TARGET DEVELOPMENTS AT LUNA

Denise Piatti[1] and Matteo Campostrini[2]

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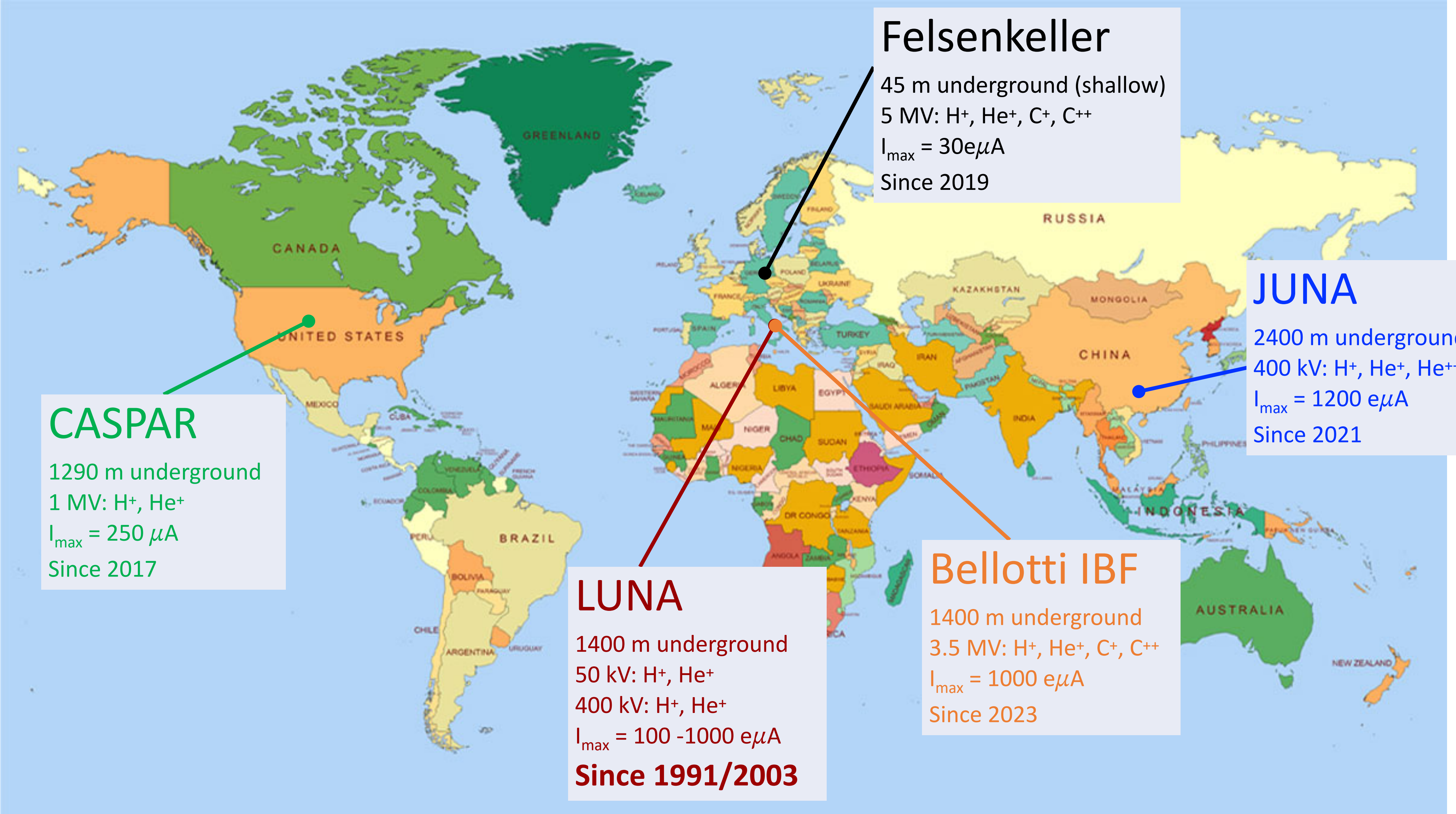
Speaking of LUNA



Felsenkeller

45 m underground (shallow)
5 MV: H^+, He^+, C^+, C^{++}
I_{max} = 30eμA
Since 2019

JUNA

2400 m underground
400 kV: H^+, He^+, He^{++}
I_{max} = 1200 eμA
Since 2021

CASPAR

1290 m underground
1 MV: H^+, He^+
I_{max} = 250 μA
Since 2017

LUNA

1400 m underground
50 kV: H^+, He^+
400 kV: H^+, He^+
I_{max} = 100 -1000 eμA
Since 1991/2003

Bellotti IBF

1400 m underground
3.5 MV: H^+, He^+, C^+, C^{++}
I_{max} = 1000 eμA
Since 2023

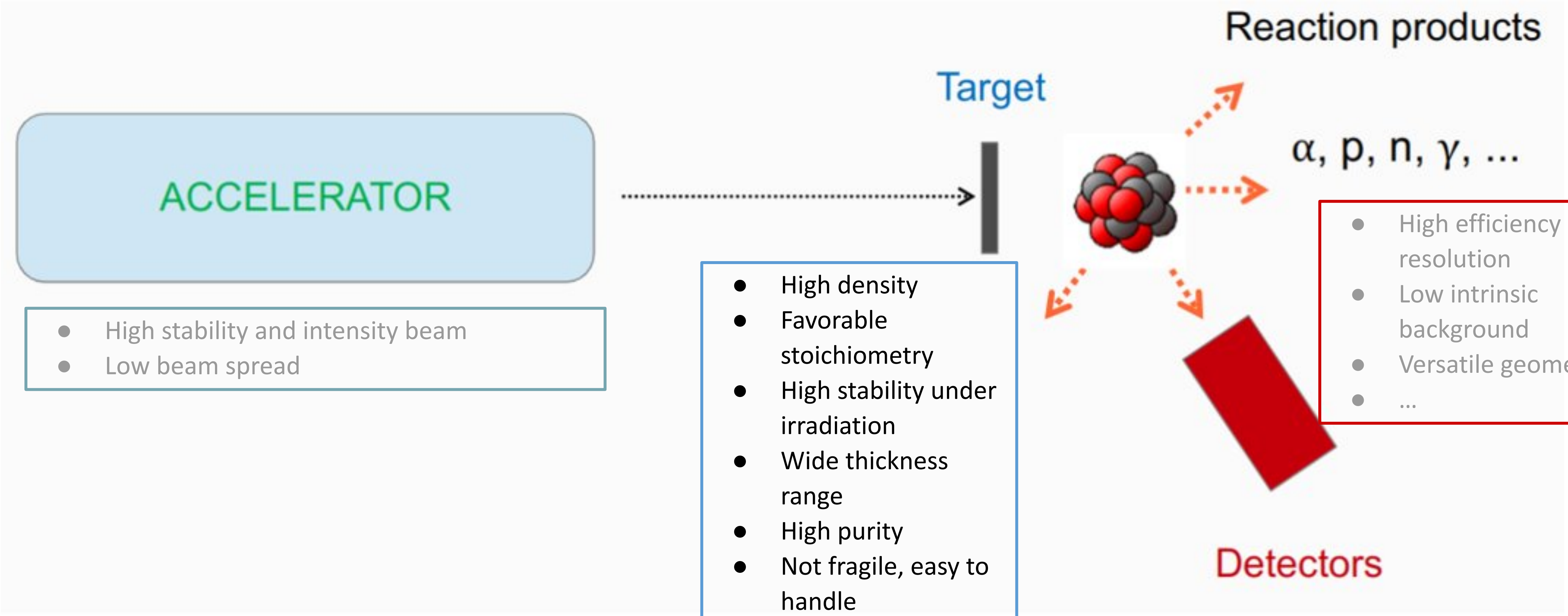
A successful 35 years long story…

Reaction	Accelerator	Astrophysical Motivation/Scenario
$D(\alpha,\gamma)^{6}Li$; $^{3}He(\alpha,\gamma)^{7}Be$; $D(p,\gamma)^{3}He$	LUNA400kV	Big Bang Nucleosynthesis (BBN), Lithium problem(s)
$^{3}He+^{3}He$; $D(p,\gamma)^{3}He$	LUNA50kV	pp-chain and Solar neutrinos
$^{6}Li(p,\gamma)^{7}Be$	LUNA400kV	Stars, cosmic-ray spallation and BBN; Resonance NOT confirmed
$^{12,13}C(p,\gamma)^{13,14}N$	LUNA400kV	CNO cycle kick off reactions; only few, poorly constrained data
$^{14,15}N(p,\gamma)^{15,16}O$	LUNA400kV	CNO cycle bottleneck;
$^{17,18}O(p,\alpha)^{14,15}N$	LUNA400kV	CNO cycle; crucial for oxygen isotopic abundance in AGB stars
$^{16,17,18}O(p,\gamma)^{17,18,19}F$	LUNA400kV	CNO cycle and CNO leak
$^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$	LUNA400kV	NeNa cycle; affecting abundances up to P
$^{23}Na(p,\gamma)^{24}Mg$	LUNA400kV	NeNa-MgAl cycle link
$^{25}Mg(p,\gamma)^{26}Al$	LUNA400kV	MgAl cycle; poorly constrained resonances dominate the rate
$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$	LUNA400kV	s-process crucial for production of isotopes heavier than iron

LUNA

… but also painful…

LUNA performs direct measurement for which some ingredients are required:



- High stability and intensity beam
- Low beam spread

- High density
- Favorable stoichiometry
- High stability under irradiation
- Wide thickness range
- High purity
- Not fragile, easy to handle
- Enriched on demand
- Cheap
- …

- High efficiency *and* resolution
- Low intrinsic background
- Versatile geometry
- …

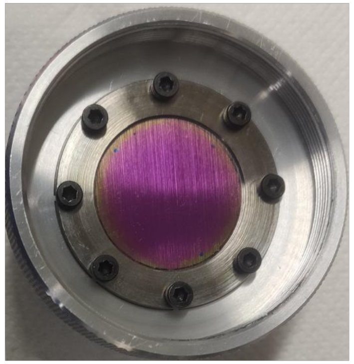
… indeed

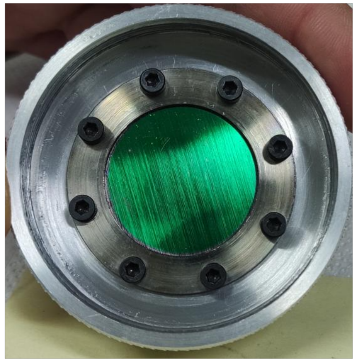
The perfect target is a unicorn!

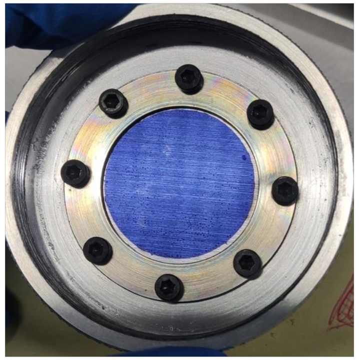
LUNA Solid Targets - Oxygen Targets

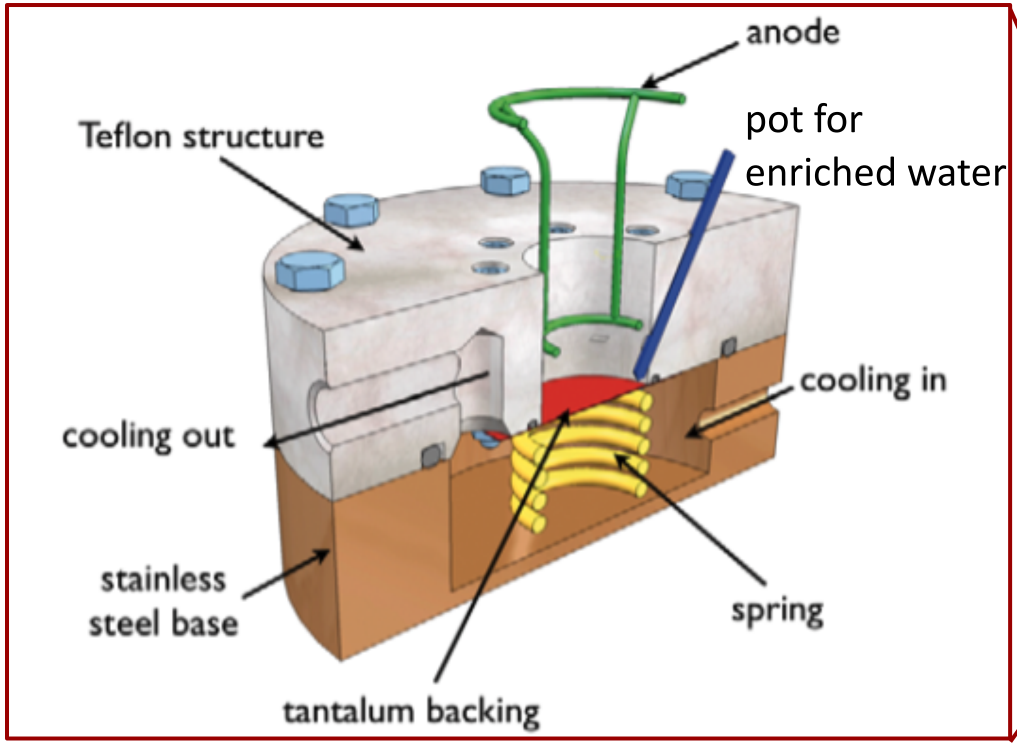
The (recent) aim: the first direct determination of the 64.5 keV resonance of the $^{17}O(p,\gamma)^{18}F$ reaction

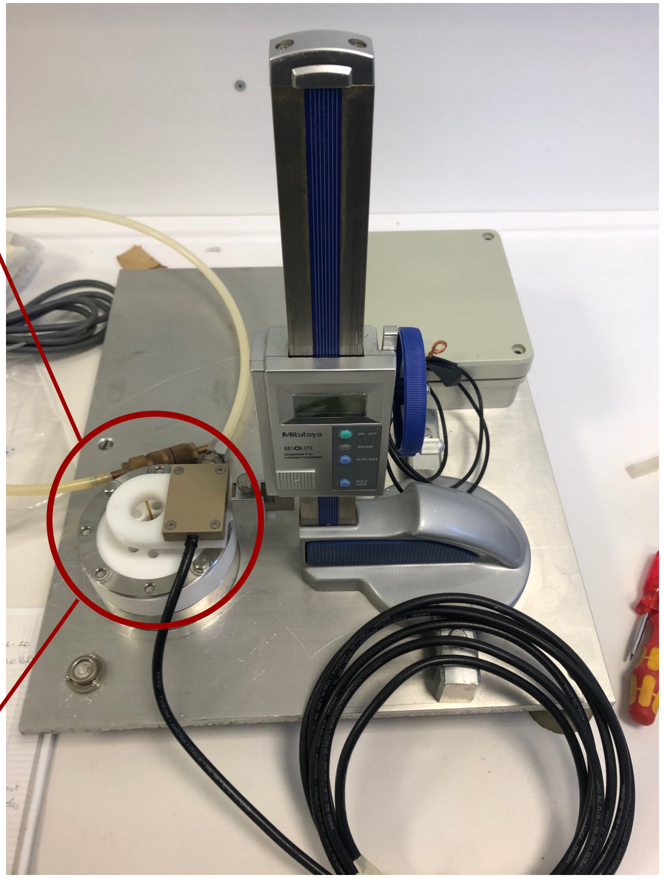
Technique: anodic oxidation of Ta in enriched (at 90% level in ^{17}O) water solution which acts as the electrolyte











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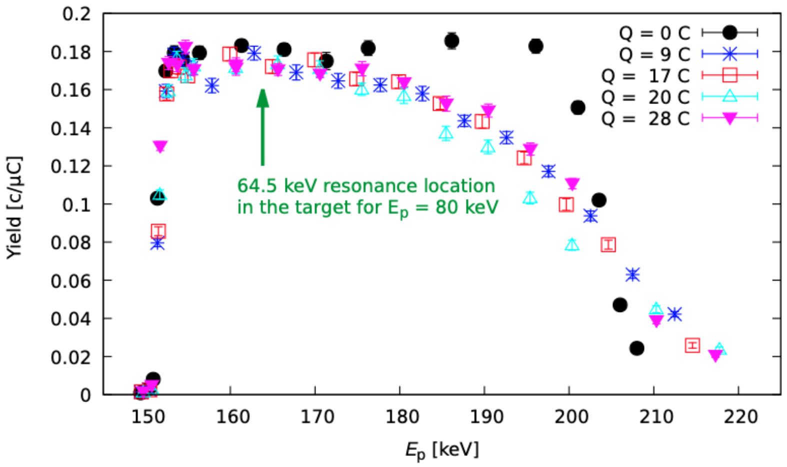
The (recent) aim: the first direct determination of the 64.5 keV resonance of the $^{17}O(p,\gamma)^{18}F$ reaction

Technique: anodic oxidation of Ta in enriched (at 90% level in ^{17}O) water solution which acts as a electrolyte

Target features [Gesué, R.M. et al., PRL 133 (2024), Caciolli, A. et al, EPJ A 48 (2012) and references therein]:



- easy and fast to produce (1h per target on average)
- uniform
- well known target stoichiometry, Ta_2O_5
- well known target stability (10-20% degradation with Q_{tot} = 25-30 C)
- well known voltage-thickness relation in the range 50 - 400 nm
- target areal density of 10^{17}-10^{18} atoms/cm^2
- online characterization via NRRA doping the solution with ^{18}O
- if handled with care no contaminants introduced in the production

SO FAR IT SEEMS VERY CLOSE TO THE UNICORN!!!!

BUT….

LUNA Solid Targets - Oxygen Targets

SO FAR IT SEEMS VERY CLOSE TO THE UNICORN!!!!

BUT

Ta backing is a sponge for contaminants (bulk and surface) [Campostrini, M. et al., EPJ ST 233 (2024)]:

- Good electrical
- and thermal conductivity
- high Z
- and of course suitable for anodic oxidation

- Superficial Fluorine can be reduced by 3 orders of magnitude via acid bath
- Boron contamination is reduced by 2 orders of magnitude via acid bath
- Deuterium, however, could be reduced by a factor of 4 applying a Mo coating to the Ta but this was not useful for the $^{17}O(p,\gamma)^{18}F$ investigation

- Low H permeability [Katsuka H., J. Phys. Chem. Solids 43 (1982)]

AND GUESS WHAT…

LUNA Solid Targets - Oxygen Targets

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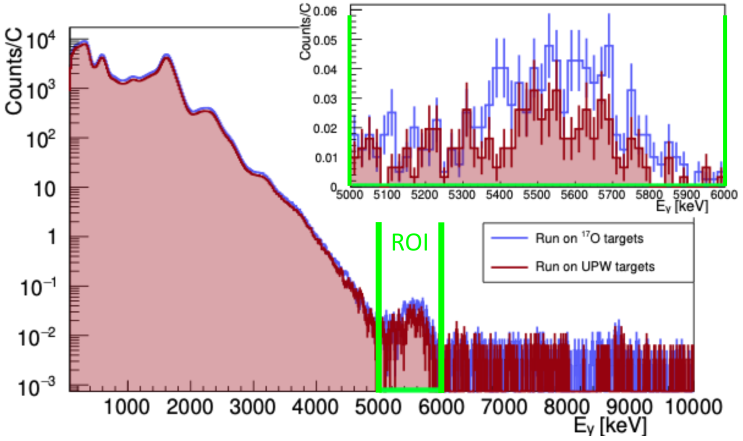
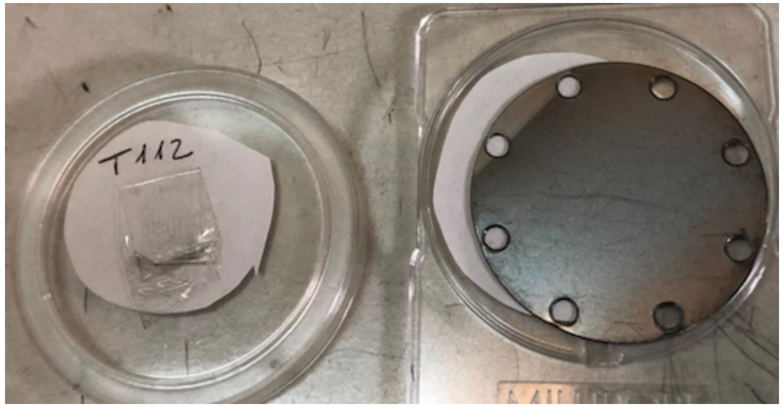


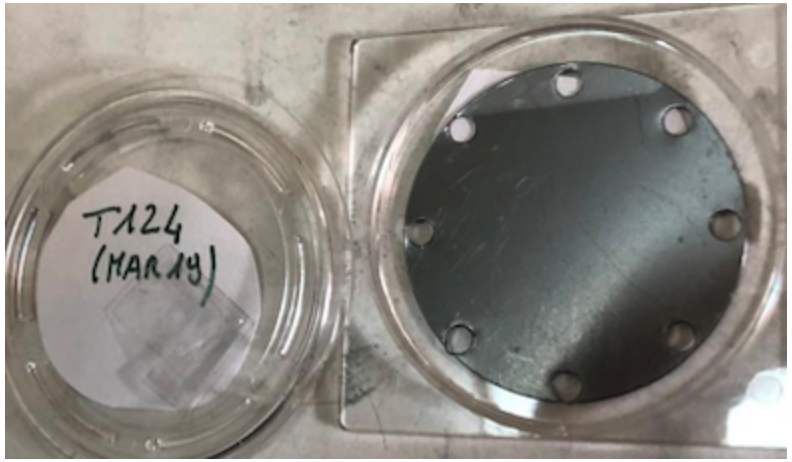
At this point you can only be smart [Gesué, R.M. et al., PRL 133 (2024)]

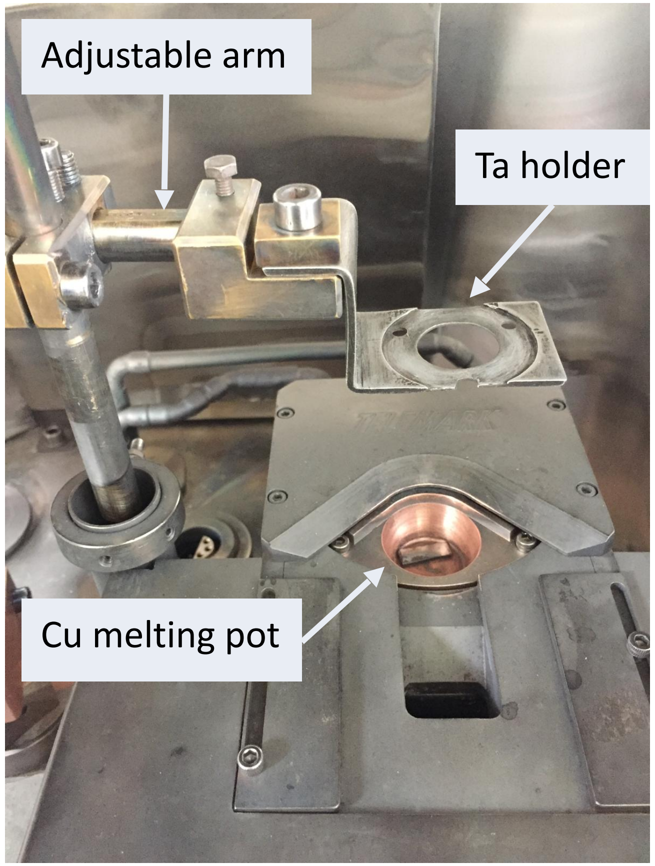
LUNA Solid Targets - Carbon Targets

<u>The aim:</u> the measurement of the $^{13}C(\alpha,n)^{16}O$ reaction cross section.

<u>Technique:</u> Evaporation (PROUDLY) performed at ATOMKI, using a Leybold UNIVEX 350 vacuum evaporator, 99% enriched ^{13}C powder and Ta as backing







LUNA

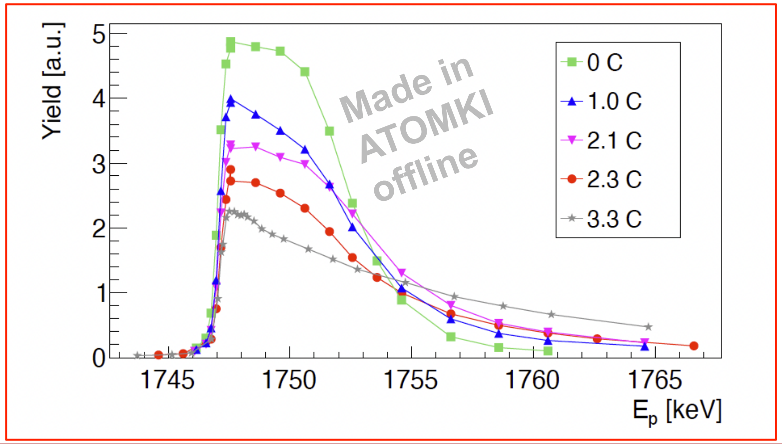
LUNA Solid Targets - Carbon Targets

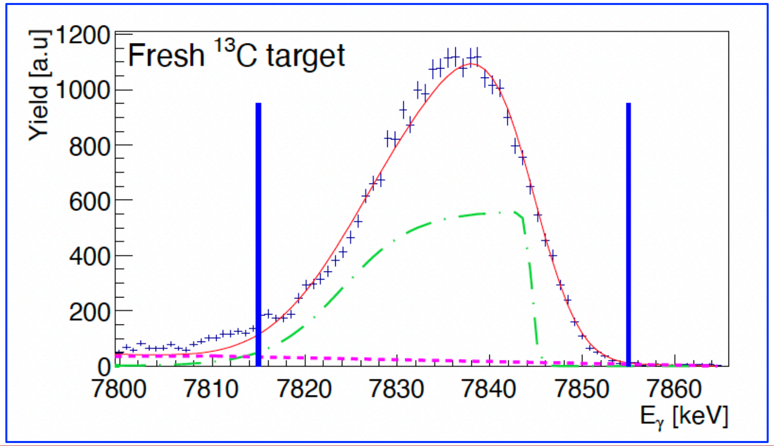
The aim: the measurement of the $^{13}C(\alpha,n)^{16}O$ and $^{12,13}C(p,\gamma)^{13,14}N$ reaction cross sections.

Technique: Evaporation (PROUDLY) performed at ATOMK, using a Leybold UNIVEX 350 vacuum evaporator, 99% enriched ^{13}C powder and Ta as backing

Target Features [Ciani, G.F. et al, PRL 127 (2021) and Ciani, G.F. et al., EPJ A 56 (2020)]:

- powder stable with time
- uniform
- high stability under proton irradiation
- target stability under α irradiation was poor -> setup designed to change target often
- Online monitoring such as NRRA not available -> Peak shape analysis



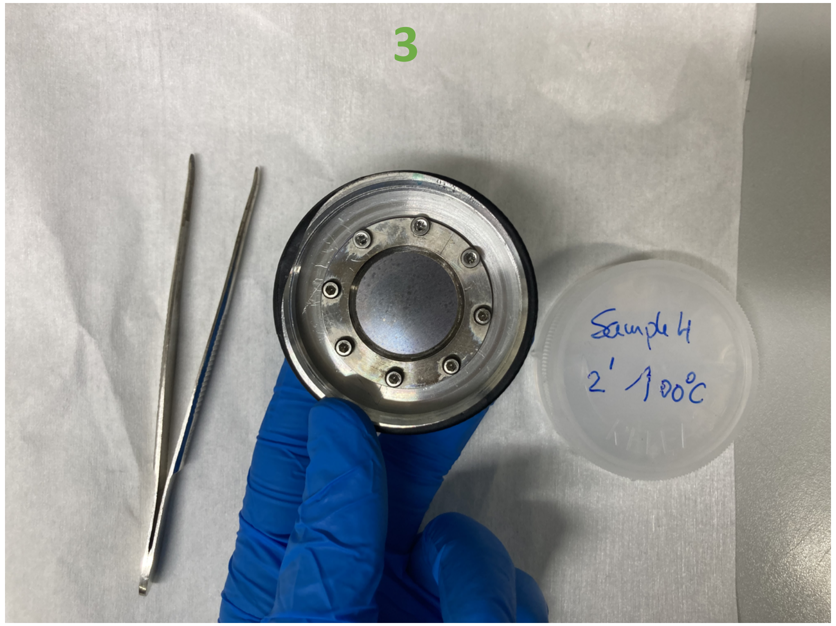


LUNA Solid Targets - Fluorine Targets

<u>The aim:</u> the measurement of the $^{19}F(p,\gamma)^{20}Ne$ reaction cross section

<u>Technique</u>:

1. Evaporation starting from CaF_2 powder, performed in ATOMKI (favorable stoichiometry but bad stability)
2. Implantation on Ta and Fe, performed at University NOVA in Lisbon, with 10^{15}-10^{17} atoms/cm^2
3. *Fluorination*, performed by external company, Ta was dipped in gaseous F_2 at 500 mbar for 2' and at 100°



LUNA Solid Targets - Fluorine Targets

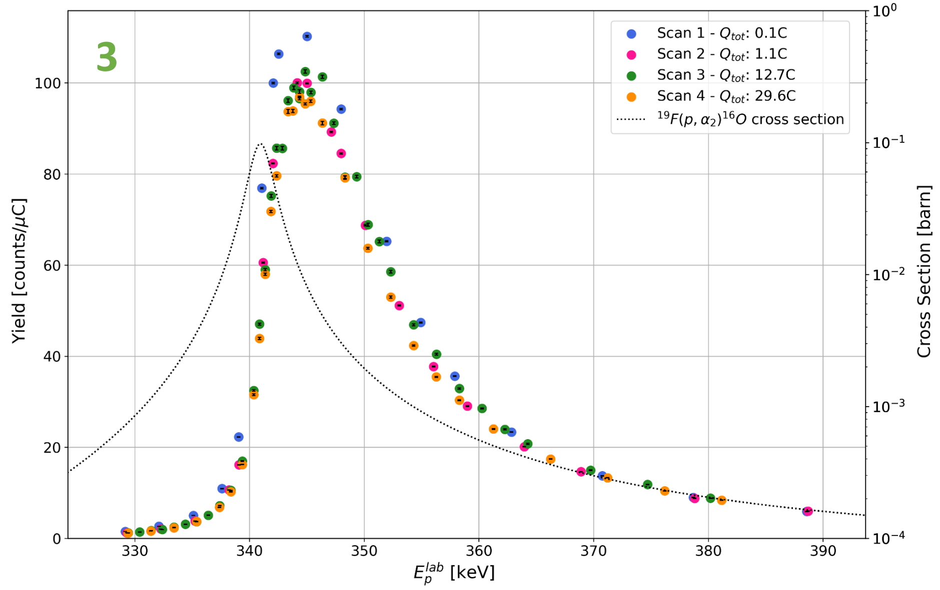
The aim: the measurement of the $^{19}F(p,\gamma)^{20}Ne$ reaction cross section

Technique:

1. Evaporation starting from CaF_2 powder, performed in ATOMKI (favorable stoichiometry but bad stability)
2. Implantation on Ta and Fe, performed at University Nova in Lisbon, with 10^{15}-10^{17} atoms/cm^2 and HZDR in Dresden
3. *Fluorination*, performed by external company, Ta was dipped in gaseous F_2 at 500 mbar for 2' and at 100°

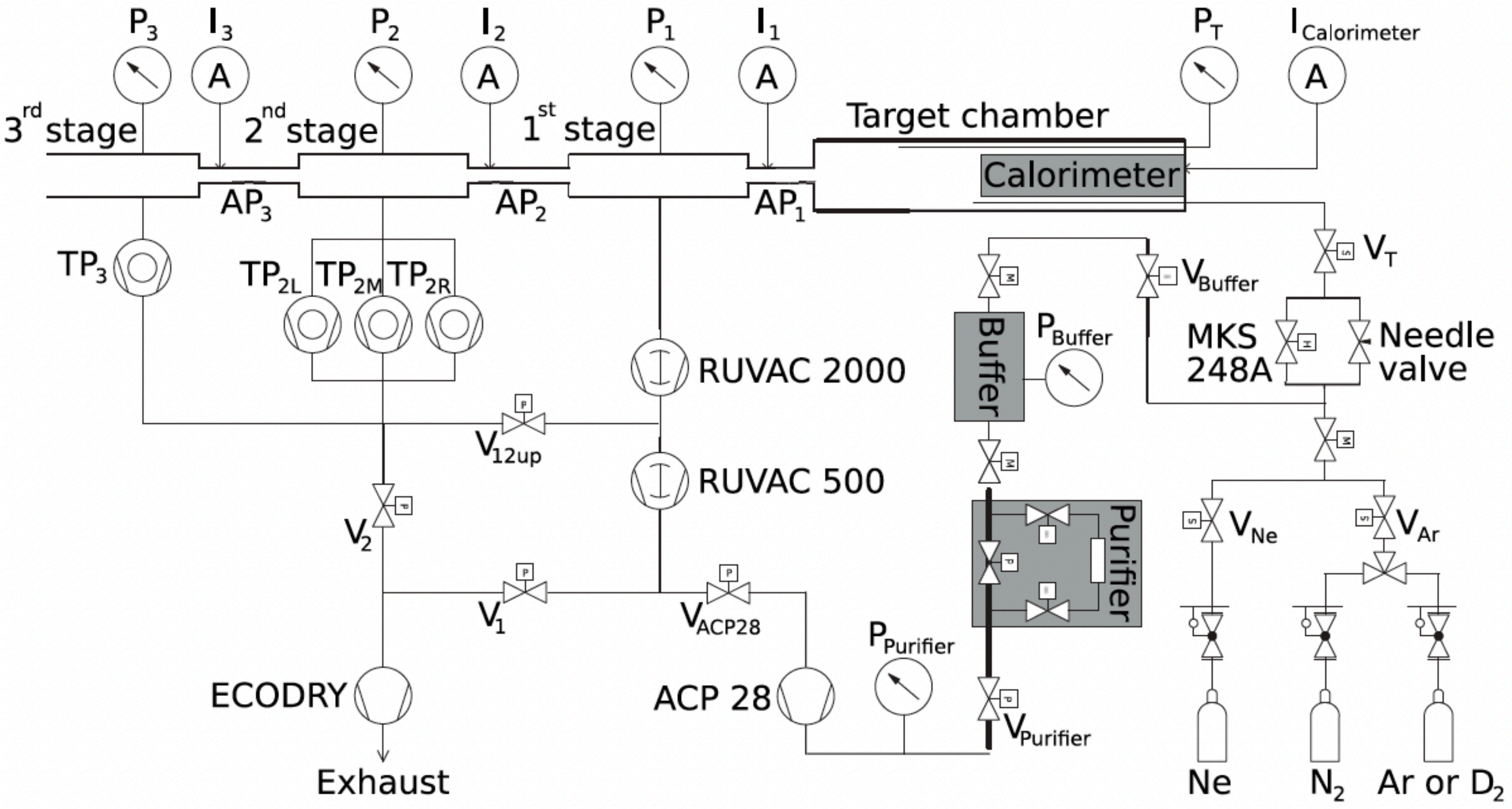
Target features:

- both target types thin as desired
- and stable up to high accumulated charge
- stoichiometry under investigation
- Boron content similar in both Fe and Ta



A paper is in preparation!

LUNA Targets - Gas target



[Ferraro F., et al., EPJ A 54 (2018); Mossa V., et al., EPJ A 56 (2020) and reference therein]

- Three differential pumping stages windowless gas target
- Pressure in the chamber 0.3 - 2 mbar and kept constant within 0.5%
- Target density of 10^{15} atom/cm^2
- High stability under irradiation
- Recirculation mode for expensive gas
- Calorimeter for current reading
- High precision obtained for the p+D measurement
- High purity BUT contaminants along beamline and at the beam stop must be annoying (B, C, N and F)

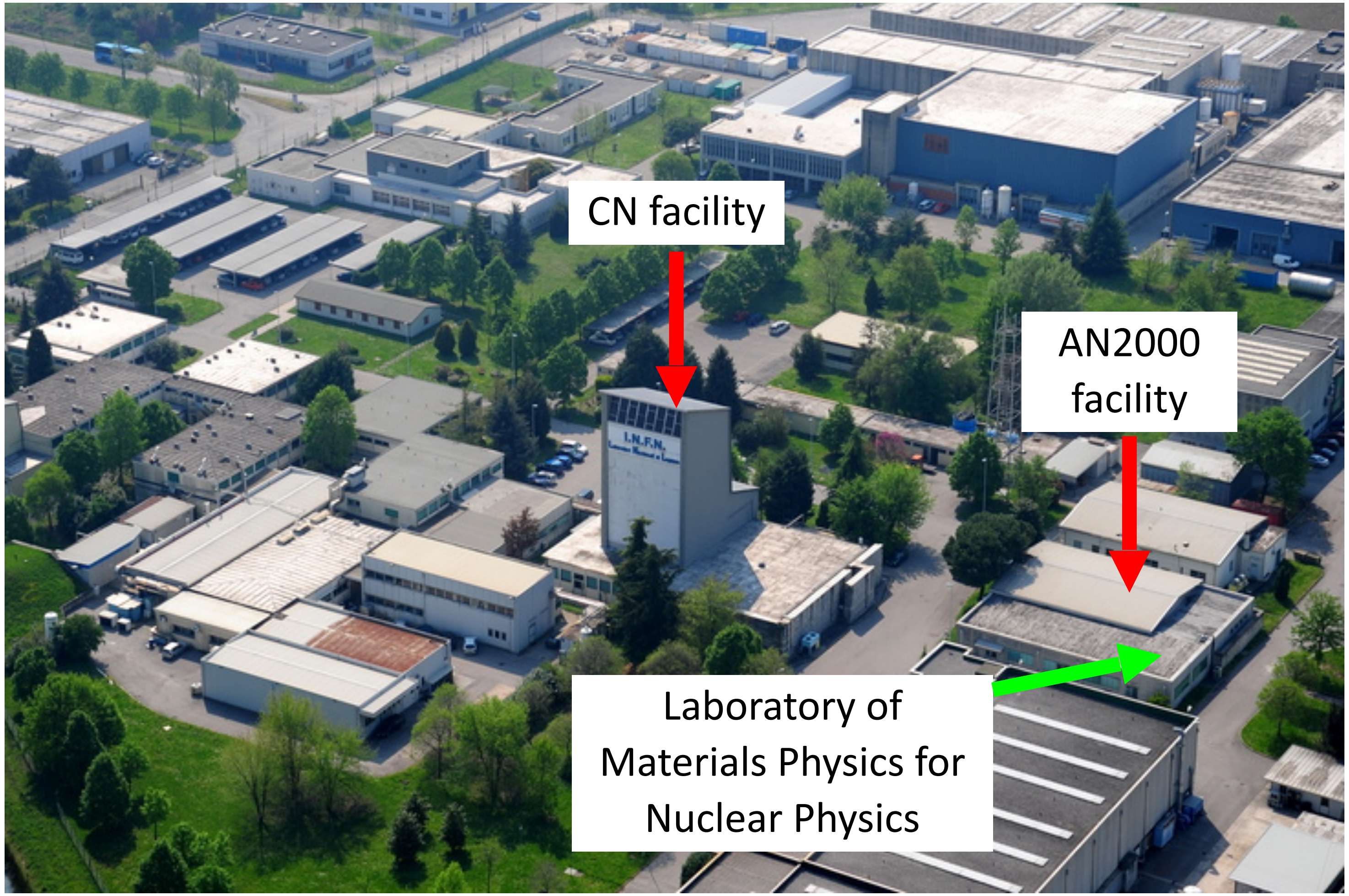
Ultrasonic bath to reduce contaminants level and runs w. noble gas to subtract it

Speaking of Perspectives

NATIONAL LABORATORIES OF LEGNARO (LNL)

Other Laboratories involved in targets production:

- **LNL (Padua-Italy)**
- **LNGS (L'Aquila-Italy)**
- **ATOMKI (Debrecen-Hungary)**
- **University NOVA (Lisbon-Portugal)**
- **HZDR (Dresden-Germany)**
- **Edinburgh University (UK)**
- **Notre Dame (USA)**
- **……**



Legnaro WG activities

LNL Group:

- Valentino Rigato (DT)
- Carlo Roncolato (PT)
- Matteo Campostrini (IIIT-TD)

Research Fields:

- **Surface engineering and materials synthesis**
- **Characterizations (IBA, morphological Compositional and structural analysis)**
- **High Vacuum deposition systems design and development**
- **Ion beam irradiation**
- **Detector testing**

INFN CSN3 nuclear physics

Solid targets development and characterization

INFN CSN5 interdisciplinary physics

Functional coatings with nanostructured multilayers
Sigle ion irradiation for quantum technologies
Ion-matter interaction and beam induced damage

INFN Technological Transfer

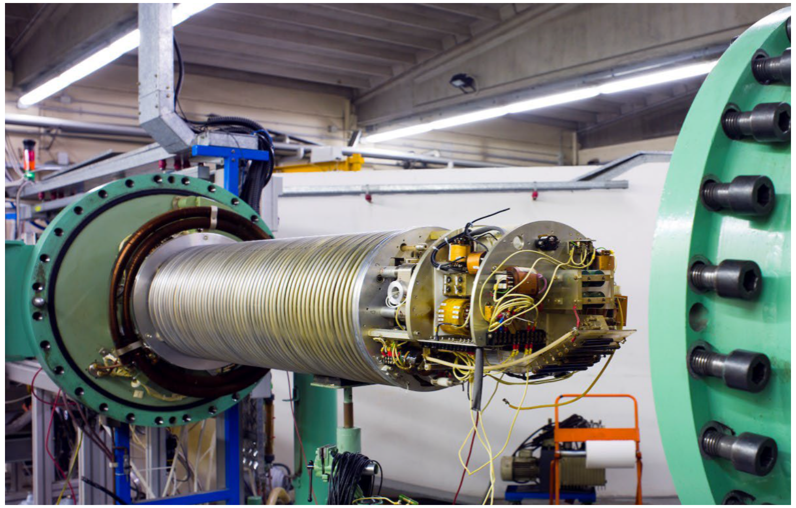
Large area irradiations, accelerated tests for satellite components
Nanostructured coatings Mechanical reinforcement coatings

Legnaro laboratory activities and user's support

LNL Target service (technical support and IBA characterization)
SPES (target analysis, beam diagnostics, coatings…)
Accelerator Division (Beam characterization, coating for RF accelerator windows)
……..

LNL ion beam facilities

AN2000



Available beams:

- $^{1}H^{+}$ 0.2÷2.0 MeV
- $^{3}He^{+}$ 0.2÷2.0 MeV
- $^{4}He^{+}$ 0.2÷2.0 MeV
- ➢ $^{1}H^{+}$ and $^{4}He^{+}$ μ-probe 2-5 μm spot size

Main activities:

- IBA (EBS, NRA)
- ASIDI (Single ion irradiation)
- ASIF (large area irradiation LE-facility)
- Detector testing
- Quantum technology

CN

Available beams:

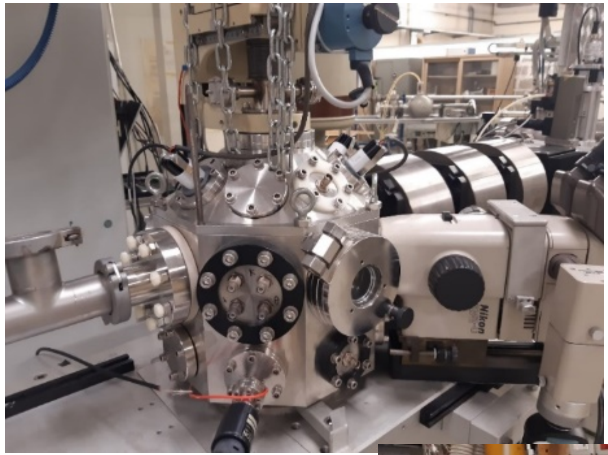
- $^{1}H^{+}$ 0.8÷5.5 MeV
- $^{2}H^{+}$ 0.8÷5.5 MeV
- $^{3}He^{+}$ 0.8÷5.5 MeV
- $^{4}He^{+}$ 0.8÷5.5 MeV
- ➢ Pulsed beam

Main activities:

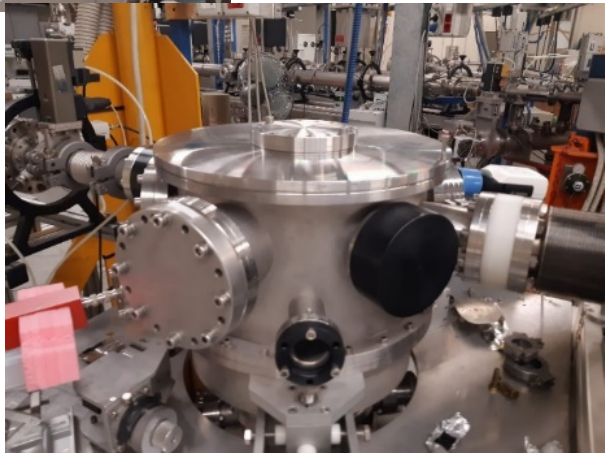
- IBA (EBS,NRA and PIXE)
- ASIF (large area irradiation HE-facility)

LNL ion beam facilities

AN2000

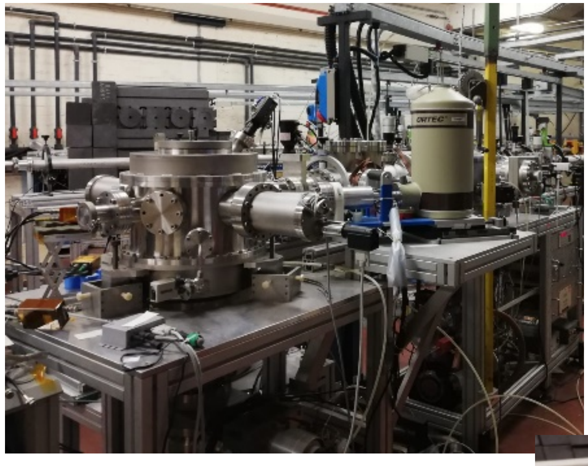


μ-probe scattering chamber
(2-5 μm spot size)

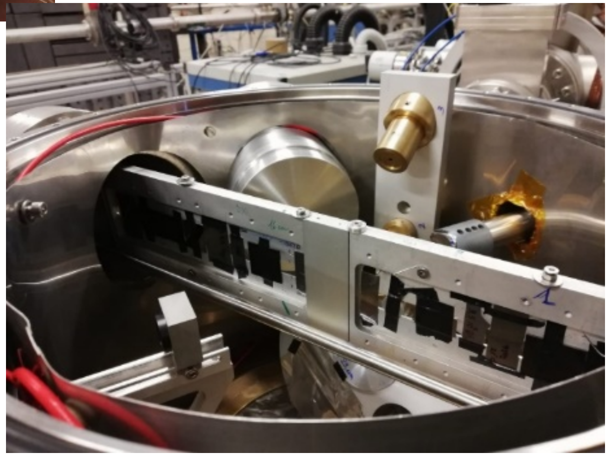


IBA scattering chamber
(1-25 mm^2 spot size)

CN



Total IBA scattering chamber
(1-25 mm^2 spot size)



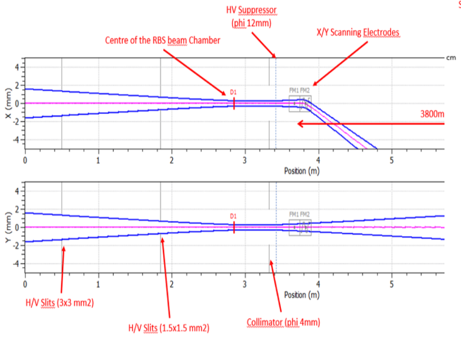
Irradiation Activities…

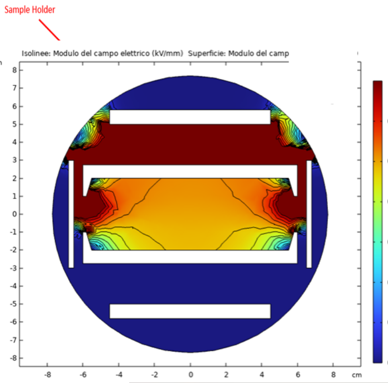
Large area ion beam irradiations

Large area ASIF irradiation facility

(ASI Supported Irradiation Facilities)

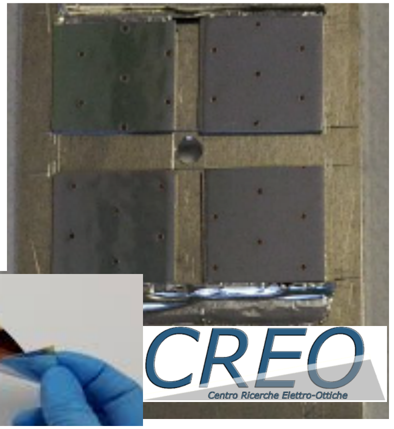
- Monochromatic Beams: 1H+, 4He+
- Energy: 0.2÷5.5 MeV
- Spatial uniformity: target ≤ ±1%
- XY beam scanning (up to 20cmx20cm)



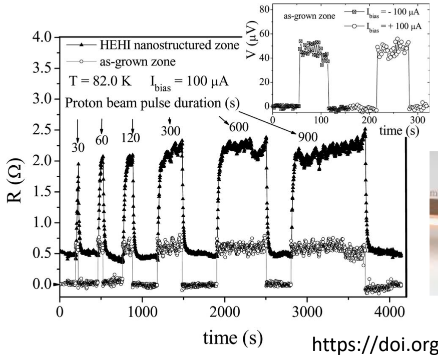


Beam dynamics design

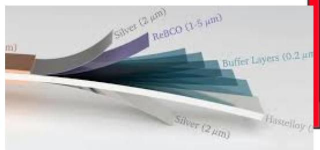
satellite optical components

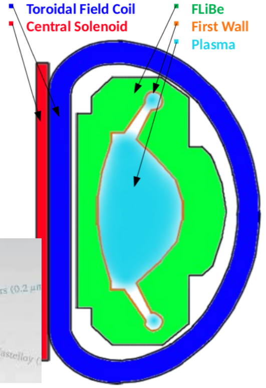


High temperature Superconductive materials (REBCO), compact fusion reactor

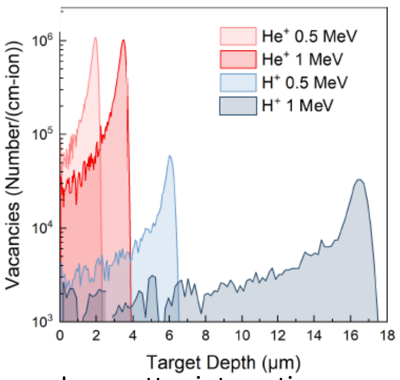


https://doi.org/10.1063/1.2982370





Single Photon Emitters production for Quantum Technology



Ion-matter interaction

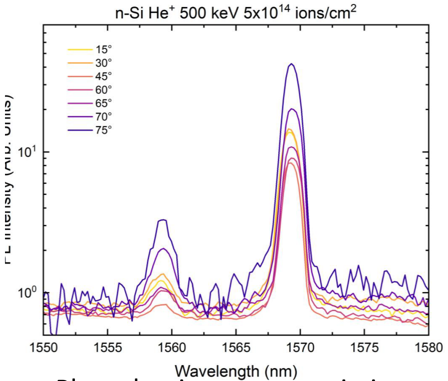
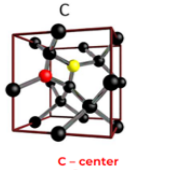
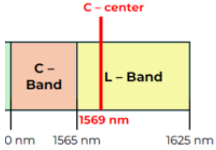


Photo luminescence emission



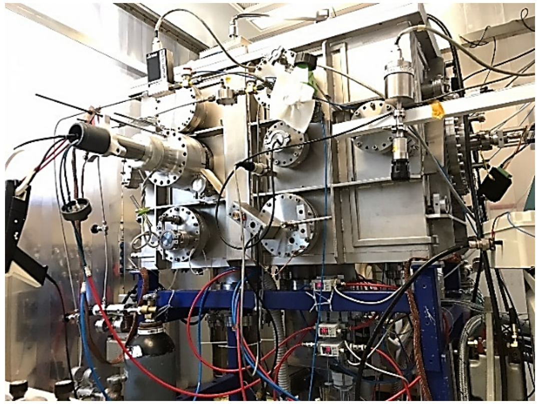


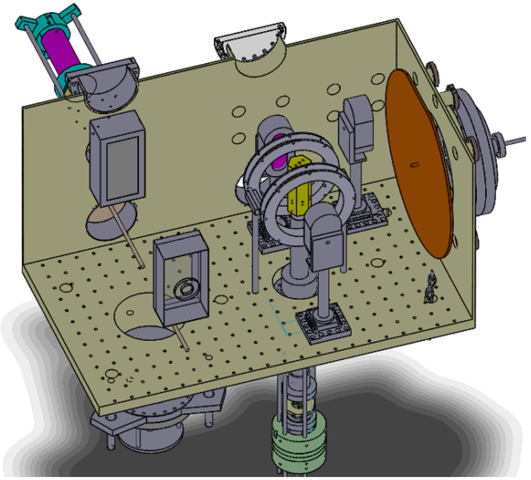
Laboratory of Materials Physics for Nuclear Physics

INFN Istituto Nazionale di Fisica Nucleare

LUNA

Pure metal and compounds materials synthesis





Characteristics:

- 3 sputtering source (50mmx140mm)
- 2 sputtering source (150mmx230mm)
- Active gettering system
- Optical emission plasma diagnostics for reactive processes
- Different power supply technologies (HiPIMS, DC, pulsed-DC, RF)
- 2 different sample holder

Materials:

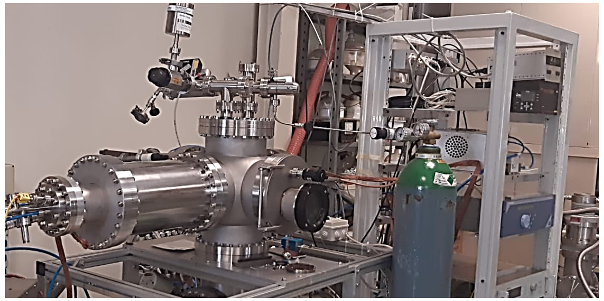
Pure materials (Ta, Ti, Zr, Cr, Cu, Nb…)

Compounds:

- Oxides (natural O, ^{16}O and ^{17}O)
- Nitrides (natural N, ^{14}N, ^{15}N)
- Hydrides (natural H, Deuterium)

Sputtering systems

Alkali materials (Na, Mg,…)



Materials:

$NaNbO_3$, Mg_2Si

Characteristics:

Heated sample holder (up to 600 °C)

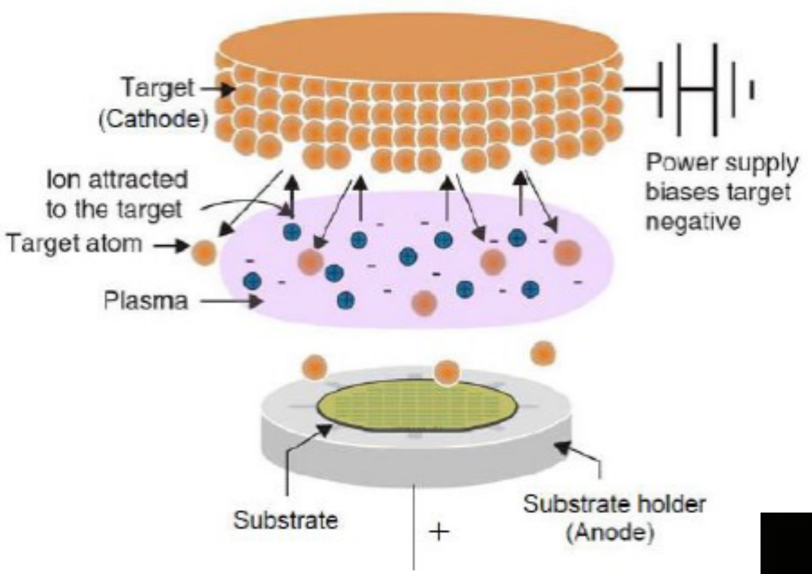
Characterization techniques:

- Optical microscope
- SEM (Scanning electron microscope)
- EDS (Energy-dispersive X-ray spectroscopy)
- AFM (Atomic force microscope)

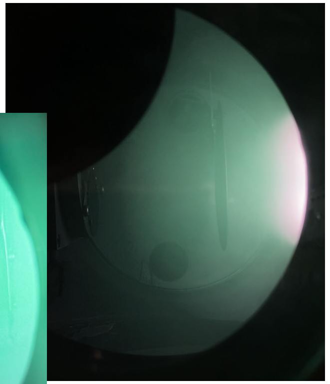
Avaible in other collaborators laboratory:

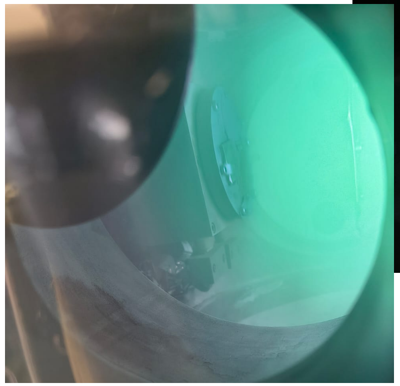
- XRD (X-ray Diffraction)
- Raman
- TEM (transmission electron microscope)
- STEM (scanning TEM)
- FIB (focused ion beam)

Magnetron sputtering PVD deposition process



DOI: 10.13140/RG.2.1.3855.5605





Magnesium Silicide (Mg_2Si) deposition (Argon plasma process gas)

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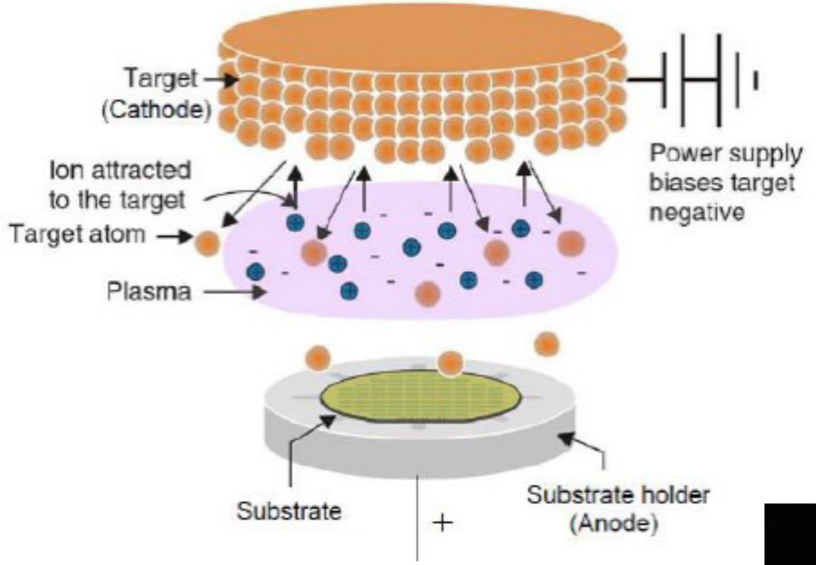
Magnetron sputtering PVD deposition process



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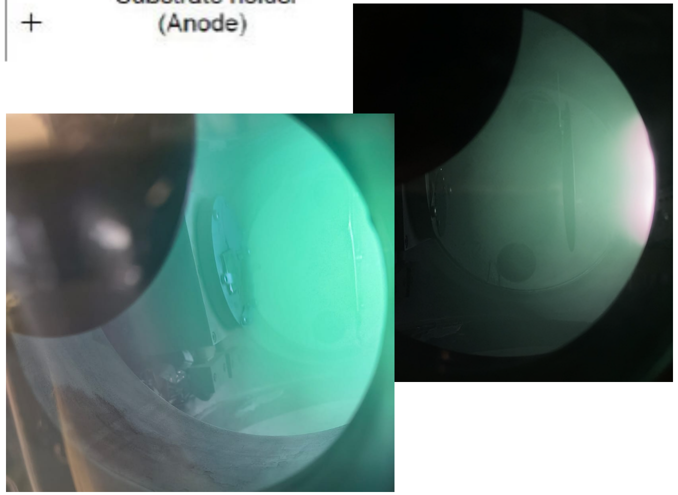
Magnesium Silicide (Mg_2Si) deposition (Argon plasma process gas)



Process control and system improvements

High quality coatings →	Ion bombardment assisted film growth
Low Oxygen contamination →	Active gettering system
Synthesis of compound targets using REACTIVE magnetron sputtering technology →	Nitrides, Oxides and Hydrides with natural and isotopically enriched gas
Plasma study and monitoring →	Optical emission spectroscopy (UV-VIS) and Time resolved OES

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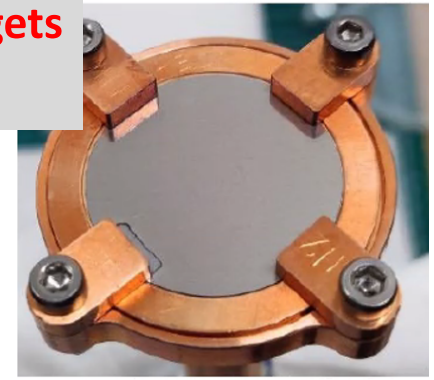
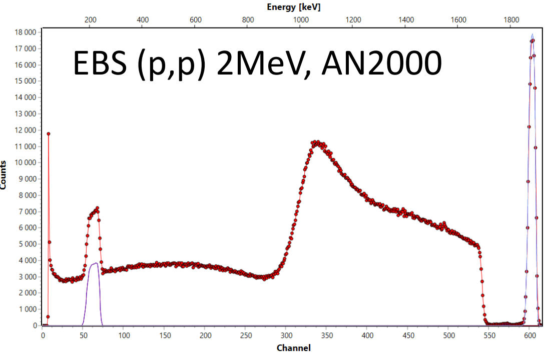
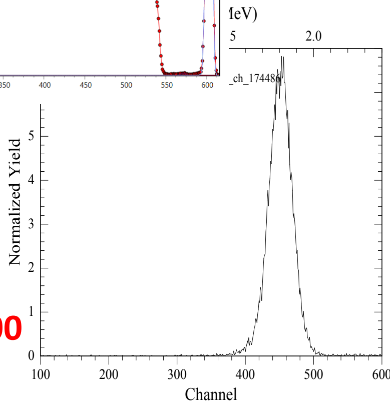
Hydrides targets
ZrD_2

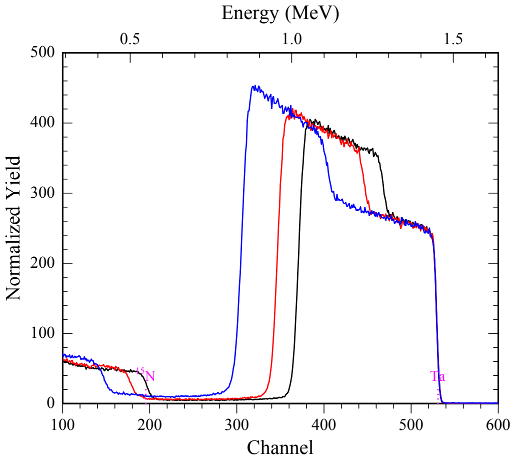




NRA
$D(^3He, p)^4He$
1MeV ^3He AN2000

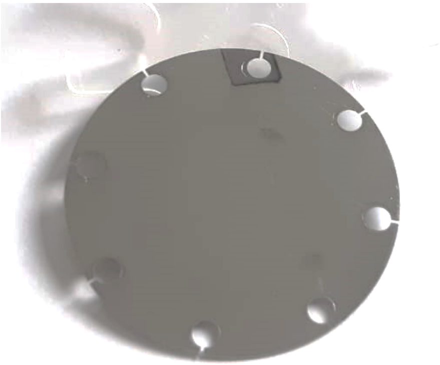


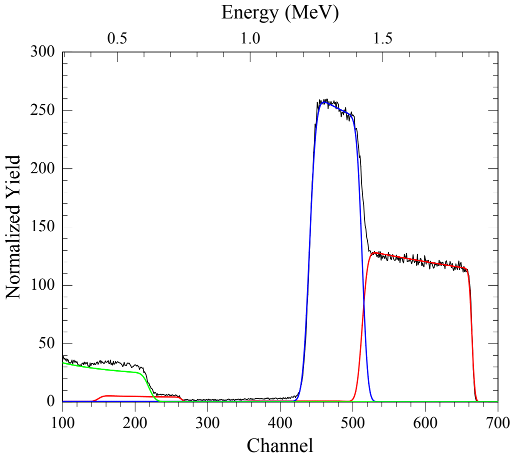
Nitrides targets
$Ta^{15}N$



EBS (α,α) 1.6MeV, AN2000

Oxides targets
$Ta_2{}^{nat}O_5$





EBS (α,α) 2MeV, AN2000

LNL is involved in LUNA experiments

Targets production, characterization and experimental supports

$^{14}N(p,\gamma)^{15}O$ — SoCIAL: SOlar Composition Investigated At Luna

$^{23}Na(p,\alpha)^{20}Ne$ — ELDAR: Elements in the Lives and Deaths of stARs

$^{24}Mg(p,\gamma)^{25}Al$

experiments at **LUNA400**

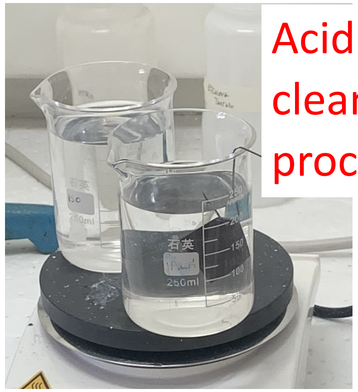
$^{14}N(p,\gamma)^{15}O$ — **First experiment at Bellotti facility**

$^{12}C+^{12}C$ — CaBS: Carbon Burning in Stars

experiments at **BELLOTTI ion beam facility**

$^{14}N(p, \gamma)^{15}O$ target production and characterization (first IBF experiment)

- Fluorine contaminant reduction
- Oxygen contaminant reduction
- RBS characterization
- High endurance target

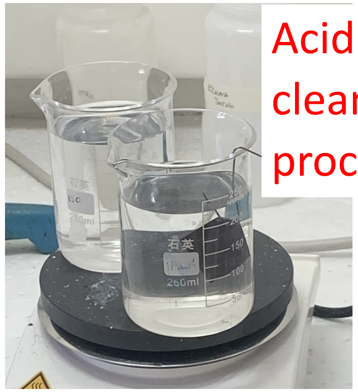


Acid cleaning procedure

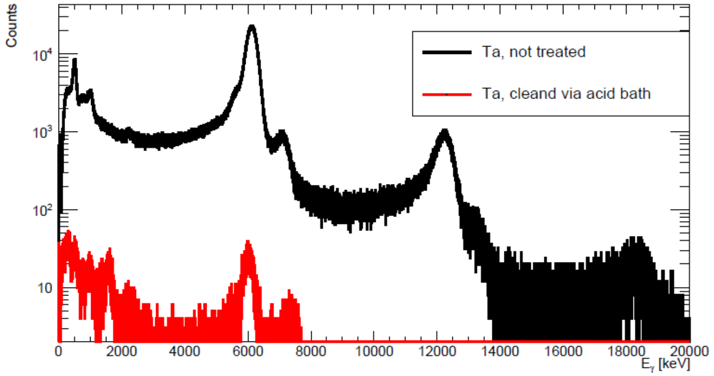
$^{19}F(p,\alpha\gamma)^{16}O$ @ LNGS facility

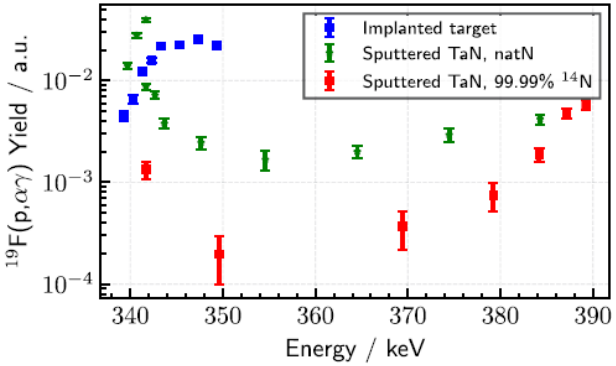
$^{14}N(p,\gamma)^{15}O$ target production and characterization (first IBF experiment)

- Fluorine contaminant reduction
- Oxygen contaminant reduction
- RBS characterization
- High endurance target



Acid cleaning procedure





$^{19}F(p,\alpha\gamma)^{16}O$ @ LNGS facility

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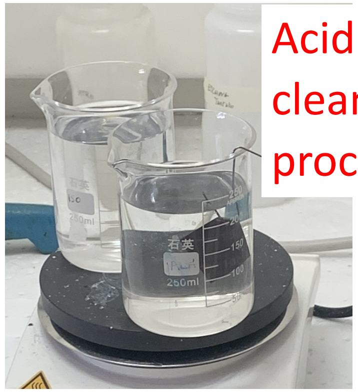
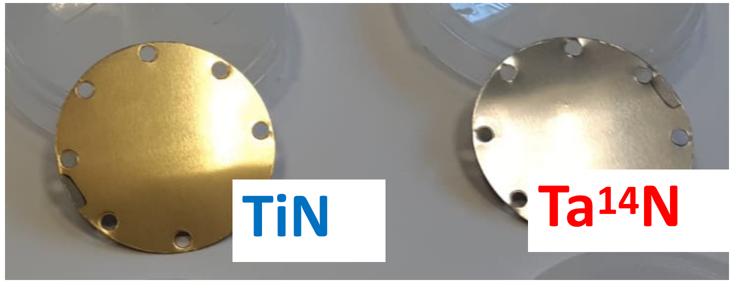
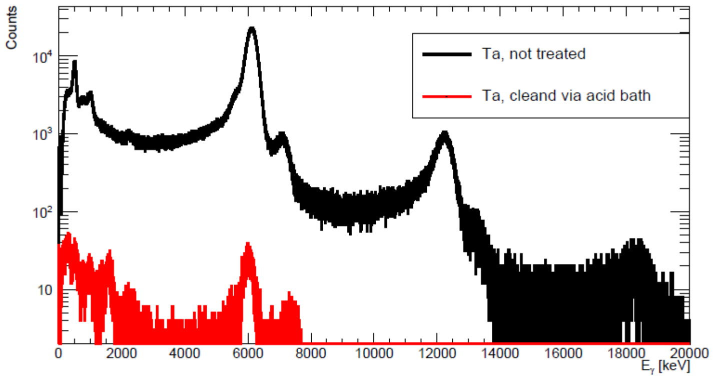
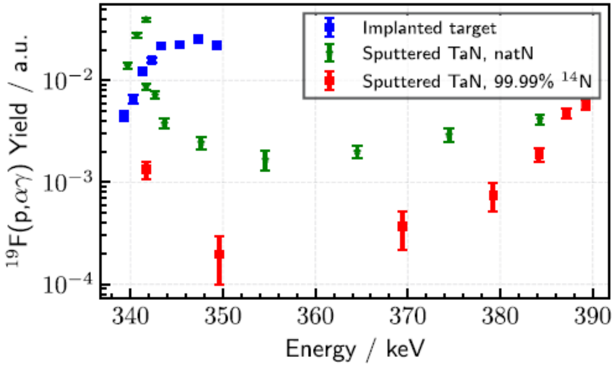


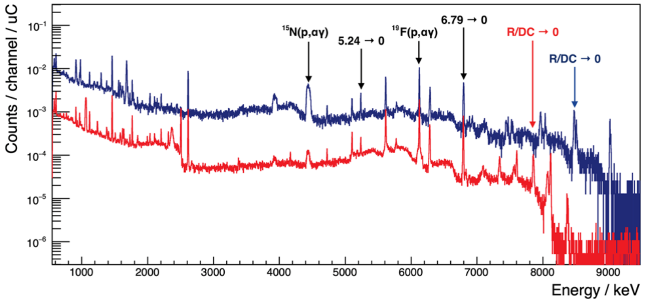
Acid cleaning procedure

^{14}N isotopically enriched (99.99%)







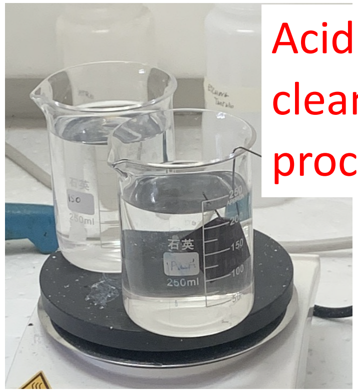


$^{19}F(p,\alpha\gamma)^{16}O$ @ LNGS facility

$^{14}N(p, \gamma)^{15}O$ experiments

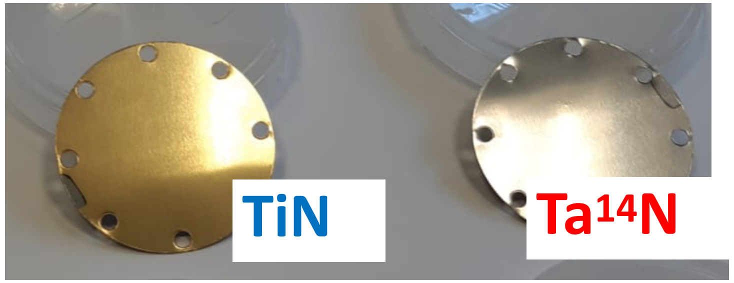
$^{14}N(p, \gamma)^{15}O$ target production and characterization (first IBF experiment)

- Fluorine contaminant reduction
- Oxygen contaminant reduction
- RBS characterization
- High endurance target



Acid cleaning procedure

^{14}N isotopically enriched (99.99%)



DOI: 10.1140/epja/s10050-025-01658-7
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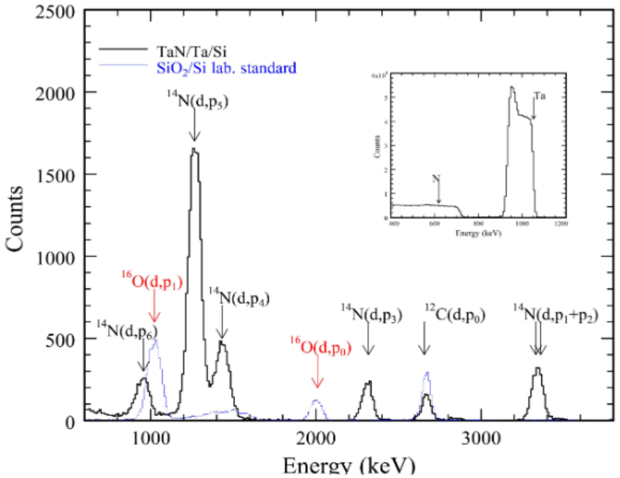
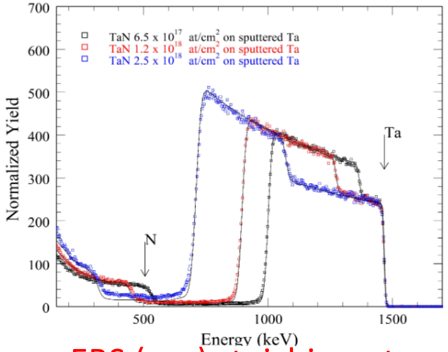
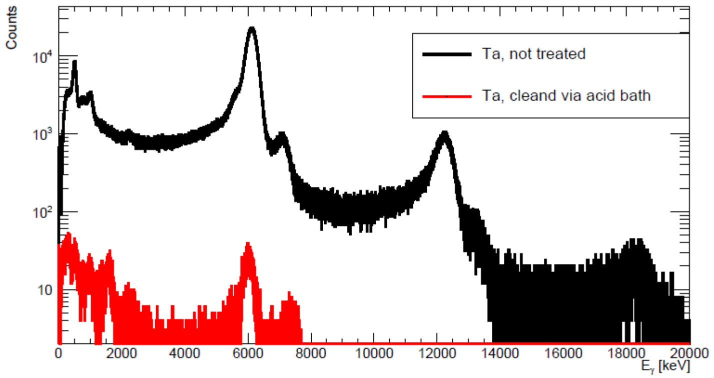
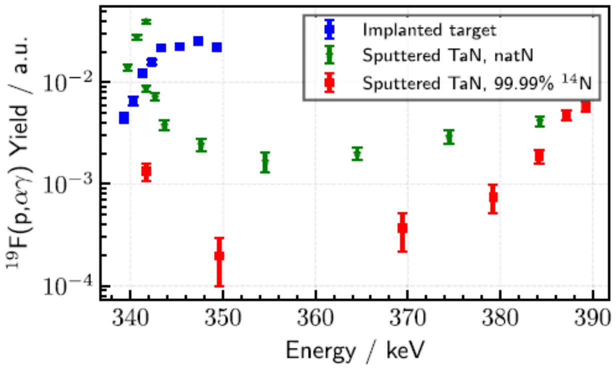


NRA Oxygen No detectable $^{16}O(d,p_0)^{17}O$

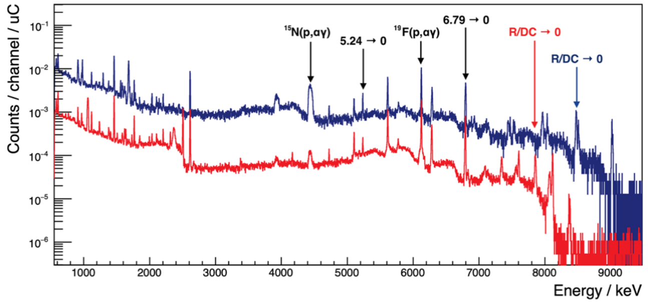


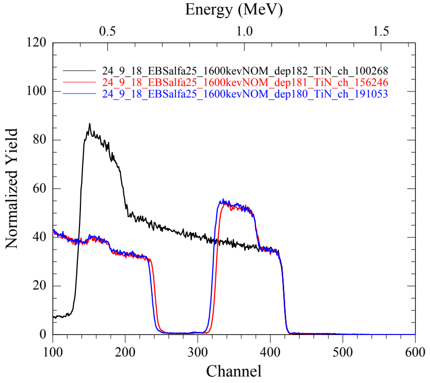
EBS (α,α) stoichiometry measurement TaN compound





$^{19}F(p,\alpha\gamma)^{16}O$ @ LNGS facility





EBS (α,α) measurement stoichiometry TiN compound

$^{12}C + ^{12}C$ experiment

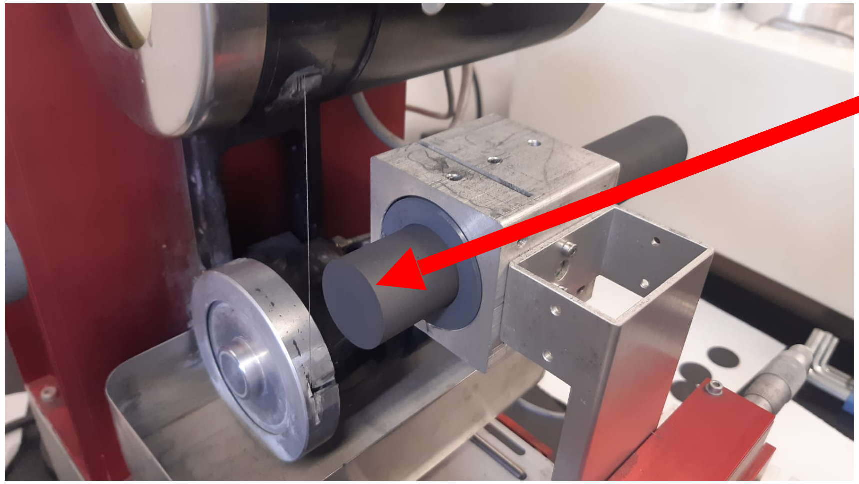
Target design and production

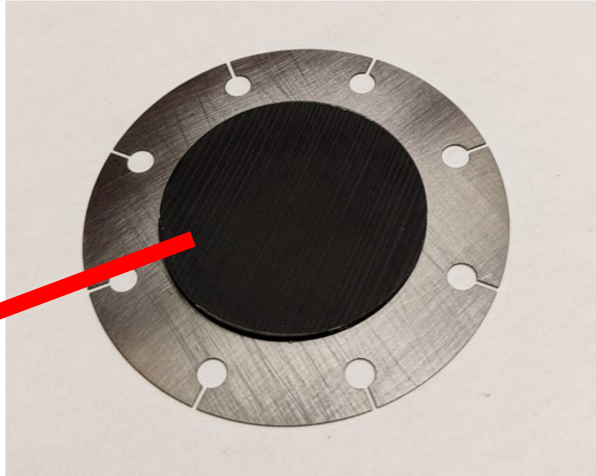
High lifetime:

- Max ^{12}C implantation power: 400 W
- Expected lifetime: 50-100 C
- Characterization pre/post irradiation with IBA (AN2000, CN), SEM – EDS, AFM, RAMAN

Purity : semiconductor grade

Structure: selected fine grain size





Target design and production

High lifetime:

- Max ^{12}C implantation power: 400 W
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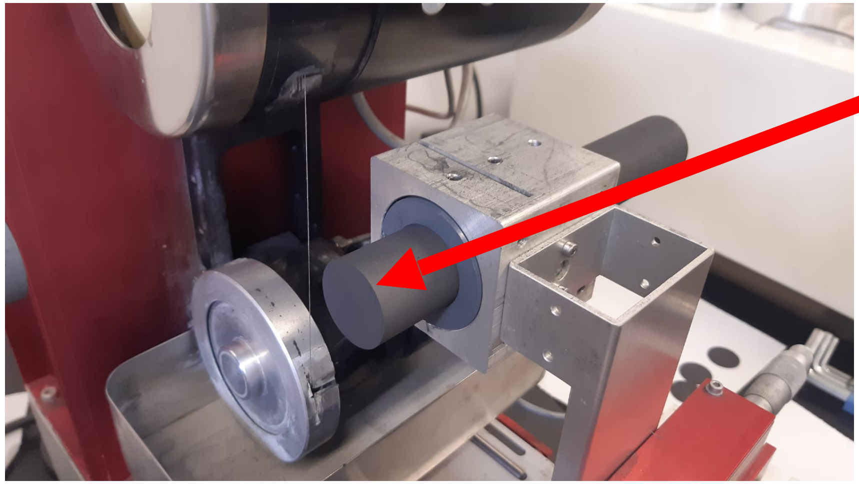
- Characterization pre/post irradiation with IBA (AN2000, CN), SEM – EDS, AFM, RAMAN

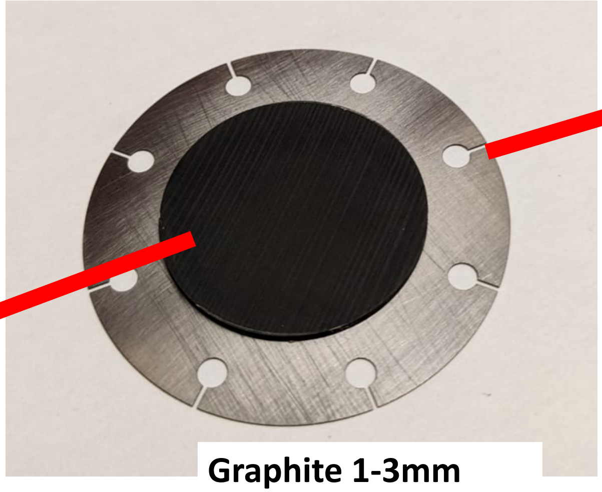
Purity : semiconductor grade

Structure: selected fine grain size

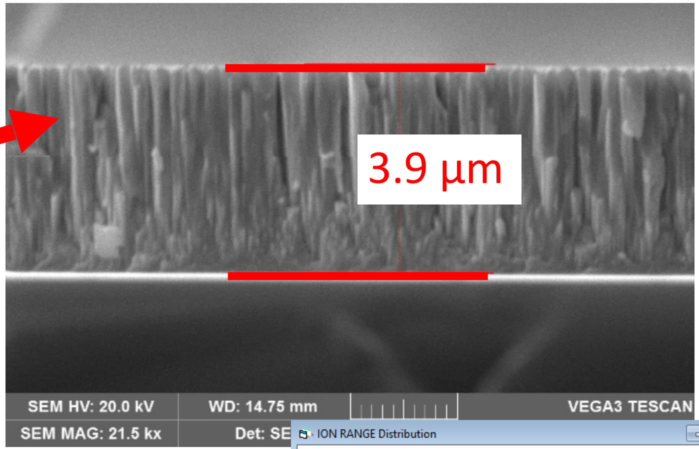
Thich Ta-PVD coating:

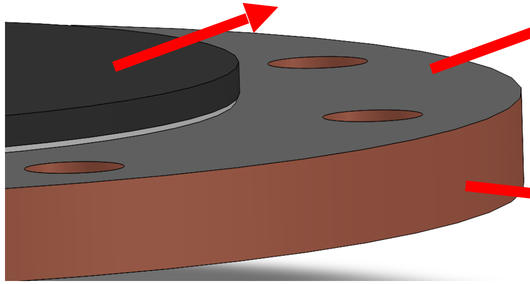
prevent BIB for eventual target failure





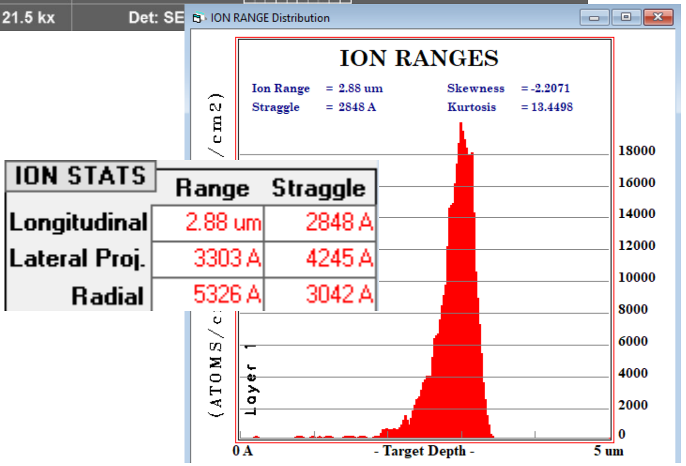
Graphite 1-3mm





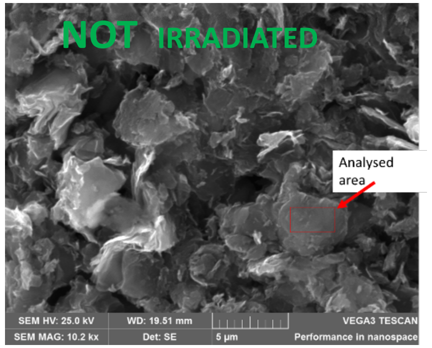
Tantalum coating >3µm

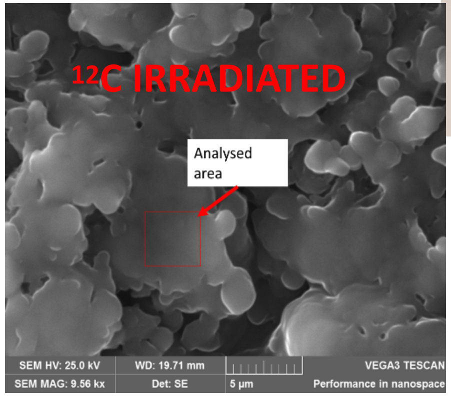
Cu backing ~1-3mm

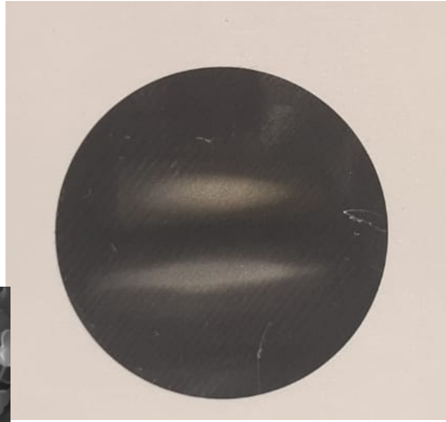


$^{12}C + ^{12}C$ experiment

Target testing and analysis

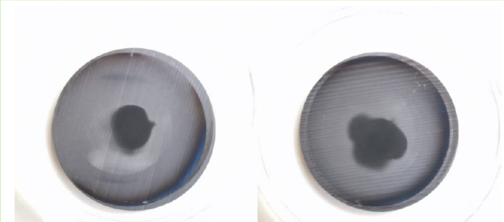






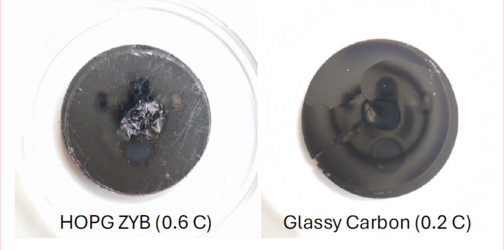
Graphite irradiated target

Sintered Graphite



No evidence of damage after 7.5C of 2.9MeV of $^{12}C^{+}$ beam

Other Carbon



Strong damage after 0.6C of 2.9MeV of $^{12}C^{+}$ beam

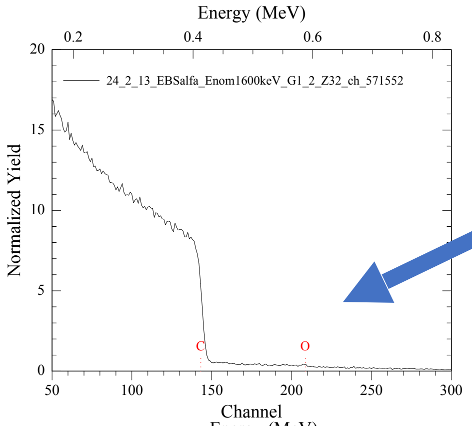
Preliminary irradiation test performed at Felsenkeller HZDR (2024) E. Masha (HZDR) unpublished data
LUNA test performed at IBF 2025 F. Ferraro (LNGS) unpublished data

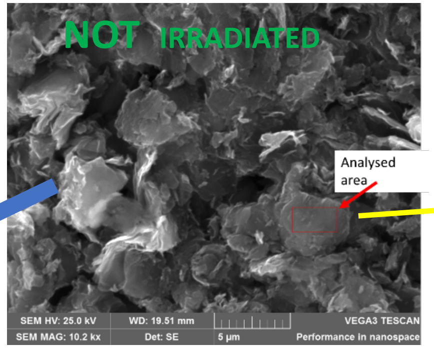
$^{12}C + ^{12}C$ experiment

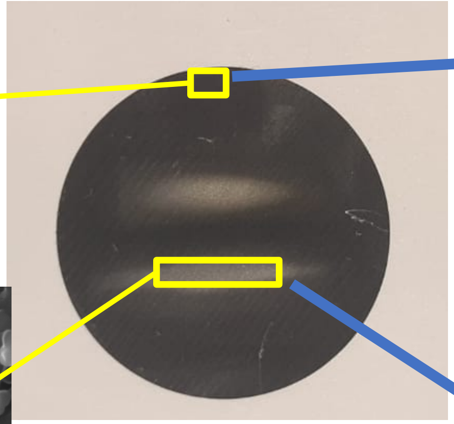
Target testing and analysis

RAMAN spectroscopy proves amorphization of graphite surface

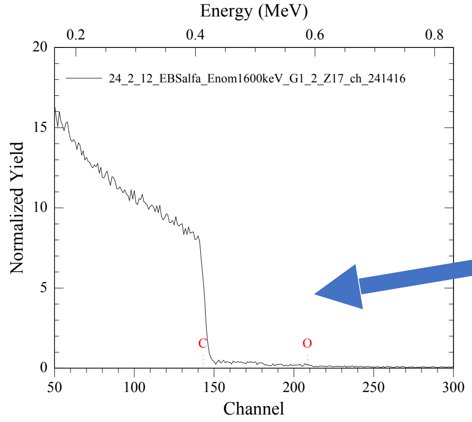
IBA analysis shows no contamination on irradiated regions

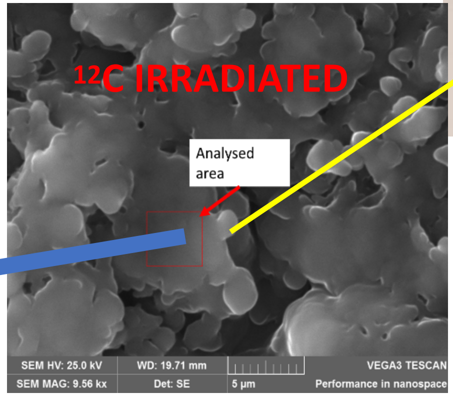






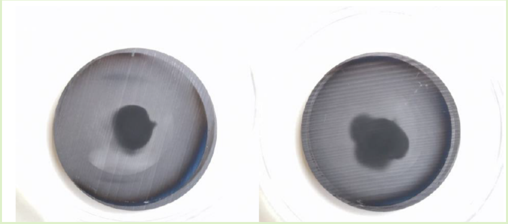
Graphite irradiated target





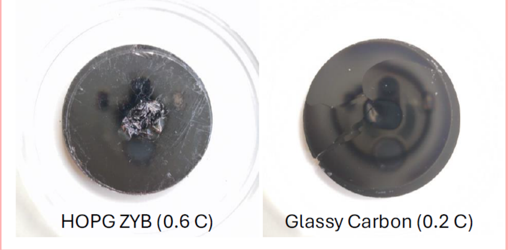
(RAMAN analysis F. Pezzoli (Bicocca University)

Sintered Graphite



No evidence of damage after 7.5C of 2.9MeV of $^{12}C^{+}$ beam

Other Carbon



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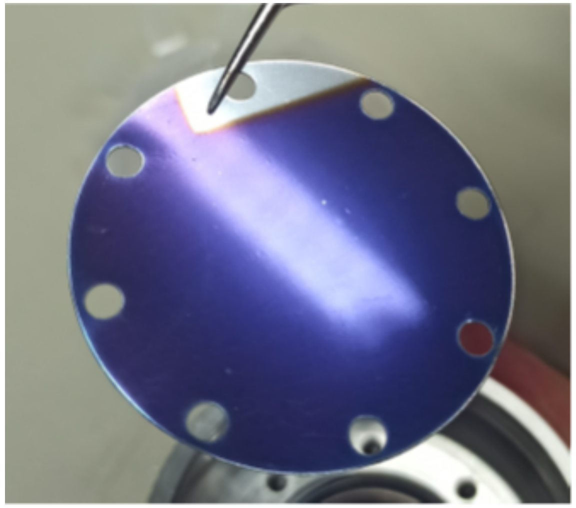
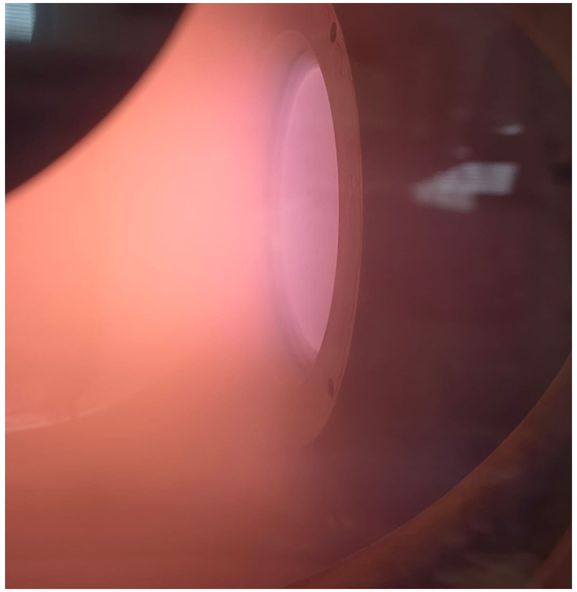
Preliminary irradiation test performed at Felsenkeller HZDR (2024) E. Masha (HZDR) unpublished data

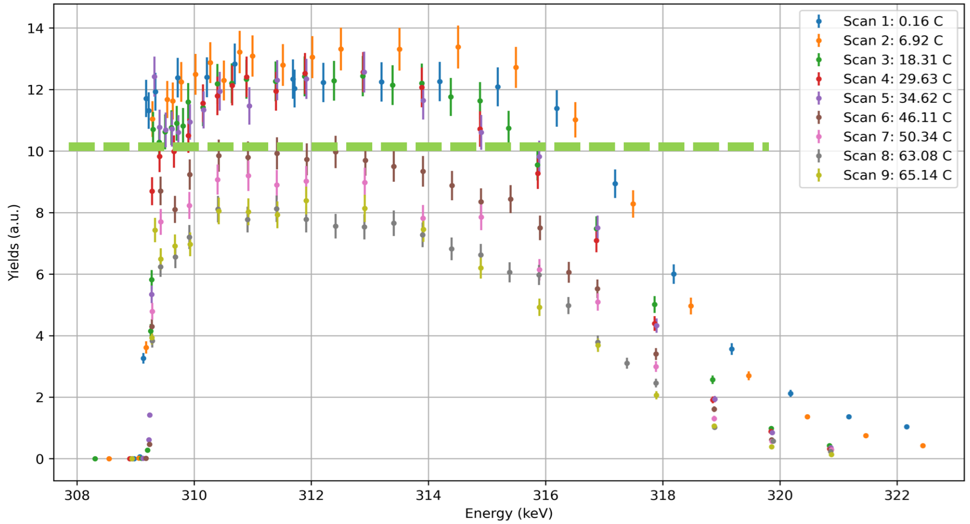
LUNA test performed at IBF 2025 F. Ferraro (LNGS) unpublished data

$^{23}Na(p,\alpha)^{20}Ne$ experiment

First test of $NaNbO_3$ Sputtered Target endurance tests $^{23}Na(p,\gamma)^{24}Mg$, BGO detector







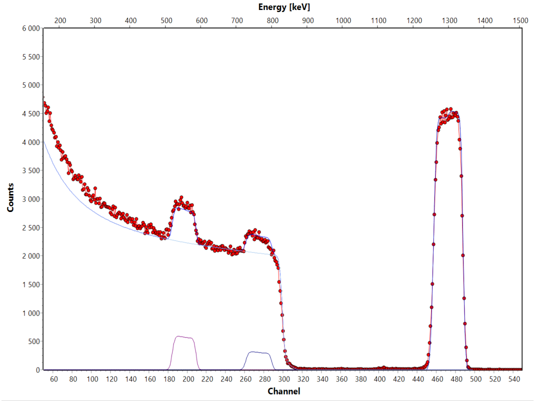
NO degradation up to 35C

$^{23}Na(p,\gamma)^{24}Mg$, BGO detector

L. Barbieri and C. Bruno (PI)

The target was:

- ✓ stable in air
- ✓ good adhesion
- ✓ good uniformity
- ✓ RBS confirm a good stoichiometry
- SEM and EDS shows nanometrically crystal enriched in Na



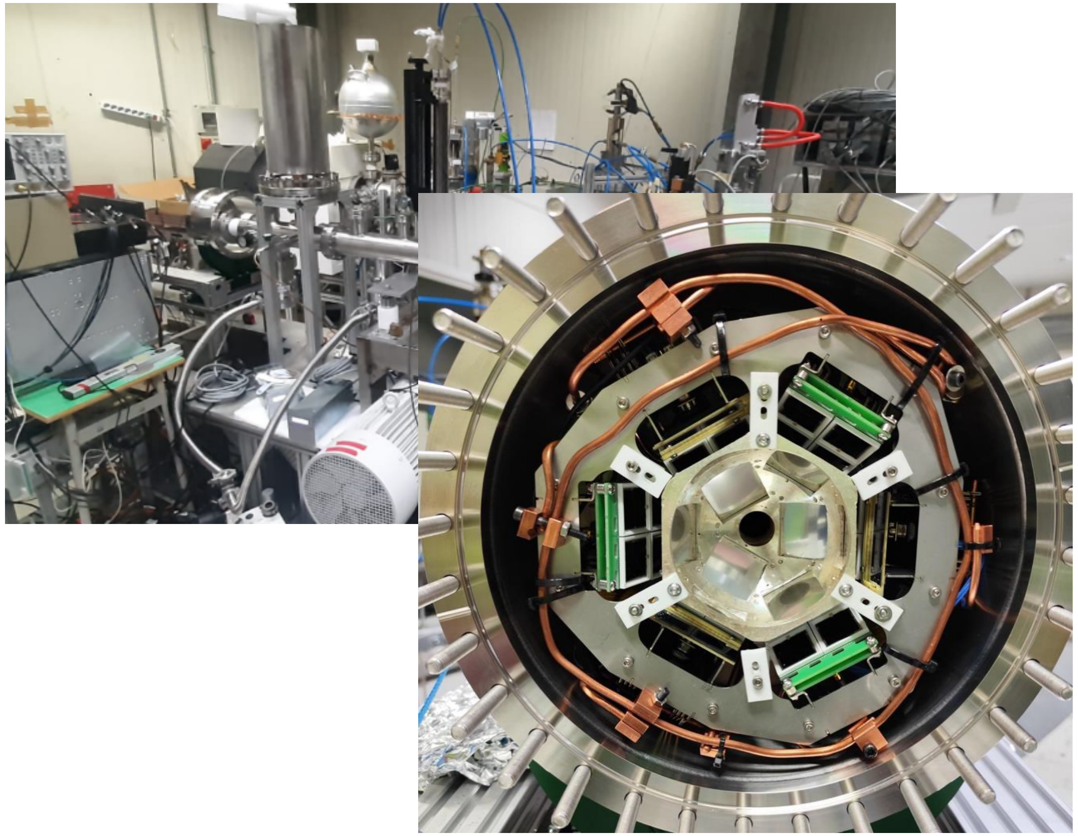
RBS spectrum $NaNbO_3$ /SI

$E\alpha$=1.6MeV

Θ_{EBS}=160°

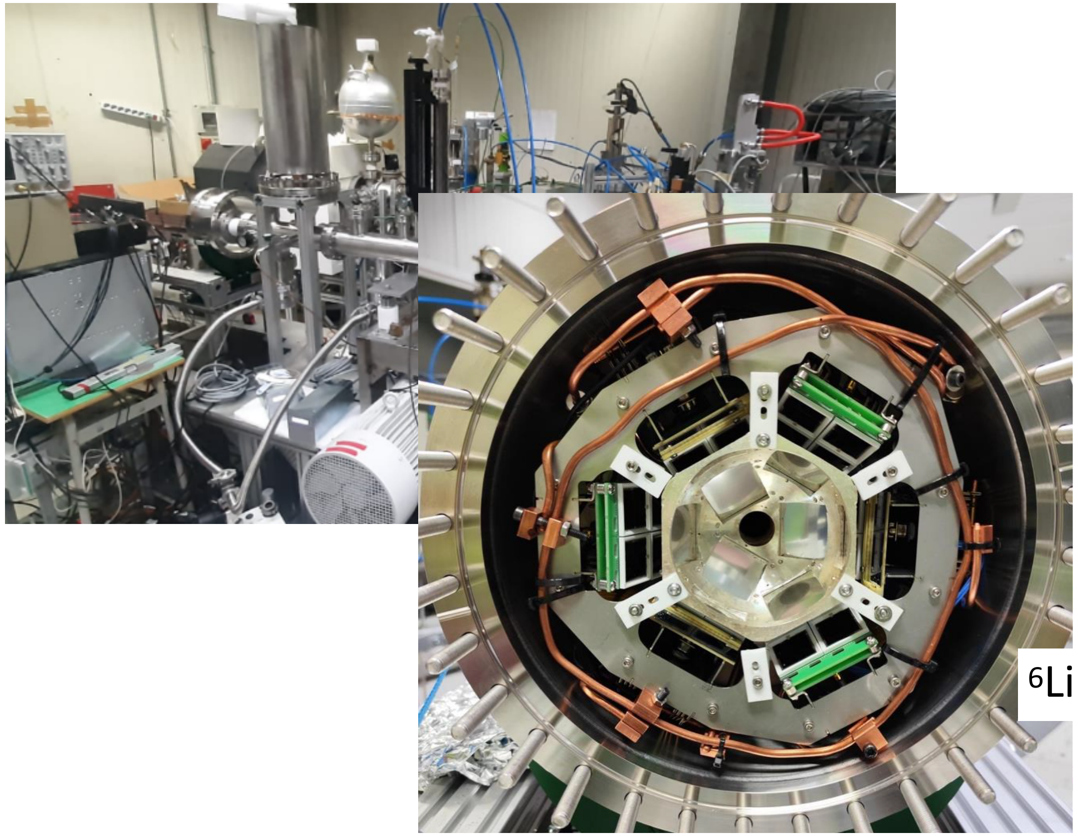
^{23}Na(p,α)^{20}Ne experiment

ELDAR experiment setup for ^{23}Na(p,α)^{20}Ne analysis (PI C. Bruno)



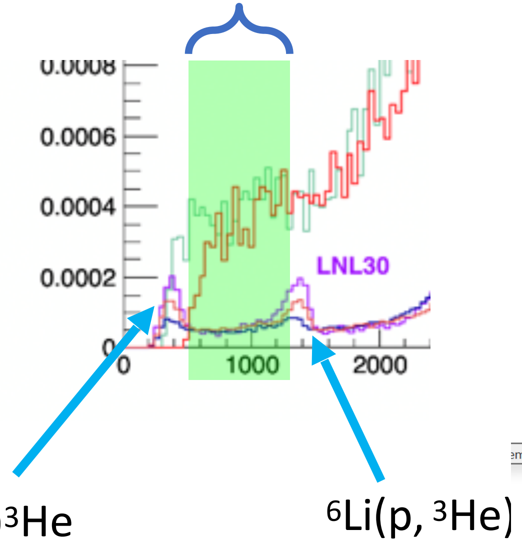
^{23}Na(p,α)^{20}Ne experiment

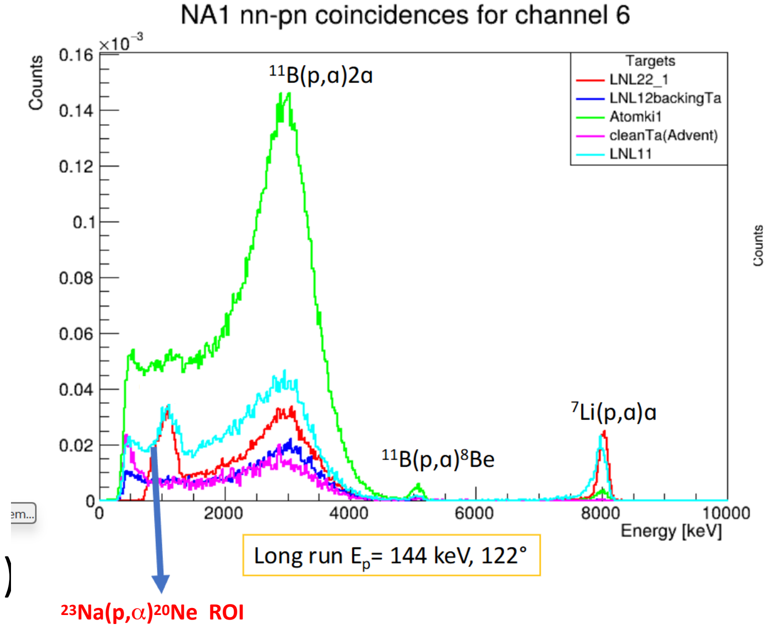
ELDAR experiment setup for ^{23}Na(p,α)^{20}Ne analysis (PI C. Bruno)



The measurement cannot be performed due to the BIB caused by ^{11}B and ^{6}Li contamination

^{23}Na ROI

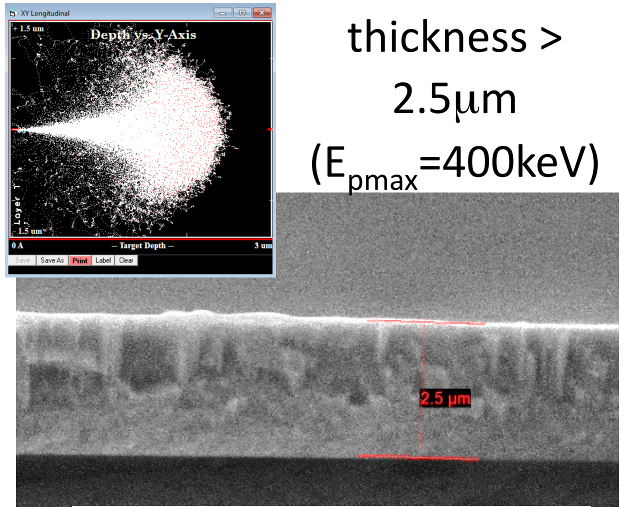




L. Barbieri and C. Bruno

$^{23}Na(p,\alpha)^{20}Ne$ experiment

B reduction using PVD Ta thick coating



thickness > 2.5µm (E_{pmax}=400keV)

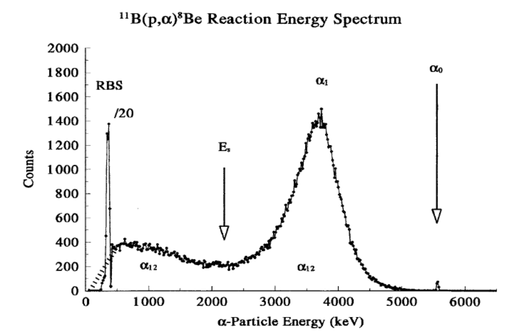


Fig. 1. Energy spectrum of α-particles from $^{11}B(p,\alpha)^8Be$ reaction at incident beam energy of 660 keV and detector at 150°.

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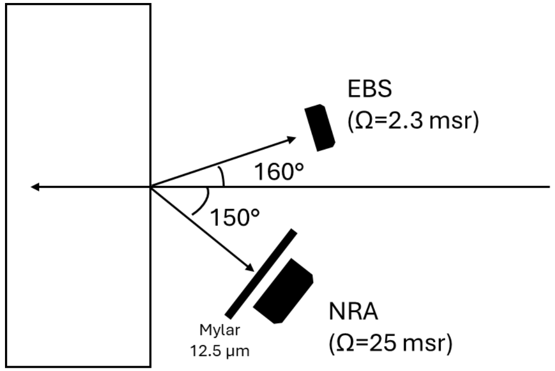
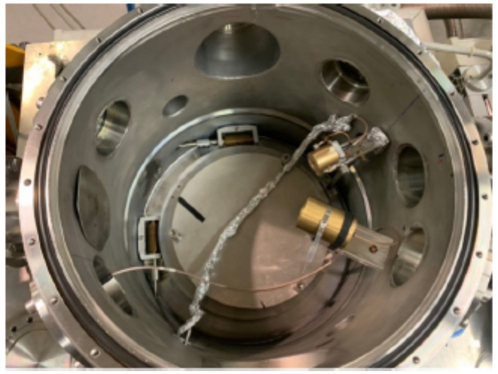
SETUP for NRA @ AN2000





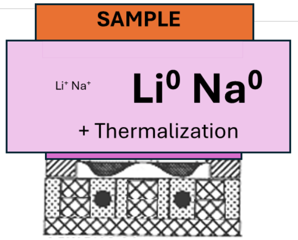
Li reduction in Vapour phase

NEW setup with diode sputtering (No magnetic field)

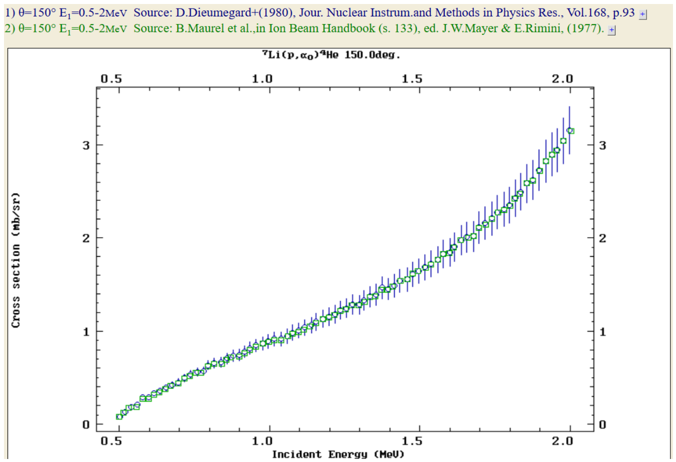
44: 40 min, HPS, 175 mm, **diode** , 4.5E-3 mbar, 150W
45: 80 min, HPS, 175 mm, **diode** , 1.0E-2 mbar, 150W
46: 80 min, HPS, 120 mm, **diode** , 1.0E-2 mbar, 150W
47: 80 min, HPS, 120 mm, **diode** , 1.0E-2 mbar, 200W
48: 60 min, HPS, 120 mm, **diode** , 1.0E-2 mbar, 250W
49: 60 min, HPS, 120 mm, **diode** , 1.0E-2 mbar, 300W

OLD TARGET

50: 60 min, HPS, 120 mm, **diode** , 1.0E-2 mbar, 300W
51: 50 min, HPS, 120 mm, **diode** , 2.0E-2 mbar, 400W
52: 50 min, HPS, 120 mm, **diode** , 4.5E-3 mbar, 400W



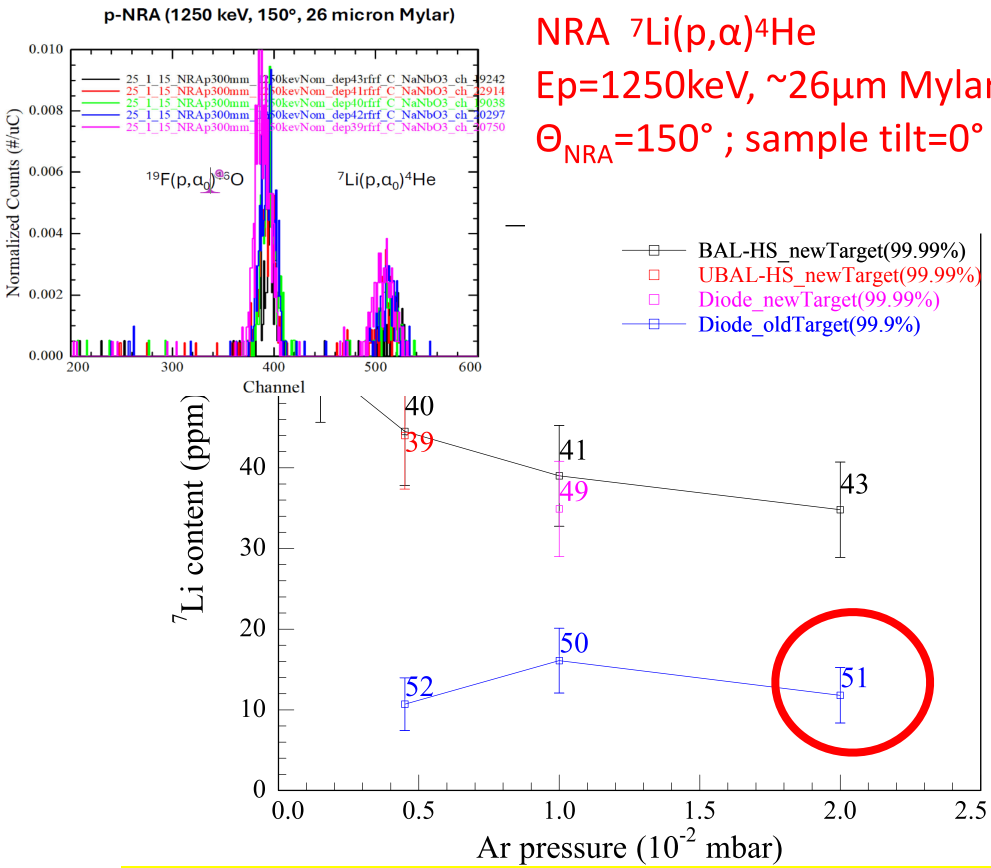
DIODE CONFIGURATION



$^{23}Na(p,\alpha)^{20}Ne$ experiment

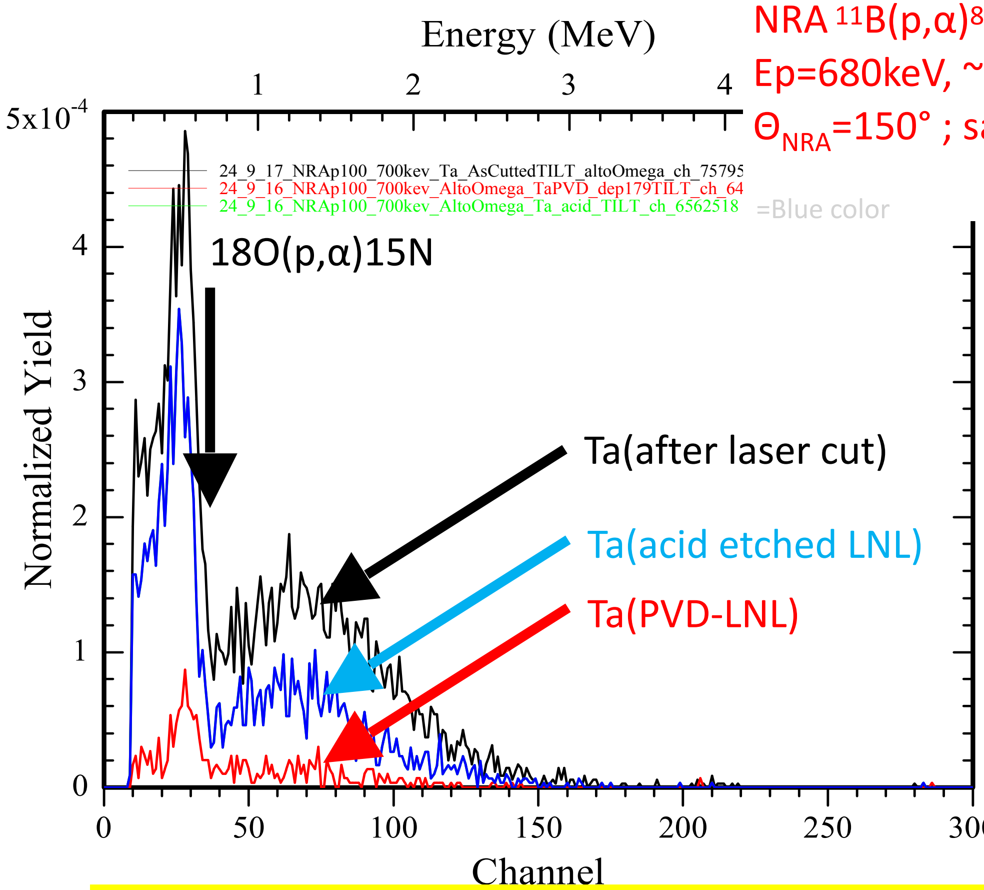
Boron and Lithium contamination reduction: results

NRA $^{7}Li(p,\alpha)^{4}He$
Ep=1250keV, ~26µm Mylar
Θ_{NRA}=150° ; sample tilt=0°



Lithium content reduction ~ 80%
~2 ppm of ^{6}Li

NRA $^{11}B(p,\alpha)^{8}Be[2\alpha]$
Ep=680keV, ~13µm Mylar
Θ_{NRA}=150° ; sample tilt=70°



Boron content reduction ~ 90%
~2-3 ppm of ^{11}B

LUNA Collaboration

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Thank you for your attention