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The Effect of Hexapole and Vertical Fields on α-particle confinement in heliotron configurations

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Collisionless mono-energetic α-particle confinement in three-dimensional magnetic fields obtained from the magnetic coils of the Large Helical Device (LHD) is calculated. It is found that the inward shift of magnetic axis due to the vertical field improves the α-particle confinement. In contrast to the vertical field, both large positive and negative hexapole fields do not improve the confinement. The study of the β effect and Mercier criterion calculations for different hexapole fields are also presented.

KEYWORDS: heliotron configurations, LHD, hexapole and vertical field, alpha particle confinement

§1. Introduction

The Large Helical Device (LHD at the National Institute for Fusion Science, Japan) is the largest active heliotron device. Recent work by Murakami et al[1)] concerns about the neoclassical transport optimization in which the magnetic axis has been shifted radially by evaluating the mono-energetic transport coefficient and the effective helical ripple. The optimum configuration is found when the magnetic axis has a major radius of 3.53 m, which is 0.22 m inward shifted from the 'standard' configuration of LHD. A strong inward shift of the magnetic axis in the LHD can diminish the neoclassical transport to a level typical of so-called 'advanced stellarators', like Wendelstein 7-X (see, e.g.[2)]).

In our previous paper, Ref.[3)] , it was shown that a quasi-omnigenous structure of the magnetic field (Ref.[4,5)]) can be achieved by optimization of conventional inward shifted LHD-like heliotron configurations with the aspect ratio of 6.5 and $N = 10$ period. For the $N = 10$ quasi-omnigenous configuration obtained, there are almost no lost α-particles during 0.05 seconds of their time of collisionless flight. However, in Ref.[3)] , significant modifications of plasma boundary shape have been performed in the way of optimization calculations to achieve such a good α-particle confinement property. In particular, the largest modification was made for R_{21} component in the Fourier representation of the plasma boundary shape (here 2 is the poloidal index and 1 is the toroidal index which is normalized by N), which corresponds to the increase of the rotating triangularity of the plasma shape. The question araised from these modifications is whether it is possible to achieve such a significant variation of plasma boundary shape by real LHD coil system. In this paper we explore numerically the possible effect of the relevant magnetic field components, taking into account mainly the effect of vertical and hexapole fields obtained from the real LHD coil system on collisionless α-particle confinement. We also present the β effect and the ideal Mercier criterion for the configurations obtained to define the possible optimal combination of the LHD coil fields.

The paper is organized as follows. Section 2 describes the numerical tools used in the calculations. Section 3 briefly presents the relationships between hexapole, vertical fields and plasma boundary shape properties of the LHD. It also shows the effect of these fields on α-particle confinement and the Mercier criterion which is followed by the summary.

§2. Numerical tools

3D numerical codes are an essential part of stellarator theoretical achievements of the last years. In this paper we use KMAG[6)] , DESCUR[7)] , VMEC[8)] , JMC[9)] and MCT[10)] numerical codes.

The KMAG is the field line tracing code with the Biot-Savart law from the given coil geometry. The hexapole and vertical fields are varied in this paper by changing the coil current ratio (mainly currents within the three pairs of poloidal coils).

We obtain the Fourier spectrum of the plasma boundary magnetic surface from 60 magnetic field line tracing intersections with 20 toroidal cross-sections using the DESCUR code.

The calculations of 3D ideal MHD equilibria for given fixed boundary with the VMEC code. The VMEC code solves the 3D MHD ideal inverse equilibrium equations by gradient method using a representation for the magnetic field that assumes nested flux surfaces. In this paper we use the 5.20 version of the VMEC code which is suitable for stellarator systems without net toroidal current. The modification of the VMEC code, version VMEC2000 - 6.80 was recently improved to calculate plasma equilibrium for low aspect ratio systems with net toroidal current, like NCSX and QOS[11)] . In these equilibrium calculations, 33 flux surfaces and 113 VMEC poloidal and toroidal Fourier components are used for the representation of equilibrium quantities.

The JMC code calculates the magnetic field strength B in Boozer coordinates[12)] . The maximal poloidal mode index in our runs is 9, the maximal toroidal mode index is 8. The transformation from VMEC angular variables to Boozer coordinates is helpful because of the simplicity of the co- and contra-variant magnetic field vector representations. In this paper we use 162 magnetic field components obtained from the JMC code in Boozer coordinates. The Mercier criterion[13] is also calculated in the JMC code.

To check the α-particle confinement properties, the MCT code is used, which follows 2000 collisionless monoenergetic (3.52 MeV) α-particle drift orbits during a typical confinement time of 0.05 seconds for a plasma volume of 1000 m^3 and B_0 of 5 T and with a given Boozer spectrum of the magnetic field and given profiles of equilibrium flux quantities.

§3. Effect of hexapole and vertical fields on α-particle confinement

We briefly describe the coil system of the LHD[14]. For the flexible currentless plasma operation of the LHD, the magnetic field properties such as the rotational transform, plasma position/shape, plasma-wall clearance should be controlled by the external coils. For these purposes the three-layer structure of the helical coils are adopted to adjust the helical pitch parameter and the divertor-wall clearance. The applied vertical magnetic field are obtained from helical and poloidal coils. Three pairs of poloidal coils provide controllability such as adjustment of the axis position by dipole field component, the triangularity by hexapole field component etc. When the vertical field component, B_Z, with poloidal coils is decomposed as the followings, the dipole, quadrapole and hexapole components are defined as B_D, B_Q and B_H, $B_Z = B_D + B_Q X + B_H X^2 + ...$ and $X = (R - R_{axis})/R_{axis}$[15].

At the beginning, we explore the effect of the vertical magnetic field which changes the major radius of the magnetic axis, R_{axis}, and changes the triangularity of plasma boundary shape. The basic improvement of α-particle confinement with more inward shifted magnetic axis position are shown in Fig. 1(a). Here we present pairs of points which correspond to the numbers of lost α-particles starting from the quarter of plasma radius (with flux surface label $s = 0.0625$, lower points) and from the half of plasma radius (flux surface label $s = 0.240$, upper points). The error bar shows the accuracy of these MCT calculations based on the Monte-Carlo method.

The highest losses of more than 20% is estimated in $R_{axis} = 3.81$ m magnetic configuration. The lowest losses of just a few percents have been found for $R_{axis} = 3.45$ m. The large vertical field is connected also with the increase of the rotating triangularity of the plasma boundary shape R_{21} and with non-planar magnetic axis. The R_{21} component is the largest for $R_{axis} = 3.45$ m case with $R_{21}/R_{00} = 3.7 \times 10^{-3}$. For the case of $R_{axis} = 3.81$ m, $R_{21}/R_{00} = -1.3 \times 10^{-3}$ as shown in Fig.1(b). Here the calculations have been made in a low β currentless regime, where β indicates the volume averaged beta value. These results seem to be corresponding to the tendency for the improvement of the neoclassical diffusion due to the inward shift of the magnetic axis obtained numerically in Ref.[1] and in the LHD experiments[16]. Here, we have chosen the case with $R_{axis} = 3.60$ m for the further investigations of hexapole fields effect. In general, the hexapole fields do not change the magnetic axis position and the rotating triangularity R_{21}, however, these fields change so-called constant triangularity of the plasma boundary shape, which is expressed by R_{20} component.

The effect of the hexapole fields is shown in Fig. 2(a). It can be clearly seen there the optimal hexapole field value $H = 129\%$. Here, H denotes the hexapole component produced with the poloidal coils which is normalized by one with the helical coils, that is, $H = 100\%$ corresponds to zero as the total of the hexapole components, and almost zero triangularity. The $H = 129\%$ corresponds to the triangularity with $R_{20}/R_{00} = 7.9 \times 10^{-4}$. Both positive ($H = 600\%$ gives $R_{20}/R_{00} = 6.0 \times 10^{-3}$) and negative ($H = -400\%$ gives $R_{20}/R_{00} = -5.7 \times 10^{-3}$) changes of the hexapole fields do not improve α-particle confinement. In Fig. 2(b), the relationship between H and R_{20}/R_{00} is shown.

Figure 3 presents the β effect on α-particle confinement in the configurations with $R_{axis} = 3.60$ m with different hexapole fields of $H = -400\%, 129\%$ and 600%. In these calculations we use the pressure profile given by the formula $p(s) = p_0(1 - s)(1 - s^4)$, where s is a flux surface label. This is a typical profile observed in LHD experiment and frequently utilized in the analysis. For hexapole field value of $H = 129\%$, β does not change very much the α-confinement properties. For $H = -400\%$ case, the fraction of lost particles starting from $s = 0.0625$ is increased almost 1.5 times and has the maximum for $\beta = 0.036$. For $H = 600\%$ case it is found an optimal value of β near 0.027, however the β effect on the confinement in this case is not so strong. Large positive and large negative hexapole fields decrease the equilbrium β limits, then VMEC equilibrium code has a poor convergence for $H = 600\%$ and $H = -400\%$ cases with the values of β larger 0.04.

We also perform the calculations of the ideal MHD Mercier stability criterion with the JMC code for $R_{axis} = 3.60$ m and $\beta = 0.01$ case to define the optimum value of the hexapole field (Fig.4). In according to this figure, the case of $H = 129\%$ (green) is more stable than the cases with both large positive hexapole field of $H = 600\%$ (blue) and negative field of $H = -400\%$ (red).

§4. Summary

The effect of the vertical and hexapole fields on the collisionless α-particle confinement and the ideal MHD Mercier stability have been numerically calculated in LHD. The significant improvement of the confinement in the inward shifted axis configuration with $R_{axis} = 3.45$ m was found. However such a strongly inward shifted configuration is less stable with respect to the Mercier modes. In the configuration with $R_{axis} = 3.60$ m, the effects of the hexapole fields and β effect have been investigated. It was found both large positive and large negative hexapole fields do not improve the α-particle confinement and the stability with respect to the Mercier modes. The different values of β do not influence very much on the confinement in the configuration with small hexapole field. The configurations with strong positive or negative hexapole fields have lower equilibrium β limit, more unstable and have larger α-particle losses. These numerical results should be checked in LHD experiments and also can be taken into account for the new compact 6-period torsatron L-V (being designed at the General Physics Institute, Moscow, Russia)[17] .

Large rotating triangularity of $R_{21}/R_{00} \approx 0.1$ can minimize the poloidal variation of the second adiabatic invariant on the magnetic surfaces and significantly decrease α-particle losses. In this study we could not obtain such a large rotating triangularity of the plasma boundary shape with the real LHD coil system. Further work, for example, introducing additional coils can clarify this issue which is important for future heliotron reactor devices.

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1) Murakami S., Wakasa A., Maaβberg H., et al, Nucl. Fusion **42** (2002) L19.
2) Lotz W., Nührenberg J., Schwab C., in Plasma Physics and Controlled Nuclear Fusion Research 1990 (Proc. 13th Int. Conf., Washington 1990) IAEA, Vol. 2, IAEA, Vienna (1991)603.
3) Isaev M., Nührenberg J., Mikhailov M.I. et al., submitted to Nucl. Fusion (2002).
4) Cary J., Shasharina S., Phys. Rev. Letters **78** (1997) 674.
5) Spong D. et al. Phys. Plasmas **5** (1998) 1752.
6) Nakamura Y. et al, J. Plasma Fusion Res. **69**(193) 41.
7) Hirshman S.P., Meier H.K., Phys. Fluids **28** (1985) 1387.
8) Hirshman S.P. and Betancourt O., J. of Comput. Physics **96** (1991) 99.
9) Nührenberg J., Zille R., Theory of Fusion Plasmas (Varenna 1987), Editrice Compositori, Bologna (1988) 3.
10) Fowler R.H., Rome J.A. and Lyon J.F., Phys. Fluids **28** (1985) 338.
11) Sanchez R., Isaev M., Hirshman S.P., et al., Comput. Phys. Comm. **141** (2001) 55.
12) Boozer A.H., Phys. Fluids **26** (1983) 496.
13) Mercier C., et al., Nucl. Fusion **1** (1960) 121.
14) Iiyoshi A. et al., Nuclear Fusion **39** (1999) 1245.
15) Yamazaki K., Motojima O. and LHD Design Group, "Proc. of the 1st ITC on Plasma Phys. and Contr. Nuclear Fus", NIFS-PROC-3(1990) 252.
16) Yamada H. et al., Nucl. Fusion **41** (2001) 901.
17) Isaev M., Grebenshchikov S.E., Shchepetov S.V. et al., submited to Plasma Phys. Rep. (2002).

Figure Captions

Fig. 1. (a) Numbers of lost α-particles in the vacuum LHD configurations versus the magnetic axis position, R_{axis}, calculated with the MCT[10] with launching surfaces $s = 0.0625$ (lower points) and $s = 0.240$ (upper points). The total number of followed α-particles equals to 2000. (b) Relationship between R_{axis} and the rotating triangularity.

Fig. 2. (a) Numbers of lost α-particles versus the hexapole field amplitude for vacuum cases of $R_{axis} = 3.60$ m. The conditions for α-particle calculations are the same as used in Fig. 1. (b) Relationship between the hexapole field amplitude and the triangularity.

Fig. 3. The β effect on α-particle confinement in the configurations with $R_{axis} = 3.60$ m with different hexapole field $H = -400\%$, 129% and 600%. Plasma pressure profile is given by the formula $p(s) = p_0(1-s)(1-s^4)$, where s is a flux surface label.

Fig. 4. The Mercier criterion calculated with the JMC code for $\beta = 0.01$ in the configurations with $R_{axis} = 3.60$ m with different hexapole fields of $H = -400\%$ (red), 129% (green) and 600% (blue). The same pressure profile is used as in Fig. 3.

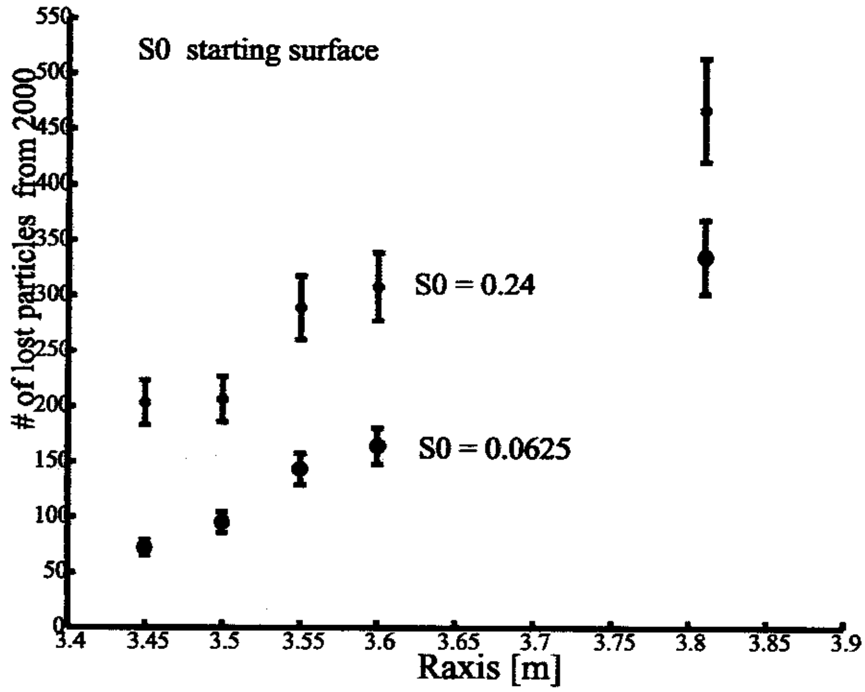
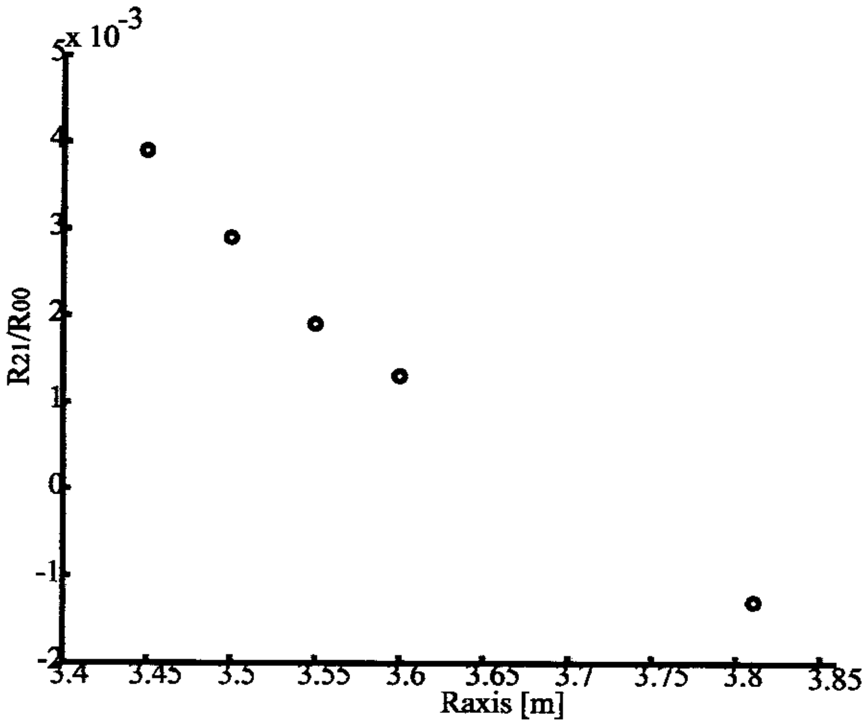

S0 starting surface
S0 = 0.24
S0 = 0.0625
# of lost particles from 2000
Raxis [m]

Fig.1(a)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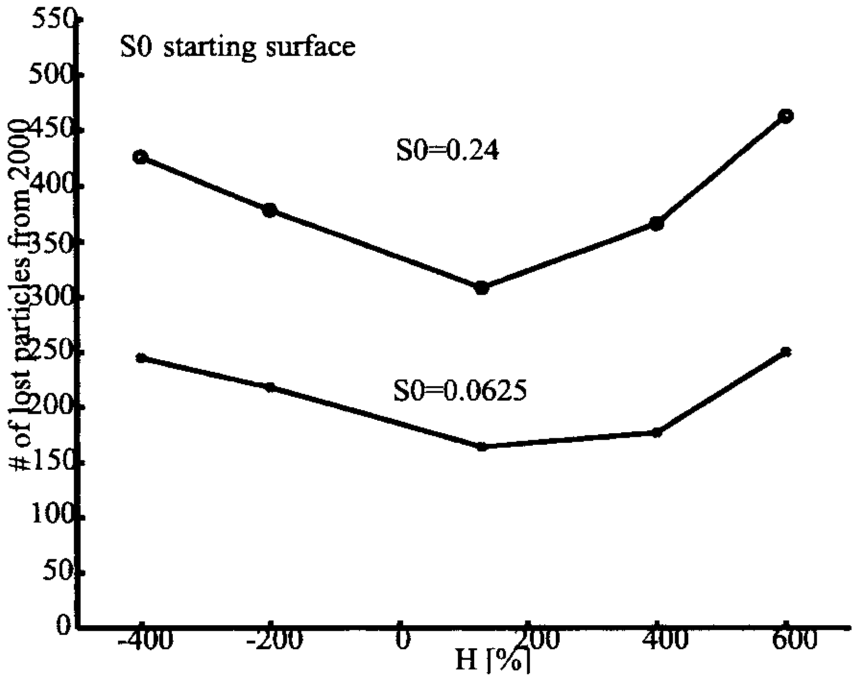
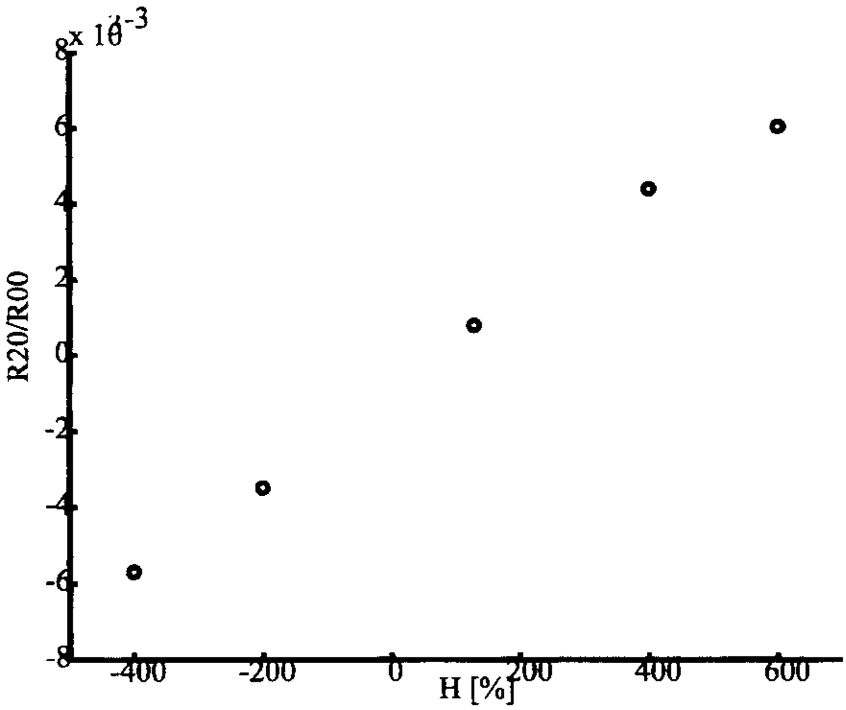
R21/R00
Raxis [m]

Fig.1(b)



S0 starting surface
S0=0.24
S0=0.0625
# of lost particles from 2000
H [%]

Fig.2(a)



x 10^-3
R20/R00
H [%]

Fig.2(b)

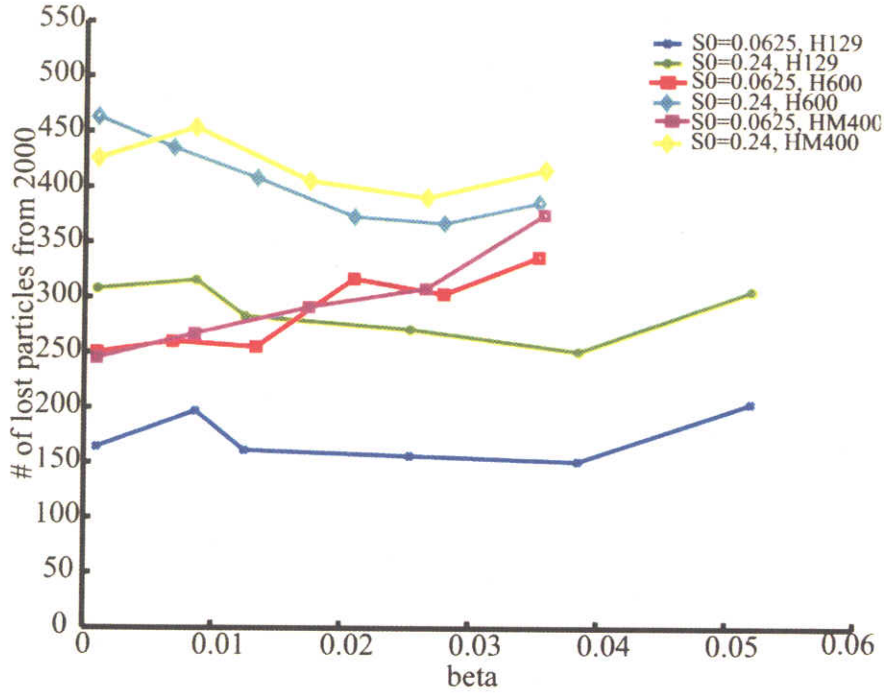

S0=0.0625, H129
S0=0.24, H129
S0=0.0625, H600
S0=0.24, H600
S0=0.0625, HM400
S0=0.24, HM400
# of lost particles from 2000
beta

Fig.3

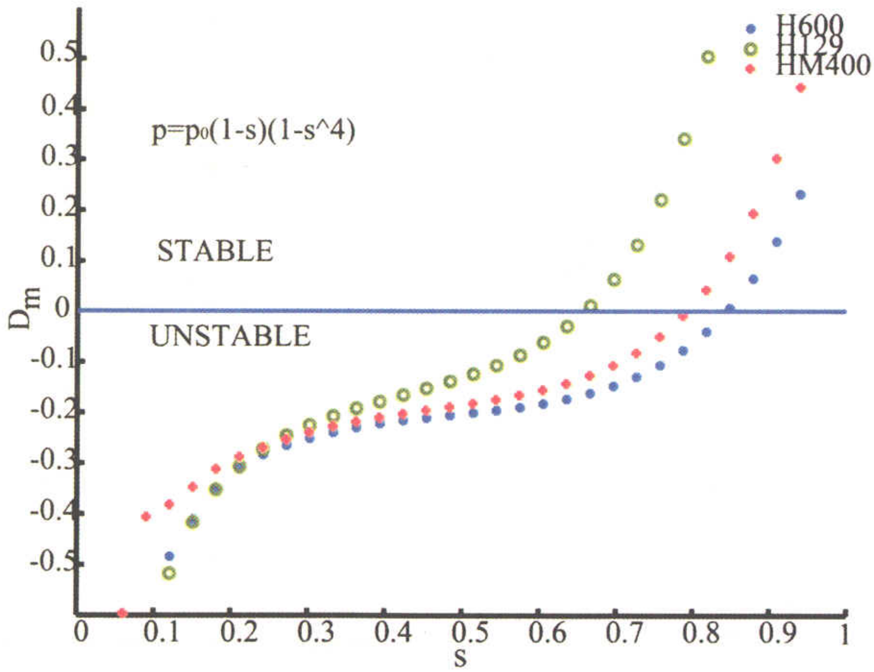

H600
H129
HM400
p=p0(1-s)(1-s^4)
STABLE
UNSTABLE
Dm
s

Fig.4