

Towards a free-neutron target for direct neutron-induced reaction measurements on radioactive nuclei in storage rings

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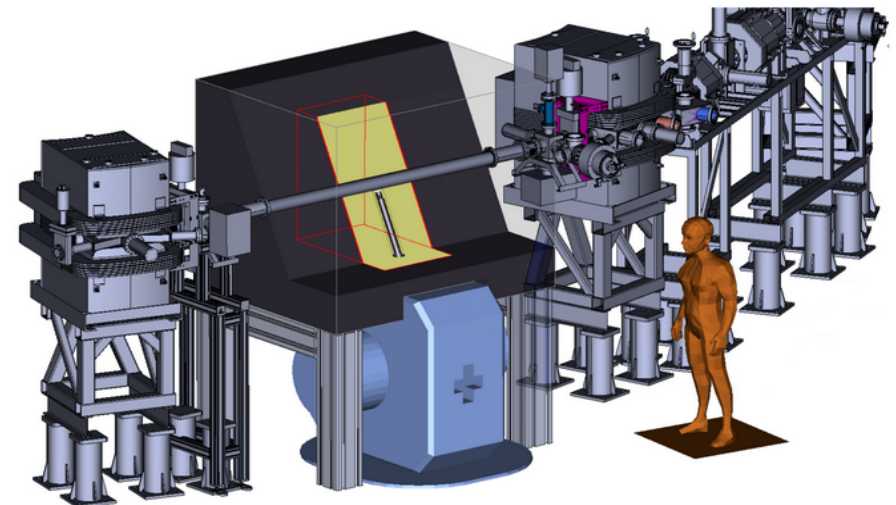
Iris Dillmann

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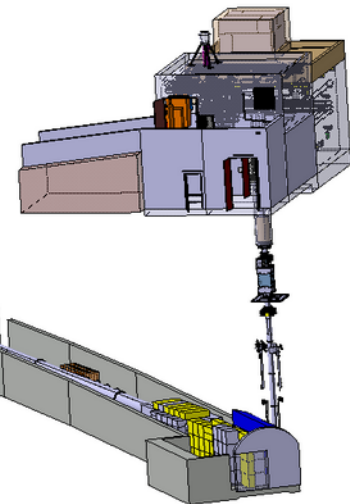
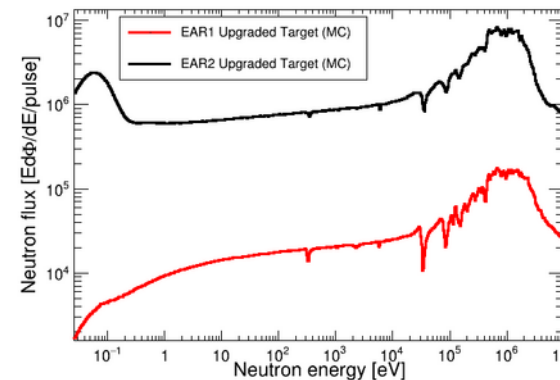
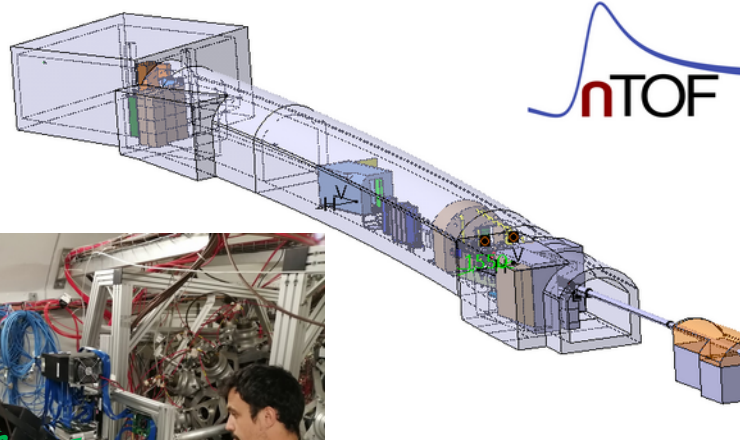
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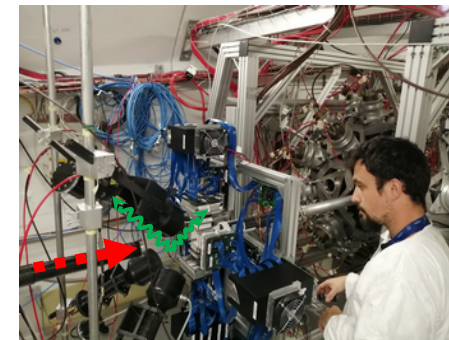
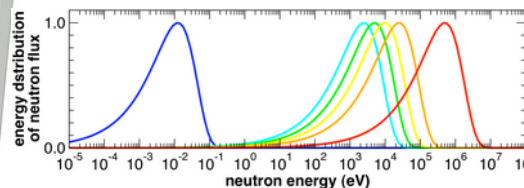
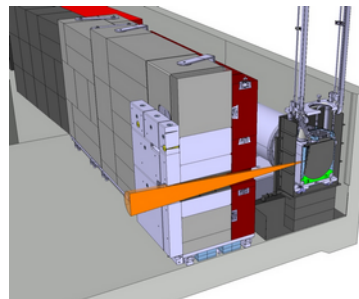


State of the art: direct (n, γ) measurements

- Neutron capture (n, γ) drives synthesis of heavy elements in stars (s, i, r-process)
- **70 years of experiments: ~95% of stable isotope cross sections measured**
- **State-of-the-art technique: neutron time-of-flight (TOF)**
 - Pulsed neutron beam $\rightarrow$ radioactive or stable target $\rightarrow$ detect γ -rays
 - n_TOF @ CERN: three experimental areas — EAR1 (185 m), EAR2 (20 m), NEAR (3 m)
 - n_TOF flux: 10^4 – 10^7 n/cm²/pulse (spallation from PS protons on Pb)
 - Activation technique (NEAR): for cases where TOF is not sensitive enough

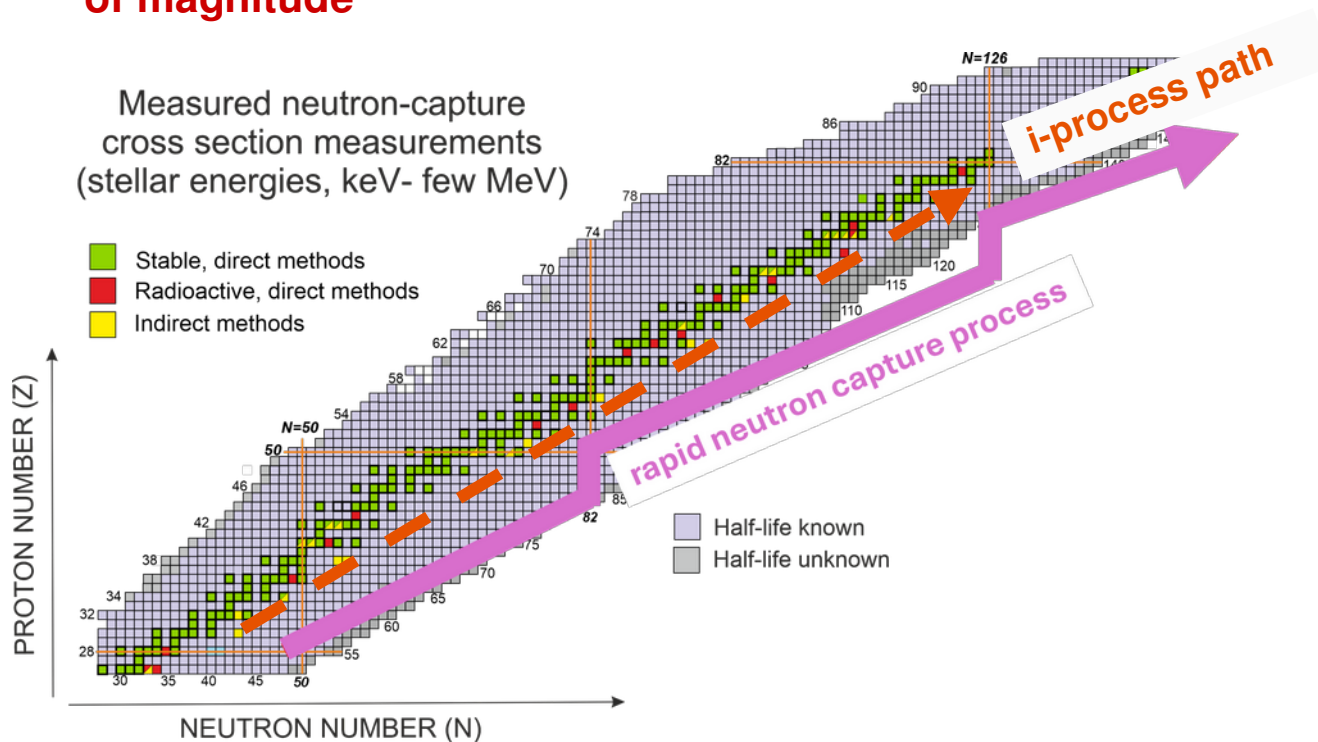
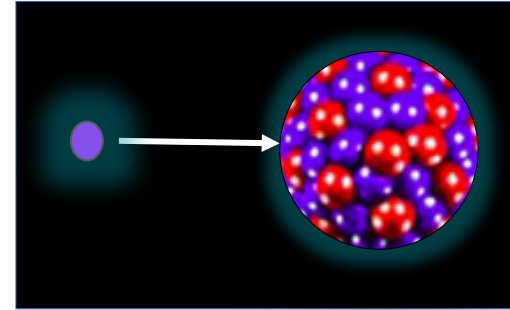


**NEAR at
3 m**



The fundamental barrier: reach of direct (n, γ) techniques

- **Direct kinematics: neutron beam $\rightarrow$ radioactive target sample**
 - Requires: $>10^{14}$ atoms, $t_{1/2}$ = minutes to years
 - For $t_{1/2}$ = seconds–milliseconds: completely impossible
- **Nuclear chart of measured (n, γ) cross sections:**
 - Green: stable nuclei measured directly $\rightarrow$ most of valley of stability covered
 - Orange: very few radioactive nuclei measured directly
 - Yellow: indirect methods only (surrogate, β -Oslo)
- **i-process path (dashed): requires nuclei with $t_{1/2} \sim$ seconds $\rightarrow$ not accessible**
- **r-process path: >5000 nuclei with $t_{1/2} =$ ms $\rightarrow$ purely theoretical models, uncertainties of orders of magnitude**

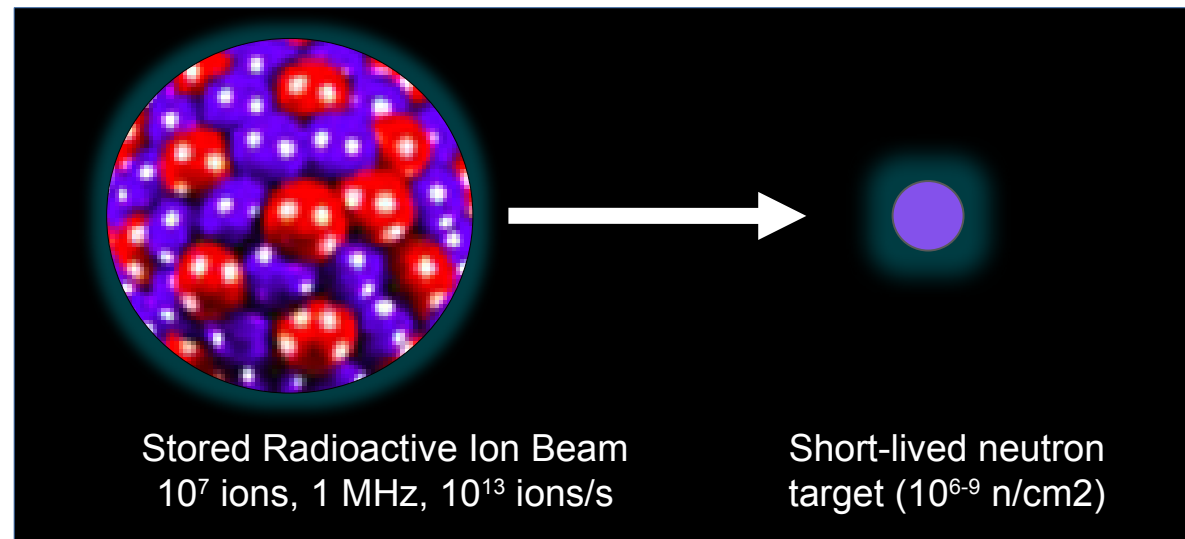


Only 17 radioactive nuclei measured in ~ 70 years!

The solution: inverse kinematics in a storage ring

- **The concept: radioactive ions circulate as the beam; thermal neutrons act as the target**
 - Proposed by Reifarth & Litvinov (2014) and Reifarth et al. (2017) — reactor and spallation-based neutron targets
- **The missing piece: a suitable neutron target has never been demonstrated in a storage ring**
 - The concept remains unvalidated — **experimental proof-of-concept is urgently needed**
- Neutron target requirement: $\eta_n \geq 10^6\text{--}10^9 \text{ n/cm}^2$ (depending on facility and scientific goal)
- **Our proposal: the first full demonstration — focus on feasibility, modularity, and cost-efficiency**
 - A supercompact cyclotron-driven neutron target that can be integrated into an existing storage ring
 - Proof-of-concept demonstrator at CRYRING@GSI — validate the inverse-kinematics methodology end-to-end

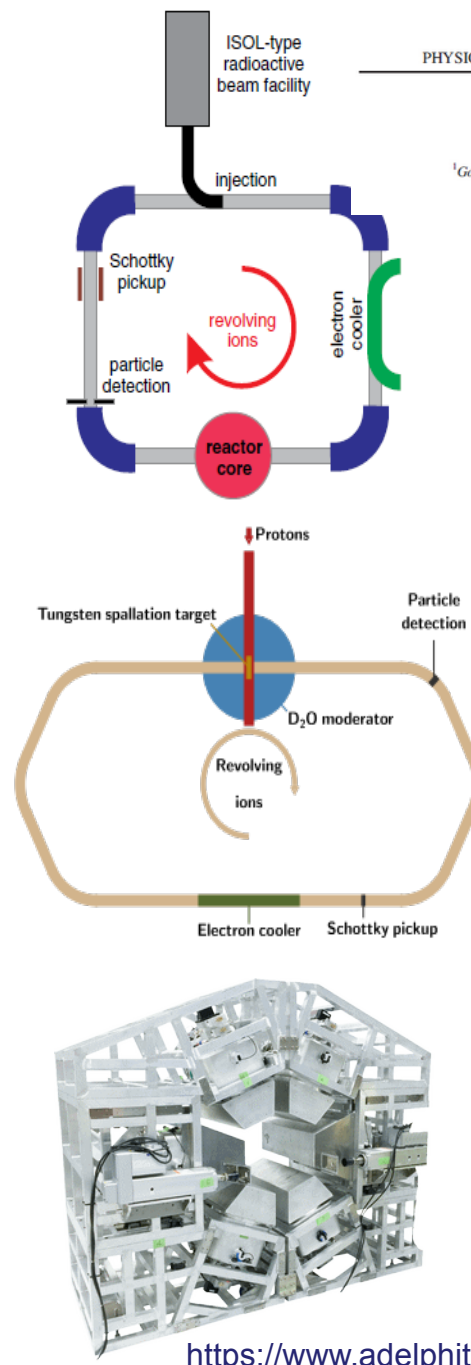
*See invited talk by
Beatriz Jurado!*



Previous efforts for a free-neutron target

- Luminosity $L = \eta_n \times I$,
reaction rate = $L \times t \times \sigma$ [mb] counts/day
- Nuclear reactor:**
 $\eta_n = 2.2 \times 10^{10}$ n/cm², $L = 2.2 \times 10^{23}$ cm⁻²s⁻¹ →
~20×σ[mb] counts/day
- Spallation source (Reifarh 2017):**
 $\eta_n = 8 \times 10^9$ n/cm², → ~7×σ[mb] counts/day
- LANL-NTD (ongoing demonstrator):** $\eta_n = 3 \times 10^7$ n/cm²
Single pass experiment, no storage-ring
- D-D / D-T neutron generators (Dillmann 2023, e.g. 5-array Adelphi):**
 - Technological limit for compact neutron generators < 10¹¹ n/s
 - $\eta_n = 10^5$ n/cm² → ~10⁻⁴×σ[mb] counts/day

None of the existing approaches is both feasible and able to be integrated into a RIB facility + storage ring for **demonstration purposes**



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 014701 (2014)

Measurements of neutron-induced reactions in inverse kinematics

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PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 044701 (2017)

Spallation-based neutron target for direct studies of neutron-induced reactions in inverse kinematics

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(Received 29 November 2016; published 6 April 2017)

Eur. Phys. J. A (2023) 59:105
<https://doi.org/10.1140/epja/s10050-023-01012-9>

Regular Article - Experimental Physics

THE EUROPEAN
PHYSICAL JOURNAL A



Measuring neutron capture cross sections of radioactive nuclei

From activations at the EZK Van de Graaff to direct neutron captures in inverse kinematics with a storage ring at TRIUMF

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<https://www.adelphitech.com/>

Direct neutron reactions in storage rings utilizing a supercompact cyclotron neutron target

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 (Received 17 August 2025; accepted 9 April 2026; published 3 June 2026)

We propose a new approach for a high-density free-neutron target, primarily aimed at nuclear astrophysics reaction studies in inverse kinematics with radioactive ions circulating in a storage ring. The target concept integrates four key subsystems: a neutron production source driven by a supercompact cyclotron utilizing ${}^9\text{Be}(p, xn)$ reactions, an optimized moderator/reflector assembly using either heavy water or beryllium oxide with a graphite reflector shell to thermalize fast neutrons, a cryogenic liquid hydrogen moderator to maximize thermal neutron density in the interaction region, and beam pipe geometries that enable neutron-ion interactions while maintaining vacuum conditions for ion circulation. This integrated approach focuses on feasibility by incorporating readily available technologies. Using a commercial supercompact cyclotron delivering a proton beam of $130\text{ }\mu\text{A}$, the design achieves thermal neutron areal densities of $\sim 3.4 \times 10^6\text{ n/cm}^2$ for a proof-of-concept demonstrator at the CRYRING ion-storage ring at GSI Darmstadt. This autonomous accelerator-target assembly design enables deployment at both in-flight and ISOL facilities to exploit their complementary production mechanisms. Potential upgrades based on higher-energy and/or higher-current cyclotrons will enable an increase in areal density to $\sim 10^9\text{ n/cm}^2$. In combination with a customized low-energy storage ring and a radioactive ion-beam facility, the proposed solution could deliver luminosities above $10^{23}\text{ cm}^{-2}\text{ s}^{-1}$, thereby enabling neutron capture measurements of $\sim\text{mb}$ cross sections within a few days of experiment. The proposed system represents a significant milestone toward enabling large neutron-capture surveys on short-lived nuclei, thereby opening a new avenue for understanding the synthesis of heavy elements in our universe.

DOI: [10.1103/5d87-m8bn](https://doi.org/10.1103/5d87-m8bn)



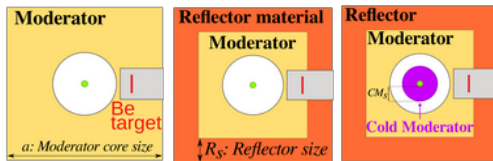
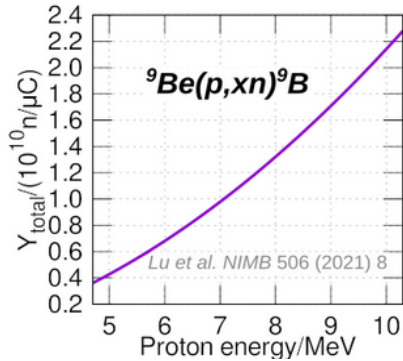
IBA Cyclone KEY
($>130\text{ }\mu\text{A}$, 9.2 MeV)



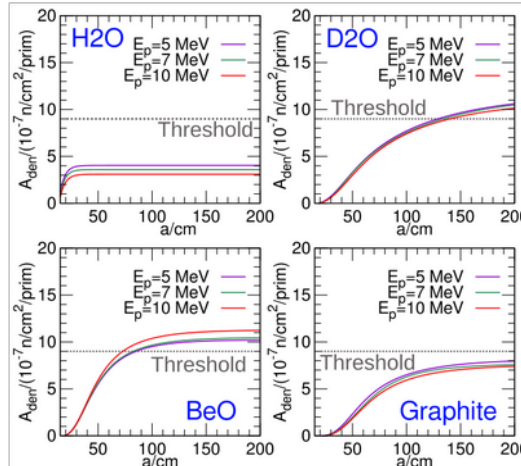
Tarifeño-Saldivia et al, PRAB (2026) 061601

Conceptual design of a feasible free-neutron target

Neutron source



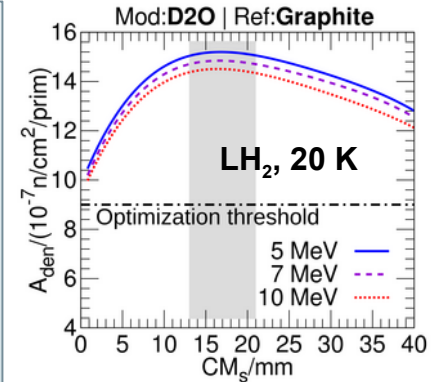
Single material moderator asymptotic performance



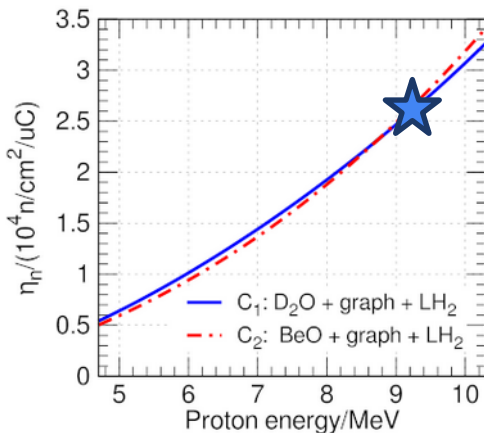
Moderator/Reflector Cost-effective design

- **Market cost prospective**
Ratio 1:100:1000 (Graphite:D2O:BeO)
- **Configuration C1 (D₂O-based)**
 - + Moderator: D₂O, 70x70x70 cm³
 - + Reflector: Graphite, 50 cm thick
 - + A_{den} : (9.1 - 9.7) · 10⁻⁷ n/cm²/prim, (5 – 10 MeV protons)
- **Configuration C2 (BeO-based)**
 - + Moderator: BeO, 50x50x44 cm³
 - + Reflector: Graphite, 50 cm thick
 - + A_{den} : 9.2 · 10⁻⁷ n/cm²/prim (10 MeV)
 - + 9x more expensive than C1

Cryogenic moderator boost neutron density

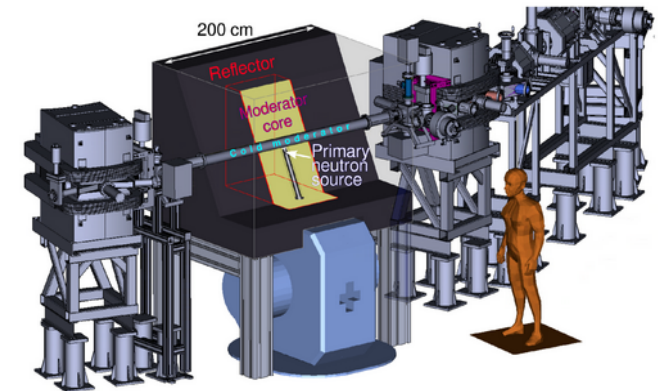


~ 60% boost in neutron target performance



NRING neutron target in a nutshell

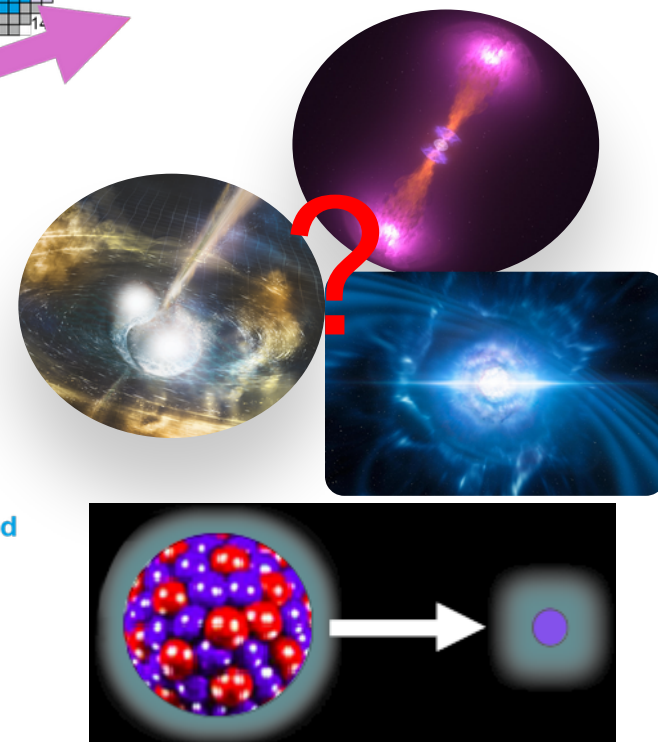
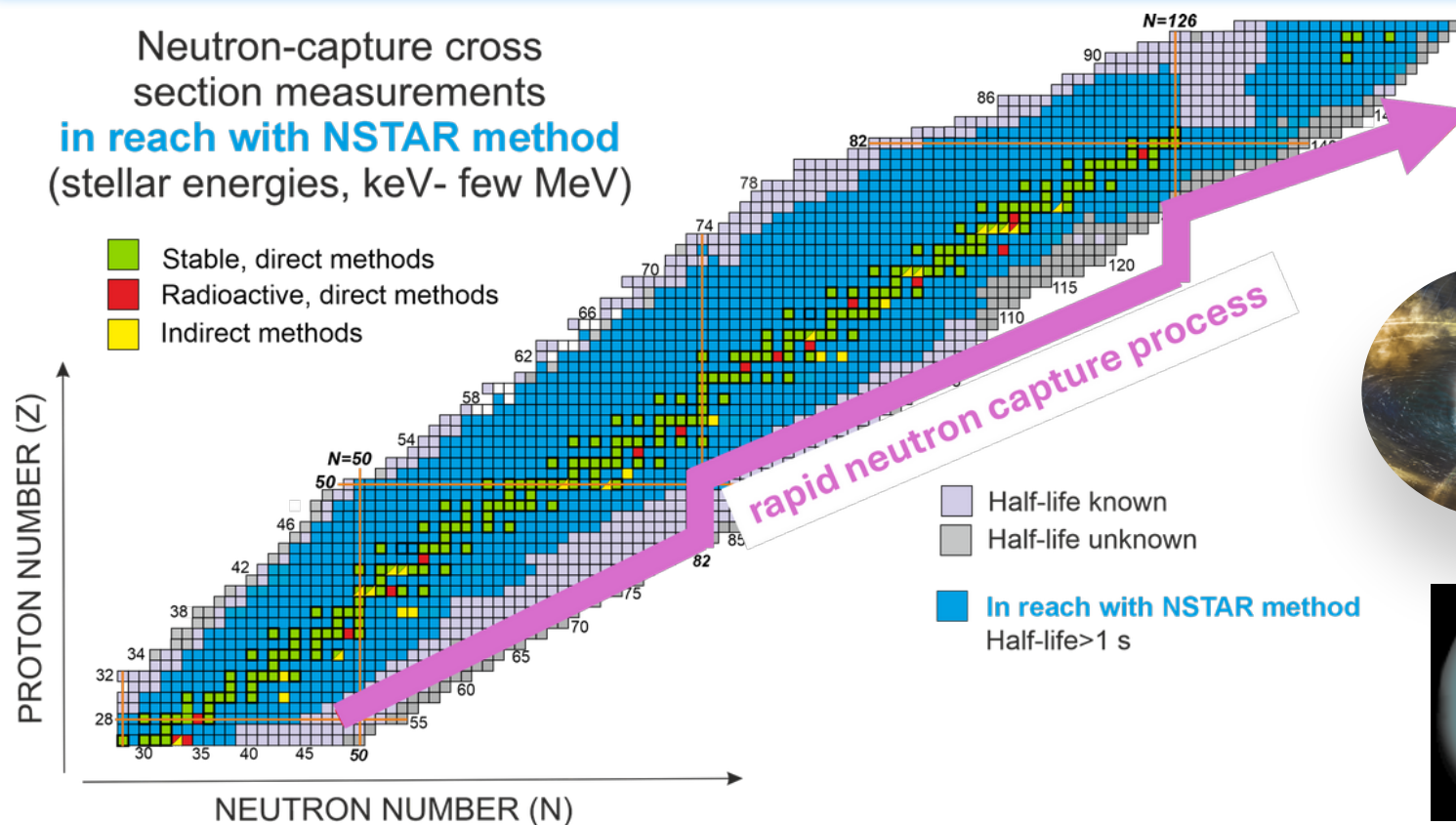
- **Cyclotron:** IBA Cyclone KEY, 9.2 MeV protons, up 130 μA current, 2.1 m² footprint
- **Moderator:** D₂O, 70 x 70 x 70 cm³
- **Reflector:** Graphite, 50 cm thick
- **Cryogenic system:** LH₂, 20 K, 13 mm thickness, 10 mm inner diameter
- **Total size:** 170 x 170 x 200 cm³
- **Areal density:** 3.4 x 10⁶ n/cm²
- **Where to find it?** [arXiv:2508.15465v1](https://arxiv.org/abs/2508.15465v1)



The potential of the NRING concept

- 70 years of neutron-capture experiments → only 17 radioactive nuclei ever measured directly
- **With the NRING method: >1000 nuclei with $t_{1/2} > 1$ s become directly accessible**
 - s-process branching points, i-process, and onset of the r-process path
 - Half-life is no longer a constraint — only production yield at the RIB facility matters
- **The path: demonstrator → dedicated facility**
 - Step 1: proof-of-concept at CRYRING@GSI — validate the technique end-to-end
 - Step 2: dedicated ISOL-based storage ring (ISR, TRISR) — boost luminosity by orders of magnitude

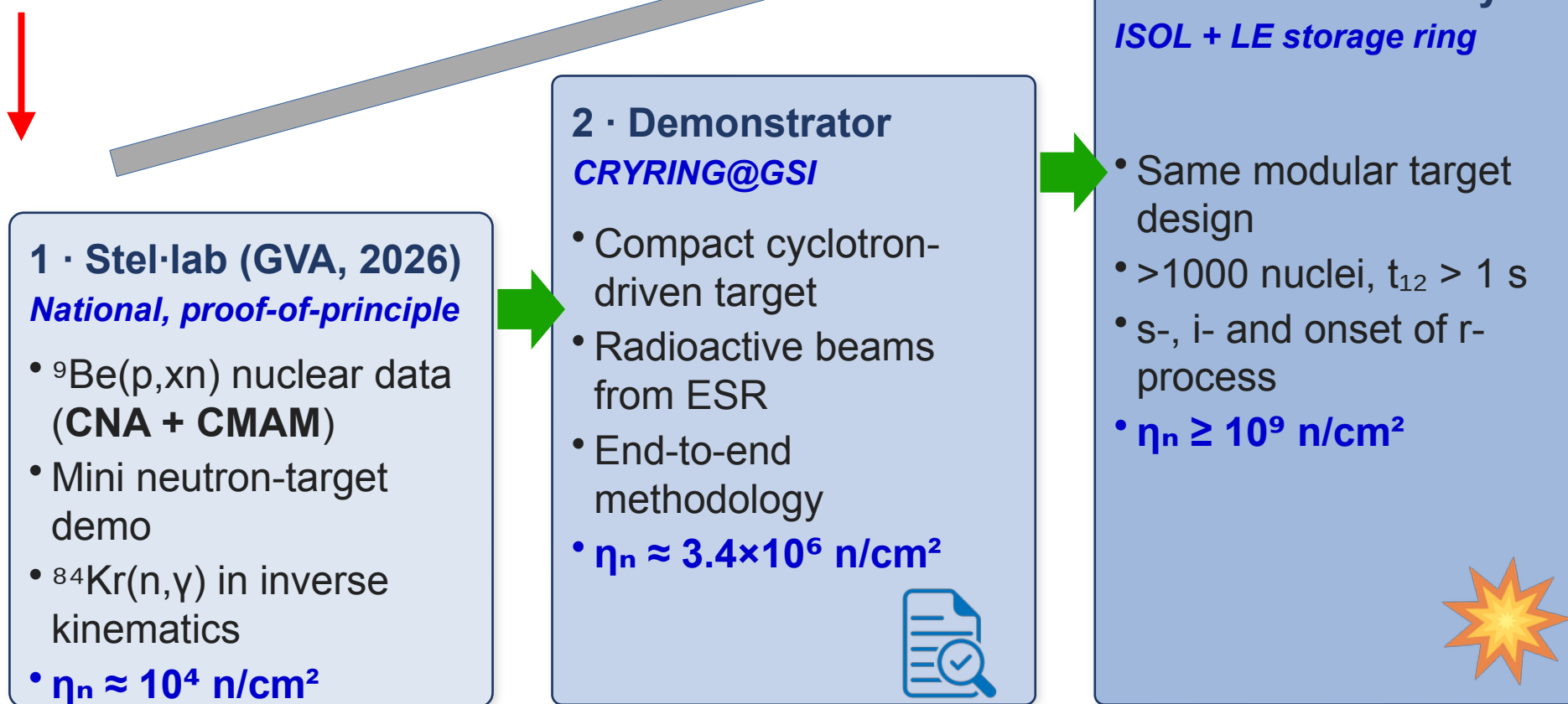
This requires an ambitious international effort (IFIC-Valencia · TRIUMF · GSI)



A staged roadmap towards direct (n,γ) at storage rings

The concept is being demonstrated step by step — from a national proof-of-principle to a full demonstrator and, ultimately, a dedicated facility

We are just here!



increasing luminosity → reach

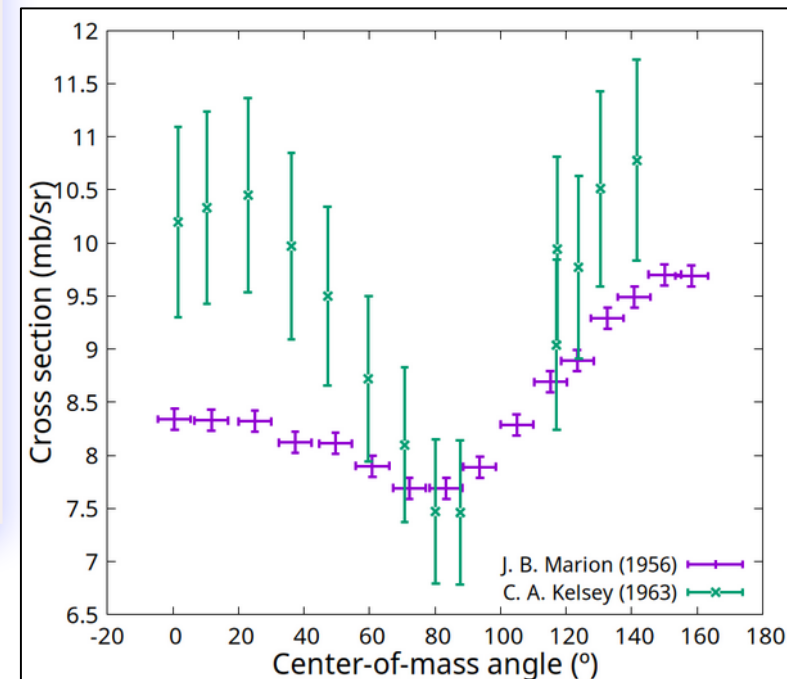
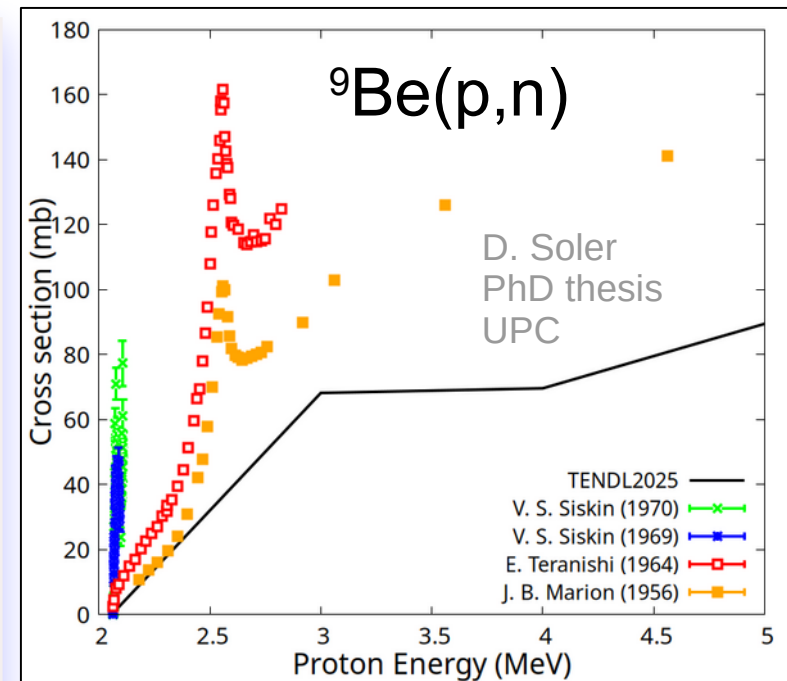
Step 1: Nuclear data: the $^9\text{Be}(p,xn)$ neutron source term

- Realistic target design needs the neutron source term — **yields, angular distributions and energy spectra** of $^9\text{Be}(p,xn)$
- Current data are insufficient for a predictive design:**
 - cross-section measurements are ~50 years old, with discrepancies above 3 MeV
 - angular distributions / spectra limited to 2.5–5 MeV (measured in the 80s–90s)
 - modern evaluations (e.g. TENDL) not validated against recent data
- PROMETEO plan: full characterization over 2.5–10 MeV at two Spanish ICTS**
- CNA-Sevilla: 2.5–5 MeV** · **CMAM-Madrid: 4–10 MeV**
 - overlap at 4–5 MeV → independent cross-check between facilities
 - kept below 13.5 MeV to avoid the $^9\text{Be}(p,t)^7\text{Be}$ channel (tritium / activation)
- Instrumentation: miniBELEN neutron counter (UPC) + Ymon (IFIC); TOF with scintillators
- Output: a validated reaction-code tool feeding the Monte Carlo target design**

combined coverage 2.5–10 MeV

CNA

CMAM

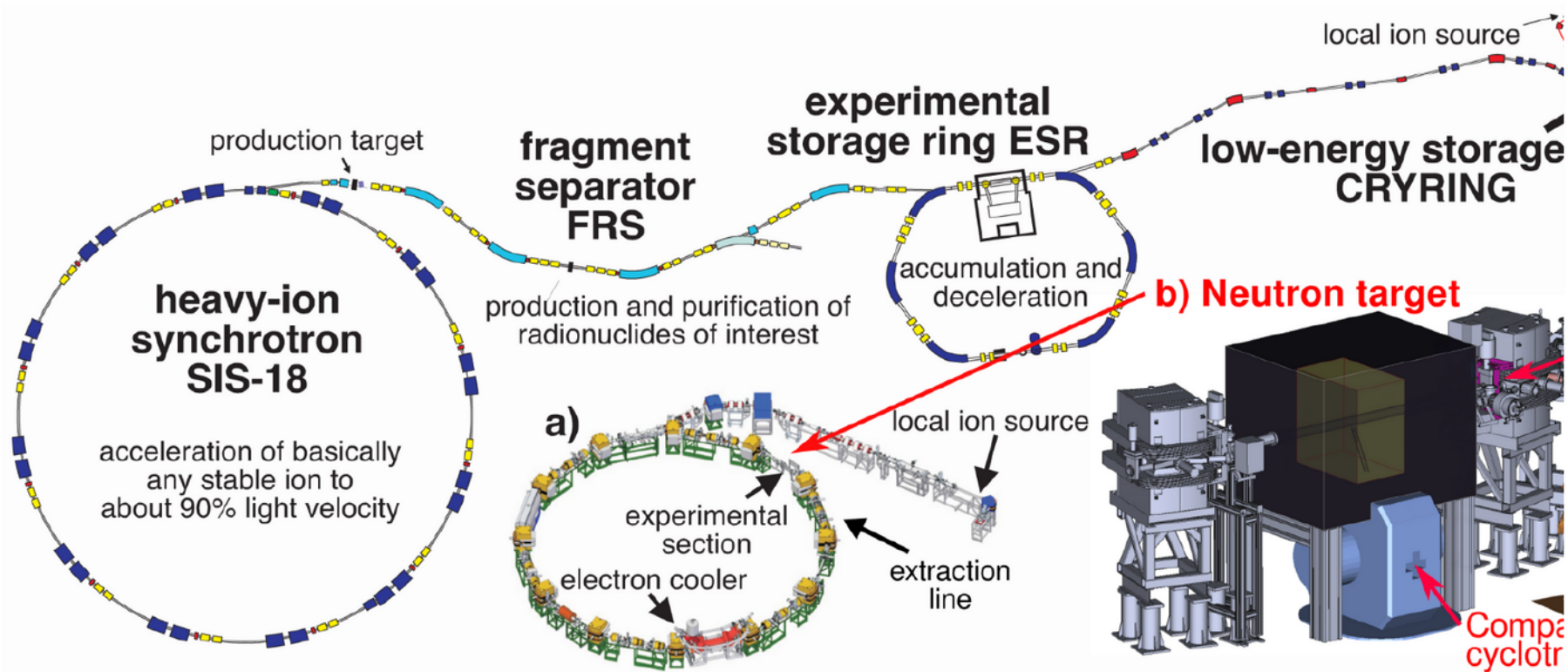


Step 1: A “DEMO-0” free-neutron target

- **First inverse-kinematics test of the free-neutron-target concept at national scale**
- Neutron source: Tandem proton beam at CMAM (compact cyclotron out of scope here)
 - Three-layer Be/Pd/Cu target + graphite moderator/reflector (Kum15)
- Ion beam: ^{84}Kr from a compact ECRIS source, circulated through the target pipe
- **Reaction: $^{84}\text{Kr}(n,\gamma)^{85\text{m}}\text{Kr}$ — first measurement in inverse kinematics**
 - benchmark via the 151 keV isomeric γ -line ($t_{12} = 4.48$ h)
 - detection with LUCRECIA (TAS) + high-resolution HPGe
- **Expected core density $\eta_n \approx 10^4$ n/cm² (Tandem at 1 μA)**
 - with realistic ECRIS Kr^+ current $\rightarrow \sim 80\text{--}800$ reactions/hour
- **Validates neutron density, online monitoring, shielding and radiation-protection tools**
- **Milestone: commissioning at IFIC $\rightarrow$ validation at CMAM — de-risks future efforts at CRYRING**

Implementation: integrated system at CRYRING@GSI

- **IBA Cyclone KEY** embedded inside the graphite reflector assembly of C1
 - Footprint $1.5 \times 1.4 \text{ m}^2 \rightarrow$ fits within moderator/reflector block without external shielding facility
- **Total system footprint: $\sim 170 \times 170 \times 200 \text{ cm}^3$ ($\approx 2 \times 2 \times 2 \text{ m}^3$)**
 - Fits within a standard storage-ring straight section — no major infrastructure modifications
- **Absolute areal density at max current (130 μA):**
 - $\eta_n = 3.4 \times 10^6 \text{ n/cm}^2$ (nominal operational value: $3 \times 10^6 \text{ n/cm}^2$)
 - Be target power: $\sim 1.2 \text{ kW} \rightarrow$ beam defocusing/wobbling + Cu cooling backing

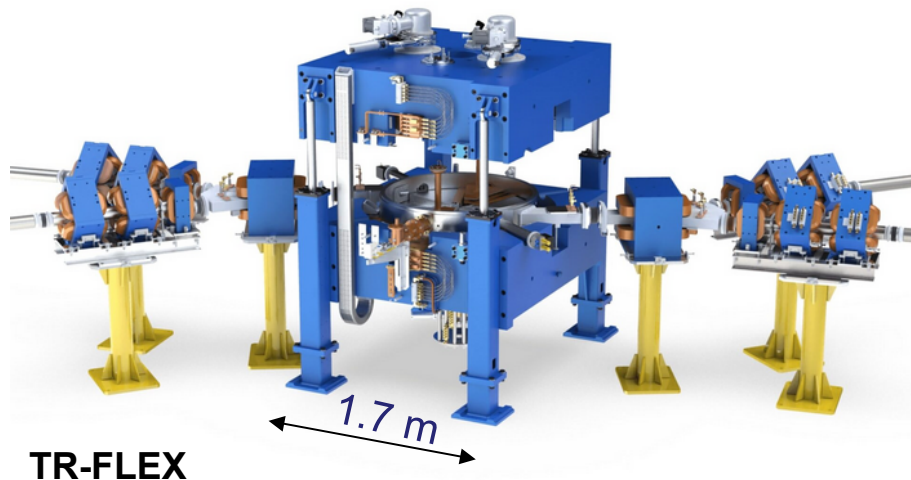


Scalability: cyclotron options for a future facility

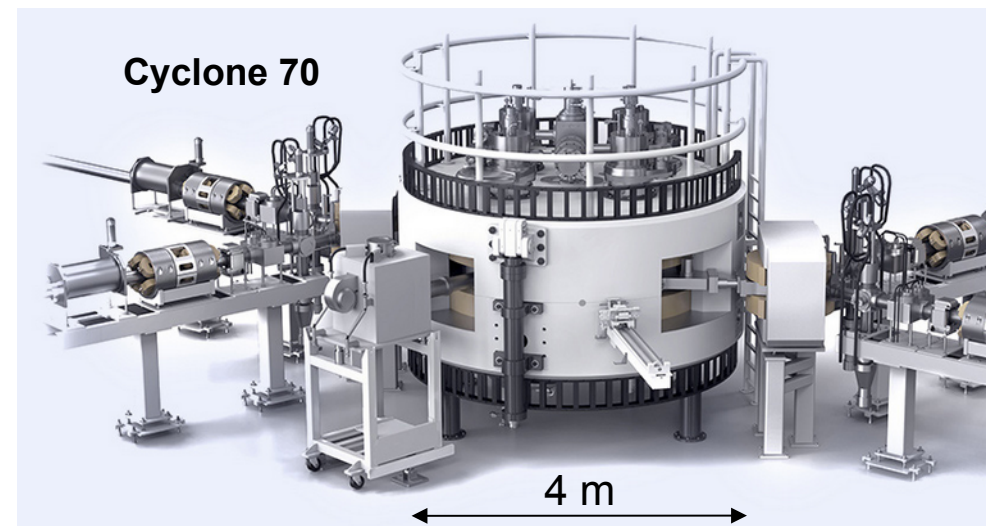
Manufacturer	Model	Footprint (m ²)	Weight (tons)	Proton Energy (MeV)	Max Current (μA)	Shielding	Thermal Areal Density (n/cm ²)	Source
IBA	Cyclone KEY	1.5x1.4	7.5	9.2	130	Self-shielding (opt)	3.4×10^6	[38]
Best	BG-95	< 2x2	22	9.5	120	Self-shielding	3.3×10^6	[39, 40]
Best	B6-15/B15p	2.2x2.2	14	10	400 (550 ^a)	Self-shielding	1.2×10^7	[41]
GE	PETtrace 800 series	1.33x1.2	20	16.5	160	Vault	6.7×10^6	[42]
IBA	Cyclone KIUBE	1.9x1.9	18	18	300	Vault	1.5×10^7	[43]
						Self-shielding (opt)		
ACSI	TR-FLEX	1.7x1.7	24	22	800	Vault	6.4×10^7	[44]
IBA	Cyclone IKON	2.2x2.2	30	22	1500	Vault	1.2×10^8	[45]
ACSI	TR-30	2.4x2.4	50	22	1600	Vault	1.3×10^8	[46]
IBA	Cyclone 70	4x4	120	30-70	750	Vault	>10⁹	[47, 48]



- **Same moderator/reflector design** — different cyclotron → order(s) of magnitude more performance
- **Low-energy tier** ($E_p \leq 10$ MeV, optional self-shielding): Cyclone KEY / BG-95, B6-15/B15p
- **Medium tier** (18–22 MeV, vault shielding): Cyclone KIUBE, Cyclone IKON
- **High-energy tier**: Ta(p,xn) at ~70 MeV (IBA Cyclone 70), Next generation (5–10 mA compact cyclotrons, in development, additional $\times 10$)

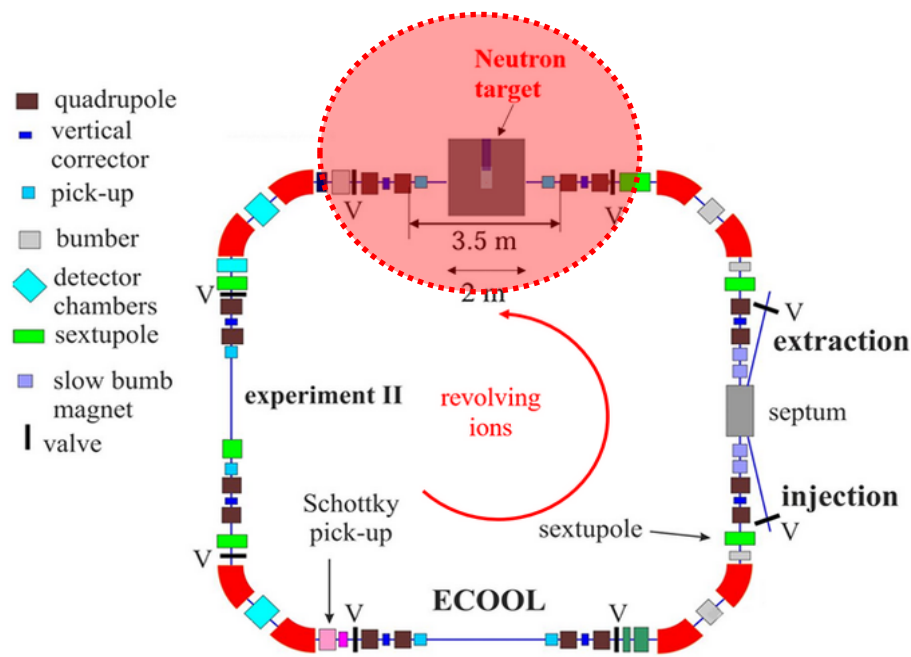


TR-FLEX



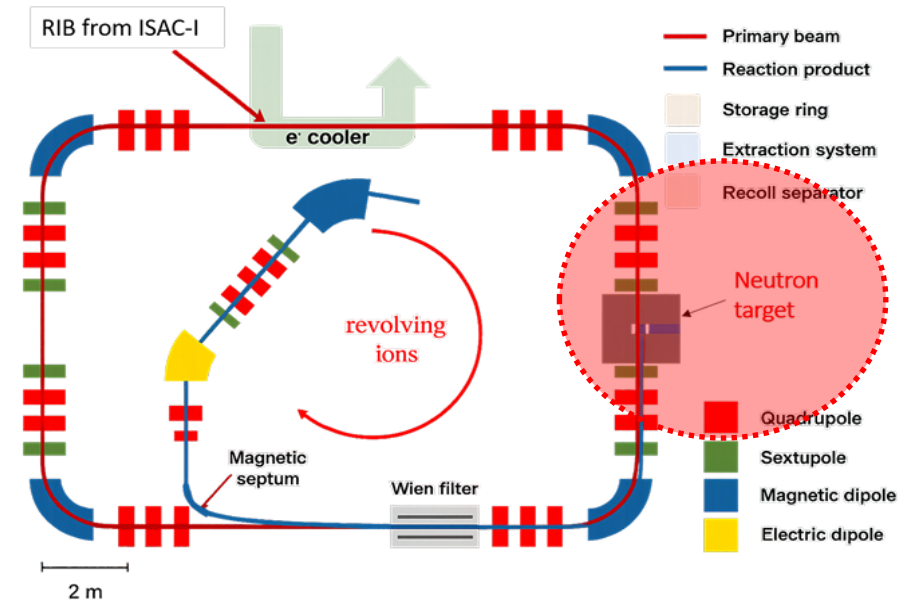
Cyclone 70

Storage-Ring options for a future “production” facility



ISOLDE

See Manfred Griesser talk at ISOLDE EPIC workshop, CERN, Geneva, 3 rd 4 th December 2019



TRIUMF

K. Pak, B. Davids, and Y. K. Kim, Nuclear Engineering and Technology 57, 103392 (2025), arXiv:2312.11859 [physics.acc-ph].

Eur. Phys. J. A (2023) 59:105
https://doi.org/10.1140/epja/s10050-023-01012-9

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Regular Article - Experimental Physics

Measuring neutron capture cross sections of radioactive nuclei

From activations at the FZK Van de Graaff to direct neutron captures in inverse kinematics with a storage ring at TRIUMF

Iris Dillmann^{1,2,*}, Oliver Kester^{1,2}, Richard Baartman^{1,2}, Alan Chen³, Tobias Junginger^{1,2}, Falk Herwig², Dobrin Kaltchev¹, Annika Lennarz^{1,2}, Thomas Planche^{1,2}, Chris Ruiz^{1,2}, Nicole Vassh¹

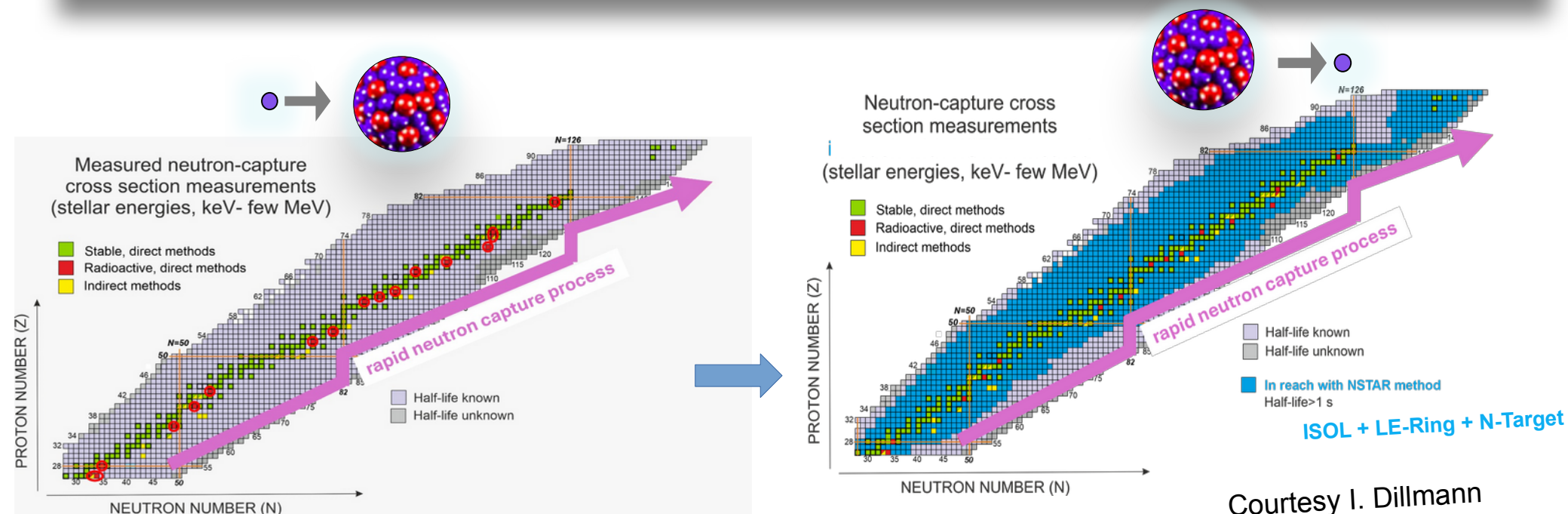
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Summary and conclusions

- Conventional direct neutron-capture techniques (TOF & activation) have come to a limit in terms of short-lived nuclei, half-lives $< \text{yr}$ may never be accessible for such methods.
- **Inverse-kinematics seems the only plausible way** to measure such reactions, considering: 5-6 oom for a $f = 1 \text{ MHz}$
- At this stage we aim for demo-experiments based on most cost-effective & compact cyclotrons commercially available
- From there scale-up in current & energy to customize a solution for production-runs at ISOL facilities (ISR, TRISR, etc)
- Hopefully in the coming decade or so open a new window for direct (n, γ) measurements at Storage Rings & ISOL facilities

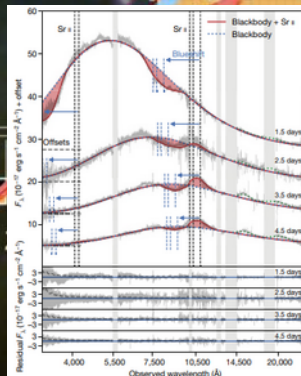
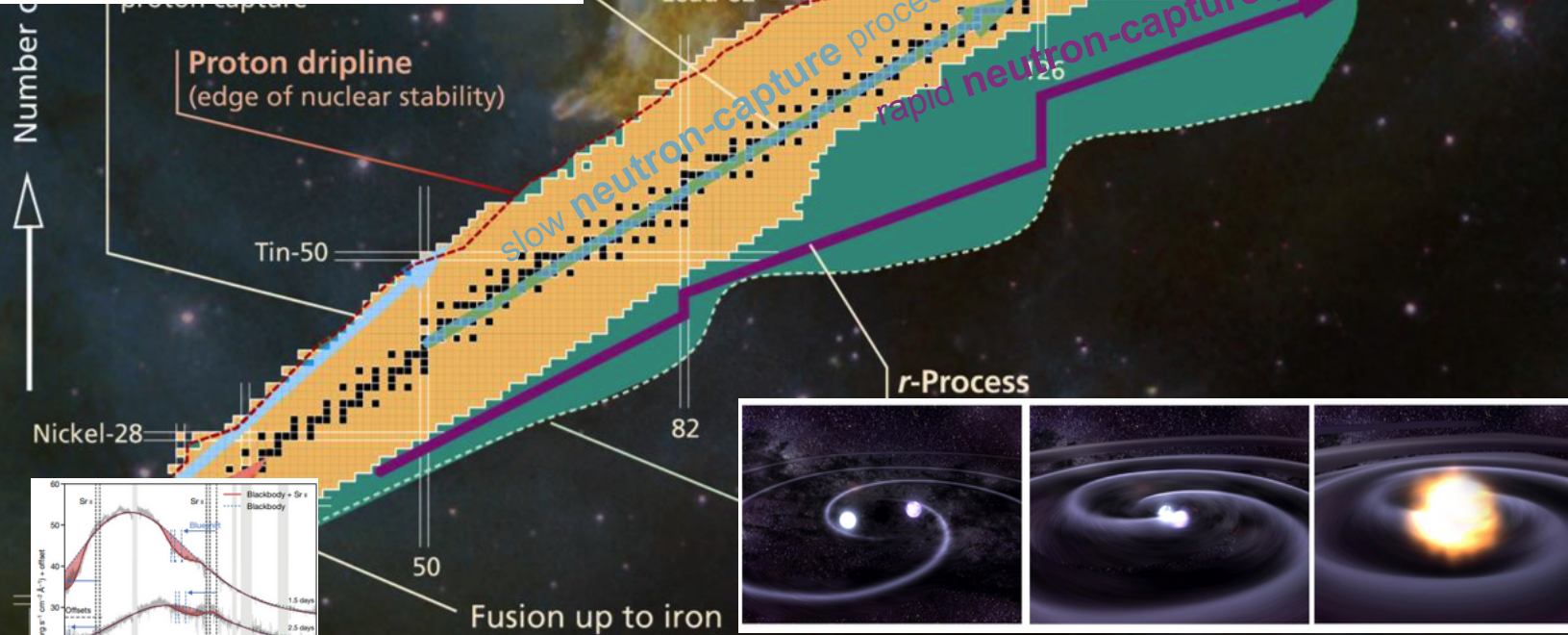
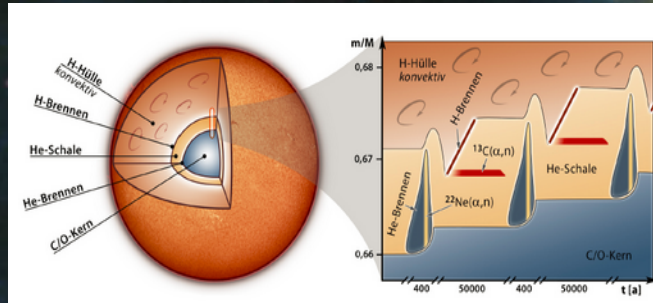


Courtesy I. Dillmann

BACKUP SLIDES

- **The challenge: direct (n, γ) measurements on radioactive nuclei**
 - State of the art, limits, and the fundamental barrier
- **The free-neutron target concept, its potential, and previous efforts**
 - Inverse kinematics in a storage ring & previous approaches
- **Conceptual design of a feasible free-neutron target**
 - Neutron source · moderator optimization · final configuration
- **Implementation and demonstration at CRYRING@GSI**
 - Integrated system · measurement roadmap · detection · first experiments
- **Scalability and future facilities**
 - Cyclotron options · storage-ring options for a production facility
- **Summary and conclusions**

Driven by (n, γ) reactions



Article
Identification of strontium in the merger of two neutron stars
 D. Watson+ 2019

<https://doi.org/10.1038/s41586-019-1676-3>
 Received: 8 February 2018
 Accepted: 14 August 2019
 Published online: 23 October 2019

Darach 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Limits in (n, γ) measurements on radioactive samples

- Seven s-process branching nuclei measured at n_TOF since 2001:
 - ^{151}Sm , ^{93}Zr , ^{63}Ni , ^{171}Tm , ^{204}Tl , ^{94}Nb , ^{79}Se — each requiring larger and larger effort
- **Key limitation: requires macroscopic radioactive sample (mg–g quantities, $\geq 10^{19}$ atoms)**

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

The s process: Nuclear physics, stellar models, and observations

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Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^- , 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^- , 0.159	Important branching, constrains s-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^- , 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^- , 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^- , 2.059	Important branching at $A = 134, 135$, sensitive to s-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^- , 0.269	So far only activation measurement at $kT = 25$ keV by Patronis <i>et al.</i> (2004)
^{147}Nd	10.981 d	β^- , 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^- , 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^- , 2.464	Not feasible in the near future
^{151}Sm	90	β^- , 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno <i>et al.</i> , 2004a; Wisshak <i>et al.</i> , 2006c)
^{154}Eu	8.593	β^- , 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^- , 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^- , 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during s process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^- , 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^- , 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for s-process contribution to ^{180}Ta , nature's rarest stable isotope
^{185}W	0.206	β^- , 0.432	Important branching, sensitive to neutron density and s-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^- , 0.763	Determines $^{205}\text{Pb}/^{205}\text{Tl}$ clock for dating of early Solar System

Growing difficulty for radioactive samples

- **FOM = $1/(m \cdot \sigma \cdot f)$ — experimental difficulty index**

– m = sample mass [mg], σ = cross section [mb], f = isotopic enrichment

- **Historical progression at n_TOF (2001→2025):**

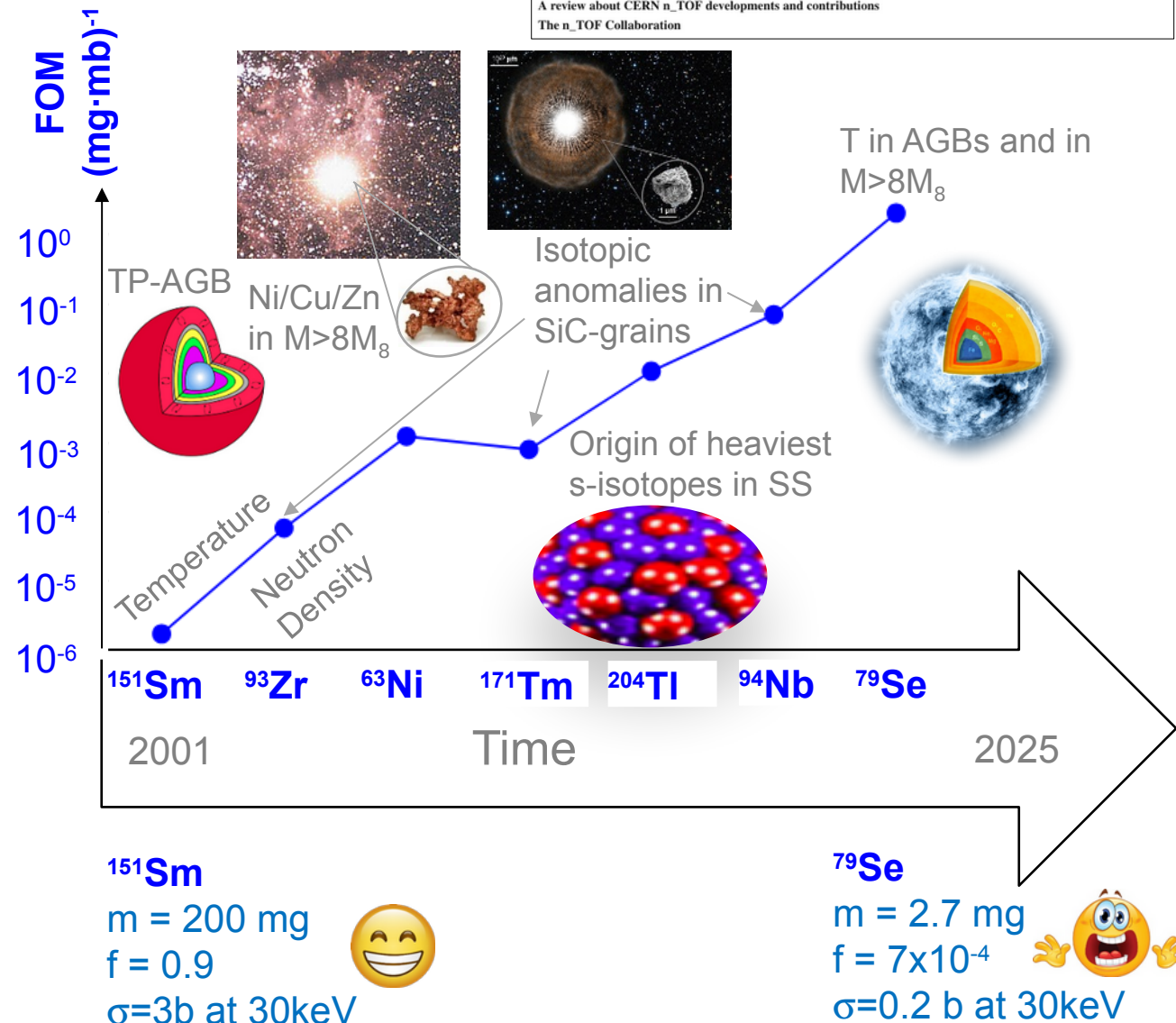
– ^{151}Sm : $m=200$ mg, $f=0.9$, $\sigma=3$ b @ 30 keV → manageable

– ^{79}Se : $m=2.7$ mg, $f=7 \times 10^{-4}$, $\sigma=0.2$ b → extreme limit of TOF

- **The limit for activation:**

- ^{147}Pm ($t_{1/2}=2.6$ yr) → only 28 ng / 10^{14} atoms available [Reinfart et al 2003]

- **TOF limit:** needs mg – 10^{19} atoms; half-lives $\ll 100$ yr → never accessible



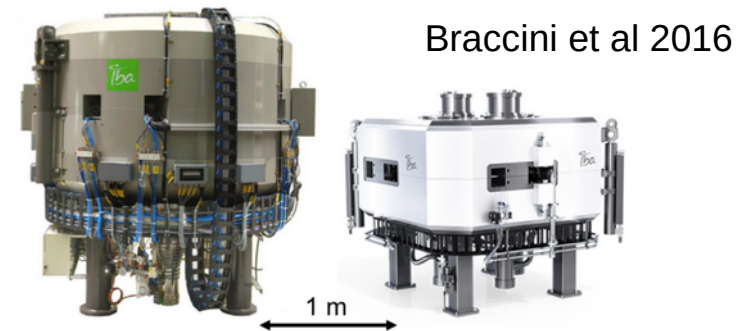
Conceptual design of a feasible free-neutron target

- **Proof-of-concept demonstrator:**
 - **CRYRING@GSI** : only low-energy storage ring in operation worldwide capable of hosting neutron-induced reaction measurements at astrophysically relevant energies
 - Design constraint: storage-ring straight section (2–4 m), UHV compatibility, 10^6 – 10^9 n/cm² target
- **Compact cyclotron for medical isotope production:**
 - Self-contained, integrable with any storage ring, cost-effective demonstrator
 - Mature technology, commercially available!
- **Integration of four key elements:**
 - (1) Storage-ring beam pipe — neutron interaction volume
 - Ø100 mm, 1 mm Al wall, 200 cm length; scoring volume Ø10 mm (ion beam region)
 - (2) Cyclotron beam pipe + Be target — neutron production
 - Ø50 mm, perpendicular to ring; Be target 25 mm from end cap; 5 mm gap to ring pipe
 - (3) Optimized moderator/reflector assembly — neutron thermalization
 - (4) Cryogenic LH₂ moderator — cold neutron density boost
- **Free neutron target:**

Thermal neutrons $E < 25$ meV — minimizes systematic uncertainties in inverse kinematics

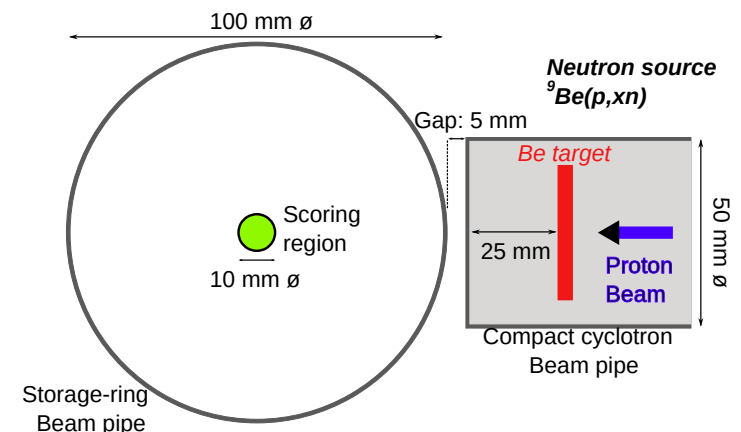


CRYRING@GSI



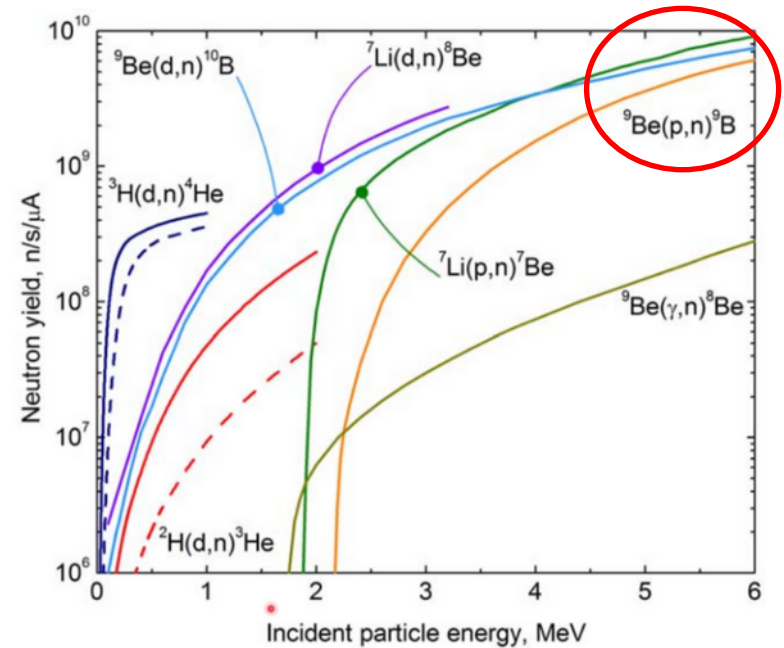
Braccini et al 2016

Figure 2: Comparison between the Cyclone 18/9 (total weight 24 tons, first design 1986) and the new KIUBE (17 tons, launched in 2016). (Courtesy IBA)



Neutron source: $^9\text{Be}(p,xn)$ and supercompact cyclotron technology

- **Selection criterion: maximum neutron yield + softest energy spectrum ($\rightarrow$ compact moderator)**
 - $^9\text{Be}(p,xn)$ vs $^7\text{Li}(p,xn)$: **Be preferred above 5 MeV** — higher stability, easier handling
 - Yield at 9.2 MeV: $Y_{\text{total}} \sim 2.4 \times 10^{10} \text{ n}/\mu\text{C}$ (Lu et al. NIMB 2021, validated vs. MCNP6 $\pm 10\%$)
- **Medical PET cyclotrons: ideal technology match**
 - 7.5–12 MeV protons, 5–150 μA , compact footprint, self-shielding options
 - Designed for hospital environments: reliability, small footprint, modularity
- **Chosen for demonstrator: IBA Cyclone KEY**
 - 9.2 MeV protons, max 130 μA , footprint $1.5 \times 1.4 \text{ m}^2$, weight 7.5 t
 - Self-shielding option $\rightarrow$ can be embedded directly in graphite reflector assembly
- *Our design focuses on proton energies up to 10 MeV*



<https://www.iba-radiopharmasolutions.com/cyclotrons/cycloner-key-0/>

Beryllium target: three-layer design to prevent hydrogen embrittlement

- **Problem: hydrogen (proton) is insoluble in Be**
Be implantation → blistering → target failure
- **Solution: three-layer Be/Pd/Cu design (Kumada et al. 2015, iBNCT BNCT facility)**
- **Layer 1 — Beryllium (600 μm = 87% of proton range):**
 - Neutron production via ${}^9\text{Be}(p,xn)$ — protons traverse almost entirely without stopping
- **Layer 2 — Palladium (intermediate):**
 - Absorbs implanted hydrogen; Bragg peak falls here (maximum energy deposition and H-implantation outside Be)
- **Layer 3 — Copper (backing/heat sink):**
 - Structural support + cooling; beam power ~ 1.2 kW → defocusing/wobbling + active cooling
- SRIM-2013 calculation: proton range in Be at 9.2 MeV = 688 μm → **600 μm Be layer optimized for our case**
- **Result: >99% of protons traverse Be → Bragg peak and H-implantation peak in Pd layer**

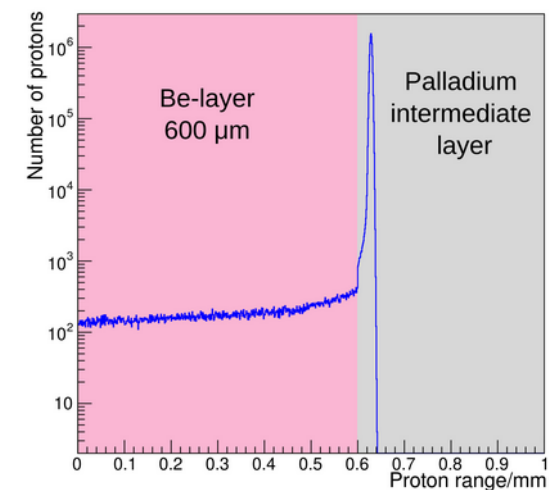
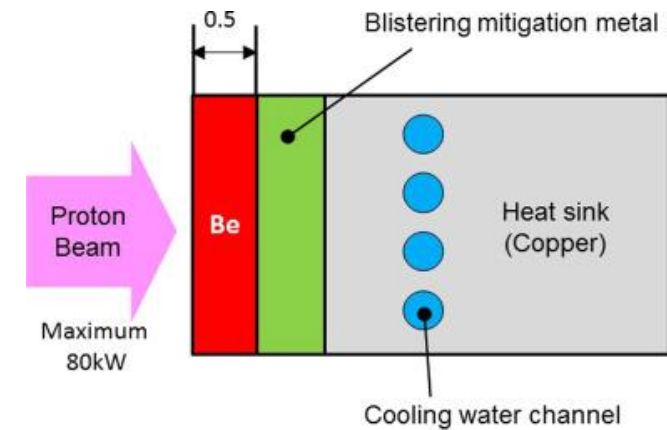


Applied Radiation and Isotopes
Volume 106, December 2015, Pages 78–83



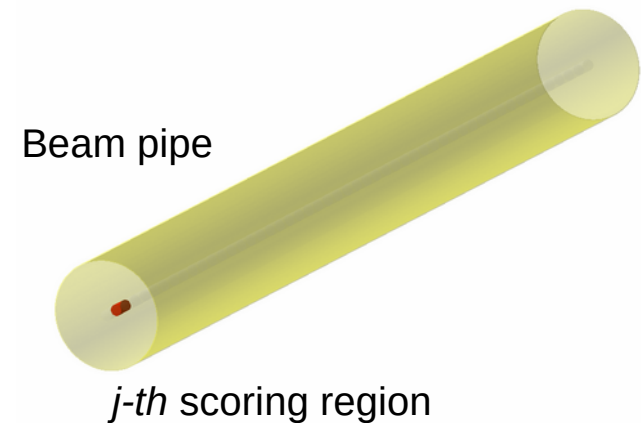
Development of beryllium-based neutron target system with three-layer structure for accelerator-based neutron source for boron neutron capture therapy

Hiroaki Kumada ^a, Toshikazu Kurihara ^b, Masakazu Yoshioka ^b, Hitoshi Kobayashi ^b, Hiroshi Matsumoto ^b, Tomei Sugano ^c, Hideyuki Sakurai ^a, Takeji Sakae ^a, Akira Matsumura ^a



Moderator material selection: performance and cost

- **Moderator figures of merit:**
 - MSDP = $\xi \Sigma_s$ (Macroscopic Slowing-Down Power) — how fast neutrons lose energy
 - MR = $\xi \Sigma_s / \Sigma_a$ (Moderating Ratio) — moderation efficiency vs. parasitic absorption
- **Materials under study: H₂O, D₂O, BeO, graphite (C)**
 - **Metallic Be excluded: extreme toxicity; OSHA 29 CFR 1910.1024 constraints**
 - BeO: sintered ceramic from qualified supplier — non-particulate solid, OSHA-compliant
- **Cost constraint — critical for demonstrator feasibility:**
 - Cost ratio (per cm³): graphite : D₂O : BeO $\approx$ 1 : 100 : 1000
- Key output: thermal areal density
$$A_{\text{den}} = \sum n_{\text{th},j} \times \ell \text{ [n/cm}^2\text{/prim]}, E \leq 1 \text{ eV}$$
- Geometry: 200 cm interaction length, 100 scoring cells (2 cm each), void scoring volume $\varnothing$ 10 mm



Three-stage optimization:

- Stage 1: single-material limits → Stage 2: moderator+reflector → Stage 3: + cryogenic LH₂

TABLE I. Neutron moderation properties for different materials in the epithermal region and number of collisions (N_{col}) to slow a 2 MeV neutron down to 1 eV. Data retrieved from [35].

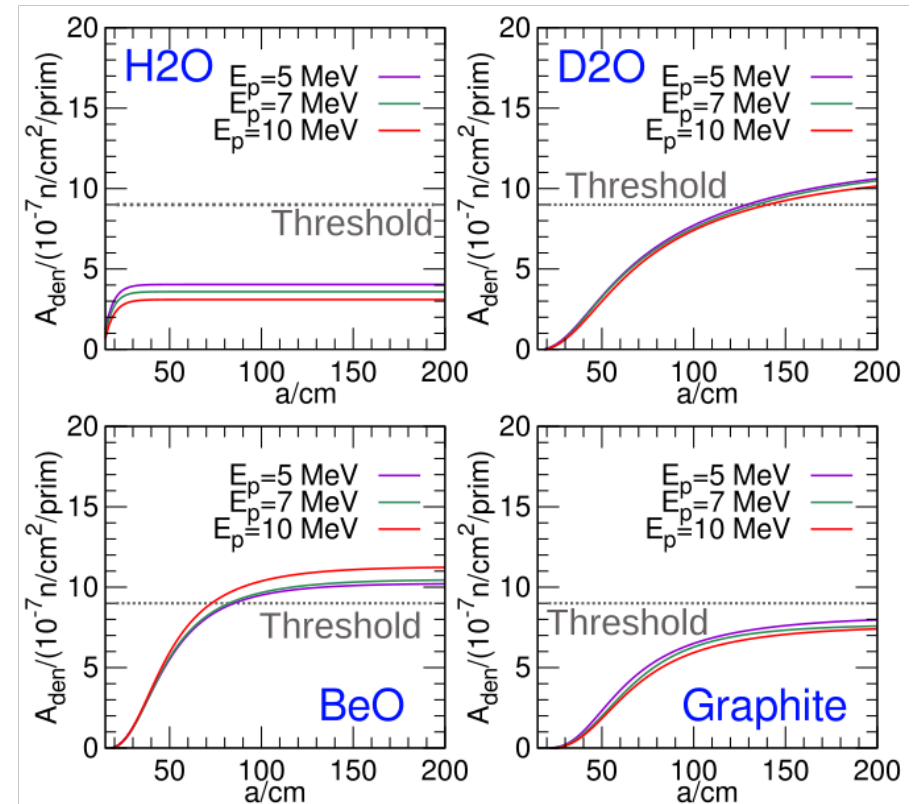
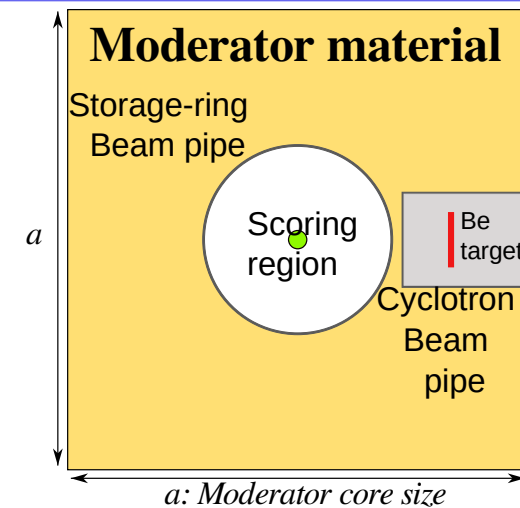
Material	N_{col}	MSDP	MR
Light water (H ₂ O)	16	142.8	62.1
Heavy water (D ₂ O)	28	17.9	4824.3
Beryllium (Be)	70	15.3	127.7
Beryllium oxide (BeO)	84	12.2	158.6
Graphite (C)	92	8.4	220.4



Code: ParticleCounter (Geant4-based), v5.4
— developed for neutron transport and detector design

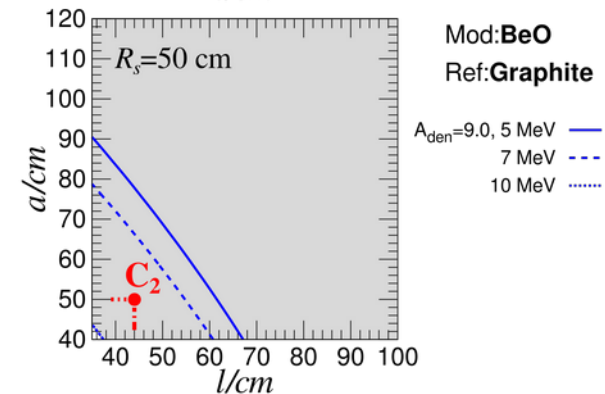
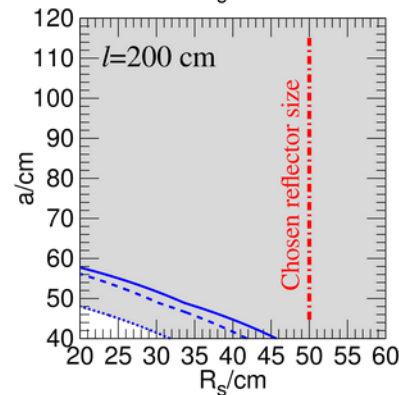
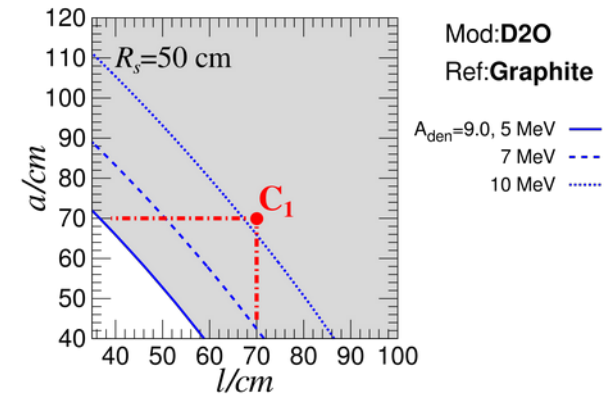
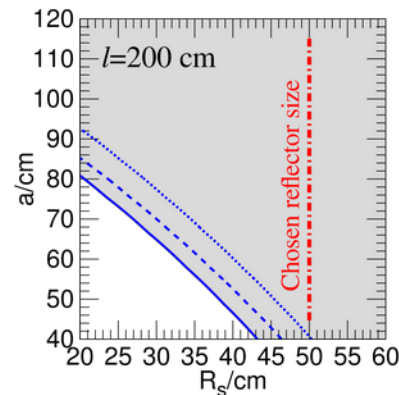
Stage 1: single-material moderator — asymptotic performance limits

- **Parameter scan: moderator size**
 $a = 18\text{--}200\text{ cm}$; $E_p = 5, 7, 10\text{ MeV}$; materials H_2O , D_2O , BeO , graphite
- **Optimization threshold: $9 \times 10^{-7}\text{ n/cm}^2/\text{prim}$**
 (dotted line in figure)
- **H_2O : saturates at 40 cm but below threshold due to neutron absorption → excluded as primary moderator**
- **D_2O : exceeds threshold at all energies; 80% asymptote at avg. 138 cm**
 - Asymptotic $A_{\text{den}} = 11.6 \times 10^{-7}\text{ n/cm}^2/\text{prim}$ — best single material
- **BeO : inverse energy trend — $\text{Be}(n,2n)$ multiplication above $\sim 7\text{ MeV}$ increases yield at higher E_p**
 - 80% asymptote at 72 cm → especially attractive for compact designs
- **Graphite: does not reach threshold as primary moderator**
 - Low cost + favorable neutron transport → excellent reflector candidate



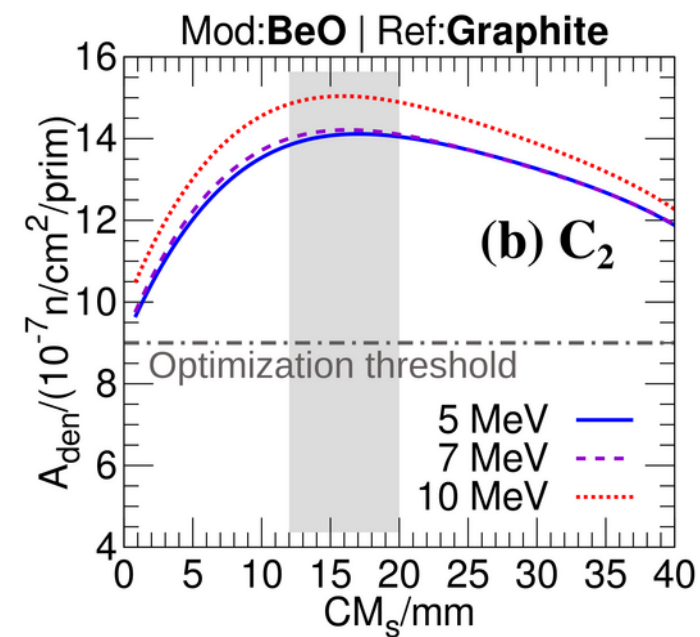
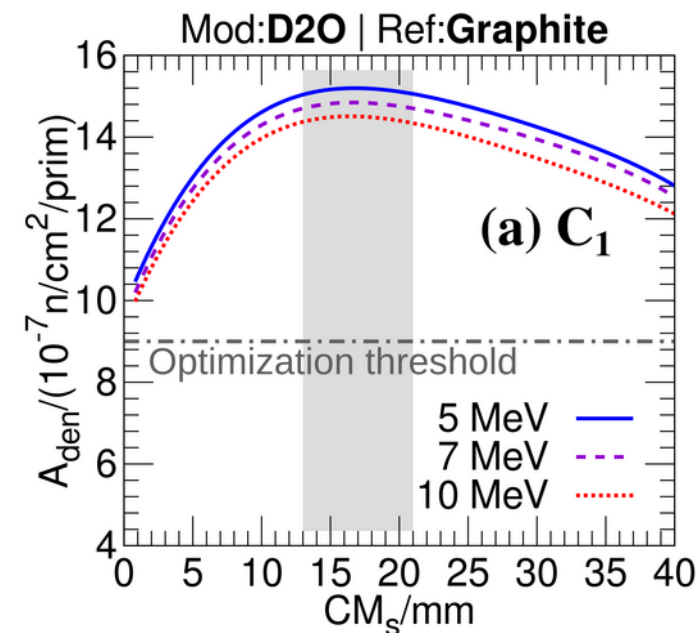
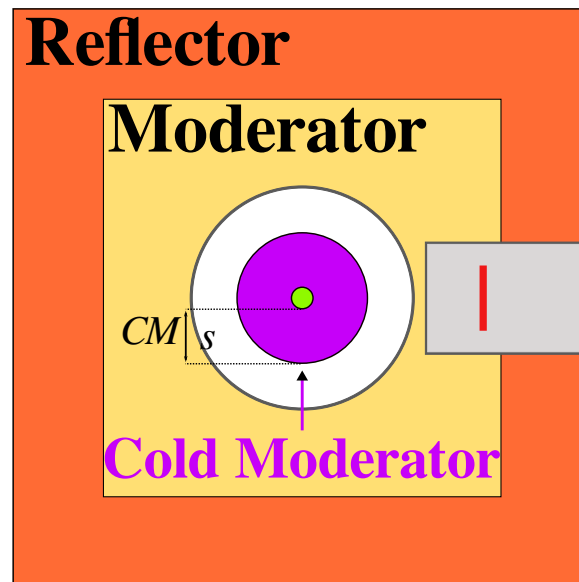
Stage 2: moderator + reflector

- Two combinations selected: (1) D₂O + graphite, (2) BeO + graphite
- Systematic two-phase optimization:
 - Phase 1: scan $a = 40\text{--}120$ cm, $R_s = 20\text{--}60$ cm ($l = 200$ cm constant)
 - Phase 2: with $R_s=50$ cm fixed, scan $a = 40\text{--}120$ cm, $l = 35\text{--}100$ cm
- Optimal reflector thickness: $R_s = 50$ cm (maximizes A_{ae^n} vs. a at all energies)
- Configuration C1 (D₂O moderator): $a = 70$ cm, $l = 70$ cm
 - Best cost/performance trade-off; A_{ae^n} above threshold for all $E_p = 5\text{--}10$ MeV
- Configuration C2 (BeO moderator): $a = 50$ cm, $l = 44$ cm
 - Minimum BeO volume; viable at $E_p > 7$ MeV (neutron multiplication advantage)
- Cost: C2 $\approx 3\times$ C1 (moderator material dominates total system cost)



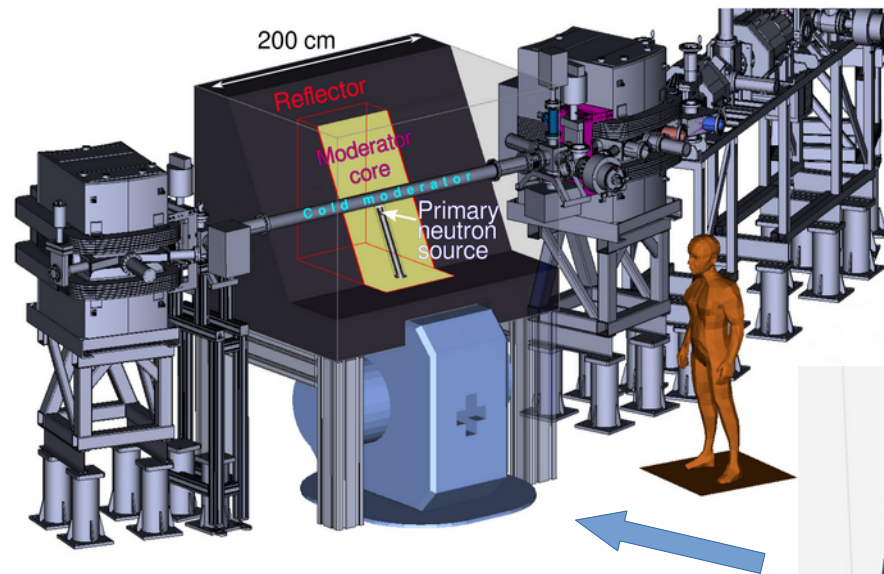
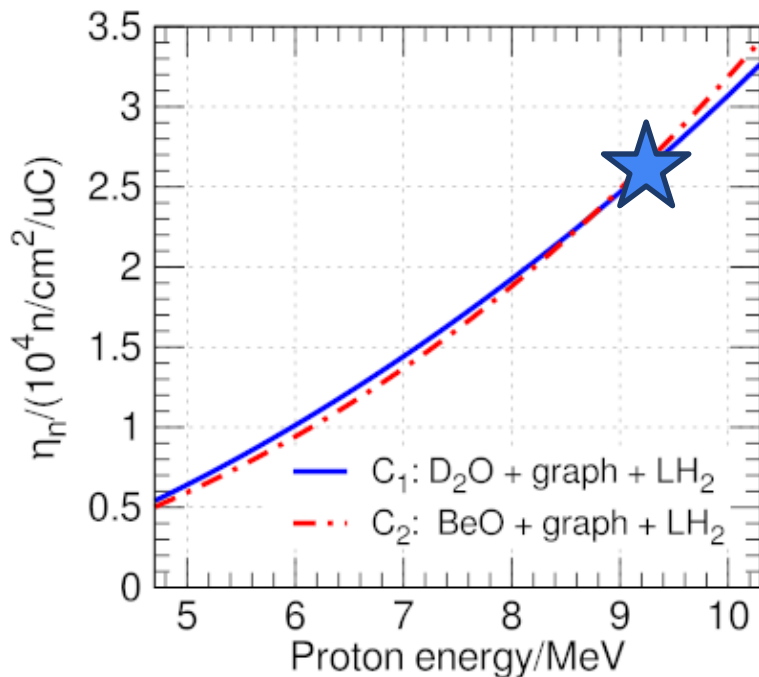
Stage 3: cryogenic LH₂ moderator — thermal neutron density boost

- **LH₂ at 20 K: optimal cold moderator material**
 - Hydrogen exists as para-H₂ (>99%): filter-like behavior below thermal energy range
 - ≥30× reduction in scattering cross section below room temperature thermal range
 - Enables low-dimensional moderators — cold neutrons traverse with minimal energy regain
 - Better radiation resistance than solid methane; safer operationally
- **Geometry: cylindrical shell inside storage-ring beam pipe, surrounding scoring volume**
 - Cold moderator thickness CMs varied 0–40 mm
- **Optimal: CMs = 13 mm — plateau region for both C1 (13–21 mm) and C2 (12–20 mm)**
- **Performance gain: ~60% above optimization threshold for both configurations**



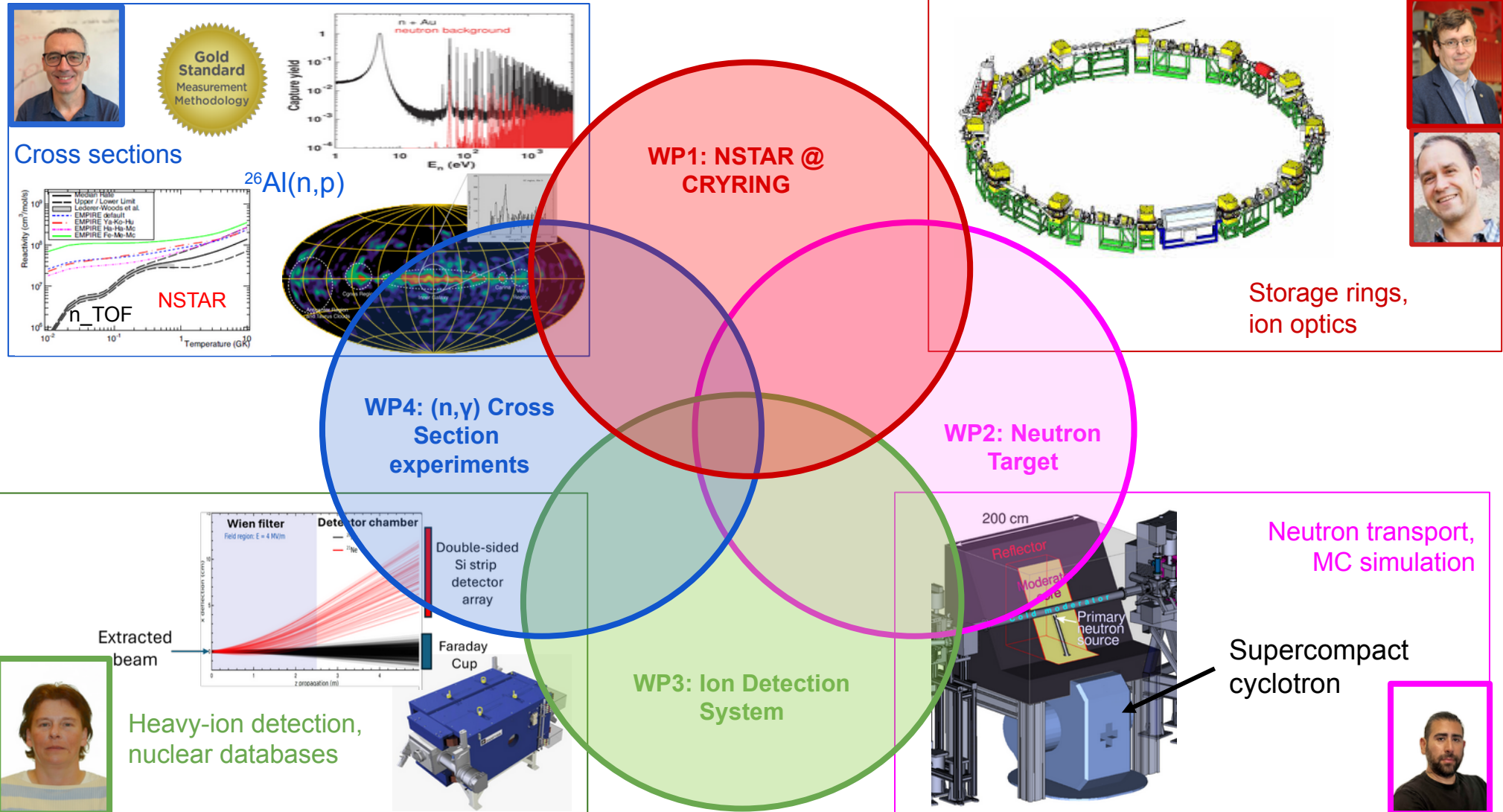
A feasible free-neutron target *in a nutshell*

- **Cyclotron:** IBA Cyclone KEY, 9.2 MeV protons, up 130 mA current, 2.1 m² footprint
- **Moderator:** D₂O, 70 x 70 x 70 cm³
- **Reflector:** Graphite, 50 cm thick
- **Cryogenic system:** LH₂, 20 K, 13 mm thickness, 10 mm inner diameter
- **Total size:** 170 x 170 x 200 cm³
- **Areal density:** **3.4 x 10⁶ n/cm²**
- **Where to find it?** [arXiv:2508.15465v1](https://arxiv.org/abs/2508.15465v1)



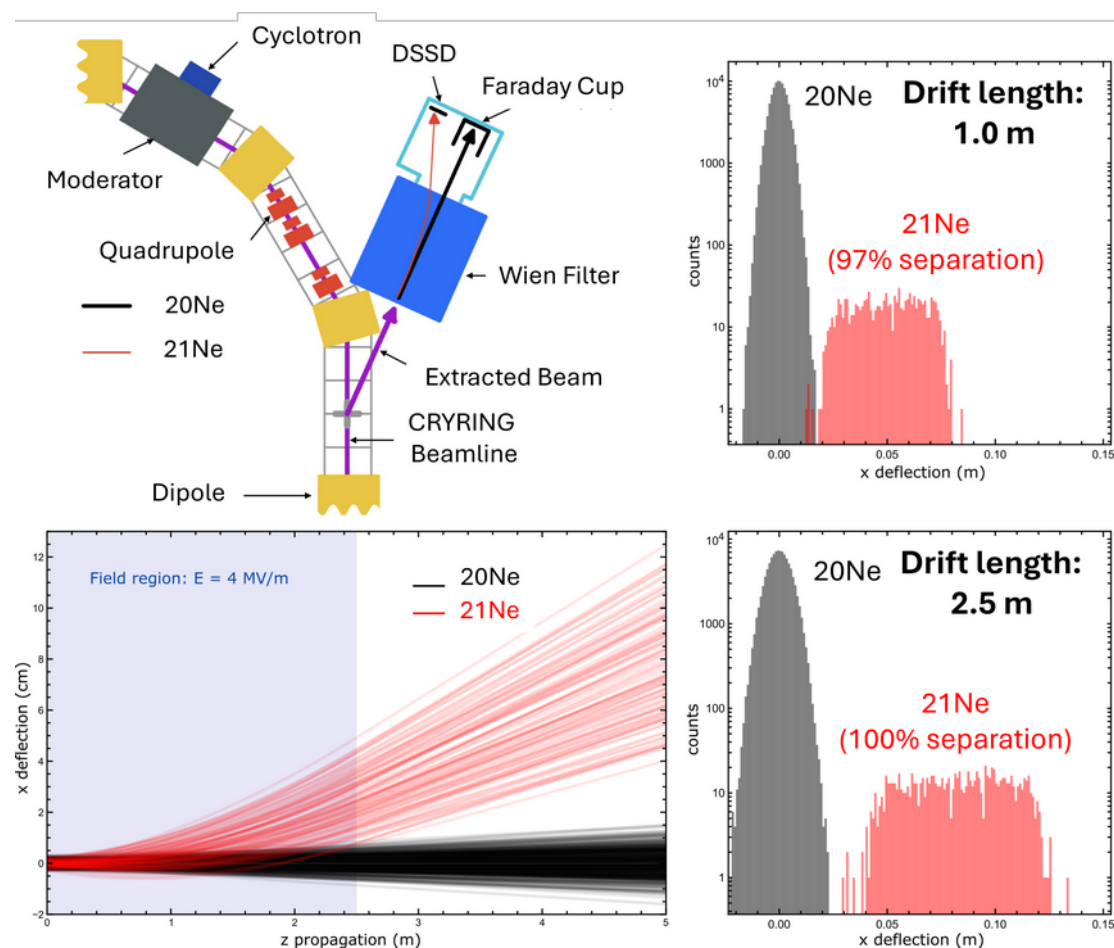
Implementation: roadmap for demonstration CRYRING@GSI

Demonstration roadmap at GSI in composed by 4 interconnected workpackages:



Detection principle: radiative neutron capture $AZ(n,\gamma)^{A+1}Z$

- **Challenge:** (n,γ) does not change ion charge $\rightarrow$ same mean magnetic rigidity $\rightarrow$ in-ring detectors cannot distinguish parent from daughter
- **Key observable: velocity difference**
 - Daughter $A+1Z$ is heavier $\rightarrow$ circulates at $v' = A/(A+1) \times v_{\text{parent}}$
- **Solution: Wien velocity filter ($E \times B$ separator)**
 - Beam + reaction products extracted together $\rightarrow$ Wien filter separates by velocity
 - Example: $^{20}\text{Ne}^{3+}/^{21}\text{Ne}^{3+}$ at 1.68 MeV/u
 - 100 mm pole gap, 3 kV/mm E-field $\rightarrow$ full separation within 3 m drift
 - Detection: DSSD for reaction products, Faraday cup for unreacted beam
- **Future (dedicated ring):** Wien filter integrated in lattice $\rightarrow$ products extracted without losing beam $\rightarrow$ enables accumulation



Demonstration experiments at CRYRING: first measurement candidates

- **Areal density:** $\eta_n = 3.4 \times 10^6 \text{ n/cm}^2$ (Cyclone KEY, 130 μA , 9.2 MeV)
- **With stable beams — methodology validation:**
 - $^{20}\text{Ne}(n,\gamma)^{21}\text{Ne}$, $^{20}\text{Ne}(n,p)^{20}\text{F}$, $^{20}\text{Ne}(n,\alpha)^{17}\text{O}$ — cross sections known, clean reference
 - $^{149}\text{Sm}(n,\gamma)$: $\sigma = 1820 \text{ mb}$ @ $kT=30 \text{ keV}$; two TOF experiments agree within 10% → ideal benchmark
- **With radioactive beams from ESR:**
 - $^{26}\text{Al}(n,p)^{26}\text{Mg}$, $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ — astrophysical importance (nova/AGB nucleosynthesis)
- **Expected luminosity at CRYRING:**
 - $L \approx 5 \times 10^{18} \text{ cm}^{-2}\text{s}^{-1} \rightarrow 50\text{--}1000 \text{ counts/day}$ for favorable cases (σ : 100-2000 mb)
 - Enable demonstration within a few days of experiment
- **Proof-of-concept scope: validate methodology, calibrate detection, quantify systematic uncertainties**

$^{26}\text{Al}(n,p)$, $^{26}\text{Al}(n,\alpha)$

$^{21}\text{Ne}(n,\gamma)$, $^{149}\text{Sm}(n,\gamma)$

