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Towards a new generation of neutral beam system for future fusion reactors

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***Abstract*— The operation of a fusion reactor will involve the injection in the plasma core of high energy (1 MeV) high power deuterium atom beams. These systems called Neutral Beam Injectors (NBI) are based on the acceleration of several tens of amperes of deuterium negative ion (D^-) beams. Furthermore, in conventional NBI systems, the neutralization of the negative-ion beam, which occurs by collisions with a gas target (D_2), is limited to 55 % and is at the origin of an important loss of negative-ions during the acceleration and of heavy thermal loads. The overall injector efficiency will be low, ranging around 25 %. CEA-IRFM, with academic laboratories in France and EPFL Switzerland, is presently studying a new generation of NBI system dedicated to future fusion reactors. They aim at demonstrating the feasibility of D^- beam neutralization by photo-detachment where a high power photon flux (~3 MW) generated within a Fabry-Perot cavity will overlap, cross and partially photo-detach a high current 1 MeV negative ion beam sheet, leading to a more-than-90% photo-detachment rate. The aspect ratio of the beam-line is specifically designed to maximize the overlap of the ion beam by the photon beam. The article presents the principle and features of this new injector concept, and the main achievements of the related R&D.**

Index Terms— Neutral beam Injection, Photo-neutralization, Helicon antenna, negative ion beams.

I. Introduction

The ignition phase of future fusion machines requires more than 50 MW of external heating power in addition to the natural ohmic heating produced by the tokamak plasma inductive current. This external heating will be partly provided by the NBI (Neutral Beam Injector) system, which is based on the injection of powerful energetic beams of neutral atoms (D° at 1 MeV) carrying kinetic energy into the plasma core

In conventional NBI systems (ITER type), the source is connected to a multi-gap, multi-aperture electrostatic accelerator, which accelerates negative ions from the source up to 1 MeV. This powerful ion beam is then partially neutralized in a gas cell, the so-called “neutralizer” where stripping reactions occur ($D^-_{fast} + D_2 \rightarrow D^0_{fast} + D_2 + e^-$), which cause part of the NI beam to be converted into energetic neutrals. Beam neutralization on a gas target is a simple and reliable method, but the neutralization efficiency is limited to 55 % and this process requires a large amount of injected gas. In spite of a very high pumping speed provided by cryopumps (~5 10^6 l/s of pumping speed), it is the main cause of high background pressure in the accelerator, leading to heavy D^- beam losses (~28% D^- losses) [1,2], and a poor performance in term of electrical efficiency (less than 25%) on ITER. It is apparent that for the next fusion reactors, there are significant advantages to greatly reducing the gas load and increasing the neutralization efficiency. Given the scientific objectives of ITER, it is crucial that next-generation of NBI systems be more efficient, by implementing novel technologies which surpass today’s performances.

II. Photo-neutralization of negative ion beams

Other neutralization concepts have been explored worldwide over the last decades, i.e., neutralization by metal foils, other gas, alkali metal vapor jets [3], by plasma [4], beam-beam neutralization with high current RF quadrupoles [5]. All of them have faced major issues, such as additional pollution, increase of the beam divergence, huge electrical power consumption and are consequently not seriously considered as reactor relevant by the fusion community.

IRFM, in collaboration with academic laboratories in France and EPFL (Lausanne, Switzerland), has performed since 2008 [6], a feasibility study of NI beam neutralization by photo-neutralization [7]: a photon with an energy hν large enough, i.e. at least as energetic as the extra-electron’s binding energy of the D^- (~0.75 eV) ion, can be absorbed by the energetic anion and trigger a detachment reaction:

$$D^-_{fast} + h\nu \rightarrow D^0_{fast} + e^- \text{ (photo-detachment process).}$$

Photo-neutralization coupled to an adapted Negative Ion (NI) source simultaneously offers a complete suppression of the gas injection in the neutralizer and, potentially, an excellent beam neutralization rate. The new injector concept takes an original and fundamentally novel route for NBI, proposing a photo-detachment based neutral beam system and aims at more than 70 % electrical efficiency, by reducing the collateral loads. Preliminary works have led to significant advances in the comprehension and control of underlying fundamental processes of a photo-neutralizer. On the other hand, to reach the highest photo-neutralization rates, the interaction of the initial NI beam with the photo-detaching laser beam has to be maximized requiring a novel high-energy NI beam system which is in complete scientific and technological rupture with the conventional one. This consists in the development of an intense blade-like negative ion beam to maximize the overlap by the photon beam.

III. Present state of knowledge on a Photo-neutralization based NBI system

The main outcomes of the feasibility studies performed over the last few years regarding the new injector concept are as follow:

-i) The photo-detachment cross-section has been measured to be in the range of σ =3.6 to 4.5 10^{-21} m^2 for λ= 1064 nm [8,9]. It gives insight into the way of designing both the beamline and its photo-neutralizer. Indeed, for a 1 MeV D^- beam sheet of 1 cm width, neutralization rate of 50 % requires a photon beam of 3 MW.

-ii) This high power photon beam could be achieved within a high finesse (10,000) Fabry-Perot optical cavity powered by a 1 kW CW mono-frequency highly stabilized laser [7]. Indeed, the constructive interference at resonance which occurs between reflected waves results in a substantial enhancement (amplification) of the intra-cavity power with respect to the incoming one.

-iii) The photo-neutralization of a H^- beam in a Fabry-Perot cavity at reduced scale (see Fig. 1) was recently demonstrated experimentally at the Aimé Cotton Laboratory (LAC) at Orsay (France): a 1.2 keV H^- beam crosses the intra-cavity 10 kW continuous wave photon beam. The cavity amplification is ~1000. It is filled with an external 10 W laser, and the photo-detachment rate amounts to ≈ 50% as expected.

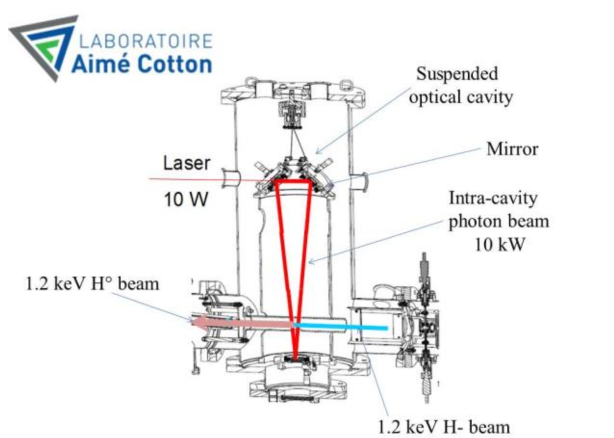

Fig. 1: Reduced scale photo-neutralization testbed at LAC.

iv) The optical cavity is insensitive to the ion beam current: A 10 A D^- ion beam corresponds to only 2,5 $\times 10^{20}$ ions/s, while a 3 MW light beam represents 1.6 x 10^{25} photons/s. Then, the photo-detachment of such ion beam only uses 10 W of laser power out of the 3 MW intra-cavity beam [7].

v) The cavity is composed of four high reflectivity mirrors (mirror diameter ~10 cm) implanted above and below the ion beam (see Fig. 2); the intra-cavity laser beam propagates in the same plane as the ion beam. Under this specific arrangement, the 1 MeV D^- beam is crossed by four 3 MW laser beams (providing 50 % photo-detachment each) leading to a neutralization rate of 93 %, and a neutral beam power of 9 MW per beam sheet.

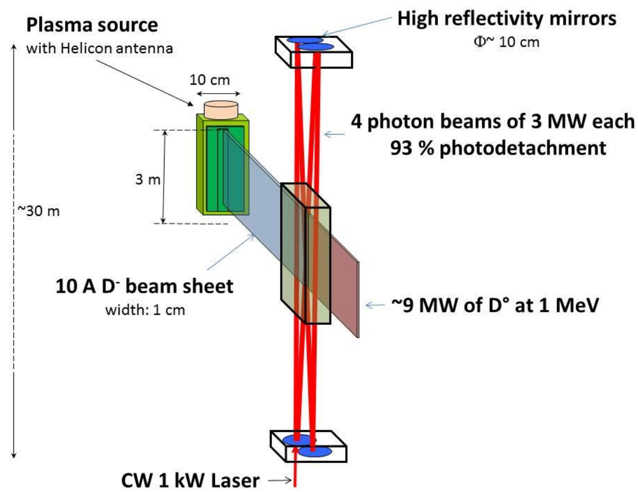

Fig. 2: Implantation of the optical cavity along a single ion beam sheet. The energetic ion beam sheet is fully overlapped and crossed by four intra-cavity photon beams of 3 MW each leading to 93% of photo-neutralization.

-vi) The optical tanks containing the mirrors (under high vacuum ~10^{-5} Pa) will be located in technical galleries (outside the reactor nuclear island), 15 m above and below the injector tank to protect them against the harsh reactor environment (see Fig. 3). Moreover, to prevent misalignment due to mechanical vibrations of the reactor building and the seismic noise, passive and active mechanical mitigation systems will contribute to keep the mirror fine alignments.

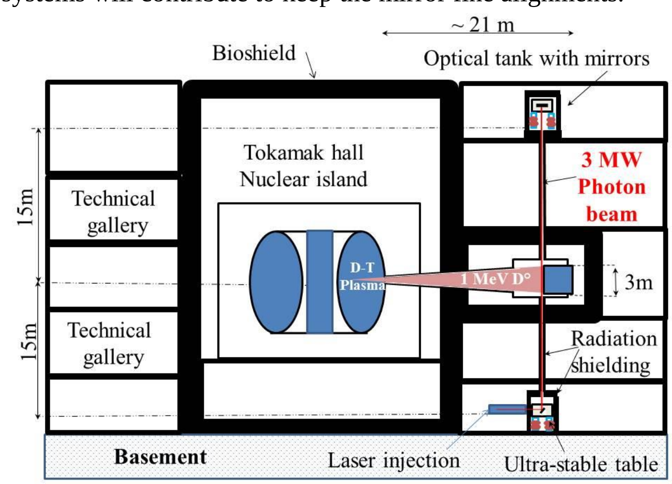

Fig. 3: Implantation of a photo-neutralizer in a reactor building.

The photo-neutralizer concept is partially based on the Gravitational Wave (GrW) detectors technology, which recently proved its maturity with the detection of gravitational waves at the LIGO facility [10]. However, major differences between the GrW detectors and a photo-neutralizer of course exist (see table1): GrW detectors accommodate a Fabry-Perot Michelson interferometer with a stored photon power of 100 kW on the LIGO facilities[10]. One of the next objectives of “Advanced LIGO” is to increase the stored photon power up to 700 kW [11], that remains moderate when compared to a photo-neutralizer (target: 3 MW stored power).

GrW detectors are designed to sense extremely small relative changes of the two cavity arm lengths in interference ($\delta L/L = 10^{-21}$ at around 100 Hz [10, 11]). As a consequence, when compared to the extreme specifications required for GrW detectors, the specifications, as concerns the sensitivity to different noises, like mechanical vibrations, are much less stringent for a photo-neutralizer (see table 1), the sole function of which is to store a high photon power.

	GrWD	**Photo-neutralizer**
Setup	Two cavities in interference, common mode : frequency reference	A single cavity : frequency reference
Mechanical vibration mitigation level	**Achieved** $< 10^{-20}$ m Hz$^{-1/2}$ @ 100 Hz (limited by fundamental noise)	10^{-12} m Hz$^{-1/2}$ @ 1 kHz
Stored photon power	**Achieved:** 100 kW on LIGO Advanced LIGO **objective:** 700 kW	**3 MW**
Cavity	Roundtrip: 6000 m (linear cavity)	Roundtrip: 120 m (ring cavity)
Mirrors	**Achieved** Diameter: ~30 cm Planeity: < 0.5 nm RMS over Ø=15 cm Roughness: < 0.1 nm RMS Coating absorption: 1 ppm	Diameter: 10 cm Planeity: 1 nm RMS over Ø=5 cm Roughness: 0.1 nm RMS Coating absorption: 1 ppm
External CW Laser (λ=1064 nm)	**Achieved** Power : 200 W Single mode, single frequency, Locked on the cavity	**Power : 1000 W** **Single mode, single frequency, Locked on the cavity**

Table 1: Comparison of the main specifications between the GrW detectors and the photo-neutralizer. Color code: green: available technology; red: R&D objective.

An issue, due to this stored power, is that the power absorbed by the mirrors can indeed lead to some perturbation, in spite of the high mirror reflectivity and low photon absorption rate (~ 0.5 to 1 ppm range). The power (~ 1 to 3 W) absorbed by each mirror coating from the 3 MW photon flux may induce a thermo-mechanical deformation [12] large enough to perturb the optical performance of the cavity. This thermal problem still requires specific studies both for the development of advanced mirrors and adaptive optics, and for compensation of the thermal distortion (thermal lensing), to control the mirror planeity in the nanometer range, maintain the mode stability within the cavity and minimize the intra-cavity diffraction losses.

At this time, 200 W single mode and single frequency laser amplifier is available. It could represent the elementary component for ~1 kW laser system based on coherent beam combination [13, 14, 15].

-vii) The beamline has to be designed to provide a 1 MeV, 10 A D^- ion beam sheet of 1 cm in width in the photo-detachment region, which has to be crossed and fully overlapped from top to bottom by the intra-cavity Gaussian $TEM_{0,0}$ photon beam propagating in the plane parallel to the ion beam (see Fig. 2). The beam sheet is created by a long (3 metre high) and thin ion source referenced to the ground potential (see on Fig. 4, the potential distribution along the injector), while the neutralizer cell is held at the high voltage (1 MV); the overall injector electrical setup is greatly simplified by comparison with the source held at the high voltage on conventional NB systems.

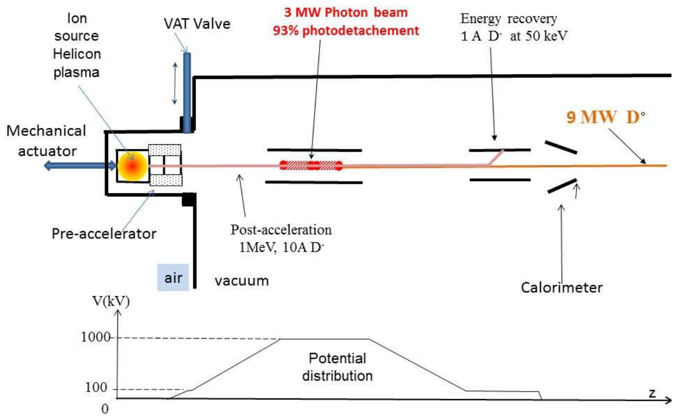

Fig. 4: Principle of one beam sheet (Top view)

The D^- are extracted from the ion source, accelerated and shaped in a blade-like beam up to 100 keV in the pre-accelerator stage by the use of electrodes (grids) with slotted apertures. With photo-neutralization (no gas injection in the neutralizer cell), the background pressure along the beam is very low (~10^{-4} Pa), the D^- stripping losses are negligible (with less than 1% in the post-acceleration gap, there is no need to intercept the stray electrons), thus a single gap accelerator (to 1 MeV) is proposed. The 1 MeV non-neutralized fraction of negative ions (D^-) can be decelerated at the exit of the photo-neutralizer cell down to a low energy (~50 keV) and collected onto the cooled recovery electrode, decreasing in this way the load of the 1 MV power supply.

This energy recovery system allows attaining very high overall injector efficiency (~70%) even with incomplete photo-neutralization. The nickname "SIPHORE" of this new injector concept stands for SIngle gap accelerator with PHOto-neutralization and energy REcovery system.

An important feature of the device is that the power required by the external laser (which fills the 3 MW optical cavity) is in the range of a few kW and is thus negligible with respect to the overall power consumption.

The ion source being grounded, the set "ion source and pre-accelerator" is movable along the beam axis (see Fig. 4) via a mechanical actuator. This feature allows to finely adjust the post-acceleration gap length to match with the ion beam optics (the negative beam intensity). Moreover, keeping the same operating conditions on the source and pre-accelerator, i.e., 10 A of D^- at 100 keV, the injector can operate over a wide energy range, i.e., from 100 keV during the ramp-up phase and then, a progressive increase of the beam power and energy up to 1 MeV to comply with the heating and current drive phases.

viii) A complete SIPHORE beamline would be composed of several independent beam sheets (beam modules) implanted side by side and spatially oriented to focalize each neutral beam sheet within the Tokamak aperture (input port). Fig. 5 shows a beamline powered by an ITER-type power supply (1 MV 60 A) with six beam modules in parallel; the total neutral power coupled to the plasma core would be 48 MW.

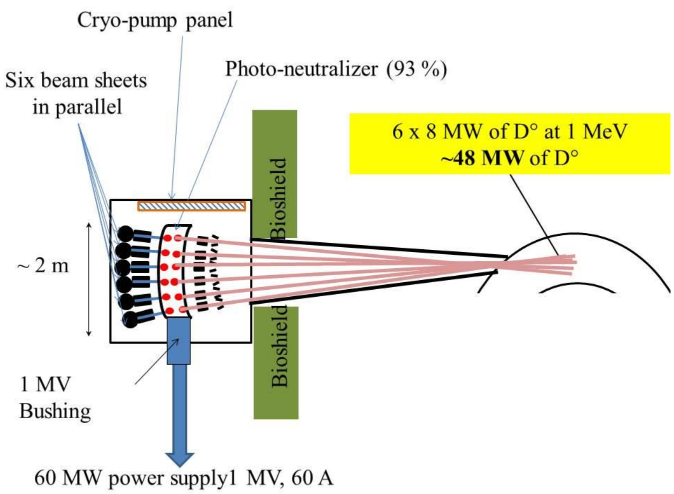

Fig. 5: Top view of the SIPHORE injector based on six beam modules in parallel. The neutral power injected in then plasma core ranges around 48 MW.

This modular concept, where each set of ion source and pre-accelerator is independent and referenced to the ground potential, benefits from other noticeable advantages:

-1) the modularity offers more flexibility and degrees of freedom to finely tune each source and pre-accelerator parameter (D^- current density, extraction voltage, etc.) in order to control each ion beam optic.

-2) keeping a constant drain current on the main power supply (1 MV 60 A power supply), each beam sheet can be independently triggered (or interrupted) in the microsecond range by the conventional high-speed circuit breakers (Tetrode) of the pre-accelerator power supplies. Thus, the power deposition in the plasma could be temporally and spatially modulated (like a gun-machine);

-3) this topology should ease the source and pre-accelerator maintainability by remote handling (see Fig. 6): intermediate gate vacuum valves (with vertical gate displacements) can be implanted between the injector vacuum tank and the source tank: each set "ion source & pre-acc." can be independently disconnected (or plugged) without any deconditioning (without breaking the vacuum tank) of the injector.

-4) With the grounded ion source connected to the tritium plant of the reactor, energetic tritium beams could be envisaged. Each T° beam would provide plasma heating, current drive and efficient fueling of the plasma core.

A reactor equipped with four NB tanks providing each 50 A of energetic T°, i.e., 1.25 x 10^{21} T° per second, would fully replenish the tritium fuel burn-up in the plasma core. This direct tritium injection in the core would minimize the overall tritium consumption by the plant.

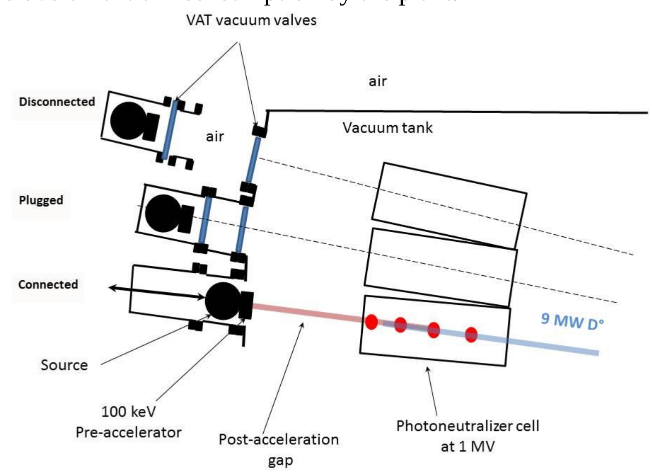

Fig. 6: Implantation of the set "source & pre-accelerator" for a high injector availability and an easy maintainability by remote handling.

IV. Ion source development for SIPHORE

The high aspect ratio of the injector requires the development of a new ion source and accelerator to provide the 10 A of D^- per sheet at the relevant D^- current density extracted from the plasma source, namely J_{D^-} ~250 A/m^2. Conventional NI sources (ITER type), relying on a radio-frequency (RF) inductively coupled plasma which crosses a transverse magnetic barrier are impacted by a plasma asymmetry due to the Hall effect [16-18]: the plasma is polarized, resulting in a vertical electron magnetic drift, while the positive ions are non-magnetized. Figure 7 shows the vertical electron current density perpendicular to the magnetic field lines [18] occurring in the ITER source prototype with only one RF driver at the back (BATMAN source at IPP Garching [19]). This plasma asymmetry was first described by numerical models [20] and later observed in the experiments [19, 21].

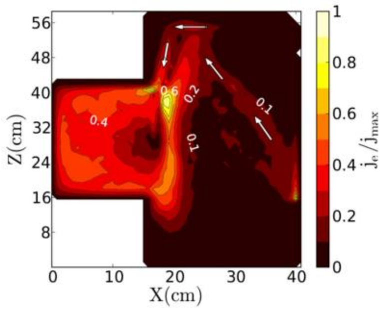

Fig. 7: 3D simulation of the electron flow (vertical cross section) in the BATMAN source (ITER source prototype with one driver). The extraction grid is the YZ plan on the right. It is clear that this source concept cannot be adapted for the production of a long blade-like NI beam which requires a high D⁻ extracted current uniformly distributed over the 3 m long (and thin) extraction surface.

A new ion source, called "Cybele", is under development at IRFM (see Fig. 13); it is based on a magnetized plasma column (B // to the source vertical axis) supplied by a high power (10 kW) resonant helicon antenna (see Fig. 8).

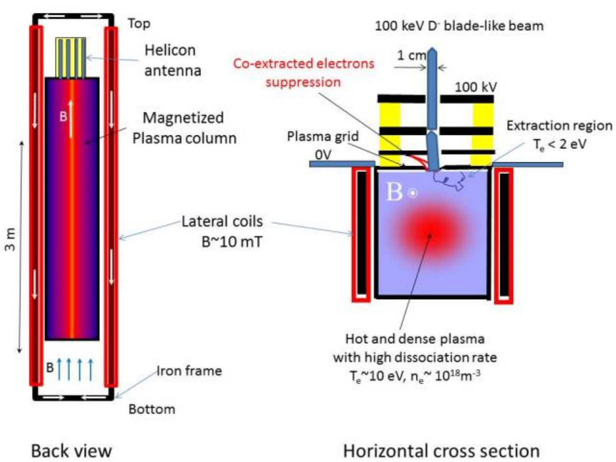

Fig. 8: Principle of the ion source concept:

Left: *Back view of the source with the two lateral coils which generate a uniform vertical magnetic field (B~10 mT) in the source volume.*

Right: *Horizontal cross section of the source and 100 keV pre-accelerator: the D⁻ beam is extracted from the plasma source by a slit aperture on the plasma grid, the co-extracted electrons are deflected by the vertical magnetic field diffusing from the source.*

The vertical magnetic field in Cybele is created by the leakage magnetic field of two external electric coils sitting on both sides of the source (see Fig. 8 left and Fig. 13). The coils are set around an iron rectangular core to enhance the B-field intensity in the source volume up to 13 mT. The negative ions (NI) will be mainly produced both in the plasma volume (atomic and molecular reactions) and by D° bombardment of the slotted plasma grid (metallic plate marking the transition between the plasma and the accelerator) (see Fig. 8 right). To enhance NI production, i.e., the electron capture by the atom, a cesium layer can be deposited on this metal surface (grid) in contact with the plasma. In the extraction region, the plasma has to be cold (T_e < 2 eV) to avoid destruction of the D⁻ by collisions with hot electrons (the electron affinity level of the D⁻ atom is only 0.75 eV). The Extraction Grid (EG) is biased (~10 kV) to extract ions from the source, while the co-extracted electrons will be deflected (swept out from the ion beam) by the vertical magnetic field which diffuses from the source. The ion beam is then accelerated up to 100 keV, and to compensate the deflection by the magnetic field (diffusing from the source), a D⁻ beam steerer will be required for a perfect alignment to the photo-neutralizer axis.

Furthermore, the ability of a helicon antenna to generate a dense plasma column (with high ionization degree) uniformly distributed along the B-field lines makes it the ideal candidate for the production of a long and dense magnetized plasma column (see Fig. 8 left).

For this purpose, IRFM has collaborated since 2012 with EPFL Lausanne (Switzerland) to develop a Helicon antenna specifically designed to fit with CYBELE ion source operating conditions, i.e., magnetic field ~10 mT, low operating pressure < 0.3 Pa, high power ~10 kW. It is a new type of helicon plasma driver developed at EPFL for which a resonant "birdcage" network is used as exciting antenna [22, 23]. A drawing of the antenna is shown in Fig. 9. The antenna is made of conducting parallel legs distributed around a cylindrical alumina tube (Ø= 9.5 cm) in contact with the plasma. Each leg is connected at both ends to its closest neighbors by means of capacitors. In a first approximation, this structure can be seen in a first approximation as a parallel arrangement of (L, C) elements, and presents a set of resonant frequencies corresponding to the normal modes of the structure. When excited at one of its resonant frequencies, an azimuthally sinusoidal distribution of current with strong amplitude is generated in the antenna legs. The RF fields generated by these current distributions fit well the helicon wave field structure, and then produce an efficient Helicon excitation. At this time, stable operation in both hydrogen and deuterium have been obtained at EPFL at the relevant operating conditions of Cybele

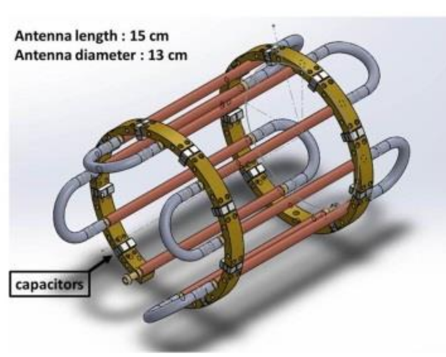

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Fig. 9: Helicon antenna [22, 23], which consists of a 9 leg cylindrical resonant network used for helicon excitation. The capacitor value is 3840 pF to bring the m=1 resonance close to 13.56 MHz.

Figure 10 shows the recent plasma jet obtained on the RAID testbed at EPFL: the antenna provides a 1.5 metre long, stable and dense (n_e~7 10^{17} m^{-3}) hydrogen plasma column with only 3 kW of RF power. The plasma column exhibits a nearly constant diameter, demonstrating a uniform plasma distribution along the source axis.

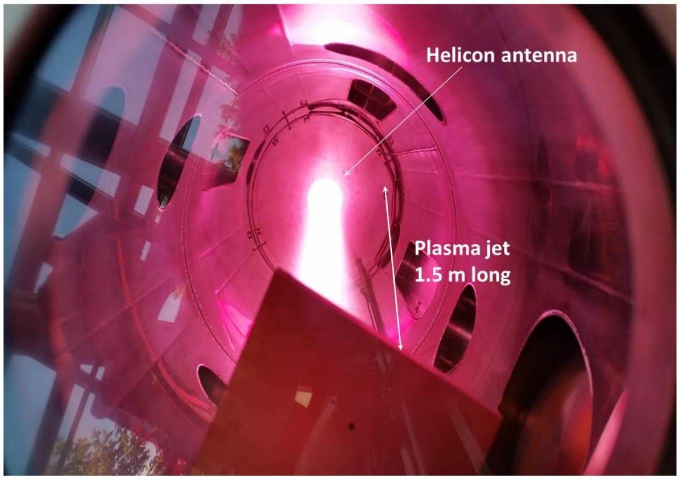

Fig. 10: Two meters long Hydrogen Plasma jet produced by a 3 kW helicon antenna at EPFL laboratory. The Helicon operating pressure is 0.3 Pa, and magnetic field B//= 10 mT.

Preliminary measurements were performed on the RAID testbed using compensated Langmuir probes and laser photo-detachment diagnostics.

The probes reveal the production of highly dissociated and dense hydrogen/deuterium plasmas (n_e~ 7. 10^{17} m^{-3}, dissociation rate ~40-50%) in the source centre (see Fig. 11), and the presence of negative ions on the plasma column edge (see Fig. 12) [24].

All these first results, obtained in cesium-free plasma, point toward the resonant helicon antenna as a promising candidate for negative ion sources for future NBI applications.

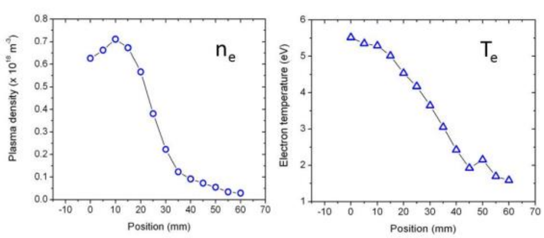

Fig. 11: Radial profiles of the plasma column at ≈68 cm from the resonant antenna; letf) electron temperature; right) electron density obtained with a compensated Langmuir probe

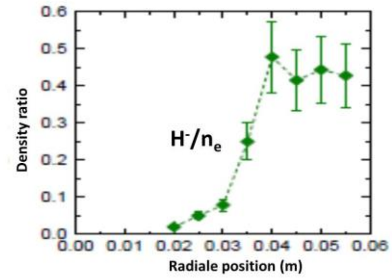

Fig. 12: Radial profile of the n_{H^-}/n_e ratio measured on the RAID testbed by laser photo-detachment diagnostics.

This new antenna has been recently installed and commissioned on the Cybele source (see Fig. 13), and the first plasma column has been obtained.

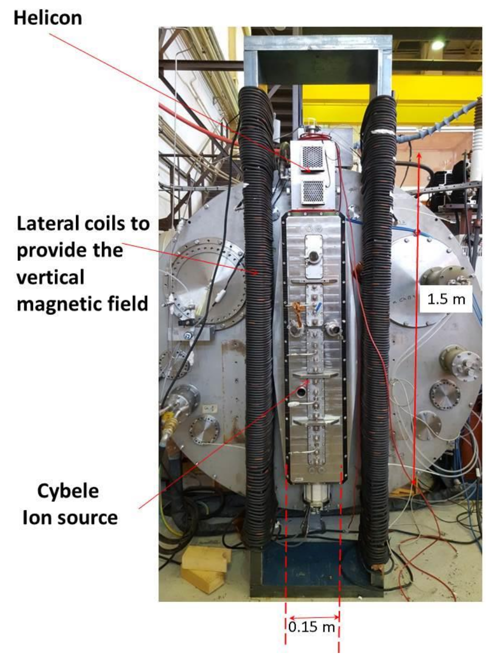

Fig. 13: Cybele ion source at IRFM equipped with the 10 kW helicon antenna developed at EPFL.

V. Conclusion

A new concept of neutral beam system based on the photo-detachment of energetic blade-like negative ion beams is proposed. The centrepiece of the system is the photo neutralizer where a high power photon flux (~3 MW) generated within a resonant Fabry Perot cavity will overlap, cross and partially photo-detach an intense negative ion beam at high energy. This specific arrangement should lead to a 93 % photo-detachment rate of a 10 A D^- 1 MeV narrow beam sheet, yielding 9 MW of D° per beam sheet. A complete injector would be composed of several independent beam sheets (six or more beam modules) implanted side by side and spatially oriented to focalize the neutral beam sheet within the Tokamak input port. With six beam sheets in parallel, the total neutral power per injector tank coupled to the plasma core would be 48 MW with an injector wall-plug efficiency of 70%.

This modular concept offers more flexibility to finely control the fusion plasma profile by a temporal and spatial modulation of each beam optic. On the other hand, thanks to the photo-neutralization, the ion source will be at the ground potential; this offers many additional advantages and features to the injector: a simplified electrical setup, an easy access and maintainability by remote handling, and the possibility to consider energetic tritium beams both for plasma heating, current drive and high efficiency fueling of the plasma core of the reactor.

The ongoing R&D around this new injector concept, which involves several laboratories in France and EPFL in Switzerland, addresses the two main key issues of the concept:
-1) the development of a new negative ion source concept based on an Helicon antenna (a Bird-cage helicon antenna developed at EPFL) coupled to an accelerator using rectangular slits instead of circular apertures to provide an intense blade-like NI beam;
-2) a feasibility study of a negative ion beam by photo-neutralization in resonant Fabry-Perot cavities.

Up to now, a reduced scale intra-cavity photo-neutralization experiment carried out at LAC laboratory (France) recently achieved a 50% photo-detachment rate on a low energy H^- beam (~1 keV) in CW regime.

Although a 3 MW optical cavity for photo-neutralizer is less demanding in stabilizing techniques than GrW detectors, its specific issue presently addressed in French laboratories is the thermo-mechanical mirror deformation induced by the high photon flux and the necessity for compensation methods by adaptive optics.

Ultimately, if feasible, the development at mid-term of a full scale high power optical cavity for photo-neutralizer would rely on the mature technology and knowledge acquired over the past decades in the field of Gravitational Wave detectors.

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