Progress on the ETE Spherical Tokamak
(Experimento Tokamak Esférico)

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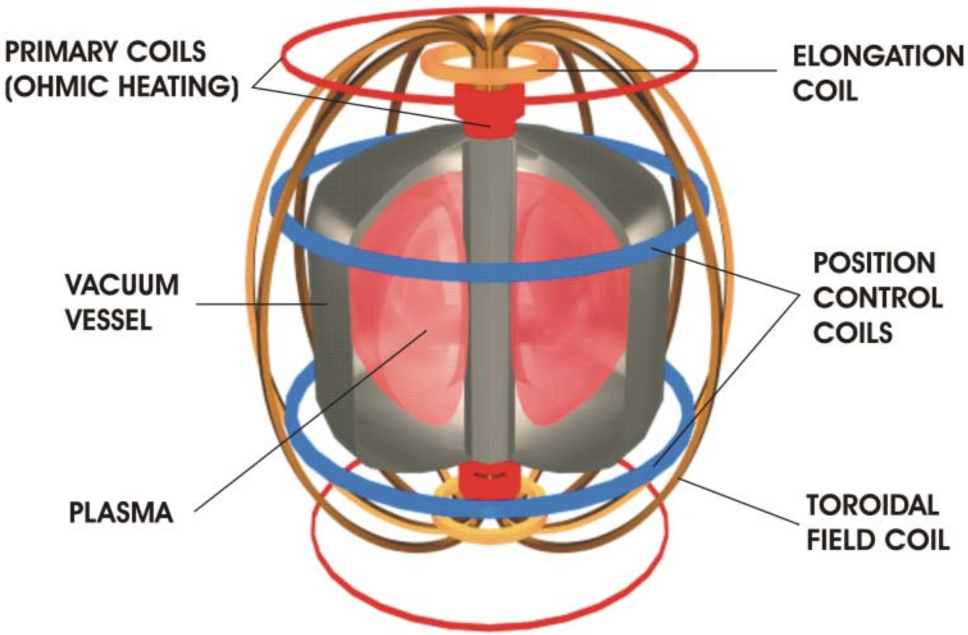
combined with the
7th Brazilian Meeting on Plasma Physics
30 November – 5 December, 2003
São Pedro, SP, Brazil

ETE Spherical Torus

General view of the Spherical Tokamak Experiment on July 2003.

ETE main parameters and objectives



Major radius R_0 = 0.3 m

Minor radius a = 0.2 m

Aspect ratio A = 1.5

Elongation κ = 1.6 – 1.8

Triangularity δ = 0.3

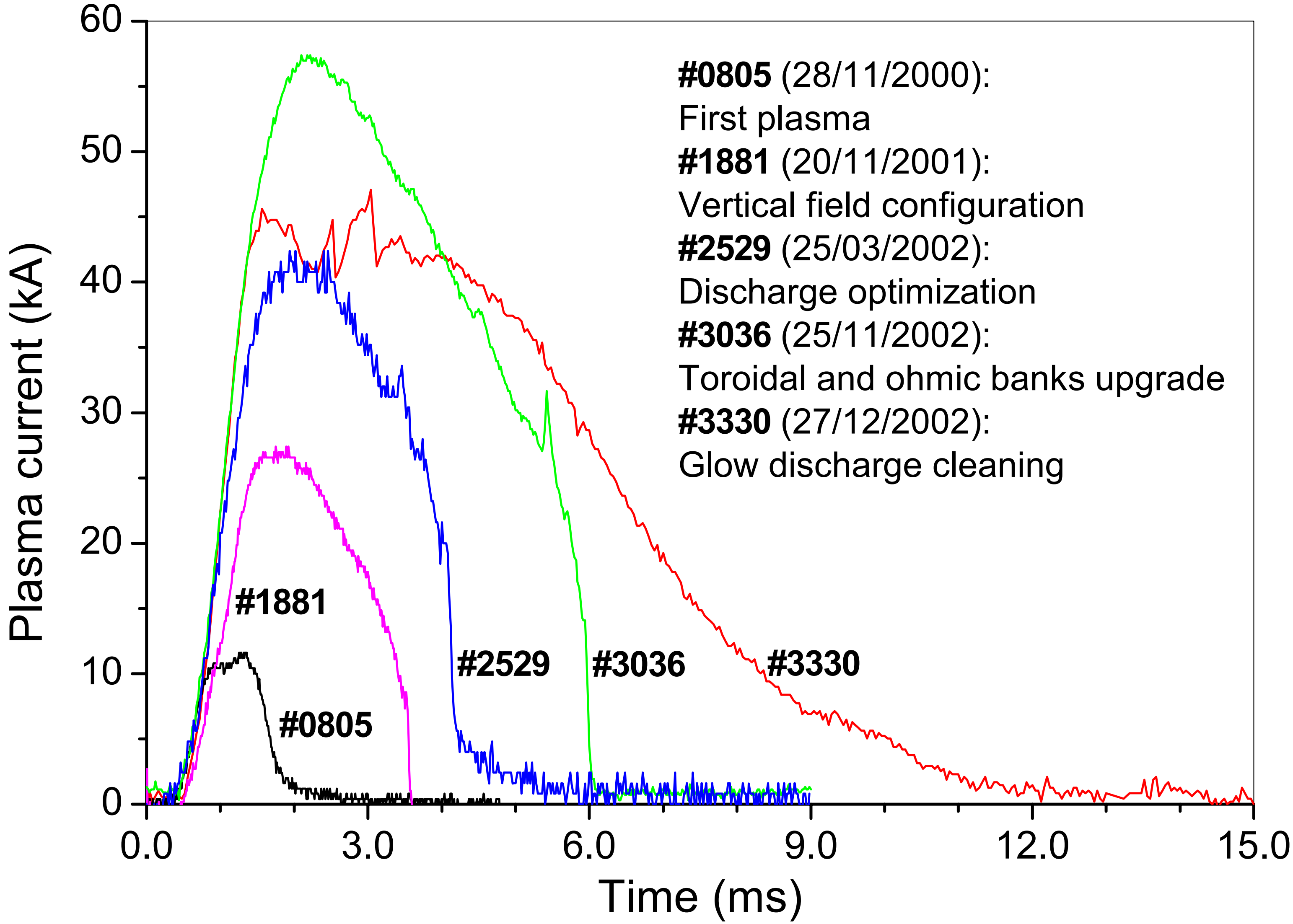
Magnetic field B_0 = 0.4 – 0.6 T (<0.8 T)

Plasma current I_p = 0.2 – 0.4 MA

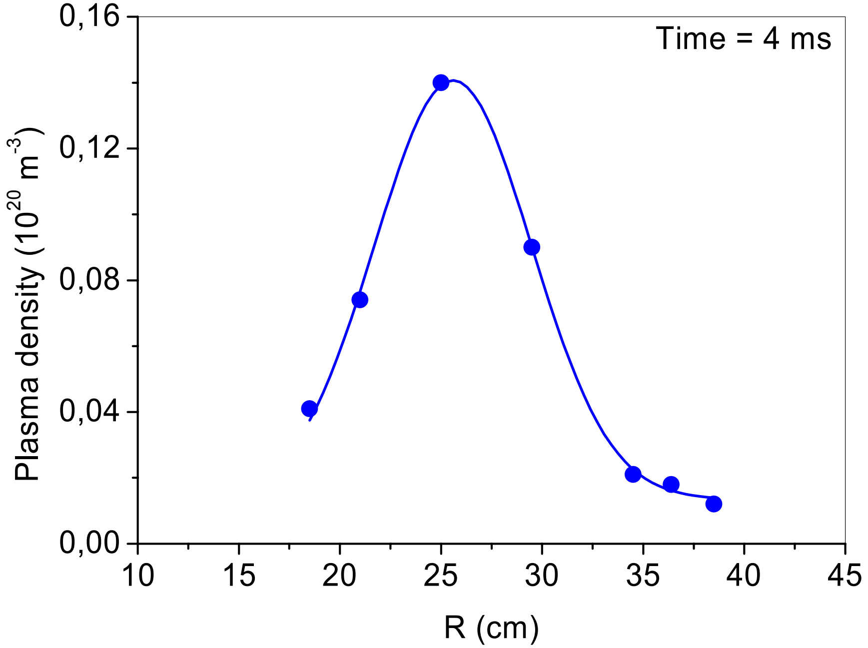
Pulse duration t < 15 – 50 ms

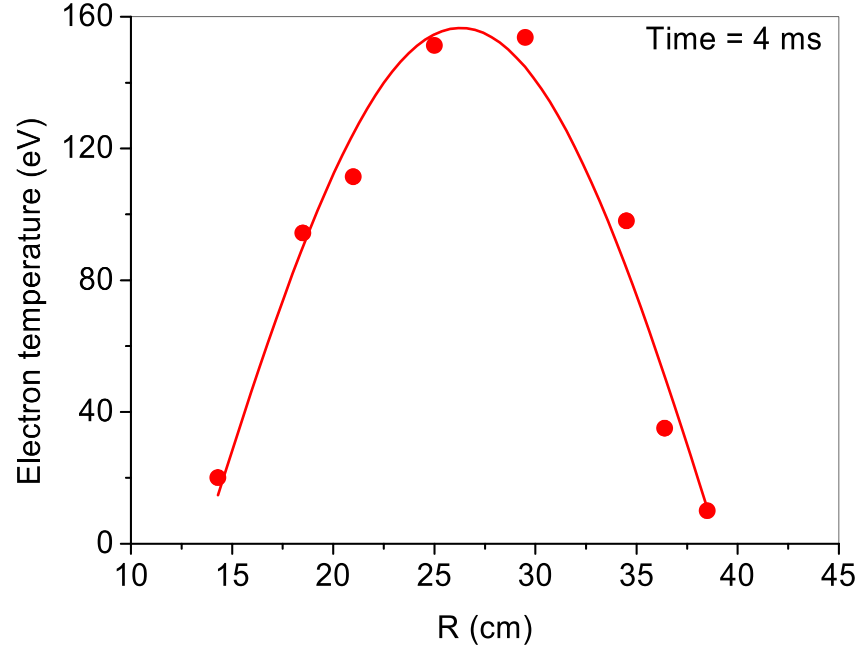
- Explore the physics of low aspect ratio.
- Investigate plasma edge conditions.
- Undertake diagnostics development.
- Develop auxiliary plasma heating methods (RF – USP).
- Follow worldwide spherical tokamak advancements.

Plasma current evolution



Present plasma parameters





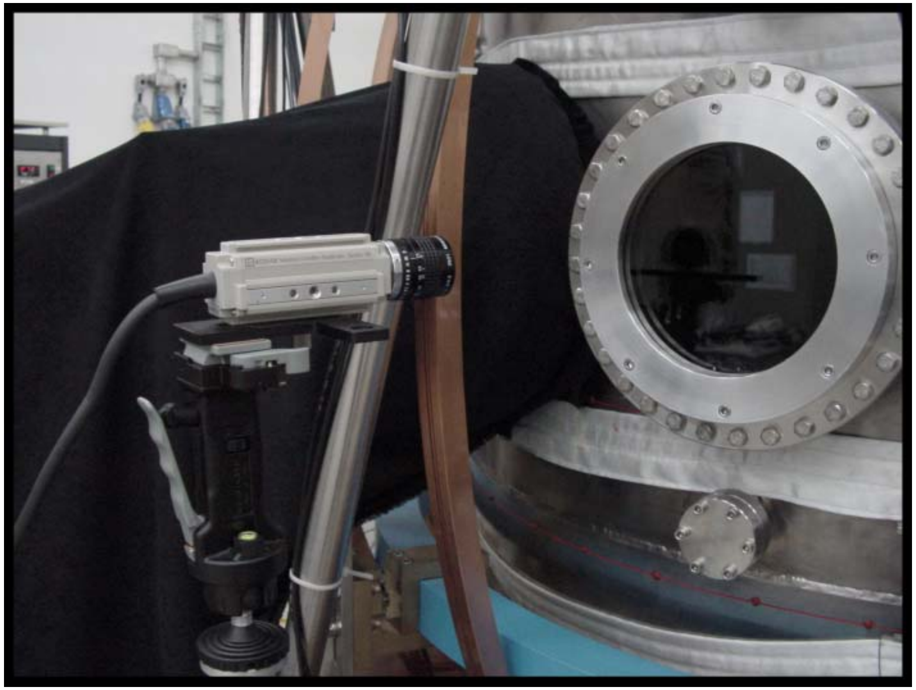
• Current ≤ 60 kA – Pulse duration ≤ 12 ms.

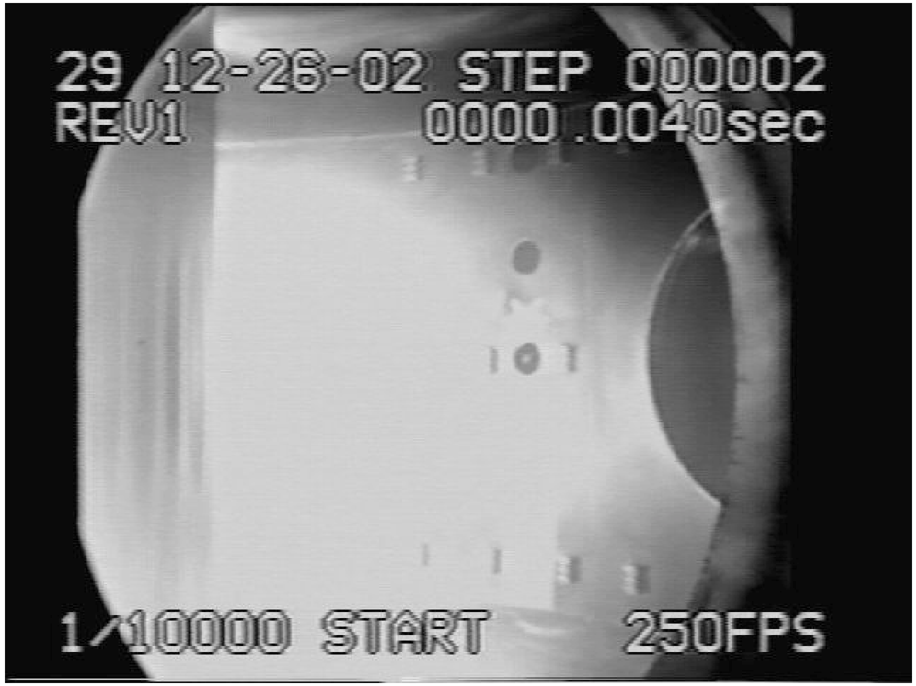
Thomson scattering measurements:

• Density ≤ 0.35×10^{20} m^3 – Temperature ≤ 160 eV.

• Peaks at $R_0 \cong 26$ cm with $A \cong 2.2$ (design values $R_0 = 30$ cm and $A = 1.5$).

Plasma pictures

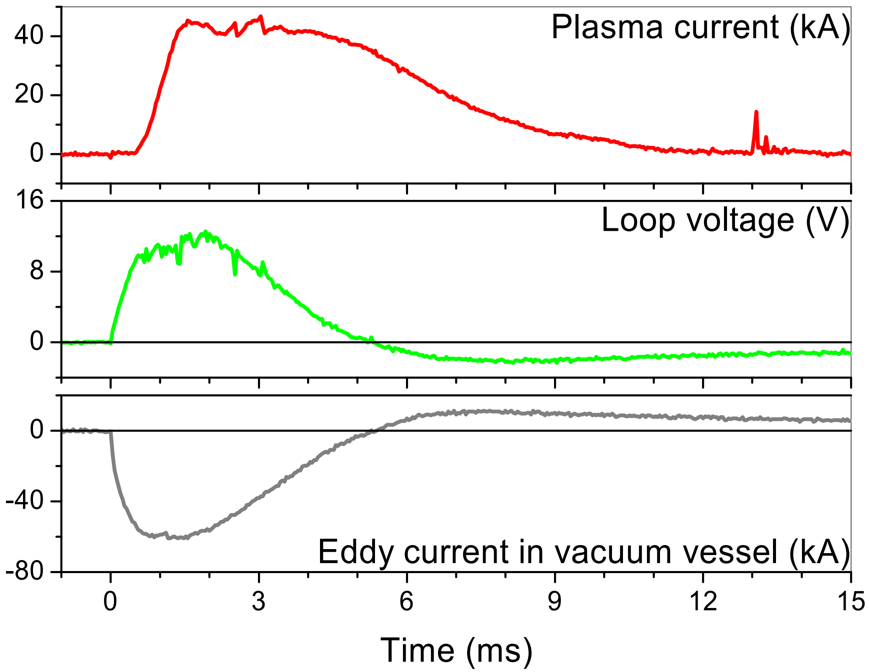


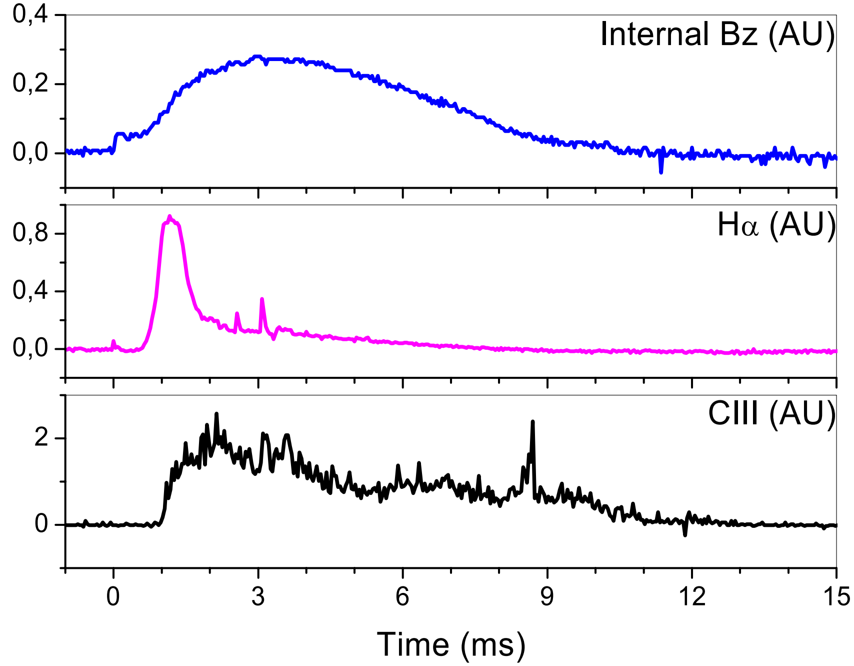


• High-speed CCD camera (1/500 to 1/20,000 frame speed).
• 30 to 500 FPS (upgrade to 10,000 FPS).

• Pictures, as well as (n_e, T_e) profiles, show plasma displaced to the inner side.
• Need improved position and shape control taking into account eddy current effects.

Typical shot

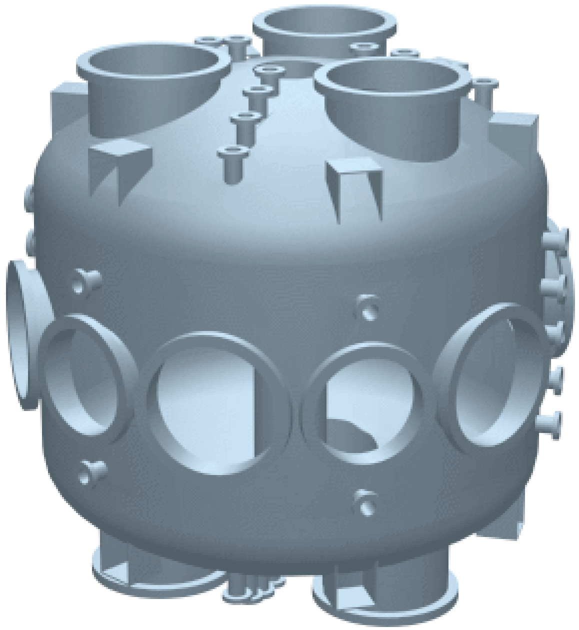


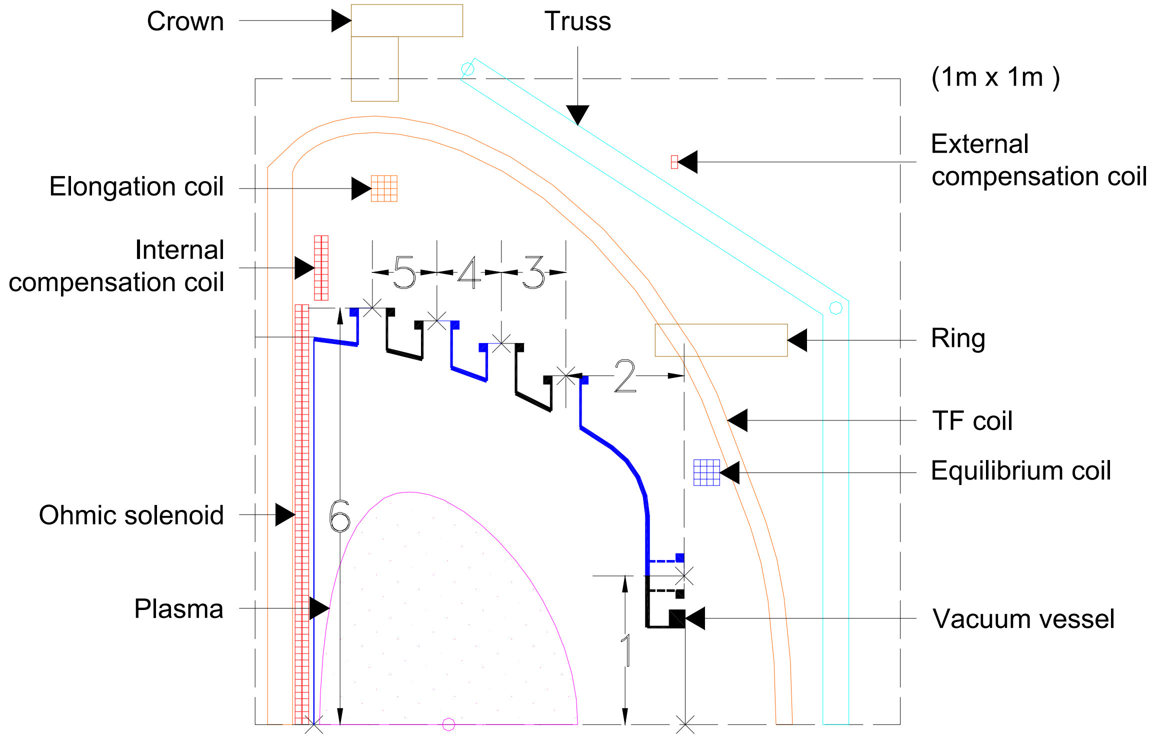


- Parameters at ~1/3 of first phase, compatible with installed capacitor banks (~1/4).

- Plasma current = 40~60 kA, Pulse duration = 8~5 ms (>12 ms with glow discharge).
- Internal reconnection events in plasma current and H_{α}.
- Current induced in vacuum chamber = ~60 kA.

Foucault currents in the vacuum vessel

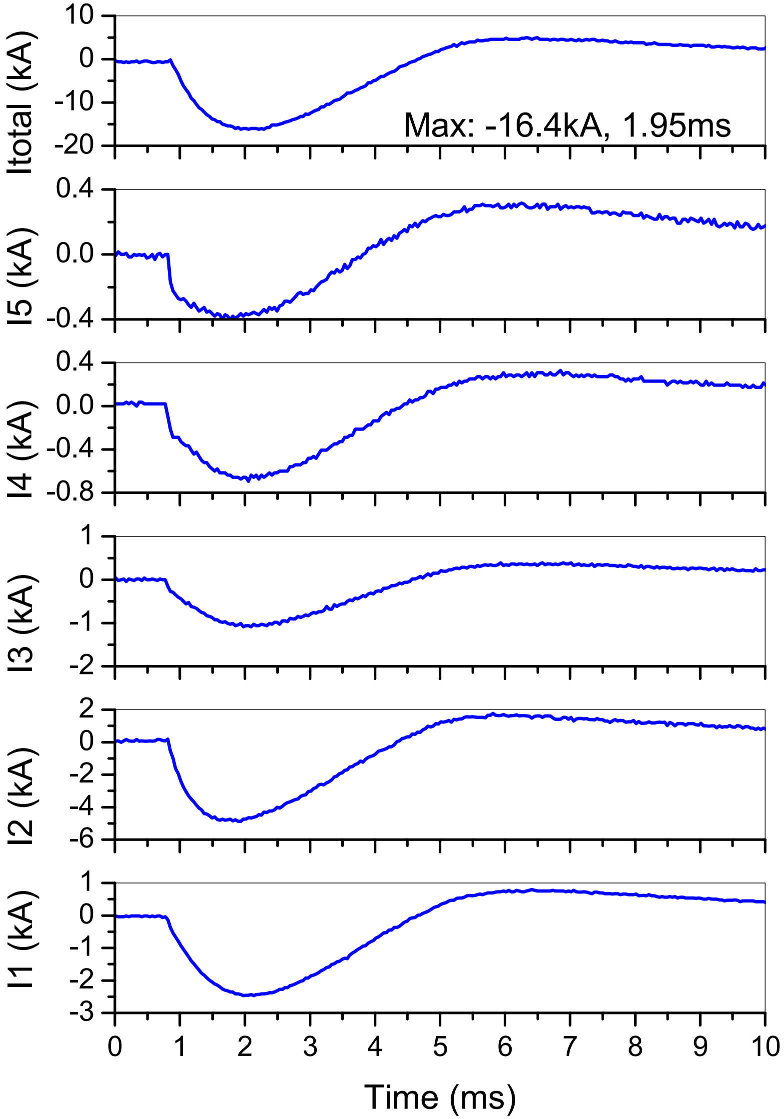


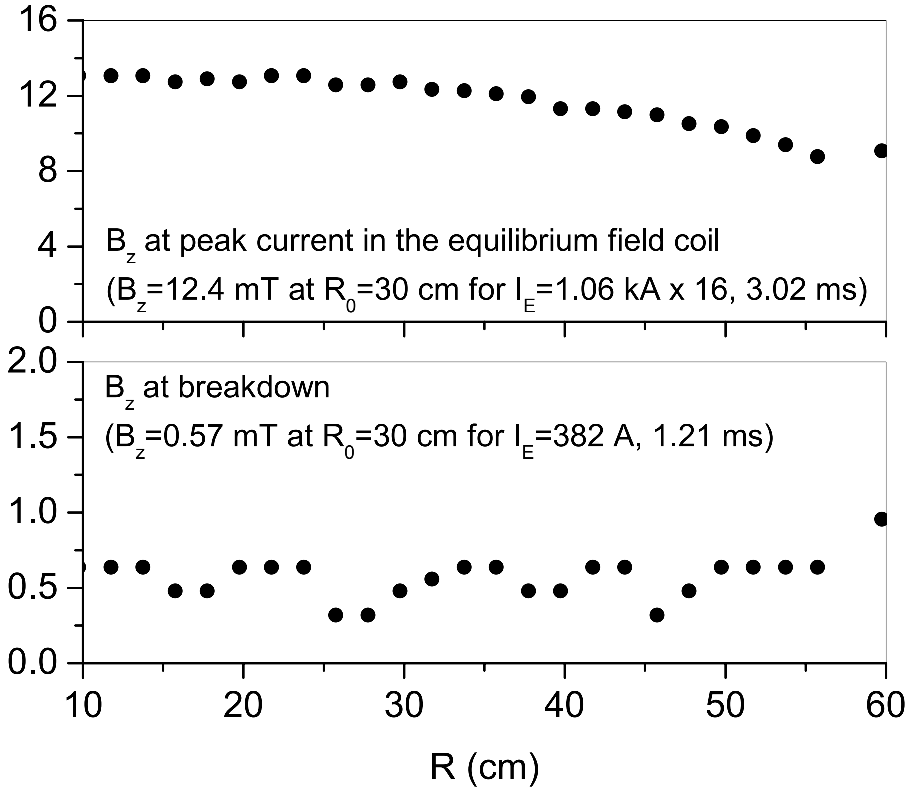


• Distribution of eddy currents induced by the poloidal field coils on the vacuum vessel was determined experimentally and fitted by a set of filaments.

Stray magnetic fields on the ETE spherical tokamak
C.S. Shibata, **E. Del Bosco**, J.G. Ferreira, L.A. Berni.

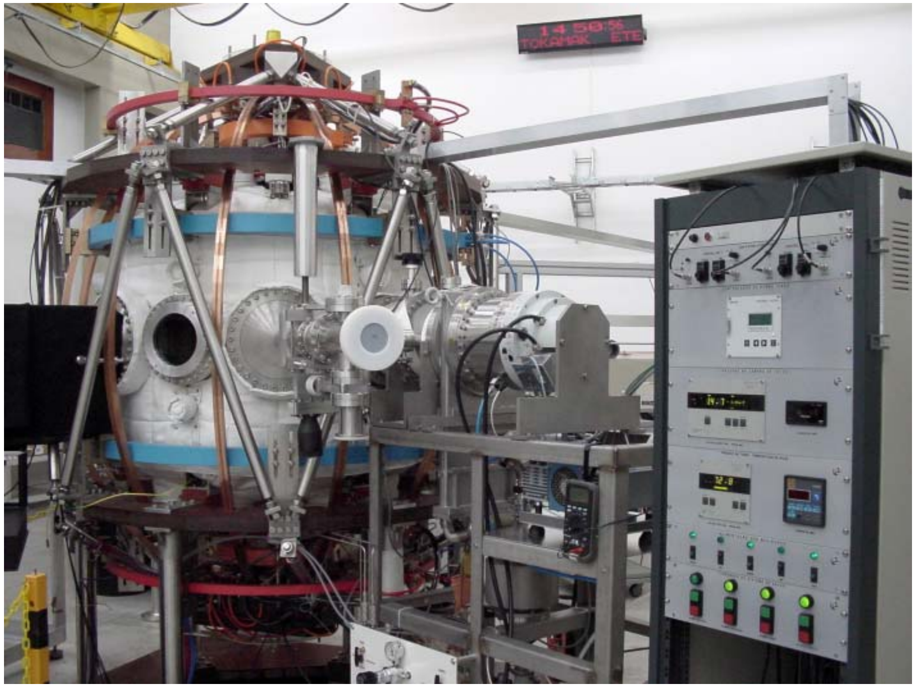
Foucault currents and vertical equilibrium field





- Eddy currents introduce large error field that can be compensated by properly triggering the equilibrium field coils.
- Plasma startup model including eddy currents.

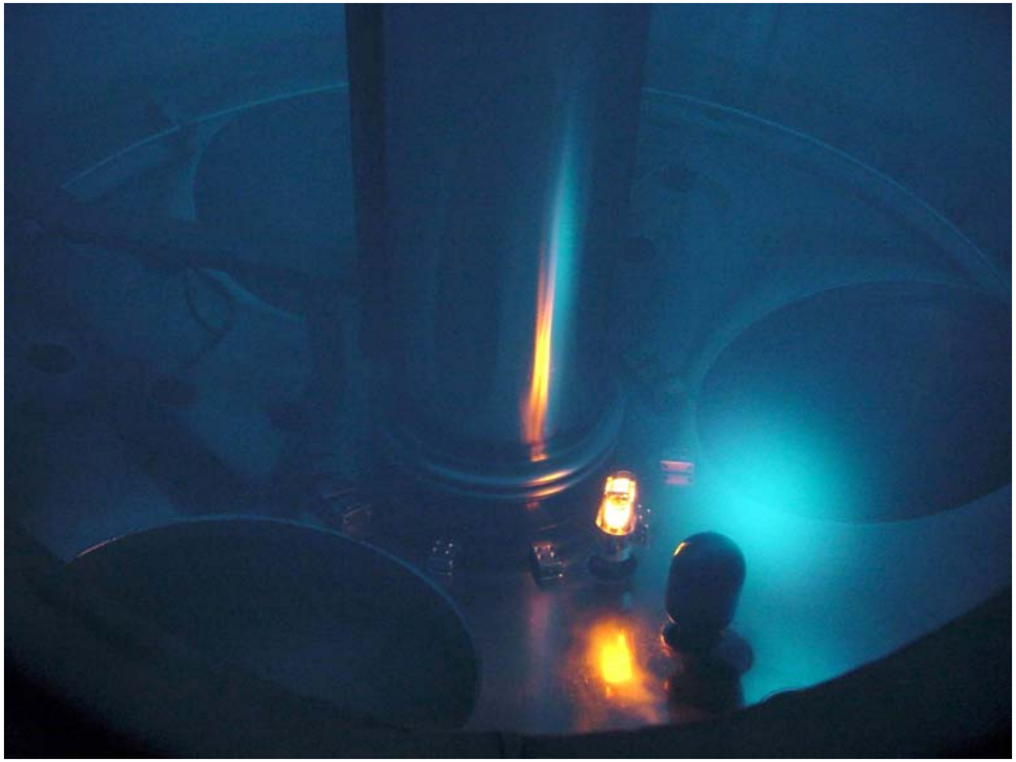
Backing and glow discharge cleaning

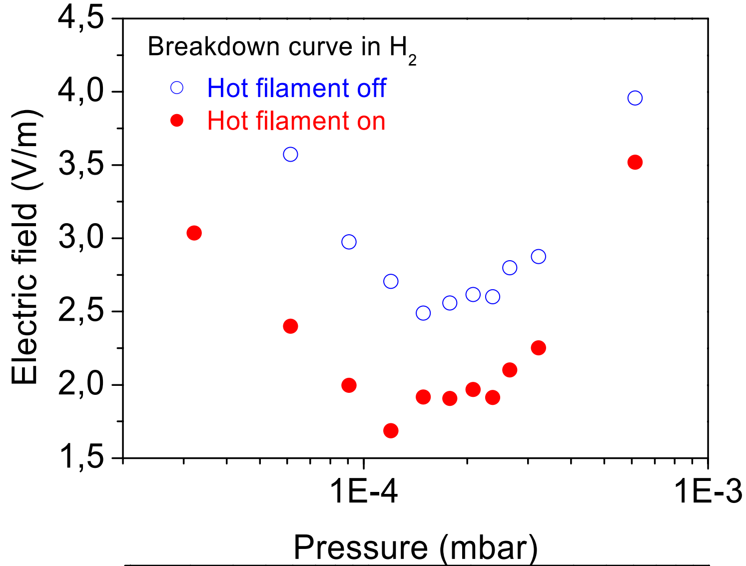


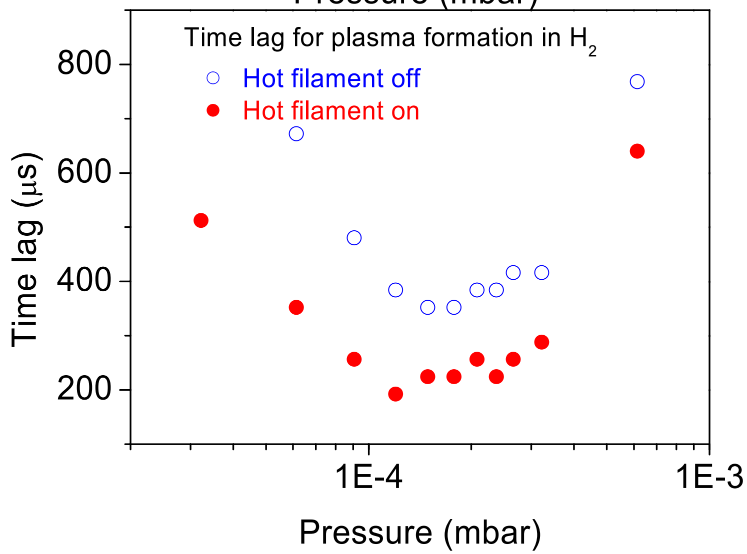
- Vacuum vessel covered by hot tapes (11 kW) and a thermal insulation blanket.
- Baking up to 120°C so far (limited by viton seals) but can go up to 200°C.
- Glow discharge (500 V/0.5 A, refrigerated anode) with He at 2.4×10^{-3} mbar.
- Base pressure < 8×10^{-8} mbar after baking (2-3 days) and glow (~50 hours).

Baking system for improvement of vacuum conditioning of the ETE vacuum vessel
J.G. Ferreira, E. Del Bosco, L.A. Berni, W.A. Vilela, H. Patire Jr.

Vacuum conditioning and breakdown



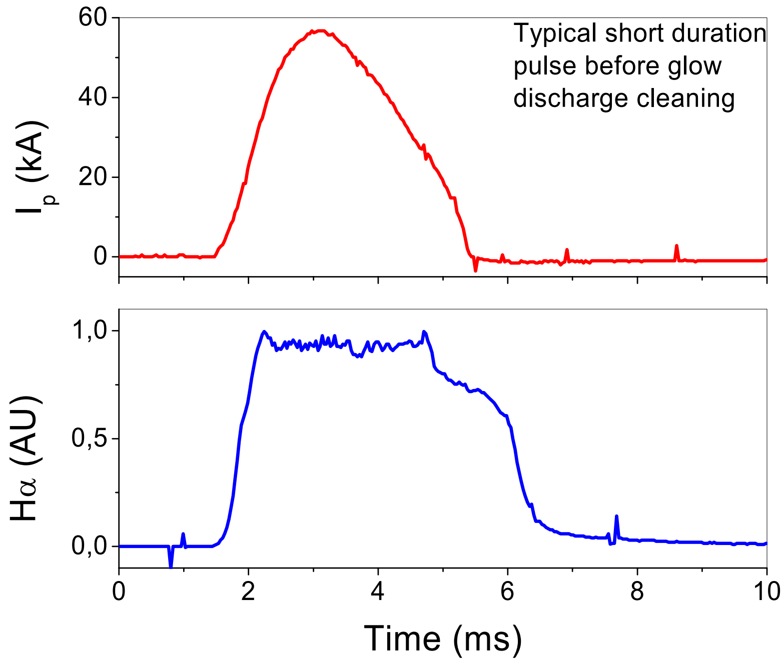


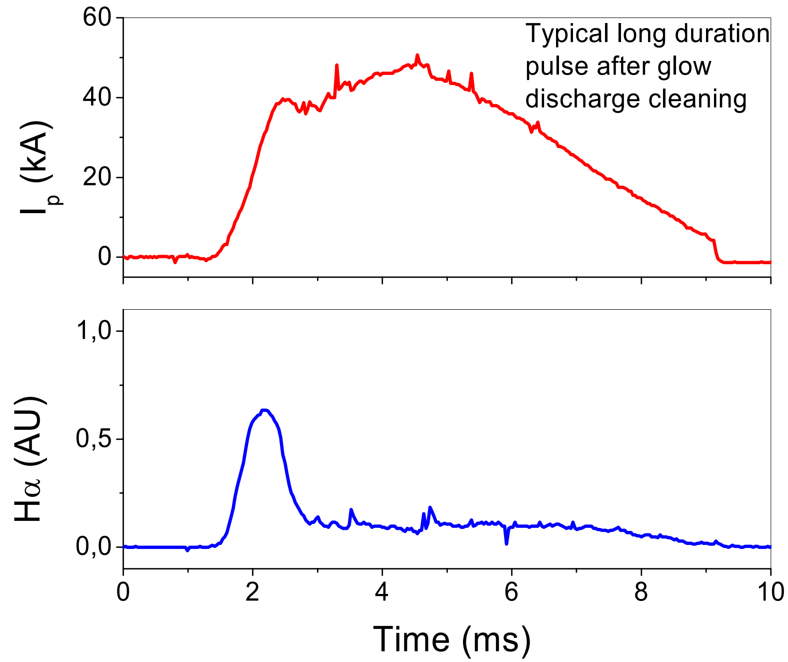


Glow discharge and biased hot filament (4A/75V).

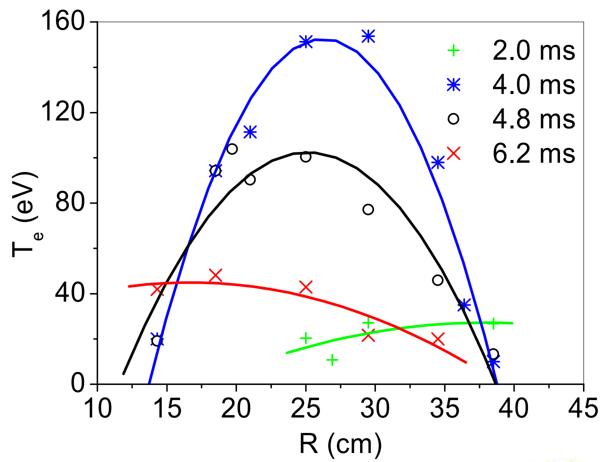
- After conditioning, breakdown becomes less sensitive to compensation of stray magnetic fields (can change B_V without readjusting trigger times).

Operational scenarios





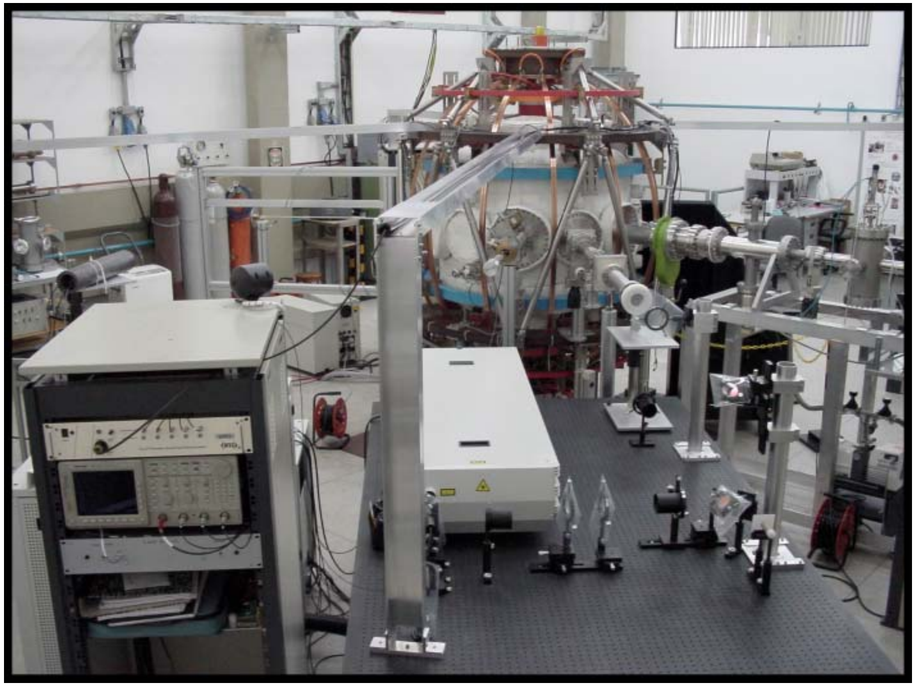
- Conditioning so far removes mostly H_2O/H_2 from the walls, reducing recycling $\Rightarrow$ increases T_e and t_p.
- Conditioning improvement should optimize removal of O_2, allowing to overcome the radiation barrier.

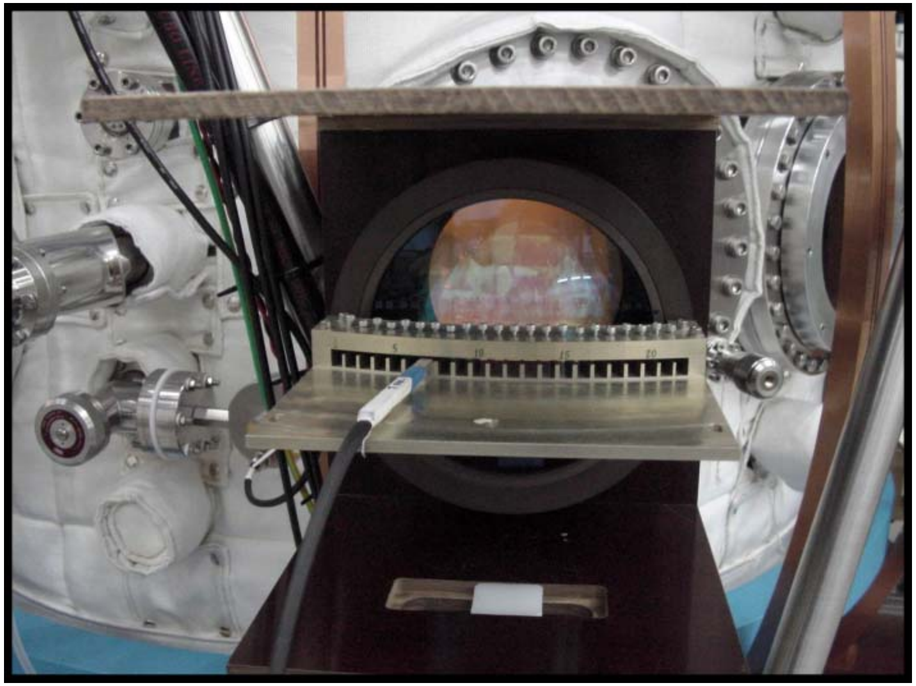


Operational scenarios of the ETE spherical tokamak

E. Del Bosco, L.A. Berni, J.G. Ferreira, R.M. Oliveira, G.O. Ludwig, C.S. Shibata.

Thomson scattering system

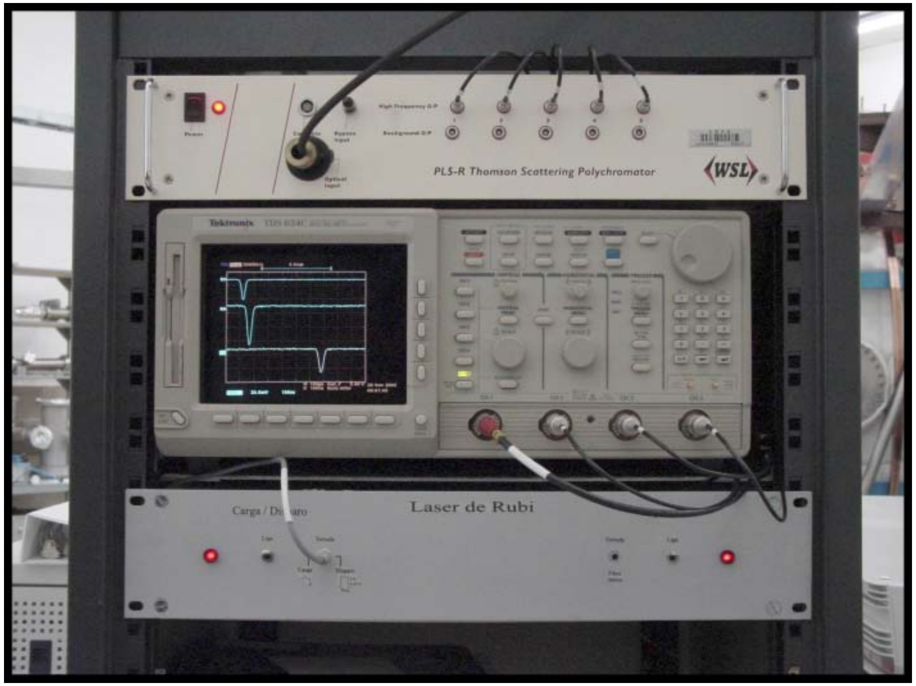


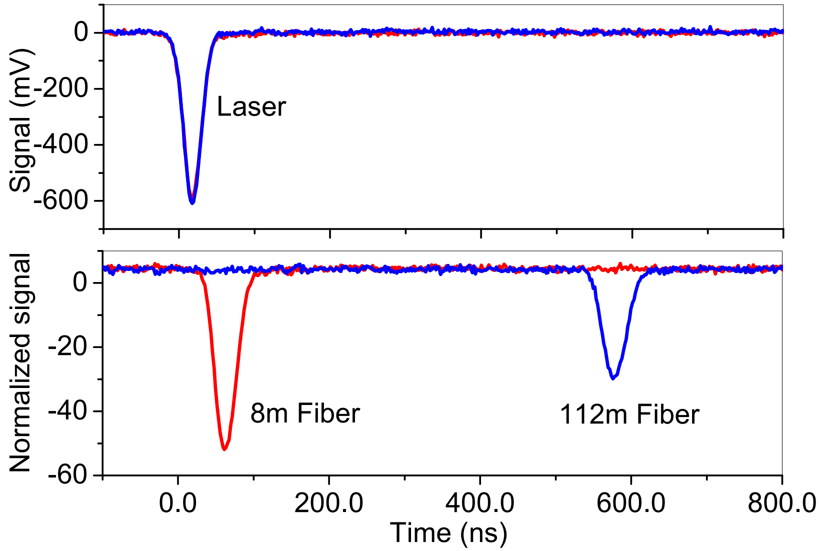


- 10 J, 20 ns pulse duration, Q-switched ruby laser.
- f/6.3 lens images the scattered light on 4.5 mm × 1.5 mm optical fiber bundles.
- 5-channels filter polychromator with avalanche photodiodes.
- Up to 22 plasma positions (15 mm) along 50 cm of the laser beam trajectory.

- Temperatures measured in ETE from 20 to 160 eV – densities $\leq 3.5\times10^{19}$ m^{-3}.

Thomson scattering system upgrade





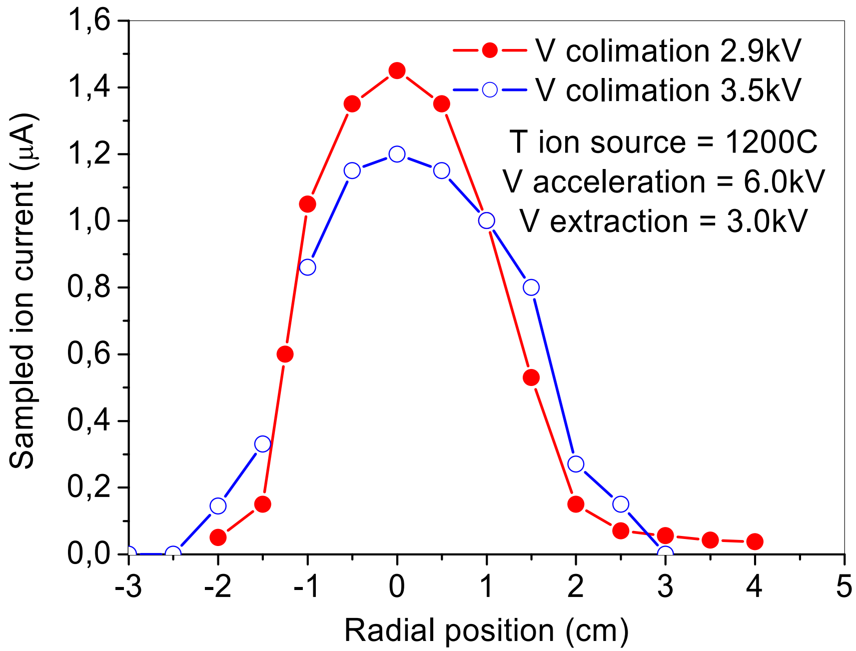
Measured attenuation of time-delayed signals in channels 1 and 8: loss = 84%, dispersion = 73%, total = 61%.

- Multipoint diagnostic based on time-delay technique using fibers of different lengths.
- Simultaneous temperature and density profiles – ten spatial points per polychromator.

Thomson scattering diagnostic on the ETE tokamak: status and progress

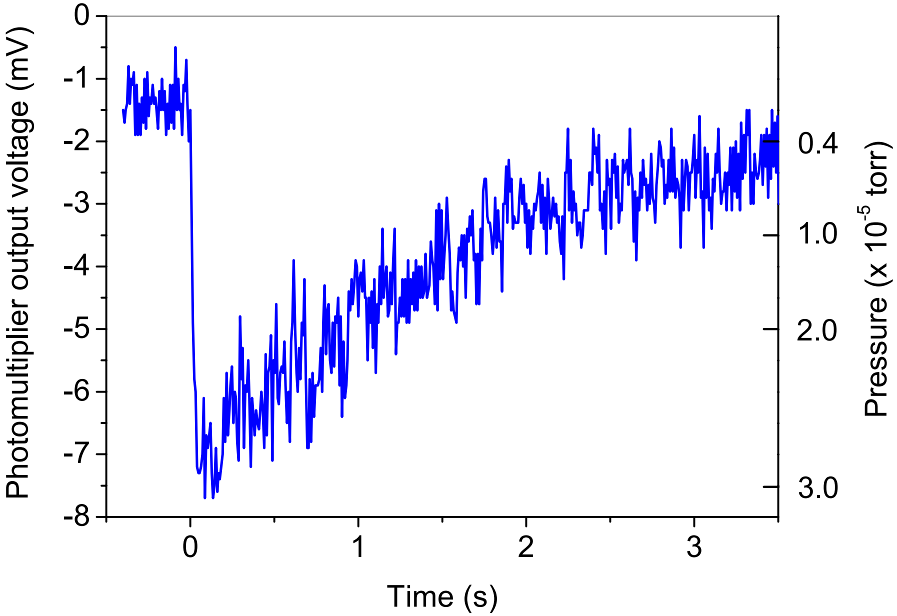
L.A. Berni, E. Del Bosco, J.G. Ferreira, R.M. Oliveira, M.P. Alonso.

Lithium beam probe development

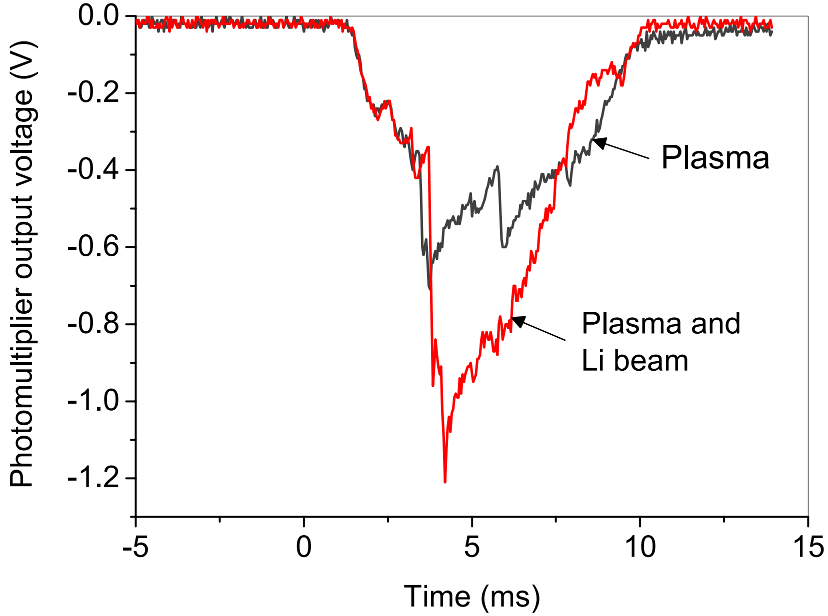


- 10 keV neutral lithium beam probe for measurements of the edge plasma density and its fluctuations.
- Current density up to 1 mA/cm^2 (glassy β–eucryptite source).
- Plasma density measured in He glow discharge at 3.3×10^{-4} torr $\Rightarrow$ $n_e=2\times10^{17}$ m^{-3}.

First results of the lithium beam probe



Gas injection by fast puff valve and pump out.

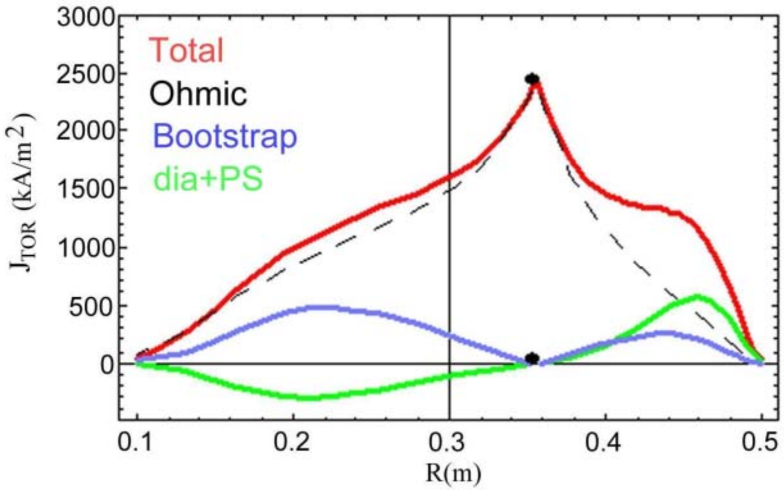


Light emitted at 670.8 nm, I_p=50 kA, R=0.48 m, t=5 ms $\Rightarrow$ $n_e=1.2\times10^{19}$ m^{-3}.

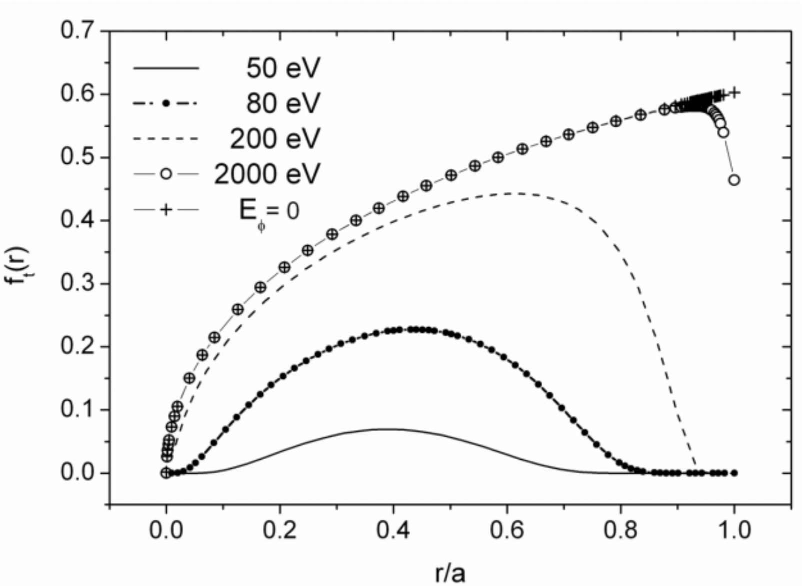
First results of the fast neutral lithium beam diagnostic probing the edge plasma of the ETE tokamak

R.M. Oliveira, M. Ueda, L.A. Berni.

Electric field effects on the neoclassical resistivity



Usual neoclassical theory: $f_t(r) \approx \sqrt{2\varepsilon(r)}$

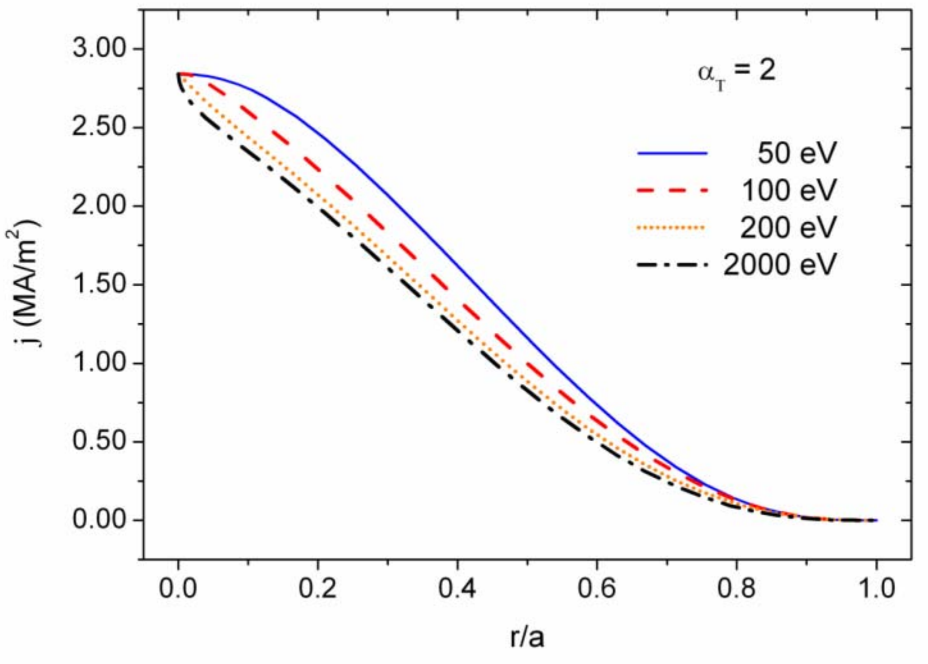


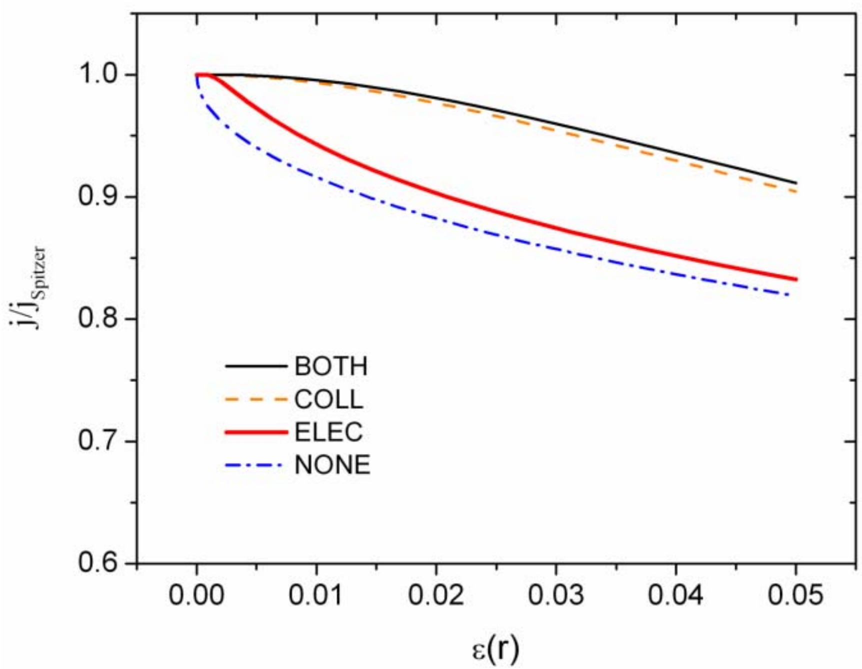
- Self-consistent equilibrium calculations that include neoclassical effects show singular behavior of the current density profile on the magnetic axis.
- Trapped particle fraction goes to zero as $f_t \approx \varepsilon^{1/2} \Rightarrow$ infinite j_T gradient on axis.

- Driven electric field *E* reduces the pitch angle of trapped particles by parallel acceleration $\Rightarrow$ detraps particles near magnetic axis.

$$f_t(r) \approx \sqrt{2\varepsilon(r)}\exp\left(-\frac{\mathcal{E}_{\perp c}(r)}{T_e(r)}\right), \quad \mathcal{E}_{\perp c}(r) = \frac{eER_0 q(r)}{0.725\varepsilon(r)}$$

Detrapping by electric field and collisions

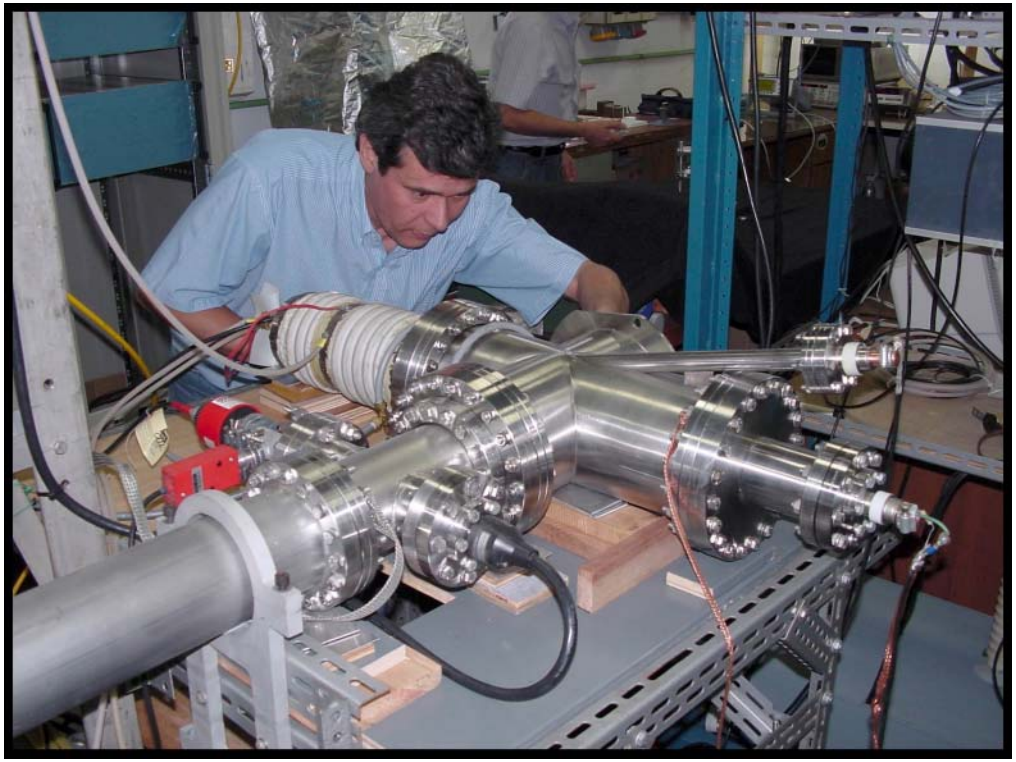




• The electric field detrapping is significant only at low electron temperatures.
• Collisions have a larger detrapping effect, except in startup conditions.

Neoclassical resistivity modified by the driven electric field in tokamak plasmas
M.C.R. Andrade, G.O. Ludwig, J.G. Ferreira, T.N. Todd.

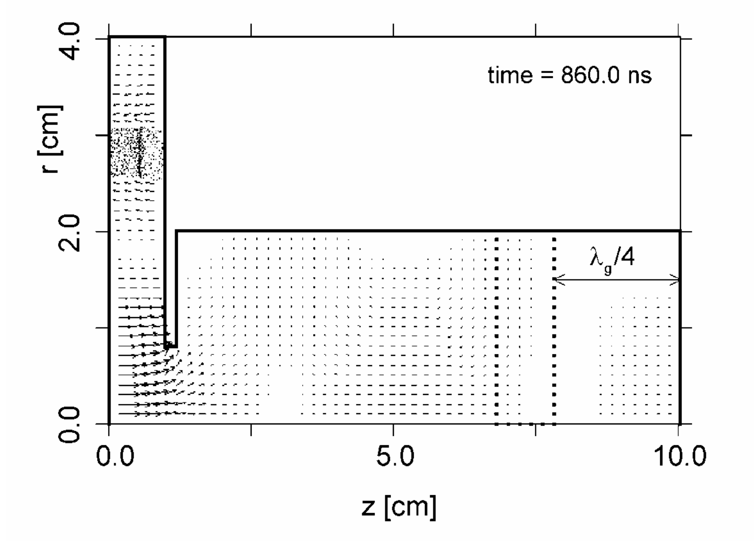
Monotron for plasma heating experiments



$f = 6.7$ GHz $\quad I_0 = 5$ A

$E_0 = 10.0$ keV $\quad \langle E \rangle = 7.91$ keV

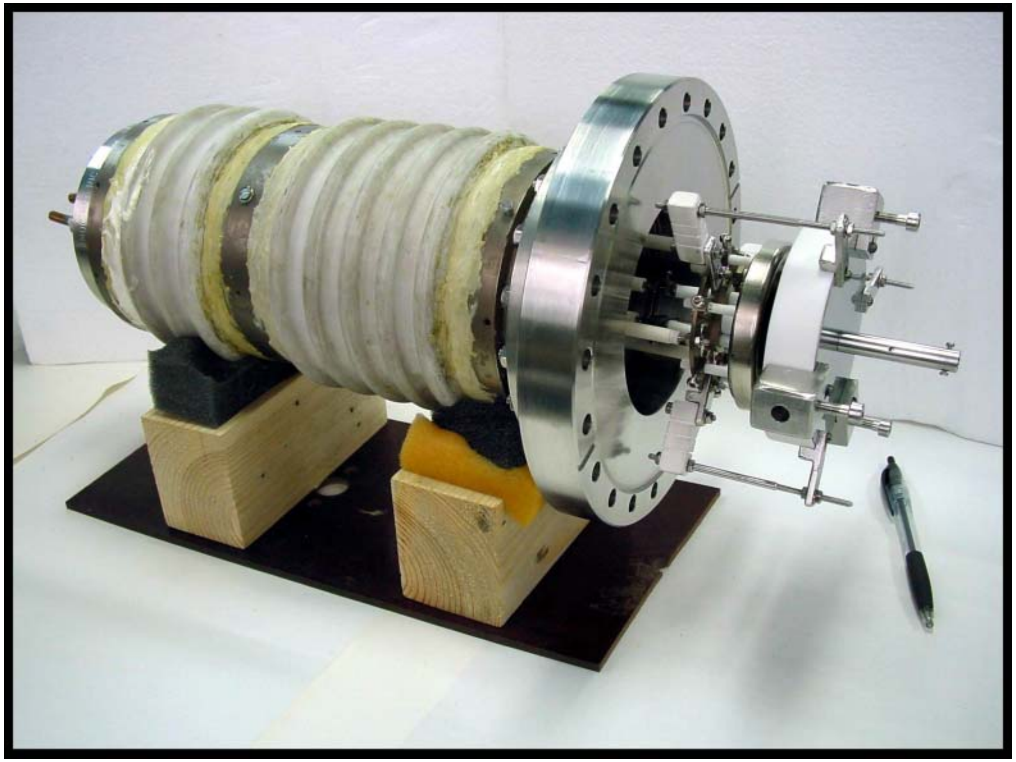
$\eta_{tot} = \eta_{elet} \times \eta_{circ} = 0.20 \times 0.75 = 0.15$

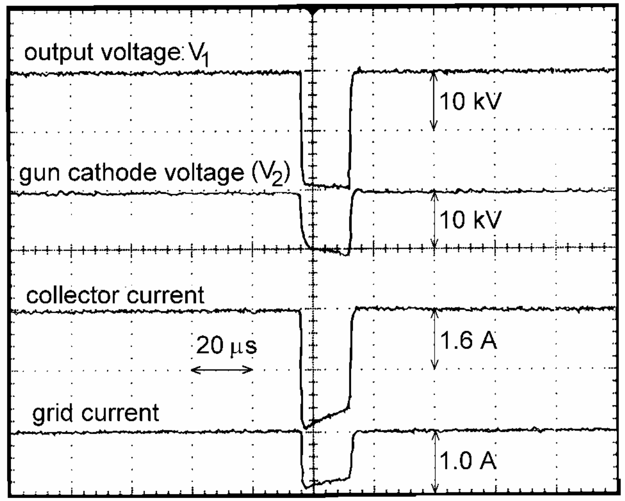


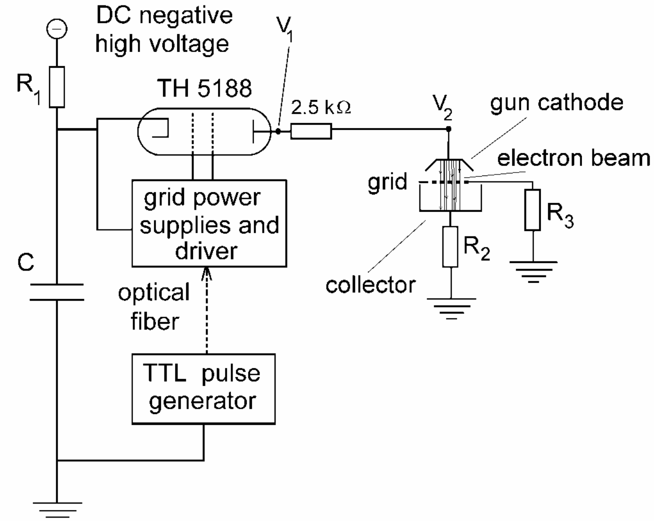
- Transit-time microwave tube – cylindrical cavity excited by a hollow electron beam.
- Novel twin-cavities concept should attain 40% electronic efficiency – comparable to gyrotrons, but simpler design (no magnetic field, large power handling capability).

The monotron as a gridded microwave tube. **J.J. Barroso**.

Electron gun for monotron

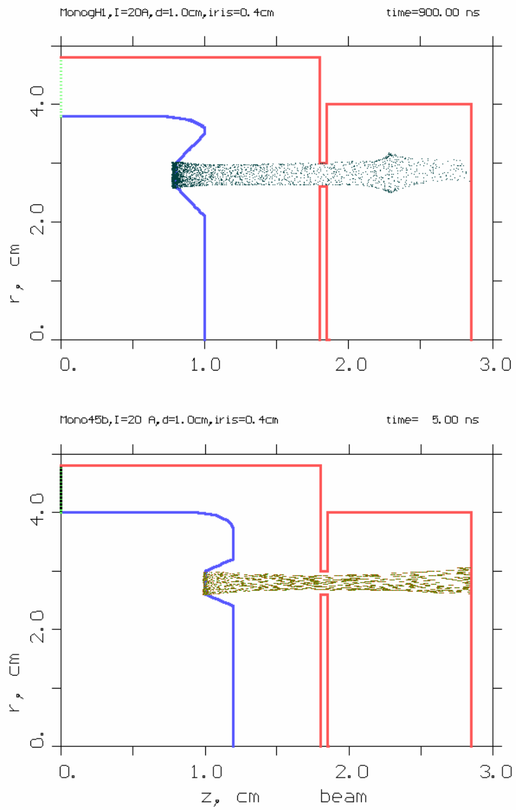






- Gun prototype – tests with 10kV fixed voltage and current adjusted by varying cathode temperature.
- Collector current ~3.1 A, grid current ~0.9 A ⇒ large fraction intercepted.

Improved electron gun



• Previous paraxial design at the Pierce angle of 67.5°.

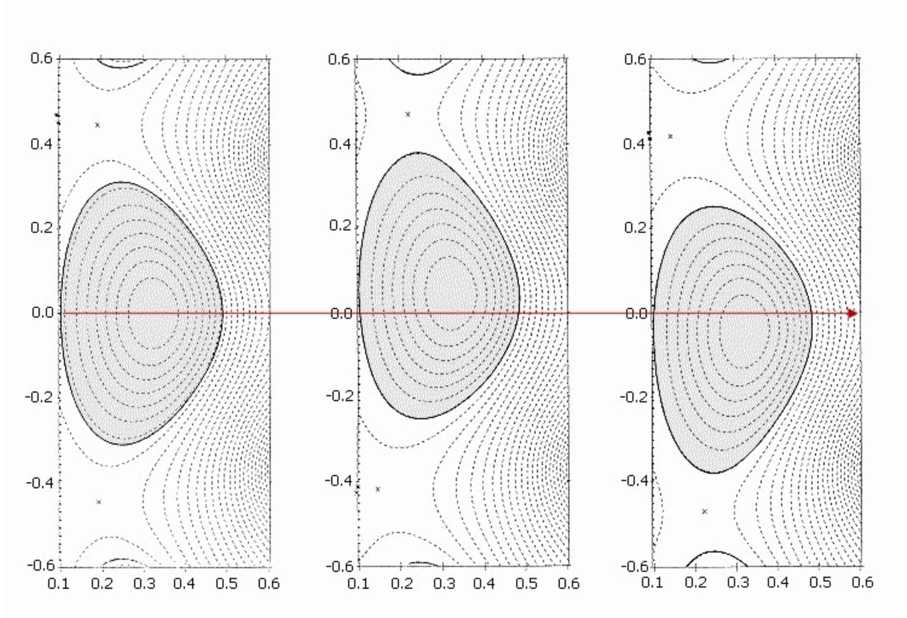
• New design at 45° collimates electron beam – uses improved filament support.

• Annular nickel strip coated with a (Ba,Sr,Ca)O film ⇒ 3 A/cm² (800 K).

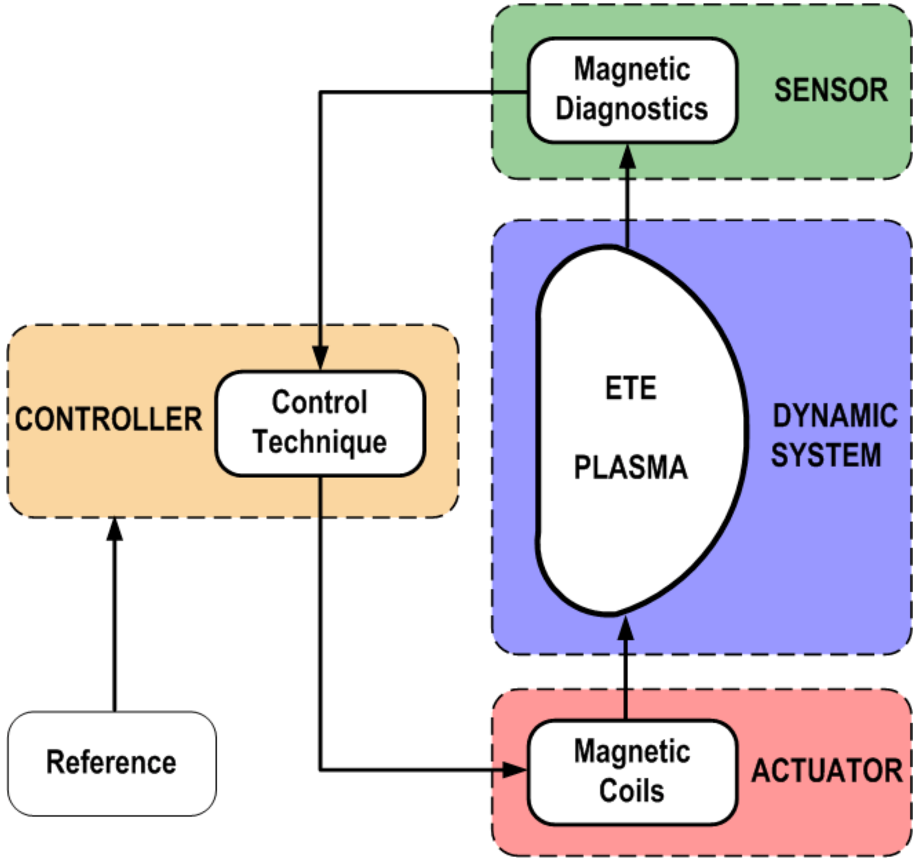
Generation of a 5 A, 10 kV hollow electron beam by a Pierce gun

J.J. Barroso, **P.J. Castro**, J.O. Rossi, J.A.N. Gonçalves, H. Patire Jr.

Vertical position control

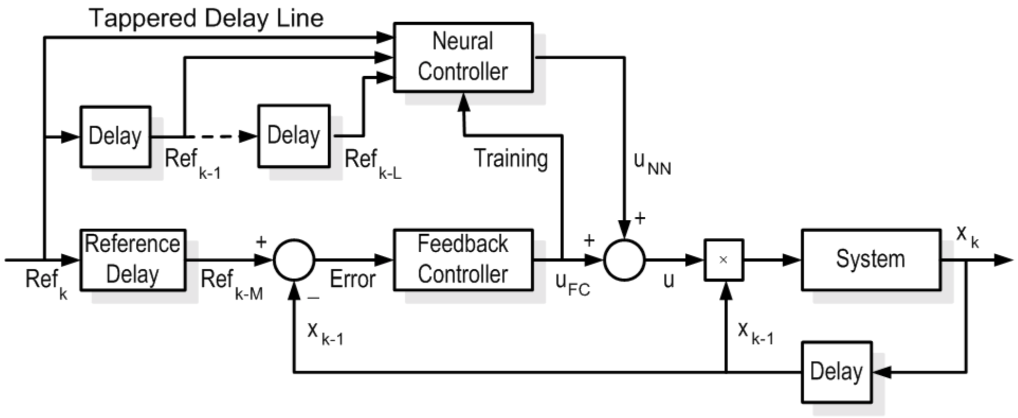


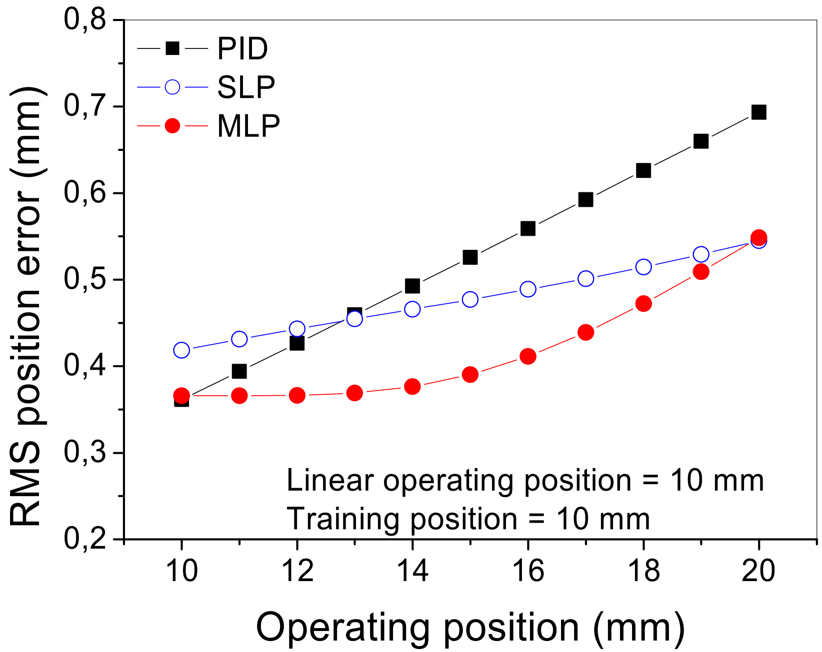
Simulation of vertical displacement in ETE:
1 mT signal in magnetic sensor $\Rightarrow$ 5.55 mm



- The instability of the vertical position in the elongated plasma cross section complicates the control of the current, position and shape in ETE.

Neural controller tested in a simple system





• The nonlinear controller gives a smaller error, enlarging the region of operation.

• The performance near the origin is similar to that of the feedback controller.

• Feedback controller (PID) for a magnetic levitation device compared via simulation against feedback error learning (FEL) controllers of the linear (single layer perceptron - SLP) and nonlinear (multiple layer perceptron – MLP, one hidden layer) types.

Intelligent control based on neural controller for application in the ETE tokamak
L.F.W. Barbosa, G.O. Ludwig, C.L. Nascimento Jr.

ETE expectations and world spherical tori

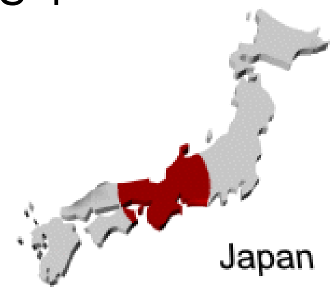
Major radius R_0 = 0.3 m
Minor radius a = 0.2 m
Aspect ratio A = 1.5
Elongation κ = 1.8
Triangularity δ = 0.3
Magnetic field B_0 = 0.6 T
Plasma current I_p = 0.4 MA
Auxiliary power W_{aux} = 0.3 MW
$0.1 < n_e < 0.7 \times 10^{20}$ m^{-3}
$800 > T_e > 150$ eV

Expected ETE parameters with 300 kW of auxiliary heating.

MAST

NSTX, CDX-U, Pegasus, HIT-II

TST-2, TS-4



Globus-M

ETE

SUNIST (testing)

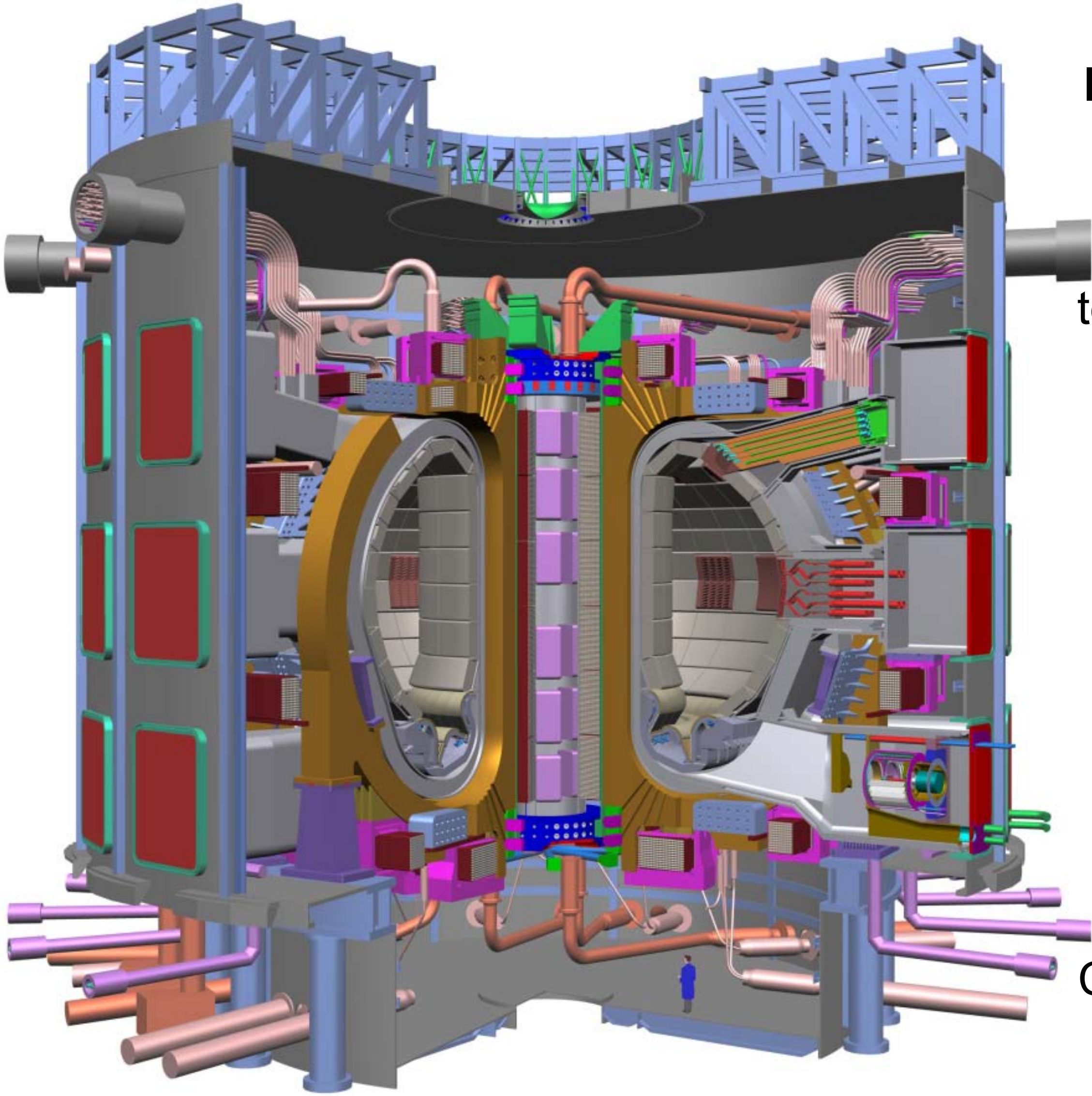
China

PROTO-SPHERA

(proposed)

Italy

Tokamak fusion development



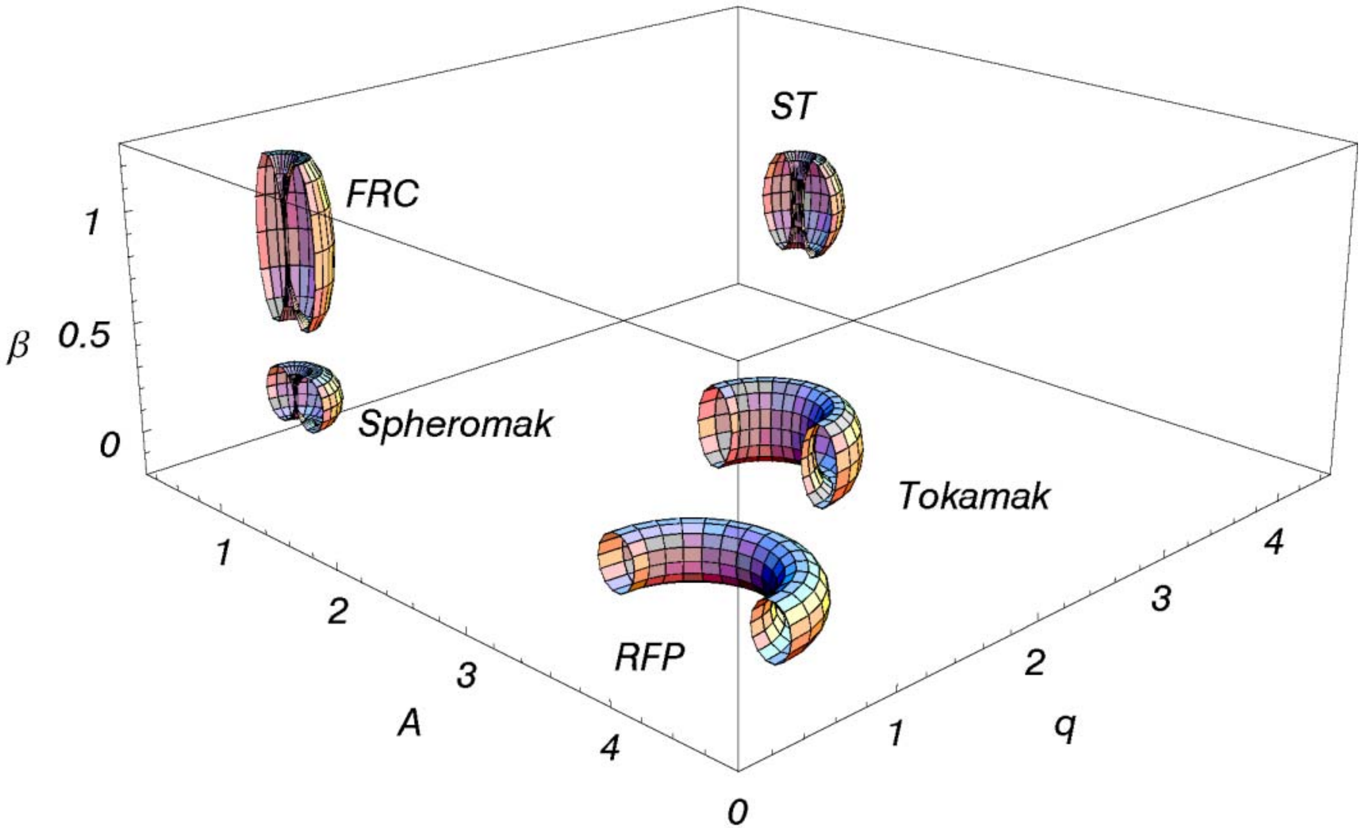
ITER (International Thermonuclear Experimental Reactor) – experiment capable to produce a self-sustaining reaction. Next step toward demonstrating the feasibility of fusion energy.

International project (European Union, Russia, Japan, Canada, China, EUA, Republic of Korea). Brazil – Portugal collaboration?

½ hour pulse duration, 500 MW fusion power, facility for testing fusion power-plant technologies.

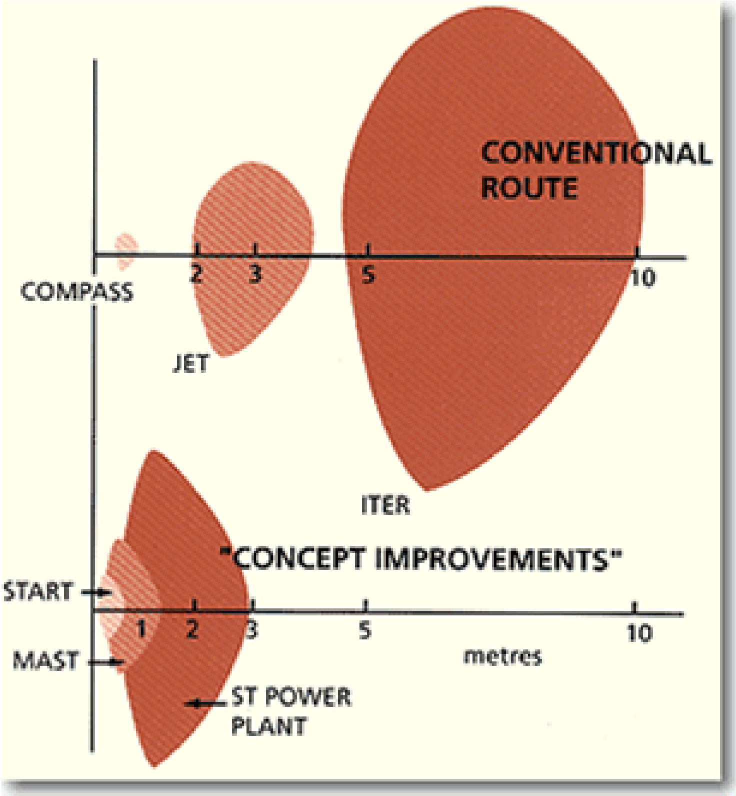
Construction – 10 years, US5\times$10^9
Source: http://www.iter.org

Axisymmetric configurations

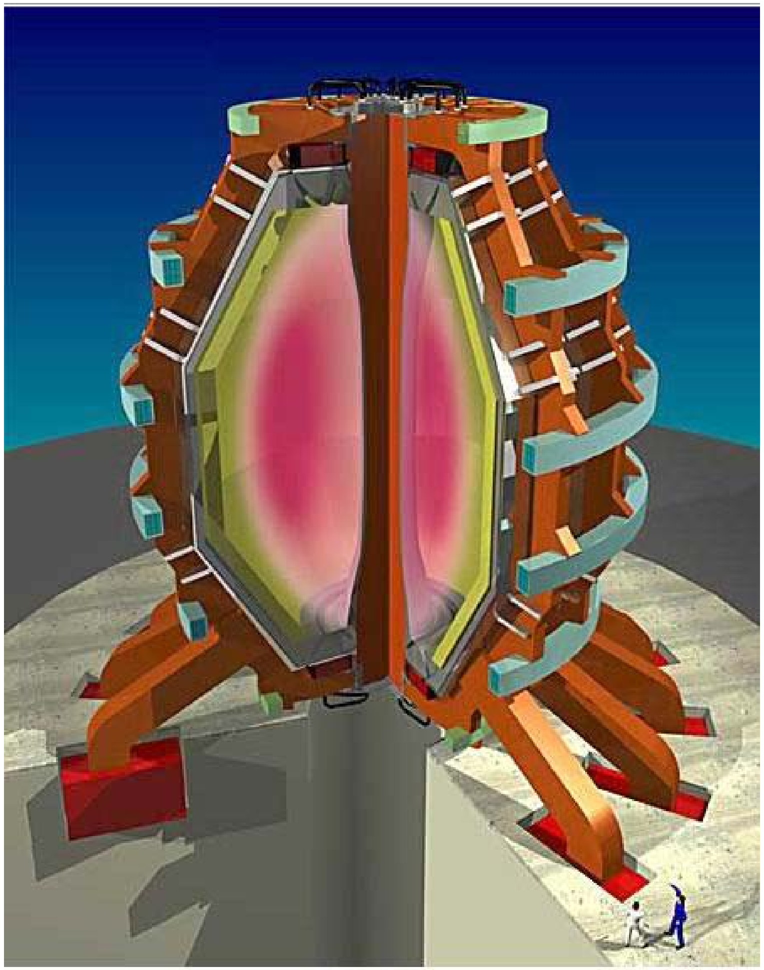


The spherical torus presents both the **strong toroidicity** effects of compact tori (notably magnetic shear) and the **good stability** properties provided by the external toroidal field of conventional tokamaks.

Compact reactors

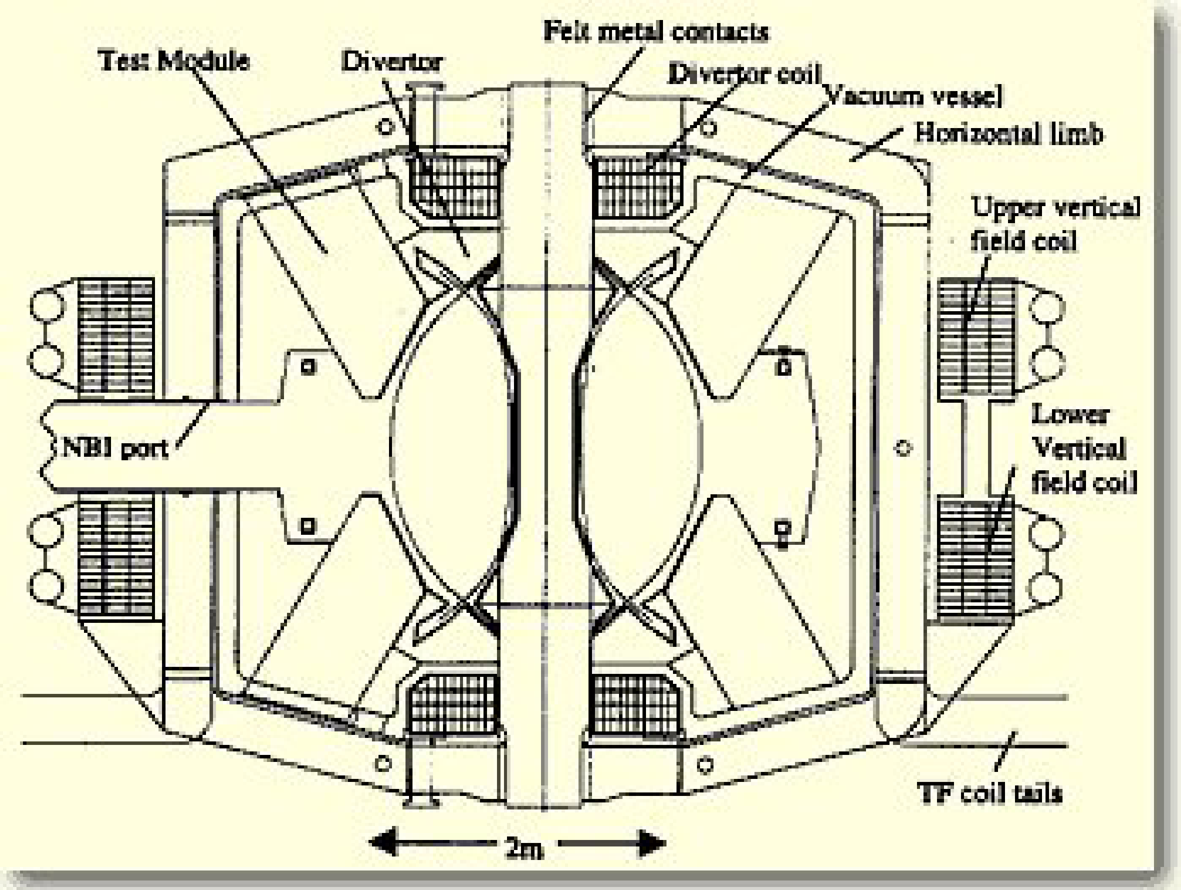


The spherical torus is the most promising concept for confining a self-sustaining fusion reaction – depending on future progress, a near burning plasma experiment will test the application of the ST in post-ITER reactors.



Source: http://www.fusion.org.uk

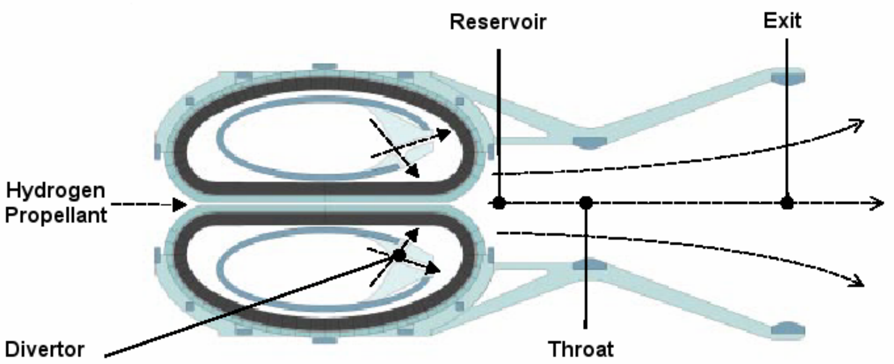
Components test facility

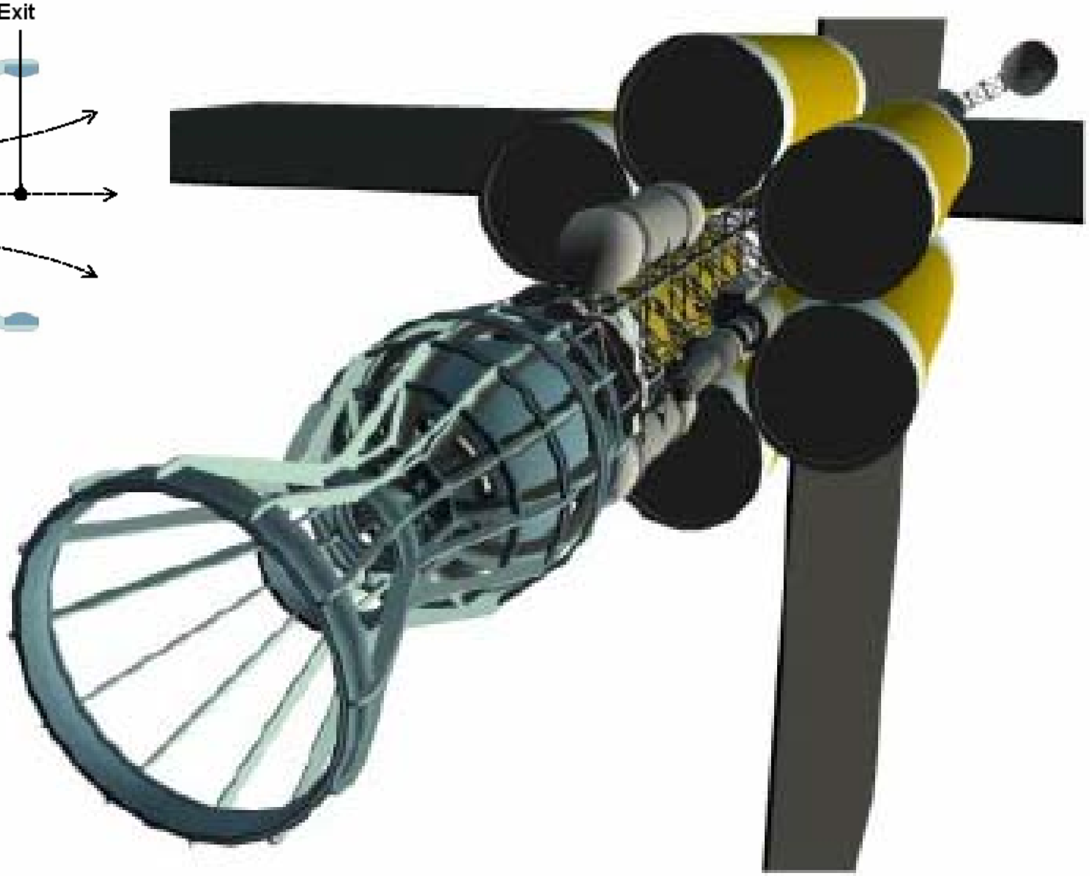


Source: http://www.fusion.org.uk

Spherical tokamaks may constitute intense volumetric neutron sources that will be needed, as ITER progresses, to develop and test components and materials for future power plants, or in the transmutation of nuclides.

Space travel





- R_0 = 2.48 m, a = 1.24 m, κ = 3.
- B_0 = 8.9 T, I_p = 66 MA.
- DHe^3, T = 50 keV, n = 5×10^{20} m^{-3}
- Fusion power = 7.9 GW.
- Flow rate = 0.08 kg/s, Thrust = 28 kN, Jet power = 4.8 GW.
- 172 ton crew payload from Earth to Jupiter in 118 days (4.7 AU).

Realizing "2001: A Space Odyssey": Piloted Spherical Torus Nuclear Fusion Propulsion. C.H. Williams, L.A. Dudzinski, S.K. Borowski, A.J. Juhasz, J. Spacecraft Rockets **39**, 874-885 (2002).

Closing remarks

For lovers of Science Fiction and the ultimate applications of fusion:

Riding the Torch. Norman Spinrad, *The Mammoth Book of Fantastic Science Fiction – Short Novels of the 1970s*, Carrol and Graf Publishers Inc., New York, 1992.

For those who want to know more about the activities of the Associated Plasma Laboratory in the areas of Plasma Science, Plasma Technology and Fusion Plasma:

http://www.plasma.inpe.br

Enjoy your stay in São Pedro.