Interpreting structures observed in pellet ablation profiles on the stellarator TJ-II

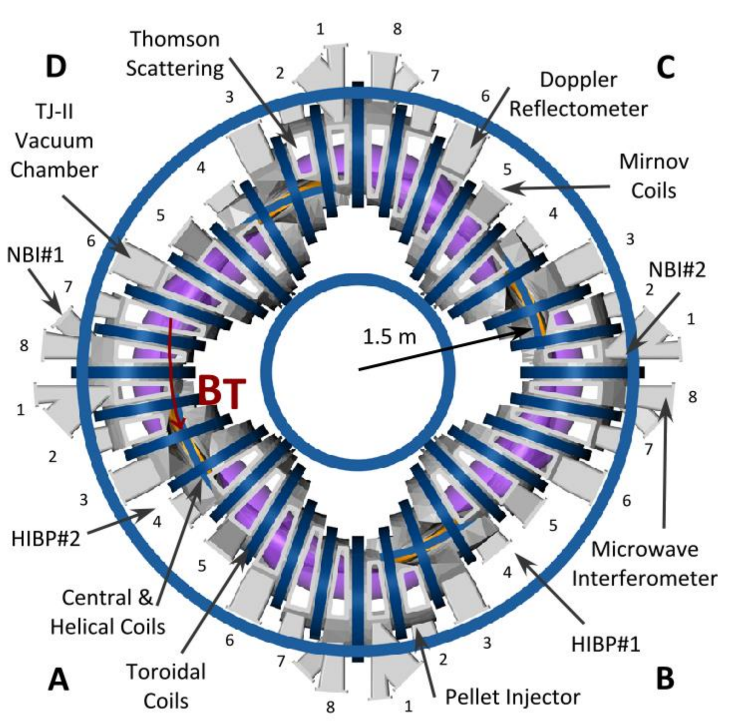
K. J. McCarthy, I. García-Cortés, B. van Milligen, A. Baciero, R. Carrasco, T. Estrada, R. García, J. Hernández-Sánchez, B. López-Miranda, F. Medina, D. Medina-Roque, M. Navarro, N. Panadero, I. Pastor, M. C. Rodríguez & TJ-II team

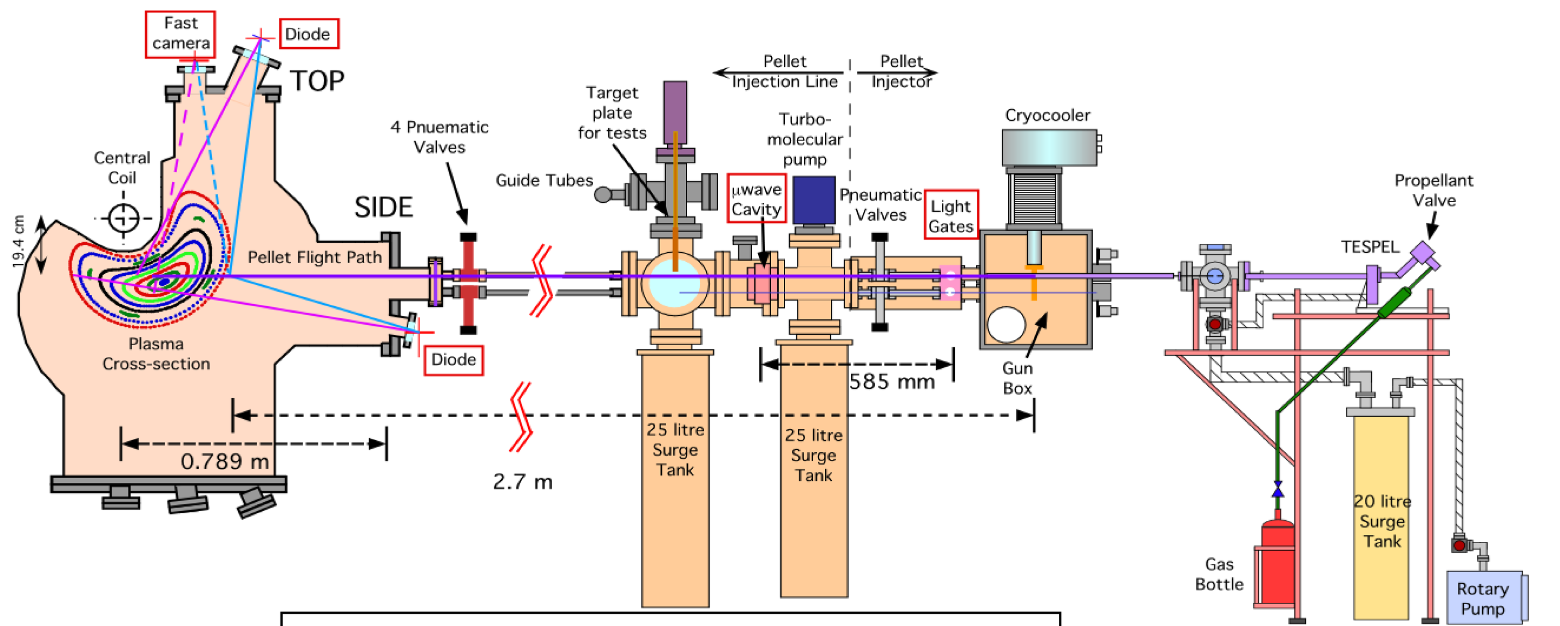
[1]*Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*

Abstract

Cryogenic pellets are used to fuel the core of magnetic confinement fusion plasmas. In stellarators, work on TJ-II shows a relationship between the radial locations of low-order rational surfaces and enhanced post-injection plasma performance [1]. Recent work has highlighted also the importance of low-order rational surface placement with regard to the edge gradient region[2]. Here, Hα ablation profiles are found to sometimes exhibit significant transient dips in signal level when pellets are injected into plasmas having low-order rational surfaces in their core. It is found that such structures can be removed if the net plasma current is varied so as to modify the rotational transform profile. Examples of pellet ablation profiles with/without structures as well as of rotation transform profiles are presented.

TJ-II and its Pellet Injector





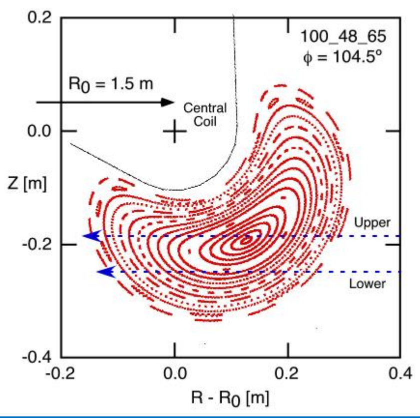
Pipe-gun type Pellet Injector[3]
- 3 pellet sizes: D = 0.66, 0.76 and 1 mm
- V_p = 800 to 1200 m/s

Pellet injection & ablation

Pellet ablation rate in TJ-II

$$\dot{N}\,[H/s] = 1.94\times10^{14}\cdot n_e^{0.45}\cdot T_e^{1.72}\cdot r_p^{1.44}\cdot \varepsilon^{-0.16}\cdot A_p^{-0.28}\cdot Z_p^{-0.56}\cdot(\gamma-1)^{0.28} \quad (1)^{4,5}$$

ε = 0.0053 eV, A_p = 1, Z_p = 1, and γ = 7/5

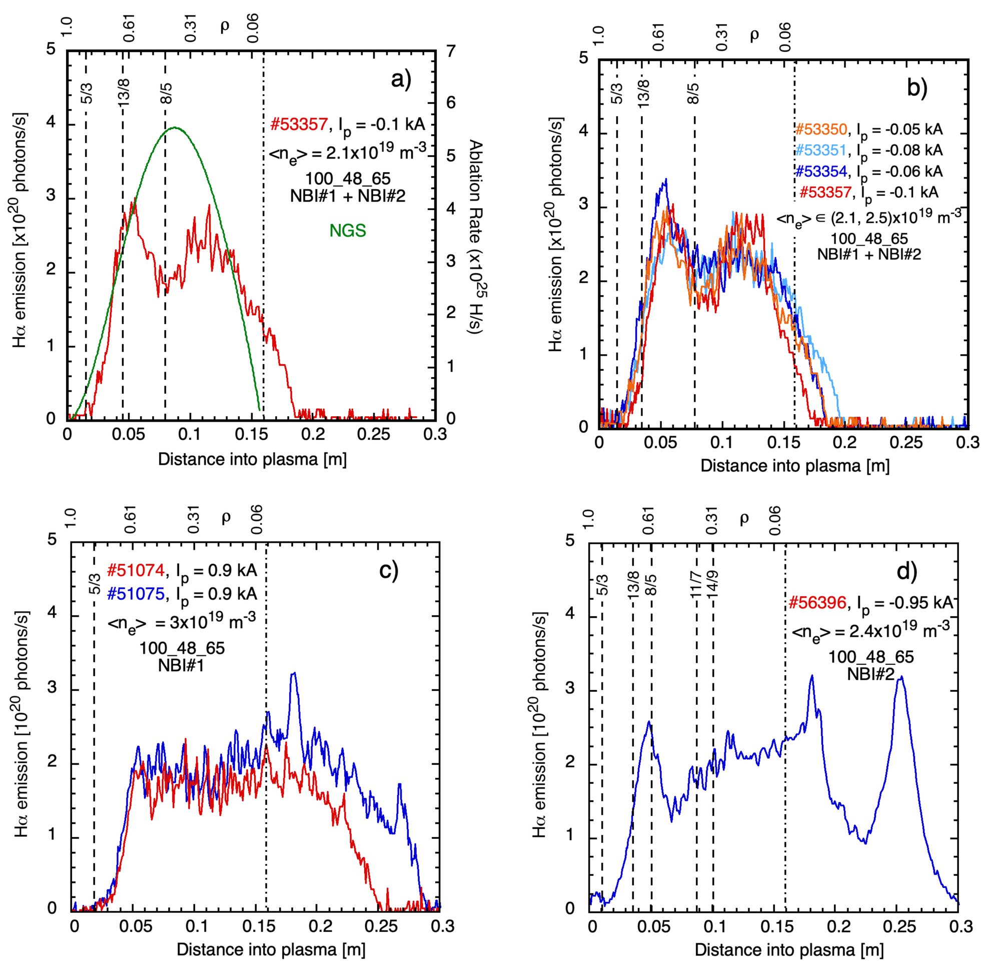


TJ-II[6]
- R = 1.5 m, *a* = 0.22 m, B_0 = 1.08 T, V_{plasma} = 1.1 m³.
- $1.55 \le \iota_0/2\pi_{vacuum} \le 1.64$ (for 100_44_64)
- ECRH ≤ 500 kW, T_e < 1.5 keV
- NBI ≤ 1 MW through port, T_e < 400 eV.

Hα ablation profiles after pellet injection into TJ-II

Hα profiles for Injections into 100_48_65

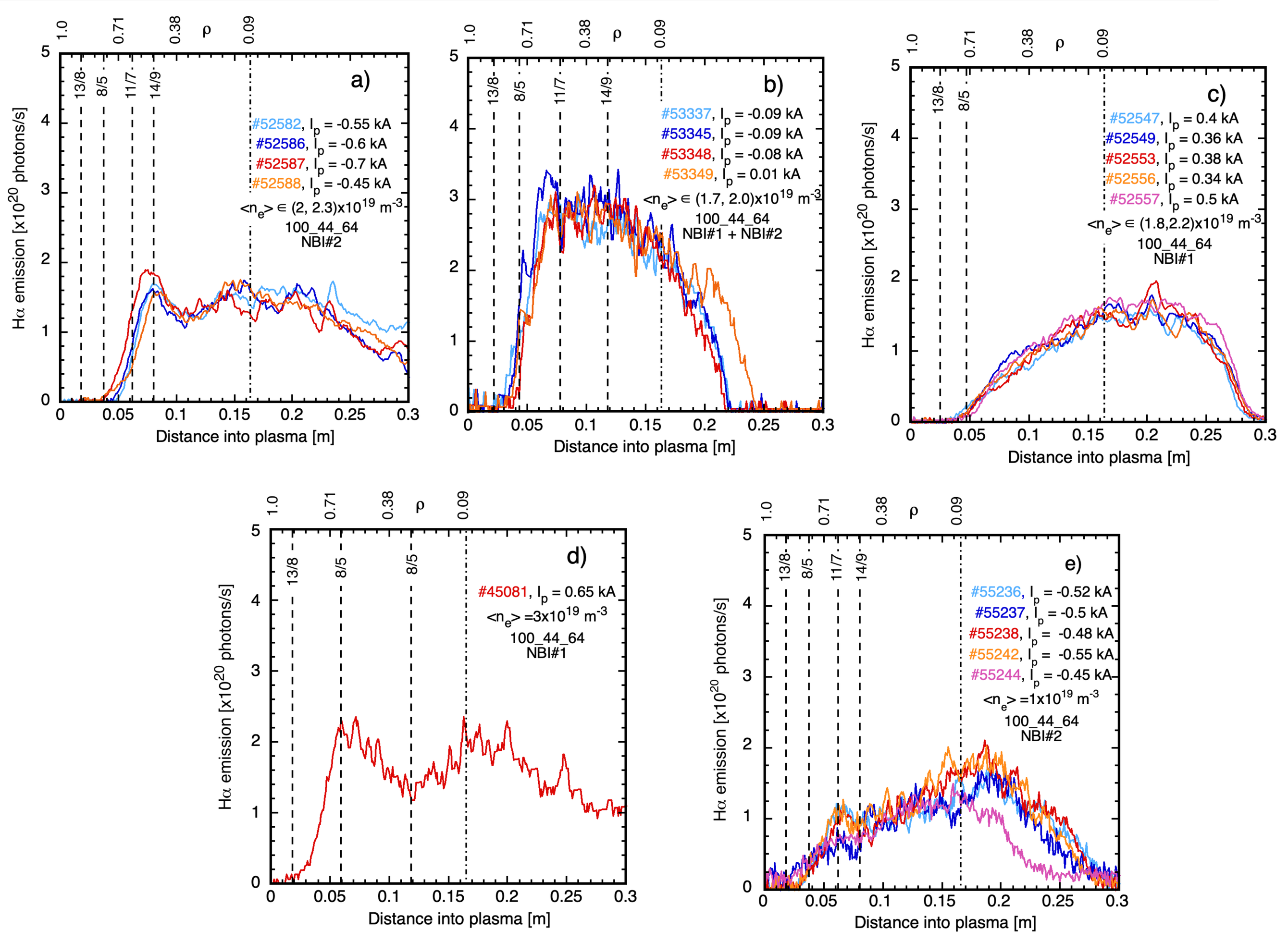
$\iota_0/2\pi_{vacuum}$ = 1.591



Hα profiles for intact PIs into plasmas made using balanced (both NBIs) or unbalanced (single NBI) heating. a) PI into discharge with I_p = -0.1 kA (predicted ablation rate in green), b) PIs into reproducible discharges of the same series with I_p ~0 kA, c) PIs into discharges with I_p = 0.9 kA and d) a PI into a discharge with I_p = -0.95 kA. Plots are as a function of distance from plasma outer edge. Vertical dash-dash lines indicate predicted locations of low-order rational surfaces for I_p. <n_e> is target line-averaged density.

Hα profiles for Injections into 100_44_64

$\iota_0/2\pi_{vacuum}$ = 1.551

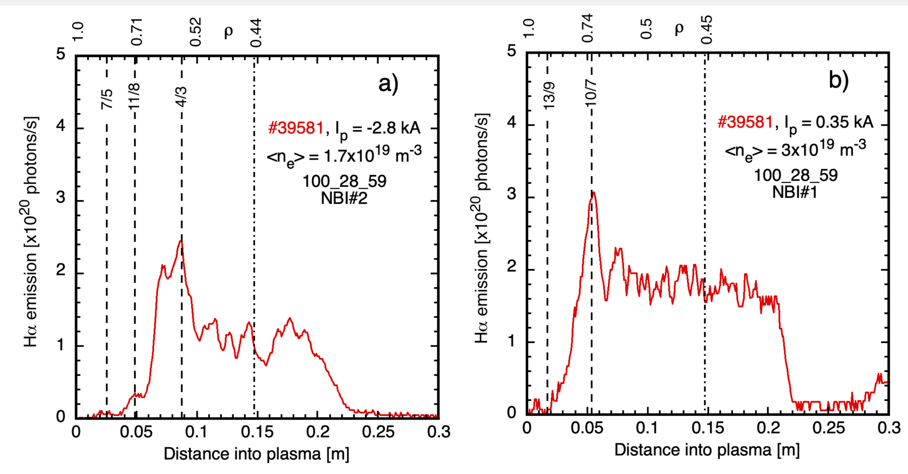


Hα profiles for PIs into discharges heated by different NBI set-ups. a) NBI#2, b) NBI#1 plus NBI#2, c) NBI#1 only, d) NBI#1 only and e) NBI#2 with reversed toroidal B field. Plasma currents, I_p, measured at injection times are indicated and the locations of selected low-order rational surfaces (vertical dash-dash lines) predicted using eq. 2 are shown. Vertical dash-dot lines where a pellet has its nearest approach to the magnetic axis. Vertical dash-dash lines indicate predicted locations of low-order rational surfaces for I_p. <n_e> is target line-averaged density

Hα profiles for injections into other configurations

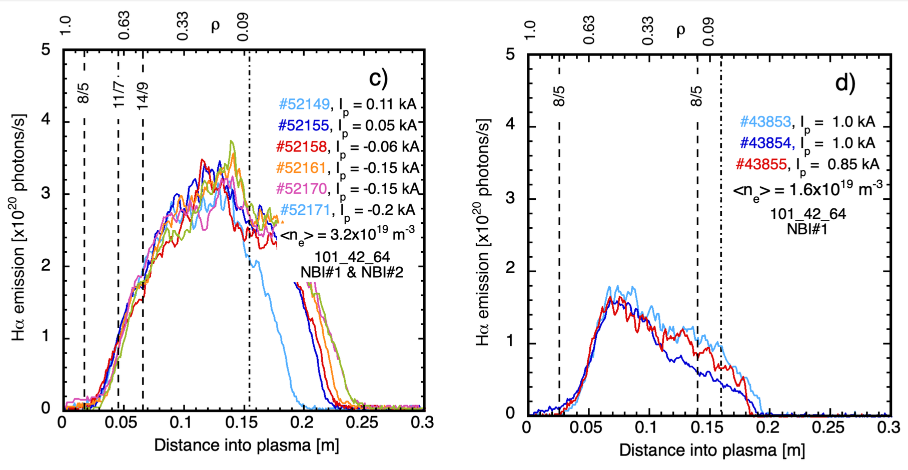
100_28_59

$\iota_0/2\pi_{vacuum}$ = 1.375



101_42_63

$\iota_0/2\pi_{vacuum}$ = 1.534

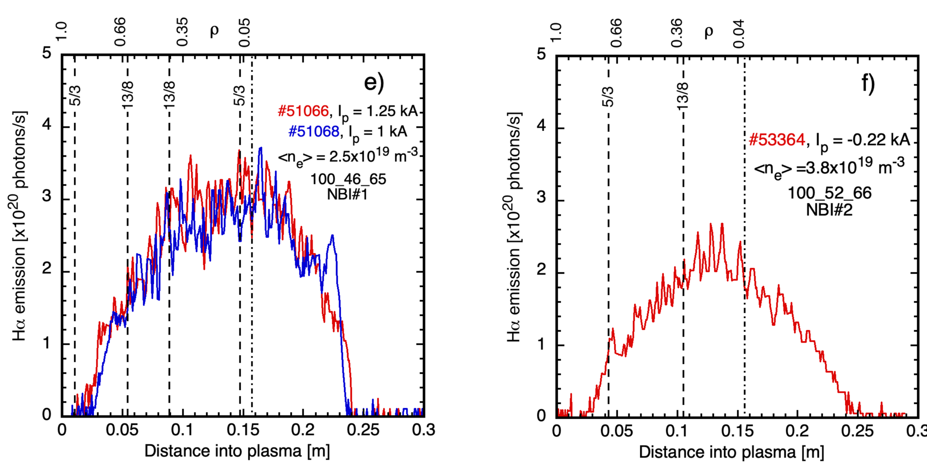


100_46_66

$\iota_0/2\pi_{vacuum}$ = 1.575

101_52_66

$\iota_0/2\pi_{vacuum}$ = 1.631



Balmer Hα profiles for PIs into plasmas created using different magnetic configurations with balanced (both NBIs) or unbalanced (single NBI) heating. Plots are for 100_28_59 discharges with a) NBI#2 only and I_p = -2.8 kA, and b) NBI#1 only and I_p = 0.35 kA, into 101_42_64 discharges with c) nearly-balanced NBI heating and $I_p \in$ (-0.2 kA, 0.11 kA) and with d) NBI#1 only and $I_p \in$ (0.8 kA, 1 kA), into e) 100_46_66 discharges with NBI#1 only and $I_p \in$ (1 kA, 1.25 kA), and into a f) 100_52_66 discharge with NBI#2 only and I_p = -0.22 kA. Vertical dash-dot lines where a pellet has its nearest approach to the magnetic axis. Vertical dash-dash lines indicate predicted locations of low-order rational surfaces for I_p. <n_e> is target line-averaged density

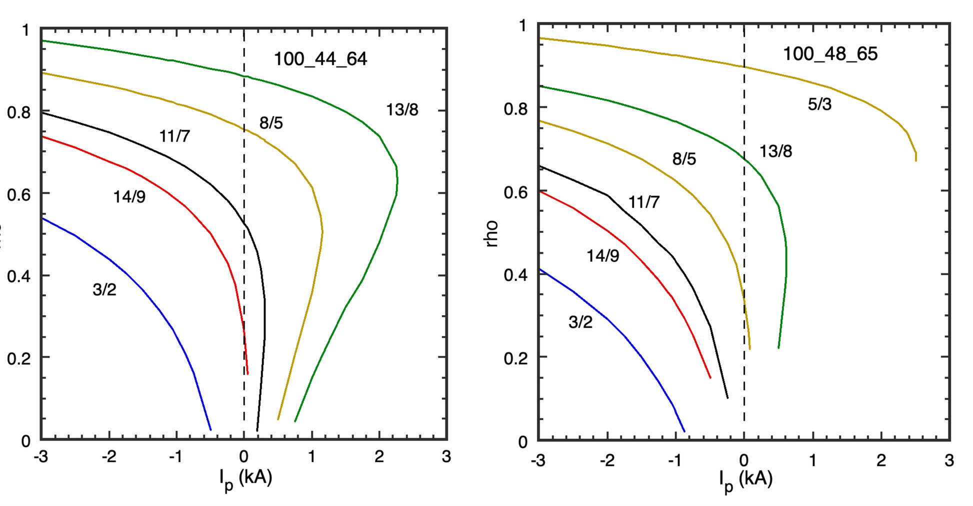
How low-order rational surfaces can modify pellet Hα ablation profiles the TJ-II

How net plasma current, I_p, can modify $\iota(\rho)/2\pi$ in TJ-II

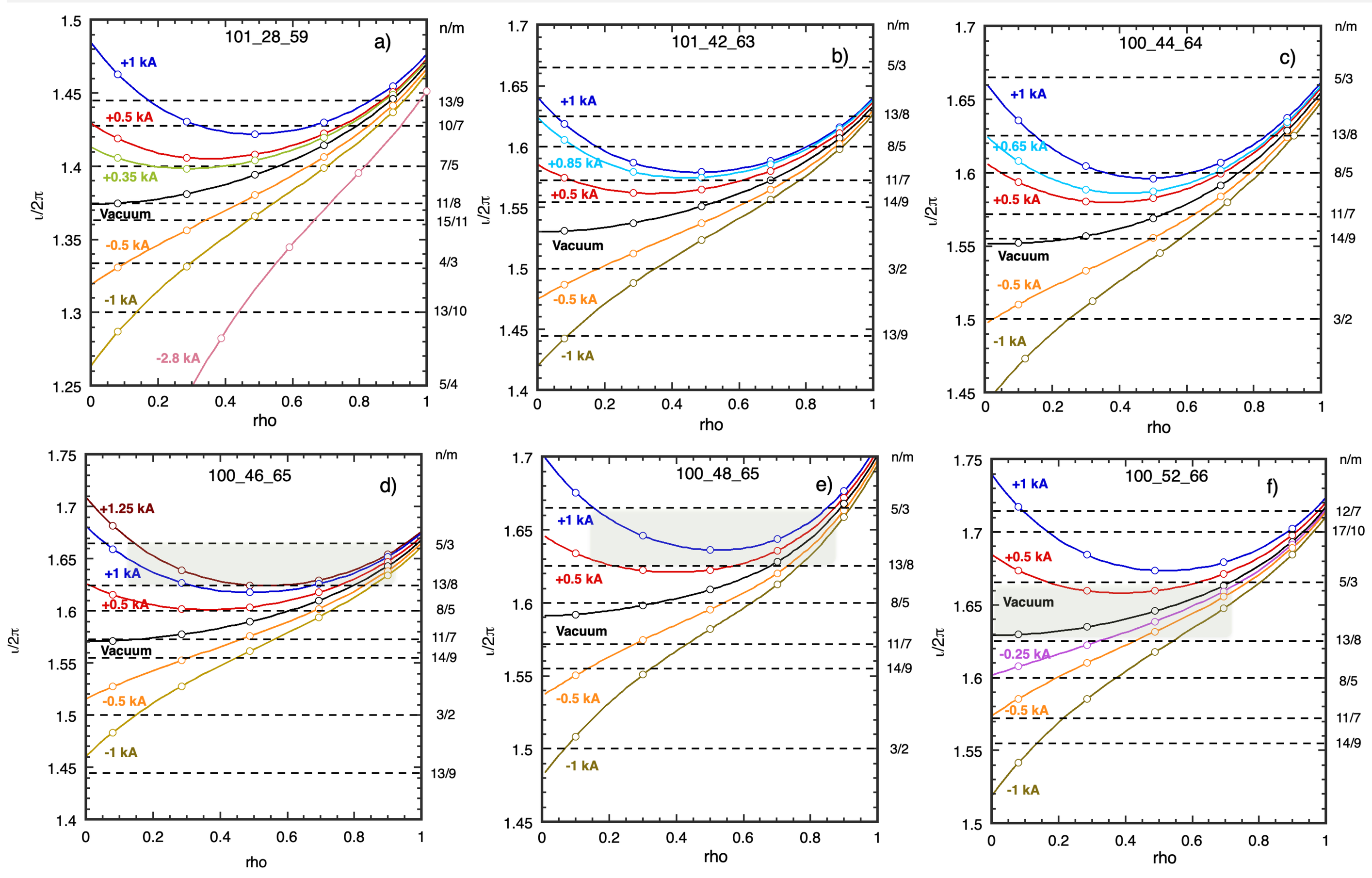
$$(\iota(\rho)/2\pi)_{plasma} = (\iota(\rho)/2\pi)_{vacuum} + C(\rho)\cdot I_p \quad (2)^{7}$$

$C(\rho) = A\exp(-\rho/B)$, A = 0.1107 kA⁻¹ and B = 0.3557.

Radial location of selected low-order rational surfaces as a function of I_p



Rotation transform profiles for vacuum and selected I_p values for magnetic configuration of interest



Discussion

- ✓ Oscillations due to striations (cloud detachments)[8] are observed frequently in Hα profiles, their duration being longer for NBI heated plasmas.
- ✓ Profiles with significant transient drops in Hα intensity are also observed in TJ-II - such dips not reproduced by eq. 1 or HPI2[9].
- ✓ Such structures are observed for both balanced- and unbalanced-NBI heated plasmas and for different magnetic configurations.
- ✓ Causes such as pellet deflection due to asymmetric particle impacts or unbalanced NBI heating (no associated structures)[10], NBI fast ion[10], neutral beam atoms, fast electrons (destroy pellets)[11], Hα emissions from detached plasmoids (Hα weak)[12] or pellets passing through a rotating island (non-reproducible)[8] can be discounted.
- ✓ These structures are observed when certain low-order rational surfaces occur inside ρ = ~0.8 (Hα light is not detected outside of this radius).
- ✓ When structures are present, they appear close to, or just inside, the radial locations of these low-order rational surfaces.
- ✓ Such structures are absent from Hα profiles if I_p is predicted to expel such low-order rational surfaces from the rational profile.
- ✓ Given that the number of toroidal turns of a field line needed to cover a flux surface increases exponentially near low-order rational surfaces, it can be argued that a pellet's ablation rate should drop in the vicinity of such surfaces.

References

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