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Density limits and control in RFP's

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Motivation

A common issue for magnetic confinement fusion devices is the operation at high plasma density, with a twofold aspect. On the one hand, operational density limits, if present, have to be identified and understood. On the other hand, the capability of operating the plasma devices close or even beyond the limit has to be pursued. These two aspects are intimately connected to the more general issue of density control, which, in turn, articulates in terms of recycling control and refueling capabilities.
Summarizing, present RFP-mod results show three kinds of operational density limits: the hard $n/n_g = 1$ Greenwald limit which kills the plasma discharge, the $n/n_g < 0.4$ where current sustainment is severely hampered and the soft $n/n_g < 0.3$ threshold that prevents the access to the advanced regimes with QSH.

Open issues and gaps

The $n/n_g = 1$ Greenwald limit

As in Tokamaks, in RFPs a high density limit well described by the empirical Greenwald law has been documented [1, 2]. This limit has been related to the magnetic topology. In the toroidal region where the plasma is shrunk due to the m=0 tearing modes and a chain of m=0 magnetic islands well detached from the wall is present a poloidally symmetric radiating belt is found. The region of enhanced radiation is also a stagnation point of the toroidal flow so that density accumulates, favored by a sufficiently low diffusivity and the little toroidal component of the parallel flow at the magnetic field reversal surface. As a consequence the temperature decreases and the process leads to a thermal instability. Analogies exist between all the previous phenomenology and the MARFES observed in Tokamaks at the density limit, suggesting that the physics could be similar, but with a peculiar root in the RFP magnetic topology.
If RFP's and Tokamaks share important aspects of the upper density limit, both differ from the Stellarator case, where the upper density limit has clearly been identified as an edge limit following the Sudo scaling and in any case is well beyond the Greenwald threshold. This type of asymmetric behavior of the limit in the three magnetic topologies, whether it is due to the non-current-carrying nature of the Stellarator or to the different topological symmetries, has not been understood yet.

The impact of the density limit in RFP's on the reactor prospective is quite unknown. Unlike Tokamak devices, in the RFP the plasma current is not limited by stability constraints but it is a sort of free parameter only constrained by engineering limits on the magnetizing coils that provide the required driving loop voltage and wall loading. Due to the lack of a reference RFP reactor extrapolated from present scaling and understanding, it is impossible to quantify the cost of increasing plasma current due to the presence of the Greenwald density limit.

The current sustainment: $n/n_g < 0.4$-0.5 limit.

In RFX-mod, an objective difficulty has been found in sustaining densities also well below the Greenwald value, with $n/n_g > 0.4$-0.5, at high plasma currents, of the order of

1.5MA: when the density exceeds the previous value, the plasma current decreases with a decay rate increasing with the Greenwald fraction.

The current understanding is that at high plasma current and density there is a positive feedback action between increasing loop voltage, trying to sustain plasma current, and neutral influx from the wall. An increased density cools the plasma calling for additional loop voltage which in turn increases the density up again till $n/n_g=1$ is reached. This behavior seems peculiar of the high recycling value to the carbon first wall, which, on the other hand, is very effective in withstanding high power loads. From the recent RFX-mod T_e scaling, $T \propto I^{0.93}(n/n_g)^{-0.35}$, follows for the input power that $P = VI \propto I^{0.6}(n/n_g)^{0.5}$. This shows that increasing plasma current increases the wall power load reducing the ability to control the plasma density. This calls for tests of different materials as the first wall or for first wall coatings capable of withstanding high power load with low recycling. Future experiments with Lithium coating or Lithium limiter could give some answers to this question. A completely different solution could be the adoption in RFPs too of toroidal or poloidal divertors, whose viability is now considered more optimistically after RFX-mod showed how the Virtual Shell can heal the plasma-shell proximity issues. However, besides the wall issues, it appears that even away from a situation of excessive recycling it is difficult to sustain the RFP plasma current beyond $n/n_g=0.4-0.5$, as an increase in density would decrease the current by increasing the plasma resistivity. As a pure ohmic device in which the applied loop voltage has the additional burden of generating and sustaining the toroidal field it is not surprising that current and density are not decoupled as in auxiliary heated tokamaks. A self consistent model of the RFP should help understanding these findings and clarify whether this is an intrinsic limit of the RFP or if it is the result of specific processes, such as for instance the effect at the edge of m=0 modes or the consequence of excessive error fields. Finally, auxiliary heating and especially current drive would be very useful to explore also new operational regimes where density control could be a less severe problem.

The soft $n/n_g < 0.3$ limit.

Because this limit develops at lower density values it seems more critical with respect to the Greenwald density.

The advanced Quasi Single Helicity (QSH) regimes, spontaneously developing at high currents with ameliorated confinement that manifests primarily with the occurrence of internal electron transport barriers, are presently not obtained at a Greenwald fractions > 0.3. However, the increasing persistence and duration of QSH with the Lundquist number S [3] suggests that the limit will vanish moving to higher plasma currents, as increasing plasma current will increase S. Indeed using Spitzer resistivity $S \propto BT^{3/2}$ and using the RFX-mod T_e scaling $S \propto I^{2.35}(n/n_g)^{-0.525}$. Therefore, provided T_e scaling is maintained at higher plasma current and neglecting for the moment PWI issues, one can extrapolate that around I=2.2 MA it will be possible to get at $n/n_g=1$ the high S values that presently allow the access to the QSH regime. This means that above I=2.2 this soft limit should disappear. At higher current, as mentioned above, higher power loading is to be expected as well. One possible solution to the problem could be, especially at very high absolute densities, the addition of small quantities of highly radiating impurities to create a radiative shield at the edge.

Impact on future experiments and devices

Clearly, density behavior and control interfere with several aspects of any type of magnetic confinement devices. Several peculiarities of the RFP's require further investigation but also aspects of general interest call for more experiments.
In this respect, the discussion presented above suggests that R& D should address :
- test on different wall materials and first wall coatings in RFP's (ex. Lithium) in order to better control recycling and explore the effect on pressure profiles (β) and global confinement
- conceive and test alternative means to refuel the plasma, such as supersonic beams and plasma guns
- improve/upgrade pellet injector systems to allow better flexibility
- develop conceptual studies for toroidal or poloidal (helical?) divertors in RFP's
- extend experiments beyond the density limit especially trying to work with low recycling wall and refueling the plasma via cryogenic pellets
- explore high current (> 2MA) regimes to verify the present S scaling at high n/n_g and try to achieve pellet refueled QSH high density regimes
- probe the effectiveness of radiative shields to protect the wall and verify the impact on the confinement properties of the RFP
- develop a self consistent model of the RFP to understand the impact of different recycling regimes and the behavior of the RFP in high density regimes
- investigate on the Stellarator, Tokamak and RFP density limit
- test heating current drive auxiliary schemes for decoupling current and density
- develop a conceptual RFP reactor to identify- plausible operational scenarios within engineering limits of plasma current and plasma wall loading as scalings are improved.

[1] M.E. Puiatti et al., Phys. of Plasmas 16 (2009) 012505
[2] Wyman M.D. et al., Nucl. Fus. 49 (2009)015003
[3] Carraro L. et al., in Fusion Energy 2008 (Proc. 22nd Int. Conf.Geneve, 2008) (Vienna: IAEA) EX/P3-9