Ideal MHD Stability Boundaries of the PROTO-SPHERA Configuration

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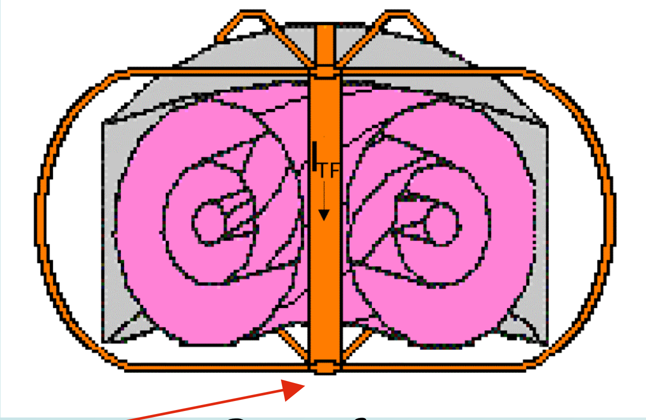


Spherical Tokamaks allow to obtain:

- High plasma current I_p (and high <n>) with low B_T
- Plasma β much higher than Conventional Tokamaks
- More compact devices

But, for a reactor/CTF extrapolation:

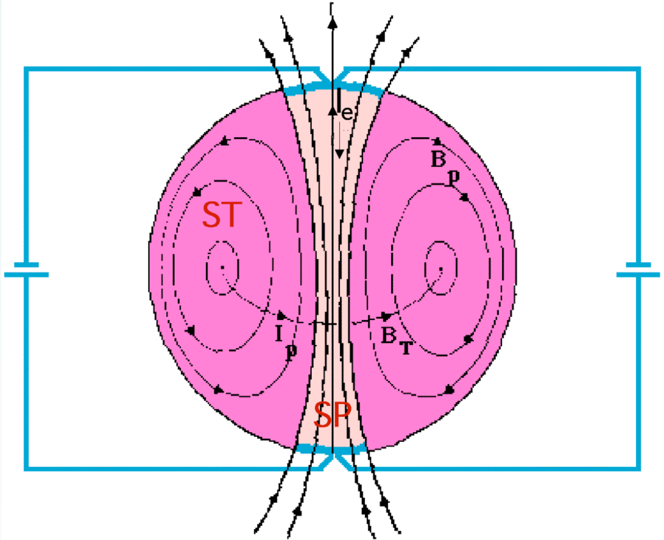
- No space for central solenoid (Current Drive requirement more severe)
- No neutrons shield for central stack (no superconductor/high dissipation)

Intriguing possibility ⇒ substitute central rod with Screw Pinch plasma ($I_{TF} \rightarrow I_e$)

Potentially two problems solved:

- Simply connected configuration (no conductors inside)
- I_p driven by I_e (Helicity Injection from SP to ST)

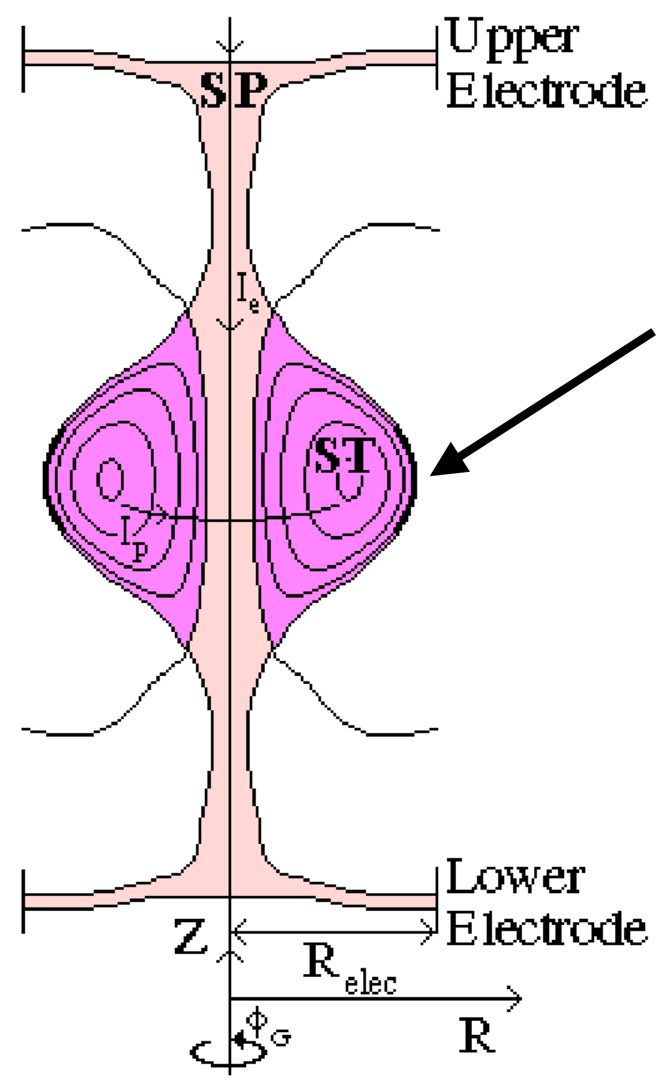
Flux Core Spheromak (FCS) →



Theory: Taylor & Turner, Nucl. Fusion 29, 219 (1989)
Experiment: TS-3; N. Amemiya, et al., JPSJ 63, 1552 (1993)

But Flux Core Spheromaks are:

- injected by plasma guns
- formed by ~10 kV voltage on electrodes
- high pressure prefilled
- with ST safety factor $q \lesssim 1$



***New configuration proposed*:**

PROTO-SPHERA

"Flux Core Spherical Tokamak" (FCST), rather than FCS

Disk-shaped electrode driven Screw Pinch plasma (SP)

Prolated low aspect ratio ST ($A=R/a \geq 1.2$, $\kappa=b/a \sim 2.3$)
to get a Tokamak-like safety factor ($q_0 \geq 1$, $q_{edge} \sim 3$)

SP electrode current	$I_e=60$ kA
ST toroidal current	$I_p=120 \div 240$ kA
ST diameter	$R_{sph}=0.7$ m

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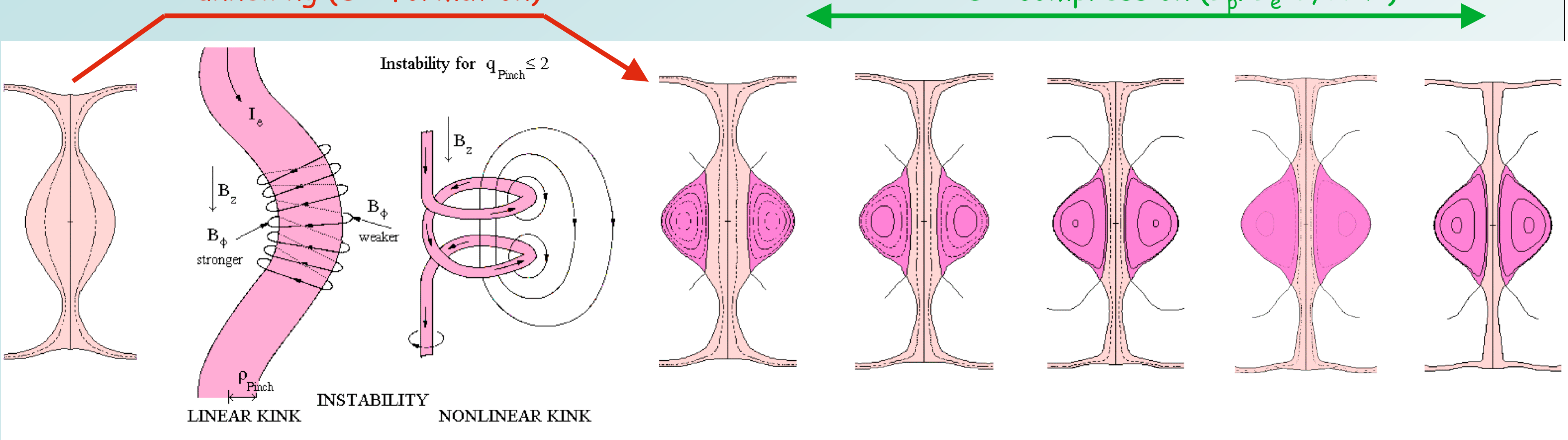
Stability should be improved and helicity drive may be less disruptive than in conventional Flux-Core-Spheromak

PROTO-SPHERA formation follows TS-3 scheme (SP kink instability)

Tunnelling (ST formation)

ST compression (I_p/I_e ↑, A ↓)



T0
I_e=8.5 kA

I_e 8.5→60 kA

T3
I_p=30 kA
A=1.8

T4
I_p=60 kA
A=1.5

T5
I_p=120 kA
A=1.3

T6
I_p=180 kA
A=1.25

TF
I_p=240 kA
A=1.2

- I_p/I_e ratio crucial parameter (strong energy dissipation in SP)
- MHD equilibria computed both with *monotonic (peaked pressure)* as well as *reversal safety factor profiles (flat pressure, μ parameterized)*

Some level of low n resistive instability needed (reconnections to inject helicity from SP to ST)

but

SP+ST must be ideally stable at any time slice

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Ideal MHD analisys to assess I_p/I_e & β limits

Characteristics of the free-boundary Ideal MHD Stability code

Plasma extends to symmetry axis (R=0) | Open+Closed field lines | Degenerate |B|=0 & Standard X-points

Standard $\vec{\xi}$ decomposition

$$\vec{\xi} = \xi^{\psi}\vec{\mathbf{e}}_{\psi} + \eta^{\psi}\frac{\vec{\mathbf{B}}\wedge\vec{\nabla}\psi_T}{B^2} + \left(\frac{I\eta^{\psi}}{B^2} - \mu\right)\vec{\mathbf{B}}$$

$$\vec{\mathbf{e}}_{\psi} = \frac{\vec{\nabla}\psi_T}{\left|\vec{\nabla}\psi_T\right|^2} + \frac{\beta_*}{B^2}\vec{\mathbf{B}} - \frac{\gamma_*}{B^2}\left(\vec{\mathbf{B}}\wedge\vec{\nabla}\psi_T\right)$$

inappropiate

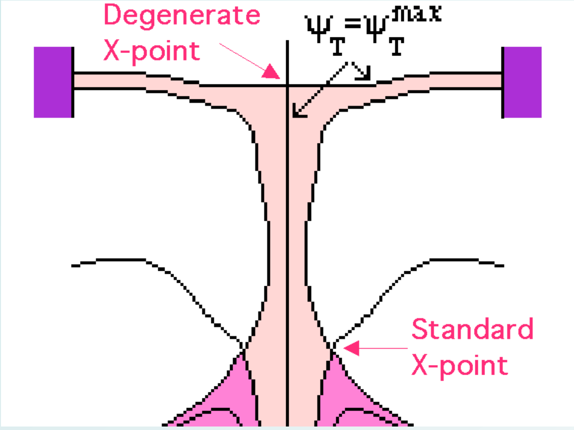
$\vec{\nabla}\psi_T \to 0$ like $\left|\vec{\nabla}\psi_T\right| \propto R$ but, after degenerate X-point (|B|=0), $\psi_T = \psi_T^{max} \neq$ R=0:

$\xi^{\psi}(\psi_T^{max})$=0 cannot be imposed

Solution: $\xi^{\psi}=\xi R^N$ $(N\geq 1)$; $\eta^{\psi}=\eta B$

$$\Downarrow$$

$$\vec{\xi} = \xi R^N\vec{\mathbf{e}}_{\psi} + \eta\frac{\vec{\mathbf{B}}\wedge\vec{\nabla}\psi_T}{B} + \left(\frac{I\eta}{B} - \mu\right)\vec{\mathbf{B}}$$



Fourier analysis of:

$$\xi = \sum_{\ell}\xi_{\ell}(\psi_T)\sin(m_{\ell}\theta - n\phi)$$

$$\eta = \sum_{\ell}\eta_{\ell}(\psi_T)\cos(m_{\ell}\theta - n\phi)$$

$$\mu = \sum_{\ell}\mu_{\ell}(\psi_T)\cos(m_{\ell}\theta - n\phi)$$

Normal Mode equation $\delta\vec{\vec{W}}\cdot|\vec{x}\rangle = \omega^2\delta\vec{\vec{K}}\cdot|\vec{x}\rangle$

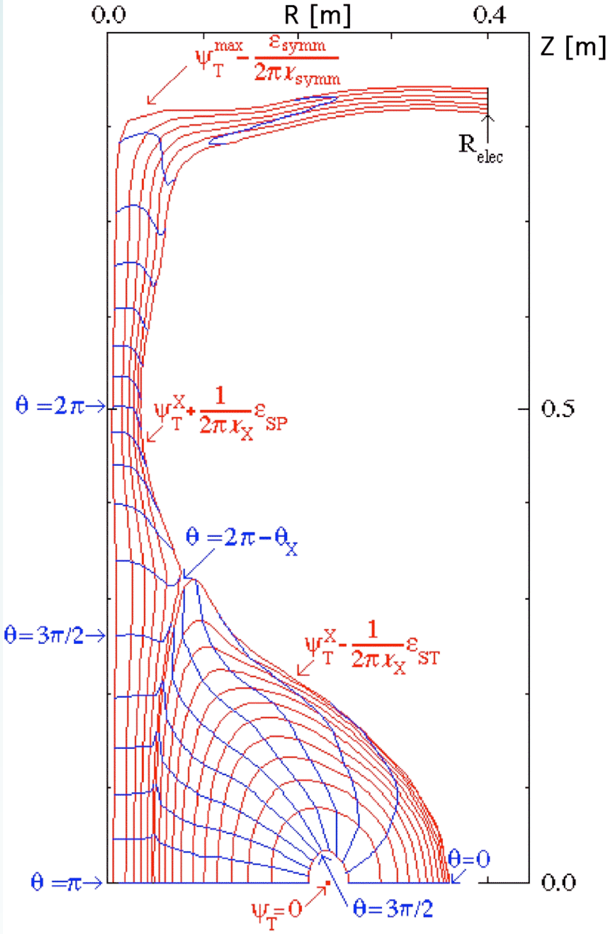
$$|\vec{x}\rangle \equiv (\xi_{\ell}^j, \eta_{\ell}^j, \mu_{\ell}^j)$$

solved by 1D finite element method

$\delta\vec{\vec{K}}$ Kinetic Energy

$\delta\vec{\vec{W}} = \delta\vec{\vec{W}}_p^i + \delta\vec{\vec{W}}_p^c + \delta\vec{\vec{W}}_v$ Potential Energies

**Boozer magnetic coordinates (ψ_T,θ,φ)
joined at SP-ST interface
to guarantee ξ^{ψ} continuity**

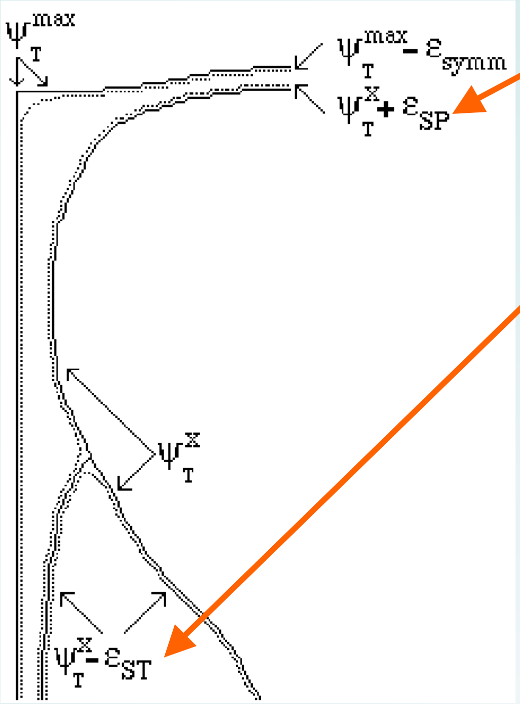


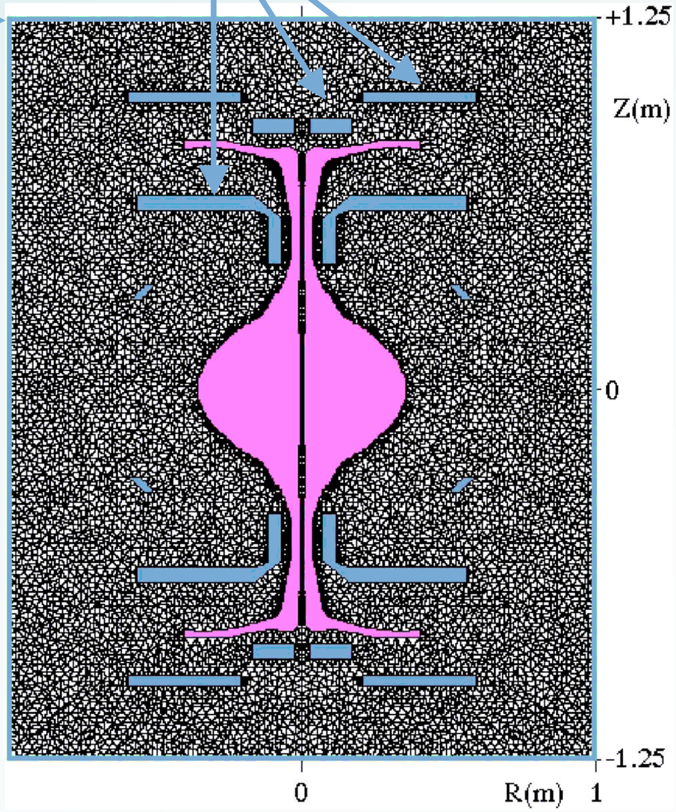
Vacuum term computation (multiple plasma boundaries)

Using the perturbed scalar magnetic potential Φ, the vacuum contribution is expressed as an integral over the plasma surface: $\delta W_v = \frac{\mu_0}{2} \oiint_{S_\psi} \Phi \vec{\nabla}\Phi \cdot d\vec{S}_\psi$

Computation method for δW_v based on 2D finite element: it take into account any stabilizing conductors (vacuum vessel & PF coil casings)

Vacuum contribution to potential energy not only affect $\psi_T = \psi_T^{max}$: contribution even to the radial mesh points $\psi_T = \psi_T^X - \varepsilon_{ST}$ and $\psi_T^X + \varepsilon_{SP}$





Stability results for time slices T3 & T4

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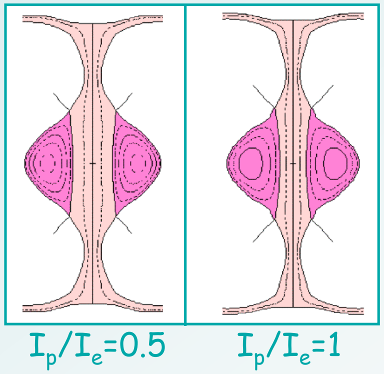


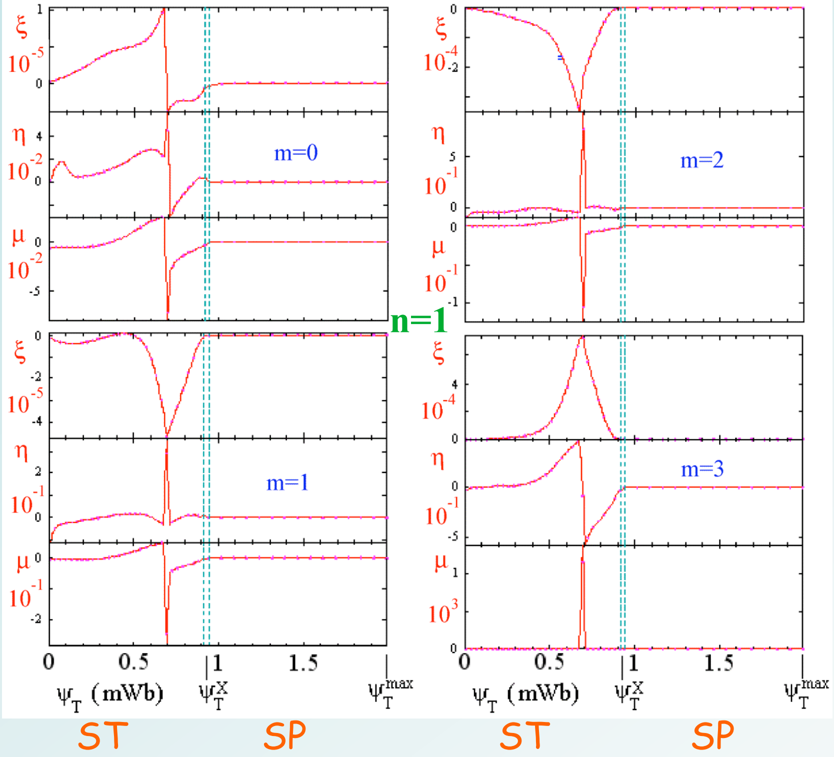
Both times ideally stable (ω^2/ω_A^2 >0) for n=1,2,3
(q profile monotonic & *shear reversed*)

→ Oscillations on resonant surfaces

Equilibrium parameters:

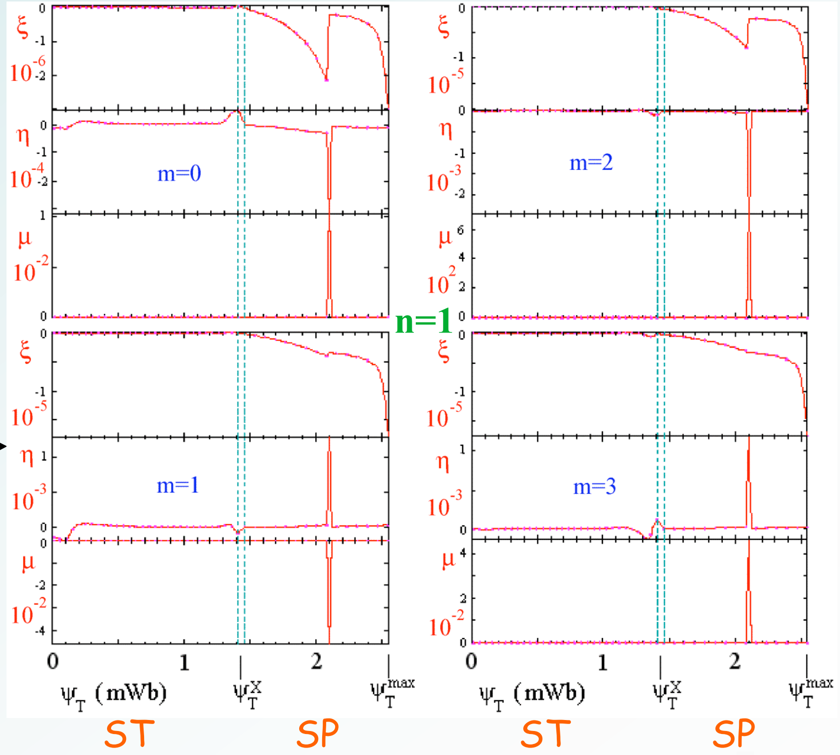
T3: I_p=30 kA, A=1.8(*1.9*), κ=2.2(*2.4*), q_{95}=3.4(*3.3*), q_0=1.2(*2.1*), β_p=1.15 and β=22(*24*)%

T4: I_p=60 kA, A=1.5(*1.6*), κ=2.1(*2.4*), q_{95}=2.9(*3.1*), q_0=1.1(*3.1*), β_p=0.5 and β=21(*26*)%

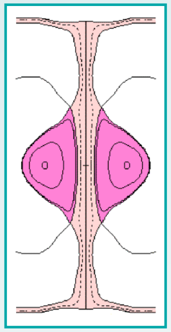


T3

T4



Stability results for time slices T5



$I_p/I_e=2$

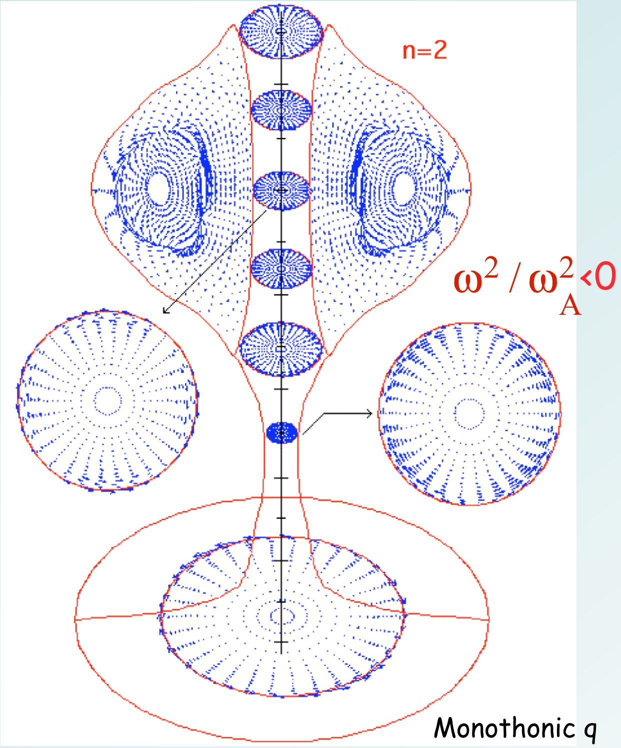
With "reference" $\beta_p=0.3 \Rightarrow$ n=1 stable, n=2 & 3 unstable

Equilibrium parameters:

T5 (monothonic q): I_p=120 kA, A=1.3, κ=2.1, q_{95}=2.8, q_0=1.0, β=25%

T5 (reversed q): I_p=120 kA, A=1.4, κ=2.5, q_{95}=3.5, q_0=2.8, β=33%

ST drives instability: only perturbed motion on the ST/SP interface



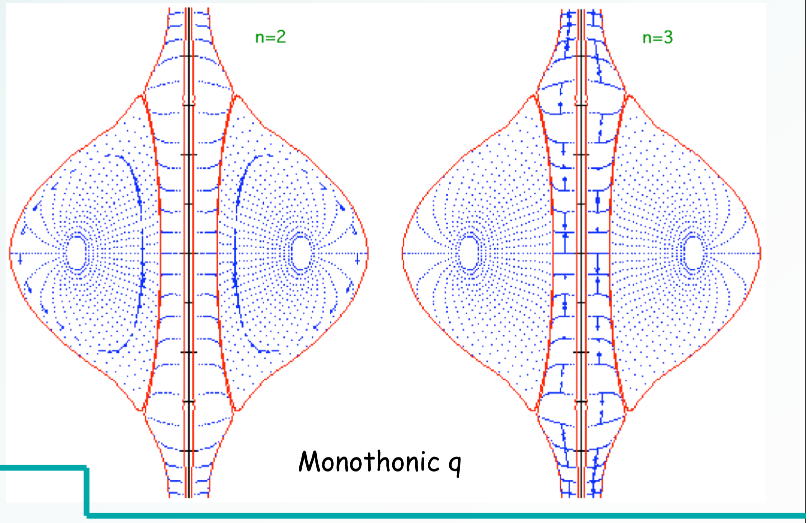
Stability restored with β_p=0.2

Equilibrium parameters:

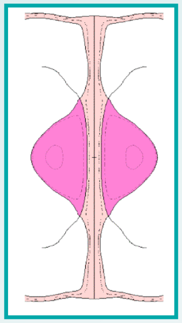
T5 (monothonic q): I_p=120 kA, A=1.4, κ=2.2, q_{95}=2.7, q_0=1.2, β=16%

T5 (reversed q): I_p=120 kA, A=1.4, κ=2.4, q_{95}=2.7, q_0=1.9, β=18%

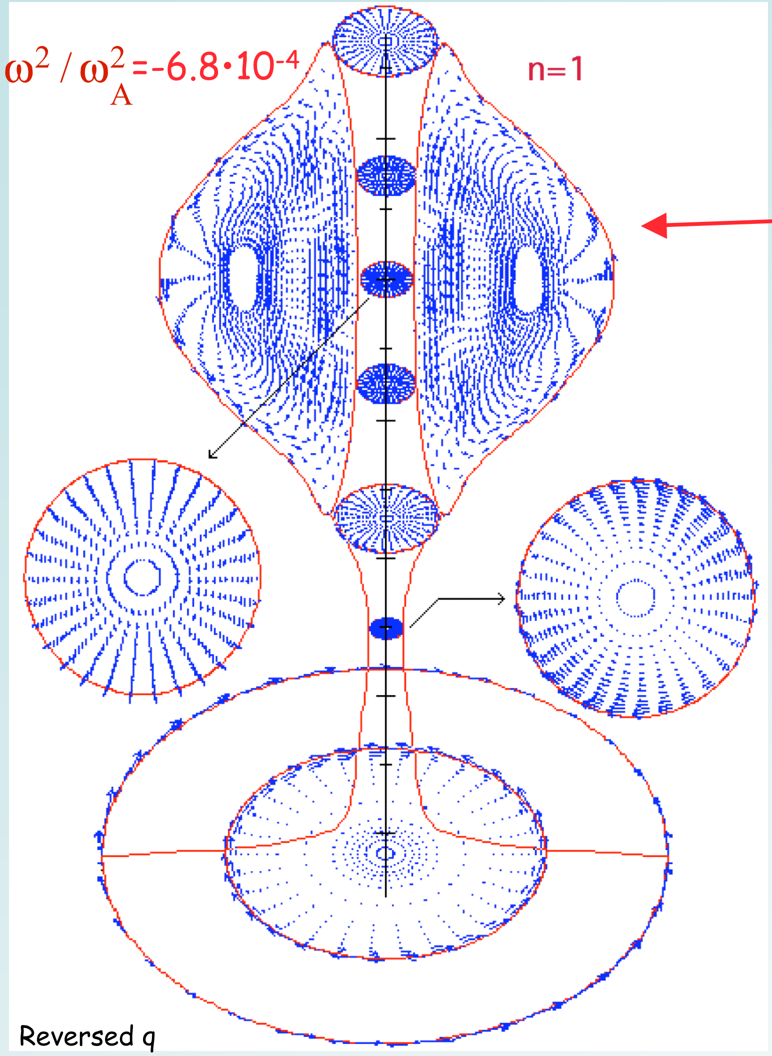
Stable oscillation on the resonant q surfaces



Stability results for time slices T6



Screw Pinch drives instability:
ST tilt induced by SP kink



With “reference” $\beta_p=0.225$:

Monothonic q → n=1 stable, n=2 & 3 unstable

Equilibrium parameters:

T6: I_p=180 kA, A=1.25, κ=2.2, q_{95}=2.6, q_0=0.96, β=25%

Reversed q → n=1, n=2 & 3 unstable

Equilibrium parameters:

T6: I_p=180 kA, A=1.29, κ=2.5, q_{95}=3.2, q_0=2.3, β=33%

Weak effect of vacuum term:
for n=1 ω/ω_A^2 $-6.8\cdot10^{-4} \rightarrow -7\cdot10^{-4}$ if PF coil casings suppressed

With “lower” $\beta_p=0.15$:

Monothonic q → n=1,2,3 stable

Equilibrium parameters:

T6: I_p=180 kA, A=1.29, κ=2.2, q_{95}=2.5, q_0=1.12, β=15%

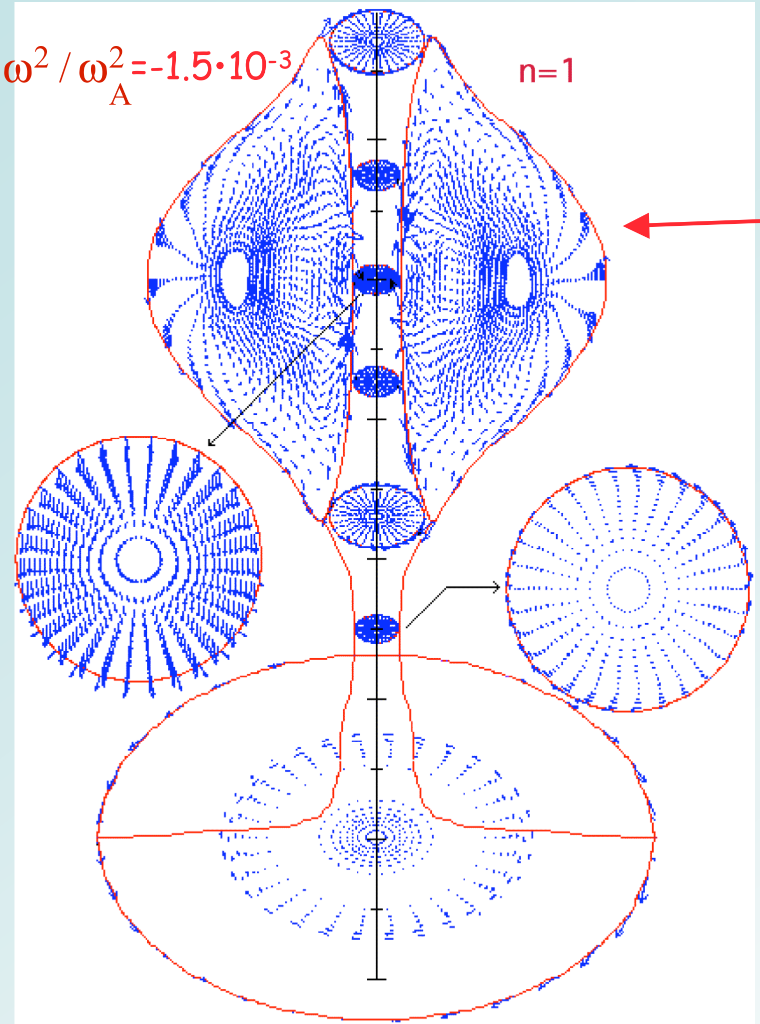
Reversed q → n=1,2,3 stable

Equilibrium parameters:

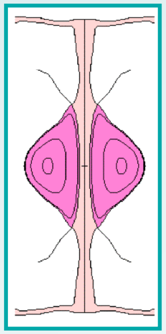
T6: I_p=180 kA, A=1.32, κ=2.5, q_{95}=2.5, q_0=1.83, β=19%

Stability results for time slices TF

Screw Pinch drives instability:
ST tilt induced by SP kink
(kink more extended with respect to T6)



Reversed q



$I_p/I_e=4$

With “reference” $\beta_p=0.225$:

Monothonic q → n=1 stable, n=2 & 3 unstable

Equilibrium parameters:

TF: I_p=240 kA, A=1.22, κ=2.2, q_{95}=2.65, q_0=1.04, β=19%

Reversed q → n=1 & 2 unstable, n=3 stable

Equilibrium parameters:

TF: I_p=240 kA, A=1.24, κ=2.4, q_{95}=2.89, q_0=1.82, β=23%

With “lower” $\beta_p=0.12$

Monothonic q → n=1,2,3 stable

Equilibrium parameters:

TF: I_p=240 kA, A=1.24, κ=2.3, q_{95}=2.55, q_0=1.13, β=16%

With further lowered $\beta_p=0.10$

Reversed q → n=1,2,3 stable

Equilibrium parameters:

TF: I_p=240 kA, A=1.26, κ=2.4, q_{95}=2.55, q_0=1.64, β=14%

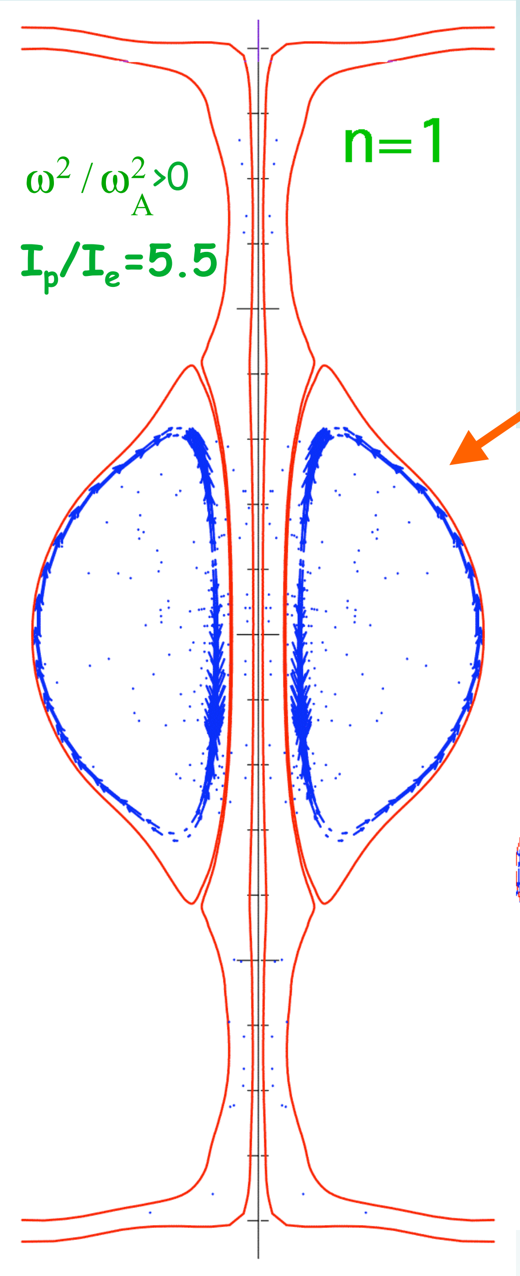
Reversed shear profiles less effective in stabilizing SP kink

Effect of ST elongation on I_p/I_e limits

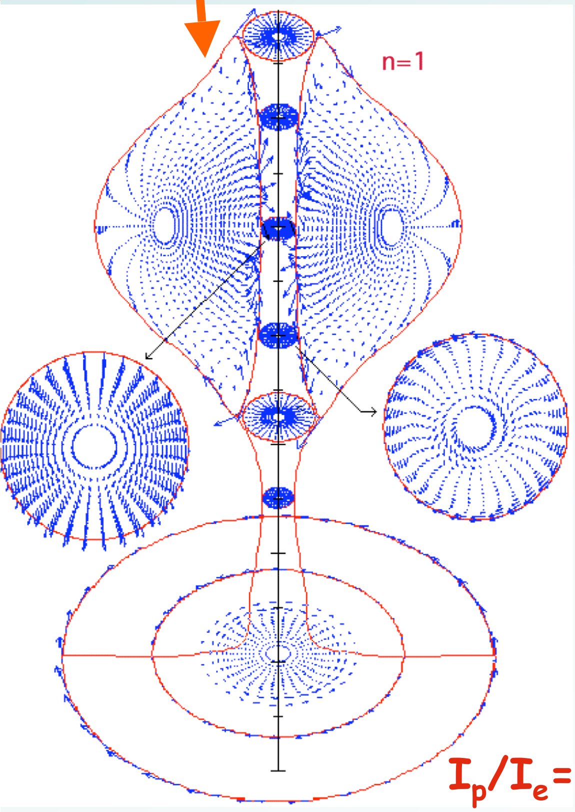
SPHERA
(2xPROTO-SPHERA)

Stable for n=1,2,3

Equilibrium parameters:
I_p=2 MA
I_e=365 kA
A=1.23
κ=3.0
q_{95}=2.99, q_0=1.42
β=13%
(*monothonic q*)



Increasing κ allow for higher I_p/I_e ratio



I_p/I_e=5

$\omega^2 / \omega_A^2 = -4.4 \cdot 10^{-2}$

PROTO-SPHERA

Unstable for n=1
Stable for n=2 & 3

Equilibrium parameters:
I_p=300 kA
I_e=60 kA
A=1.20
κ=2.3
q_{95}=2.7, q_0=1.15
β=15%
(*monothonic q*)

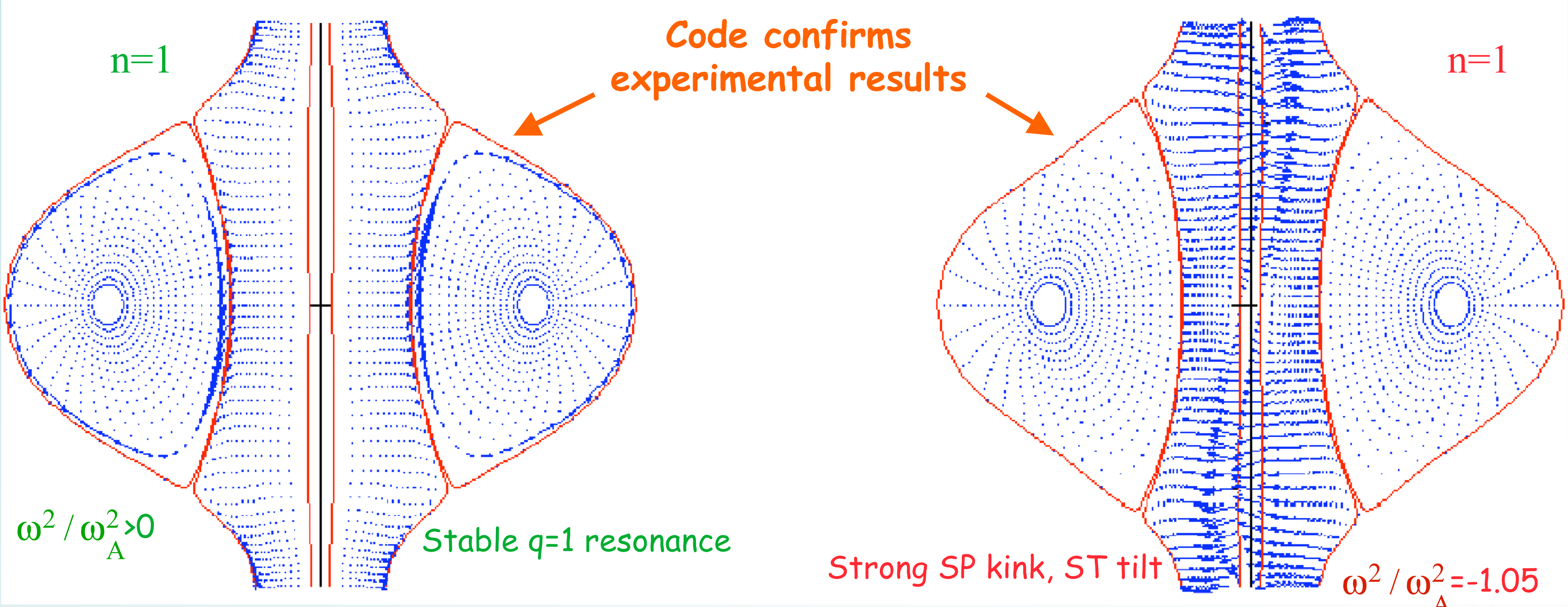
Comparison with TS-3 (1)

Tokio Device had:

- Simple “linear” electrodes
- Oblated Spherical Torus
- q<1 all over the ST (Spheromak)

I_p=50 kA, I_e=40 kA
I_p/I_e~1 , A~1.8

I_p=100 kA, I_e=40 kA
I_p/I_e~2 , A~1.5



n=1

Code confirms experimental results

n=1

$\omega^2/\omega_A^2>0$

Stable q=1 resonance

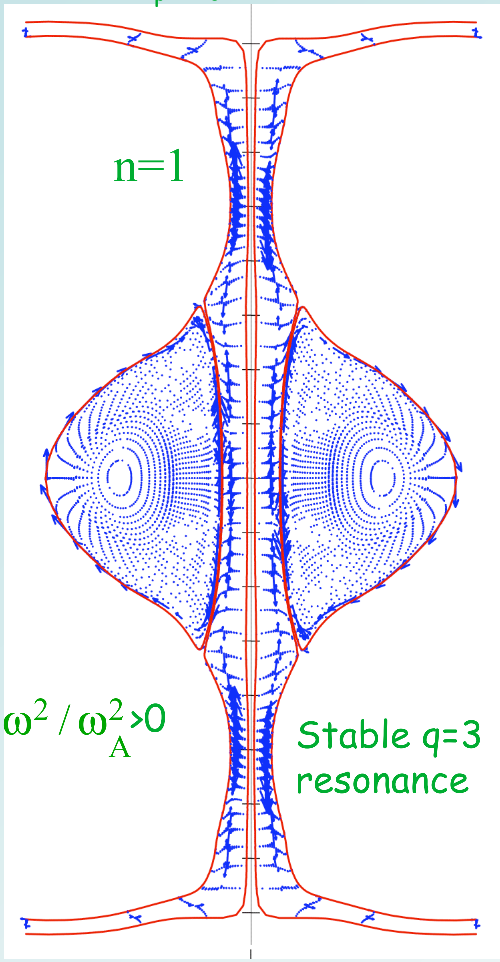
Strong SP kink, ST tilt

$\omega^2/\omega_A^2=-1.05$

Comparison with TS-3 (2)

(effect of the SP shape)

T5 (β=16%)
I_p=120 kA, I_e=60 kA
I_p/I_e=2 , A~1.3



T5-*cut* (β=16%)
I_p=120 kA, I_e=60 kA
I_p/I_e=2 , A~1.3

If the fully stable T5 is "artificially cut" to remove degenerate X-points as well as disk-shaped SP

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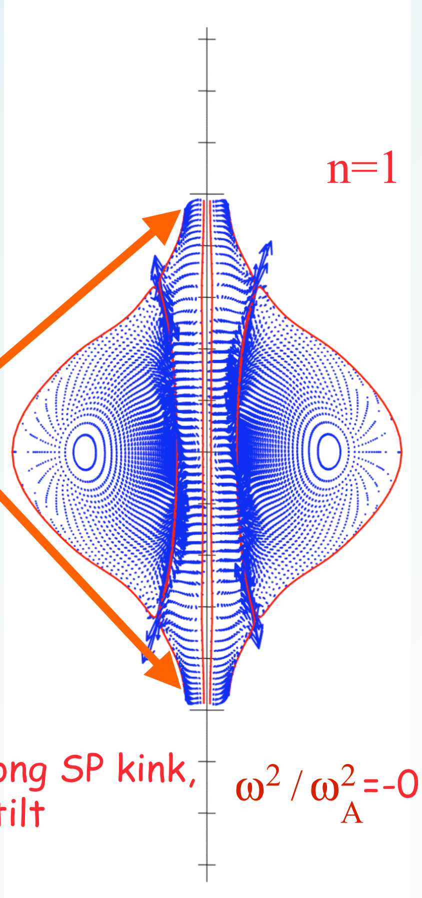
Strong n=1 instability appears, despite higher κ & q_{95}



Strong SP kink, ST tilt

ω^2 / ω_A^2=-0.17

Conclusions

Ideal MHD stability results for PROTO-SPHERA

- **PROTO-SPHERA stable at full β 21÷26% for I_p/I_e=0.5 & 1, down to 14÷16% for I_p/I_e=4 (depending upon profiles inside the ST)**
  Comparison with the conventional Spherical Tokamak with central rod:
  β_{T0}=28÷29% for I_p/I_e=0.5 to β_{T0}=72÷84% for I_p/I_e=4

- **Spherical Torus dominates instabilitiy up to $I_p/I_e \approx 3$; beyond this level of I_p/I_e, dominant instability is the SP kink (that gives rise to ST tilt motion)**

- **Spherical Torus elongation κ plays a key role in increasing I_p/I_e**

- **Comparison with TS-3 experimental results:**
  disk-shaped Screw Pinch plasma important for the configuration stability