

# Complete(?) vision of complementary experiments at IFMIF-DONES

## *A summary review*

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*Based on the achievements of the WP8 of the DONES Preparatory Phase EU Project*

IFMIF-DONES Users Workshop  
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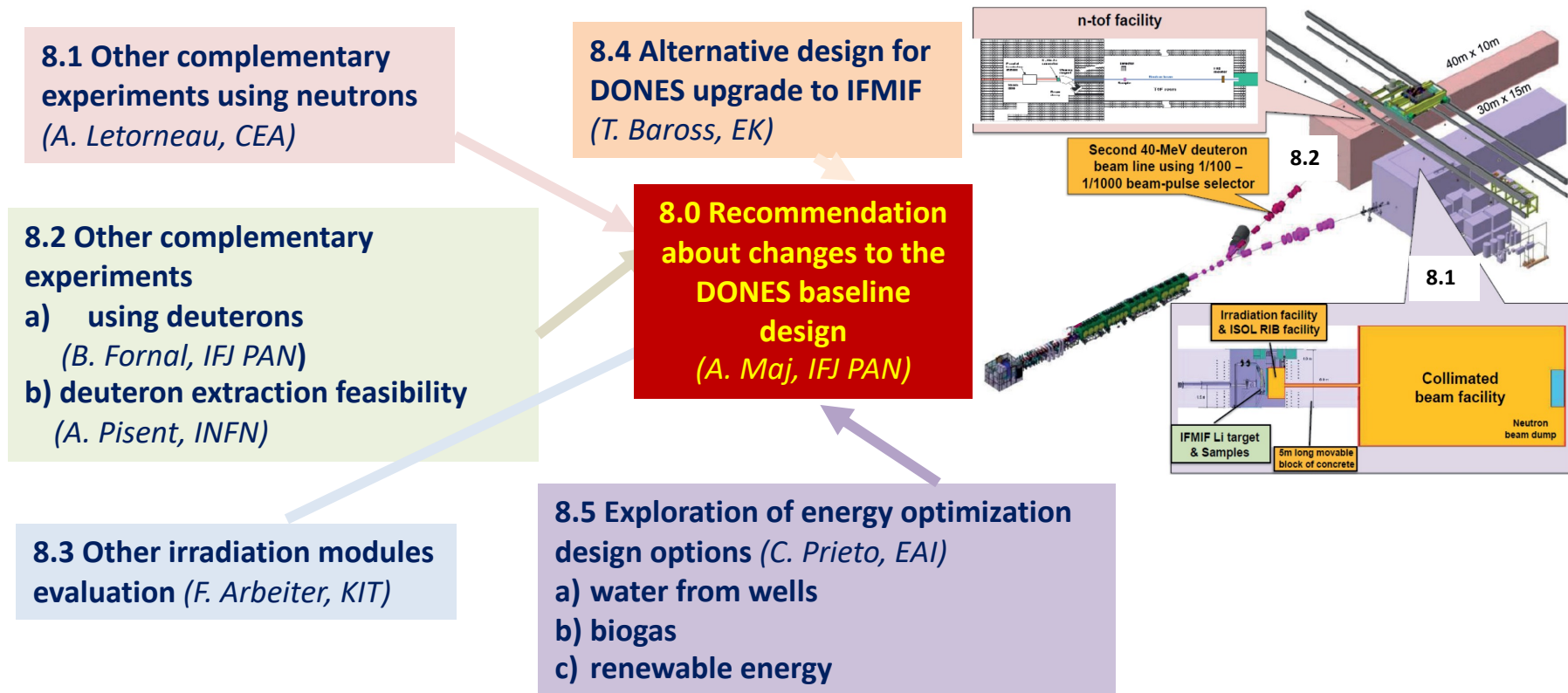
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The main objective of this work package is to analyse in some detail **a number of possible design variants** of the facility with improved performance that could be of interest for the **possible use of the facility by other scientific communities**, outside of the fusion one; and to explore the possible **upgrade of the facility to the full IFMIF performance**.

The work was organized in the **6 tasks**:





**8.0 Recommendation about changes to the DONES baseline design**  
(A. Maj, IFJ PAN)

**8.1 Other complementary experiments using neutrons** (A. Letorneau, CEA)

A talk by Alain Letournau (today)

**8.2 Other complementary experiments**  
a) **using deuterons**  
(B. Fornal, IFJ PAN)  
b) **deuteron extraction feasibility**  
(A. Pisent, INFN)

Partly covered by Javier Praene and Daniel Cano-Ott (today)

A talk by Santiago Becerril-Jarque (yesterday)

**8.3 Other irradiation modules evaluation** (F. Arbeiter, KIT)

A talk by Frederic Arbeiter (yesterday)

**8.4 Alternative design for DONES upgrade to IFMIF** (T. Baross, EK)

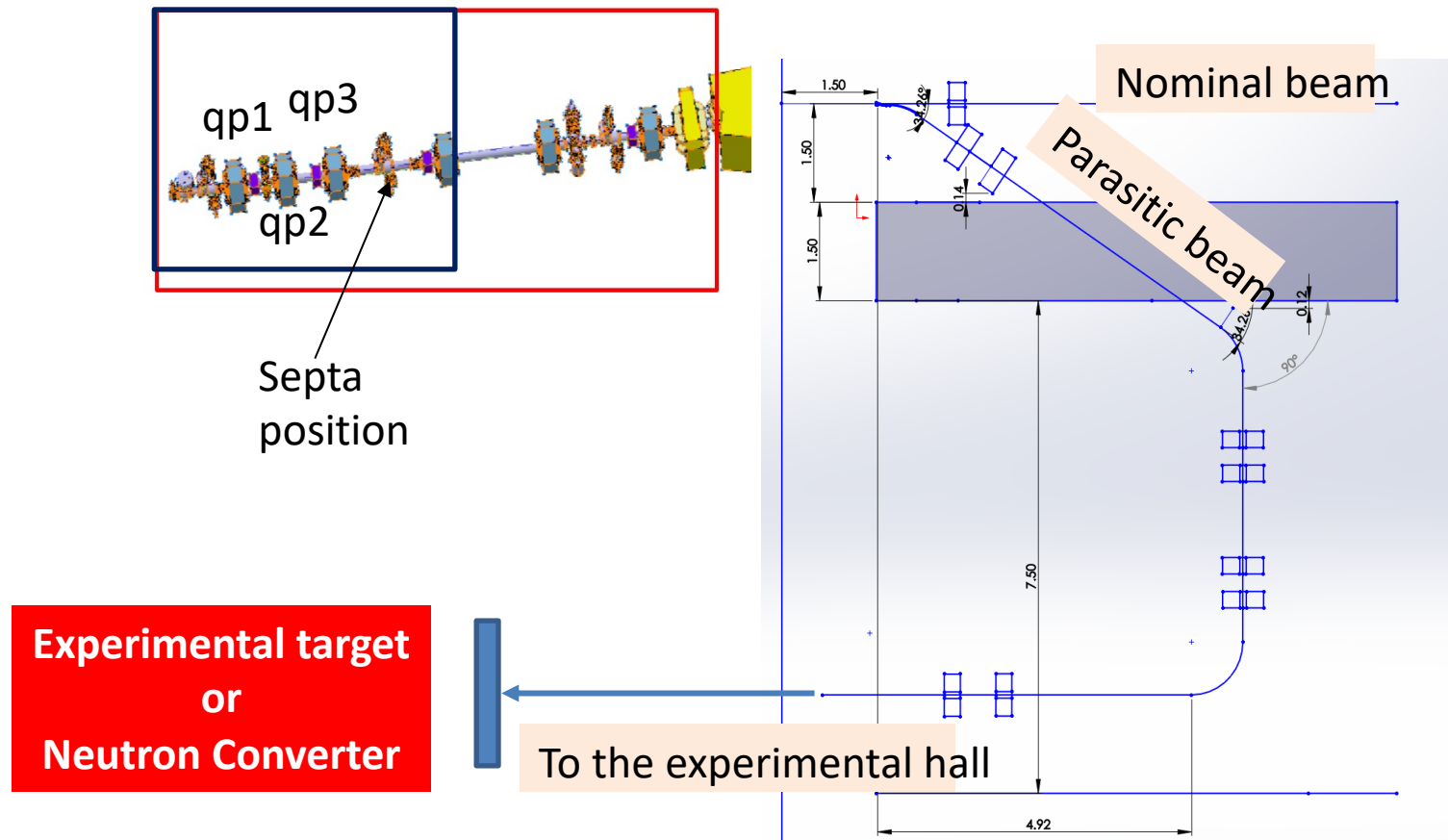
**8.5 Exploration of energy optimization design options** (C. Prieto, EAI)



Collaborating institution: **INFN**, CEA, CIEMAT, GANIL, IFJ PAN Krakow

The goal of this task was to study the possibility **to extract a deuteron beam for experiments**, with the minimum perturbation of the DONES facility activity (less than 1% of the intensity). Various scenarios have been compared for the use of a deuteron beam. In particular the possibilities to extract a beam at 5 or 40 MeV, and the possibility of extracting a beam with different time structures and different switching technologies.

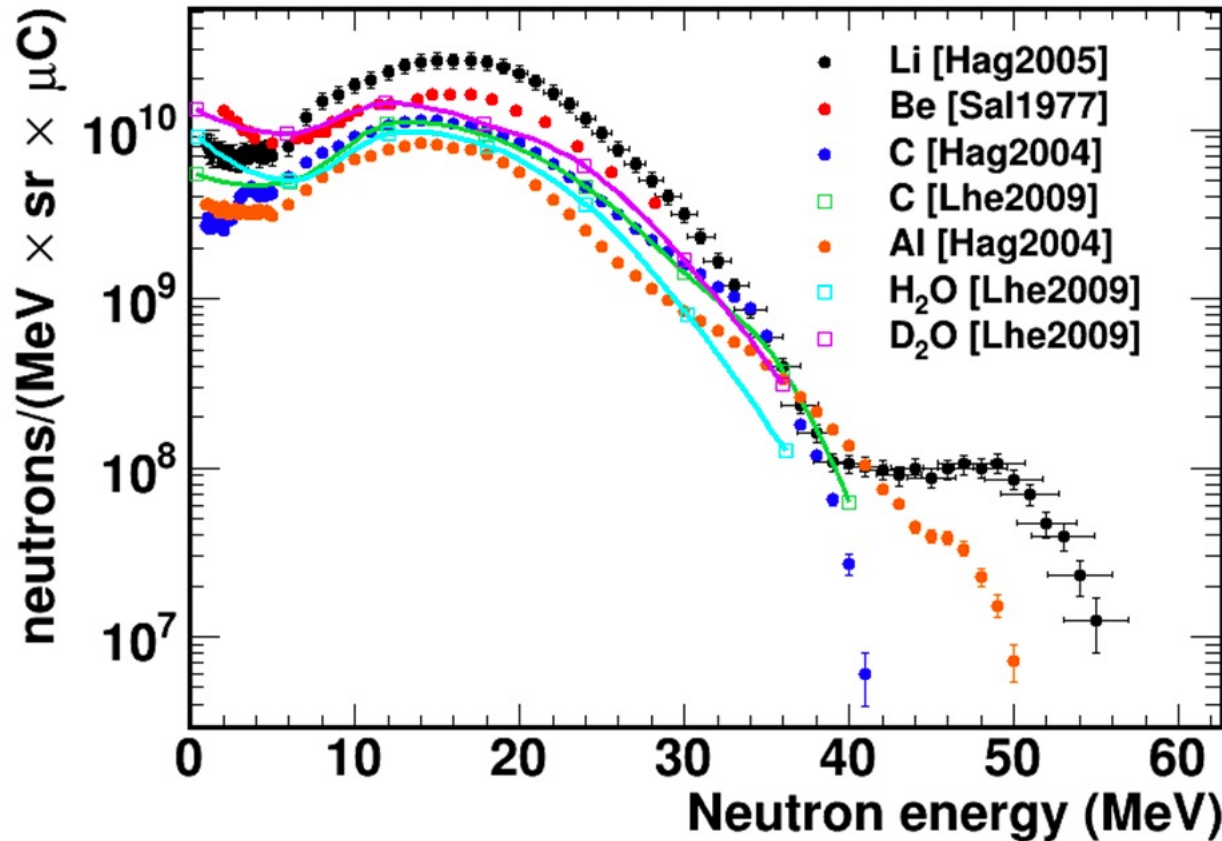
The **most promising scenario is to have a fast chopper (meander line) at 40 MeV**, immediately at the end of the linac, able to extract **one single bunch (over 10 000)** and deviate it through an electrostatic followed by a magnetic septum into a dedicated transfer line to the experiments one floor below.





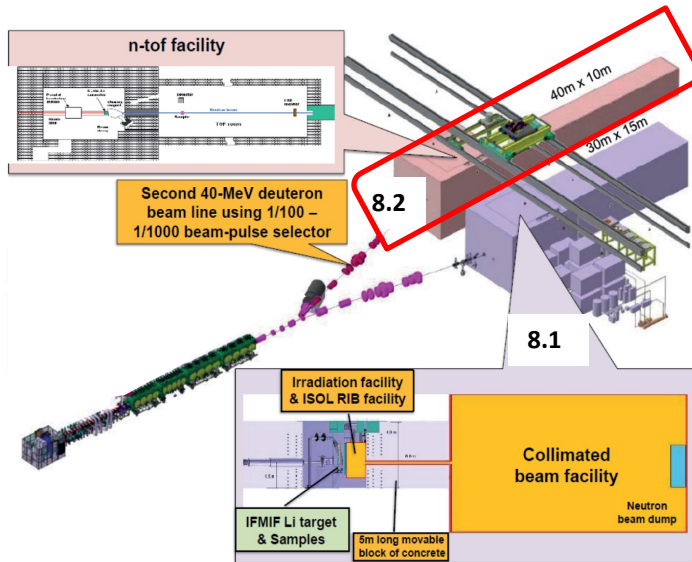
### Possible Deuteron-Neutron Converters

Thick target neutron production at 0 deg.



Cf. Daniel's talk

Thick target neutron production yields at forward angles for different materials



Collaborating institutions:  
**IFJ PAN Krakow**, CEA, CIEMAT, fnuc@DONES group

The activity within task 8.2.1 was **focused on the identification** of noteworthy and **unique experiments** that can be addressed in the nuclear physics field. The measurements can be conducted **with pulsed 40-MeV deuteron beam** or **pulsed neutron beam produced in deuteron-induced reactions**. The draft of the **catalogue** with the description of such experiments **has been prepared** and divided into five chapters referring to a possible experimental campaign at DONES i.e.:

- 1) Gamma spectroscopy of the nuclei produced in fast-neutron-induced fission reaction**
- 2) Production of radionuclides with a high intense deuteron beam:  $^{44}\text{Ca} (d,2n) ^{44}\text{Sc}$ ,  $^{64}\text{Ni} (d,2n) ^{64}\text{Cu}$ ,  $^{186}\text{W}(d,2n)^{186}\text{Re}$**
- 3) Investigation of pygmy dipole resonance (PDR) via  $(n, n'\gamma)$  and  $(d, d'\gamma)$  reactions**
- 4) Half-life measurements of long-lived isotopes**
- 5) Deuteron-induced reactions**



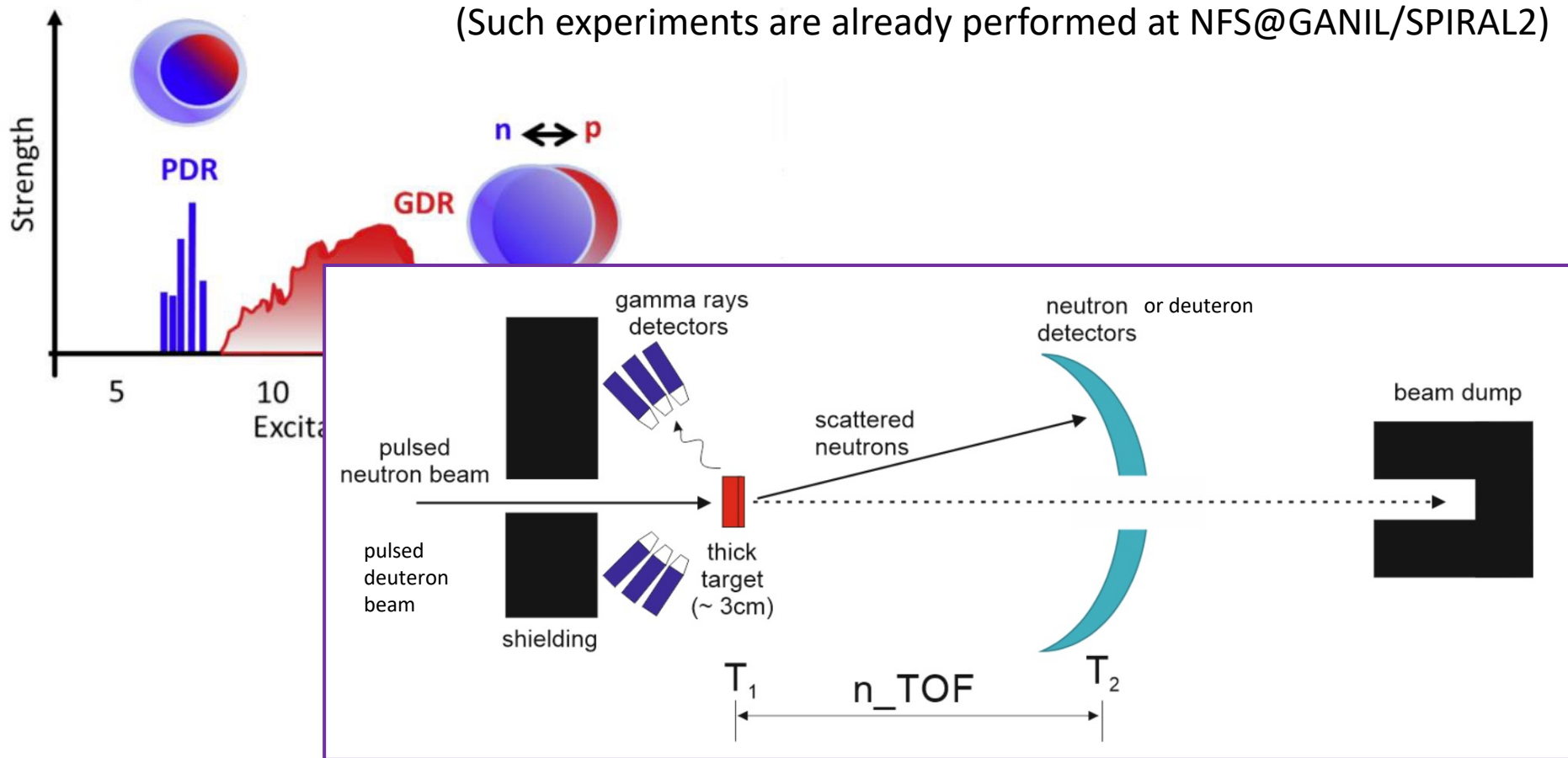
**Preliminary catalogue of possible experiments with pulsed deuteron or secondary neutron beams**

Proposal	Neutron converter	Beam requirements	Target characteristics	Detection system	Uniqueness @ DONES	Foreseen outcome
<b>Gamma spectroscopy of nuclei produced in fast-neutron-induced fission reactions</b>	Be 1 cm thick	pulsed deuterons; repetition time: few hundreds ns; pulse width: 1-2 ns	radioactive fissile actinide targets; milligram samples; Zr or Be backing	HPGe detectors; GFM spectrometer; TOF measurement	pulsed intense beam; long duration of measurement; combining with GFM spectrometer;	gamma-ray spectroscopic studies of hitherto inaccessible exotic nuclei near the doubly-magic $^{78}\text{Ni}$
<b>Production of radionuclides with high intense deuteron beam</b>	without	continuous or pulsed deuterons;	powder targets; backing	HPGe detectors; pneumatic transfer system	high beam intensity; long irradiation time	production of Cu-64, Re-186g, and in vivo Sc-44m/Sc-44g generator
<b>Investigation of pygmy dipole resonance (PDR) in nuclei via (n, n') and (d, d') reactions</b>	without or Be 1 cm thick	pulsed deuterons; repetition time: few hundreds ns; pulse width: 1-2 ns	stable targets;	PARIS detector; neutron detectors; TOF measurement	pulsed intense beam; two probes (n and d); complementary to the studies in other labs	studies of the fine structures of pygmy dipole resonances in various nuclei, e.g., $^{64}\text{Ni}$ , $^{124}\text{Sn}$ , $^{208}\text{Pb}$ ... with neutron and deuteron probes
<b>Half-life measurements of long-lived isotopes</b>	Be 1 cm thick	continuous	stable targets; > 1 gram samples;	HPGe detectors; pneumatic transfer system	high beam intensity; long irradiation time	precise half-lives measurements of long-lived $^{79}\text{Se}$ , $^{93}\text{Zr}$ , $^{107}\text{Pd}$ , $^{129}\text{I}$ , $^{129}\text{Xe}$ , $^{135}\text{Cs}$ , ... isotopes
<b>Deuteron-induced proton transfer reactions (d,n)</b>	without	pulsed deuterons; repetition time: few hundreds ns; pulse width: 1-2 ns	stable and radioactive	neutron detectors; HPGe detectors; TOF measurement	pulsed intense beam;	precise spectroscopic factor determination for low-lying states in nuclei located in close proximity of the stability valley
<b>Deuteron-induced reactions with charged particles in the exit channel</b>	without	pulsed deuterons; repetition time: few hundreds ns; pulse width: 1-2 ns	stable and radioactive	split-pole magnetic spectrometer; HPGe detectors;	pulsed intense beam;	precise spectroscopic factor determination for low-lying states in nuclei located in close proximity of the stability valley
<b>Neutron Time-of-Flight (n-TOF) facility</b>	various	pulsed deuterons; repetition time: ~ 1 s; pulse width: some ns	stable and radioactive	neutron detectors; HPGe detectors; fission product detectors	pulsed intense beam; long duration of measurements; long base for n-TOF	precise cross section measurements of neutron-induced reactions on stable and rare radioactive targets



## Study of the pygmy dipole resonance with $(n,n'\gamma)$ or $(d,d'\gamma)$ reactions

(Such experiments are already performed at NFS@GANIL/SPIRAL2)

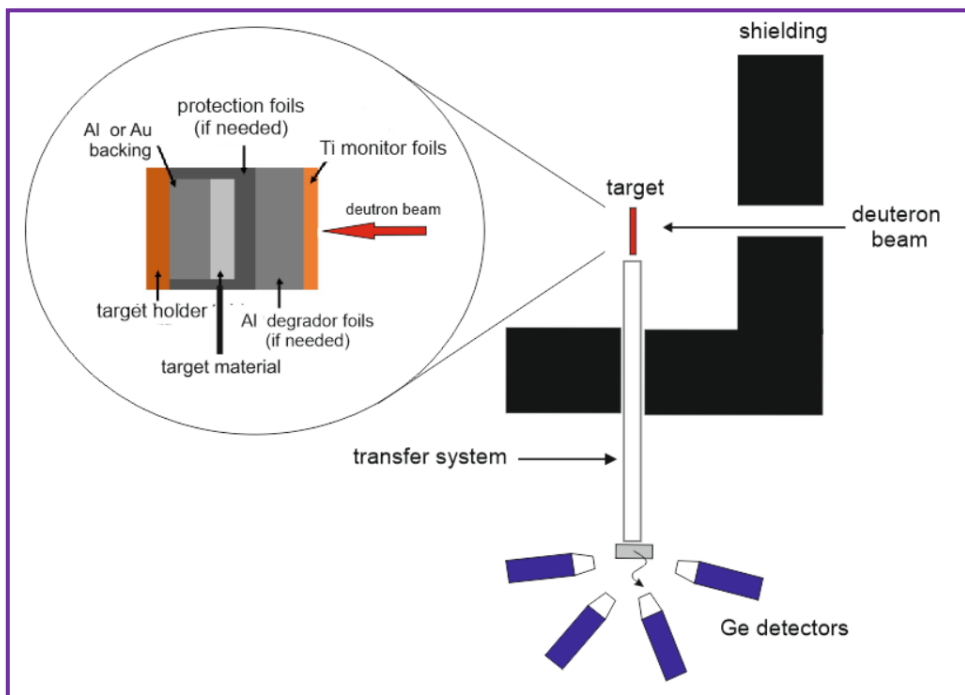


The DONES facility is an excellent place to systematically study PDR excitations in nuclei from different regions of the nuclear chart using neutrons or deuterons as a probe. The high intensity of the neutron/deuteron beam and the possible long duration of the experiments will ensure high statistics data which is crucial for obtaining detailed information on the nature of pygmy dipole resonances.



## Production of radionuclides ( $^{44}\text{Sc}$ , $^{64}\text{Cu}$ , $^{186}\text{Re}$ ) with a high intense deuteron beam

	Reaction threshold (MeV)	Half-life	Time of max prod.	Isotopic fraction (%)
$^{44}\text{Ca}(d,2n)^{44g}\text{Sc}$	6.9	3h 58m 12s	2d 2h 43m	51.4
$^{44}\text{Ca}(d,2n)^{44m}\text{Sc}$	7.2	2d 10h 36m 0s	21d 18h 10m	19.8
$^{64}\text{Ni}(d,2n)^{64}\text{Cu}$	4.8	12h 42m 3s	5d 17h 23m	46.4
$^{186}\text{W}(d,2n)^{186g}\text{Re}$	3.6	3d 18h 0m 0s	29d 2h 24m	2.8

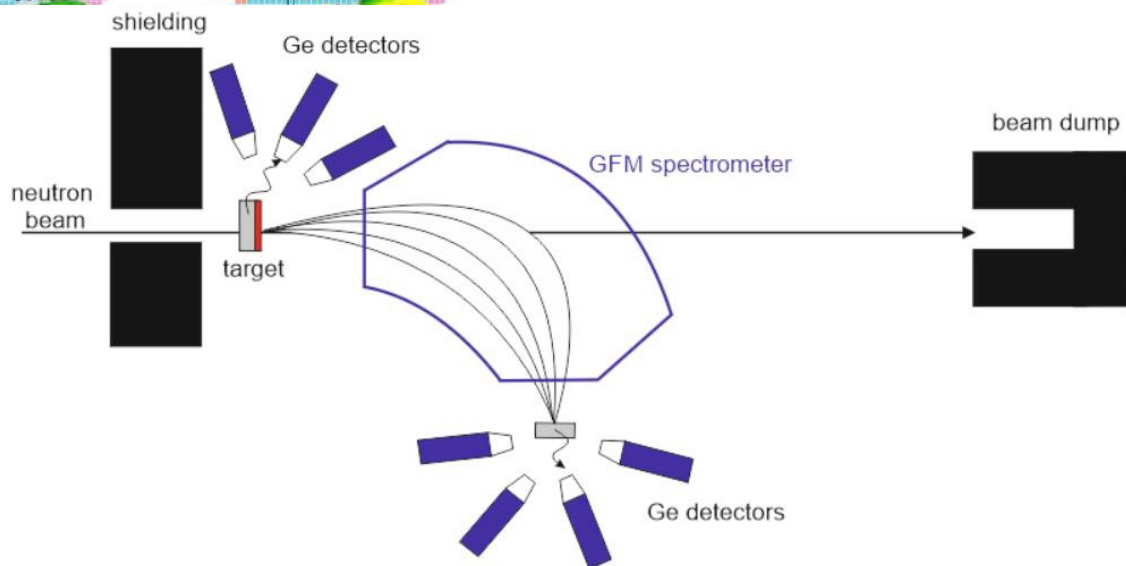
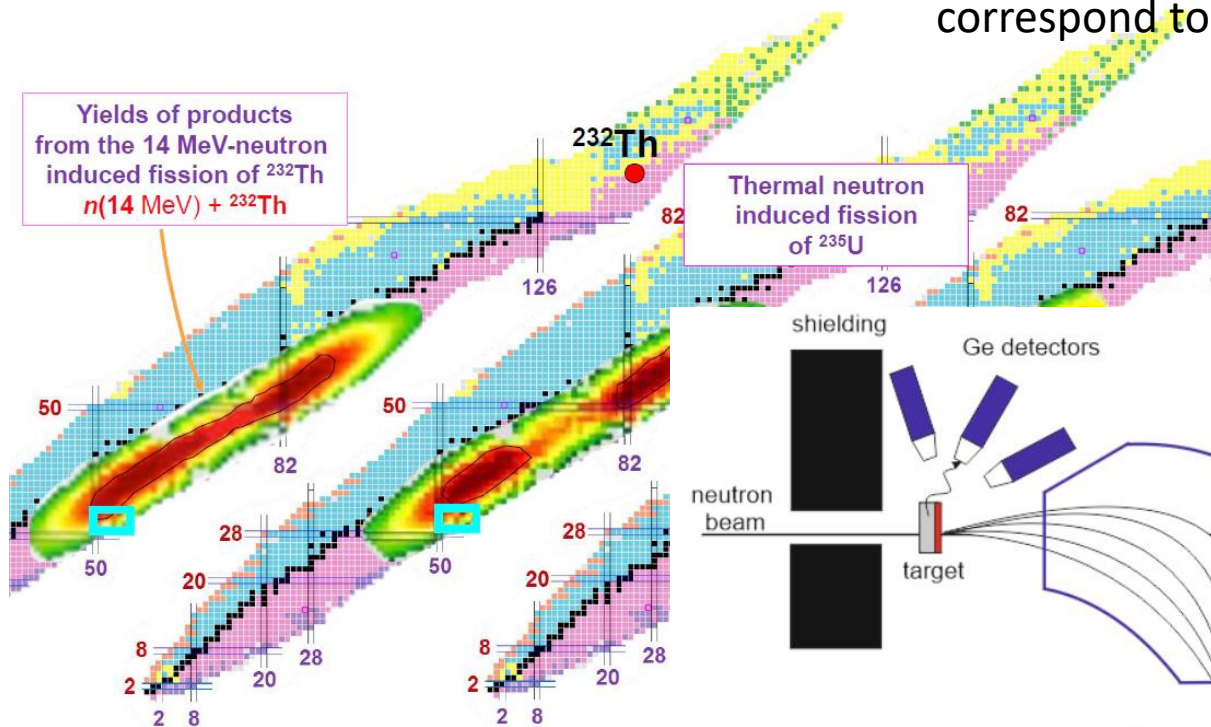


The very intense deuteron beam is ideal for the effective irradiation of samples and leads to the production of radionuclides with high activity.



## Gamma spectroscopy of the nuclei produced in fast-neutron-induced fission reaction

Distribution of the fission products which correspond to different target materials.



The secondary beam line at DONES offers unprecedented opportunity for gamma spectroscopy studies of neutron-rich nuclei, as it should allow accessing excited states and observing their gamma decay in nuclei which could not be reached for nuclear structure investigations so far.



### Goals of the task:

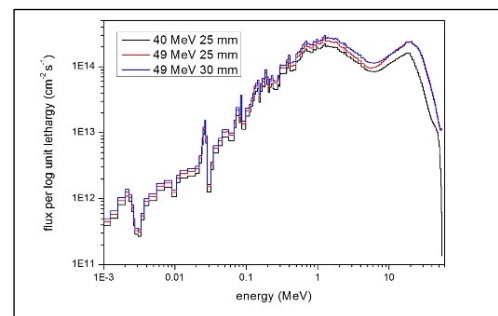
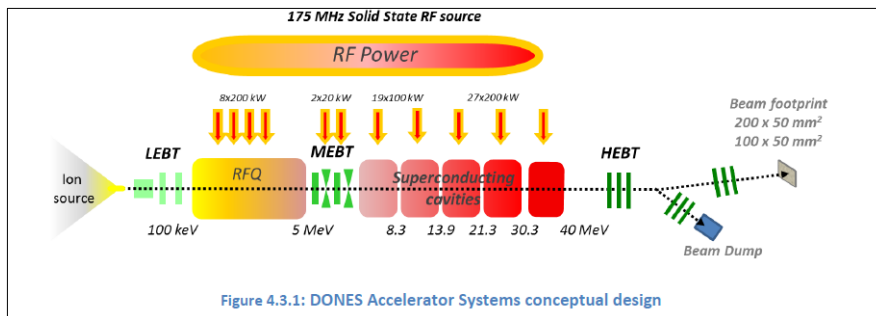
- Collection the different characteristics for the alternative options.
- Collection the pros and cons related to all scenarios.
- In the future: comparison the alternative with the standard additional accelerator option.

Collaborating institutions:

**EK Budapest**, INFN, CEA, CIEMAT, IFJ PAN Krakow



	B. Beam Current 125 to 180 mA (beam power raised to 7.2MW)	C. Beam energy increase 40 MeV to 50 MeV.
<b>Concept</b>	<b>The neutron spectrum is proportional to the number of deuterons, so the flux shall be <math>180/125 = 1.44</math> times higher.</b>	<b>The beam energy shall be increased from 40 MeV to 50 MeV by additional high energy cryo-modules.</b>
<b>Additional components</b>	New source for a 200 mA D+ beam, under emittance(0,3 micron RMS norm)	RF power sources, cryo modules and cooling.
<b>R &amp; D</b>	The possibility of increasing the power through the power couplers has to be carefully studied as the nominal DONES specifications (125 mA/40 MeV) are already a challenge	Li-Target, Test Cell may need to be redesigned (neutron on higher energy) Injector and RFQ shall be redesigned at higher current (beyond LIPAc limits).
<b>Space req.</b>	Additional cryo-module, longer RFQ.	Additional RF power sources
<b>Pros/Cons</b>	Pros: The neutron spectrum remains the same, Cons: Lot of R&D: Injector, RFQ, ion source extraction	Pros: Seems to be less R&D Cons: The change of neutron spectrum shift towards higher energy above 10 MeV may not relevant. Li-target, Test Cell may need to be redesigned.





**Complementary experiments at DONES**, which are worldwide unique/competitive, such as:

- **Nuclear physics studies with fast and moderated neutrons**, including
  - Neutron-rich isotopes produced by neutron induced fission,
  - Neutron irradiation of interest for nuclear astrophysics applications.
- **Nuclear physics experiments using extracted pulsed deuteron beam**, as for example:
  - Measurements using the neutron time-of-flight (TOF) method - creation of the world's leading n-TOF facility for selected ranges of neutron energies,
  - Gamma spectroscopy studies of neutron-rich nuclei induced by pulsed neutron beam,
  - Studies of pygmy dipole resonances in stable nuclei induced by both neutrons and deuterons,
  - Investigation of the decay of isomeric states in products of reactions induced by deuterons on different stable and radioactive targets,
- **Neutron scattering experiments in biology with fast and moderated neutron beams.**



**Applications** which are unique/important both worldwide and for Spain, such as:

- **Production of medical radionuclides** by neutrons and high intensity parasitic deuteron beams,
- **Neutron imaging and tomography** station with moderated and fast neutrons combined with Neutron Activation analysis.

**Enhancing fusion material testing programme** by installing in the Test Cell extra irradiation modules, such as:

- In-Situ Creep Fatigue Test Module (CFTM),
- In-Situ Ceramic Breeder Irradiation Module (ICBIM),
- In-Situ Irradiation Module for Diagnostics (IIMD).

Analysis of the **alternatives to adding a second linac accelerator for the DONES upgrade to IFMIF**, although not fully conclusive, shows a potentially interesting idea to investigate in more detail: **the option of adding a second ion source** and merge beams from the two sources before the LEBT system.



It is also very important to emphasise, that the realization of the WP8 tasks resulted as **an added value in the formation of the Spanish nuclear physicists' group fNUC@DONES** (<http://fnuc-at-dones.es>) , gathering researchers interested in using the DONES facility for the complementary experiments. This group had considerable impact on the realization of some of the WP8 deliverables and outcomes listed above. The great interest of the local Spanish, multidisciplinary community, is very important for the support and realization of the whole Project.

Moreover, the general awareness of the IFMIF-DONES project and of the opportunities for multidisciplinary research developed by WP8 was enhanced among the Spanish and European nuclear physics communities thanks to its presentation at the **dedicated NuPECC** ([www.nupecc.org](http://www.nupecc.org)) **meetings**.



## 1. With the highest priority

- Define in detail the requirements and start the preparation of technical arrangements for **neutron experiments in the experimental hall**,
- Start prototyping activities for the **extraction of the deuteron beam** using the Meander Line System method and reserve the necessary space for the **experiments with extracted deuteron beam and Time-of-Flight facility**

## 2. With the high priority

- Implement the **enhanced fusion material testing programme** by installing in the Test Cell additional irradiation modules

## 3. With the moderate priority

- Perform **technical design study of the option of adding a second ion source** and merge beams from the two sources before the LEBT system



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[D8.2-1] Ł.W. Iskra, B. Fornal, D. Cano-Ott, E. Mendoza et al., Report on possible complementary experiments to be developed in DONES using deuterons,

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[D8.2-2] A. Pisent, L. Bellan et al, Evaluation of the extraction of a deuteron beam for other complementary experiments,

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[D8.3-1] F. Arbeiter et al., Catalogue of possible irradiation modules for DONES,

<https://idm.dones.irb.hr/op/op.ViewOnline.php?documentid=263&version=1>

[D8.3-2] F. Arbeiter et al., Report on conceptual design of other irradiation modules for DONES,

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[D8.4-1] T. Baross et al., Report on Alternative for DONES upgrade to IFMIF,

<https://idm.dones.irb.hr/op/op.ViewOnline.php?documentid=246&version=1>

[D8.5-1] R. Lopez et al., Report on Feasibility and Impact on DONES Design of the Use of Water from Wells, <https://idm.dones.irb.hr/op/op.ViewOnline.php?documentid=92&version=1>

[D8.5-2] A. Diaz et al., Report on Feasibility and impact on DONES design of the use of Biogas,

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[D8.5-3] C. Prieto Mozo et al., Report on Feasibility and Impact on DONES design of the Production of Renewable Energy Linked to the Facility,

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