POLOIDAL FIELD REQUIREMENTS FOR DIVERTOR AND PUMP LIMITER DESIGN

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Poloidal divertors in tokamaks have proven successfull in controlling impurities at high energy flows /1/ - /3/, promise to solve with high probability the helium pumping problem of a reactor, and have recently also allowed access to a new discharge regime with improved energy confinement /4/. Their basic drawback is considered to be the increased poloidal field effort compared to a conventional limiter design.

This poloidal field effort has been quantitatively assessedby us in comparative design studies for poloidal divertor and limiter tokamak configurations for two devices (ASDEX Upgrade and INTOR) under reactor-similar geometrical restrictions. The following assumptions were made about the necessities of a tokamak reactor:
- a limiter has to be a toroidal pump limiter
- an elongated, D-shaped plasma cross-section is needed also in case of limiter configurations to achieve high ß-values
- all active poloidal field (PF)-coils are outside the toroidal field (TF)-coils.

For both devices, only configurations with target plates and pumping chambers below the bulk plasma have been considered. Calculations were carried out using different versions of the Garching equilibrium code package which applies the numerical methods described in /5/. The results are valid both for rather flat ($j \sim \psi - \psi^2$; ψ : poloidal flux function) and more peaked toroidal current densities ($j \sim \psi$).

1. ASDEX UPGRADE CONFIGURATIONS

ASDEX Upgrade /6/ is planned as a successor experiment to ASDEX, differing from the latter essentially through its higher plasma current and a reactor-similar poloidal divertor configuration. It utilizes a PF system with all coils outside the TF coils and foresees operation with double null (DN) and single null (SN) divertors and with a pump limiter (L).

The optimization criterium for the divertor configuration was to realize in a given vacuum vessel (main field volume) the largest possible plasma volume, leaving adequate space for target plates and pumping access. The PF system, on the other hand, depends critically on the required mix of quadrupole and hexapole fields to produce the D-shaped configurations: as the currents necessary increase like the second and third power with the distance coil to plasma center, respectively, even moderate hexapole moments will tend to dominate the effort in reactor-like situations.

The above criteria strongly favour SN over DN configurations: for a similar shape of the interiour flux surfaces, the volume available is more than 50 % larger in an unsymmetrically positioned SN configuration /fig. 1b/ than in a verticaly centered case with two identical divertor regions. From the magnetics point, the SN configuration can be viewed at as a DN with a superposed radial field shifting the plasma closer to one of the two stagnation points. As the distance between these two stagnation points is larger than between the ones bounding the true DN configuration the required coil currents are also reduced as compared to the DN case.

The volume utilization of the DN configuration at given height of the stagnation points can be improved by using hexapole fields to increase its midplane diameter and, correspondingly, its triangularity $\theta = c/a$. This involves however a further dramatic increase in the required coil currents, which for ASDEX Upgrade then become a factor 2.2 larger in total ampere-turns /fig. 1a/ than those of the SN configuration at the same plasma current. DN operation is therefore only foressen at reduced parameters to study phenomena like poloidal asymmetries in the scrape-off transport. The stability of the vertical displacement mode for the SN and DN configurations shown is the same, as the smaller triangularity of the SN case is compensated by a smaller elongation.

The basic pump limiter configuration of ASDEX Upgrade has a similar shape of the interiour flux surfaces as the SN divertor case, but is vertically centered /fig. 1c/. The plasma surface is defined by

$$R = R_0 + a \cdot \cos(\varphi + \theta \cdot \sin\varphi)$$

and

$$z = b \sin\varphi,$$

with $b/a = 1.6$ and $\theta = 0.1$ and is similar in shape to the top half of the SN separatrix. The total ampere-turn requirements of the PF-coils for this case are about 35 % less than those for the optimal divertor configuration. This relative small difference can be explained by the strong similarity in ths flux surface structure. Even in the limiter case stagnation points exist close to the plasma surface, defining a separatrix that would become plasma boundary if the limiter were removed. Only minor change in the external currents would then be required to connect the flux surface passing through the lower stagnation point to the old, L-case, plasma boundary in the top half to form an SN configuration.

Most of the actual difference in the PF requirements between the configurations of fig. 1b and 1c arises from the shift of the plasma centre relative to the centre of the PF coil system in the case of the divertor tokamak. This enhances somewhat the totally needed currents, but particularly produces a top-bottom asymmetry in their distribution. As a consequence of the latter, quadratic measures of the coil currents (like their magnetic energy) change stronger than $\Sigma/I_M/$.

Designing the ASDEX Upgrade PF-system we have maintained a separate, nearly stray-field free OH system with a long central solenoid. It can be shown however that during the final flat-top phase of a tokamak discharge, when OH and plasma currents are antiparallel, the stray fields produced by a short central solenoid aid the formation of a separatrix, reducing thereby the required currents in the other PF-coils. This effect has been utilized in the INTOR design studies, by subdividing the central OH coil into separately fed segments.

2. INTOR LIMITER AND DIVERTOR CONFIGURATIONS

The PF system of INTOR is additionally complicated by the distance of the PF coils which compared to the plasma dimensions is relatively larger, and the geometrical restrictions on coil location arising from maintenance and assembly requirements. Divertor configurations studied for this device in recent time have been of the SN-type, since its advantages had been pointed out in /7/.

Our PF study mainly concerned the comparative design of a SN divertor /fig. 2a/ and a pump limiter /fig. 2b/, for identical main field coils. Both plasma configurations shown have similar surface shapes in the top half (corresponding to $b/a = 1.45$, $\theta = 0.15$) where the modest values of elongation and triangularity are needed to avoid in the scrape-off layer the formation of a separatrix opening up and leading to wall contact in the top half of the plasma vessel. PF coil locations and currents for the low and the high ß-case of the two configurations are shown in tables 1 and 2 of ref. /8/, where the OH contributions corresponding to the expected consumption of resistive and inductive fluxes are also included. Comparison of the usual figure of merit shows a $\Sigma/I_M/$ = 86.1 MAT for the SN divertor and of 81.6 MAT for the limiter case during the high ß-phase (I_P = 6.4 MA). These numbers are, however, inflated (and the relative differences thereby decreased) by the common OH contribution necessary to adjust the flux balance. A more reasonable comparison consists in neglecting the currents in the central core in both cases: the remaining $\Sigma/I_M/$ amounts to 51 MAT for the SN divertor and about 39 MAT for the limiter case, with a $\sim$30 % difference in this figure of merit.

3. CONCLUSIONS

The PF design calculations described above have shown that a SN divertor configuration is by far optimal compared with a DN configuration. The unexpected modest difference between the total currents required for limiter and SN divertor underlines the reactor potential of the SN configuration concerning the PF effort. The obtained, large values for $\Sigma/I_M/$ for the limiter case are of course due to the prescribed elongated, D-shaped plasma cross-sections: only about 6 MAT would be required in the INTOR case of section 2 to keep in equilibrium a circular plasma column. The contribution of the coil currents for the required additional quadrupole and hexapole moments to $\Sigma/I_M/$ dominate in a situation like INTOR or ASDEX Upgrade, while in a situation like JET with very close PF coils their contribution is swamped by the dipole field balancing the hoop force.

Table 1

PF coil locations and currents for ASDEX Upgrade ($ß_p$ = 2.2) per MA plasma current

Coil		1o	1u	2o	2u	3o	3u
position	R[m]	1.6	1.6	3.05	3.05	3.55	3.55
	Z[m]	2.34	-2.34	1.66	-1.66	0.60	-0.60
currents	[MA]						
DN		3.6	3.6	-2.28	-2.28	0.3	0.3
SN		0.85	2.50	-0.31	-1.08	-0.45	-0.35
L		1.0	1.0	-0.12	-0.12	-0.65	-0.65

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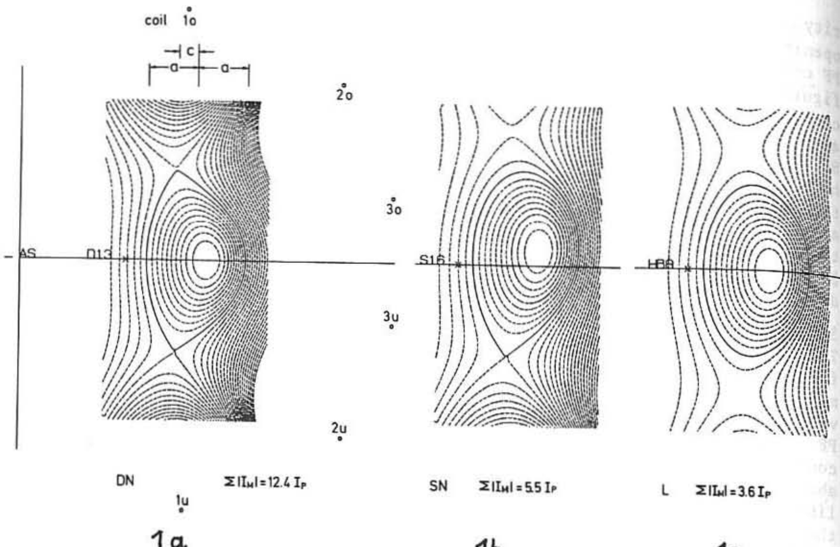

Fig. 1a-c: DN, SN and Pump Limiter Configuration for ASDEX Upgrade ($\beta_p = 2.2$). The multipole currents are given in table 1 ($R_p = 1.65$ m, $a = 0.5$ m)

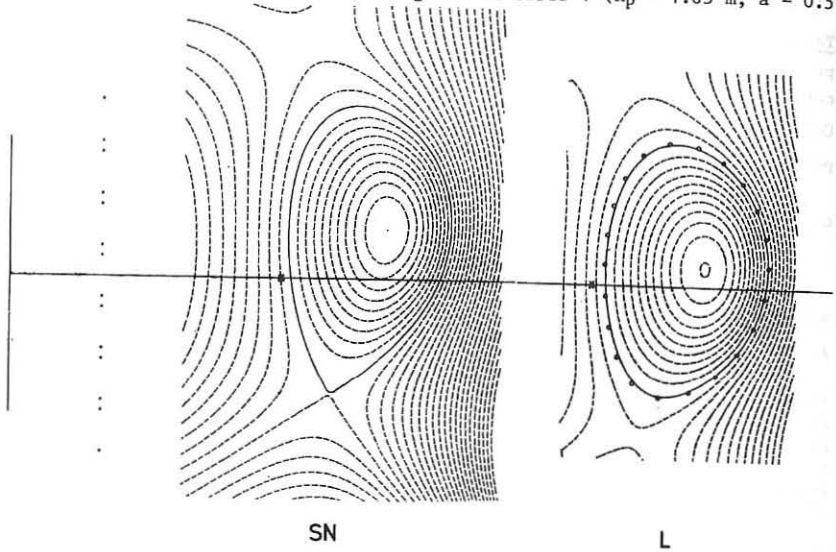

Fig. 2a-b: SN and Pump Limiter Configuration for INTOR ($\beta_p = 2.7$, $R_p = 5.3$ m, $a = 1.2$ m)