LUNA3

Nuclear solid targets for the 2024-2025 experimental campaigns at LUNA400 and IBF.
Production and characterization at LNL.

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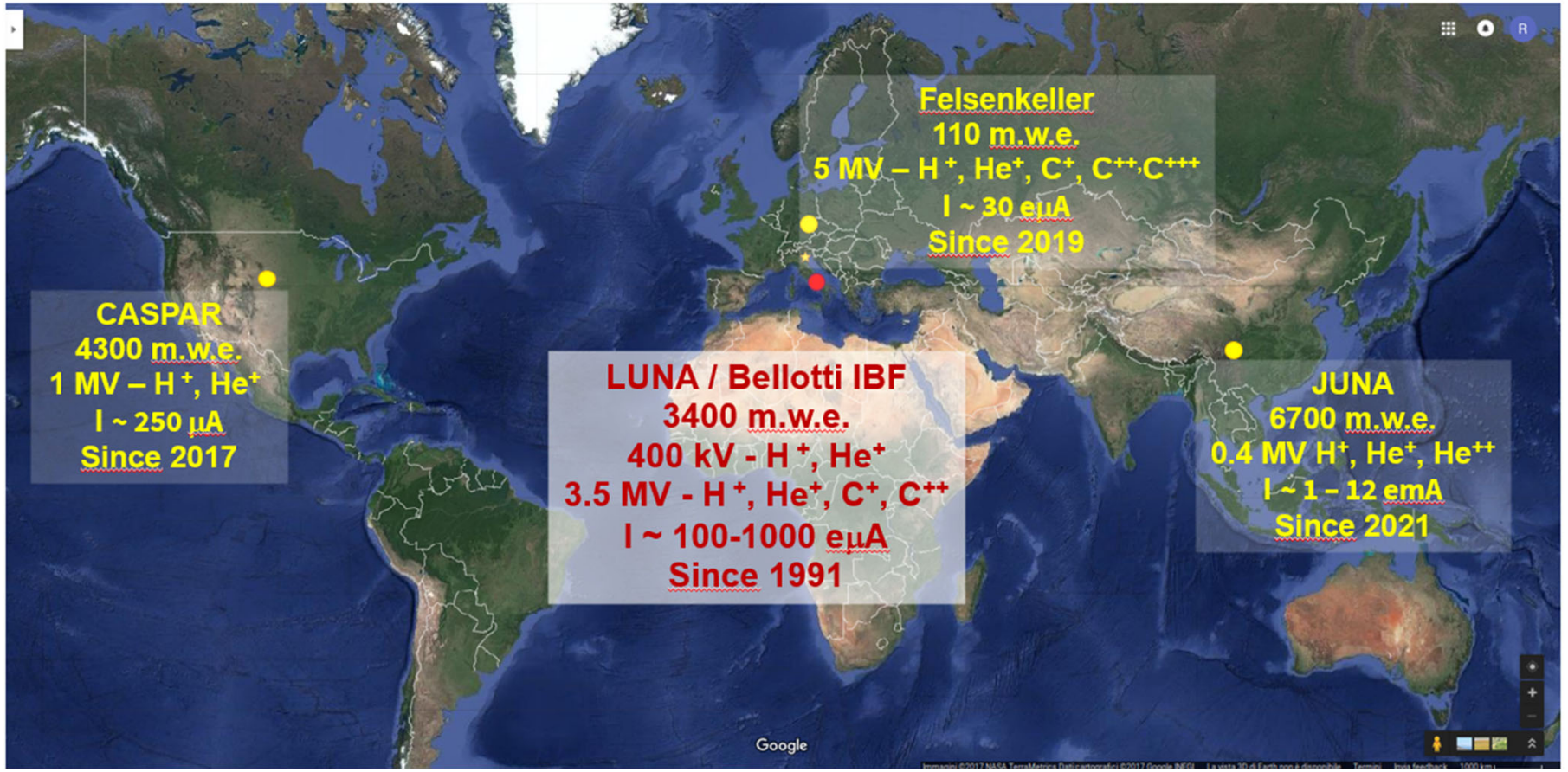
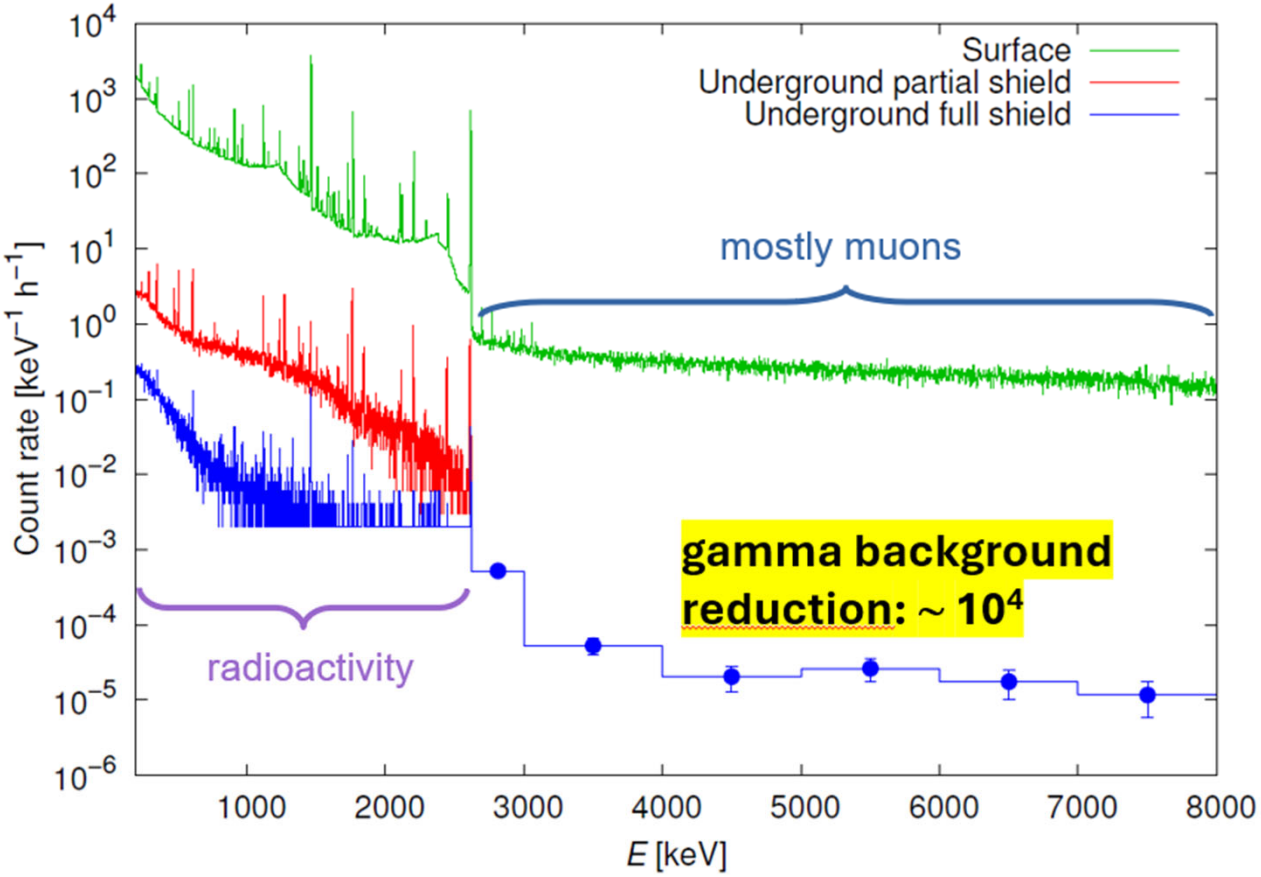
INFN Roma1, ROMA, Italy
Università di Torino and INFN, TORINO, Italy
Osservatorio Astronomico di Collurania, TERAMO and INFN LNGS, Italy

Underground laboratories for Nuclear Astrophysics



Gamma background reduction @ LNGS



LUNA @ LUNA 400

Measurements approved by LUNA CB and ongoing (2024):

- $^{23}Na(p,\alpha)^{20}Ne$ — ELDAR: Elements in the Lives and Deaths of stARs — commissioning ongoing; Sodium Target investigation ongoing
- $^{14}N(p,\gamma)^{15}O$ — SoCIAL: SOlar Composition Investigated At Luna — Data taking

LUNA @ the new **IBF of LNGS**

Program approved by the PAC (2024-2025):

- $^{14}N(p,\gamma)^{15}O$ → approved and started

Data taking ongoing with TaN solid targets
well known resonance at low E
perfect as commissioning measurement

- $^{22}Ne(\alpha,n)^{25}Mg$ → approved and started

erc SHADES
Elements in the Lives and Deaths of stARs

- $^{12}C+^{12}C$ → approved

work is going on detector / shielding and carbon target optimization (mid 2024 and 2025)

MUR CaBS
Carbon Burning in Stars

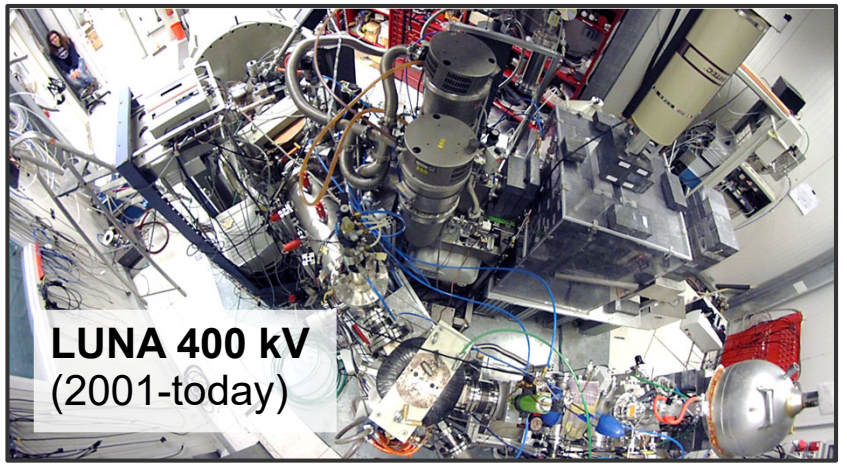
LUNA 400 and the the new IBF facility at LNGS

- Ensures **stability below 10^{-5}**, terminal voltage ripple of 1.5×10^{-5} and uninterrupt operation time greater than 24 hours

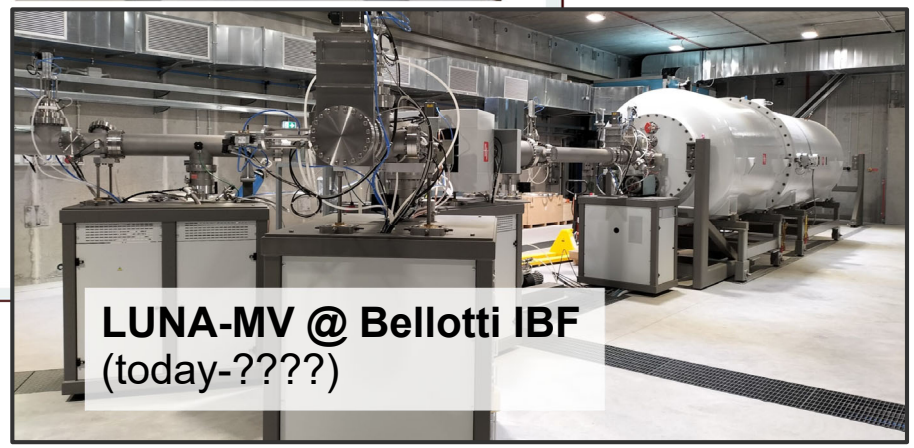
Ion specie	Beam Intensity (eμA)	
	TV range 0.3 MV–0.5 MV	TV range 0.5–3.5MV
$^{1}H^{+}$	500	1000
$^{4}He^{+}$	300	500
$^{12}C^{+}$	100	150
$^{12}C^{+2}$	60	100

Table 1: Beam intensity on target at different terminal voltage.

(See A. Sen et al. 2019)



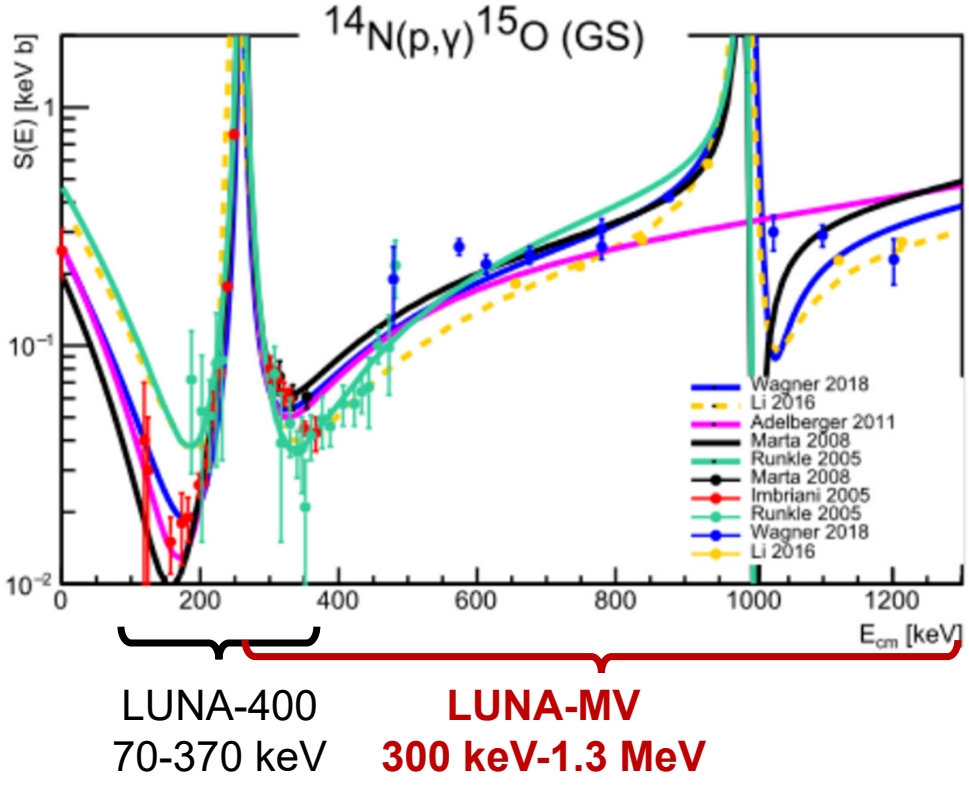
LUNA 400 kV
(2001-today)



LUNA-MV @ Bellotti IBF
(today-????)

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

$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle



Goals of the high-energy experiment

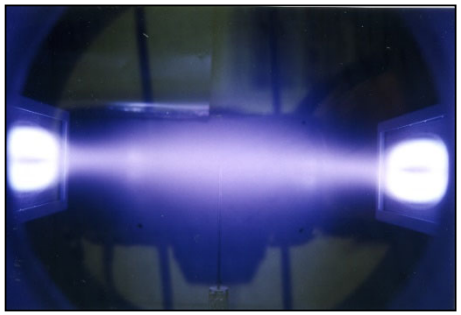
- non-resonant component
- weak transitions (to ground state)
- summing-in corrections
- angular distribution

… all of this in a wide energy range!

Thin Solid Targets

$Ti^{(14)}N$ and $Ta^{(14)}N$ and Ta (PVD)

- High purity
- High endurance/ lifetime under proton irradiation
- Low ion beam induced gamma background

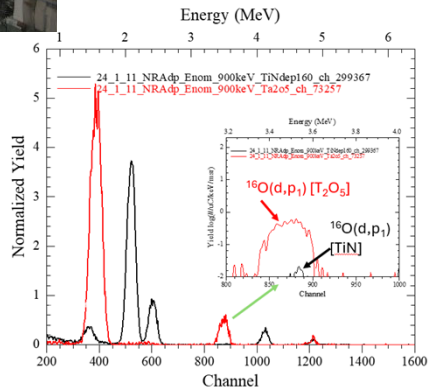


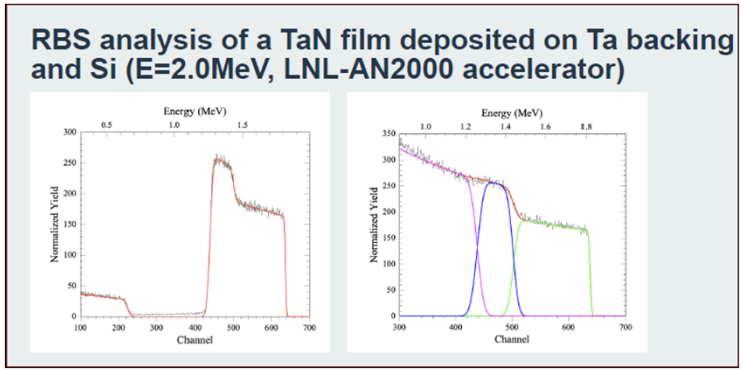
PREPARATION (Lab. di fisica dei materiali)

- Reactive sputtering (^{14}N isotopic. enriched gas)
- Plasma diagnostics, real time optical diagnostics
- HiPIMS, Pulsed DC plasmas

CHARACTERIZATION

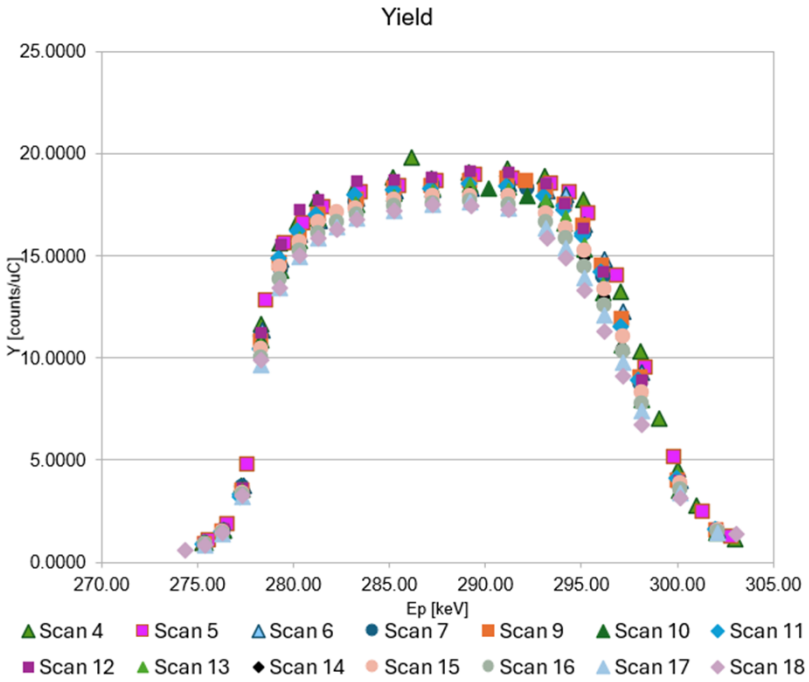
- **IBA** (EBS, NRA (d,p), (d,α) @ AN2000 and CN)
- **SEM-EDS**
- **AFM**

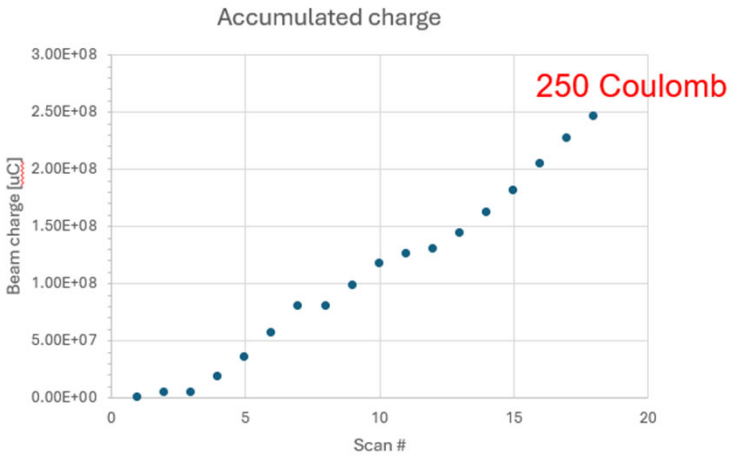




LUNA 400 dep 158_2056_3

TiN/Ta (developed at LNL, lifetime tests)

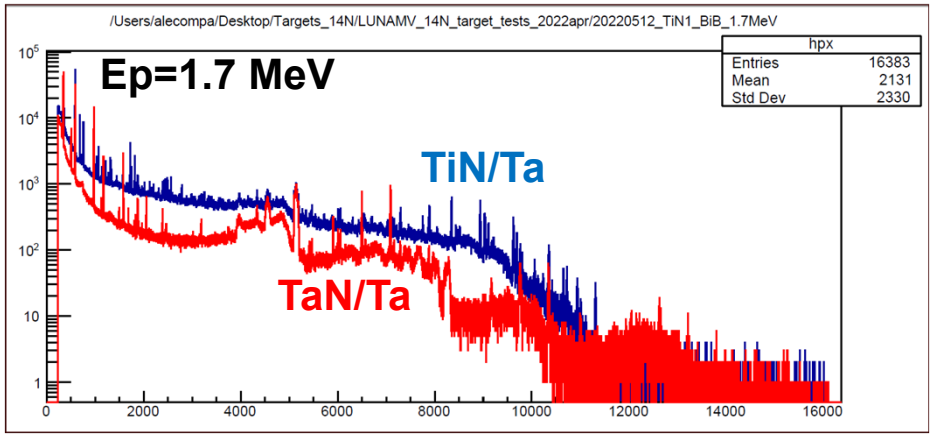




LUNA MV – running experiments

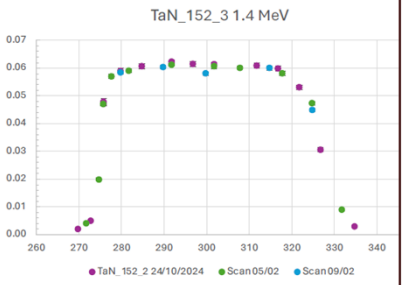
TaN/Ta coating developed at LNL

- Reactive sputtering (14N isotopic. enriched gas)
- Plasma diagnostics
- HiPIMS, Pulsed DC
- High density, high purity



Summary of February data taking

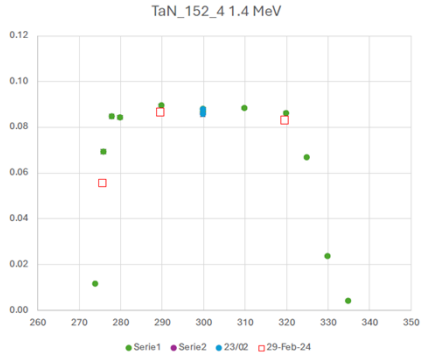
- Target TaN_152_3 (LNL, Sputtered, ~50 keV thick):
  - Characterization
  - Long runs at 460 keV (18 C) and 400 keV (24C) with configuration A.
  - Dismounted after 44 C.

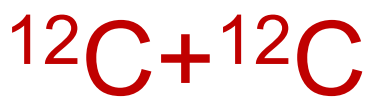


Run number	Target	Start time	Stop time	Livetime (s)	Dead time ADC0	Beam Energy (keV)	Current (uA)	Current on collimator (uA)	Initial Beam Power (W)	Charge (uC)	Estimated total charge on target (uC)	Detector configuration	Valid run
482	TaN_152_3	02/06/2024 10:09:26	02/06/2024 14:50:19	16809.3	0.3%	464.09	384	69	177	4599337	5851264	55-135-90	Yes
485	TaN_152_3	02/06/2024 15:48:06	02/06/2024 18:41:38	10373.6	0.4%	464.10	402	85	185	4296553	10147817	55-135-90	Yes

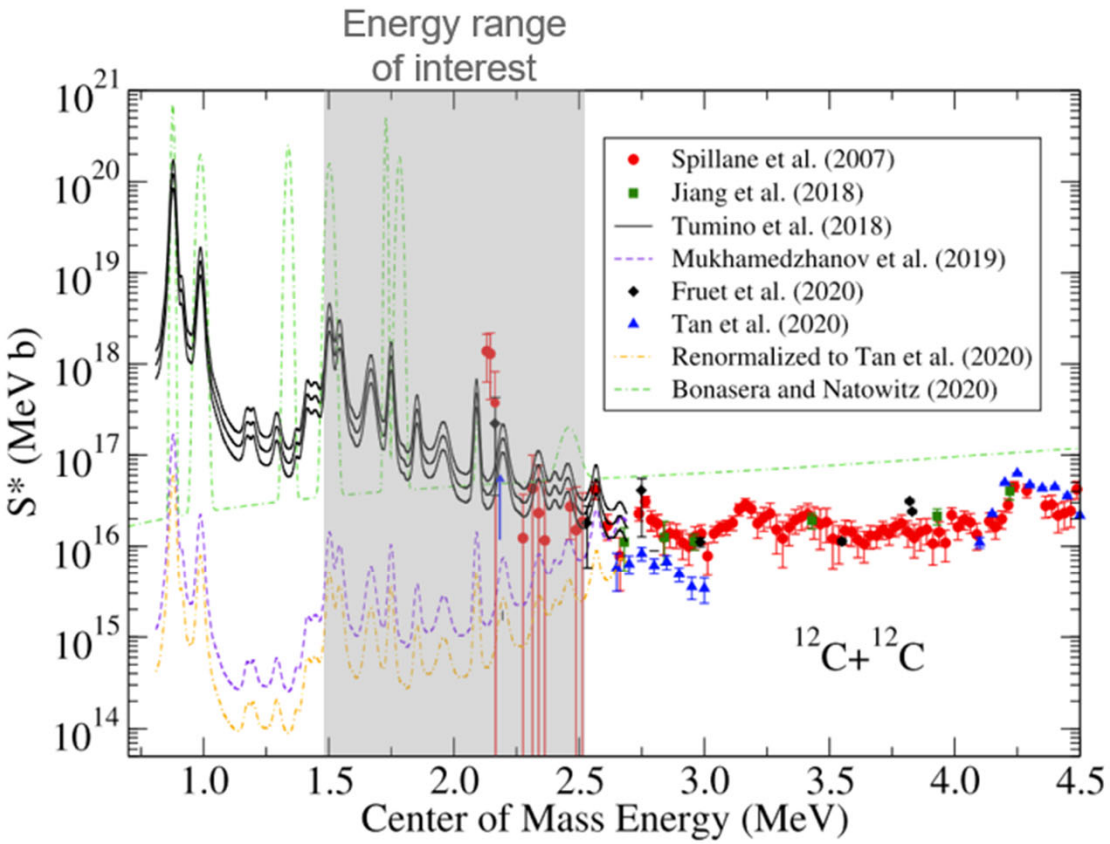
Summary of February data taking

- Target TaN_152_4 (LNL, Sputtered, ~50 keV thick):
  - Characterization and efficiency runs at 0, 5 and 10 cm for setup configuration B.
  - Long runs from **400 keV to 1000 keV** with new angles.
  - We tried to keep the current low (<200 W on target) to prevent degradation.
  - Target remained stable in this regime.
  - Dismounted after 33 C




12C+12C

$^{12}C+^{12}C$: trigger of C burning in the stars



Several datasets and models

Direct measurements above 2.1 MeV (large scattering, large uncertainties)

Only indirect measurements below 2.1 MeV (problems with normalization and other discrepancies)

Very large uncertainty below 2.5 MeV (energy range of interest)

$^{12}C+^{12}C$: trigger of C burning in the stars

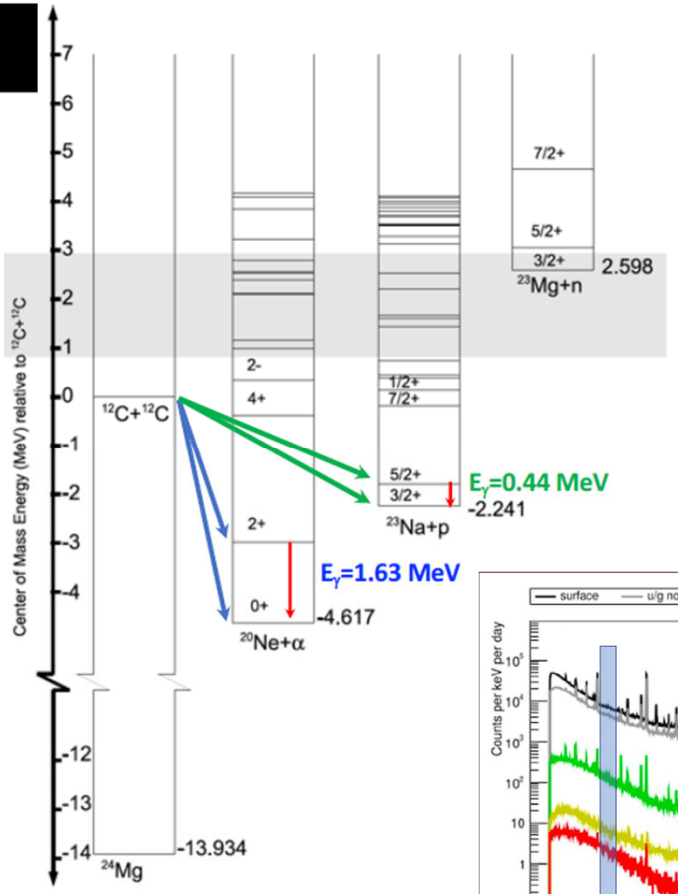
The $^{12}C+^{12}C$ study via γ detection

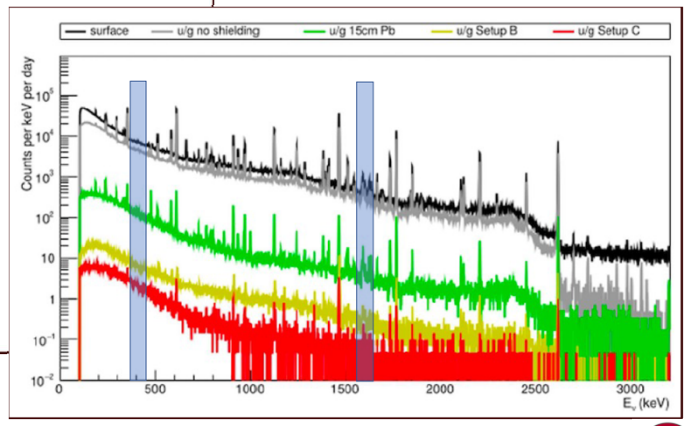
$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha$ Q = 4.62 MeV

γ-rays and α particles energies for excited states for $^{12}C(^{12}C, \alpha)^{20}Ne$ (Q = 4.617 MeV)				
E_X (MeV)	J^p	Main γ transitions (MeV)	ID	$E_{\alpha-max}$ (MeV) (E^{CM} = 2 MeV)
0.0	0^+		α_0	8.6
1.63	2^+	*1.63 → 0* **1.63**	α_1	6.8

$^{12}C+^{12}C \rightarrow {}^{23}Na + p$ Q = 2.24 MeV

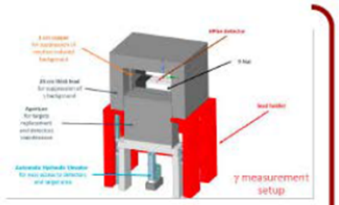
g-rays and p particles energies for excited states for $^{12}C(^{12}C, p)^{23}Na$ (Q = 2.241 MeV)				
E_X (MeV)	J^p	Main g transitions (MeV)	ID	E_{p-max} (MeV) (E^{CM} = 2 MeV)
0.0	$3/2^+$		p_0	5.3
0.44	$5/2^+$	0.44 → 0 **0.44**	p_1	4.8

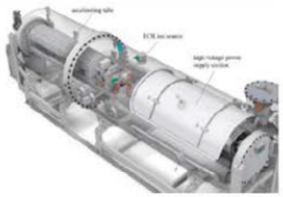




$^{12}C+^{12}C$: trigger of C burning in the stars

Expected setup efficiency and sensitivity

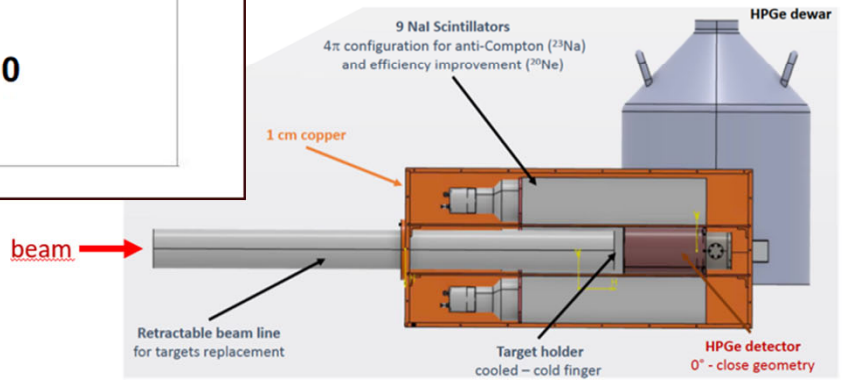




Minimum daily reaction rate to reach 50% statistical uncertainty, considering detection efficiency, beam current (200 pμA) and data taking time (60 days). Units: reactions/day

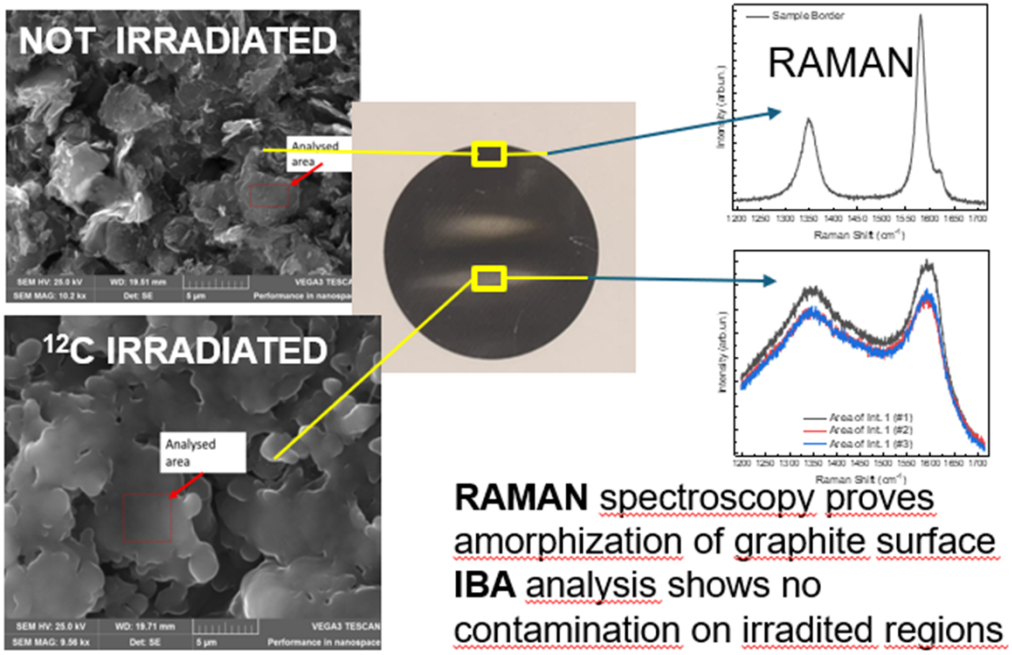
	$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ E_γ=1634 keV	$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ E_γ=440 keV
HPGe	**5**	**13**
HPGe + anti-Compton (depending on funding)	3	**10**

Detector Setup

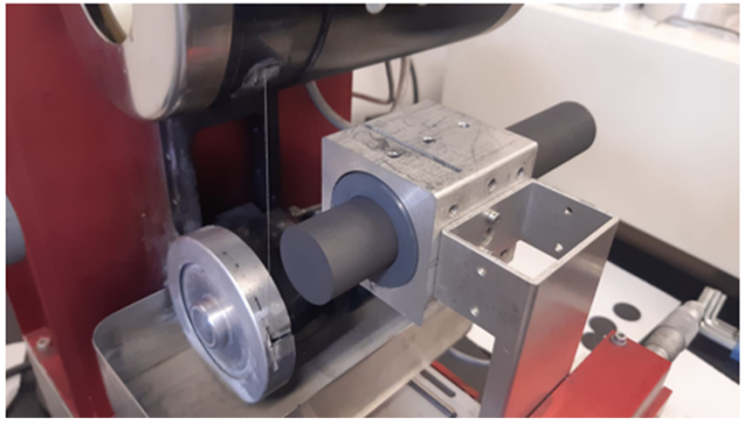


Carbon target development @LNL

- **High lifetime:**
  - ✓ ^{12}C implantation power: <= 400 W
  - ✓ Expected lifetime: 50 - 100 C
  - ✓ Characterizatio pre/post irradiation with IBA (AN2000, CN), SEM – EDS, AFM, RAMAN
- **Purity:** semiconductor grade
- **Structure**: fine grain (1μm-5μm)
  - ✓ Accomodate expansion
  - ✓ Dynamic Monte Carlo simulations
- **Optimised heat dissipation**
  - ✓ COMSOL FEA analysis

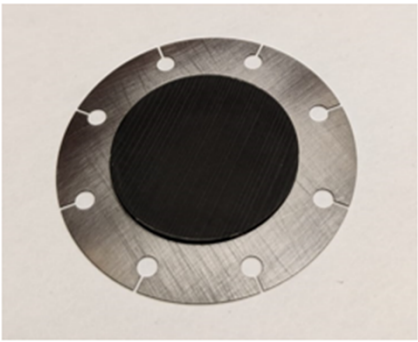


RAMAN spectroscopy proves amorphization of graphite surface
IBA analysis shows no contamination on irradited regions



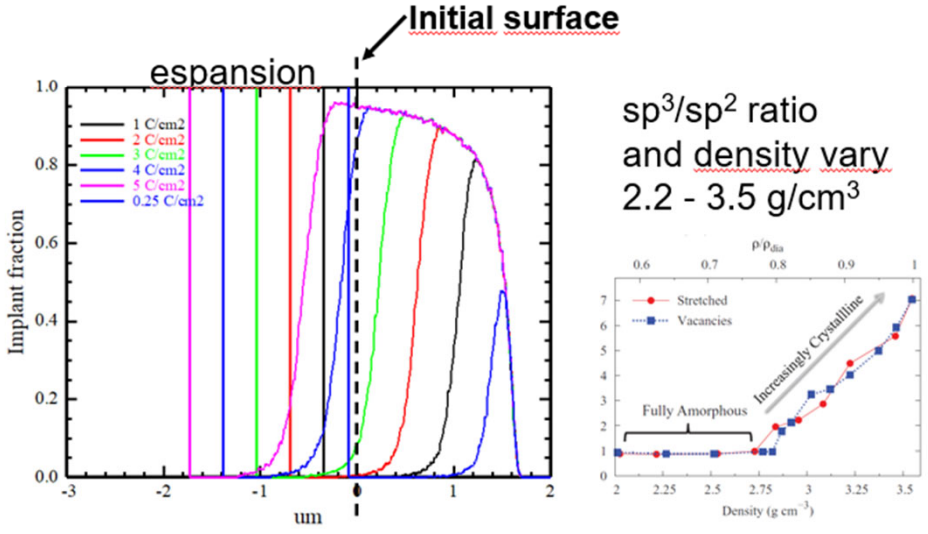
PREPARATION

- ✓ Diamond wire saw cut (graphite)
- ✓ Tantalum PVD deposition
- ✓ Glue (high thermal conductivity, high vacuum compatible, NASA certified)



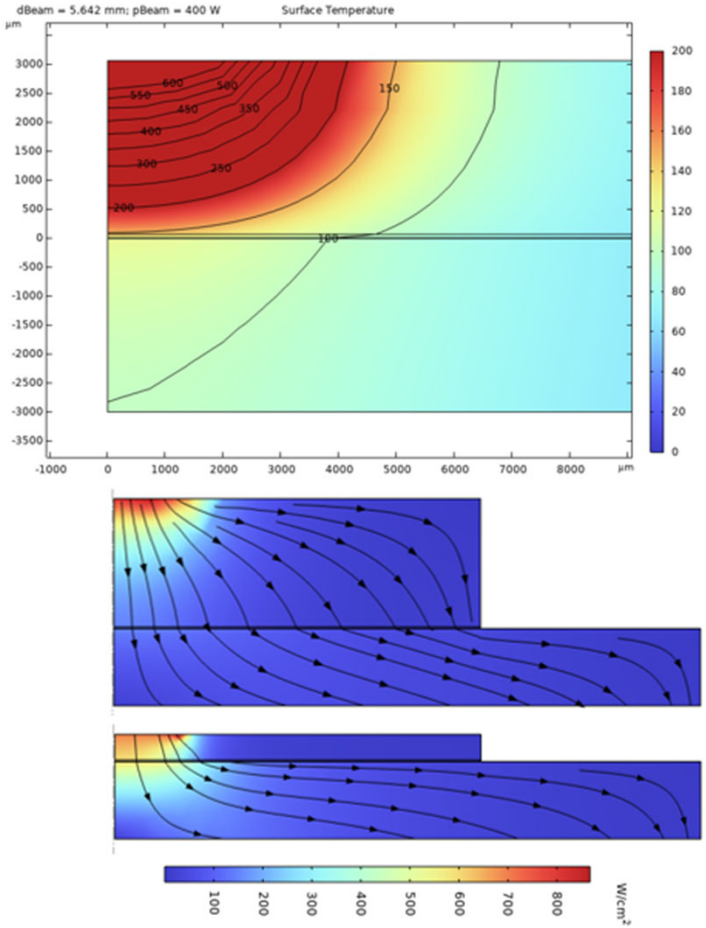
Target design

- Dynamic Monte Carlo BCA



sp^3/sp^2 ratio
and density vary
2.2 - 3.5 g/cm^3

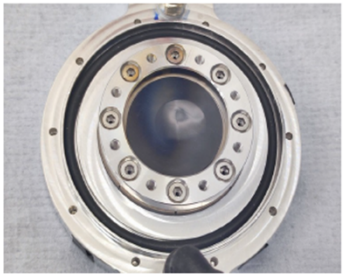
- Heat dissipation

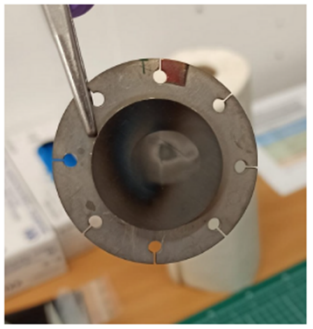


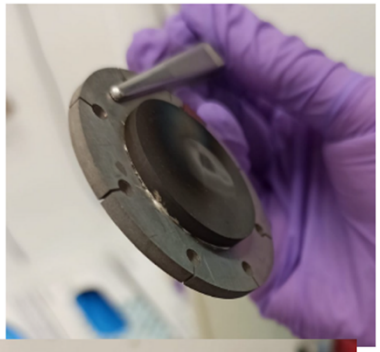
IRRADIATION TESTS @Felsenkeller (10-60 W, ^{12}C)

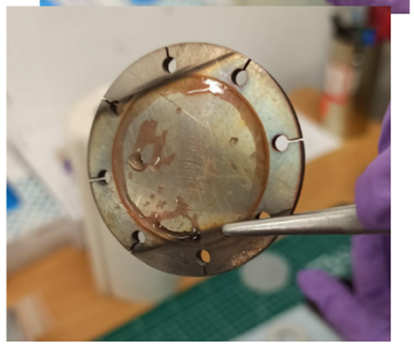
Status on Monday 25.03.24

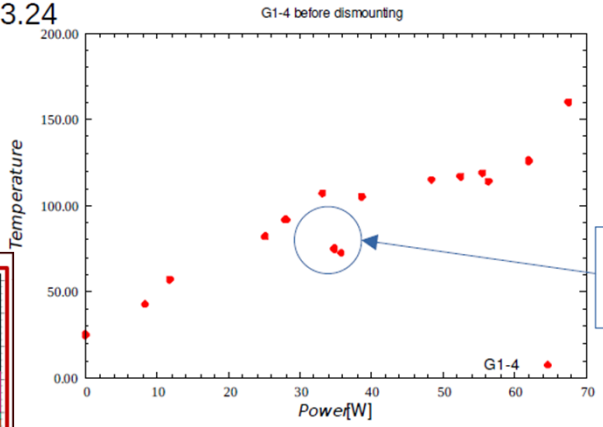
- E_{beam} = 8.85 MeV
- Beam = $^{12}C^{3+}$
- Target = **G1_4**, thickness = 3mm
- Backing = Cu+Ta
- $Q_t \approx 2.3$ C
- Dismounted on: 25.03.24





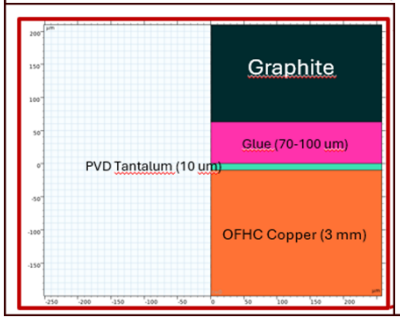






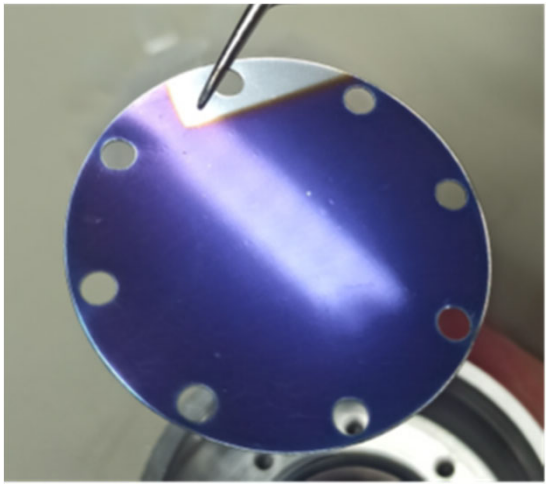
Same results reported on Frid. 22.03

Playing with beam parameters



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

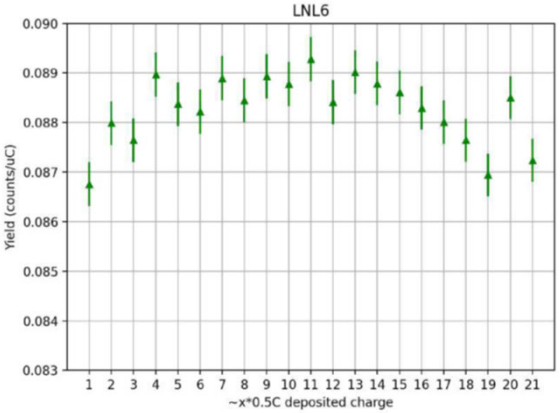
IRRADIATION TESTS @LUNA 400



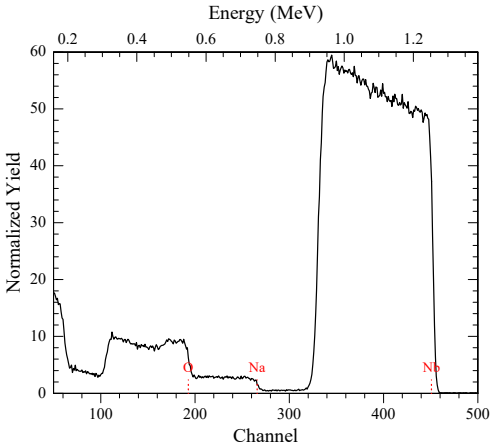
$Na_xNb_yO_3$

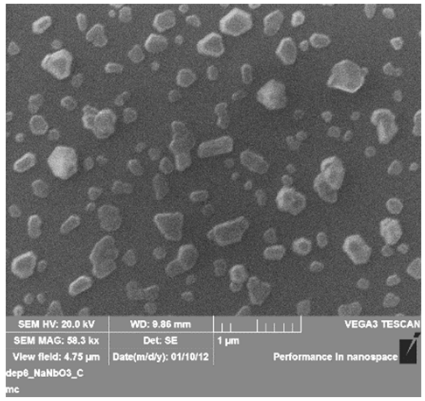
Sodium Niobate target deposited on tantalum for $^{23}Na(p,\alpha)^{20}Ne$ reaction

Sputtered Sodium Niobate target is best candidate for the experiment at LUNA400

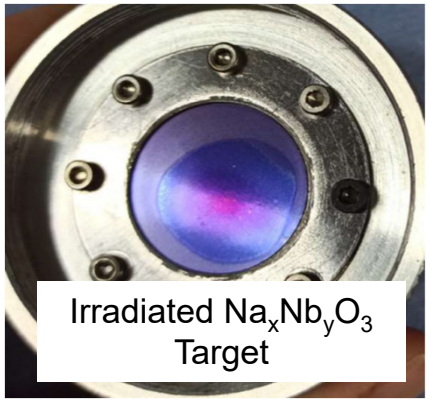


E_p = 311.63, Q = 11.5 C
Long run target stability





Deposition process optimization underway. First endurance results are positive compared to evaporated sodium tungstate.



Irradiated $Na_xNb_yO_3$ Target

Summary And Perspectives

LNL is committed to provide solid targets with specific features (endurance, purity, low BIB…) to the LUNA collaboration and participate to WP and Executive Board.

New materials solutions are under investigation for future experimental campaingns, including un-common alcaline species.

The specific experience and expertize is appreciated

- Novel methods of preparation via pulsed (HiPIMS) plasma PVD
- Characterization of physical properties
- Simulation of material properties