Conclusions of the paper

Successful production of High $\beta_p$ plasma ($\varepsilon\beta_p \geq 1$)

Naturally self Organized Inboard Poloidal field Null-IPN configuration

$\beta_p$ Equilibrium Limit

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

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

Negative trianlarity at high $\beta_p$

$\beta_p$ can be raised by achieving negative $\delta$ 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

**Quest Parameters**

- Major radius \( R = 0.68 \text{ m} \)
- Minor radius \( a = 0.40 \text{ m} \)
- \( B_t @ f_{ce,8.2 \text{ GHz}} = 0.29 \text{ T} \)
- HFS limiter = 0.22 m
- Flat divertors = ± 1 m
- Discharge gas = \( \text{H}_2, \text{He}, \text{both} \)
- ECW source = 2.45, 8.2, 28 GHz

**Mirror Ratio**

- Mirror Ratio (\( M \)) = 0.9
- Mirror Ratio (\( M \)) = 1.3
- Mirror Ratio (\( M \)) = 3

**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 \( B_y / B_t \sim 0.1 \) has been found most suitable.
- Such plasma is regularly obtained in both fundamental (8.2 GHz) and 2\(^{nd}\) harmonic (28 GHz) EC waves [Idei et. al., IAEA-EX/P1-38 (2014)].

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

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

**QUEST tokamak (early photograph)**
### III-a: Fully non-inductive IPN plasma

**Fully non-inductive IPN Plasma:**
- $I_p$ is driven fully non-inductively ($V_{\text{loop}}=0$).
- $\beta_p^* = \beta_p + \frac{l}{2}$ 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 $\beta_p$ limit).
- Without external $I_p$ control, IPN-IL-IPN transition is self-organized.

**Equilibrium of IPN Plasma:**
- $\beta_p^*$ varies linearly with $B_d/I_p$ and all the data fits into $B_d/I_p = c0 + c1 \beta_p^*$ relationship. Shape factor seems not to be dominant.
- $\Delta/a$ increases rapidly with $\beta_p^*$ during IL to IPN transition and remains constant during the entire IPN region.
- $R_{\text{in}}$ data consistently shows that at $\beta_p^* = 3$, IL to IPN transition occurs.
- $R_{\text{in}} \sim I_p$ 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.
**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.
- $\beta_p^*$ 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.

- With high $\beta_p^*$ formation and IL $\rightarrow$ IPN transition, plasma boundary is modified suitably to form an oblate radially outward shifted plasma.
- Magnetic measurements show elongation ($\kappa$) and inverse aspect ratio ($\varepsilon$) both reduced during IPN formation.
- IPN plasma is held in equilibrium for a duration in excess of 1 s.
### III-c: Summary of IPN plasma

**Summary of high \( \beta_p \) IPN plasma:**

- \( B_z \sim I_p \) varies linearly, \( \varepsilon \beta_p \) rises with \( B_z \) and IL \( \rightarrow \) IPN transition occurs.
- Plasma does not disrupt, but it self adjusts to decrease \( \varepsilon \) and sustain IPN.
- \( \kappa = b/a \), decreases sharply with \( \beta_p \) and saturates at 0.6 prohibiting plasma shape to become further oblate at higher \( \beta_p \).
- During transition, plasma first becomes oblate and then this oblate plasma moves outward as \( \beta_p \) increases further.
- \( \beta_p \) decays as \( I_p^{-1} \) (NI plasma), independent of configuration and a transition discriminates IPN and IL at \( I_p = 25 \text{ kA} \).
- By keeping \( I_p \) fixed, contribution of non thermal pressure (\( \langle p \rangle_{\text{hot}} \)) component of energetic electrons in determining \( \beta_p \) is verified.

**Other measurements of IPN plasma:**

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

**Visible camera image recorded tangentially from the outboard side. Flux contours are superimposed**
**IV : Analytic model for IPN Equilibrium**

**Self organization with negative triangularity**
- At high $\beta_p$, plasma naturally self organizes itself to reduce the $\kappa$ (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 $\beta_p$ due to the reduction in $\kappa$.
- A simple analytic solution of Grad-Shafranov equation is applied to investigate such aspect [Shi POP 2005, Weening POP 2000]

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

$$\psi(R,Z) = \frac{4Z^2}{E} \left[ \frac{R^2}{K} (1-D) + D \right] - \frac{R^2}{K} + \frac{R}{K} \text{ln} \left[ \frac{R^2}{K} - \frac{R^2}{K} + 1 \right] \quad \text{------Solution}$$

- $D =$ triangularity, $E =$ elongation , $H =$ diamagnetic factor.
- $\beta_p^*$ computed from model agrees well with the measurements for critical value of IL-IPN transition.
- Model agrees with the experimental findings that, negative $\delta$ shaping is favorable for high $\beta_p$ 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 $\beta_p$ 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 $q^* = \pi a(1+\kappa^2)B_p/\mu_0 I_p$ is determined and shows a sharp reduction during the transition phase.
> Similar reduction of edge $q$ is also indicated from the model output.
A characteristic feature of high $\beta_p$ IPN plasma is its intrinsic rotation \( \omega \) 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 \( \sim 8 \text{ cm} \) and spot dia of each fiber fov \(< 2.5 \text{ cm} \).

Usual operating time resolution is 50 ms with minimum of 11 ms.

Significant toroidal rotation \( \Omega \) of order of 20 km/s is observed in IPN plasma. Poloidal rotation however, is small compared to \( \Omega \) and is \(< 5 \text{ km/s} \).

In breakdown phase, \( \omega \) is \( \sim 5-15 \text{ km/s} \) 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

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