Negative Hydrogen Ion Sources for Fusion Tutorial for NIBS 2020

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on behalf of the ITER NBI contributors

ITER, France
RFX, Italy
QST, Japan
NIFS, Japan
IPR, India
IPP, Germany
Fusion – The energy source of the sun

Hydrogen $\rightarrow$ Helium

$4H \rightarrow \ldots \rightarrow ^4He + \ldots + 26.7$ MeV

$\beta^+$ decay

15 mill. °C 1.4 mill. km

on Earth: Hydrogen isotopes $\rightarrow$ Helium

Deuterium $^2H$

Tritium $^3H$

from water
0.015%
20 l $\rightarrow$ 0.1 ml

from lithium
$^6Li + n \rightarrow ^4He + T$

Helium

Neutron

$^4He + 3.5$ MeV

n + 14.1 MeV

Energy

D + T $\rightarrow ^4He + n + 17.6$ MeV

Fusion on Earth needs 10 times higher temperature as in the sun!
The fusion experiment ITER

Largest multinational scientific mission.

1985: Project starts
2006: ITER Agreement officially signed
2019: > 65% ready

To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes.

To produce a burning plasma.

Q>10 for 400 s (Q > 5 for 3600 s)
Output (fusion power): 500 MW
Input (heating power): 50 MW

Size: 24 m diameter, 30 m height
Weight: 23 000 tons (3 x Eiffel tower)
Neutral beam systems for ITER

NBI: Neutral Beam Injection of energetic neutral atoms (H or D)
To achieve with ECRH and ICRH the plasma temperatures and profiles for DT phase
Electron \(\uparrow\) Ion cyclotron resonance heating

**Installed power**
- ECRH: 20 MW
- ICRH: 20 MW
- NBI: 33 MW

**NBI Functions**
- Heating
- Current drive
- Plasma rotation
- Diagnostics

**2 + 1 HNB beam lines**
- 1 DHB beam line sharing port with HNB-1

HNB: heating
DNB: diagnostic neutral beam
ITER NBI systems and their requirements

Heating beams (50% EU, 50% JA): **33 MW** (2 injectors) for 3600 s, **1 MeV Deuterium**, **870 keV Hydrogen**

Diagnostic beam (100% IN): **2.2 MW, 100 keV Hydrogen**, 3s ON/20s OFF 5Hz

Source area: 1 m x 2 m

RF-driven ion source
Why negative hydrogen ions?

Neutralisation efficiency at a beam energy of 1 MeV D

Neutralization Efficiency

Energy / (keV/amu)

Neutralization Efficiency

@ 500 kV/amu

Neg. ions
~ 60 %

Pos. ions
< 10 %

Neg. ion based systems make high energy range accessible
JT-60U / JT-60SA, LHD
$U_{\text{acc}} \approx 150$ kV, $j = 20$ mA/cm$^2$

Positive ion based systems are routinely operating world wide
JET, AUG, TFTR, DIII-D, JT-60U, ...
$U_{\text{acc}} \approx 100$ kV, $j \approx 200$ mA/cm$^2$
Concept of ion sources – Arc sources and RF-driven sources

Arc sources

- Hot cathodes (2000 – 3000 K)
- DC voltage (≈ 100 V)
- Arc current (1000 A)

Filaments require regular maintenance

RF sources

- Inductively driven source
- RF power supply (≈ 100 kW)
- RF frequency 1 MHz

Long lifetime, routine operation for positive ions at AUG

Multi-aperture grid system (AUG)
- 774 apertures, 8 mm in diameter
- 3 grids for acceleration & focussing

RF concept chosen by ITER in 2006
NBI systems at LHD at NIFS, Japan

<table>
<thead>
<tr>
<th></th>
<th>negative</th>
<th>positive</th>
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<tbody>
<tr>
<td>Beam energy [keV]</td>
<td>190</td>
<td>80 &amp; 90</td>
</tr>
<tr>
<td>Injection power [MW]</td>
<td>5.5 - 6.9</td>
<td>9</td>
</tr>
<tr>
<td>Pulse length [sec]</td>
<td>10 (max)</td>
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<td>Beam divergence [mrad]</td>
<td>5</td>
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Arc sources, operation mostly in hydrogen

Towards 100 s of $\text{H}^-/\text{D}^-$ beams with 500 keV, 22A (130 A/m$^2$)

Based on arc sources

Achievement of beam acceleration
500 keV, 156A/m$^2$, 118 s
By using 1/8 scale ion source

Achievement of $\text{H}^-$ ion production
15 A for 100 s → under progress

Large ion source & accelerator is combined, and starts from 2023.
R&D for the ITER ion source – a size scaling route

ITER beam lines: HNB, DNB
NBTF: SPIDER, MITICA

800 kW RF power coupled by 8 drivers to illuminate 1280 apertures arranged in 16 beamlet groups

Source area of $1 \times 2 \, \text{m}^2$

Prototype source \(~2 \, \text{A}\)

20 A

40 A

Cs evaporation

BATMAN Upgrade @ IPP

ELISE @ IPP
The test facility for NBI at Consorzio RFX, Italy

**SPIDER @ 100 keV**
started in June 2018

**MITICA @ 1 MeV**
starts in 2023

**Critical challenges:**
- Extraction of 40 A negative ion beam from a large-size RF source
- Acceleration 1 MeV with accurate beam optics
- Development of high-voltage, gas-insulated transmission lines
- Voltage holding (1 MV) over pulses of 3600 seconds

Full ITER beam line
The test facility for NBI at Consorzio RFX, Italy

The beam source of MITICA (full size HNB prototype)
The 1 MeV acceleration R&D at QST, Japan

Vacuum-insulated beam source for ITER

Vacuum insulation design by using meter-class large grid

By using 5-stage accelerator, long pulse MeV-class beam acceleration tests over 100 s – 1000 s

Proof-of-Principle beam acceleration test to support MITICA/NBTF and the final design for ITER
ELISE – A half size ITER source

ELISE is dedicated to

- **Provide input** for design, commissioning and operation of ITER NBI systems
- **Demonstrate** ITER parameters in large sources
  - Extracted currents (ions and electrons)
  - Beam homogeneity
- **Develop** most efficient source operation scenarios

### Parameter and targets

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Plasma: 3600 s
Beam: 10 s every ~150 s (HV supply)
ELISE – A half size ITER source

First plasma and beam: Feb. / Mar. 2013

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The grid system

Three grids

PG and inner surfaces of the ion source are coated with molybdenum to avoid Cs interaction with Cu.

Two segments

Extraction grid

Power density of 32 MW/m² by co-extracted electrons
Present status – Source performance

Extracted current density [A/m²]

- **ITER target H₂**
- **ITER target D₂**

**Record pulses in H₂**
- for 1000 s
- for 3600 s

**Main challenges**
- Cs management
- Long pulses
- Co-extracted electrons

- Short pulses (20 s)
- Long pulses (> 400 s)

**Initial experiments**
- 2013

**Experiments with moderate RF power**
- 2014

**Experiments with high RF power**
- 2015
- 2016
- 2017
- 2018
- 2019

**Solving technical issues**

**Focus on D₂**
Typical long pulse behaviour

Source performance is probed by short pulse extraction of 10 s every 3 min

- **Stable** negative ion current density (within 10%)
- Strong **temporal dynamics** of co-extracted electrons

Interlock of extraction grid is set to 125 kW/segment although designed for 200 kW (ITER: 600 kW for all 4 segments)

Requires careful Cs conditioning and measures to suppress co-extracted electrons
Achievements of ELISE in 2018 – Towards ITER targets

Parameter for hydrogen (almost*) achieved in consecutive pulses

* due to technical limitations (HV power supply & RF generators)

Demonstration of first operational phase at ITER (up to 2035)

Footprint of beam at calorimeter
Deuterium operation – Achievement so far: 200 A/m² (67%) for almost 1 h

**Strong isotope effect in terms of co-extracted electrons**

Transition from hydrogen to deuterium at identical source parameters

- Drastic increase of co-extracted electrons
- Strong increase of Cs density close to plasma grid

at almost the same ion current density

In general: co-extracted electrons

- are factor 2 – 4 higher in D
- limit the source performance
- require more Cs (~ factor 2)
One of the key elements – The Cs dynamics

Simulation of the average Cs flux
Three phases: vacuum, plasma, extraction

- **Back streaming** pos. ions sputter Cs and provide additional Cs
- **Continuous extraction** \(\Rightarrow\) still not sufficient to stabilize Cs flux
- **Unlimited Cs reservoirs** in the back-plate: higher and stable flux

![Simulation graph](image)

**Insights by CW extraction at SPIDER (soon at ELISE)**
Beam characterisation

Diagnostics for beam divergence and homogeneity

Arrangements of apertures
640 apertures, 8 beamlet groups

Beam emission spectroscopy
20 lines of sight

IR calorimetry
2D fit on IR footprint

Grid system

H⁻ BEAM

Vertical array of 16 LoS

Horizontal array of 4 LoS

2.7 m

3.5 m
Beam characterisation: group of beamlets - single beamlet

ITER requires a divergence of < 7 mrad (0.4°) in the core of a single beamlet

ELISE grid system: simulation give a divergence of 0.6 -0.8° (3 grids with max. 60 kV acceleration)

Horizontal LoS sees zig-zag deflection caused by deflection field (EG magnets)

Single beamlet lower than group of beamlets

Agreement with simulation
ITER R&D at dedicated test facility at NIFS, Japan

Versatile diagnostics of plasma and beam for fundamental understanding

H_α image of H⁻ extracted distribution

5 x 3 beamlet pattern on a CFC tile monitored with infrared camera

S. Geng et. al., Fusion Eng. Des. 121 (2017) 481
Roadmap: Beam (operational experience) and technology development in parallel
Learning curve on 3 test beds: ROBIN, TWIN, INTF

- 27 mA/cm² H⁺ beams @ 25 keV
- High Cs consumption (impurity control)
- e⁻/H⁺ > 1
- Experiments restarted after cesiated source cleaning

TWIN TEST BED
- Plasma production exp. initiated (50 kW two drivers)
- RF generator problems
- Accelerator system under proc.
ITER diagnostic beam developed at IPR, India

INTF @ ITER-India lab
Protoype DNB beam line
Unique 21.6 m path length to establish beam parameters and transport

- Several technologies developed enroute
- Components (DNB) under fabrication

Integration and commissioning: Q3 2021
Ion sources for fusion – Take-Home message

- Strong activities for ITER to make it a success!
- International coordination, only feasible with high commitment of participating institutes to ITER.
- Cutting edge physics and technology.
- We are on a good path with many contributions with distributed responsibilities and know-how.
- ITER is prepared with the NBI R&D activities worldwide. In fact, NBTF is the first ITER facility in operation.

- Still huge challenges in front of us
  - Achievement of Deuterium target values
  - Co-extracted electrons limiting the source performance
  - Cs management for large sources
  - 1 MeV holding and beam acceleration with accurate optics
  - Reproducibility and reliability

Fact Sheet

- 40 A, 1 MeV D⁻ for 1 h
- 46 A, 0.87 MeV H⁻
- 60 A, 100 keV H⁻ for DNB
- 800 kW RF (8 drivers), 0.3 Pa
- 7 Electrodes
- 15 beamlet groups
- 1280 beamlets
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