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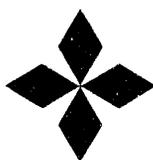# APPLICATION OF DIVERTOR CRYOPUMPING TO H-MODE DENSITY CONTROL IN DIII-D

by
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✦ GENERAL ATOMICS

APPLICATION OF DIVERTOR CRYOPUMPING
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ABSTRACT

In this paper we describe the method and the re-
sults of experiments where a unique in-vessel cryopump-
baffle system was used to control density of H-mode plas-
mas. We were able to independently regulate current and
density of ELMing H-mode plasmas, each over a range of
factor two, and measure the H-mode confinement scaling
with plasma density and current. With a modest pump-
ing speed of ≈ 40 kℓ/s, particle exhaust rates as high as
2×10^{22} atom/s^{-1} have been observed.

INTRODUCTION

Development of an effective particle control tech-
nique is essential for the viability of a tokamak fusion
reactor. In burning plasmas, particle control is primarily
needed for helium ash exhaust and impurity control. In
present devices, particle control provides the experimen-
tal flexibility necessary for systematic investigations of
energy and particle transport and rf current drive.

In typical H-mode plasmas, the good confinement
regime of tokamaks, the plasma density increases rapidly
after the transition to the H-mode. In DIII-D, the
plasma density eventually saturates at a level propor-
tional to the plasma current, n_e $(10^3 \mathrm{cm}^{-13})$ $\approx 6 \times I_P$
(MA). This co-linearity prevents an independent deter-
mination of scaling of the plasma confinement with n_e
and I_p. Furthermore, the ultimate density reached in
H-mode is too high for planned DIII-D current drive
experiments. In the past, helium glow and other wall
conditioning techniques have been used successfully in
controlling density in L-mode plasmas [1]; however, sim-
ilar efforts on H-mode plasmas have produced only small
effects.

The DIII-D advanced divertor system [2] was de-
signed and built with the primary goal of particle control
in H-mode plasmas. The system consists of an integrated
divertor bias electrode, a baffle, and an in-vessel cryop-
ump. The combination of the bias ring electrode, the
baffle, and the vessel wall form the cryopump plenum
(Fig. 1). A toroidal gap separating the bias ring from
the divertor floor defines a short duct to the pumping
plenum. Biasing applications [3] include enhancement

and regulation of particle flux into the pumping plenum.
Results of biasing studies and baffle pressure measure-
ments in the absence of pumping have been reported
earlier [3,4,5]. In this paper we describe the method
and results of H-mode density control experiments using
the in-vessel cryopump – baffle system, in the absence of
biasing. Simultaneous pumping and biasing experiments
have not yet been done.

DIII-D PUMPED DIVERTOR CONCEPT

A necessary condition for active density control is
a capability to exhaust particles at a rate faster than the
external particle sources. The dominant external particle
source in DIII-D plasmas is the neutral beam injection
system, which typically deposits 20 Torrℓ/s ($\sim 1.5 \times 10^{21}$
particles per second) into the core plasma. In addition,
depending on the condition of the graphite vessel and
divertor armor, the vessel walls can pump away or add
particles at rates as high as 100 Torrℓ/s. A design ob-
jective of the DIII-D pumped divertor project was to
achieve a particle exhaust rate greater than or equal to
the neutral beam injection source.

In earlier generation closed divertor devices for the
purpose of particle and impurity control, the entire vol-
ume of the divertor plasma was pumped. This approach,
as the following discussion will show, required very large
pumping speeds of the order of several hundred thou-
sand ℓ/s. The pumped divertor concept described here,
specifically designed for the open geometry of the DIII-D
divertor plasmas, is effective with an order of magnitude
lower pumping speed. In this scheme, a fraction of the di-
vertor recycling neutrals is scooped off directly by placing
the divertor recycling zone at the opening of a toroidal
pumping plenum. Detailed description of the pumping
concept and optimization studies can be found in earlier
publications [6-8] Here we present a semi-quantitative
discussion on how the concept works.

The pumping plenum pressure and the particle ex-
haust rate can be estimated by equating particle flux
into the plenum, Γ_N, to the sum of the pump exhaust
and the rate of particles escaping back into the plasma,
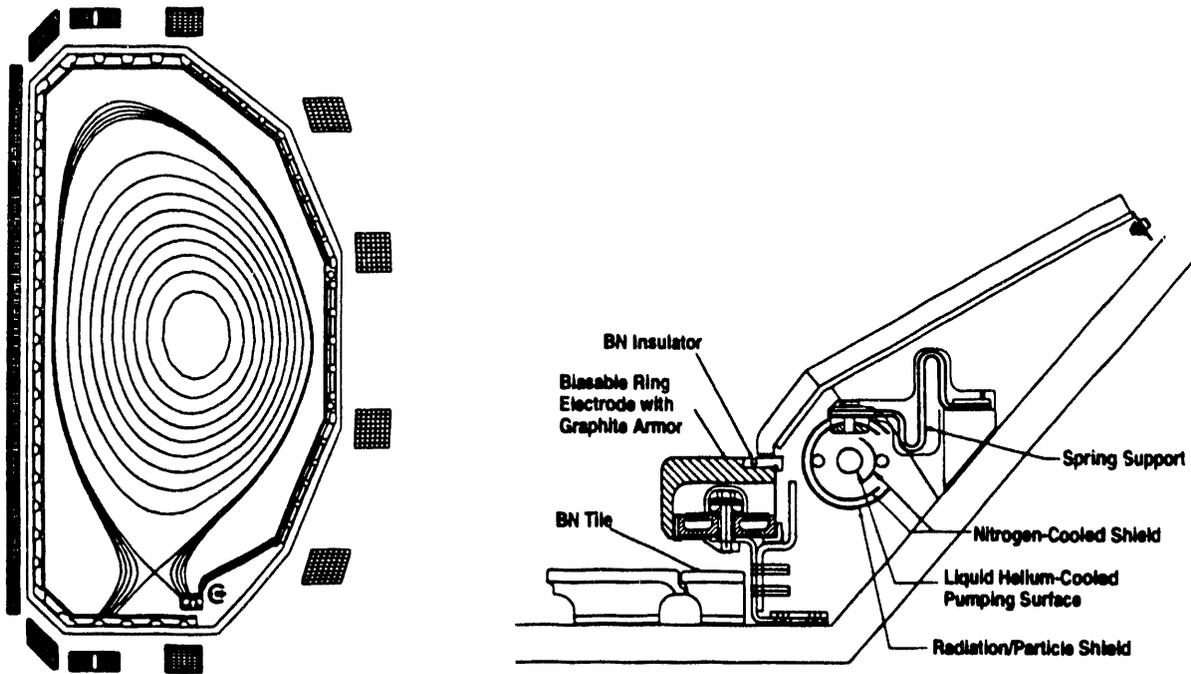i.e. $\Gamma_N = P(C + S)$, where P is the pressure, C is the

FIG. 1. A cross sectional view of the DIII–D advanced divertor configuration, showing the bias ring and the cryopump. The gap between the bias ring and the vessel floor armor defines the opening to the pumping plenum.

aperture conductance and S is the pumping speed. Here for the sake of simplicity we assume that Γ_N is independent of S. Then, this relationship shows that the pump exhaust reaches 50% of the incident flux when $S = C$. Since the exhaust rate increases slowly with gap $S > C$, which incurs greater engineering complexities and cost, a pumping speed equal to the conductance of the duct was selected as the design goal.

The quantity Γ_N is a function of the divertor plasma parameters and the plenum aperture conductance. For a given divertor plasma, initially Γ_N increases rapidly with increasing height of the toroidal duct defining the pumping plenum aperture. However, Γ_N is nearly at its maximum value when the duct height is equal to or greater than either the neutral particle mean free path or the width of the SOL. Any further increase in the duct height beyond this point increases the required pumping speed without significantly increasing the exhaust rate.

Since it was anticipated that the most difficult density control conditions are in low collisionality plasmas, we selected a duct height of ≈3.5 cm, equal to the divertor SOL width of typical DIII–D divertor plasmas. For this duct height, we estimate $\Gamma_N = 100$ Torrℓ/s, roughly 10% of the divertor ion flux for a typical DIII–D divertor plasma. Thus the pump exhaust rate $S \times P = \frac{1}{2}\Gamma_N = 50$ Torrℓ/s. Finally, given a duct length of ≈10 cm, determined by biasing considerations, we arrive at a duct conductance and pumping speed of 50,000 ℓ/s which is then the pumping speed goal.

DIVERTOR PUMP DESIGN AND CONSIDERATIONS

The DIII–D vessel was designed to be compatible with either in-vessel or appendage pumps. As seen in Fig. 1, the vessel bottom is larger than the top to allow for installation of in vessel cryo- or getter-pumping. In addition, 24 high conductance pumping ports are available for either appendage or re-entrant pumps. In practice, since most of the designated pumping ports have been taken by valuable plasma diagnostics, the conceptual design effort was narrowed to getter and cryopumps. Because of the inaccessibility of an internal getter source, we only considered long life getters of the Tore-Supra type [9]. This type of pump relies on rejuvenation of a passivated gettering surface by overcoating the surface with only a very thin layer of titanium and then baking at high temperature. As a result, the getter wire would last much longer compared to the conventional thick layer method. However, measurements [9] showed that although the pumping speed of a surface rejuvenated in this fashion is nearly as good as a fresh coating, its particle throughput is greatly reduced and would not meet the DIII–D requirements.

Cryopumping is a well established technology and it has been successfully used in tokamak subsystems such as neutral beam heating drift ducts and as appendage vessel pumps. However, the DIII–D divertor cryopump is the first application of this technique inside a tokamak plasma chamber. Because of the adverse environment of the DIII–D plasma chamber, including disruptions, heat load, and baking cycles to 450°C, the design of the cryopump posed a challenging engineering problem.

2

A major concern in the conceptual design of the pump was the possibility of arcing between the cryogenic elements and the surrounding structure. During plasma disruptions, toroidal voltages of a few hundred volts are induced. Because of presence of ionizing radiation, a wide range of possible gas pressures (0.1 to 50 mTorr) and variable path lengths along the field lines, the arcing problem is analytically intractable and insulation along the field lines impractical. However, the induced voltage between the pump and the vessel could be reduced to a safe limit, for any combination of accessible path length and pressure, by either breaking the cryopanel into at least three toroidal segments, or by building an electrically toroidally continuous cryoloop that remains always near vessel potential. A segmented liquid helium pump would have required more ports, vacuum feedthroughs, and cryotransfer lines and connectors, which would have significantly reduced the system reliability. On the other hand a toroidally continuous structure, which was ultimately chosen, brings problems of its own. In particular, in a toroidally continuous structure, induced currents during the plasma startup and plasma disruptions significantly increase heat loads and forces on the cryo-elements. Other difficult design issues include: thermo-mechanical stresses during vessel bake-out (up to 450°C) and cryopump operation, and heat loads on the cryopanels due to thermal radiation, neutral particles, inductive heating, and plasma radiation.

Details of the system design, construction and testing can be found in earlier publications and proceedings of this conference [10-17]. The pumping speed of the installed system was measured during an applied pulsed heat load of 300 W in the absence of a plasma. At an ambient pressure of 5 mTorr, the pumping speed is approximately 40,000 ℓ/s.

ACTIVE DENSITY CONTROL EXPERIMENTS

The efficacy of divertor pumping was tested by observing the rate of density decay after moving the divertor strike point from an initial position, several SOL widths away from the opening to the pumping plenum, to its optimum pumping position. In general, divertor pumping is found to be more effective in L-mode than in H-mode because of the comparatively broader and denser SOL of L-mode plasmas. Typically in L-mode plasmas the density decay time constant is ≤ 100 ms, and densities as low as 3×10^{12} have been obtained. In contrast, in ELMing H-mode plasmas, the initial density decay time constant is typically 0.5 s. In the remainder of this paper we will discuss only the results from ELMing H-mode plasmas.

We used a combination of gas puffing and divertor pumping to control the plasma density. The pumping rate, as shown in Fig. 2, was controlled by magnetically adjusting the position of the divertor strike point relative to the pumping plenum aperture. To assure stability, the
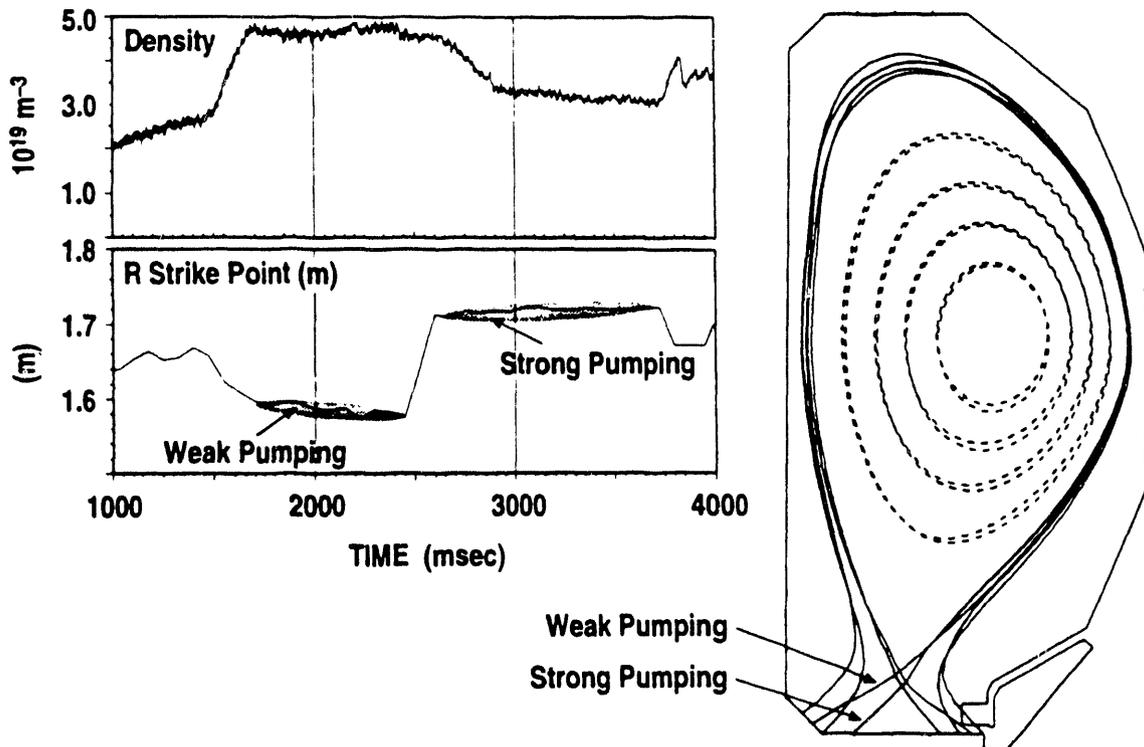

FIG 2.   Magnetic control of pumping. The divertor pumping rate is controlled by adjusting the position of the divertor strike point relative to the pumping plenum aperture.

3

feedback logic is programmed such that, normally, simultaneous gas puffing and divertor pumping are not allowed. With this feedback system during H–mode shots, the pump exhaust rate is typically a few tens of Torrℓ/s; when the divertor strike point is placed at its optimum pumping position with the density feed back active, exhaust rates as high as 200 Torrℓ/s are observed.

Using the above procedure, we were able to control the density and current of H–mode plasmas independently. Fig. 3 displays examples of H–mode plasmas where the plasma density was varied at constant I_p over a range of a factor of two, and conversely, I_p was varied at constant density over a range of a factor of two. Preliminary analysis suggests that H–mode confinement is only a weak function of n_e and increases almost linearly with I_p. Results of local and global transport studies in density controlled H–mode plasmas will be presented in a separate paper [18].

In low to moderate powered H–mode plasmas, with the divertor strike position placed at the optimum pumping position and the gas puff system deactivated, plasma density levels off at approximately 50% of the unpumped H–mode value. In higher power plasmas a locked mode limits the lowest attainable H–mode density. Fig. 4 shows the growth of rotating a 2/1 Mirnov mode which slows down and locks. After the mode locks, the plasma reverts back to L–mode, as indicated by a rapid drop in β_N [$\beta_N \equiv \beta(\frac{a \times B_T}{I_p})$] and plasma density.
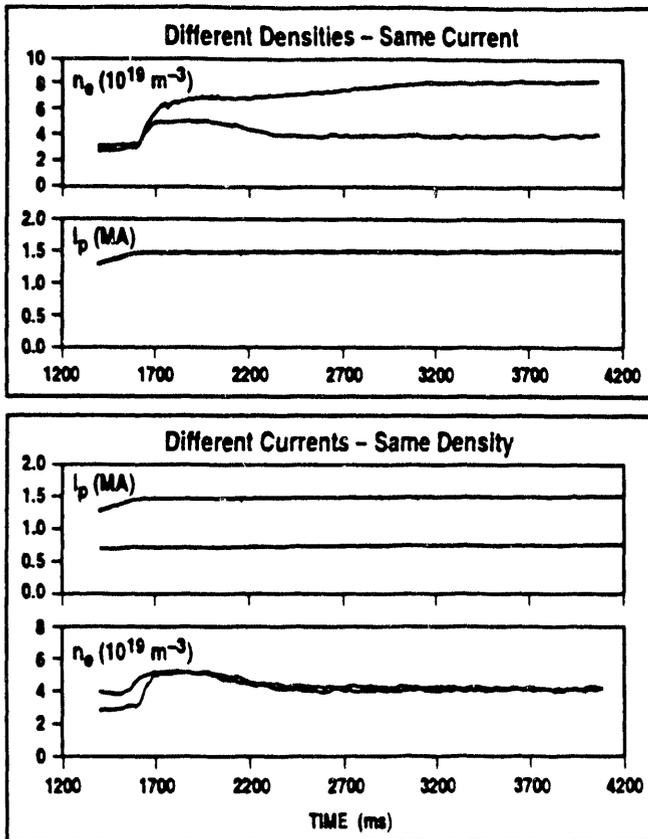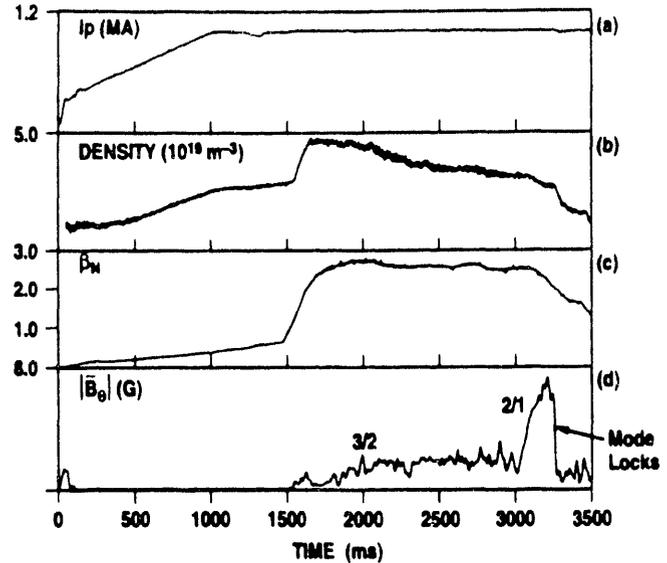

FIG. 4. (a) Plasma current, (b) line average electron density, (c) $\beta_N \equiv B\,(I/aB_T)^{-1}$, (d) magnetic fluctuations. The growth and locking of a 2/1 Mirnov mode limits the lowest attainable H–mode density in plasmas with moderate to high heating power.

ROLE OF THE WALL ON PARTICLE BALANCE

Normally in DIII–D plasmas, the graphite vessel walls (here by wall we mean the divertor target plates and the exposed area of the vessel armor together), behave as a strong particle sink. This is demonstrated in Fig. 5, Shot 1 where in the absence of significant pumping, plasma particles account for only 10% of the injected cold gas and NBI particles. By the end of this shot, the wall particle inventory, as deduced from the difference between the known particle sources and sinks, has increased by nearly 150 Torrℓ. Based on this observation one might expect that the graphite wall pumping would work in parallel with the divertor pump in reducing the plasma density. The experimental data show that, on the contrary, the wall can work against the pump. This is demonstrated in Fig. 5, Shots 2 and 3, where after the divertor pump was activated at $t \simeq 1600$ ms, the wall behaves as a particle source. This surprising result is understood by noting that pumping reduces the ion flux to the divertor target without significantly affecting the heat flux, thus breaking the previously existing particle balance between the target and the plasma. This process is similar to the sudden density rise after the L to H–mode transition [19,20] where the rate of density rise initially is much greater than the external particle sources.

In the shot shown in Fig. 5, Shot 2, by the end of the shot the wall particle inventory has increased only slightly whereas, by the end of the the the shot shown in Fig. 5, Shot 3, there is a large particle deficit. The

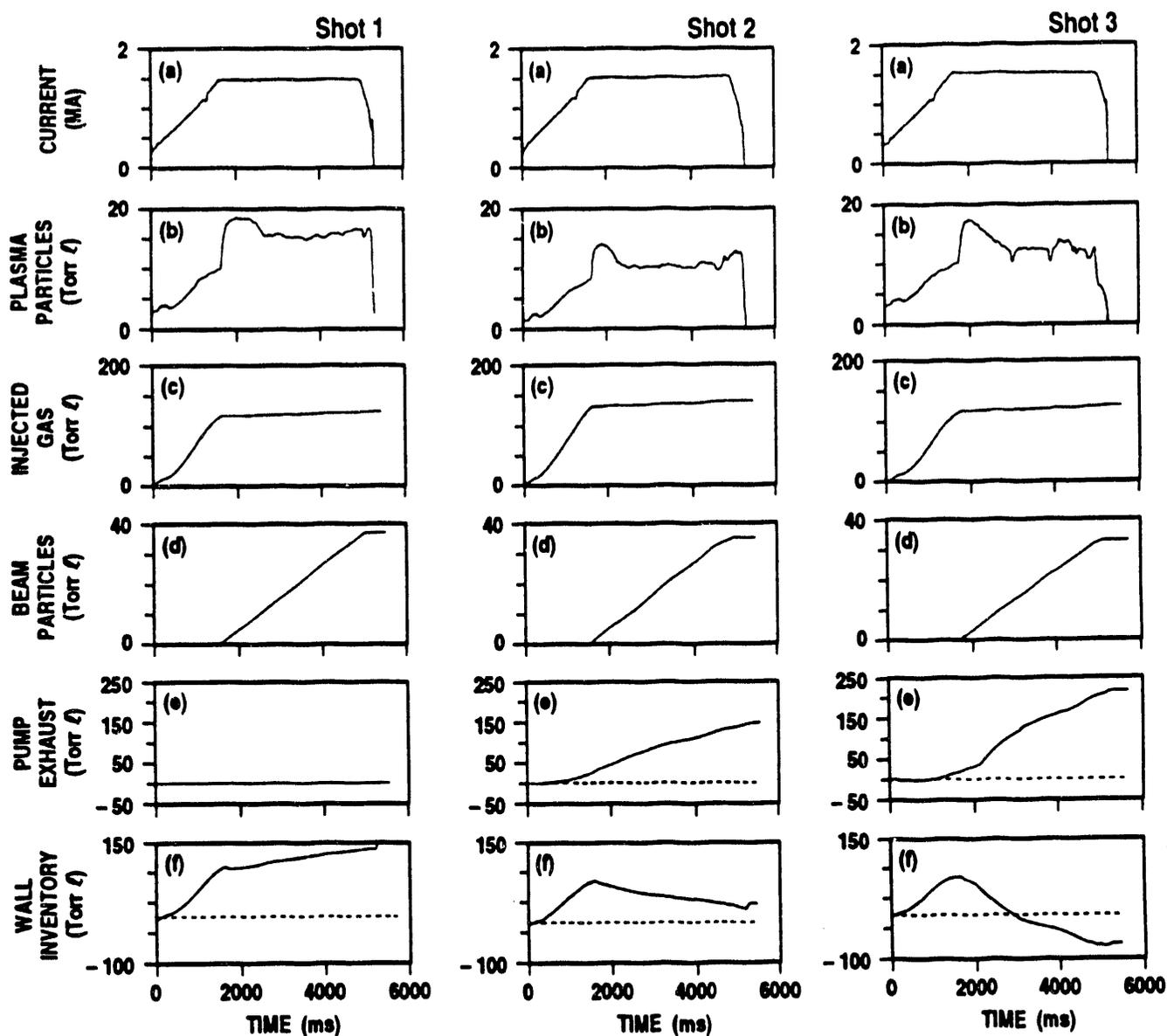FIG. 3. Example of density regulated H–mode plasmas.

FIG. 5. Comparison of particle balance in pumped and unpumped plasmas. (a) plasma current, (b) particle content of the plasma, (c) injected neutral beam particles, (d) integrated pump exhaust, (e) change in wall particle inventory. Shot 1 - unpumped plasma; except for a brief period after the L-H transition at $t \simeq 1600$ ms, wall particle inventory increases continuously throughout the shot. Shot 2 - pumped plasma with pure He glow preceding the plasma shot; after the pump is activated at $t \simeq 1600$ ms, wall particle inventory decreases. Shot 3 - pumped plasma with He glow containing some deuterium; at the end of the shot the wall particle inventory is reduced by ≈ 70 Torrℓ.

difference between these two shots is the initial condition of the wall before the plasma shot. In the former case, the shot was preceded by pure helium glow discharge cleaning whereas in the latter case the glow discharge initially contained some D_2.

It is important to note that, independently of the initial wall conditions, after ≈ 3 s of divertor pumping, the pump exhaust rate is approximately equal to the neutral beam particle source, and as this observation suggests, the initial wall condition does not significantly affect the lowest attainable density of the long pulse plasmas.

DIVERTOR PUMPING EFFECT ON CORE PARAMETERS

Divertor pumping modifies the core plasma density, temperature, and current profiles. Typically in H-mode plasmas, the profiles evolve for the first two seconds after

the start of pumping before reaching a quasi steady state. As the plasma density decreases the electron and ion temperatures increase such that the plasma pressure profile remains roughly unchanged. However, in most cases the increase in the central ion temperature is much higher than that of the electron temperature. This difference is explained by the lower energy exchange rate between the plasma ions and electrons at lower density and the fact that, in the parameter range for these plasmas, most of the neutral beam heating power is delivered to the plasma ions.

Fig. 6 shows a comparison of n_e and T_e profiles of pumped and unpumped shots measured at $t = 4.1$ s, 2.5 s after the start of pumping. Divertor pumping reduced the electron density gradient and increased the electron temperature gradient just inside the separatrix. Reduced recycling during divertor pumping can explain the change in the density gradient in this region, although a concurrent change in particle transport can not be ruled out. In the core plasma, with $\rho \leq 0.6$, the density gradient is nearly a factor of two higher in the higher density plasma. Since in this region the recycling source is insignificant while the neutral beam particle deposition profile is much broader at the higher density, it follows that particle

transport timescale in this region increases nonlinearly with density. We should note that a similar peaking of the density profile was not observed in the low current plasmas.

SUMMARY AND CONCLUSIONS

We have used an in-vessel cryopump – baffle system to control density of H–mode plasmas. Particle exhaust rates as high as 2×10^{22} atom/s^{-1} were observed, which exceed ITER requirements. Although an in-vessel cryopump is not a reactor-relevant option, this result demonstrates that in ITER the desired particle exhaust rate can be attained with a modest pumping speed.

We were able to independently regulate plasma current and density of H–mode plasmas, each over a range of factor two. Preliminary analysis shows that the global H–mode confinement time, similar to the L–mode, increases linearly with plasma current and is insensitive to plasma density.

In general, with lower plasma density, the electron and ion temperatures increase such that the plasma pressure profile remains roughly unchanged. However, because of a reduced rate of energy transfer from ions to electrons, in most cases the central ion temperature increases much more than the electron temperature.

We have observed evidence of core particle confinement improvement with plasma density. This result suggests that low density operation may be more favorable for ITER, since for a burning plasma it is necessary that $\tau_P/\tau_E \lesssim 10$ [21]. Further work is in progress to determine the current and density scaling of the ratio of thermal to particle diffusivity.

FIG. 6. Electron density and temperature profiles of two otherwise similar H–mode shots with different densities.

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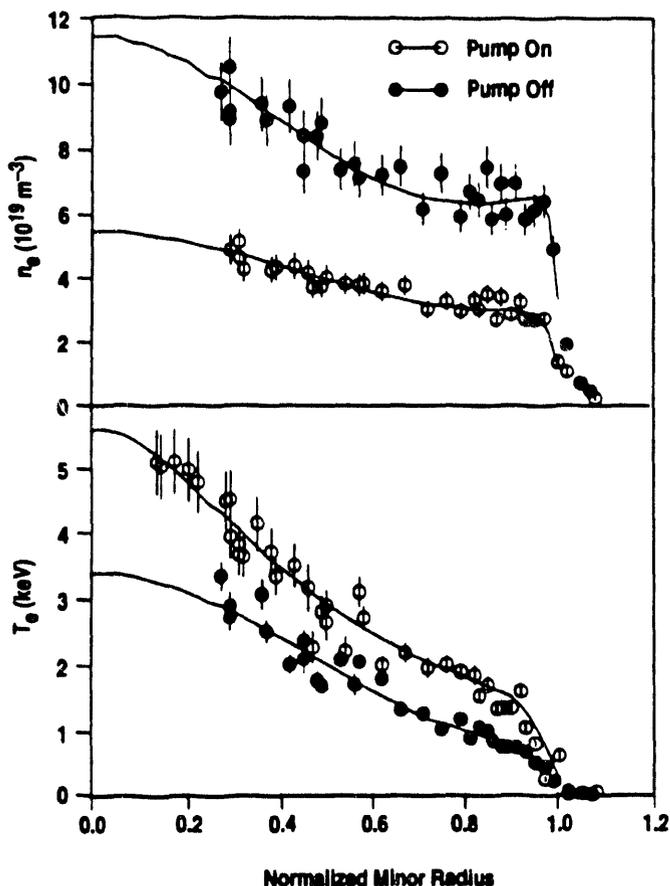
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