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Direct Radiative Neutron Captures for Short-Lived Nuclei - A New Approach

Iris Dillmann
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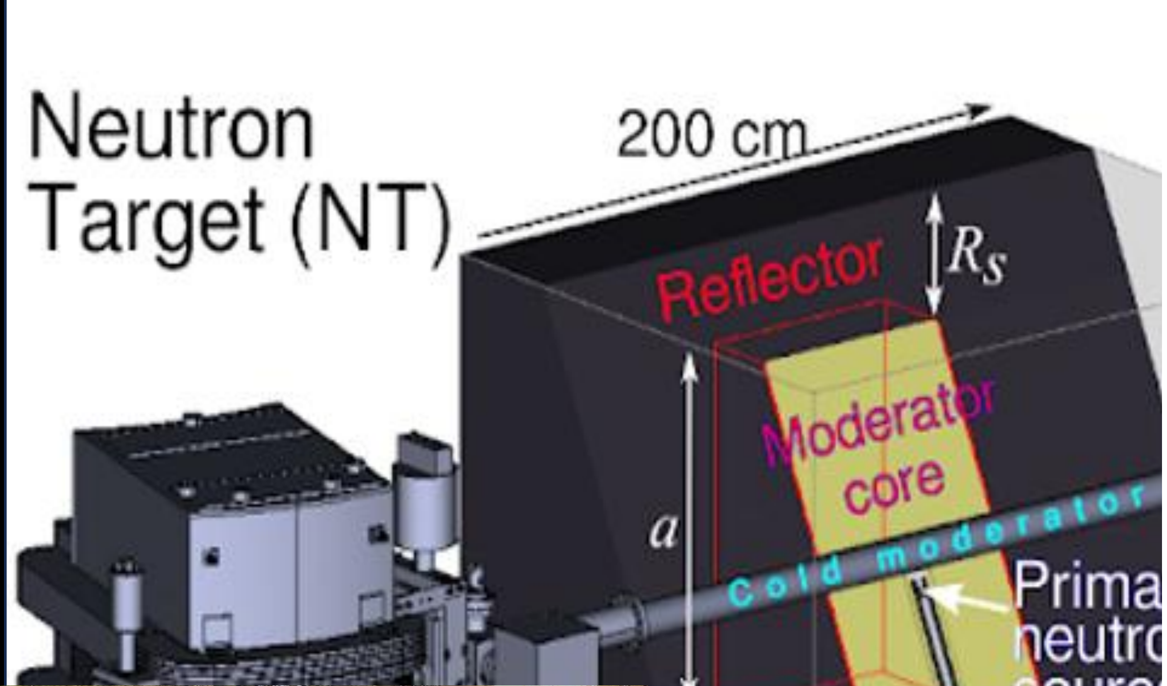
Ariel Tarifeno-Saldivia
Yury Litvinov




The NSTARs and friends

Discovery, accelerated

What is next?

Beam

Target

Neutrons → Stable/ long-lived nuclei → Measure decay or reaction products

down to ~10^{15} atoms

Storage Ring

Short-lived nuclei → Neutrons → Measure reaction product

<u>Direct</u> measurement of (n,γ) cross section of <u>short-lived radioactive</u> nuclei

Revolution frequency ~100 kHz → luminosity x10^5 !

TRIUMF

(Modern) Heavy RIB Storage Rings

Operational
Under construction
Postponed
Proposed
~~Cancelled/closed~~

Fragmentation facility

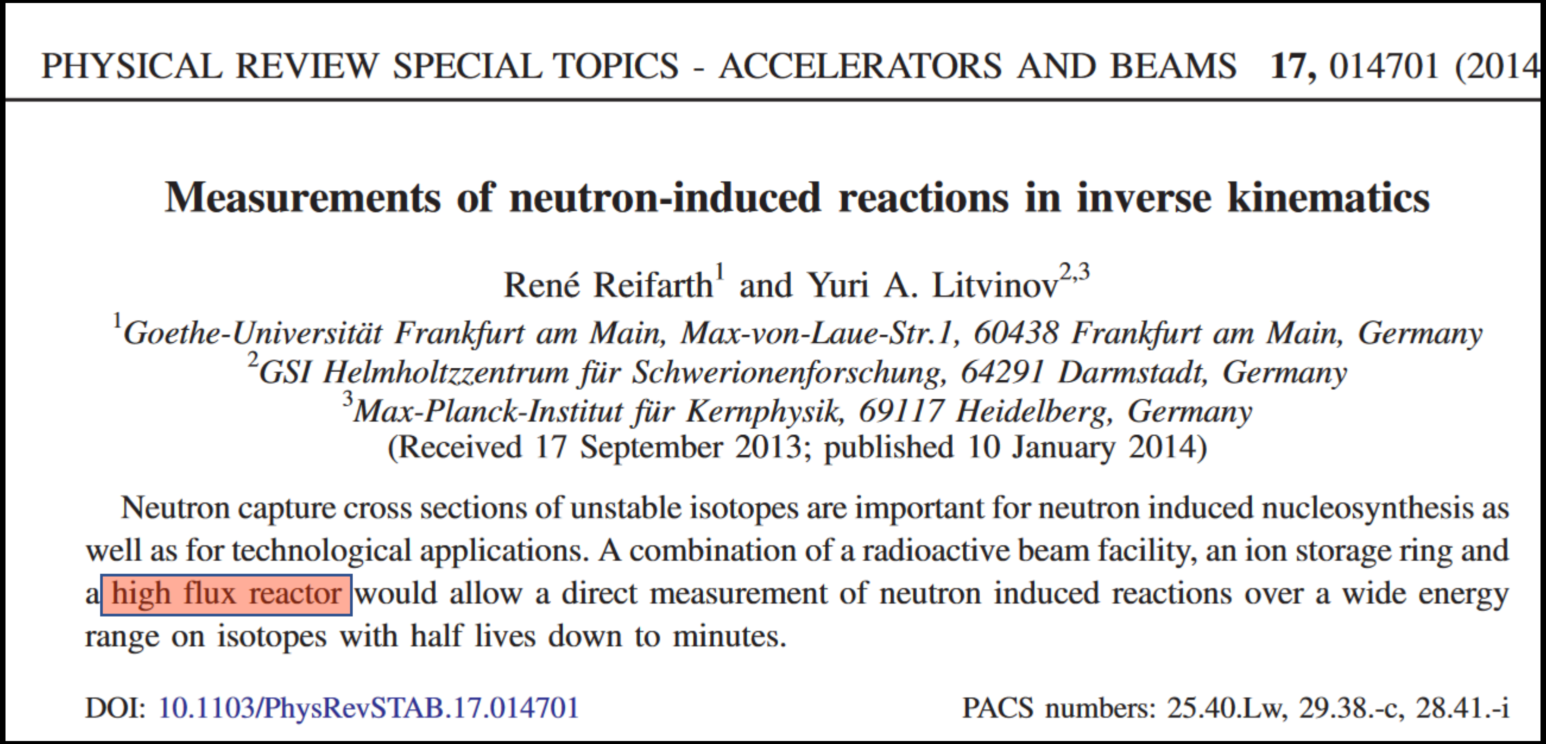
- Experimental Storage Ring (ESR) at GSI Darmstadt (since 1990)
- Cooler-Storage Ring (CSRe) at HIRF in Lanzhou (since 2010)
- Rare RI Ring (R3) at RIKEN Nishina Center (since 2012)
- CRYRING at GSI Darmstadt (1992-2014, since 2016)
- Collector Ring (CR) and High-Energy Storage Ring (HESR) at FAIR (>203x)
- Spectrometer Ring at HIAF in Huizhou (2025)

+ Neutron Target

ISOL facility

- ~~Test Storage Ring (TSR) at CERN-ISOLDE (2012)~~ (1988-2013)
- ISOLDE Storage Ring (ISR, proposed) at CERN-ISOLDE (>203x)
- TRIUMF Storage Ring (TRISR, proposed) at TRIUMF-ISAC (>203x)
- Los Alamos Storage Ring (proposed) at LANSCE (>203x)

Storage Ring + High-Flux Reactor



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

Measurements of neutron-induced reactions in inverse kinematics

René Reifarth[1] and Yuri A. Litvinov[2,3]
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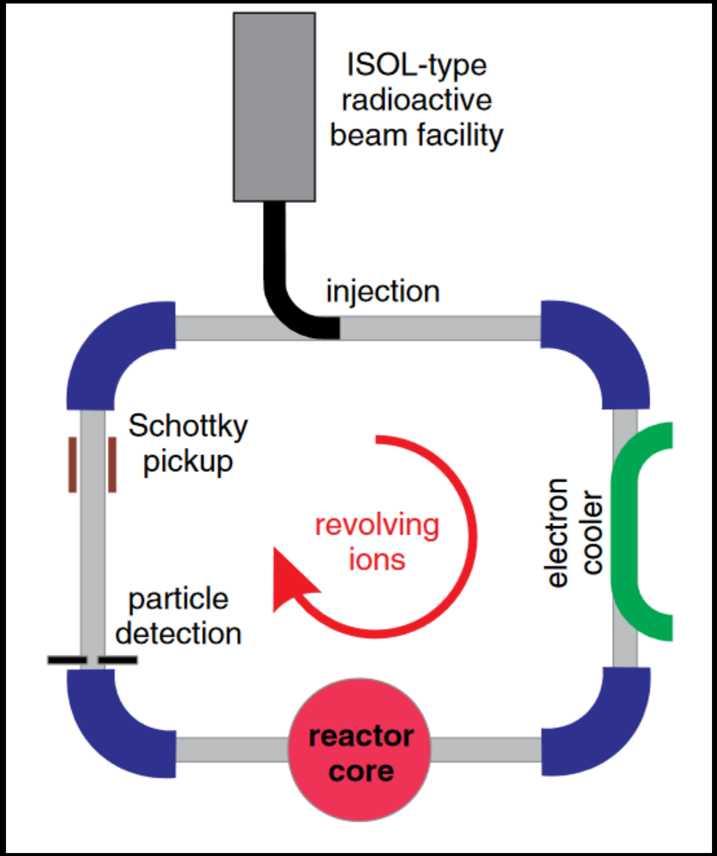
(Received 17 September 2013; published 10 January 2014)

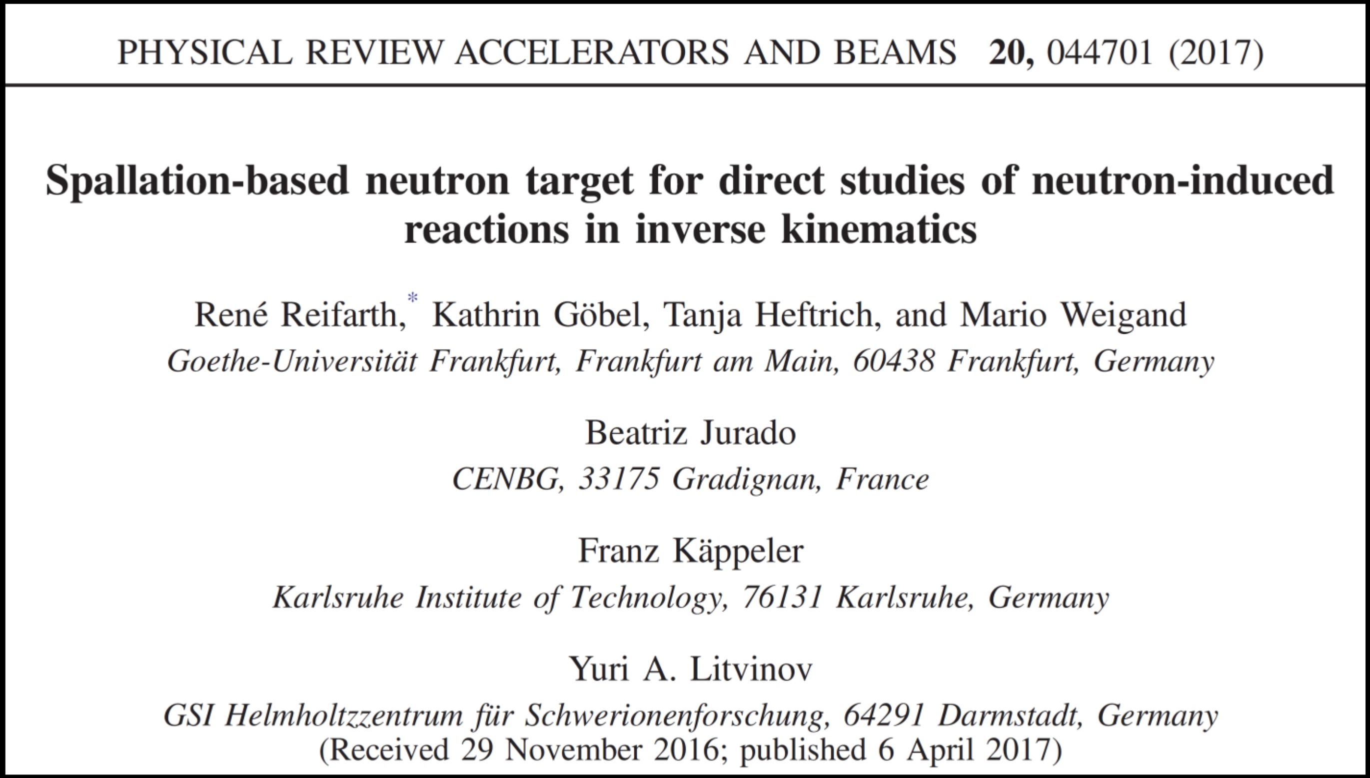
Neutron capture cross sections of unstable isotopes are important for neutron induced nucleosynthesis as well as for technological applications. A combination of a radioactive beam facility, an ion storage ring and a high flux reactor would allow a direct measurement of neutron induced reactions over a wide energy range on isotopes with half lives down to minutes.

DOI: 10.1103/PhysRevSTAB.17.014701 PACS numbers: 25.40.Lw, 29.38.-c, 28.41.-i



No ISOL facility near reactor
Difficult: Storage ring through reactor core

Storage Ring + Spallation Neutron Target



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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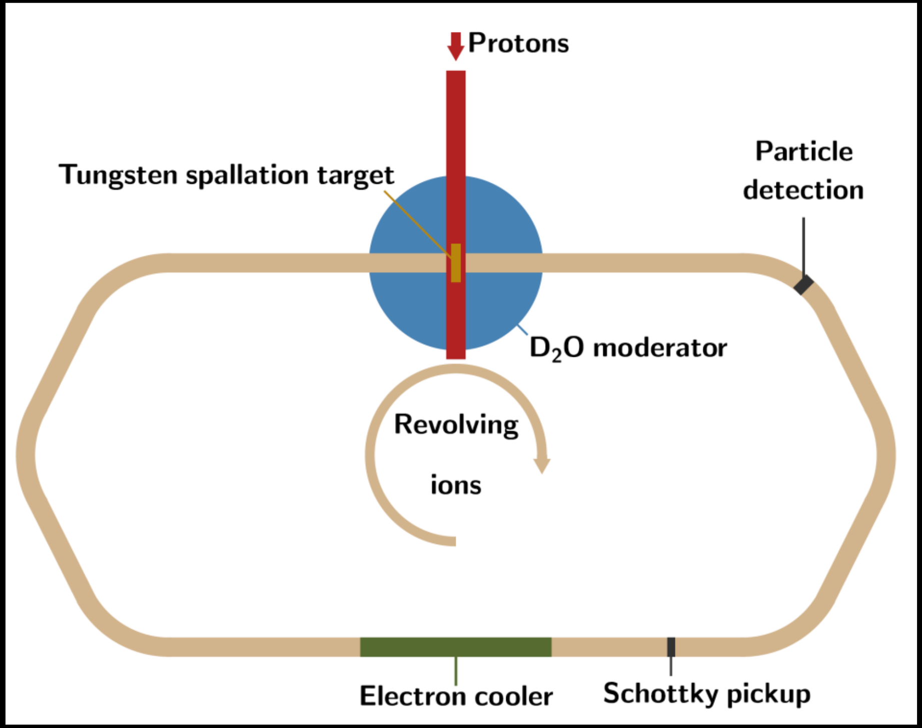
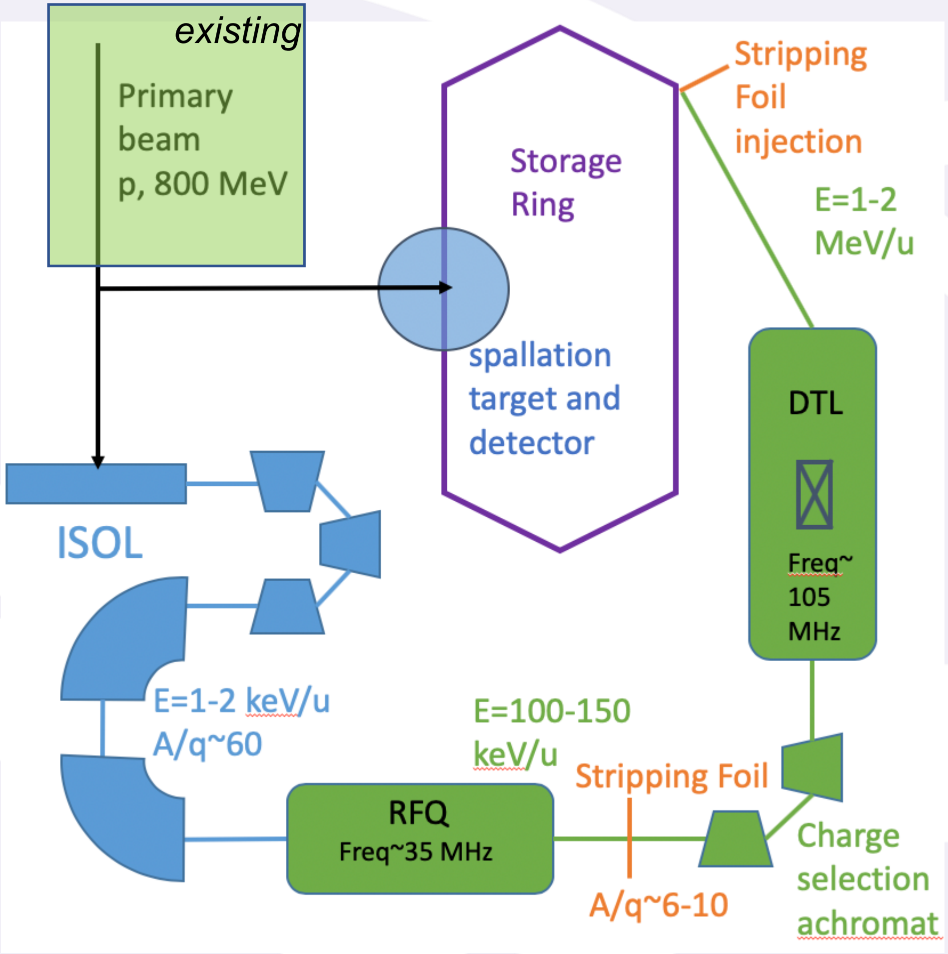


→ *Los Alamos Project (S. Mosby, A. Couture, R. Reifarth)*
But no ISOL facility and storage ring at LANL

Los Alamos Neutron + Storage Ring Project

LANL is exploring subsystem concepts, technologies

- LANSCE-based concept would produce radionuclides via **ISOL technique**
- Initial focus on “fast” (**5 – 15 MeV/A** beam energy) reactions
- Produce **neutron field via spallation** using existing accelerator
  - Investigating **moderator material choices** and associated trade space
- **Recoil separator-based reaction** tag could extend reach to shorter nuclear lifetimes
  - Beginning investigation of detector technologies, consequences of choosing this approach

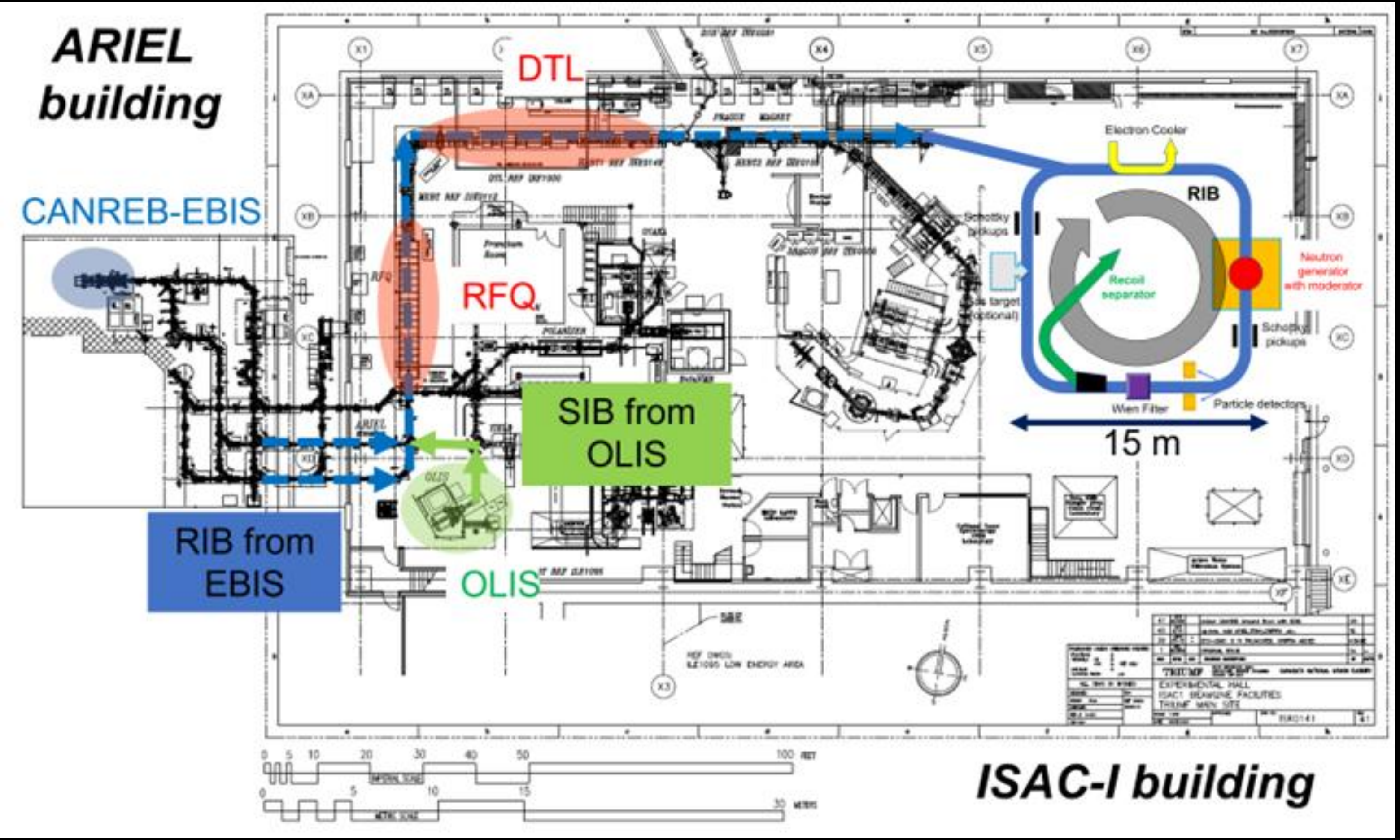


from Shea Mosby (LANL)

Los Alamos National Laboratory preprint LA-UR-21-30261 (2021)

The TRIUMF Storage Ring (TRISR) Project

Existing ISOL facility + Storage Ring + Neutron Target



Focus on neutron capture cross sections for heavy nuclei (r- and i-process) :

E= 0.1-2 MeV/u

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The TRIUMF Storage Ring (TRISR) Project

Existing ISOL facility + Storage Ring + Neutron Target

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https://doi.org/10.1140/epja/s10050-023-01012-9

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

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,a], Oliver Kester[1,2], Richard Baartman[1,2], Alan Chen[3], Tobias Junginger[1,2], Falk Herwig[2], Dobrin Kaltchev[1], Annika Lennarz[1,3], Thomas Planche[1,2], Chris Ruiz[1,2], Nicole Vassh[1]

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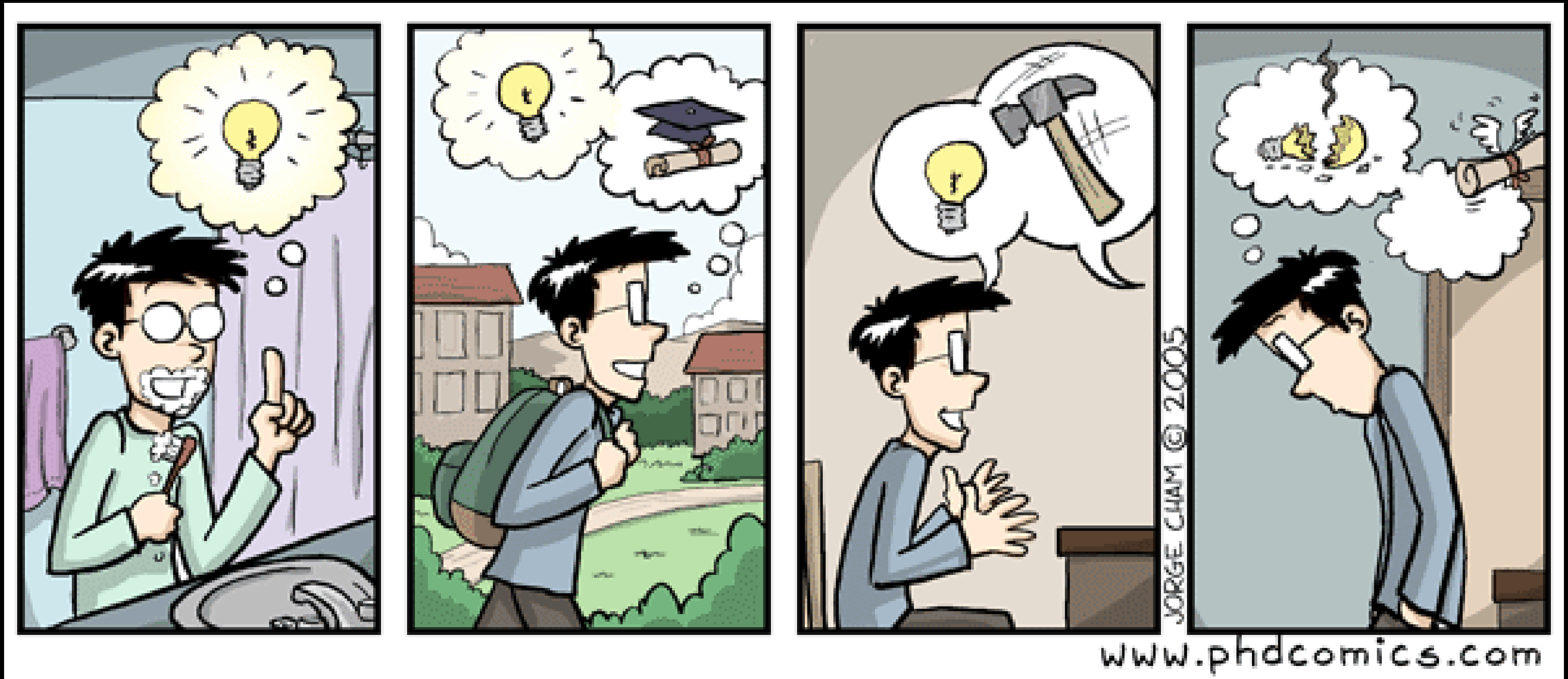
(Little) Problem



No facility (yet) with RIB + Storage Ring + Neutron Target

Discovery, accelerated

The NSTAR Project

Submitted to Physical Review Accelerators and Beams

Direct Neutron Reactions in Storage Rings Utilizing a Supercompact Cyclotron Neutron Target

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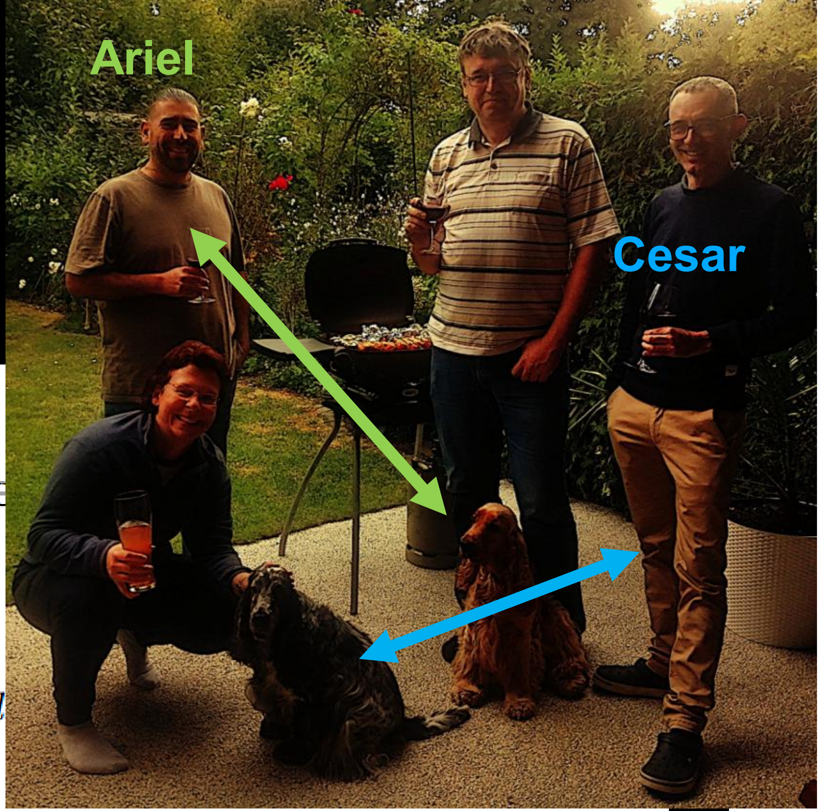
Institut für Kernphysik, Universität zu Köln, Köln, Germany

(Dated: August 22, 2025)

https://arxiv.org/pdf/2508.15465

The NSTAR Project



Submitted to Physical

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Key Factor: Neutron Target Design

- High-Flux Reactor: Very high flux but very expensive
- Spallation Neutron Source: High flux but still expensive
- (Compact) Acc-Driven Neutron Source: Good flux but large
- Neutron Generator: So-so neutron flux and very cheap

Key Factor: Neutron Target Design

- High-Flux Reactor: Very high flux but very expensive
- Spallation Neutron Source: High flux but still expensive
- (Compact) Acc-Driven Neutron Source: Good flux but large
- High-intensity cyclotron-driven neutron source
- Compact cyclotron-driven neutron source: Best compromise
- Array of compact neutron generators: scalable and needs space
- Neutron Generator: So-so neutron flux and very cheap

The NSTAR Project: Proof-of-Concept

ERC Synergy Grant application: Limitations

1) Need an existing storage ring facility → space constraints
2) Need existing RIB facility
3) Provide physics results within 6 years project duration
4) Funding constraints (max. 14 MEuros)

https://arxiv.org/pdf/2508.15465

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The NSTAR Project: Proof-of-Concept

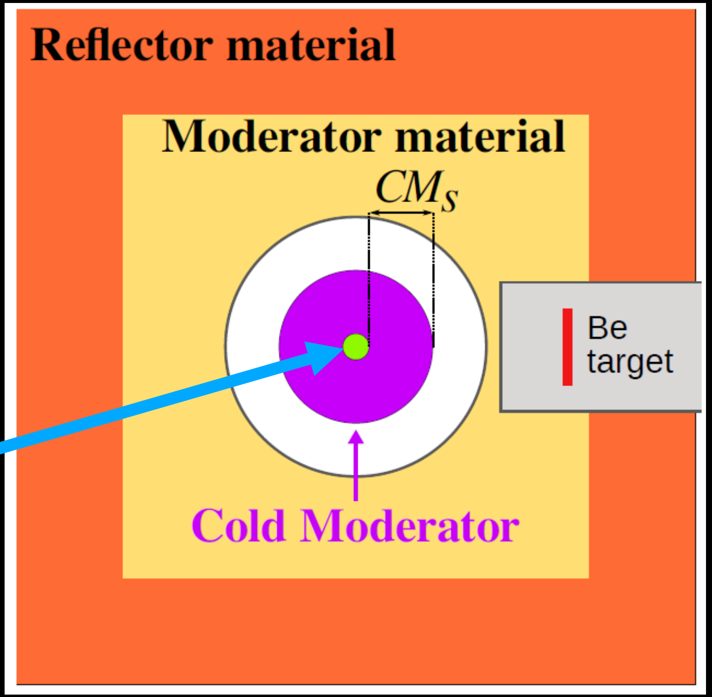
- Existing (low-energy) storage ring: CRYRING at GSI Darmstadt
- Energy range: E>100 keV … few MeV
- Existing RIB facility: GSI Darmstadt
- Supercompact cyclotron: 9 MeV p, ~130 μA → $^{9}Be(p,n)$
- (Cryogenic) Neutron moderator-reflector target
- Beam and reaction products extracted

→ **Expected areal neutron density: ~$3 \cdot 10^{6}$ n/cm^{2}**

https://arxiv.org/pdf/2508.15465

The Cryogenic Moderator-Reflector

- D_2O or BeO ceramics as moderator
- Graphite as reflector
- 20K liquid H2 as cryogenic material
  - → **~14-15*10^{-7} n/cm^2/primary**



Storage ring beampipe (diameter ~1 cm!)

TABLE II. Final proposed configurations for the compact neutron target optimized for storage-ring integration.

Configuration	Moderator Material	Moderator a [cm]	Moderator l [cm]	Reflector Material	Reflector R_s [cm]	Cold Moderator Material	Cold Moderator Temp. [K]	Cold Moderator CM_s [mm]	Proton Energy E_p [MeV]	Thermal Areal Density A_{den} [10^{-7} n/cm^2/prim]
C_1	D_2O	70	70	graphite	50	LH_2	20	13	5–10	14.3–15.0
C_2	BeO	50	44	graphite	50	LH_2	20	13	>7	14.0–15.0

https://arxiv.org/pdf/2508.15465

The Supercompact Cyclotron

TABLE III. Selection of commercial compact proton cyclotrons. Technical specifications and suitability for implementation of the free neutron target are based on proposed configuration with a D_2O moderator (see configuration C_1 Table II). For proton energies up to 10 MeV, the total areal density is taken from calculations in Fig. 9. For proton energies larger than 10 MeV, calculations are assuming a thermal areal density per primary neutron $A_{den} = 5 \times 10^{-7}$ n/cm^2/prim and neutron yields from Ref. [18] (E_p >10 MeV).

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 Self-shielding (opt)	1.5×10^7	[43]
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	–	[47, 48]

[a] Measured at Argonne National Laboratory

- IBA Cyclone KEY is best solution for limited space in CRYRING
- p up to 9.2 MeV
- Current up to 130 μA

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

https://arxiv.org/pdf/2508.15465

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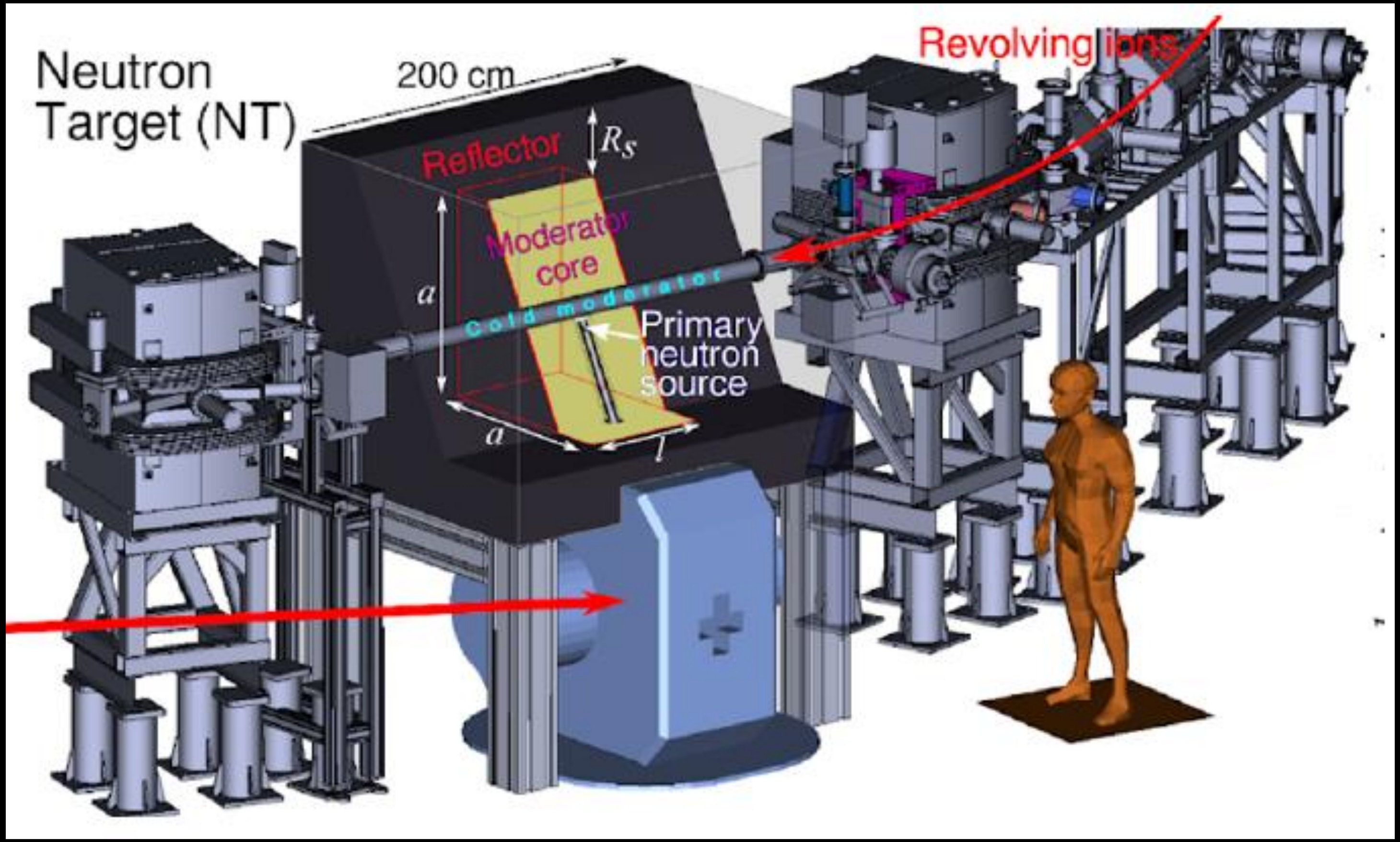
Assembly at CRYRING

Cyclotron



https://arxiv.org/pdf/2508.15465

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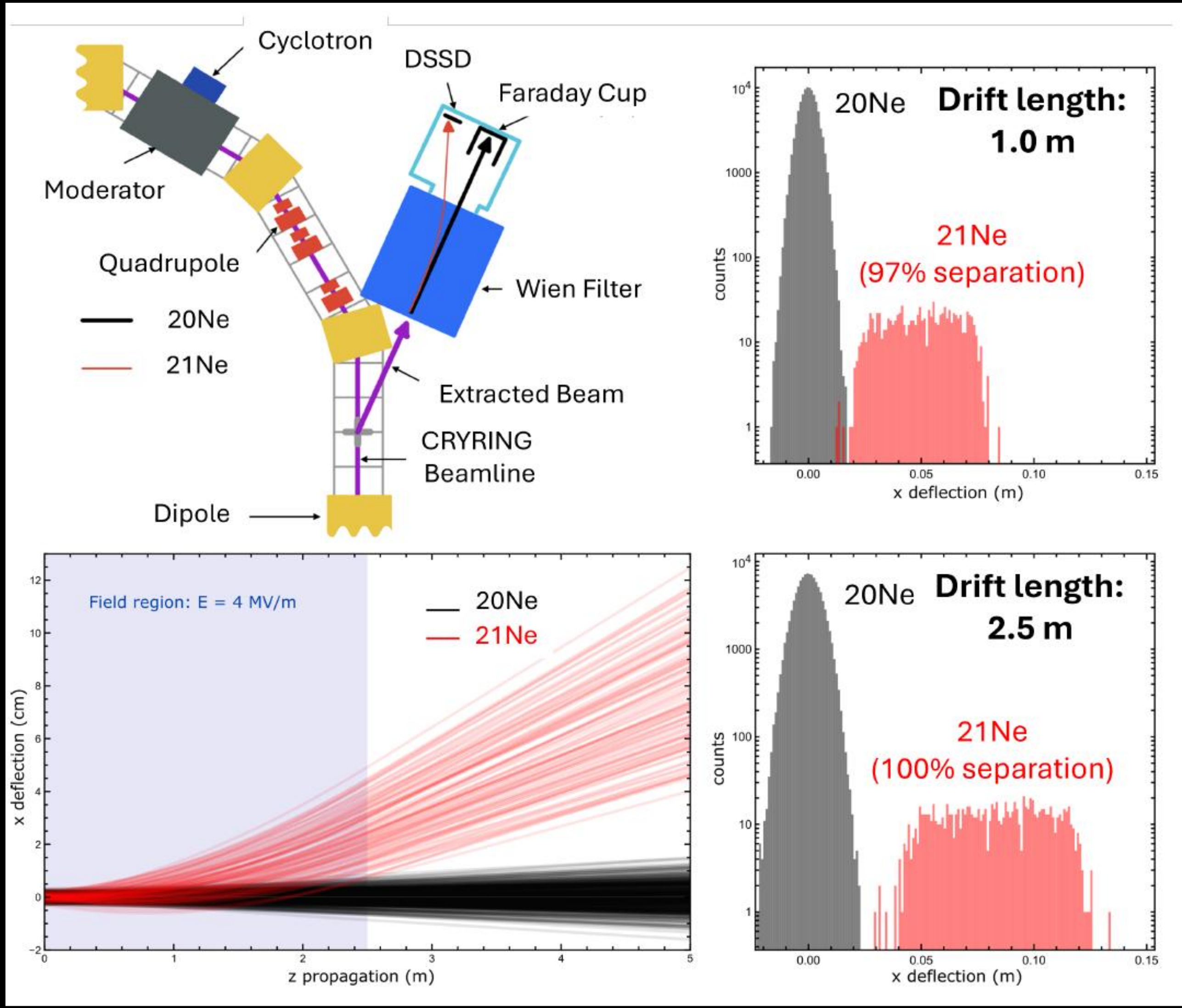
Extraction of beam and reaction product



- Beam and (n,γ) product *cannot* be distinguished inside ring (momentum conservation)
- But: Different velocities!
  → Extraction into ***Wien velocity filter***
  → Full separation achieved after ~2.5m drift length
- Detection via Faraday Cup (beam) and DSSD (Reaction products)

https://arxiv.org/pdf/2508.15465

Discovery, accelerated

Proof-of-Concept Experiments (First 6+y)

- Limitations: E_n>100 keV … 10 MeV
- Availability at CRYRING: Local ion source and RIB
- Beam intensities: need 10^8 - 10^9 ions stored
- (n,γ) and (n,2n): Wien filter *[Note: (n,2n) not astro focus!]*
- (n,p) and (n,α): Detection inside ring (particle detectors)

Validation experiments:

- Stable beam + (n,p)/(n,α)
- Stable beam + (n,γ)
- Long-lived radioactive beam (n,p)/(n,α)
- ^{81,85}Kr(n,γ) via fragmentation?

Beyond NSTAR: Future "dream" facility

Dream: No funding constraint, no space constraint

- New storage ring at ISOL facility (ISOLDE? TRIUMF? Other facility?)
- High-current cyclotron (100 μA → mA)? CANS? Spallation neutrons?
- Adapted Neutron moderator-reflector target
- Wien filter inside ring matrix → only n-capture reaction products extracted → detection in recoil separator → duty factor increase

Several orders of magnitude gain

Possible scaled areal neutron density: ~10^9 n/cm^2
→ Cross sections down to mb!

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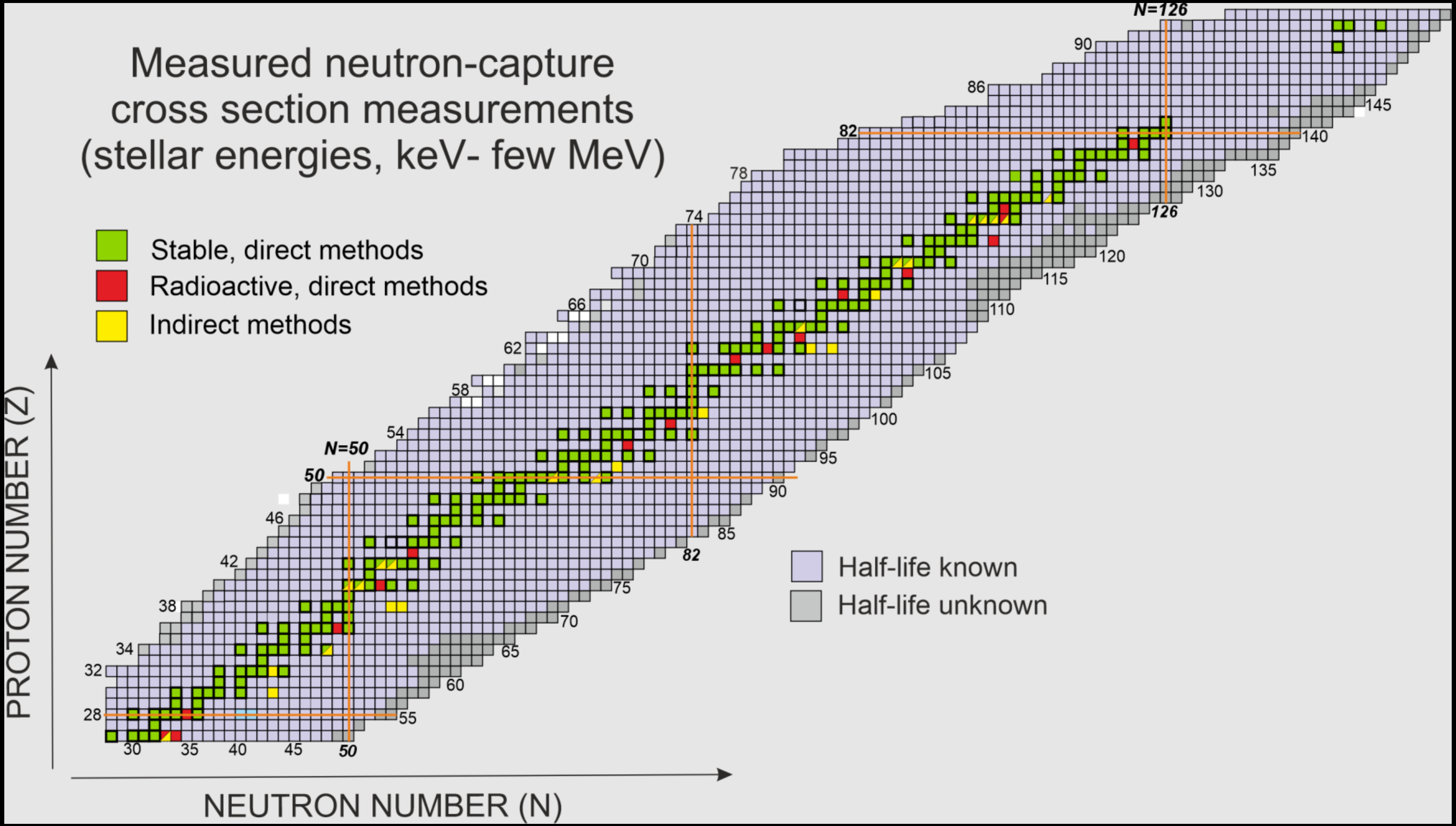
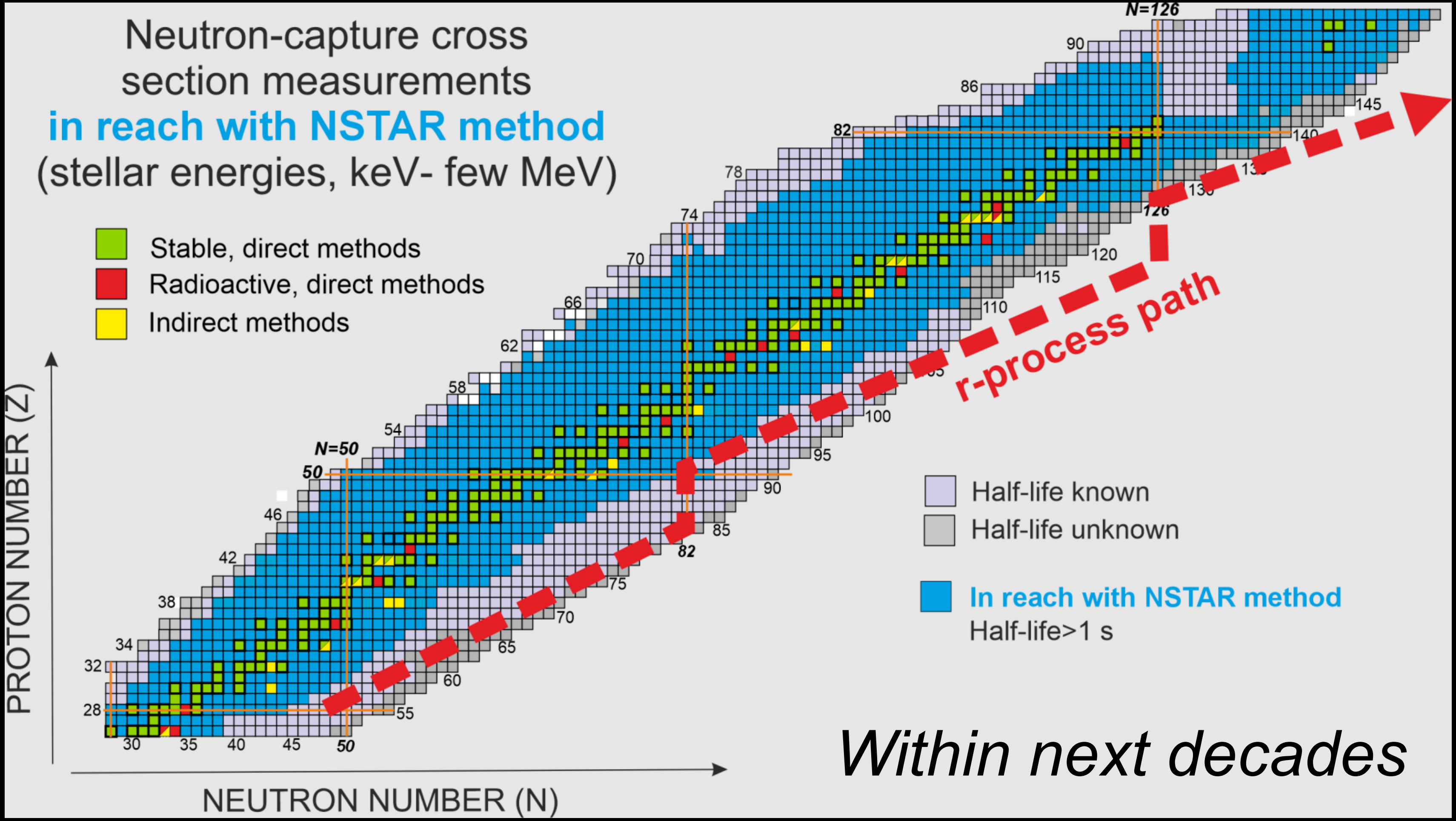
Status Quo



Discovery, accelerated

The NSTAR project: Future “dream” facility



TRIUMF

Thank You!
Merci!
hay č xʷ q̓ə!

www.triumf.ca
@TRIUMFLab

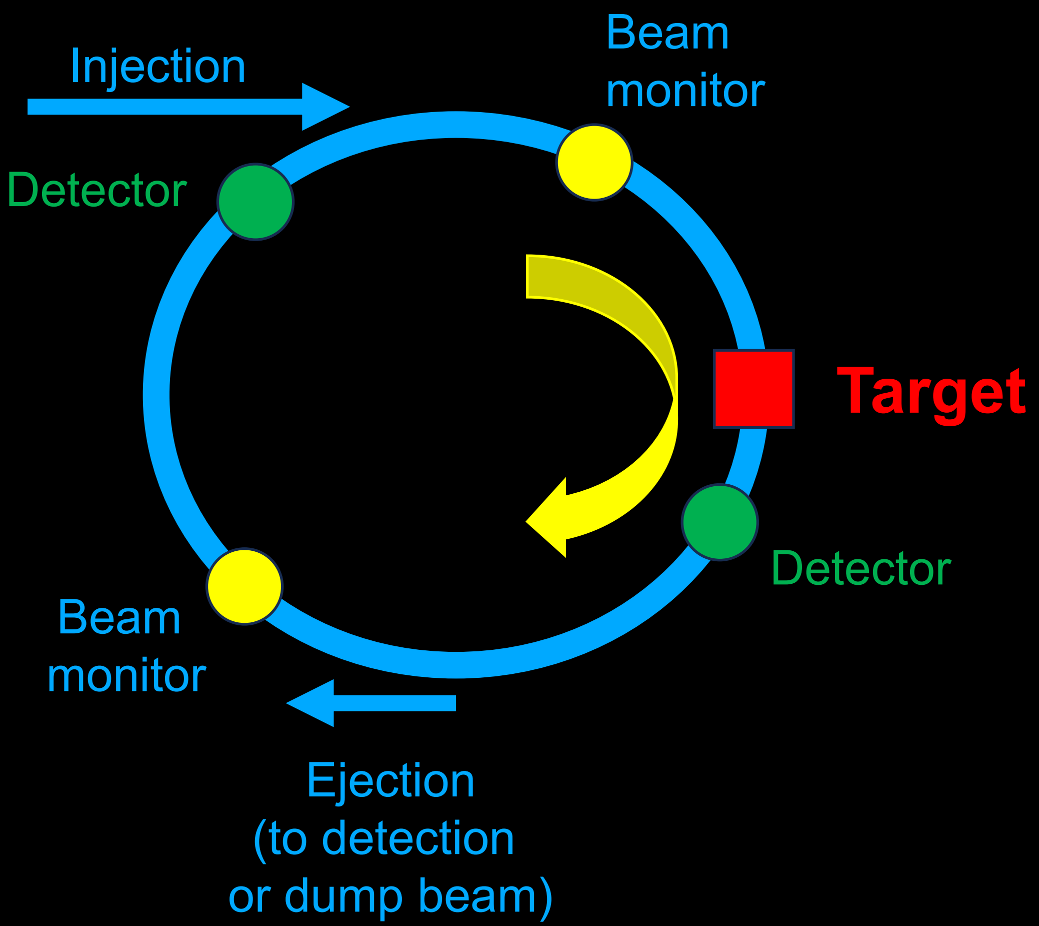
Phases in a storage ring

1. Injection of (radioactive) beam

2. Beam is orbiting and accumulated. Momentum spread can be reduced by cooling techniques

3. Beam orbit is changed to “interaction” orbit or target turned on (reactions)

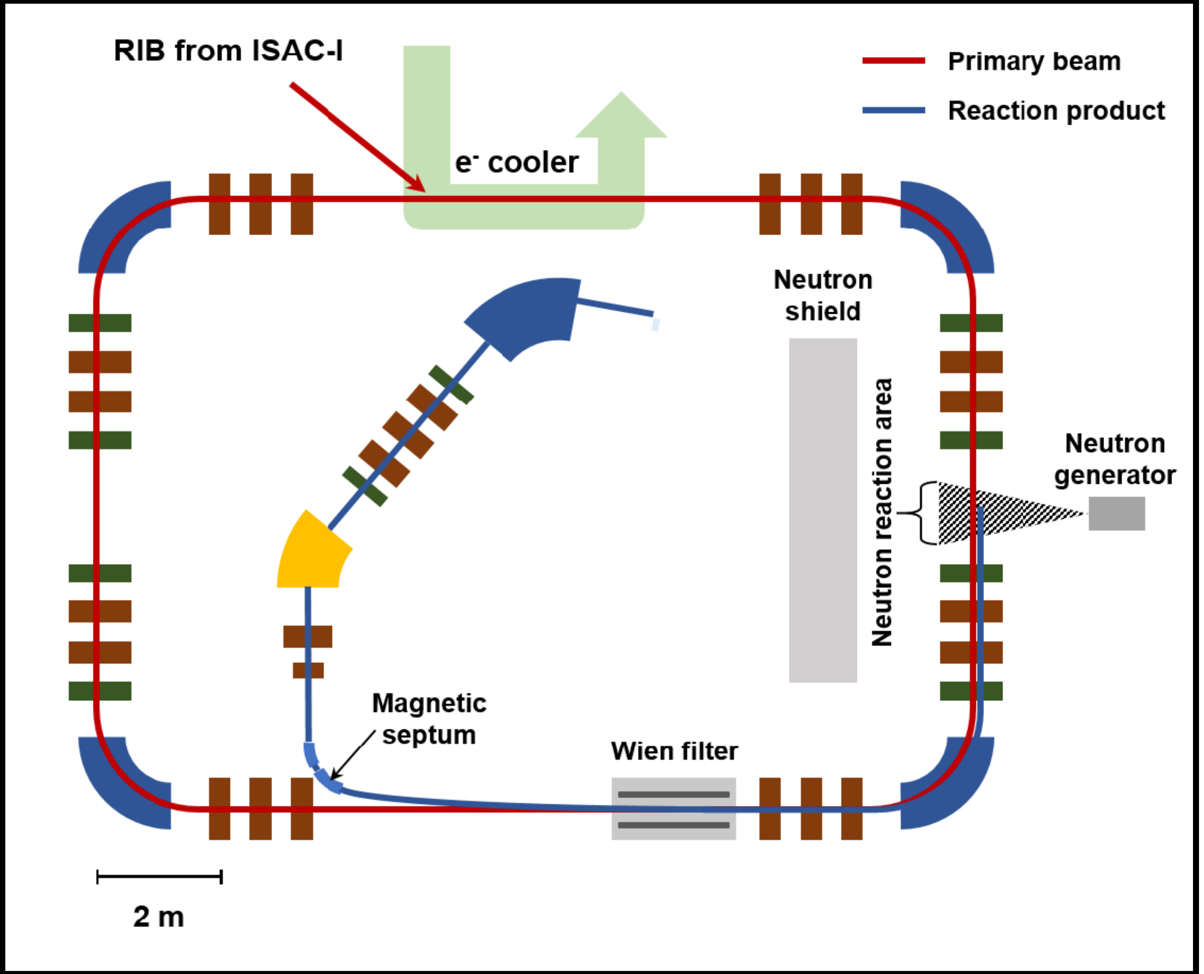
4. Detection of reaction products inside or outside of ring / Dump beam



How to separate beam and reaction products?

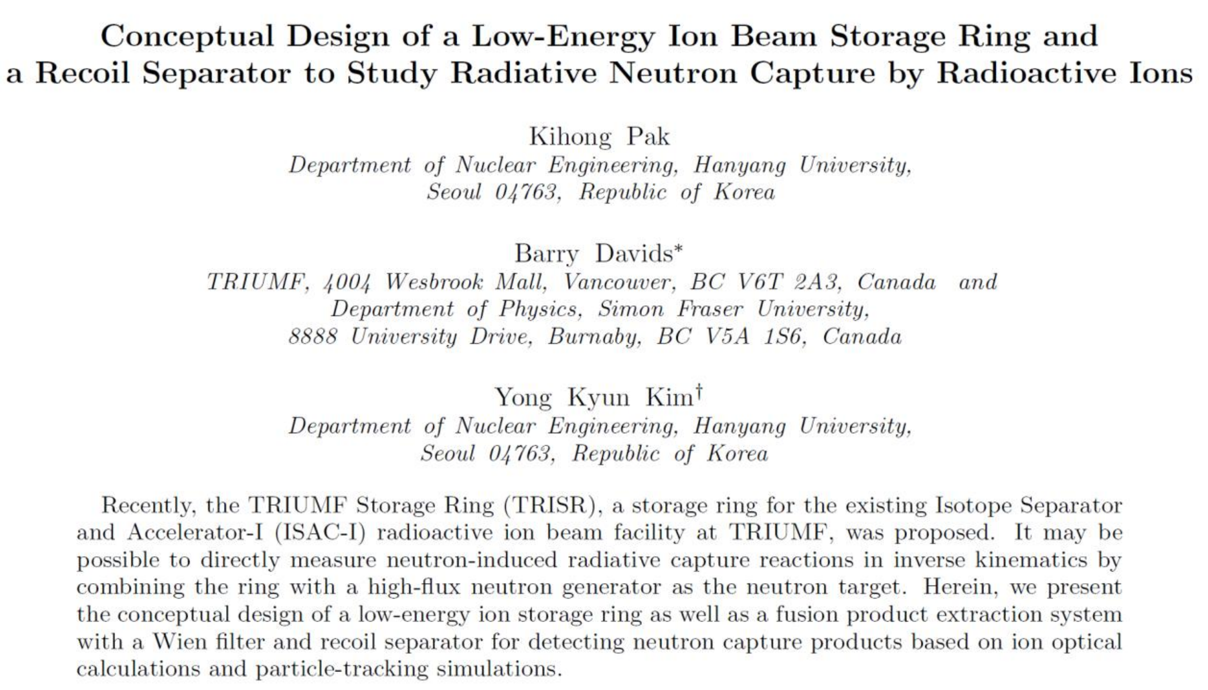
Cannot use dipoles + particle detectors for (n,γ) anymore like for (p,γ) reactions…

- Schottky pickups
  Problem: Sensitivity for E<500 keV/u
- **Wienfilter + Recoil Separator**
  Problem: Never done before



https://arxiv.org/pdf/2312.11859.pdf

Extraction of beam with a Wienfilter



Conceptual Design of a Low-Energy Ion Beam Storage Ring and a Recoil Separator to Study Radiative Neutron Capture by Radioactive Ions

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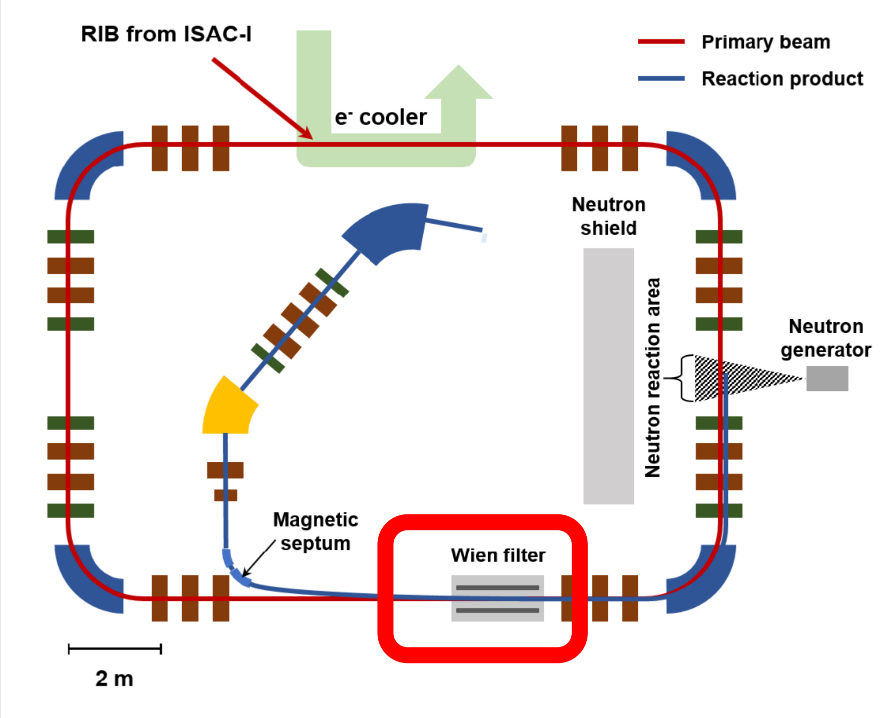
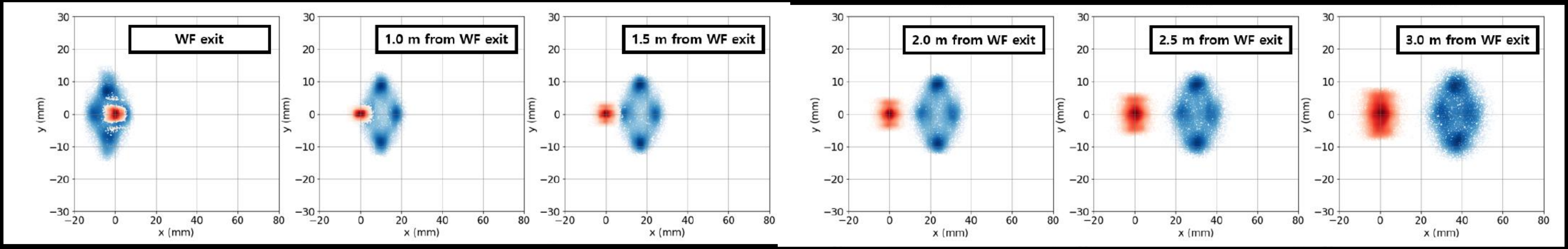
Recently, the TRIUMF Storage Ring (TRISR), a storage ring for the existing Isotope Separator and Accelerator-I (ISAC-I) radioactive ion beam facility at TRIUMF, was proposed. It may be possible to directly measure neutron-induced radiative capture reactions in inverse kinematics by combining the ring with a high-flux neutron generator as the neutron target. Herein, we present the conceptual design of a low-energy ion storage ring as well as a fusion product extraction system with a Wien filter and recoil separator for detecting neutron capture products based on ion optical calculations and particle-tracking simulations.



- Calculations done with COSY INFINITY
- Separate beam and reaction products with Wienfilter and magnetic septum - **never done before for a storage ring!**
- Extraction into recoil separator

https://arxiv.org/pdf/2312.11859.pdf

Extraction of beam with a Wienfilter: $^{80}Zn(n,\gamma)^{81}Zn$



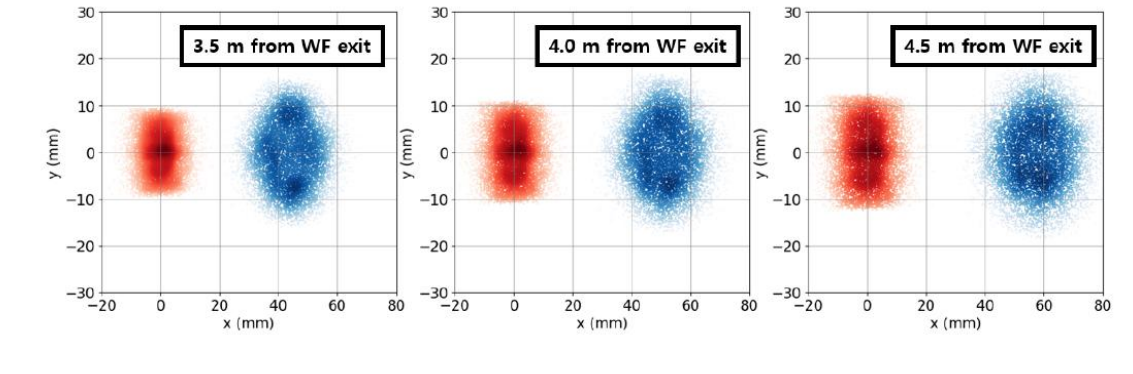


FIG. 5. Position distributions of the beam (red) and recoil (blue) ions after passing through the Wien filter at various downstream distances.

https://arxiv.org/pdf/2312.11859.pdf

- WF: E= 35 kV cm^{-1}, l= 2m, aperture 10 * 10 cm^2
- $^{80}Zn^{15+}$ at 150 keV/u,
- Transverse emittance: 0.2 π μm
- Assume 1 γ emitted after capture

→ ~40mm separation of $^{81}Zn^{15+}$ and $^{80}Zn^{15+}$ after 4m → magnetic septum

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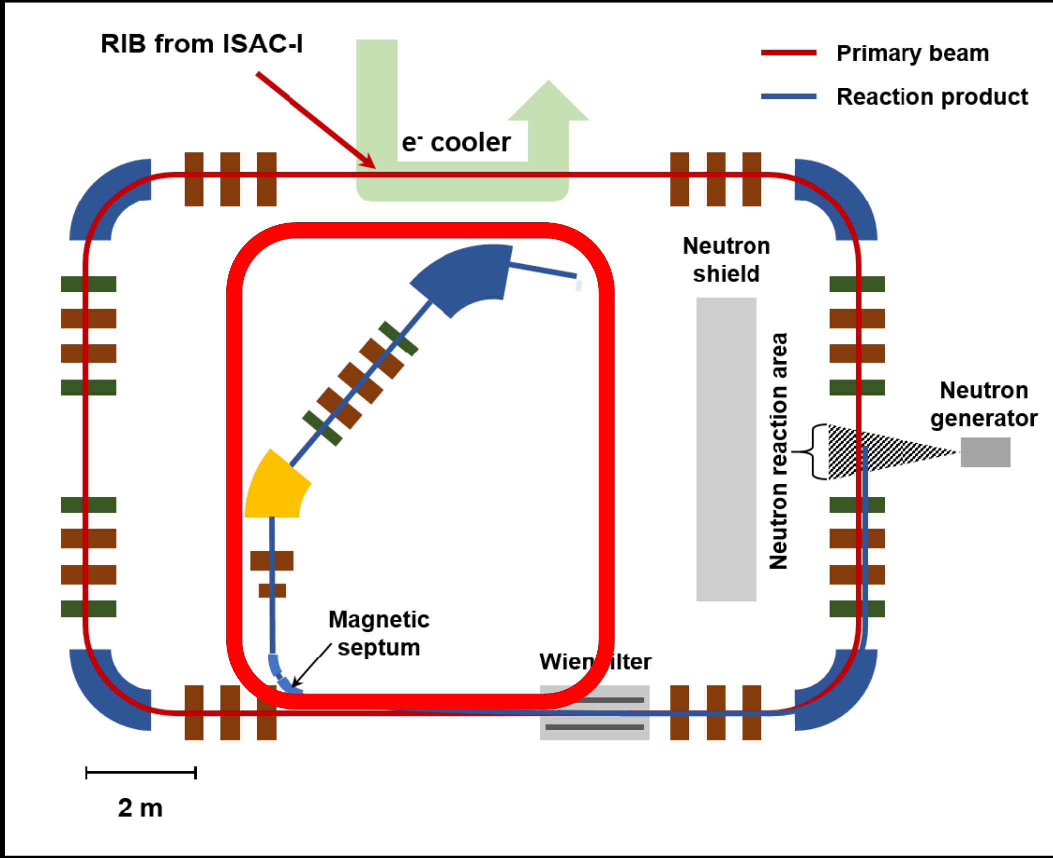
Conceptual recoil separator study



- Based on experiences and designs for DRAGON and EMMA
- 5Q, 2S, 40deg electrostatic deflector, 60deg magnetic dipole
- L= 11 m

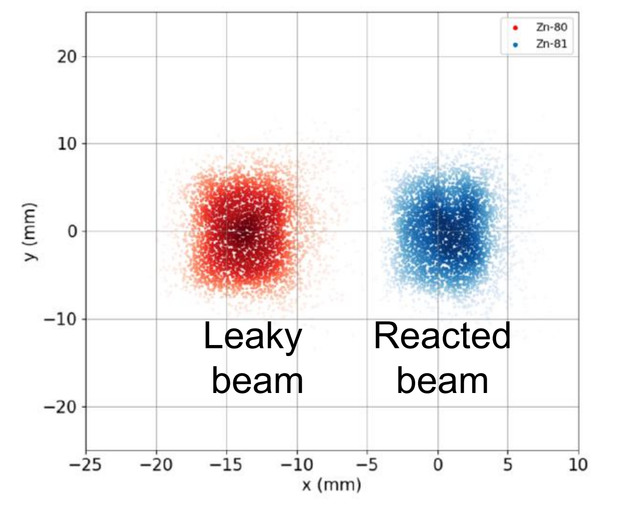


FIG. 10. Calculated position distributions of beam and recoil ions in the focal plane of the recoil separator.

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