ITALIAN NATIONAL AGENCY
FOR NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

ENEA-INMRI

Iride:
The particle Source

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ENEA-Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti - Casaccia

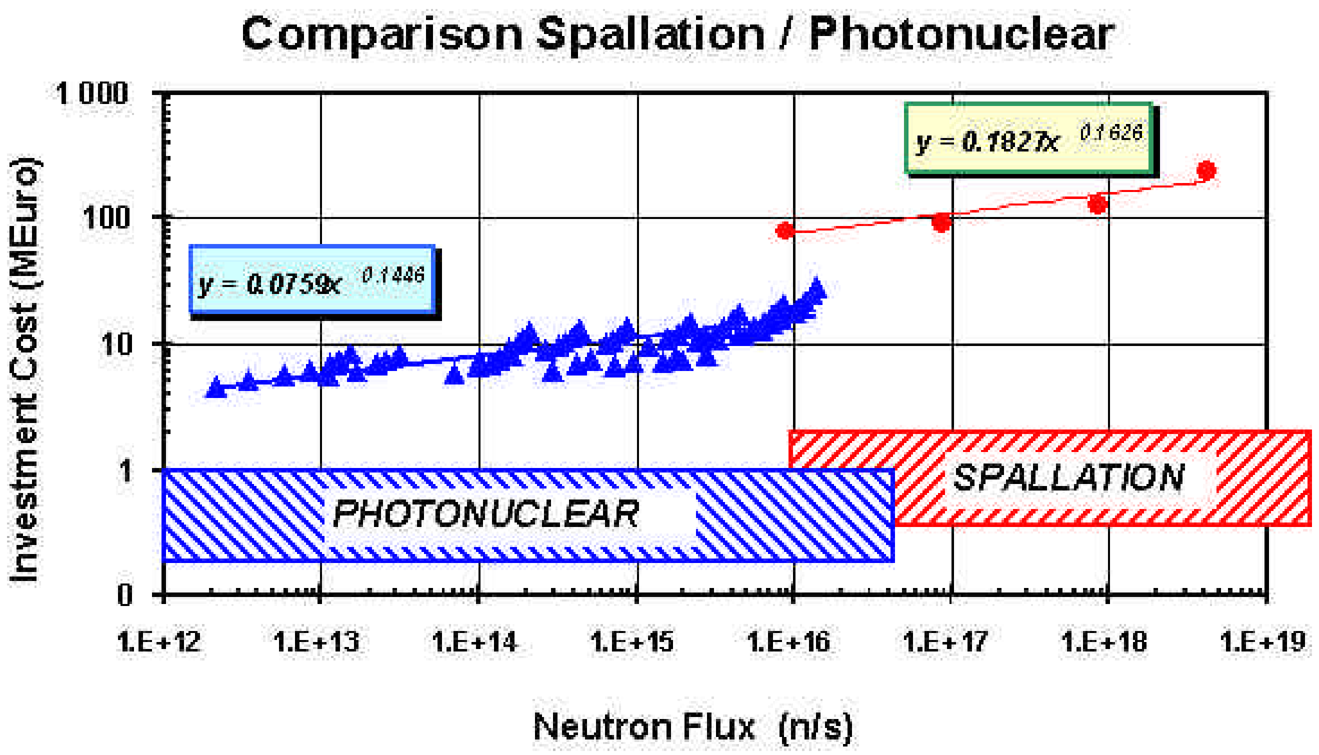
Frascati, LNF *June 10-11, 2013*

Outline

- The Starting Point: Measurements of photo-produced neutrons at **Daϕne : the n@BTF Project**. ---> "quickly" described
- Some brief considerations on spallation vs photo-production accelerator driven systems
- IRIDE: particle yield and energy spectra
  - Source term: study and design of an optimised target for neutron production
  - Preliminary MC estimations of the particle yields (not only neutrons: p, pi, muons, etc)
  - Expected Source Strength comparison with the corresponding ones of other worldwide accelerator driven facilities
  - Description of the thermo-mechanical issues: an analytical approach and need of FE method simulations for the thermo-mechanical issues

Spallation vs Photoneutron sources

- Spallation sources are very effective in producing neutrons. Example: 100 MeV e- on U target--> 0.11 n/e-, so 900 MeV are needed to produce 1n. On the contrary, on the same target 1GeV p --> 30 n (a factor 30 more effective)... **but they are large and expensive**.
- Electron drivers although are much less effective in neutron production are rather cheap and compact machine that might also bring advantages in terms of reliability



Above a given neutron rate (10^16 n/s) the spallation will be preferred while for the lower fluxes, the photonuclear process will tend to be more convenient

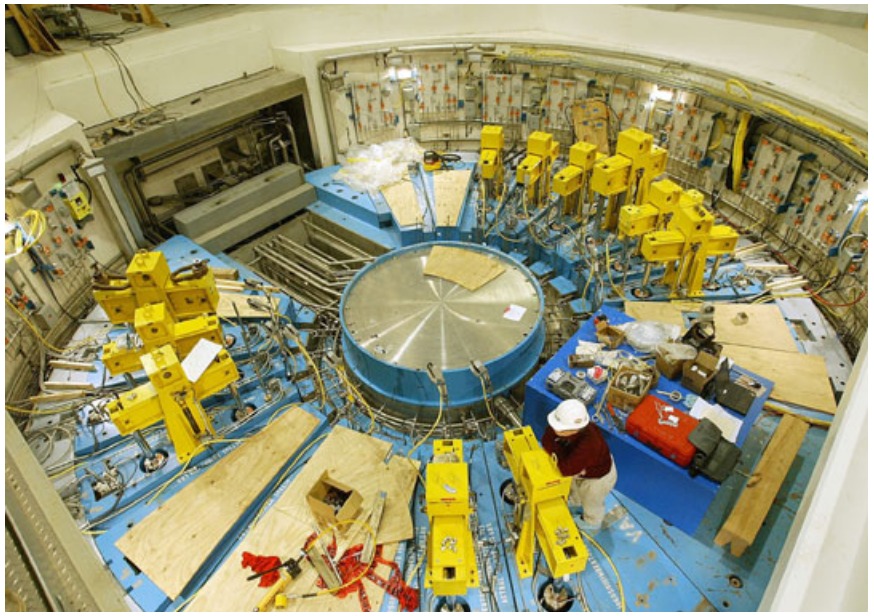
To obtain very high neutron fluxes by photo-production, much higher electron beam intensity will be necessary. This will increase the electron accelerator complexity, resulting in a less convenient solution from an engineering and economical point of view.

Plot reference:

Ref: D. Ridikas, H.Safa, M.L.Giacri – Conceptual Study of Neutron Irradiator Driven By Accelerator – *7th Information Exchange Meeting on Actinide and Fission Product P&T (NEA/OCDE), Jeju, Korea, 14-16 Oct. 2002*

Neutron Sources around the world

- SNS (Spallation Neutron Source) at Oak Ridge
- ISIS (Spallation Neutron Source) in England
- n-TOF (Spallation Neutron Source) at CERN
- IPNS (Intense Pulsed Neutron Source) at ANL
- LANSCE (Spallation Neutron Source) Los Alamos Neutron Source
- Gelina (Geel Electron Linear Acceleration) in Geel Belgium (Photo-production)
- n-ELBE (Photo-production) at Rossendorf, Germany
- ORELA at Oak Ridge (Photo-production)
- ...... ESS (European Spallation Source) at Lunde Sweden



SNS at Oak Ridge

Electron Beam Neutron Sources

- Conventional Linac

	Nation	Institute	Beam Energy	Target
GELINA	Belgium	IRMM	105 MeV (Avg.)	U
ORELA	USA	ORNL	180 MeV	Ta
Gaerttner Linac	USA	RPI	60 MeV	Ta
KURRI Linac	Japan	Kyoto U.	46 MeV	Ta
IREN	Russia	JINR	200 MeV	U
PNF	Korea	POSTECH	100 MeV	Ta

- SC Linac

  : nELBE (FZD, Germany, 40 MeV, Pb liquid target)

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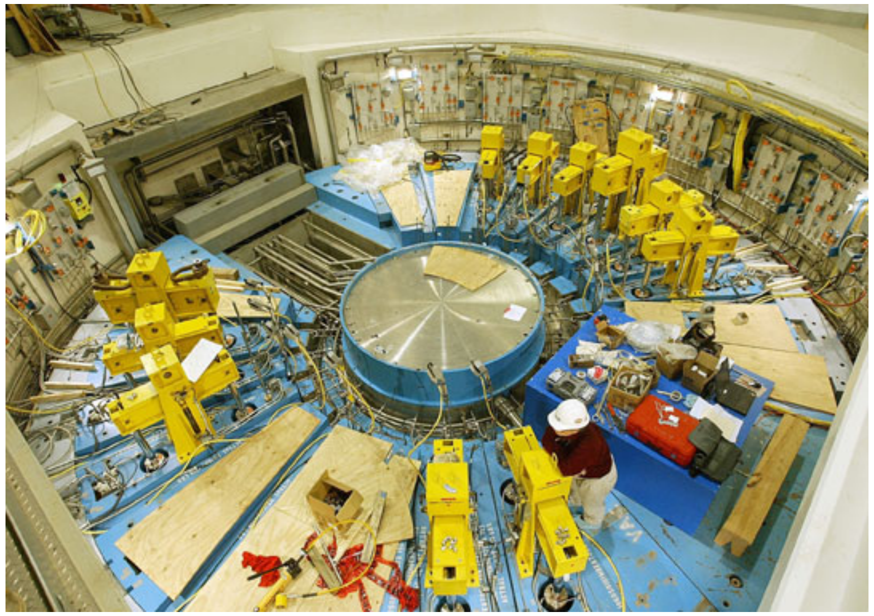

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Iride SC Linac

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N@BTF

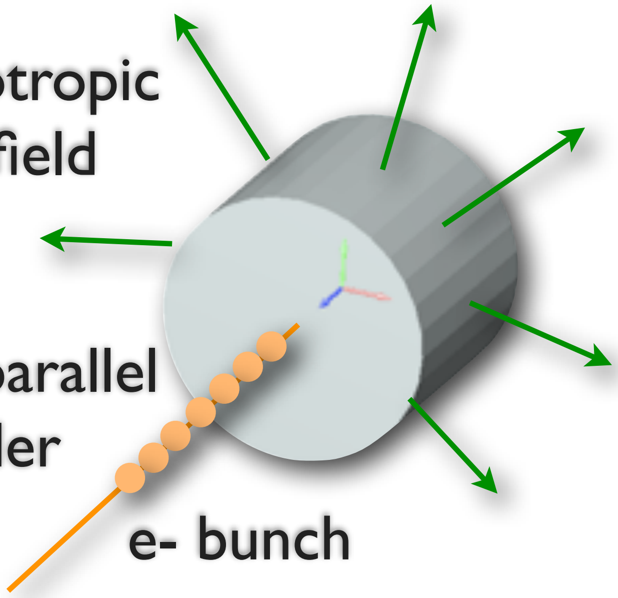
OPTIMISED TARGET
&
EXPERIMENTAL APPARATUS

Acquired know-how and MC validations

The Optimized Target

Optimization criterion: recursive process on calculating neutron fluence leaving the target, increasing linear dimensions (Rand L)
Best solution: the one for which, a new step would have affected only marginally the photoneutron yield (gain of only few %).
L from 15 to 20X0 gain less than 3% (so final choice 17 X0 on the plateau); Same considerations: R final choice 10 X0.

W cylinder R=35 mm L =60 mm(Z=74; ϱ=19 g/cm3; X0=0.35 cm; MR=0.9



Quite isotropic neutron field

BEAM axis parallel to the cylinder target's axis

e- bunch

n_yield= 2.12E-01
neutron/primary
integrated on all the spectrum
and solid angle
escaping from the target

Neutron absorbed in the target= 3%
NEU-BAL=0.212451
n-produced=0.21809

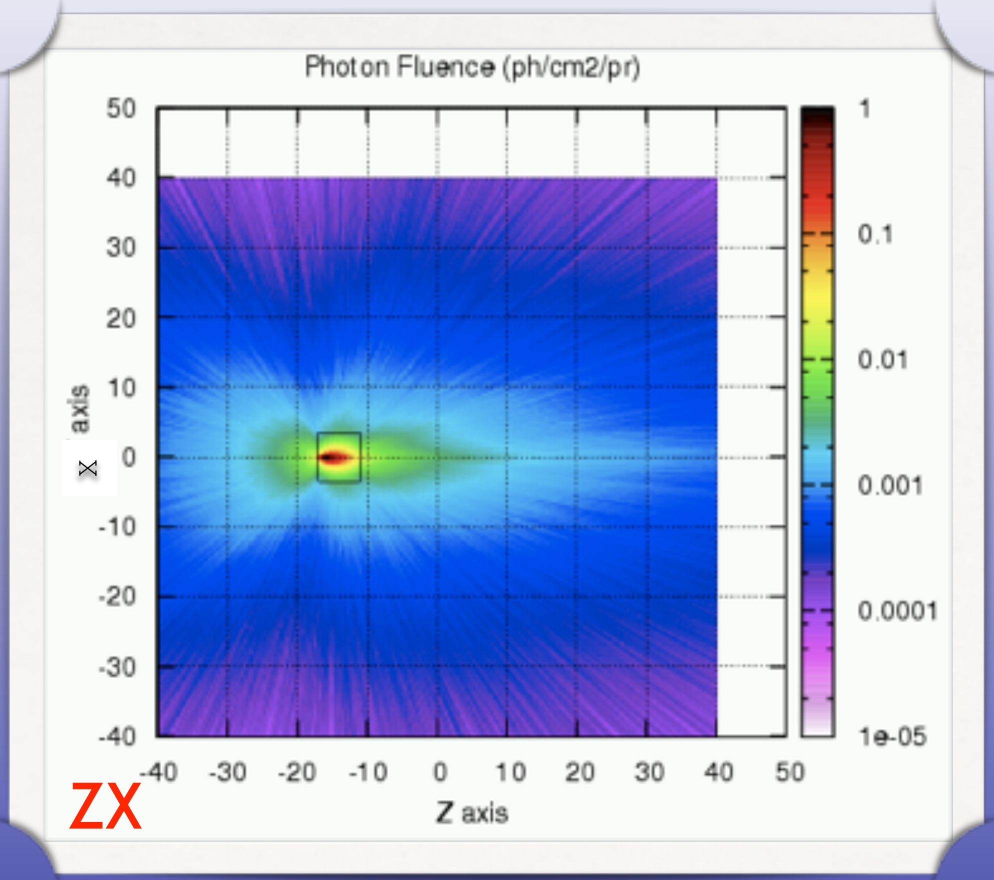
Maximum rate @ 0.7 MeV=
0.1343 n/primary
integrated on all the solid angle

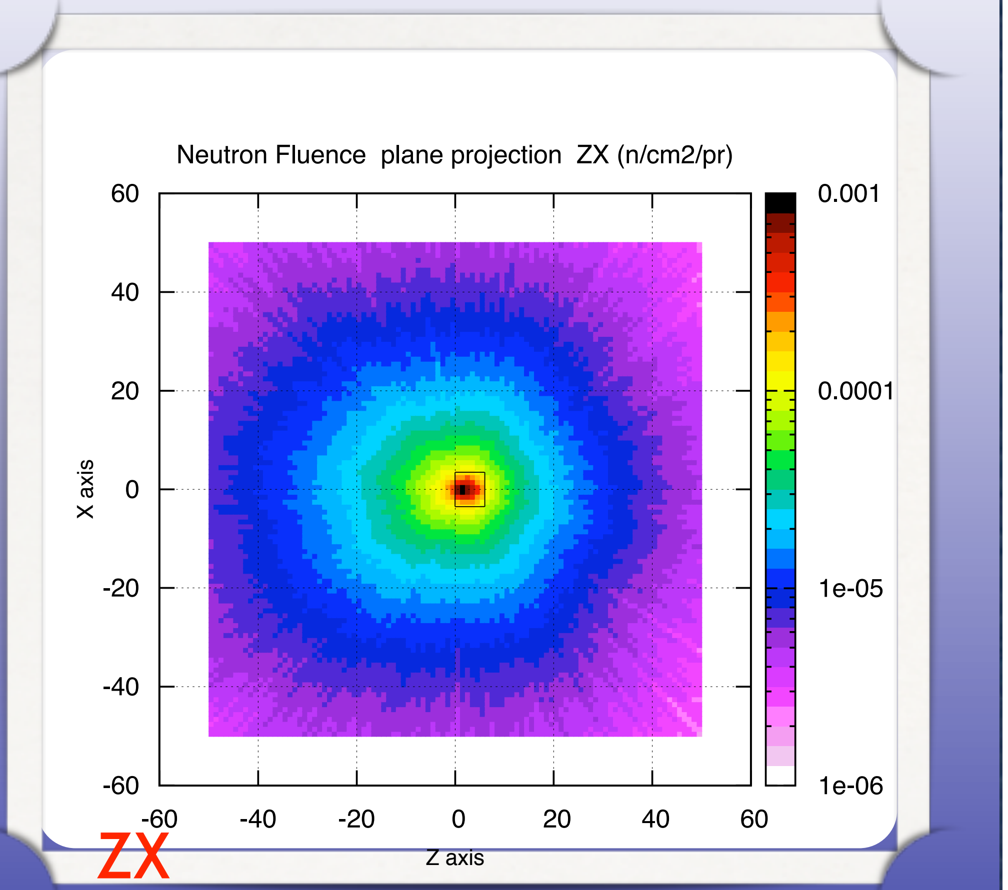
Since the maximum electron beam spot size on the target is enclosed in a circle of 1.cm radius and the accuracy by which we can set the beam position is better of few mm, we can be confident that all the energy of the primary electrons wil be ever deposited in the target

Expected Neutrons and Photons:

(target in vacuum)

Spatial distribution





Higher intensity and hardest Gammas in forward direction. More than 2 order of magnitudes of difference in photon fluxes @ 90° and 0 ° wrt beam direction

Quite well isotropic

The photon and neutron fluxes have been calculated by the USRYIELD card for each direction

Expected Neutrons and Photons:
(target in vacuum)

Neutron and Photon Flux (Target and air around).
(Calculation with 25000 primaries)

Angle wrt beam direction	Photons[ph/cm2/pr] @0.5 m	Neutron [n/cm2/pr] @0.5 m
0°	1.16559E-02 +/- 1.207616 %	5.78188E-06 +/- 0.5680834 %
-30°	3.18765E-04 +/- 2.074163 %	7.32548E-06 +/- 1.397449 %
30°	2.00091E-03 +/- 0.6900502 %	6.98712E-06 +/- 0.2340965 %
-45°	2.55639E-04 +/- 1.500333 %	6.73067E-06 +/- 1.536476 %
45	9.85524E-04 +/- 0.7157903 %	6.37311E-06 +/- 0.8208705 %
-60	1.80074 E-04 +/- 3.305821 %	5.84105E-06 +/- 1.092179 %
60°	4.76631E-04 +/- 1.785744 %	5.35342E-06 +/- 1.501851 %
90°	9.61925E-05 +/- 4.184312 %	4.37955E-06 +/- 1.058816 %

Photon and Neutron Flux integrated on all the solid angle.
They are inversely proportional to the square of distance

	Photons[ph/cm2/pr]	Neutron [n/cm2/pr]
@ 0.5 m	6.2910217E-04 +/- 0.3605311 %	5.8066257E-06 +/- 0.5866572 %
@ 1.0 m	.5729200E-04 +/- 0.3733959 %	1.4539921E-06 +/- 0.5513448 %

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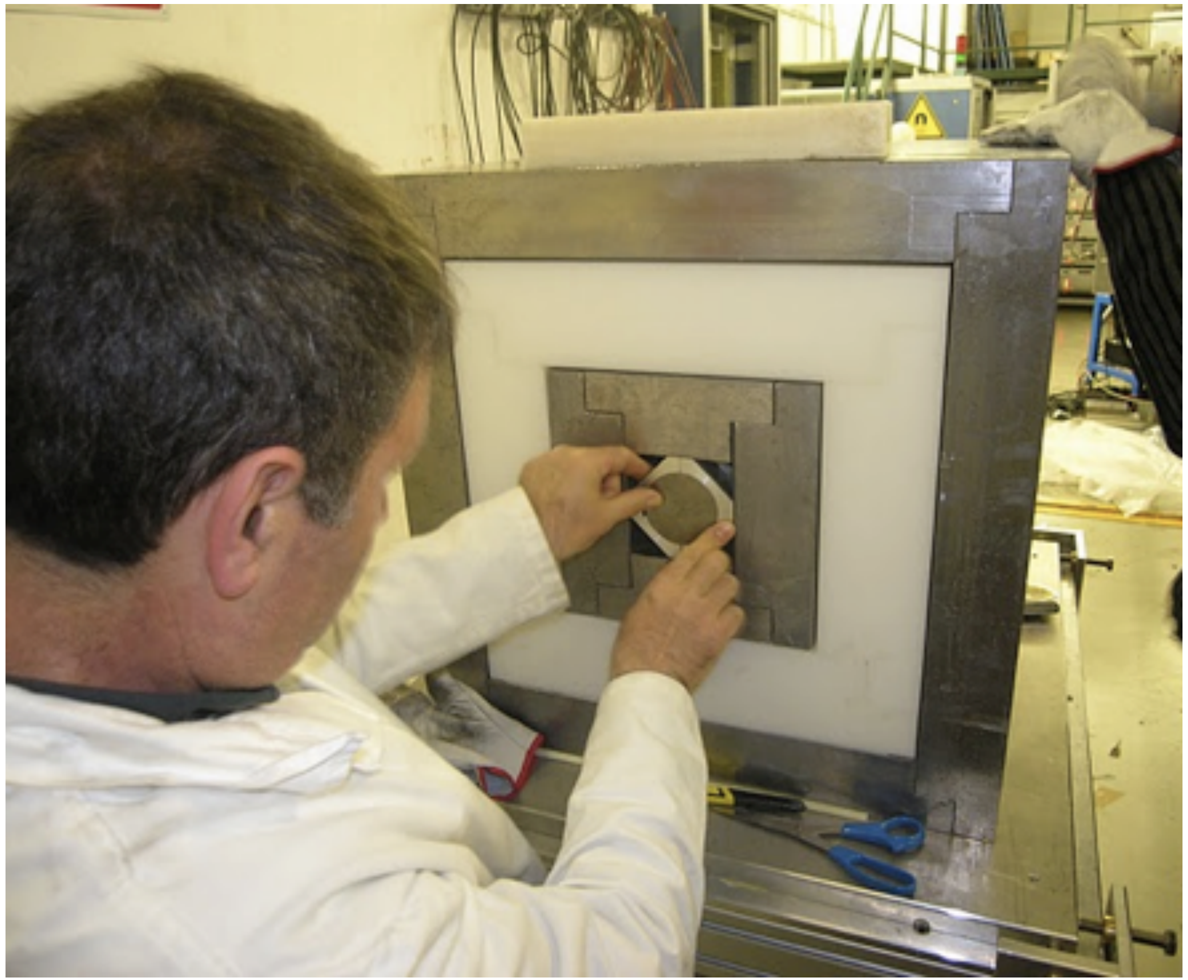
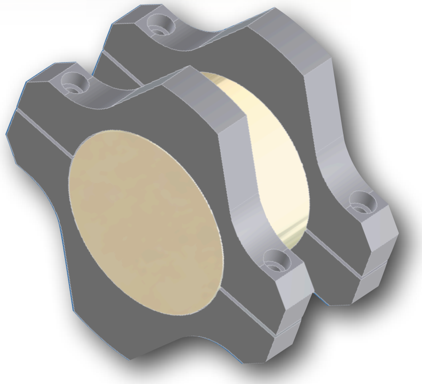
Final Experimental SET-UP

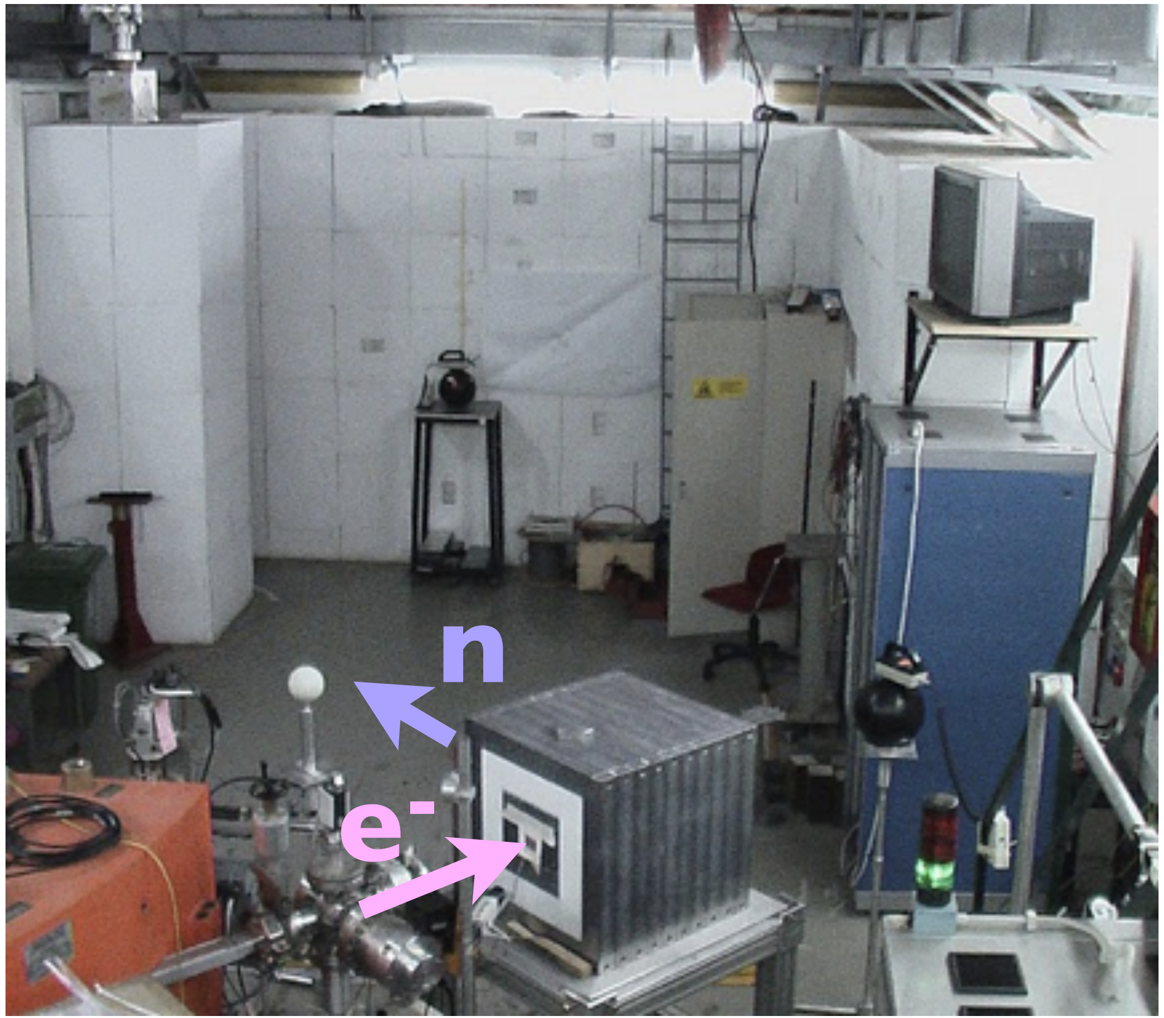


April 2010

Aluminum centering rings=
1.5 cm thickness



First Measurements May 2010

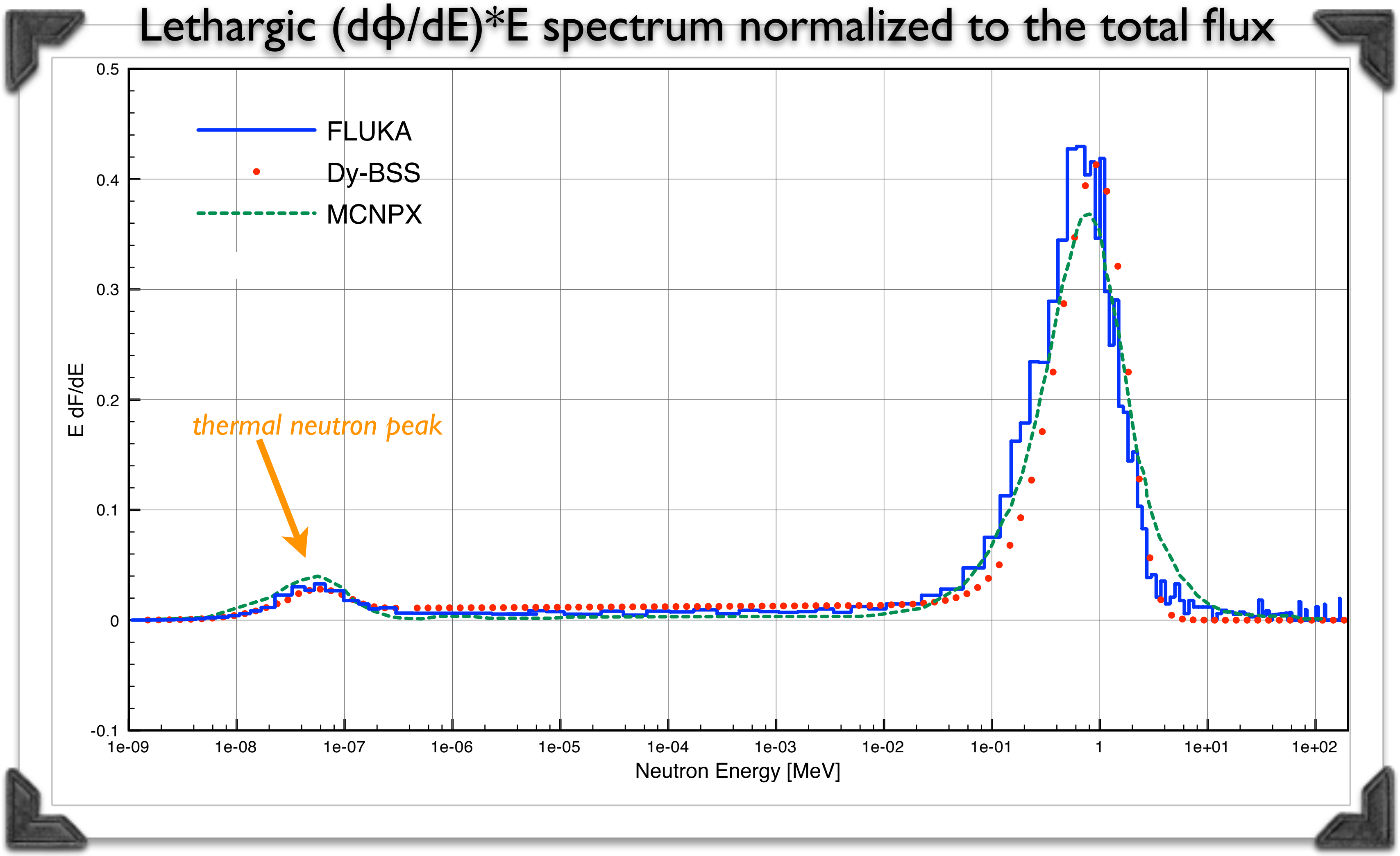


2 environmental detectors: response from thermal up to 20 MeV. The constance of ratio of their readings assure to have done measurements in a satisfactory repeatability or irradiation condition within ±1.5%

Experimental and Computational neutron Spectra

The point of test was at ~150 cm from the target and at 90° wr to the impinging electron beam line

Lethargic (dϕ/dE)*E spectrum normalized to the total flux



thermal neutron peak

The flux above 10 keV is 6.53E-7 /cm2/pr

As expected, more than 80% is found around the Giant resonance (from 10 KeV up to 20 MeV)

Statistical uncertainty in the calculations less than 4%

Total Neutron Flux per primary particle		
Ex. Measurement	FLUKA	MCNPX
8.04E-7 ±3%	**8.10E-7 ±4%**	**8.02E-07 ±0.2%**

Max neutron Flux currently available in BTF

Neutron Flux at 1.5m from shield = 4E+5 n/cm2/s corresponds to Equivalent Dose=45 mSv/h

This make us confident in being reliable in source term estimation by MC

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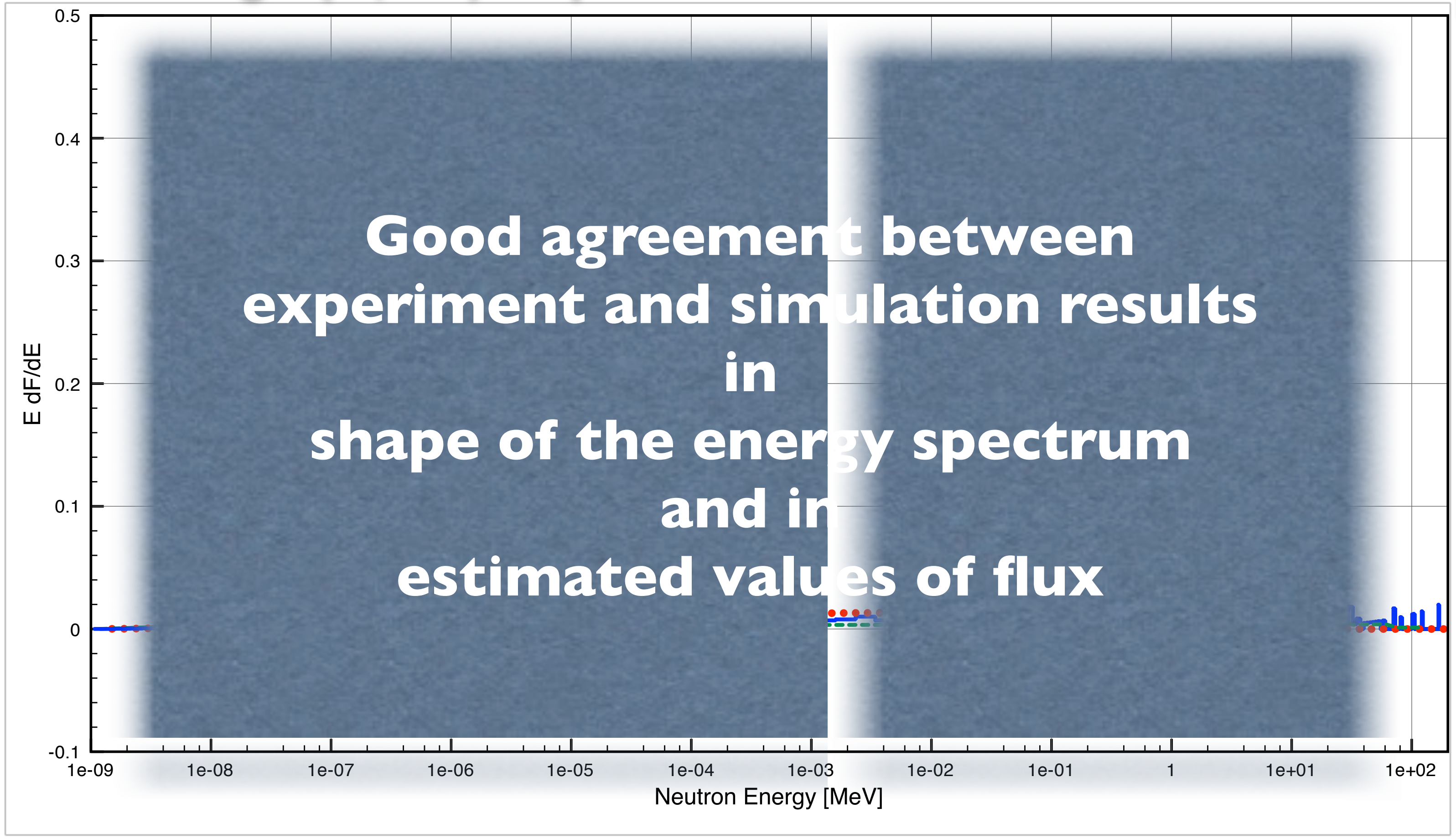

Good agreement between experiment and simulation results in shape of the energy spectrum and in estimated values of flux

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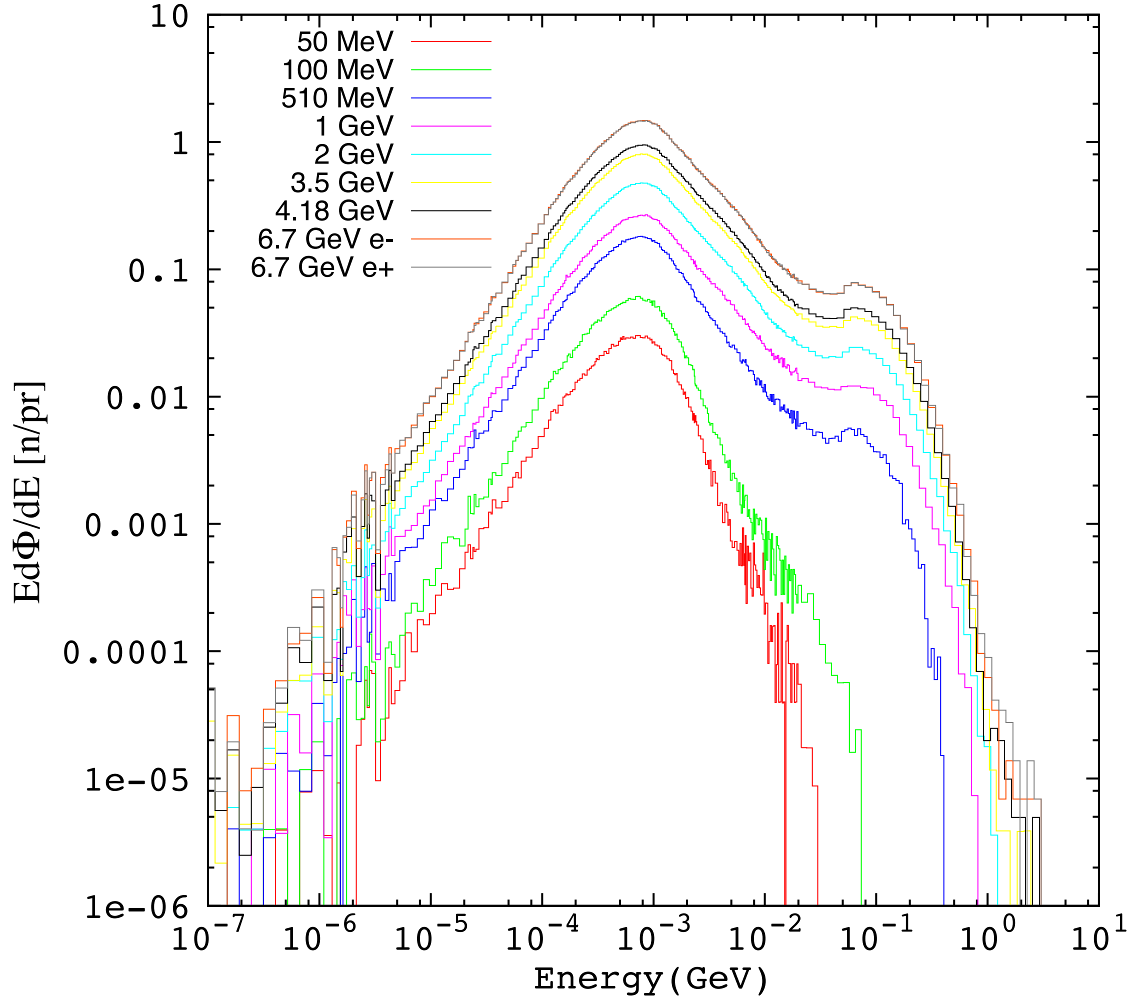
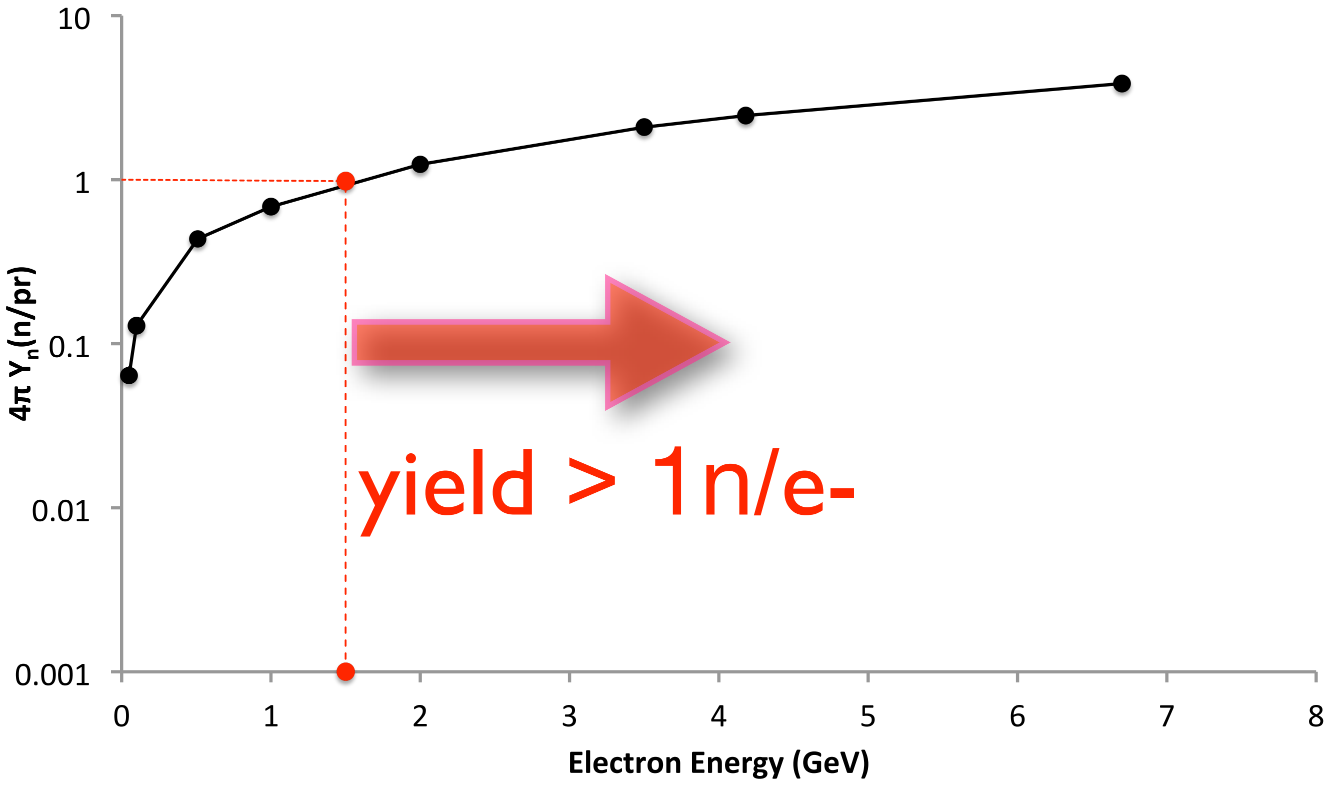
IRIDE

THE NEUTRON SOURCE

PRIMARY ELECTRON ENERGY RANGE:
1-3 GEV

Neutron source vs primary electron energy: some preliminary predictions for the W case





yield > 1n/e-

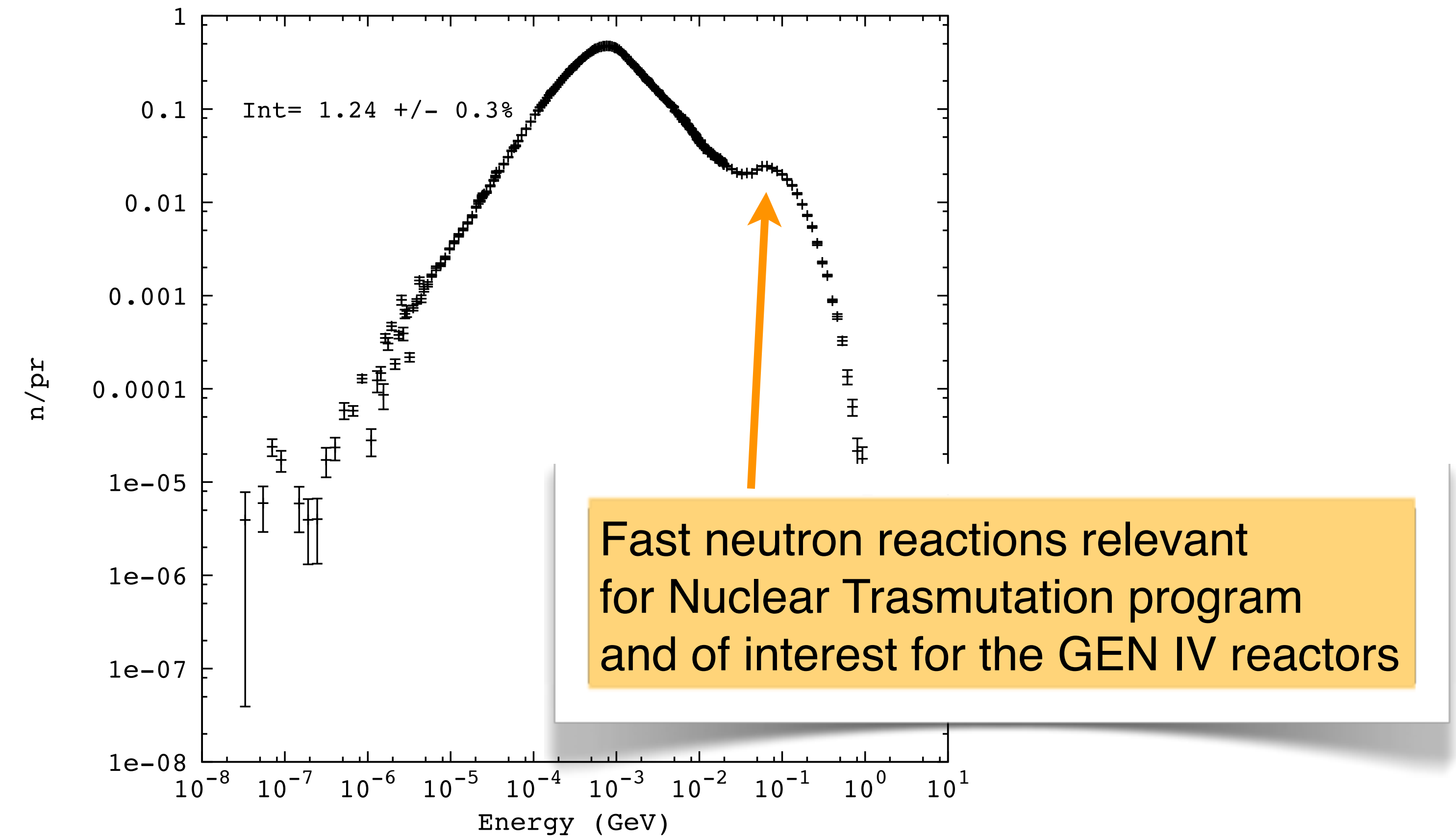
Energy (GeV)	1
n_{tot}/e^-	0.68 ± 0.57%
$\frac{1}{n_{tot}}\int_{10MeV}^{\infty}\Phi(E)\,dE$ [%]	6
$\frac{1}{n_{tot}}\int_{20MeV}^{\infty}\Phi(E)\,dE$ [%]	4
$\frac{1}{n_{tot}}\int_{100MeV}^{\infty}\Phi(E)\,dE$ [%]	1

Increasing the energy of the primary electrons above 500 MeV, the contribution of the neutrons produced in the upper part of the continuous spectrum becomes no more negligible, even if it is still much lower respect to the one coming from the Giant Dipole Resonance.

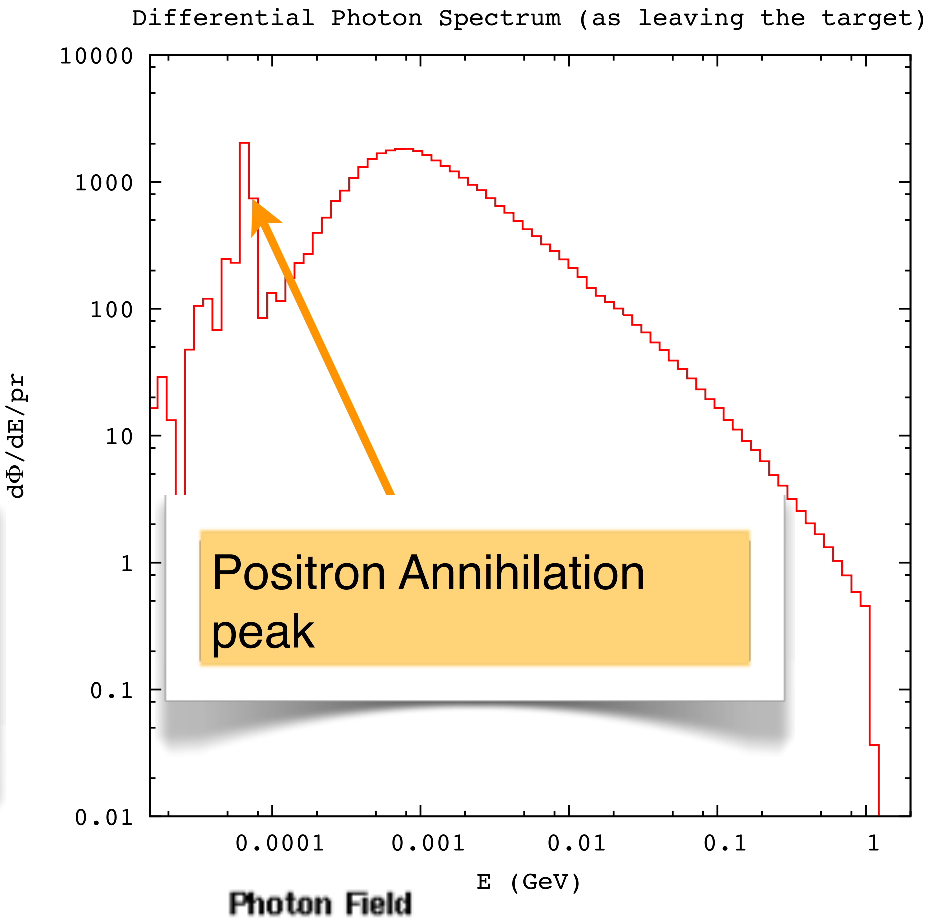
We have estimated that the percentage of neutrons above 20 MeV is a factor 4 higher for 1 GeV electrons than for 100 MeV electrons.

Fluka Estimation accuracy < 1%

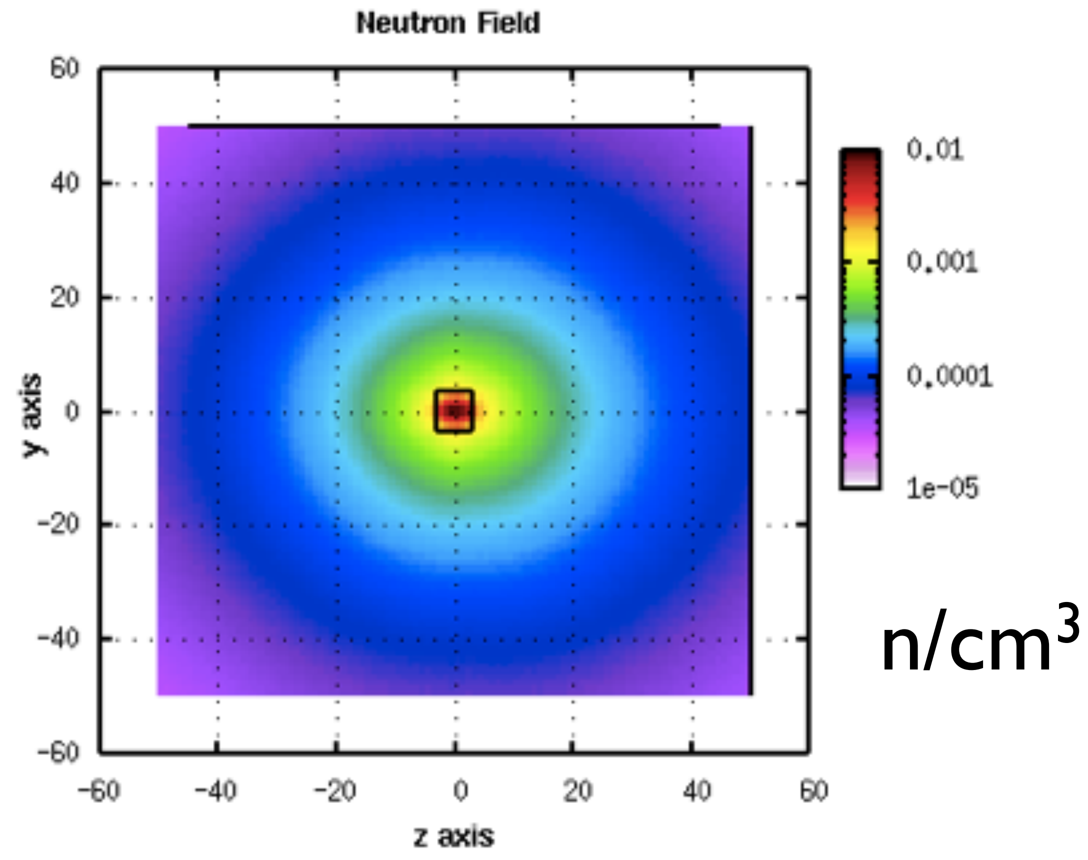
Neutrons and Gammas produced in the target for 2 GeV electrons

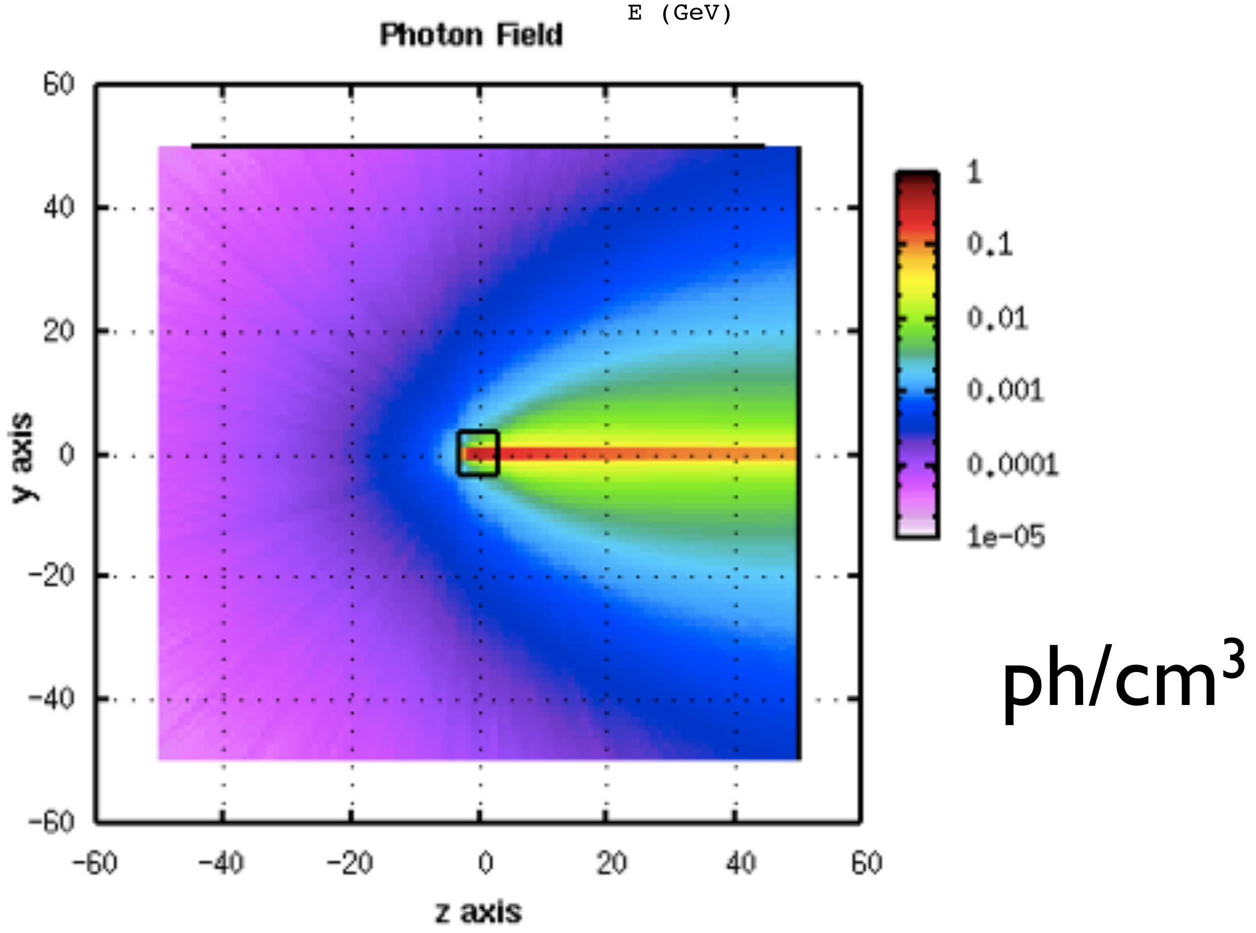


Fast neutron reactions relevant for Nuclear Trasmutation program and of interest for the GEN IV reactors



Positron Annihilation peak

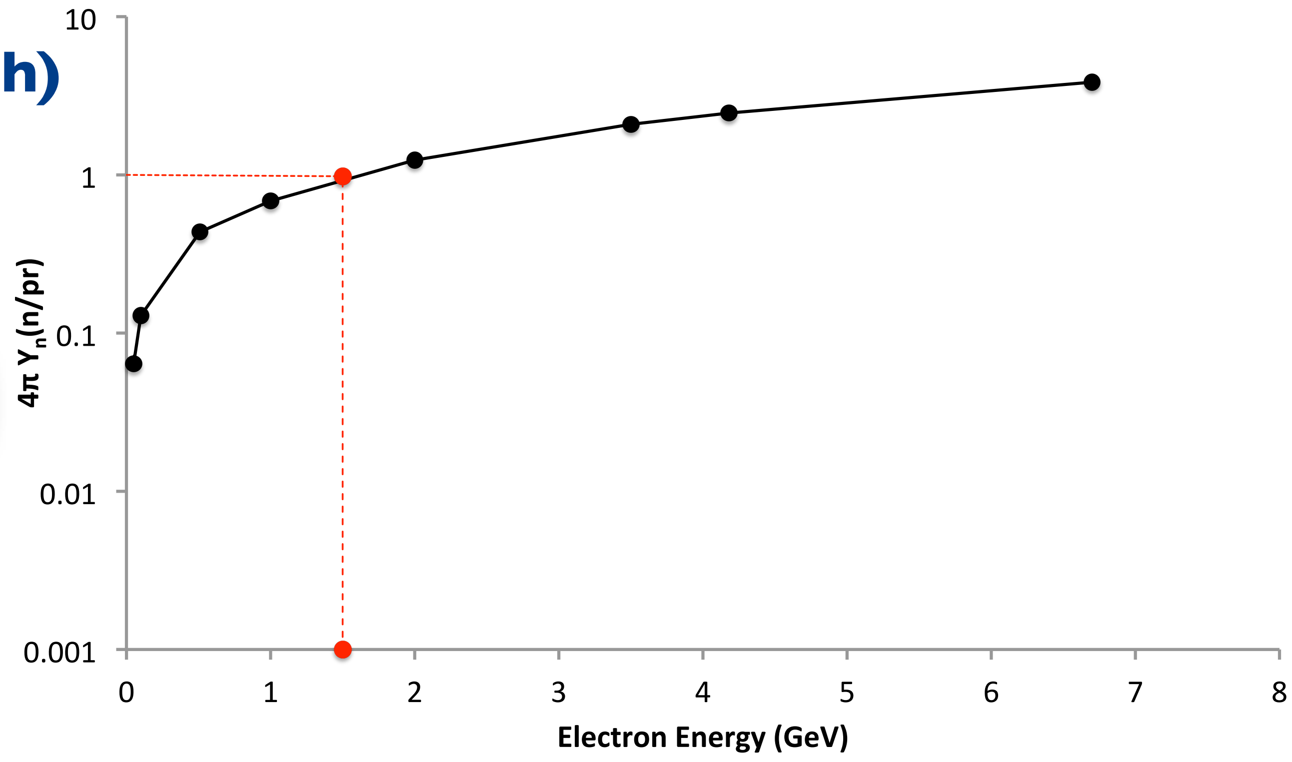




IRIDE neutron source:
expected neutron rate for the opt. W target and 2GeV e-

Calculation of the total yields (Source Strength)

Electron Energy (GeV)	Neutron Yield (n/pr)
2	1.2



Hypo: 250 KW deposited on target

assuming almost all the primary electron energy is deposited on the target

This corresponds to a mean electron current of about 8E+14 e-/s → I(avg)=0.13 mA

Expected Emission Rate @ 250 KW → Yield=9E+14 n/s

current of neutrons leaving the target

W target: the expected emission rates vs the deposited power

Deposited Power (kW)	Primary Electron Energy (GeV)	Expected Average Emission Rate
30	1	1.30E+14
250	1	1.00E+15
400	1	1.70E+15
30	3	4.30E+13
250	3	3.30E+14
400	3	5.60E+14

At energies above 1 GeV and for a given thick target (i.e, able to enclose the whole electromagnetic cascade), **the neutron production rate depends exclusively on the electron rate**, i.e. to the ratio between power and electron energy,. This because the yield per primary goes toward saturation

IRIDE VERSUS OTHER FACILITIES:

“QUANTITATIVE” COMPARISON OF THE SOURCE STRENGTH

AND

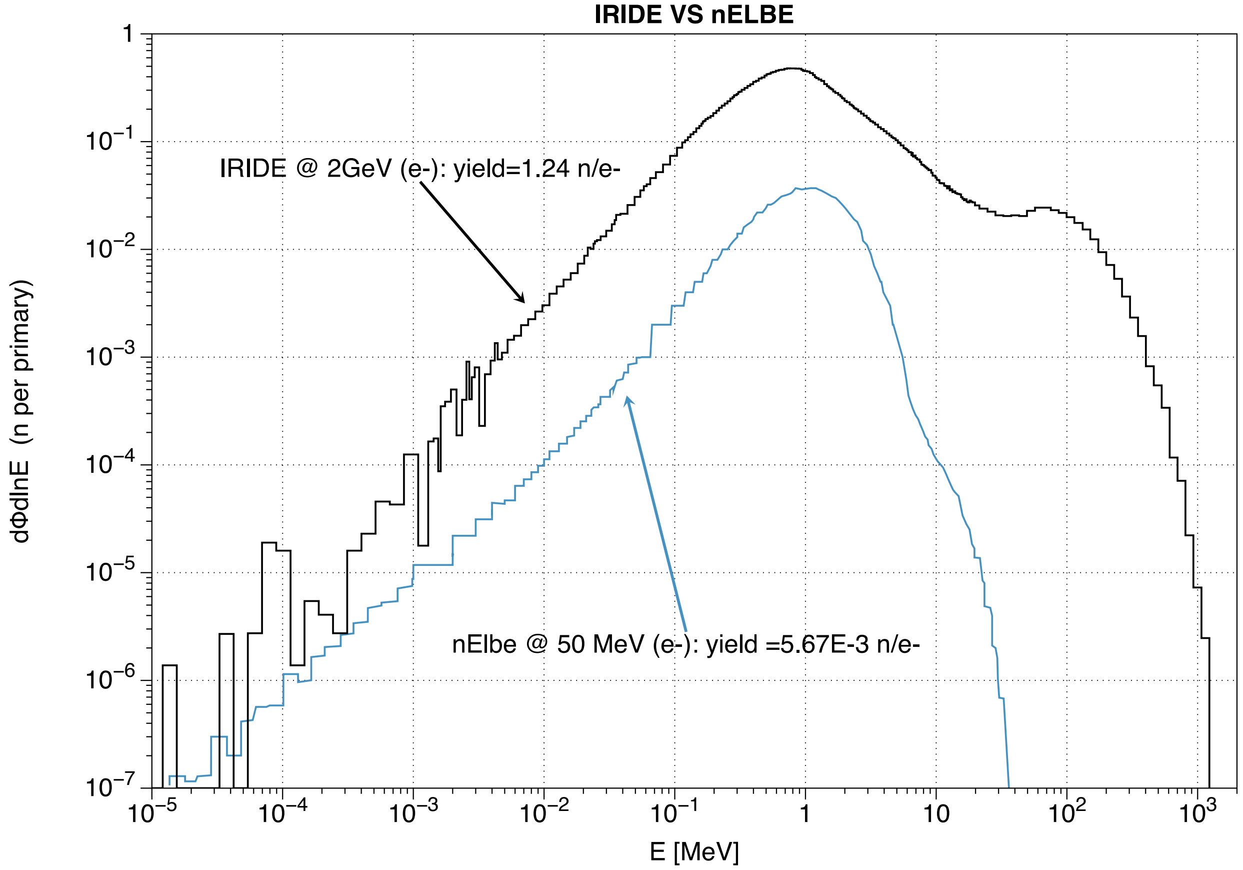
“QUALITATIVE” COMPARISON FOR THE ENERGY SPECTRUM

Source Strength Comparison:
Iride vs some other accelerator driven neutron facilities

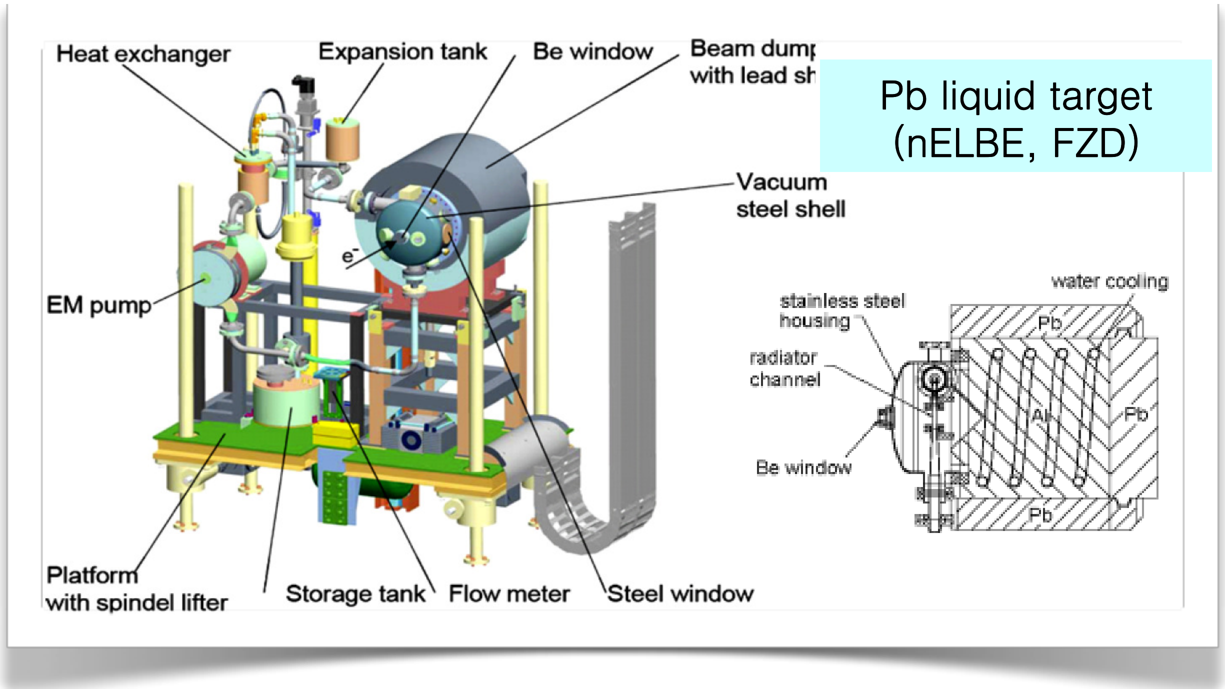
Facility Parameters	**nElbe***	**Gelina****	**nToF**	**ISIS**	**IRIDE**
Source	SC e- Linac	e-Linac	p spallation	p spallation	SCe- Linac
Part E (MeV)	40	120	20000	800	2000
Max Power (kW)	18	11	45	160	250 (30)
Neutron/s ***	3.40E+13	3.20E+13	8.10E+14	1.00E+16	9.4E+14(1.1E+14)
Flight Path (m)	4	8-400	185	60	?
Pulse width (n)	<0.4	1-2000	7	300	?
Rep Rate (Hz)		up to 900	0.278-0.42		?
Best Intrinsic Resolution (ns/m)		0.0025	0.034		?

** see next talk of Anna Ferrari ** talk given by Jan Heyse *****Estimated**

Iride vs nElbe: source term comparison

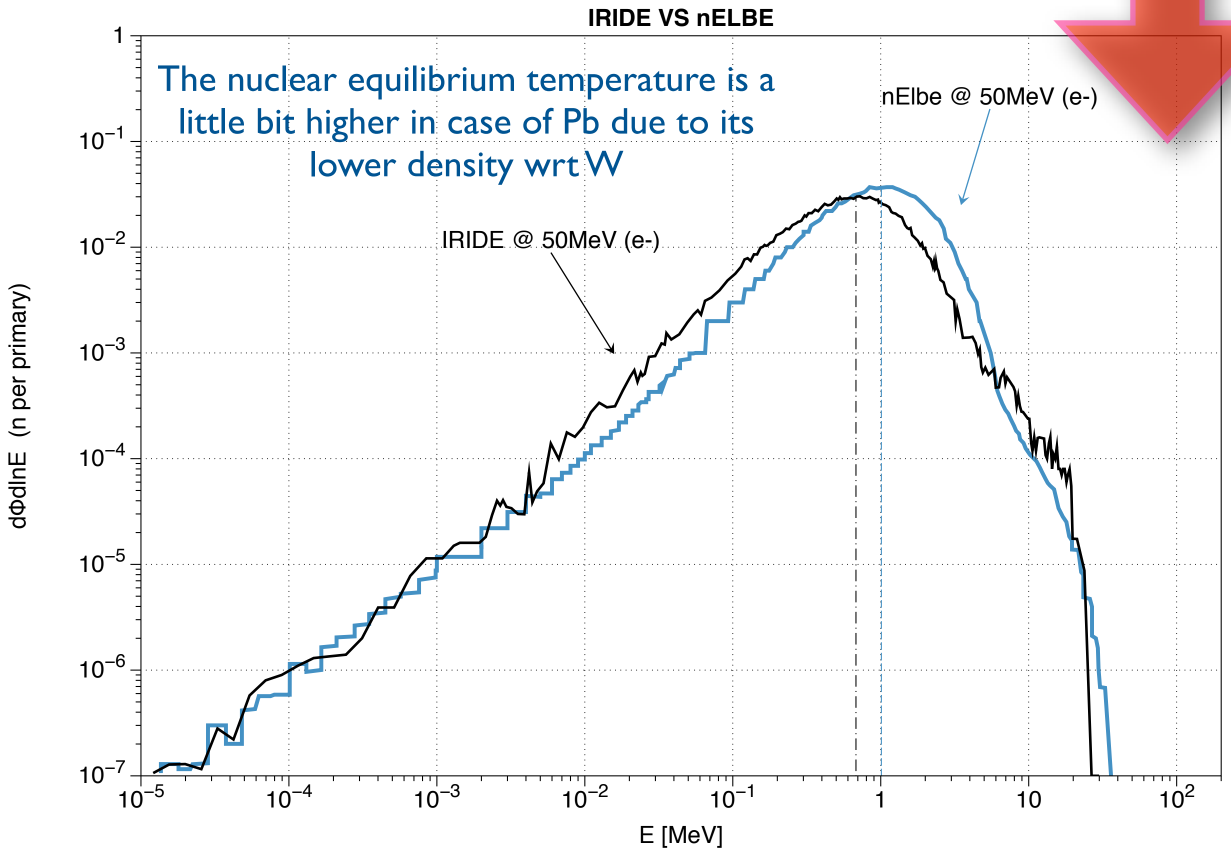


nELBE:
SC Linac;
30-40 MeV electrons on liquid Pb
Avg Current:1 mA (18 kW)



Pb liquid target
(nELBE, FZD)

benchmark case:
IRIDE and nELBE with e- @50 MeV--



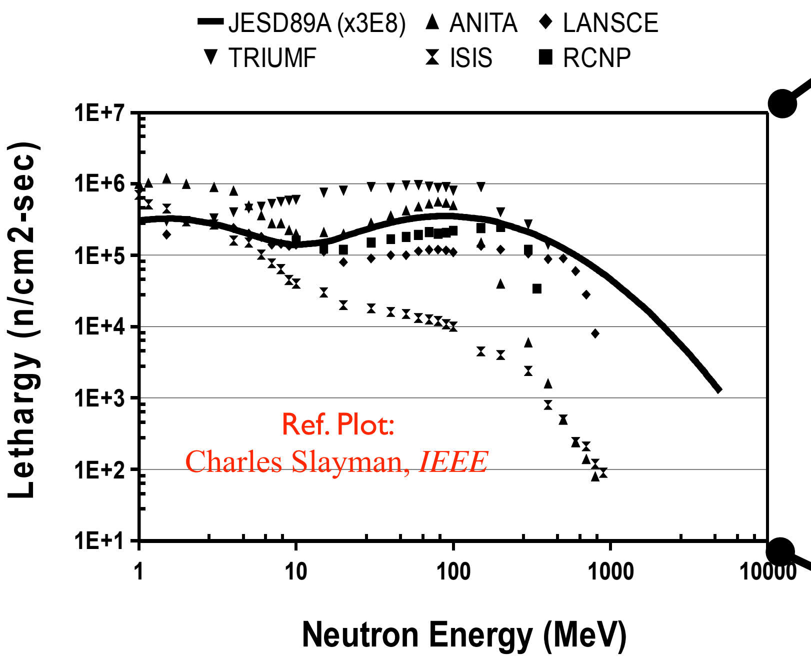
The nuclear equilibrium temperature is a little bit higher in case of Pb due to its lower density wrt W

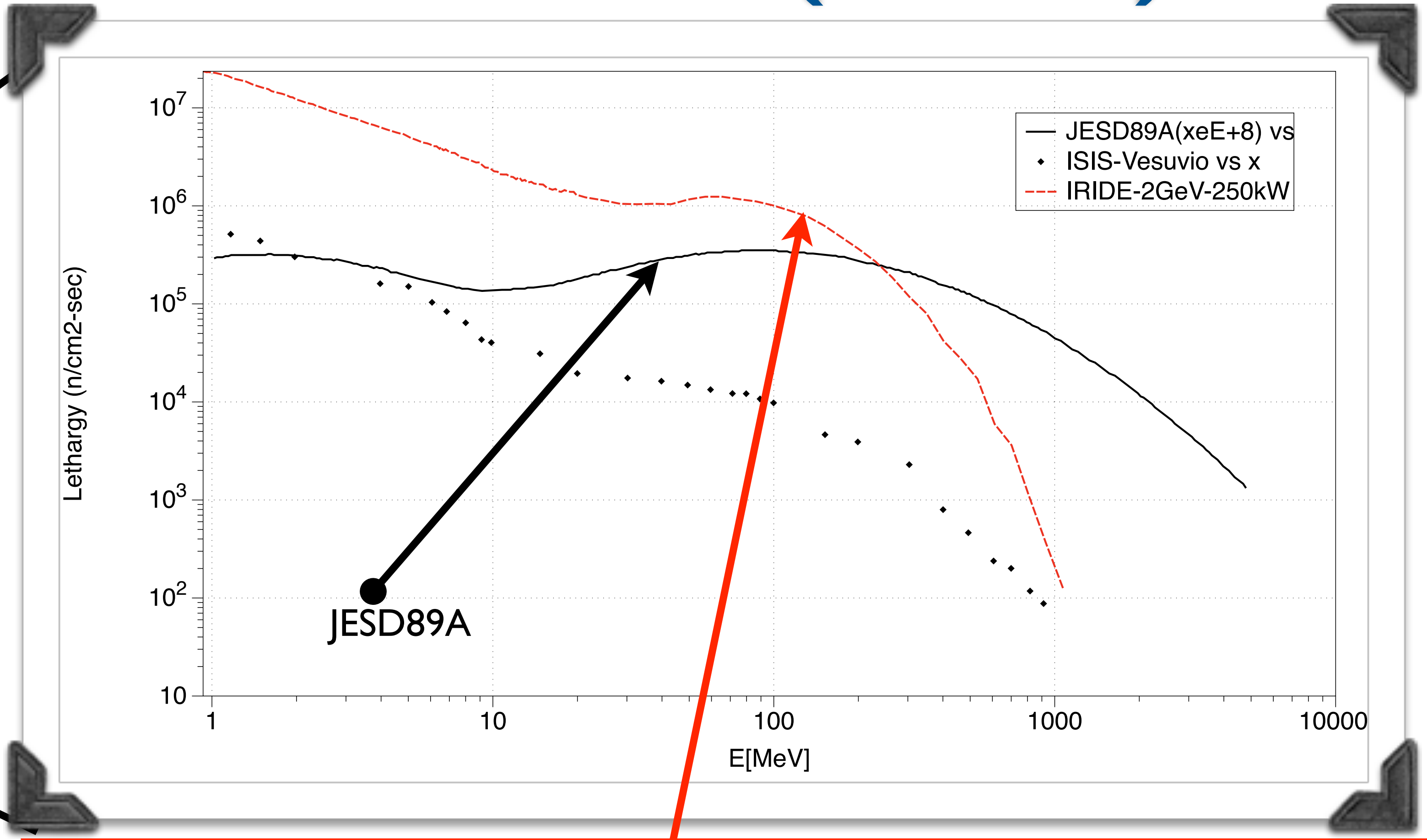
Neutron Yield [n/e-]

FACILITY	Ee-(MeV)	Yield (n/e-)
Iride	2000	1.2
nElbe	40	5.67E-03

Iride and terrestrial Cosmic Ray Spectrum: indirect comparison with ISIS source (Vesuvio)

Lethargy plot of high energy terrestrial neutron spectrum





JESD89A is the most broudly referenced standard for accelerated neutron soft error testing

IRIDE:
A suitable extraction line could be designed to extract the high energy spectrum that seems to be promising to replicate the terrestrial neutron spectrum above 1 MeV

Cosmic Ray high energy spestrum

Several facilities throughout the world offer high energy broad spectrum neutron sources for accelerated soft error testing, but none accurately replicate the terrestrial neutron spectrum across the range of 1MeV to 1GeV.

The spectrum for IRIDE has been estimated at 11.055 m from the source ($\Phi = S/4*\Pi*R^2$)
(the same distance of VESUVIO from the target in ISIS)

The VESUVIO beam line at the ISIS spallation neutron source was set up for neutron irradiation tests in the neutron energy range above 10 MeV.
REF. APPLIED PHYSICS LETTERS 92, 2008, C.Andreani A. Pietroaolo et al.

Vesuvio beamline at ISIS (800 MeV proton on heavy metal target). It is designed for termal neutron scattering measurements in condensed matter and the beam is heavily moderated by water.

IRIDE:
NOT ONLY NEUTRONS

The optimized target could be composed of different nested materials, depending on the particles we are interested in extracting:
this means a “high Z” core and a “medium Z” external blanket to lower the coloumbian barrier for charged particles

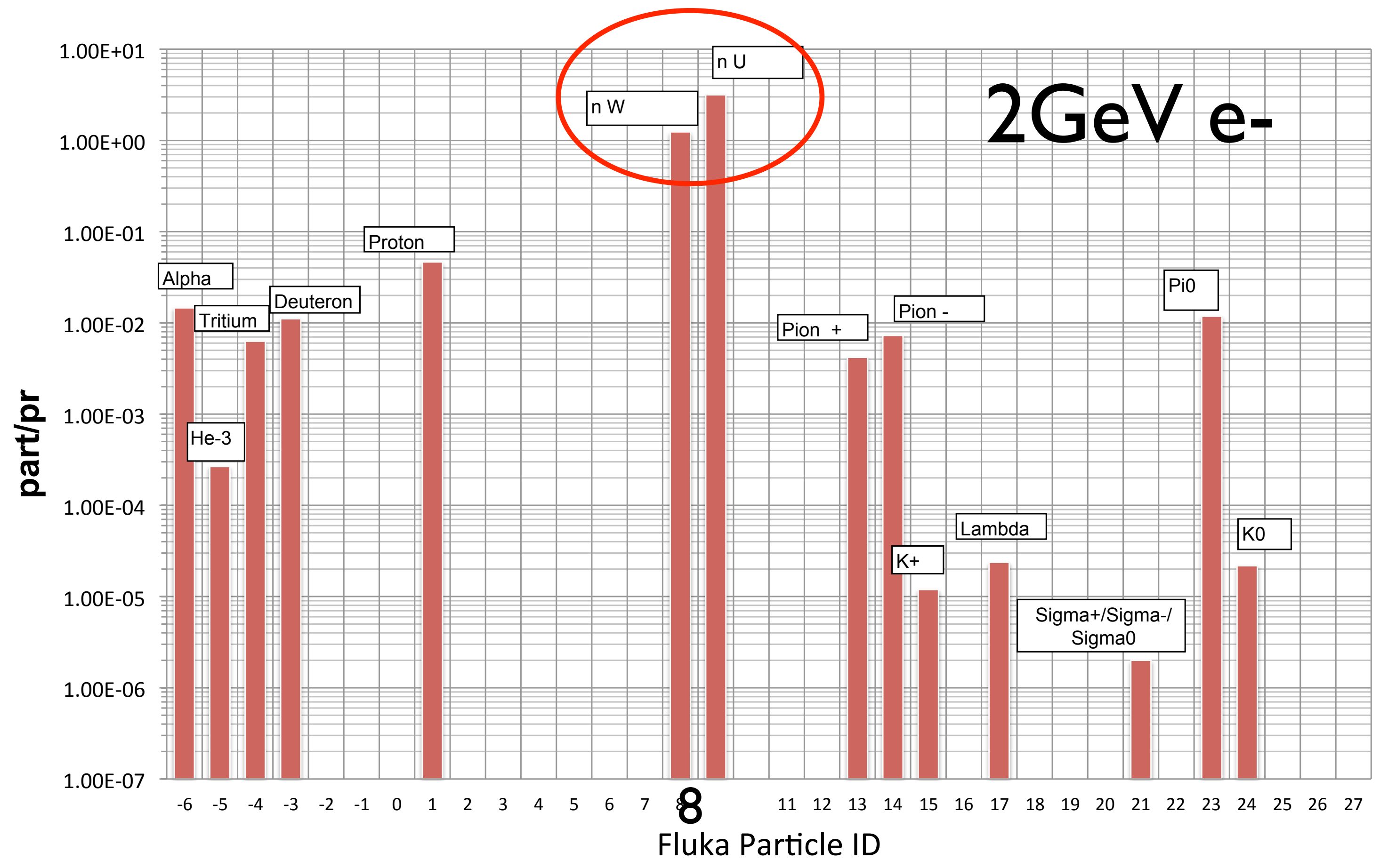
Emanuele Ripiccini
(phD student of G. Cavoto, Univ Sapienza, Rome):
studying the possibility to optimize the target to produce muons
(Geant4)

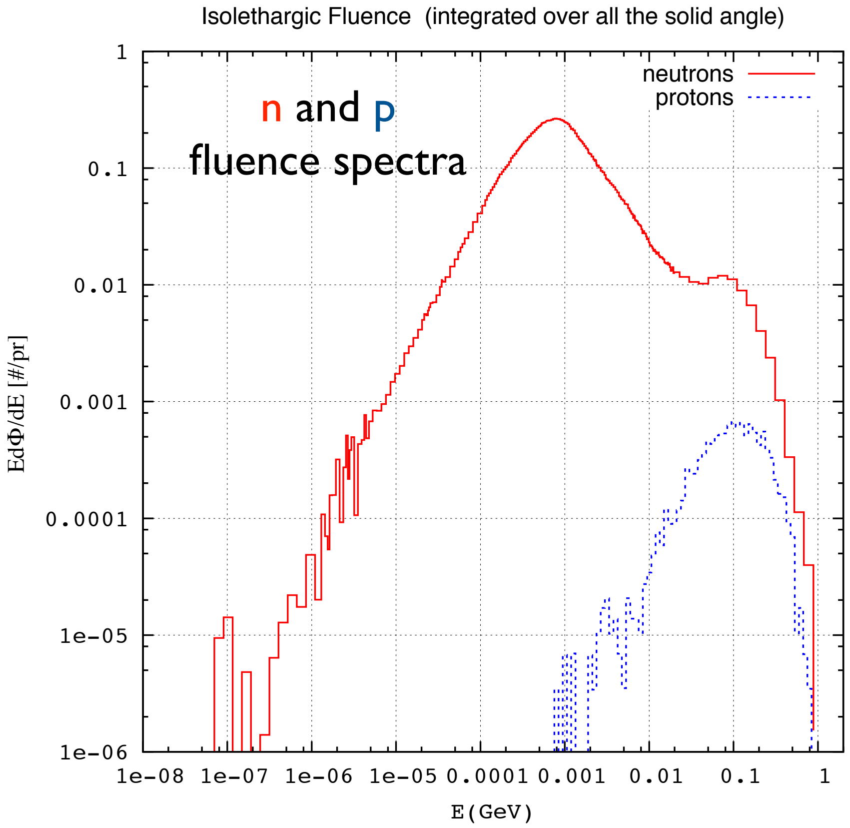
Carlo Mancini Terracciano
(phD student of R.Faccini. Univ Sapienza, Rome):
studying the possibility to optimize the target to produce protons
FLUKA

Secondary Particles from W target (2 GeV electrons)

photoproduction:

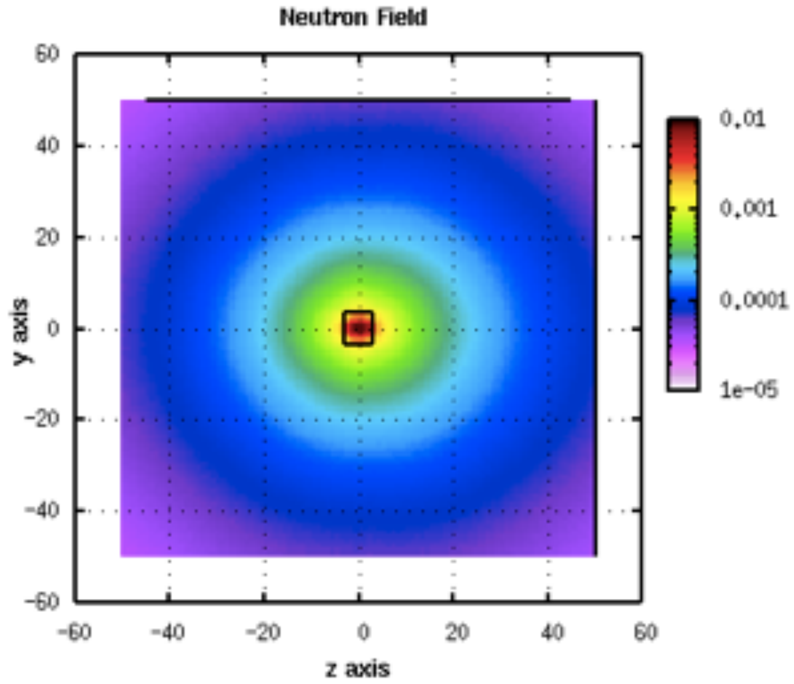
n_yield in U target (same dimensions of W target) is almost **a factor 3 (3.68/1.2)** larger than in W,



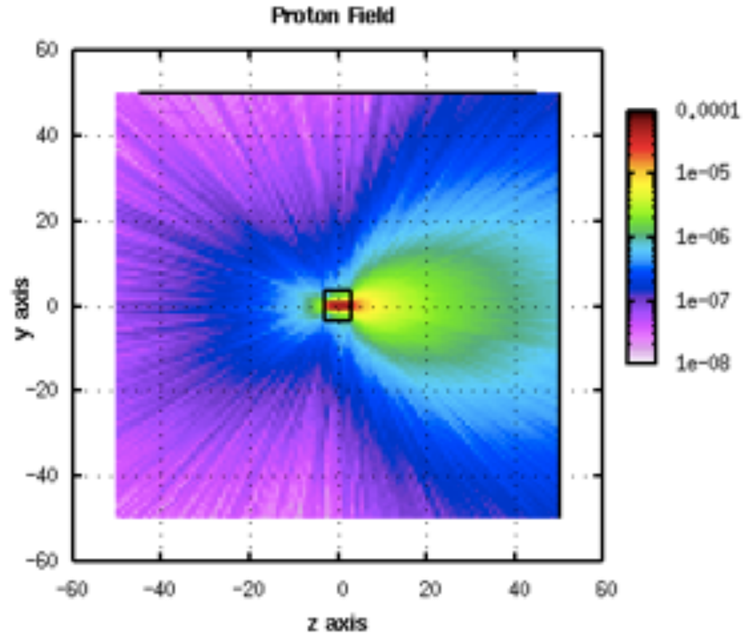


proton(e-1GeV)	1.30E-03

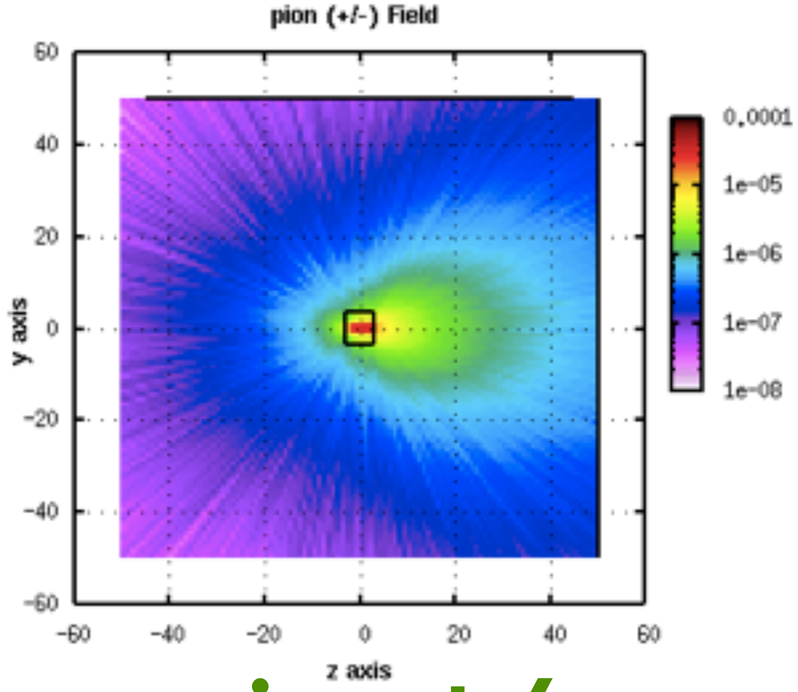
pion+/- (e-1GeV)	5.45E-04/8.48E-4



neutron



proton

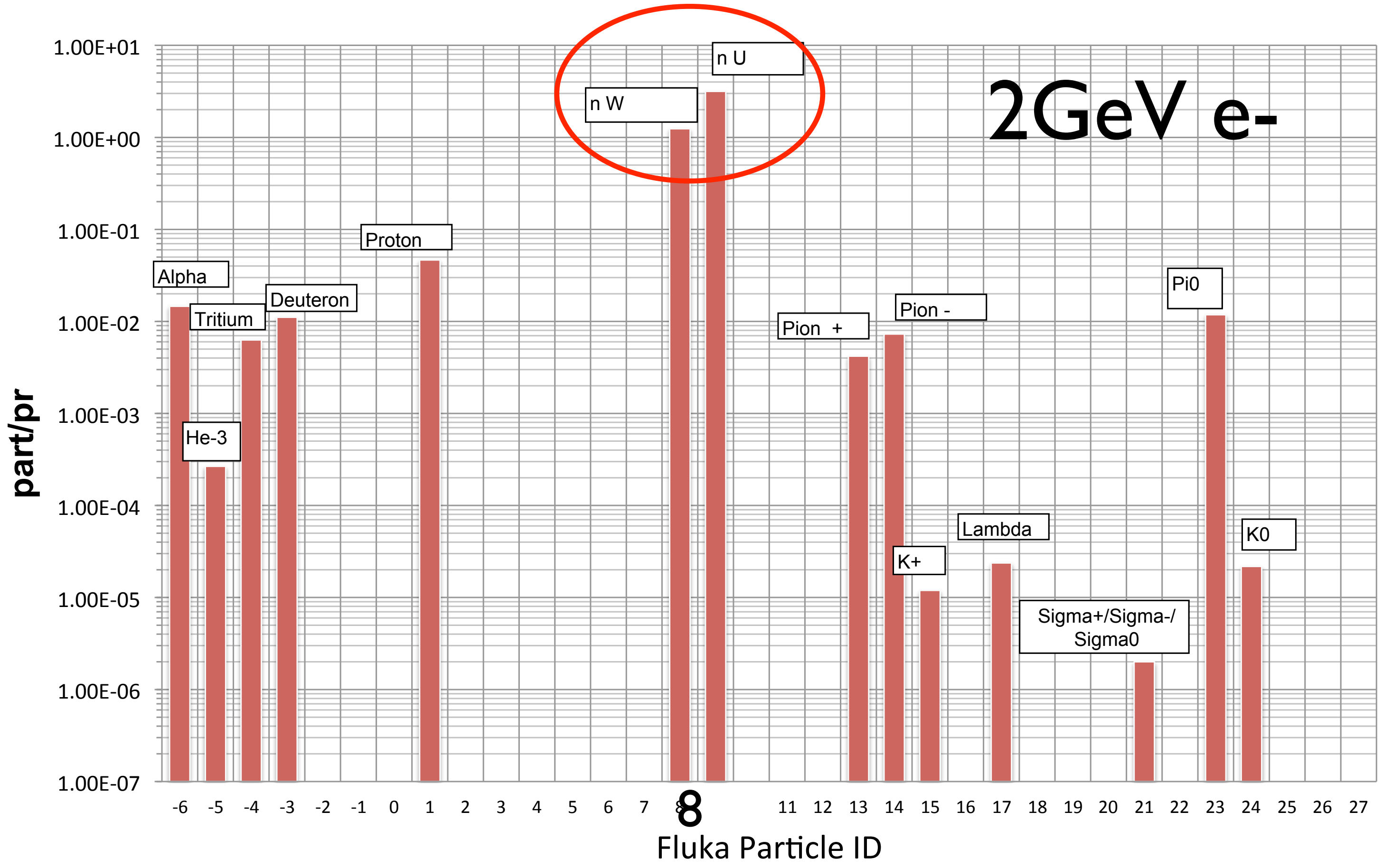


pion+/-

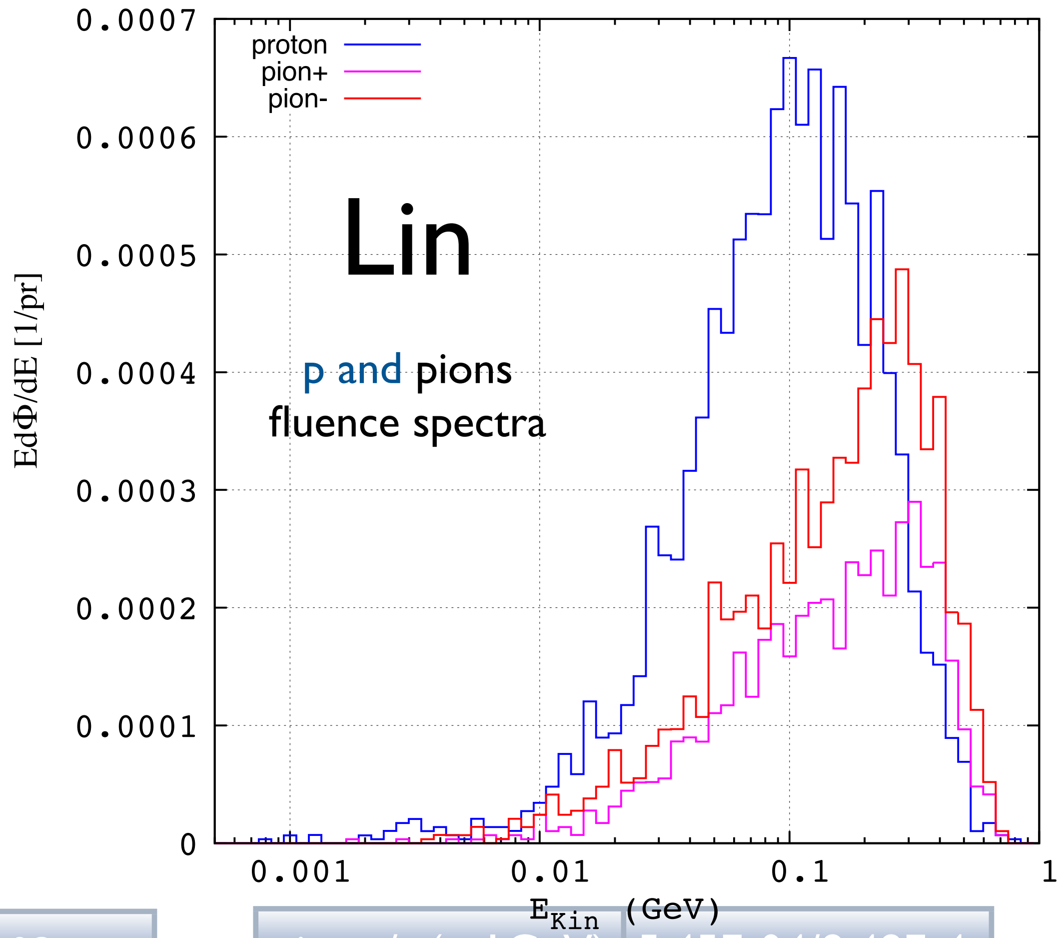
Secondary Particles from W target (2 GeV electrons)

photoproduction:

n_yield in U target (same dimensions of W target) is almost **a factor 3 (3.68/1.2)** larger than in W,



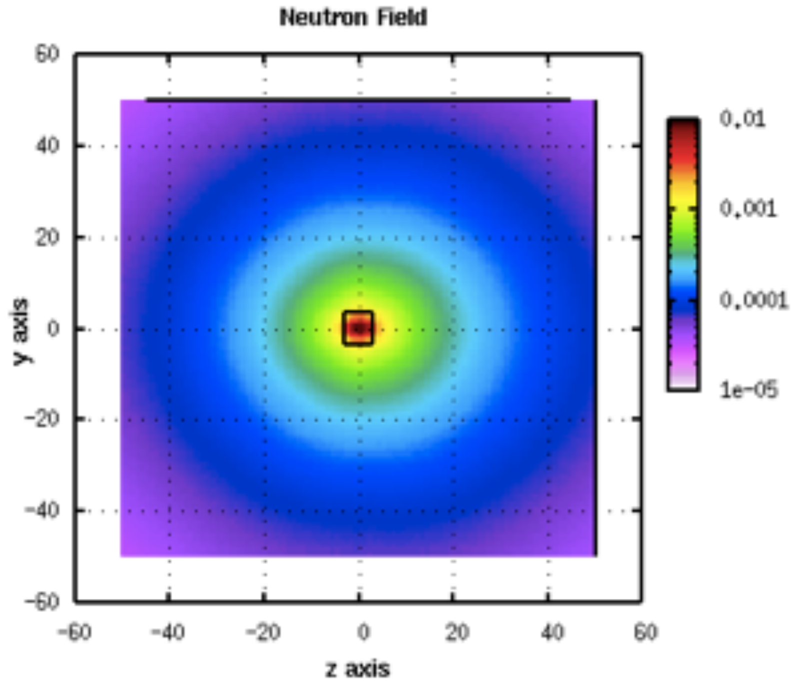
2GeV e-



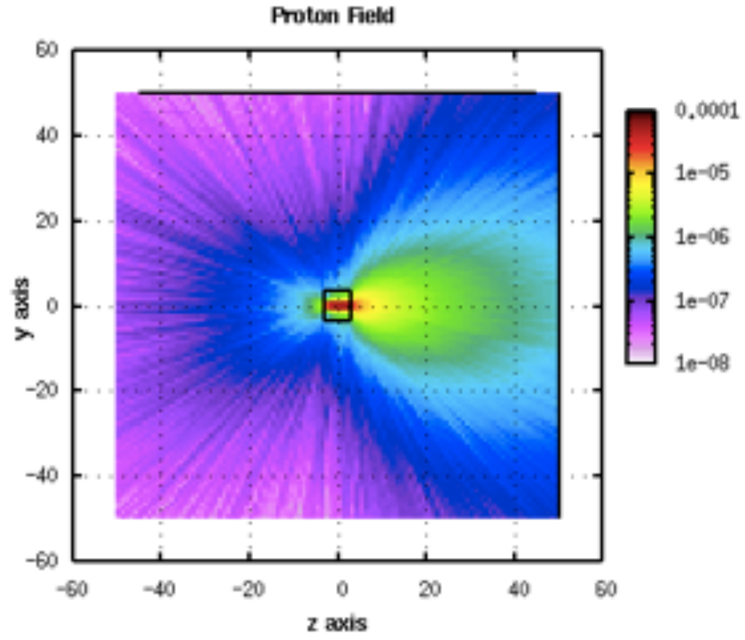
Lin

p and pions fluence spectra

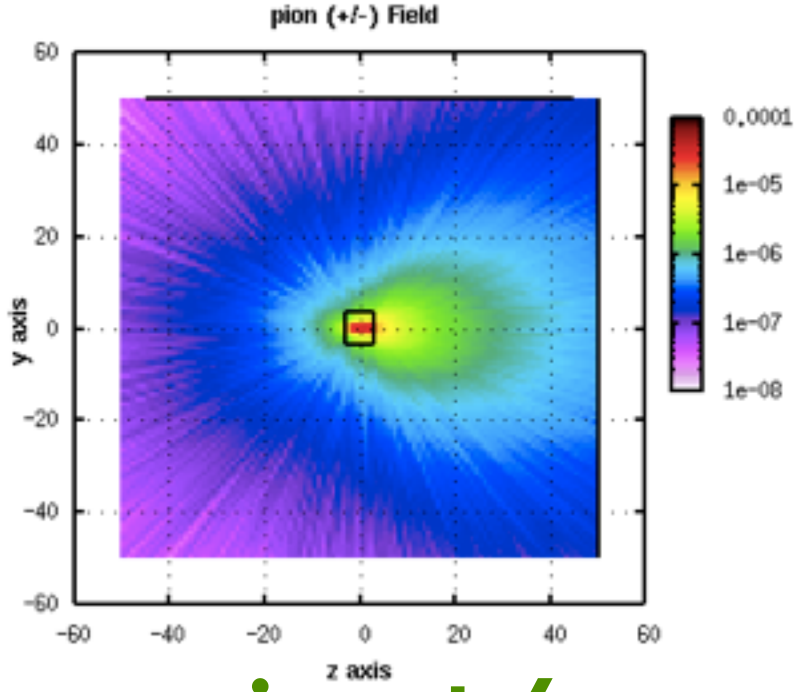
proton(e-1GeV)	1.30E-03
pion+/- (e-1GeV)	5.45E-04/8.48E-4



neutron



proton



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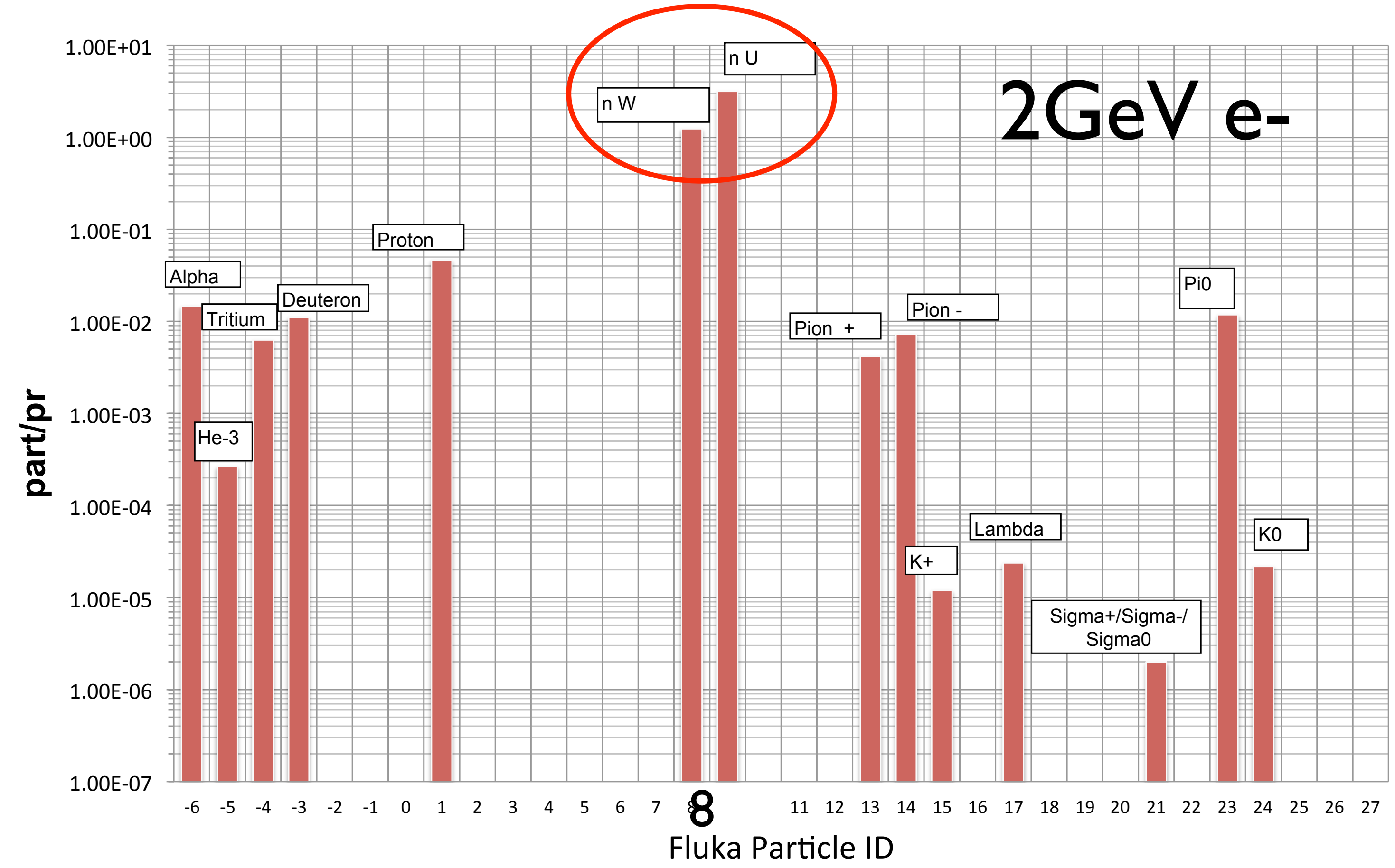

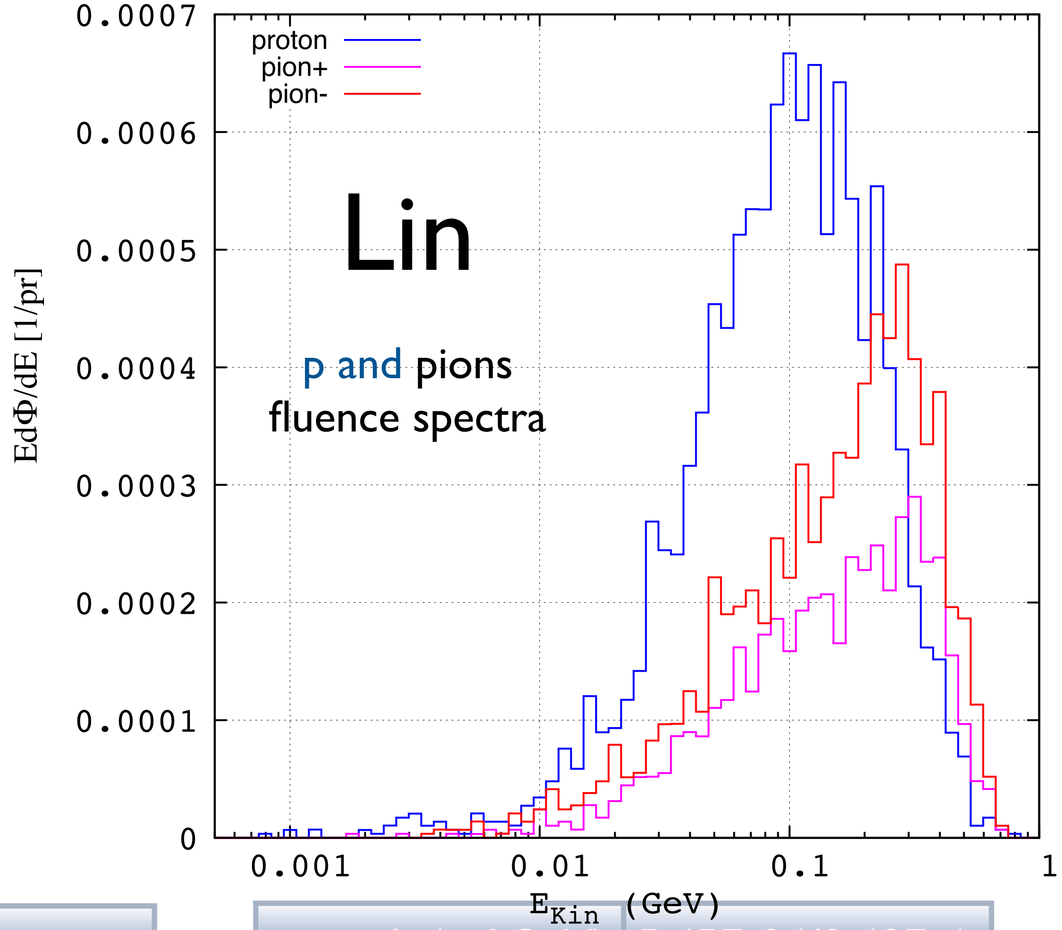

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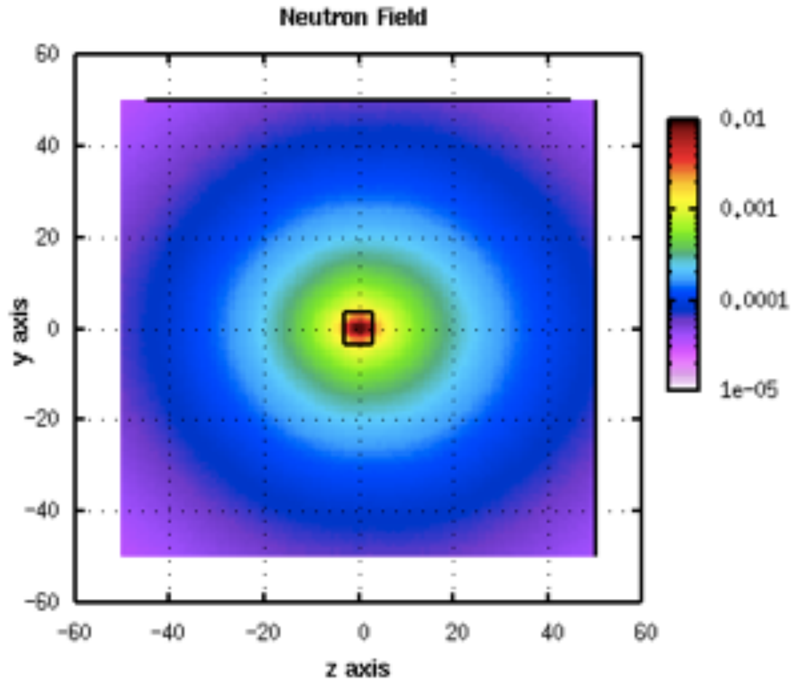
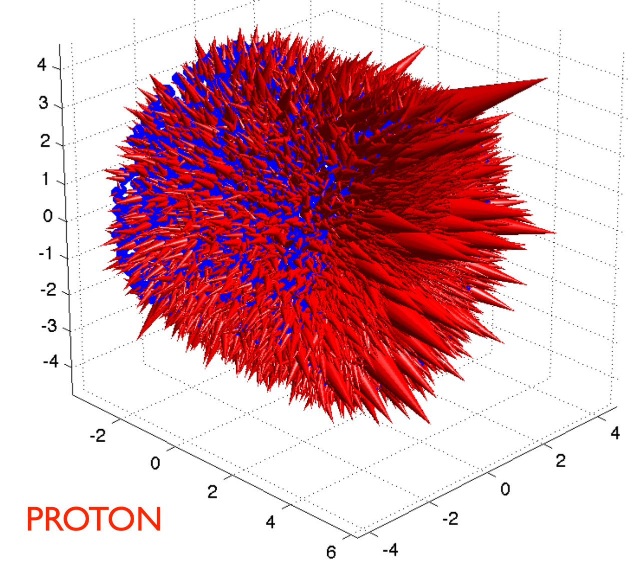
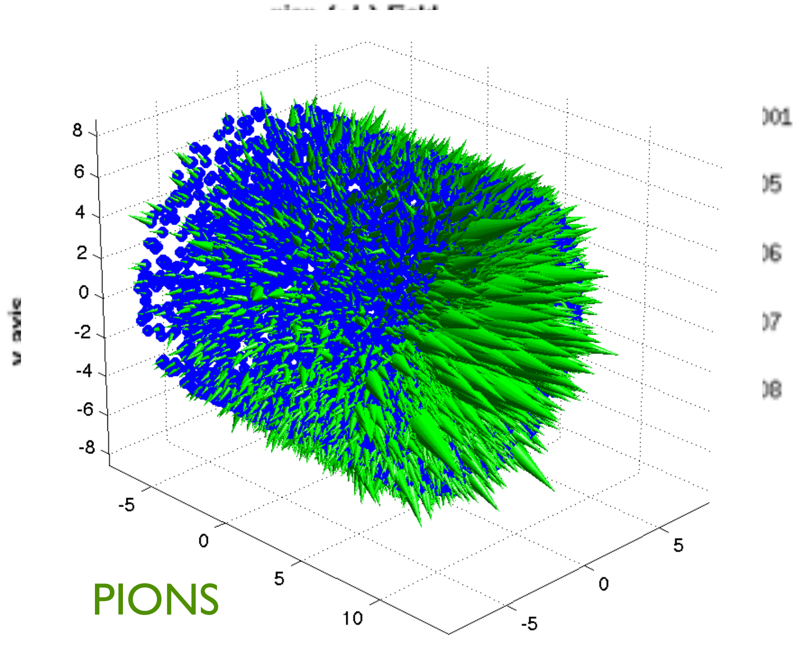


The higher momentum protons are escaping mainly from the forward flat surface



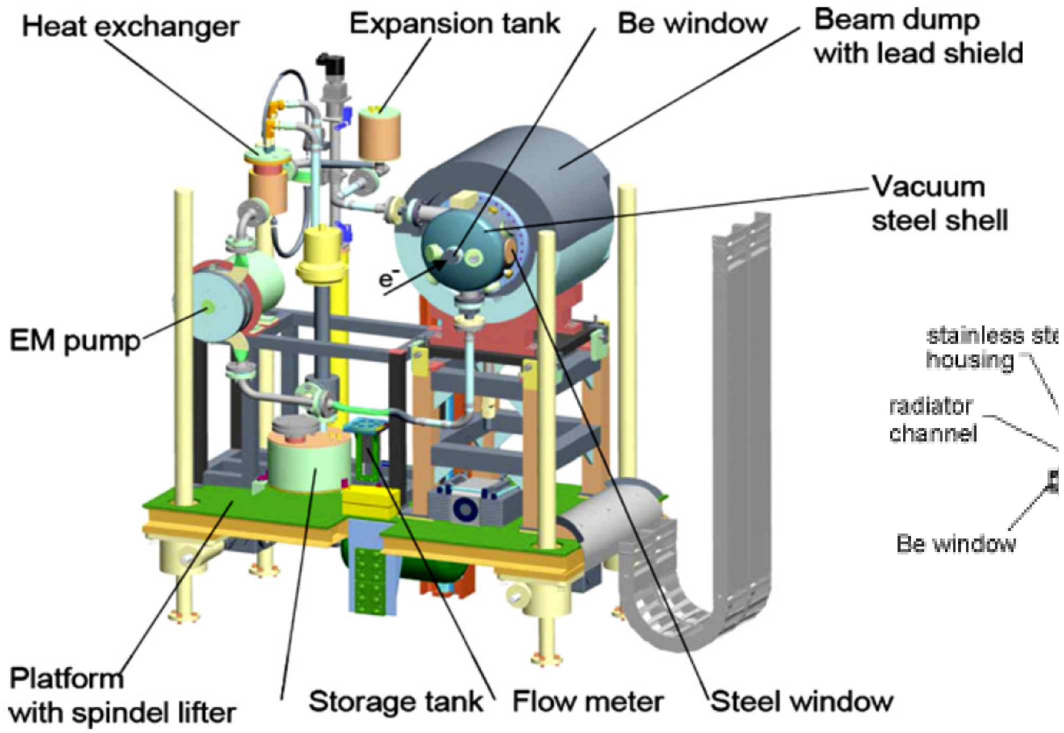


neutron **proton** **pion+/-**

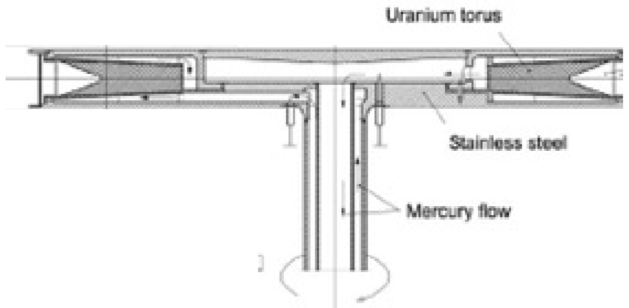
THE THERMAL PROBLEM FOR SOLID ELECTRON DUMP

Mechanical Design Service
(servizio di Progettazione meccanica)
(Univ. Sapienza, Rome):
thermo-mechanical design of the the target:
support/cooling

Targets of Accelerator driven Neutron sources

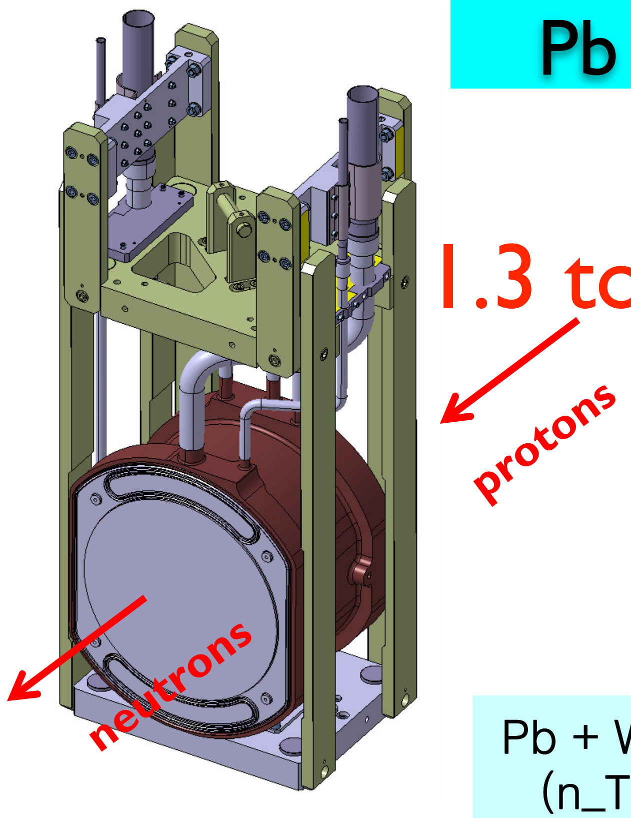


nElbe
Pb liquid target



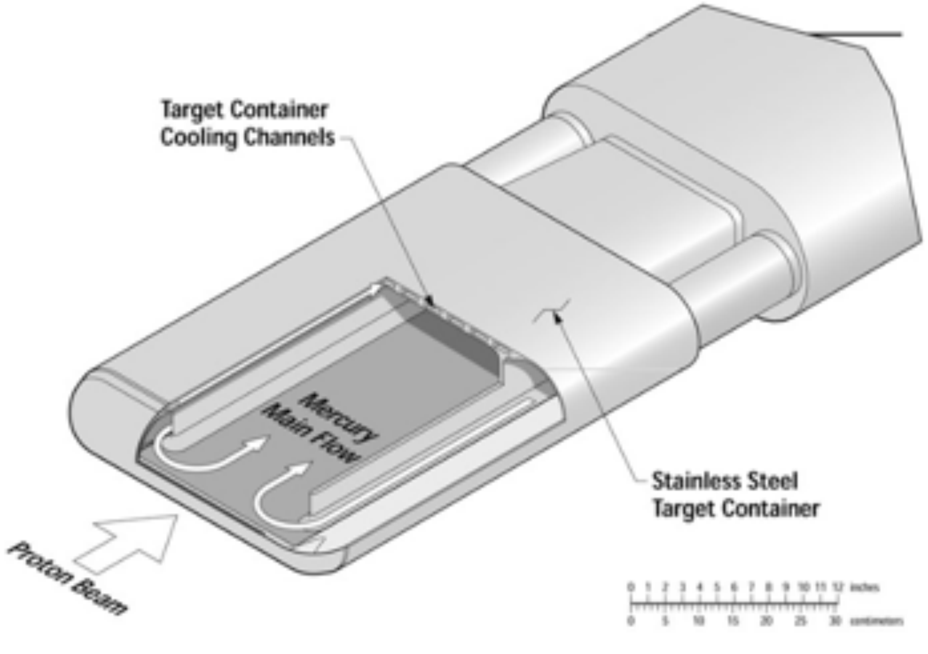
Outer diameter of U disk=31.4 cm
Inner diamter =17.6 cm

U + Hg cooling
(GELINA, IRMM)



1.3 tonne Pb cylindical
L=40 cm
R=20 cm

Pb + Water cooling
(n_TOF, CERN)



30cm

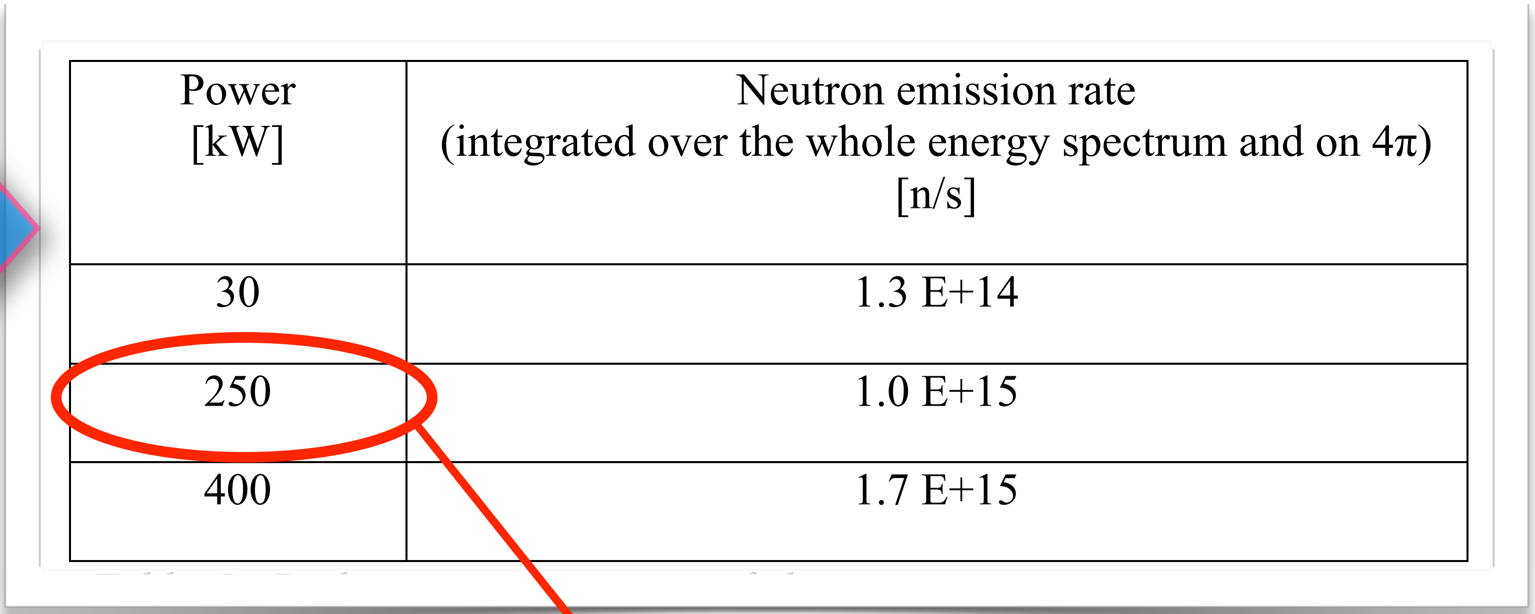
SNS
Mercury target

Target optimisation criteria

- Maximize the neutron yield with respect to the electron beam characteristics: choose the best material and geometry (es. Uranium target !!!!!)
- Minimize the photon/neutron ratio
- Minimize the activation of the target and cooling system
- Keep the maximum temperature below a safe limit with respect to the melting (and other mechanical problems such as corrosion ..)
- Use a cooling system solution that preserves the emission rate and does not affect the neutron energy spectrum
- Minimize the mechanics and apparata all around the target (suitable support, displacement controller, etc..)

What about the need of cooling the IRIDE target: preliminar analytical estimation on W

Preliminary estimation of the maximum neutron emission rate that can be obtained with a W thick target
(DaΦne BTF likle)
with 1 GeV electrons as a function of the energy deposited in the target



Power [kW]	Neutron emission rate (integrated over the whole energy spectrum and on 4π) [n/s]
30	1.3 E+14
250	1.0 E+15
400	1.7 E+15

Stationary Solution under the assumptions:

- uniformly deposited trough the target
- T_0=300 K

$$T(r) - T_0 = \frac{q'''R^2}{4\lambda}\left(1 - \frac{r^2}{R^2}\right)$$

$$T_{\max} = \frac{q'''R^2}{4\lambda} + T_0$$

Pdep=250 kW

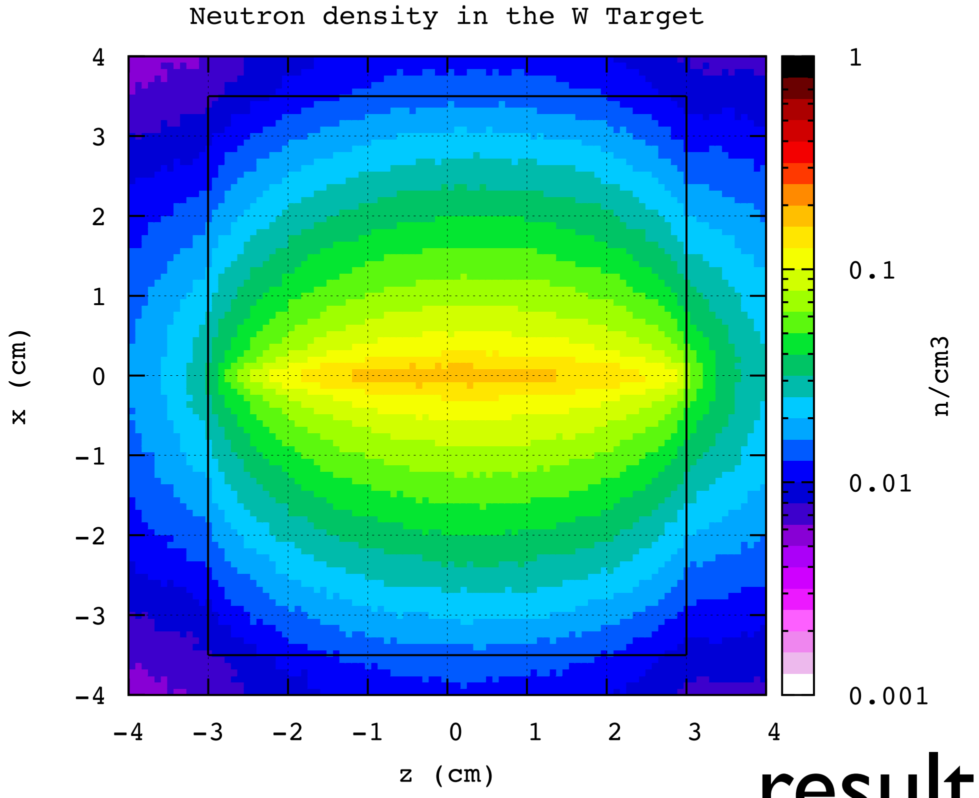
q'''=1.5E+9 W/m3 --->Tmax= 2500 K.

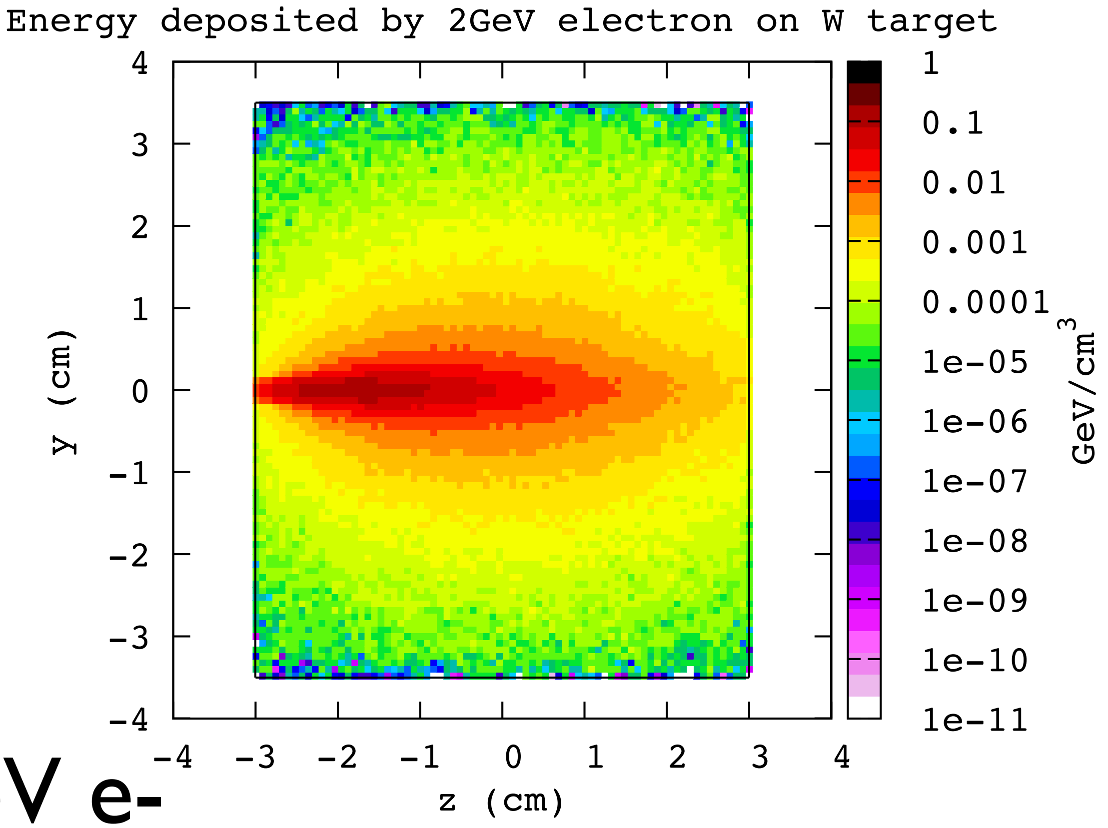
This value can double if we consider the energy deposited with a more realist beam spot size of 1.5 cm
In this cas the melting Temperature of the Tungsten (3700 K) can be exceeded

Finite element simulations for multi-physics Analysis (for example by the code Ansys): in order to **take into account** the **most severe duty cycle** by which the target is supposed to be irradiated (time shape of the electron beam) and **the real profile of the energy deposited in the target**

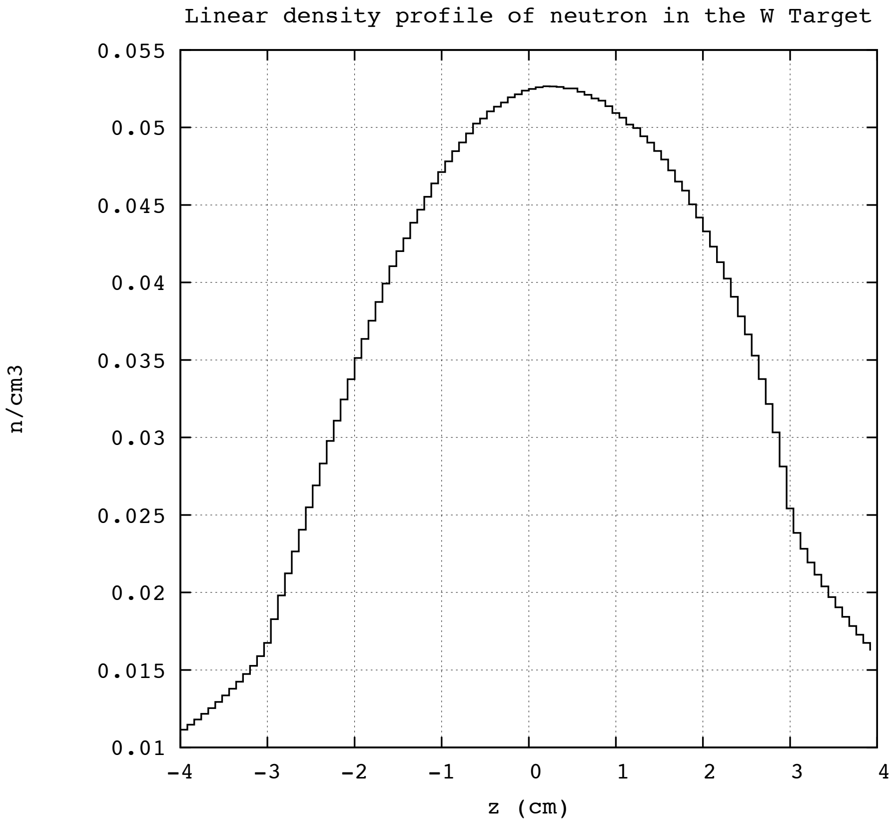
W target : energy and neutron density profile

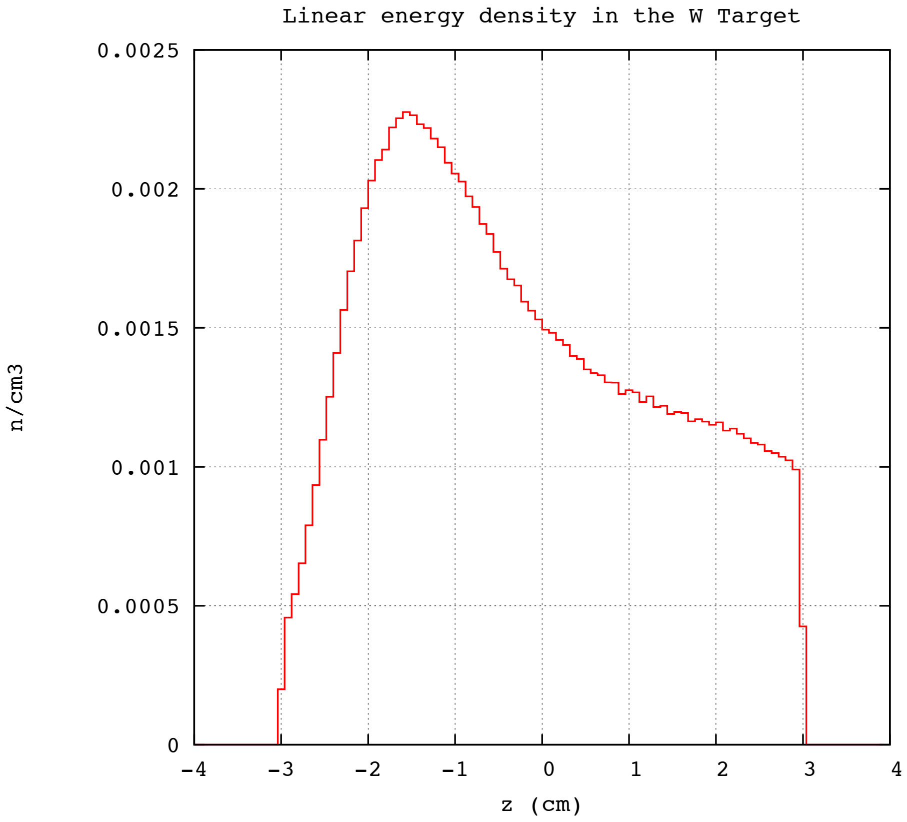
Even if the energy deposition profile has a peak in the first 2 cm from the inlet boundary the neutron density profile inside the target is quite well symmetric (as a proof of the well optimised target dimensions)


Neutron density in the W Target

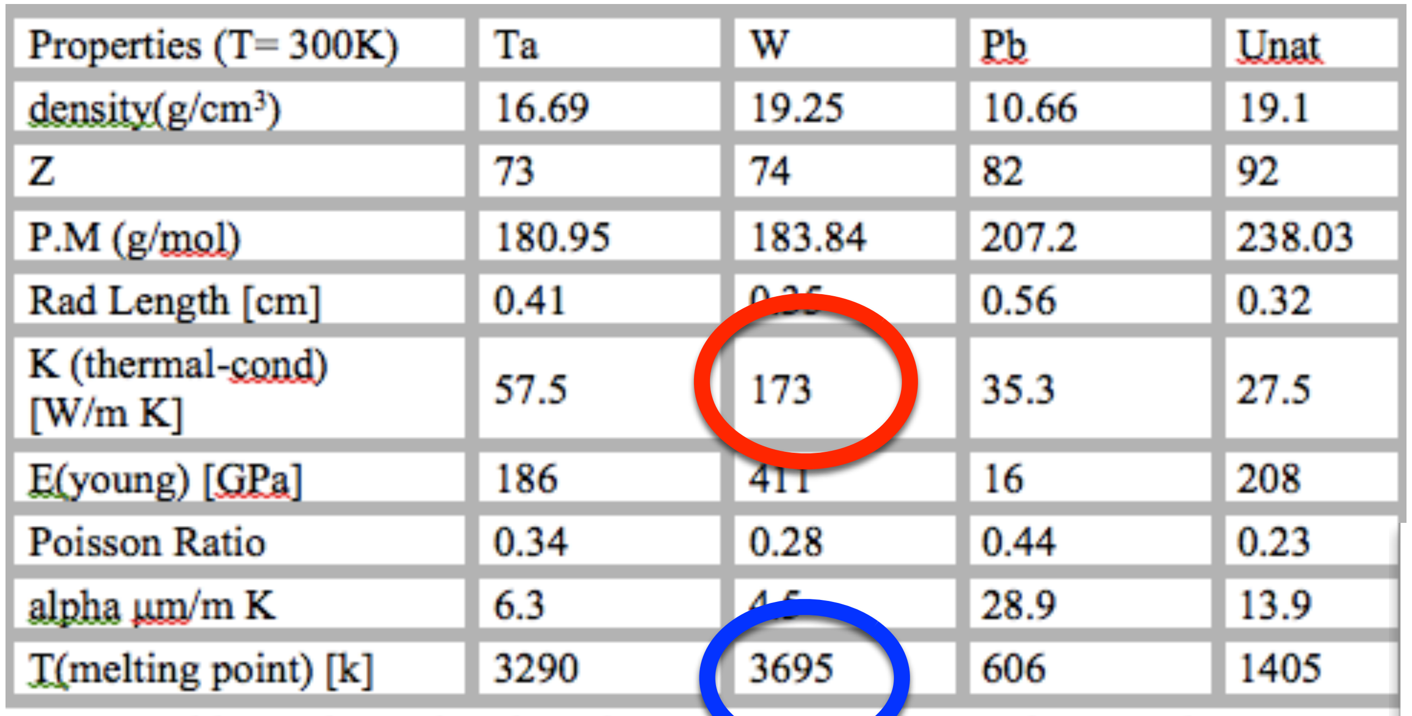

Energy deposited by 2GeV electron on W target

results for 2GeV e-


Linear density profile of neutron in the W Target

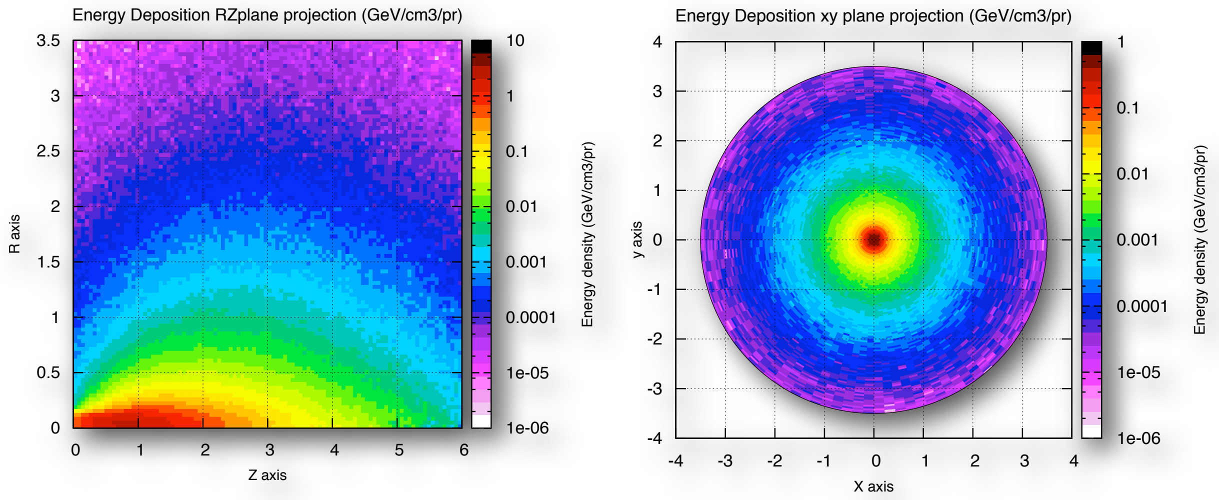

Linear energy density in the W Target

The thermal problem: material properties



Properties (T= 300K)	Ta	W	Pb	Unat
density(g/cm³)	16.69	19.25	10.66	19.1
Z	73	74	82	92
P.M (g/mol)	180.95	183.84	207.2	238.03
Rad Length [cm]	0.41	0.35	0.56	0.32
K (thermal-cond) [W/m K]	57.5	173	35.3	27.5
E(young) [GPa]	186	411	16	208
Poisson Ratio	0.34	0.28	0.44	0.23
alpha μm/m K	6.3	4.5	28.9	13.9
T(melting point) [k]	3290	3695	606	1405

Table 4: Thermal and Nuclear properties of several materials



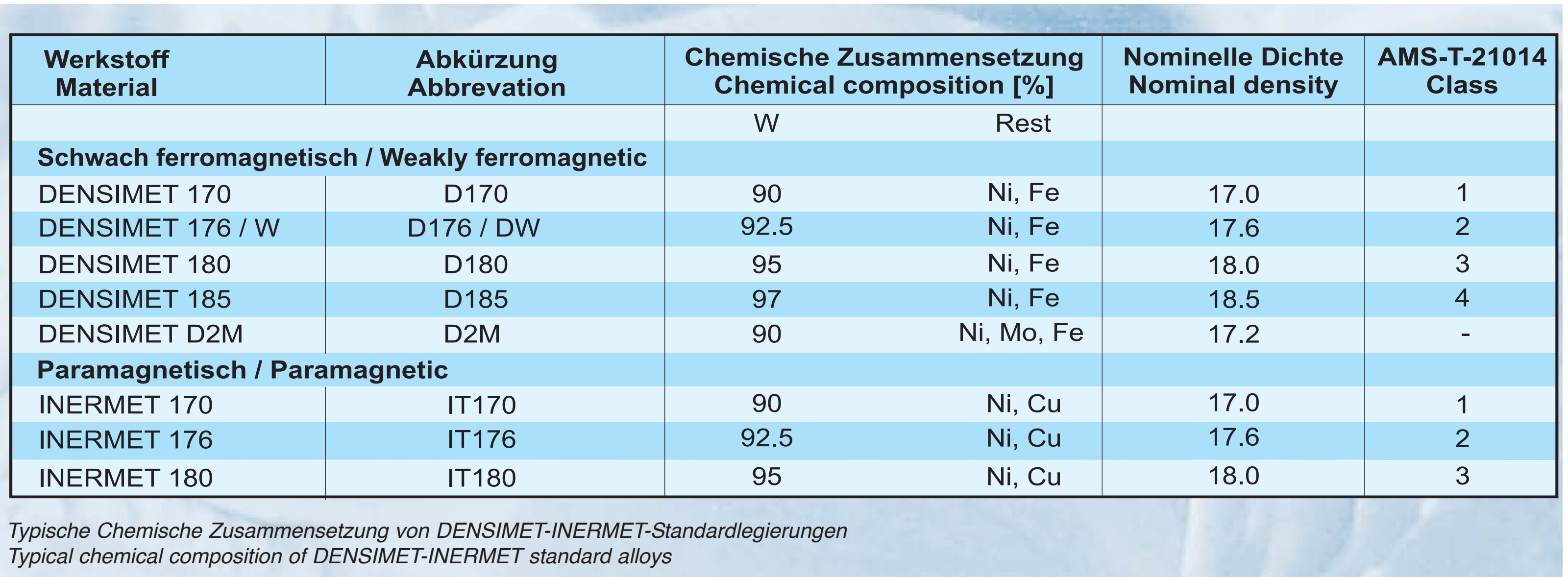
Energy Deposition profile in zr and xy

Thermal Diffusivity: index of effectiveness in heat exchange $k/(\rho\ C)$

in W ≃ 3 times larger than in Ta

Unfortunately it decreases increasing the bulk temperature

Because a suitable segmentation of the target has to be considered as a possible thermal solution, W alloys (Densimet and Inermet: 90% W+Ni+Fe) could be taken into account as valuable materials for the target (since much better machinable than nat-W)



Werkstoff Material	Abkürzung Abbreviation	Chemische Zusammensetzung Chemical composition [%]		Nominelle Dichte Nominal density	AMS-T-21014 Class
		W	Rest		
Schwach ferromagnetisch / Weakly ferromagnetic					
DENSIMET 170	D170	90	Ni, Fe	17.0	1
DENSIMET 176 / W	D176 / DW	92.5	Ni, Fe	17.6	2
DENSIMET 180	D180	95	Ni, Fe	18.0	3
DENSIMET 185	D185	97	Ni, Fe	18.5	4
DENSIMET D2M	D2M	90	Ni, Mo, Fe	17.2	-
Paramagnetisch / Paramagnetic					
INERMET 170	IT170	90	Ni, Cu	17.0	1
INERMET 176	IT176	92.5	Ni, Cu	17.6	2
INERMET 180	IT180	95	Ni, Cu	18.0	3

Typische Chemische Zusammensetzung von DENSIMET-INERMET-Standardlegierungen
Typical chemical composition of DENSIMET-INERMET standard alloys

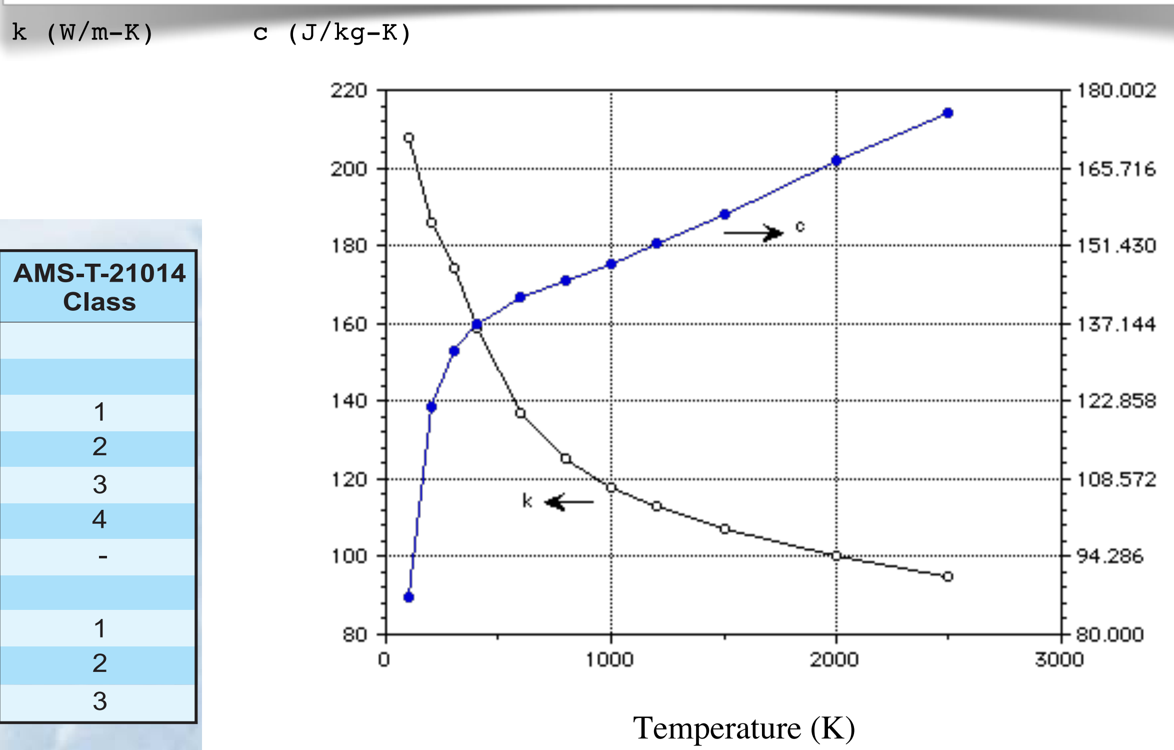


Figure 1 : Thermal conductivity and specific heat of tungsten.

Conclusion, Plans and ongoing activities

- MC codes have been validated to suitable design the optimised target
- Some quantitative and qualitatives comparisons with the major neutron sources facilities have been performed and others are in progress. Thanks to
    - Ian Anderson & Philips Ferguson from SNS
    - Jan Heyse from Gelina
    - Anna Ferrari from nElbe
    - Stuart Ansell from ISIS
- Optimal technical solutions for the target have to be envisaged in the frame of a coupled analysis neutronic-thermomechanical: in progress
- Study of the extractions line according to the main scientific and technological requirements: MC time dependent simulations (**collaboration with A. Fassò and A. Ferrari)** and MCStas

THANK YOU
FOR YOUR ATTENTION