The 2024 International Topical Meeting on Nuclear Applications of Accelerators

Norfolk, VA, USA | March 17-21, 2024

Design of a compact accelerator-driven neutron source at the HZDR ion beam center

R. Rachamin, Sh. Akhmadaliev, C. Bischoff, U. Kentsch, S. Facsko

Institute of Ion Beam Physics and Materials Research

Helmholtz-Zentrum Dresden-Rossendorf

HZDR

HI ACTS | Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Introduction

- Neutron beams are used in a wide range of applications
  - to understand matter at the atomic and molecular levels

- Neutron production
  - nuclear research reactors
  - large accelerator-driven spallation neutron source facilities
  - **Compact Accelerator-driven Neutron Sources (CANS)**

- CANS produce neutrons by low-energy nuclear reactions
  - can be built at low cost with low maintenance efforts
  - offers neutrons more easily for science, training, and industrial applications

- A CANS is planned to be constructed at the HZDR ion beam center
  - in the framework of the innovation platform Hi-Acts

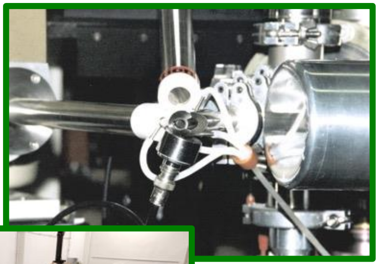
The Ion Beam Center (IBC) at HZDR

Leading European user facility for physics and materials research using ion beams

Applications:

- **Ion implantation and materials modification**
- **Ion beam analysis**
  - Rutherford Backscattering Spectrometry (RBS)
  - Elastic Recoil Detection (ERD)
  - Nuclear Reaction Analysis (NRA)
  - Particle induced X-Ray and γ- Emission (PIXE/PIGE)
- **Accelerator mass spectrometry (AMS)**

PIXE/PIGE



ERDA

RBS

NRA

Ion Beam Modification

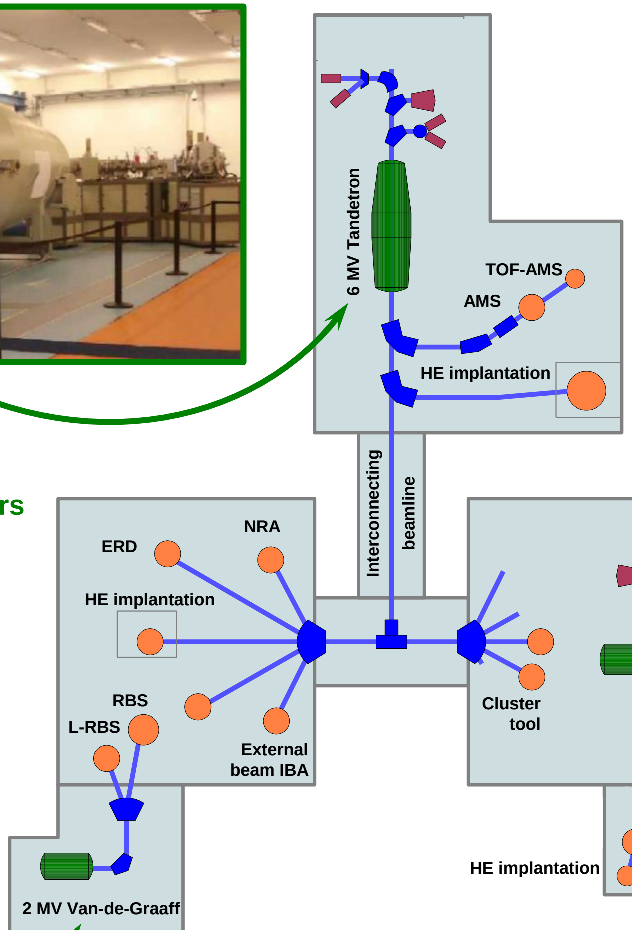
Ion Beam Analysis

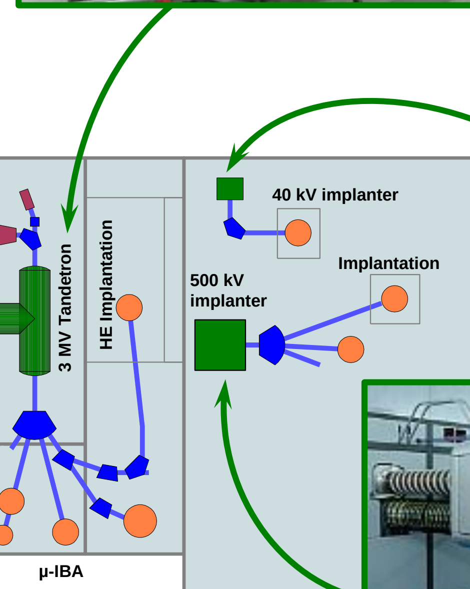
A Schematic Overview of the IBC

6 MV Tandetron

3 MV Tandetron

40 kV Implanter





- Accelerators & Implanters
- Ion sources
- Magnets & Beamlines

2 MV Van-de-Graaff

500 kV Implanter

Applications:

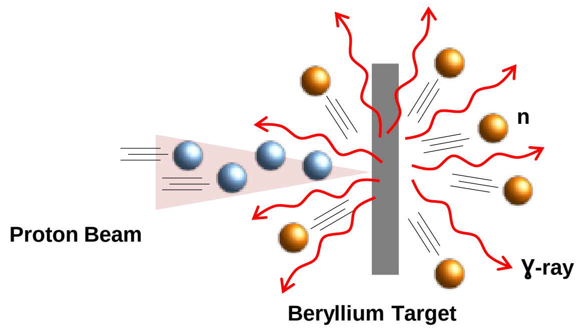
- Ion implantation
- Irradiations for biology and medicine
- Ion beam analysis (NRA, ERDA, PIXE, PIGE)
- Accelerator mass spectrometry (AMS)

Member of the Helmholtz Association
Reuven Rachamin I Institute FWIZ-B I www.hzdr.de

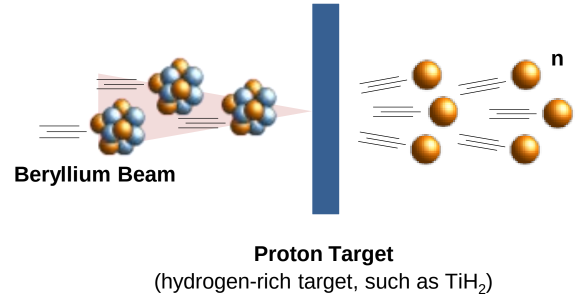
Design of CANS at the IBC

- The CANS design will take advantage of the **6 MV Tandetron** properties
  - Ions of almost all stable elements (H,…, Au, except Ne, Ar, Kr, Xe)
  - Energies: 12 MeV (H), 18 MeV (He), heavy ions 60 MeV
  - Current: max. 10 µA / typ. 6µA (H), 3 µA (He), 100-150 µA (O, C, Si, Au)

- Two options for neutron production are considered
  - interaction of a **proton or helium beam** with a **beryllium target**
  - interaction of a **heavy ion beam** with a **hydrogen-rich material as a target**



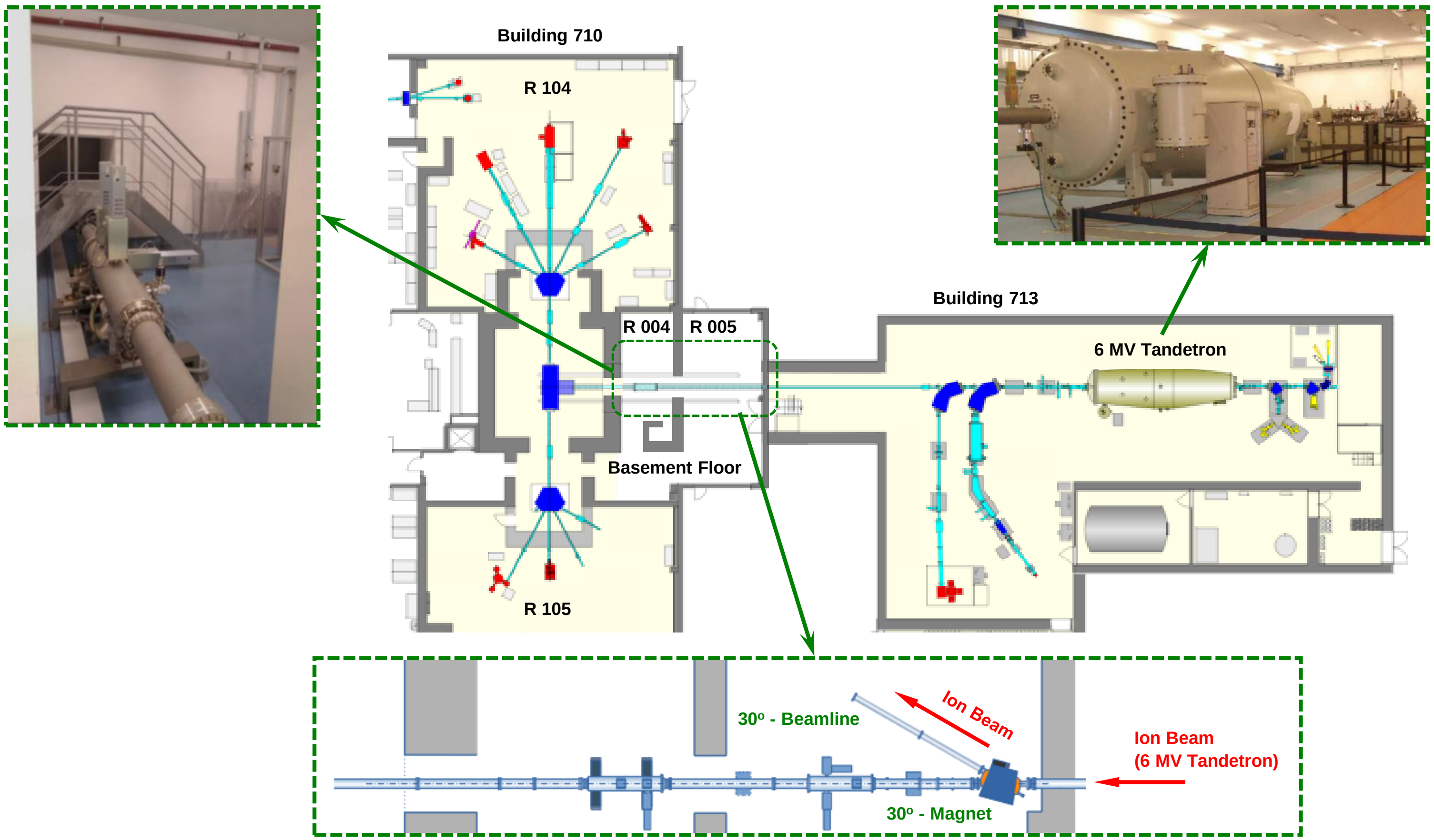
Main Option



Alternative Option
Inverse Kinematic Reaction Scheme

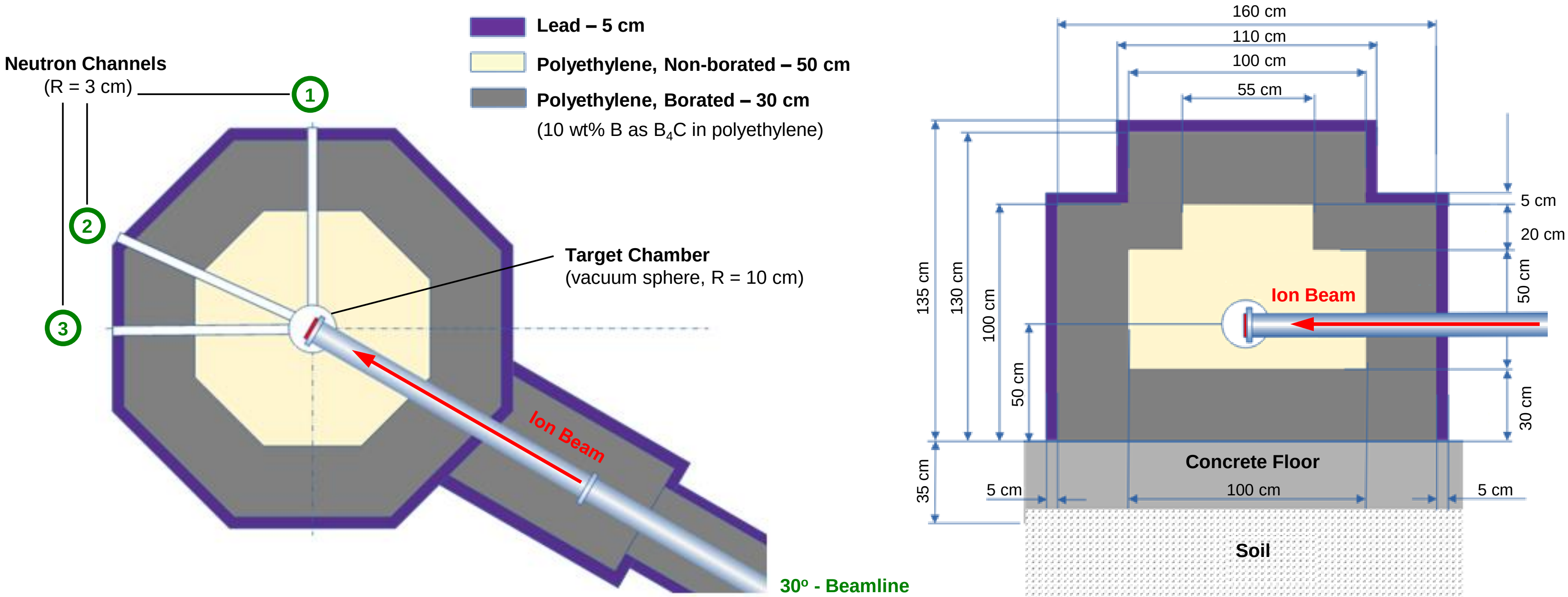
Design of CANS at the IBC

- The neutron source will be constructed in R 005 (Building 710)



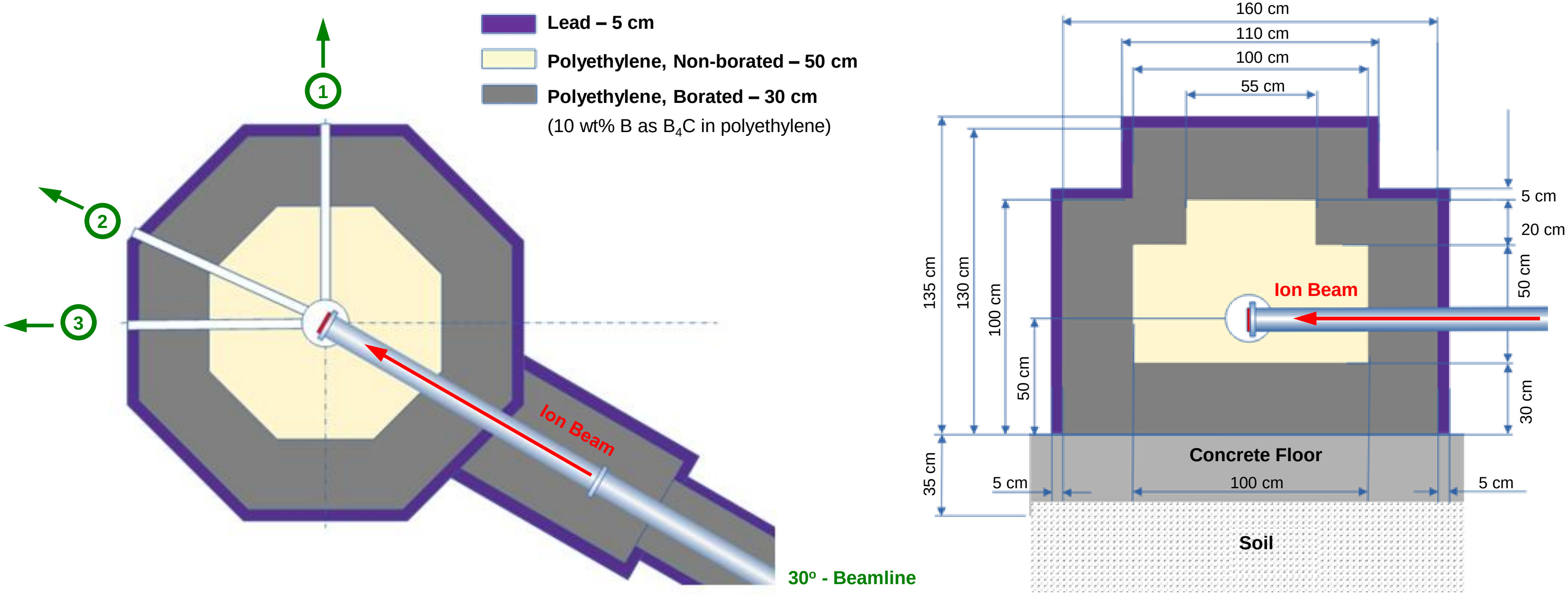
- The ion beam will be delivered to R 005 via a new **beamline with a 30° deflection magnet** (to be installed in the following months)

Design of CANS at the IBC



- A thin disc target will be installed at the end of the 30° ion beamline
- The target will be surrounded by a vacuum chamber (sphere with a radius of 10 cm)
- The target chamber will be surrounded by shielding structured in an octagon shape
- Three channels will pass along the shielding to form **Three Neutron Beamlines**

Design of CANS at the IBC



① **Production of Radionuclides for Nuclear Medicine (e.g. ^{99m}Tc)**

Production of radionuclides via neutron activation technique

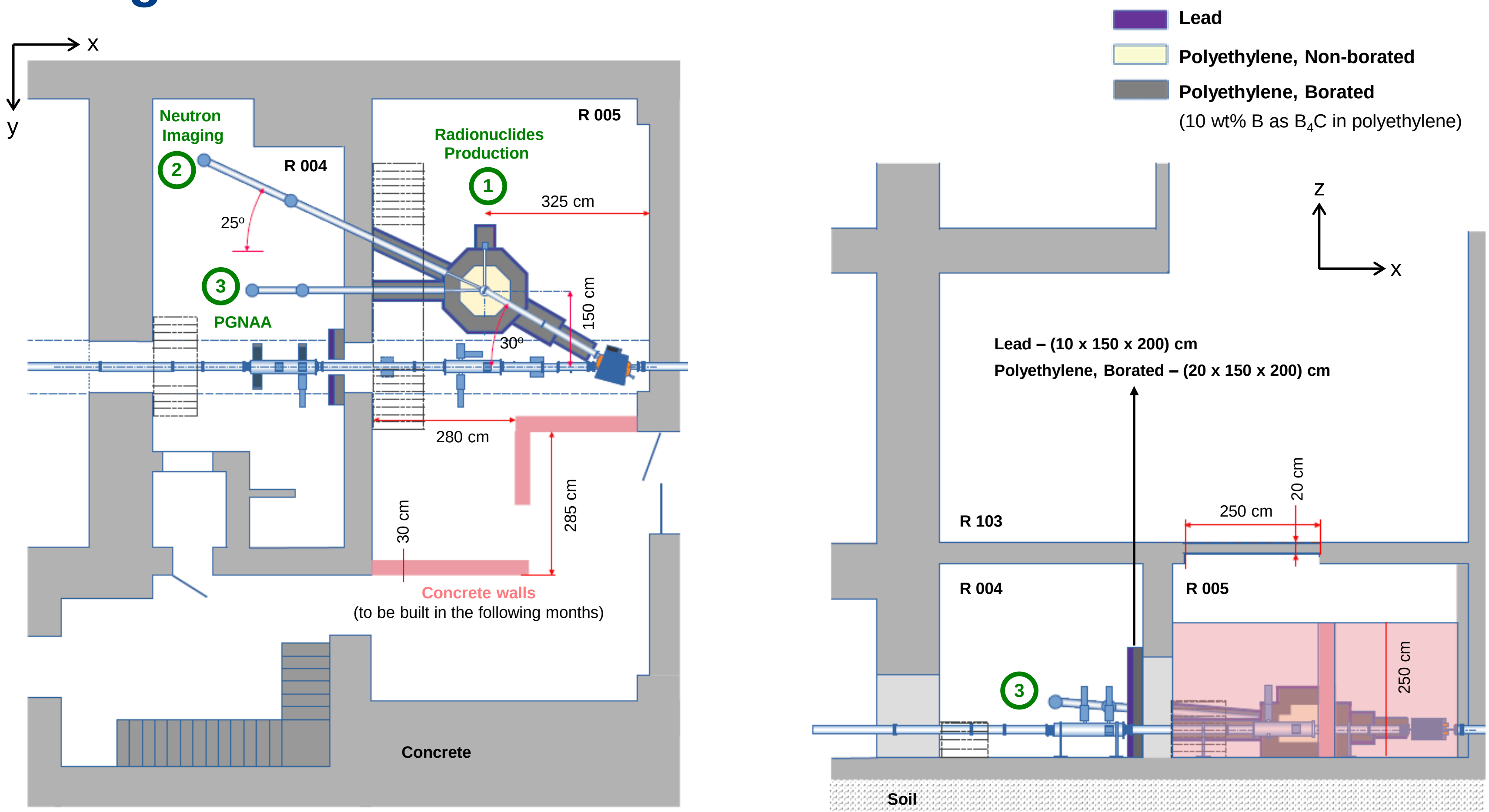
② **Neutron Imaging**

Nondestructive technique for analyzing the structure of a sample

③ **Prompt Gamma Neutron Activation Analysis (PGNAA)**

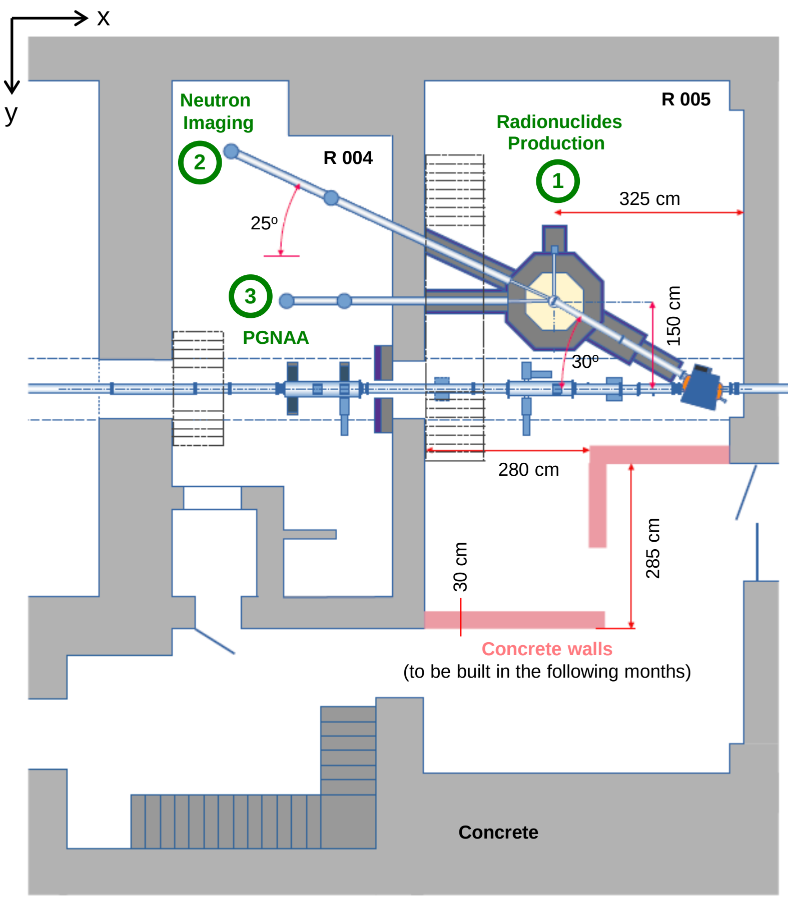
A measurement technique for nondestructive elemental analysis

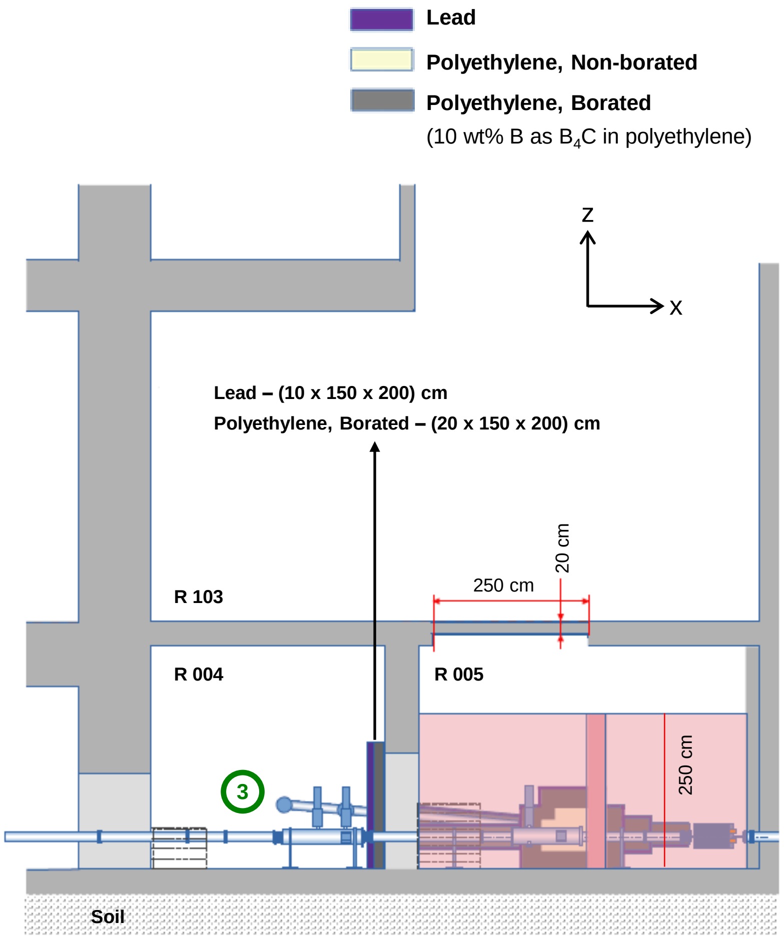
Design of CANS at the IBC



- **Radionuclide Production** will be performed in R 005
  - channel 1 will lead to a neutron chamber of 10x10x10 cm surrounded by borated polyethylene and lead

Design of CANS at the IBC





- **Neutron Imaging** and **PGNAA** will be performed in R 004
  - channel 2 & 3 will lead to a neutron guide (SS cylindrical tube) ending in R 004
  - up to the wall, the neutron guides will be shielded by borated polyethylene and lead

Evaluation of the CANS Design (Monte Carlo Calculations)

- Monte Carlo (MC) simulations were performed to evaluate the CANS design
  - using the FLUKA MC code (version 2023.3.1)

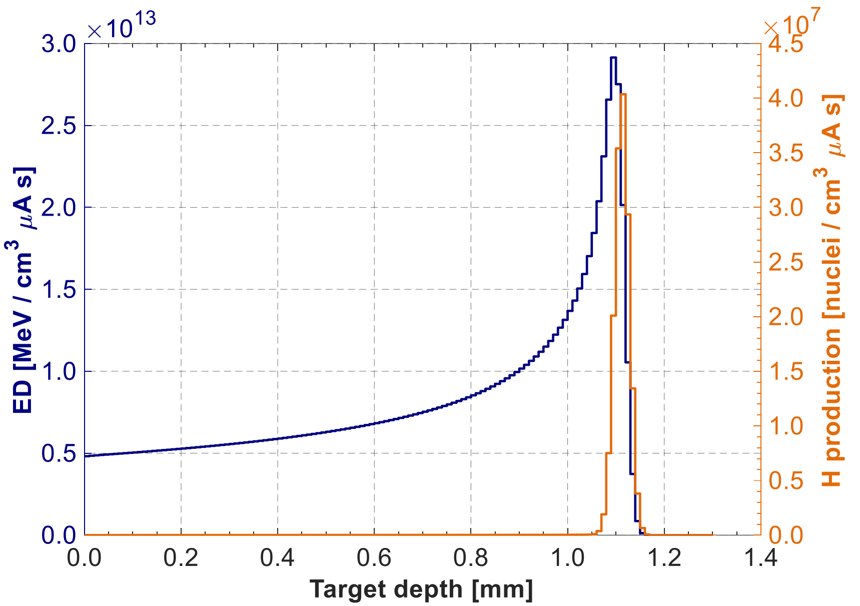
- The main simulations were performed for a 12 MeV proton beam hitting a thin beryllium target (a cylindrical disc with a radius of 5 cm)

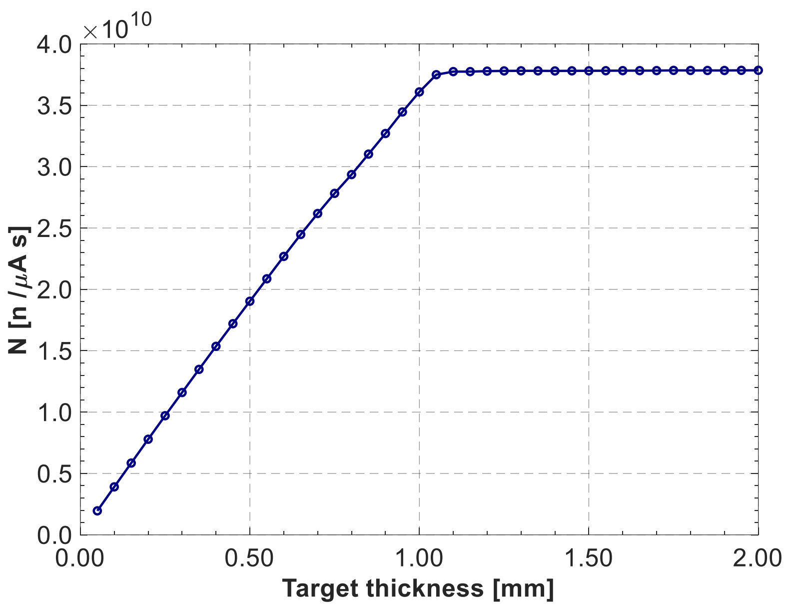
- Evaluated parameters
  - target thickness and neutronic properties of the $^{9}Be(p,n)^{9}B$ reaction
    - via a simple beam-target model
  - neutronic and radiation protection parameters of the CANS design
    - via a full 3D model of the IBC rooms with the CANS design

- Additional simulations were performed to evaluate the neutron production from several heavy ion beams hitting a thin TiH_2 target
  - via a simple beam-target model

Neutron Production Evaluation - $^{9}Be(p,n)^{9}B$

Target Thickness

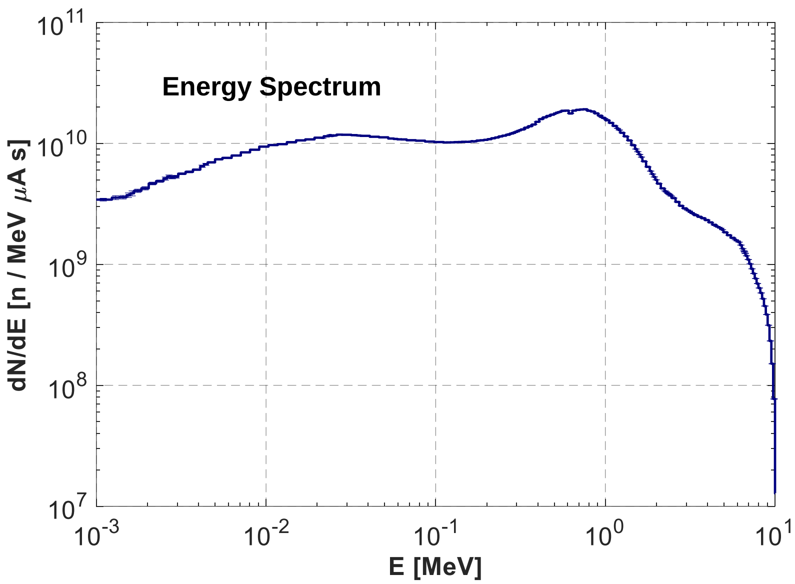


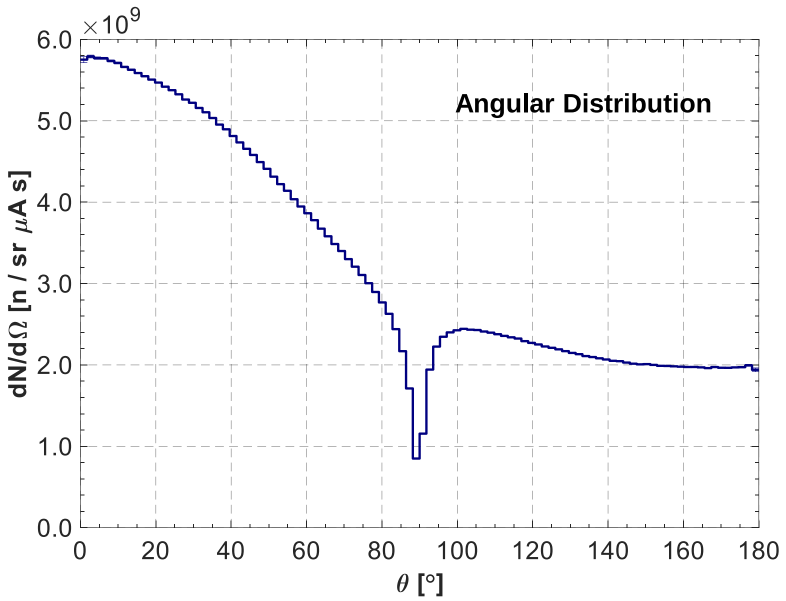


- When the protons stop inside the target, they become hydrogen gas and cause blistering in the target
  - blistering occurs near the range where the protons lose most of their kinetic energy
- After about 1.1 mm, the neutron yield reaches saturation
  - the proton energy reduces to energy below the threshold energy of the $^{9}Be(p,n)^{9}B$ reaction

Neutron Production Evaluation - $^{9}Be(p,n)^{9}B$

Neutron Yield





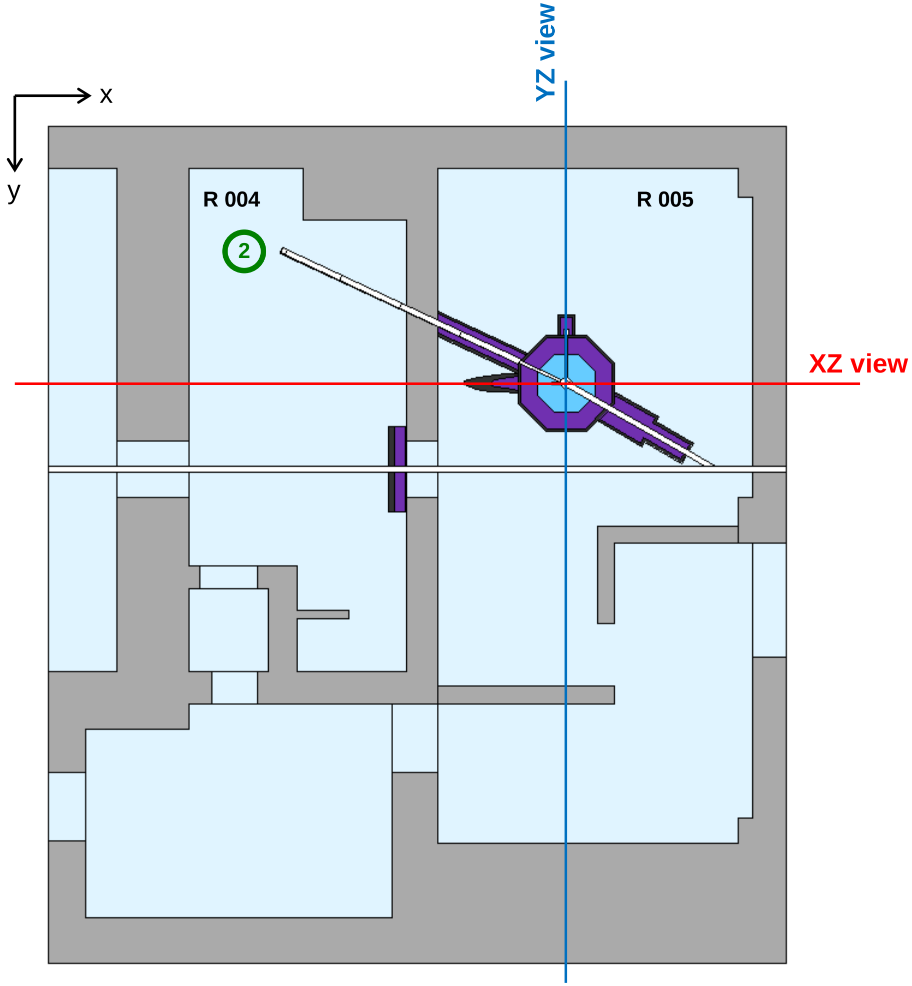
Beam type	Total photon yield ×10[10] [p / s μA]	Neutron yield ×10[10] [n / s μA]			Optimal thickness [mm]
		Forward (0º-90º)	Backward (90º-180º)	Total	
proton	0.0572 ± 0.0001	2.4097 ± 0.0004	1.3676 ± 0.0003	3.7773 ± 0.0005	1.0

- **Total Neutron yield from 12 MeV proton beam hitting a 1 mm beryllium target is**

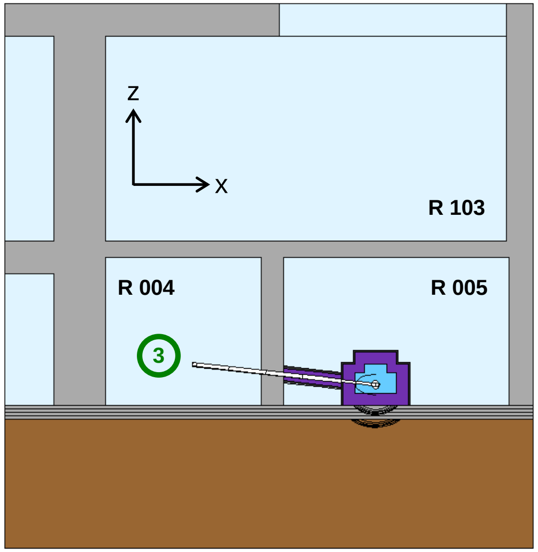
3.77 ×10[10] [n / s μA]

3D FLUKA Model

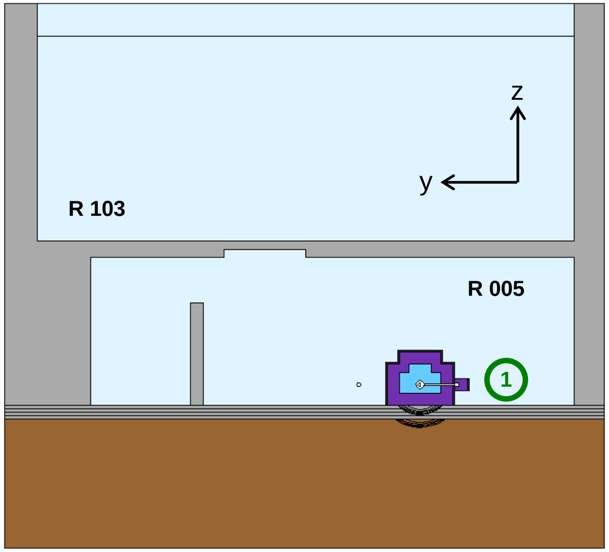
IBC Rooms with the CANS Design



XY view (50 cm above the floor of the basement)

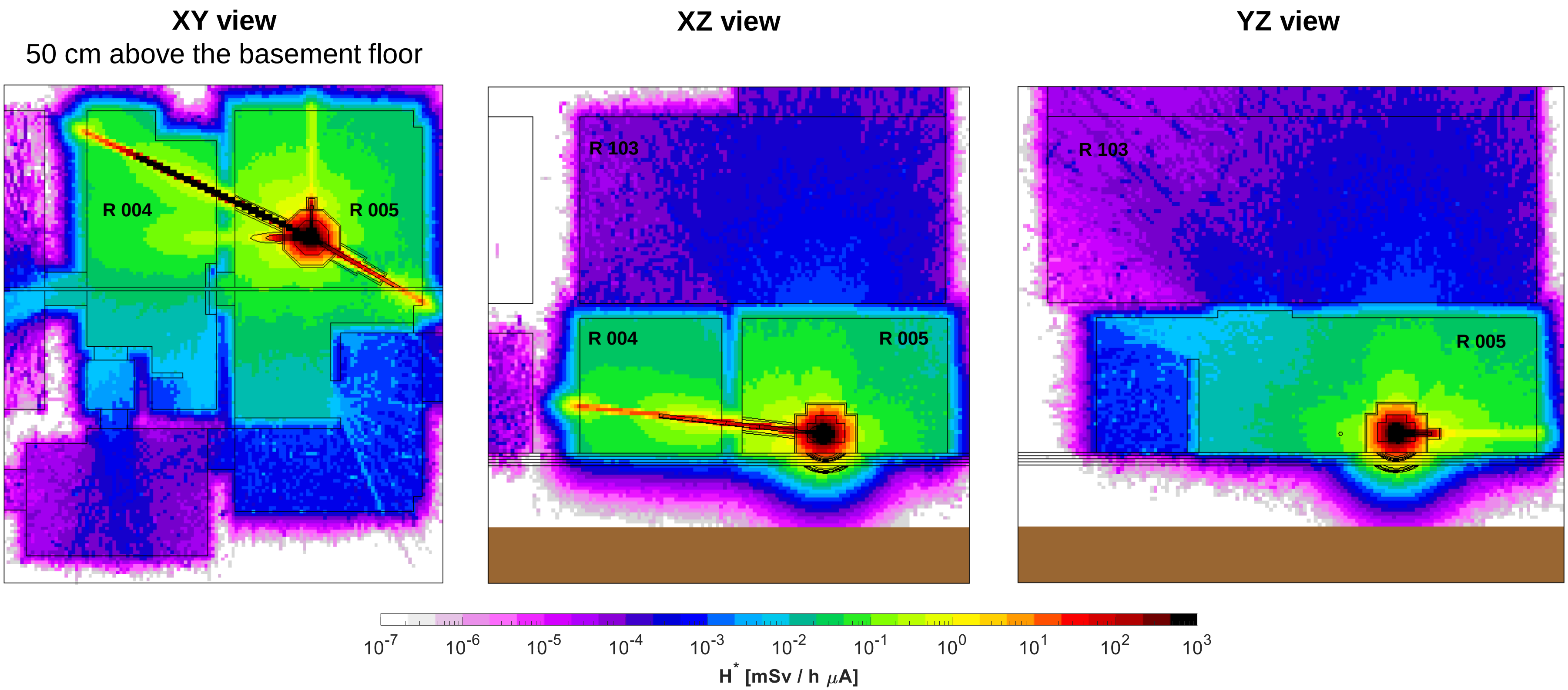


XZ view (along the red line)



YZ view (along the blue line)

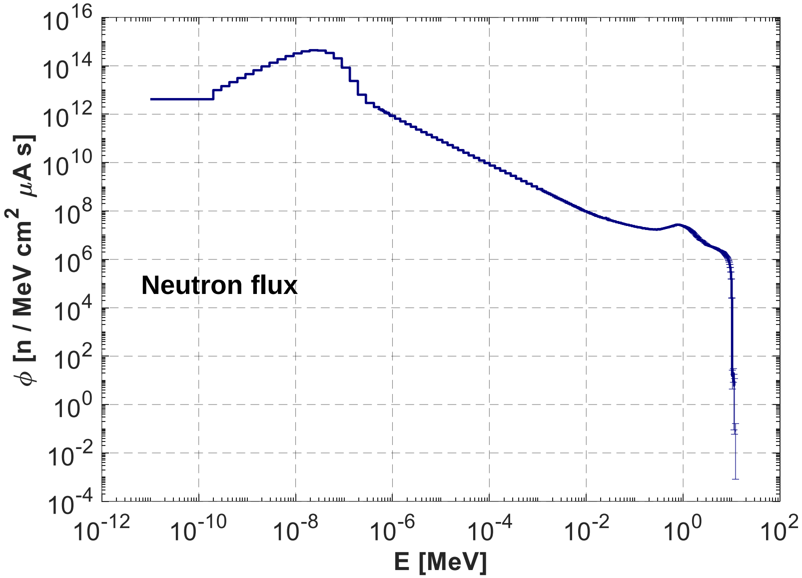
Ambient Dose (H*) Evaluation - $^{9}Be(p,n)^{9}B$

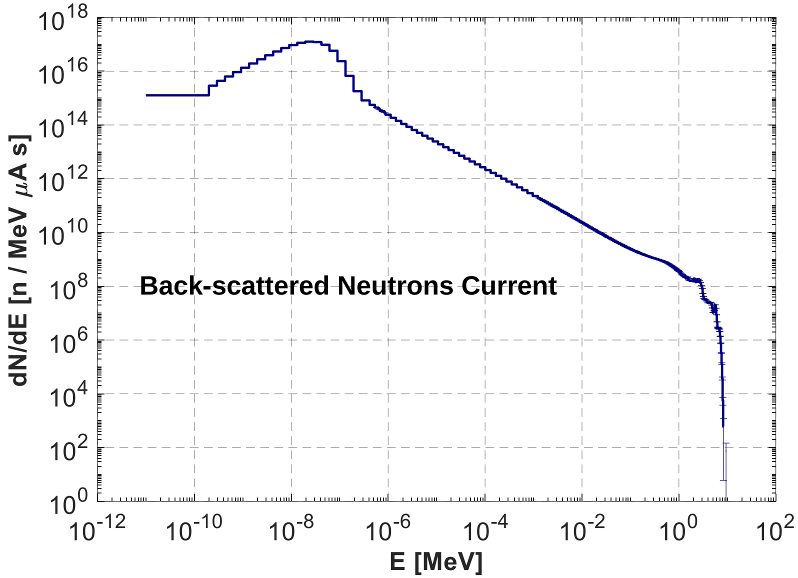


- The H* value on the outer surface of the shielding (**R 005**) is about **0.3-0.5 [mSv / h μA]**
- In **R 004**, the highest H* values are at the end of the neutron guides (about **1.0-2.0 [mSv / h μA]**)
- In **R 103** (above the neutron source), the H* values are in the range of **1.0-2.0 [μSv / h μA]**

Neutron Characteristics Evaluation - $^{9}Be(p,n)^{9}B$

Neutron Flux & Current in the Target Chamber





- Neutrons are streaming back from the shielding to the target chamber
- The neutron flux in the target chamber
  - neutrons produced directly by the target (fast neutrons)
  - back-scattered neutrons (thermalized neutrons)

Neutron Characteristics Evaluation - $^{9}Be(p,n)^{9}B$

Neutron Current along the Neutron Beamlines

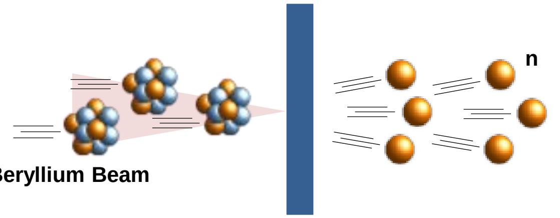
Beamline No.	Neutron current ×10^{9} [n / s μA]			
	Target chamber to neutron channel	Neutron channel to neutron chamber	Neutron channel to neutron guide	End of the neutron guide
1	1.05930 ± 0.00079	**0.01174 ± 0.00008**	----	----
2	1.37964 ± 0.00090	----	0.01468 ± 0.00010	**0.00088 ± 0.00002**
3	1.07189 ± 0.00072	----	0.01509 ± 0.00009	**0.00120 ± 0.00003**

- Delivered neutron flux
  - **Beamline 1** (Radionuclide Production): 4.15 ×10^{5} [n / s cm^{2} μA]
  - **Beamline 2** (Neutron Imaging): 1.27 ×10^{4} [n / s cm^{2} μA]
  - **Beamline 3** (PGNAA): 1.73 ×10^{4} [n / s cm^{2} μA]

! Neutron guides: a simple SS316L cylindrical tube (outer diameter of 10 cm, wall thickness of 0.3 cm)

Neutron Production Evaluation

Inverse Kinematic Reaction Scheme

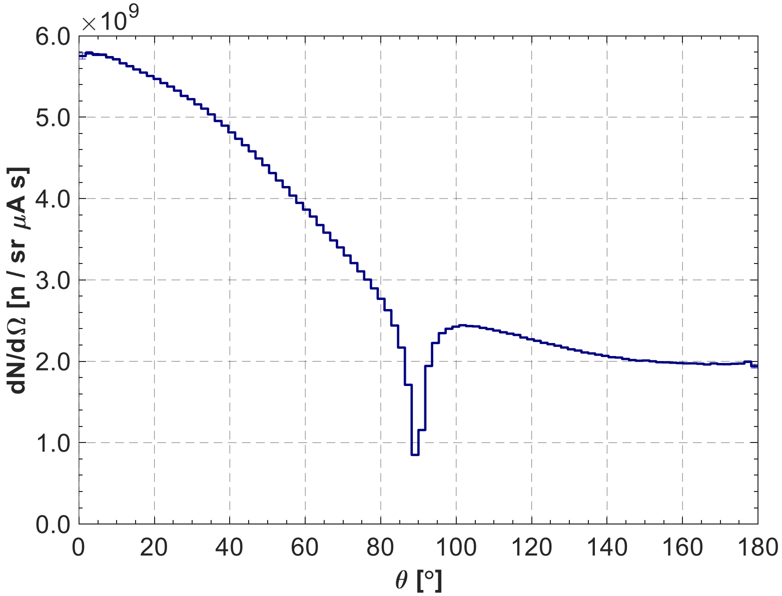


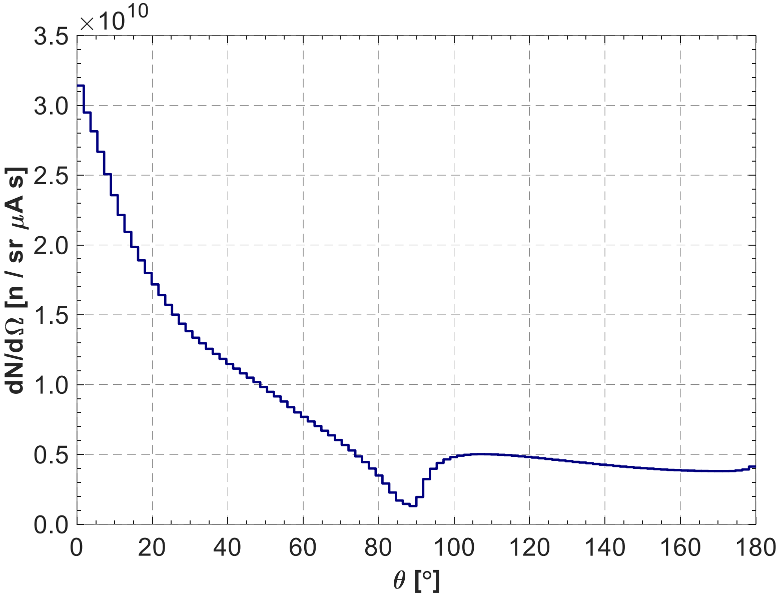
Photon and neutron yield from different beam type hitting a TiH_2 target

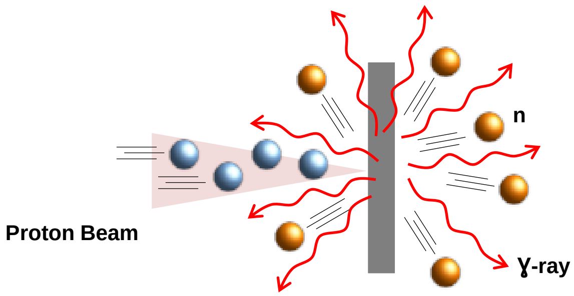
Beam type	Charge	Energy [MeV]	Total photon yield $\times 10^{10}$ [p / s μA]	Neutron yield $\times 10^{10}$ [n / s μA]		
				Forward (0^o-90^o)	Backward (90^o-180^o)	Total
Proton	**+1**	**12**	**0.0572 ± 0.0001**	**2.4097 ± 0.0004**	**1.3676 ± 0.0003**	**3.7773 ± 0.0005**
^{7}Li	**+3**	**24**	**7.3417 ± 0.0008**	**5.3286 ± 0.0005**	**2.7721 ± 0.0003**	**8.1007 ± 0.0008**
^{6}Li	+3	10	1.1466 ± 0.0003	0.4724 ± 0.0001	0.3686 ± 0.0001	0.8410 ± 0.0002
^{9}Be	**+4**	**30**	**6.3863 ± 0.0006**	**5.6193 ± 0.0005**	**2.4248 ± 0.0003**	**8.0441 ± 0.0007**
^{12}C	+3	12	1.0696 ± 0.0003	0.4643 ± 0.0002	0.2840 ± 0.0001	0.7483 ± 0.0002
^{13}C	+3	12	1.1749 ± 0.0003	0.7194 ± 0.0002	0.3871 ± 0.0001	1.1065 ± 0.0003
^{14}N	+3	20	2.6828 ± 0.0005	1.4175 ± 0.0003	0.7452 ± 0.0002	2.1627 ± 0.0004
^{16}O	+5	30	3.0621 ± 0.0013	2.0329 ± 0.0009	0.9057 ± 0.0005	2.9386 ± 0.0013

Neutron Production Evaluation

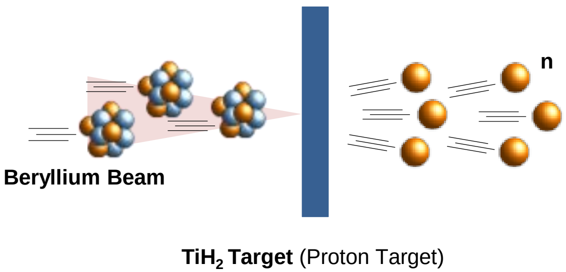
Neutron Yield – Angular Distribution







VS.



$$\frac{\text{forward } (0^\circ\text{–}90^\circ) \text{ yield}}{\text{backward } (90^\circ\text{–}180^\circ) \text{ yield}} = \mathbf{1.76}$$

$$\frac{\text{forward } (0^\circ\text{–}90^\circ) \text{ yield}}{\text{backward } (90^\circ\text{–}180^\circ) \text{ yield}} = \mathbf{2.32}$$

Summary

- CANS is planned to be constructed at IBC
  - opens new opportunities for material analysis

- The design was evaluated via MC simulations
  - for optimization and radiation protection permission

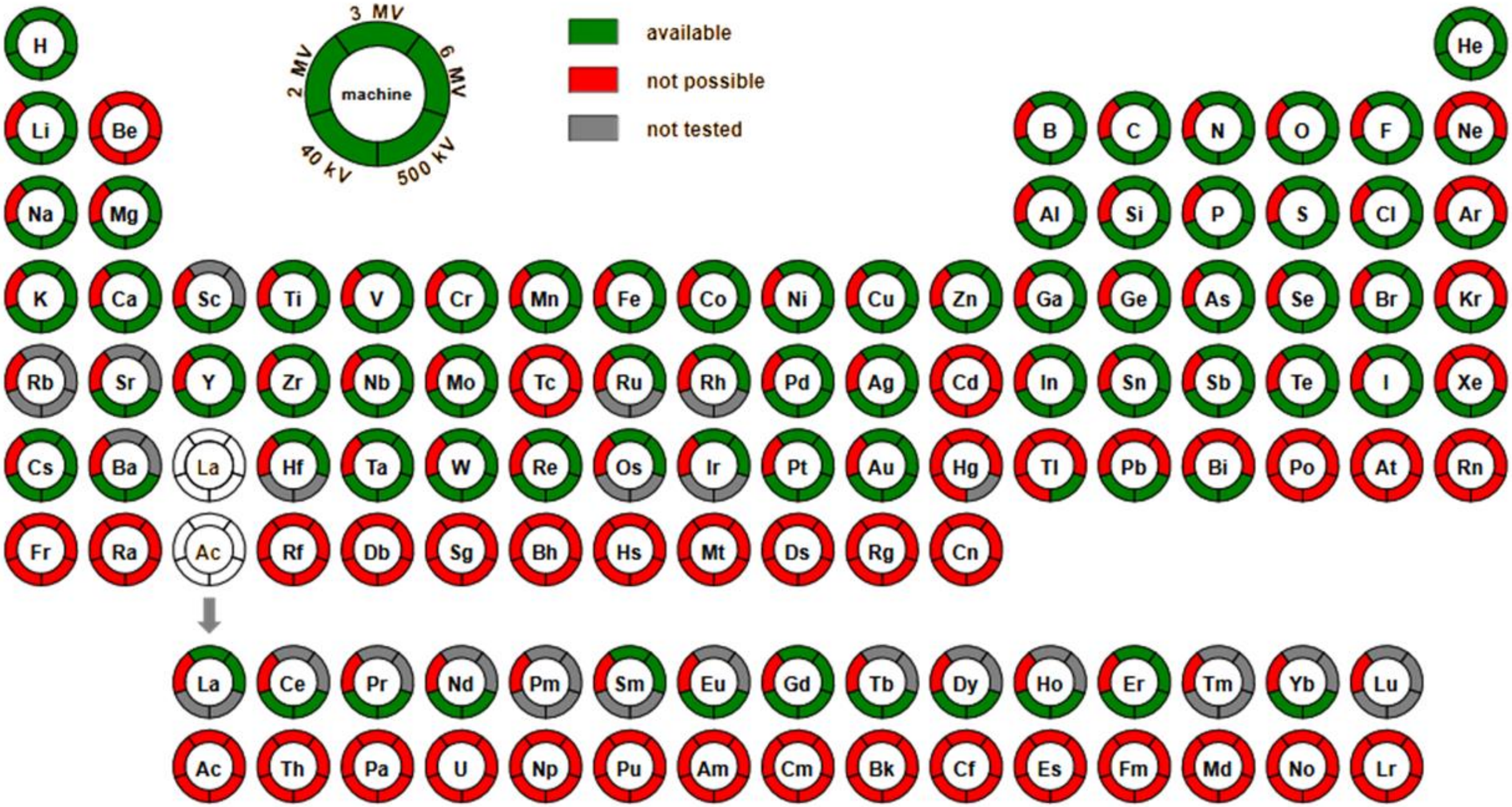
- Ongoing and future tasks
  - building reconstruction in R 004 and R 005
  - installation of new ion beamline with 30° deflection magnet
  - construction of the shielding
  - tests with Be-target and proton beam. radiation measurements
  - tests with TiH_2-target and a heavy ion beam. radiation measurements
  - installations of neutron beamlines. radiation measurements
  - installation of experimental equipment for neutron imaging and PGNAA

Thank you for your attention!

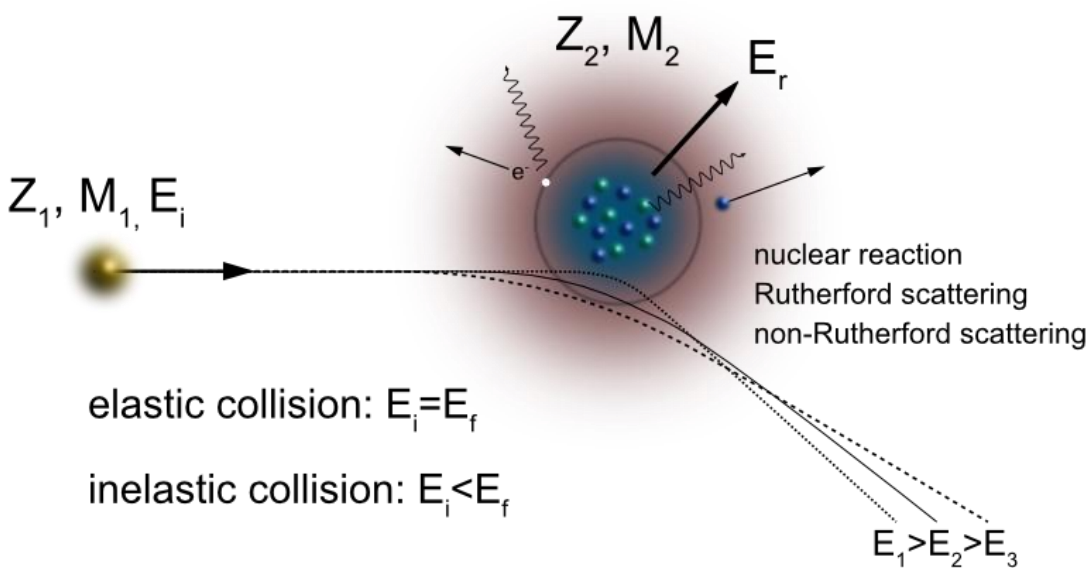
This work is funded by by Hi-Acts - Helmholtz Innovation Platform for Accelerator-based Technologies & Solutions

Ion Beam Center - Helmholtz-Zentrum Dresden-Rossendorf, HZDR

Available Ions at IBC



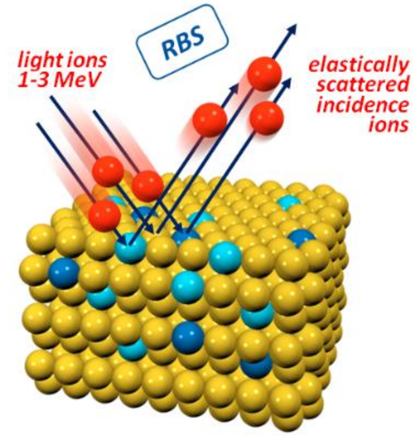
Classical Ion Beam Analysis – Basic Principles



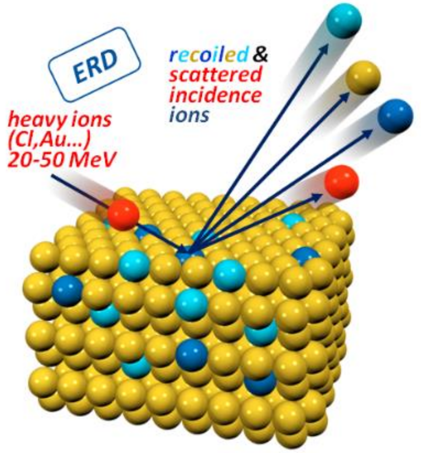
- Scattered and secondary particles are detected after collision
  - **Rutherford Backscattering, Elastic Recoil Detection Analysis, Nuclear Reaction Analysis**

- X-rays and ɣ-rays are detected after the reaction
  - **Particle Induced Emission**

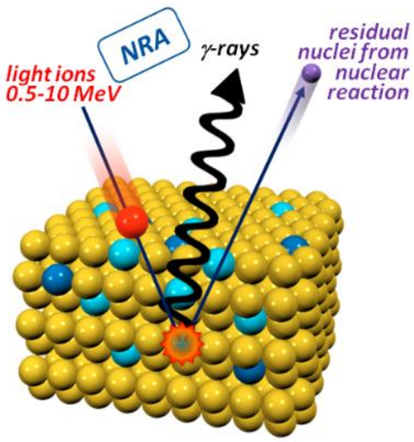
Ion Beam Analysis at the IBC



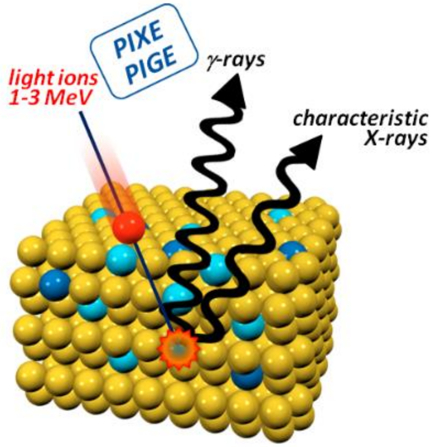
Rutherford Backscattering Spectrometry (RBS)



Elastic Recoil Detection (ERD)



Nuclear Reaction Analysis (NRA)



Particle induced X-Ray and
ɣ- Emission (PIXE/PIGE)

Ion Beam Analysis at the IBC