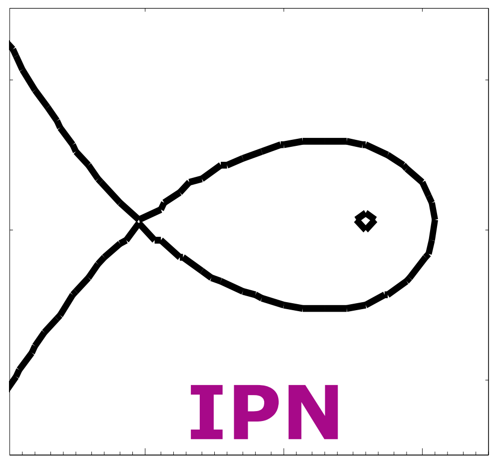
Conclusions of the paper

Successful production of

High β_p plasma

($\varepsilon\beta_p \geq 1$)

Naturally self Organized Inboard Poloidal field Null-IPN configuration



β_p Equilibrium Limit

A critical $\beta_p^* = 3$, defines Limiter (IL) → IPN transition

$\varepsilon\beta_p$ raised to Limit, IPN is self organized at high β_p by adjusting ε

Negative triangularity at high β_p

β_p can be raised by achieving negative δ shape.

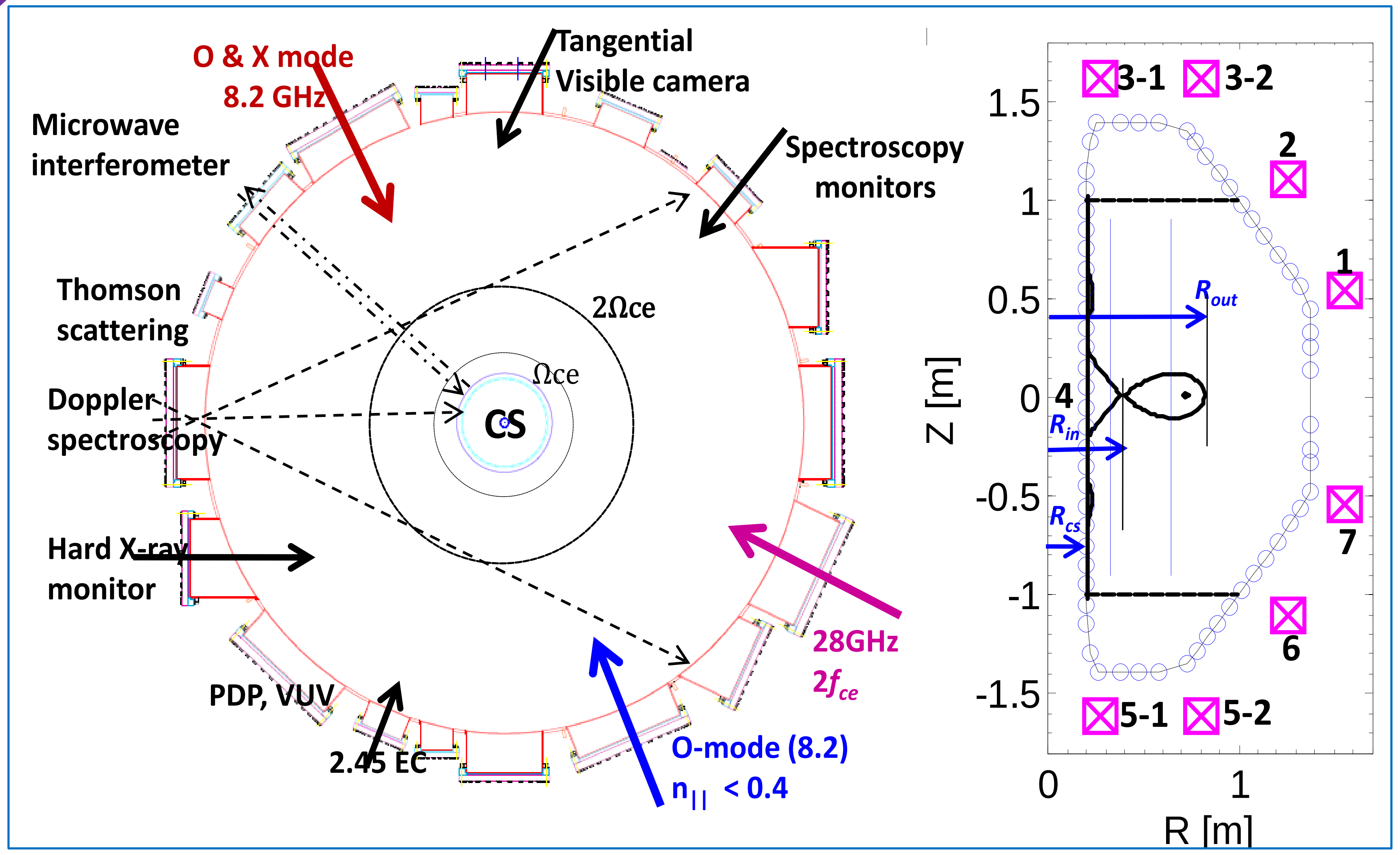
No use of shaping coils

IPN plasma rotates spontaneously

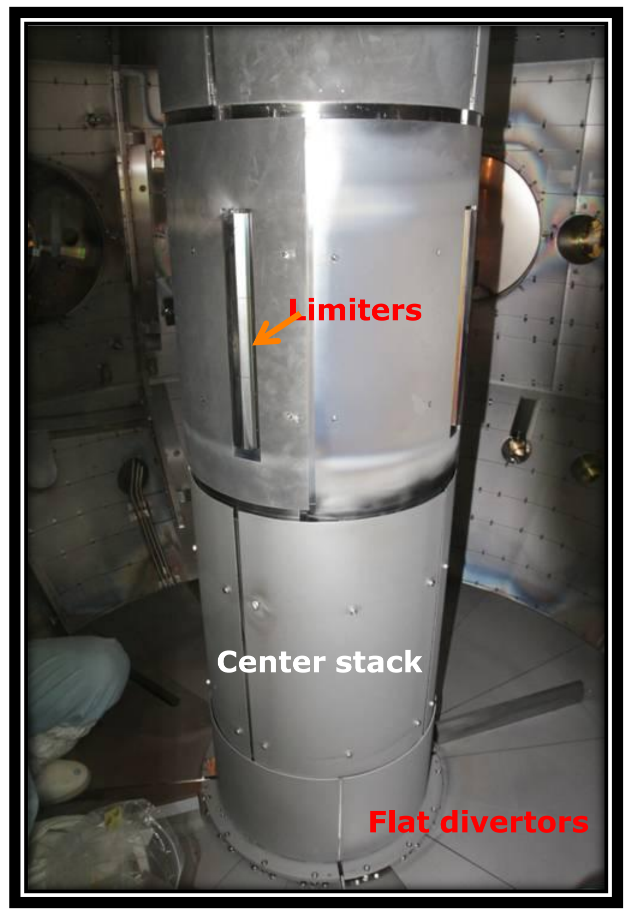
No External torque, ECRH only

Rotation is self organized in steady state (~ 600 s, fully Non-Inductive)

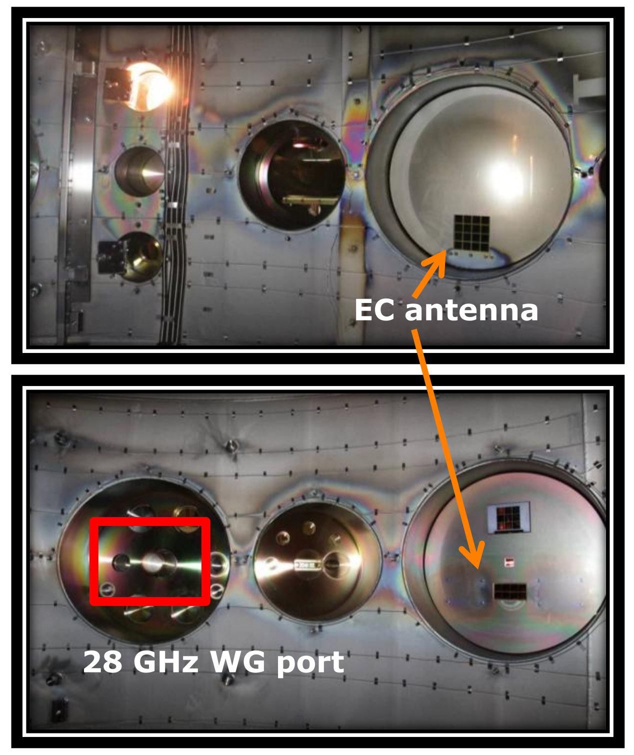
II. The Device : QUEST Spherical Tokamak



Cross-sectional view of QUEST vessel with diagnostics



Inside of Vacuum vessel showing Center stack and flat divertor plates

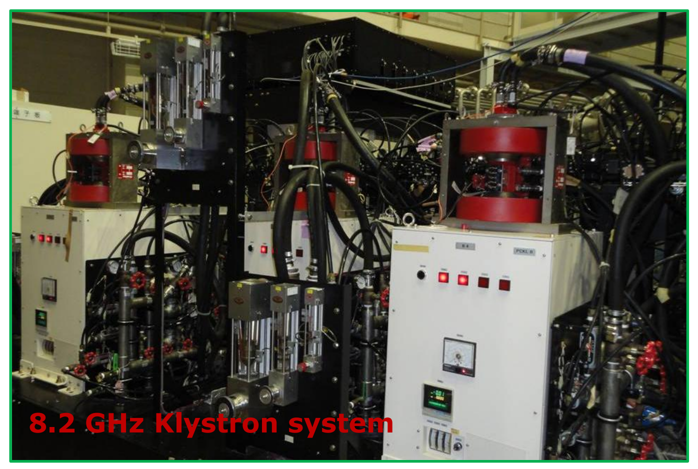


4x4 and 4x2 antenna for 8.2 GHz EC injection. Circular waveguide antenna for 28 GHz also shown

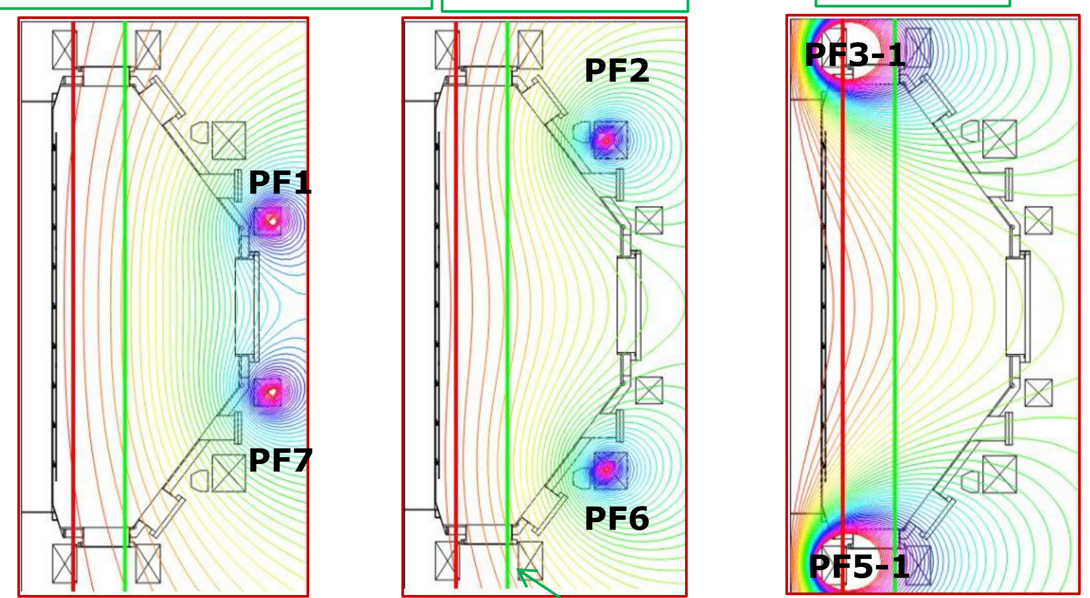
QUEST tokamak (early photograph)

QUEST parameters

- Major radius $R = 0.68$ m
- Minor radius $a = 0.40$ m
- Bt @ $f_{ce\_8.2GHZ}$ = 0.29 T
- HFS limiter = 0.22 m
- Flat divertors = ± 1 m
- Discharge gas = H_2, He, both
- ECW source = 2.45, 8.2, 28 GHz

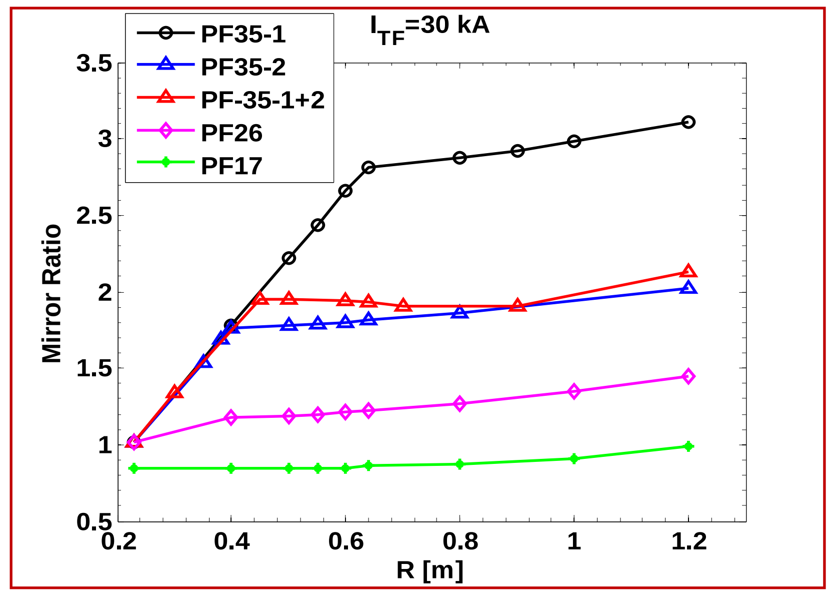


Mirror Ratio= 0.9 **M= 1.3** **M= 3**



8.2 GHz fundamental Resonance and 28 GHz 2nd harmonic

8.2 GHz 2nd harmonic resonance



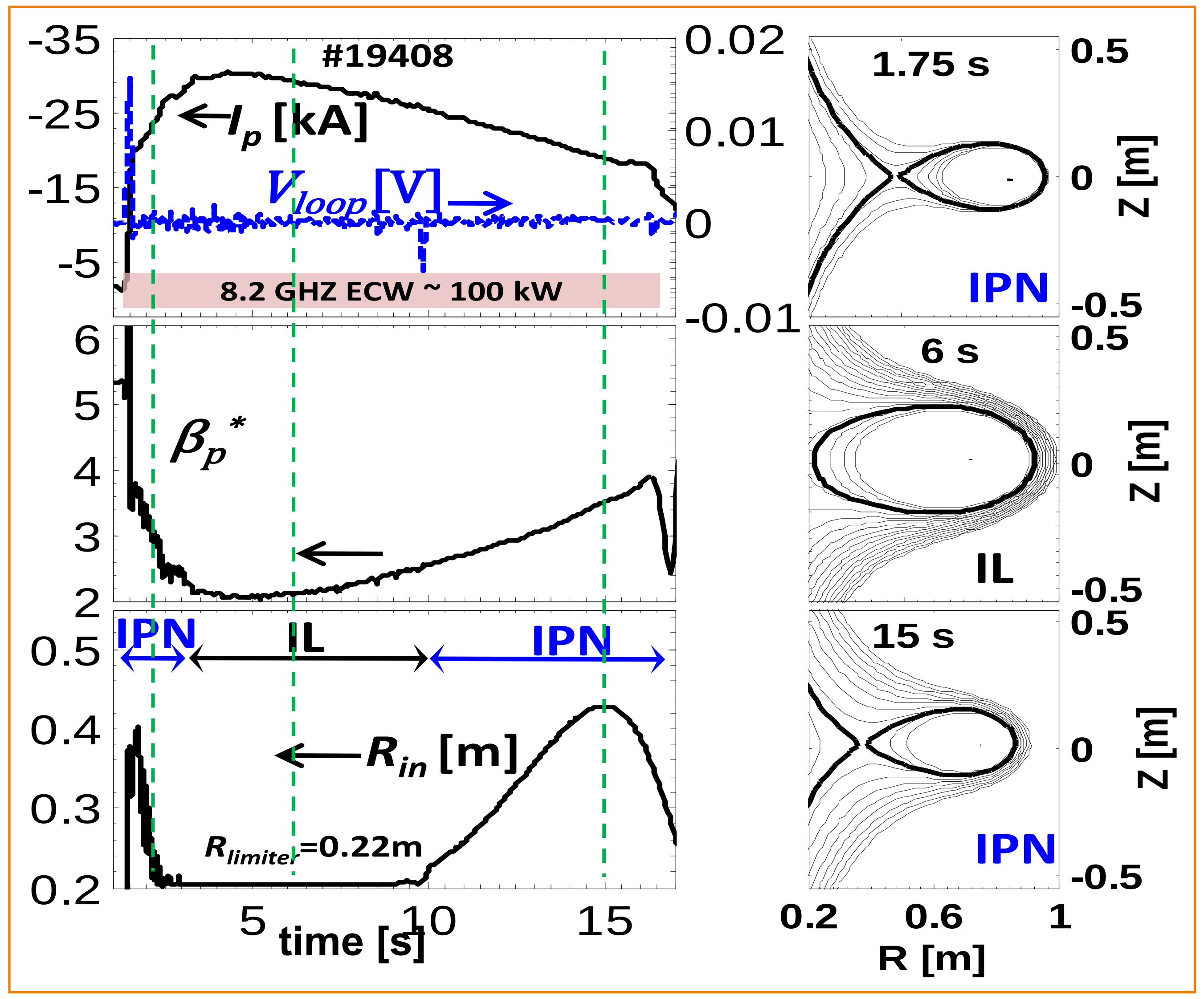
Mirror Ratio (M)= B_{max}/B_{min} on a particular flux surface.

M is a radial function and can be selected with different combination of PF coils.

Fully Non-inductive Plasma start-up:

- ❑ Fast and fully non-inductive plasma current start-up has been demonstrated [*Tashima et. al.* NF 2014] in QUEST by confined energetic electrons created by EC waves under suitable magnetic configurations.
- ❑ For this high magnetic mirror ratio ($M \geq 2$) and $B_z/B_t \sim 0.1$ has been found most suitable.
- ❑ Such plasma is regularly obtained in both fundamental (8.2 GHz) and 2nd harmonic (28 GHz) EC waves [Idei et. al., IAEA-EX/P1-38 (2014)].

III-a: Fully non-inductive IPN plasma



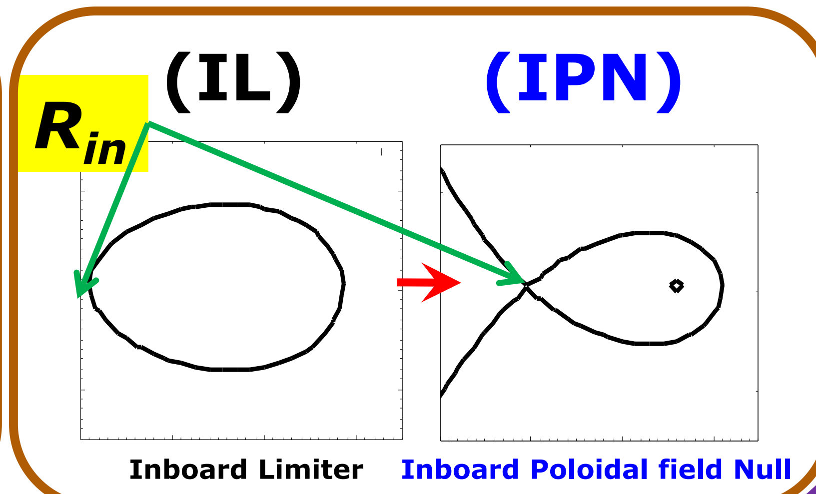
Typical high β_p plasma discharge in fully non-inductive current drive. Magnetic flux surfaces show IPN→IL→IPN transition at three discrete times.

Fully non-inductive IPN Plasma:

- ❑ I_p is driven fully non-inductively (V_{loop}=0) ,
- ❑ $\beta_p^* = \beta_p + l_i/2$ is computed from Shafranov's formula for radial force balance.
- ❑ With $\beta_p^* \geq 3$, natural poloidal magnetic field null appears: IPN formation (consequence of equilibrium β_p limit).
- ❑ Without external I_p control, IPN-IL-IPN transition is self organized.

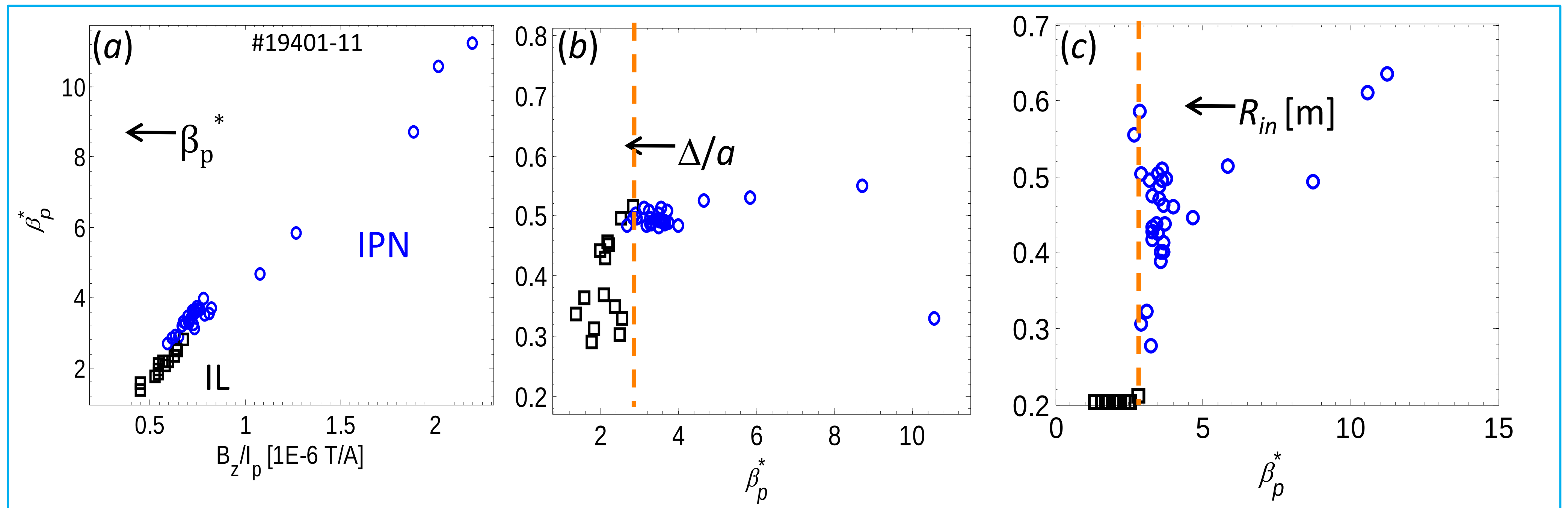
$$B_z = \frac{B_\theta(a)\varepsilon}{2}\left[\ln\frac{8R_0}{a} - \frac{3}{2} + \langle\beta_p\rangle + \frac{l_i}{2}\right], \quad \langle\beta_p\rangle + \frac{l_i}{2} = \beta_p^*$$

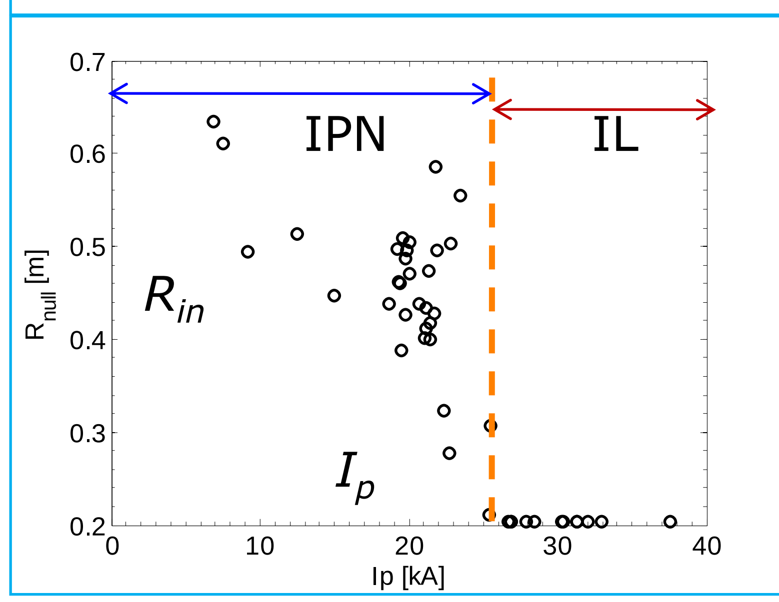
$$\beta_p = \frac{\langle p\rangle}{\langle B_p\rangle^2 / 2\mu_0}; \langle B_p\rangle = \mu_0 I_p / 2\pi a$$



Equilibrium of IPN Plasma:

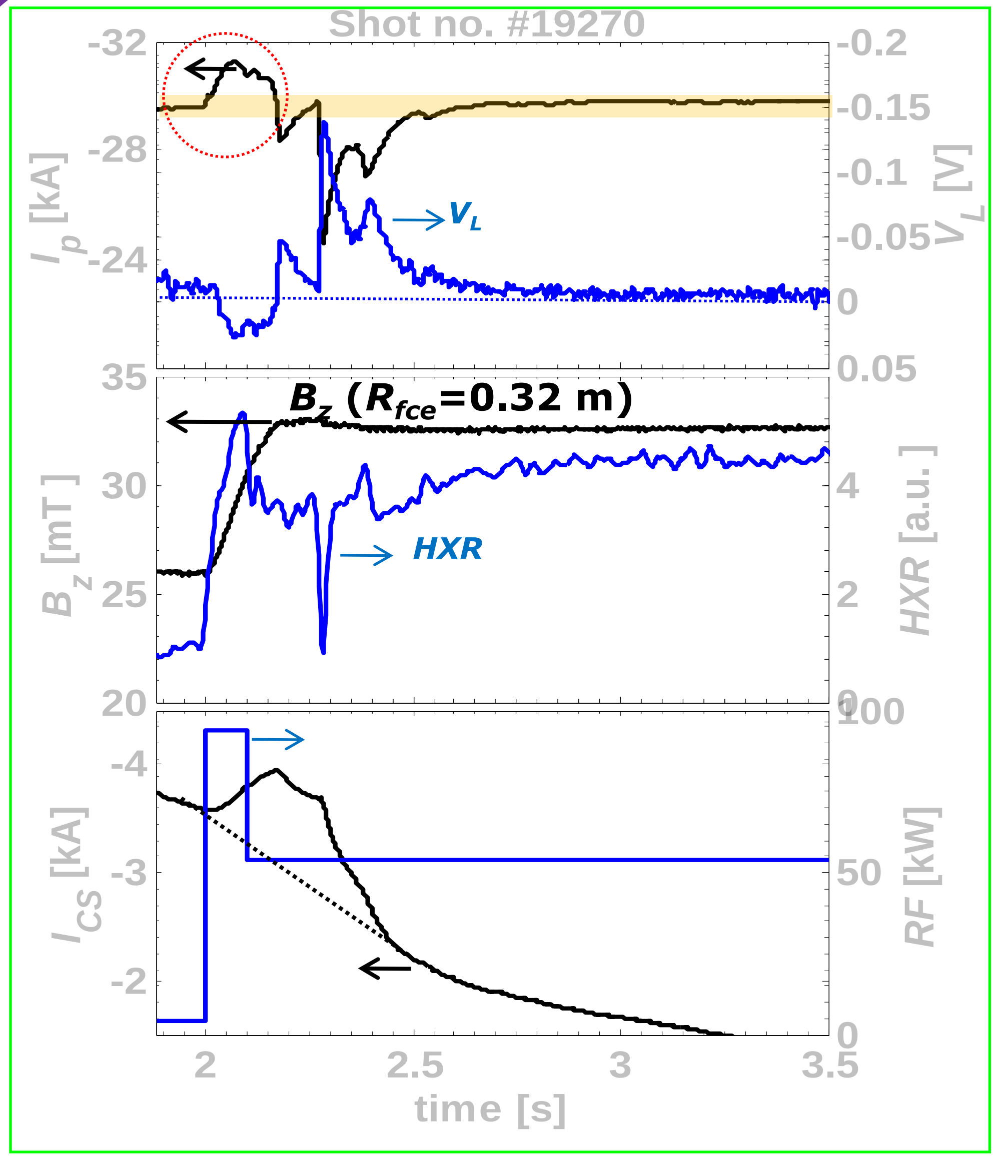
- ❑ β_p^* varies linearly with B_z/I_p and all the data fits into B_z/I_p = c0+c1 β_p^* relationship. Shape factor seems not to be dominant.
- ❑ Δ/a increases rapidly with β_p^* during IL to IPN transition and remains constant during the entire IPN region.
- ❑ R_{in} data consistently shows that at β_p^*=3, IL to IPN transition occurs.
- ❑ $R_{in} \sim I_p$ relation shows inverse relationship and a critical $I_p \sim$ 25 kA, below which, IPN configuration is realized.





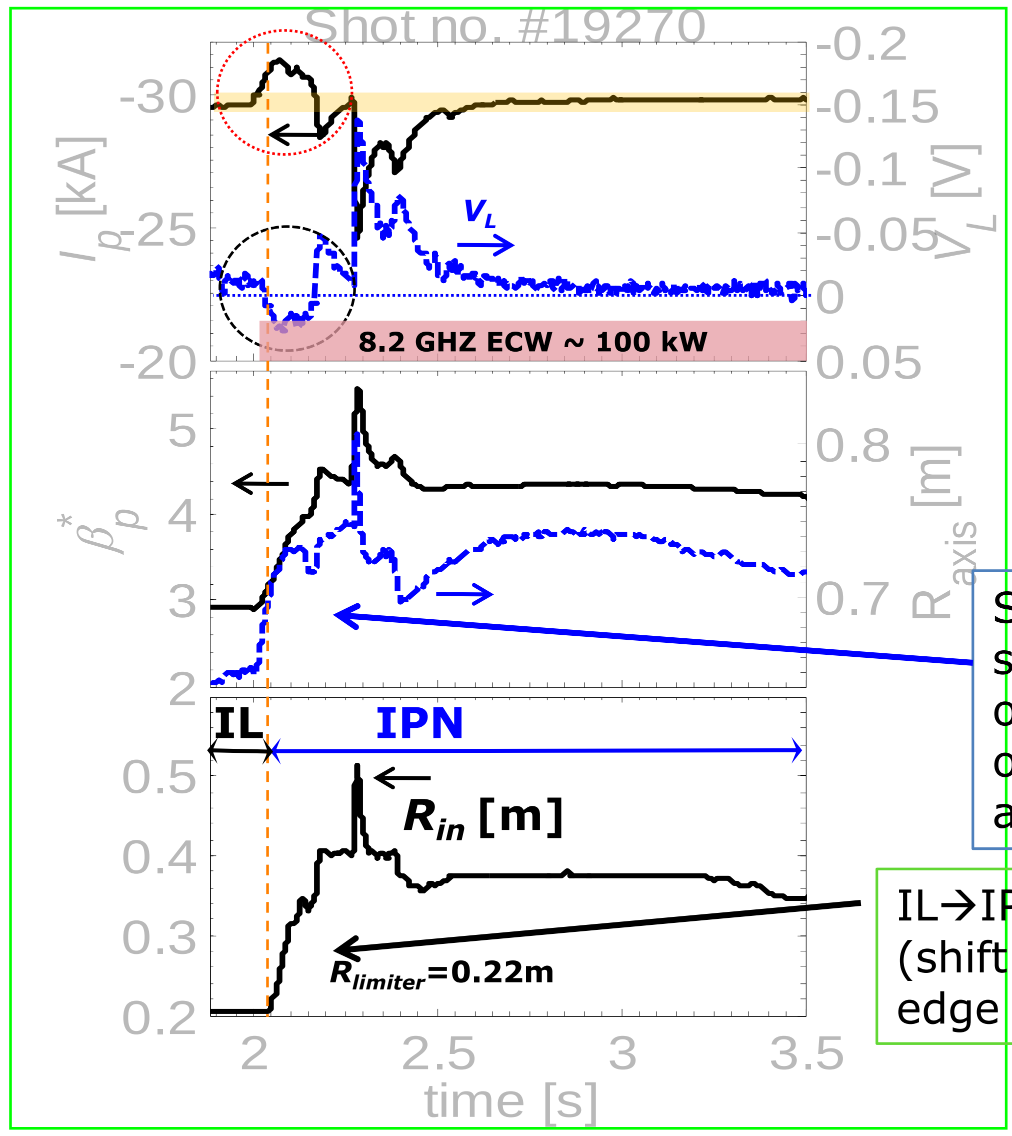
Summary of many similar discharges plotted at discrete time intervals for the equilibrium parameters for IPN plasma.

III-b: EC overdriven Ohmic plasma



EC overdriven Ohmic plasma:

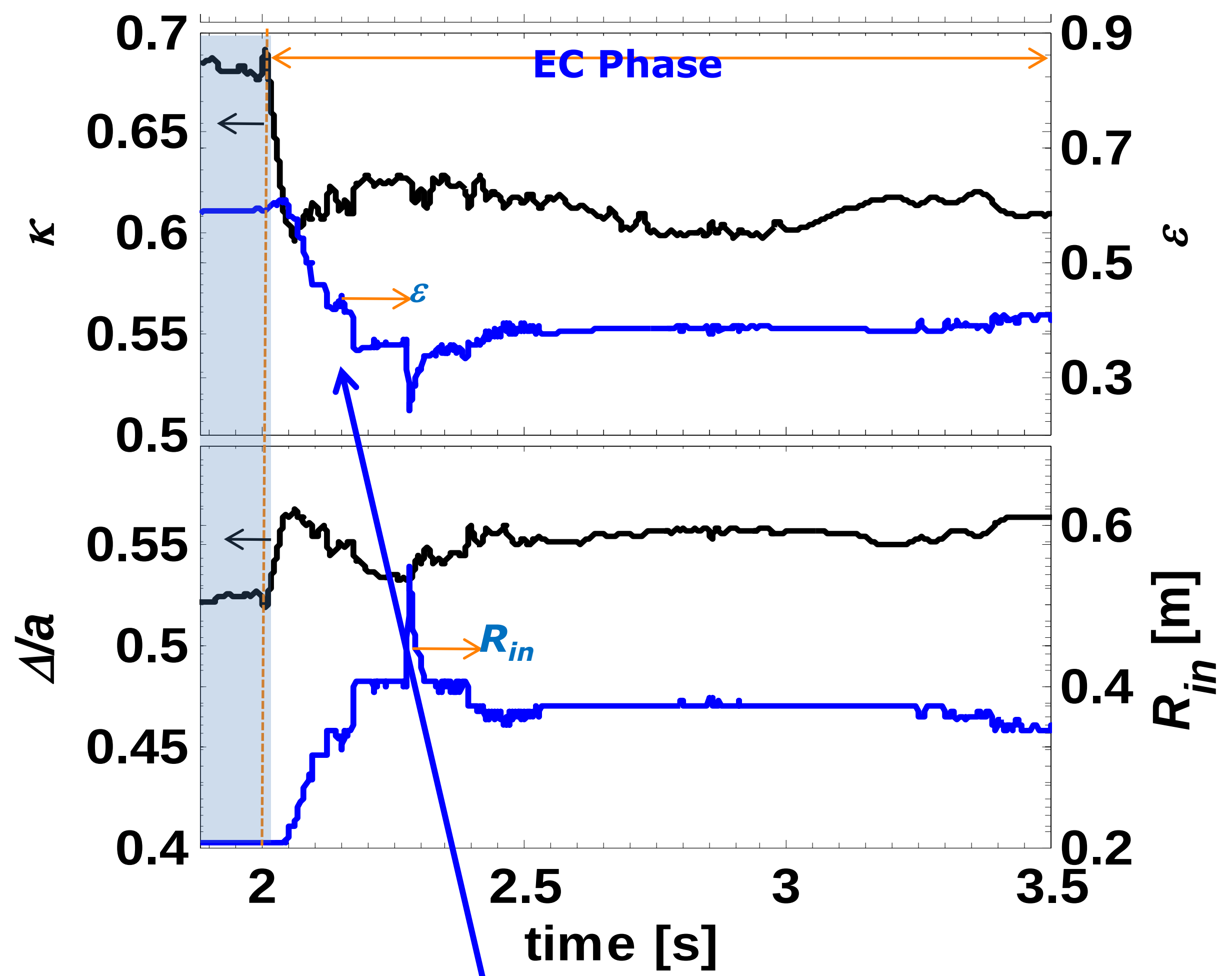
- ❑ In absence of Ip control, contribution of Bp could not be verified.
- ❑ In Ohmic target : Ip is kept fixed by feedback
- ❑ With EC: Ohmic circuit recharging.
- ❑ High HXR counts on EC application detected: Energetic electrons ~ 100 keV
- ❑ Bz is ramped up suitably to keep the EC overdriven plasma in equilibrium.
- ❑ β_p^* shows prompt increase in EC phase along with radial outward shift of magnetic axis.
- ❑ A null point appeared in high field side soon after EC injection. Rin position moved up to 0.4 m.



Shafranov shift outward shift of magnetic axis

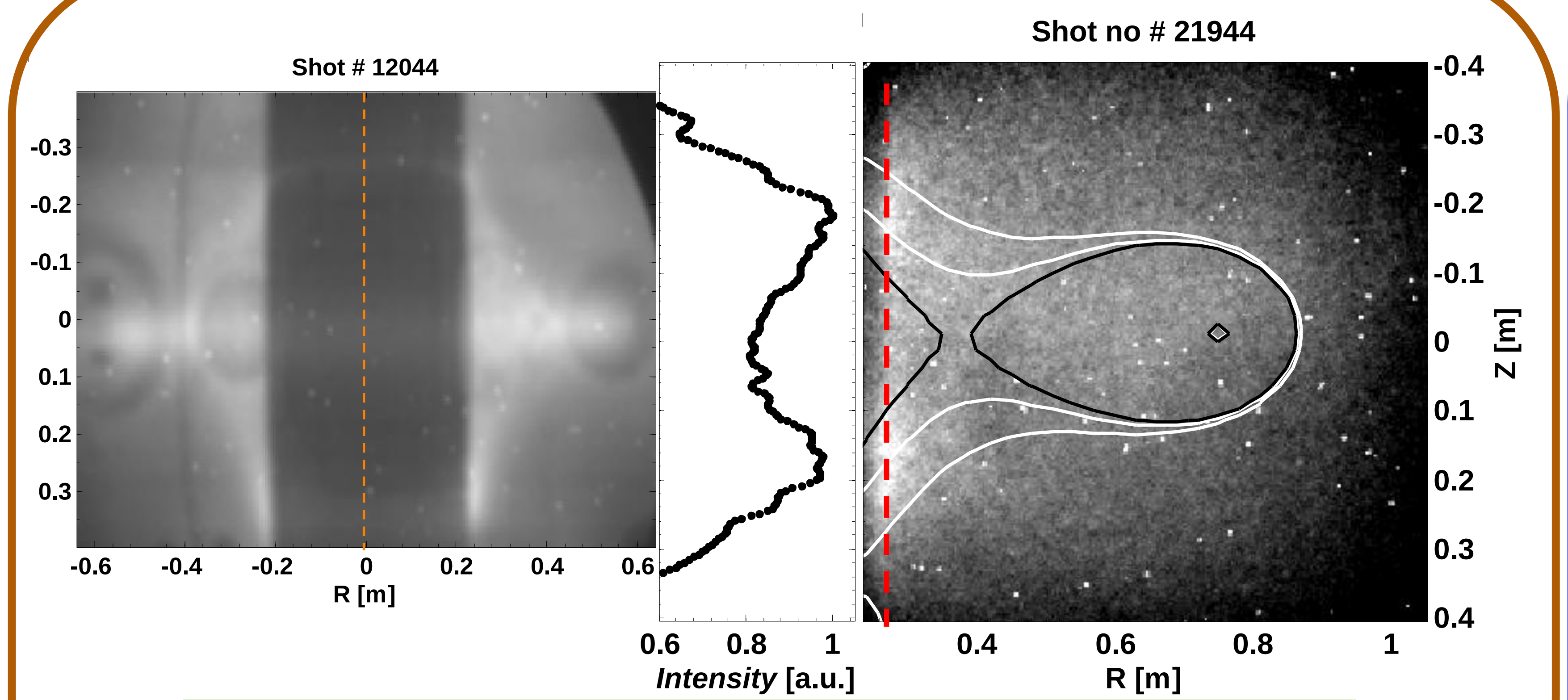
IL→IPN transition (shift of inboard edge into the vessel)

- ❑ With high β_p^* formation and IL→ IPN transition, plasma boundary is modified suitably to form an oblate radially outward shifted plasma.
- ❑ Magnetic measurements show elongation (κ) and inverse aspect ratio (ε) both reduced during IPN formation.
- ❑ IPN plasma is held in equilibrium for a duration in excess of 1 s.

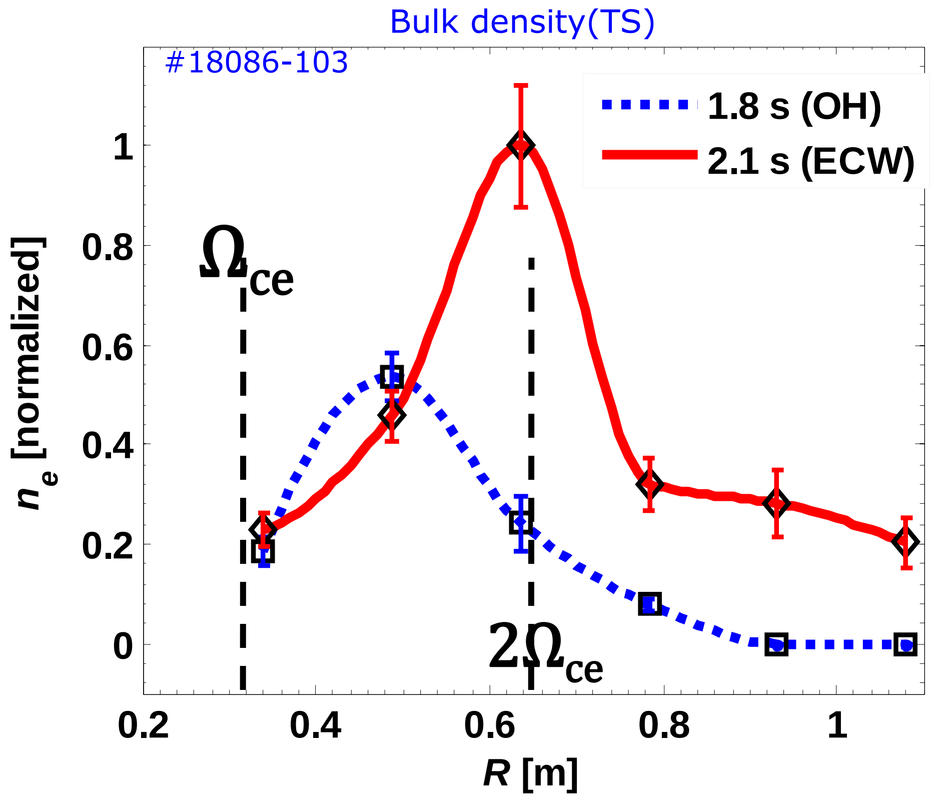


With IL→IPN transition (decrease of elongation and inverse aspect ratio)

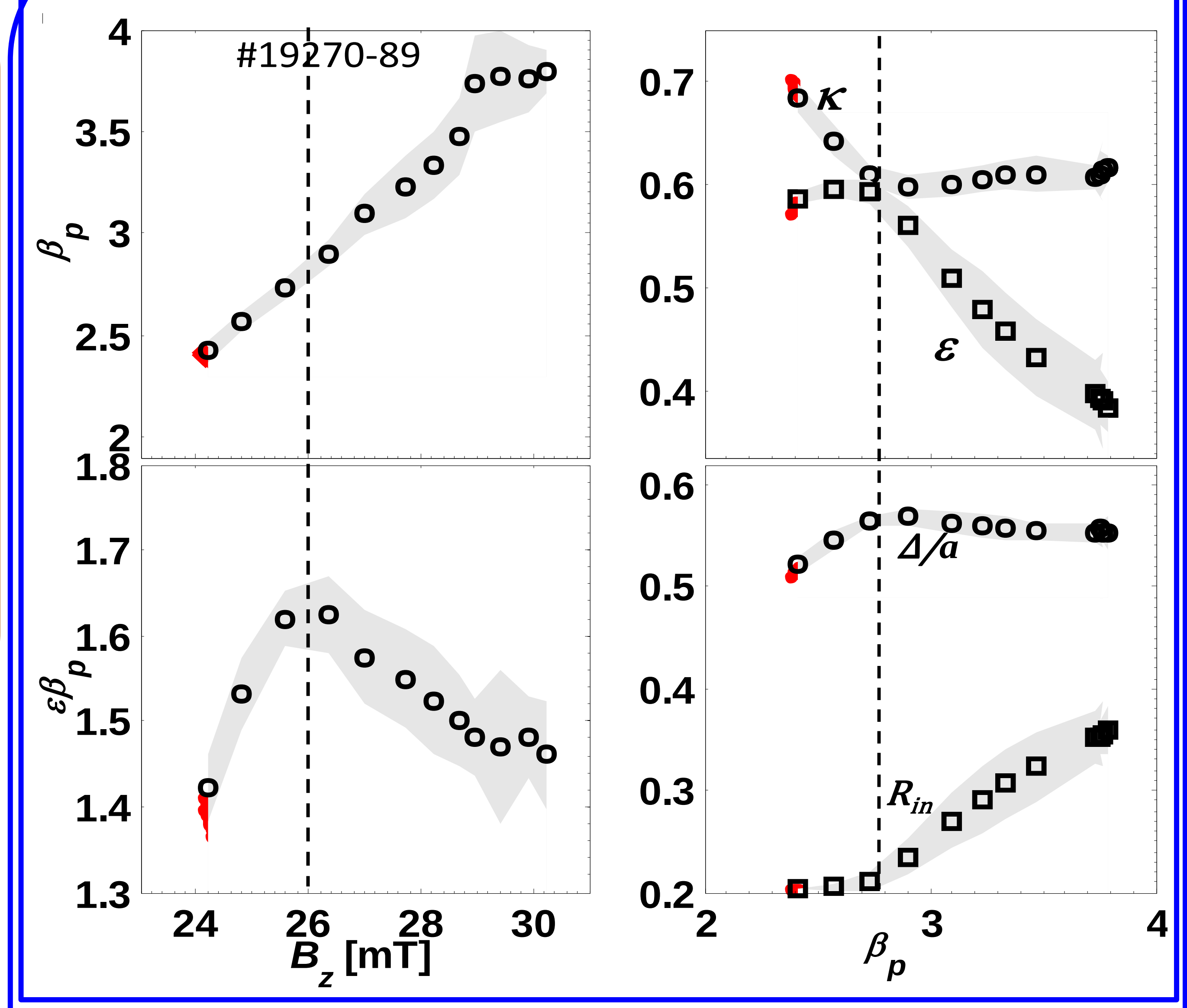
III-c: Summary of IPN plasma



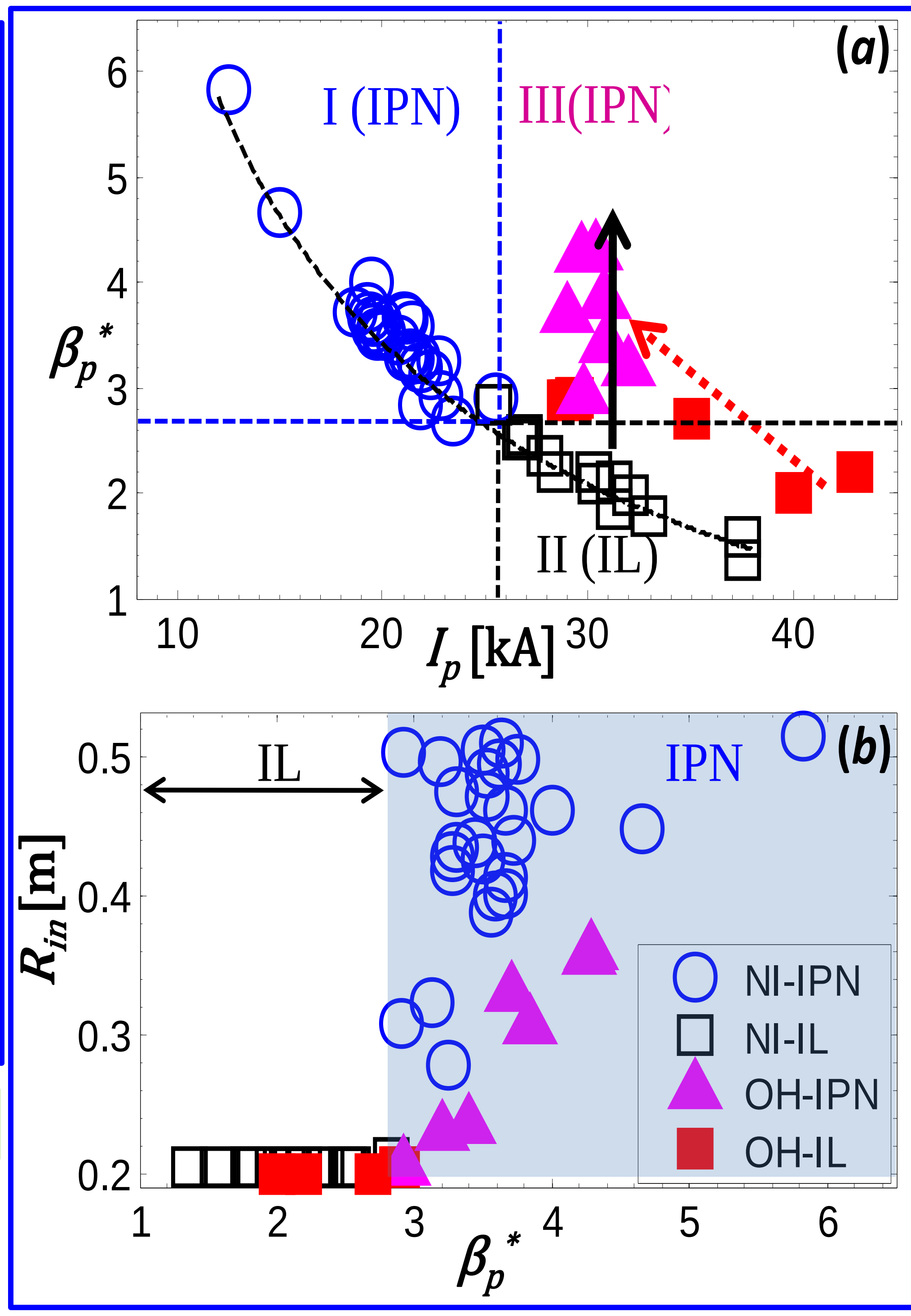
Visible camera image recorded tangentially from the outboard side. Flux contours are superimposed



Non-thermal component



Vertical broken lines depicts IL→IPN transition



Other measurements of IPN plasma:

- ❑ Visible light emission shows strike points of separatrix on the CS→ agrees with flux loop measurements.
- ❑ Bulk density profile (TS) : outward shift of density centroid with IL→IPN transition, independently signaling high β_p formation.
- ❑ Non-thermal (energetic electrons) density profile: Outward skewed profile, indicating outward plasma shift.

Summary of high β_p IPN plasma:

- ❑ Bz~Ip varies linearly, $\varepsilon\beta_p$ rises with Bz and IL→ IPN transition occurs
- ❑ Plasma does not disrupt, but it self adjusts to decrease ε and sustain IPN.
- ❑ $\kappa = b/a$, decreases sharply with β_p and saturates at 0.6 prohibiting plasma shape to become further oblate at higher β_p.
- ❑ During transition, plasma first becomes oblate and then this oblate plasma moves outward as β_p increased further.

- ❑ β_p^* decays as I_p^{-1} (NI plasma), independent of configuration and a transition discriminates IPN and IL at $I_p = 25$ kA
- ❑ By keeping I_p fixed, contribution of non thermal pressure ($\langle p\rangle_{hot}$) component of energetic electrons in determining β_p is verified.

IV : Analytic model for IPN Equilibrium

Self organization with negative triangularity

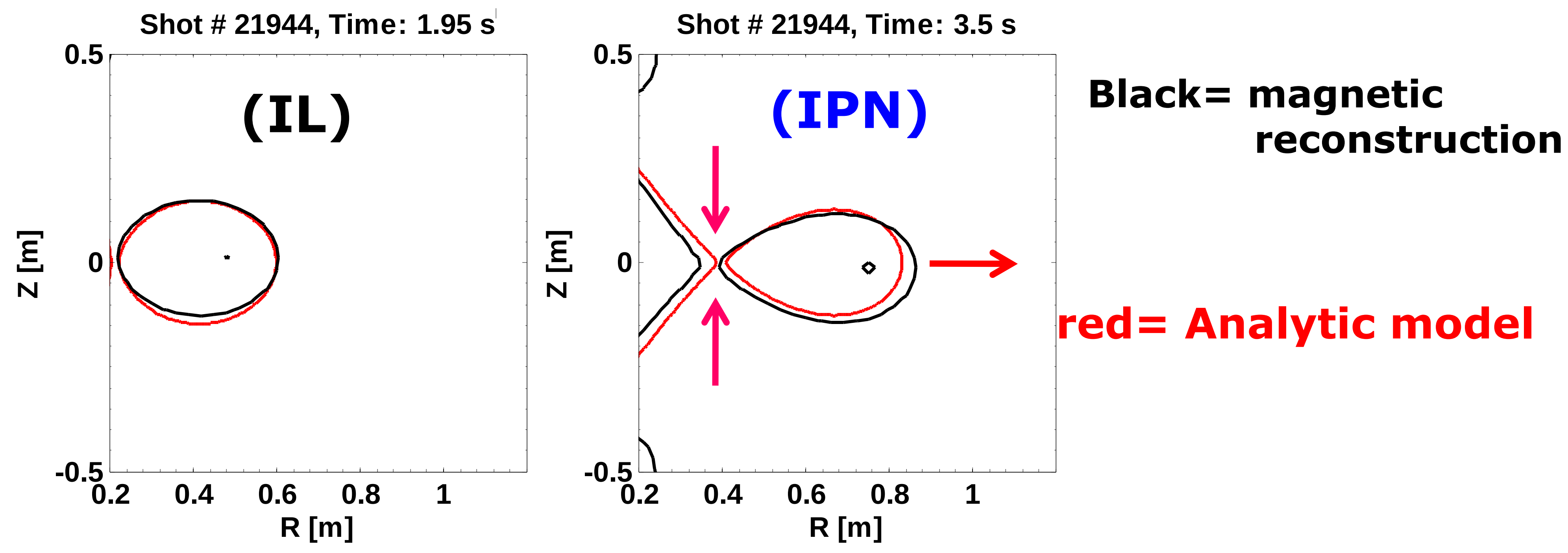
- At high β_p, plasma naturally self organizes itself to reduce the κ (TFTR, *Sabbagh et. al. PoF 1991*) as observed in the present case.
- A new additional self organization feature is observed, where self adjustment mechanisms work on the plasma shape so as to become more negatively triangular ($\delta < 0$).
- This new feature overcompensates the diminution of β_p due to the reduction in κ.
- A simple analytic solution of Grad-Shafranov equation is applied to investigate such aspect [*Shi POP 2005, Weening POP 2000*]

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\psi}{\partial R}\right)+\frac{\partial^2\psi}{\partial Z^2}=-\mu_0^2 G\frac{\partial G}{\partial\psi}-\mu_0(2\pi R)^2\frac{\partial p}{\partial\psi}$$ -----(G-S Equation)

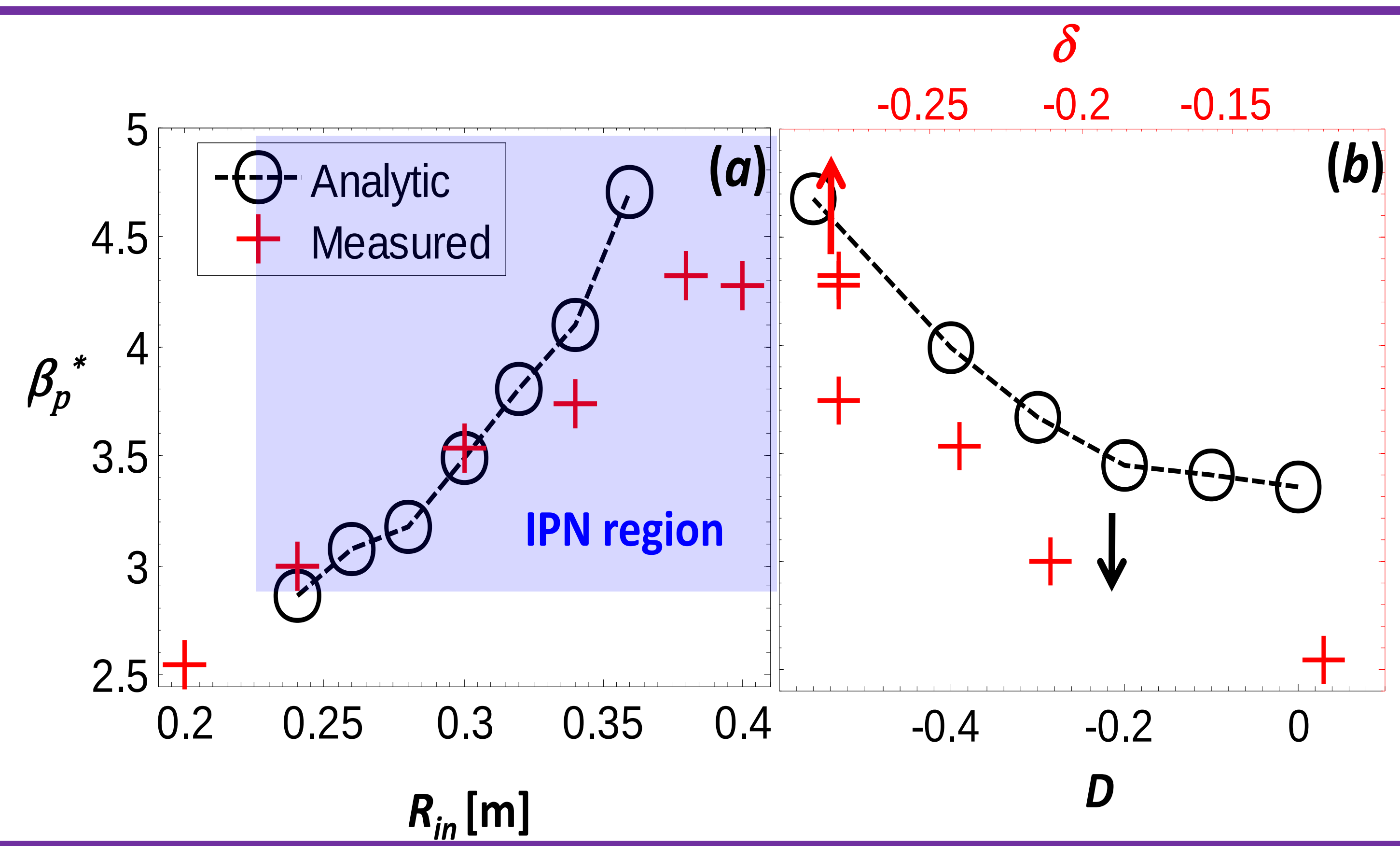
$$\psi(R,Z)=\frac{\psi_b}{w_b^2}\left[\frac{4Z^2}{E^2R_0^2}\left\{\frac{R^2}{R_0^2}(1-D)+D\right\}+\left(\frac{R^2}{R_0^2}-1\right)^2+H\left\{\frac{R^2}{R_0^2}\ln\left(\frac{R^2}{R_0^2}\right)-\frac{R^2}{R_0^2}+1\right\}\right]$$ ---Solution

D = triangularity, E =elongation , H = diamagnetic factor.

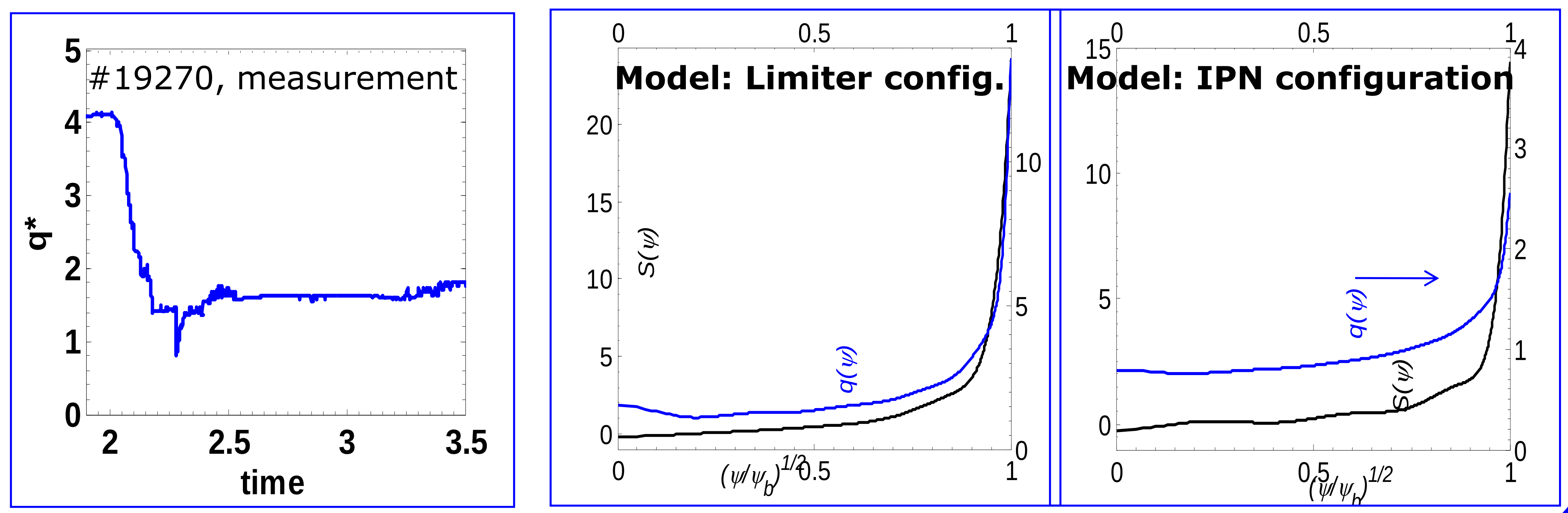
- β_p^* computed from model agrees well with the measurements for critical value of IL-IPN transition.
- Model agrees with the experimental findings that, negative δ shaping is favorable for high β_p sustainment.



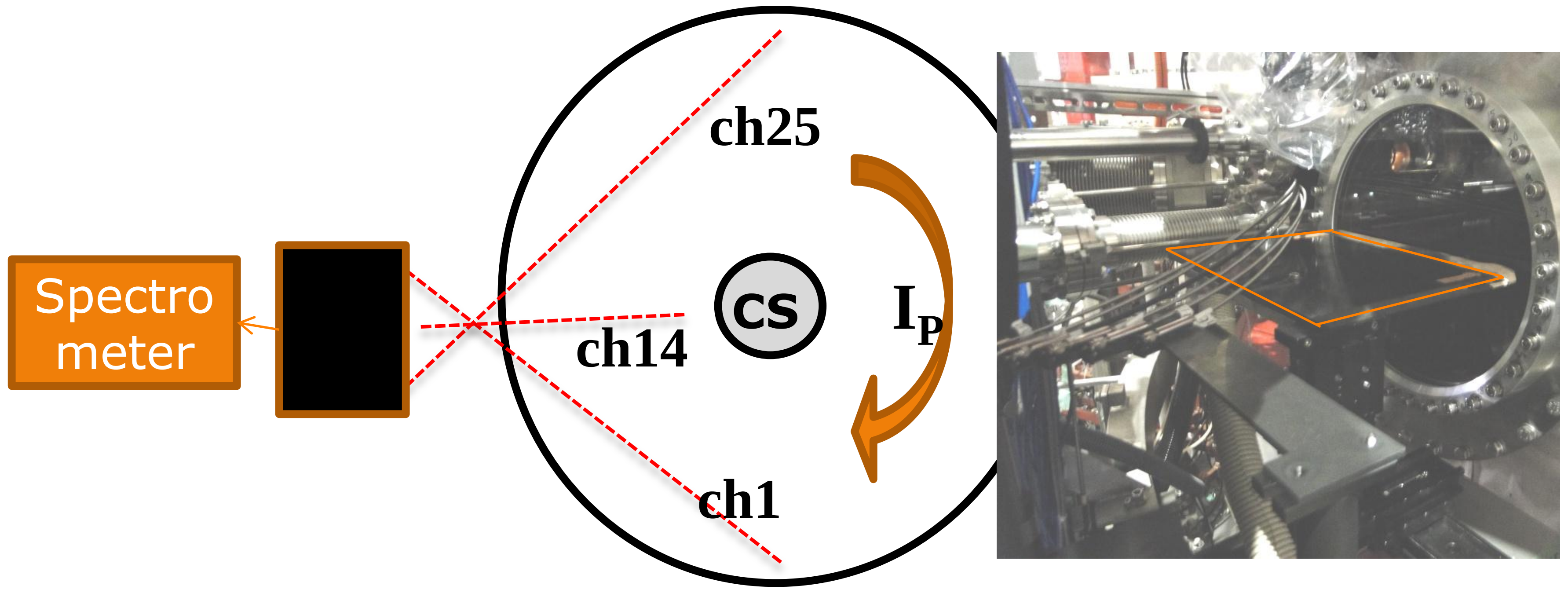
- With suitable choice of E,H and D parameters in the analytic model, equilibrium magnetic flux surfaces are computed.
- At high diamagnetic factor, high β_p IPN plasma configuration is achieved.
- Flux boundaries obtained through model and magnetic measurements closely agrees with each other.



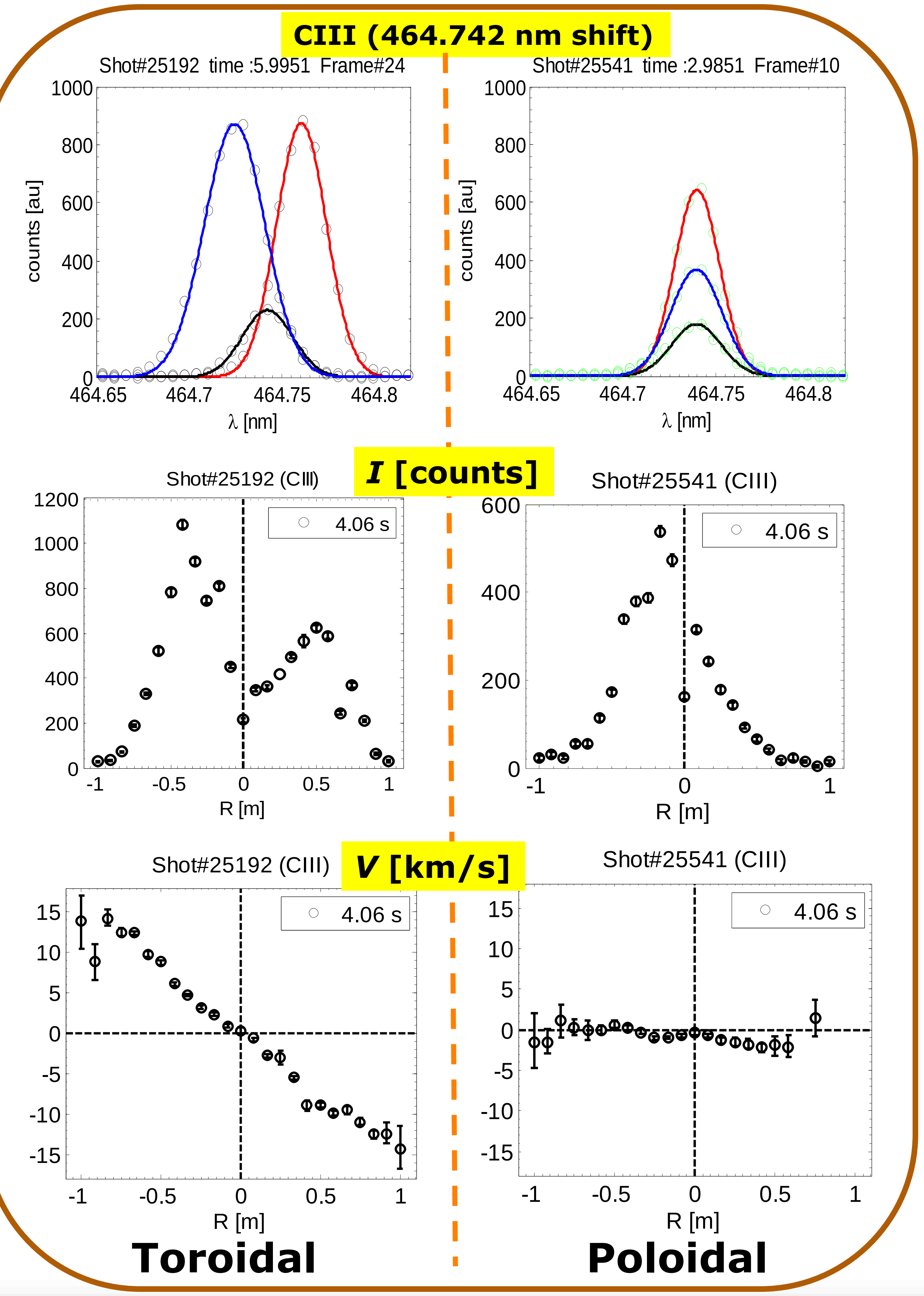
- With the help of the simple model, magnetic surface quantities like safety factor (q) and sheer (S) is determined.
- In IPN configuration, a similar quantity $q^* = \pi\varepsilon a(1+\kappa^2)B_0/\mu_0 I_p$ is determined and shows a sharp reduction during the transition phase.
- Similar reduction of edge q is also indicated from the model output.

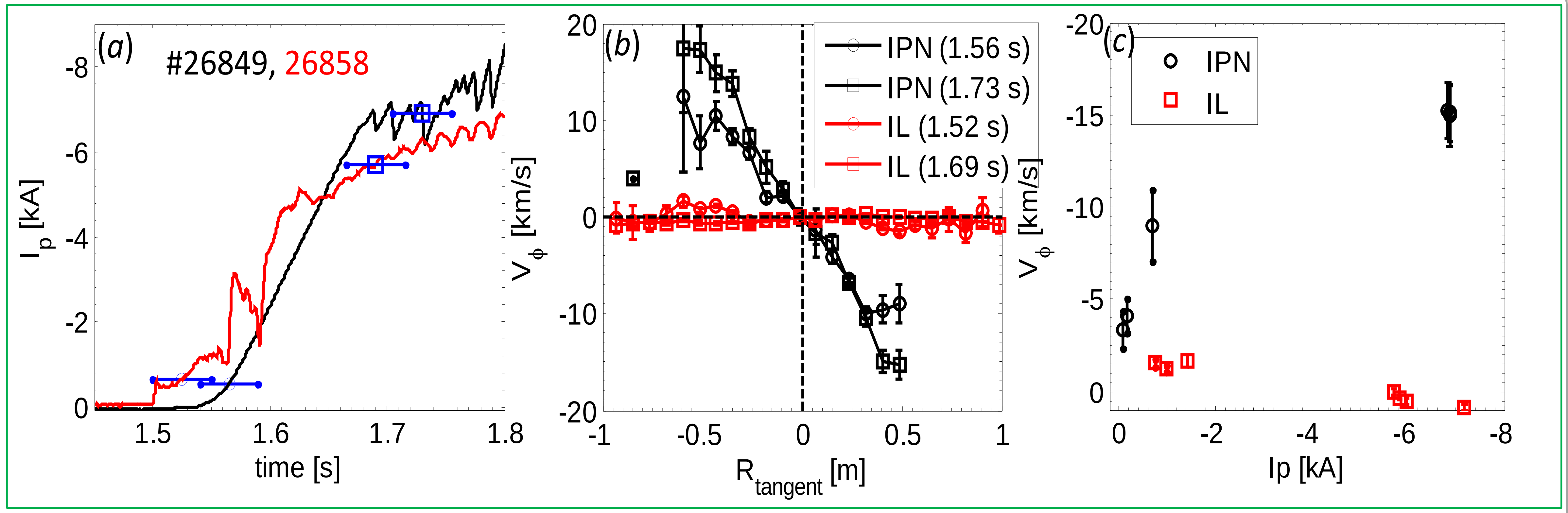


V : Intrinsic Rotation in IPN plasma



Toroidal rotation set-up (Top view)





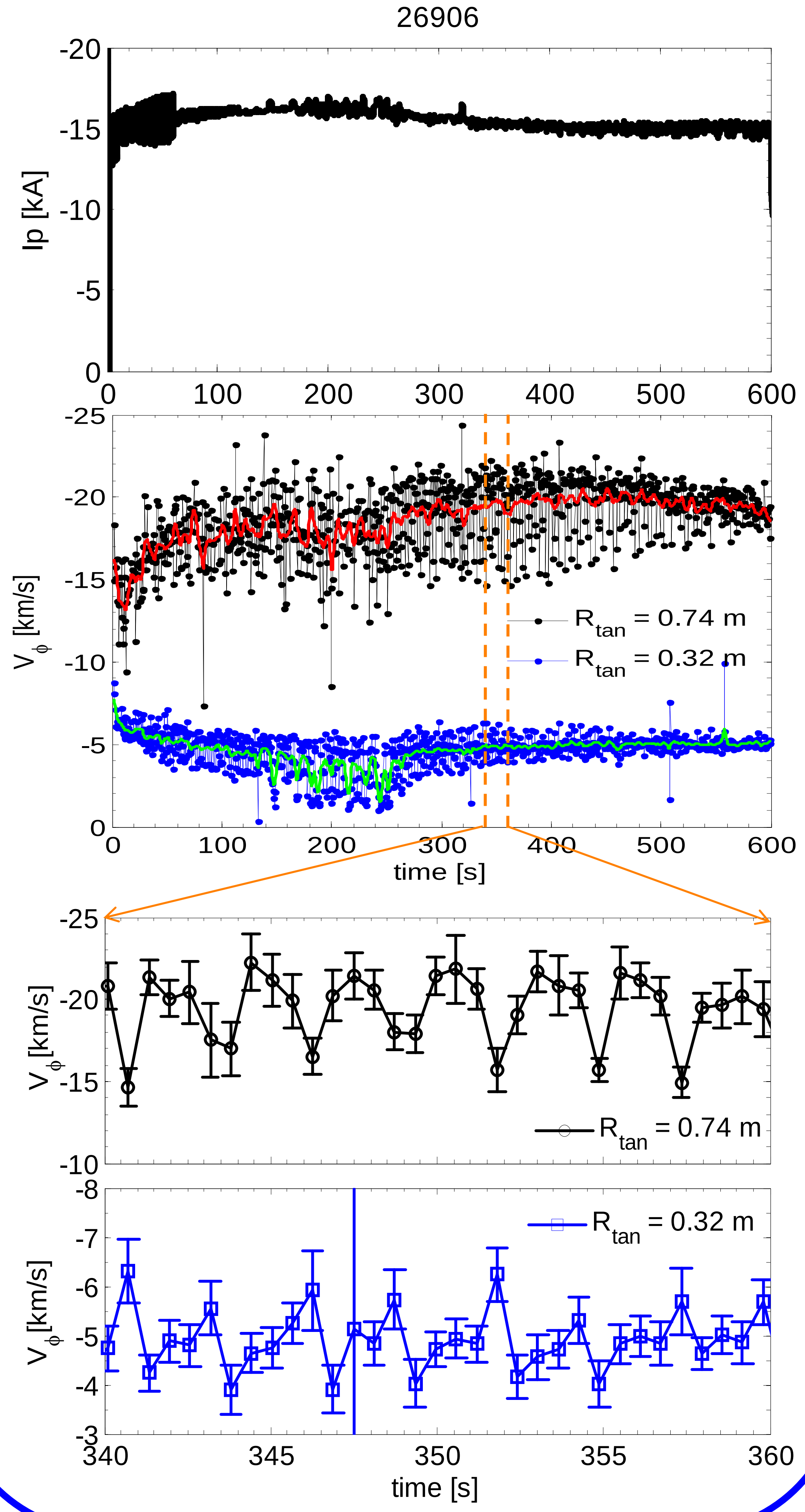
Toroidal rotation during current start up (open magnetic field configuration) under low (red) and high (black) magnetic mirror ratio.

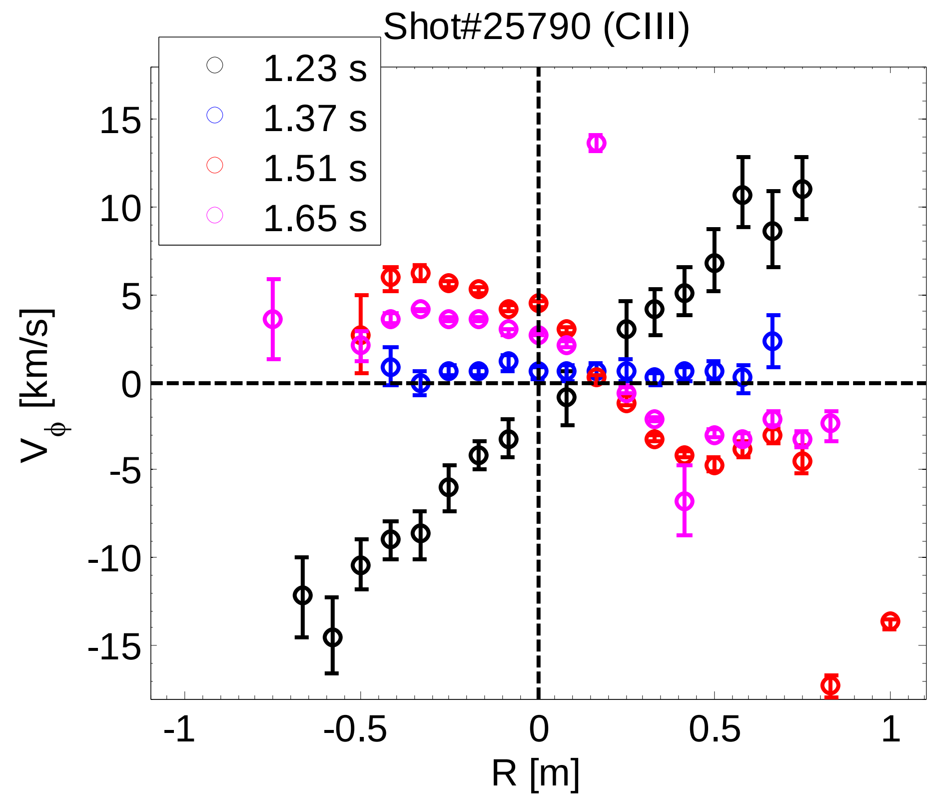
Spontaneous rotation in IPN plasma :

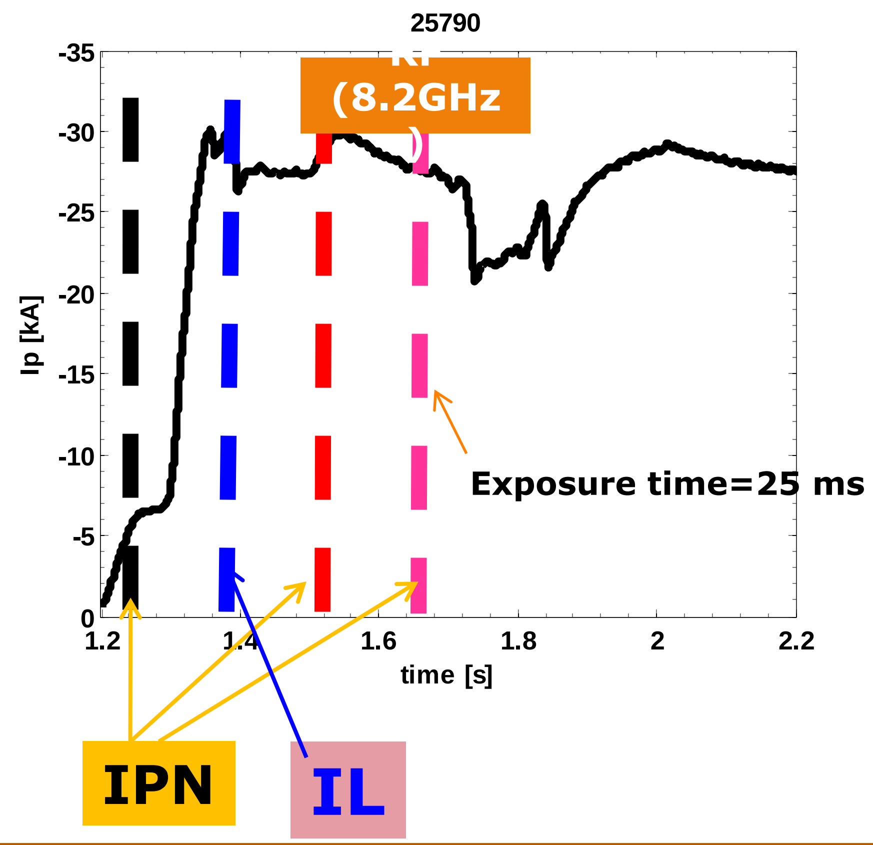
- ❑ A characteristic feature of high β_p IPN plasma is its intrinsic rotation **without any external momentum input**.
- ❑ The rotation profile is measured with the help of a 25 channel fiber optic fan array installed at the outboard mid-plane to collect visible emission from plasma ions.
- ❑ Both bulk ions (He II) and impurity ions (C III) emission is recorded through a **1 m grating** spectrometer.
- ❑ **Radial resolution** of fiber FOVs at plasma center is ~ **8 cm** and spot dia of each fiber fov **< 2.5 cm**.
- ❑ Usual operating time resolution is 50 ms with **minimum of 11 ms**.
- ❑ Significant toroidal rotation (V_ϕ) **of order of 20 km/s** is observed in IPN plasma. Poloidal rotation however, is small compared to V_ϕ and is < 5 km/s
- ❑ In breakdown phase, (**open magnetic field lines**), V_ϕ **~ 5-15 km/s** is observed only under high mirror ratio M= 2 (IPN start-up).
- ❑ At low **M= 1.2 (IL start up), no such rotation** is observed.

VI : Self sustained Rotation in Steadystate

Sustained rotation for 600 s







Four time slices where, measurements is done are shown in dotted line. With Ip < 7 kA,

Spontaneous rotation in IPN plasma in Steady state :

- ❑ Spontaneous toroidal rotation in IPN plasma is demonstrated in steady state for 600 s.
- ❑ Rotation is always in co-current direction and has maximum of ~ 20 km/s
- ❑ Rotation profile responds to external gas fuelling and has been seen out of phase in inboard and outboard side of the plasma.

- ❑ Similar rotation profile is measured in Ohmic plasma with EC injected into it.
- ❑ In pure OH plasma, plasma boundary is IL and almost negligible flow has been observed.
- ❑ With EC injection, IL is transformed to IPN
- ❑ Rotation reversal is observed with EC injection.

THANK YOU

For your attention