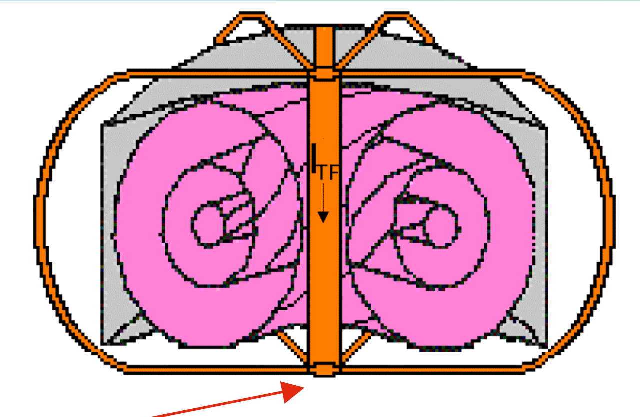
Ideal MHD Stability Boundaries of the PROTO-SPHERA Configuration

F. Alladio, A. Mancuso, P. Micozzi, F. Rogier*

Associazione Euratom-ENEA sulla Fusione, CR Frascati C.P. 65, Rome, Italy

[*]ONERA-CERT / DTIM / M2SN 2, av. Edouard Belin - BP 4025 – 31055, Toulouse, France



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:

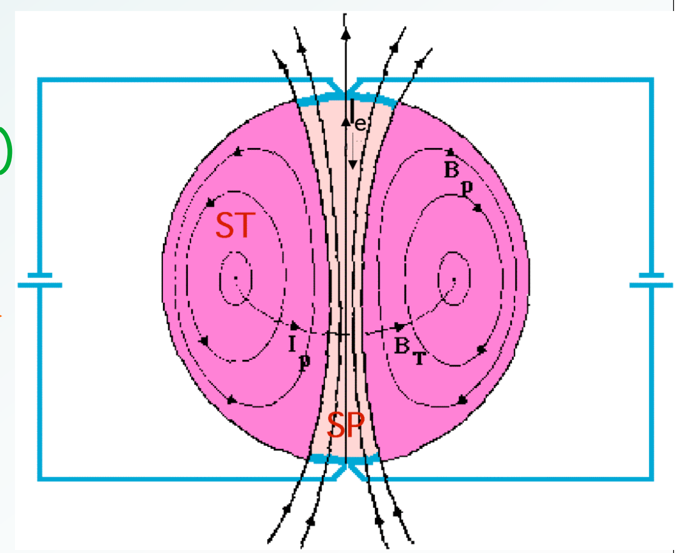
- No space for central solenoid (Current Drive requirement more severe)
- No neutrons shield for central stack (no superconductor/high dissipation)

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)

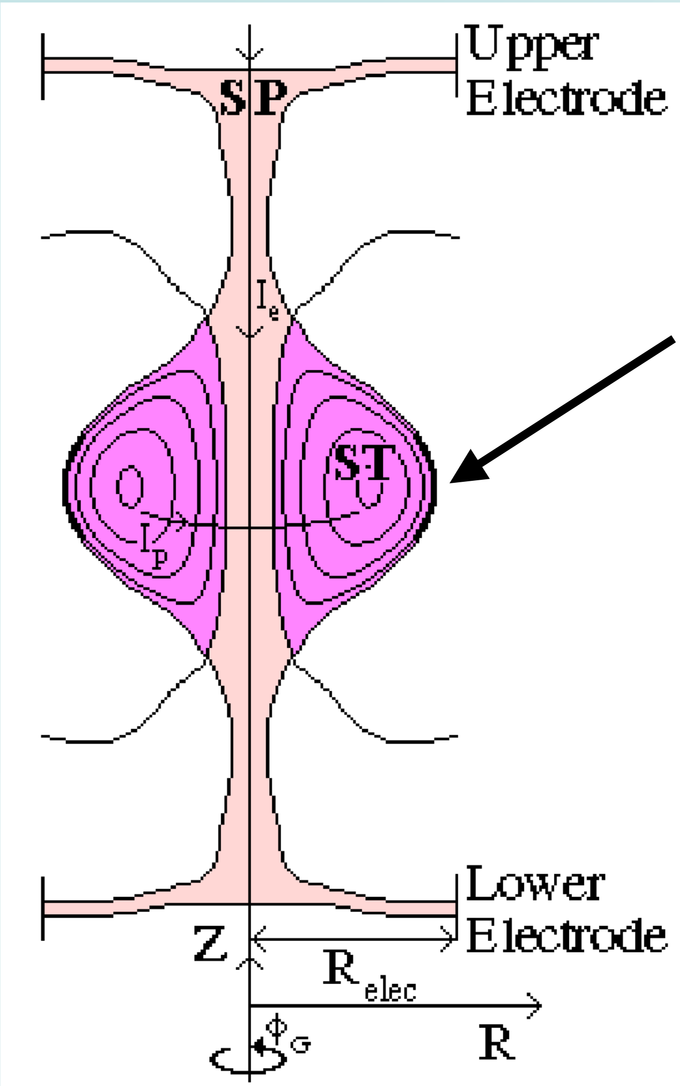
Flux Core Spheromak (FCS)



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≤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÷240 kA
ST diameter	R_{sph}=0.7 m

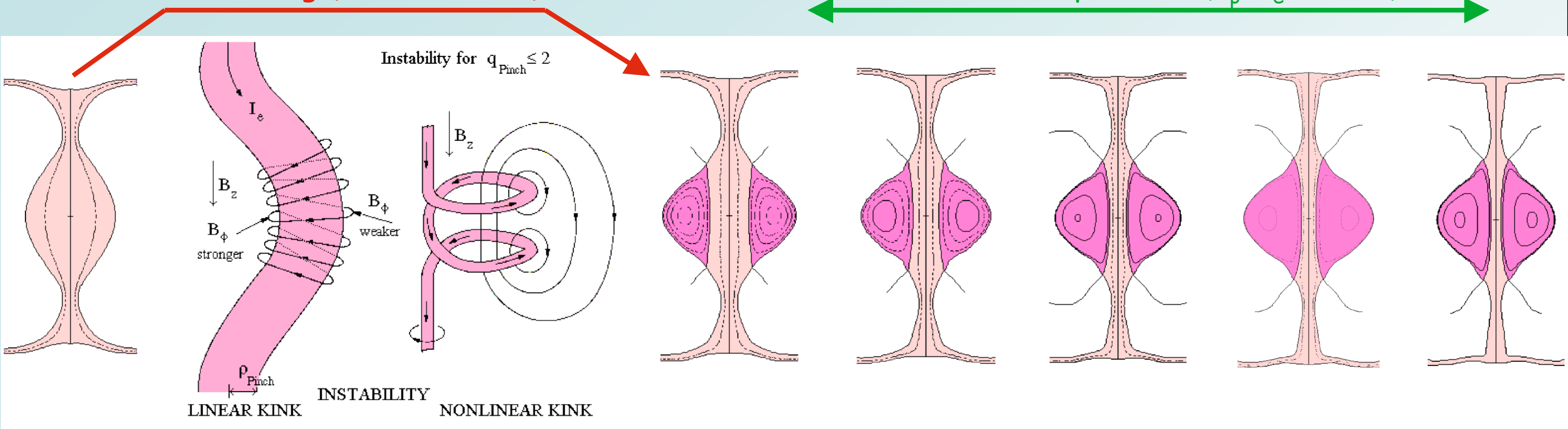
⇓

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 ($I_p/I_e \uparrow$, $A \downarrow$)



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, $\mu=\mathbf{J}\cdot\mathbf{B}/B^2$ 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

⇓

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

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

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

inappropiate

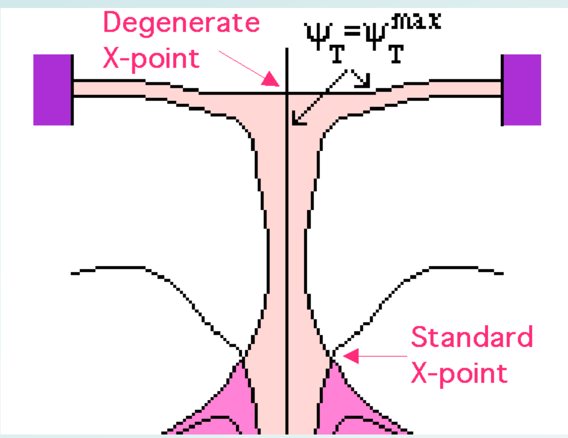
$\vec\nabla\psi_T \to 0$ like $\left|\vec\nabla\psi_T\right| \propto R$ but, after degenerate X-point (|B|=0), $\psi_T = \psi_T^{max} \neq$ R=0:

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

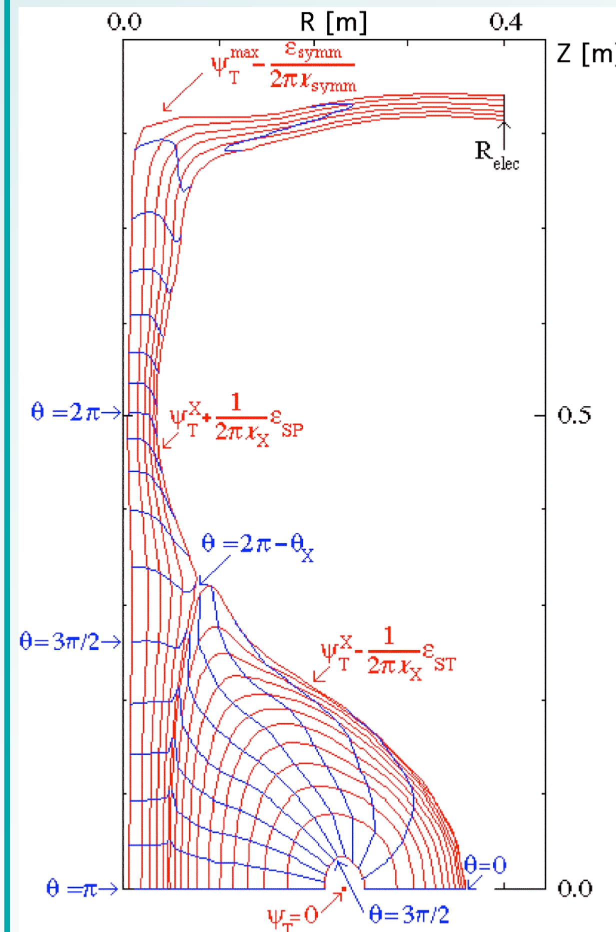
Solution: $\xi^\psi = \xi R^N$ $(N \geq 1)$; $\eta^\psi = \eta B$

⇓

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



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



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 $\delta\vec W \cdot |\vec x\rangle = \omega^2 \delta\vec K \cdot |\vec x\rangle$

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

solved by 1D finite element method

$\delta\vec K$ Kinetic Energy

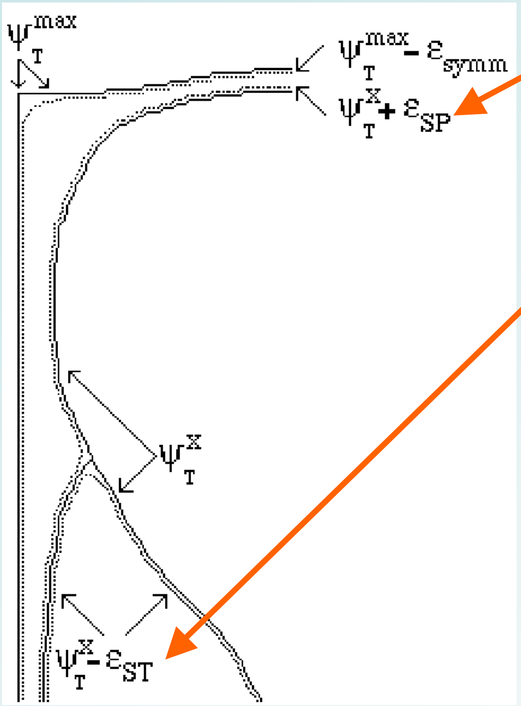
$\delta\vec W = \delta\vec W_p^i + \delta\vec W_p^c + \delta\vec W_v$ Potential Energies

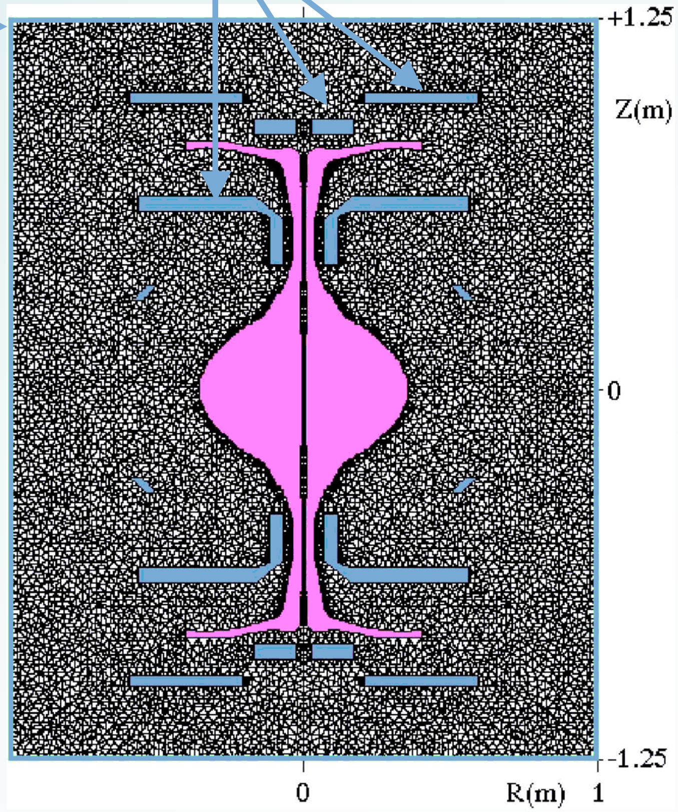
Vacuum term computation (multiple plasma boundaries)

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

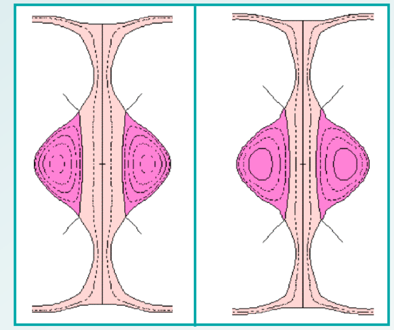
Computation method for δW_v based on 2D finite element: it take into account any stabilizing conductors (vacuum vessel & PF coil casings)

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

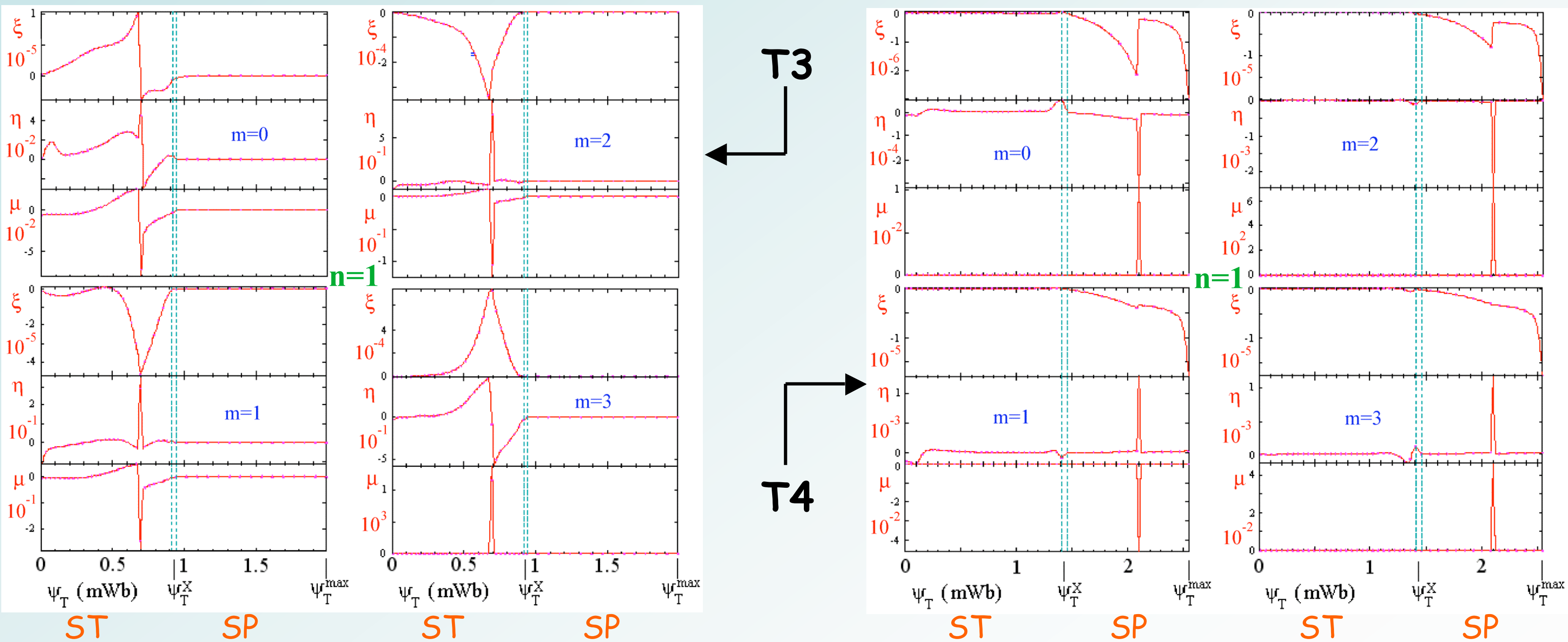


Both times ideally stable (ω^2/ω_A^2>0) for n=1,2,3 → Oscillations on resonant surfaces
(q profile monotonic & *shear reversed*)

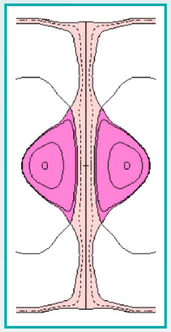
Equilibrium parameters:

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*)%



Stability results for time slices T5


$I_p/I_e=2$

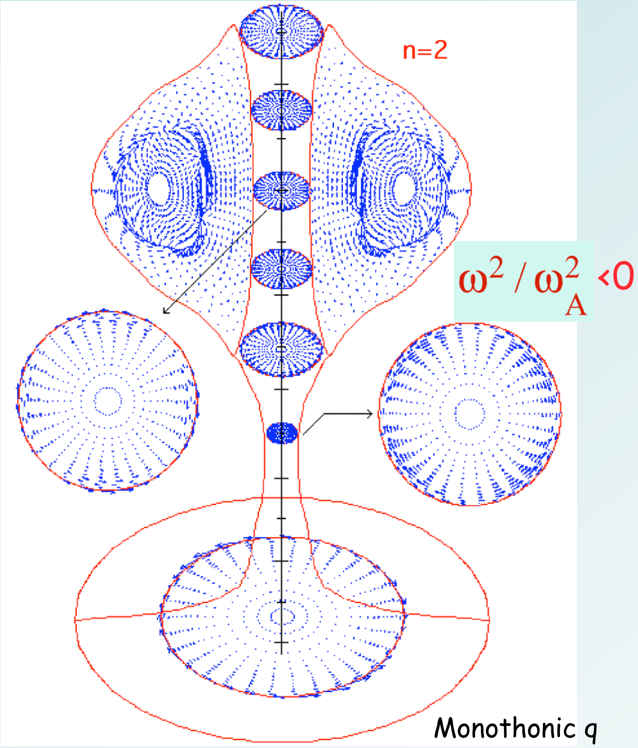
With "reference" β_p=0.3 ⇒ n=1 stable, n=2 & 3 unstable

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



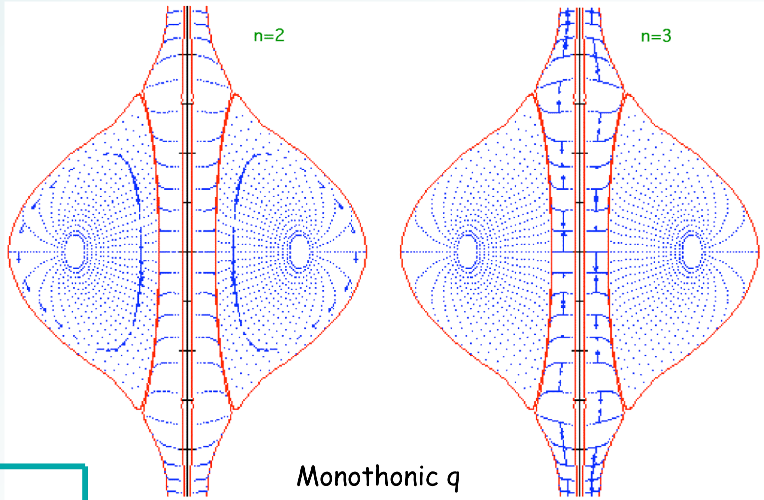
Stability restored with β_p=0.2

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%

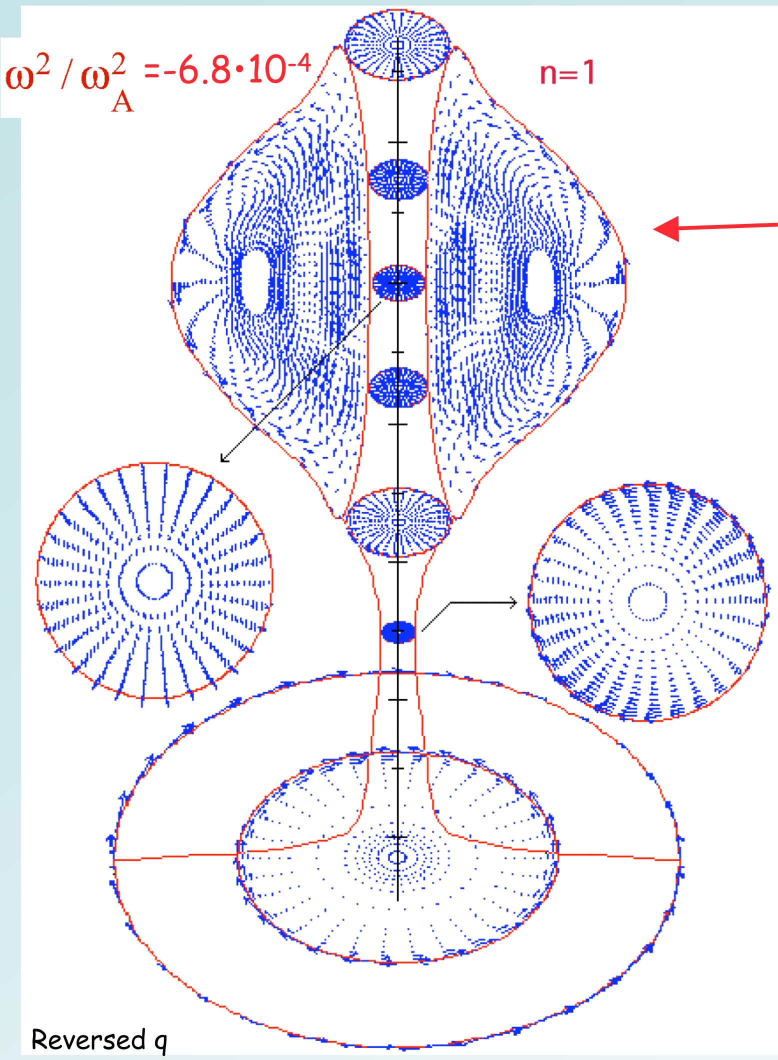
T5 (reversed q): I_p=120 kA, A=1.4, κ=2.4, q_{95}=2.7, q_0=1.9, β=18%

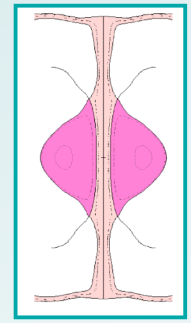
Stable oscillation on the resonant q surfaces



Stability results for time slices T6

Screw Pinch drives instability:
ST tilt induced by SP kink





I_p/I_e=3

With "reference" β_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•10^{-4} → -7•10^{-4} if PF coil casings suppressed

With "lower" β_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%

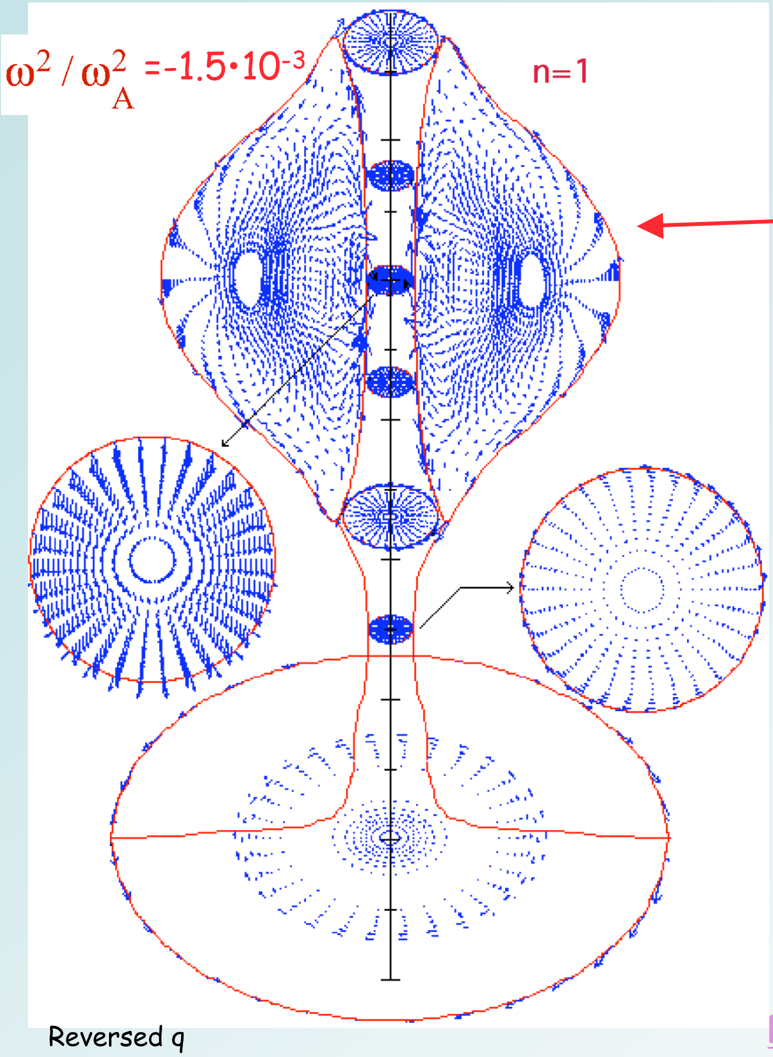
Reversed q → n=1,2,3 stable

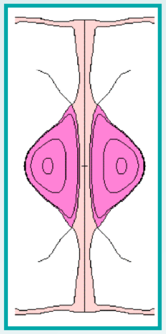
Equilibrium parameters:

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)





With "reference" β_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" β_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 β_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

PROTO-SPHERA
(b/a≈3)

Stable for n=1,2,3

Equilibrium parameters:

I_p=329 kA

I_e=60 kA

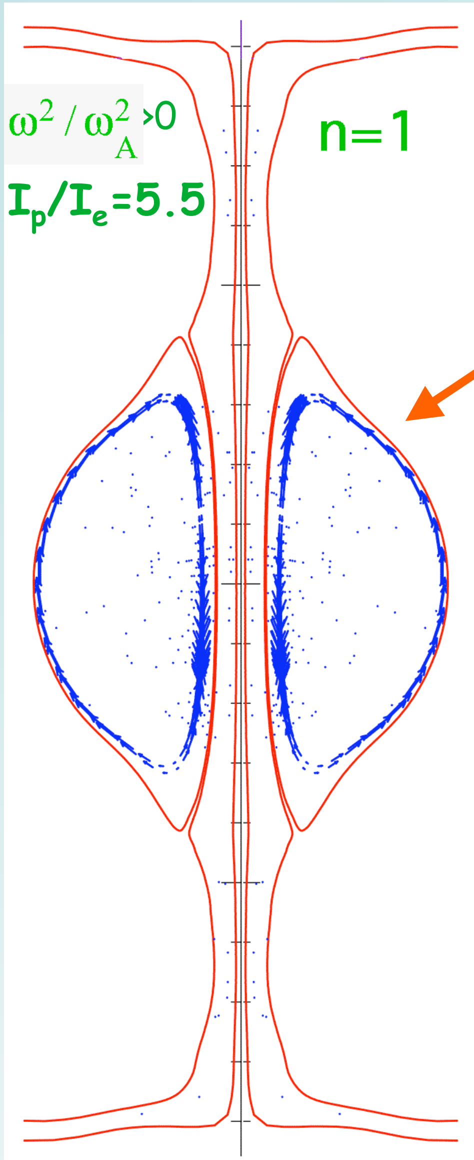
A=1.23

κ=3.0

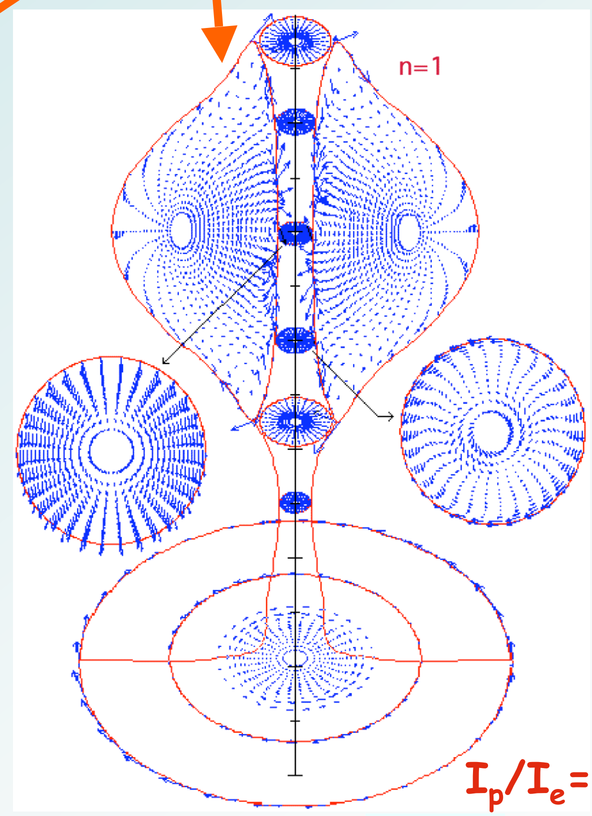
q_{95}=2.99, q_0=1.42

β=13%

(*monothonic q*)



Increasing κ allow for higher I_p/I_e ratio



ω^2/ω_A^2 =-4.4·10^{-2}

PROTO-SPHERA
(standard b/a)

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*)

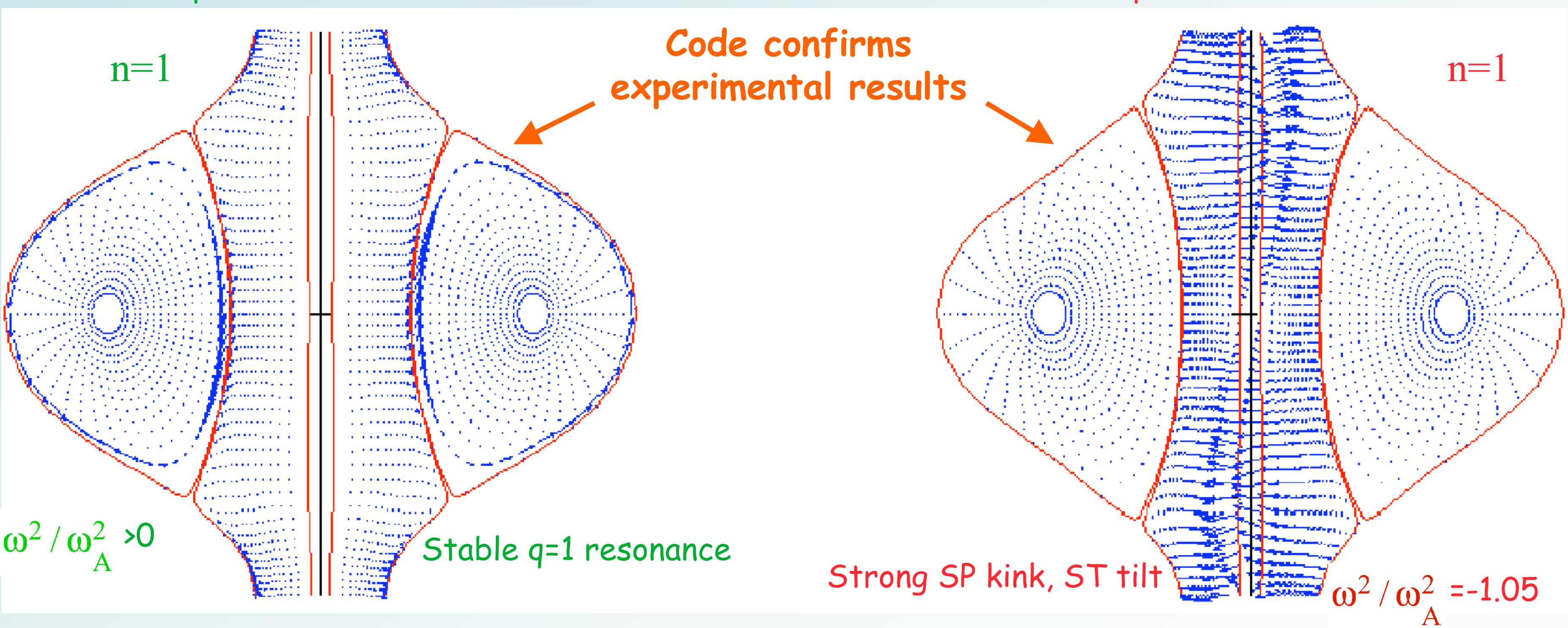
Comparison with TS-3 (1)

Tokio Device had:

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

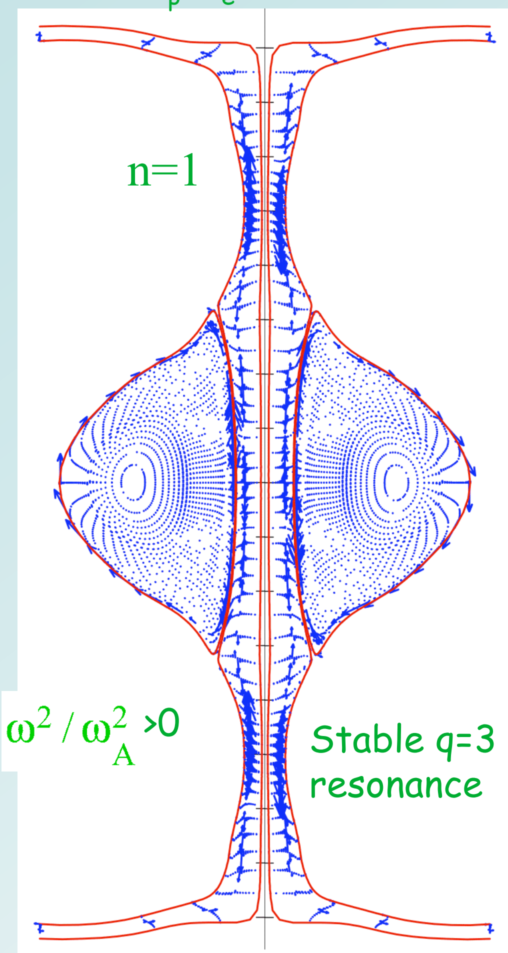
I_p=50 kA, I_e=40 kA
I_p/I_e~1 , A~1.8

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



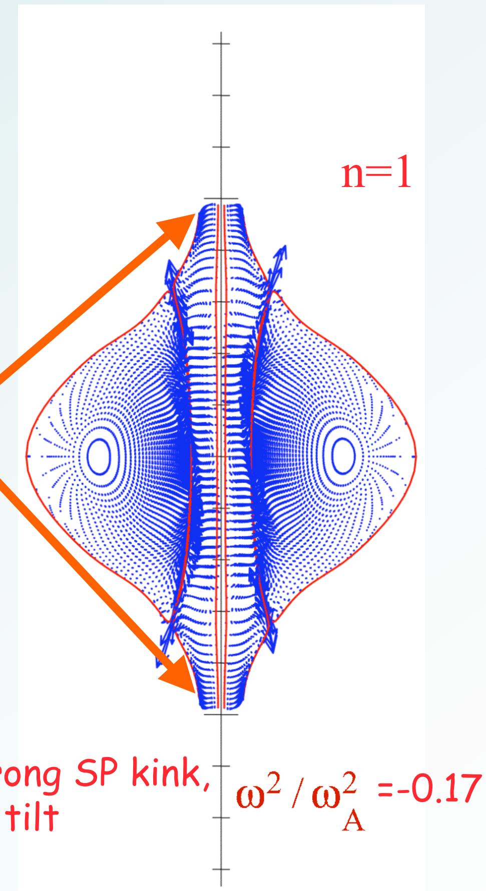
Comparison with TS-3 (2)
(effect of the SP shape)

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



If the fully stable T5 is "artificially cut"
to remove degenerate X-points
as well as disk-shaped SP
⇓
Strong n=1 instability appears,
despite higher κ & q_{95}

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



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

Ideal MHD stability of Flux Core Spherical Torus rather insensitive to internal ST profiles
⇒ configuration quite robust from an ideal point of view

Resistive instabilities behaviour is the main experimental point of PROTO-SPHERA