The particle control systems at the edge of the Reversed Field Pinch experiments

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Abstract

Plasma performance in Reversed Field Pinch (RFP) devices, as in the tokamak, is strongly affected by neutrals at the edge. So far only few experiments have been dedicated to an active control of the neutral particle using conventional solutions of axisymmetric magnetic divertors or throat limiters.

The alternative “vented pump limiter” concept is more attractive for a RFP experiment due to the edge plasma and confinement properties of this magnetic configuration.

In the paper the application of a vented pump limiter to a RFP is discussed and the prototype module of the “vented pump limiter” designed for the RFX experiment is presented.

Finally the optimization of this concept for a next step RFP device is presented.

1. Introduction

The particle control of magnetically confined plasmas has been demonstrated to be essential in attaining enhanced confinement regimes in particular for the tokamak experiments [1].

In recent years a detailed investigation of the mechanisms underlying the particle transport has been undertaken in plasmas confined in Reversed Field Pinch (RFP) configuration, but the experimental application of either magnetic divertors or mechanical limiters in existing devices has not been deeply developed.

Nevertheless the current and density profiles and the confinement properties of a RFP configuration suggest that the particle control at the plasma edge could be even more critical for a RFP experiment than for a tokamak [2,3].

In this paper a short review of particle control systems in the tokamaks and in the RFPs is proposed, then a description of edge plasma and of recycling properties in the RFX experiment are briefly reviewed.

An innovative approach of a particle control system for RFX is proposed, based on an evolution of the limiter in the open configuration without leading edge, conceptually introduced by P.K.Mioduszewski [4] and tested in Tore Supra [5].

The design of a prototype module of this limiter designed for the RFX experiment [6,7], where the first wall is dominated by the presence of a complete graphite coverage (2016 tiles), is presented. Finally the conceptual design of a nearly full pumping wall for a future RFP experiment is conceived.

2. Particle control systems

2.1. Particle control in tokamaks

In a tokamak plasma the particle control systems are essential to reach any enhanced confinement mode [1]. The neutral particles at the plasma edge hamper the formation of the radial electric field structure which is necessary for the appearance of an enhanced confinement regime [1]. This evidence is independent of the system used to control the particles at the edge.

However, to establish a strong “wall pumping” effect capable of reducing the particle inventory at the edge, a very careful control of the wall conditioning is required for those devices, such as TFTR [8], where no active particle control systems are installed. Further experiments have also proved that the wall can be depleted and more easily maintained in a condition where the “wall pumping” is effective if an active particle control system is present [9].

Two categories of active particle control systems have been installed in tokamaks: poloidal magnetic divertor and mechanical divertor (or limiter). A comparison between the poloidal magnetic divertor and the limiter in the closed configuration (throat limiter) [4,10] has been carried out in [11].

2.2. Particle control in RFPs

A toroidal field divertor has been conceived for a RFP stationary reactor to remove He ashes and impurities [12,13].

However experiments have been performed on small scale devices in Japan by using poloidal, toroidal divertor [3,14,15] and throat limiter [16]. The experiments did not produce conclusive results: some beneficial effects have been recorded, but an increase of impurity content, an early discharge termination and an increase of the fluctuations have been also evidenced.

In all the other experiments the particle control is only performed by the passive behavior of the first wall. Nevertheless the wall conditioning plays a crucial role to determine the plasma performances [17,18].

2.3. Drawbacks of conventional particle control systems

The conventional particle control systems, if applied to a RFP, show some drawbacks that are well known to the RFP research community.

2.3.1 Drawbacks of magnetic divertors

a) The poloidal and toroidal magnetic divertors produce a radial magnetic field at the edge that locally distorts the RFP configuration with a negative effect on the plasma performance.
b) The poloidal and toroidal magnetic divertors could affect the MHD stability and enhances the magnetic fluctuations that increase the transport and modify the “dynamo” processes of the RFP configuration.
c) The neutralizing plates for the poloidal and toroidal magnetic divertors and the particle removal pumps require a significant room to be installed, with a consequent increase of the stabilizing wall distance that affects the MHD stability and increases the magnetic fluctuation amplitude with the same effects mentioned in b).
d) In principle, the toroidal magnetic divertor reduces the requirements in terms of technology and costs with respect to the poloidal one, but the complexity of the system in the internal part of the torus can not be neglected; moreover several toroidal divertors are needed along the torus.

2.3.2 Drawbacks of the throat limiter

a) In the RFPs the decay lengths of the power and of the particles are short (some mm) and they are very similar to each other [19] unlike in the tokamaks where the latter is larger than the former [10]. Therefore the leading edge of the throat limiter is thermomechanically more stressed in a RFP with a consequent enhanced erosion of the component and therefore an increase of plasma impurity content.

b) The throat limiter increases the distance between the last closed magnetic surface and the stabilizing conducting wall enhancing the magnetic fluctuations with the same negative effects of magnetic divertors.

In conclusion for the RFP configuration it is necessary to overcome the disadvantages of the classical particle control systems applied in the tokamaks by introducing alternative concepts that prevent the alteration and the worsening of the confinement.

3. Edge plasma properties and recycling in RFX

3.1 Edge plasma properties

It has been found that in the RFP configuration the particle transport at the edge is anomalous and mostly driven by electrostatic turbulence at the edge [20]. Though the nature of the instabilities driving the turbulence is still under investigation, methods to control them and to reduce the related transport have been applied in RFX [21]. Moreover asymmetric thermal load has been also observed due to the presence of suprathermal electrons[22].

In RFX the density profiles are found to be flat or hollow in the core [23], with steep density gradients in the edge region, where the ionization source is located. The temperature profile has been obtained by Langmuir probes and thermal He beams and shows low temperatures (10-100 eV) and shallow gradients .

The thermal load on RFX is toroidally and poloidally asymmetric. The toroidal asymmetry being due to the presence of locked modes while the poloidal asymmetry between the electron and the ion drift side is due to the suprathermal electrons. As in most RFPs, it has been found that the parallel energy flux is non-isotropic. An asymmetry equal or larger than a factor of two is routinely measured at the edge between the parallel and antiparallel directions along the magnetic field, which has been associated to a flow of suprathermal electrons [24]. When an object is inserted into the plasma, an electron drift side is identified corresponding to the direction where suprathermal electrons come.

The diffusion coefficient at the edge has been estimated by different methods [25] to be of the order of 10 m^2/s, consistently with the Bohm-like transport. This estimate allows the connection length of limiters or other obstacles inserted into the plasma to be evaluated.

The $(E \times B)/B^2$ flow velocity at the edge has been directly measured (by Gundestrup probes [26]) and it has been found in agreement with that estimated by radial electric field measurements. The flow velocity (in the toroidal direction, since the main field is poloidal at the edge) results of the order of 20km/s and has a characteristic double shear [27] confirmed also in other experiments [28]. The shear value of the flow velocity is in the order of 10^6 which has been found marginal for turbulence suppression.

Estimate of connection length is complicated in RFP's by stochastic magnetic field which results in a radial diffusion of the magnetic field lines due to magnetic turbulence. The magnetic diffusion estimated as $a*b/B^2$ gives radial excursion of several millimeters per meter along the magnetic field line.

3.2 Recycling

In RFX the average particle confinement time is of the order of few milliseconds and, in order to sustain the electron density, the fluxes of atomic hydrogen are of the order of 10^{23} s^{-1}. In most of the circumstances the hydrogen flux required to refuel the plasma originates entirely from the recycling processes at the wall. In absence of any conditioning procedures the wall easily saturates, leading to a complete loss of density control. Thus, the capability to control the plasma density strictly reflects the capability to control the hydrogen concentration on the plasma facing components. Various techniques have been experimented to condition the wall: hot wall operations (up to 280°C), Glow Discharge Cleaning (GDC) in He, boronization with GDC in Diborane.

In general, the presence of locked MHD modes which localize the plasma-wall interaction hampers the attempts to condition the wall, the power density can reach 100 MWm^{-2} and cause surface overheating, Radiation Enhanced Sublimation and strong hydrogen outgassing. However, means to minimize the latter problem have been devised and successfully applied by adding an external electromagnetic torque which forces the toroidal rotation of the modes.

In the discussion below the following definition of effective recycling is used: the ratio between the electron density reached at a certain time during the discharge and the total gas (normalised to the volume) injected up to that time. With this definition the effective recycling is 1 when the plasma density equals the total gas injected.

Fig. 1 shows the total desorbed gas as measured by neutral gas pressure gauge, the total gas puffed into the vessel and the effective recycling as a function of the shot number for several discharges after a GDC. The "effective" recycling coefficient in approximately 20 shots moves from 0.1 to 0.7. By summing up the differences between the amount of injected gas and the amount of gas desorbed after the pulse for the sequence of discharges after a He GDC session, one can estimate that the wall reaches saturation after absorbing approximately $1\cdot 10^{20}$ atoms/m^2. These values are comparable within a factor of two with the amount of hydrogen pumped out during GDC in He. For instance, 40' of He GDC that are typically performed to restore a reference wall condition, extract from the wall the equivalent of approximately 2.4 10^{20} atoms/m^2.

The amount of gas that the wall can absorb before it reaches saturation after a boronization is about ten times higher than in a non-boronized wall conditioned with He GDC.

Soon after a boronization the first wall has a strong pumping capability and larger amounts of gas (~70 *mbar l*) have to be used to sustain the discharge. For approximately 25 shots only

20% of the injected fuelling gas is desorbed after the discharge as shown in Fig. 2. Correspondingly the effective recycling coefficient may be very low. This ratio slowly increases and stabilizes below 100%. In this phase He GDC sessions of 40' can bring the gas desorbed fraction to 20%. The extended reservoir capacity associated to the boronized wall makes the density control relatively simple: it is for instance possible to perform a complete density scan in both directions during an experimental session while with a non-boronized wall it is very difficult to recover from high density regimes.

It should however be mentioned that soon after boronization a fairly large amount of He is trapped into the wall. The presence of He may affect the overall recycling and compensate for the efficient hydrogen pumping capability. Moreover too an empty surface soon after a wall conditioning procedure may result in difficult start up as well as in an excessive variation of the density value during the discharge. One efficient way to reliably control the density in such conditions is to add to the standard 40' of GDC in He few minutes of GDC in H in order to provide an adequate and reproducible gas reservoir.

The effects of borinization are annihilated especially by carbon redeposition that follows the strong plasma wall interactions in presence of wall-locked modes. When the wall is baked up to 280°C recycling is drastically reduced and a very large amount of filling gas has to be injected into the vessel to sustain the plasma current ramp up phase. However, especially at plasma currents approaching 1MA, typically characterized by large ohmic input power, the density often builds up rapidly during a single discharge. An excess of density may cool the plasma and lead to a premature quench of the plasma current. In such circumstances the "effective " recycling varies during the discharge and from relatively low values may reach and even exceed one. A possible explanation is that the strong power loading (of the order 100 MW/m^2) associated to the locking of the modes leads to a local overheating of the tiles, at temperatures that imply strong hydrogen outgassing. CCD images and external thermocouples confirm that surface temperature exceeding 1600-1800 °C can easily be reached. Such events accompanied by strong density increase make the density control in the subsequent discharges very difficult, unless a new He GDC is performed. Operations with a hot wall but soon after boronization are immune from such events for at least a few tens of shots (30-60). The data of Fig. 3 refer to this condition and clearly show that very large amounts of fuelling gas are required (170 mbar·l) because of the very low effective recycling values.

All the procedures that have been applied have had a positive impact on the attempt of controlling recycling. However no one of those procedure are considered as a conclusive solution to the problem, all having drawbacks and limitations.

3.3 Density limit

The fact that in RFX in most of the circumstances the electron density control depends essentially on recycling appears to have consequences also on some operational limits.

Such limit shows up as an upper value of the electron density for any given current, in a manner very similar to the Greenwald limit found in Tokamaks. Fig. 4 shows the electron density value as a function of the average current density for a number of hydrogen shots. All the points of the data set lay below the Greenwald line, corresponding to $n_e = 1 \cdot 10^{-14} Ip/(a^2)\ m^{-3}$ [29]. The exact nature of the experimental density limits in RFX has not been clarified yet. For instance it may be associated with a local radiation limit which would destroy the good confinement properties of the plasma edge by cooling the plasma and enhancing the magnetic field diffusion. However another possible explanation derives from the simultaneous observation that the density gradient at the edge is linearly proportional to the average density [23], which suggests that the way hydrogen is refuelled, i.e by slow recycled particles, causes a reduction of the average ionization length as the density increases and, consequently, an outward displacement of the electron source. It is possible to show that as the edge density increases, the shearing rate of the radial electric field - defined as Er/ρ_L where ρ_L is the Larmor radius of hydrogen - which is thought to play a fundamental role in stabilizing turbulence, may decrease. The Greenwald limit could in such a way be related to a shearing rate reaching a critical threshold with respect to the turbulence characteristic lengths.

It is interesting to notice that in case of pellet fuelled discharges, in which the electron source is set well inside the plasma, density data sit in the upper region of the standard discharge in Fig. 4 and can even exceed the Greenwald limit. The possibility to reliably control recycling seems therefore to be essential to make reproducible high density RFP discharges a viable scenario and to push forward the present density limits. This is even more important if one considers that in RFP's energy confinement increases with increasing density.

The limit discussed above is of non disruptive nature and, as such, has to be distinguished from the fast terminations which in RFX have been found especially in high density high current discharges. These last terminations manifest as a sudden drop of the central electron temperature, a simultaneous peaking of the electron density and final current quench [30]. Also in this case a conclusive explanation is lacking, though it has been stressed the role that a hydrogen saturated wall would have by suddenly releasing its particle content under the heavy thermal load caused by wall-mode locking.. Under certain circumstances, when the amplitude of the wall-locked modes is particularly large and the first wall has been loaded by a previous sequence of high density discharges or even by a particularly high filling gas a sudden release of hydrogen, accompanied by carbon and oxygen, takes place. The following cooling of the local plasma if large enough can dramatically increase the penetration length of the gas and directly affect the core, increasing its resistivity and hampering the magnetic relaxation processes essential to the RFP. Control of the wall-locked mode position by means of externally applied fields has been demonstrated to be effective in preventing the fast termination phenomenon; however a better control of recycling is expected to reduce the probability of fast terminations even in presence of wall locked modes.

4. The "vented limiter"

In 1982 Mioduszewski proposed three different solutions of mechanical limiters without leading edges (open configuration) [4,10].
The open pump limiter configuration, and in particular the third solution presented in [4] (called “venetian blind” configuration), has been revised and applied for the first time in Tore Supra with the name of “vented limiter” [5]. The efficiency of the “vented limiter” in collecting and in removing the neutral particles and in the wall depleting has been experimentally confirmed and numerically evaluated to be of the same order of magnitude of a classical throat limiter [5,31,32,33]. The “vented limiter” concept is shown in fig.5 applied to a RFP experiment, where the magnetic field lines at the plasma edge are almost poloidal. The “vented limiter” is able to collect either ions coming from the plasma, neutralized on the side surfaces of the blades, or neutral particles, coming from dissociation and charge exchange processes at the plasma edge [5,21,22,23,24].

4.1. "Vented limiter" advantages

The “vented limiter” is very attractive for a RFP device and basically overcomes the drawbacks of the classical solutions exposed in section 2. The main advantages of a “vented” structure are:

a) The “vented limiter” does not modify the electromagnetic configuration of the RFP plasma.
b) The distance between the conducting stabilizing wall and the plasma can be minimized independently from the presence of the “vented limiter”, because it is not necessary to introduce the "vented limiter" inside the plasma.
c) The magnetic field lines and the particle trajectories at the edge of a RFP are almost poloidal with a $|1/q|$ ranging from 30 to 40 (where q is the safety factor at the plasma edge), in standard operation. Therefore the limiter can be simply designed with many poloidal slots [4], where the side surfaces of the blades are the neutralizing surfaces (see fig.5).
d) The "vented limiter" does not requires an accurate knowledge of the SOL parameters [5,33] and of the particle connection length.
e) The "vented limiter" can be extended in the toroidal and poloidal direction overcoming the uncertainties in the knowledge of the RFP edge plasma characteristics and increasing the particle exhaust efficiency of the "vented limiter". The extension over a large first wall portion claims for a distributed pumping, which is normally installed in the RFP devices, due to the restriction on the maximum port diameter [7].

The proposal by J.N.Downing [35] of a limiter with a pumping volume extended over all the first wall surface can be ascribed to the "vented limiter" concept. The limit of that proposal was the absence of a uniformly distributed set of poloidal slots necessary to neutralize and to reflect the particles into the pumping duct and to collect the neutral particles coming from the recycling processes.

5. The design of a "vented limiter" for RFX

5.1. Vented limiter design

A prototype module of the vented pump limiter has been designed for the RFX experiment.
The design requirements of easy and fast installation and removal, avoiding any major shut down of the machine, led to the solution of a prototype having dimensions compatible with the in vessel insertion through one of the equatorial pumping ports, having the inner diameter Ø149 mm.
The prototype limiter is composed of the neutralization grid and a support system having also the functions of inserting and positioning the grid inside the vessel, as shown in figure 6.
The overall size of the grid is 414 mm along the toroidal direction and 207 mm along the poloidal direction. These dimensions correspond to the area covered by four first wall tiles placed around the pumping port and correspond to the 0.24% of the total first wall surface.
The grid is composed of four modules connected to the support beam by means of vertical axis hinges, which allows the modules to be rotated for 90°. This rotation allows the insertion through the pumping duct of one module at a time, as represented in figure 7. After the insertion of the modules the support bars are fixed together by means of clamping systems, having also the function of precise positioning along the longitudinal axis of the pumping port.
Each module of the grid consists of 22 blades made by CFC, having a thickness of 4 mm; graphite spacers of 5 mm are located in between two consecutive blades. The typical dimensions of the blades are presented in figure 8.
The shape of the blades has been designed to obtain a uniform power deposition on the plasma facing surface and a ratio of 10 between the allowable power flux and the maximum incident power flux. The shape has been calculated adopting a characteristic decay length of the power flux λ_Q = 4 mm .
The slot amplitude has been optimized to guarantee the best neutralization effect of plasma particle in the edge region of the RFP plasma.
The rear surface of each blade is plane and delimit a pumping duct region between the grid and the vacuum vessel.
The blades and the spacers are supported by metallic frames connected to the support beams. The frame, made by TZM rods (Ø 6 mm) and lateral plates has to withstand the electromagnetic forces due to the time variation of the magnetic flux linked by the grid and to the halo currents flowing from plasma edge to the blades. The maximum intensity of the halo currents flowing in each rod has been estimated to be 1 kA, increasing linearly towards the middle axis of the

module. Hence the first contribute is uniform (55N/m), while the second one increases linearly along the rods (maximum value 300 N/m). The whole grid is subjected to a radial force and tilting moments both in vertical and horizontal planes, which have been considered for the mechanical design of the hinge connection and of the stainless steel support beams.
Each support beam is composed of four square tubes, to give the necessary stiffness to the system and to accommodate cables for thermocouples and Langmuir probes, one vacuum connection to measure the pressure at the limiter and one vacuum connection to inject gas into the limiter.
The end of the beam is connected to a rotating flange which will allow the rotation of the whole grid around the longitudinal axis of the system. This will be useful both for installation and to optimize the angle between the slots and the magnetic field lines.

5.2. Vented limiter expected efficiency

If the expected particle exhaust efficiency is comparable with the tokamak experiments it would be $\varepsilon \approx 6$ % (where ε is the ratio between the particle flux exhausted from the pump limiter and the plasma particle outflux) [5,21,22,23].
The total number of particles colliding with the limiter (Φ_{lim}) is:

$$\Phi_{lim} = \Gamma_{//0} \; \lambda_\Gamma \; l_{lim} = 1.65 \; 10^{20} \quad (1/s) \qquad (1)$$

where:

$\Gamma_{//0}$ =	$1 \cdot 10^{23}$	$(m^{-2}s^{-1})$	maximum parallel plasma particle flux [20]
λ_Γ =	4	(mm)	decay length of the particle flux in the SOL
l_{lim} =	0.414	(m)	toroidal extension of the limiter

According to the estimated particle exhaust efficiency the number of hydrogen particles collected by the limiter and evacuated by the pumping system is:

$$\Phi_{exhaust} = \varepsilon \; \Phi_{lim} = 1 \; 10^{19} \; (1/s) = 4 \cdot 10^{-2} \; (Pa \cdot m^3/s) \qquad (2)$$

Reducing the pumping speed of the turbo pump by a factor of two in order to account for the obstruction of the limiter supporting system, the estimated pressure at the limiter is in the range of 10^{-1} Pa for H particles or $5 \cdot 10^{-2}$ Pa for H_2.
The prototype of the "vented limiter" will experimentally verify the possibility of collecting and removing a significant fraction of the neutral particles at the edge of the RFX plasma but it will not be able to perform a complete edge particle control.

6. A preliminary design of an extended "vented limiter" for a RFP

The "vented limiter" efficiency can be increased by extending both its poloidal and toroidal dimensions. The hypothetical "vented limiter" device for a next RFP experiment is shown in fig.9.
In this proposal the poloidal extension of the "vented limiter" is increased up to 60° and a complete toroidal limiter is foreseen. The pumping system shall be increased by installing 24 pumping stations equally distributed around the vessel. With this layout of “vented limiter” a full active particle control should be attainable.

7. Conclusions

The "vented limiter" allows to install an active particle control system in a RFP experiment without any modification of the magnetic field configuration and minimizing the distance between the plasma and the stabilizing wall.
A "vented limiter" prototype for the RFX device has been presented. The construction and installation of this prototype is foreseen after the restart of the RFX operation.
Finally the extension over a wider portion of a RFP device is proposed to fully accomplish the particle control in a RFP plasma.

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Fig.3 Total gas injected and gas extracted after the pulse, together with the effective recycling for three experimental sessions with a baked wall (280°C) after boronization

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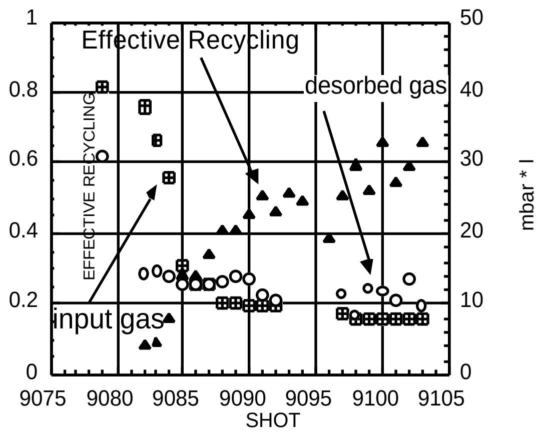

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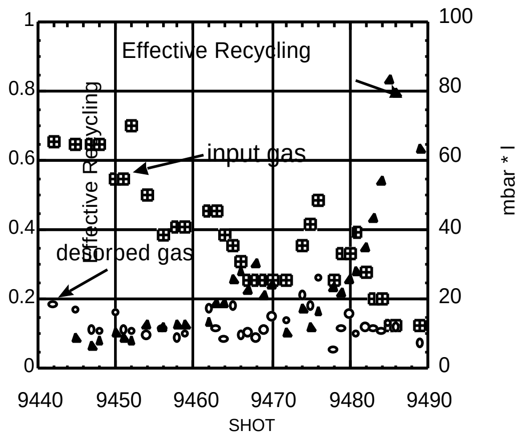


Fig.2 Total gas injected and gas extracted after the pulse, together with the effective recycling for two experimental sessions preceded by boronization

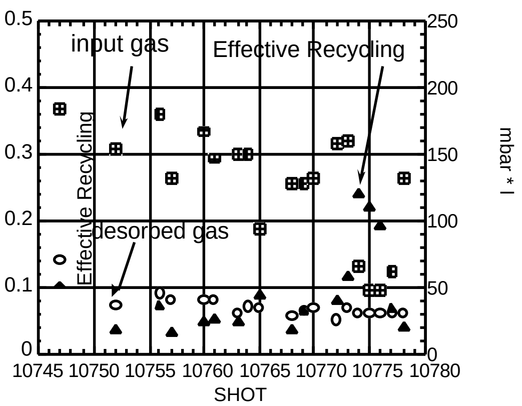


Fig.3 Total gas injected and gas extracted after the pulse, together with the effective recycling for three experimental sessions with a baked wall (280°C) after boronization

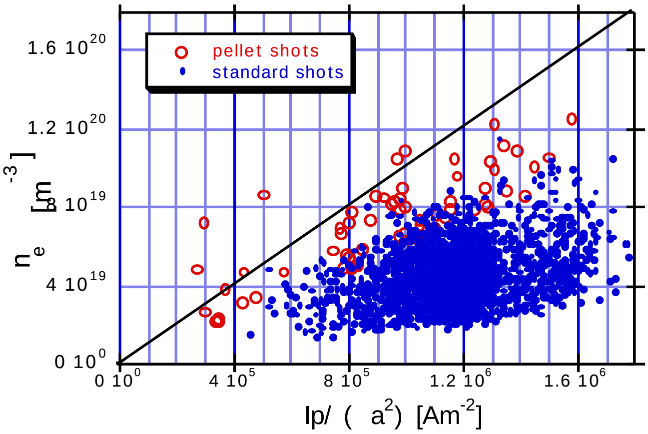


Fig.4 Electron density vs. the average toroidal current density. The equivalent of the Greenwald limit for Tokamaks is also shown

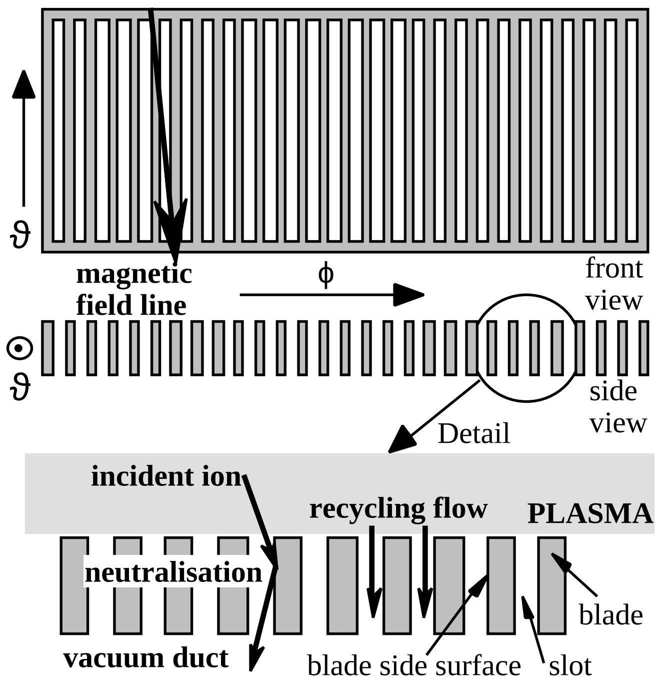


Fig.5 The "vented limiter" concept

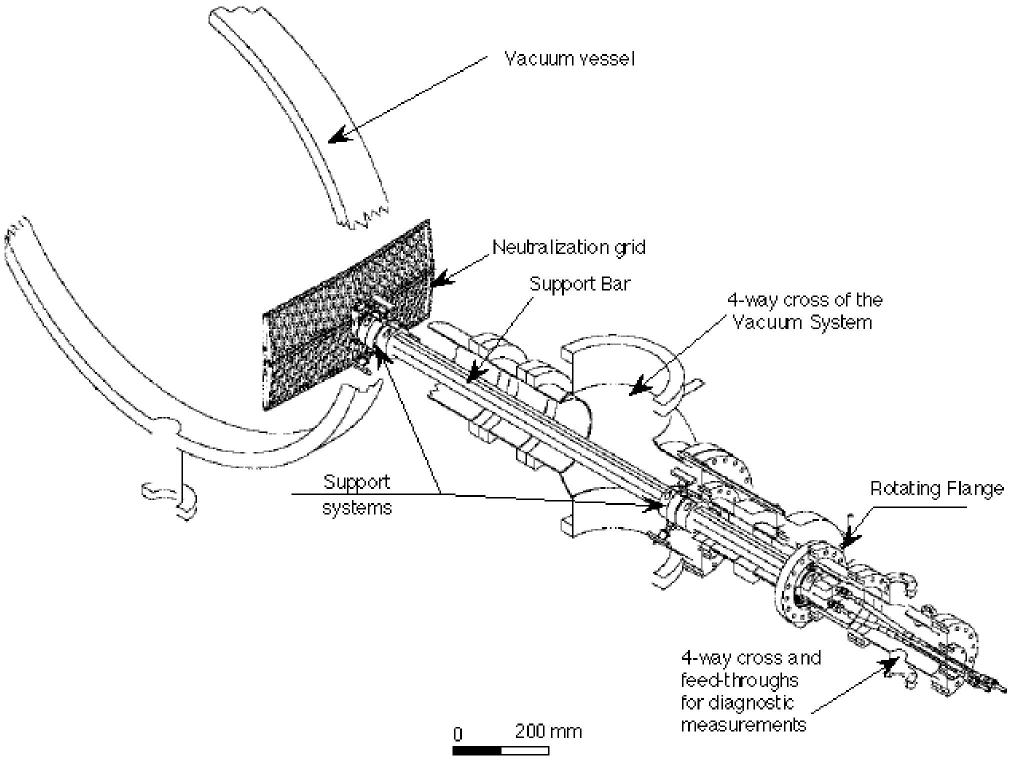
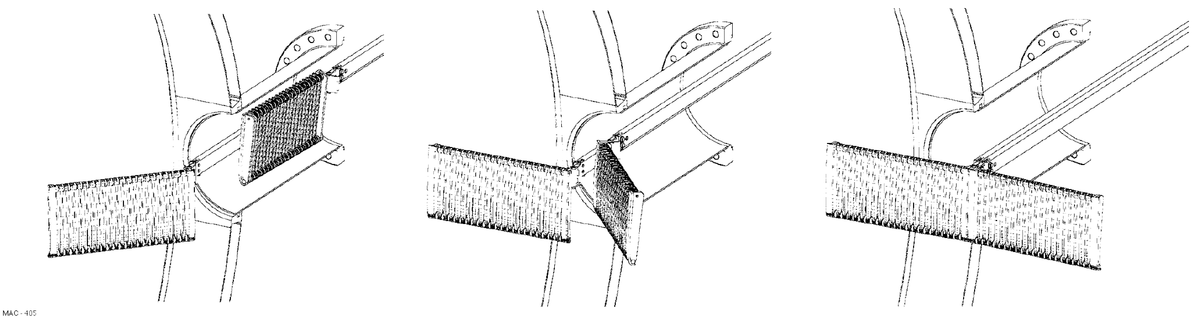


Fig.6 The prototype of vented limiter for RFX



(a) (b) (c)

Fig.7 Scheme of the prototype installation. Insertion through the pumping duct of the two lower modules (a), rotation inside the vessel (b), moving back to the final position (c). Same operations for the upper modules.

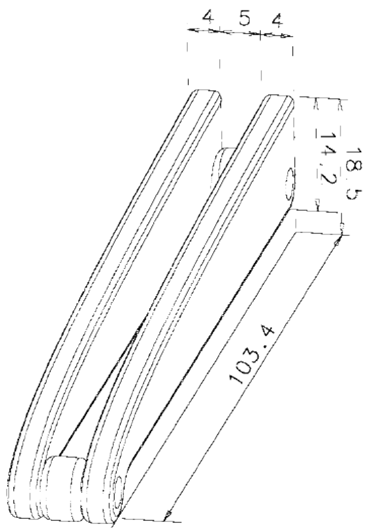


Fig.8 Detail of two blades and one slot of the grid.

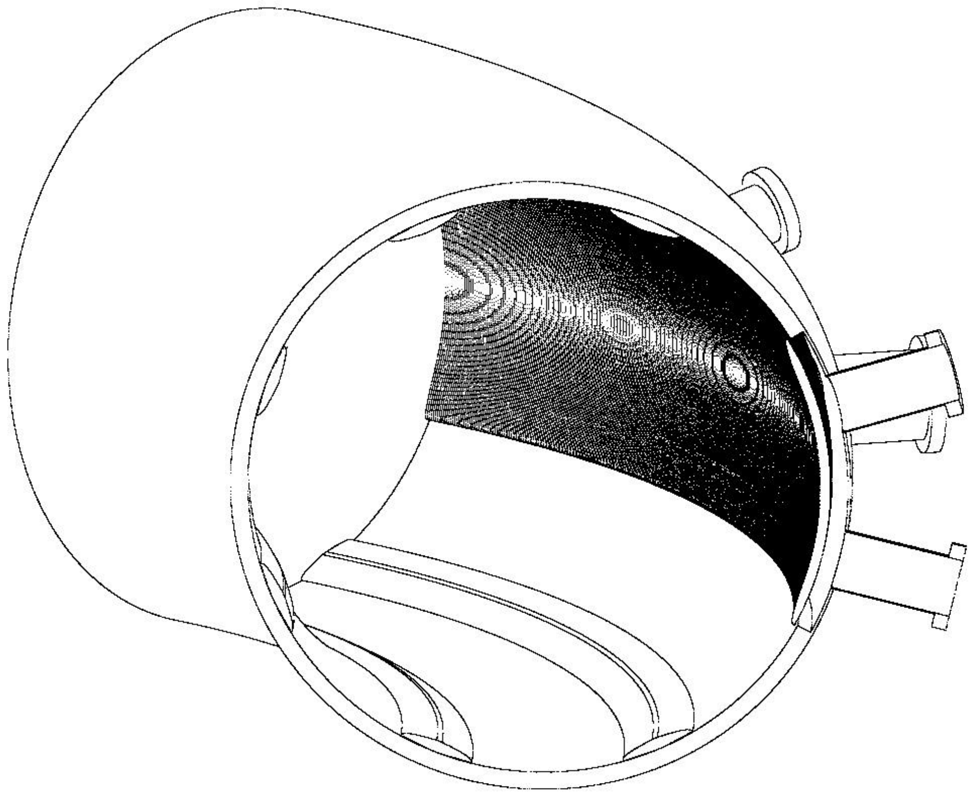


Fig.9 An extended version of the "vented limiter" for a next step RFP device