Tore Supra

Development of long-pulse tokamak physics and technology

Abstract:

" Tore Supra "

Development of long-pulse tokamak physics and technology

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The primary goal of the Tore Supra program is to develop the physics and technology of long-pulse tokamak operation. Correspondingly, Tore Supra is equipped with unique capabilities to achieve high performance, long-pulse plasma discharges, including superconducting toroidal field (TF) coils (NbTi cooled with He II at 1.8 K), long-pulse heating and non-inductive current drive systems, actively cooled plasma-facing components and a real-time plasma control system. The total operating time of the TF coils at cryogenic temperatures is 65,000 hrs so far. The heating and CD systems include 8 MW of LH power at 3.7 GHz, 12 MW of ICRF at 40-80 MHz, and under development 3 MW of ECRF at 118 GHz. Among the achievements are the nominal 30s-pulse at 1.7 MA, a totally non-inductively driven pulse of 70s, and the longest pulse of 120s, as well as highly radiative discharges with confinement enhancement comparable to ELMing H-mode. The achievements on the way to long-pulse operation as well as future upgrades (the CIEL project) will be discussed.

Objectives and Long-term Strategy of Tore Supra

Development of Steady State Physics and Technology for Fusion

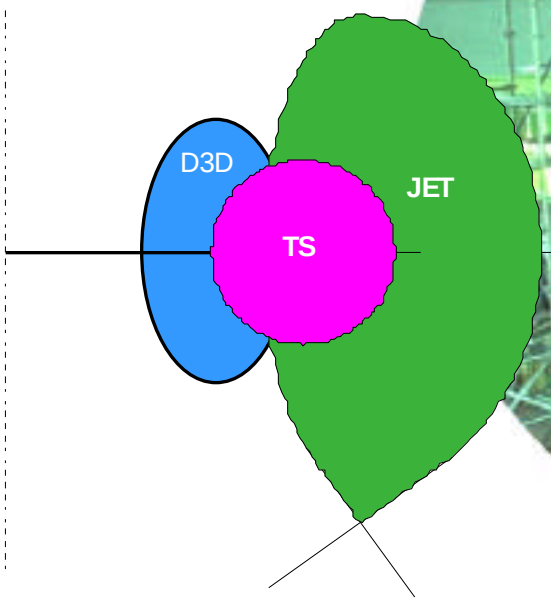
- Superconducting magnet technology
- Plasma-facing components and fuelling for steady state
- Steady state heating and current drive
- Exploration of new operating regimes in steady state
- Support/Exploration of ITER design choices

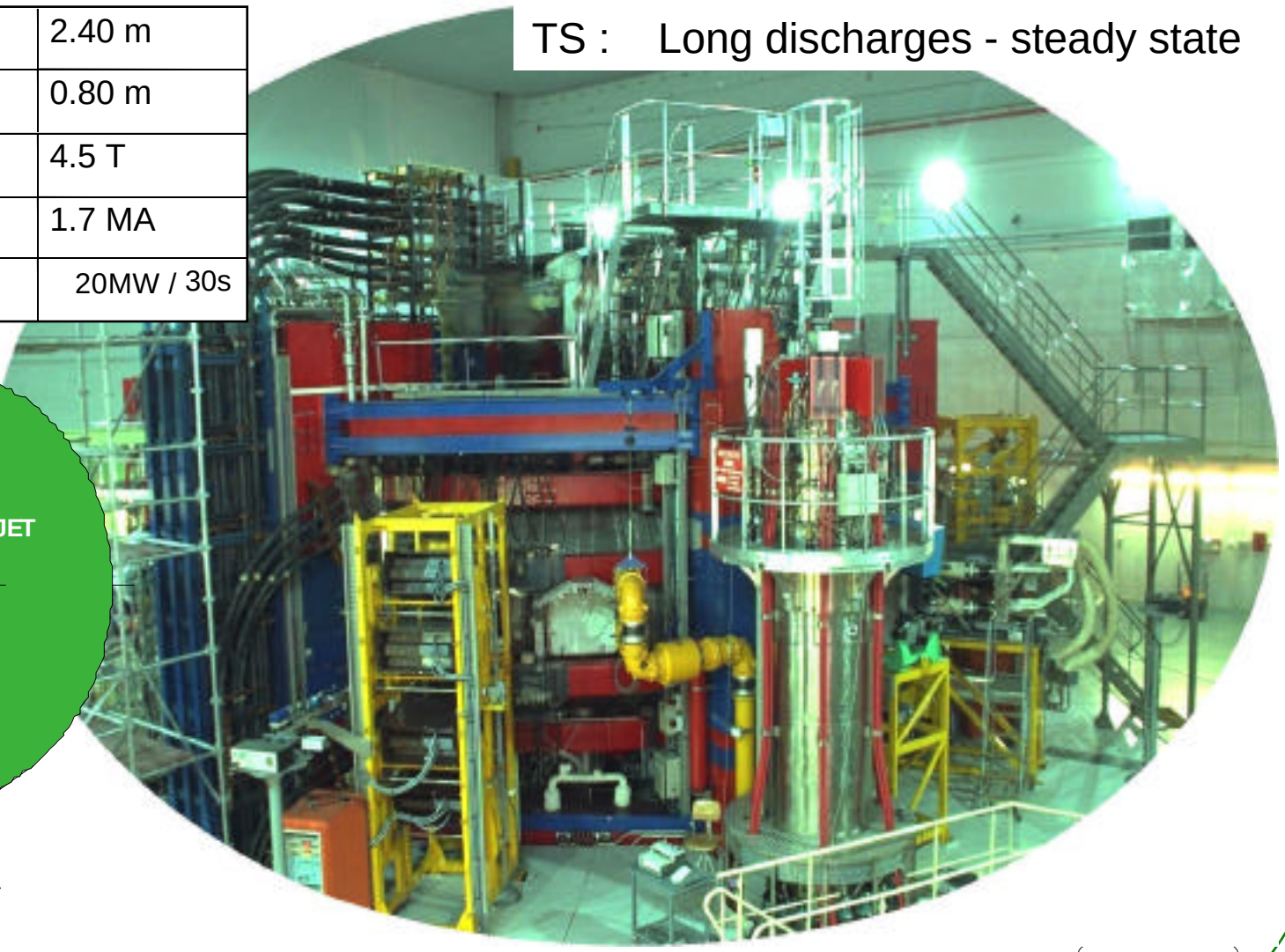
Tore-Supra : Main Parameters

JET : High performance DT

TS : Long discharges - steady state

Plasma major radius	2.40 m
Plasma minor radius	0.80 m
Magnetic field on axis	4.5 T
Plasma current	1.7 MA
Additional heatings	20MW / 30s





ToreSupra Design Parameters

Major Radius:	2.40 m
Minor radius:	0.8 m
Toroidal field at R=2.4 m:	4.5 T
Maximum field in conductor:	9 T
Toroidal field magnet weight:	160 t
Toroidal field magnetic energy:	600 MJ
Plasma current:	1.7 MJ
Pulse length:	30 s
Repetition rate:	4 pulse/h
ICRF heating power:	12 MW
LH heating power:	8 MW

Superconducting Toroidal Field System

Coils and field:

- 18 coils : NbTi conductor wound in double pancakes, cooled with superfluid He at 1.8 K.
- Nominal field = 9 T on the conductor and 4.5 T on axis (4 T routinely)

Cooling:

- 20 tons of stainless steel screens; cooled at 80 K; 7 days from 273 k
- 120 tons stainless steel casing; cooled at 4.5 K; 7 days from 80 K
- 50 tons of NbTi conductor; cooled at 1.8 K by He II; 1 day from 4.5 K

Operation:

- Operation time of 11 years, in periods of typically 1 year
- Operating availability ~ 94% in recent years
- 65,000 h at cryogenic temperatures (25,000 at T<2.1 K)

Plasma-Facing Components

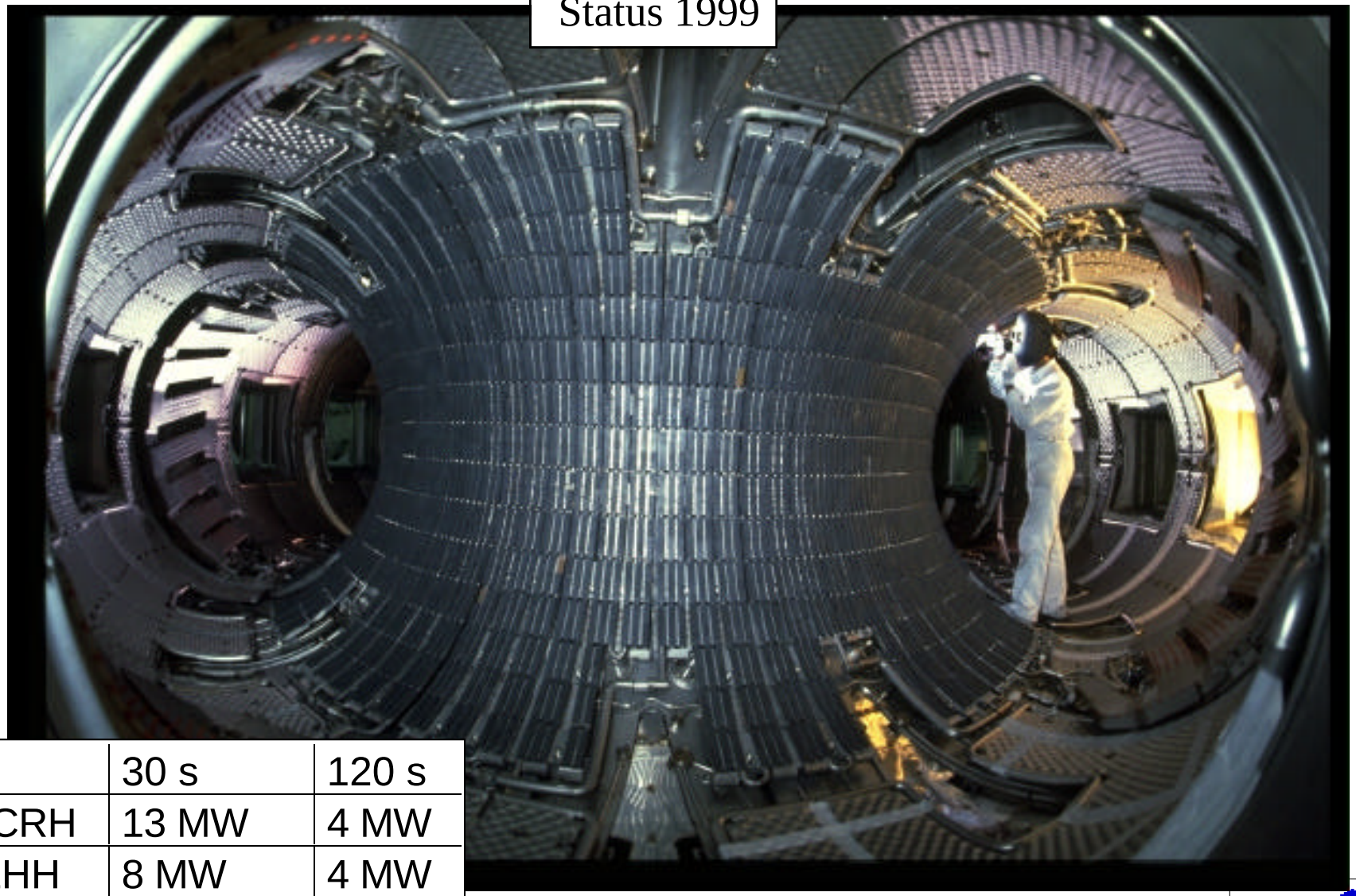
All plasma-facing components are actively water-cooled (230°C maximum)

- Cooling system has 2 functions:
  - **baking the PFCs at ~ 200 °C**
  - **removal of plasma power at steady state conditions**
- First generation developed in early 1980s, capabilities limited due to uneven brazing and brazing flaws
- Second generation, based on carbon-fiber composites and improved brazing techniques, had improved power handling capabilities
- Third generation of PFCs developed with new attachment technologies between CFCs and hardened copper heat sink

==> expect reliable operation at 10 MW/m^2 in steady state

Plasma-Facing Components and Energy Exhaust

Status 1999



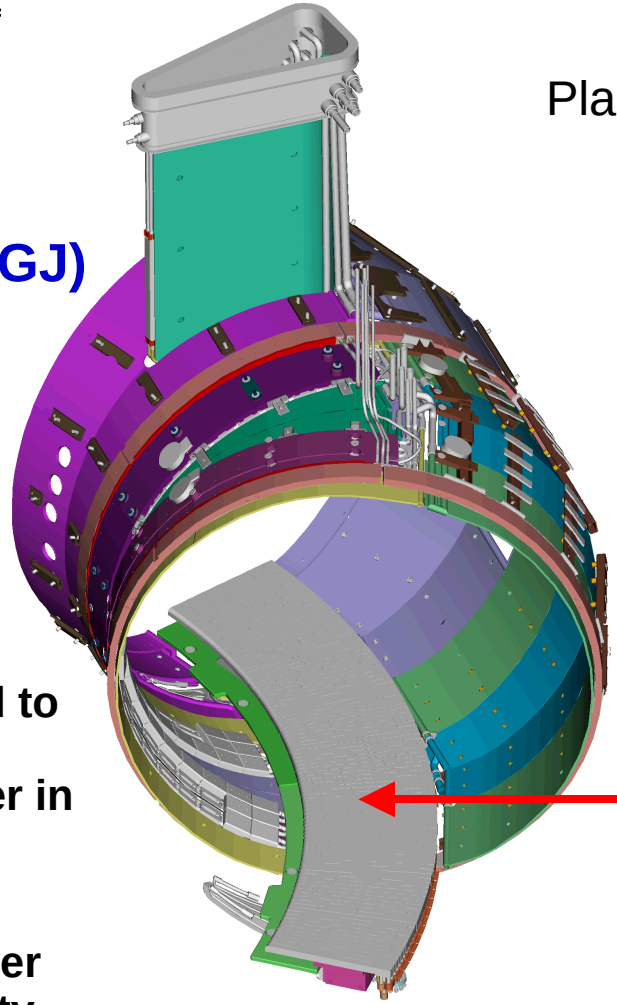
	30 s	120 s
ICRH	13 MW	4 MW
LHH	8 MW	4 MW

Tore Supra Improvements: (1)
"CIEL" Project

25 MW - 1000 s

==> 25 GJ

(ITER-FEAT: 60 GJ)



Planning:

Fabrication of components: ongoing

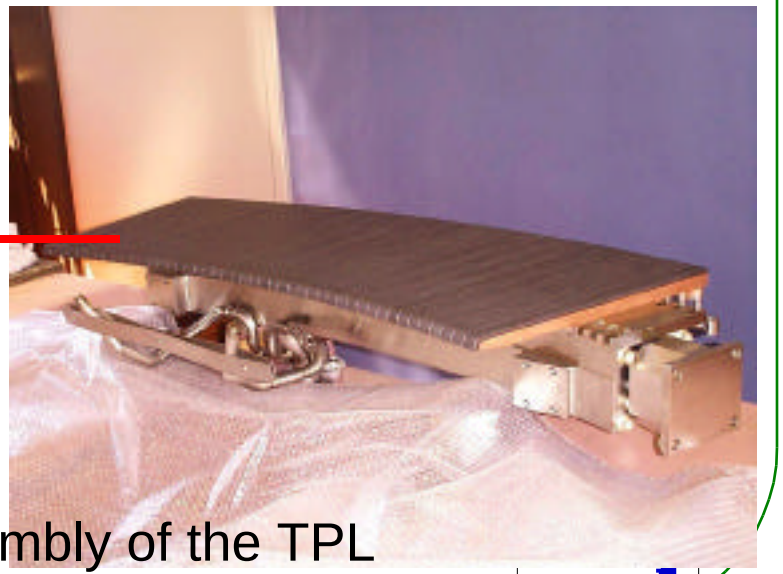
Installation : y2000

TS restart : spring 2001

New Toroïdal Pump Limiter designed to remove 15MW convective power in steady-state.

10MW radiative power exhaust capability

8 to 12 MW / m^2



Partial assembly of the TPL

Heating and Current Drive Technology

Development of fully water-cooled, steady state systems

‘Lower Hybrid’ System:

- 2 launchers: 3.7 GHz; 210-s capability, 8 MW system, 6.5 MW coupled
- Major current drive and current profile tool for confinement studies

‘Ion-Cyclotron Range of Frequencies’ System:

- 3 resonant double-loop antennas of ORNL-CEA design
- 40-80 MHz, 6 x 2.2 MW tetrodes with 30-s capability
- Maximum of 10 MW was coupled; 4.2 MW with one antenna

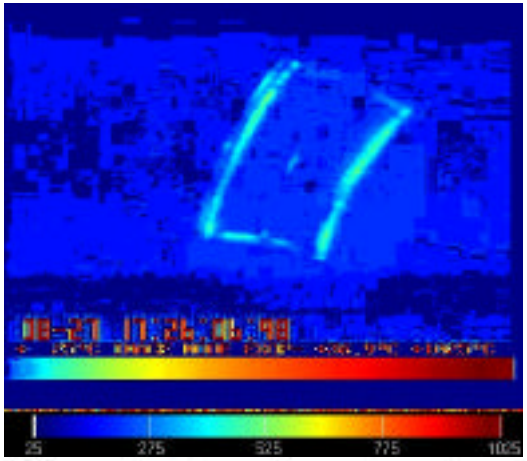
‘Electron-Cyclotron Frequency’ System: (under design)

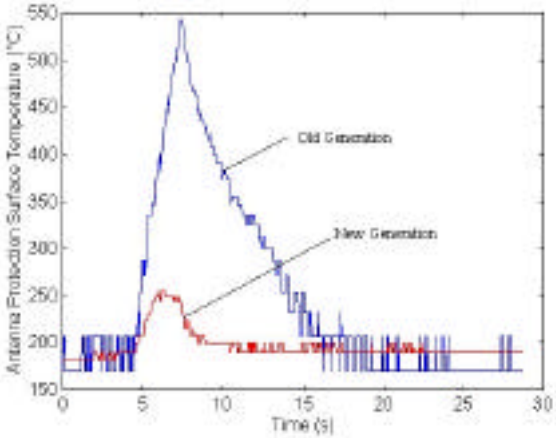
- 6 x 0.5 MW gyrotrons at 118 GHz with 210-s capability
- Prototype has achieved 0.5 MW for 5-s pulses and cycling fatigue tests

Tore Supra Improvements: (2)
Advanced Antenna Design

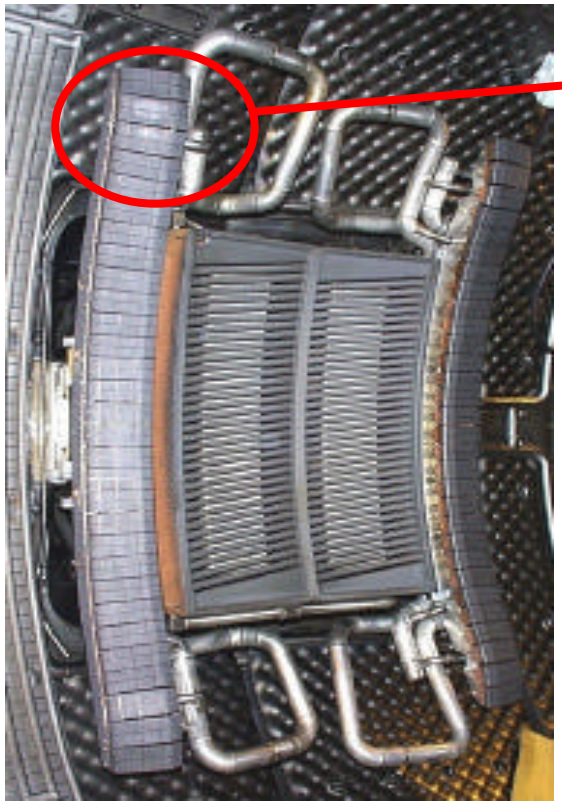
Example of physics engineering :
New edge protection of the antennas

Infra Red Thermography monitoring





New generation



High heat flux finger
(5-10 MW/m^2)

Old generation

Tore Supra Improvements: (3)
Auxiliary Heating and Current Drive

Present performance

	30 s	120 s
ICRH	13 MW	4 MW
LHH	8 MW	4 MW

Performances to fit in the CIEL capability :

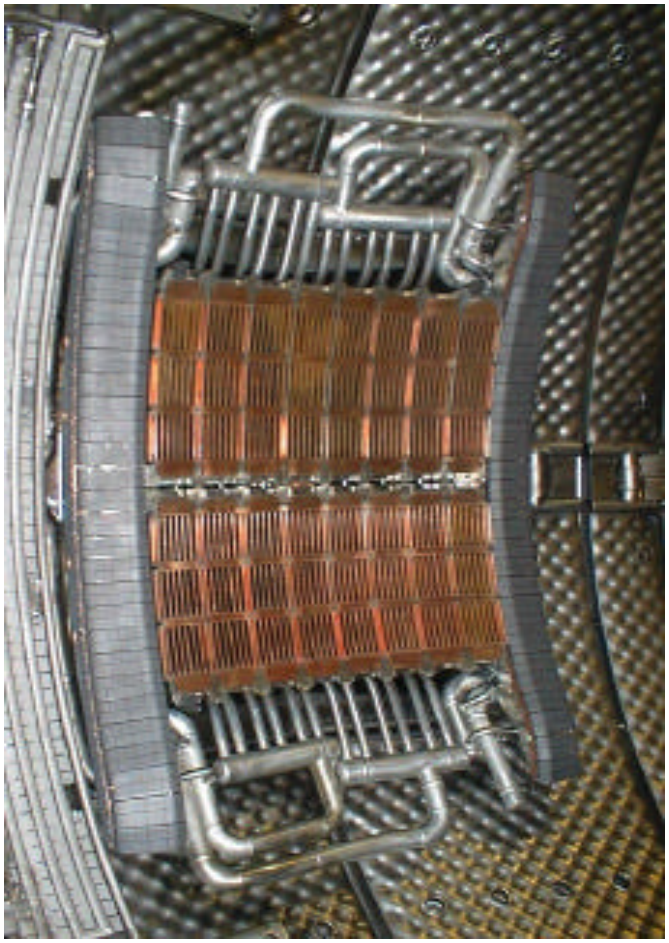
25 MW - 1000 s

Required improvements:

Generators (Diacrodes and Klystrons)

Antennas and launchers

New LHH launcher installed in summer 1999



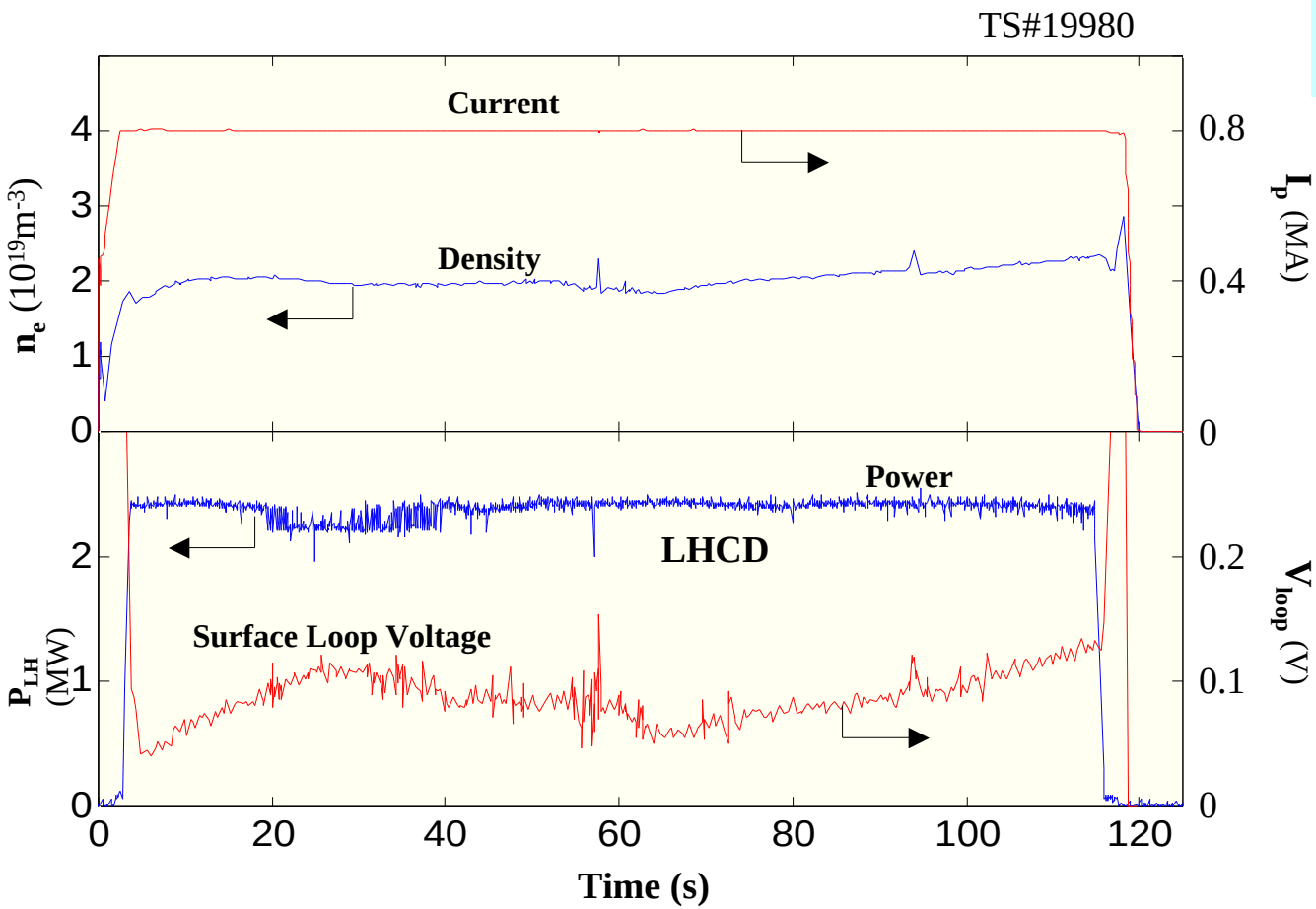
Operating Regimes - Accomplishments

The objective of reaching long-pulse, high-performance plasma discharges, has required very close integration between *physics* and *technology*.

- 120-s discharge at moderate power: 2-3 MW;
  - achieved with a large fraction of LH current drive
  - identified several issues of power and particle control in long-pulse operation
- 70-s discharge at 2×10^{19} m^{-3} and I_p=0.6 MA, with **zero loop voltage**
- 20-s - 30-s pulses at medium power: 6-7 MW
  - allowed "advanced tokamak" studies under steady state conditions
- 1-2-s pulses at high power: 10-12 MW;
  - studies of the highest performance under transient conditions

Long-Discharge Experiment (1)

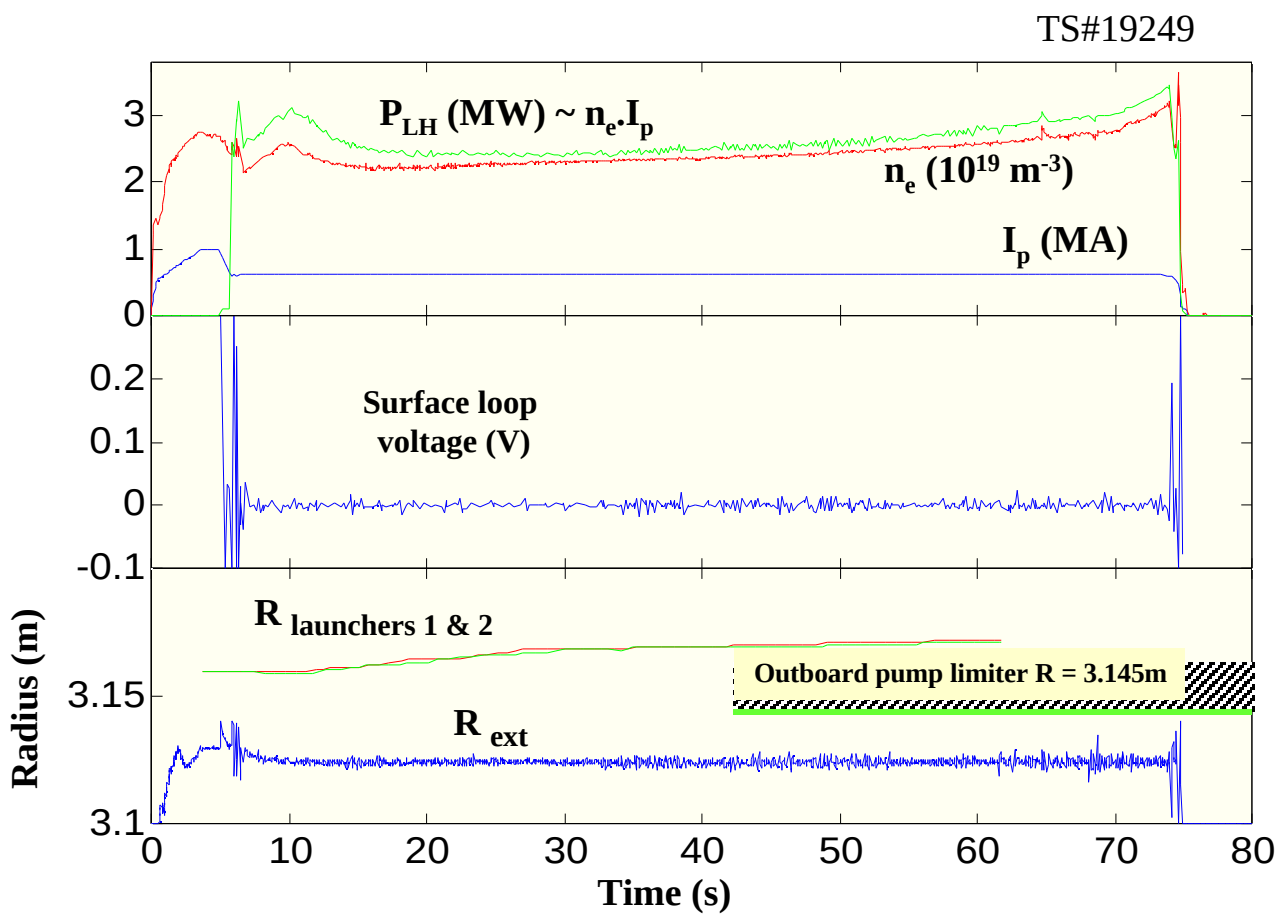
280MJ Total Injected Energy



Loop Voltage ≠ 0

90% non-inductive current

Long-Discharge Experiment (2)



$V_{loop} = 0$

2 Feedback Controls :

Plasma Surface Flux

⇑ ⇓

OH Poloidal Power

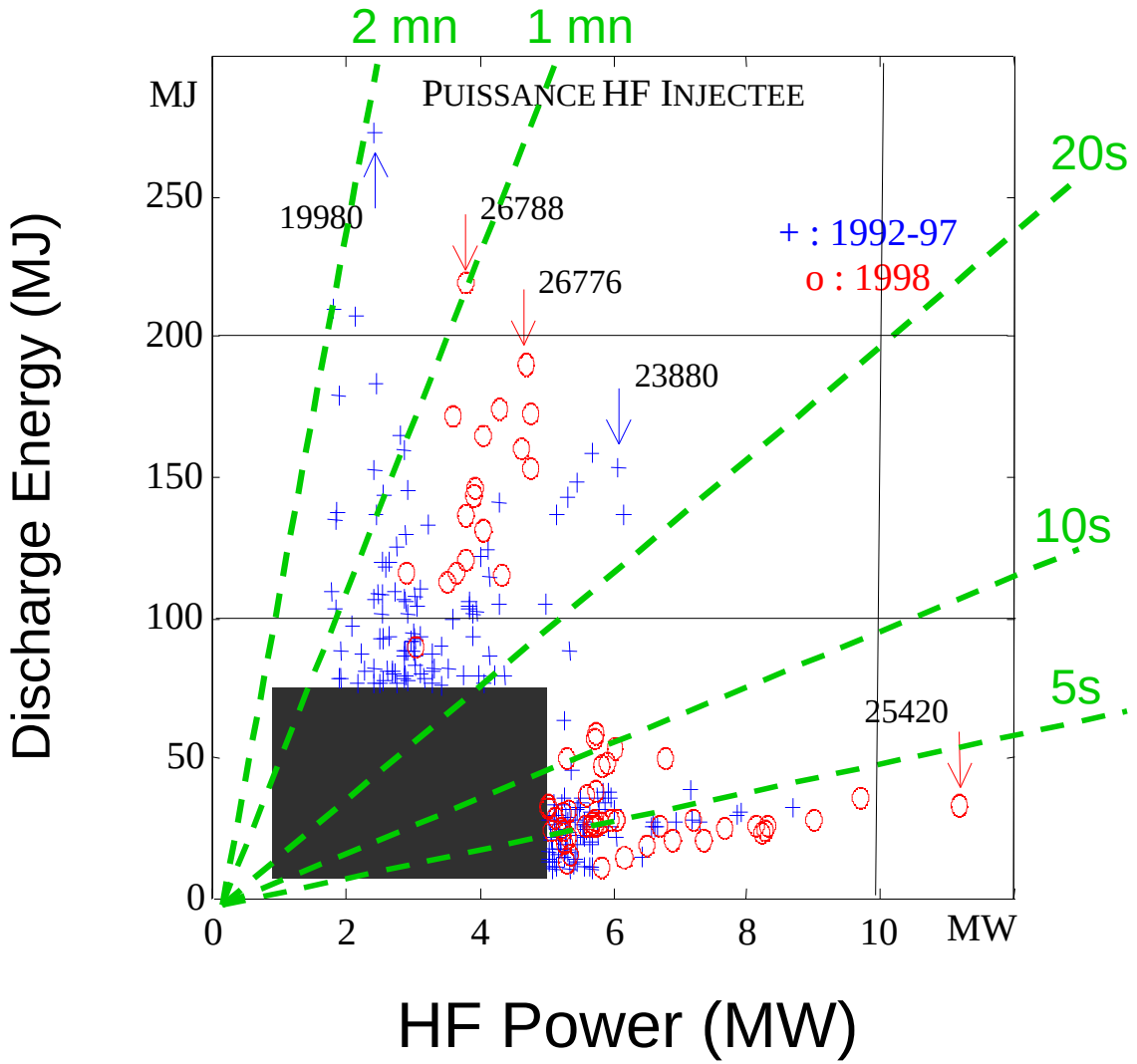
&

Plasma Current

⇑ ⇓

LH Power

HighEnergy - High Power Discharge Space



Physics Studies - Highlights

- Long-Pulse Scenarios
- Ergodic Divertor
- Plasma Boundary
- Auxiliary Heating and Current Drive
- Transport and Turbulence

Long-Discharge Scenarios

- Very long pulses (up to 2 min) at moderate power levels (2-3 MW) allowed to identify several issues of power- and particle control under steady state conditions.

- Moderately long pulses (20-30s) at significant power levels (6-7MW) allow “advanced tokamak” studies under steady state conditions.

- High power (10-12 MW), short pulses (1-2 s) for the study of highest performance under transient conditions.

Ergodic Divertor

- Feedback control of the edge Te by Langmuir probes and gas injection made it possible to achieve stable plasma conditions and good RF coupling without the occurrence of detachment or disruptions.
- 3 density regimes have been observed: low density (linear with core density); high-recycling regime (cubic); and detached (density drop) occurring around 10 eV.
- Vented neutralizer plates allow particle collection; validated model.
- Optimum plasma radiation obtained at 20 eV at the edge; radiation is maximum for given core impurity content. Record poloidal beta of 0.5 for 5s.
- Te measurements at the edge reveal transport barrier with ergodic divertor; dynamic behavior of barrier is observed by ramping E.D current up and down.
- Impurity transport near the neutralizer plates has revealed local recycling of hydrocarbons and friction forces on ion transport.

Auxuliary Heating and Current Drive

- Improved confinement comparable to ELMy H-mode with ICRH H-minority heating has been observed at n=0.8nG. Improvement of electron and ions.
- Minority He3 mode operation of ICRH has been shown to provide Te=Ti to increase capability to study electron and ion transport.
- Fully non-inductive, steady state discharges at significant power levels and plasma densities: t=70s, I=0.6MA, n~2x1019m-3. The loop voltage was kept at zero via control of the LH power (3 MW). Discharge duration was much in excess of resistive time scale.
- Real-time current profile control has been achieved via feedback on the LH antenna phasing. The peaking of the plasma current (l_i) is actively controlled via the n// spectrum. LH and ICRF are being used as tools for profile control to achieve enhanced confinement modes under steady state conditions.
- Steady state discharge of 2 min with a large fraction of LH current drive. A total of 280 MJ was coupled to the plasma and removed by the cooling system. ==> Valuable experience for the “CIEL” project.

Radiative Discharges

- Highly radiative plasmas are achieved with limiter- and ergodic divertor discharges:
- In limiter discharges 50-70% radiation at densities up to 70% Greenwald density and improved confinement with H>1.5.
- Real-time feed back control (electron temperature, radiation level) is being developed via fueling and/or impurity seeding to optimize radiation.
- Best radiative discharges are achieved with ergodic divertor plasmas.
- Plasmas exhibit several characteristics of RI-mode discharges.

Plasma Transport and Turbulence

- Plasma rotation has been measured with crystal x-ray spectrometer and cx spectroscopy
- Analysis of plasma stability is performed, in particular for those discharges where improved confinement is observed. In the case of optimized shear discharges with transport barriers, it is shown that the barrier forms due to reversed shear conditions and that the barrier can become steeper whereas the shear does not reverse anymore, suggesting that another mechanism becomes responsible for improvement in local confinement.
- Modeling of ITG turbulence is carried out. 3D fluid modeling is used, showing that the characteristic scale of the turbulence decreases with the normalized Larmor radius according to Gyro-Bohm scaling.
- Correlations between turbulence and poloidal flow velocity

“CIMES”

“CIMES” = Composants pour L’Injection de Matiere et D’Energie Stationaire”

- Tore Supra systems designed in the 80’s, with objectives as foreseen at the time (1.7 MA, 30s, 15 MW)
- Since then, much progress :
  - **Technology: ITER defines needs for the next step (1000s FDR, 500s FEAT)**
  - **Physics: bootstrap, ITB, feasible route towards ss tokamak reactor**
- This progress allows to define more ambitious goal for Tore Supra:

  > 20 MW for 1000s
  - **Technology tests for power and pulse length are relevant for the next step**
  - **Demonstration that advanced regime extrapolates to steady state**

Tore Supra Upgrade Projects "CIEL" and "CIMES"

- To perform long-pulse, high performance discharges means to integrate physics and technology in all relevant fields:
  - **Power exhaust**
  - **Heating and current drive**
  - **Particle control (fueling & exhaust)**
  - **Plasma control (feedback loops…)**

- The CIEL project is designed to handle power and particle exhaust

- The CIMES project proposes to upgrade heating and current drive systems and the pellet injector to fully take advantage of the exhaust capabilities provided by CIEL:

P_{ICRH}= 9 MW, P_{LHCD}= 12 MW, P_{ECRH}= 2 MW (25 M€ over 9 years)