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FRANZ and Small-Scale Accelerator-Driven Neutron Sources

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IPAC'15, Richmond, VA

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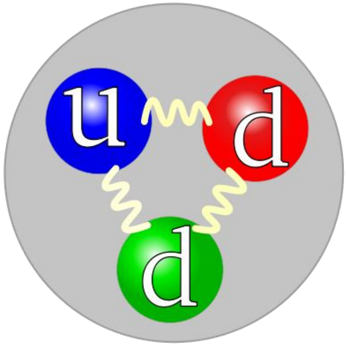
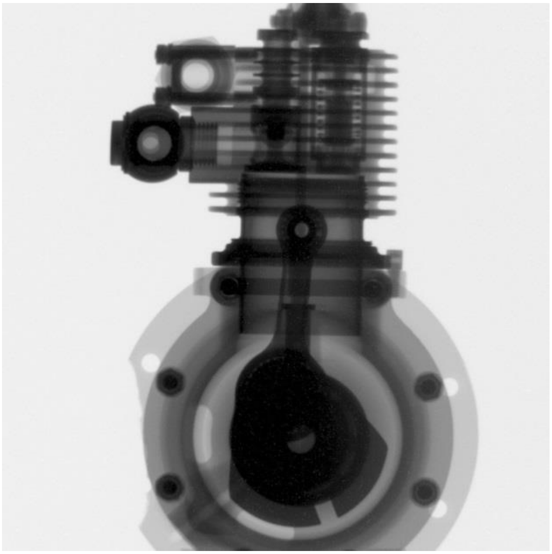
Outline

1) Introduction: Neutron Production
2) Small-Scale Accelerator-Driven Facilities
   - Concept & Opportunities
   - Challenges: High-Intensity Beam, High-Power Target, Time Structure
3) Frankfurt Neutron Source FRANZ
4) Conclusion

Introduction: Neutron Research

- Electrically neutral.
- Sensitivity for magnetic properties, different isotopes, light elements in particular.
- High penetration depth in material.
- Material Science.
- Neutron imaging.
- Understanding of neutron capture processes relevant for nuclear astrophysics.
- Cancer treatment (BNCT).



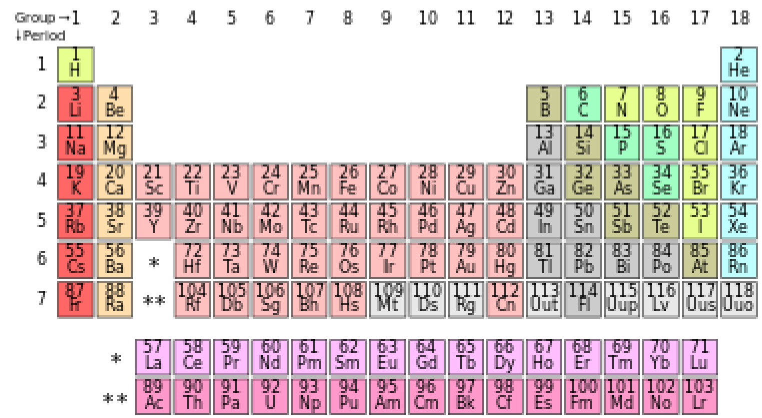


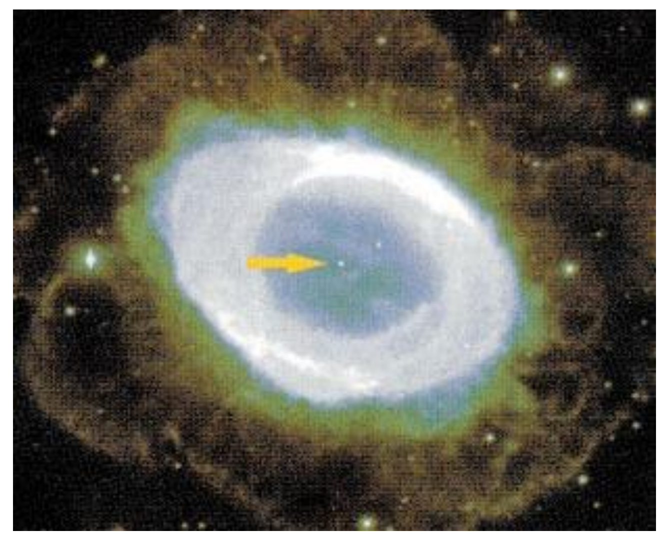
<http://nmi3.eu/news-and-media/neutron-imaging-past-present-and-future.html> rev. 2015-04-30

Introduction: Nuclear Astrophysics

Stellar nucleosynthesis:

- About 50% of the element abundances beyond iron are produced via the s-process.
- s-process takes place in AGB stars.
- Neutron temperature: k_BT = 8 keV to 90 keV [Reifarth et al., 2014].
- Modelling requires neutron capture cross-sections from 1 keV to 400 keV.
- Requires neutron sources with high flux in this energy region.

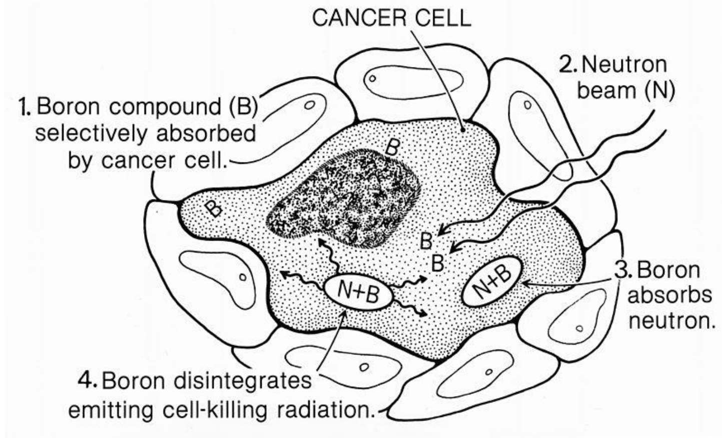




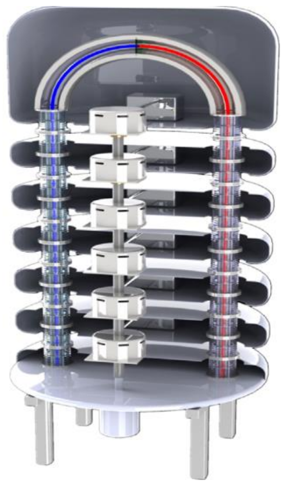
Picture: C. Arlandini et al., Nachr.,- FZK 33 2/2001,p. 178

Introduction: BNCT

- Boron Neutron Capture Therapy (BNCT): Boron-10 (which is selectively incorporated into tumor cells) captures n and decays into short-ranging α and ^{7}Li that destroy cancer cell.
- Currently, 8 initiatives to develop accelerator-based BNCT.
- Flux of $10^9 \frac{\text{n}}{\text{s}\cdot\text{cm}^2}$ required (high duty cycle).
- Epithermal neutrons: W_n = 0.5 eV to 10 keV



http://commons.wikimedia.org/wiki/File:Boron_neutron_capture_therapy_%28bnct%29_illustration.jpg



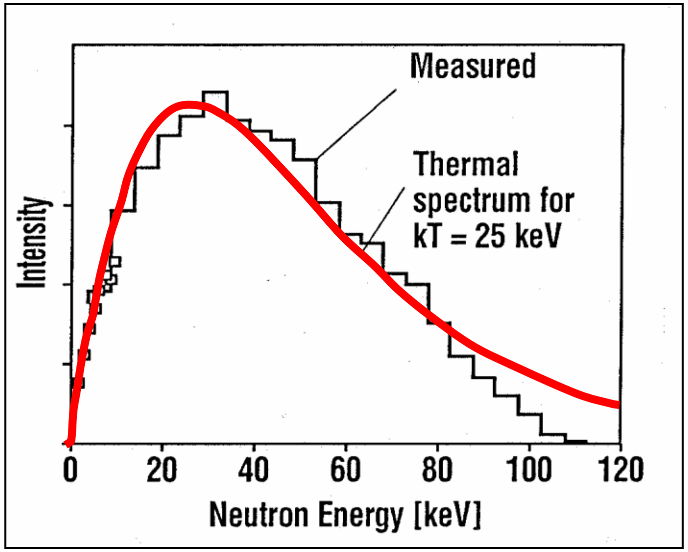
A. Kreiner et al., Applied Radiation and Isotopes 88, 185–189 (2014).

Small-Scale Accelerator-Driven Facilities

- Neutrons produced via nuclear reactions using light-ion beams:
  - ^{7}Li(p,n)^{7}Be (threshold: 1.88 MeV; highest n yield, 1 keV..500 keV neutrons, Li difficult to handle)
  - ^{9}Be(p,n)^{9}B (threshold: 2.06 MeV; lower n yield, MeV neutrons)
  - ^{9}Be(d,n)^{10}B (no threshold, lower n yield, MeV neutrons).
- Neutron yield: $10^{11}..10^{12}$ n/mA/s
- Accelerator: p, d with $W_b \approx$ 2 MeV..13 MeV
- Small-scale facilities (cost-efficient, affordable for hospital/university)

See C.-K. Loong at al., Physics Procedia 60, 264-270 (2014)

$^7\mathrm{Li(p,n)}^7\mathrm{Be}$ spectrum



Beer et al., Nachrichten - FZK, 33, 189–200 (2/2001).

W_b = 1.912 MeV

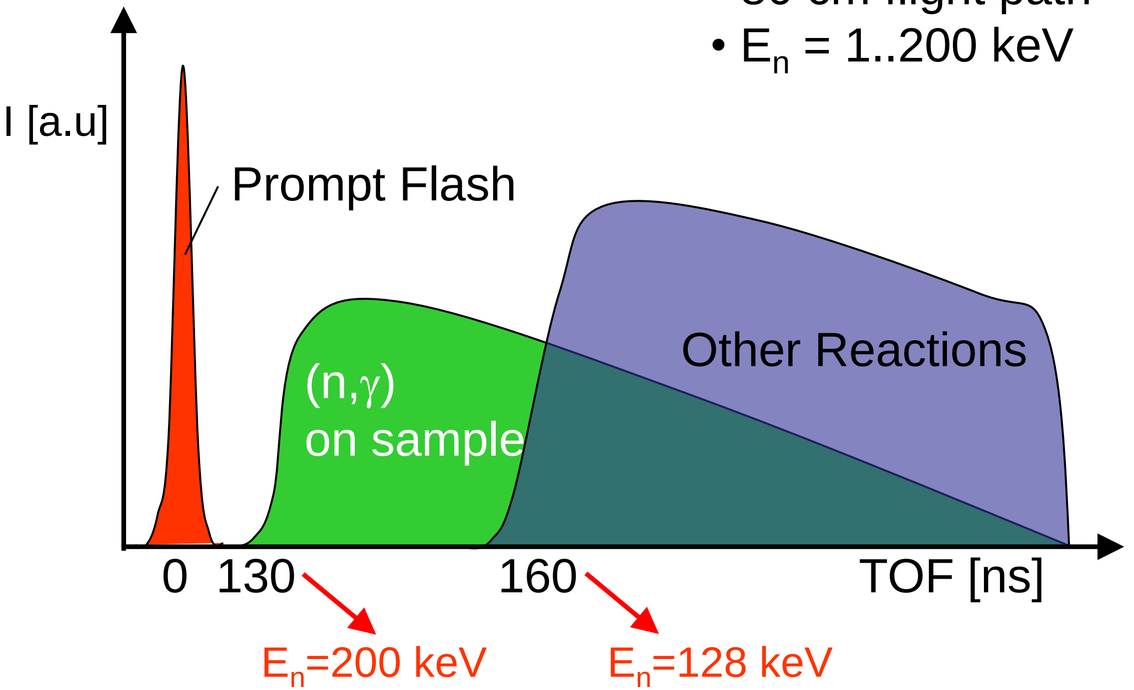
Refined concepts:
- R. Reifarth et al., J. Phys. G: Nucl. Part. Phys. 41, 053101 (2014).
- P. Mastinu et al., NIM A 601 (2009) 333–338

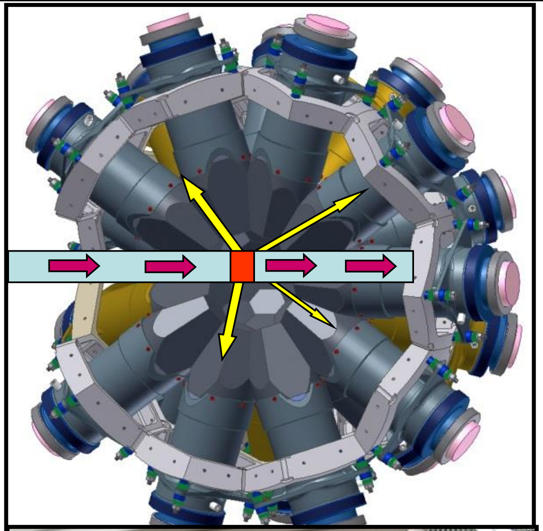
Time-of-Flight (TOF) Method

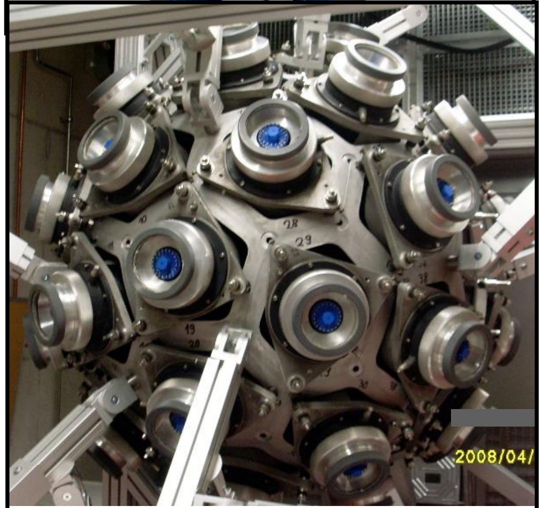
- TOF method allows to measure the neutron capture cross-sections as a function of the neutron energy.
- Pulsed primary beam required.
- Adequate neutron spectrum assures low background.

© R. Reifarth

- 80 cm flight path
- E_n = 1..200 keV







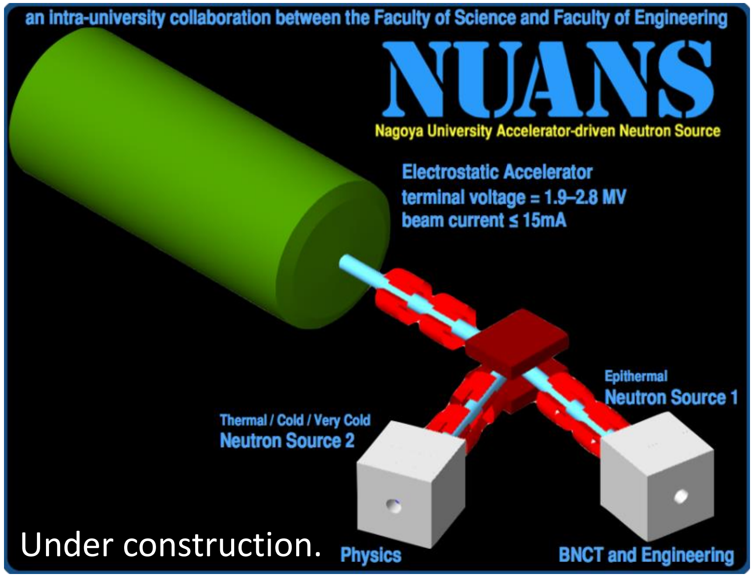
4π BaF_2 detector at Frankfurt.

Challenges: High Intensity

Compact, cost-efficient, reliable facilities – with high primary beam intensity (I_b > 10 mA), high-power target and flexible time structure.

a) Electrostatic Accelerators

NUANS, Nagoya Univ., Japan:
Dynamitron, p, 2.8 MeV, 15 mA

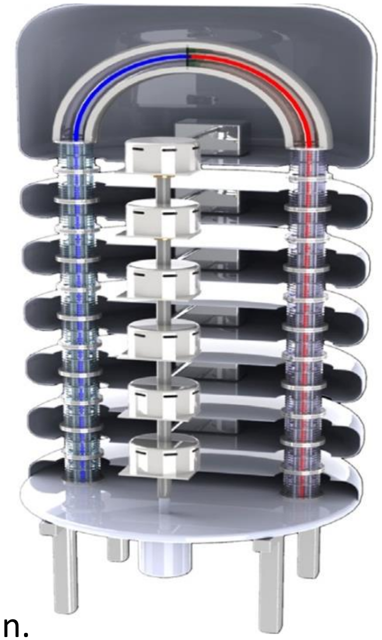


JCANS, <http://phi.phys.nagoya-u.ac.jp/JCANS/index.html>, rev. 2015-04-24

Katsuya Hirota, IPAC'15, WEPWA019

TESQ, Buenos Aires, Argentina:
p, 2.8 MeV, 30 mA

Tandem Electrostatic Quadrupole for BNCT.



Under Construction.

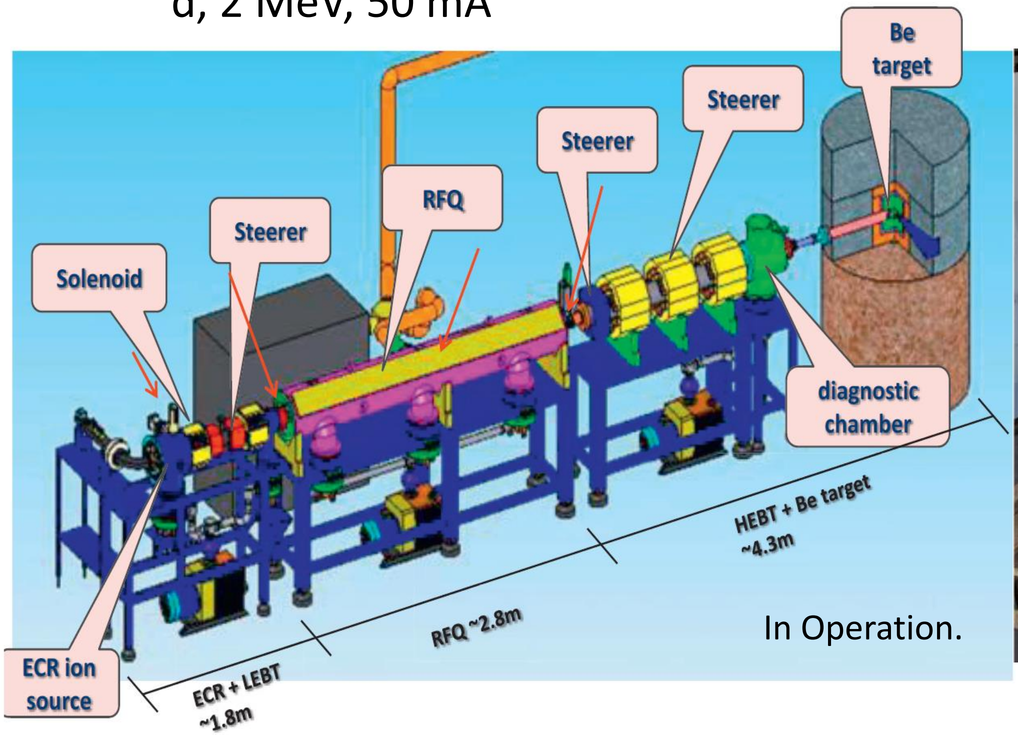
A. Kreiner et al., Applied Radiation and Isotopes 88, 185–189 (2014).

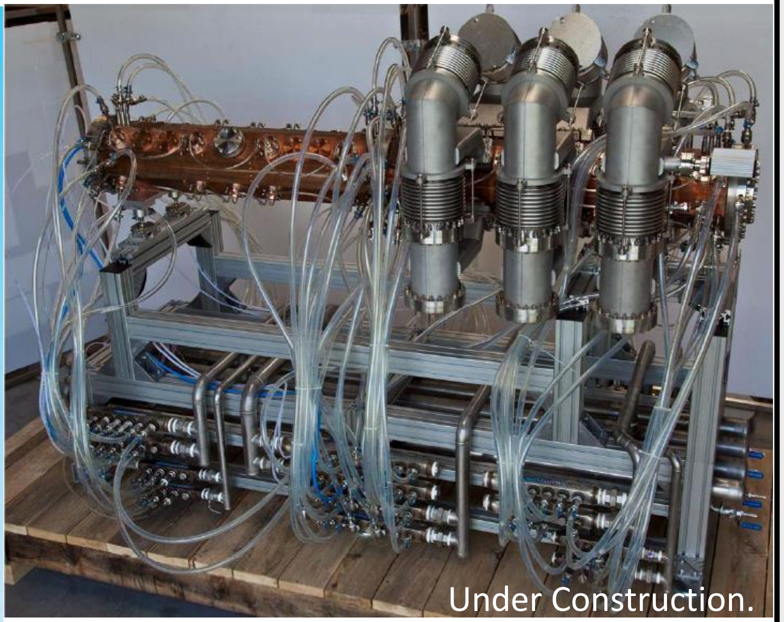
High Intensity

b) RFQ

PKUNIFTY, Peking Univ., China:
d, 2 MeV, 50 mA

LENOS, LNL, Legnaro, Italy:
p, 5 MeV, 50 mA





E. Fagotti , Talk, UCANS II (2011),

4-rod RFQ: 201.5 MHz,
1%..10% duty cycle, Be target

4-vane RFQ: 352.2 MHz,
CW, 7.1 m long, Be target

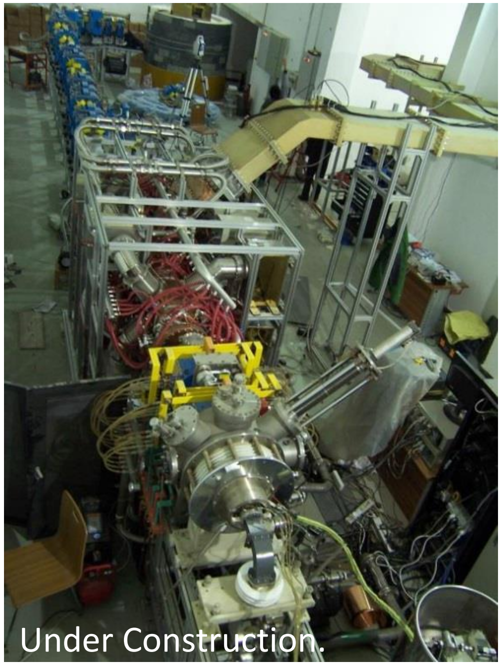
Y. Lu, Physics Procedia 60, 212–219 (2014).

P. Mastinu et al., Physics Procedia 26, 261–273 (2012)

High Intensity

c) RFQ + DTL

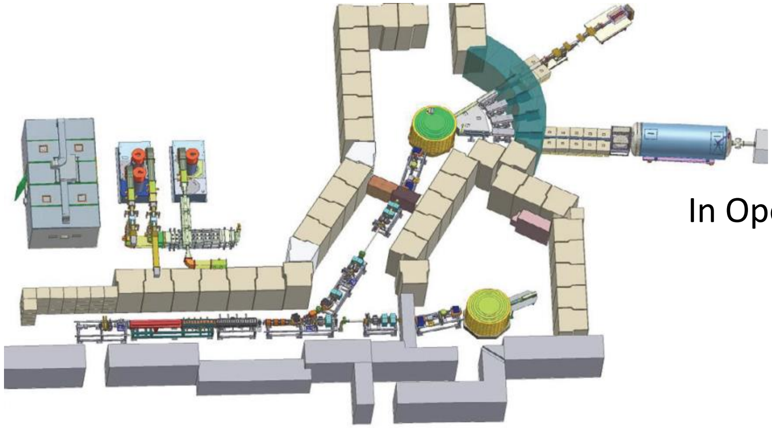
CPHS, Tsinghua Univ., China:
p, 50 mA



3 MeV RFQ, 13 MeV DTL,
2.5% duty factor, W_b = 16 kW,
Be target

X.Wang et al., Physics Procedia 60, 186–192 (2014).

LENS, Indiana Univ., USA: p, 13 MeV, 25 mA.



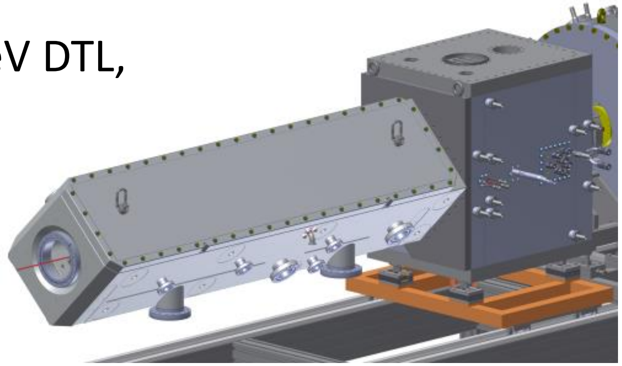
In Operation.

T. Rinckel et al., Physics Procedia 26, 161–167 (2012).

1.8% duty factor, W_b = 6 kW, Be target

FRANZ, Frankfurt Univ., Germany: p, 2 MeV, 50 mA.

700 keV RFQ, 2 MeV DTL,
2.4 m total length,
CW, Li target



Under Construction.

High-Power Targets

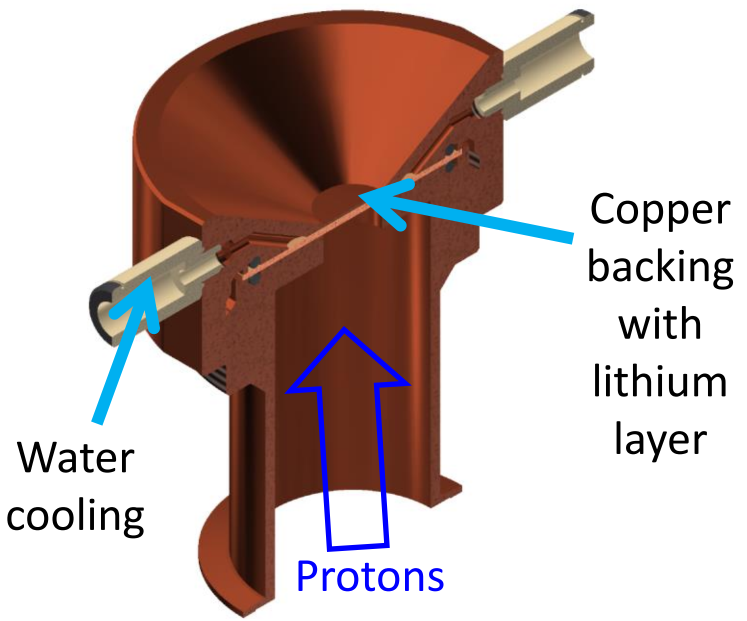
Examples:
Lithium-Targets

- 4 kW, 14 mm beam → 2.6 kW/cm^2 → > 100 kW/cm^3.
- Lithium melting point ≈ 180°C.

FRANZ: solid lithium layer

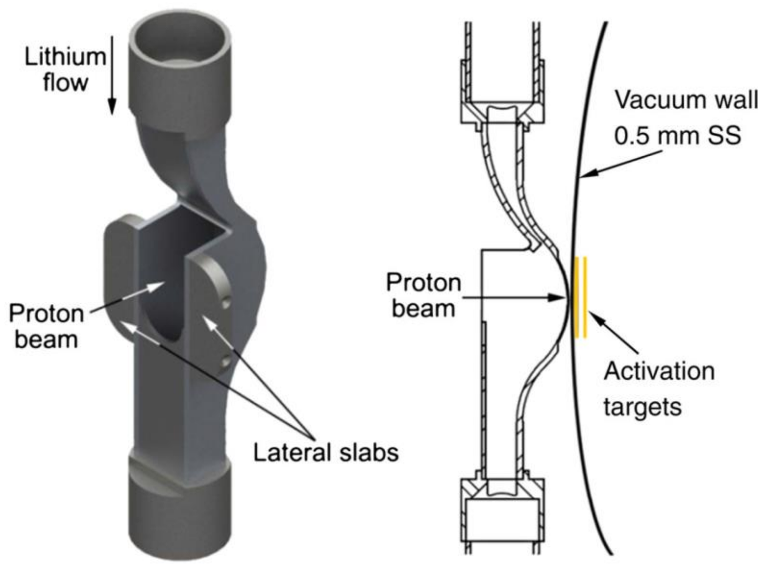
SARAF: liquid lithium target (windowless setup)

Designed for 4 kW (14 mm beam size).



S. Schmidt, Ph.D. thesis, Univ. Frankfurt (2014).

Successfully commissioned with W_b = 2.3 kW.

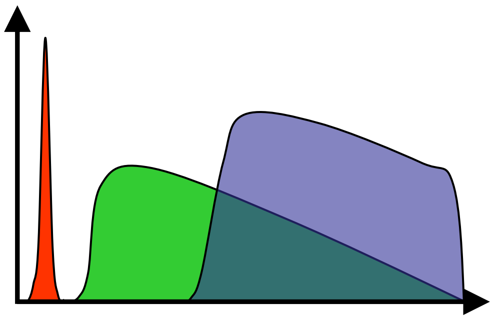


M. Paul et al., J. Radioanal. Nucl. Chem., 12.03.2015.

Option: Liquid Metal cooling → P. Mastinu et al., Physics Procedia 26, 261–273 (2012).

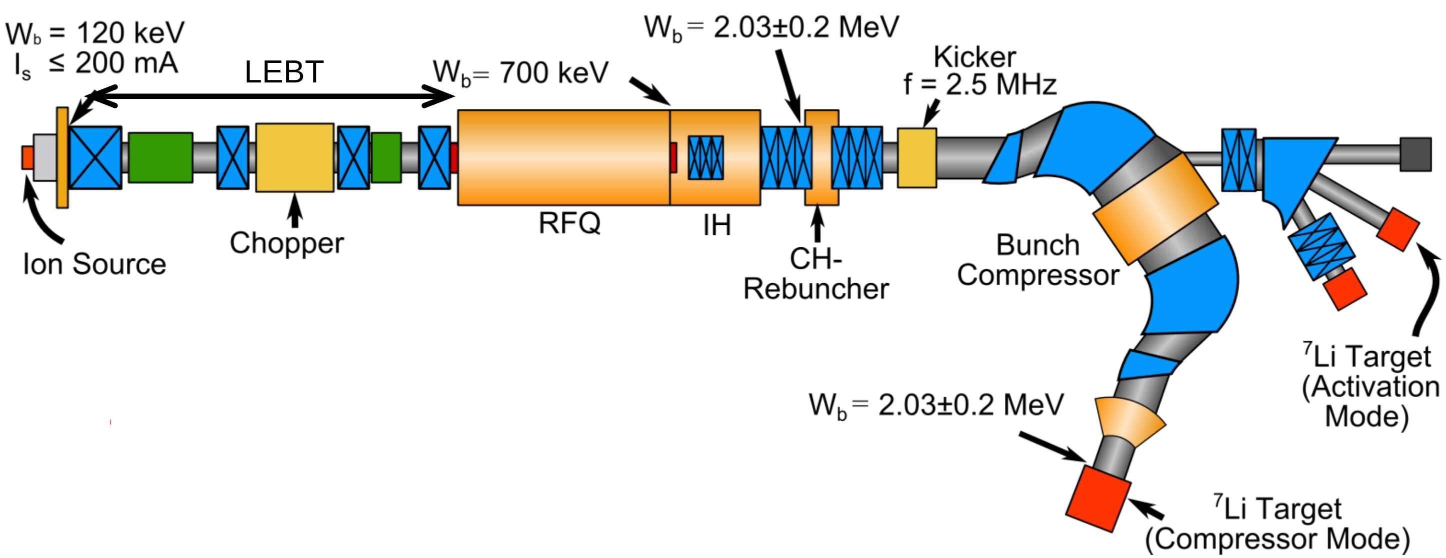
Flexible Time Structures

- CW (or high duty cycle): high average flux (activation measurements, BNCT). Can lead to challenging cooling scenarios.
- Short pulses: allow TOF, pulsed neutron imaging.



- Special case (FRANZ): short pulses (high peak intensity) with repetition rate so high that ion source and RFQ-DTL have to be operated in DC/CW.

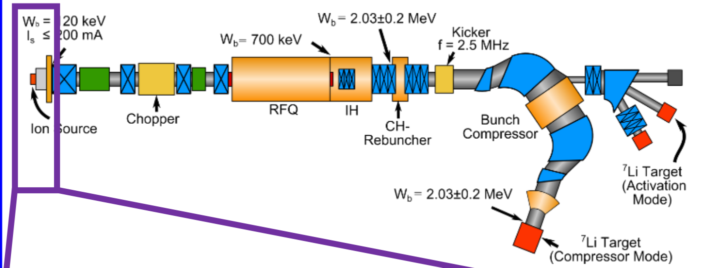
Frankfurt Neutron Source FRANZ



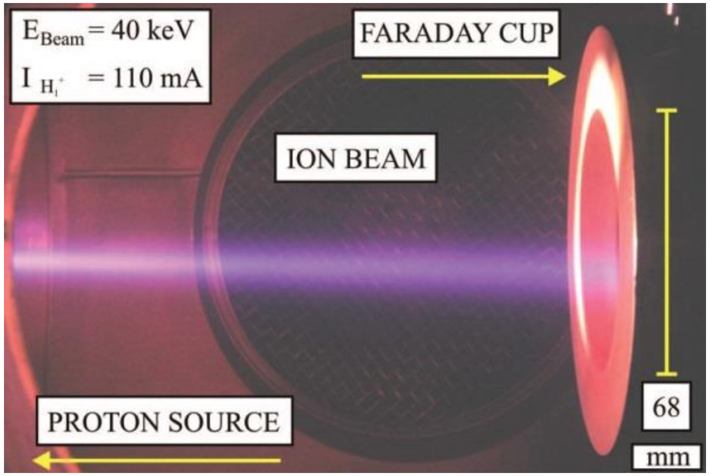
Activation Mode	high average neutron flux	measurement of the *integrated* n-capture cross sections	p, 2 MeV	2 mA	cw operation
Compressor Mode	**high (peak) neutron flux**	***energy-dependent* measurements of n-capture cross sections (using TOF)**	**p, 2 MeV**	**50 mA**	**1 ns, 250 kHz (at the target)**

Frankfurt Neutron Source FRANZ

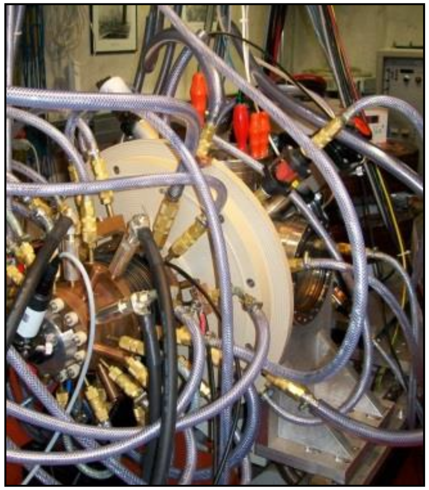
Frankfurt Neutron Source FRANZ

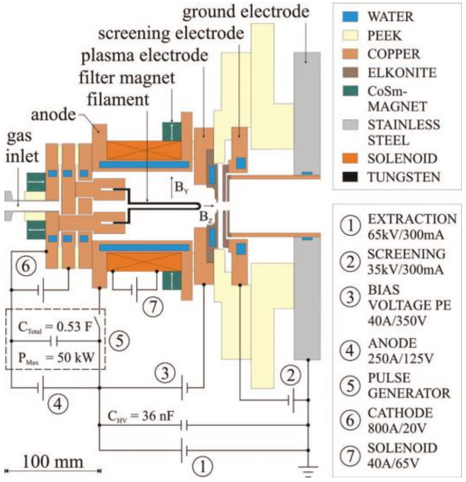


High-Current Ion Source

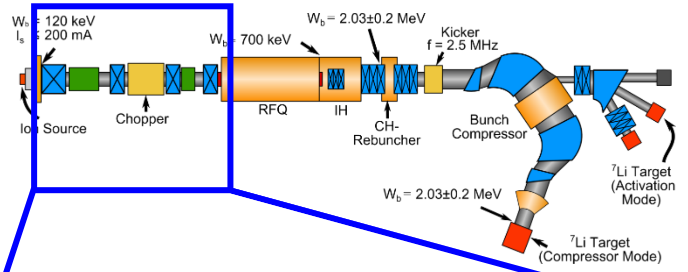


- Arc-discharge driven ion source.
- Proton current: 50 mA (240 mA).
- Current density: 480 mA/cm^2.
- DC operation.
- Proton fraction > 90 %.
- $\varepsilon_{rms,\ norm}$ < 0.08 mm· mrad.
- Beam energy: 120 keV.



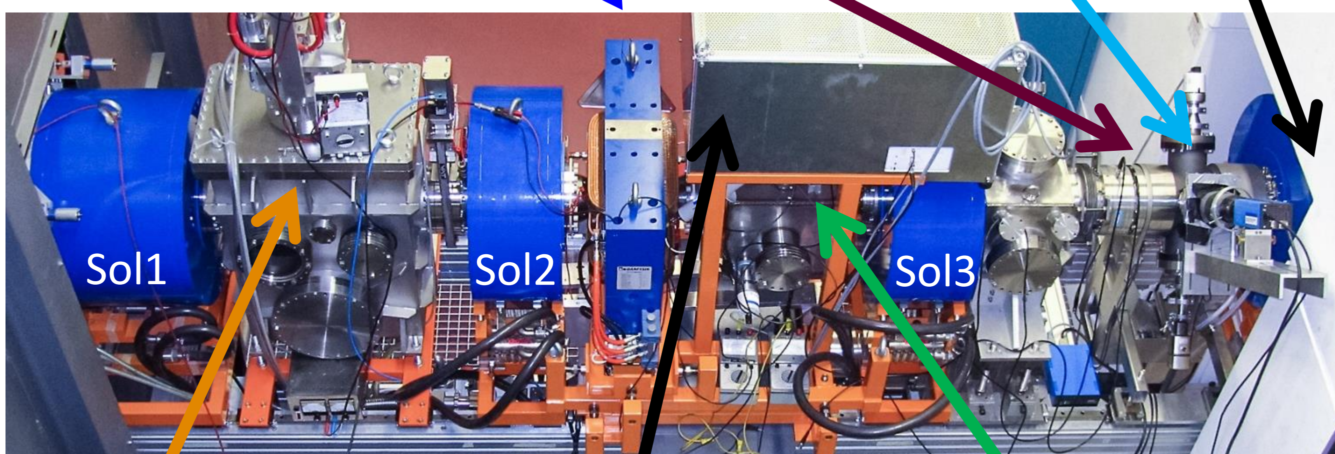


Frankfurt Neutron Source FRANZ



Low Energy Beam Transport (LEBT) Section

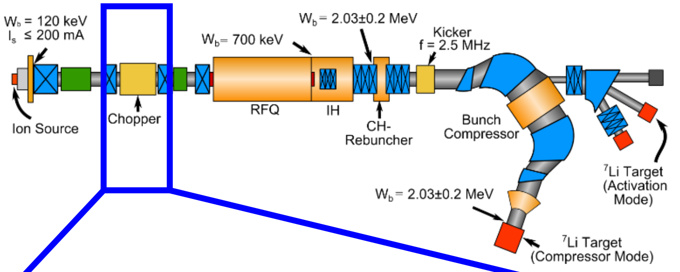
- 4 Solenoids.
- Chopper.
- SC comp. (Sec. 1).
- No SC comp. (Sec. 2, pulsed).
- Installed and commissioned with 14 keV He^+ beam.



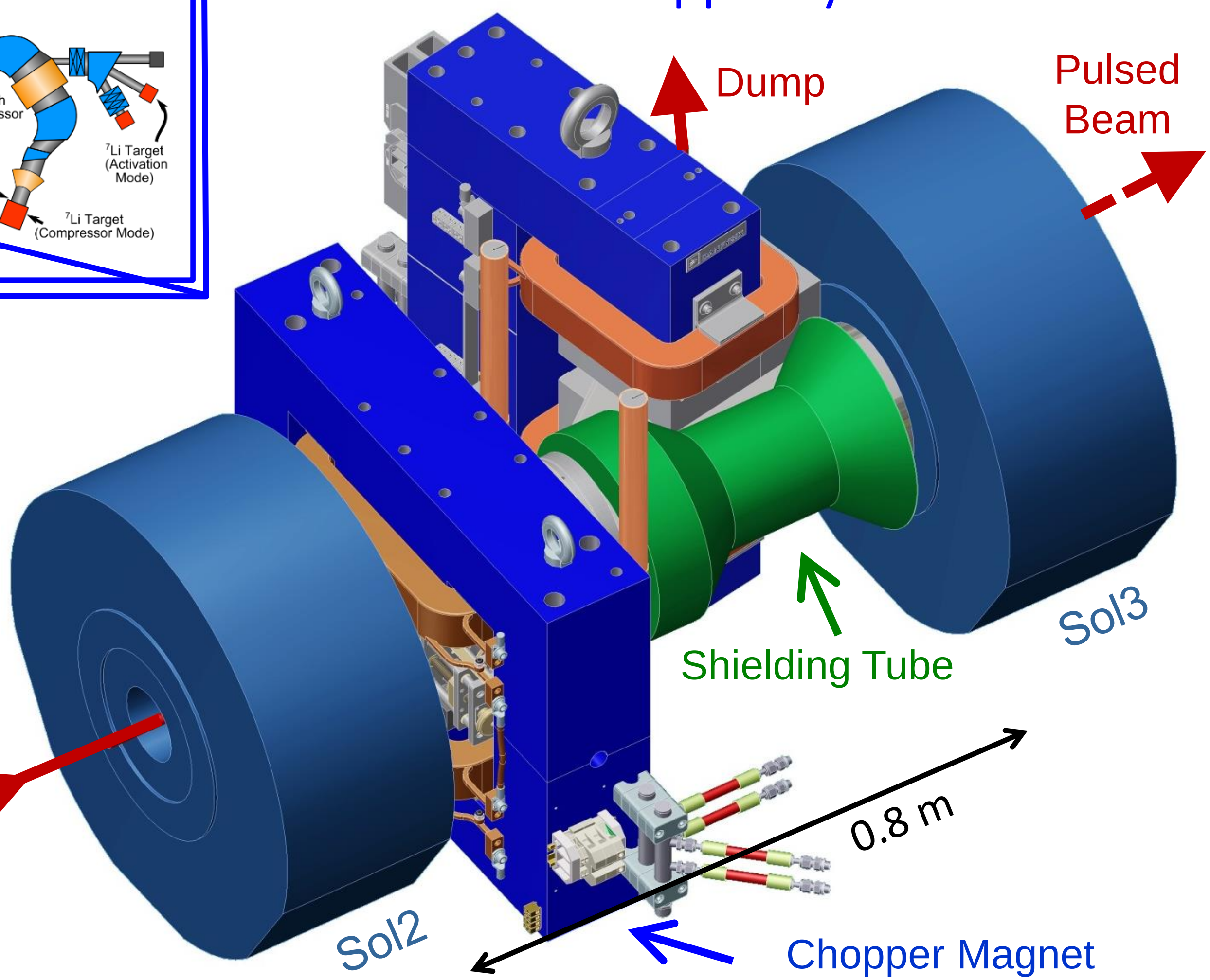
P. Schneider, IPAC'15, THPF024.

Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ



E×B Chopper System

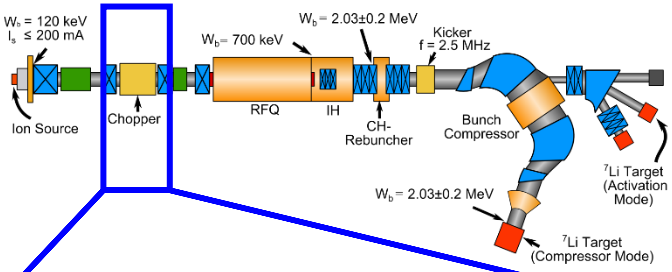


Chopping parameters

- p, 50 mA, 120 keV.
- Pulse length: 50 ns..350 ns.
- Rep. rate: 250 kHz.

Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ

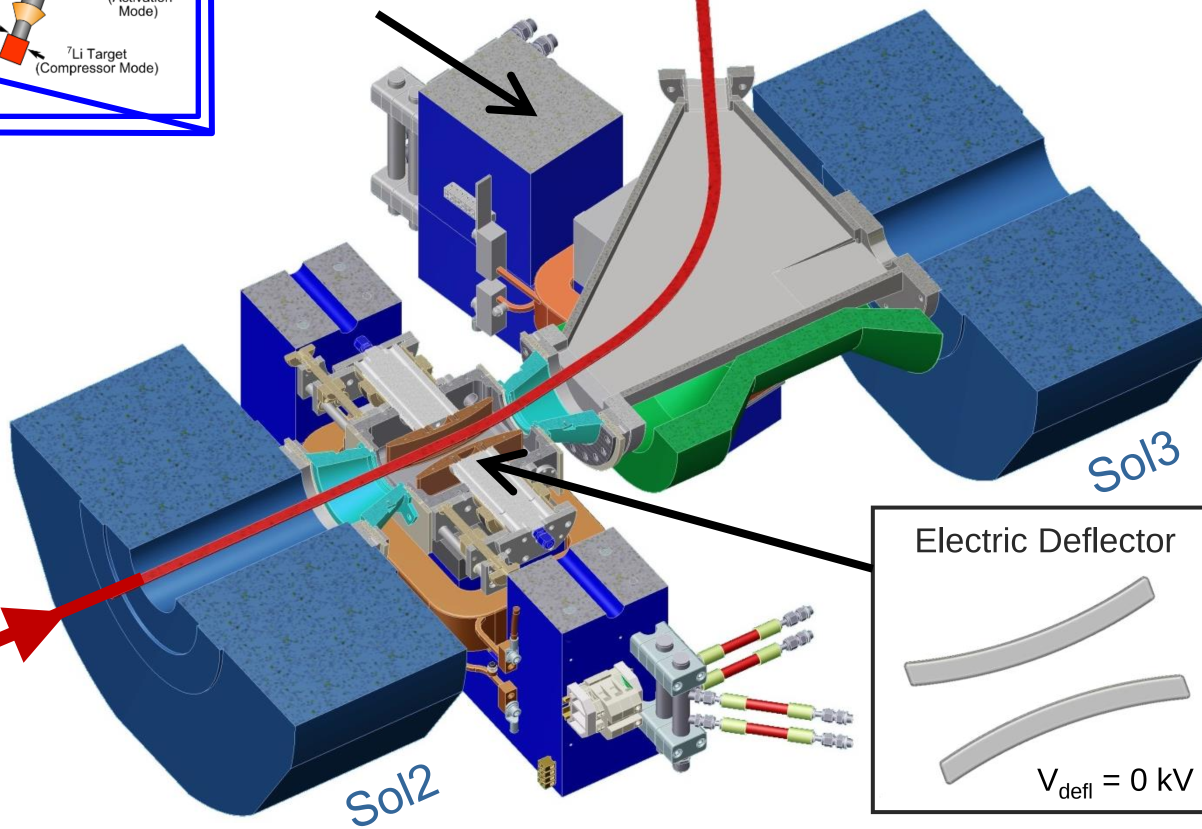


Chopping parameters

- p, 50 mA, 120 keV.
- Pulse length: 50 ns..350 ns.
- Rep. rate: 250 kHz.

E×B Chopper System

Beam-Separation:
O. Payir, IPAC'15, THPF023



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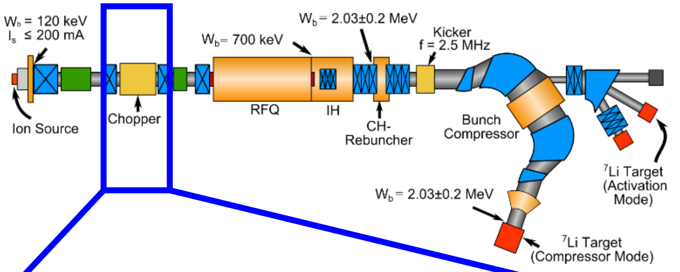
Frankfurt Neutron Source FRANZ



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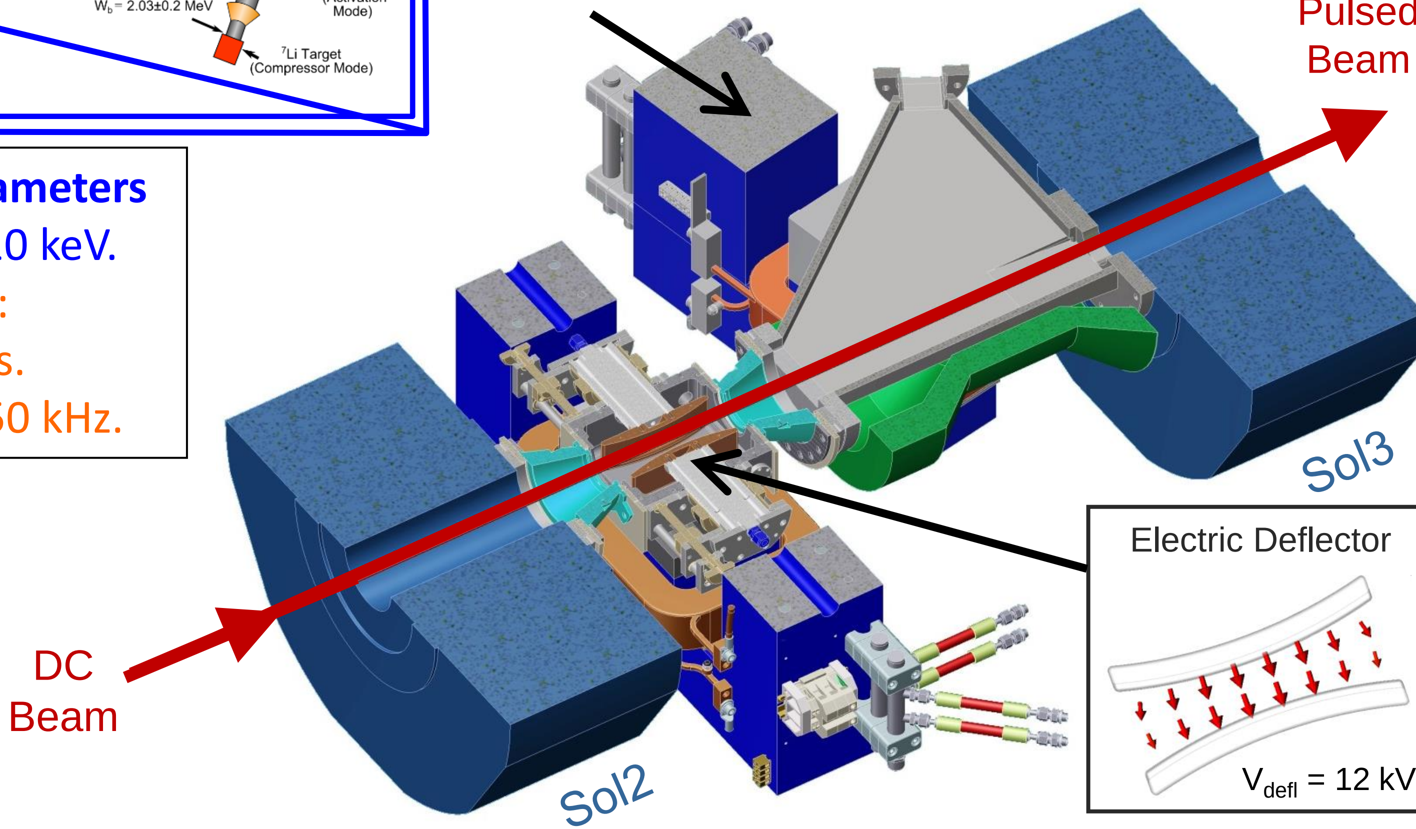
E×B Chopper System

Beam-Separation:
O. Payir, IPAC'15, THPF023

$$\int (\vec{F}_{\mathrm{elec}} + \vec{F}_{\mathrm{mag}})\ \mathrm{d}z \stackrel{!}{=} 0$$



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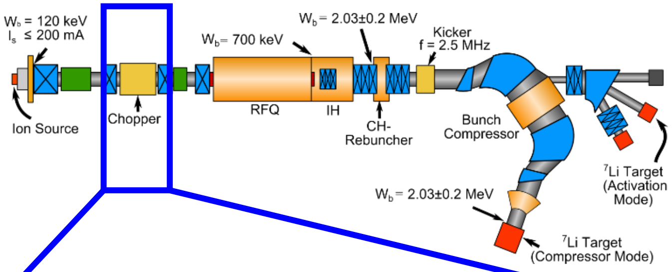
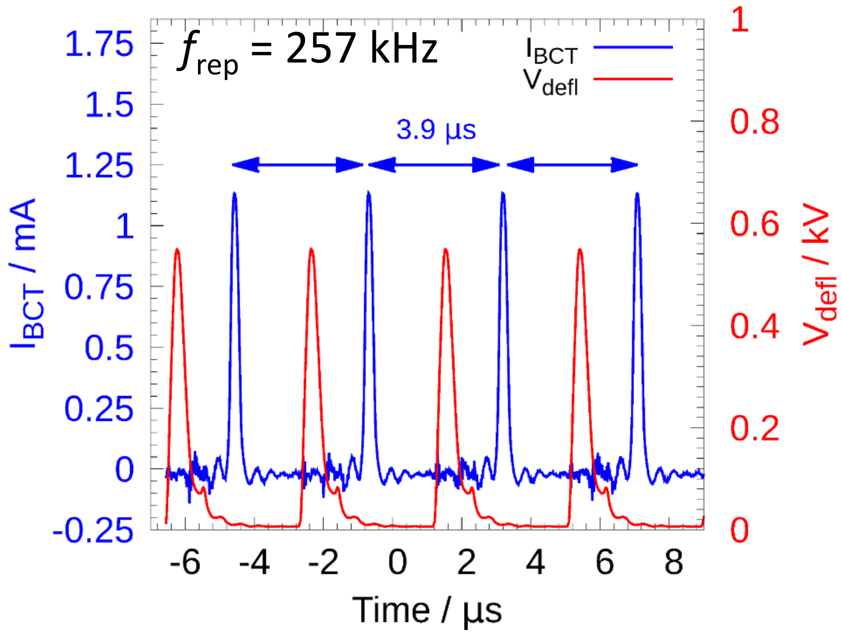
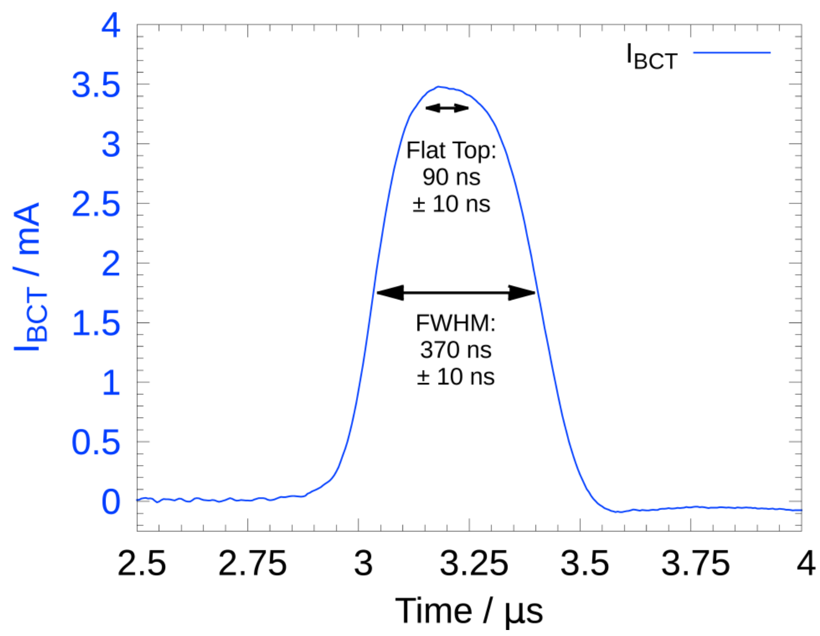


E×B Chopper System

Beam Pulse Measurements,
He^+, 14 keV
$r_{aperture}$ = 50 mm
I_{dipole} = 40.0 A





Frankfurt Neutron Source FRANZ

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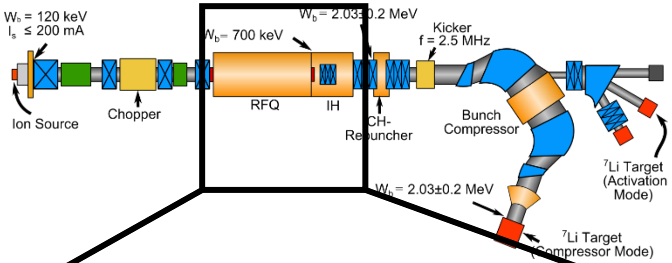
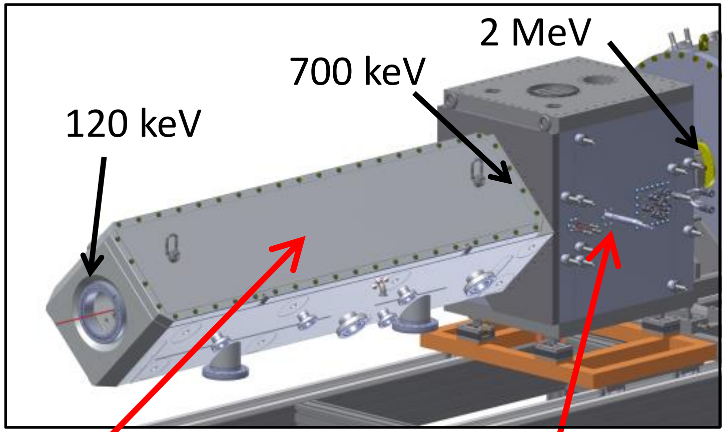


2 MeV Linac Section

- Total length: 2.4 m.
- f_{rf} = 175 MHz.
- 4-rod RFQ manufactured. Awaiting delivery.
- IH cavity to be copper plated.
- Coupling allows operation with single power amplifier.
- CW operated.
- Thermal losses.

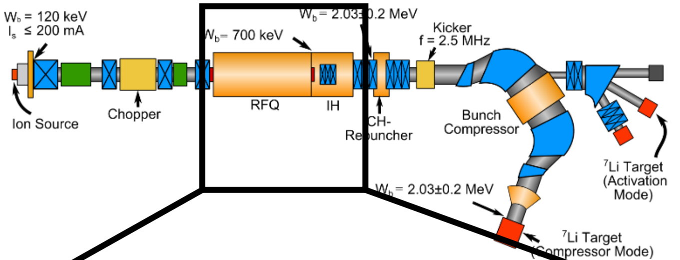


H. Podlech, A. Schempp

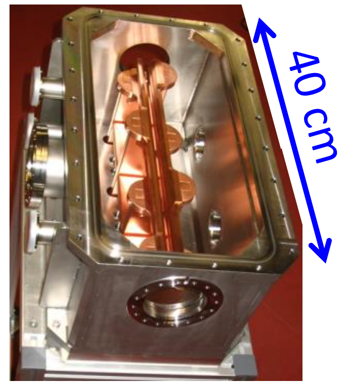
M. Heilmann, U. Ratzinger

Frankfurt Neutron Source FRANZ

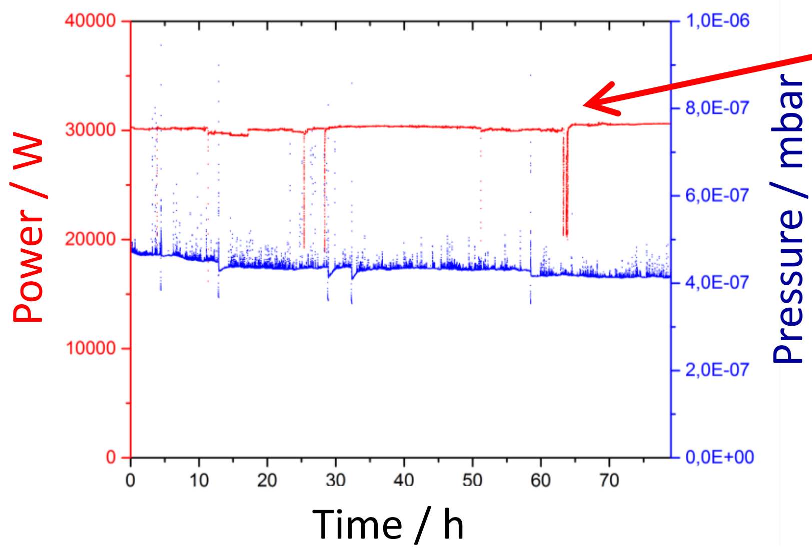
Frankfurt Neutron Source FRANZ



RFQ Prototype Module

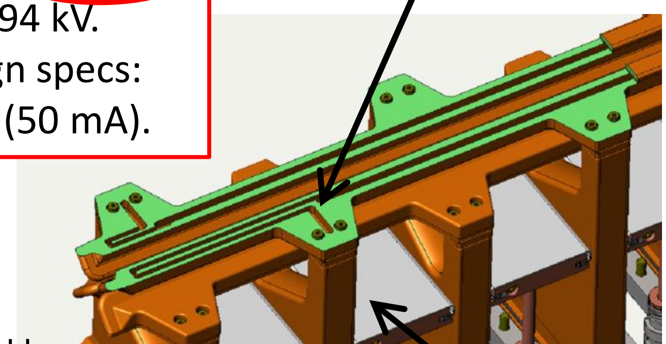


RF Power Test



- 30 kW → 75 kW/m (t ≈ 200 h).
- 45 kW → 115 kW/m (t ≈ h) → 94 kV.
- RFQ design specs: 59 kW/m (50 mA).

Milled cooling channels covered with 3 mm thick copper plating.

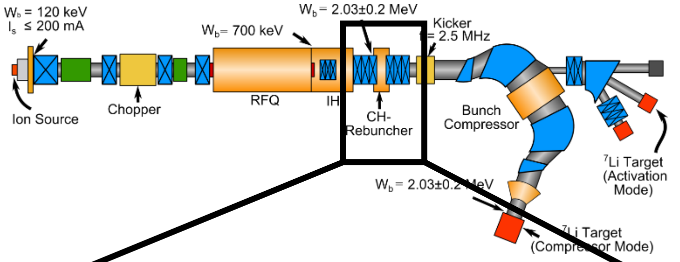


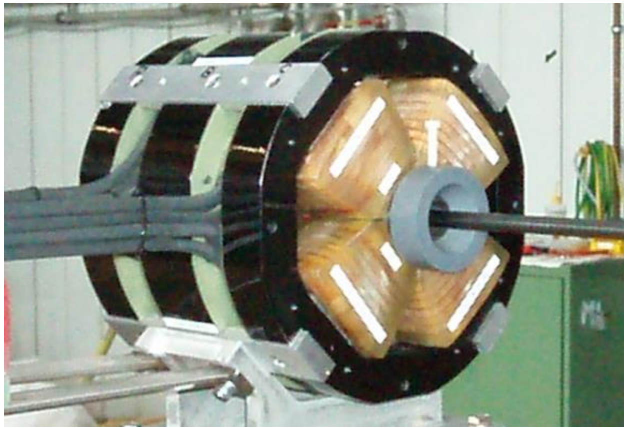
Manufactured by NTG company

Brazed silver tuning plates.

Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ

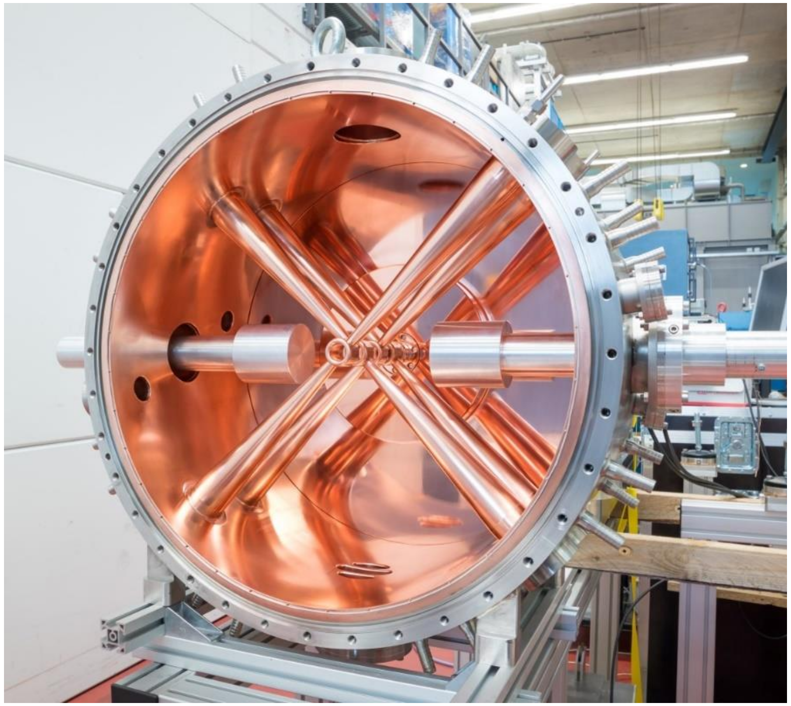




2 external QP triplets:

- Aperture: 30–38–30 mm.
- $\frac{1}{r}\int B\,\mathrm{d}z$: 2.1–3.0–2.1 T.

Medium Energy Beam Transport (MEBT) Section

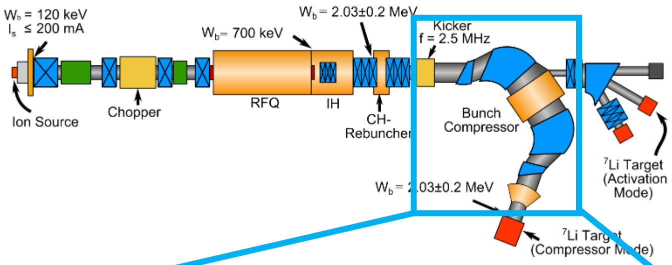


RT CH rebuncher cavity:

- 5 gaps.
- Energy variation ΔW_b = ± 0.2 MeV.
- f_{rf} = 175 MHz.

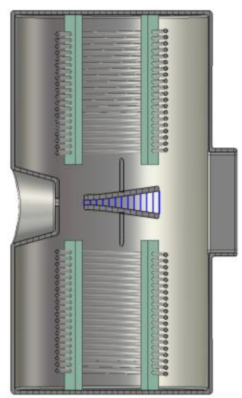
Frankfurt Neutron Source FRANZ

Frankfurt Neutron Source FRANZ

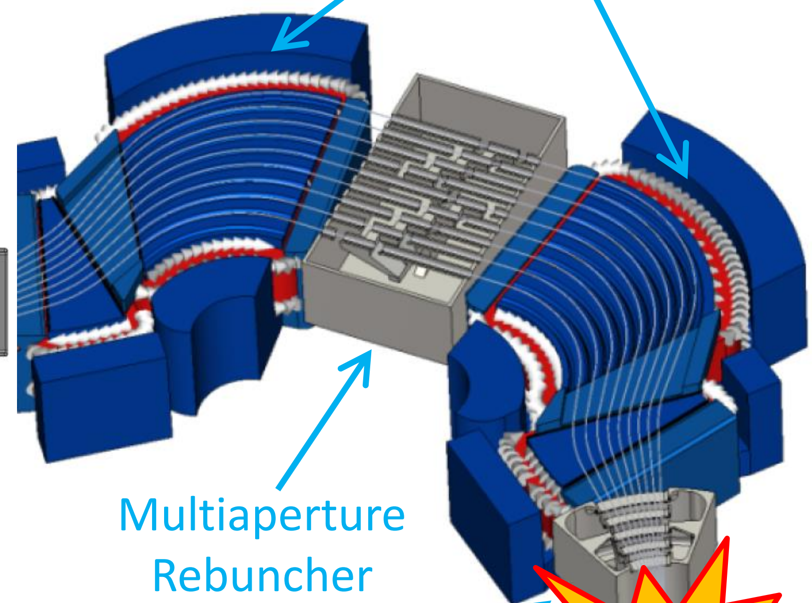


Bunch Compressor

- Mobley-type bunch compressor, extended for high beam intensity.
- Electric kicker:
  - f = 2.5 MHz.
- Magnetic ion guiding system.
- Multiaperture rebuncher.
- Final focus rebuncher:
  - 6 gaps, 11.5 kW.



2.5 MHz Kicker



t_p = 1 ns, 250 kHz

Frankfurt Neutron Source FRANZ

FRANZ is currently under construction at Frankfurt University:

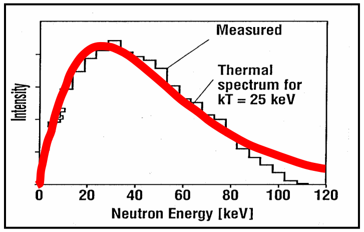
- Deliver neutrons for nuclear astrophysics and material sciences.
- Accelerator test bench.
- Education of students in accelerator physics.

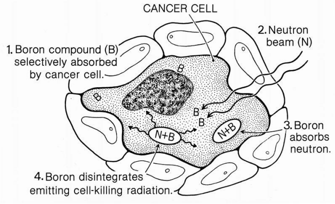
Experimental Hall, IAP

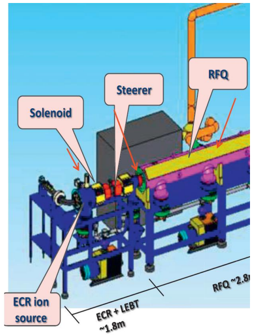
Physics Building, Goethe-Universität Frankfurt

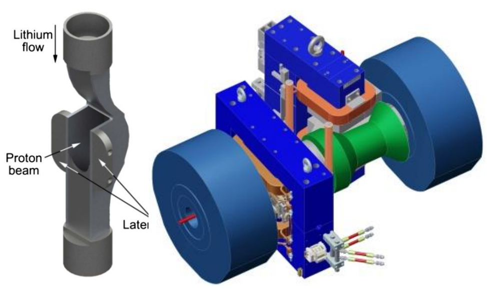
Conclusion

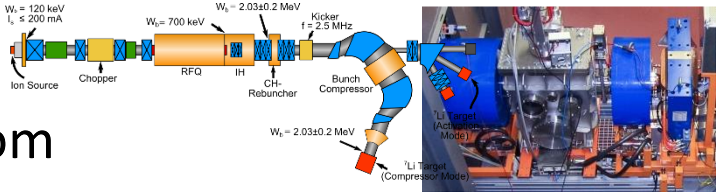
- Small-scale accelerator-driven neutron sources can provide intense neutron beams at modest sizes and costs.
- The neutron energy range of keV to MeV is especially suited for nuclear astrophysics and BNCT.
- Challenges are: compact, high-intensity facilities with high-power targets and flexible time structures.
- FRANZ, under construction at Frankfurt University, is based on a 2 MeV, 50 mA proton driver, which allows operation from cw (2 mA) to short, 1 ns pulses at 250 kHz.











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Thank you for your attention!