Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

Attività ENEA sulla fusione nell'ambito della collaborazione con INFN

Presentato da M. Ciotti NUC-PLAS
In collaborazione con Fabio Panza

Outline

1. Lithium Technolgy for IFMIF-DONES
2. Contributo del Laboratorio NIXT (ENEA) ai programmi INFN-E e INFN n-ToF
3. Contributi ENEA all'ICRH per DTT
4. Laser-initiated p+11B fusion reactions
5. Reattori ibridi fusione-fissione per la produzione di trizio
6. ENEA-INFN sulla neutronica

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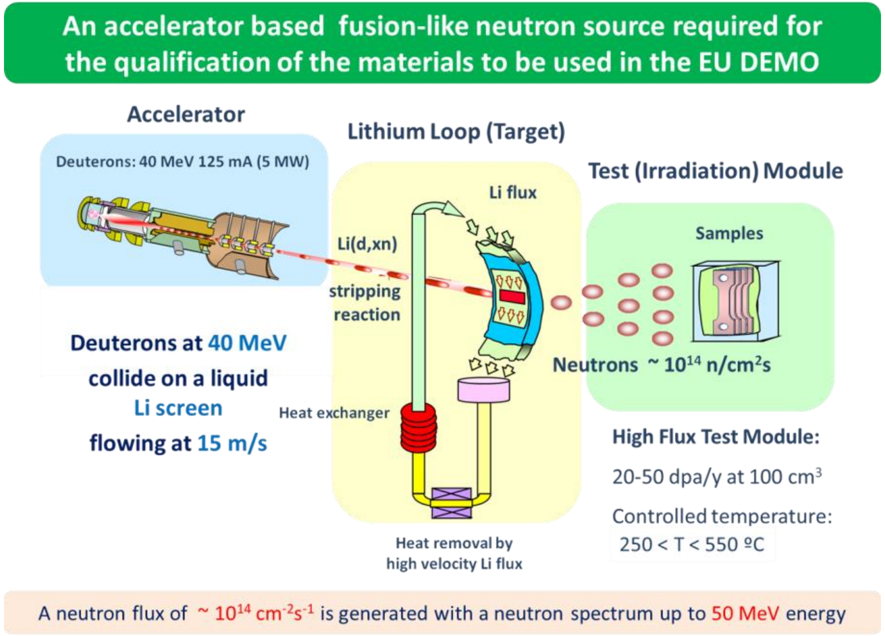
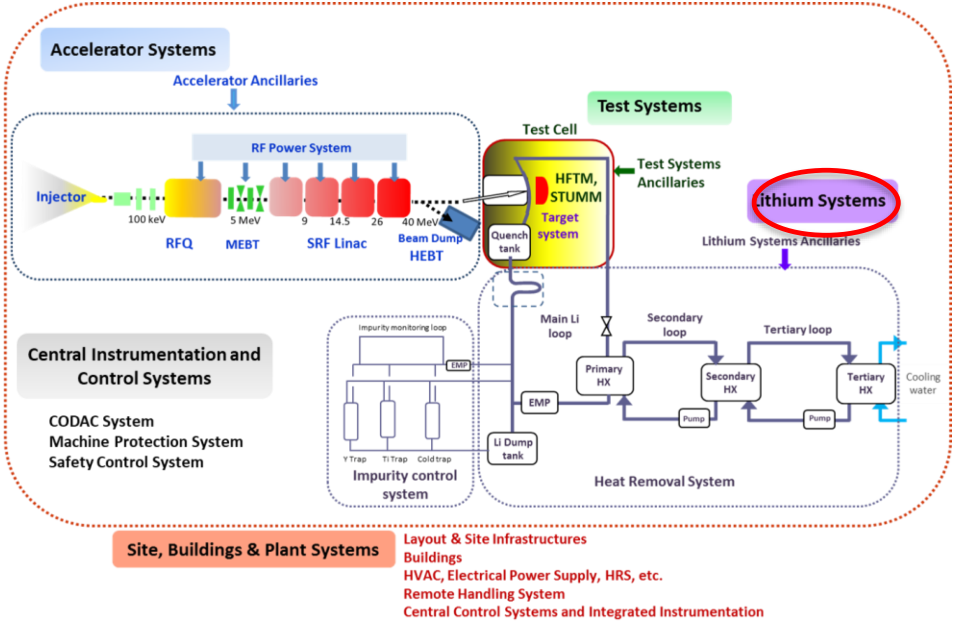
Lithium Technolgy for IFMIF-DONES

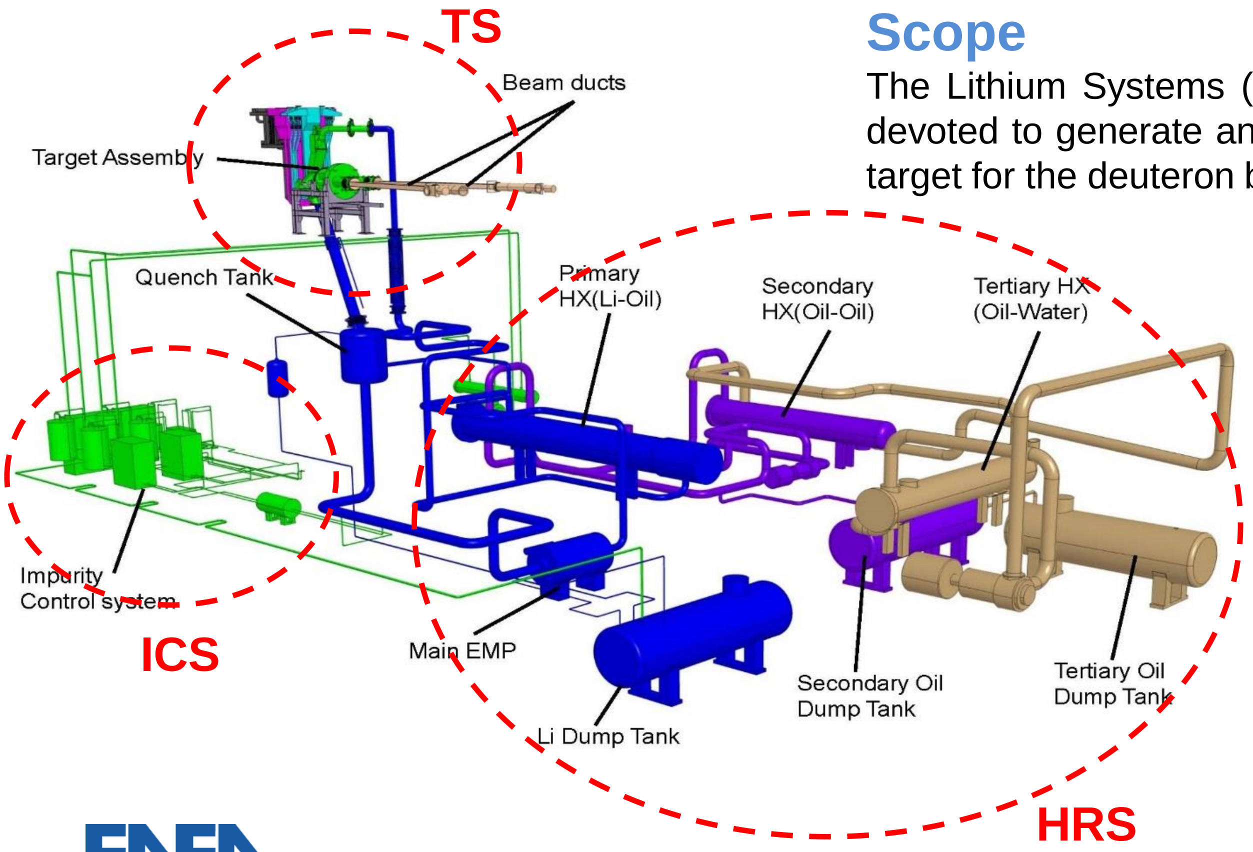
M. Tarantino, D. Bernardi, P. Favuzza, G. Miccichè, F.S. Nitti
Dipartimento Nucleare

IFMIF-DONES plant configuration





Lithium Systems overview



Scope

The Lithium Systems (LS) in the IFMIF-DONES plant are devoted to generate and maintain a stable flowing liquid Li target for the deuteron beam interaction

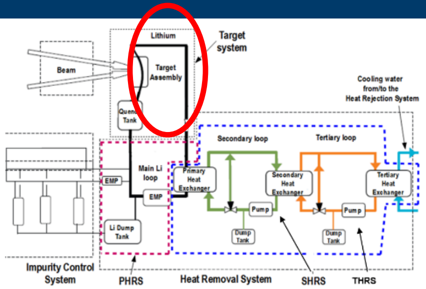
Four subsystems can be identified:

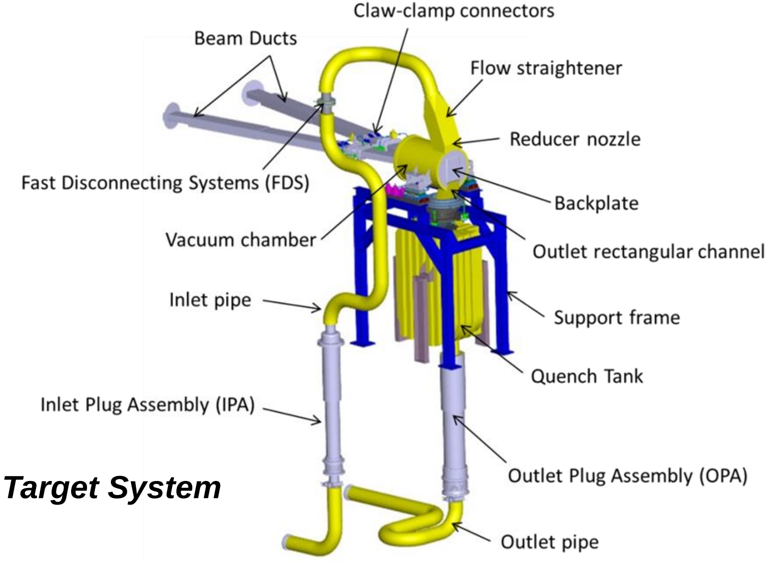
- *Target System (TS)*
- *Heat Removal System (HRS)*
- *Impurity Control System (ICS)*
- *Ancillary Systems (LSA)*

Target System

The Target System is the core of the plant, it has two main functions:

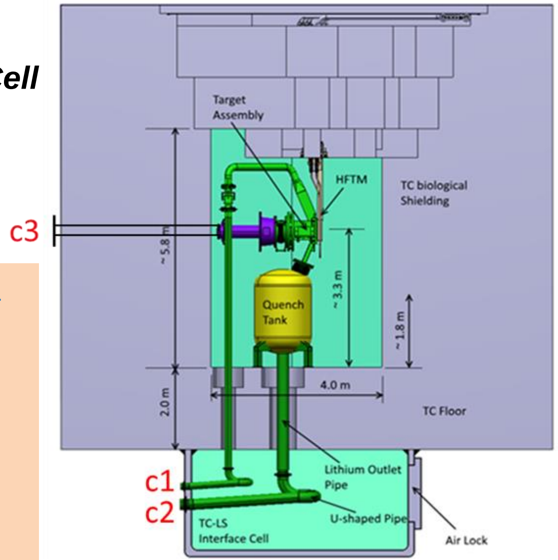
- Stop the deuteron beam, by means a flowing lithium target, and generate the neutron field for the High-Flux Test Module (HFTM) irradiation
- Remove the thermal power deposited by the beam





Target System

Test Cell



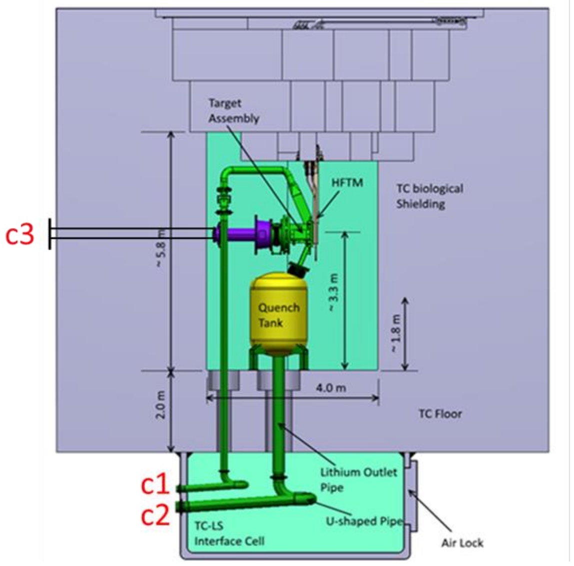
Heat flux: 500 - 1000 MW/m^2
Li jet thickness: 25 ± 1 mm
Li inlet T: 300 °C
Li velocity: 15 m/s
Chamber pressure: 10^{-2} Pa
Main material: EUROFER-97

Target System

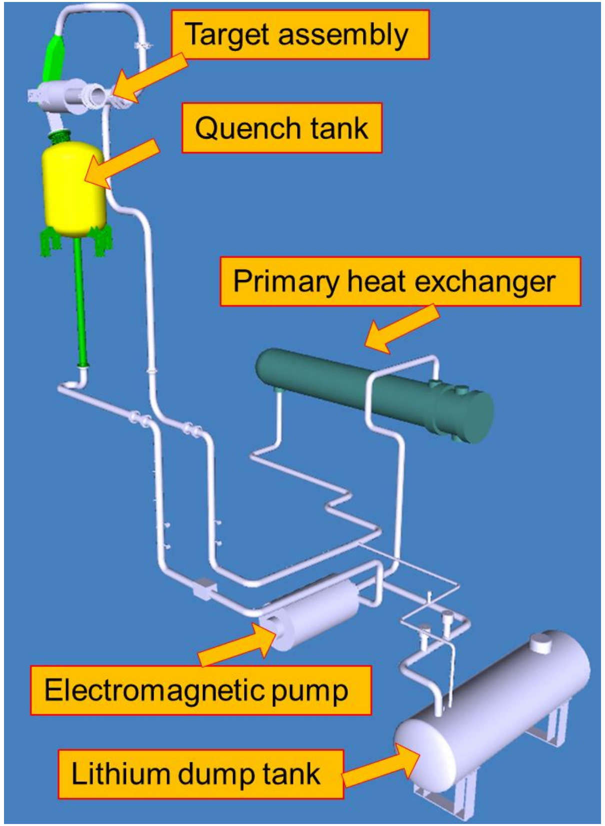
Very challenging system:

- High heat flux (up to 1 GW/m^2)
- Strong nuclear (neutron+gamma) radiation
- RH compatible
- High vacuum operation
- Extremely accurate tolerances and dimensional precision
- High availability (1 fpy of continuous irradiation)

Design well advanced!
Main contribution from ENEA during the past IFMIF-EVEDA project and EUROfusion WPENS FP8



HRS - Primary Li Loop



The **Primary Loop** is the main circuit of the Heat Removal System whose function is to remove the thermal power produced by the beam in the Target Assembly. Lithium, flowing in the Primary Loop, transfers its heat duty to the Secondary Loop through the "Primary Heat Exchanger" (Li-oil HX)

ITEMS	SPECIFICATIONS
Fluid	Liquid Lithium
Design temperature	350°C
Design pressure	0.76 MPa (g)
Maximum Flow Rate	0.104 m^3/s
Piping Flow Speed of Lithium	< 6 m/s
Material	Stainless Steel 316L
Pipe nominal diameter	6"
Pipe internal diameter	154.1 mm
Pipe schedule	40

Update design is being developed by a EU Industrial Consortium (Ansaldo Nucleare, Empresarios Agrupados, Framatome).

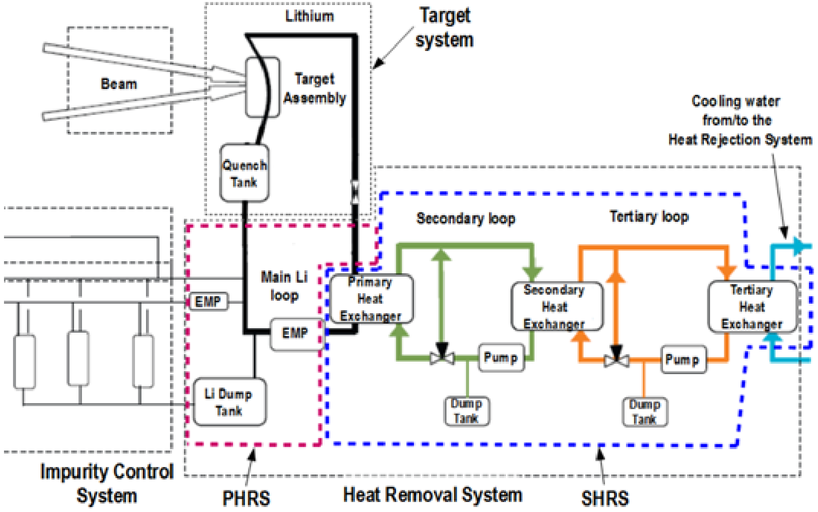
HRS - Secondary and Tertiary Loops

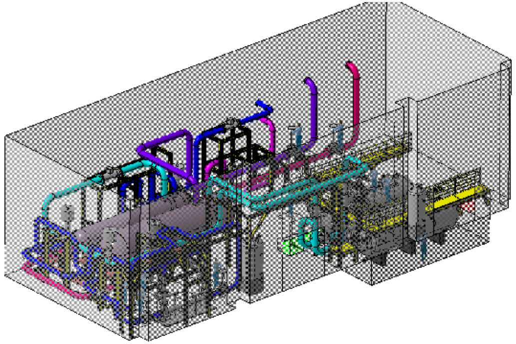
These subsystems are devoted to evacuate the thermal power deposited in the lithium by the D+ beam towards the general water cooling system of the plant

Two oil loops in series are foreseen:

- Secondary oil loop incl. Li-oil & oil-oil HXs
- Tertiary oil loop incl. oil-water HX

No direct contribution from ENEA/Italy in the past but it might be of future potential interest for the Italian industry





Overall view of the layout

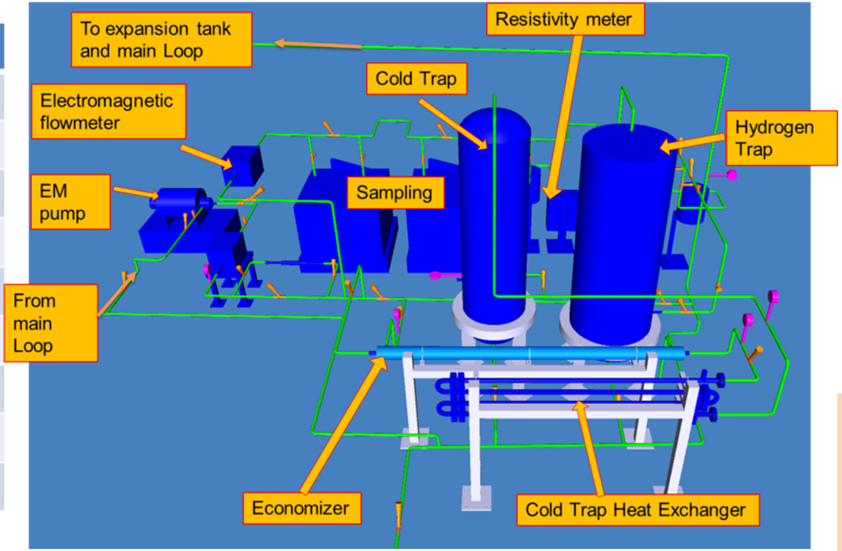
Impurity Control System (ICS)

The **Impurity Control System** is a branch circuit of the Primary Lithium Loop and it is designed to fulfil the following functions:

- Confine the sources of radioactivity such as **Tritium, Beryllium-7 and activated corroded/eroded metallic elements**
- Monitor and control **impurity levels in the Li loop** (including O, C, N, Be, H, T etc…)

The ICS consists of a main loop - Impurity Control Loop - and one daughter sub-loop, the Impurity Monitoring Loop; the first is dedicated to impurity removal, by means of a Hydrogen Trap and a Cold Trap, while the second is a sampling/analysis system.

ITEMS	SPECIFICATIONS
Fluid	Liquid Lithium
Design temperature	350°C
Design pressure	0.16 MPa (g)
Maximum Flow Rate	0.65 l/s
Material	Stainless Steel 316L
Pipe nominal diameter	3/4”
Pipe internal diameter	20.9 mm
Pipe schedule	40
Pipe total lenght	≈ 80 m



ENEA is involved since a long time in the definition of the lithium purification procedures; Li sampling and off-line analyses; corrosion/ erosion studies (Lifus 6 loop)

Update design of ICS is being developed by a EU Industrial Consortium (ANN, EAI, FA).

ENEA

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INFN

Contributo del Laboratorio NIXT (ENEA) ai programmi INFN-E e INFN n-ToF

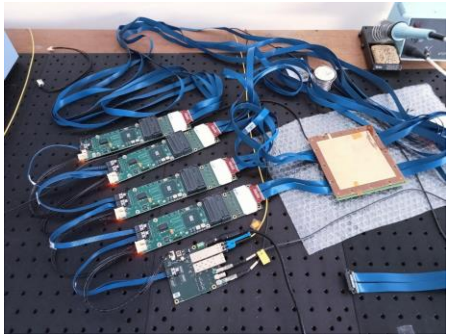
G. Claps, D. Pacella, F. Cordella, V. De Leo, A. Tamburrino, V. Piergotti

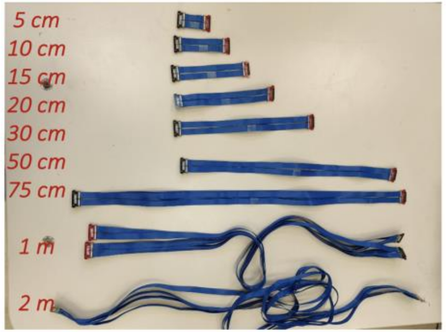
Contributo del Laboratorio NIXT (ENEA) ai programmi INFN-E e INFN n-ToF

G. Claps, D. Pacella, F. Cordella, V. De Leo, A. Tamburrino, V. Piergotti

GEM Gas Detector for X-ray radial camera of ITER

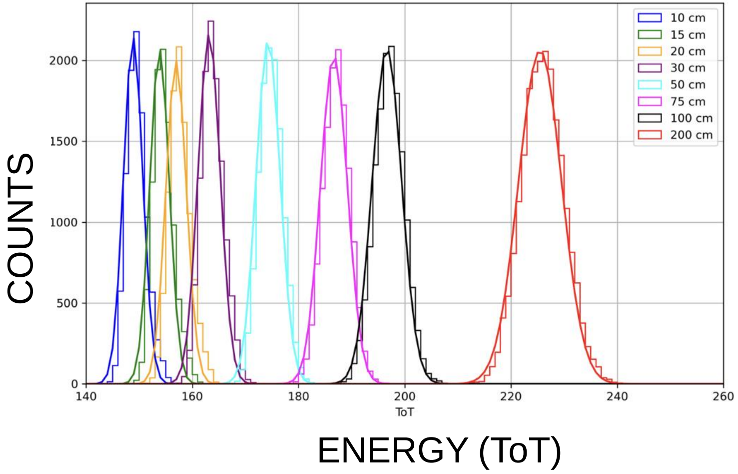
Development of a GEM gas detector with remote front-end electronics for X-ray radial camera of ITER under high fusion neutron fluxes (**10^7 n/s/cm²**)





Cable lengths

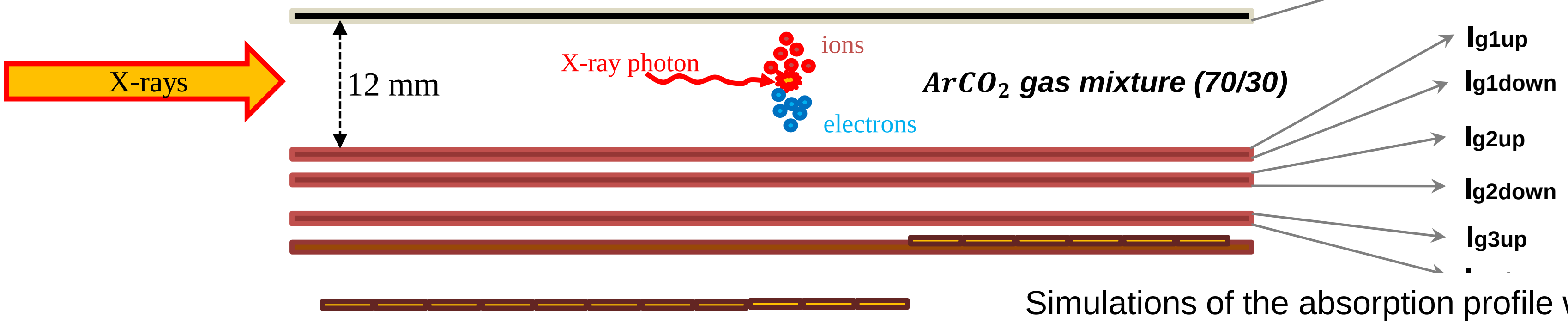
Response to a monoenergetic input



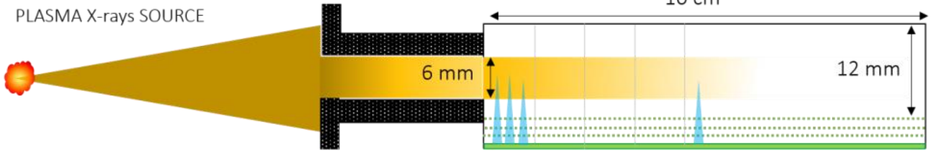
The side entrance X-ray GEM camera, with its f.e. electronics shielded and located 1-2 meters away, can operate at ITER in the 10-80 keV energy range, even with a 14 MeV neutron flux of **10^7 n/s/cm²**

Soft X-ray spectroscopy for Laser Plasmas with side-on GEM detector

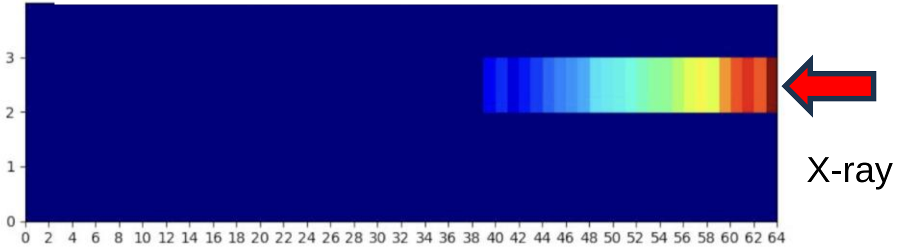
The X-ray spectrum is derived by the absorption profile



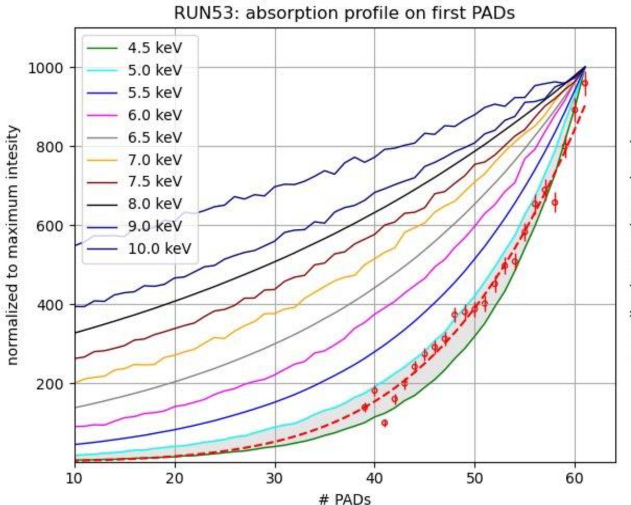
Side-on GEM detector



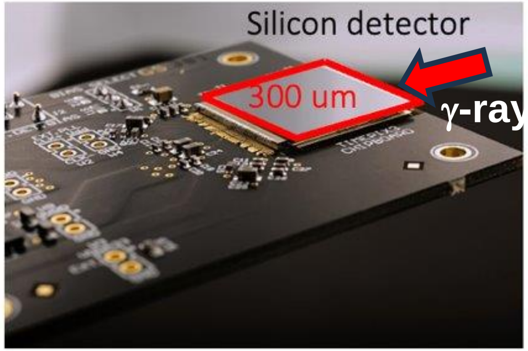
X-ray absorption in the Ar/CO2 gas mixture



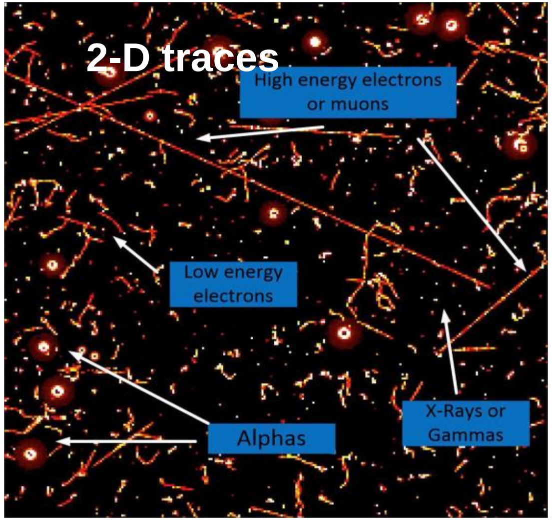
Simulations of the absorption profile with different temperatures of the ablated plasma



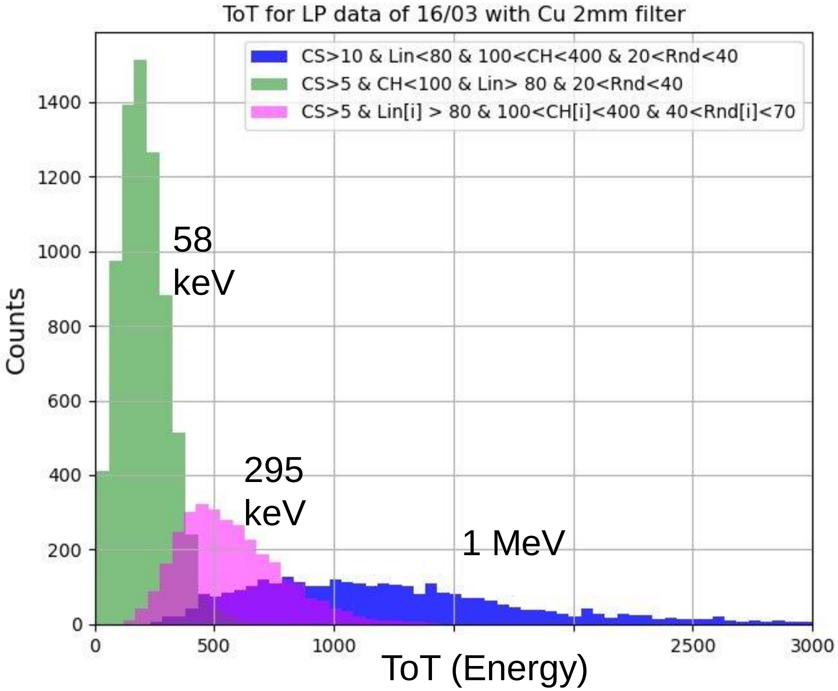
Gamma-ray diagnostic for Laser Plasmas with a side-on silicon Timepix3 detector by means of the 2-D morphology of the traces



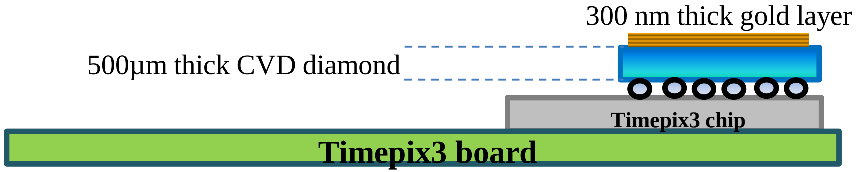
14 x 14 mm^2 detector

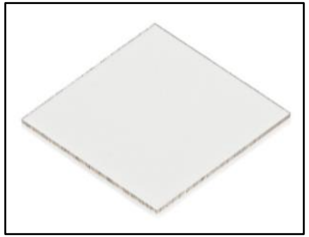


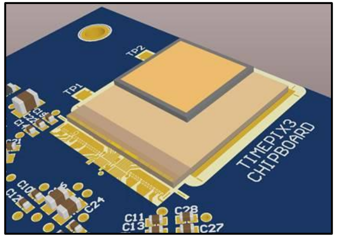
Two major gamma-ray emissions are observed at 58 keV and 295 keV, with a tail extending to 1MeV

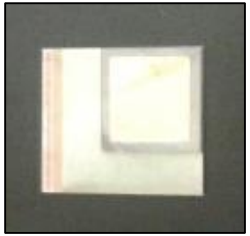


Diamondpix detector for fast neutron detection in nuclear fusion

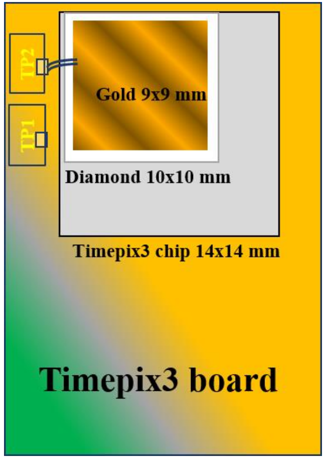


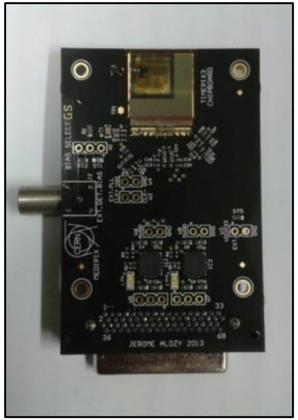




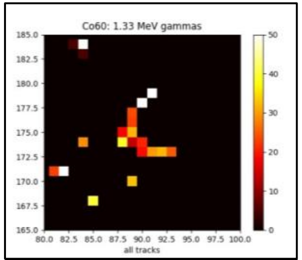


A CVD polycrystalline diamond has been bump-bonded to a Timepix3ASIC

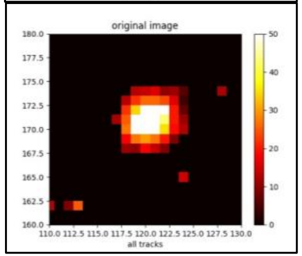




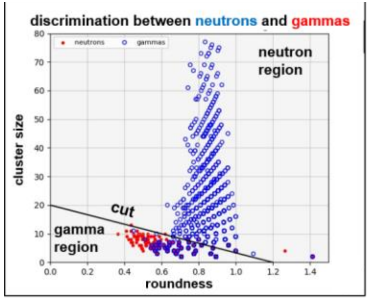
gamma track



neutron track

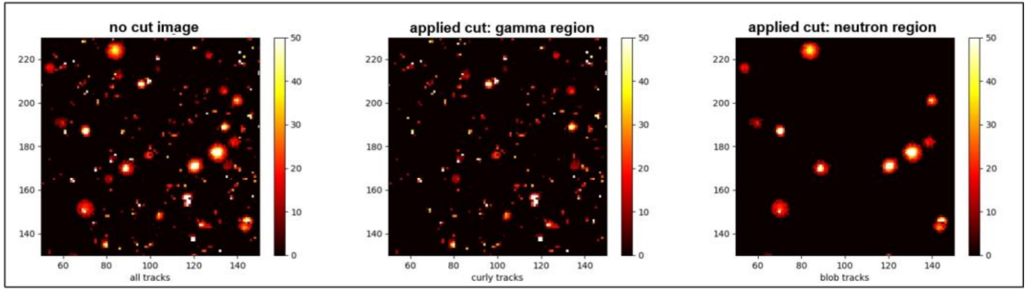


FNG facility, ENEA Frascati



Neutrons discrimination against gammas

14 MeV neutrons



An algorithm has been developed to select tracks based on their morphological parameters and released charge

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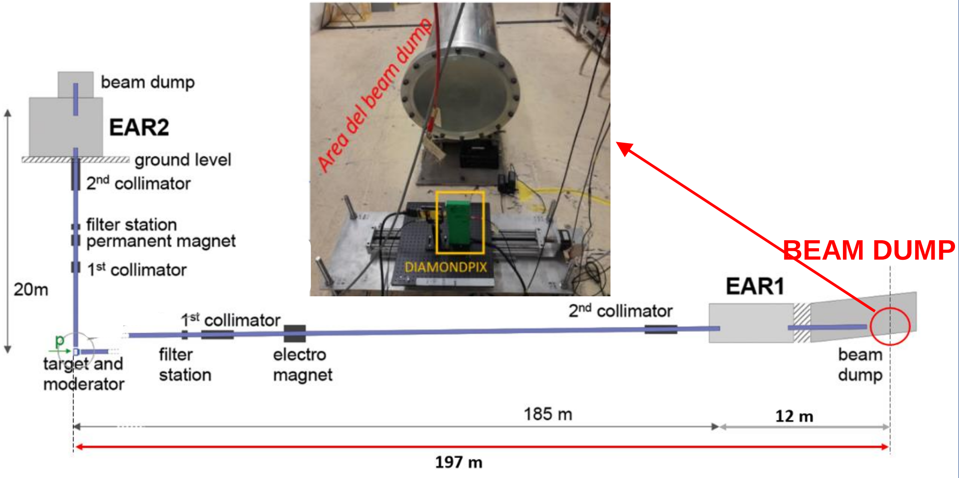
G. Claps et al., Diamondpix: A CVD diamond detector with timepix3 chip interface, IEEE Trans. Nucl. Sci. **65** (2018) 2743

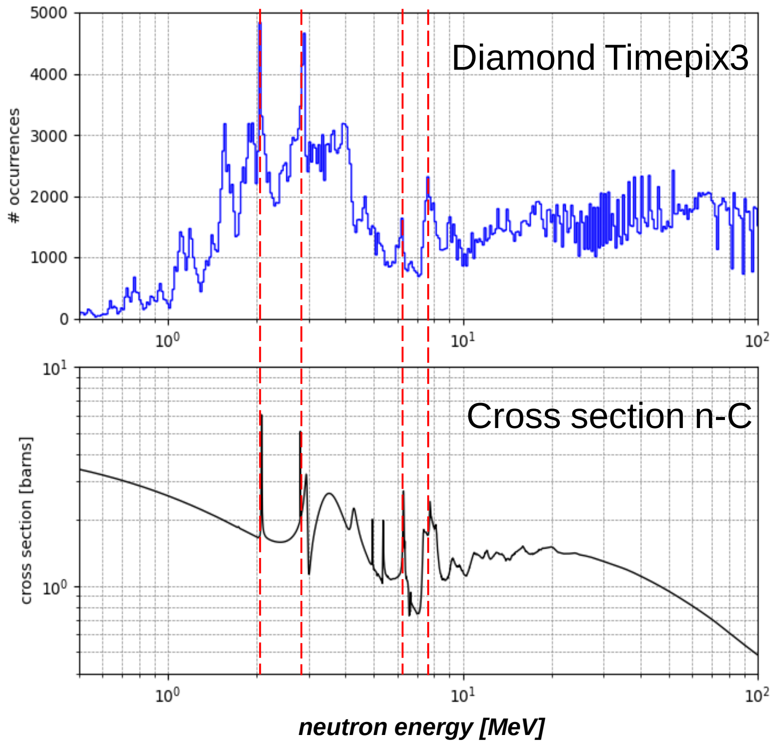
Time of flight measurements on the n_TOF facility (CERN)

Experimental set-up on the n_TOF facility



ACQUISITION PARAMETERS

- **TPX3 was controlled by the Katherine module**
- **DATA-DRIVEN MODE**
- **ACQUISITION MODE: ToT & ToA (charge and time)**
- **Acquisition time window: 150 ms (1 GeV – 10 meV)**



Several ToF peaks corresponding to carbon resonances are observed, validating the spectrum reconstruction and enabling the selection of the desired energy range

ENEA

Contatti

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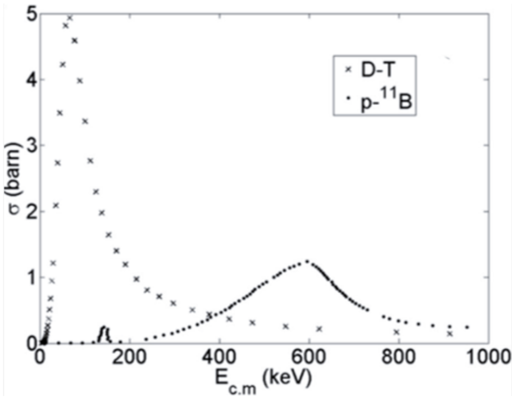
Laser-initiated p+^{11}B fusion reactions

F. Consoli (ENEA), G. A. P Cirrone (INFN)

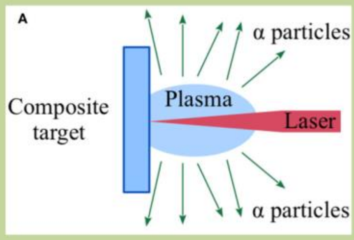
Laser-initiated p+^{11}B fusion reactions

F. Consoli (ENEA), G.A.P. Cirrone (INFN)

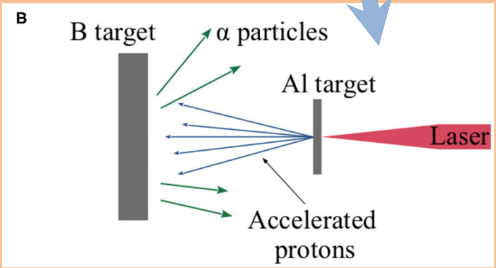
- $^{11}B(p,\alpha)2\alpha$ fusions by means of laser-plasma interaction demonstrated [1-2].
- A significant yield achieved → potential future employment in non-thermal conditions for
- energy production and other applications. <u>Institutions and company involvement</u>
- Study of low-rate nuclear reactions in plasmas also important for astrophysical researches
- Two main approaches. Scheme A: "in-target" and B "pitcher-catcher", with energetic nanosecond and picosecond pulsed lasers.

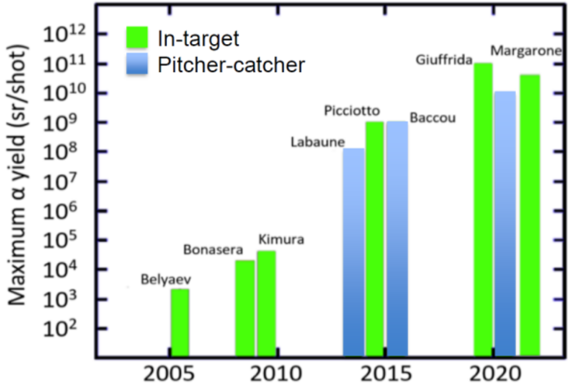


<u>Scheme A</u>. H and B plasma by laser pulses on composite targets: i.e. B-doped plastic or Si enriched with H and B. ns and/or ps laser pulses.



<u>Scheme B</u>. Laser accelerated protons sent to a boron target or to a boron plasma. ps or fs laser pulses



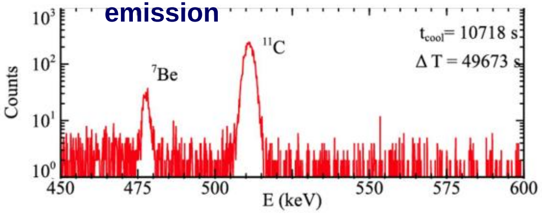


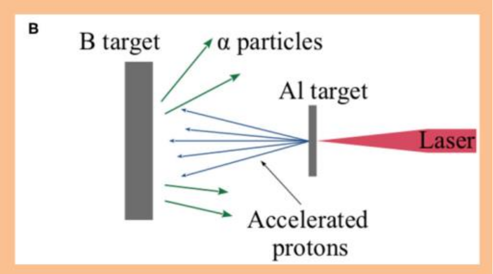
[1] VS Belyaev et al, Phys Rev E. (2005) 72, 026406; [2] A. Picciotto et al, Phys Rev X. (2014) 4, 031030; [3] DC Clayton. Principles of Stellar Evolution and Nucleosyntesis. Chicago Press (1983); [4] F. Consoli, et al, Front. Phys. (2020) 8, 561492

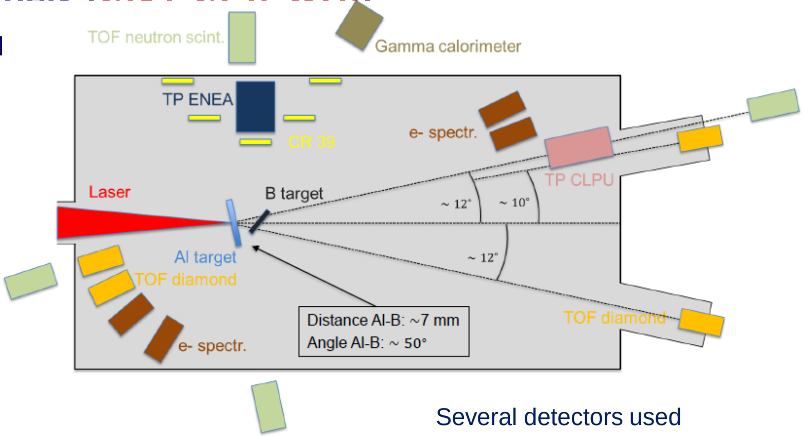
Pitcher-catcher experiments in high repetition rate femtosecond laser (1) - 2022

- **Previous experiments with significant alpha yields were performed with energetic and single pulse lasers. Alternative: exploiting of high energy and high repetition rate lasers.**
- **Broad collaboration: ENEA (PI), INFN-LNS, Texas A&M University (US), University of Tor Vergata, University of Perugia, University of Pisa, University of Bordeaux (FR), Institute of Plasma Physics and Laser Microfusion (PL), Queen's University of Belfast (UK), ELI Beamlines (CZ), Institute of Plasma Physics of Czech Academy of Sciences (CZ)**
- **VEGA III Petawatt Laser, CLPU, Salamanca, Spain: 30 J, 200 fs, $5 \cdot 10^{19}$ W/cm^2 intensity on 6 μm Al target**
- **Significant activation (^{11}C, ^{7}Be) produced on ^{11}B, sign of p+^{11}B fusions in activation on secondary targets (^{67}Ga, ^{67}Cu, ^{63}Zn)**
- **Clear signature of alpha pa**

Gamma radioactive emission

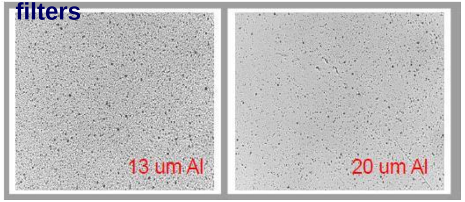






Several detectors used

Tracks on CR39 detectors with Al filters



[1] M. Rodrigues et al, Matter Radiat. Extrem., 2024; [2] M. Scisciò et al, submitted Matter Radiat. Extrem., [3] K. Batani at al, subm HPLSE; [4] M Hualt et al, subm Phys Plasmas

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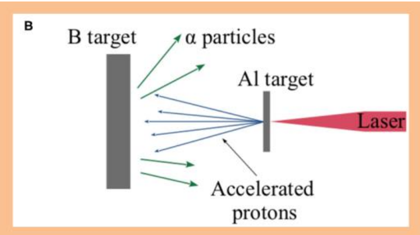
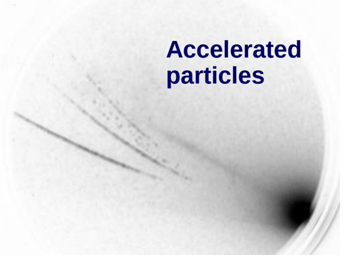
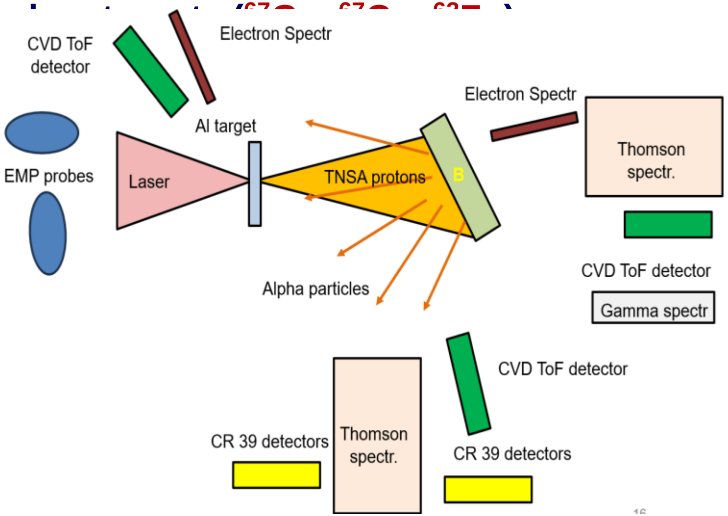
INFN Istituto Nazionale di Fisica Nucleare

Pitcher-catcher experiments in high repetition rate femtosecond laser (2) - 2024

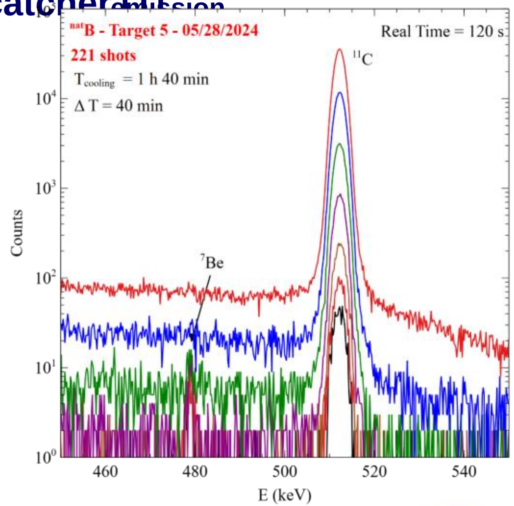
- **Previous experiments with significant alpha yields were performed with energetic and single pulse lasers. Alternative: exploiting of high energy and high repetition rate lasers.**
- **Broad collaboration: ENEA (PI), INFN-LNS, Texas A&M University (US), University of Tor Vergata, Università di Milano Bicocca, University of Bordeaux (FR), Institute of Plasma Physics and Laser Microfusion (PL), ELI Beamlines (CZ), Institute of Plasma Physics of Czech Academy of Sciences (CZ)**
- **L3-ELIMAIA, ELI-BEAMLINES, Czech Republic: 10 J, 25 fs, 5 · 10^{20} W/cm^2 intensity on 6 μm Al target**
- **Significant activation (^{11}C, ^{7}Be) produced on ^{11}B, sign of p+^{11}B fusions in B catcher [1]**
- **Significant activation on secon**
-







Gamma radioactive emission [1]



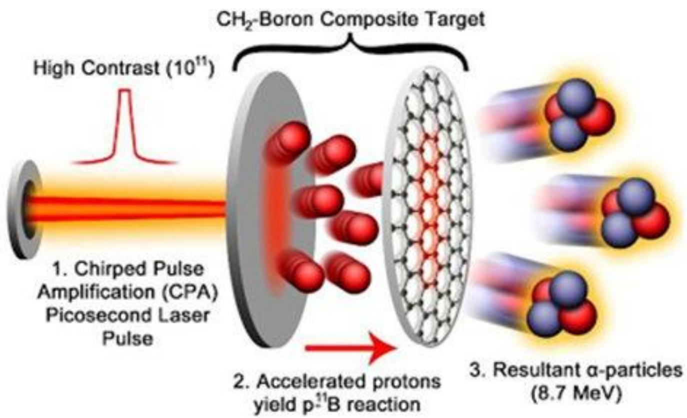
[1] M. Rodrigues et al, Matter Radiat. Extrem., 2024; [2] M. Scisciò et al, submitted Matter Radiat. Extrem., [3] K. Batani at al, subm HPLSE; [4]M Hualt et al, subm Phys Plasmas

The Italian “FUSION” initiative

FUsion StudIes of prOton boron Neutronless reaction
in laser-generated plasma

Financed by INFN,
Spokepersons: GAP Cirrone
(INFN) and F Consoli (ENEA)

Laser induced p-^{11}B reactions in both in plasma and pitcher-catcher configuration



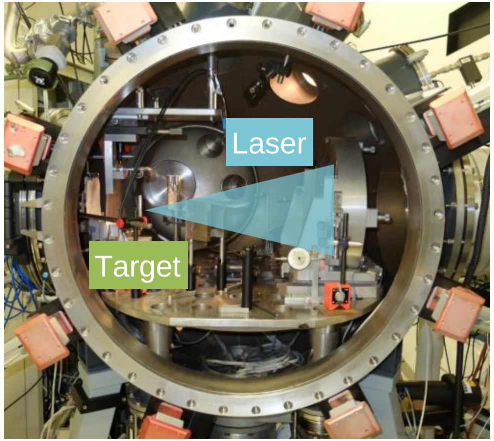
Basic understanding of fusion mechanism in plasma

Realisation of new targets for the p11B reaction improvement

Development of new diagnostics

Maximisation of the alpha yields in plasma

Ion stopping power measurements in plasma and development of new computational approach

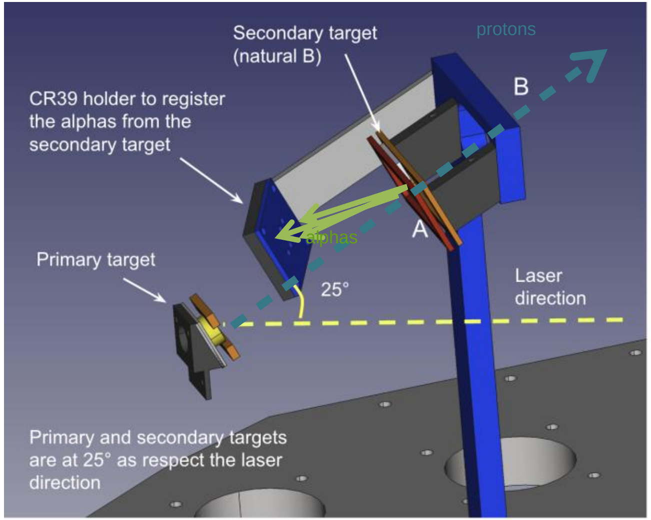


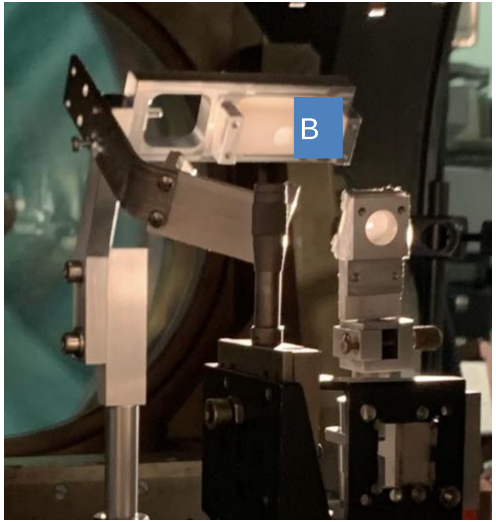
Consoli F et al., (2020) Front. Phys. 8:561492

Cirrone, Giuffrida et al. (2020)Phys Rev E 2020 Jan;101(1-1):013204.

The PALS interaction chamber (Prague, CZ)

FUSION first experiments, Feb 2024, PALS, Prague





Four different targets

Diagnostics: Time of Flight, Thomson Spectrometer, gamma detectors, electron spectrometers

6 MeV protons measured in backward

Boron activation measured

Analysis is ongoing

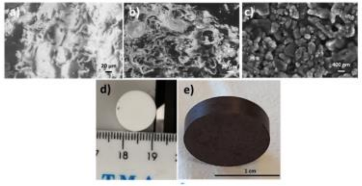
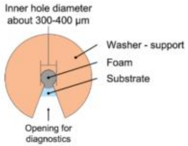


Figure 16. SEM pictures of target surfaces: a) reference; b) resin/boric acid 2:1 wt.; c) resin/boron 2:1 wt.; d) picture of a typical reference target; e) target of resin/boron 5:1



Contatti

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Agenzia nazionale per le nuove tecnologie,
l’energia e lo sviluppo economico sostenibile

Contributi ENEA all’ICRH per DTT

S. Ceccuzzi (ENEA), D. Mascali (INFN)

Design activities for the ICRH system of DTT

Solid-state transmitters → **task ITP**: ENEA, eni

Transmission line & matching, feedthrough, integration → **task ILP**: ENEA, Università di Roma Tor Vergata, Create

Antennas → **task IAP**: ENEA, Create, INFN LNS (Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud), Politecnico di Torino

INFN-LNS and ENEA contribute together to the design of DTT ICH antenna

ENEA contribution to the ICRH system of DTT (1/4)

Enea contribution to this joint activity mostly concern:

- contribution to RF design and modelling,
- analysis & design of cooling circuit,
- antenna shape and diagnostics.

Contributors

- Reference person at INFN: **D. Mascali**
- Reference person at ENEA: **S. Ceccuzzi**
- ENEA contributors: N. Badodi, A. Del Nevo, M. Eboli, F. Giorgetti, M. Iafrati, P. Maccari, R. Marinari, G.L. Ravera.

ENEA contribution to the ICRH system of DTT (2/4)

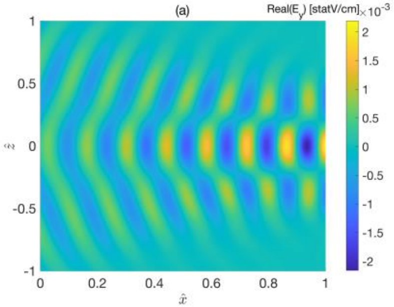
Enea contribution to this joint activity mostly concern:

- contribution to RF design and modelling, →
- analysis & design of cooling circuit,
- antenna shape and diagnostics.

- Fruitful cooperation in the **design**, with development and successful benchmark of advanced design tools:

Coupled power [a.u.] vs. P_{cen}/P_{out} and Δϕ respectively varying in the ranges [0.1-10], [-40,40], with P_{cen} (P_{out}) = coupled power by central (lateral) straps, and Δϕ = phasing deviation from 0π0

- Strong interaction on the **modelling** of plasma waves, also thanks to visits of ENEA staff to INFN- LNS in 2021 and vice versa in 2023 and 2024.

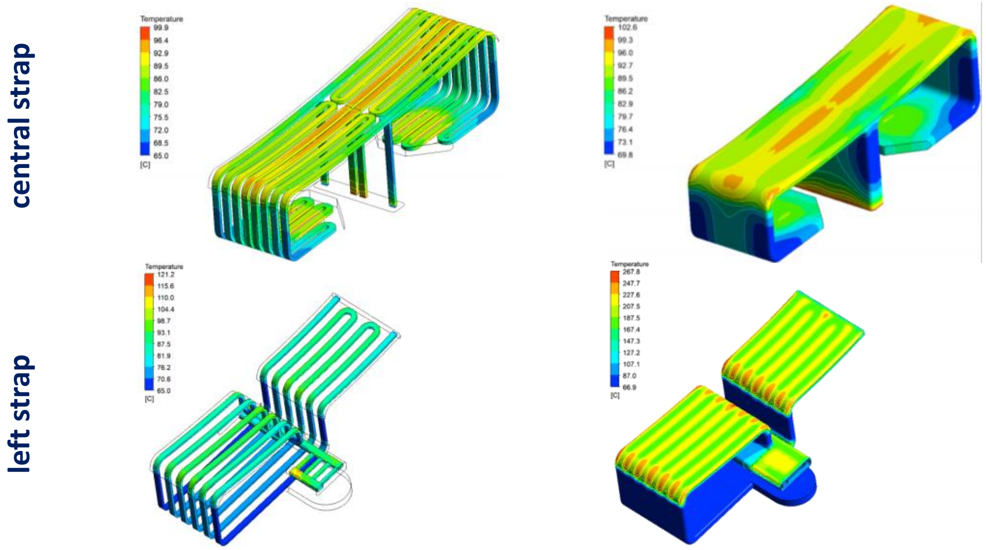


ENEA contribution to the ICRH system of DTT (3/4)

Enea contribution to this joint activity mostly concern:

- contribution to RF design and modelling,
- analysis & design of cooling circuit, →
- antenna shape and diagnostics.

- Strong efforts by ENEA-Brasimone in studying how to cool different antenna parts, e.g.:



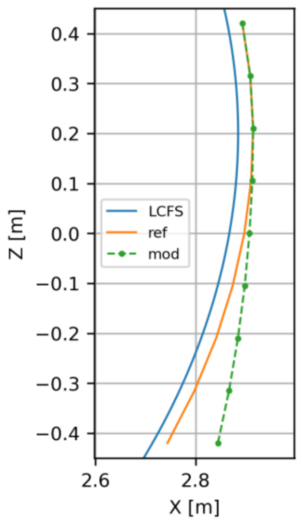
R. Marinari, NURETH-20, 2023
R. Marinari, 33rd SOFT, 2024

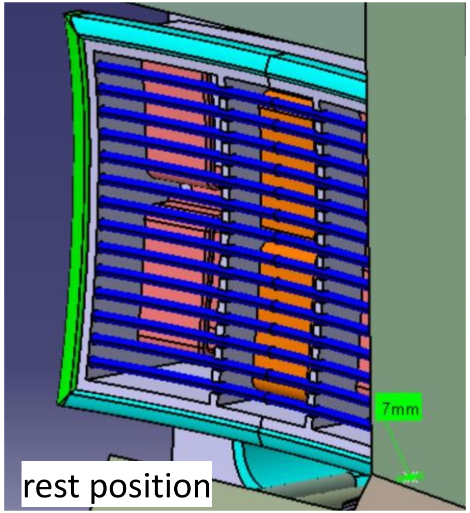
ENEA contribution to the ICRH system of DTT (4/4)

Enea contribution to this joint activity mostly concern:

- contribution to RF design and modelling,
- analysis & design of cooling circuit,
- antenna shape and diagnostics. →

- Toroidal and poloidal curvatures were defined, looking for a trade-off between plasma shape in the single-null scenario and the antenna shadowing by the first wall when in rest position.





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Reattori ibridi fusione-fissione per la produzione di trizio

F. Panza (ENEA), M. Ripani (INFN)

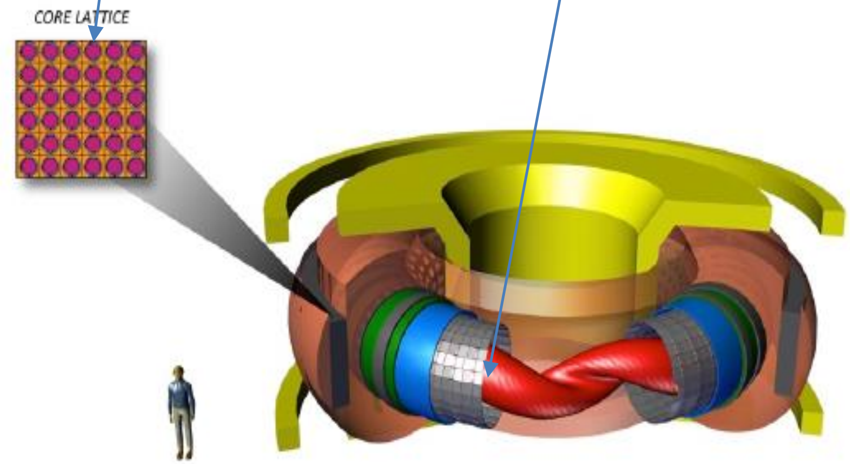
Fusion-fission hybrid systems

In a hybrid reactor, the neutron flux emerging from **nuclear fusion reactor** is used to induce fissions (or transmutations) in a **fission blanket** in subcritical mode (k<1).

FFHS can be used for:

- Energy generation
- Radioactive waste transmutation
- Nuclear fuel production (fertilization)
- **Tritium breeding (currently produced by CANDU reactors)**

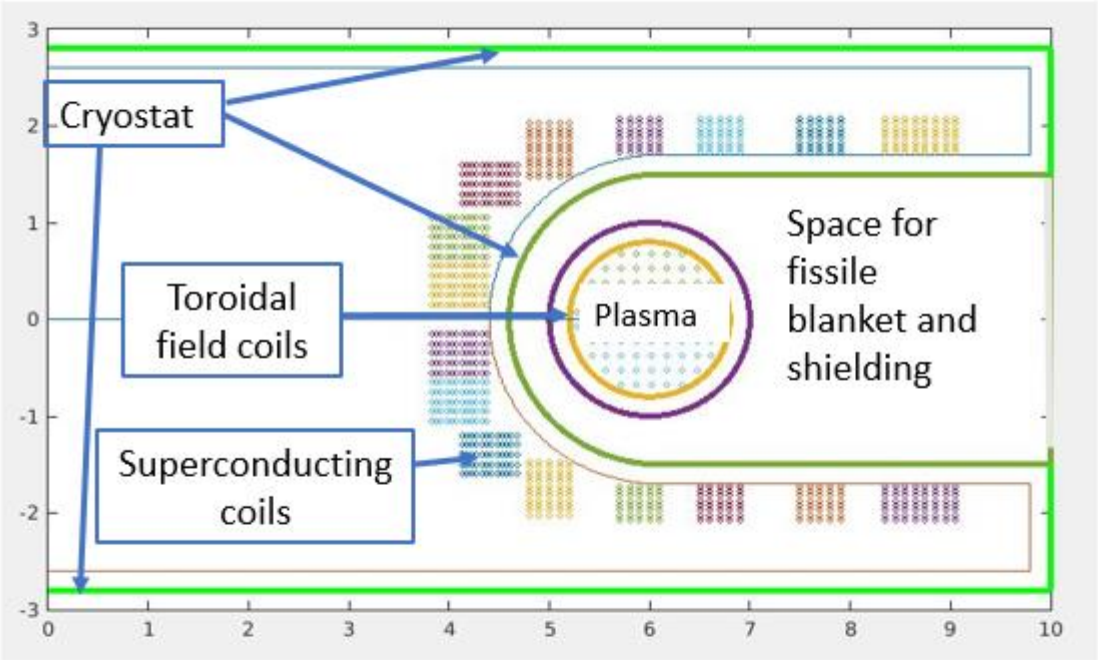
These systems could represent an intermediate step towards the industrializatio of nuclear fusion



RFP fusion core

Machine section and performances

R = 6 m
a = 0.8 m
Plasma current = 11.6 MA
T_e = 11.3 keV
$P_{ohmic\_heating}$ = 70 MW
P_{fusion} = 108 MW
P_{alfa} = 21.6 MW
$P_{neutron}$ = 86.4 MW
n = 3.8×10^{19} neutron/s
$n_{flux} = 2 \times 10^{13}$ n/(cm²· s)



Operation mode:
T_{burn} = 70 s
T_{dwell} = 15 s

ENEA

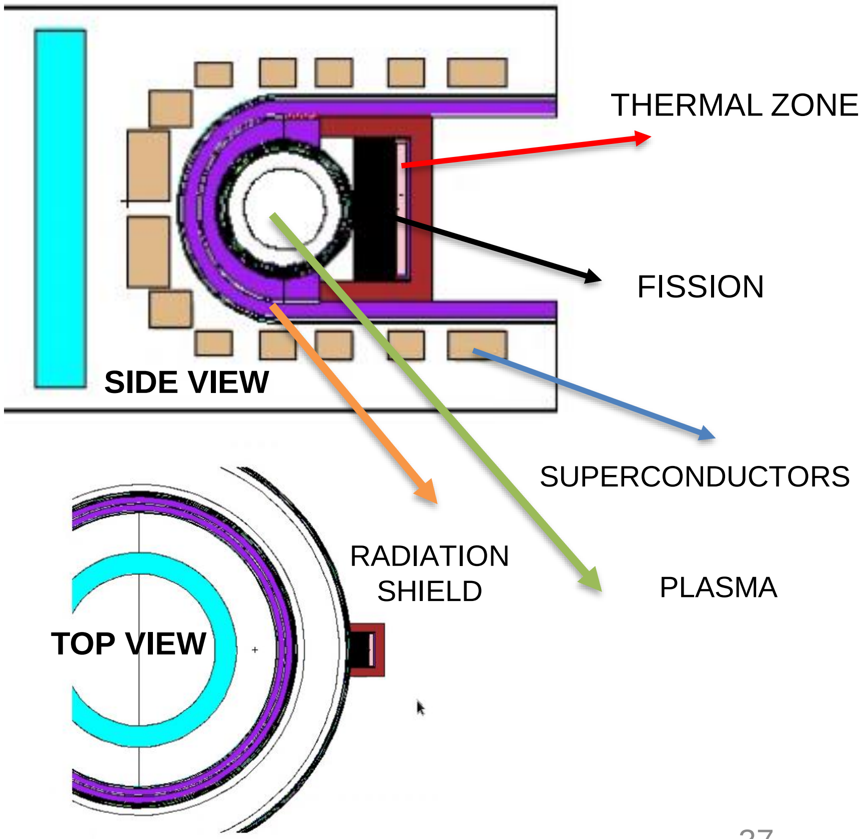
Fission blanket

An RFP-based hybrid system concept has been studied (R=6 m, a=0.8 m). The proposed fission blanket is characterized by a multi-zone design:

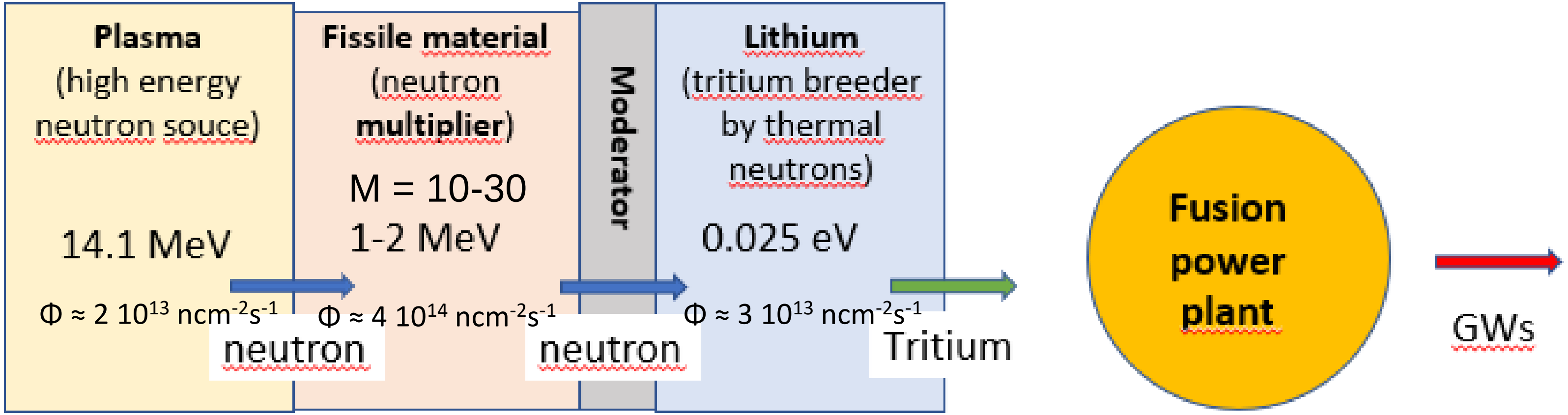
- A fast core (fuel MOX- cooling fluid Molten salt)
- A thermal neutron spectrum zone for lithium irradiation (FLiBe)

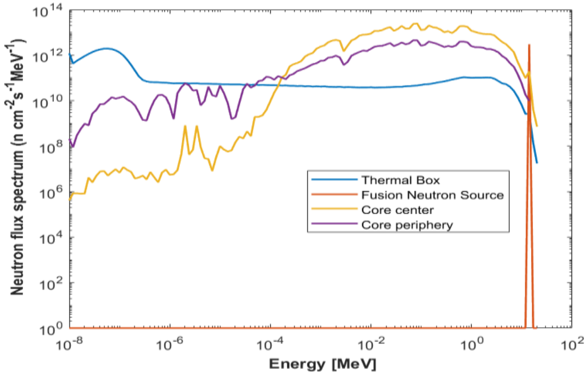
Core dimensions: 50 x 110 x 200 cm^3

Molten salt cooling system: NaF – ZrF_4



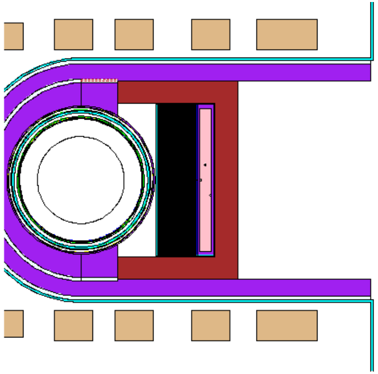
Tritium production strategy

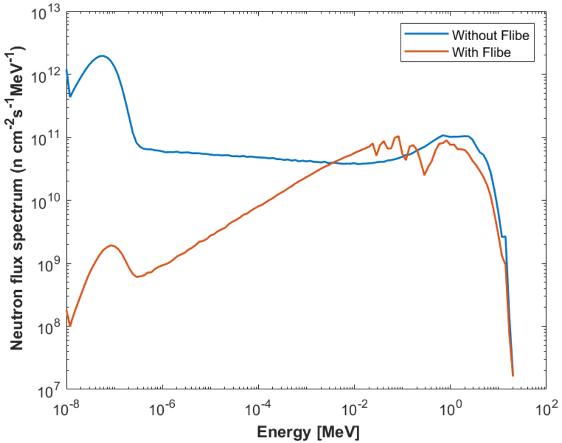


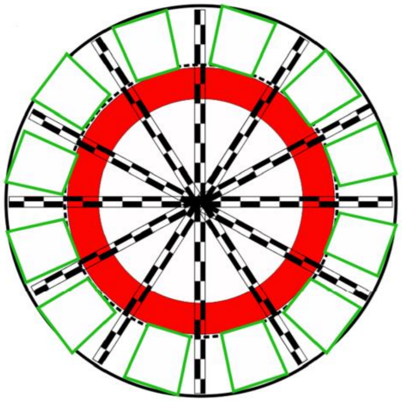


Tritium breeding blanket

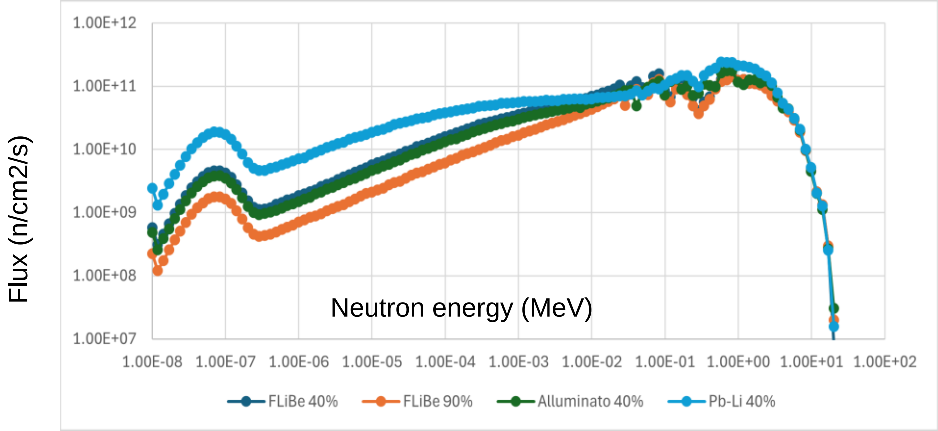
- k=0.97; Pcore=42 MW; Pbox = 10 MW
- Conversion zone dimensions = 197*110*15 (cm*cm*cm)
- Initial FLiBe mass (Li6 enrichment: 40%) = 645 kg
- Estimated tritium production for the entire machine (12 modules) = 5.56 mg/s (TBR = 29)
- No tritium extraction efficiency has been considered (the presented results take only into account the tritium production process). An optimistic efficiency evaluation can be considered about 50%.
- **A similar FFHS can in principle produce the fuel (ε=50%) for a 1/1.5-GW pure fusion device**







Alternative brreding materials



Materiale	TBR
FLiBe (40% Li-6)	29
FLiBe (90% Li-6)	65
Alluminate (40% Li-6)	**27**
Pb-Li (40% Li-6)	6.22

- FLiBe, Pb-Li can be useful for a pure fusion blanket (Be and Pb can be used as neutrons moultiplicators)
- Be caould be avoided for its toxicity
- For thermal neutrons the presence of a multipicator is not necessary and can give the possibility to have a higher Li concentration inside the blanket
- A solid blanket (alluminate or silicate) seems to be a good choice also for the extraction method (helium or water)
- A low Li-6 enrichment (or natural concentration) are suggested

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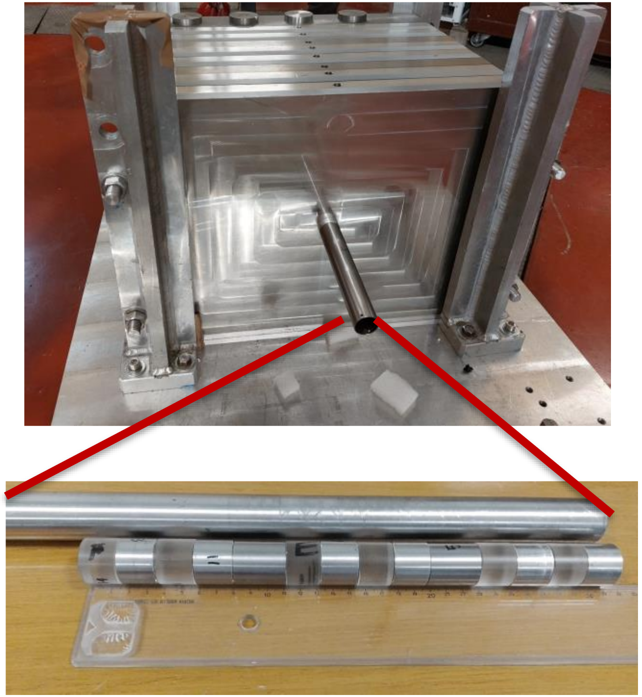
ENEA-INFN sulla neutronica

A. Pietropaolo ENEA – FUSEN
B. R. Bedogni INFN - LNF

Attività in collaborazione su task Eurofusion

Shielding Mock-up : **BB-S.05.02-T008-D012**



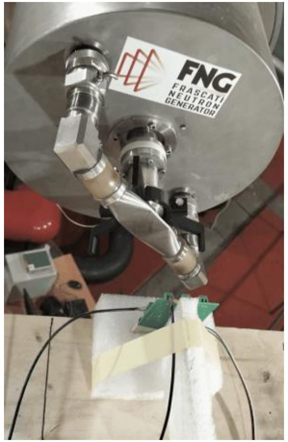
Presso il generatore di neutroni di Frascati (FNG) è stato condotto un esperimeno ik ui scopo era di valutare le componenti termiche e veloci del campo neutronico in posizioni selezionate all'interno di un blocco di schermatura ***DEMO-relevant*** formato da parti metalliche e plastiche mediante misure in tempo reale.

I rivelatori attivi utilizzati sono stati del tipo SiC (Carburo di silicio) in due versioni:

Un rivelatore nudo per misure di neutroni veloci

Uno con un coating di Litio per le misure dei neutroni termici

Progetti INFN con partecipazione di personale ENEA come associato INFN



Progetto CMS-BRIL: sviluppo di uno spettrometro neutronico a singola sfera per il monitoraggio del fondo dell’esperimento CMS al CERN

Progetto ENTER_BNCT: studio di sensori di neutroni compatti al carburo di Silicio per monitoraggio dei fasci terapeutici BCNT

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