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

ICIS 2017 Conference

Alain SIMONIN
IRFM, CEA CADARACHE
France

GENEVA, 16th October 2017
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%

RF

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%

~60 MW

~200 MW

~1.7 GW gross Electric power

~1.2 GW Green electric power on the grid
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

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

Photo-neutralization requires photon flux in the $\text{MW range}$
High photon flux ⇔ Resonant Fabry-Perot cavity

High reflectivity mirrors

L = L₀ n

Resonance ⇔ 2 L = q λ ⇔ Constructive interferences

Photon power stored within the cavity:

Pᵢᵣ = P₀ x S

P₀ = 1 kW, S ~3000, Pᵢᵣ ~ 3 MW

Pᵢᵣ => δν

High cavity sensitivity to variations of the optical length:

vibrations, etc.
Locking of the cavity resonance technique: **Pound-Drever-Hall method**

Cavity Resonance when: \( 2L = q\lambda \)

\[ \delta L \propto \delta \lambda \]

Cavity vibration

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 coating absorption rate $\sim 1$ ppm

$3$ MW of photon power $\Rightarrow 3$ W of thermal power absorbed by the mirror
$\Rightarrow$ Thermal distortion of the mirror surface

$\delta L \sim 100$ nm

Mirror temperature distribution

Reference: D. Fiorucci; Ph-D thesis
Nice-Sophia Antipolis University,
Côte d’Azur Observatory
Nice, France; June 2015

Mirror distortion (peak $100$ nm) $\Rightarrow$ wave deformation $\Rightarrow$ photon scattering (losses) !

Need to implement adaptive optics to keep the mirror planarity $\sim 1$ nm range
Principle of a photo-neutralization Based NB system

Ion source & Pre-accelerator

10A D⁻ beam sheet Width: 1 cm

3 m

~15 m

10 cm

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%

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

0.2 m

Photon beam

1 MeV D°

Technical gallery

15m

Technical gallery

15m

Basement

15m

Tokamak hall
Nuclear island

D-T Plasma

Ion source

3 m

Implantation of the NB system on the reactor (side view)
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 $H^0$ 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**

- **Helicon antenna**
- **accelerator**
- **Magnetized plasma column**

**Horizontal cross section**

- Co-extracted electrons
- Accelerator
- Cesium layer
- Coils

**Dimensions**

- 1 m
- 15 cm
- 1 cm
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: $\delta v \sim 150$ Hz
- Highly stabilized Laser: $\delta v/\nu \sim 10^{-24}$

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

Mirror $\Phi = 10$ cm
Comparison of the main specifications between the GrW detectors and the photo-neutralizer.

<table>
<thead>
<tr>
<th></th>
<th>GrWD</th>
<th>Photo-neutralizer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Setup</strong></td>
<td>Two cavities in interference, common mode : frequency reference</td>
<td>A single cavity : frequency reference</td>
</tr>
<tr>
<td><strong>Mechanical vibration mitigation level</strong></td>
<td>Achieved:  $&lt; 10^{-20}$ m Hz$^{-1/2}$ @ 100 Hz (limited by fundamental noise)</td>
<td>$10^{-12}$ m Hz$^{-1/2}$ @ 1 kHz</td>
</tr>
<tr>
<td><strong>Stored photon power</strong></td>
<td>Achieved:  100 kW on LIGO</td>
<td><strong>3 MW</strong></td>
</tr>
<tr>
<td></td>
<td>Advanced LIGO <strong>objective:</strong> 700 kW</td>
<td></td>
</tr>
<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:  Diameter: ~30 cm \ Planarity: $&lt; 0.5$ nm \ RMS \ over $\phi$=15 cm \ Roughness: $&lt; 0.1$ nm \ RMS \ Coating absorption: 1 ppm</td>
<td>Diameter: 10 cm \ Planarity: 1 nm \ RMS \ over $\phi$=5 cm \ Roughness: 0.1 nm \ RMS \ Coating \ absorption: 1 ppm</td>
</tr>
<tr>
<td><strong>External CW Laser ((\lambda)=1064 nm)</strong></td>
<td>Achieved:  Power : 200 W \ Single mode, single frequency, Locked on the cavity</td>
<td>Power : 1000 W \ Single mode, single frequency, Locked on the cavity</td>
</tr>
</tbody>
</table>

*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
Development of numerical models for Cybele

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

Validation by experiment on Cybele

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

Diamagnetic plasma rotation

$$\mathbf{E} \times \mathbf{B}$$

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