(Subcritical) system experiments

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International Training Course (ITC-8)
3-6 February 2009
Politecnico di Torino

Spallation target experiments

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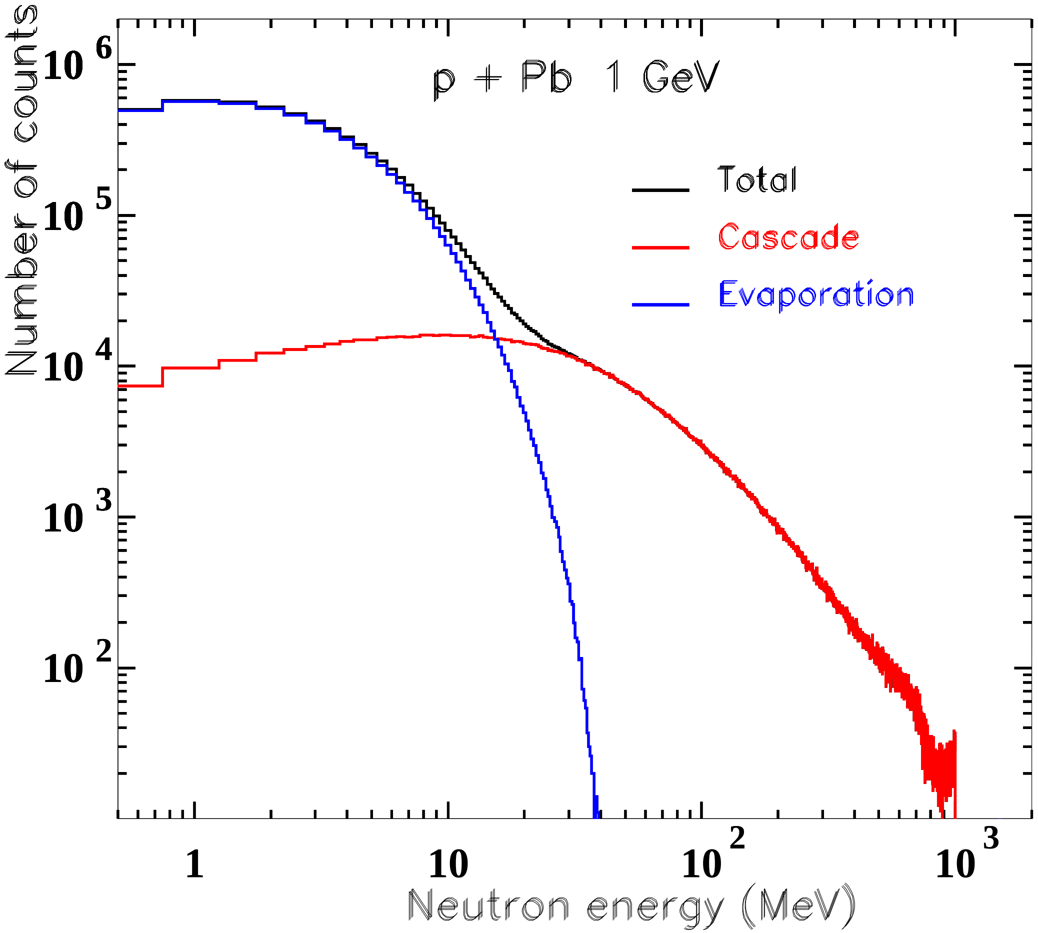
Introduction

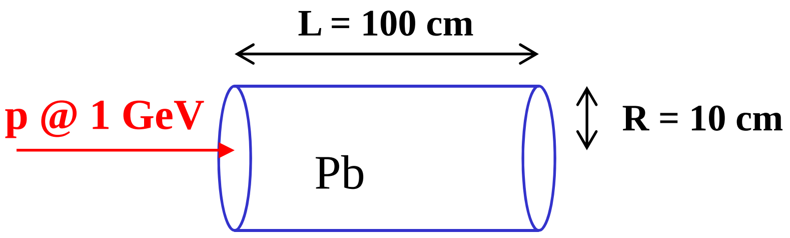
- Difference between thin and thick target
- A lot of target systems around the world… for many different uses…!
- Some examples to identify common features and problems
- The example I know the best: MEGAPIE
  - Nuclear and neutronic assessment
  - Measurements campaign
  - Modeling
  - Lessons learnt

Interaction in a thin target

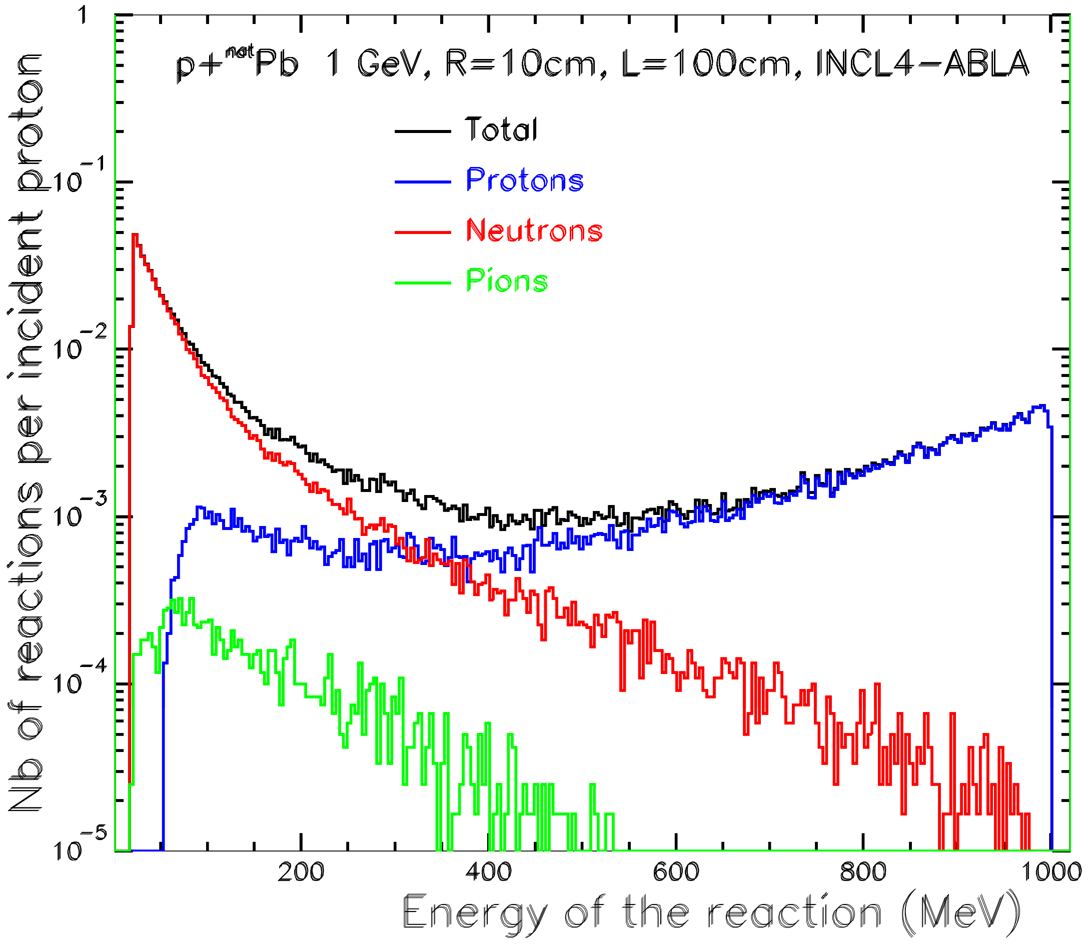
- **~2 neutrons with E > 20 MeV (intra-nuclear cascade)**
- **~15 neutrons with E < 20 MeV (evaporation)**
- **Energy carried out by cascade neutrons is 85% (95% for protons)**



Interaction in a thick target

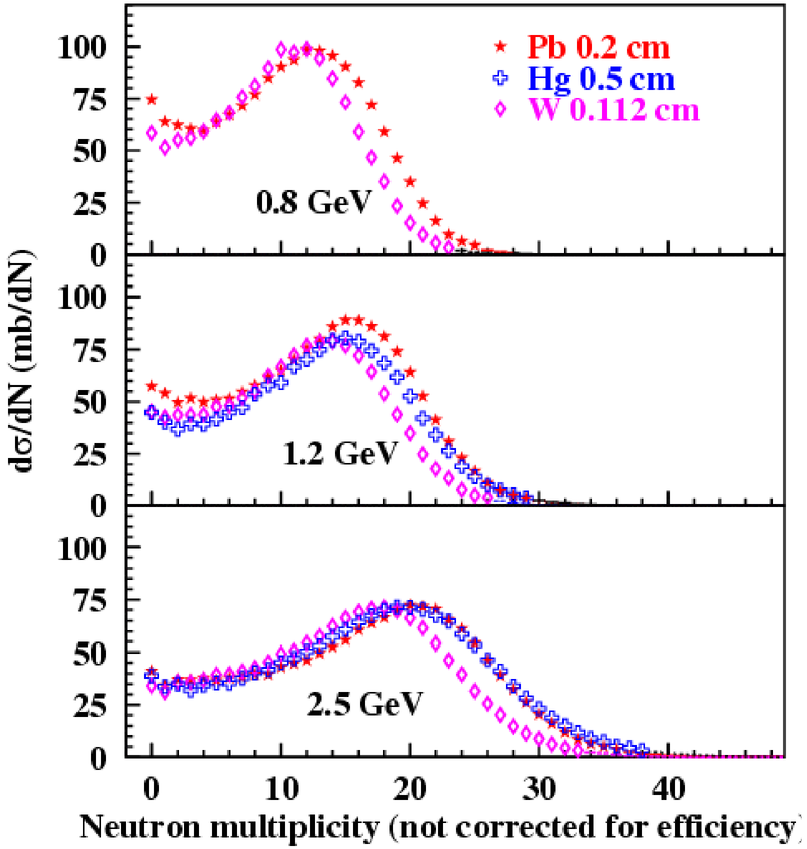


- Protons interact before slowing down
- 3.5 reactions per incident proton in average
- Large number of secondary neutron interactions



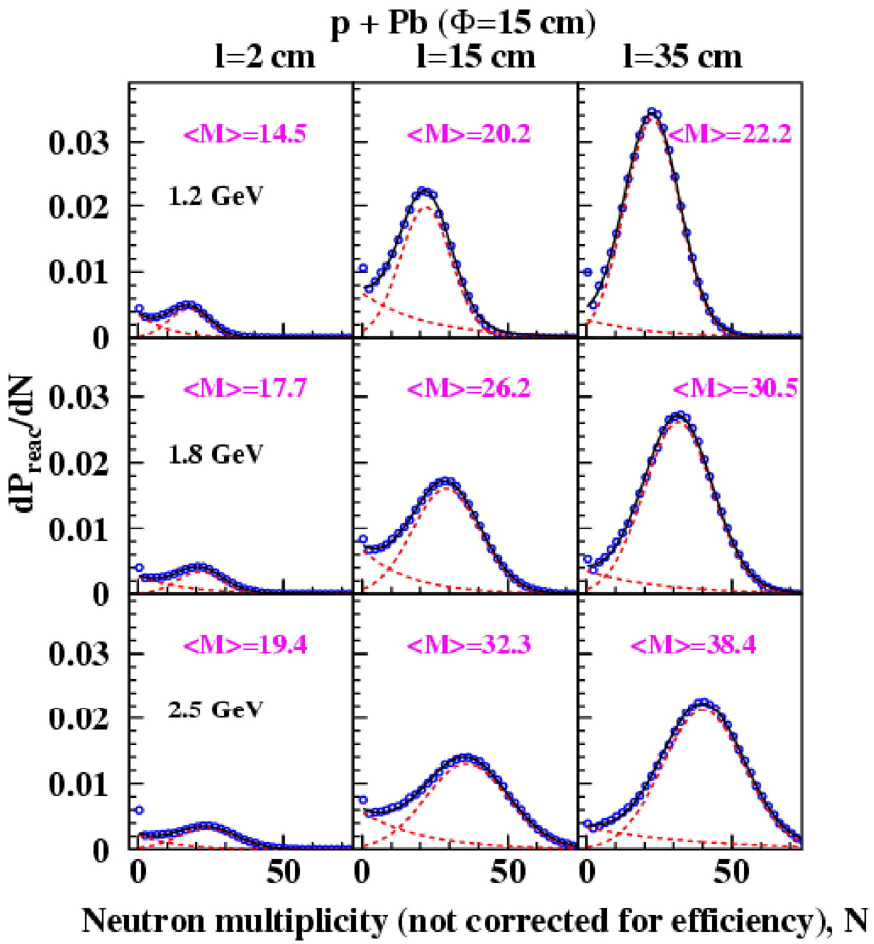
Neutron multiplicity: thin vs thick target

Thin target



A. Letourneau et al., Nucl. Instr. Meth. B170 (2000) 299

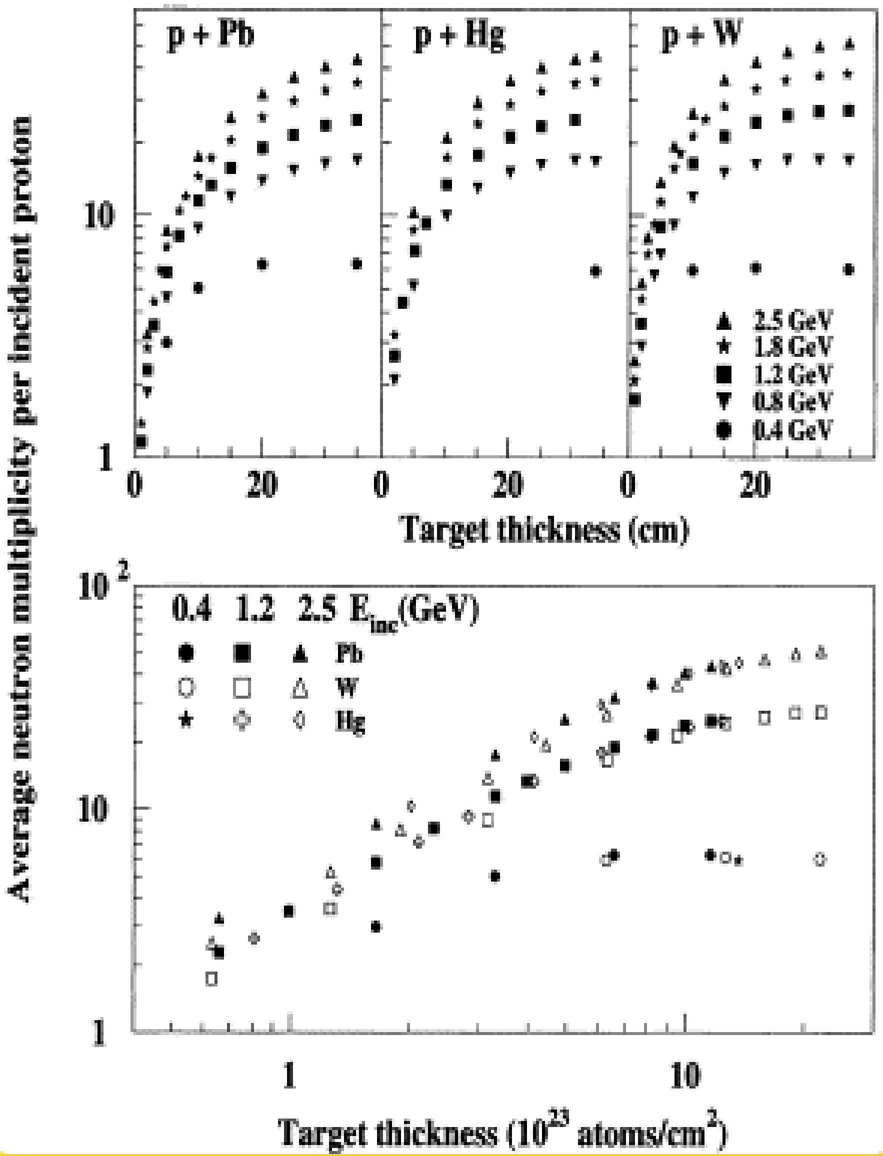
Thick target



Increase of M_n with target thickness due to intra-nuclear cascade

Choice of the target material

A. Letourneau et al., Nucl. Instr. Meth. B170 (2000) 299

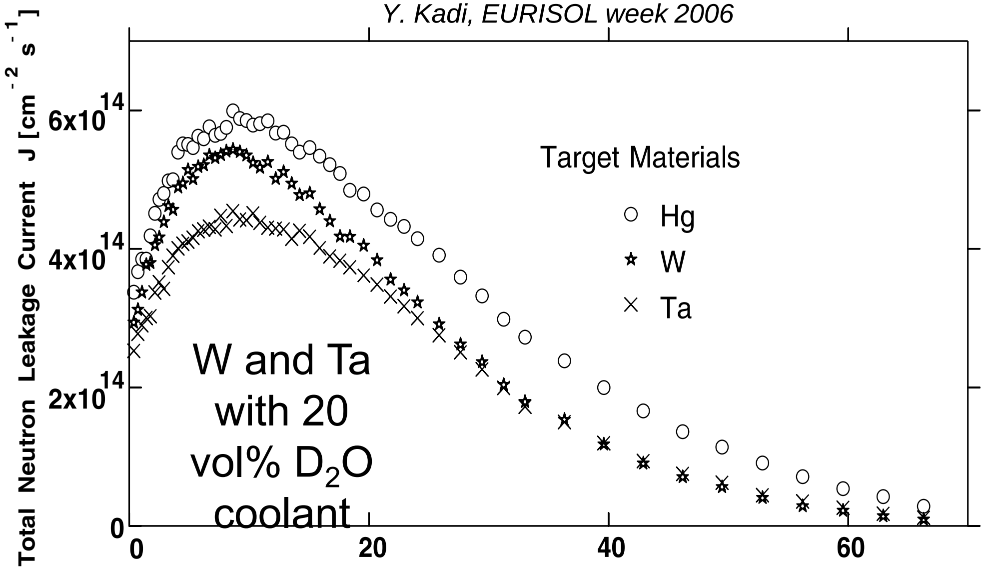


Neutron production

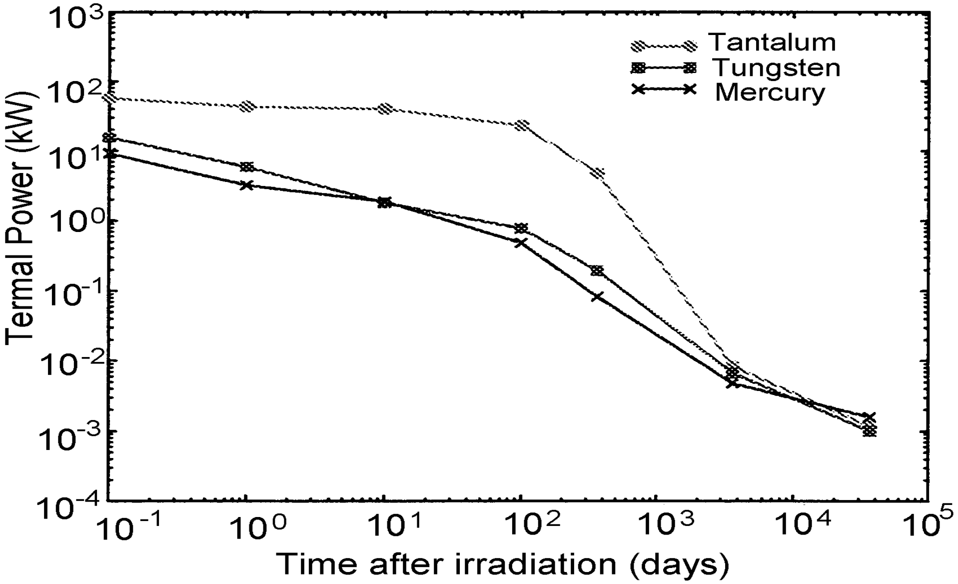
- **increases with target thickness and saturates above 30 cm**
- **is similar for W to Pb for the same atom density**

➔ **choice of material from technological criteria**

Choice of the target material: the Hg case



Calculated neutron leakage for different target materials



Calculated decay power for 200 days of operation in a 5 MW beam

Choice of the target material

Solid targets :

W, Ta, depleted U

- Spallation products confined
- No container
- Simplicity
- Limited power evacuation
- Necessity of a coolant

  ➜ reduced density of spallation material
- Irradiation damage (dpa, gas production.. .) can lead to embrittlement of the target

Liquid targets :

Hg, Pb, Pb-Bi eutectic

- Target = coolant

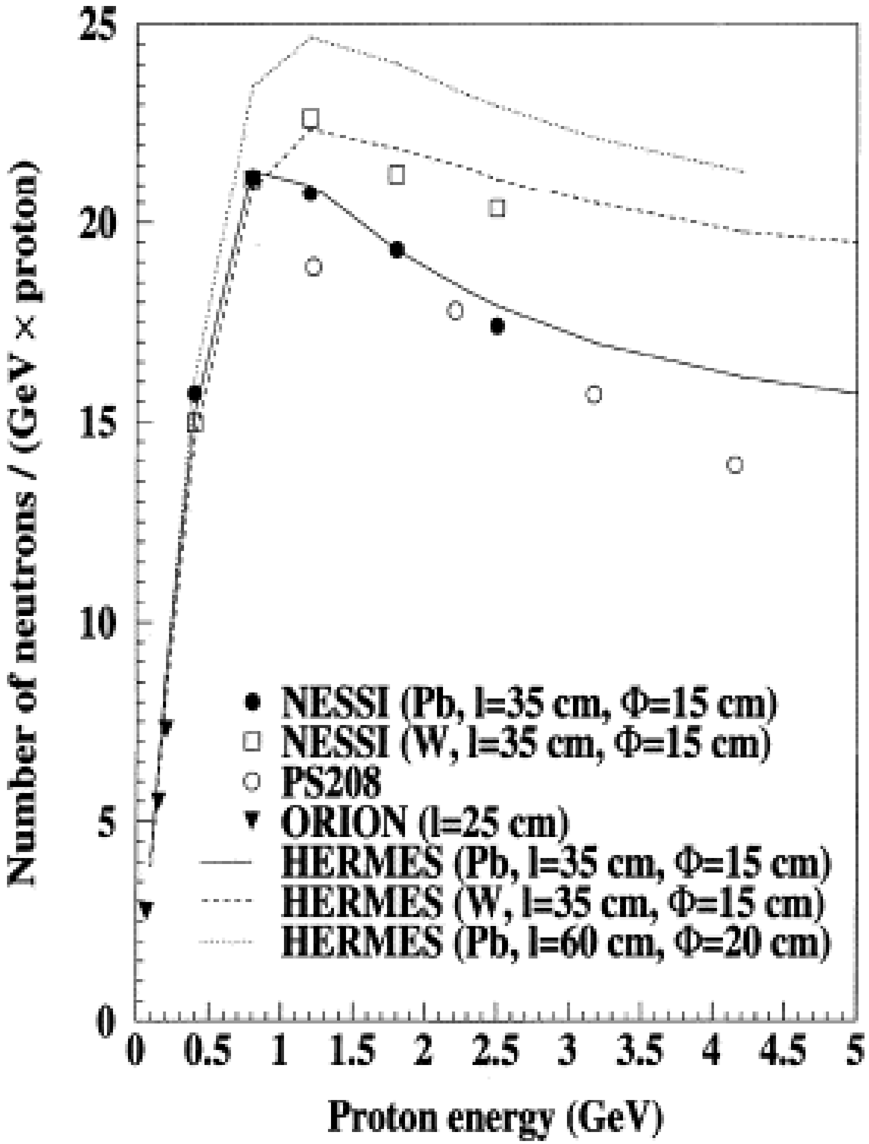
  ➜ high compactness
- Volatile spallation products can be removed during operation
- No structural damages in target
- Damages in window and container
- Corrosion due to liquid metal
- Highly activated circulating fluid
- Ancillary heater(s) necessary to keep Pb or LBE liquid

Choice of the incident energy

- In heavy metal targets (Pb, W, Ta, Pb-Bi) around 20 neutrons per incident proton and GeV

- Maximum efficiency around 1 GeV

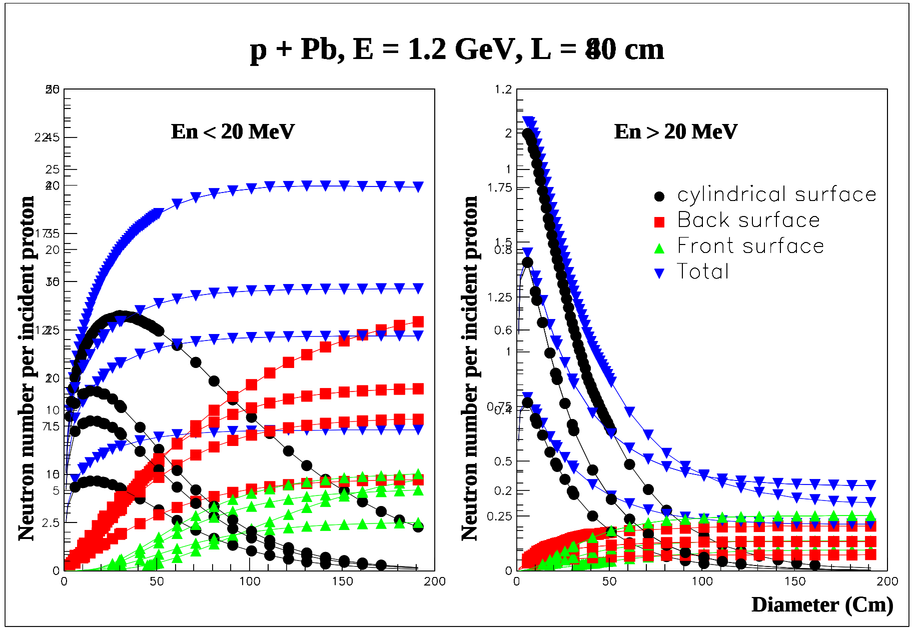
A. Letourneau et al., Nucl. Instr. Meth. B170 (2000) 299

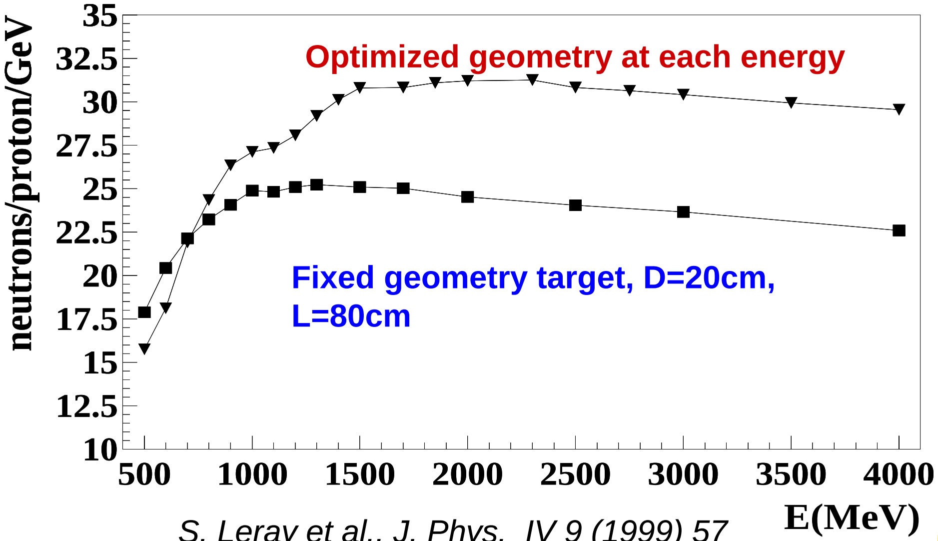


Choice of the incident energy

Target length and diameter optimization

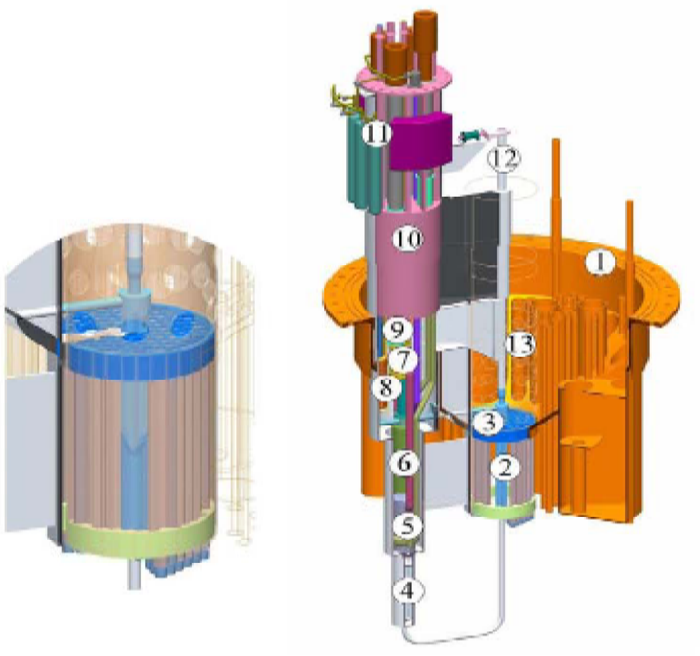
- ➔ maximize lateral low energy n
- ➔ minimize high-energy leaks





S. Leray et al., J. Phys. IV 9 (1999) 57

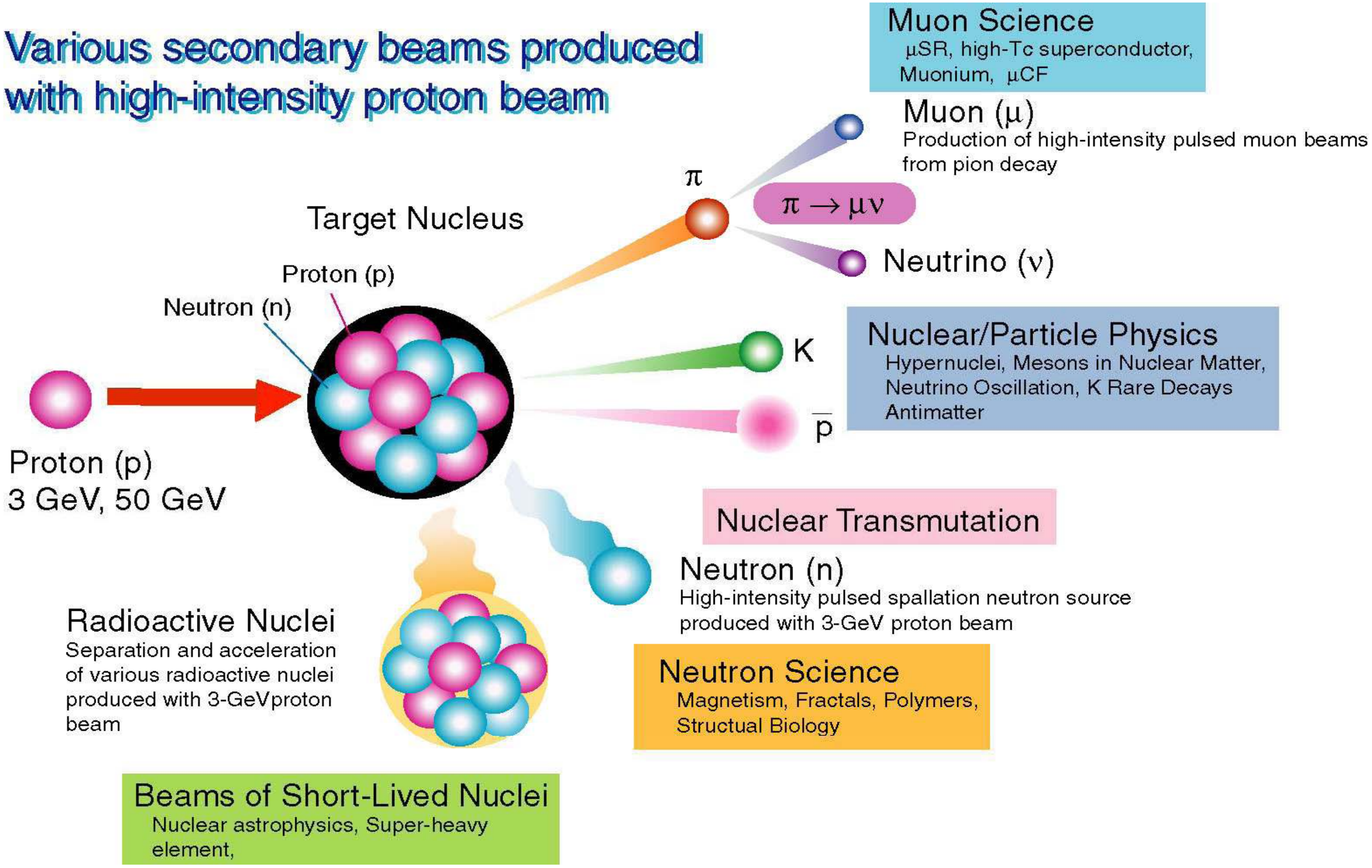
Some examples: MYRRHA



1. diaphragm
2. spallation target
3. core support plate slot
4. heat exchanger
5. turbine & pump
6. electromagnetic pump
7. hydraulic drive
8. Pb-Bi conditioning system
9. vacuum system with cryopumps
10. shielding bloc
11. regeneration circuit with absorber pumps
12. proton beam line
13. core barrel

- Target boundary conditions
  - Produce ~10^{17}neutrons/s to feed subcritical core @ $k_{eff}\approx 0.95$
  - Accept 600 MeV x 2.5 mA or 350 MeV, 5 mA proton beam
  - Evacuate deposited heat 1-1.43 MW depending on beam choice
  - Erosion limit: v<2.5 m/s
  - Lifetime: > 1y

Some examples: J-PARC



Various secondary beams produced with high-intensity proton beam

Muon Science
µSR, high-Tc superconductor, Muonium, µCF

Muon (µ)
Production of high-intensity pulsed muon beams from pion decay

Neutrino (ν)

Nuclear/Particle Physics
Hypernuclei, Mesons in Nuclear Matter, Neutrino Oscillation, K Rare Decays Antimatter

Nuclear Transmutation

Neutron (n)
High-intensity pulsed spallation neutron source produced with 3-GeV proton beam

Neutron Science
Magnetism, Fractals, Polymers, Structual Biology

Radioactive Nuclei
Separation and acceleration of various radioactive nuclei produced with 3-GeVproton beam

Beams of Short-Lived Nuclei
Nuclear astrophysics, Super-heavy element,

From Sawada, EXA05

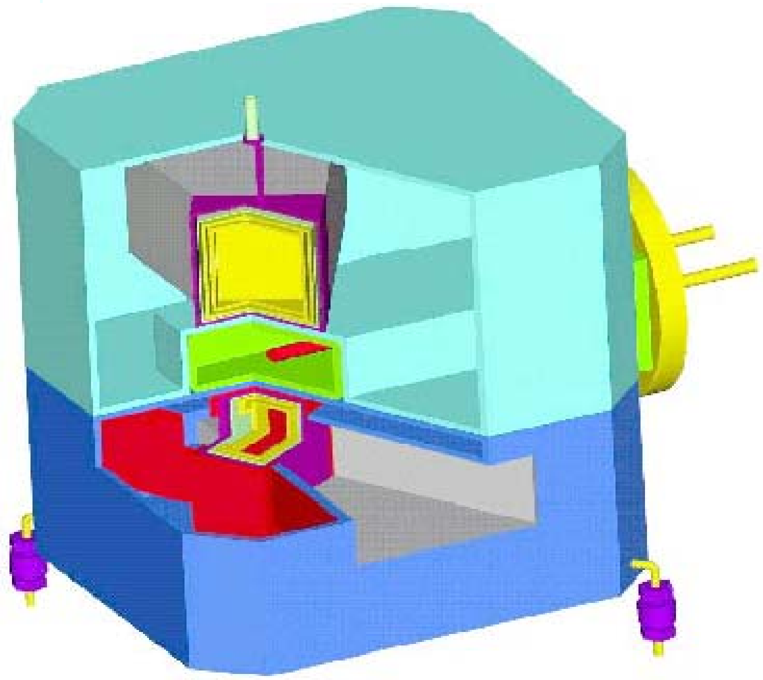
Some examples: J-PARC

ADS Target Test Facility (TEF-T)

- **Liquid lead-bismuth**
- **600 MeV-200 kW proton beam**
- **1.5 10^{14} n/cm^2/s**

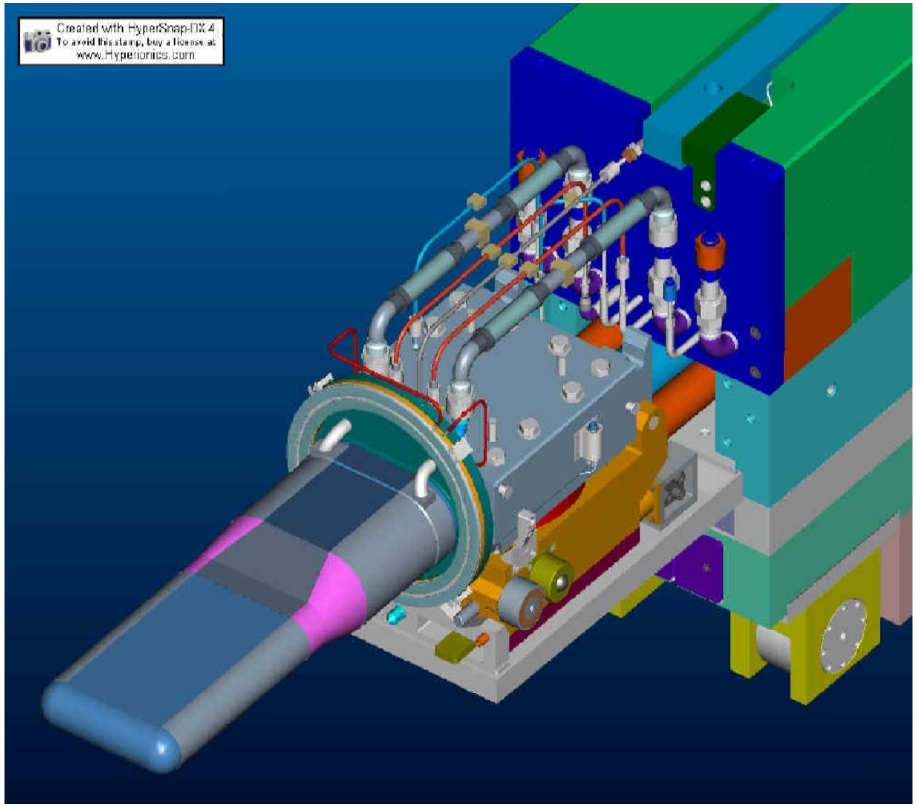
Some examples: ISIS

- **Proton energy : 800 MeV**
- **Proton current: 60 µAmps**
- **Average power : 48 kW**
- **Pulse rate : 10 Hz**
- **Proton beam size : 1.5 cm FWHM**
- **Target : Tungsten (W) clad in tantalum (Ta)**
- **Target coolant : D20**
- **Reflector : Beryllium**
- **Reflector coolant : D20**



Some examples: SNS

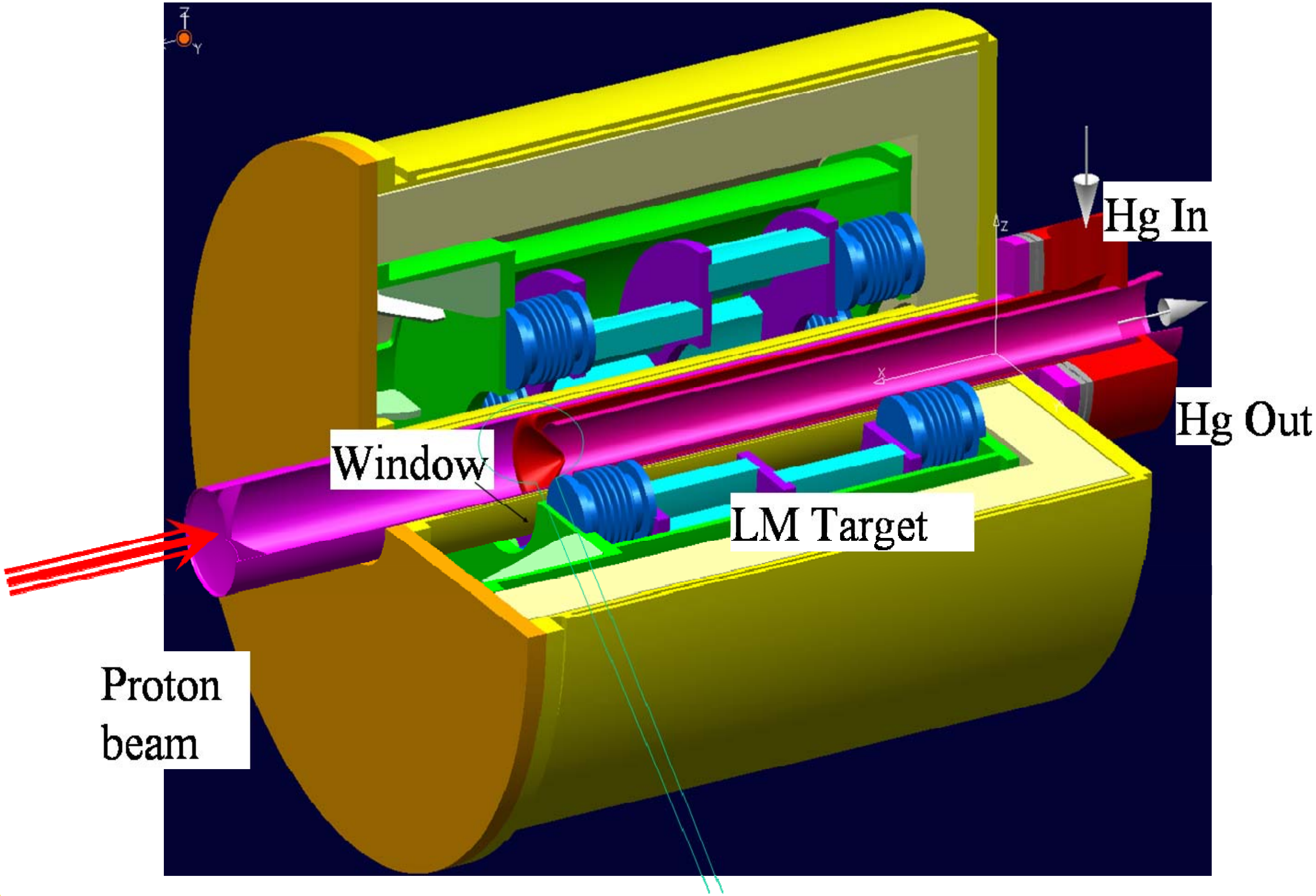
- **Nominal Operating Pressure : 0.3 MPa**
- **Flow Rate : 340 kg/s**
- **Vmax (In Window) : 3.5 m/s**
- **Total Hg Inventory : 1.4 m3**
- **Pump Power : 30 kW**



- **Power absorbed in Hg : 1.1 MW**
- **Temperature**
  - **Inlet to target : 60ºC**
  - **Exit from target : 90ºC**

Some examples: EURISOL

Hg converter and secondary fission targets



The MEGAPIE project

- A key experiment in the ADS roadmap

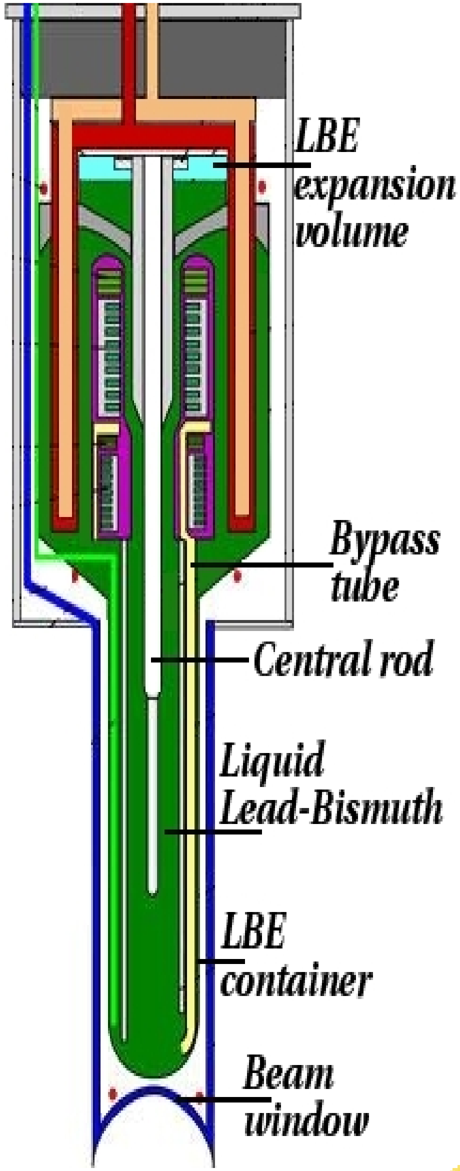
- **MEGAwatt Pilot Experiment (MEGAPIE) (1 MW)** initiated in 1999 in order to design, build and operate a liquid lead-bismuth spallation target

- Operate it into the Swiss spallation neutron facility SINQ at PSI

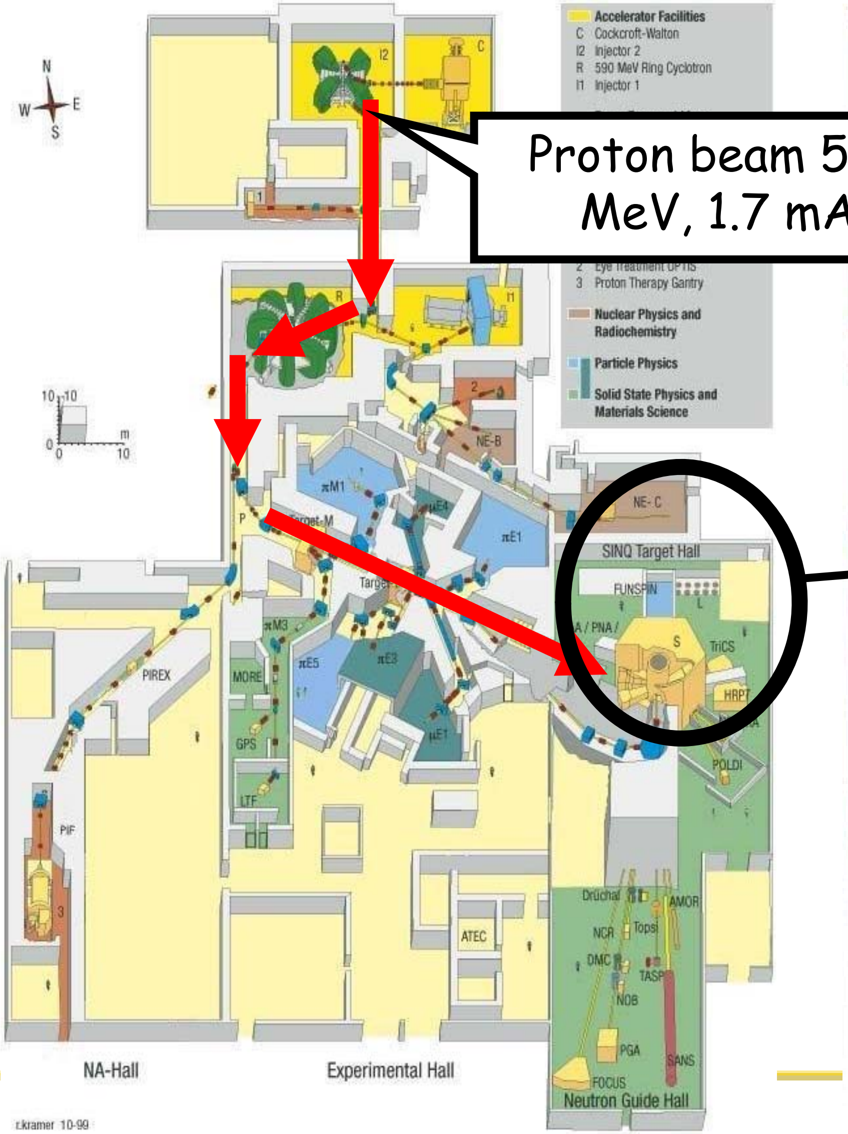
- Minimum design service life fixed at 1 year (6000 mAh).

The MEGAPIE challenges

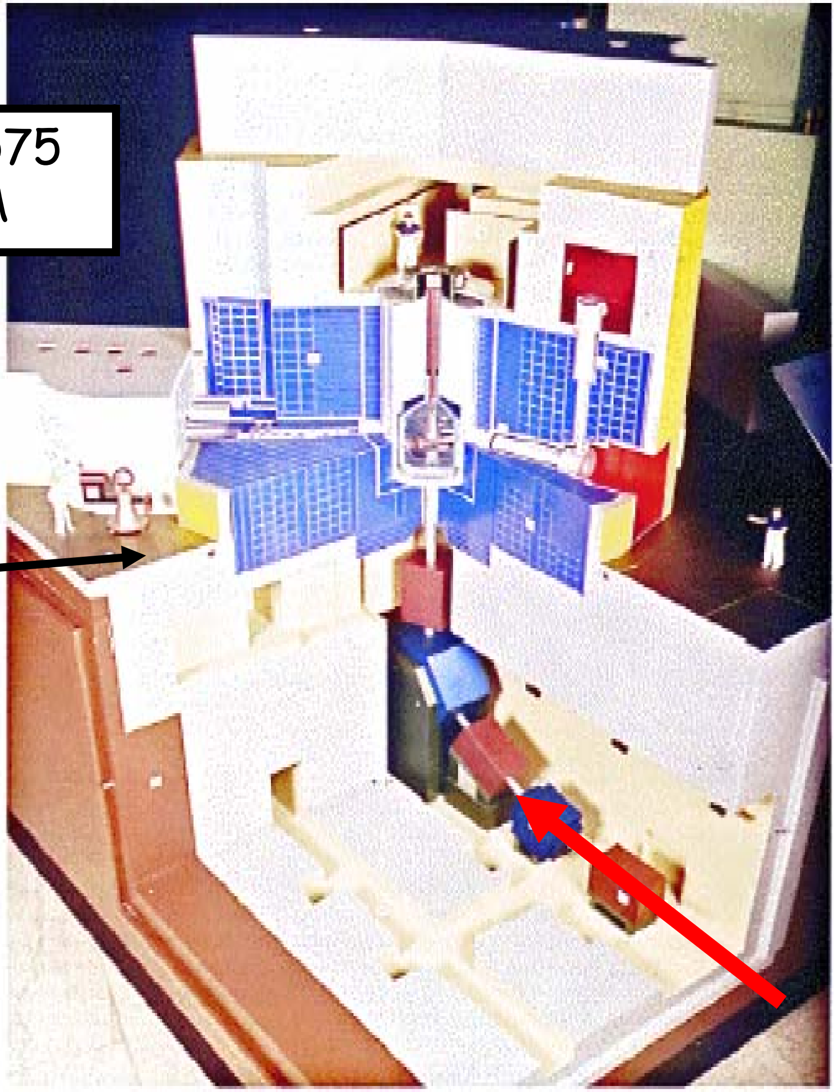
- Design a completely different concept of target in the same geometry of the current spallation targets used at PSI
- Develop and integrate two main prototypical systems : a specific heat removal system and an electro magnetic pump system for the hot heavy liquid metal in a very limited volume
- Design a 9Cr martensitic steel (T91) beam window able to reach the assigned life duration
- License a LBE in relevant conditions-to operate a LBE target
- Develop the decommissioning strategy and waste management



The MEGAPIE installation at PSI



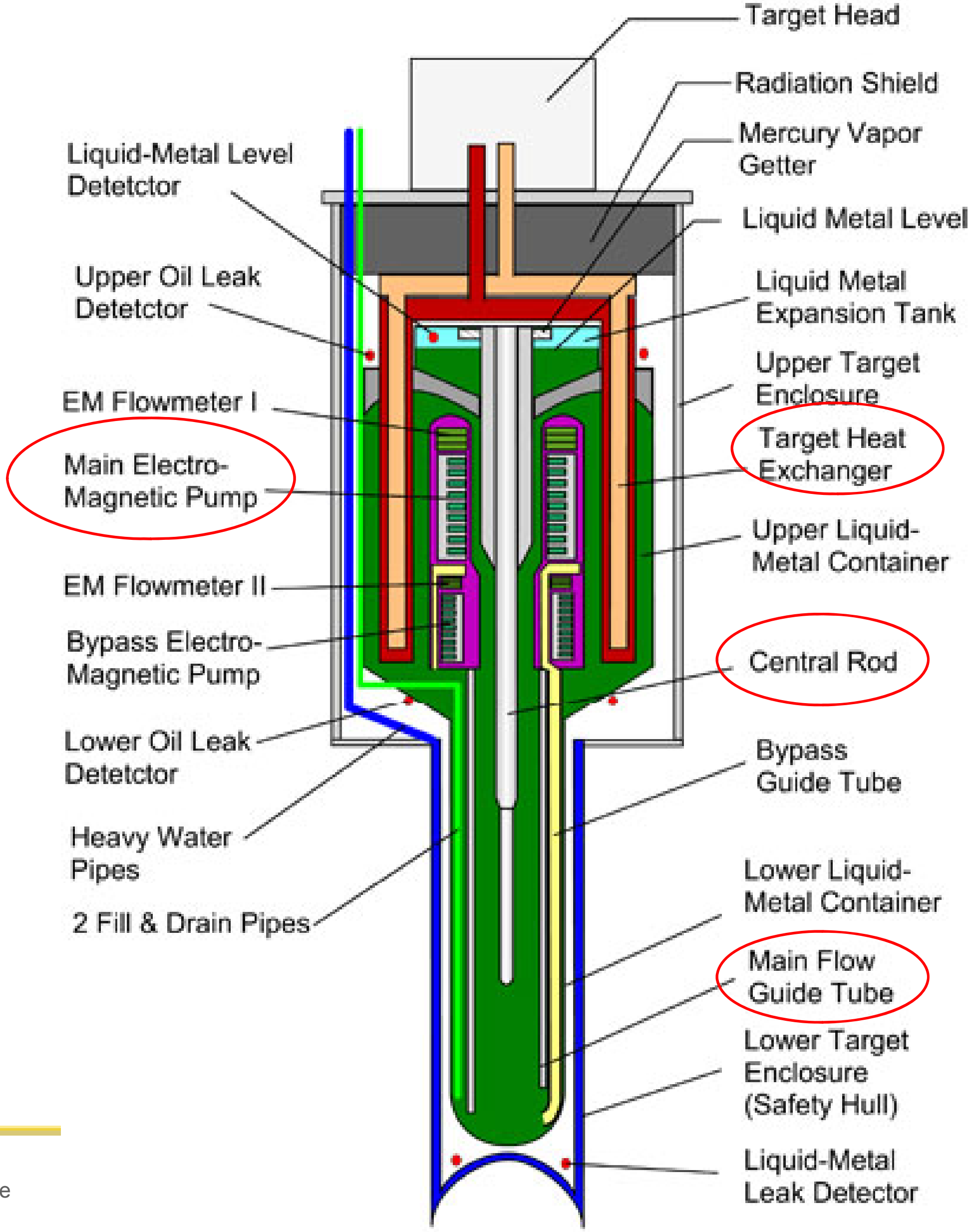
Proton beam 575 MeV, 1.7 mA



The MEGAPIE target

CHARACTERISTICS

- Irradiation time: 5 months
- Proton energy: 575 MeV
- Beam intensity: 1,4 mA
- Volume: 80 l of liquid Pb-Bi

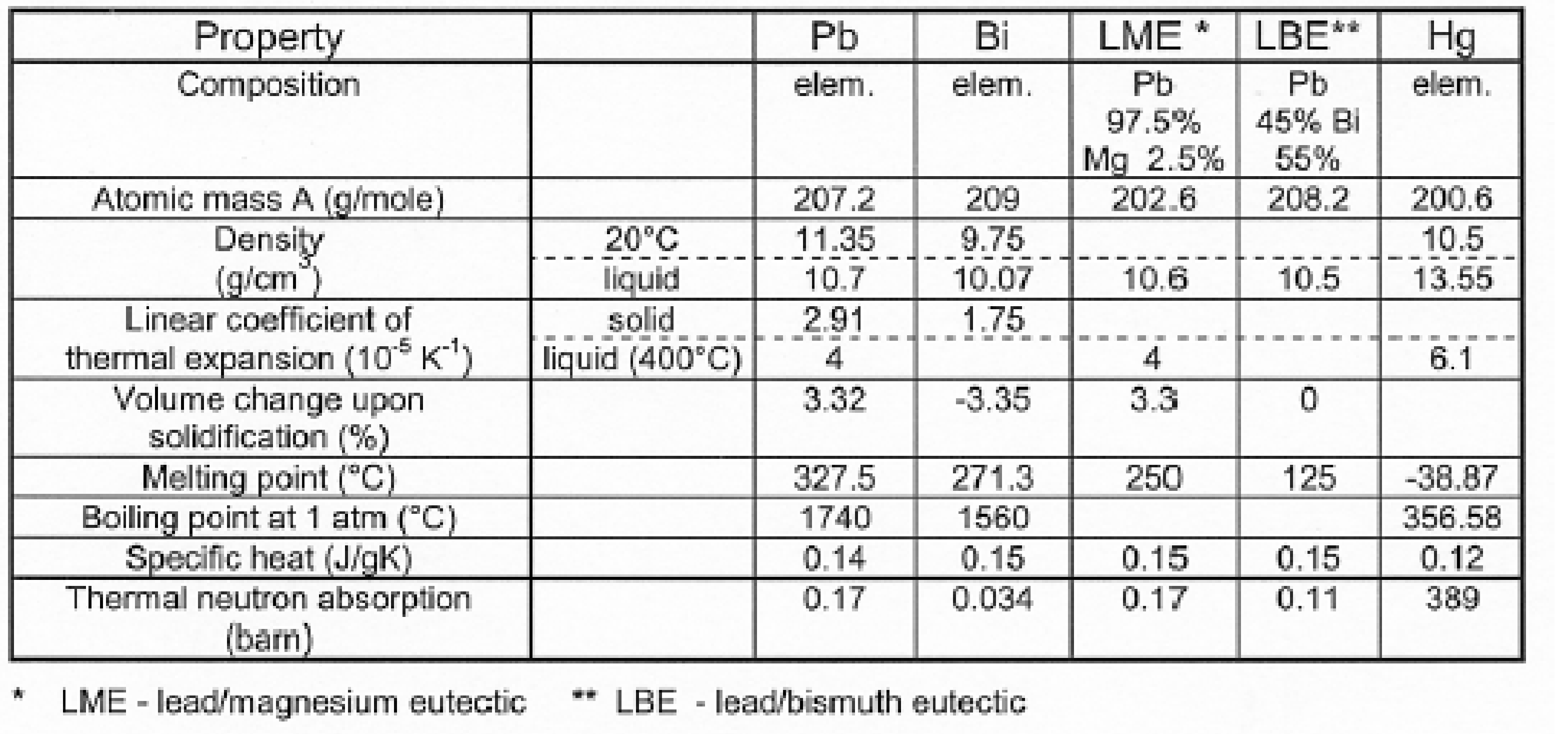


The MEGAPIE target

The choice of LBE

Lead-bismuth eutectic(Pb44.5%-Bi55.5%) has been selected, due to its attractive neutronic and physical properties:

- heat transfer coefficient
- low melting point (125°C)
- Nevertheless bismuth induces to the production of activation products (i.e. polonium,...)



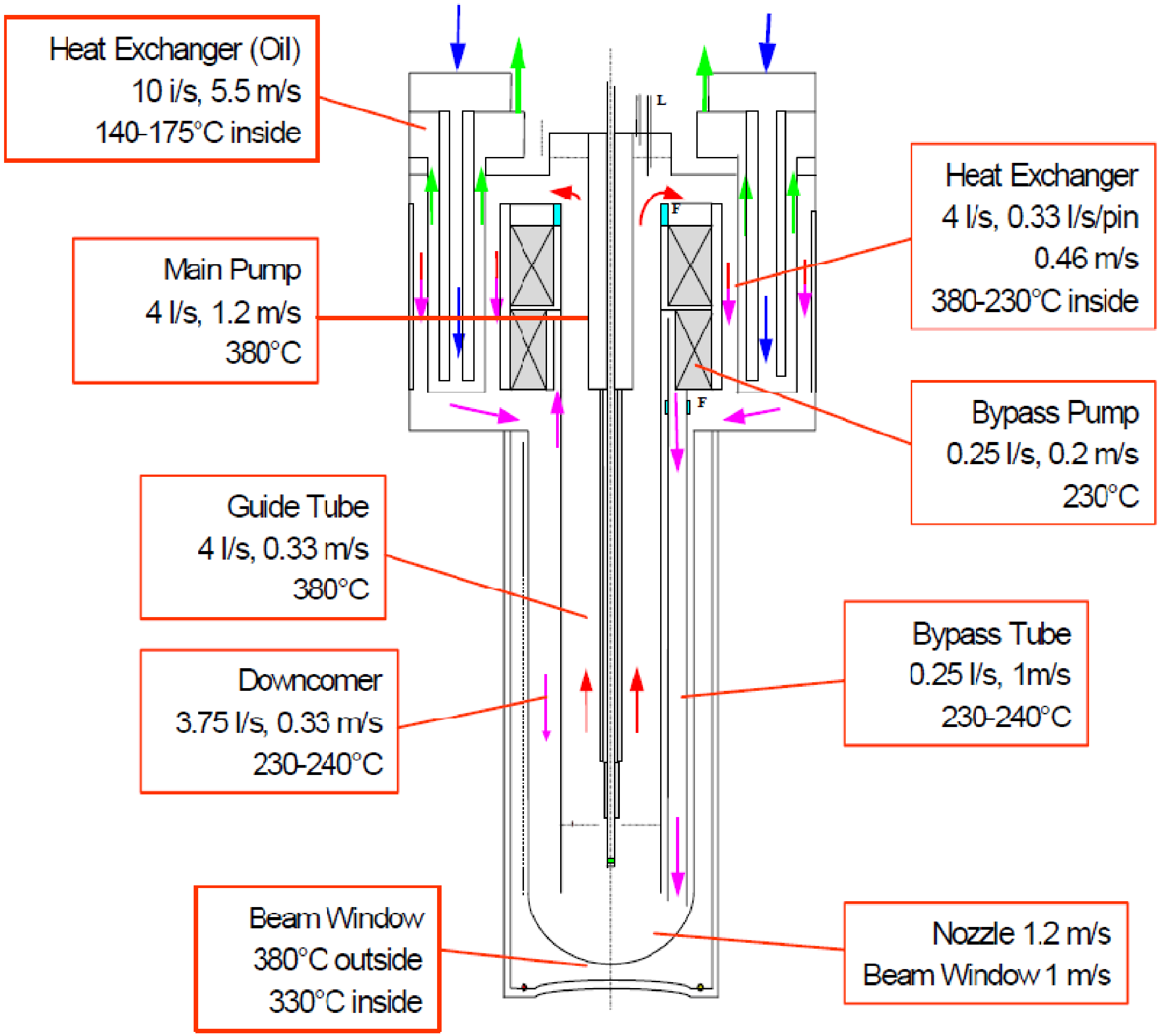
Property		Pb	Bi	LME *	LBE**	Hg
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Density (g/cm^3)	20°C	11.35	9.75			10.5
	liquid	10.7	10.07	10.6	10.5	13.55
Linear coefficient of thermal expansion (10^{-5} K^{-1})	solid	2.91	1.75			
	liquid (400°C)	4		4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting point (°C)		327.5	271.3	250	125	-38.87
Boiling point at 1 atm (°C)		1740	1560			356.58
Specific heat (J/gK)		0.14	0.15	0.15	0.15	0.12
Thermal neutron absorption (barn)		0.17	0.034	0.17	0.11	389

* LME - lead/magnesium eutectic ** LBE - lead/bismuth eutectic

The choice of T91 beam window

- Compared to austenitic steel 316L, T91 has:
  - higher strength
  - much better resistance to heat deposit (due to a lower thermal expansion coefficient and a higher thermal conductivity).
    - As a result, thermal stresses are about twice as high in 316 as in T91 for a given geometry and heat deposit
  - better corrosion resistance in Pb-Bi due to a low nickel content
- For applications under irradiation up to high doses at temperatures higher than about 400°C, T91 has additional advantages over 316 :
  - Much lower swelling
  - better resistance to the "high temperature helium embrittlement" phenomenon
- The main weakness of martensitic steels is the existence of the Ductile-to-Brittle Transition temperature (DBTT) which is shifted as a result of irradiation.
  - This shift is small for 9Cr martensitic steels up to high doses at irradiation temperatures higher than 400°C.
  - At lower irradiation temperature, a significant DBBT shift occurs.**(T91 : (0.1C, 0.32Si, 0.43Mn, 8.73Cr, <0.01W, 0.99Mo, 0.19V, 0.031Nb, 0.029N, 0.24Ni))**

MEGAPIE: main characteristics



Heat Exchanger (Oil)
10 i/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

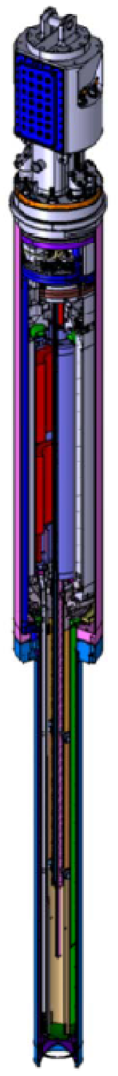
Beam Window
380°C outside
330°C inside

Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

Nozzle 1.2 m/s
Beam Window 1 m/s



The MEGAPIE neutronics: motivation

- MEGAPIE is the first high power liquid metal target built
- It needed a full characterization of the facility from the neutronics point of view (inner and outer flux)
- Gain experience and give recommendations for
  - HLM target technology
  - ADS development

- Calculation of important quantities and their influence on the target design:
  - neutron fluxes,
  - power deposition in the target,
  - shielding,
  - dose rates,
  - activation,
  - gas production,
  - radiation damage.

- The main tools were Monte Carlo codes; benchmarking experiments also provided useful data.

General reference: X9 summary report PSI Bericht Nr. 05-12, December 2005, ISSN 1019-0643 and references therein

The MEGAPIE neutronics: tools

From the design, through the operation and to the post-test analysis we needed:

- Modeling:
  - Benchmark and validate MC tools (FLUKA, MCNPX),
  - Integrate a VERY complex geometry (target & facility)
  - Calculate fundamental neutronic quantities (p, n, g fluxes, activation, dose rates, power deposition, …)
  - Provide a "mapping" of the neutron flux
  - Study the impact of a large spectrum of variables (physics models, materials, geometry, beam, …)

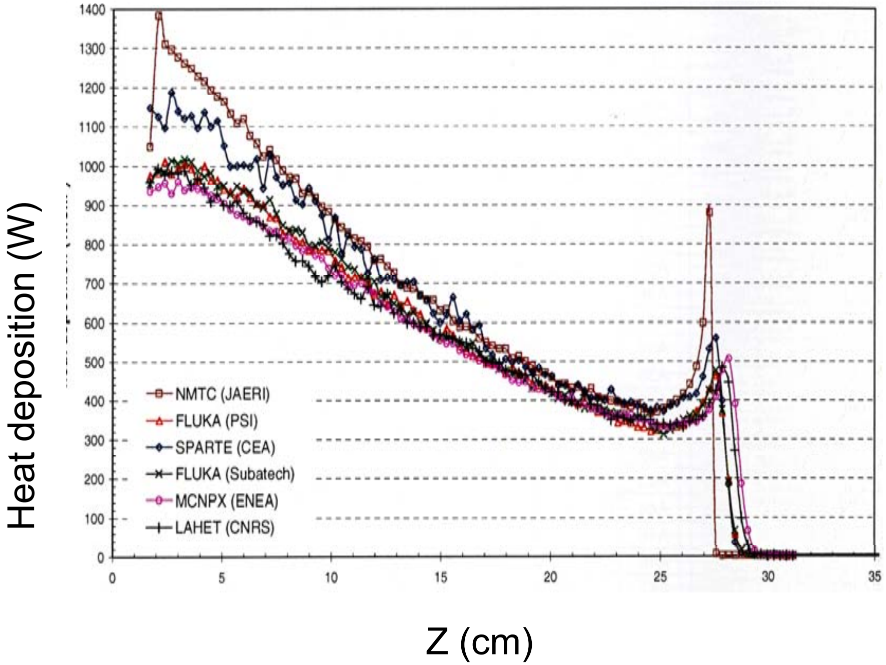
- Measurement:
  - Overall characterization of the facility (matrix of observables)
  - Compare with and validate calculations
  - Span over a large energy range (from thermal to 575 MeV)
  - Span over a large fluency range
  - Need to use different techniques
  - Take benefit of startup phase vs nominal irradiation conditions

Neutronic benchmark

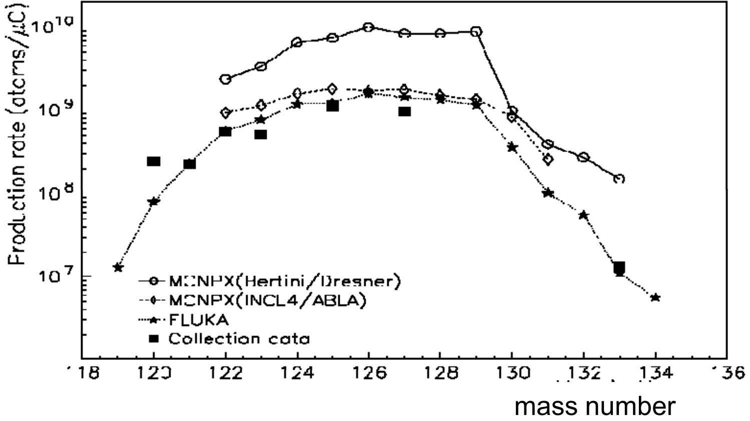
- This initial benchmark exercise was a very important code inter-comparison
- The choice led to FLUKA and MCNPX codes for the prosecution of the work for the following reasons:
  - Consistently good results in the benchmark
  - Code expertise
  - Strong development work for both codes, with constant upgrades of models/cross section sets.

Lesson learned:

Code validation is of fundamental importance at the beginning of a large project

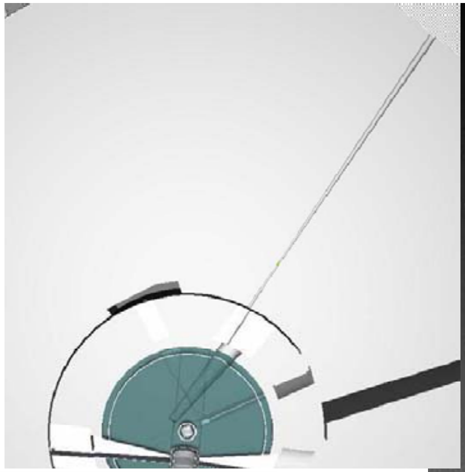


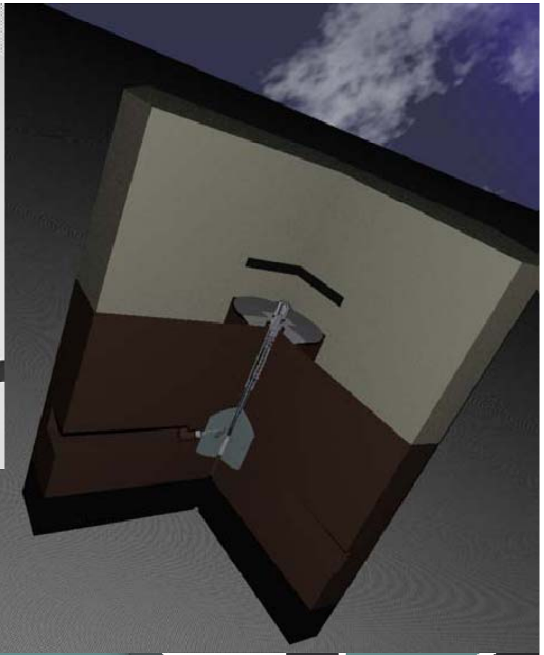
L. Zanini et al. NDST2004

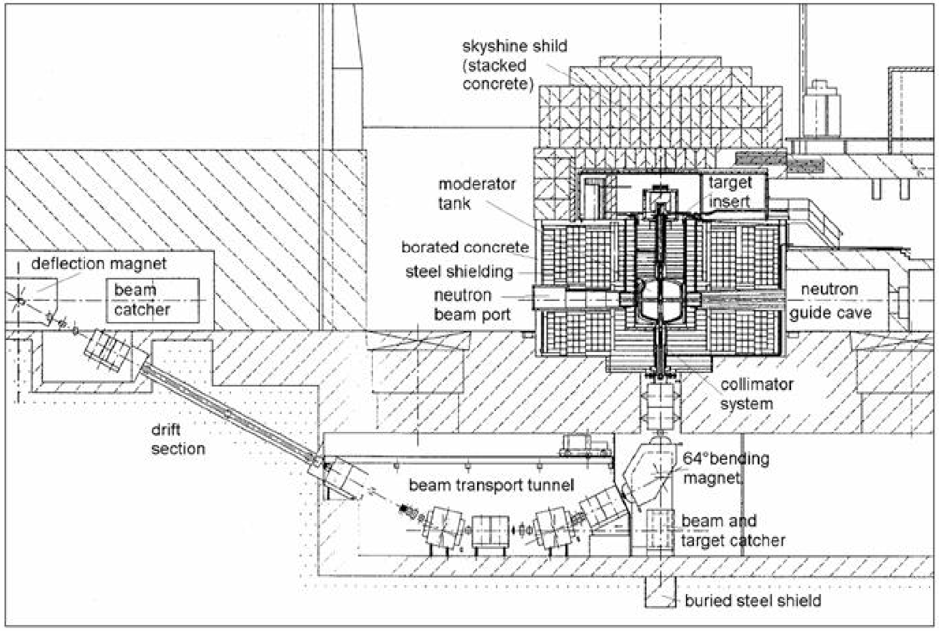


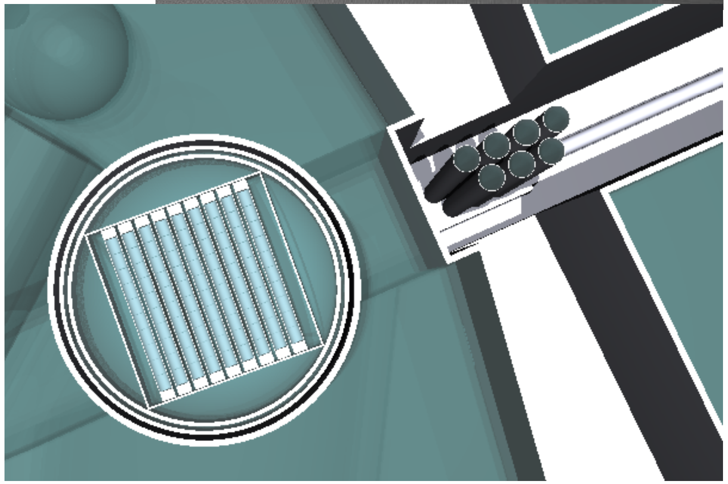
The MEGAPIE modeling

- Geometry
- Materials (including impurities)
- Beam profile
- Irradiation history
- Physics models

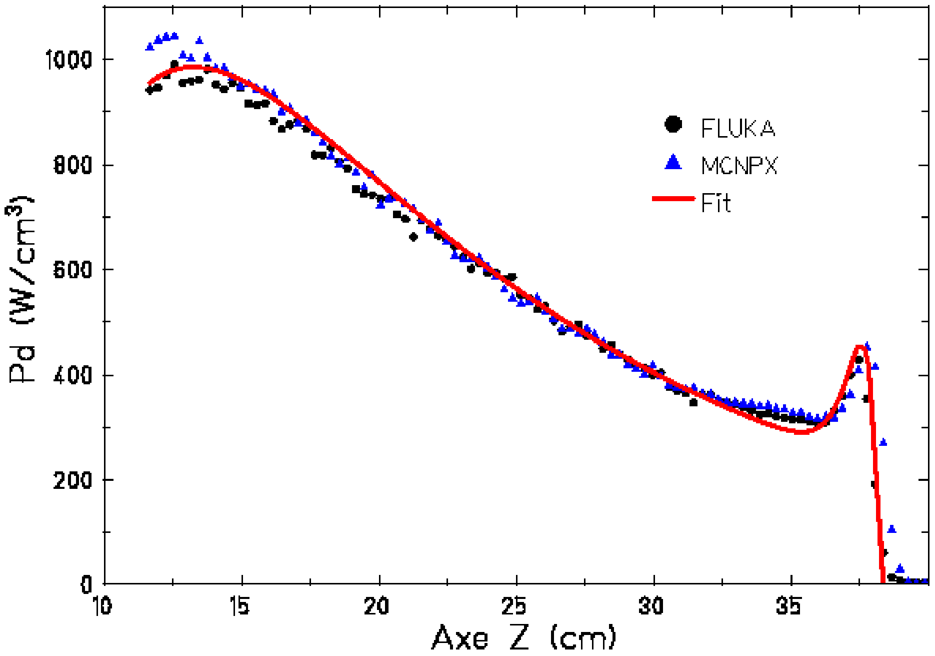


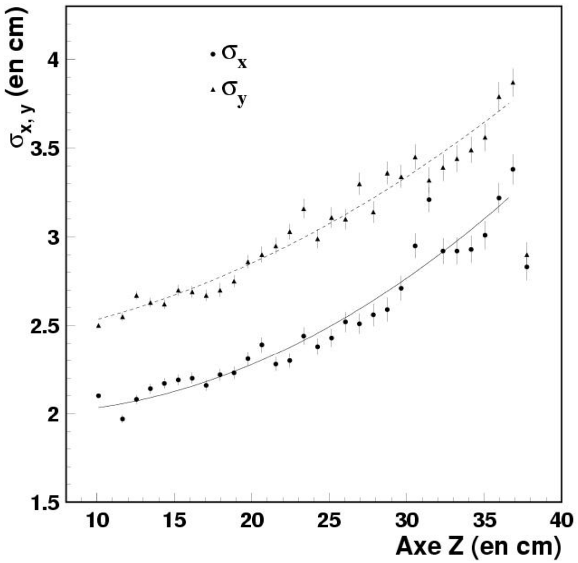






Power deposition in the LBE





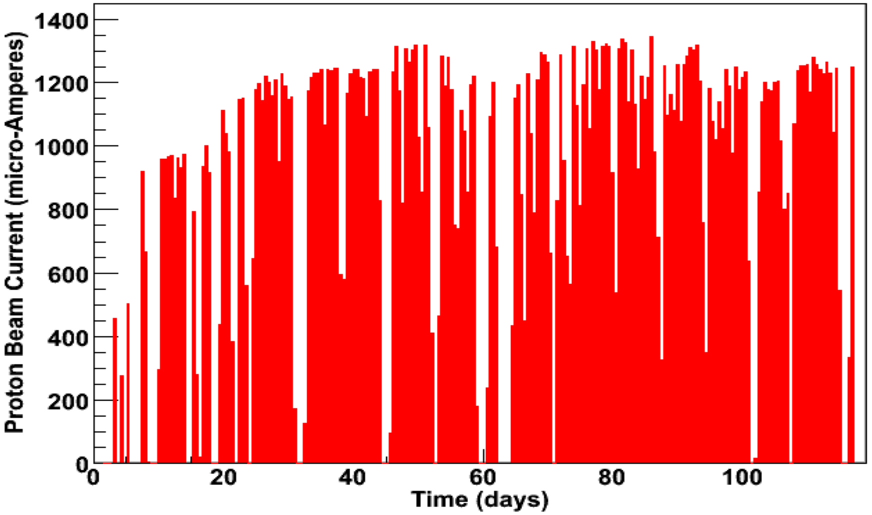
- Determine the power deposition in the Pb-Bi
  - dissipated power in the central part of the target
  - evolution of the axial components of the power deposition

- These results have been fitted with an analytical function and used as **input for thermo-hydraulics calculations.**

The MEGAPIE operation

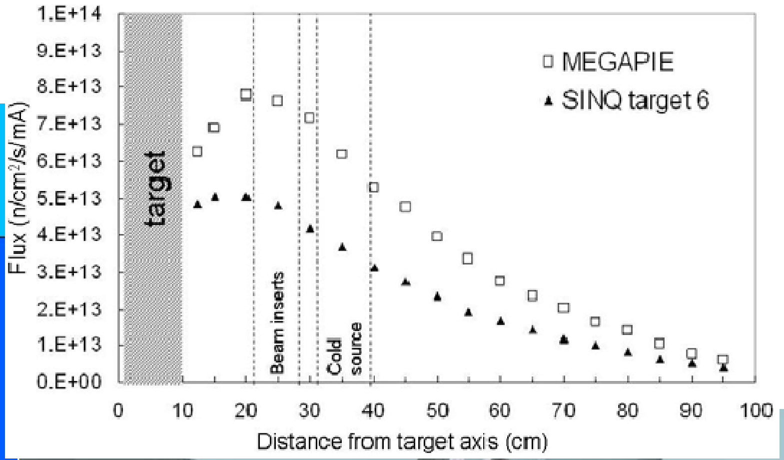
Operated successfully as the neutron source for SINQ hall during 2006 :

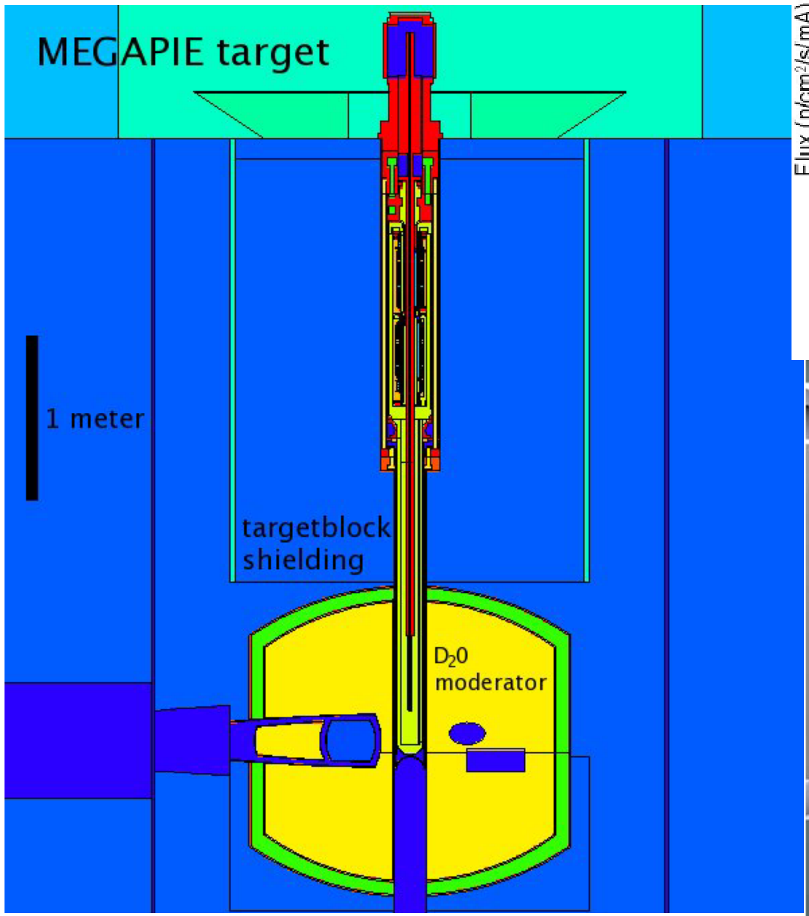
- 4 month beam on, average 960 uA
- 80 % more neutron production than current SINQ solid targets

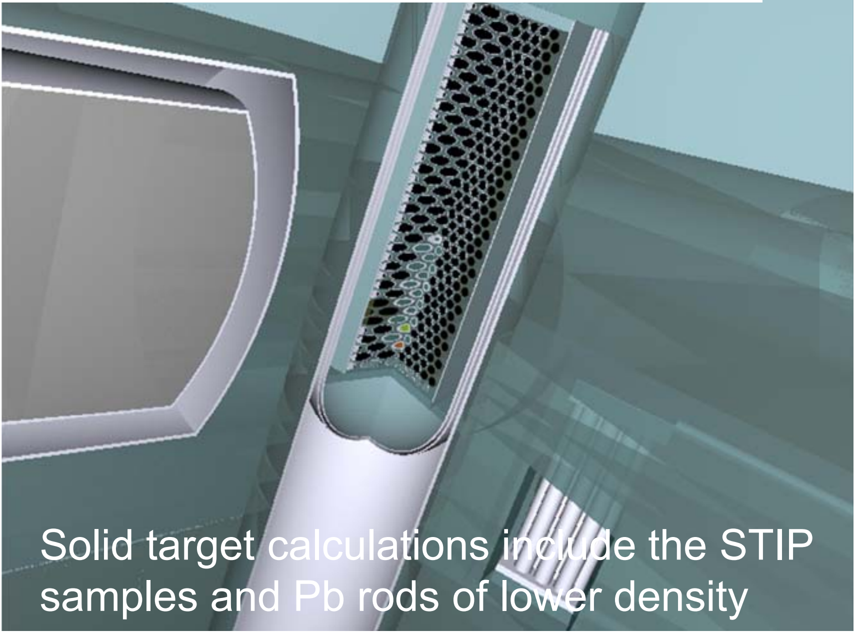


The target modeling: solid vs MEGAPIE

Validation of simulation codes and re-assessment of the target performances at the measured positions of the fluxes

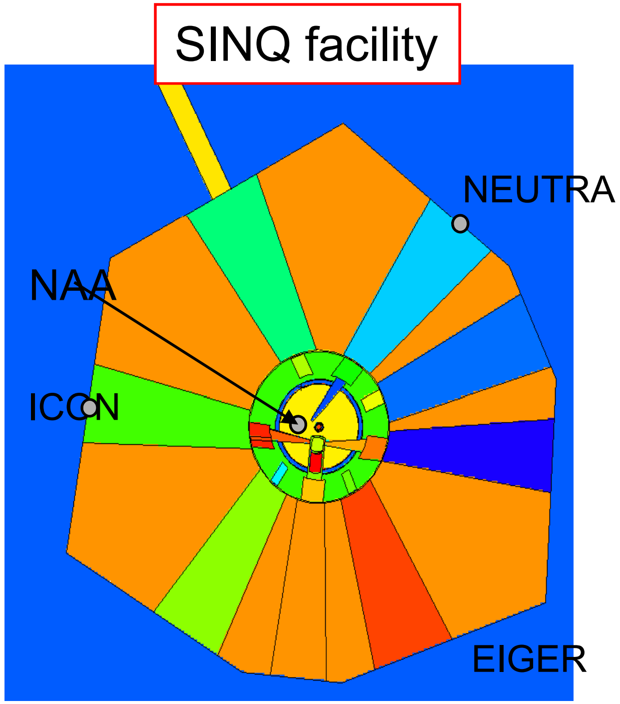


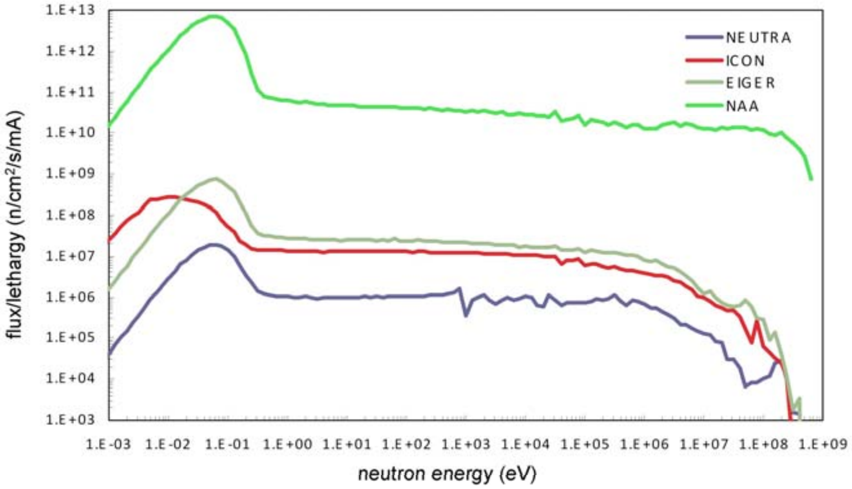


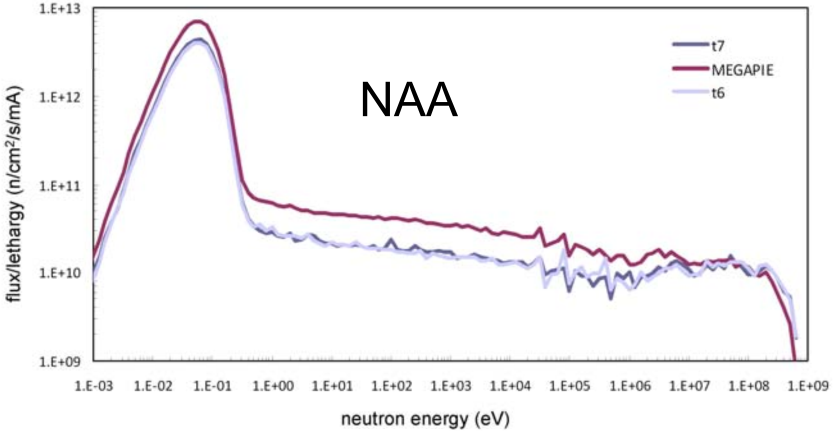


Solid target calculations include the STIP samples and Pb rods of lower density

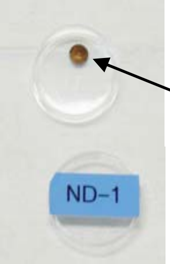
The modeling: outer flux

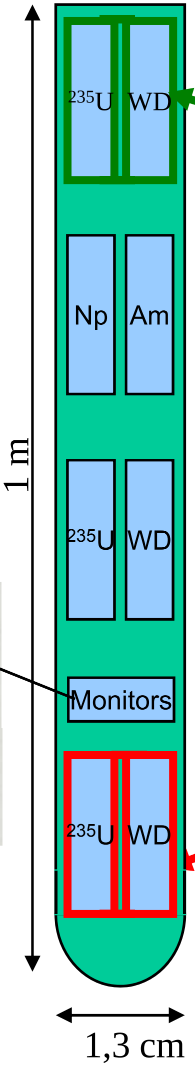




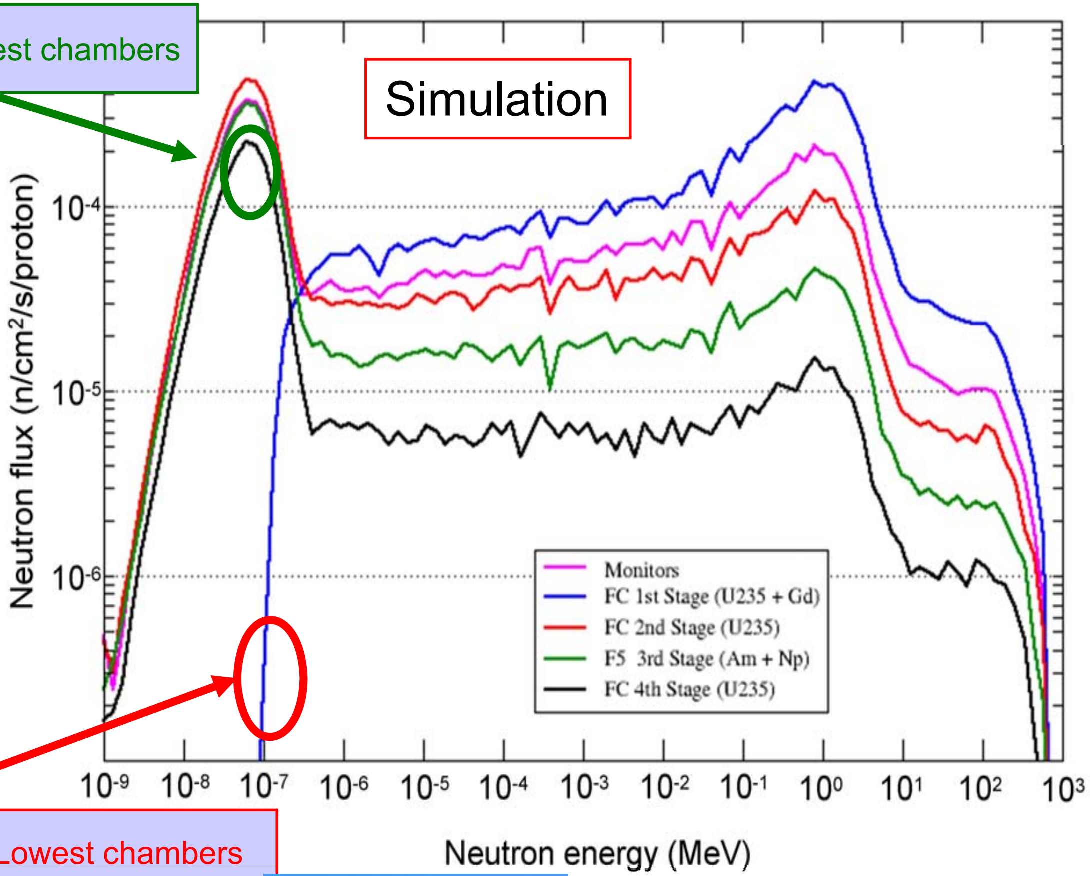


Inner neutron flux





Highest chambers



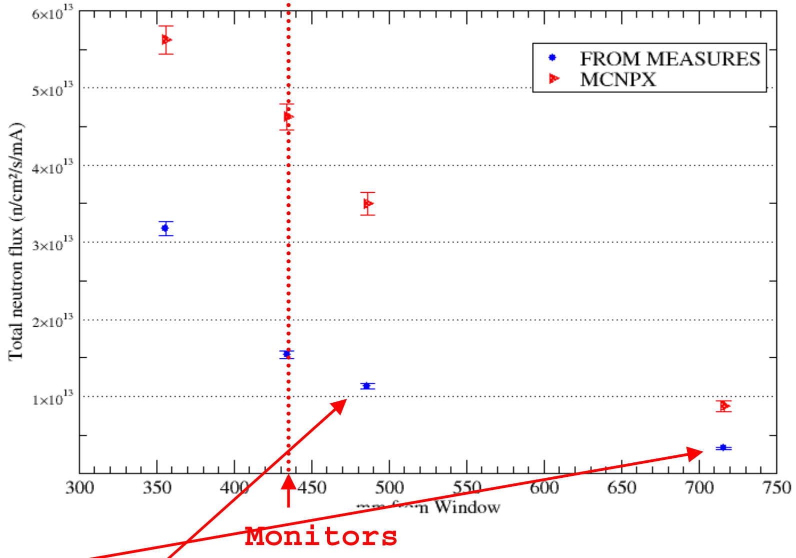
Lowest chambers
+
Gadolinium shield

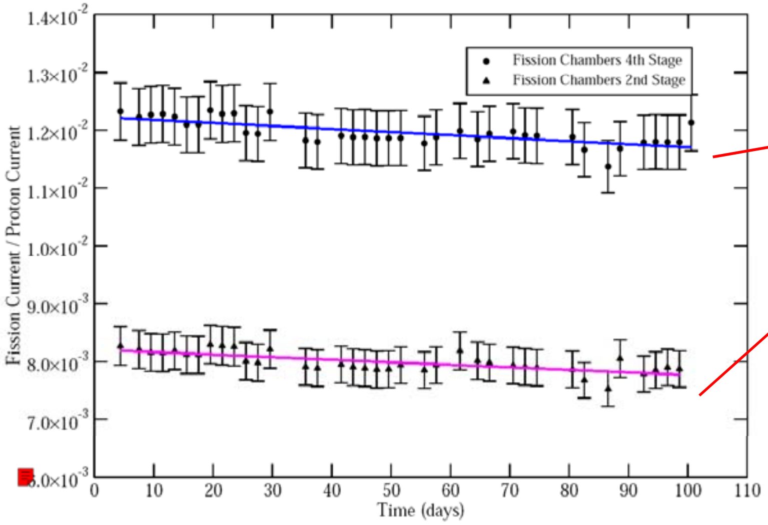
Micro fission chamber

S. Chabod et al., NIM A 556-2 (2007)

Inner neutron flux

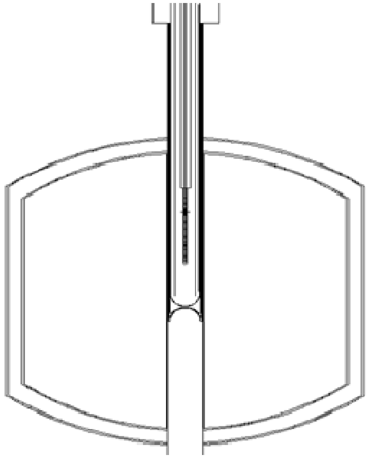
- Online monitoring of neutron flux
- Very tough experimental conditions
- Small ^{235}U burn-up (6%)
- Extraction of neutron flux from fission current (given a spectrum from MC)

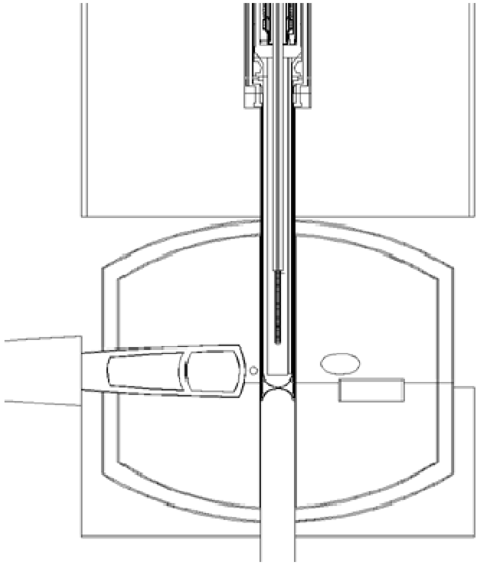


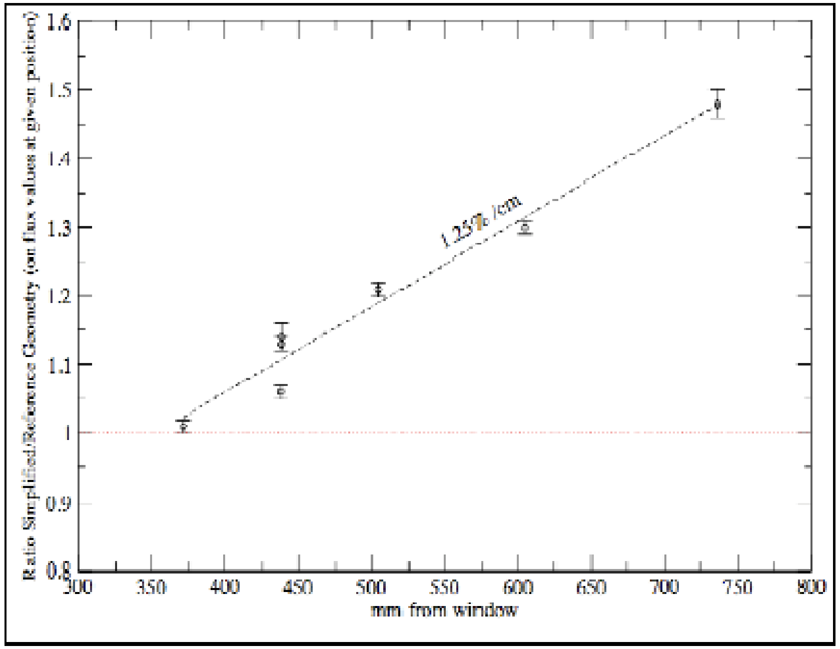


- Discrepancy of a factor ~2 between measures (FC & monitors agree!)
- Deep sensitivity analysis on MC parameters and experimental systematics
  - *S. Panebianco et al., proc. AccApp07*
  - *F. Michel-Sendis et al., proc. ICRS08*
- Beam divergency effect under study

Effect of structures

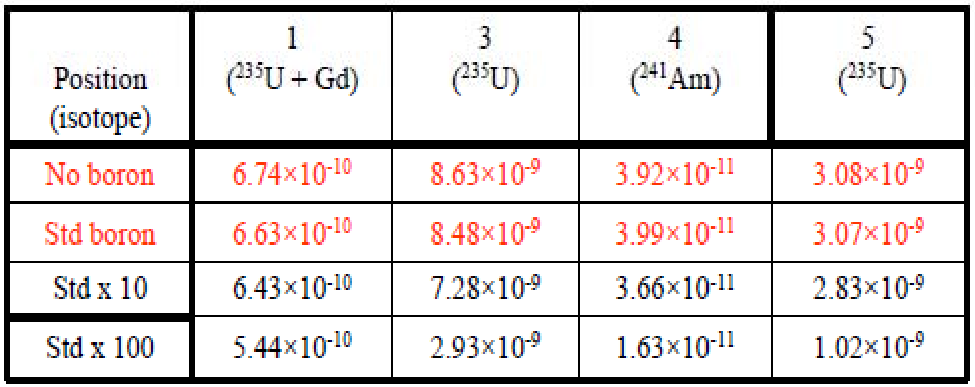






Effect of boron impurities

Simulated fission rates (fissions s^{-1} mA^{-1}) for different boron concentrations in LBE. The Bertini spallation model was used is MCNPX. Std boron= 2 weight ppm.



Position (isotope)	1 (^{235}U + Gd)	3 (^{235}U)	4 (^{241}Am)	5 (^{235}U)
No boron	6.74×10^{-10}	8.63×10^{-9}	3.92×10^{-11}	3.08×10^{-9}
Std boron	6.63×10^{-10}	8.48×10^{-9}	3.99×10^{-11}	3.07×10^{-9}
Std x 10	6.43×10^{-10}	7.28×10^{-9}	3.66×10^{-11}	2.83×10^{-9}
Std x 100	5.44×10^{-10}	2.93×10^{-9}	1.63×10^{-11}	1.02×10^{-9}

Effect of beam shape

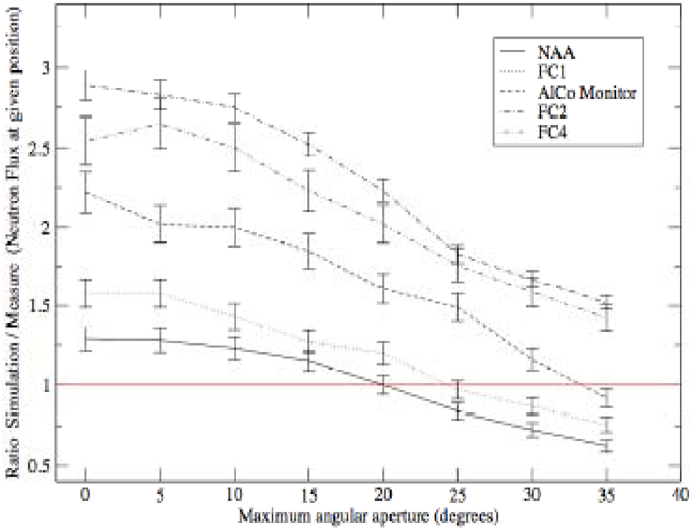
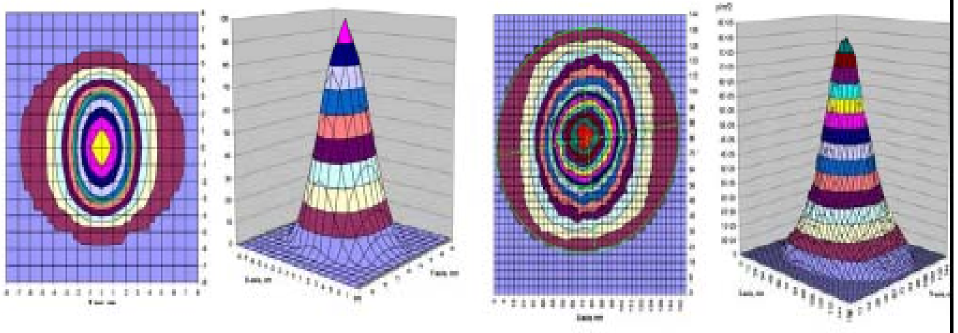
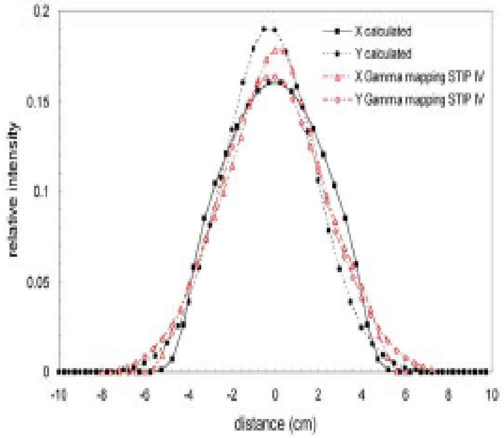


Figure 3.14. Ratios between calculated and measured neutron flux as a function of the the proton source angular aperture.

calculated

Gamma mapping target 4

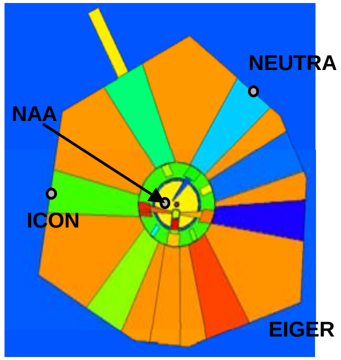


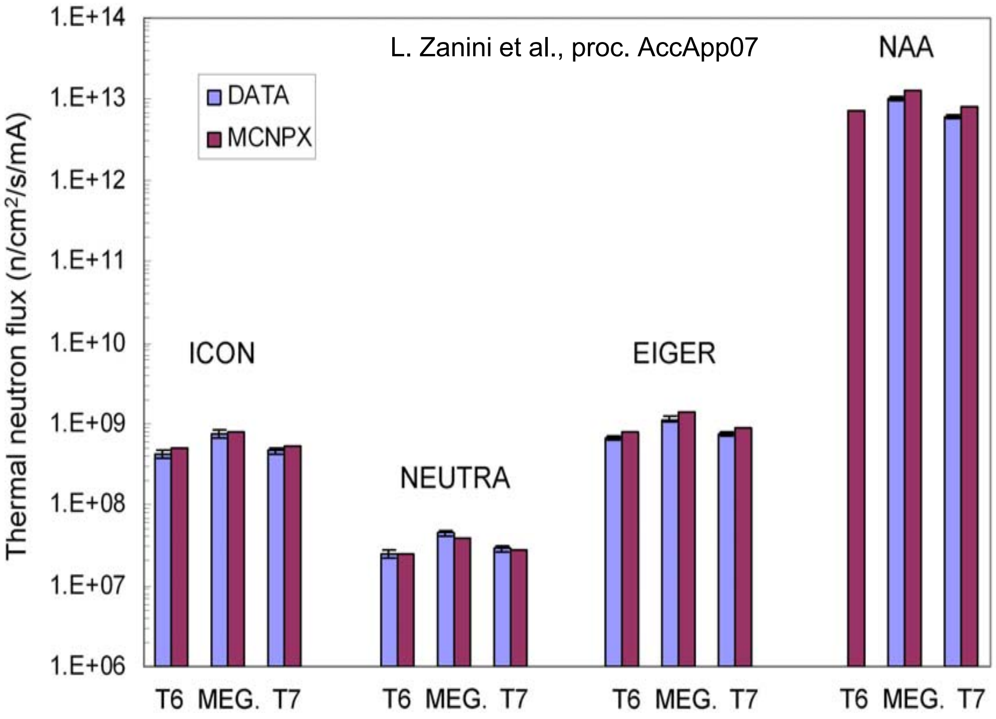


10-15% effect

Thermal neutrons measurement

Experimental technique: activation method (thin Au foils w/wo Cd)
self-shielding correction applied



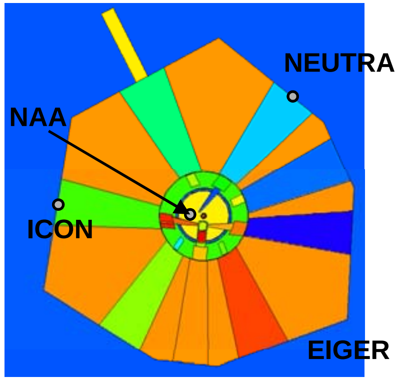


L. Zanini et al., proc. AccApp07

Increase of neutron flux at the thermal beam line MEGAPIE/solid target of about 1.7
Good agreement with simulated flux

Epithermal neutrons measurement

Experimental technique: activation method (thin Au foils w/wo Cd)
self-shielding correction applied



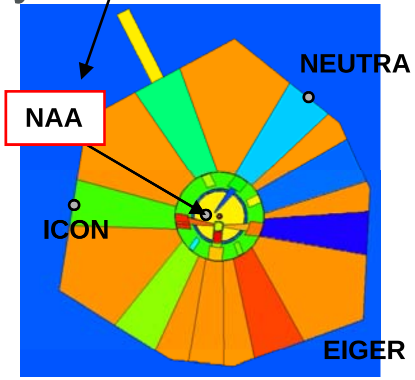
L. Zanini et al., proc. AccApp07

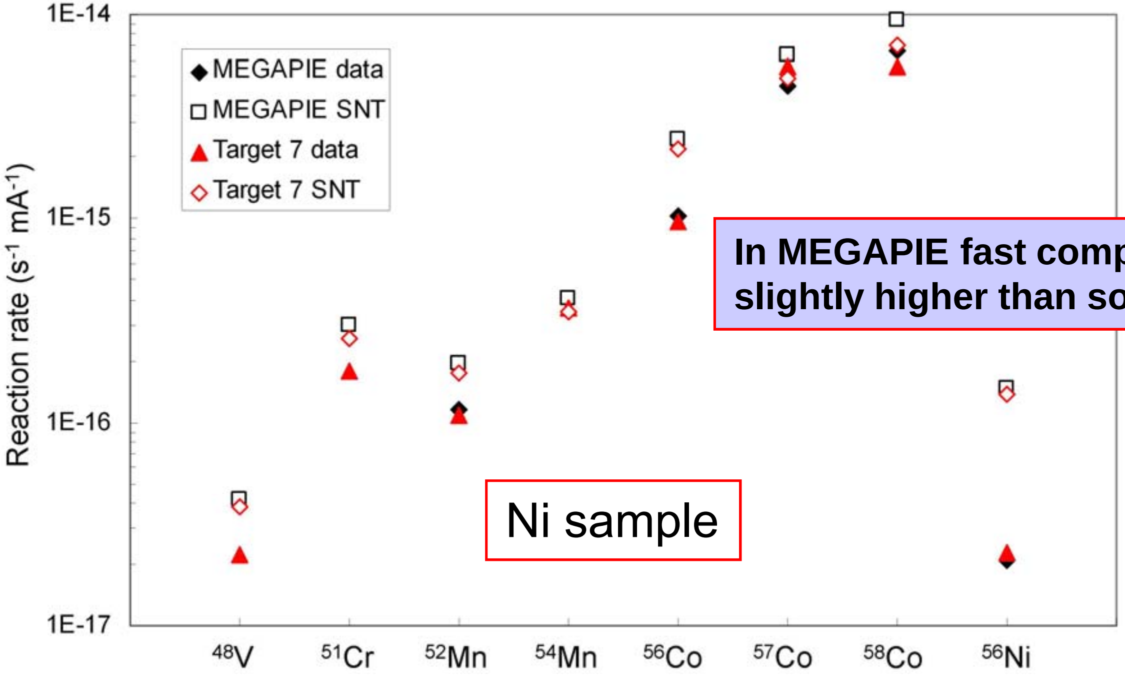
	Φ(epi) / (Φepi+ Φth) experimental	Φ(epi) / (Φepi+ Φth) calculated
ICON		
T6	0.13	0.13
MEGAPIE	0.19	0.15
T7	0.10	0.12
NAA		
MEGAPIE	0.045	0.038
T7	0.034	0.034

The epithermal component with MEGAPIE is larger than with the solid targets
The experimental value are 20-25% higher than the predicted one

Fast neutrons measurement

Experimental technique: reaction rates measurements from a set of activation foils sensitive to threshold reactions (above 1 MeV)





In MEGAPIE fast component slightly higher than solid target

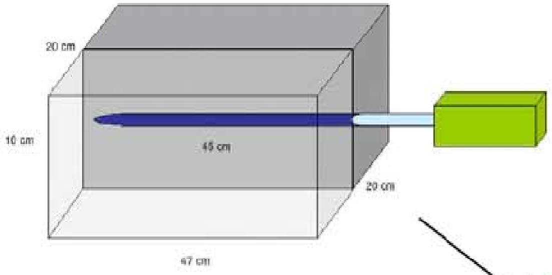
Ni sample

Calculations performed with SNT code *(A. Konobeyev et al., subm. NIM A)*
Main contribution comes from neutron from 20 to 150 MeV: *(n,xnp)* reactions
Agreement between calculations and measurement depends on the nuclide
→ improvement of evaluated data (JEFF, IEAF,…)

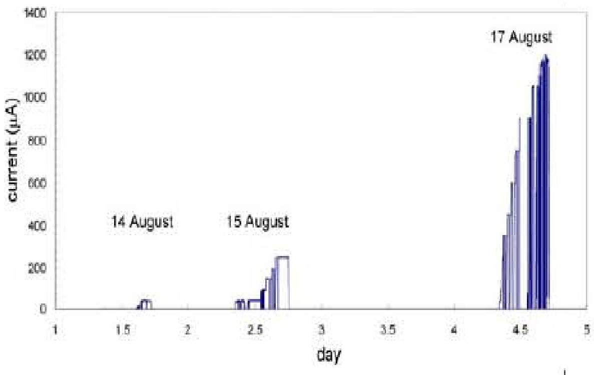
Neutronics: recommendations

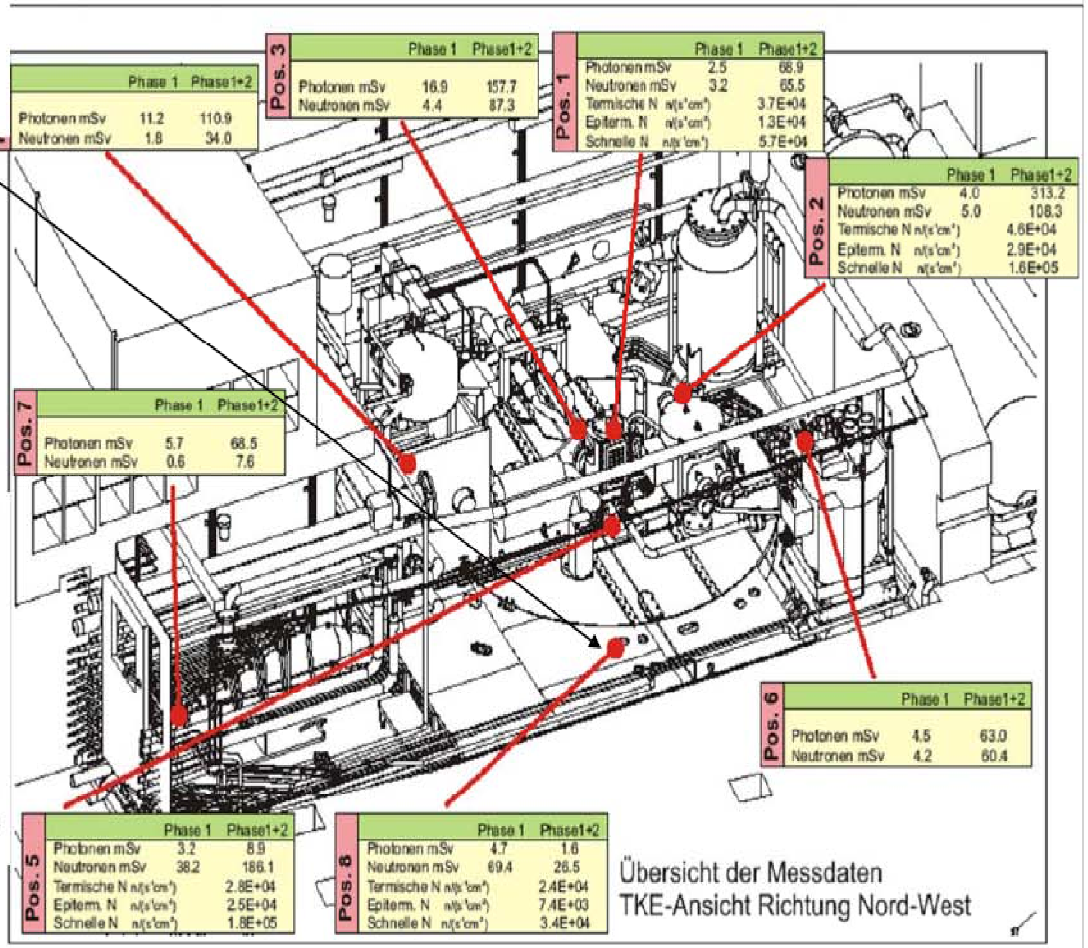
- We stress the importance of correct simulations (geometry, materials, beam profile, models)
- More sensitivity studies
  - Importance of correct beam profile
  - Importance of structural materials
- Better measurements: activation foils should be < 5%
- More spectral measurements at different parts of the facility

Delayed neutron measurement



^{3}He tube inside CH_2 box placed above the MEGAPIE target





	Phase 1	Phase1+2
Photonen mSv	11.2	110.9
Neutronen mSv	1.8	34.0

Pos. 3	Phase 1	Phase1+2
Photonen mSv	16.9	157.7
Neutronen mSv	4.4	87.3

Pos. 1	Phase 1	Phase1+2
Photonen mSv	2.5	68.9
Neutronen mSv	3.2	65.5
Termische N $n/(s \cdot cm^2)$		3.7E+04
Epiterm. N $n/(s \cdot cm^2)$		1.3E+04
Schnelle N $n/(s \cdot cm^2)$		5.7E+04

Pos. 2	Phase 1	Phase1+2
Photonen mSv	4.0	313.2
Neutronen mSv	5.0	108.3
Termische N $n/(s \cdot cm^2)$		4.6E+04
Epiterm. N $n/(s \cdot cm^2)$		2.9E+04
Schnelle N $n/(s \cdot cm^2)$		1.6E+05

Pos. 7	Phase 1	Phase1+2
Photonen mSv	5.7	68.5
Neutronen mSv	0.6	7.6

Pos. 6	Phase 1	Phase1+2
Photonen mSv	4.5	63.0
Neutronen mSv	4.2	60.4

Pos. 5	Phase 1	Phase1+2
Photonen mSv	3.2	8.9
Neutronen mSv	38.2	186.1
Termische N $n/(s \cdot cm^2)$		2.8E+04
Epiterm. N $n/(s \cdot cm^2)$		2.5E+04
Schnelle N $n/(s \cdot cm^2)$		1.8E+05

Pos. 8	Phase 1	Phase1+2
Photonen mSv	4.7	1.6
Neutronen mSv	69.4	26.5
Termische N $n/(s \cdot cm^2)$		2.4E+04
Epiterm. N $n/(s \cdot cm^2)$		7.4E+03
Schnelle N $n/(s \cdot cm^2)$		3.4E+04

Übersicht der Messdaten
TKE-Ansicht Richtung Nord-West

Delayed neutron measurement

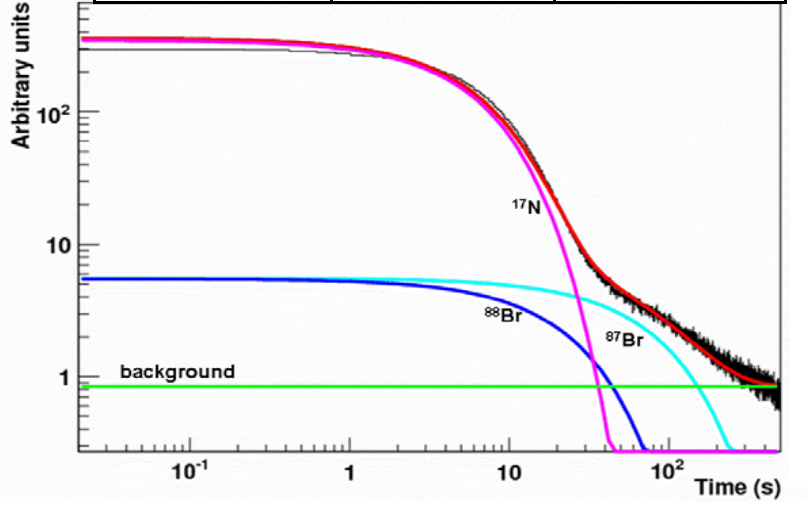
- → **Fit of the data**
  - → **Precursors identified in solid target experiment***

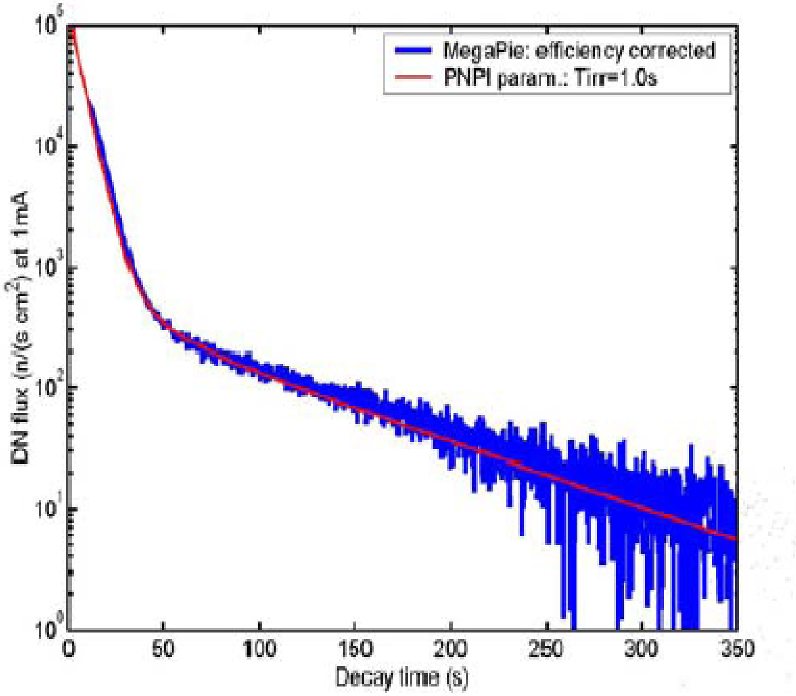
. * *D. RIDIKAS et al., Europ. Phys. Journ. A,* ***32****, 1-4 (2007)*

$$a(x)=\sum_{i=1}^{n} a_i(x)=\sum_{i=1}^{n} a_i^a \frac{1-\exp(-\lambda_i \tau_a)}{1-\exp(-\lambda_i T)}\exp(-\lambda_i \tau_d(x))$$

τ_a ~0.5 s irradiation
T ~20 s relaxation
***τ_d ~10 s* heat exchanger**

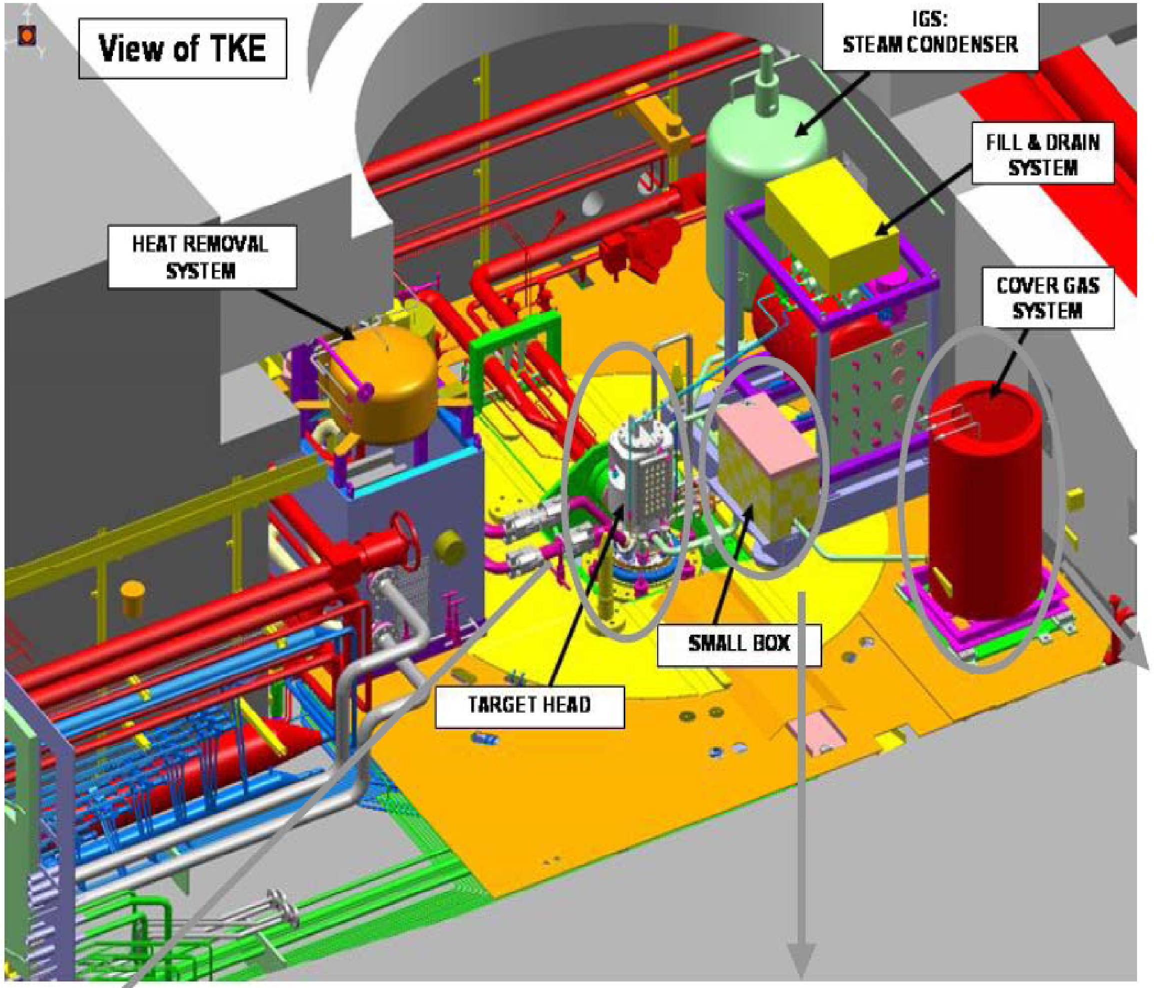
Precursor	Half-life, s	a_i (%)
^{87}Br	**55.60**	**4.3**
^{88}Br	**16.29**	**3.3**
^{17}N	**4.173**	**92.4**





DN densities in agreement with solid target experiment

Gas measurement: setup



Gas operation goal:

- handling and control radioactive gases
- handling and control the pressure
- analysis of the gas production

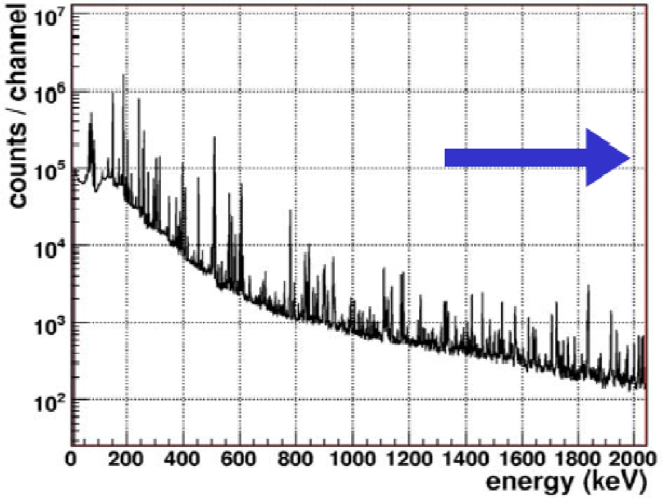
~13 liters shielded decay tank and small sampling unit

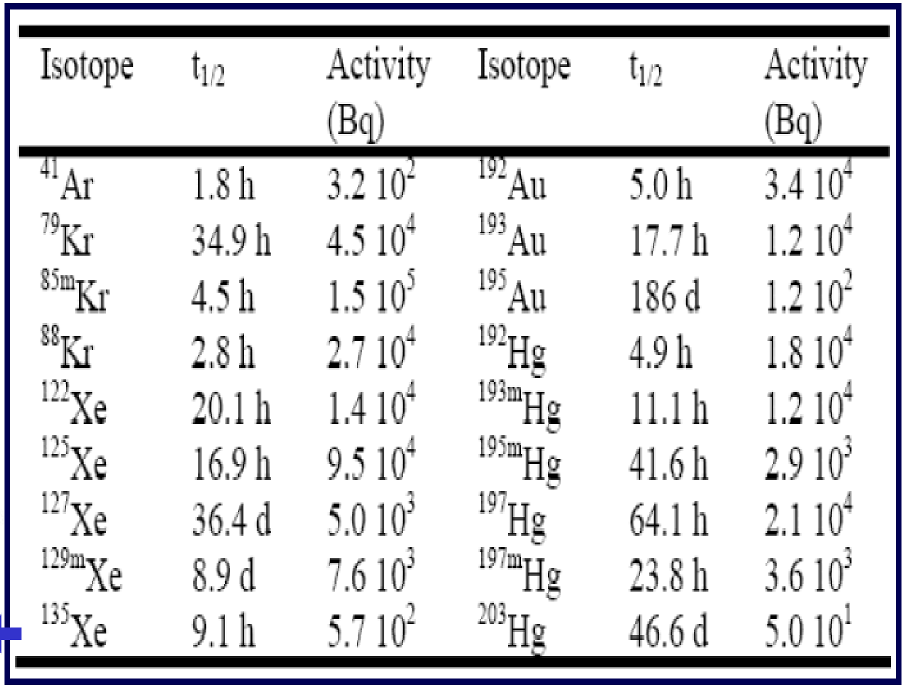
LBE expansion volume (~2 liters)

Pb shielded box containing valves for operation and pressure transducers

Gas measurement: procedure

A gas sampling is performed two days after the beginning of irradiation (1mA·h of accumulated charge) in order to access short half-life isotopes.





Isotope	$t_{1/2}$	Activity (Bq)	Isotope	$t_{1/2}$	Activity (Bq)
^{41}Ar	1.8 h	3.2 10^2	^{192}Au	5.0 h	3.4 10^4
^{79}Kr	34.9 h	4.5 10^4	^{193}Au	17.7 h	1.2 10^4
^{85m}Kr	4.5 h	1.5 10^5	^{195}Au	186 d	1.2 10^2
^{88}Kr	2.8 h	2.7 10^4	^{192}Hg	4.9 h	1.8 10^4
^{122}Xe	20.1 h	1.4 10^4	^{193m}Hg	11.1 h	1.2 10^4
^{125}Xe	16.9 h	9.5 10^4	^{195m}Hg	41.6 h	2.9 10^3
^{127}Xe	36.4 d	5.0 10^3	^{197}Hg	64.1 h	2.1 10^4
^{129m}Xe	8.9 d	7.6 10^3	^{197m}Hg	23.8 h	3.6 10^3
^{135}Xe	9.1 h	5.7 10^2	^{203}Hg	46.6 d	5.0 10^1

Au → Hg decay

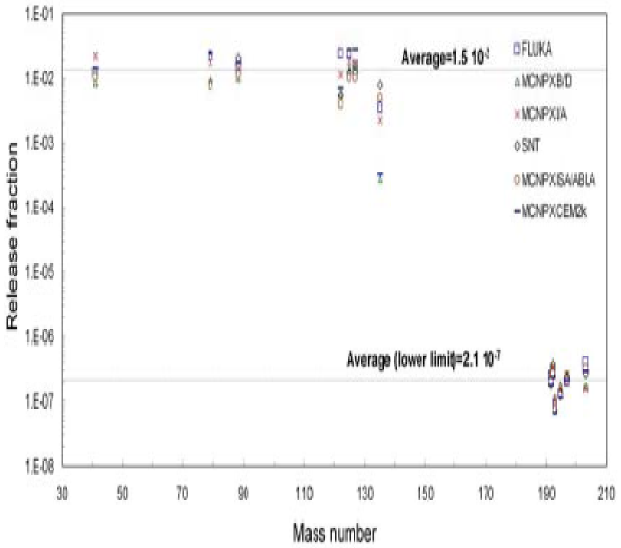
Two different gas sample have been measured and have revealed :

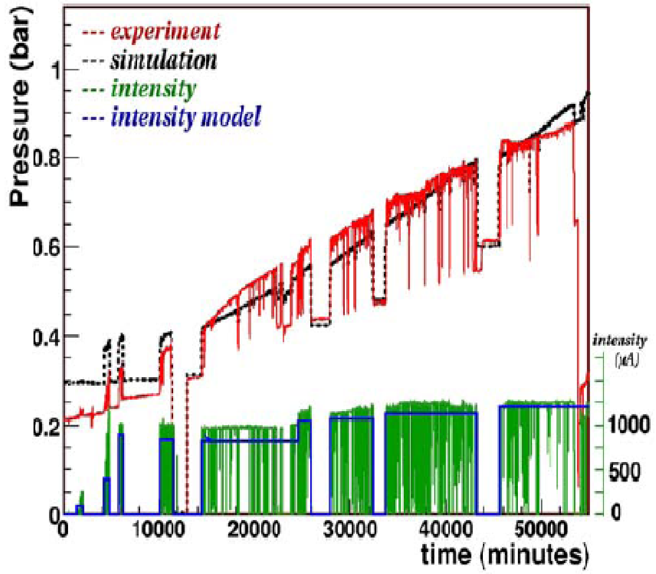
$A_{nb\text{-}s1} \approx 1.4\ A_{nb\text{-}s2}$ → indication on uncertainty (~40%)

$A_{Hg\text{-}s2} = A_{Au\text{-}s2} = 0$ → doubt in mercury behavior…

Gas measurement: results

- Successful measurements of radionuclides at different irradiation times.
- Estimation of the release fractions at the beginning of irradiation and towards the end.
- Good agreement with calculations. Mass distributions allow selecting best models.
- Agreement of results with estimations on release of Hg and Po from the design phase (but measurements not precise).
- No mass measurement of stable isotopes, but indirect information from pressure measurements (in fair agreement with calculations).





Gas measurement: issues

Measurement has revealed traces of ^{208}Po which is supposed to be weakly released. Further investigations *(Y. Tall et al., IS419 experiment, 2008)* show that Po is not expected to be directly released at MEGAPIE operated conditions.

→ It is reasonable to assume that measured ^{208}Po comes from ^{208}At released and decay.

→ experimental and simulated data give a release factor for At close to 10^{-6}.

Measured amounts of mercury in the expansion tank have a high uncertainty. This may due to possible isotopes sticking on the CGS pipes and walls.

→ The precise Hg during sampling procedure should be understood.

→ Analysis of the cold trap will be done during the Post Irradiation Experiment.

Leaks of radioactive Xe isotopes (~1% of the total) were detected in the insulation gas system and a high amount of migrated tritium were detected in Dyphil oil (10^6 time higher than expected value calculated from reaction induced by spallation neutron only).

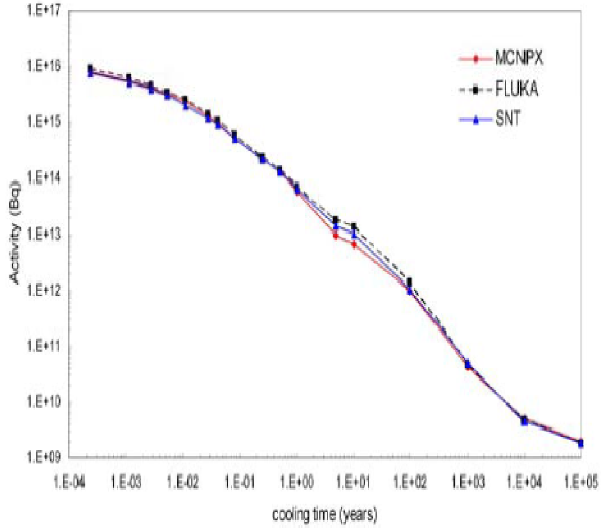
→ Radioactive gas leaks should be inspected in order to be prevented.

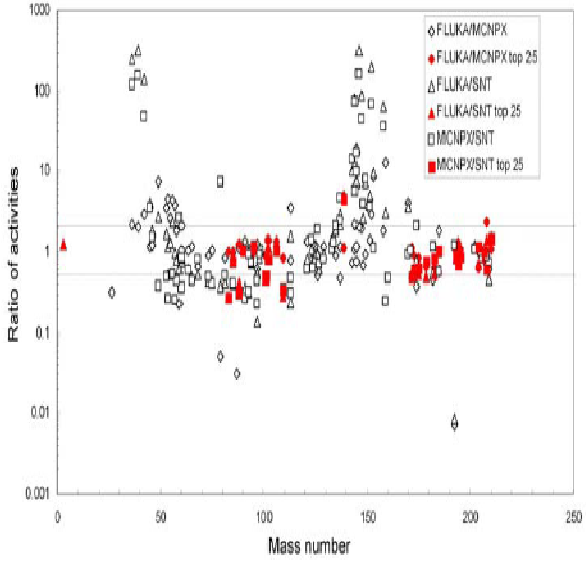
Gas measurement: recommendations

- Feedback to operation issues:
  - Leak tightness is difficult to achieve
  - Radiation damage in pressure sensors to be investigated
  - Gas sampling operation to be improved
- Feedback to scientific/safety issues:
  - Need for reliable mass spectroscopy measurements, especially for H an He isotopes
  - Understanding the behaviour of Hg in the CGS

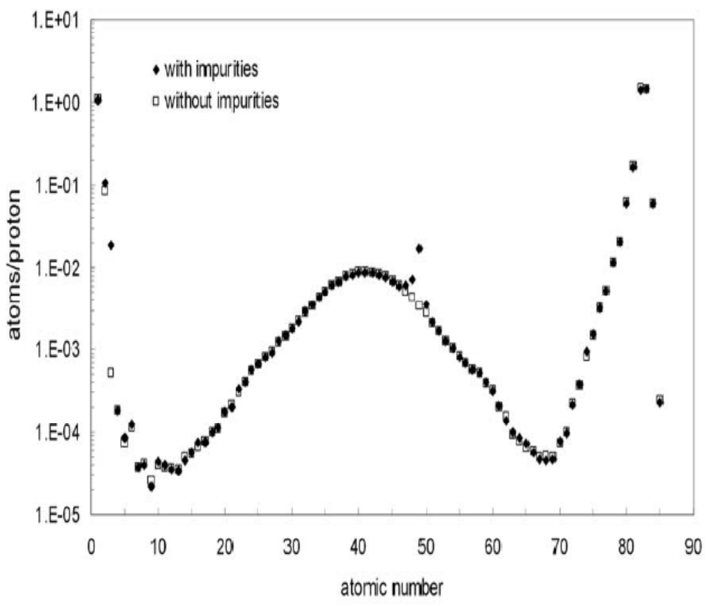
Target activation

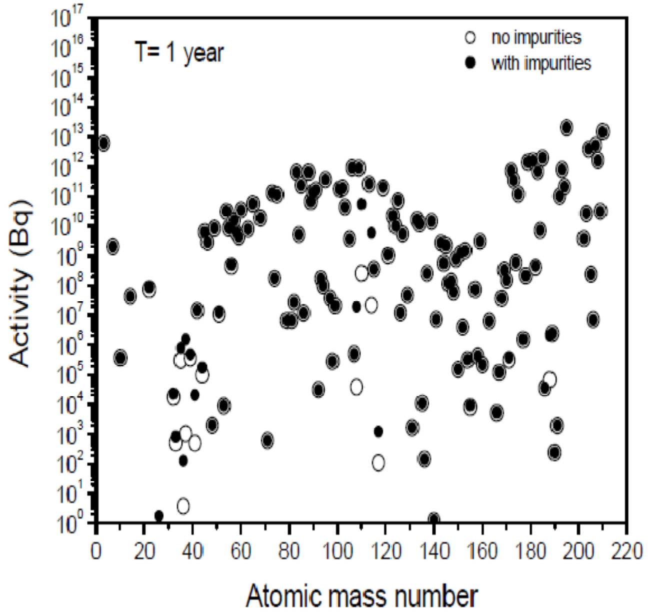
- Activation of LBE and target structure.
- Large effort with different code systems:
    - MCNPX/CINDER'90
        - Different spallation/evaporation models
    - MCNPX/FISPACT
    - MCNPX/SNT
    - FLUKA/ORIHET
- Origin of nuclides produced (contributions from protons and neutrons).
- Effect of impurities.





Target activation: effect of impurities





The only significant differences are for lithium (Z=3), cadmium and indium (Z=48, 49). The isotopes showing larger production rate in the LBE with impurities are ^{7}Li (from (n,α) reaction on the ^{10}B impurity), ^{116}In (capture in ^{115}In) and ^{114}Cd (inelastic reactions in In and Sn impurities).

After one year of cooling, there are only a few isotopes with activity greater than 10^{9} Bq, which show a significantly higher activity with the impurities: ^{114}In and ^{114m}In (factor 270 increase) and ^{110m}Ag (factor 210 increase). These isotopes come from thermal neutron capture in the In and Ag impurities.

Conclusions

- Neutronic performance of an ADS target with window has been studied in great detail
- System of „tools“ (measurement techniques, Monte Carlo strategies) developed, essential for the design and construction of future ADS
- Importance of good calculation tools and of proper use of them
  - Materials definition
  - Beam profile definition
  - Geometry definition
  - Physics models and cross section libraries
- Importance of neutronic measurements inside the target, where the fast component is dominant
- Importance of gas measurements as gas production is one of the key safety issues in an ADS
  - Improve and control leak tightness
- Delayed neutrons must be taken into account