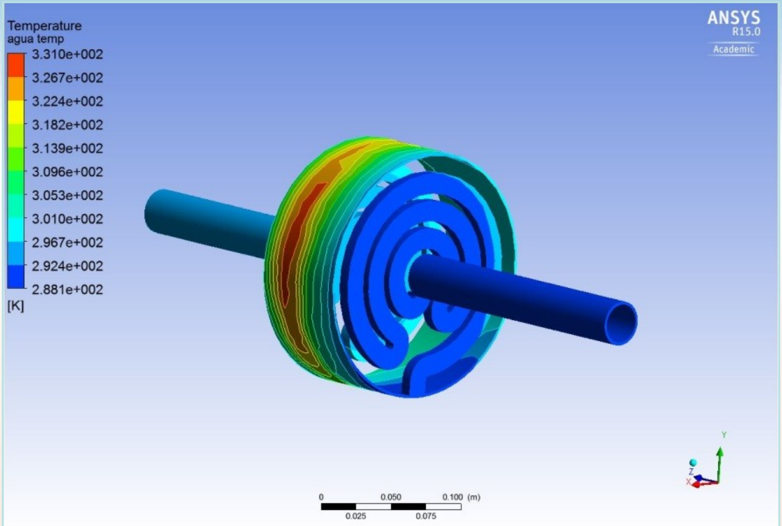
13.1.2.2.2. Side Dependent

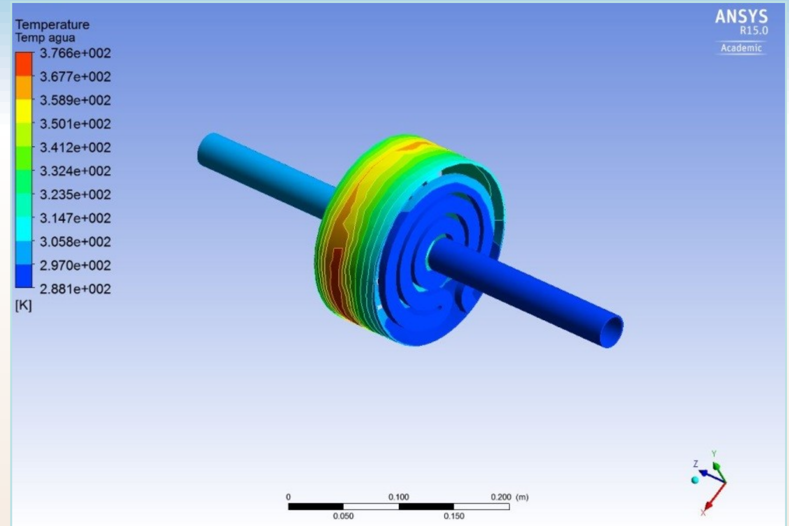
Side Dependent has no suboptions.

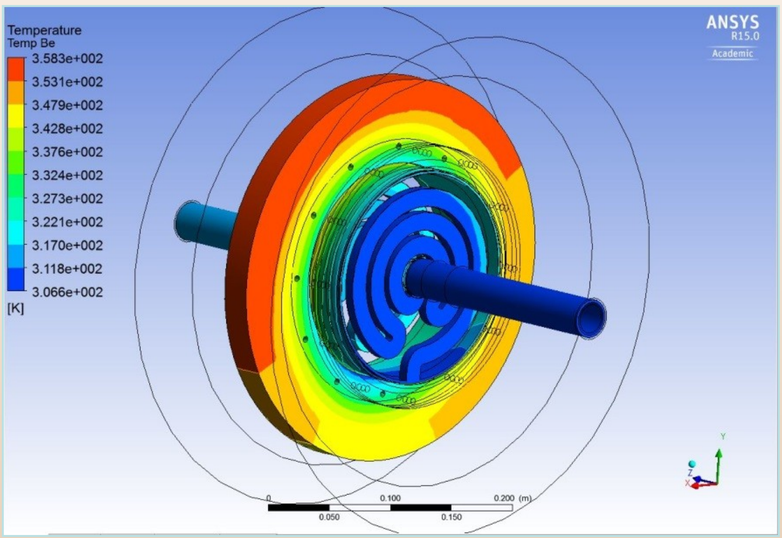
13.1.2.3. Electric Field

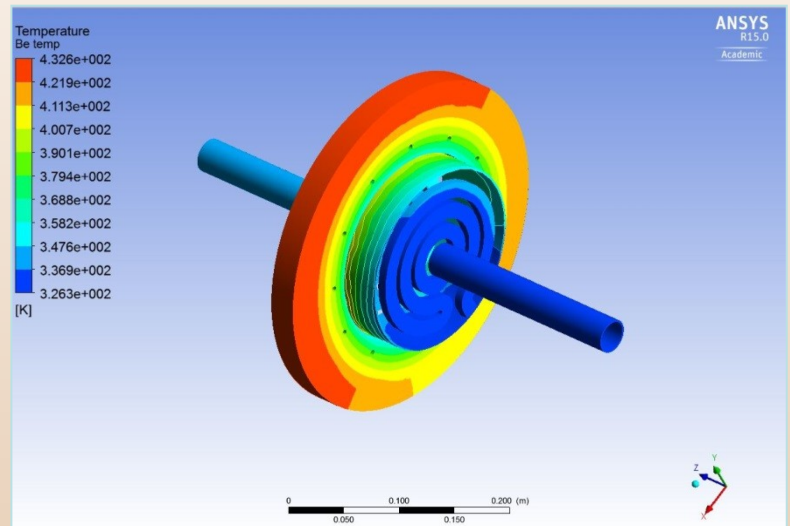
Determines whether or not electric field models are applied between the sides of the interface.

The options are:









021.wbpj

T_{Bemin} = 33 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 85 °C $T_{agua-max}$ = 58 °C

m. = 0,18 l/s 1m/s 2,5 kW

Heat Transfer Model: conservative interflux

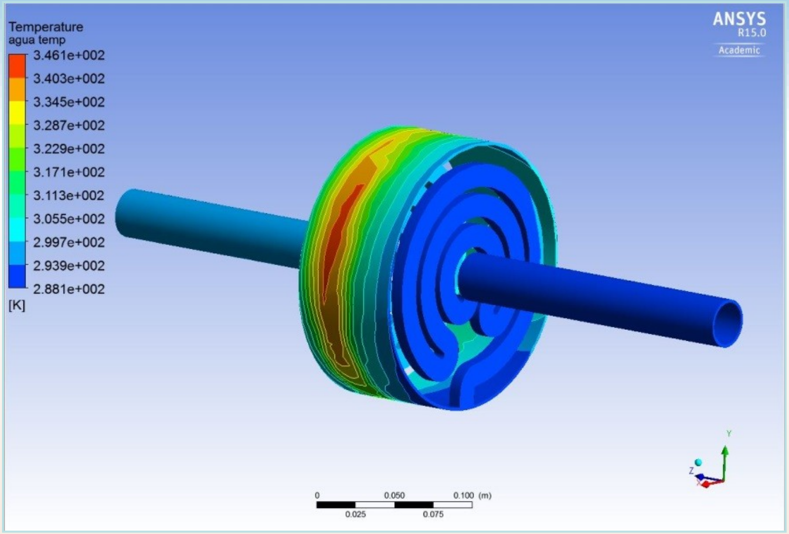
020.wbpj

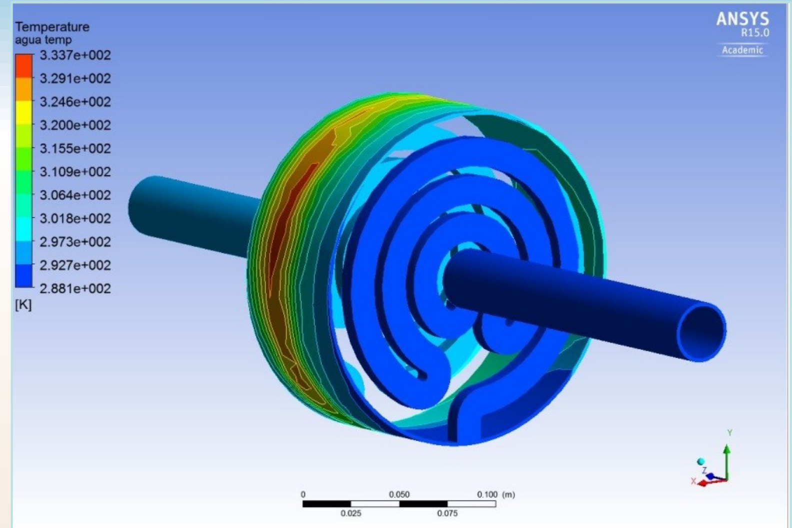
T_{Bemin} = 53 °C $T_{agua-min}$ = 15 °C

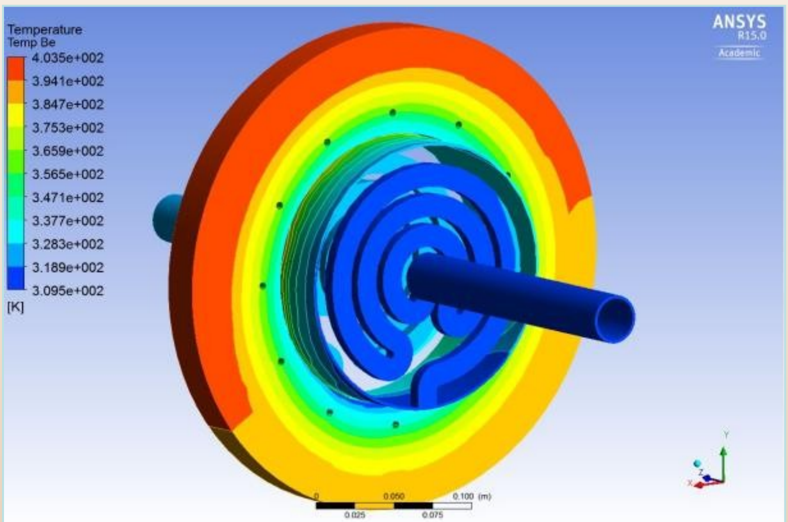
T_{Bemax} = 159 °C $T_{agua-max}$ = 103 °C

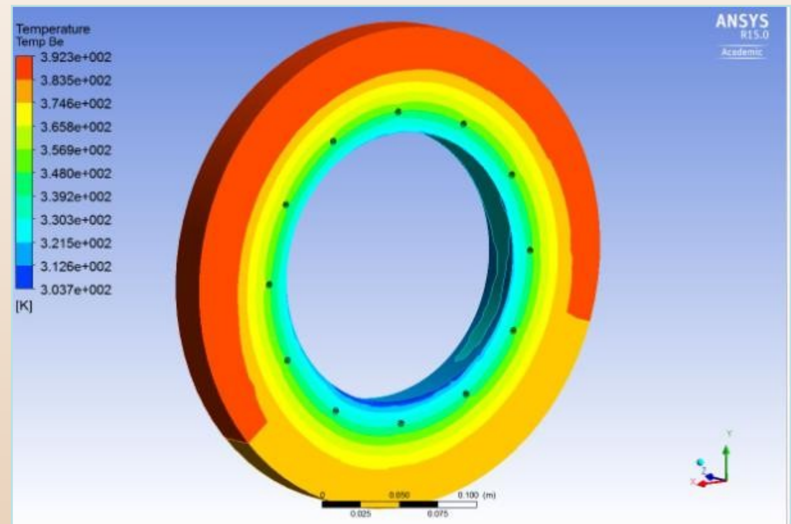
m. = 0,09 l/s 0,5 m/s **5 kW**

Heat Transfer Model: conservative interflux









023.wbpj

T_{Bemin} = 36 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 130 °C $T_{agua-max}$ = 73 °C

m. = 0,18 l/s (1 m/s)   **5 kW**

Heat Transfer Model: conservative interflux

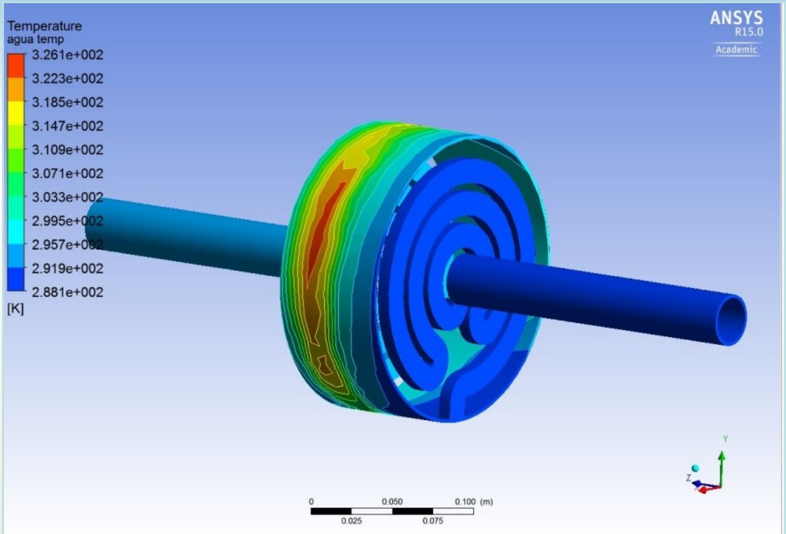
024.wbpj

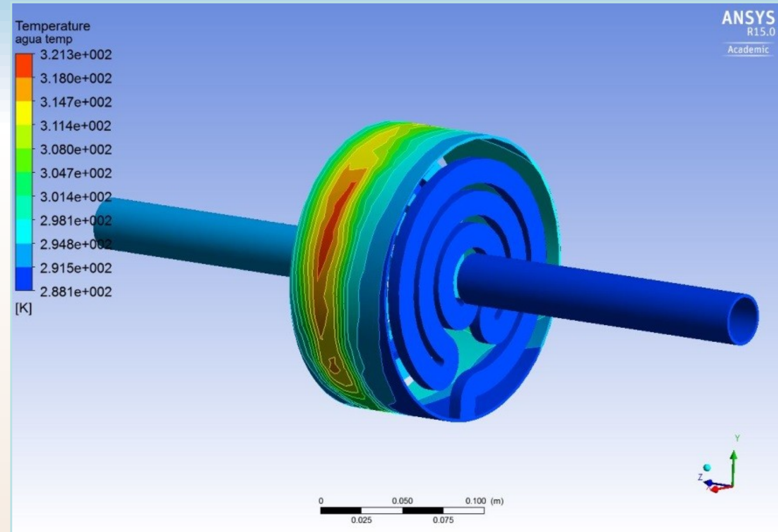
T_{Bemin} = 31 °C $T_{agua-min}$ = 15 °C

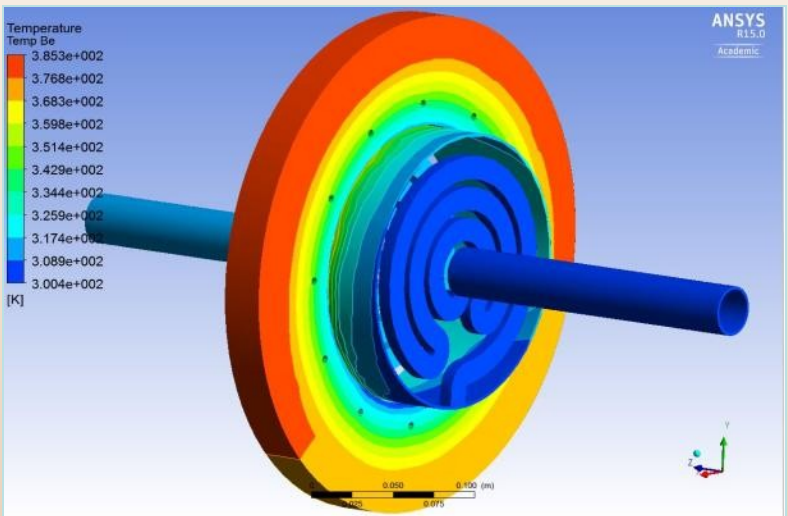
T_{Bemax} = 113 °C $T_{agua-max}$ = 61 °C

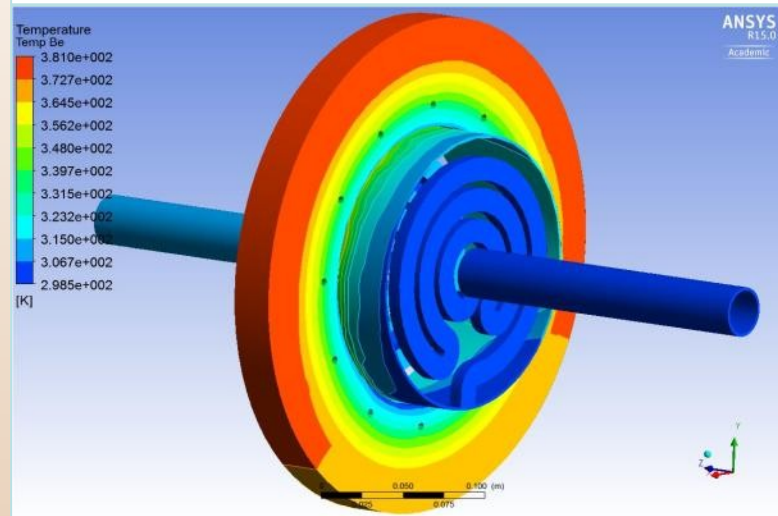
m. = 0,283 l/s (1,5m/s)   **5 kW**

Heat Transfer Model: conservative interflux









025.wbpj

T_{Bemin} = 27 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 112 °C $T_{agua-max}$ = 53 °C

m. = 0,377 l/s (2 m/s)

Heat Transfer Model: conservative interflux

026.wbpj

T_{Bemin} = 25 °C $T_{agua-min}$ = 15 °C

T_{Bemax} = 108 °C $T_{agua-max}$ = 48 °C

m. = 0,471 l/s (2,5 m/s)

Heat Transfer Model: conservative interflux

item	Proton beam energy, current	STATUS
QMN system	35-70 MeV 10-100 μA↑ (possible upgrade)	**QMN line has high priority (multi-disciplinary).** Thin Li and Be target system to be designed within 2014, in concert with the rotating target. Multi-angle collimator preliminary study began.
Rotating target	70 MeV, 50-100 μA↑ (possible upgrade)	0-level prototype, funded by INFN, is ready for extensive power tests with test disks (Al and Pb) in 2014. ANSYS calculations underway. Construction of the final target with Be disk in 2015.
W-target	*70 MeV, 500 μA (35 kW)*	*High power dissipation studies are proceeding in the context of APOTEMA, the experiment for the production of the radioactive marker ^{99}Te from ^{99}Mo with the SPES cyclotron. The design of the moderator system is on hold (given limited funding, manpower, and change in priorities).*
Direct proton line	35-70 MeV, max 1 μA	Foreseen