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ICRF facility experience

ICRF facility overview — *launchers, transmission lines, transmitters*

Best results — *highest power / energy shots*

Technological issues — *internal matching component*

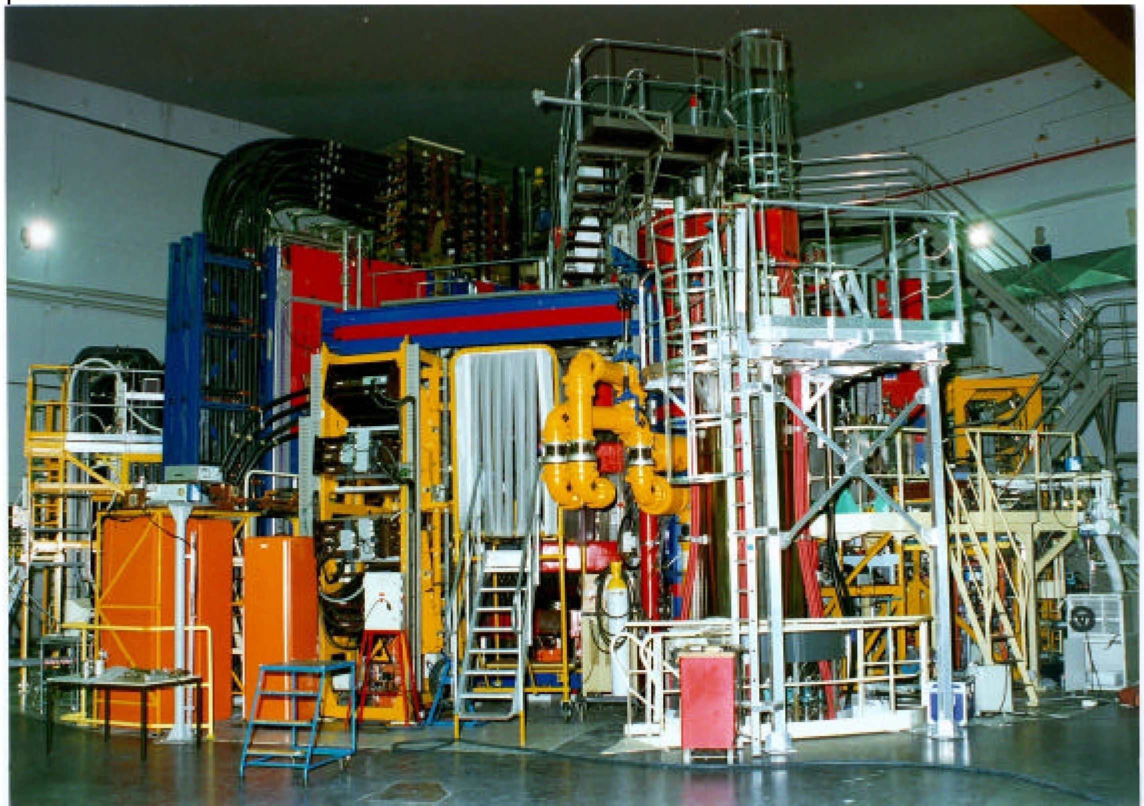
edge localised hot spots

Future plans — *CIMES*

S. BRÉMOND

On behalf of TS ICRF Team

TORE SUPRA OVERVIEW



- NbTi Supraconducting TF coils
- B_T= 4.5 T at magnetic axis
- R0 = 2.35 m
- a = 0.8 m
- Ip = 1.7 MA
- RF heating:
  - ICRH (3 launchers)
  - LH (2 launchers 6 MW)
  - ECRH (300 kW, being installed up to 2.4 MW)
- New CIEL configuration (25 MW 1000 s exhaust capability)

ICRF FACILITY OVERVIEW

Number of plug-in launchers	3
Number of straps (toroïdally adjacent) per launcher	2
Number of power feed line / vacuum windows / transmitters	6
Frequency range	35 – 80 MHz
Nominal RF power of one generator on a VSWR<1.1	2.2 MW 30 s
RF pulse duration / duty cycle	30 s / 0.125
Type of transmission line	9" 30 Ω

First ICRF shot : 1991

Maximum coupled power : 10 MW

Maximum coupled energy : 130 MJ

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TORE SUPRA ICRF LAUNCHERS

Screened

- B4C coated Faraday screen bolted on the antenna box

- tilted bars (7°)

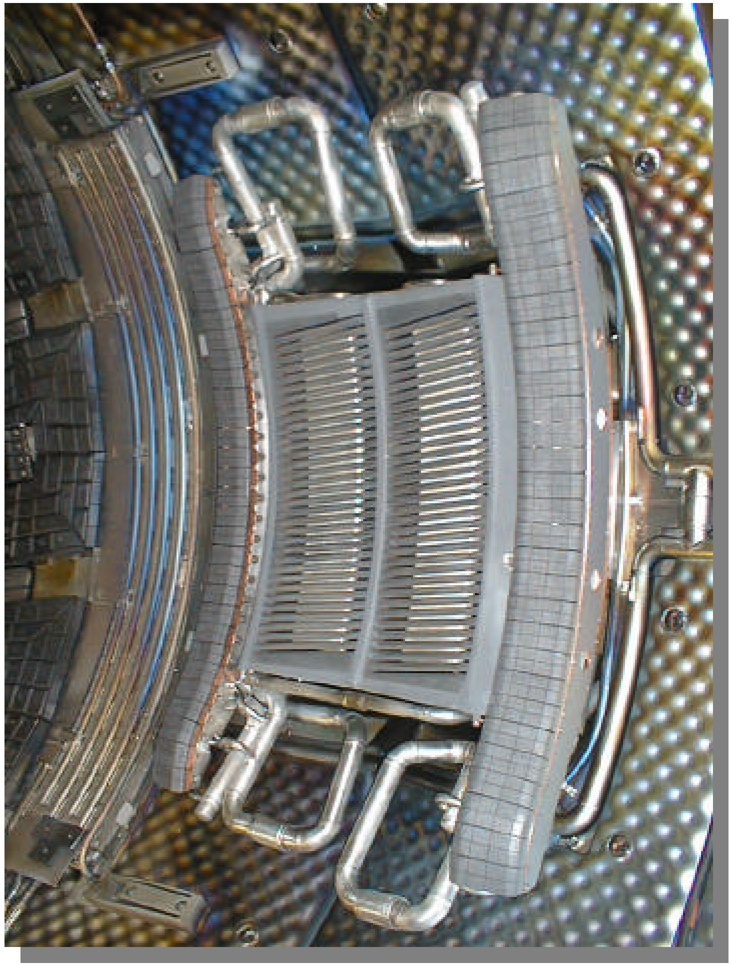
- septum between the two straps

Partially cooled

- lateral protections covered with CFC tiles (presently 10 MW/m2 exhaust capability) and FS cooled by 150°C water

- straps and capacitors cooled by room temperature water

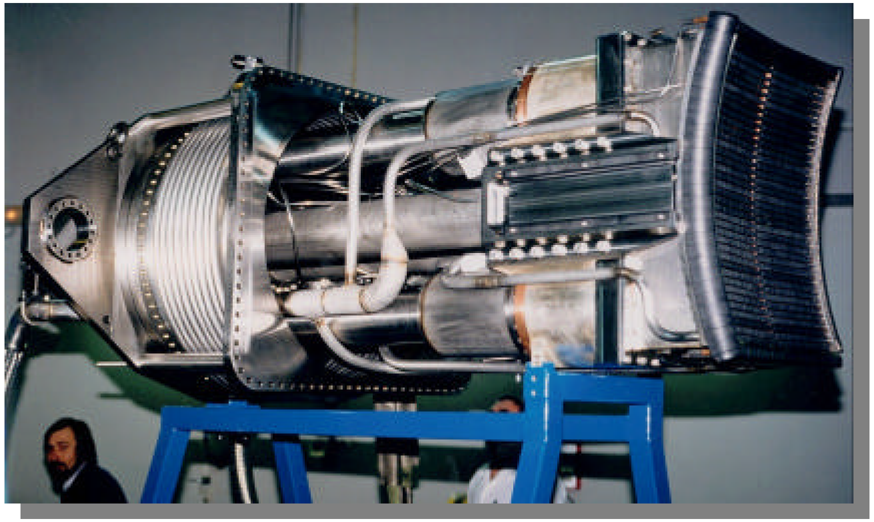
Radially movable

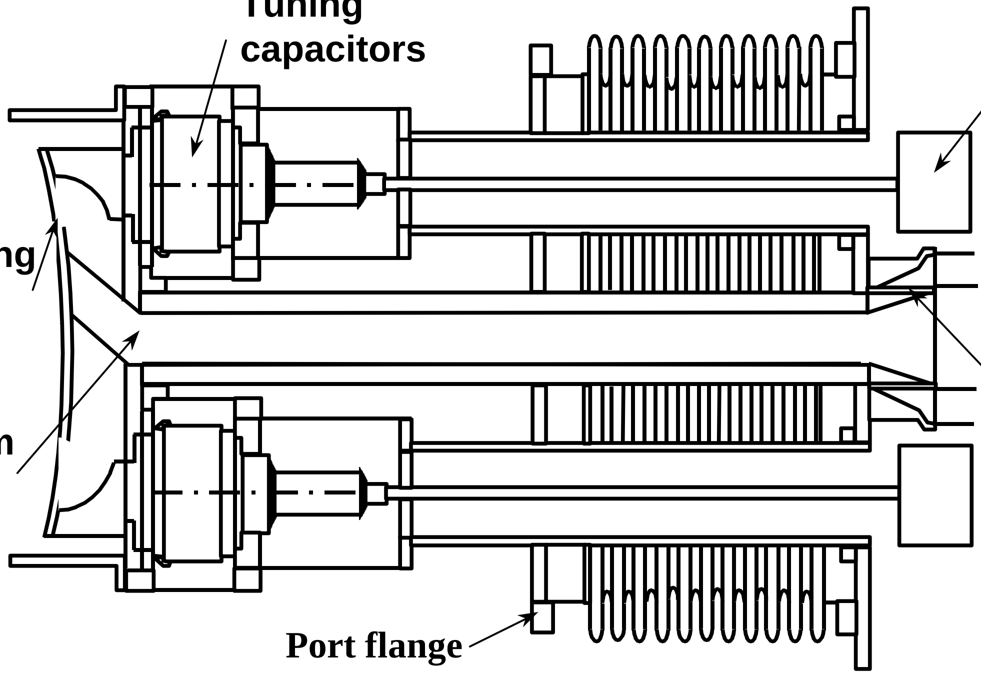


Present status of TS ICRF launchers

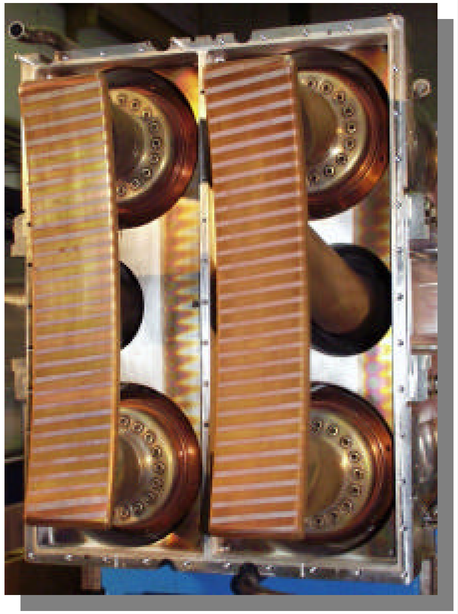
RESONANT DOUBLE LOOP CONFIGURATION

Unique operational tokamak provided with RDL antennas (originally proposed by ORNL)





INTERNALLY MATCHED ANTENNAS



***RDL** : extent of the resonant circuit -where high RF voltage and current occur- limited to the strap itself and the two matching capacitors*

***advantages** over conventional loop antenna structure:*

(i) losses in the transmission lines minimised

(ii) feed line voltage stand-off requirements (especially at the vacuum window) minimised:

11 kV for 2 MW in a 30 W line

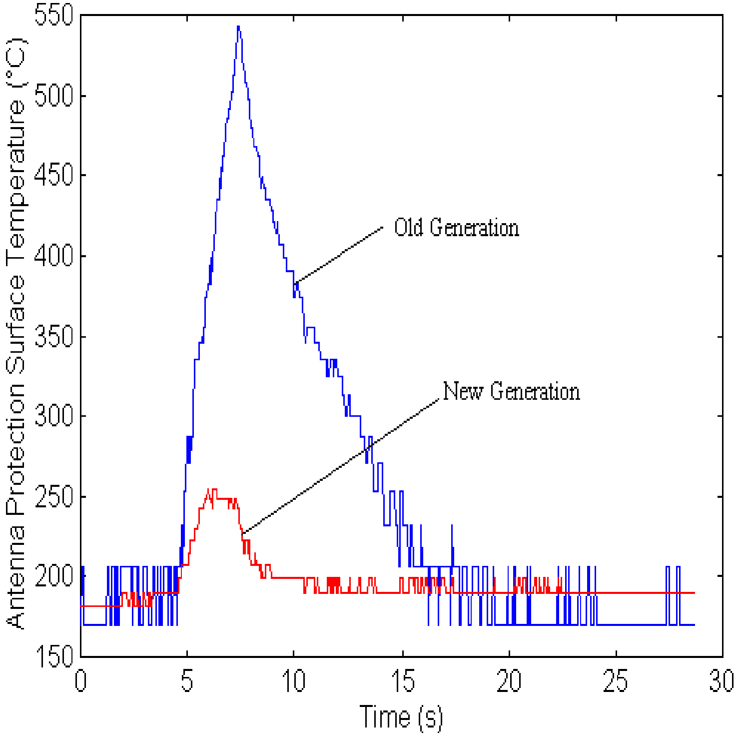
power density world record 16 MW/m^2

4 W/m typical value of loading resistance to be compared to 0.15 W /m in vacuum (96% efficiency)

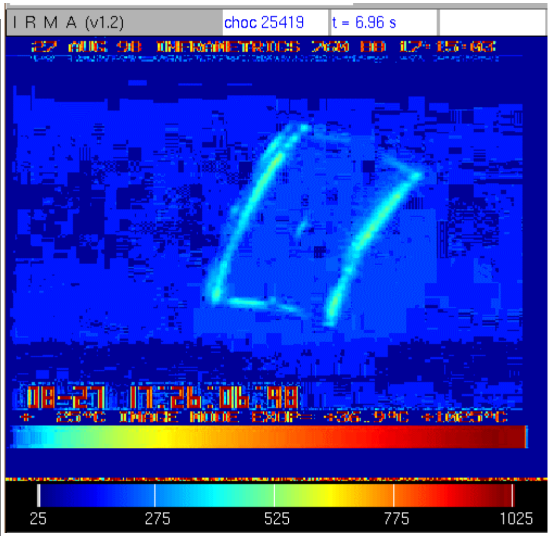
***Automatic matching system** : closed loop control of the capacitor electrodes position,*

time constant ~ 100 ms

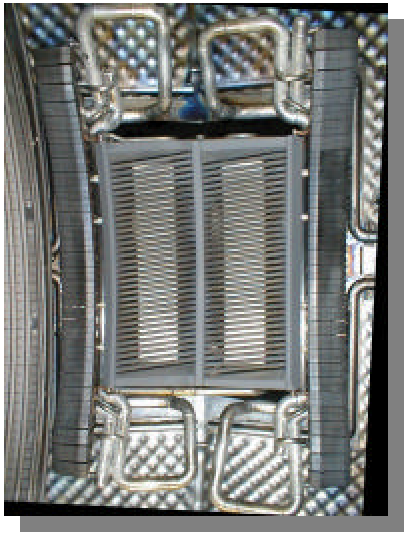
PROTECTION HEATING LIMIT: NEW vs OLD PRIVATE LIMITER



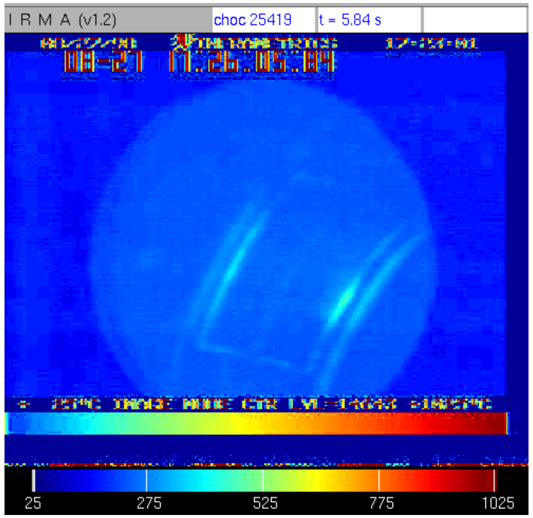
Old Private limiter



IR picture



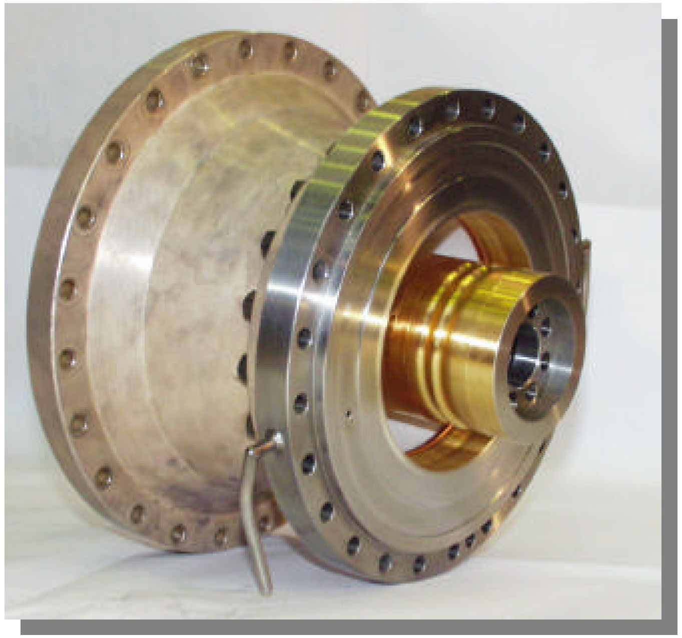
New Private limiter



IR picture

VACUUM WINDOW

- 30 W window
- alumina ceramic cylinder
  brazed to soft copper sleeves



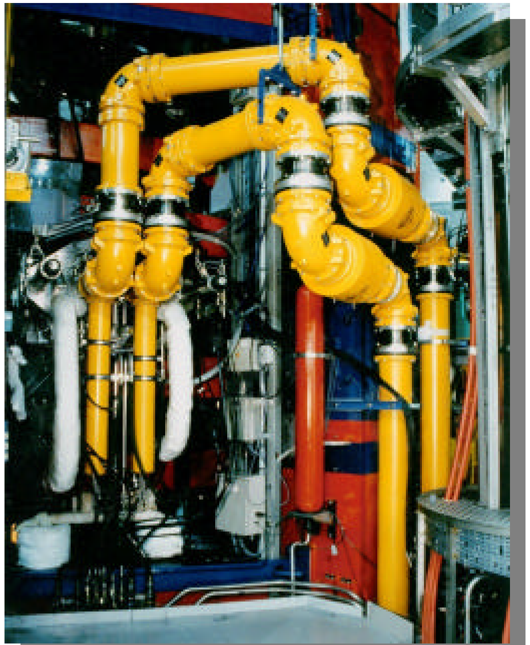
Present limitation :

- specified for 2MW (11 kV, 365 A) / 30 s
- tested at 30 kV 30 s, 45 kV 100 ms
- Thermomechanical calculations:
  may withstand up to 2 MW ~ 100 s
  additional cooling required to extent pulse length

TORE SUPRA ICRF TRANSMISSION LINES

9" 30 W (230 / 140 mm outer/inner conductor) coaxial line

- *pressurised with 3 bars nitrogen*
- *Aluminium / Copper outer / inner conductor*
- *ceramic rods support*



Present limitation :

thermal limitation to 700 kW CW

(instead of 2 MW 30 s)

TORE SUPRA

ICRF TRANSMITTERS

30 - 80 MHz frequency band capability

RF power chain : synthetiser, modulator, solid state wide band amplifier + 3 stages tetrode amplifier

- Tetrode tubes associated to coaxial cavities pretuned for 5 selected frequencies:

42, 48, 57, 63, 76 MHz with ± 2 MHz bandwidth at -1 dB

weaker part: decoupling capacitor?

Thomson Tubes Electronic (presently THALES) tubes

- first / second stage: TH 561 / TH 535

- high power stage: TH 526 upgraded to TH 525 upgraded to TH 525A

THALES ICRF HIGH POWER SOURCES

Present limitations:

- ***Tubes operational limits** for VSWR < 1.1*

- short pulses (< 30 s) Output power / Anode dissipation

TH 526: 2 MW / 0.9 MW 42-80 MHz

TH 525: 2.2 MW / 1.3 MW 42-63 MHz

1.2 MW / 1.3 MW 76 MHz

TH 525A (better anode cooling):

2.2 MW / 2 MW 42-63 MHz; ~1.8 MW (VSWR = 2)

1.2 MW / 2 MW 76 MHz

- long pulses (thermal limitation on grids and socket)

1.5 MW CW (thermal equilibrium at 1000 s) (1.2 MW CW VSWR=1.5)

no improvements achievable with tetrodes: diacrodes?

TH 628: 2 MW CW VSWR<1.5; "ITER" 2 MW CW VSWR=2

- ***Sharing of the DC anode Voltage Power Supply of the high output stage by a pair of generators (competition between screen grid current and anode voltage) separate PS to be provided (under way)***

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TORE SUPRA ICRF FACILITY

BEST RESULTS

Highest power shots :

4.5 MW (4 MW 1s) with 1 launcher
8 MW (7.5 MW 1s) with 2 launchers
10 MW (9.3 MW 2s) with 3 launchers

Highest energy shots :

80 MJ (3 MW 27s) with 1 launcher
130 MJ with 3 launchers

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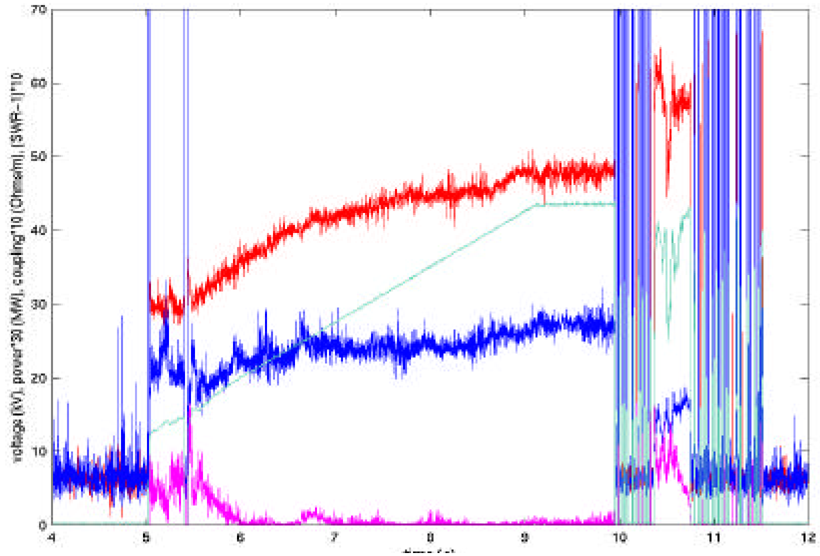
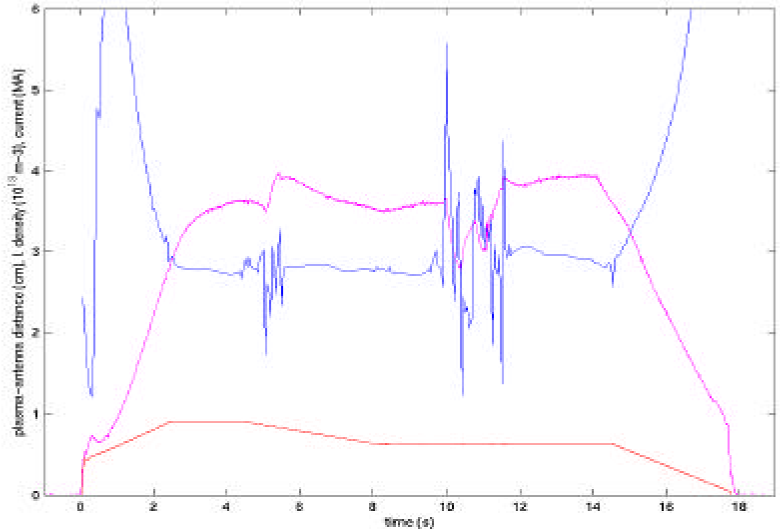
Maximum plasma operation
RF voltage

(ends of straps)

60 kV 500 ms
45 kV currently achieved

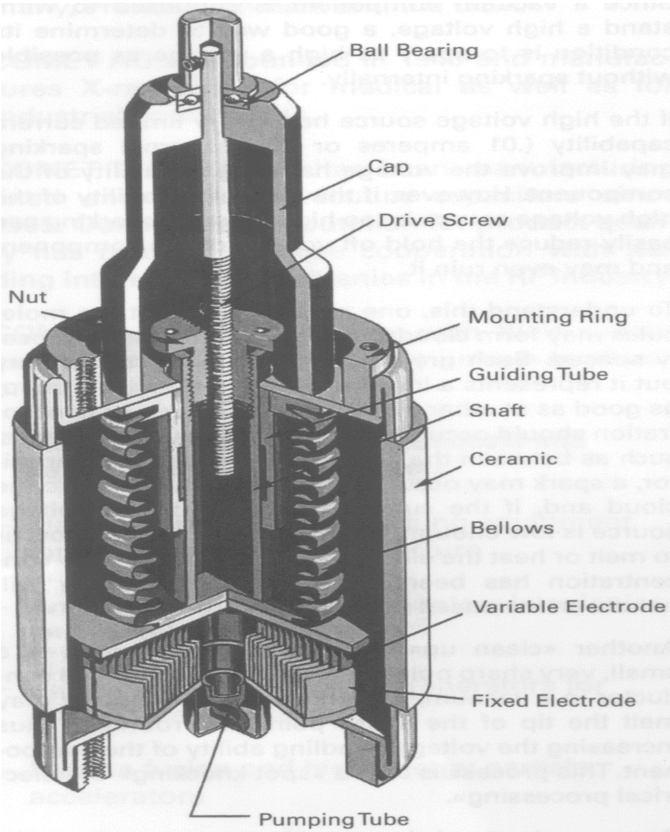


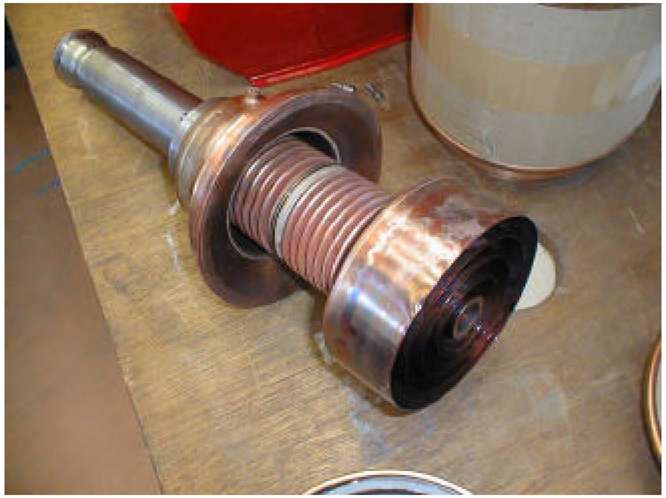


Tore Supra pulse 28119

INTERNAL MATCHING COMPONENT ISSUE

COMET vacuum sealed
tuning capacitors presently used





COMET CAPACITOR LIMITATIONS

Present Limitations

- Maximum peak working Voltage specified (capacitive part) TS type : 54kV
- Current limited by temperature rise (maximum steady state temperature at the ceramic metal interface 150 °C) e.g TS type figure

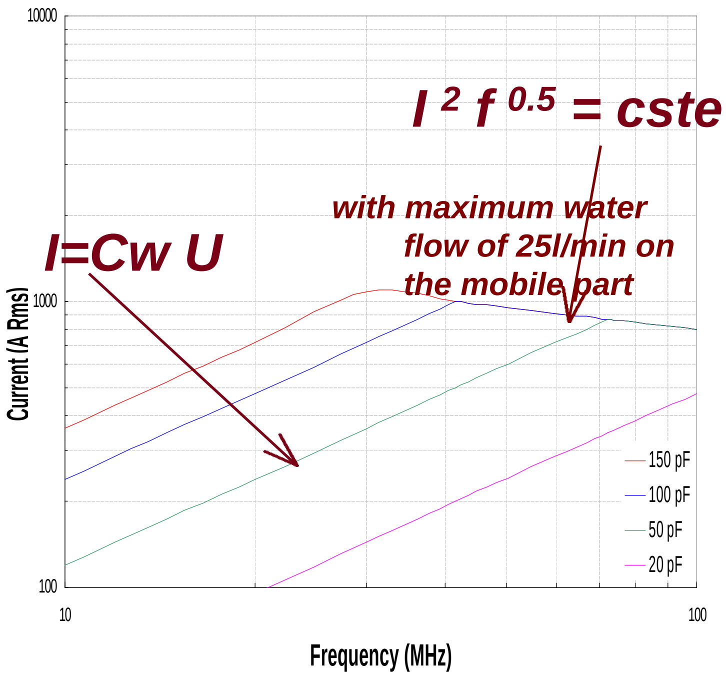
Thermomecanical calculations

made for TS type: time constant ~ 40s

limitation ~ 2 min?

Current limit for CV7W 15-150 E

Capacitor voltage - current ratings



Caution for use (cooling)

- Minimum water flow (to prevent overheating of the bellows due to trapping of air bubbles)
- Very low Maximum inlet pressure (to lower mechanical stresses on the bellows)

  TS type : 1 bar specified;
- Non corrosive water

  TS demineralized water

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COMET CAPACITOR RELIABILITY ISSUE

About 40 units used since the beginning of TS IC system (10 years)

Several failures experienced with TS COMET type capacitors

almost all of them due to “holes” (leak detectable with He at 10^{-5} mbar l/s) on the internal bellow (weak part of the component which must achieve both transport of the RF current, mechanical mobility and sealed vacuum isolation)

Heavy consequences (power and/or time loss) :

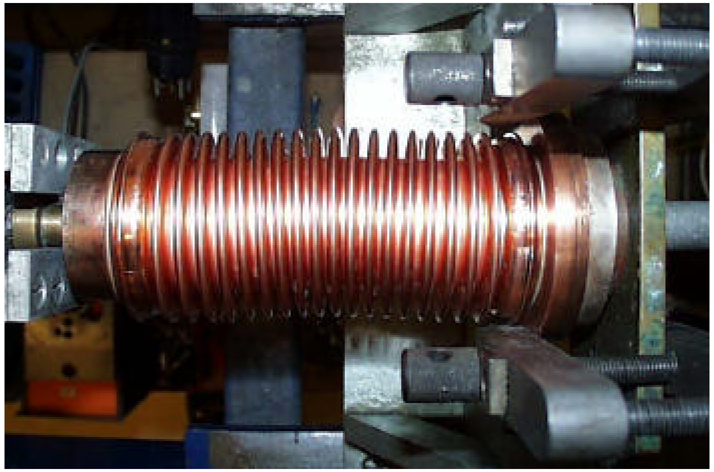
loss of the power capability of the antenna, requires to break the vacuum and dismount all the antenna (~ 5 weeks) to recover the power

Vacuum vessel containment maintained by the ceramic cylinder (Cf. Tritium barrier issue for JET): possible to continue operation without dismounting the antenna

Origin of the failures : manufacturing method (corrosion sources, snapping effect), cooling issue

INTERNAL MATCHING COMPONENT R&D

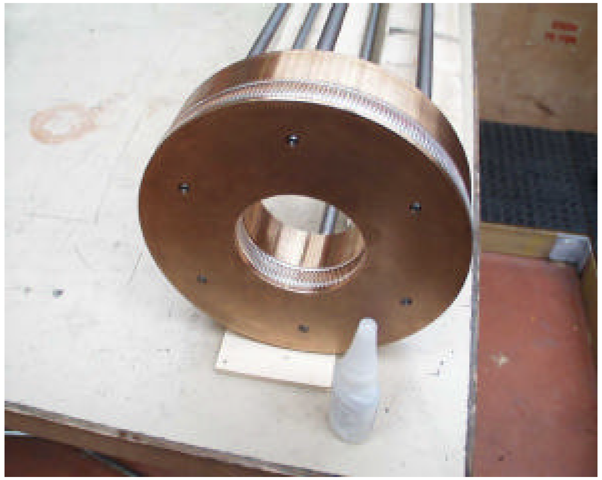
R&D on COMET capacitors using stainless steel copper plated bellows



First results: destructive fatigue test (full stroke, 3 bars) ~ 11 000 cycles
2 TS (delivered) and 3 JET-EP (tp b e delivered) prototypes capacitors to be tested

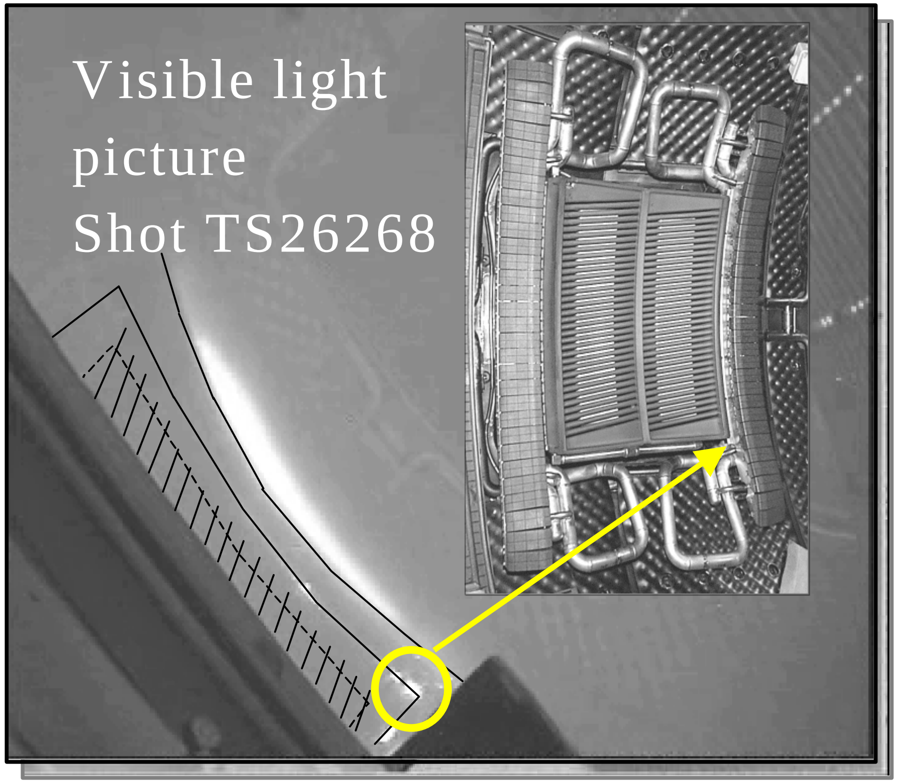
R&D on alternatives solutions

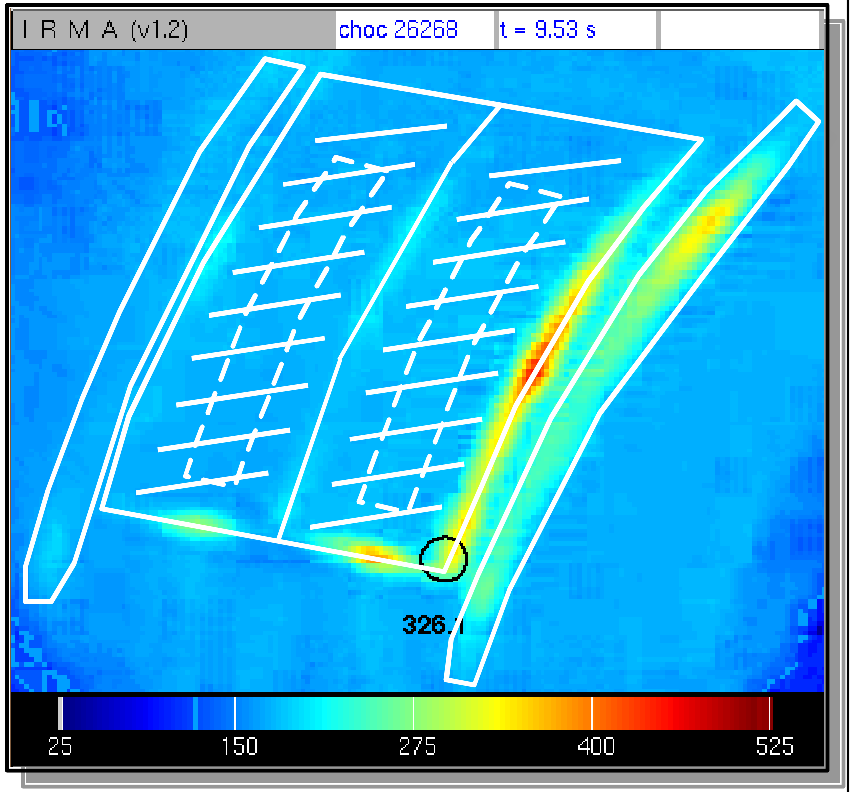
- *All-metal impedance design*
- *Sliding contacts tests*
  - *Pantechnik*
    60 A/cm 60 s
    limited operational température
  - *multilam*



EDGE LOCALISED HOT SPOTS

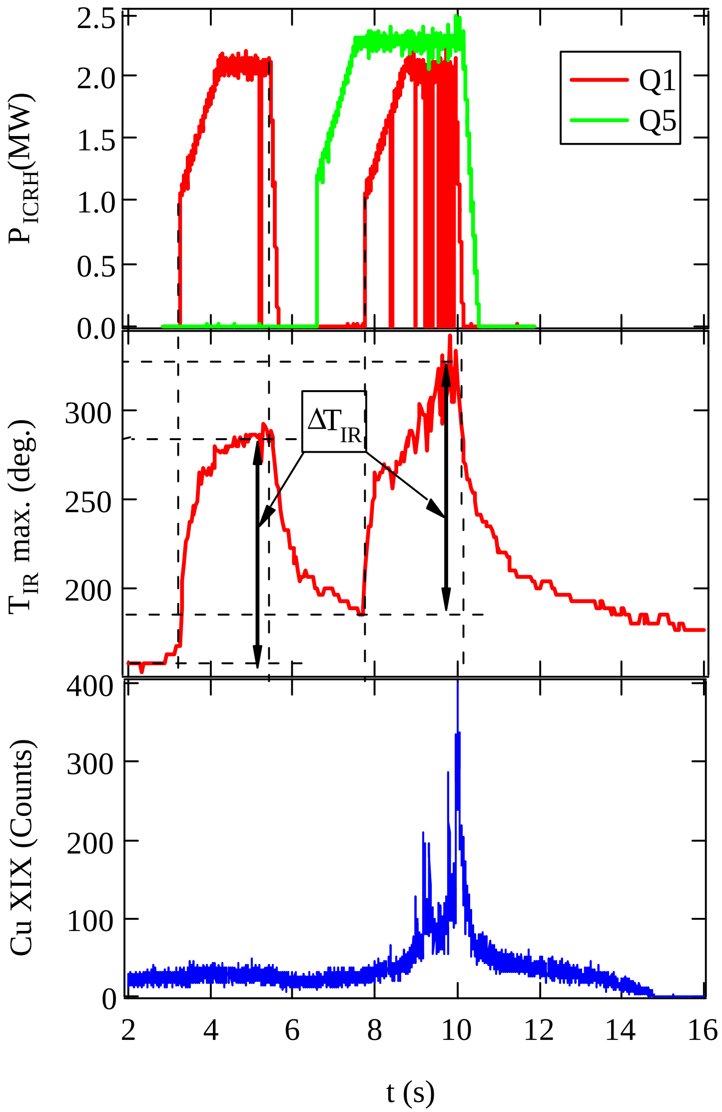
Localized hot spots (heat loads) on Faraday screen frame (clearly distinct from hot spots on septum due to edge IC parasitic layers)





may stay up to 500 ms after a disruption

HOT SPOTS EXPERIMENTAL OBSERVATIONS



- ***Only occuring on powered antenna***
- ***Time constants at switch-on and switch-off (100 ms) characteristic of a thermal process***
- ***Edge density modifications in regions connected to ICRF antennas.***

Parametric scans

- ***do not depends on:***

frequency, scenarios (Minority/FWEH), edge safety factor, peripheral IC layers, plasma vertical position

- ***do depends on:***

plasma density, distance to LFCS, power, coupling resistance, limiters configurations

Local n_e(antenna) + E_{RF} (antenna)
Þ RF sheath effect suspected

HOT SPOTS MODELLING

3-D mapping of E_{RF} with ICANT code. (S. Pécoul)

Realistic antenna geometry
Realistic plasma model

$Q_{//}=en_i c_s V_{rect}$

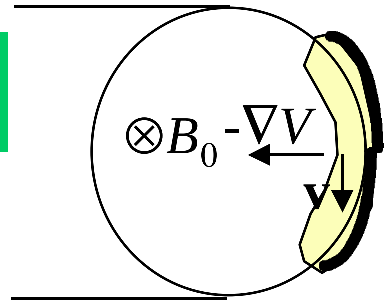
$$\tilde{V}_{RF} = \int_{field\,line} \mathbf{E_{RF}.dl} \Rightarrow \bar{V}_{rectified}$$

$\nabla V \times \mathbf{B}$ vortices
CELLS code,
(M. Bécoulet)

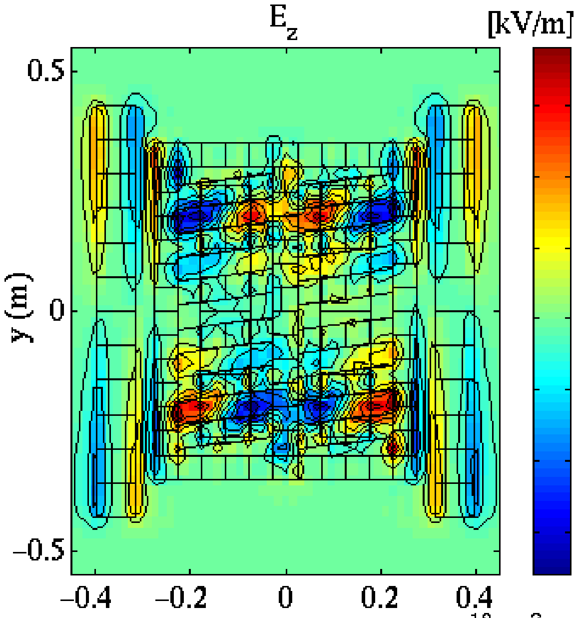
Field line tracing
Magnetic connections

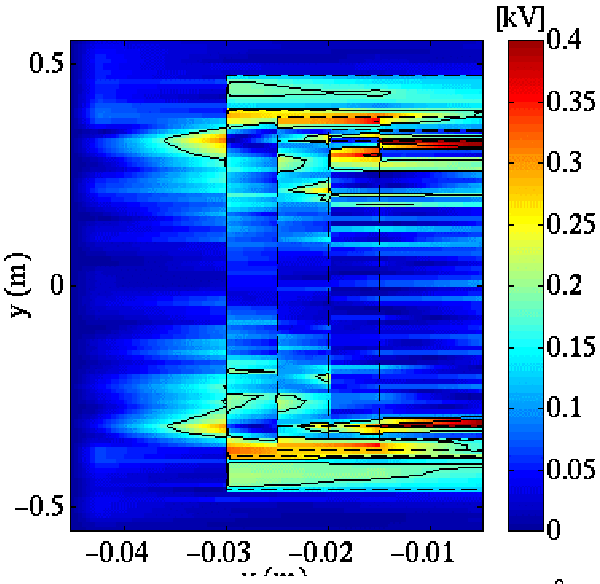
1-D RF-sheath model

Local plasma parameters



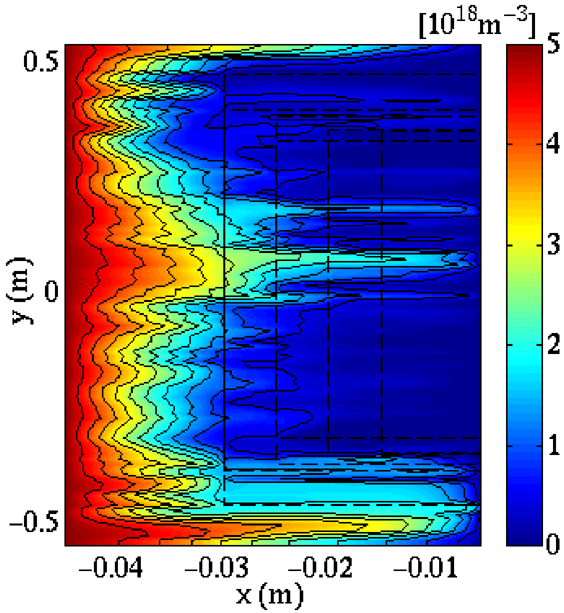
3 D Self - consistent RF field calculation

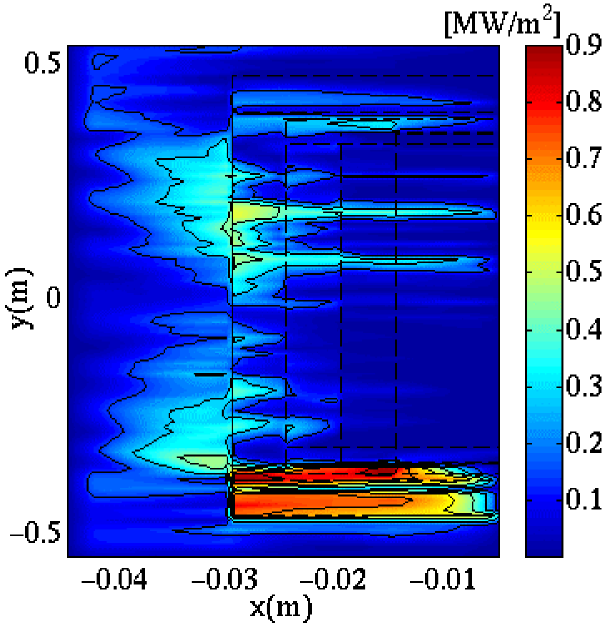




Rectified potential V_{rect} for 1MW coupled, dipole phasing

Density pattern





Heat load patterns

HOT SPOTS HISTORY AND FUTURE

1998 : - Light flashes coming from the antenna bottom right corner
- Impurities released sometimes causing disruptions
- Traces of arcs and erosion

Action: Corners modified, mettalic electrical connexion between antenna box and lateral protections, strap - bumpers radial gap increased on one launcher

1999: - no more arc, still not spots and little erosion

2001: experimental campaign to come in CIEL configuration:
B_t and I_p reversed => v_d reversed. Heat load on top left corner ?
Project : Langmuir probes on antenna structure.

FUTURE PLANS

CIMES project: Upgrade of the heating and refuelling systems of Tore Supra

Final Objectives: 20 MW RF heating & pellet injector for 1000 s

(original Tore Supra specifications: 15 MW 1.7 MA 30 s)

Stage I (LH + pellet injector) funded and started

- new 700 kW new klystrons (prototype + series o f 16 for 2 launchers)
- 1 second Mk II launcher
- pellet injector

Stage II (ICRF) foreseen in 2002

- 2 MW CW VSWR 1.5 diacrodes (prototype + series of 6 for 3 antennas)
- 3 new antennas