ONGOING R&D TOWARDS A NEW GENERATION OF NEUTRAL BEAM HEATING SYSTEMS FOR FUTURE FUSION REACTORS

ICIS 2017 Conference

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STEADY STATE FUSION REACTOR
“RECIRCULATING ELECTRIC POWER”

Tokamak

3 GW
D-T fusion power

Balance of the plant
~60 MW

Power conversion systems

1.7 GW gross
Electric power

Neutral beam system
Efficiency ~50%

Electric power
Plasma heating
~ 240 MW

Helium pumps (superconducting coils)
~200 MW

Reference: Eurofusion, DEMO2 Alternative_Design_-_March_2015_-__2L4QP3_v1_0
Neutral beam efficiency ~50%

~ 240 MW

Neutral Beam system efficiency ⇔ Main penalty on the electricity production and cost

Challenge: Achievement of powerful neutral beams with efficiency > 50%

~ 1.2 GW Green electric power on the grid

~ 200 MW

~60 MW

1.7 GW gross Electric power
Efficiency of conventional Neutral Beam systems (ITER type)

- 1 MeV D⁻ beam neutralization on gas target
- Only 55% of neutralization rate
- Overall NB system efficiency lower than 28%

➢ The goal of ITER is not to produce electricity!
➢ For future reactors: ITER NBI system efficiency too low!

Need to explore neutralization system with high conversion rate
Photo-neutralization seems ideal
- No gas injection => Strong reduction of D⁻ losses
- Potential High neutralization rate ($\eta > 80\%$)

But
- Low photo-detachment cross-section

$$\sigma \sim 3.6 \text{ to } 4.5 \times 10^{-21} \text{ m}^2 \text{ for } \lambda = 1064 \text{ nm}$$

Photo-neutralization requires photon flux in the MW range
High photon flux ⇔ Resonant Fabry-Perot cavity

Photon power stored within the cavity:

\[ P_{\text{in}} = P_0 \times S \]

\[ P_0 = 1 \text{ kW}, \ S \sim 3000, \ P_{\text{in}} \sim 3 \text{ MW} \]

High cavity sensitivity to variations of the optical length:

vibrations, etc.

\[ \delta \nu \]
Advanced stabilizing technique
Gravitational Waves Detectors (GrWD)

- Locking of the cavity resonance technique: **Pound-Drever-Hall** method
  - Cavity Resonance when: \(2L = q\lambda\)
  - Cavity vibration \(\delta L \propto \delta \lambda\)
  - Active feedback on the external Laser wavelength

**Mature technology**: First GrW detected in 2016 on LIGO facilities (USA):
\[\frac{\delta L}{L} \sim 10^{-21}\]

**Photo-neutralizer**: Requirements on the optical length variation strongly released
\[\frac{\delta L}{L} \sim 10^{-12} \text{ m Hz}^{-1/2} @ 1 \text{ kHz}\]

Achievable with available commercial technology!
Mirror thermo-mechanical deformation under high photon power (CW regime)

- Mirror coating absorption rate ~ 1 ppm
  - 3 MW of photon power => 3 W of thermal power absorbed by the mirror
  - => Thermal distortion of the mirror surface

Mirror distortion (peak 100 nm) => wave deformation => photon scattering (losses)

Need to implement adaptive optics to keep the mirror planarity ~1 nm range

Reference: D. Fiorucci; Ph-D thesis Nice-Sophia Antipolis University, Côte d’Azur Observatory Nice, France; June 2015
Principle of a photo-neutralization Based NB system

Ion source & Pre-accelerator

10A D⁻ beam sheet Width: 1 cm

~15 m

~15 m

Ring cavity (4 mirrors) Amplification: 3000

D⁻ beam sheet crossed by 4 photon beams of 3 MW each

=> 86 % photo-detachment

Photo-neutralizer cell at + 1 MV

~ 8 MW of D° at 1 MeV per sheet

CW 1 kW Laser
Modular concept
⇒ Six beamlines in // per tank
⇒ 45 MW D° per tank
⇒ Overall efficiency: ~70%

Implantation of the NB system on the reactor (Top view)

Photo-neutralization allows to achieve powerful neutral beam with high efficiency
Implantation of the NB system on the reactor
(side view)

Bioshield

~ 20 m

Tank with mirrors

0.2m

Photon beam

1 MeV D°

15m

Technical gallery

Technical gallery

15m

Nuclear island

Tokamak hall

D-T Plasma

Ion source

1 m

Basement

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Photo-neutralization experiment in cavity

Vacuum tank

Optical cavity

Laser
10 W

~1 m

10 kW intra-cavity photon beam

H⁻ beam: 1 keV and 1 mm diameter
Photo-neutralization experiment in cavity
Experimental results

Observation of H⁻ and H⁺ on micro-channel detectors

- 50% photo-detachment achieved in CW regime
- In agreement with cross section

Ion source development for photo-neutralization based NB system
Blade-like negative ion source concept

Side view

Horizontal cross section

1 m

15 cm

Magnetized plasma column

Helicon antenna

accelerator

Co-extracted electrons

accelerator

Cesium layer

coils

Helicon plasma

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Development of a 10 kW helicon antenna (Bird-cage type) at RAID testbed (EPFL)

A 3 kW, 0.3 Pa, B= 12 mT, H₂ plasma jet

Further details: Talk R. Agnello (EPFL); Tuesday, 17th October; 15h20
10 kW helicon antenna

Ion source
1.2 m high
0.1 m width

Accelerator grid
Blade-like beam (1 cm width)

Lateral coils
B~10 mT

First experimental results: Poster I. Morgal (IRFM); Tuesday, 17th October; 16h00
Conclusions

- Photo-neutralization is the only commercial solution for steady state reactors:
  - Advanced performances
    - High neutral power: up to 45 MW per beam tank
    - High wall-plug efficiency: ~70%

Perspectives:

Up to 2020: Finalise the ongoing feasibility studies
- Study of the mirror thermal effects and compensation (adaptive optics)
- Continuation of the R&D on helicon antenna & blade-like beams

After 2020:
- Proposal for a full scale high power (MW range) optical cavity
- The project would imply the involvement of experts in GrW detectors
Thank for your attention!!
3 MW optical cavity specifications

- Photon power in cavity: 3 MW
  - Enhancement factor: 3000
  - Cavity bandwidth: $\delta\nu \sim 150$ Hz
  - Highly stabilized Laser: $\delta\nu/\nu \sim 10^{-24}$

- Ring (recycling) cavity
  - Roundtrip: $L_0 = 120$ m
  - Photon beam width at FWHM: 1 cm

- Advanced mirrors:
  - Reflectivity: 99.998 %
  - Planeity: $\sim 1$ nm
  - Rugosity: $\sim 0.1$ nm
  - Coating absorption rate: < 1 ppm

- Highly stabilized CW Laser, $P_0 \sim 1$ kW
Comparison of the main specifications between the GrW detectors and the photo-neutralizer.

<table>
<thead>
<tr>
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<th>GrWD</th>
<th>Photo-neutralizer</th>
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<tbody>
<tr>
<td><strong>Setup</strong></td>
<td>Two cavities in interference, common</td>
<td>A single cavity : frequency</td>
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<tr>
<td></td>
<td>mode : frequency reference</td>
<td>reference</td>
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<tr>
<td><strong>Mechanical</strong></td>
<td>Achieved&lt;br&gt;&lt; 10^{-20} m Hz^{1/2} @ 100</td>
<td>10^{-12} m Hz^{1/2} @ 1 kHz</td>
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<tr>
<td>vibration</td>
<td>Hz (limited by fundamental noise)</td>
<td></td>
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<tr>
<td><strong>Stored photon</strong></td>
<td>Achieved: 100 kW on LIGO</td>
<td>3 MW</td>
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<tr>
<td><strong>power</strong></td>
<td>Advanced LIGO objective: 700 kW</td>
<td></td>
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<tr>
<td><strong>Cavity</strong></td>
<td>Roundtrip: 6000 m (linear cavity)</td>
<td>Roundtrip: 120 m (ring cavity)</td>
</tr>
<tr>
<td><strong>Mirrors</strong></td>
<td>Achieved&lt;br&gt;Diameter: ~30 cm&lt;br&gt;Planeity:</td>
<td></td>
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<td>&lt; 0.5 nm RMS&lt;br&gt;over Ø=15 cm&lt;br&gt;Roughness: &lt; 0.1 nm RMS&lt;br&gt;Coating absorption: 1 ppm</td>
<td>Diameter: 10 cm&lt;br&gt;Planeity: 1 nm RMS&lt;br&gt;over Ø=5 cm&lt;br&gt;Roughness: 0.1 nm RMS&lt;br&gt;Coating absorption: 1 ppm</td>
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<td><strong>External CW Laser</strong></td>
<td>Achieved&lt;br&gt;Power : 200 W&lt;br&gt;Single mode, single frequency, Locked on the cavity</td>
<td>Power : 1000 W&lt;br&gt;Single mode, single frequency, Locked on the cavity</td>
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**Color code:**
green: available technology; red: future R&D objectives
Signals of GrW detected by the twin LIGO observatories:

- Livingston, Louisiana
- Hanford, Washington

Superposition of the two signals ⇒ Same event

⇒ Detection level: $\delta L \sim 10^{-21}$ m
Laplace laboratory (Toulouse, France)
Development of numerical models for Cybele

⇒ Physics of the magnetized plasma column
⇒ Physics of the negative ion extraction

Validation by experiment on Cybele

$B = 7 \, \text{mT}, \ E \sim 1 \, \text{V/cm}$

Diamagnetic plasma rotation
$E \times B$

2D simulation PIC MCC model of the negative ion extraction from the magnetized plasma (side view)

2D simulation PIC MCC model of the magnetized plasma column (Horizontal cross section)