Stellarator Divertors

Alkesh Punjabi* and Allen H. Boozer**
*Hampton University, Hampton, VA 23668, USA, **Columbia University, New York, NY 10027, USA
alkesh.punjabi@hamptonu.edu

ABSTRACT

- Nonresonant divertors are extremely important for the development of stellarator concept as Fusion Power Plants (FPP). Nonresonant divertors are under-studied.
- In nonresonant divertors, the outgoing magnetic field lines exiting the outermost surface and eventually intersecting the wall, and the incoming lines exiting the wall and approaching the outermost surface, do so through magnetic flux tubes. The outgoing tube and its corresponding incoming tube form a pair. The pair together is called a magnetic turnstile.
- To-date, three distinct types of nonresonant stellarator divertors are found: The nonresonant divertor proper, the hybrid divertor, and the two-mode divertor.
- The number, the nature, and the type of magnetic turnstiles, their probability exponents, and their 3D structure for all three types of nonresonant stellarator divertors are presented.

I. BACKGROUND

- In 2018, Boozer and Punjabi developed a method for simulation of stellarator divertors [A. H. Boozer and A. Punjabi, Phys Plasmas **25**, 092505 (2018)].
- This method uses maps to represent the magnetic system of the nonresonant divertors. The method is related to 1984 study of MacKay *et al* [R. S. Mackay, J. D. Meiss, and I. C. Percival, Physica D **13**, 55 (1984)] on the loss of the last confining surface of the standard map as the map parameter is increased. In this study, they introduced the concepts of cantori and turnstiles.
- In 2020, Punjabi and Boozer used this method to study the nonresonant stellarator divertor [A. Punjabi and A. H. Boozer, Phys Plasmas **27**, 012503 (2020)]. They found that: "*The most novel and interesting finding of this study is that diffusive magnetic field lines can be distinguished from lines that exit through the primary and the secondary turnstile, and that below some diffusive velocity, all lines exit through only the primary turnstile. The footprints of each family are stellarator symmetric and have a fixed location on the wall for all velocities. The probability exponent of the primary turnstile is $d_1 = 9/4$ and that of the secondary turnstile is $d_2 = 3/2$.*"
- In 2022, Punjabi and Boozer developed a method to calculate the full 3D structure of the magnetic turnstiles in the non-axisymmetric topology of stellarators [A. Punjabi and A. H. Boozer, Phys Plasmas **29**, 012502 (2022)], and applied this method to the nonresonant stellarator divertor. They found that "*the cantorus just outside the outermost magnetic surface had some unexpected properties: The exiting and entering flux tubes can be adjacent as is generally expected but can also have the unexpected feature of entering or exiting at separate locations of the cantori. Not only can there be two types of turnstiles but pseudo-turnstiles can also exist. A pseudo-turnstile is formed when a cantorus has a sufficiently large, although limited, radial excursion to strike a surrounding chamber wall.*"
- After the 2022 paper, we found two new distinct type of nonresonant stellarator divertors, namely: the hybrid divertor, and the two-mode divertor.
- Here, we give a comprehensive view of all the three types of nonresonant divertors.

II. Methodology

- **HAMILTONIAN:** The magnetic field $\boldsymbol{B}$ in stellarators in generalized contravariant representation is given by $\boldsymbol{B}(\psi_t,\theta,\phi) = \nabla\psi_t \times \nabla\theta + \nabla\phi \times \nabla\psi_p(\psi_t,\theta,\phi)$ [A. H. Boozer, Phys Fluids **26**, 1288 (1983)]. ψ_p is the normalized poloidal flux, ψ_t is the normalized toroidal flux, φ is the toroidal angle of stellarator, θ is the poloidal angle. The magnetic field lines are given by the equations $d\psi_t/d\varphi = \boldsymbol{B}\cdot\nabla\psi_t/\boldsymbol{B}\cdot\nabla\phi$ and $d\theta/d\varphi = \boldsymbol{B}\cdot\nabla\theta/\boldsymbol{B}\cdot\nabla\phi$ which can be rewritten as $d\psi_t/d\varphi = -d\psi_p/d\varphi$ and $d\theta/d\varphi = d\psi_p/d\psi_t$ using the canonical representation. These equations are mathematically identical to Hamiltonian equations with $\psi_p(\psi_t,\theta,\zeta)$ as the Hamiltonian, θ as canonical position, ψ_t as canonical momentum, and ζ as the canonical time. ζ is the toroidal angle of the single period, $\zeta = n_P\varphi$, n_P = number of periods of the stellarator., and ι_0 is the rotational transform on magnetic axis. The model Hamiltonian for the trajectories of magnetic field lines in a single period of the nonresonant stellarator divertor is given by

$$\psi_p = \left[\iota_0 + \frac{\varepsilon_0}{4}\left((2\iota_0-1)\cos(2\theta-\zeta)+2\iota_0\cos 2\theta\right)\right]\psi_t + \frac{\varepsilon_t}{6}\left[(3\iota_0-1)\cos(3\theta-\zeta)-3\iota_0\cos 3\theta\right]\psi_t^{3/2} + \frac{\varepsilon_x}{8}\left[(4\iota_0-1)\cos(4\theta-\zeta)+4\iota_0\cos 4\theta\right]\psi_t^2.$$

- **MAP EQUATIONS:** $\psi_t^{(j+1)} = \psi_t^{(j)} - \dfrac{\partial\psi_p\left(\psi_t^{(j+1)},\theta^{(j)},\zeta^{(j)}\right)}{\partial\theta^{(j)}}\delta\zeta;\ \theta^{(j+1)} = \theta^{(j)} + \dfrac{\partial\psi_p\left(\psi_t^{(j+1)},\theta^{(j)},\zeta^{(j)}\right)}{\partial\psi_t^{(j+1)}}\delta\zeta;$

$\zeta^{(j+1)} = \zeta^{(j)} + \delta\zeta,\ \delta\zeta = \frac{2\pi}{3600}.$ The map preserves symplectic invariant: $\dfrac{\partial\left(\psi_t^{(j+1)},\theta^{(j+1)}\right)}{\partial\left(\psi_t^{(j)},\theta^{(j)}\right)} = +1.$

- **SHAPE PARAMETERS: $\varepsilon_0, \varepsilon_t, \varepsilon_x$**

ε_0 controls the elongation, ε_t controls the triangularity, and
ε_x controls the sharp edges on the outermost surface.
ε_0 and ε_t are kept fixed at $\varepsilon_0 = \varepsilon_t = 1/2$ for all three types of divertors.

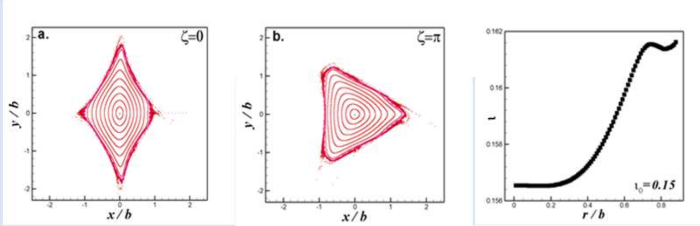
- **THREE TYPES OF NONRESONANT DIVERTORS:**

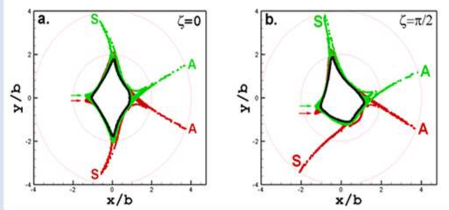
$\varepsilon_x = -0.31$ gives nonresonant divertor proper,
$\varepsilon_x = -0.1$ gives hybrid divertor,
$\varepsilon_x = 0$ gives two mode divertor.

- **Magnetic turnstiles:** In nonresonant divertors, field lines from the outermost surface and wall and back travel through magnetic flux tubes. The outgoing and incoming tube together form a magnetic turnstile. The magnetic flux in the two tubes is conserved. Collimation occurs due to layer of cantori outside the outermost surface. The intersection of the tubes with the wall gives magnetic footprint. The locations on the wall where the tubes intersect the wall are fixed.

- **PARAMETERS:** Toroidal flux inside the outermost surface = ψ_0, $\iota_0 = 0.15$, $n_P = 5$.

III. A. NONRESONANT DIVERTOR PROPER



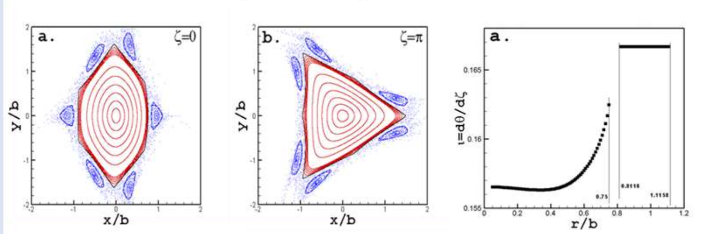


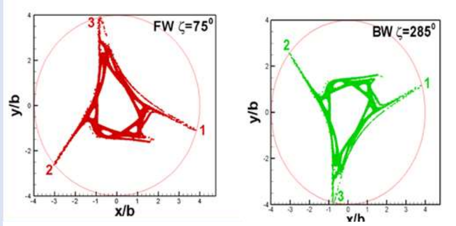
A = Adjoining turnstile, S = Separated turnstile

- Number of turnstiles: 3
- Type of turnstiles:
  2 true turnstiles and
  1 pseudo-turnstile
- Nature of true turnstiles:
  1 adjoining and 1 separated
- Probability exponents:
  $d_A = \frac{9}{4}, d_S = \frac{9}{5}$.

B. HYBRID DIVEROR

Hybrid divertor has features of both the nonresonant divertor and the island divertor. It has outermost surface with sharp edges as well as large islands outside the outermost surface.

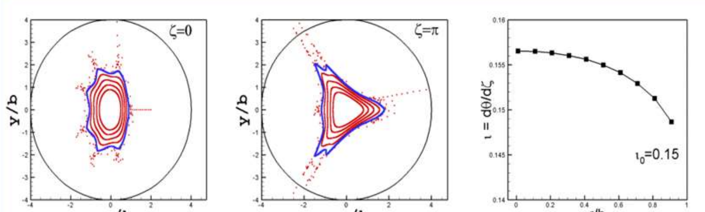


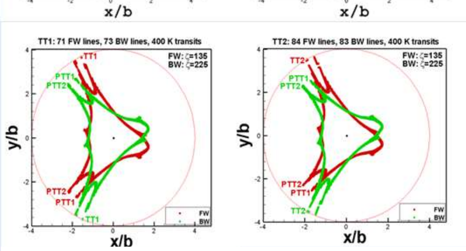


- Number of turnstiles: 3
- Type of turnstiles:
  3 true turnstiles
- Nature of true turnstiles:
  2 adjoining and 1 separated
- Probability exponents:
  $d_{A1} = \frac{9}{4}, d_{A2} = \frac{11}{5},\ d_S = \frac{22}{5}$.

1 and 2 are the adjoining turnstiles, 3 is the separated turnstile. b = minor radius. $r_{WALL} = 4b$.

C. TWO-MODE DIVERTOR





TT1 and TT2 are 1st and 2nd true turnstiles.
PTT1 and PTT2 are 1st and 2nd pseudo-turnstiles.

- Number of turnstiles: 4
- Type of turnstiles
  2 true turnstiles and
  2 pseudo-turnstiles
- Nature of turnstiles:
  All 4 turnstiles are separated
- Probability exponents:
  $d_{S1} = d_{S2} = \frac{13}{4}$.

IV. SUMMARY

Three distinct types of nonresonant stellarator divertors are found: The nonresonant proper, the hybrid, and the two-mode divertors. The two-mode divertor appears to have the longest connection length, the smallest footprints, and the lowest fraction of lines that go into turnstiles.

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