



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

**FUNFI-IT - Italian Meeting on Fusion Neutrons for Fission**  
**Museo Enrico Fermi, Rome, December 11 2024**

# **A Fission Fragments model production for astronautical applications**

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**DIAEE - Dipartimento di Ingegneria Astronautica Elettrica ed Energetica**



# Outline

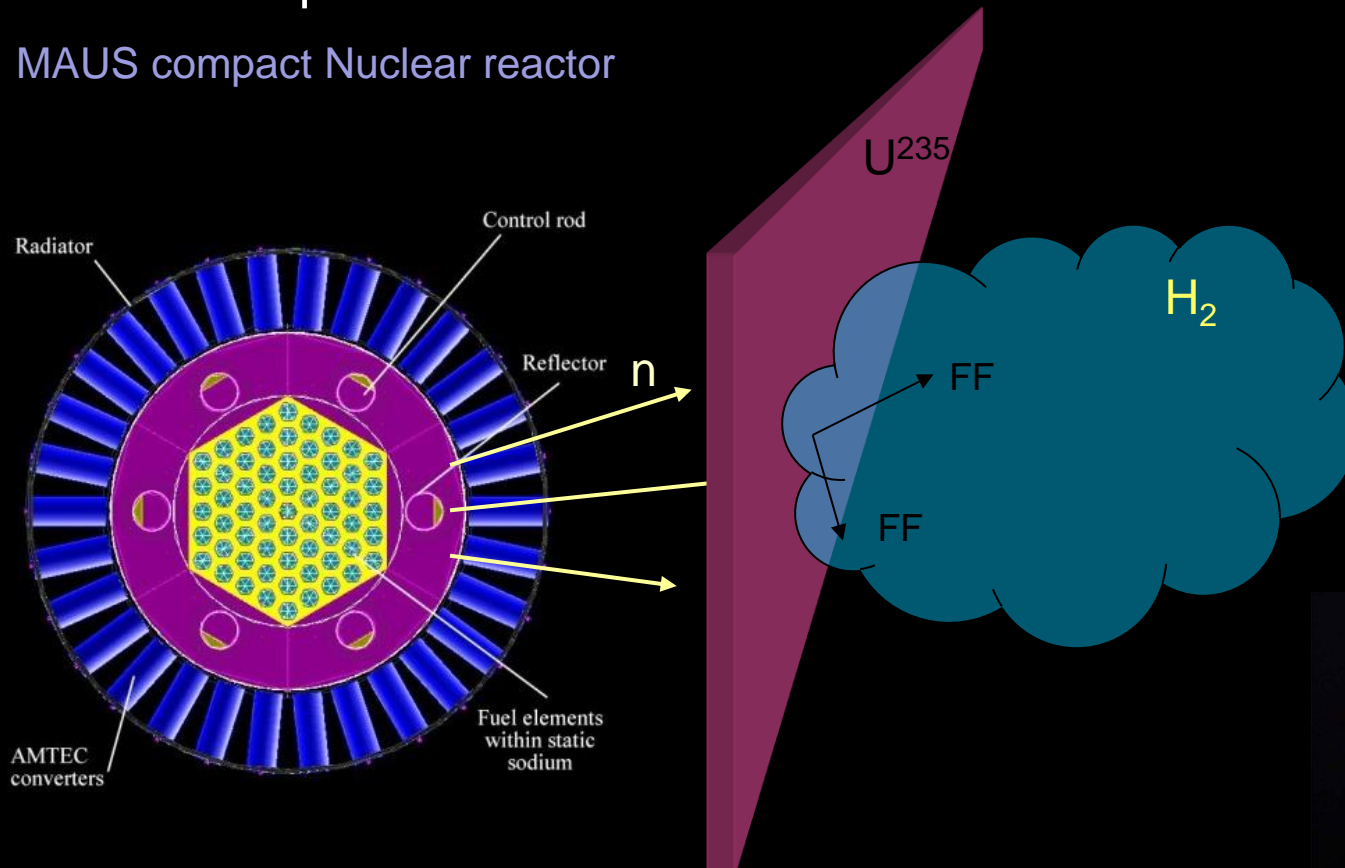
- Research purpose
- The MAUS reactor
- The simulation code
- The FF energy released to the layer
- Conclusions
- Notes on space propulsion, classification of endoreactors
- Nuclear and plasma engines for space, the P242 project



# Research purpose

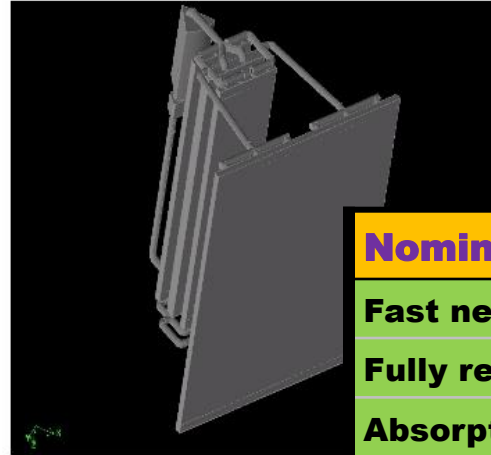
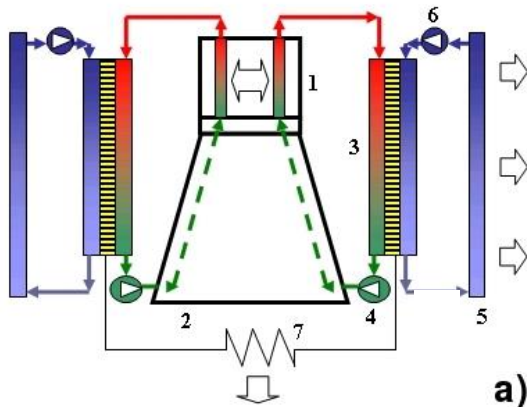
exploiting the escape neutron source coming from MAUS (compact nuclear reactor for space) to generate fissions on thin plates, in order to heat a light conventional propellant, obtaining a thrust suitable for space travel.

MAUS compact Nuclear reactor



# The MAUS reactor <sup>1/3</sup>

Multipurpose Advanced Ultracompact Space Reactor [1,2]



**Nominal electric power 30 kWe;**

**Fast neutron flux nuclear reactor**

**Fully reflected reactor**

**Absorption controlled reactor**

**Liquid metal Na as a coolant**

**Forced cooling by electromagnetic pumps**

**Energy conversion by thermoelectric effect (p-n junctions) ex-core**

**Dissipation of unconverted energy into space by radiant panels**

## Legend

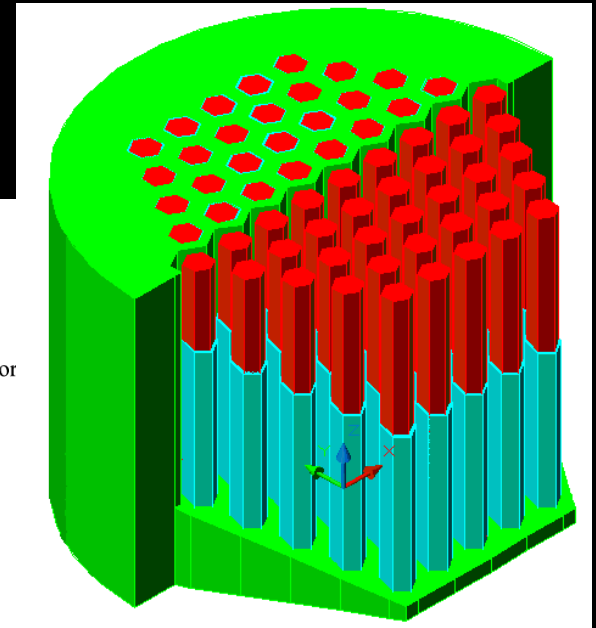
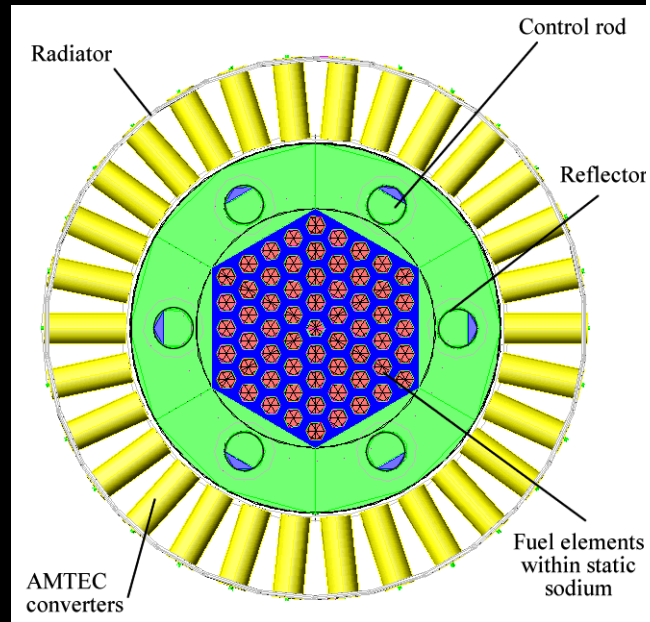
- 1 – Reactor
- 2 – Shield
- 3 – Converter
- 4 – Reactor pump circ.
- 5 – Radiator
- 6 – Radiator pump exc
- 7 – Charger

[1] "MAUS/1,5 Nuclear Reactor for Space Electric Power" M. Cumo, et al., in 12th International Conference on Emerging Nuclear Energy Systems (ICENES'2005), Brussels, Belgium, 2005.

[2] "The MAUS nuclear space reactor with ion propulsion system" E. Mainardi. Nuclear Instruments and Methods in Physics Research A 561 (2006) 331–335

# The MAUS reactor <sup>2/3</sup>

- ✓ electrical power from 1 to 30 kWe
- ✓ operation period of at least 7 years
- ✓ power production in the reactor only when the system has reached the pre-established orbit
- ✓ sufficient subcriticality at launch and appropriate design to avoid nuclear criticality accidents in the event of launch failure with consequent fall of the reactor into water

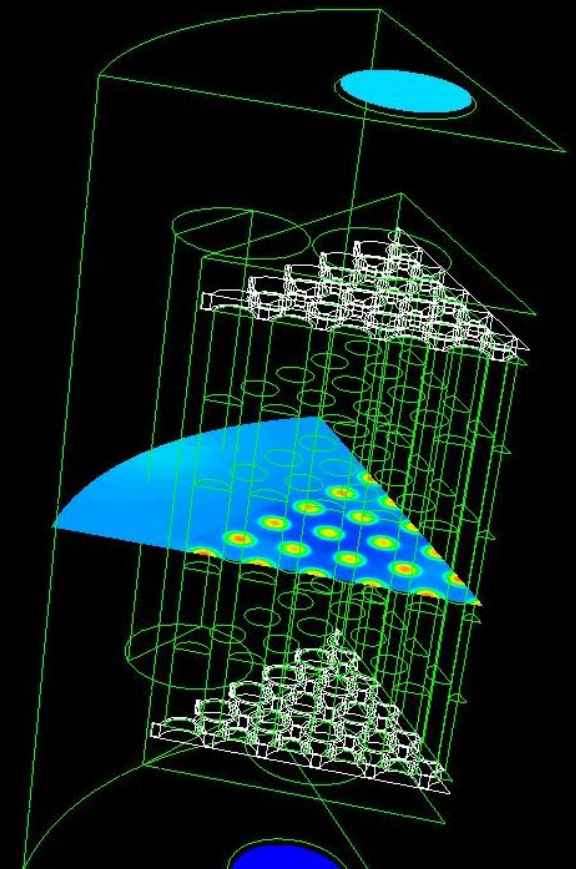
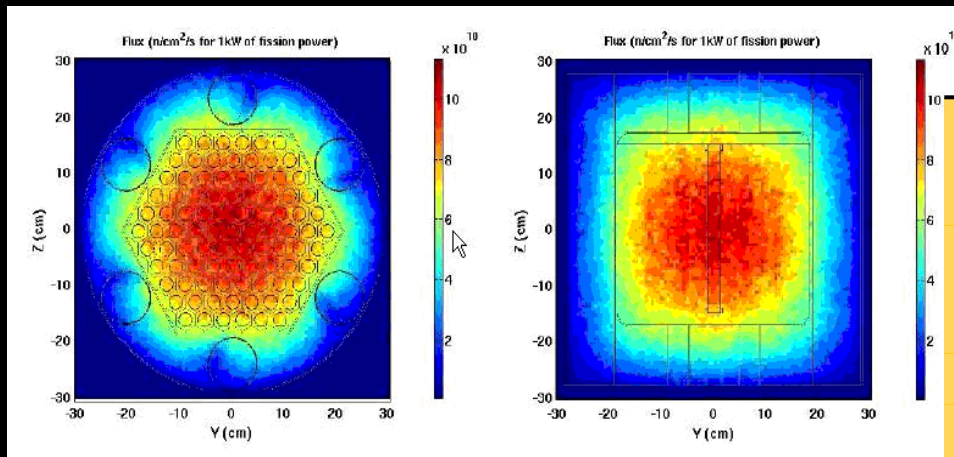
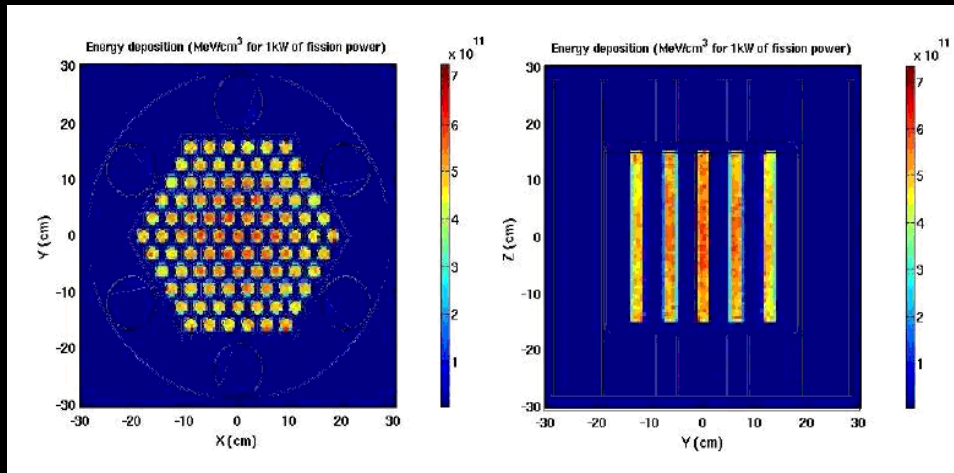


The chosen configuration is composed of a nuclear reactor, a conversion system (with AMTEC cells) placed around the reactor, a thermal radiation system towards space (placed externally to the conversion system) and a shielding system (about 20 mm from the lower base of the reactor and placed to protect the "payload"). The overall height of the system, without shield, is 450 mm, with a diameter of about 650 mm. The neutron shield is about 500 mm thick, while the gamma shield is about 50 mm thick.





# The MAUS reactor 3/3



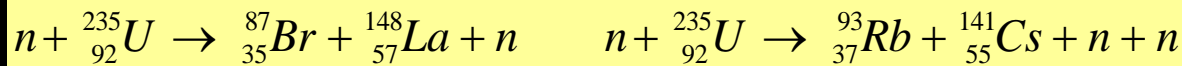
<b>Reactor type</b>	Fast with forced liquid metal refrigeration	kw
<b>Converter</b>	Thermoelectric at p-n junctions	300
<b>Radiator</b>	At surface	30
<b>Pumps</b>	Electromagnetical permanent magnets	270
	Net electrical power	30
	Radiated thermal power	270

# The simulation code 1/11

The  $U^{235}$  fission is triggered by thermal neutron having cross section  $\sigma^{235}=580b$ .

In the fission the energy released is  $Q \approx 210 \text{ MeV}$ .

In the final state are produced nuclei with mass  $A_x \approx 95$  e  $A_y \approx 140$ , examples:



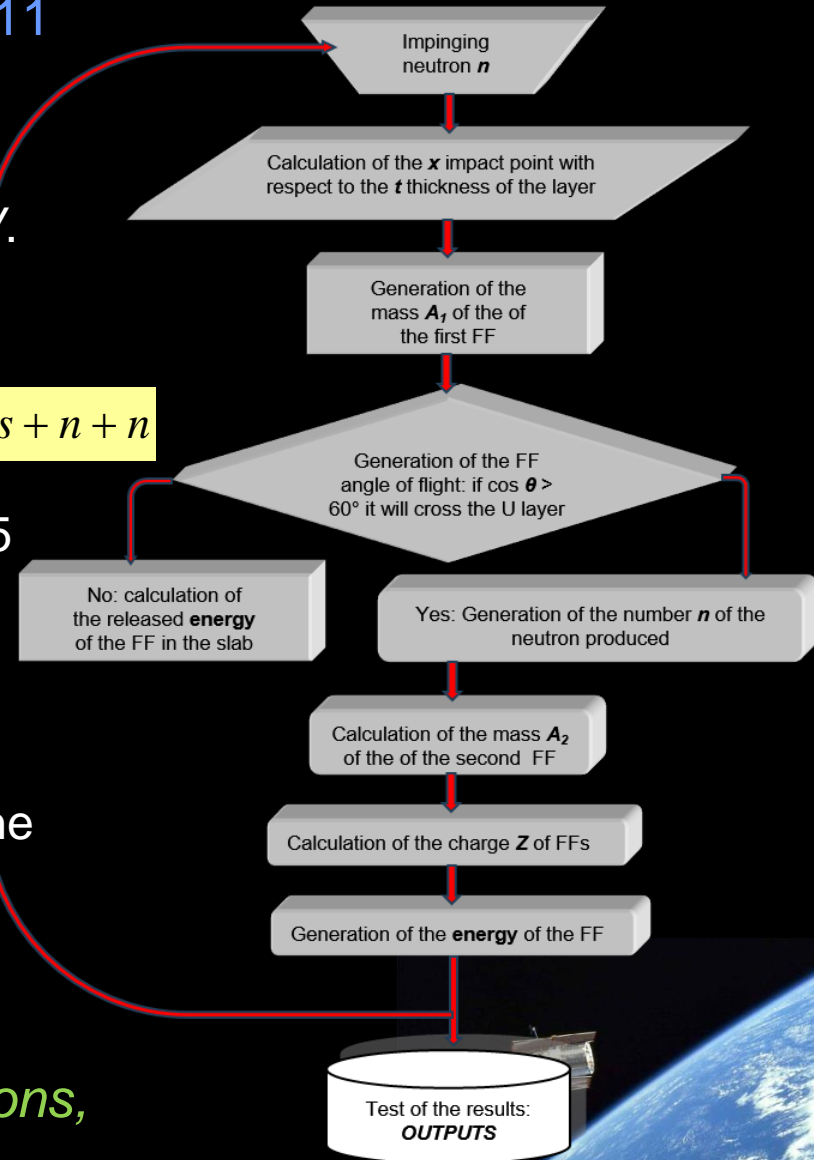
and an average number of prompt neutrons  $\approx 2.5$  with kinetic energy  $K_n \approx 2 \text{ MeV}$

Short reaction time  $\tau = (10^{16} \div 10^{14})s$

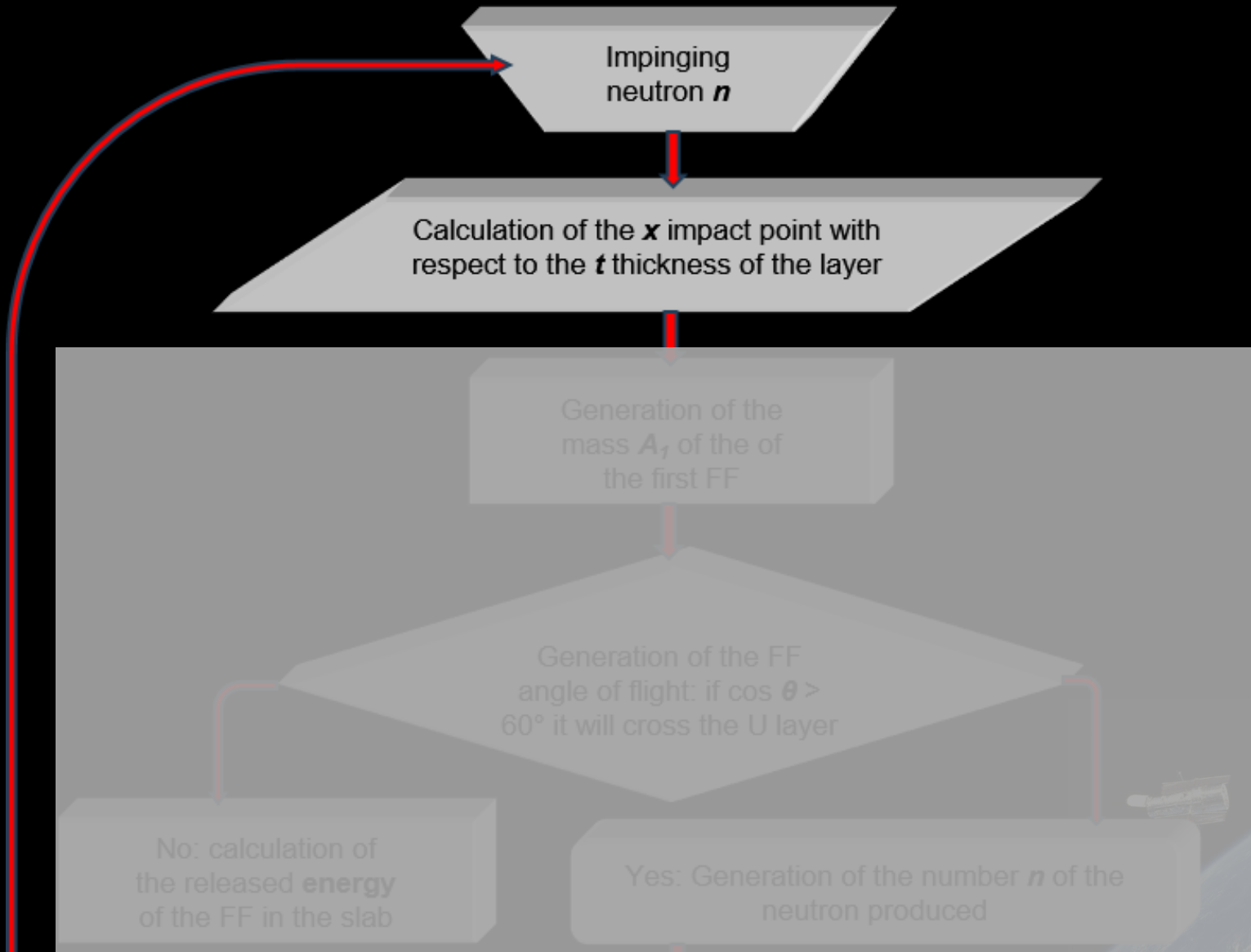
emission accompanied by photons and  $E_n$  of light products  $\approx 5 \text{ MeV}$ .

The two FFs have excess neutrons and reach the stability band with  $\beta$  emission. The energy released in  $\beta$  decays  $\approx 20 \text{ MeV}$  of which about  $12 \text{ MeV}$  in antineutrinos.

*The fission reaction is a source of neutrons, photons, electrons and antineutrinos!*



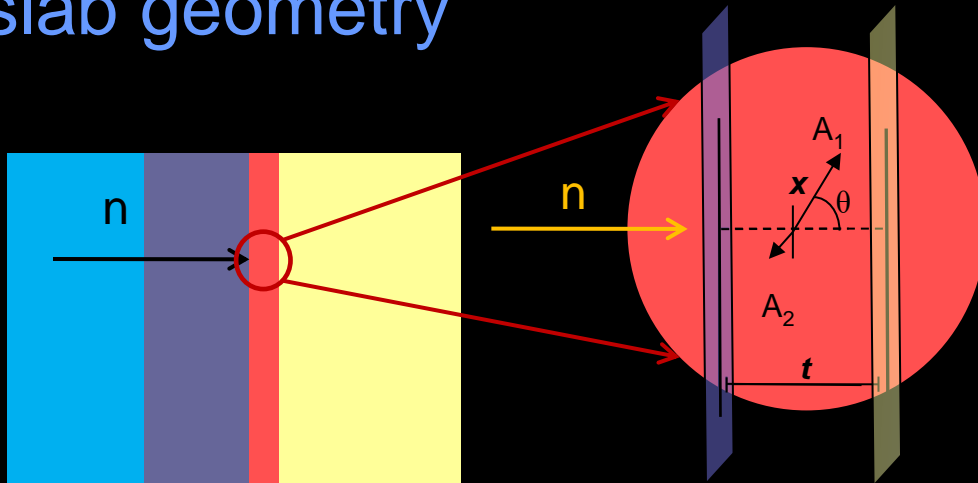
# The simulation code 2/11





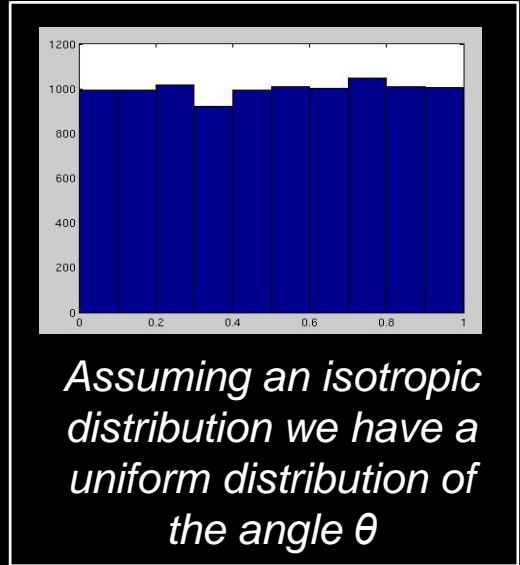
# The simulation code <sup>3/11</sup>

## slab geometry



coolant  
support  
fissile  
light gas

With the aim of excluding those interactions whose FFs both remain in the layer, we set  $\cos \theta < 60^\circ$



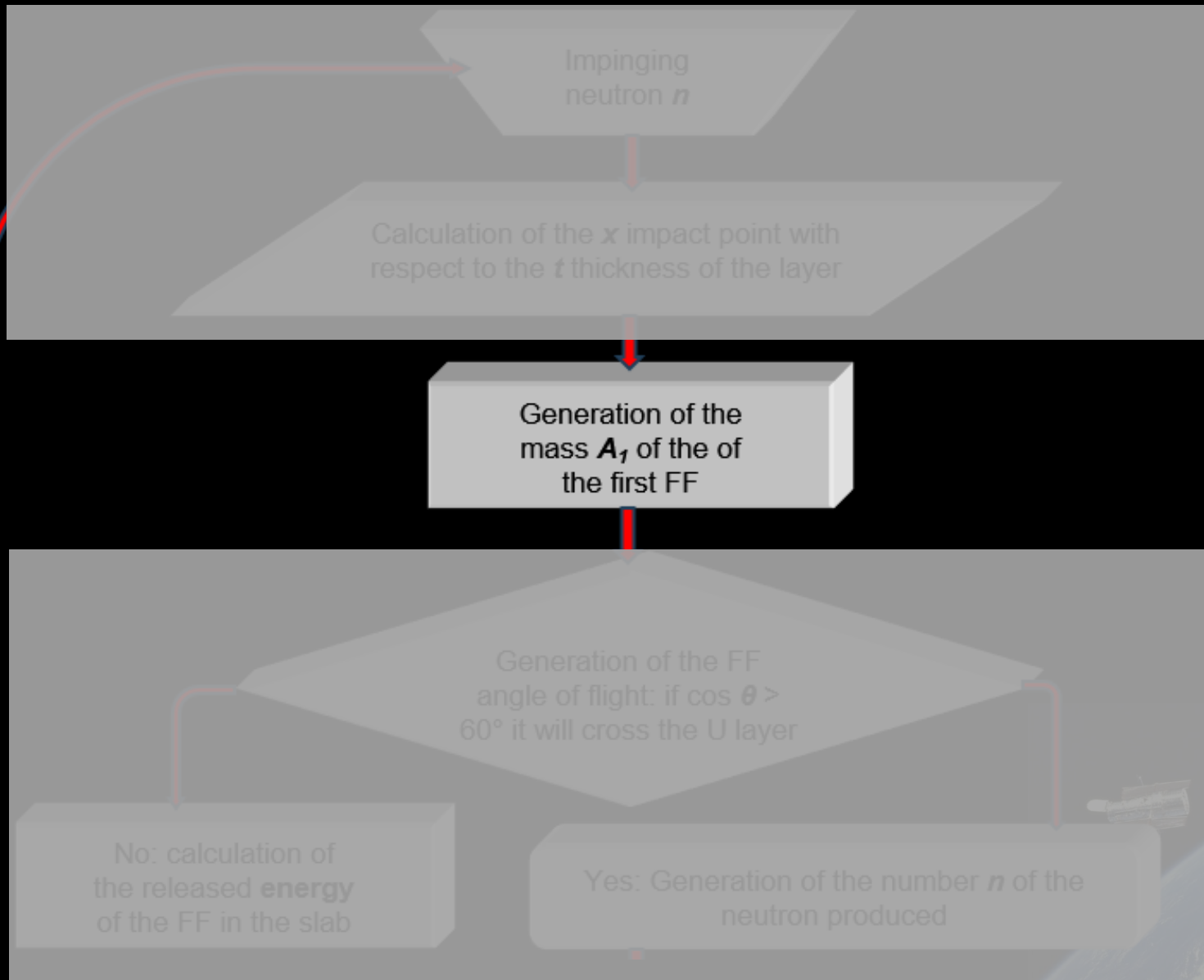
*Assuming an isotropic distribution we have a uniform distribution of the angle  $\theta$*

For each FF, being  $x_i$  the distance between the impact point and the end of the thickness  $t$ , by defining  $r_i = t - x_i$  we will verify if the interval travelled in the layer (that we will call  $r_u$ ) is greater than  $r_i$ ; therefore the condition will be:

$$r_i / \cos \theta < r_u$$

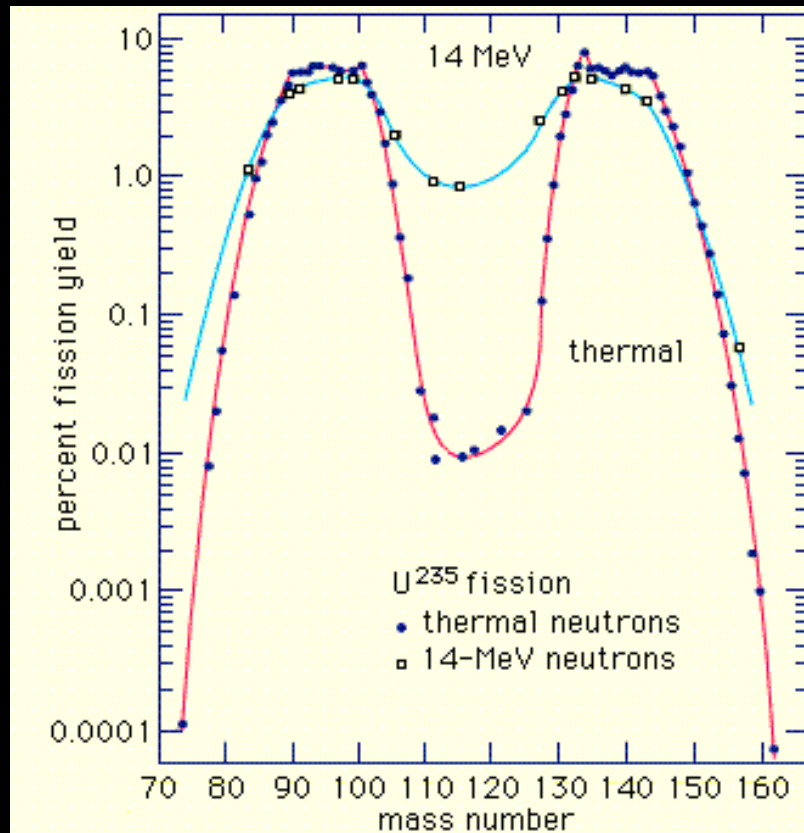


# The simulation code 4/11

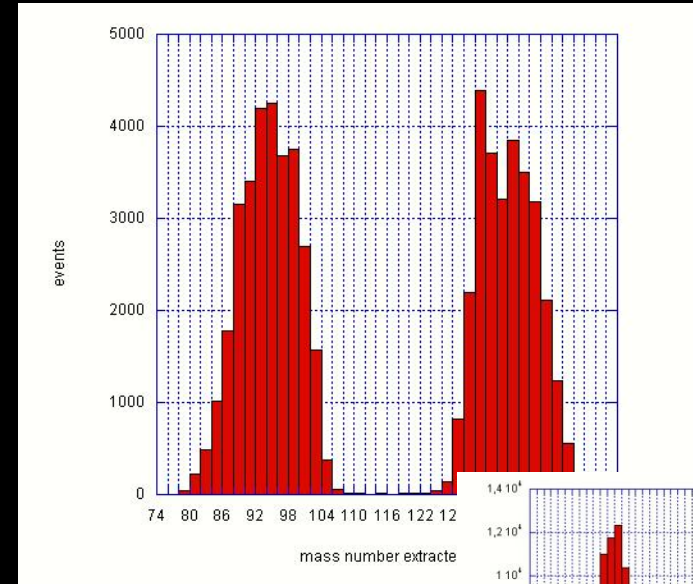


# The simulation code 5/11

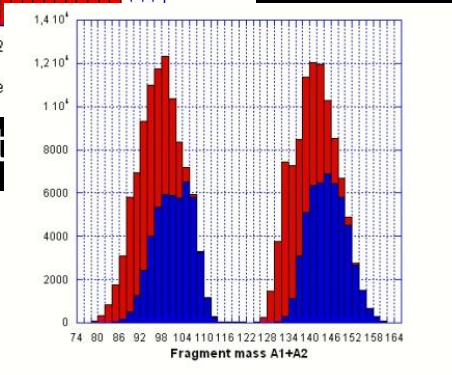
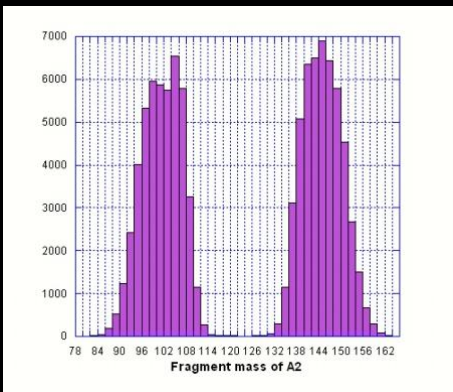
## FF distribution mass



$$A_2 = 236 - A_1 + 2n \text{ o } 3n$$



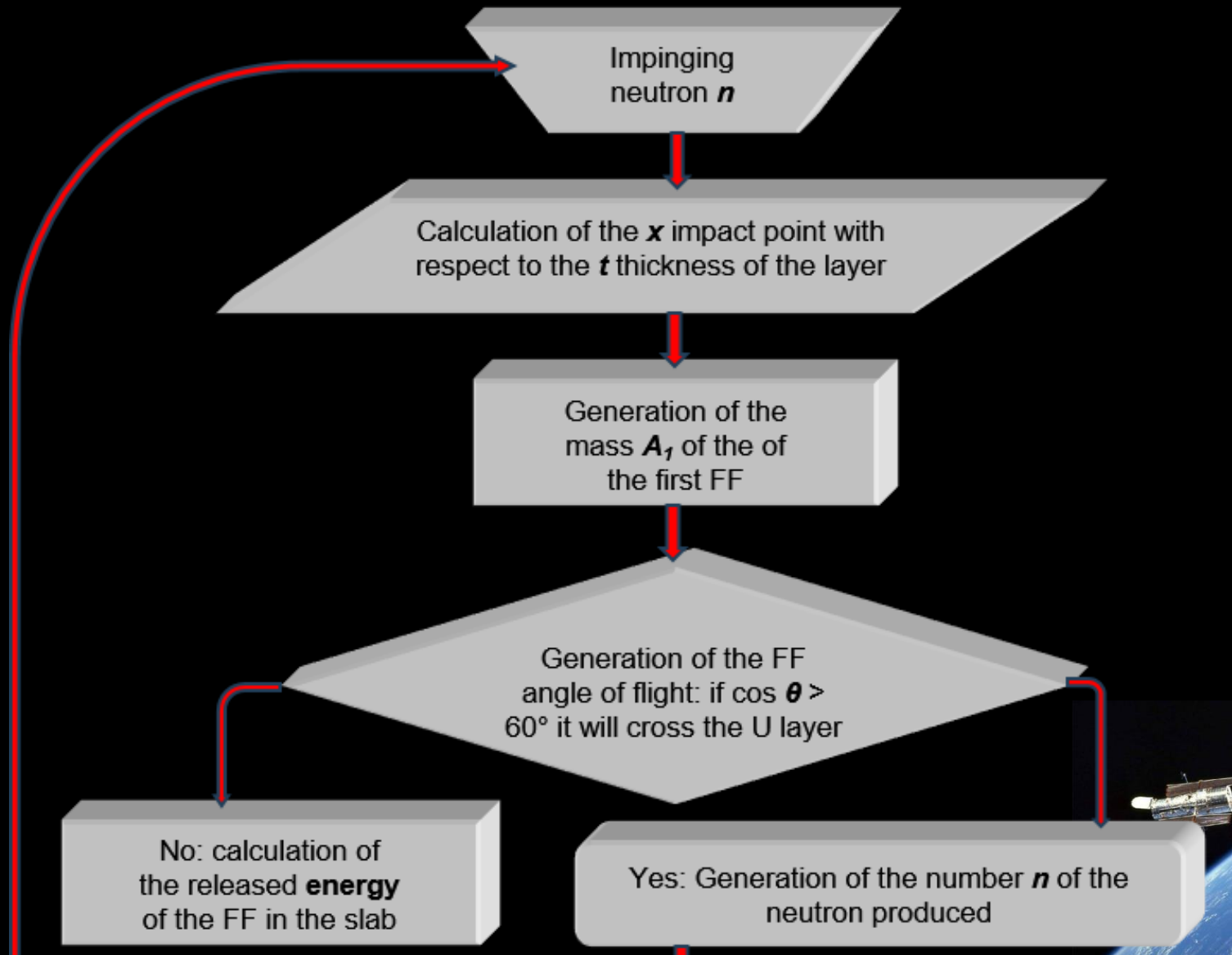
vector to reproduce t



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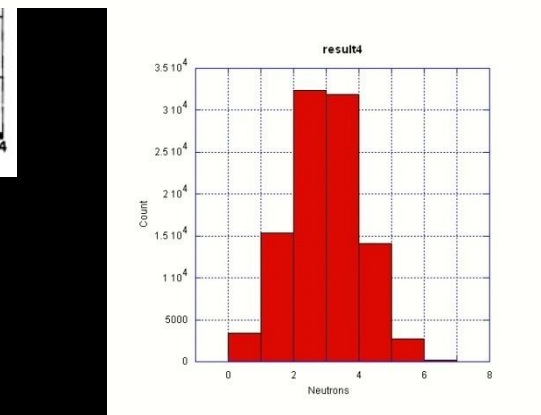
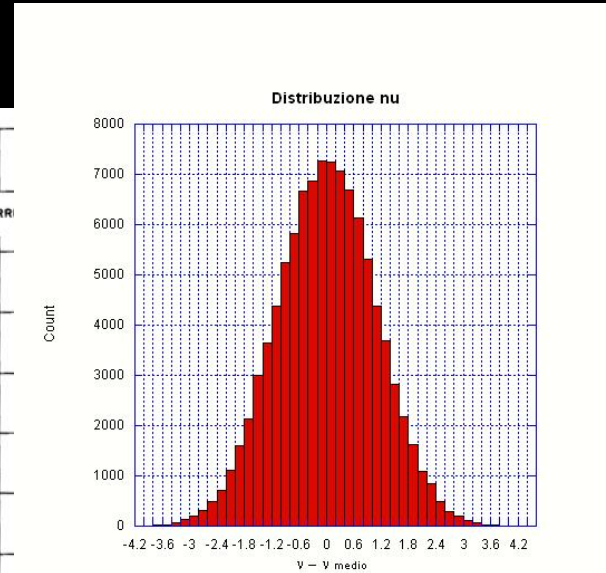
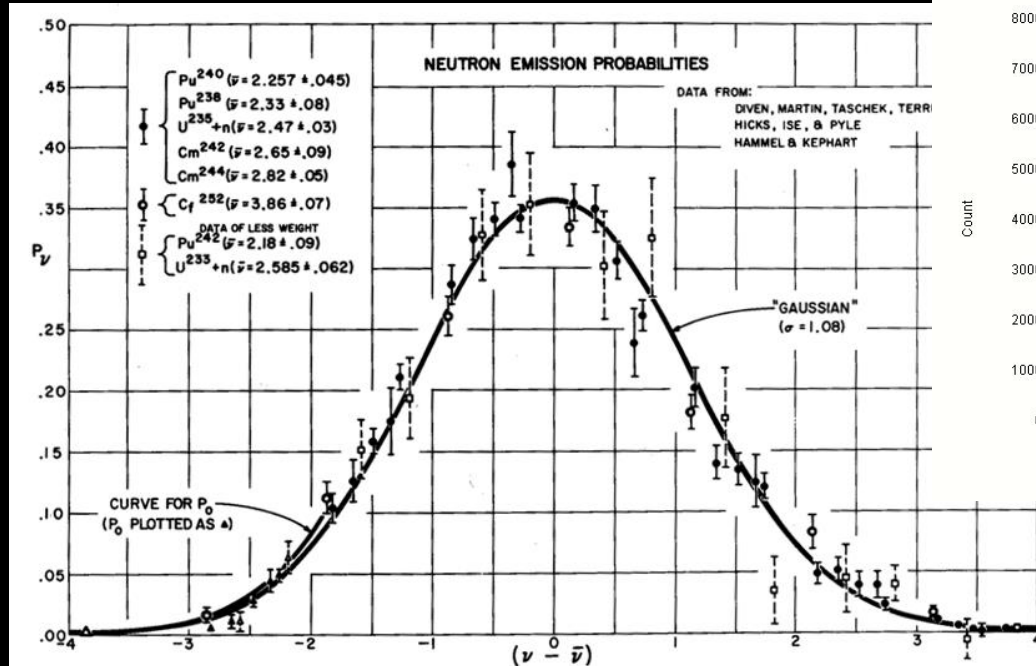


# The simulation code 6/11



# The simulation code 7/11

## neutron distribution



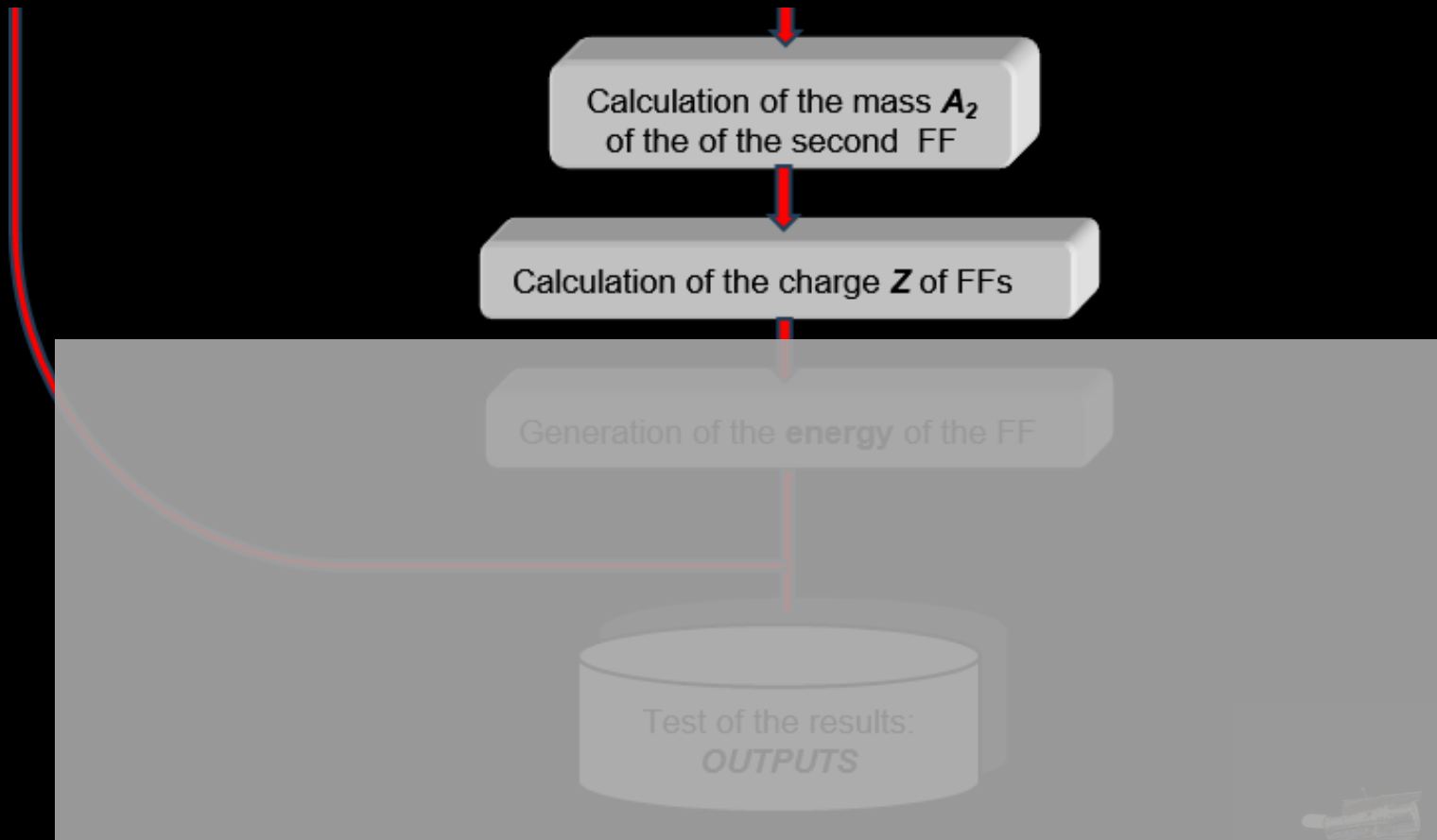
$n_{th} \sim 0.025 \text{ eV}$

$\langle n_n \rangle \approx 2.5$

$\sigma = 1.08$

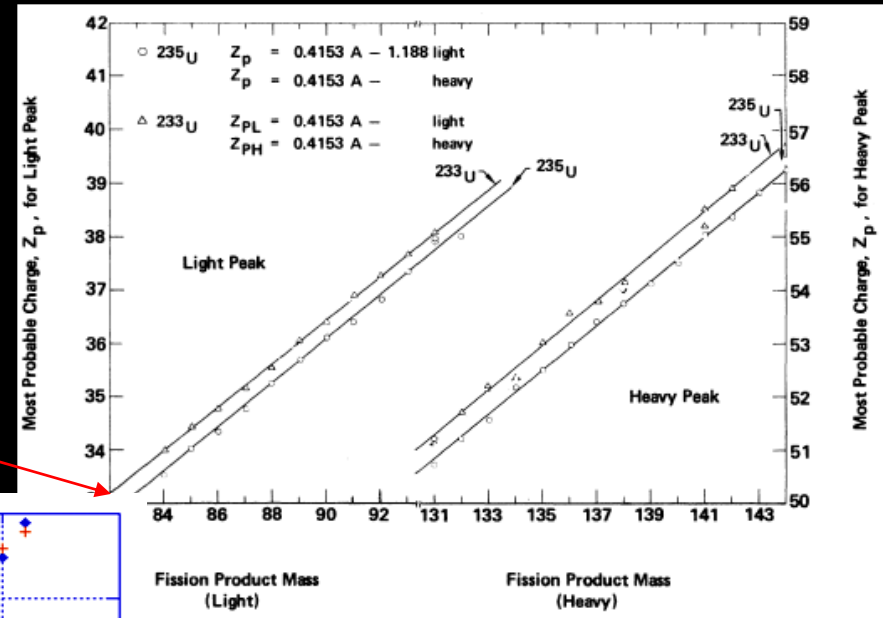
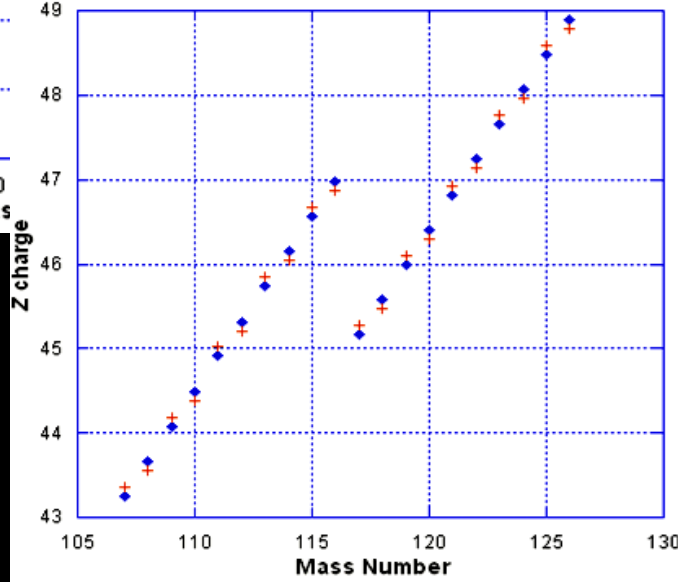
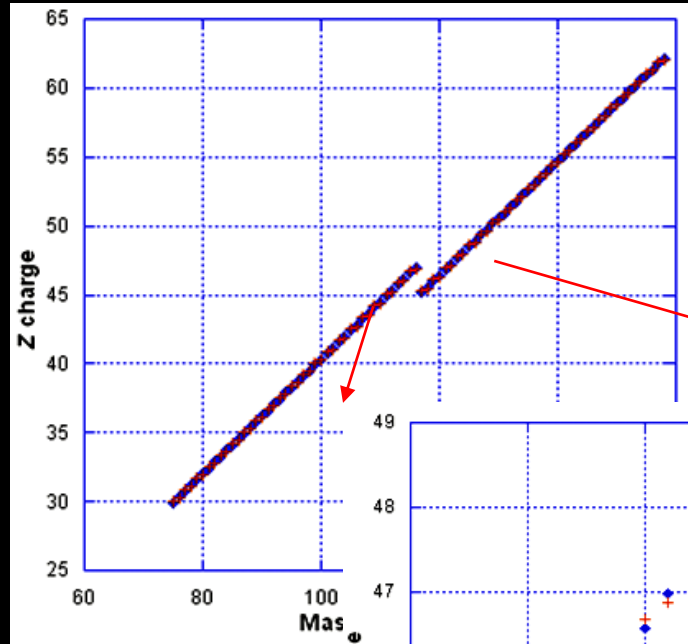


# The simulation code 8/11



# The simulation code 9/11

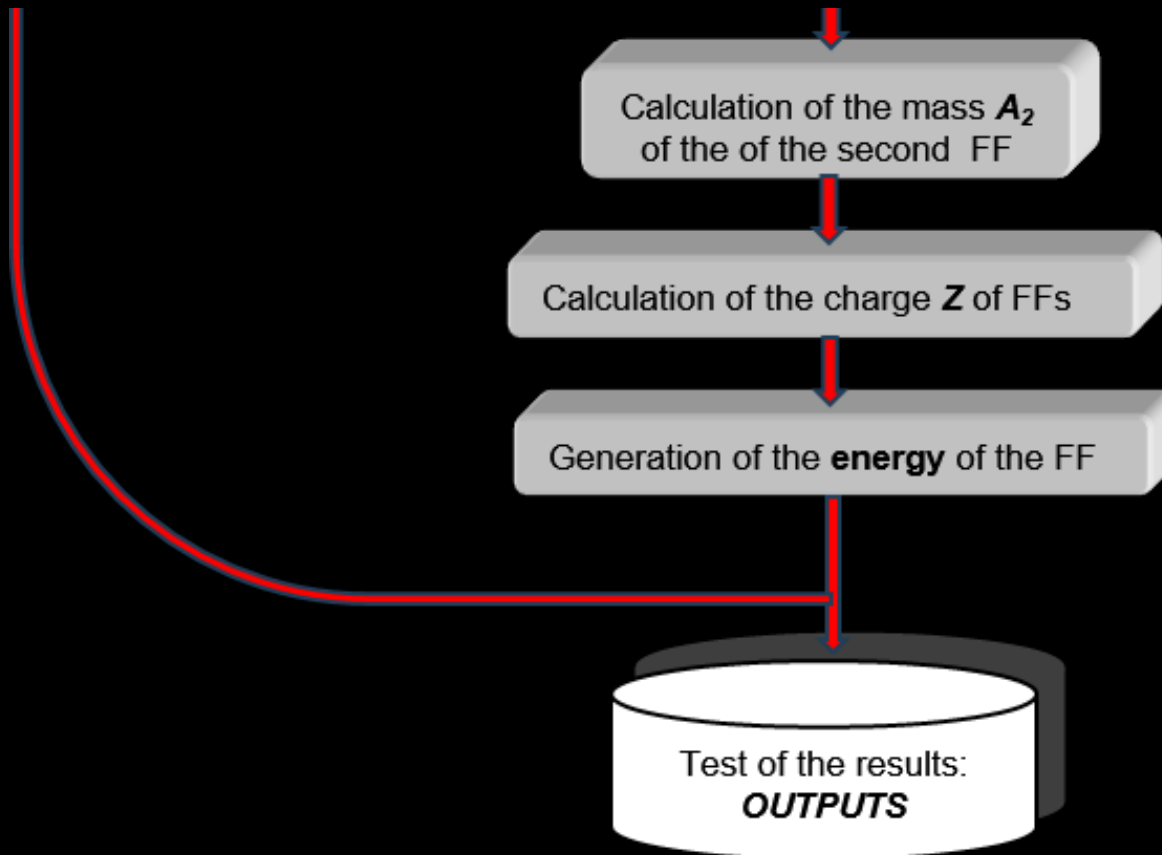
FF charge



$Z_p = 0.4153 A - 1.19$  per  $A < 116$   
 $Z_p = 0.4153 A - 3.43$  per  $A > 116$ .

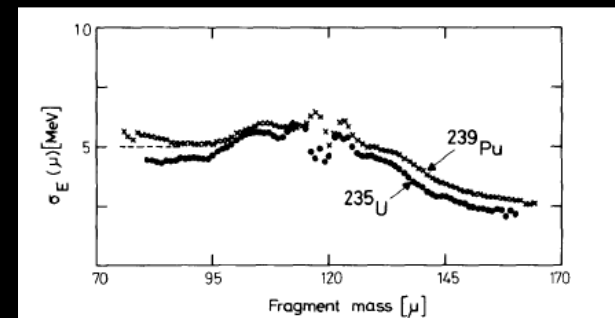
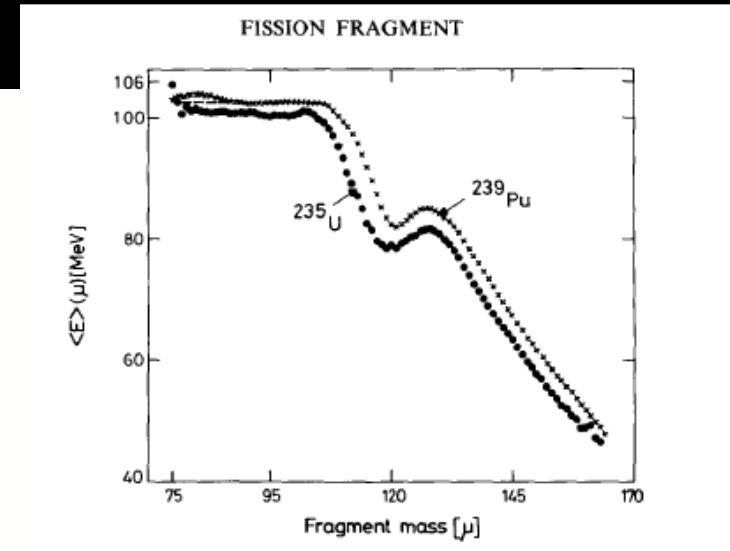
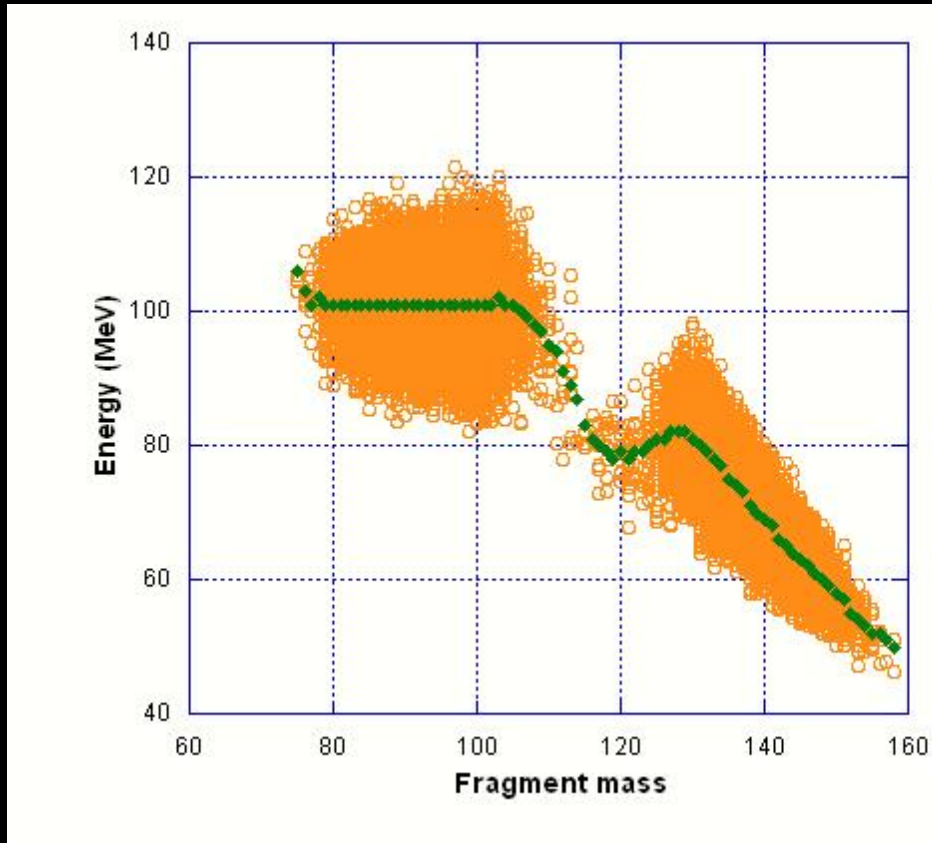


# The simulation code 10/11



# The simulation code 11/11

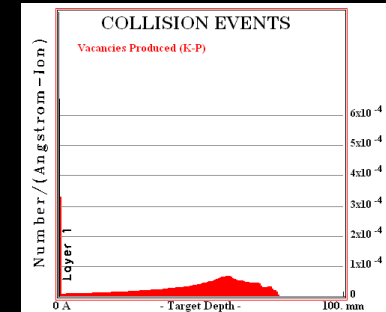
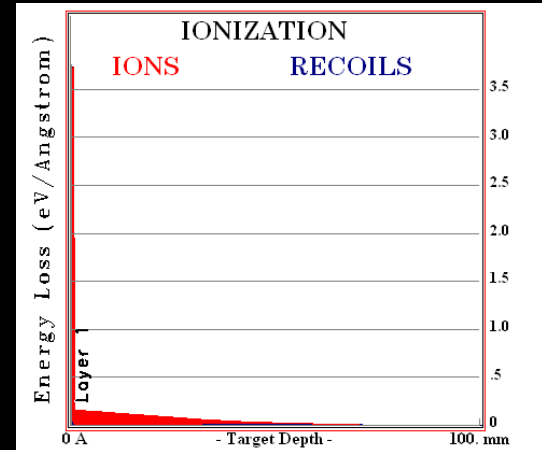
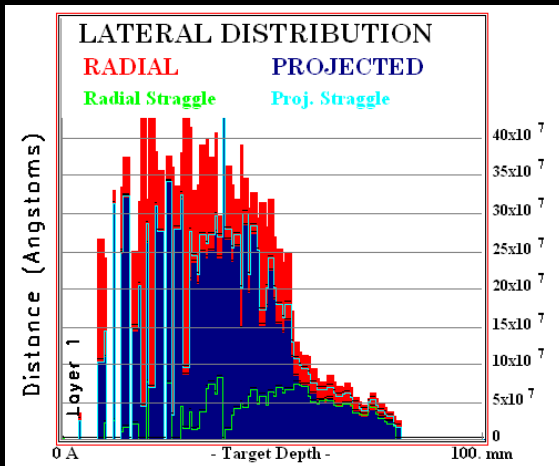
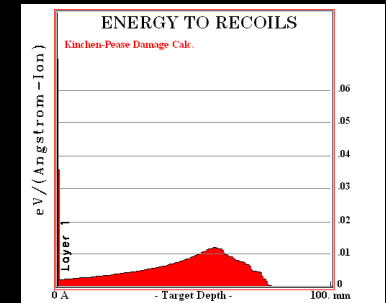
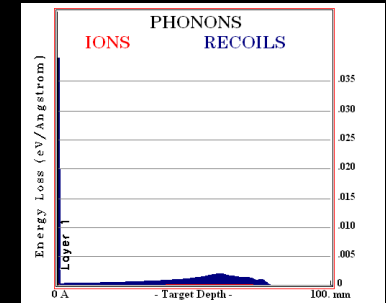
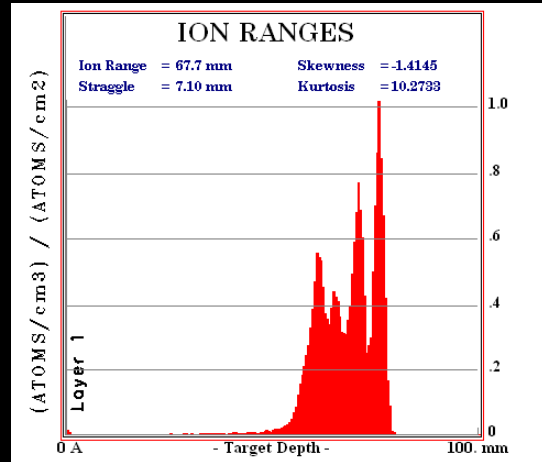
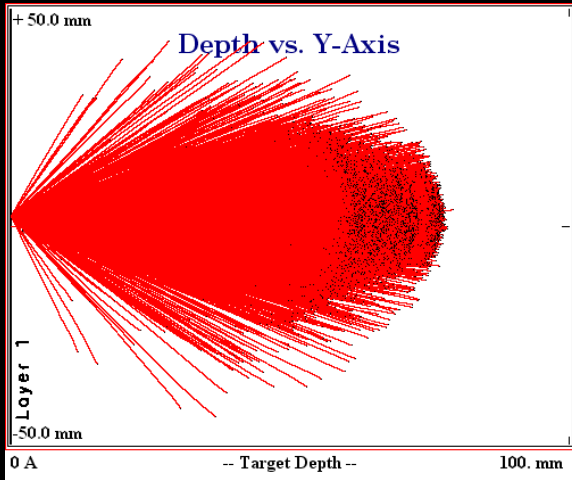
distribuzione energetica dei FF



# The FF energy released to the layer <sup>1/7</sup>

Layer 1= 1,5 $\mu$  U  
Layer 2= 10cm of H2 gas std

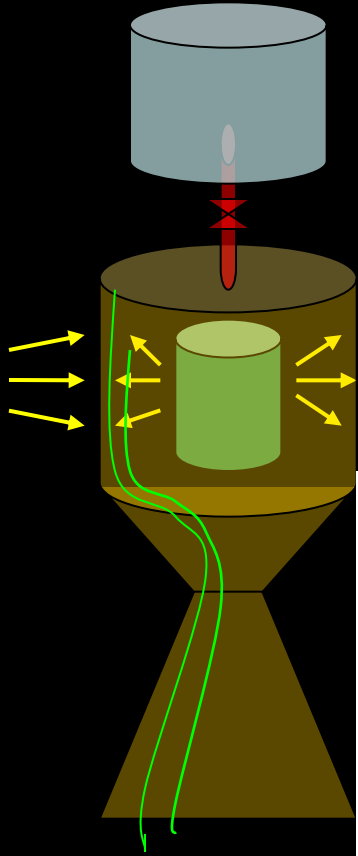
Temp +20  
Press 1atm dens 0,08376



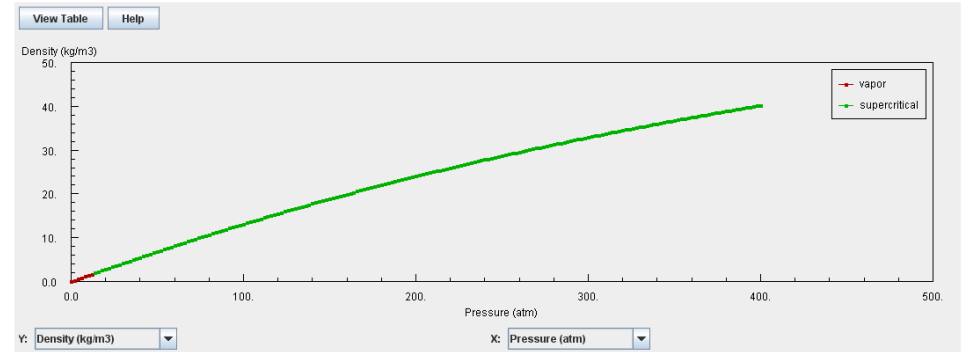


# The FF energy released to the layer <sup>2/7</sup>

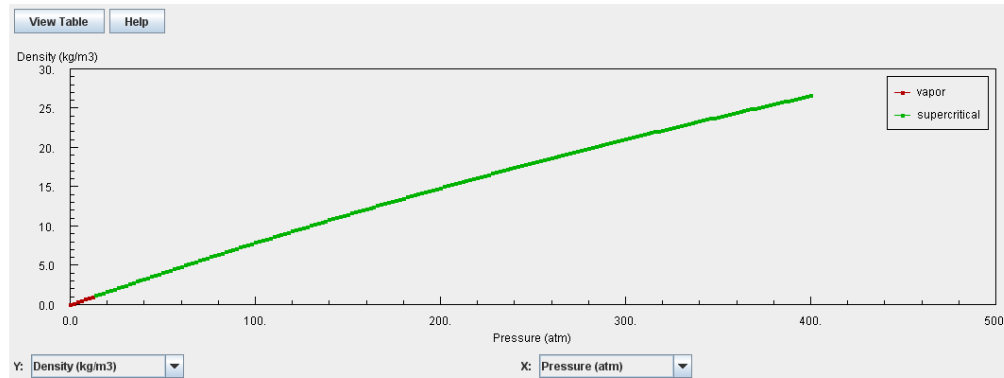
Parameters P, T -> H2 density



Isothermal Data for T = -100.00 C

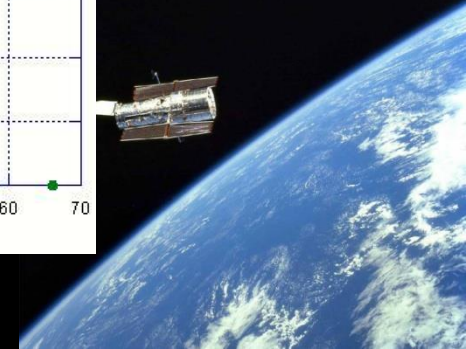
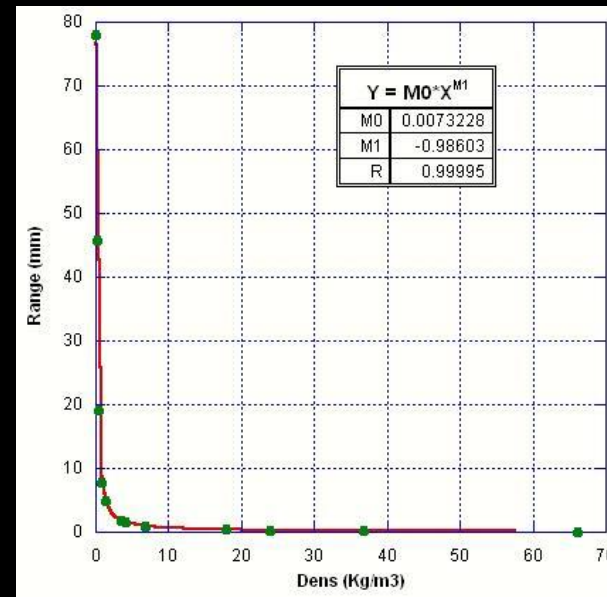
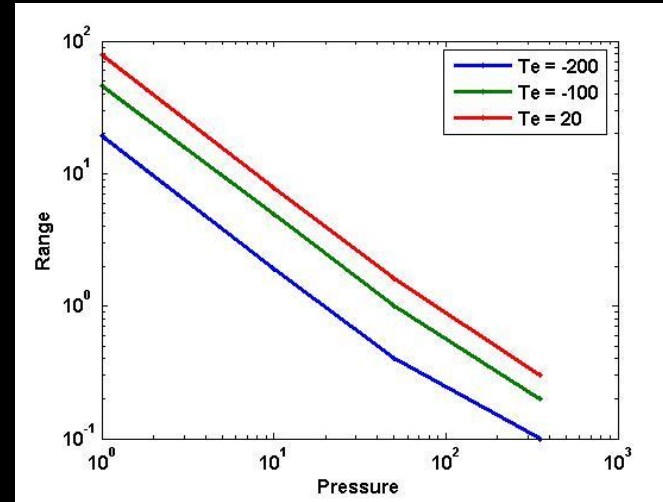


Isothermal Data for T = 20.000 C



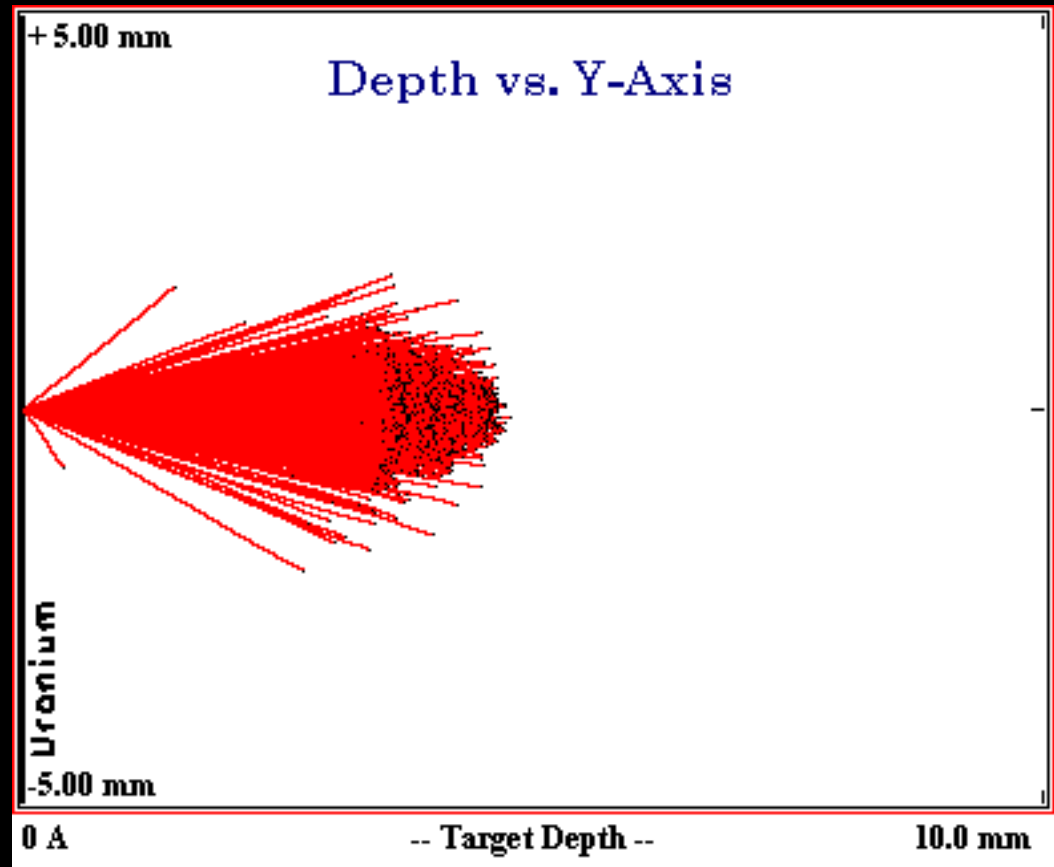
# The FF energy released to the layer 3/7

Temp °C	Press atm	Dens kg/m <sup>3</sup>	Phase	Range mm
+20	1	0,08376	Vapor	78,1
-100	1	0,14179	Vapor	45,7
-200	1	0,33666	Vapor	19,2
+20	10	0,83304	Vapor	7,81
-100	10	1,40940	Vapor	4,89
-200	10	3,42740	Vapor	1,89
+20	50	4,06670	Critical	1,62
-100	50	6,84700	Critical	1
-200	50	17,8970	Critical	0,4
+20	350	23,9030	Critical	0,3
-100	350	36,7590	Critical	0,2
-200	350	66,1470	Critical	0,1



# The FF energy released to the layer 4/7

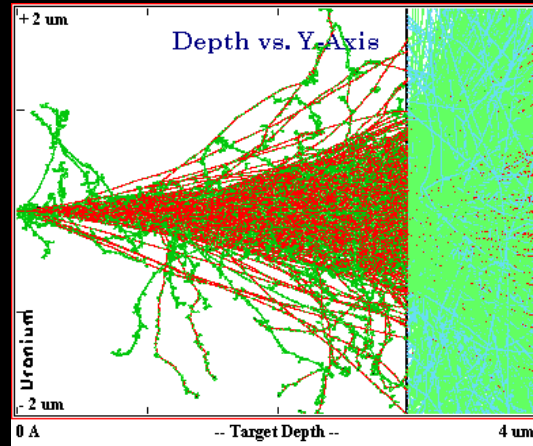
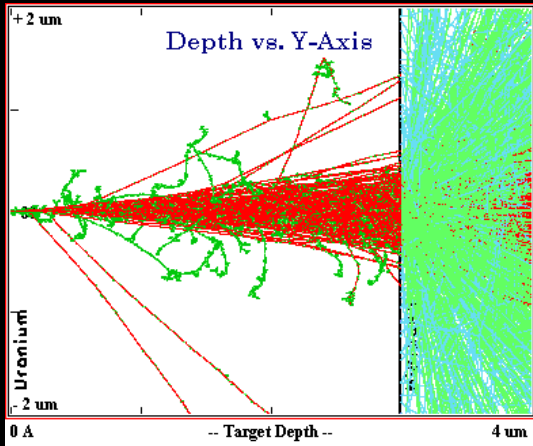
Layer 1= 1,5 $\mu$  di U  
Layer 2= 10mm H  
SRIM for 2000 FF on  
1,5  $\mu$  of Uranium and 10  
mm of **Hidrogen at  
density of 1,4 Kg/m<sup>3</sup>**  
Temp -100; Press 10atm



# The FF energy released to the layer 5/7

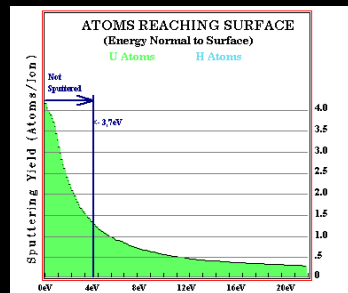
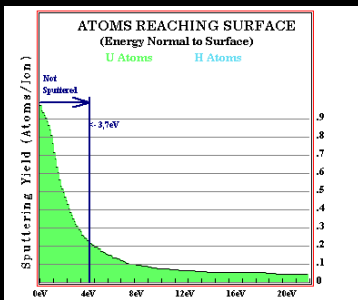
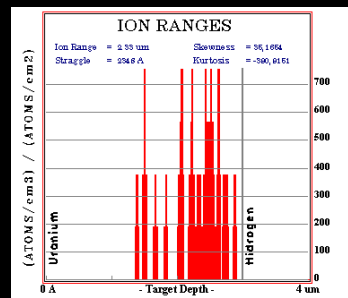
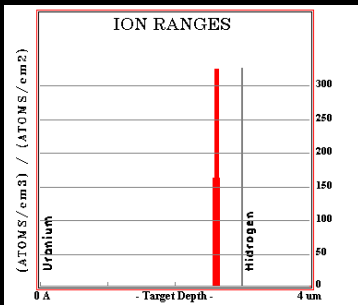
Ion Niobium 65 MeV

Ion Lanthanum 100 MeV



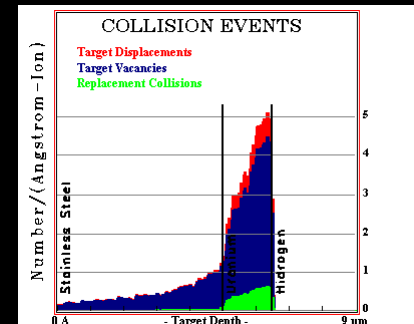
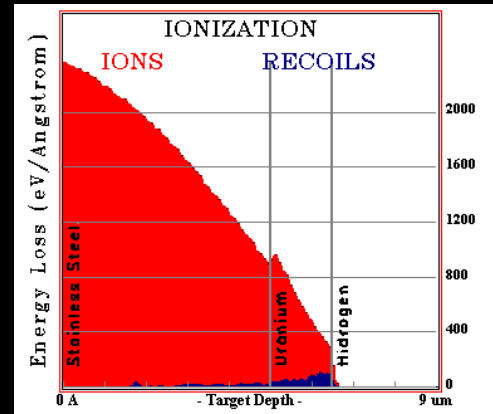
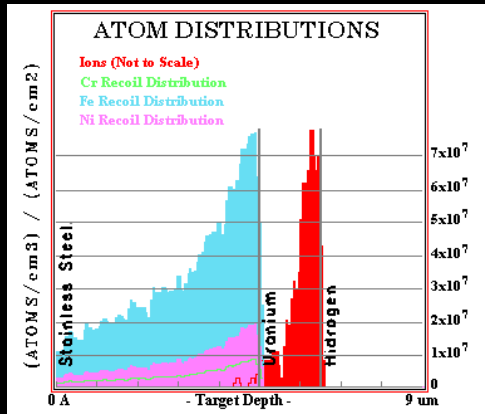
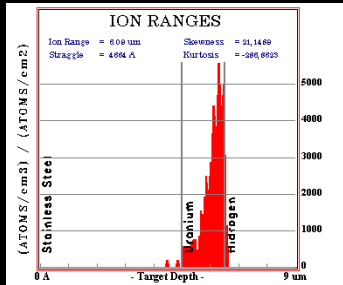
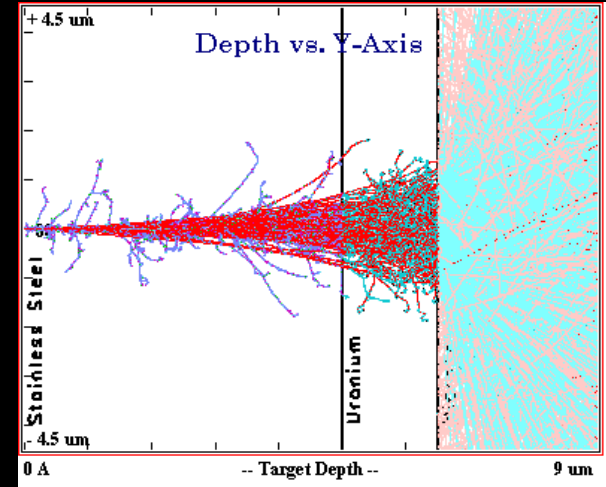
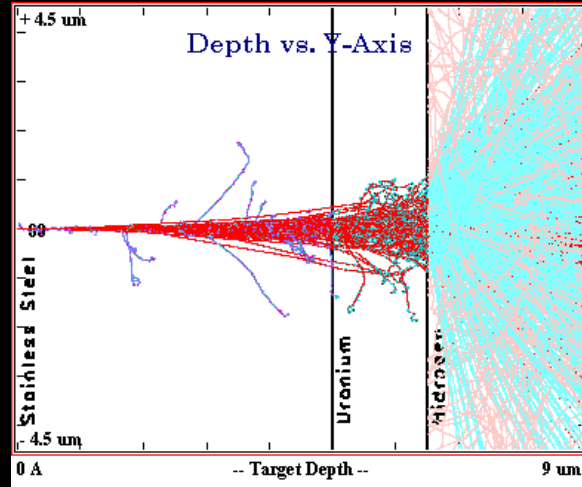
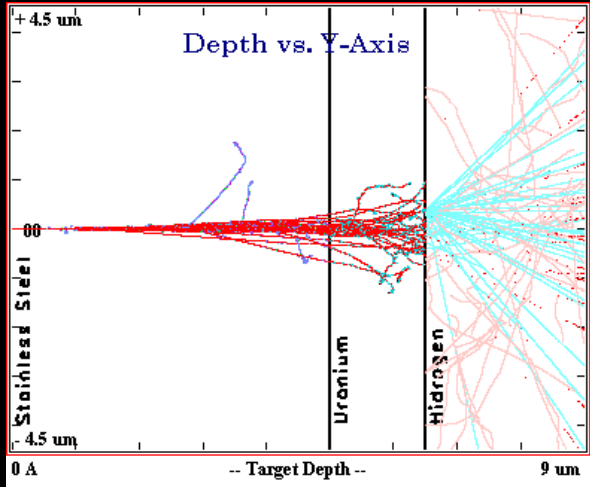
Layer 1 =  $3\mu$  di U

Layer 2 = 1mm di H gas std



# The FF energy released to the layer 6/7

5 microns of steel, 1.5 of uranium, 3.5 of Hydrogen std

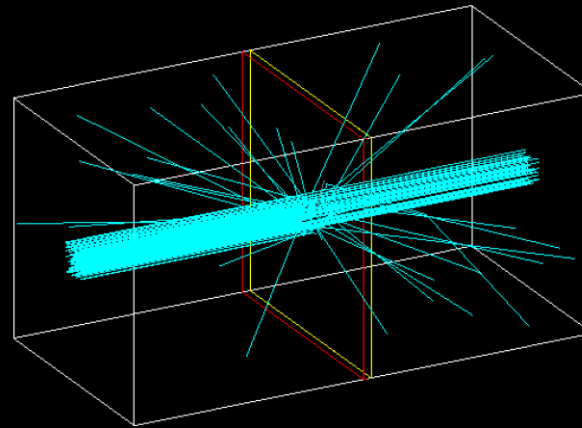
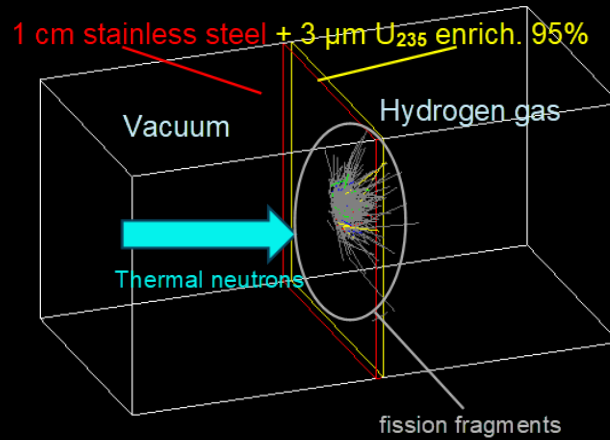




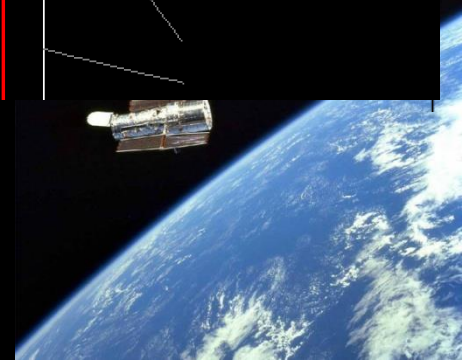
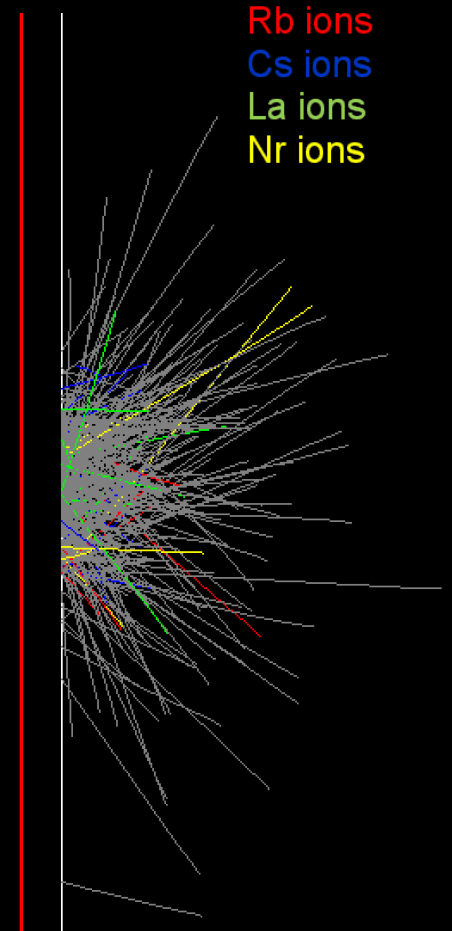
# The FF energy released to the layer 7/7

The Geant4 simulation  
FFs are highlighted with  
specific colours

The fotons contribution is  
hide



The no interacting neutrons  
simulation is shown in cyan



# Conclusions

Starting from the MAUS, a small-sized 30 kW nuclear reactor, the exploitation of its escape neutron source for a propulsion system has been hypothesized.

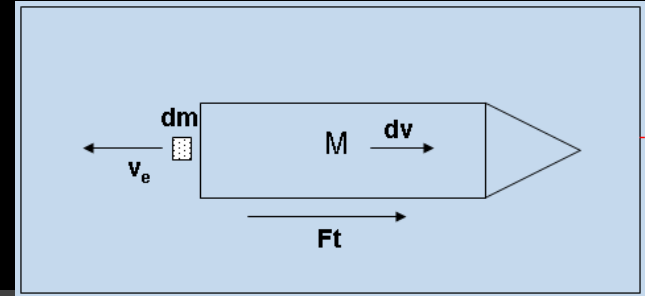
A model was created to simulate the behavior of a U235 thin fissioned slab by a thermal neutron flux to release energy through a neutral gas from the FFs.

- The code describes in particular the typology and behavior of FFs in terms of: angular distribution, mass, charge and energy. The generated data fits well with the experimental distributions.
- The model is useful not only for the design of a propulsion system but also as a complement to existing Monte Carlo codes used for transport calculations and design of nuclear systems.
- The interaction of FFs in a thin plate is studied by SRIM code by varying gase state and slab, also a Geant4 run was produced.
- The complete simulation system including transportation and conventional heating is under development, however from a first attempt to establish released energy and the erosion, it appears that much of the heating remains in the support material.



# Cenni sulla propulsione spaziale

**Spinta.** Dalla quantità di moto del sistema composto dal razzo e dal fluido espulso in un intervallo  $\Delta t$ , massa  $M$  e velocità  $V$  all'istante  $t$ , ad un sistema con massa  $M - \Delta m$  con velocità  $V + \Delta V$  e da un gas di massa  $\Delta m$  che si muove con velocità  $V - u_e$  ( $u_e$  è la velocità del getto relativa al razzo, supposta costante).



$$S = m \frac{dV}{dt} = F_e + \dot{m}_p u_e \rightarrow S = (p_e - p_a) A_e + \dot{m}_p u_e$$

**L'impulso specifico** ponderale è un parametro fondamentale per individuare le prestazioni di un propulsore; esso è definito come il rapporto tra l'impulso totale e la forza peso della massa di propellente consumato, ossia:

$$I_{sp} = \frac{I_{tot}}{m_c g_0}$$

Se  $S$  è il modulo del vettore spinta, l'impulso totale risulta come la spinta  $S$  per il tempo totale di combustione. L'impulso specifico ponderale definisce la spinta sulla portata ponderale  $\dot{\omega}$  di propellente consumato (portata in peso)

$p_e$  è la pressione sulla sezione di efflusso dell'ugello di scarico;  
 $p_a$  è la pressione ambiente, che dipende dalla quota ( $p_a = p_a(z)$ ). Nel caso di motore spaziale  $p_a = 0$ .  
 $A_e$  è l'area della sezione di efflusso dell'ugello.  
 $\dot{m}_p$  è la portata massica di propellente che fuoriesce dall'ugello.

$$I_{sp} = \frac{S}{\dot{\omega}} = \frac{S}{\dot{m}_c g_0} = \frac{u_0}{g_0}$$



<b>Propulsione</b>		<b><math>I_{sp}</math> (s)</b>
<b><i>Chimica</i></b>		
	<b>Propellenti liquidi</b>	<b>300-460</b>
	<b>Monopropellenti liquidi propellenti stivabili criogenici</b>	<b>250 400 500</b>
	<b>Propellenti solidi</b>	<b>180-265</b>
	<b>Propellenti ibridi</b>	<b>300-350</b>
	<b>LOX-LH2</b>	<b>435</b>
<b><i>Elettrica</i></b>		
	<b>Arcogetti</b>	<b>1000</b>
	<b>Resistogetti</b>	<b>300-400</b>
	<b>Motori a ioni (teoricamente fino a 100000 s)</b>	<b>3000- 5000</b>
	<b>Motori al Plasma</b>	<b>10000</b>
<b><i>Nucleare</i></b>		
	<b>Fusione</b>	<b>3000</b>
	<b>Fissione</b>	<b>1000</b>
<b><i>Radiante</i></b>		
	<b>Sole</b>	<b>700</b>
<b><i>Gas freddo</i></b>		
	<b>CO2</b>	<b>70</b>
	<b>He</b>	<b>200</b>



# Classificazione degli endoreattori

Gli endoreattori possono essere classificati in vari modi: secondo le tipologie di energia immagazzinata, trasformata e cinetica in gioco, secondo le velocità di propagazione, secondo le tipologie di alimentazione, etc

- o In funzione dello scopo della missione si hanno: **motori di accesso allo spazio** (detti veicoli di lancio, generalmente propulsione chimica (liquidi o solidi) e a più stadi (almeno due stadi); **motori da navigazione** (manovre orbitali del veicolo spaziale, correzioni di assetto, rifasamento sull'orbita, etc.)
- o In funzione dell'eventuale riutilizzabilità del propulsore, si hanno: propulsori a perdere (expendable). propulsori riutilizzabili (reusable) per successive missioni.

## Tipologie di energia negli endoreattori

L'energia primaria di un endoreattore è associata al serbatoio dei propellenti. Si può avere:

- **Energia primaria di tipo chimico**: l'energia chimica viene trasformata in termica nella camera di combustione. Si hanno propulsori a **propellente liquido (LP)**, **propellente solido (SP)**, **propellente ibrido (HP)** o **propellente gassoso (GP)**.
- **Energia primaria di tipo nucleare**, associata al nucleo atomico: si possono avere motori a decadimento isotopico oppure motori a fissione nucleare (progetto americano NERVA, testato a terra), fusione nucleare (solo in laboratorio).
- **Energia primaria di tipo elettrico**: si hanno **motori a ioni**, **al plasma** o ad **arco/resistenza**.
- **Energia primaria di tipo radiante**: la sorgente di energia è la radiazione solare (pannelli solari), laser (vele solari) o microonde.

L'energia secondaria o trasformata è di due tipi: elettrica o termica.

Gli endoreattori a energia trasformata di tipo termico sono i classici motori a razzo provvisti di una camera di combustione in cui avvengono le reazioni chimiche per la produzione del gas che viene poi accelerato tramite un ugello gasdinamico.

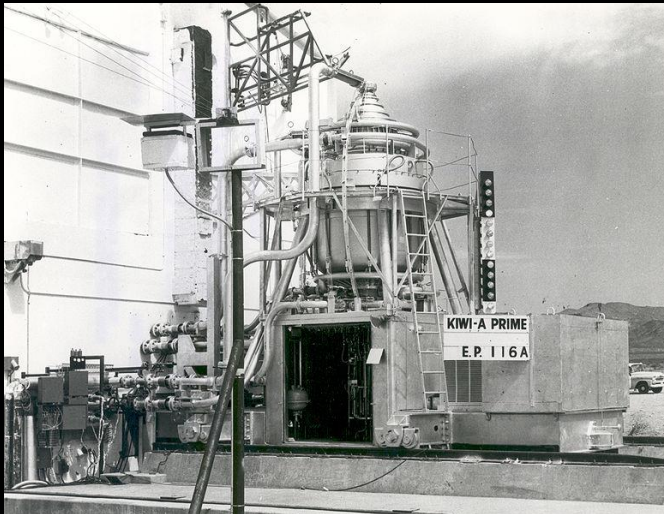
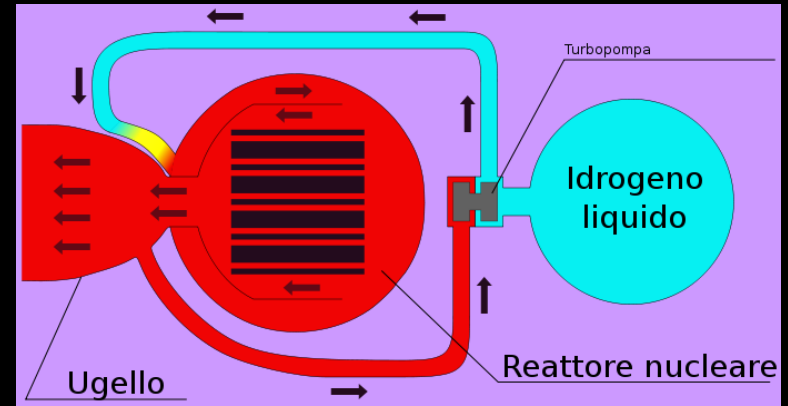




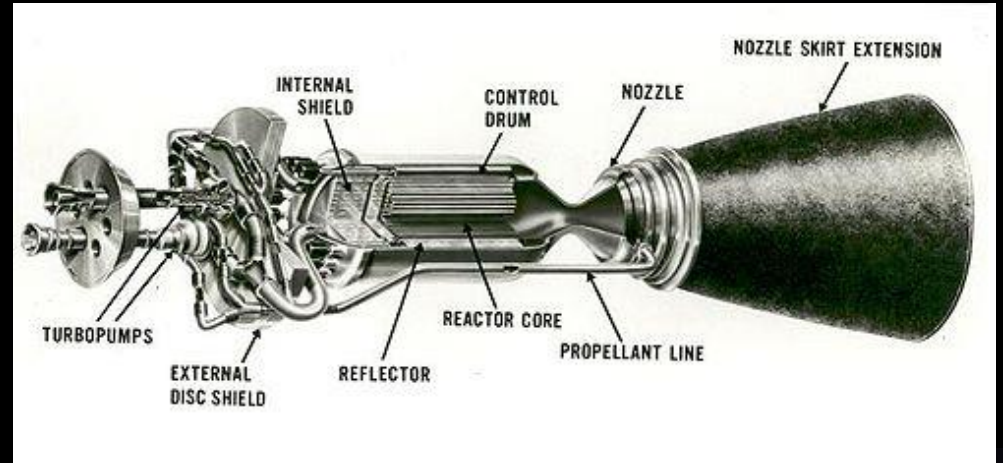
# Motori nucleari

Razzo termico nucleare  
Nucleo solido ( $I_{sp}$  800-1000s)\*  
liquido (miscele  $I_{sp}$  1500s)\*  
Gassoso ( $I_{sp}$  3000-5000s)\* v.dopo

\* Valori teorici



KIWI A



NERVA





# Motori nucleari

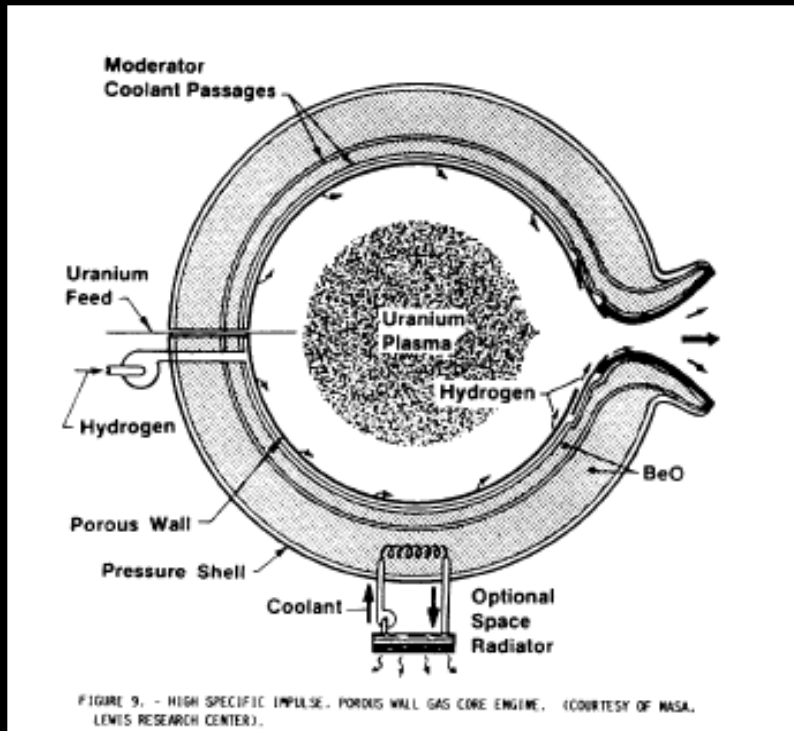
KIWI A distrutto volontariamente  
per un test di contaminazione



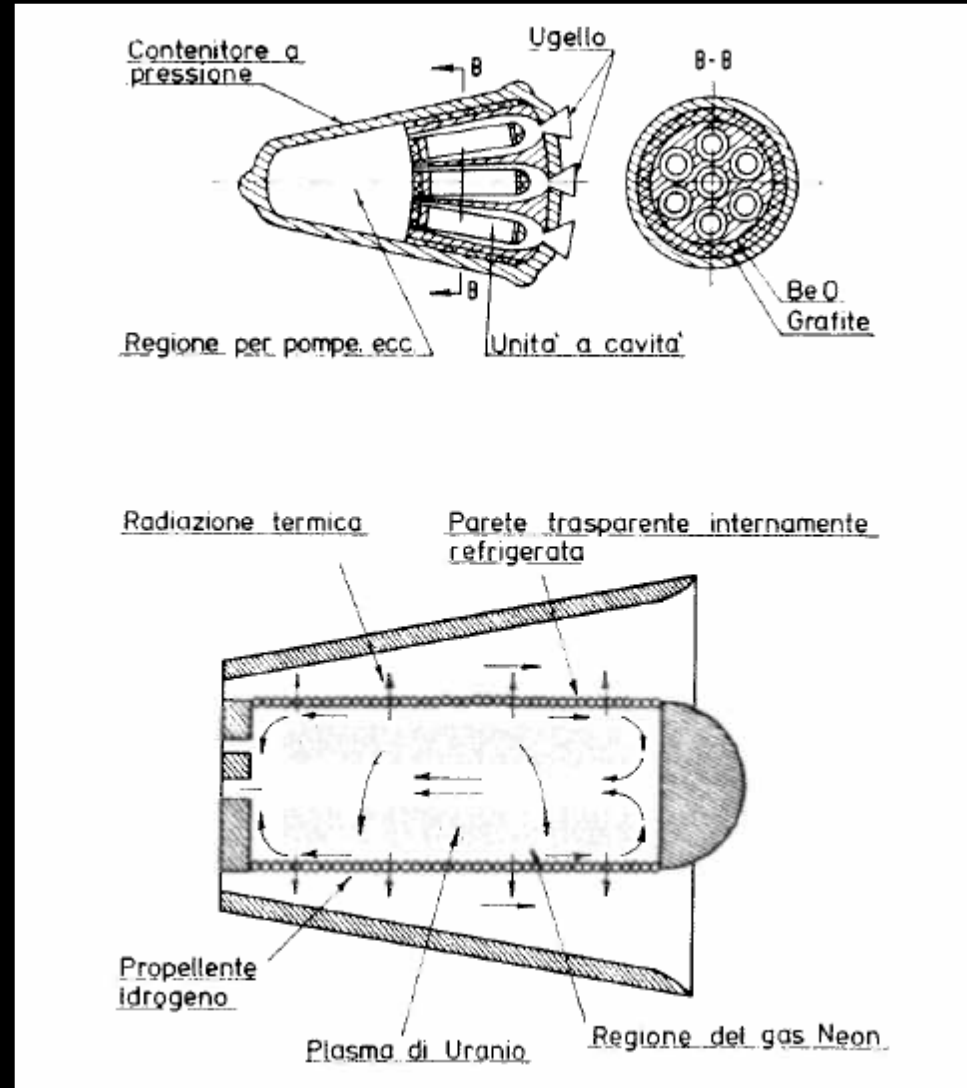
# Motori nucleari

Reattori nucleari a massa attiva gassosa ( $I_{sp}$  3000-5000s)

\* Valori teorici



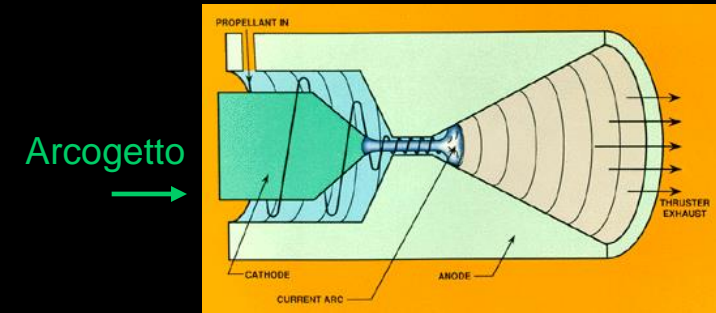
SRGCNR



LBGCNR

# Motori elettrici (ionici e al plasma)

Meccanismo di accelerazione	Impulso specifico (s)	Spinta (N)
<b>Accelerazione termogasdinamica</b> <i>Resistojet, Arcjet</i>	500 - 2000	0,15 - 0,30
<b>Accelerazione elettrostatica</b> FEEP, ionico a griglia elettrostatica, Radiofrequency ionisation thruster, <i>Helicon Double Layer</i> , Propulsore a effetto Hall	3 000 - 8 000	$10 \times 10^{-6}$ - $100 \times 10^{-3}$ - 1.5
<b>Accelerazione elettromagnetica</b> (forza di Lorentz), magnetoplasmadinamico (MPD) e LFA (Lorentz Force Accelerator), <i>Electrodeless plasma thruster</i> , <i>Pulsed plasma thruster</i>	1000 - 10 000	$1 \times 10^{-3}$ - 200



Propulsore magneto-plasmadinamico

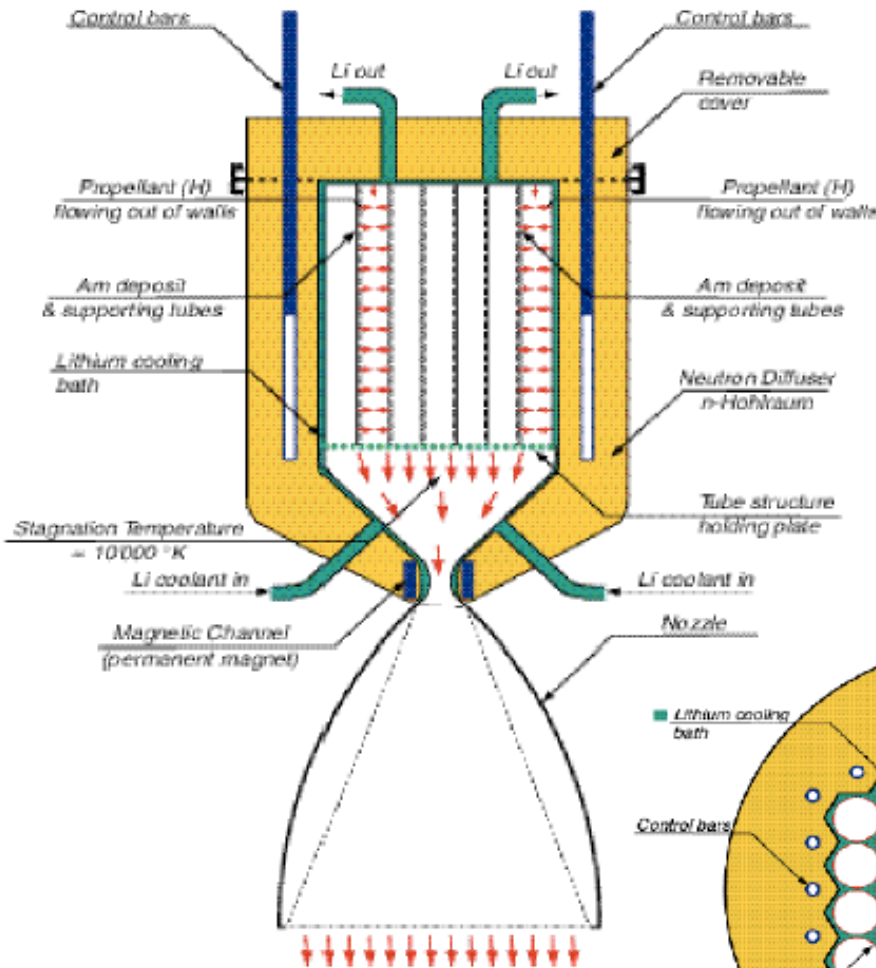


Propulsori a effetto Hall





# Il progetto P242



Nella propulsione indiretta con frammenti di fissione si utilizza l'energia dei frammenti stessi ( 80 Mev ciascuno) per riscaldare (ionizzazione) un gas a basso peso molecolare in opportuni sistemi termonucleari, che viene fatto espandere in un ugello.

- o Camera con pareti di grafite rivestite internamente da un sottile strato di fissile: Am242
- o All'interno della cavità viene fatto fluire H2, confinato da opportuni magneti permanenti che viene scaldato dai FF.

