Divertor Criteria for a TCT: Some Reasons Why

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October 1975

UWFDM-137

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October 15, 1975

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Introduction

One is continually searching for reasons why one might need to incorporate a magnetic field divertor on a tokamak reactor. It is a fairly expensive item and to date not many quantitative arguments have been put forth. It's the purpose of this note to indicate why a relatively near term tokamak reactor driven by beams (i.e. in a two component torus (TCT) mode of operation requires a divertor.

Reactor Parameters

Consider a TCT reactor having the following characteristics -

$n_e(r = 0) \equiv n_{eo} \simeq 5 \times 10^{13}$ $/cm^3$ = elec. density at r = 0

I_{inj} = 1000 Amps = beam injection current

R_o = 400 cm = major radius

a = 110 cm = minor radius

a_w = 140 cm = wall radius

q_a = 2.5 = safety factor @ r = a.

In the TCT mode, one injects (150 to 200 keV) deuterium beams into a tritium background plasma. To see the necessity for a divertor, one must find criteria to dictate an allowable neutral density in the region between the plasma edge and the wall,* called in this note the scape-off zone.

Criterion #1 - (Beam attenuation)

If one wished to have no more than say a 2.5% loss of the beam during its transit from the injector to the plasma edge (which seems reasonable) one finds that the allowably average neutral density in the beam tube and scrape

* Also one will be concerned with neutral density along the beams path in the injection tubes which penetrate the blanket and shield.

off zone must be less than 5×10^{11} /cm^3.

This number is easily calculated by considering the following facts. First, the total beam path length through the blanket and shield region (which is 1.9 m thick) and then through the scape-off zone is approximately 3 meters. Account has been taken of the injection angle which assumes a tangential injection with the magnetic axis (taken at R_o = 4m). Secondly, the penetration length of a high energy neutral beam through a neutral background gas is given by

$$\lambda \text{ penetration} = \frac{v_{beam}}{n_n \langle\sigma v\rangle_{Total}} \quad .$$

where n_n = neutral density of background gas.

If d = percent attenuation which one considers allowable (2.5 in this example) one can show that n_n must be less than or equal to n_n^{crit} where

$$n_n^{crit} = \frac{1.38 \times 10^6 \sqrt{E_b/AMU}}{L\langle\sigma v\rangle_{Total}} \ln\left(\frac{1}{1 - (d/100)}\right) \text{ cm}^{-3}$$

and

E_b = beam energy [eV]

AMU = atomic mass of a beam atom [AMU]

L = length of beam path through neutrals [cm]

d = allowable attenuation [%]

$$\langle\sigma v\rangle_{Total} = \langle\sigma v\rangle_{\substack{charge\\exchange}} + \langle\sigma v\rangle_{ionization} \quad [\text{cm}^3/\text{sec}]$$

For the device considered in this note, $E_b = 1.5 \times 10^5$, AMU = 2, L = 300, $\langle\sigma v\rangle_{Total} = (.108 + .609) \times 10^{-7}$, d = 2.5 which gives $n_n^{crit} = 4.45 \times 10^{11} \text{cm}^{-3}$ which corresponds to a pressure of 1.4×10^{-5} Torr @ 300°K.

Criterion #2

According to some fairly recent work performed at Princeton[(2)] on TCT devices of the dimensions given here, one finds that Q = fusion power out/beam power absorbed can be degraded by 10 to 20% if the neutral density in the plasma (target) is allowed too high. Quantitatively, this turns out to be a restriction on the ratio of $n_n(r = 0)$ to $n_e(r = 0)$ which turns out to be

$$\frac{n_n(r = 0)}{n_e(r = 0)} < 10^{-5} .$$

This calculation also draws upon another fact which is largely model dependent and that is the observation (from transport codes) that n_n (edge of plasma)/$n_n(r = 0) \simeq 10^3$ for TCT's of $\simeq$ 1 m minor radius and $\bar{T} \sim 5$ keV.

Coupling these two pieces of data, one sees that for $n_e(0) = 5 \times 10^{13}$ that $n_n(0)$ must be kept below 5×10^8 which translates to a neutral edge density of 5×10^{11} cm^{-3} which implies P ~ 1.5×10^{-5} Torr @ 300°K. This one notes is roughly the same requirement imposed by the 1st criterion. Now we must consider whether the criterion can be met.

Vacuum Pumping

If one were to try and exhaust the diffusing plasma by cooling it (let it hit the walls, limiters, etc.) and then vacuum pumping the neutrals, the following calculation should fill your heart with despair!

For a beam injection current of 1000 amperes, one has an injection rate of

$$\dot{n}_b = (1000 \text{ c/sec})/(1.602 \times 10^{-9} \text{ coul/part})$$

$$= 6.24 \times 10^{21} \text{ D/sec}$$

and assuming total beam absorption this is an D^+ ion input to the plasma. This $\dot{n}_b$ translates into

$$\dot{n}_b = (6.24 \times 10^{21}\ \text{sec}^{-1})(1.04 \times 10^{-22}\text{torr-}\ell/{}^\circ\text{K})(300^\circ\text{K})$$

$$\simeq 194\ \text{Torr-liters/sec @ } 300^\circ\text{K}$$

of required throughput.

In Appendix A, a calculation is performed which shows roughly that for $Q \sim 1$ (and assuming ohmic heating balances radiation losses) the particle (D + T) loss rate from the plasma, n/τ_p is $\sim 3 \times \dot{n}_b$. This means one must try to handle a throughput of 3 x 194 = 582 Torr-liters/sec @ 300 °K. To maintain $P \sim 2 \times 10^{-5}$ Torr, this requires a pumping speed of

$$S(\ell/\text{sec}) = \frac{582}{2 \times 10^{-5}} = 2.91 \times 10^{7}\ \text{liters/sec.}$$

$$= 1.46 \times 10^{7}\ \ell/\text{sec of "DT" molecules}$$

Taking the pumping speed per unit area of a black-hole to be

$$\left(\frac{S}{A}\right)_{bh} = \frac{\bar{V}}{4} \simeq 3.624(T({}^\circ K)/AMU)^{1/2}\ \text{liters/sec/cm}^2 \simeq 30\ \text{liters/sec/cm}^2$$

for an "DT" molecule (AMU = 5) at 300°K

and assuming (optimistically) that the effective speed of a real vacuum pumping system is

$$\left(\frac{S}{A}\right) \simeq \frac{1}{3}\left(\frac{S}{A}\right)_{bh} \simeq 10\ \text{liters/sec/cm}^2$$

one finds the required port area, A_{pump}, to be

$$A_{pump} = \frac{2.91 \times 10^7}{10} = 1.5 \times 10^6\ \text{cm}^2.$$

The area of the first wall of a reactor of these dimensions is

$$A_{wall} = 2\pi(140)2\pi(400) = 2.21 \times 10^6\ \text{cm}^2$$

This implies that the required pumping area ≃ 66% of total wall area.

The conclusion is inescapable, either one has to live with higher pressures or one must use a divertor which can pump the charged particles at a much higher rate.

A Divertor

The "pumping speed" of hot charged particles flowing (called effusing) along B field lines as in a poloidal magnetic field divertor is given by

$$\frac{n\bar{V}}{4}\,[(A_{eff})4]$$

where

$$A_{eff} = (\vec{\bar{V}}) \cdot \vec{A} = (2\pi\ R_o h\cos\theta) = 2\pi\ R_{oh}\frac{B_p}{B}$$

$$= 2\pi a\,\frac{h}{q_a} \quad \text{(See Fig. 1) (Ref. 4)}$$

$$\bar{V} = (8kT_i/m_i\pi)^{1/2}$$

$$h = \left(\frac{1}{n}\frac{dn}{d\gamma}\right)^{-1} \quad \text{for plasma in divertor (scape-off) zone.}$$

$$\simeq \sqrt{D_{\perp}\tau_{\parallel}}$$

$D_{\perp}$ = $\perp$ diffusion coefficient in divertor zone

$\tau_{\parallel}$ = characteristic loss time of particles flowing to collector

Using h $\simeq$ 10 cm as a typical value, one finds

$$(A_{eff}) = 2\pi\,\frac{(110)(10)}{2.5} = 2.76 \times 10^3 cm^2$$

and the total effective area is 4 times this number when one uses a double null poloidal divertor, since there are really 4 channels along which particles may leave.

To pump (i.e. allow to effuse) 1.87×10^{22} particles/sec through total area of $4(2.76 \times 10^3) = 1.1 \times 10^4 cm^2$ one must have

$$\frac{n\bar{v}}{4} = \frac{1.87 \times 10^{22} \text{sec}^{-1}}{1.11 \times 10^{4} \text{cm}^{2}} = 1.7 \times 10^{18} \ \#/\text{cm}^2/\text{sec}.$$

This may be rewritten for T_i in eV, n is $\#/cm^3$, as $n(T_i/AMU)^{1/2} = 4.32 \times 10^{12}$ and for AMU = 2.5 one has

$$nT_i^{1/2} = 6.84 \times 10^{12}$$

One can now see roughly how n and T_i must balance at the plasma edge by looking at Table 1.

Table 1

$\bar{n}(\#/cm^3)$	$[T_i(eV)]$edge
10^{13}	.47
10^{12}	46.8
4.8×10^{11}	200
2.2×10^{11}	1000
1.5×10^{11}	2000
10^{11}	4678
3.2×10^{10}	5000

Clearly, the plasma, including the divertor physics, will determine the correct balance. One sees that $T_i \sim 100$ eV range implies fairly low (average) plasma densities in the divertor zone and that is not good in terms of shielding the plasma from wall originated impurities!

Conclusion

One cannot be fooled into thinking that the vacuum pumping problem is completely alleviated by using a divertor. One merely shifts the onus of the pumping up into the divertor collection chamber. Presumably, there is more freedom and flexibility to handle this pumping chore once one is away from the plasma core and of course the high neutron fluxes. What one does alleviate is the plasma physics (Q high) and beam injection problems which is, after all, "what it's all about"!

The vacuum pumping problem is still severe and to date no satisfactory method has been proposed.

Rather than ending this note with the problem in the air, I feel it somewhat necessary to provide a little further discussion on divertor transport characteristics; $n(r)$, $T_e(r)$, $T_i(r)$ profiles, charge exchange losses etc. I will not succumb to this tempetation, however, except to refer the reader to Appendix B and reference 5.

Appendix A

$\Gamma_{inj} \equiv$ # D atoms injected and ionizedby plasma/sec.

Γ_{loss} = # (D + T) ions lost from plasma/sec

$$= \frac{n_D + n_T}{\tau_p} V_p = \frac{n_e}{\tau_p} V_p$$

where τ_p = particle confinement time

V_p = plasma volume = $2\pi R_o \pi a^2$

For an energy balance one must have

$$(E_b \Gamma_{inj} + E_\alpha n_D n_T <\sigma v>_{Fus.} V_p + P_\Omega)\tau_E = \frac{3}{2} n_e (\overline{T_i + T_e}) V_p + P_{rad}\tau_E$$

where E_b = initial beam energy $\quad V_p$ = plasma volume

P_Ω = ohmic heating power $\quad E_\alpha$ = 3.5 MeV

P_{rad} = radiation power loss

τ_E = energy confinement time

Clearly if $P_\Omega \simeq P_{rad}$, $\bar{T}_i \simeq \bar{T}_e$ and $Q \equiv \frac{E_{fus} n_D n_T <\sigma v>_{fus} V_p}{E_b \Gamma_{inj}} \sim 1$

then one has

$$\Gamma_{inj} \simeq \frac{3 n_e T_e V_e / \tau_E}{E_b (1 + .18Q)} \simeq 3\, n_e \frac{\bar{T}_e V_p}{\tau_E E_b}$$

therefore

$$\frac{\Gamma_{loss}}{\Gamma_{inj}} \simeq \frac{1}{3}\left(\frac{\tau_E}{\tau_p}\right)\frac{E_b}{T_e} \simeq \frac{1}{3}\left(\frac{1}{4}\right)\frac{150}{5} \simeq 2.5 \text{ is taken 3 to be safe.}$$

Appendix B

Taking a divertor plasma density profile[3] to go as

$$n(x) = n_o e^{-\alpha(x-x_s)} \qquad x_s = \text{dist. to separatrix}$$

and a $\bar{T}_i \simeq 100$ eV so that $<\sigma v>_{cx} \simeq 3 \times 10^{-8} \text{cm}^3/\text{sec}$, one can see that the flux of charge exchange neutrals, produced in just the divertor zone, which go to the first wall is given by

$$\Gamma_{nw} \approx \frac{1}{2} \bar{n}_n <\sigma v>_{cx} \int_{x_s}^{x_w} n(x)dx. \qquad \#/\text{cm}^2/\text{sec}$$

The factor of $\frac{1}{2}$ assumes (optimistically) that only $\frac{1}{2}$ of the charge exchange neutrals hit the wall, the other half are ionized in plasma or pumped out.

For $\alpha \simeq (1/10)\text{cm}^{-1}$, L = average distance to collector plates $\simeq$ 1000 cm, $x_w - x_s \simeq 30$ cm, that $V_i = 6.2 \times 10^6$ cm/sec, $n_o = \Gamma_o \frac{L}{\bar{V}_i} \alpha = \Gamma_o\, 1.61 \times 10^{-5}$ where Γ_o = plasma flux diffusing across separatrix into the divertor scrape-off zone and $\alpha = (DL/V_i)^{-1/2}$.

$$\Gamma_{nw} \simeq \frac{1}{2} \bar{n}_n (3 \times 10^{-8})(1.61 \times 10^{-5}\Gamma_o) \frac{1}{.1} (1 - e^{-30/10})$$

or

$$\frac{\Gamma_{nw}}{\Gamma_o} = 2.3 \times 10^{-12} \bar{n}_n$$

In order to keep $\Gamma_{nw}/\Gamma_o \leq 10\%$, one requires (for $\alpha = 1/10$)

$$\bar{n}_n < \frac{.1}{2.3 \times 10^{-12}} \simeq 4.4 \times 10^{10}.$$

If $\alpha = \frac{1}{5}$ one would have obtained

$$\bar{n}_n < 4.2 \times 10^{10}$$

If $\alpha = \frac{1}{10}$ but $T_i \simeq 500$ eV instead of 100 eV, one has

$$\bar{n}_n < 5.7 \times 10^{10}.$$

These results are easily explained. First, for flux of plasma diffusing out of the main plasma core (Γ_0), the average plasma density in the divertor goes as*

$$\bar{n} \sim \frac{1}{T_i^{1/2}} (1 - \exp(-\alpha(x_w - x_s))).$$

Thus, reducing $\alpha \sim (D_\perp \tau_{\parallel})^{-1/2}$ with T_i fixed raises $\bar{n}$ which requires that $\bar{n}_n$ be smaller in order that $\bar{n}\,\bar{n}_n \langle\sigma v\rangle_{cx}$ remain fixed. One sees that raising T_i does roughly the same thing for a fixed α provided the change is not so large as to cause $\langle\sigma v\rangle_{cx}$ to change greatly.

It may be argued however that having a low cx rate in the divertor zone is bad if it means lowering the divertor density. Clearly if $\bar{n}$ is low, then many more neutrals (and impurities for that matter) will pass unimpeded into the main plasma zone. This would produce hotter cx neutrals which can sputter more effectively.

In point of fact, what would be an ideal situation is to have a moderate density ($>10^{11}$), warm electron (>10 eV), plasma. Then the cx neutrals would not damage the wall nor penetrate too far into the main plasma. The electrons would ionize neutrals and impurities coming off of the walls. In large reactors, the synchrotron radiation may be strong enough to maintain such a plasma in the divertor zone!

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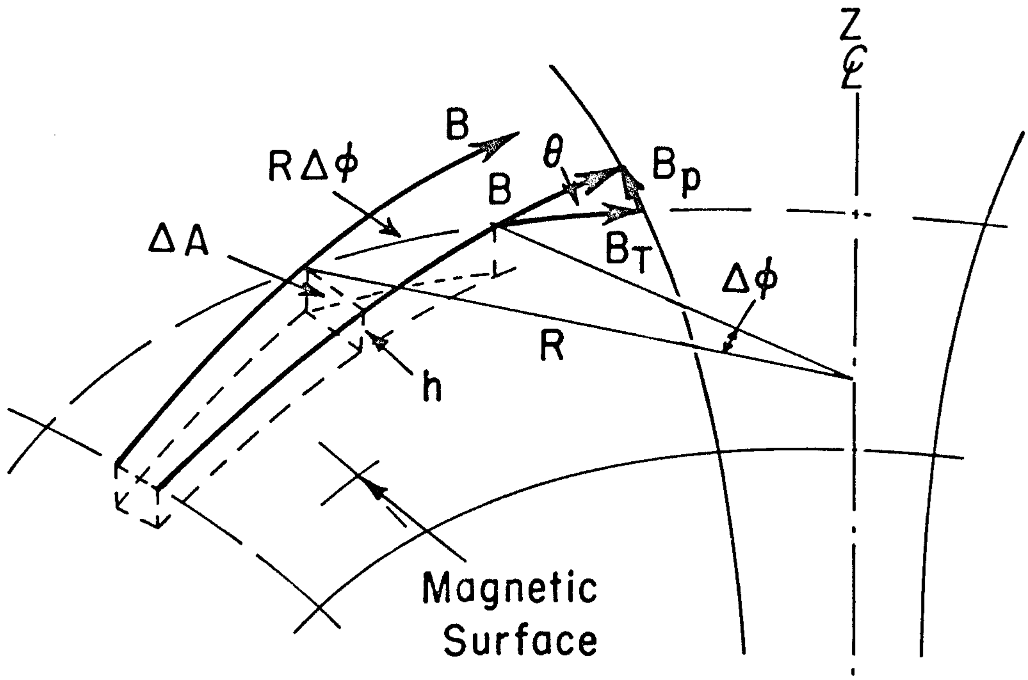
* A correction for neutrals being ionized and the presence of a small source of neutrals will cause it to be about 25% larger.

Thus, life is not rosey unless one can "burn" out to neutrals by ionization and subsequent divertor flow to a collector region. If you cannot lower $\bar{n}_n$ by pumping or burning them out, then you would like a 10^{11} or 10^{11} warm electron plasma in the divertor zone. More advanced computer calculations tell me that this may not be easily done in the divertor.

Acknowledgement

This research was partially supported by the U. S. Energy Research and Development Administration.



$$(\Delta A) = hR\Delta\phi \sin\theta$$

$$= hR\Delta\phi \frac{B_p}{B}$$

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Figure 1 - Geometry of flux tube.

References

1. This calculation parallels and amplifies a similar calculation performed by Dr. Fred Tenney, Princeton Plasma Physics Laboratory, and presented at a divertor workshop on 14 October 1975. Data used is taken from his calculation.

2. This calculation was first reportedly done by Paul Rutherford at PPPL.

3. UWFDM-68, Vol. 1, Divertor Section by A. T. Mense and G. A. Emmert.

4. MATT-1050, Divertor Section, Editor R. G. Mills.

5. "Magnetic Field Divertors on Tokamak Reactors," by A. T. Mense, Ph.D. Dissertation, Nuclear Engineering Department, University of Wisconsin, Madison, Wisconsin 1975.