CHARACTERIZATION OF D^+ SPECIES IN THE 2.45 GHz ECRIS FOR 14-MeV NEUTRON PRODUCTION

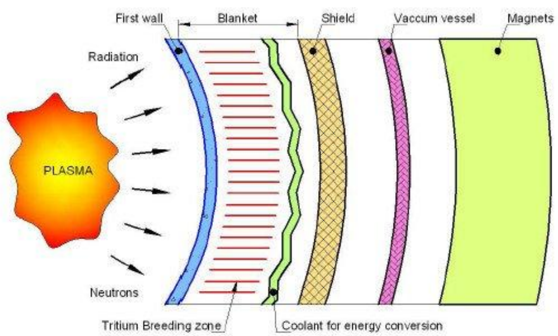
Sudhirsinh Vala
Head, Neutron and Ion Irradiation Facility
Institute for Plasma Research
Bhat, Gandhinagar, India

E-mail: sudhir@ipr.res.in

Overview of Presentation

- ✓ Motivation
- ✓ Type of Neutron Source
- ✓ Neutron Sources at IPR
- ✓ Diagnostics System
- ✓ Recent Experiment and Results
- ✓ Application of Neutron Source
- ✓ Summary

Motivation



A K Suri *et al* 2010 *J. Phys.: Conf. Ser.* **208** 012001

Nuclear Fusion

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

Application of Intense neutron sources **(Neutron flux in order of $> 10^{15}$ N/m^{2}s)**

- Radiation damage
- Material Characterization

Fusion Related Application of neutron source **(Neutron flux in order of $>10^{10}$ N/m^{2}s)**

- Cross section measurement, Neutron Activation Analysis, Nuclear parameter training, benchmark experiments for Fusion Evaluated Nuclear Data Library (FENDL), neutron spectroscopy measurements, double differential cross-section measurements, neutron diagnostics lab scale prototype experiments, characterization of electronic equipment,

In addition, other applications of 14MeV neutrons: **(Neutron flux in order of $>10^{10}$ N/m^{2}s)**

- Radio isotopes for Medical applications, explosive detection, Cancer Treatment, contraband detection, metal cleanliness, neutron radiography, etc

Type of Neutron Source

Radio-isotopic neutron sources

- Two-component sources based on (α,n) reactions: α decay from ^{239}Pu, ^{241}Am, ^{210}Po then $^{9}Be(\alpha,n)^{12}C$
- Two-component sources based on (γ,n) reactions: ^{24}Na, ^{124}Sb then $^{9}Be(\gamma,n)2\ ^{4}He$
- Spontaneous fission sources, e.g. ^{252}Cf

Fusion Neutron Source

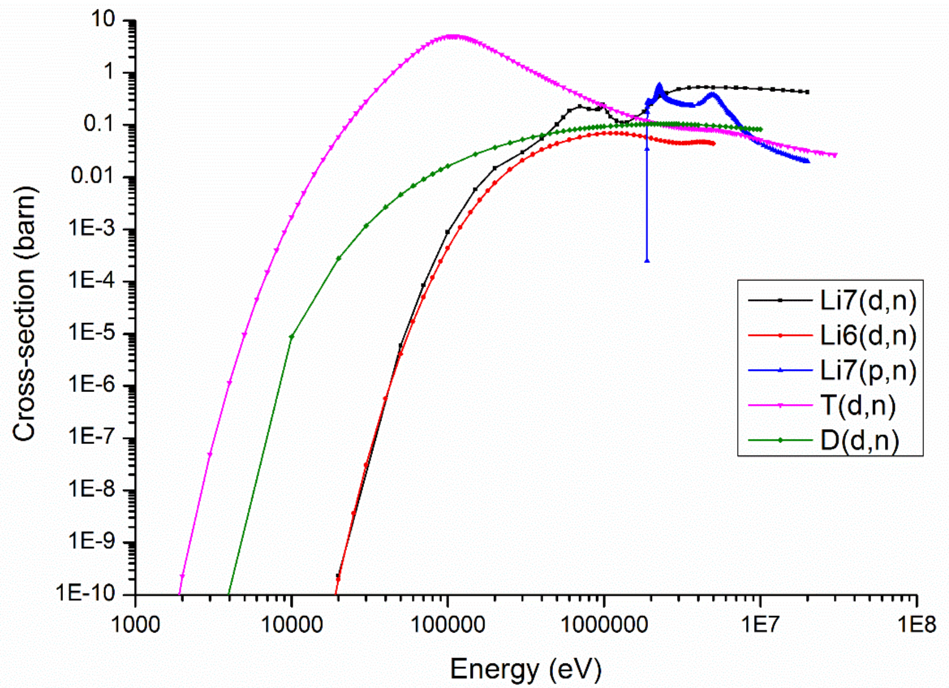
- 2.4 MeV neutrons D(d,n)3He
- 14-MeV neutrons D(t,n)4He

Spallation neutron sources

In which heavy elements such as W, Pb, U irradiated with high-energy protons or other particles are spalled into two or more fragments and many neutrons are released

Fission Neutron Source : (mostly used, they allow for determinations using different neutron reactions reactor neutron spectrum)

Different Fusion Reaction & Cross Section



Fusion relevant cross-sections

$D + D \longrightarrow {}^{3}He + n + 3.2\ MeV$

$D + T \longrightarrow {}^{4}He + n + 17.6\ MeV$

${}^{6}Li + D \longrightarrow {}^{7}Be + n + 3.4\ MeV$

${}^{7}Li + D \longrightarrow 2\,{}^{4}He + n + 15.1\ MeV$

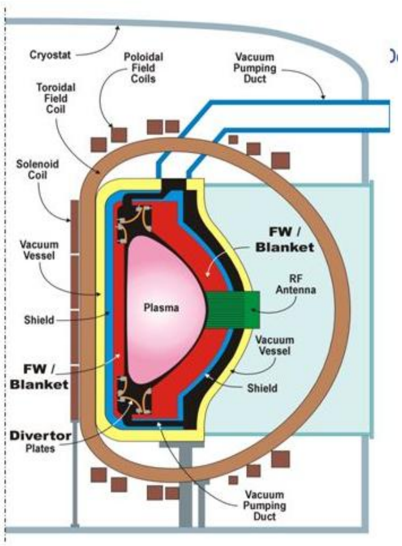
${}^{7}Li + D \longrightarrow {}^{8}Be + n + 15.0\ MeV$

${}^{7}Li + P \longrightarrow {}^{7}Be + n + 1.2\ MeV$

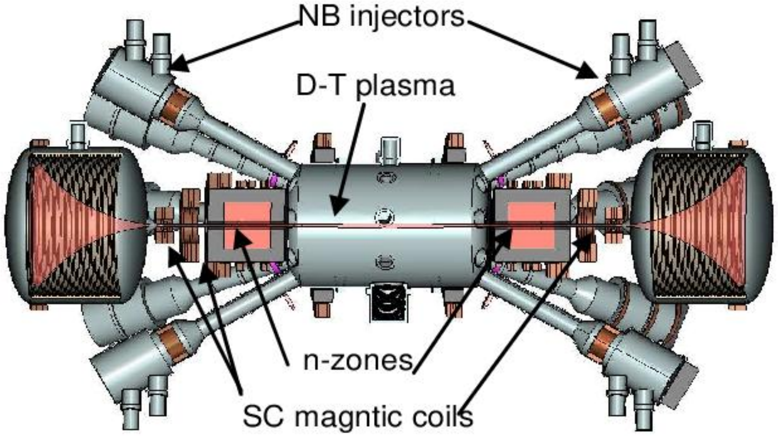
Different Type of Fusion Neutron Source

- ✓ Plasma Based Neutron Source
- ✓ Spallation Neutron Source
- ✓ Charge particle-induced Neutron Source

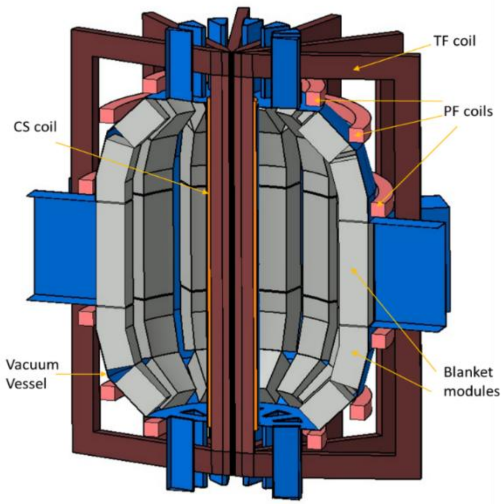
Plasma based 14-MeV Neutron Generation



Tokamak

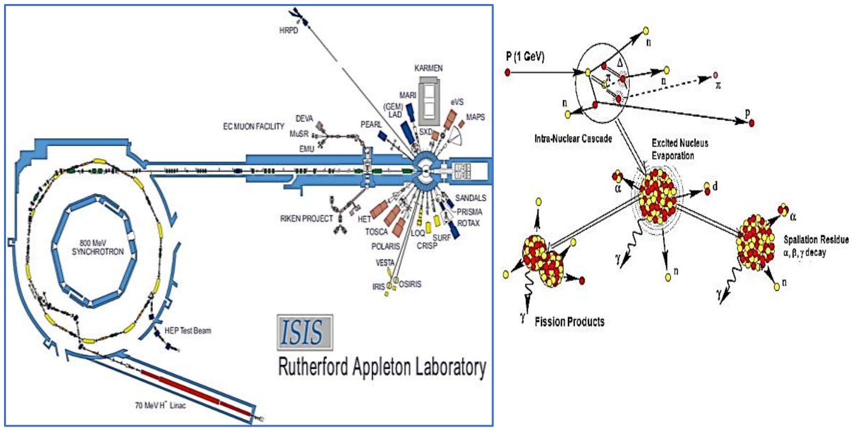


Gas Dynamic Trap (GDT)

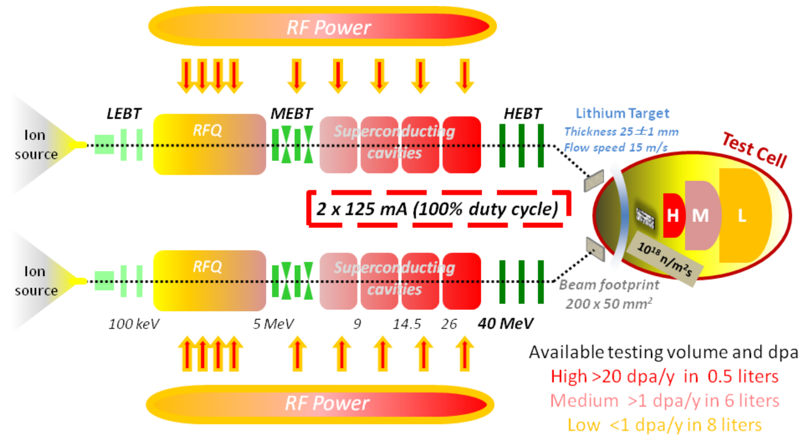


Spherical Torus (ST)

Charge particle-induced Neutron Source



Schematic diagram of Spallation Neutron Sources



Schematic of IFMIF facility

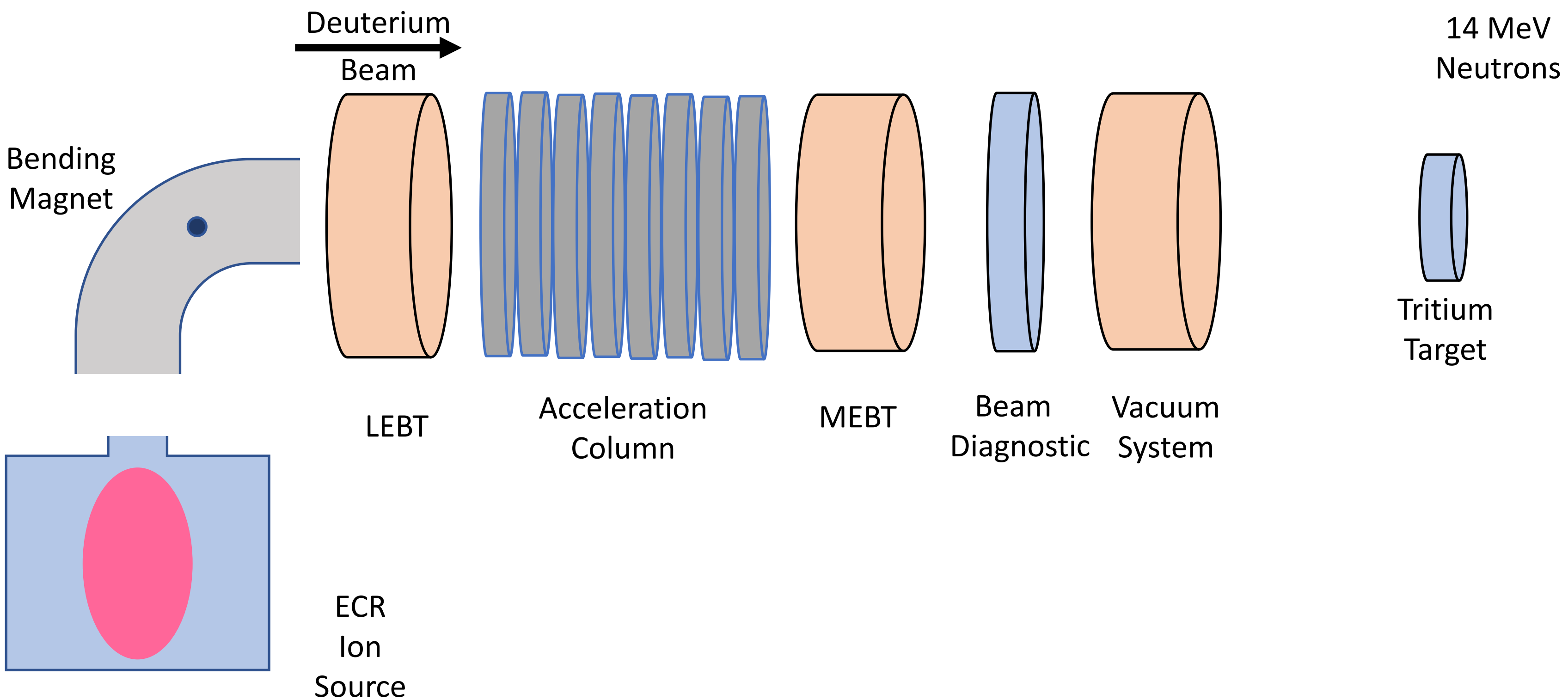
Ref: Stephen M Bennington, November 2004, Journal of Materials Science 39(22)

Ref: **J. Knaster** et al. Nucl. Fusion **53** (2013) 116001 (18pp)

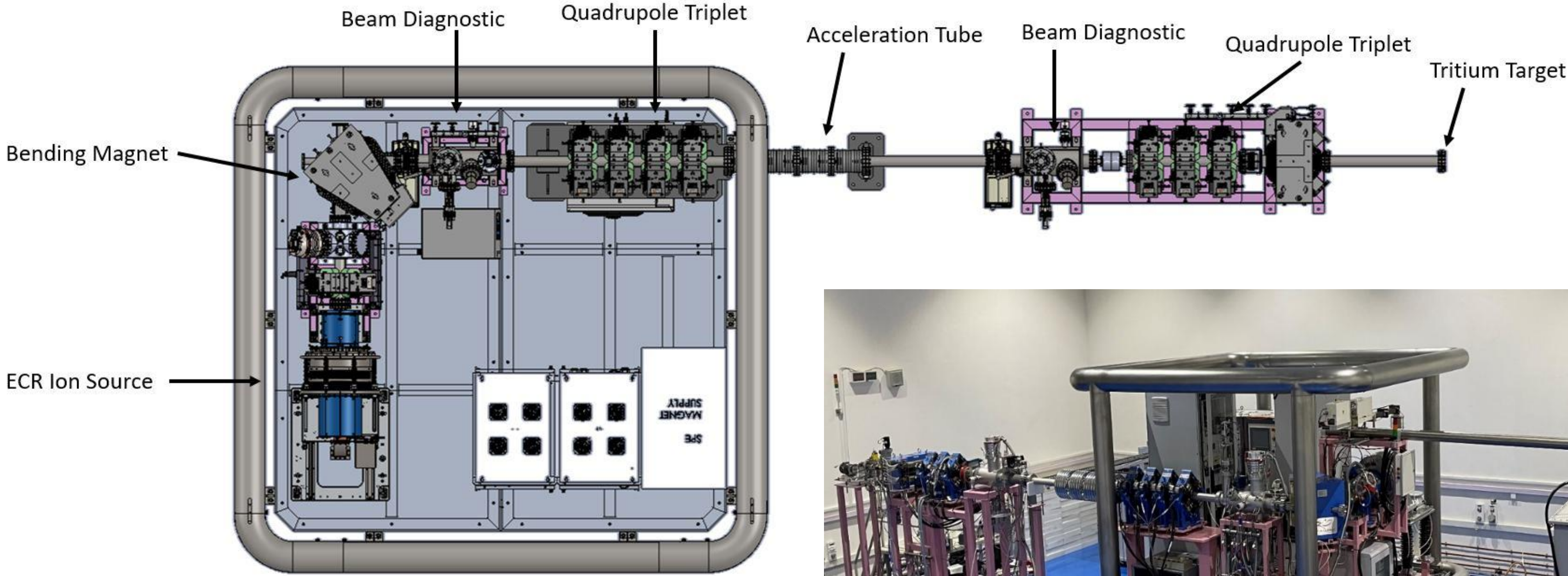
Major Accelerator based 14-MeV Neutron Source facilities worldwide

	Target	Acce. Tech	Concept	Current/Energy (mA/MeV)	Neutron Yield (n/s)	Status
IFMIF, Japan	Liquid	RFQA	Li(d,n)	2x125/40	10^{16}	Under Development
A-FNS, Japan	Liquid	RFQA	Li(d,n)	125/40	10^{15}	Under Development
HINEG-II, China	Solid	Electro	t(d,n) α	500/0.4	10^{13}	Operational
Phoenix, USA	Solid	Electro	t(d,n) α	30/0.3	10^{13}	Operational
ENEA, Italy	Solid	Electro	t(d,n) α	1/0.3	10^{11}	Operational
IPR, India	Solid	Electro	t(d,n) α	20/0.3	10^{12}	Operational

Schematic of 14-MeV Neutron & Ion Irradiation System (NIIS)



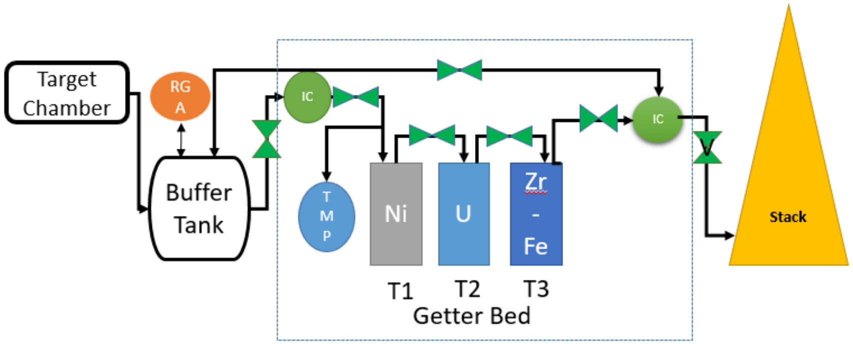
Experimental setup of 14-MeV Neutron & Ion Irradiation System (NIIS)



Highlights NIIS

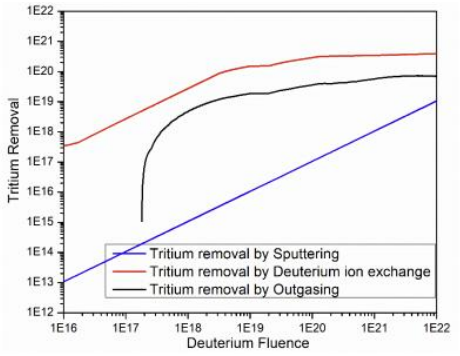
- **Neutron Yield : ~1-5 x10^{12} n/s**
- **Operation Mode: CW/pulse**
- **Neutron Energy : Thermal to 14 MeVDeuteron Ion beam : 5 to 20 mA**
- **Beam Energy: 40 to 300 KeV**
- **Moderator Assembly thermal Neutron**

Tritium Handling and Recovery System(THRS)

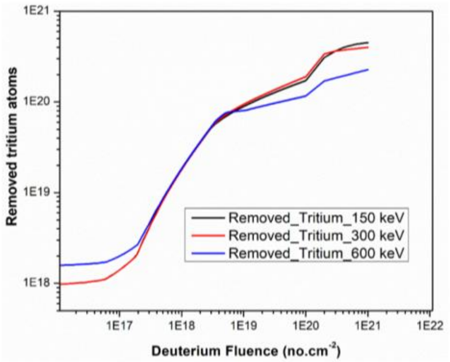


Schematic of Tritium Handling and Recovery System

Tritium Handling and Recovery System



Estimation of tritium removal

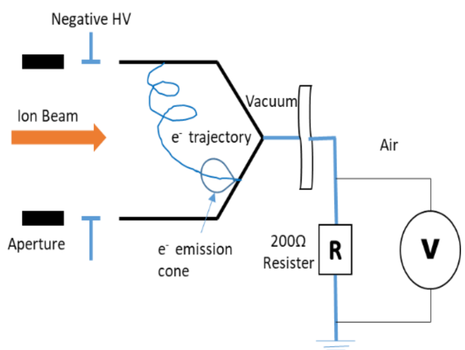


Tritium-Titanium removal due to deuterium ion irradiation

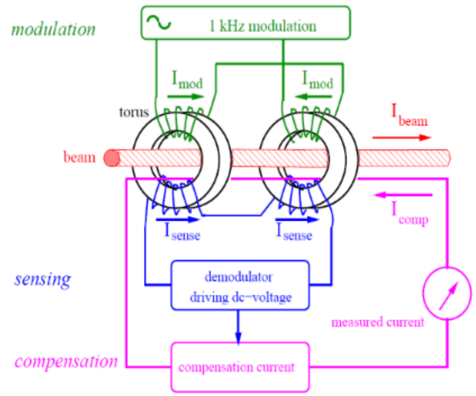
Need of THRS

- Due to following reason tritium will come out from tritiated target during bombardment of D^+ Ions.
  - Sputtering
  - D^+ Ion exchange
  - Outgassing
- Because of its radioactive nature it can not be released in atmosphere beyond certain limit.
- Also, Expensive

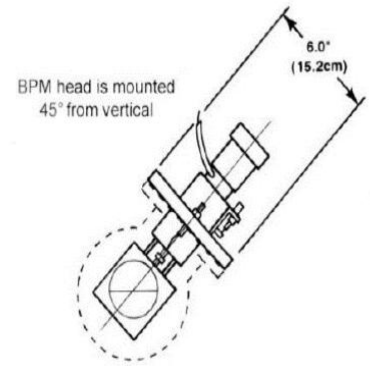
Beam Diagnostic systems of 14-MeV NG



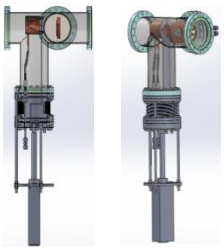
Schematic of Faraday Cup



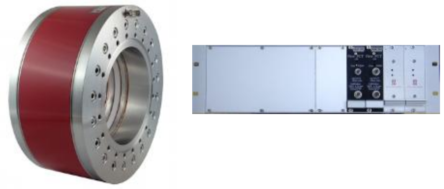
Schematic of DCCT



Installation Layout of BPM



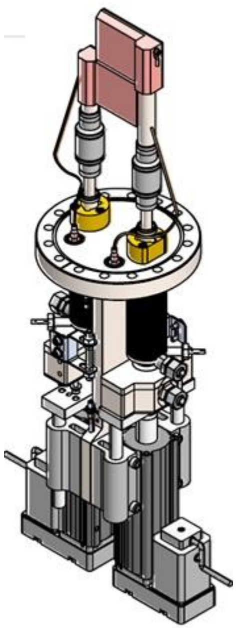
(a)Section view of FC assembly (b)(b) 3D view of FC assembly



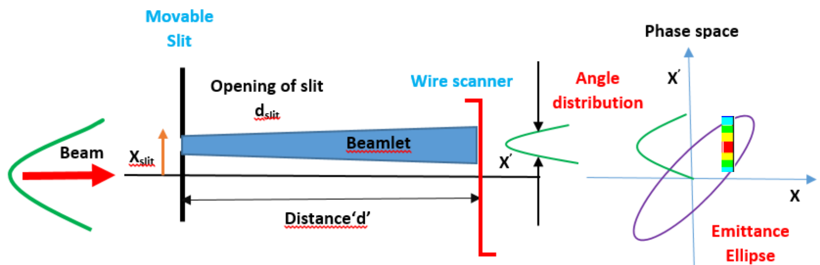
(a)Photograph of in-flange DCCT

(a)NEC Make Beam Profile Monitor (Model 82)

Deuterium Ion Beam emittance measurement



Movable Slit

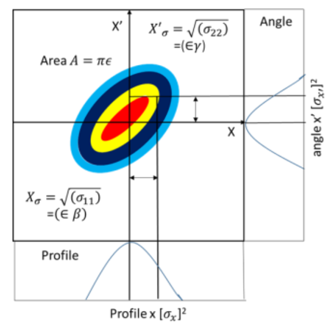


Wire Día : 1.5 mm
Distance d: 167mm & 198 mm

$$\epsilon_x = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

Emittance value ε_{rms} from

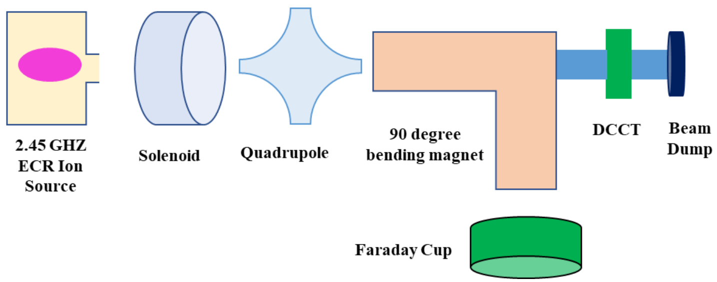
$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$



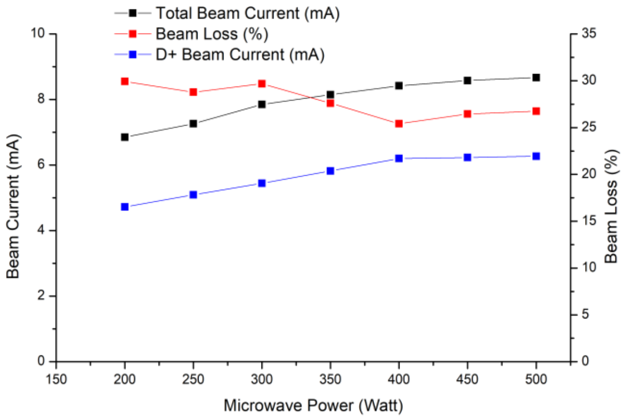
Wire Scanner
(BPM)

It is an alternative beam emittance measurement technique equivalent to standard ***Alison scanner for beam emittance diagnostics***

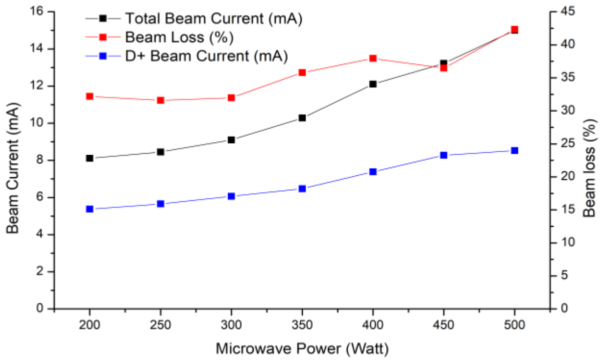
Measurement of D+ Ion Beam Fraction



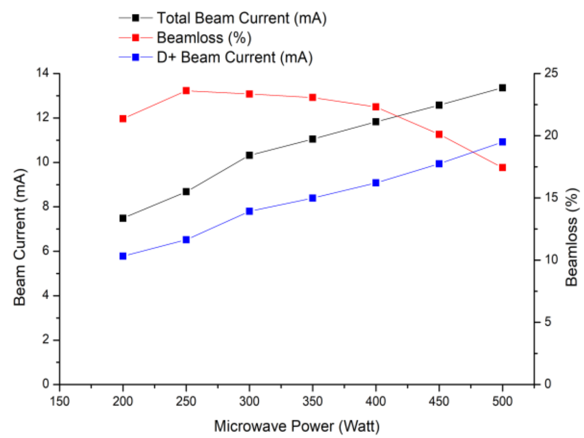
Schematic of the experimental setup for D+ fraction measurement



Measured beam loss as function microwave power at 30 kV extraction

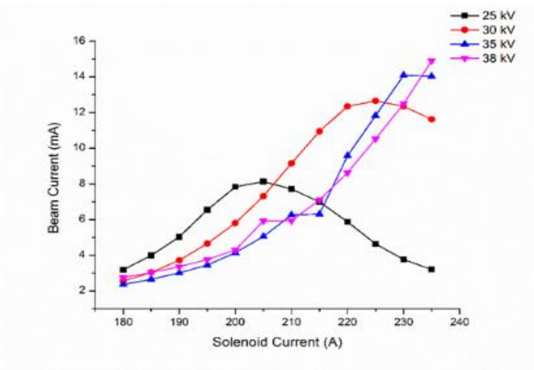


Measured beam loss as function microwave power at 35 kV extraction

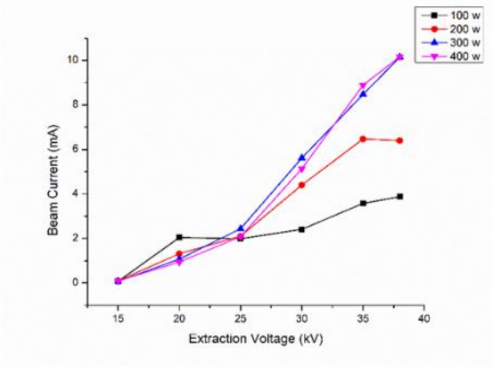


Measured beam loss as function microwave power at 38 kV extraction

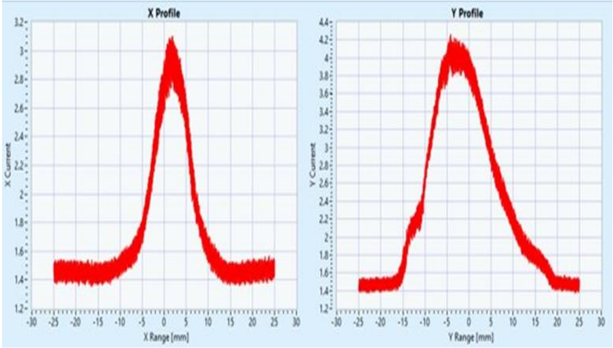
Characterization of deuterium ion beam



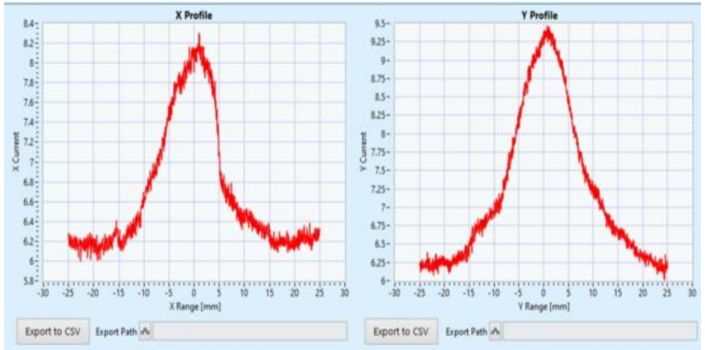
Beam current as function of solenoid current at different extraction voltage



Measured beam current as a function of extraction voltage at different MW power

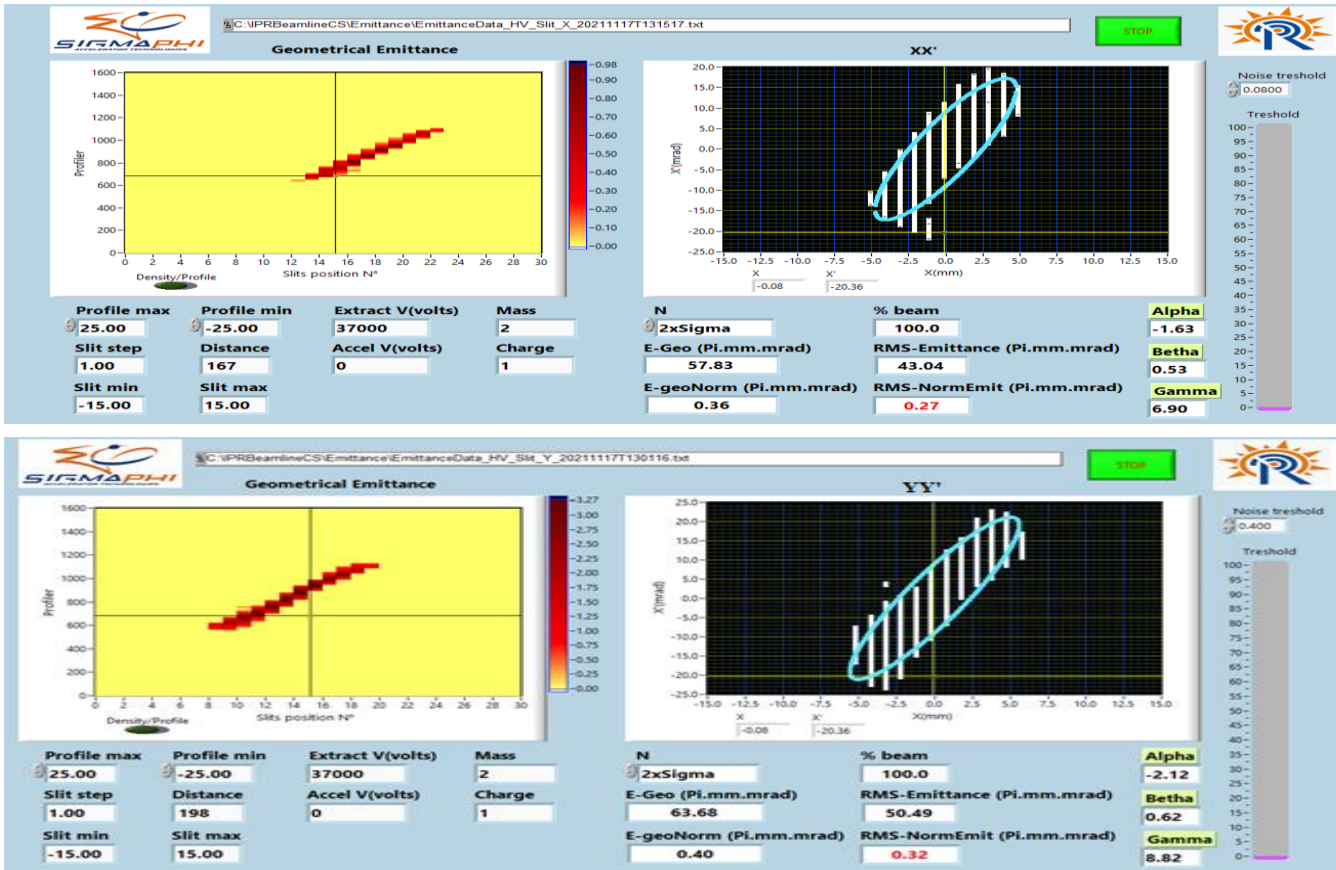


Measured deuterium ion beam profile for 5 mA beam



Measured deuterium ion beam profile for 9 mA beam

Deuterium Ion Beam emittance measurement



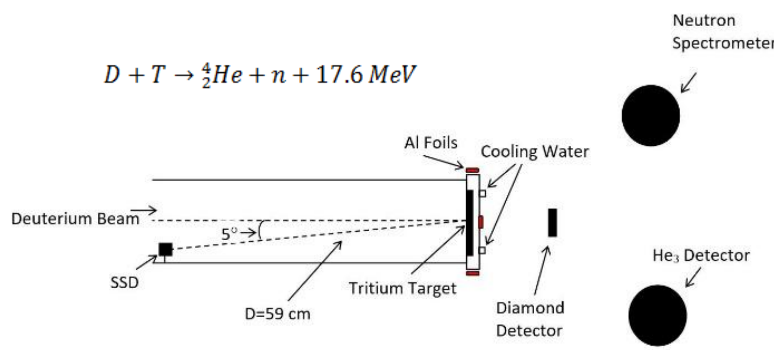
Beam Emittance Measurement results

Neutron Diagnostic systems of 14-MeV NG

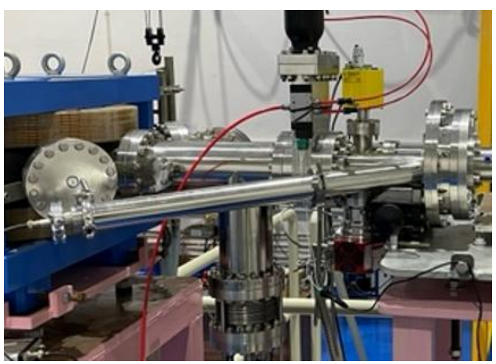
Neutron Diagnostics used to measure neutron yield, neutron flux, and Energy Spectrum

- Foil Activation (Neutron Flux)
- Associated alpha Particle (Neutron Yield)
- He-3 Proportional Counter (Neutron Yield)
- Diamond Detector (Neutron Yield)
- Neutron Spectrometer (Neutron Energy Spectrum)

$$D + T \rightarrow {}^{4}_{2}He + n + 17.6\,MeV$$

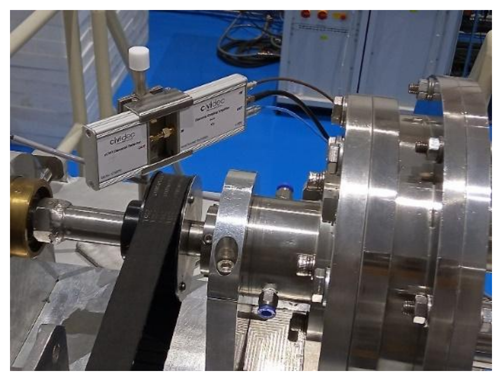


Activation Foils



Associated Alpha particle Diagnostic

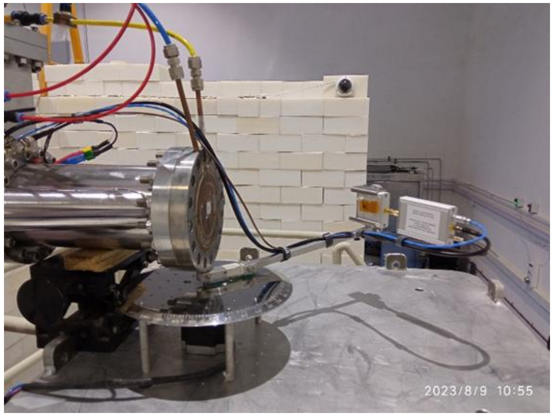
He-3 Neutron Detector



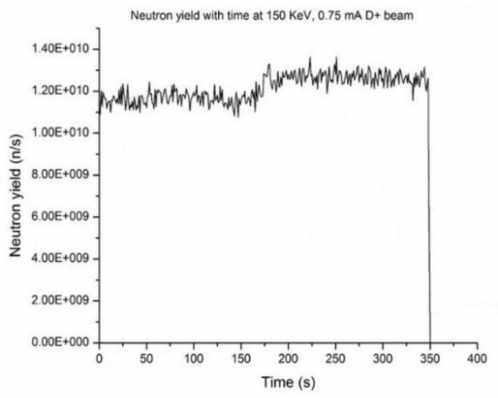
Diamond Detector

Spectrometer

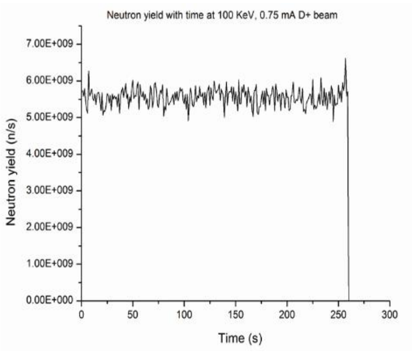
Measurement of Neutron Yield using Stationary Target



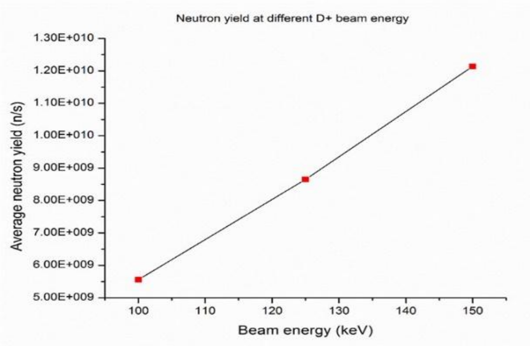
Photograph of the Stationary target assembly



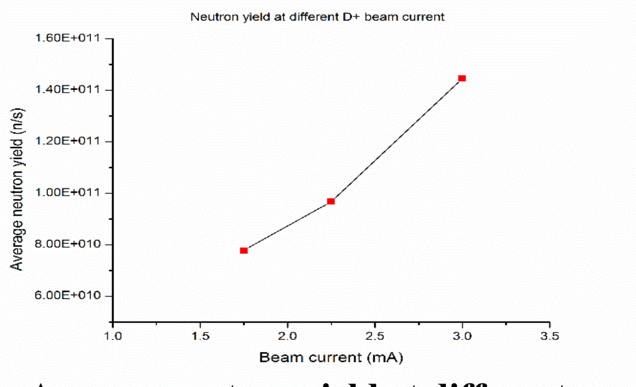
Time profile of neutron emission for 150 keV, 0.75 mA beam



Time profile of neutron emission for 100 keV. 0.75 mA beam



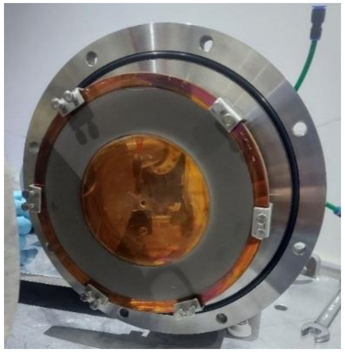
Average neutron yield at different energy at the same current 0.75 mA



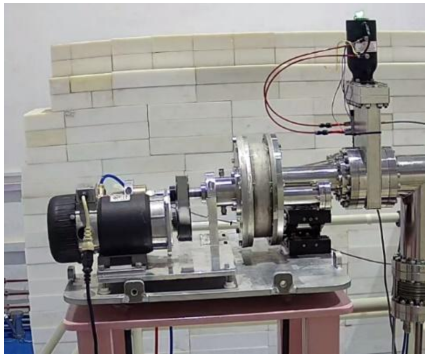
Average neutron yield at different currents with the same energy 200 keV

Measurement of Neutron Yield using Rotating Target

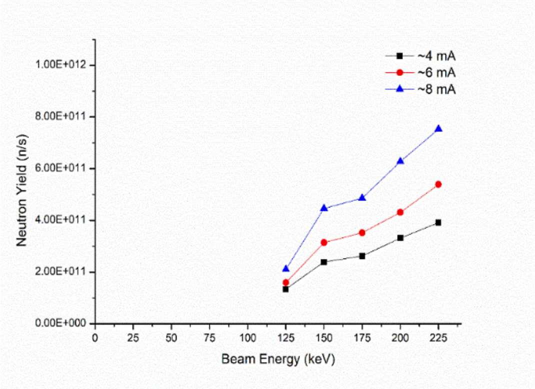
Photograph of 270 Ci TiT target



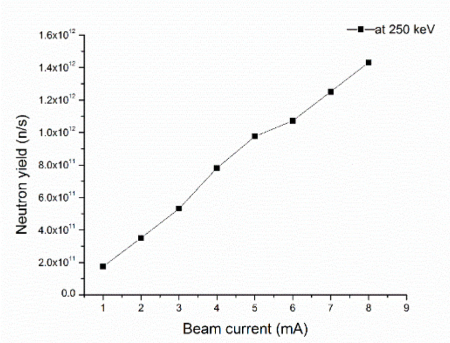
Photograph of TiT target fitted in rotating tritium target holder



Photograph of the Rotating target assembly

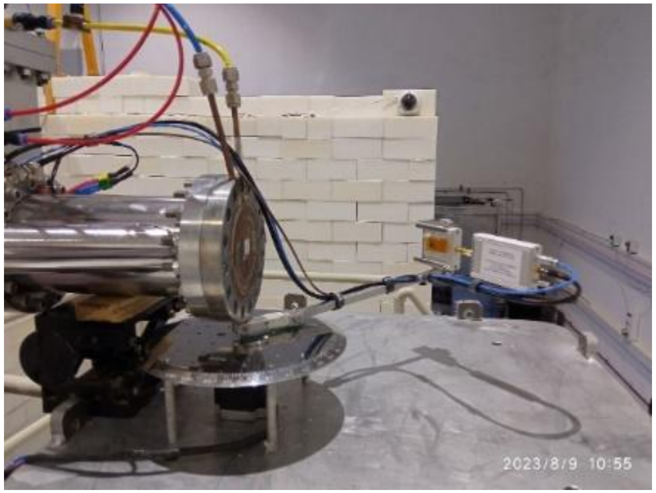


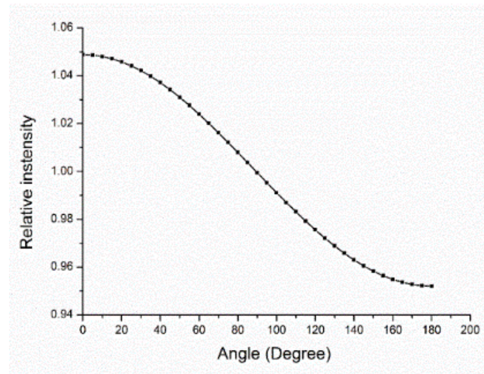
Neutron Yield as a function of beam energy at different beam currents



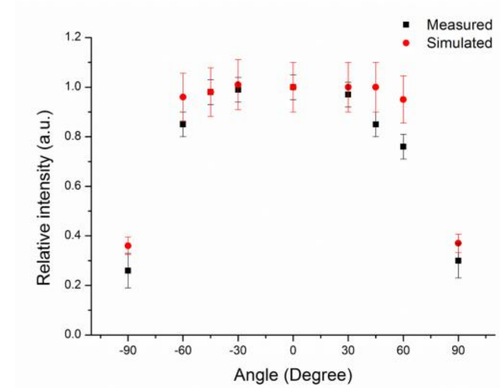
Neutron yield at different beam current

Neutron Emission Characterisation of IPR 14 MeV Neutron Generator

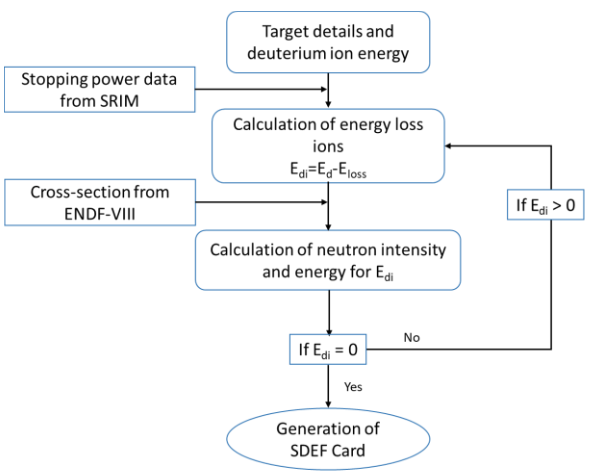


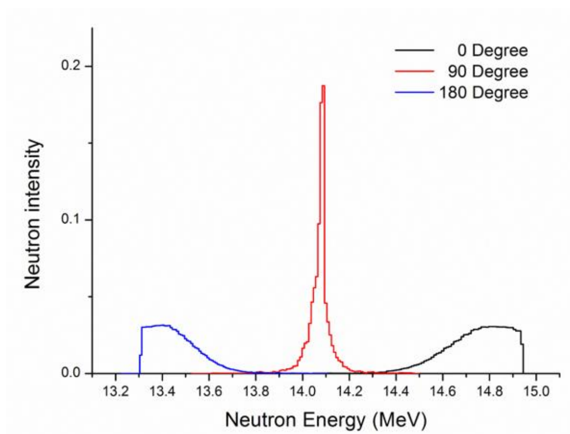


Relative intensity vs emission angle

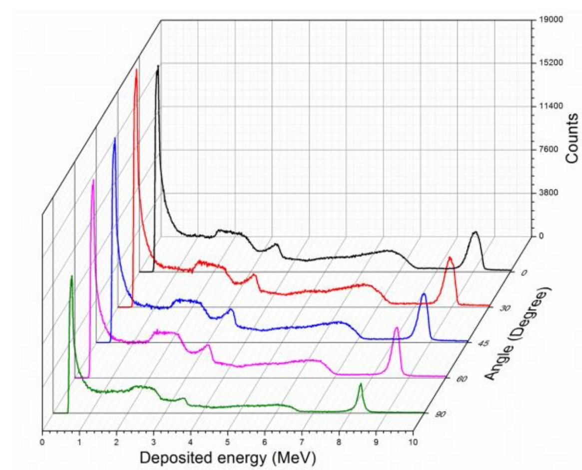


Relative neutron flux





Neutron spectra at different angles



Measured pulse height spectra at different angles

Application of Neutron Generator

Fusion-Related Application of neutron source (Neutron flux in order of >10^{10} N/m^{2}s)

- Cross section measurement,
- Neutron Activation Analysis,
- Nuclear parameter training, benchmark experiments for Fusion Evaluated Nuclear Data Library (FENDL),
- Neutron spectroscopy measurements, double differential cross-section measurements, neutron diagnostics lab scale prototype experiments, characterization of electronic equipment, etc.

Other applications of 14MeV neutrons: (Neutron flux in order of >10^{10} N/m^{2}s)

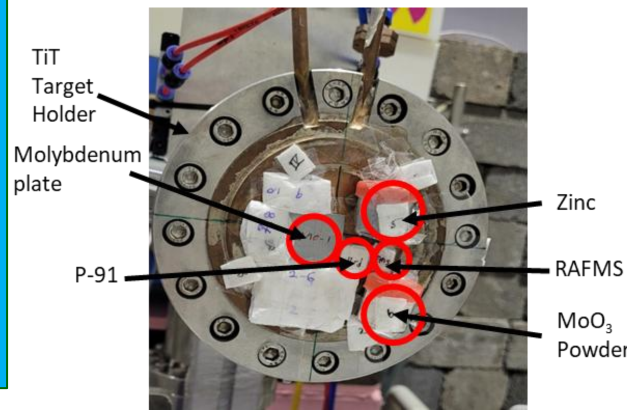
- Radiation hardness testing of Electronics related to space application
- Radiation shielding for space equipment
- Radiation detections for space application
- Applications of neutron imaging include quality assurance, materials research, prototyping, failure analysis, and many other areas of manufacturing.
- Ion irradiation damage studies of space grade materials

D-T Neutron Irradiation Experiments

Plan of Experiment Campaign-1

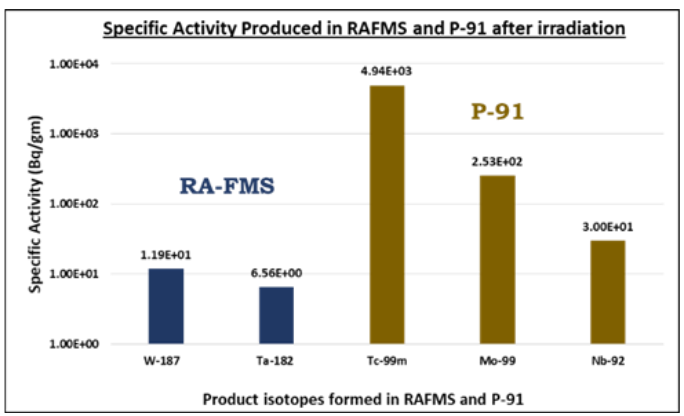
- Feasibility studies on Medical Radioisotope generation (Mo-99) using Molybdenum Foil and Molybdenum Oxide Powder
- Feasibility studies on Medical Radioisotope generation (Cu-64 & Cu-67)
- Activation Studies of P91 and RAFMS

Experimental Setup of different sample



- **Parameter of Neutron Generator**
- **Beam Energy: 150 KeV**
- **Beam Current : 3.5 mA**
- **Total Neutron Produced : 2.40E+14**
- **Time of Neutron Irradiation: 108 min 30 sec**

Results of Experiment



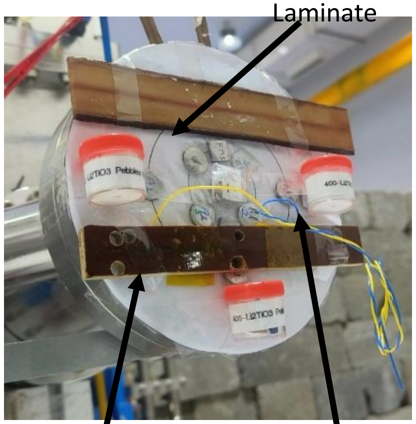
Results of Experiment

Sample	Molybdenum Metal Plate (Mo^{99})	Molybdenum Trioxide (Mo^{99})	Zinc Sample (Cu^{64})	Zinc Sample (Cu^{67})
Mass (grams)	7.01	7.24	18.6	18.6
Activity (kBq)	102	6.867	564	5.175
Specific activity (kBq/gm)	14.54	0.95	30.33	0.28

D-T Neutron Irradiation Experiments

Plan of Experiment Campaign-2

- Neutron Irradiation of Lithium titanate Powder, Lithium titanate Pellets, and Lithium titanate Pebbles for tritium production
- Radiation damage of Opto coupler, FET, PRAM
- Study of electric properties of HTS ReBCO Tape in neutron environment
- Study the shielding properties of Cyanate ester (Composite Laminate)



Experimental Setup of different sample

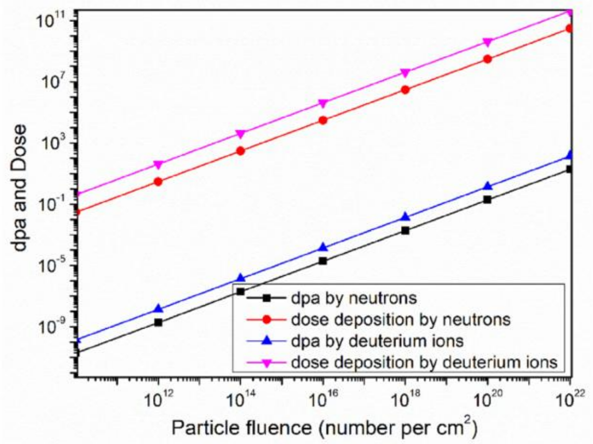
Results of Experiment

- Components were irradiated at different neutrons fluence in step wise.
- After each irradiation step, performance of the components was evaluated.
- Optocoupler got partially damaged at neutron fluence of 5.31E+11 n/cm2 and fully damaged at 1.77E+12 n/cm2.
- Repeatability for damage of Optocouple has been carried out with similar neutron fluence

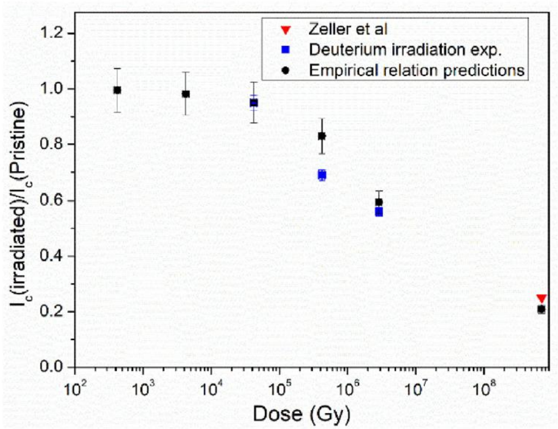
- Parameter of Neutron Generator
- Beam Energy: 150 KeV
- Beam Current : 3.5 mA
- Total Neutron Produced : 5.46E+13
- Time of Neutron Irradiation: 61 min 7 sec

D^+ ion irradiation impact on the current-carrying capacity of DI-BSCCO superconducting tape

- The DI-BSCCO (bismuth-strontium-calcium-copper oxide), YBCO (yttrium barium copper oxide) and REBCO (rare-earth barium-copper oxide) superconducting tapes have the potential to be used in the fusion reactor magnets.
- In the present work, we have irradiated the DI-BSCCO superconducting tapes with the 100 keV deuterium ions to investigate the effect of ion irradiation on their critical current (Ic).



Dose deposition (Gy) and dpa produced by the 100 keV deuterium ion and 14.1 MeV neutrons in the DI-BSCCO tape.



Comparison of the experimental and modelled results.

D-T Neutron Irradiation Experiments Plan for 24-25

- **Investigate the effects of neutron irradiation on ceramic materials regarding its insulation properties relevant to fusion reactors**
  - Select ceramic samples (e.g., alumina-based ceramics) and expose them to neutron flux.
  - Investigate dielectric breakdown, charge transport, and trapping.
- **Radiation Hardness of Electronic Components: Expose electronic components (e.g., integrated circuits, sensors) to neutron flux.**
  - Measure changes in performance, noise, and signal spikes.
  - Assess the impact on accuracy and functionality.
- **Measurement of Tritium production rate in Lithium titanate Powder, Lithium titanate Pellets, and Lithium titanate Pebbles**
- **Benchmarking Medical Isotope Production Using Fast Neutrons**
- **Multipurpose Moderator for Neutron Irradiation Experiments:**
  - Design a versatile moderator for neutron irradiation experiments.
  - Consider materials (e.g. graphite, HDPE, BPE etc) that can moderate neutrons effectively.
  - Optimize geometry and placement to achieve desired neutron energy spectrum.
  - Ensure compatibility with various experimental setups.
  - Measure the neutron yield experimentally and compare with the simulation results.

2.45 GHz ECRIS for Space Plasma Interaction eXperiment (SPIX)

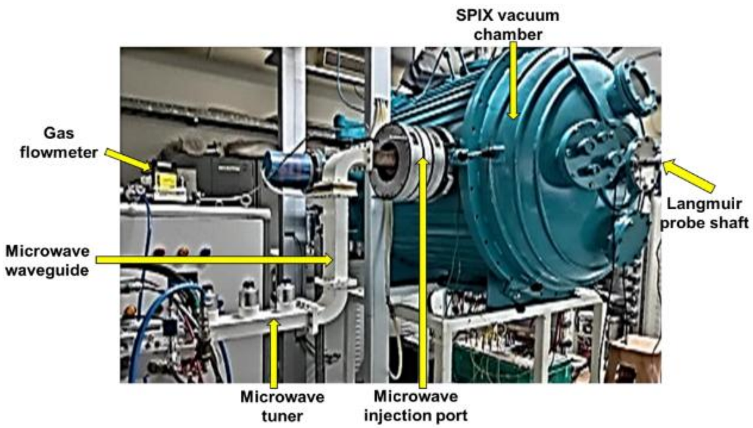
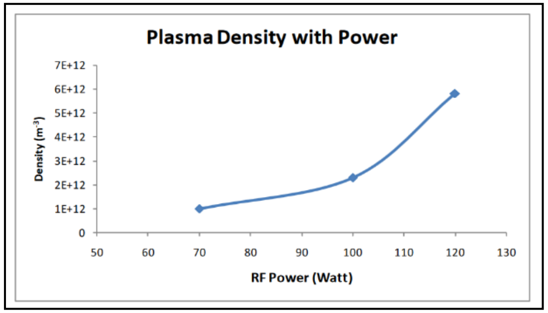
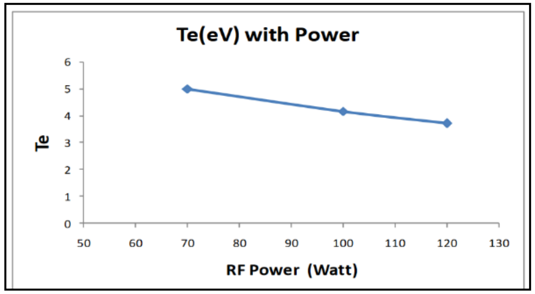


Photo of Experimental Setup



Plasma Density vs power

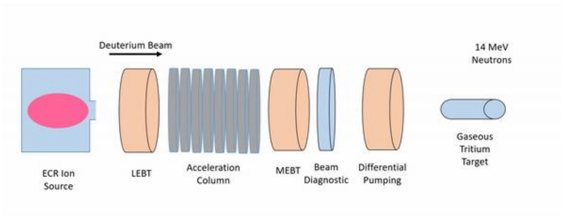


Electron Temp vs power

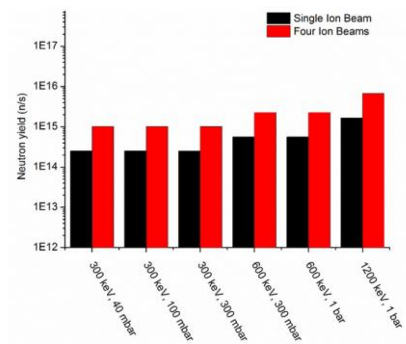
Detachable spherical 1-inch (2.54cm) diameter Langmuir probe head

- 2.45 GHz ECR Ion source has been developed and Integrated with the SPIX vacuum chamber.
- Plasma density and Temperature were measure using Detachable spherical 1-inch (2.54cm) diameter Langmuir probe head as function of microwave power.
- Measured Plasma density & Plasma temperature in the range of 9.8e11 to 5.8e12 m-3 and 3.7 to 5 eV, respectively.

Upgradation Neutron generator using Gaseous Tritium Target for 10^{15} n/s



Animation Accelerator and Gas target based 14- MeV neutron source



Neutron Yield as Function of Beam Energy at different gas pressure

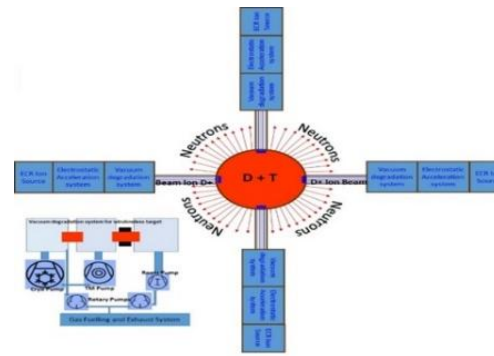
Input Parameters for Calculation

D+ Ion flux: **1.23E17 ions/cm²/s**

D-T Avg. Cross section: **2.47 barns**

Tritium atoms for **40 mbar**: **8.34E20 atoms**

Tritium atoms for four beam target: **3.3E21 atoms**



Schematic of the neutron source of ~ 10^{14} to 10^{15} n/s

Deliverables with roadmap

Phase-1

- Development of all critical component of neutron source such as 100 mA ECR ion source, High current Acceleration system, Gas based tritium target, Differential vacuum system etc.
- Neutron Production(10^{13} n/s.) using single beamline in existing building

Deliverables with roadmap

Phase-2

- Laboratory building for intense neutron source with multibeam line
- Setup intense neutron source facility to generate 10^{14} to 10^{15} n/s
- Set up facility for material testing, neutron radiography, medical isotope production facility inside laboratory building

Deliverables with roadmap

Phase-3

- ➢ Operation of neutron source for design yield
- ➢ Characterization of intense neutron source
- ➢ Start Experiment

SUMMARY

- **An accelerator-based 14-MeV neutron generator has been successfully commissioned at IPR**
- **A robust 14 mA ion beam, containing all species, was successfully extracted from the ion source. Specifically, an 11 mA D+ (deuterium) beam was obtained after passage through the analyzing magnet.**
- **14-MeV neutron generator facility has been successfully developed at IPR for neutron yield of 10e12 n/s.**
- **IPR has capability to do the Neutron Radiography for the Space and aerospace application.**
- **Neutron Generator facility is being used for radiation hardness testing of electronic component used space as well as testing of shielding material for space application.**

Team Members of NIIF

Dr. Sudhirsinh Vala
Head of Facility

Mr. Ratnesh Kumar
Scientific Officer

Mr. H. L. Swami
Scientific Officer

Mr. Mahendra Kumar Panda
Scientific Officer

Mr. Swapnil Choudekar
Technical Officer

Mr. Mitul Abhangi
Scientific Assistant

Mr. Himanshu Sharma
Scientific Assistant

Dr. Varun Savadi
Post Doc. Fellow

Dr. Zara Aftab
Post Doc. Fellow

Mr. Abhishek Saxena
Ph.D. Student

THANK YOU
FOR YOUR
ATTENTIONS !