Numerical Studies of Scrape-off Layer Connection Length in Wendelstein7-X

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The distribution of particles and power flux to plasma-facing components play a critical role in the design of next-generation fusion devices. In particular, it is a challenge to bring down the peak heat fluxes onto the divertor to manageable levels (of order 5 MW/m^2). A large value of connection length (L_c) increases the role of cross-field transport and may lead to broader power deposition profile and lower peak heat fluxes. In low-shear stellarators like Wendelstein 7-X (W7-X) very long connection lengths, about one order of magnitude longer than those of equal-sized tokamaks, can be achieved. The flexibility of W7-X coil system allows variation of connection lengths significantly. This paper describes numerical studies that identify magnetic configurations in W7-X with particularly large and particularly small L_c; thus, the effects of L_c on divertor operation can be effectively studied. It is found that a variation of a factor of 8 is possible, with average L_c values as large as 426 m for a configuration developed here. It is also shown that L_c itself, for a given magnetic configuration, varies strongly, potentially complicating an experimental analysis of its effects.

I. INTRODUCTION

The basic principle of an island divertor (ID) is that the plasma particle- and heat-fluxes are guided by field lines forming magnetic islands towards divertor targets placed away from the confined plasma in the core region, allowing for exhaust of the plasma particles as they neutralize [1]. Whereas in tokamaks, it is the rotational transform ι=1/q that makes the magnetic field lines wander towards the divertor, it is the internal rotational transform $\iota_i = r_i\ \iota'$ inside the island that moves the field lines to the target plates in a stellarator, where r_i the radial size of the island chain and ι' the shear at the location of the island chain, and L_c can be expressed as L_c = 2R/Nι_i, where R the major radius and N the number of islands, ie. L_c is very large in low shear stellarators like W7-X [1, 2].

Power exhaust is one of the major challenges in a future fusion power plant. In the scrape off-layer (SOL) region, the radial profiles are determined by competition between transport processes perpendicular and parallel to the magnetic field. SOL widths are of importance as they play a major role in characterizing the area of the divertor plate over which the outflowing plasma power is deposited. Because the parallel transport rate is orders of magnitude faster than the perpendicular transport rate, the SOL width is quite small. The heat load on the various components of the fusion device is a matter of great concern. A multitude of studies has been undertaken to determine the power fall-off length λ_q [9,10,11]. In a multi-machine database for the H-mode λ_q in JET, DIII-D, ASDEX Upgrade, C-Mod, NSTX and MAST, the regression inside the database showed that $\lambda_q \propto B_{tor}^{0.8}\ q_{95}^{1.1}\ P_{SOL}^{0.1}\ R_{geo}^{0}$[7], for large aspect ratio L $\approx \pi$Rq_{SOL}, thus exhibiting an approximately linear dependency with L_c. A heuristic model [8], in good agreement with the regression result, assumes that the magnetic gradient B and curvature drifts carry the charged particles across the last closed magnetic surface onto the open field lines in the SOL, and predicts linear proportionality between L_c and λ_q. This supports the hypothesis that L_c is a parameter that significantly affects the projected power decay length in future devices. L_c also plays an important role in determining the temperature profile of the SOL plasma [3]. It has been observed in LHD that very long L_c can reduce the heat load to the diverter while keeping the high performance of core plasma confinement intact [14]. Long connection lengths allows a significant temperature drop along field lines from hot upstream separatrix temperatures to reasonably low divertor target temperatures, and might play a role in accessing a high recycling regime [13] for these reasons, long connection lengths in the SOL are generally considered advantageous.

II. COIL SYSTEMS AND THE NINE VACUUM REFERENCE CONFIGURATIONS

W7-X is an optimized stellarator and uses 70 superconducting and 15 normal conducting coils for creating the magnetic field. The superconducting coils are responsible for generating the steady state main field to confine the plasma. Inside of the plasma vessel there are ten control coils to change the size of the islands and to sweep the islands poloidally and thereby modify the strike points of the plasma at the divertor. In addition, a set of five normal conducting trim coils increase the experimental flexibility, most notably by providing means to balance the asymmetric heat loads on the 10 divertor modules of W7-X. [4, 5, 6].

The W7-X has been optimised with respect to good MHD stability, improved neoclassical confinement,

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good confinement of fast particles, and low bootstrap current. Based on the optimization criteria, nine vacuum configurations have been defined as vacuum reference configurations (VRC), spanning a configurational space that allows studies of a number of interesting physical questions. Here, we investigate numerically how L_c varies across these nine reference configurations, and, inspired by these results and some basic intuition, present a new magnetic configuration that has particularly high values of L_c[6].

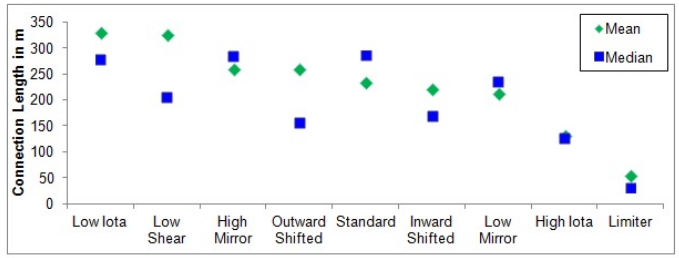

FIG. 1. Graph of Mean and Median of Connection Length vs the 9 VRC

III. NUMERICAL METHOD

The method used for the numerical study of achievable L_c for the 9 VRC of W7-X is field line tracing. A focus has been given on L_c at the positions where the divertor is in direct contact with relatively hot and dense SOL-plasma obtained using field line diffusion, also referred to as “wetted area” or “strike line” , as it receives the direct heat load from the plasma and is relevant from the point of view of the safety of the divertor. The magnetic field is computed using the Biot-Savart law and then, after finding the last closed flux surface (LCFS) for the magnetic configuration being studied, starting points are placed on it. The starting points are traced along the magnetic field line, with small random steps perpendicular to the field included to simulate perpendicular diffusion [13]. The tracing process continues until the field line hits any in-vessel material component, such as divertors, baffles, heat shields etc. The parameters to describe the perpendicular diffusion process are perpendicular diffusion coefficient $D_\perp$, mean free path λ, and velocity v. They can be adjusted to change the effective perpendicular diffusion rate. The perpendicular step are performed after a random length x with the distribution p_x=1/λ exp(x/λ). For these studies, we have chosen the value of perpendicular diffusion (D) to be 1 m^2/s based on the previous experiments in W7-AS. The parallel diffusion velocity in the code

$$< v >= \sqrt{\frac{k_B(T_e+T_i)}{m_e+m_i}} \tag{1}$$

corresponds to a temperature at the edge of approximately 1 keV [4] Although the edge temperature is unrealistically high, it is convenient since it gives localized wetted area and therefore better statistics for the region of the divertor with highest heat loads. The position and the number of strike lines varies for each of the 9 VRC. Points on the divertor found this way are points where plasma heat load is predicted to be present, since the plasma can diffuse across the magnetic field in a way similar to the random perpendicular steps taken. The magnetic field line going through this loaded divertor-surface point is then followed back in the direction from which it came, this time without taking any perpendicular steps, until the field line reaches a material surface again (typically the surface of a different divertor). Thus, the connection length of plasma-filled SOL field lines can be determined.

IV. RESULTS

The average value of L_c was calculated and compared for all 9 VRC. *Limiter* is a special configuration where the LCFS connects directly to the target plates, whereas for the other 8 configurations, the magnetic island chain at the edge intersects the target plates. Fig.1 implies that *Low Iota* (with an island chain with m=6) has the highest value of mean L_c (331 m), whereas the *Limiter* configuration without islands at the edge, has the lowest value of mean L_c (55 m). This demonstrates that the islands in the ID concept are in fact responsible for the long connection length obtained in W7-X. The wide variation in the range of connection length illustrates the flexibility of the W7-X coils system.

There is a wide variation of L_c values in the wetted area, raising the concern that the mean values alone do not suffice to describe the structure or width of the wetted area. We illustrate this in Fig.2, where we plot strike line patterns for the *Limiter* configuration on the divertor with the color at each point indicating L_c at that point. One sees that connection lengths very small and very large (up to 2000 m) are present.This feature of large variance in connection length in a magnetic configuration has also been observed in other stellarator and heliotron devices like LHD [15,16]. Two strike lines are visible on the divertor plate, one on the horizontal divertor plate elongated toroidally and the other on the vertical divertor plate (Fig.2). It is observed that the large densities of points are in orange or yellow color with L_c of 30-40 m i.e the field line travels approx. 1 turn around the machine before hitting a component. This brings down the overall mean value of connection length to a low value despite there being some very long connection lengths present as well.

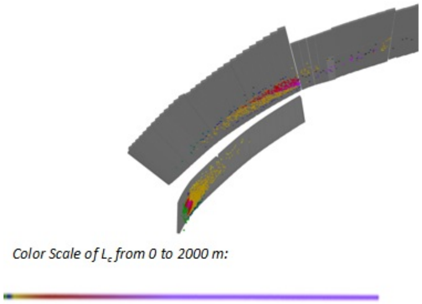

FIG. 2. Footprints of field lines on divertor targets for *Limiter* Configuration using field-line diffusion wherein color at each point corresponds to the L_c at that point.(D=1 m^2/s and V=$0.5 \cdot 10^6$m/s)

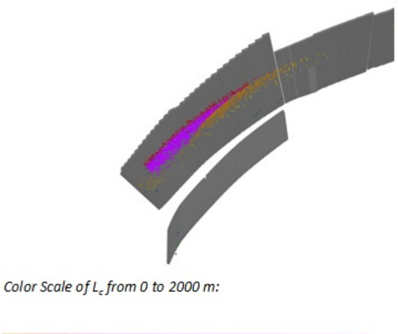

FIG. 3. Footprints of field lines on divertor targets for *Low Iota* Configuration using field-line diffusion wherein color at each point corresponds to the L_c at that point(D=1 m^2/s and V=$0.5 \cdot 10^6$m/s)

In the *Low Iota* configuration, only one strike line is observed on the horizontal divertor plate with a long toroidal extension (Fig.3). The strike points contain yellow (20-40 m), orange (40-80 m), red (80-190 m) and a large proportion of points in pink(>190 m) color i.e field line travels for more than 5 turns around the machine before hitting a component, therefore the final average L_c is quite large. It is found that *Low Iota* and *Low Shear* have the largest values of mean L_c, 331 m and 326 m respectively. We show in the following that a new configuration that is a combination of of *Low Shear* and *Low Iota* has even higher values of L_c.

The *New Configuration* is a configuration that has particularly low shear in combination with a 5/6 (low iota) island chain. Its modular coil currents are similar to those of the *Low Shear* configuration, and its planar coil currents obtained by adding the currents in the *Low Shear* and the *Low Iota* configurations. The mean L_c of this configuration is 426 m (Fig.4), significantly higher than the mean L_c of any of the 9 VRC.

The Poincaré plot [4] for this *New Configuration* (Fig.6) features islands just touching the divertor plate

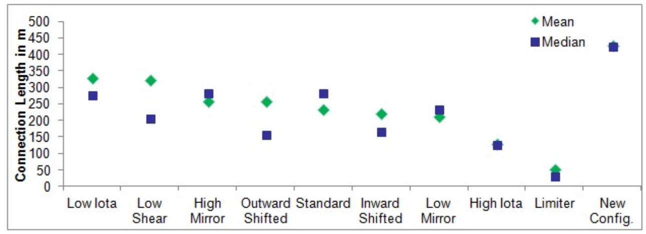

FIG. 4. Graph of Mean and Median of Connection Length vs the 9 VRC and the *New Configuration* showing the flexibility of W7-X coil system in terms of attainable connection length

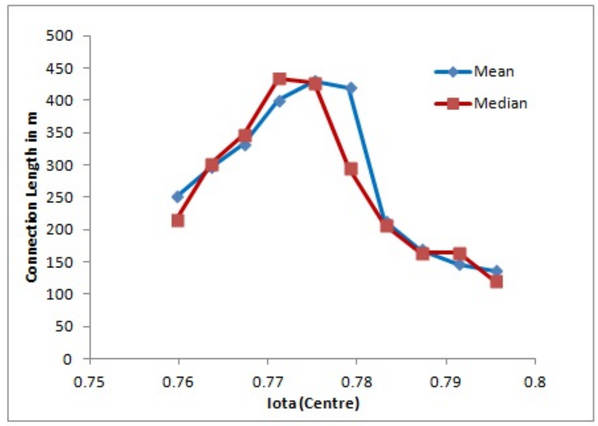

FIG. 5. The Iota Scan using iteration for the *New Configuration* depicting small variation in planar coil current altering the L_c significantly

at toroidal angle ϕ=0 plane; this presumably contributes to the high L_c obtained in this configuration. This interpretation is supported by an iota scan around this configuration, which was carried out by varying the planar coil current (Fig.5). Varying iota shifts the island chain radially in or out, and one sees that the long connection lengths are rather narrowly distributed for the iota values (island locations) very close to those of the *New Configuration*.

The L_c is evaluated and the Poincaré plot is noted for the altered configurations. It was noticed that the average L_c values dipped considerably with slight modification in planar coil current in the *New Configuration* showing the significant impact of small changes in planar coil current on the position of island w.r.t divertor which directly impacts the connection length achievable.

V. CONCLUSION

The present numerical study on the SOL connection length L_c in W7-X with a focus on L_c at the strike line position, demonstrates that L_c varies from approx-

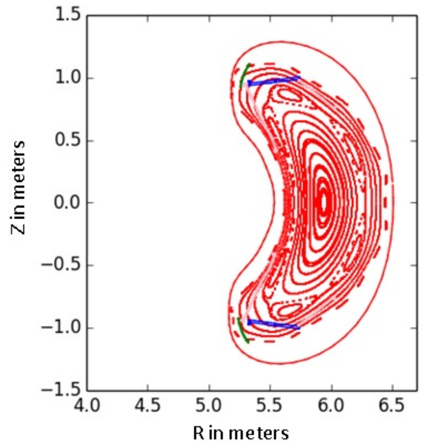

FIG. 6. The Poincaré plot for *New Configuration* with island just touching the divertor(in blue)

imately 55 m to approximately 330 m in the 9 vacuum reference configurations. Taking further advantage of the flexibility of the W7-X coil system, a new configuration was identified with a particularly high value of average L_c of 426 m. This span of almost an order of magnitude in L_c should allow a determination of the importance of L_c for divertor operation in general and for the value of λ_q in particular, although the large spread in L_c values for a given configuration could complicate such an analysis.

VI. ACKNOWLEDGEMENTS

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