

## NEON INJECTION EXPERIMENT IN THE REVERSED FIELD PINCH RFX

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### 1. Introduction.

In this paper we report on the results of two experimental campaigns of impurity injection in the hydrogen plasmas of the reversed field pinch RFX. The Reversed Field eXperiment is a large device (major radius  $R=2$  m, minor radius  $a=0.46$  m) [1] in which plasma current up to about 1.1 MA is presently driven and input power (ohmic only) up to about 100 MW can be provided. The flat top central temperature ranges between 100 eV and nearly 400 eV depending on the electron density ( $2$  to  $8 \times 10^{19} \text{ m}^{-3}$ ) and on the confinement scenario. The average power flux density to the graphite tiles which cover the liner is  $1\text{-}2 \text{ MW/m}^2$ , with peak values that reach  $\sim 100 \text{ MW/m}^2$  in the region where the resistive MHD modes are locked in phase and in space. Even though the space locking has successfully been prevented by the application of rotating error fields [2], the protection of the wall from peak power flux densities is a crucial issue in the reversed field pinch research. The results of the experimental campaigns hereafter reported represent the first systematic and successful test of viability of the concept of radiating mantel for RFPs.

The flat top plasma current of the discharges under study was around 0.8 MA.

### 2. Plasma response to the injection of neon.

In contrast to tokamak auxiliary heated discharges, where the change of the ohmic power due to the impurity seeding is in most cases a negligible fraction of the total power, experiments in RFX show that the input power can even double during light impurity seeding. Indeed, the enhancement of the resistivity via  $Z_{\text{eff}}$  may be reinforced by a possible decrease of the temperature at the plasma edge where most of the power is radiated and where poloidal currents on the order of  $I_p$  are driven by the dynamo mechanism. As a general trend at low-medium electron densities the input power ( $P_{\text{ohm}}$ ) during neon seeding increases from typically 30 MW up to 60 MW while at the highest densities ( $n_e$  above  $8 \times 10^{19} \text{ m}^{-3}$ ,  $I/N < 2 \times 10^{-14} \text{ A m}$ ) only minor changes of  $P_{\text{ohm}}$  are observed even at high level of  $P_{\text{rad}}$ . For non-seeded discharges  $P_{\text{rad}}$  increases from 1-2 MW at low density up to 6-8 MW at high density and correspondingly the power radiated ratio  $\gamma (= P_{\text{rad}}/P_{\text{ohm}})$  increases from a few percent to about 15 per cent. During neon seeding we have reached  $P_{\text{rad}}$  of 10-15 MW ( $\gamma \sim 15\text{-}20\%$ ) at the highest neon puffing rates at low density and  $P_{\text{rad}}$  of 30-40 MW ( $\gamma \sim 50\text{-}60\%$ ) at moderate puffing rate at high density.  $Z_{\text{eff}}$  ranges from 2 up to 4-5 depending on the electron density level and on the neon puffing rate. From bolometry, as already previously reported [3], the radiation volume is seen to increase only a little in radial direction with respect to non seeded discharges while a more pronounced extension in poloidal direction is observed, especially at high density where the radiation volume becomes nearly symmetrical.

In Fig.1 time traces of some relevant parameters of a medium-high density highly radiative discharge are displayed. At  $t=20$  ms neon enters the plasma and radiation starts to increase as the density,  $Z_{\text{eff}}$  and  $P_{\text{rad}}$  do. On the other hand  $I_p$  is maintained nearly constant at least up to 50 ms at the expenses of the ohmic power which increases with the resistivity. In general, the increase of the edge  $P_{\text{rad}}$  and even of  $\gamma$  does not necessarily imply that the heat flux to the plasma edge decreases. In most cases, indeed, the increase of the input power,

and consequently the increase of the power which flows to the edge might be sufficient to compensate for the loss of power radiated at the edge. In fact, from simple power balance considerations one can infer that only at very high density (when the input power increase is modest) a reduction of the edge temperature may occur as a consequence of the enhanced edge radiation. From the diagnostic point of view, the last channel of the Thomson scattering, which is at about 7.5 cm inside the LCFS, gives only indications of a slight reduction of the temperature with increasing  $P_{rad}$ , while the thermal He-beam diagnostic show that at medium density and  $P_{rad}$  a reduction of the edge temperature generally occurs simultaneously with an increase of the edge density. The poloidal beta is not significantly affected by neon seeding, although a slight tendency to increase can be seen at every density. In the more relaxed configuration which results from the induction of additional poloidal currents by external circuits, confinement is seen to increase by a factor of two in RFX. In such enhanced confinement Pulsed Poloidal Current Drive discharges [1] neon was successfully injected without provoking any reduction in confinement. In spite of the moderate level of the neon puffing rate used in these experiments, the compatibility of the radiative mantle with PPCD scenarios appears to be proved.

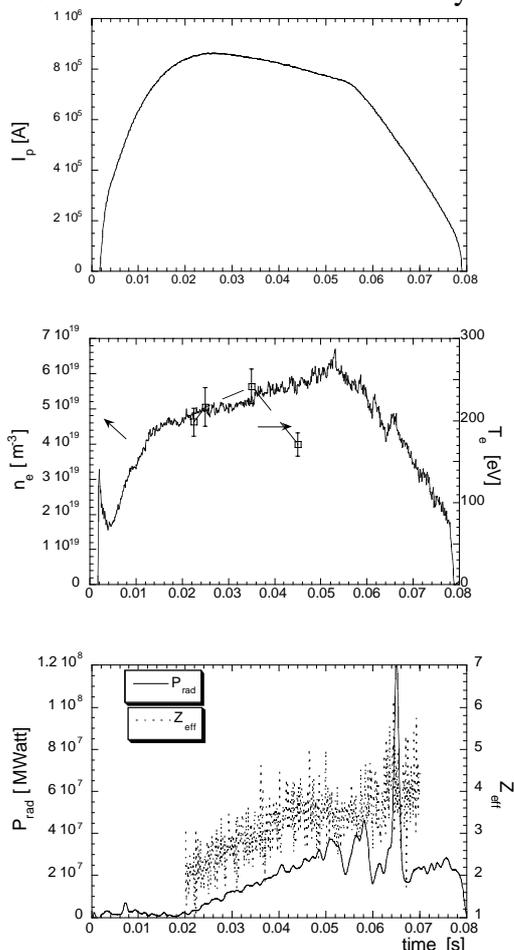


Fig. 1

**3. Radiation properties.**  
Spectral lines emitted by highly ionized neon ions in the 10 nm range are measured mainly for transport studies which are reported elsewhere [4], while the Ne VII line at 198 nm and the Ne I line at 585 nm are monitored and compared with bolometric signals. Here we limit ourselves to the study of two global quantities which are related to the radiation and transport properties of neon. The radiation potential,  $E_{rad}$ , is defined as the total energy radiated by a released neon atom during its life time. It depends on atomic physics, on the edge temperature and on transport [5] and is measured by dividing the total power radiated (from bolometry, assuming  $P_{rad}$ =power radiated by neon) by the total neon flux, which is estimated by the absolutely calibrated Ne I line with a convenient assumption on flux density symmetry. The other quantity which we refer to is the radiation efficiency, defined as the ratio of the radiated power to  $(Z_{eff}-1)$  normalized to  $n_e^2$ . It depends, as  $E_{rad}$ , on atomic physics and on transport [6]. Since, by definition,  $P_{rad} = \Gamma_i E_{rad}$  the impurity flux necessary to reach a given level of  $P_{rad}$  can be predicted once  $E_{rad}$  is determined. On the other hand, the radiation efficiency allows to predict the level of plasma contamination correlated with a given level

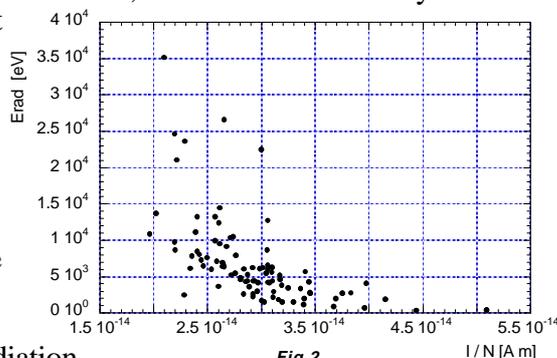


Fig.2

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of  $P_{rad}$ .

In Fig.2 the measured  $E_{rad}$  is plotted vs.  $I/N$ . Since  $I_p$  is nearly constant and the temperature decreases with increasing density, the data of Fig.2 can be seen as a plot of  $E_{rad}$  vs the edge temperature in the range 30 to 80 eV, approximately. The large spread of  $E_{rad}$  at low  $I/N$  is likely to depend on differences in the edge temperatures, because the highest values of  $E_{rad}$  refer to the highest levels of  $P_{rad}$ . It is interesting to observe that the range of variability of  $E_{rad}$ , a few to 30-40 KeV, is quite comparable with that found in tokamak plasmas. For neon radiation efficiency values in the range  $1-2 \times 10^{-39} \text{ MW m}^6$  have been measured in RFX, i.e. a factor 3-5 higher than the corresponding tokamak radiation efficiencies, according to the tokamak multi-machine scaling [7]. It can be shown that such a difference is consistent, also quantitatively, with the difference in particle flux between the two confinement systems.

#### 4. Confinement

Since, besides affecting  $P_{rad}$ , we can change  $P_{ohm}$  by changing the neon puffing rate, the range of variability of  $P_{ohm}$  at any given  $I/N$  increases substantially with respect to that without impurity seeding. In Fig 3  $\tau_E$  is plotted vs.  $I/N$  for discharges with and without neon seeding. Differently than for Xenon seeded discharges ( see below), we have assumed that for neon seeded ones the power lost by radiation ( which might affect the local temperature) enters only marginally in a global power balance since radiation is emitted predominantly at the plasma edge. Therefore we have considered that the power radiated does not cause a reduction of the heating power and we have set  $P_{heat} = P_{ohm}$ . Since the data scatter is strongly reduced by ordering with different levels of  $P_{ohm}$ , the

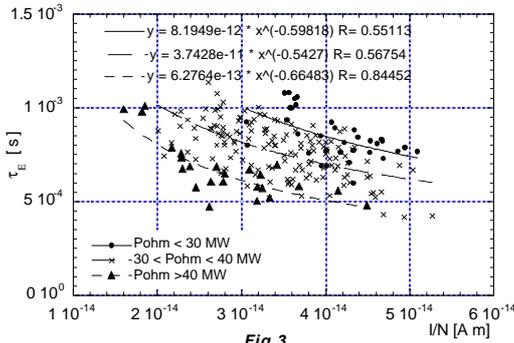


Fig.3

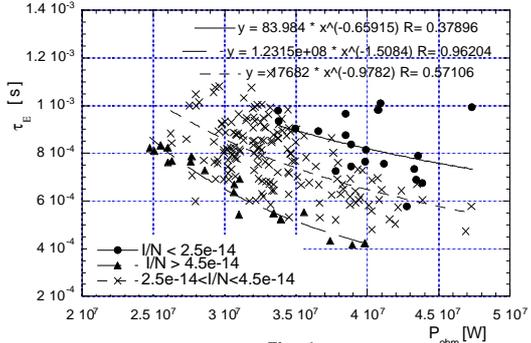


Fig. 4

$\tau_E$  dependence on  $I/N$  suggests a scaling of  $\tau_E$  with input power. In Fig 4  $\tau_E$  is plotted vs.  $P_{ohm}$  for different levels of  $I/N$ . The input power dependence of  $\tau_E$  appears to be very strong, on the order of  $P_{heat}^{-1}$  at medium  $I/N$ , which would imply poloidal beta to be approximately constant, or to decrease slightly with increasing power. Considering that the change in input power is due to a change in resistivity an alternative and complementary way to look at the data of Fig.4 is the increase of confinement with increasing Lundquist number, defined as the ratio of the resistive to the Alfvén times. However, since the radiated power is mainly localized at the plasma edge where a local cooling might occur and where poloidal current of the order of  $I_p$  flows, we cannot estimate the fraction of the input power which is additionally lost at the edge as a consequence of the neon seeding. Therefore we cannot yet estimate the change of the edge resistivity during neon puffing and firmly assess the  $\tau_E$  scaling independence of the specific experimental method used.

On the other hand we can make a very rough estimate of the change in the edge temperature needed to explain, by itself only, the request of 20-30 MW to maintain the equilibrium

current distribution. The resulting decrease of 20 -30 eV appears to be too big for the diagnostic systems to be insensitive to it. It appears, therefore, that the  $\tau_E - P_{\text{heat}}$  scaling can only partly be dependent on the method used, especially at low density where an important change on the edge temperature appears to be very unlikely to occur.

Preliminary results ( see Fig.5) from a number of Xenon seeded discharges suggest a  $\tau_E - P_{\text{heat}}$  scaling similar to that found for neon seeded discharges. The radiated power density for Xe seeded discharges is much more homogeneously distributed in radial and poloidal

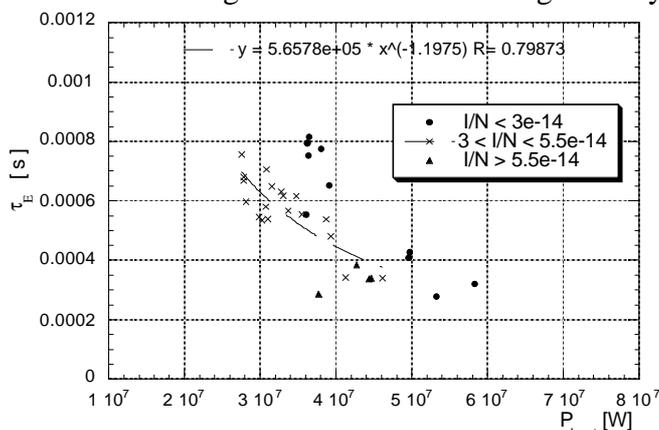


Fig. 5

direction as compared to that of neon, especially at low plasma density, so that for simplicity we have assumed full homogeneity. Consequently, we have set  $P_{\text{heat}} = P_{\text{ohm}} - P_{\text{rad}}$ , since a relevant fraction of the radiated power is emitted in the plasma center and has to be accounted for in the power balance. Not only the trends, but also the absolute numbers are similar for Ne and Xe so that we are rather confident of a

certain level of independence of the  $\tau_E - P_{\text{heat}}$  scaling on the method.

## 5. Conclusions.

The high values of the radiation efficiency found in RFX assure that a radiative layer can be created in a RFP at the expenses of a modest increase in  $Z_{\text{eff}}$ . The energy confinement time can decrease when neon is puffed in low density discharges, due to the increase of the ohmic power. We have found  $\tau_E$  to scale in neon seeded discharges about as  $(P_{\text{heat}})^{-1}$  i.e. beta constant for a given  $I/N$ , as generally found in RFPs. Moreover, if the experimental  $\tau_E$  of Figs. 3 and 4 are plotted versus Lundquist number,  $S$ , we find a  $\tau_E - S$  scaling comparable to those obtained by changing  $S$  without neon seeding. We can therefore conclude that neon seeding does not cause by itself a loss of confinement, which depends rather on the level of the heating power. The compatibility of radiative mantle at high density appears therefore to be proven. It has to be stressed that the  $\tau_E - P_{\text{heat}}$  scaling given here refers to a limited range of currents ( $0.7 \text{ MA} \leq I_p \leq 0.8 \text{ MA}$ ). Experiments at very different plasma currents are therefore necessary to draw some general conclusions on confinement and beta scaling.

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## References:

- [1] Bartiromo R., et al., Physics of Plasmas 6 (1999) 1830
- [2] Bartiromo R., this conf.
- [3] Carraro L., et al., Proc. 25<sup>th</sup> EPS Conference on Controlled Fusion and Plasma Physics (Prague,1998) paper B134PR p.790
- [4] Mattioli M., et al., "Experimental and simulated neon spectra in the 10nm wavelength region from the Tore Supra Tokamak and the Reversed Field Pinch RFX", submitted to Physical Review
- [5] Samm U., Plasma Phys. and Contr. Nucl. Fus. Research (Proc. 14th Int. Conf. Wuerzburg,1992), 1 (1992) 309
- [6] Telesca G., et al, J. Nucl. Mater. 241-243 (1997) 853
- [7] Matthews G. et al. J. Nucl. Mater. 241-243 (1997) 241