EUROfusion

25th Topical Conference on Radio-Frequency Power in Plasmas

40 Years of ICRF Operation on JET: Challenges and Achievements

P. Dumortier on behalf of the JET RF team

LPP-ERM/KMS, Brussels, Belgium, TEC Partner

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Acknowledgements

P. Dumortier[1], I. Monakhov[2], P. Jacquet[2], F. Durodié[1], E. Lerche[1], R. Lobel[2], M.-L. Mayoral[2], C. Noble[2], J. Roberts[2], H. Sheikh[2], JET Contributors[3] and the EUROfusion Tokamak Exploitation Team[4]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]LPP-ERM/KMS, B-1000 Brussels, Belgium, TEC partner
[2]UKAEA, Culham Campus, Abingdon, Oxfordshire, OX14 3DB,United Kingdom
[3]See author list of C.F. Maggi et al 2024 Nucl. Fusion 64 112012
[4]See author list of E. Joffrin et al., 2024 Nucl. Fusion 64 112019

JET

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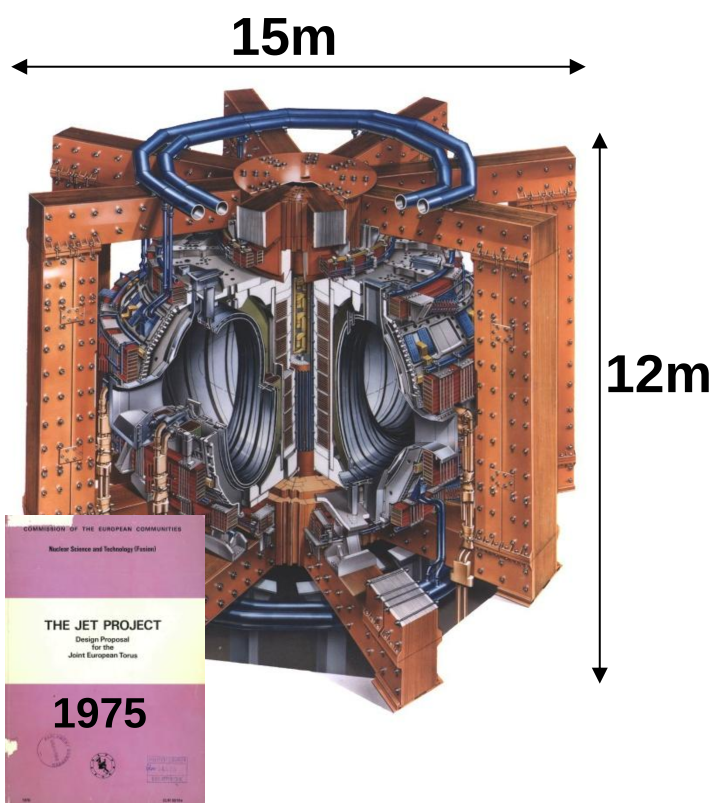
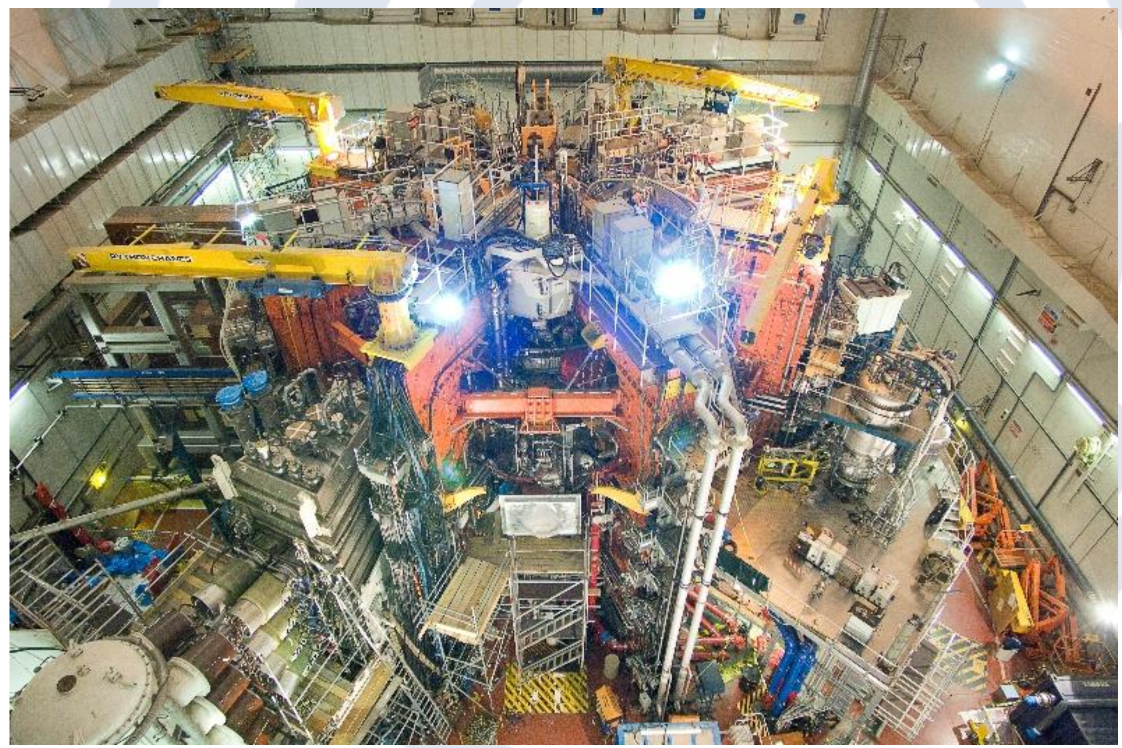
Trilateral Euregio Cluster TEC

UK Atomic Energy Authority

The JET Project

- JET started as an extremely ambitious project with many novelties such as:
  - **D-shaped** plasmas
  - Designed as a **nuclear machine for D-T operation** and **full remote handling capability**
  - Designed to **confine alpha particles**
  - **Plasma volume** and **heating power two orders of magnitude larger than existing machines**

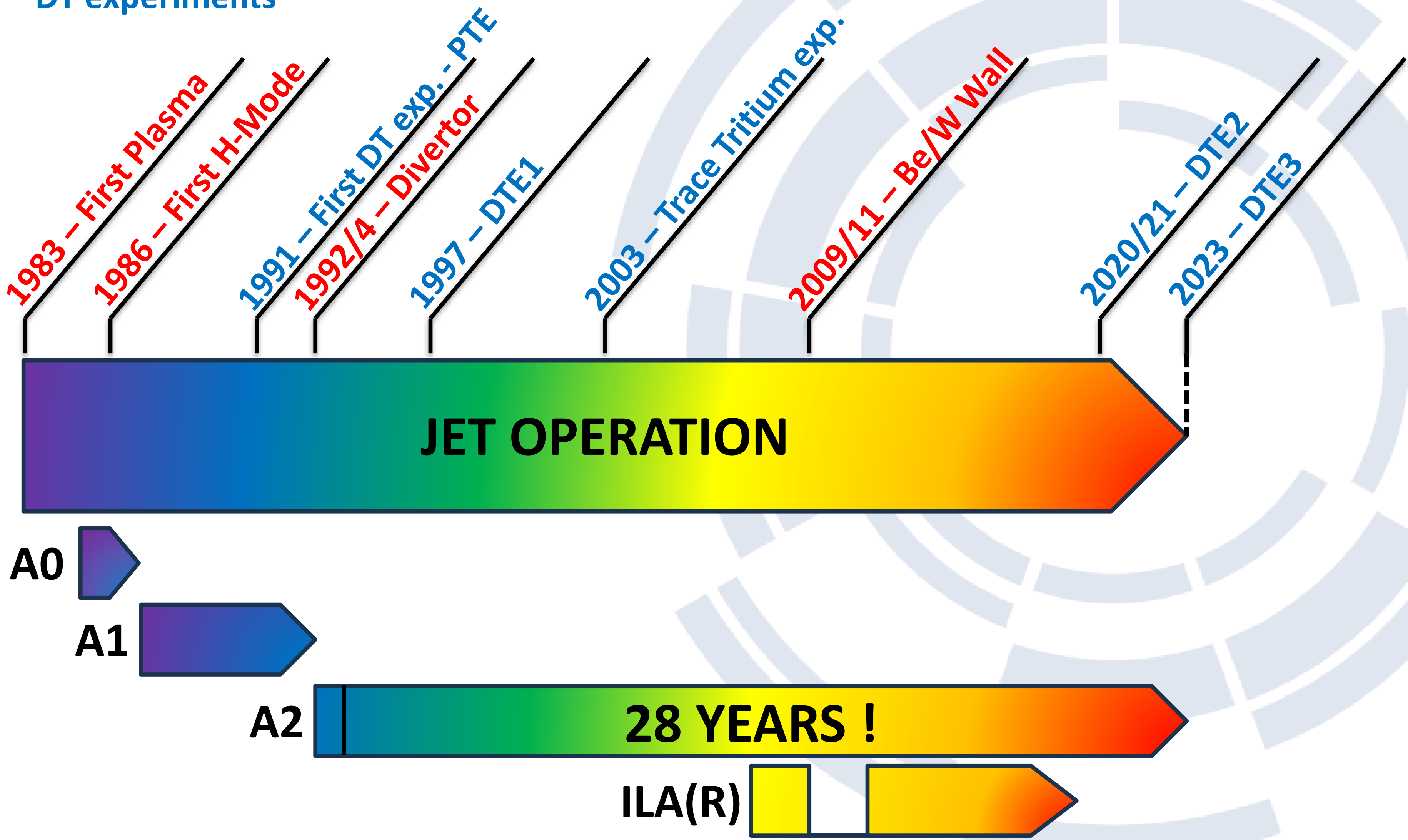




JET Operation Timeline & ICRF Antennas

Main milestones impacting ICRF

DT experiments



The JET ICRF Project

- **Everything was a challenge** ! To cite a few:
  - **Maximize coupling**
  - **Minimize impurity production**
  - Coupling **unprecedented levels of power and energy into the plasma** !
    1.5MW/antenna for 10 s i.e. 15MJ (compared to 0.1MJ in TFR and 0.8MJ in PLT)

COUPLING CHALLENGE

IMPURITY CHALLENGE

POWER CHALLENGE

MATCHING CHALLENGE

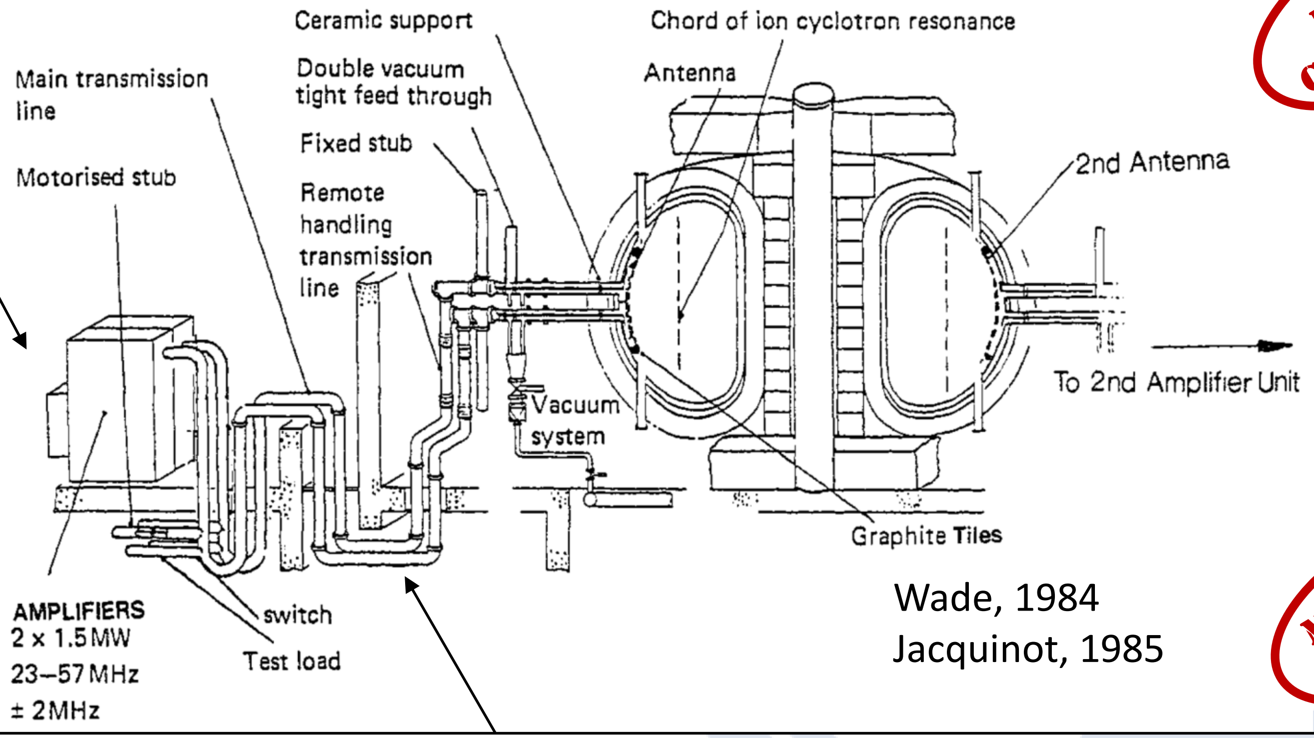
- Some elements of the **design philosophy**:
  - Use of **existing** and **proven technology** as much as possible
  - Extensive **testing** of antenna, prototypes and components on dedicated test-bed
  - Compatibility with D-T plasmas, **remote installation and maintenance**
- **Heating** of JET plasmas in a range of ion species (**H, D, He3, T**), plasma parameters and B_t
  → Large operating frequency range required : **23-57MHz**

Development of a highly flexible and versatile high power ICRF tool

The ICRF Plant & Matching System

- High power: 16 x 1.5MW amplifiers (Herfurth) – upgraded to **16 x 2MW** in 1989
- Large operating frequency range: **23-57MHz** (except 39-41MHz) in eight bands of 4MHz
- Amplifiers designed to be **broad-band** and allow **'instantaneous' frequency shifts** of ±2MHz – unique feature at these power levels and frequencies !

POWER CHALLENGE ✓



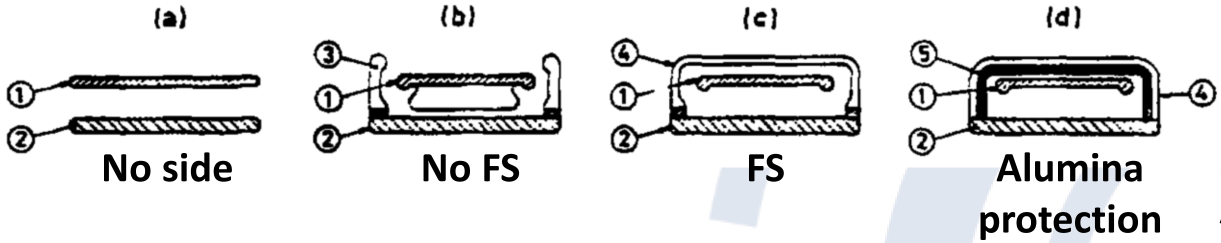
Wade, 1984
Jacquinot, 1985

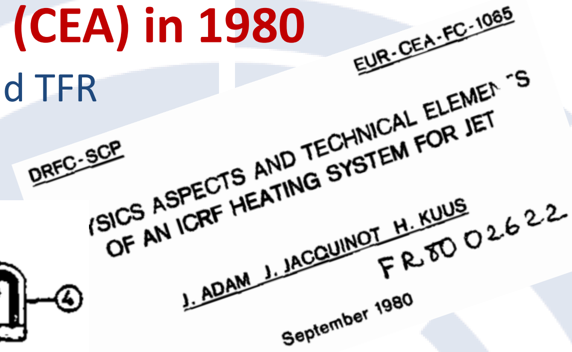
MATCHING CHALLENGE ✓

- **84m long 30Ω TL** (Spinner) – special design for JET, 3 bar pressurized, 50kV rating
- **Matching** realised by **tuning stubs** at generator end and **frequency variation** (≤100kHz)
- Prematching stub can be installed close to the antenna used in certain conditions

The early days of antenna design for JET ICRF

- **Antenna design work started at Fontenay-aux-Roses (CEA) in 1980**
  - Based on results from Diva, Erasmus, Macrotor, Microtor, PLT and TFR
  - Several options envisaged





Adam, 1980

  - Option C retained
  - 6 MW coupled in one port with 4 launching elements (LFS mount)

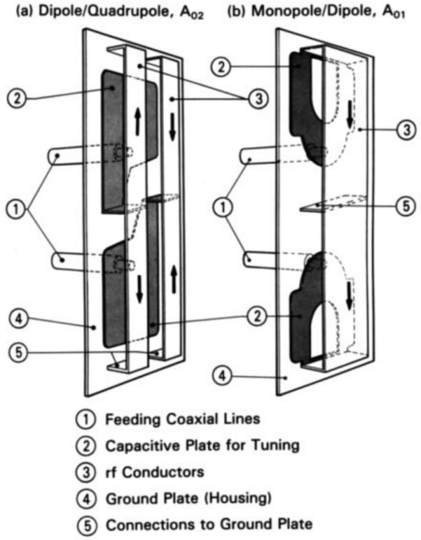
COUPLING CHALLENGE

- **Three new design features**
  - **Enhance coupling** by moving the antenna closer to the plasma -> **antenna-limiter concept**
  - Active cooling of the **15° tilted Faraday screen bars**
  - **New shapes of radiated wavelength spectra** : from usual (at the time) monopole to so-called quadrupole antenna
- **Main concern : high level of impurity**
  - Incentive to **investigate other phasings** than monopole (exclusion of long wavelengths generating edge modes)
  - Increased coupling requires antenna close to plasma edge -> **low-Z side protections**
  - **Tilted FS bars to reduce surface modes**

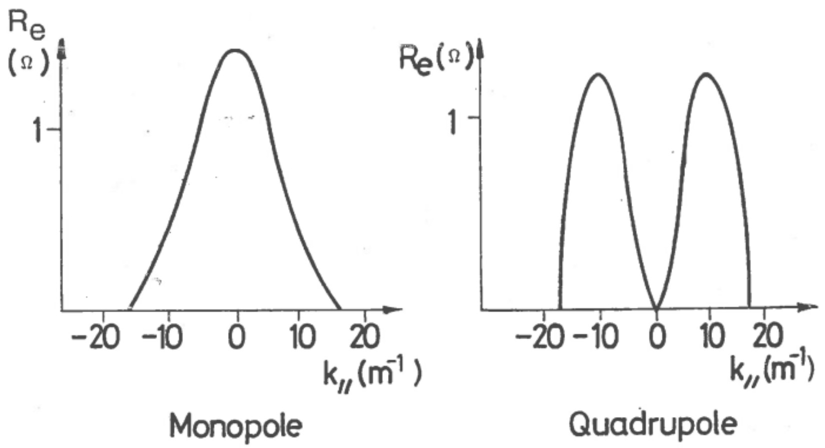
IMPURITY CHALLENGE

First generation of antennas – A0

- **1984: installation of 2 A0 antennas**
  - Designed for short pulse (uncooled)
  - **Give operational experience** for optimisation of future antennas
  - Two types of central conductor: **monopole and quadrupole**; quadrupole expected to **reduce impurity** produce at the cost of **lower coupling**
  - Antenna-limiter protected by **graphite tiles** to reduce impurity production
  - **15° tilted Faraday screen bars** to minimise excitation of surface modes
  - Tested on the TFR testbed
  - **All components tested** up to 45kVp and 1.5kAp @ 60MHz, multipactor region [50,2500] V
- **1985-1986: Start of operations**
  - Two 3MW units installed
  - Third A0 connected
  - 5MW and 10MJ coupled to the plasma
- **1987**
  - **Up to 17 MW coupled** in limiter plasmas
  - **Impurity levels decreased with tilted Faraday screen bars and dipole operation**



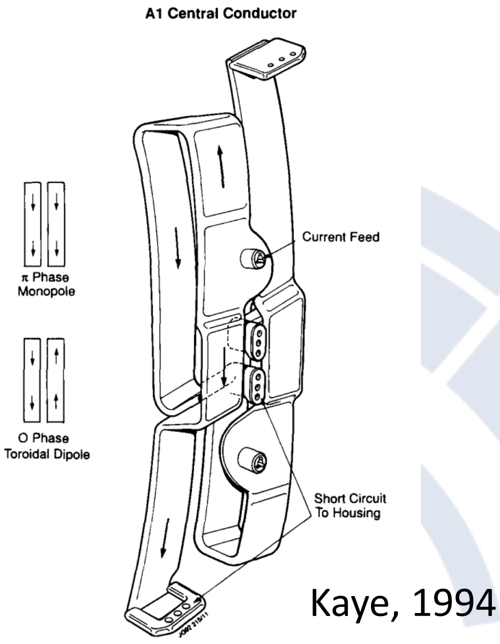
Kaye, 1986



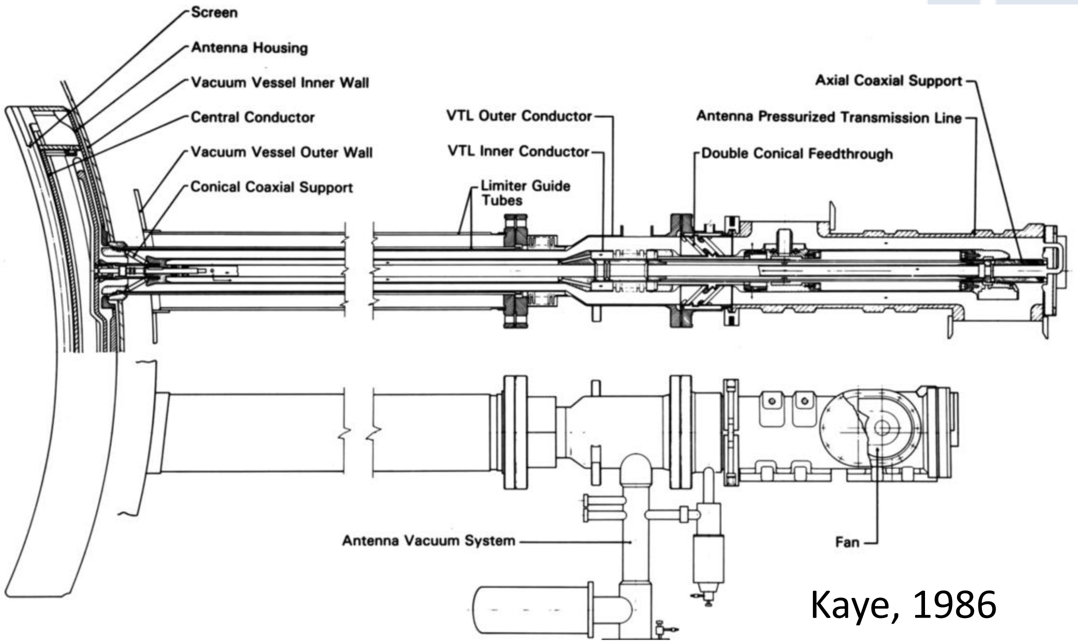
Arbez, 1984

Second step – A1 antennas

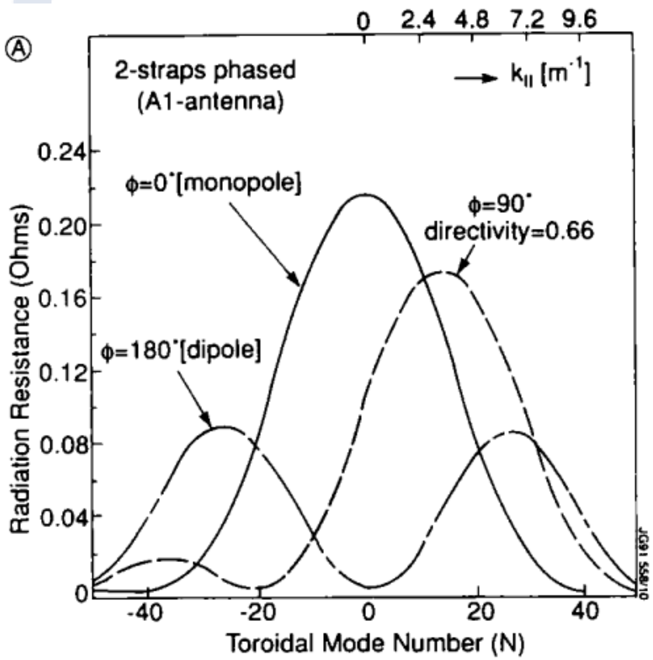
- **1987: installation of 8 A1 antennas**
  - **Integrate A0** design and **operational experience**
  - **Water-cooled** Ni screen bars and frame
  - **Tilted Ni Faraday screen bars** (operation with Be evaporation)
  - Two **conical ceramics vacuum windows** with generous corona rings
  - **Dipole** ($k_{//,max}$=7m^{-1}) or **monopole** operation ($k_{//,max}$=0m^{-1})
  - Possibility to test other phasings (**π/2** for CD)
  - Thorough **testing** of major antenna components (50kV – 20s)
  - **Automatic matching system** (stubs, trombones, frequency shift)



Kaye, 1994



Kaye, 1986



Meeting the impurity reduction challenge

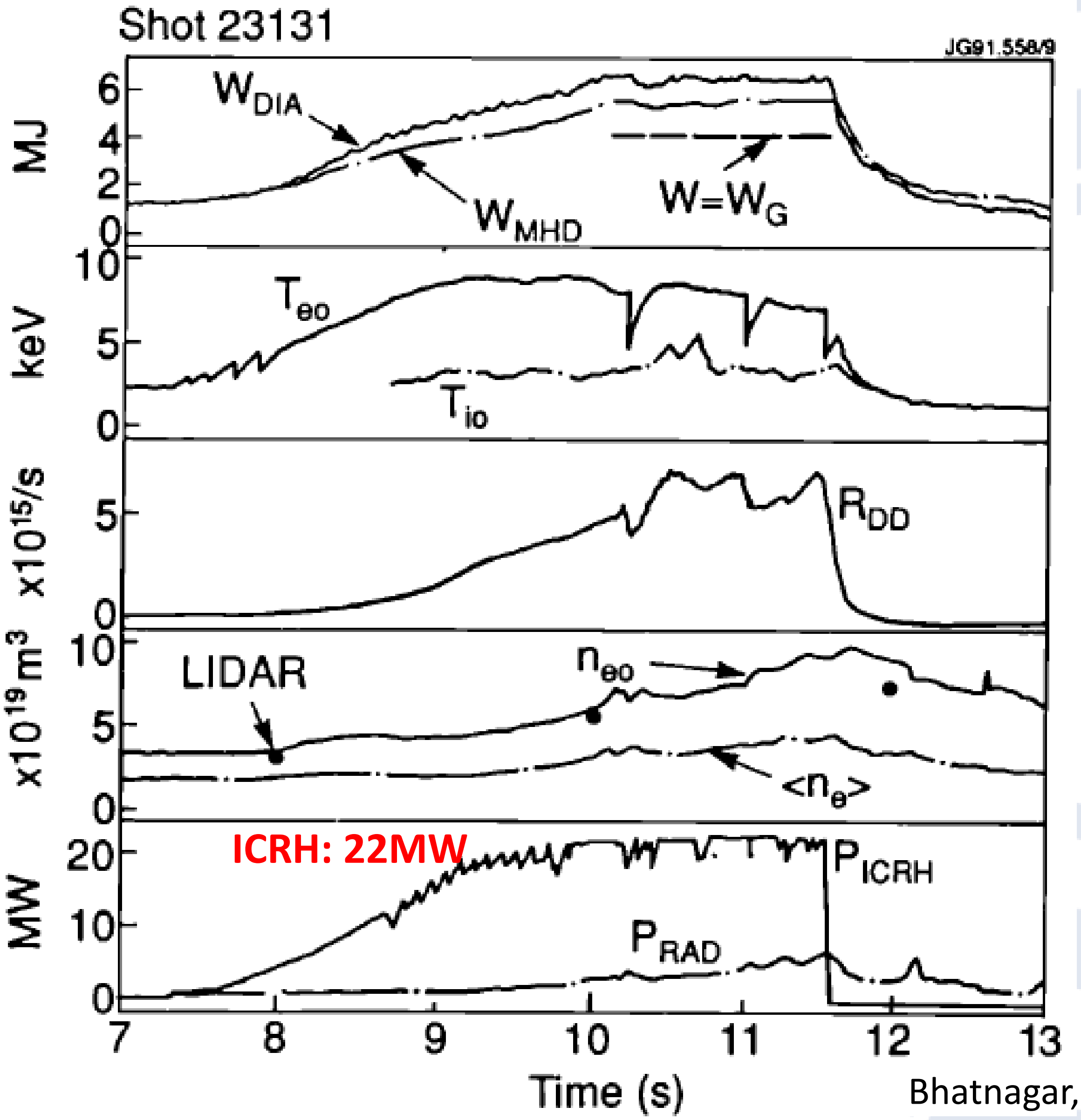
- **Overcoming the RF-specific impurity production**
  - Progress in the **understanding** and modelling of the role of **RF rectified sheath** effects
  - 1989: **Be Faraday screen bars** instead of Ni
    - Lower the Ni impurity release (low Z and self-sputtering coefficient < 1)
    - No active cooling required (simplified design)
    - Open screen design to reduce further RF losses in screen
  - Impurity levels further reduced by
    - **Aligning the Faraday screen bars** to the static magnetic field
    - **Lowering the density at the Faraday screen** by the use of side limiters
    - Preferably operate in **dipole phasing**
  - Use of **carbonization** and **Be evaporation**

IMPURITY CHALLENGE ✓

- **Achievements**
  - Coupled **22MW on plasma** (26.3MW generated)
  - Coupled **200MJ** into single plasma
  - **Long pulse** operation up to 60s
  - **RF-only H-mode** achieved (up to 12MW coupled)
  - Operation with **π/2 phasing**
  - Reliable operation on plasma up to **30kV**, electric fields of 2.2kV/mm parallel to Bt, pressure in VTL < 10^{-4}mbar
  - Arc damage at conical ceramic (support of inner conductor) unexplained and failure of **arc protection** (needs improvement)
  - Constant **R_C real time control** developed for H-mode by feedback of the **plasma position**

POWER CHALLENGE ✓
MATCHING CHALLENGE ✓
COUPLING CHALLENGE ✓

Record ICRH coupled : 22MW H minority heating in D



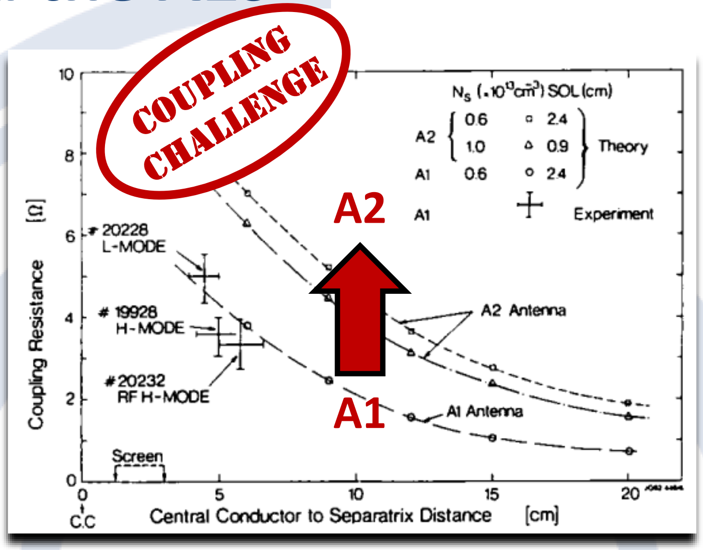
Limiter L-Mode
Monopole
$\omega=2\ \omega_{C,D}=\omega_{C,H}$

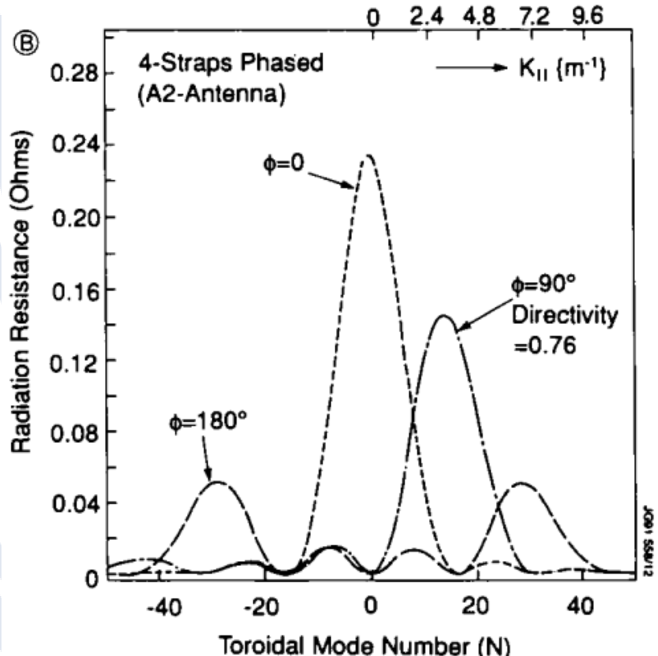
Bhatnagar, 1991

And then came the divertor… and the A2s

- **1992-1994: installation of A2 antennas during pumped divertor installation shutdown**
  - **Distance plasma-wall larger** -> needs **improved coupling**
  - Changed plasma shape (curvature)
- **Design changes driven by installation of pumped divertor and ROX of A1 operation**
  - **Four 4-straps antennas** enabling **fast wave current drive**
  - 1.5 x wider and 2 x deeper than A1 to **improve coupling**
  - Septum and sidewalls slotted to **minimise the spectrum degradation** by return currents
  - **Increased disruption forces** → Minimisation of induced loop currents on antenna by lightweight antenna box design (corrugated sheets) and FS bars fitted with 0.1Ω resistors
  - Antenna **tested at 42kV – 20s** on test-bed (limited to 30kV for ops)
  - **Tilted FS** (varying on height 13° to 18° to match B_t changes)
  - Antenna protected by **new poloidal limiters**
  - **Double conical feedthrough ceramic window**
  - Upgraded control system (arc detection, power and phase control, matching) to **optimise power handling**
  - 1995: refurbishment to cure arcing and coupling issues
  - 1996: **RFLM** – real time control & monitoring of the ICRH plant

28 years operation without any major issue !!!



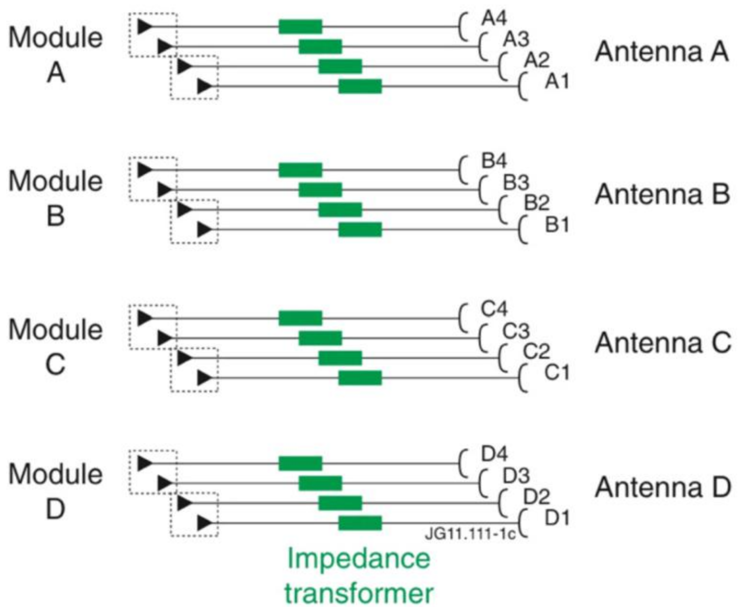


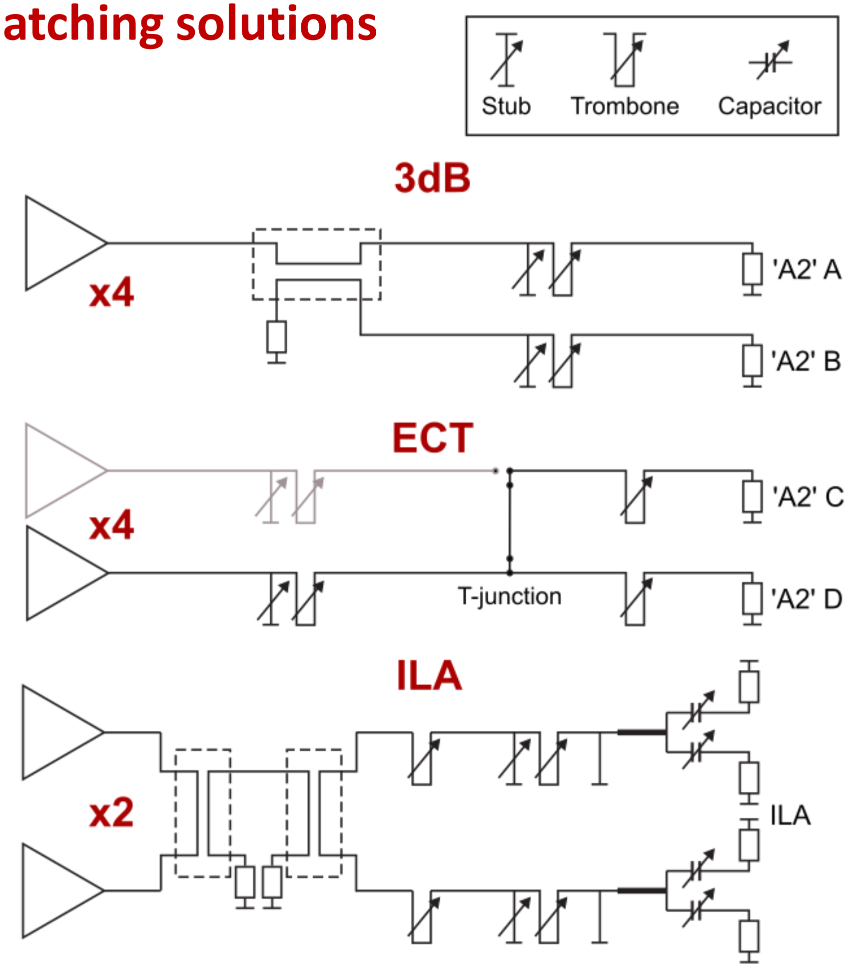
Kaye, 1994

ELM-resilient schemes

- Operation in **ELMy H-mode**
  - Matching system too slow to cope with fast load variations
    → Insufficient load tolerance of matching scheme (generator protection VSWR trips)
- Implementation of **new load-resilient matching solutions**
  - 2004/5: **3dB hybrid couplers**
  - 2008/9: **External Conjugate-T** (ECT)
  - 2008 (2015): **ILA**(R)

NEW MATCHING CHALLENGE



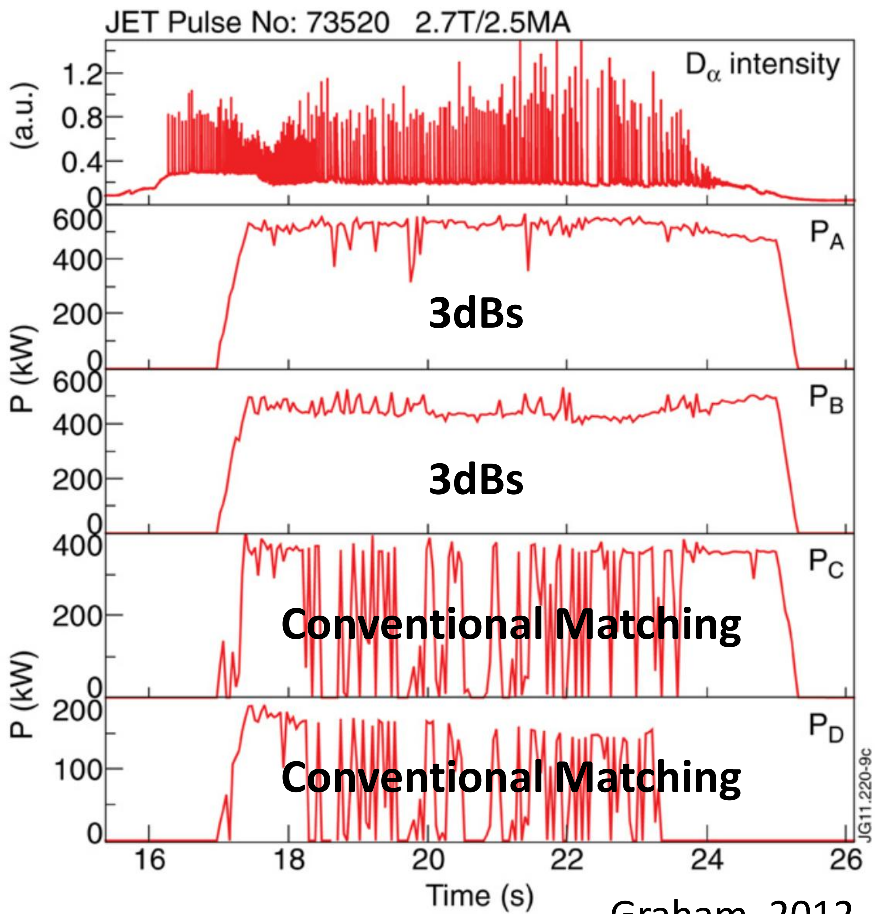


ELM-resilient schemes

NEW MATCHING CHALLENGE ✓

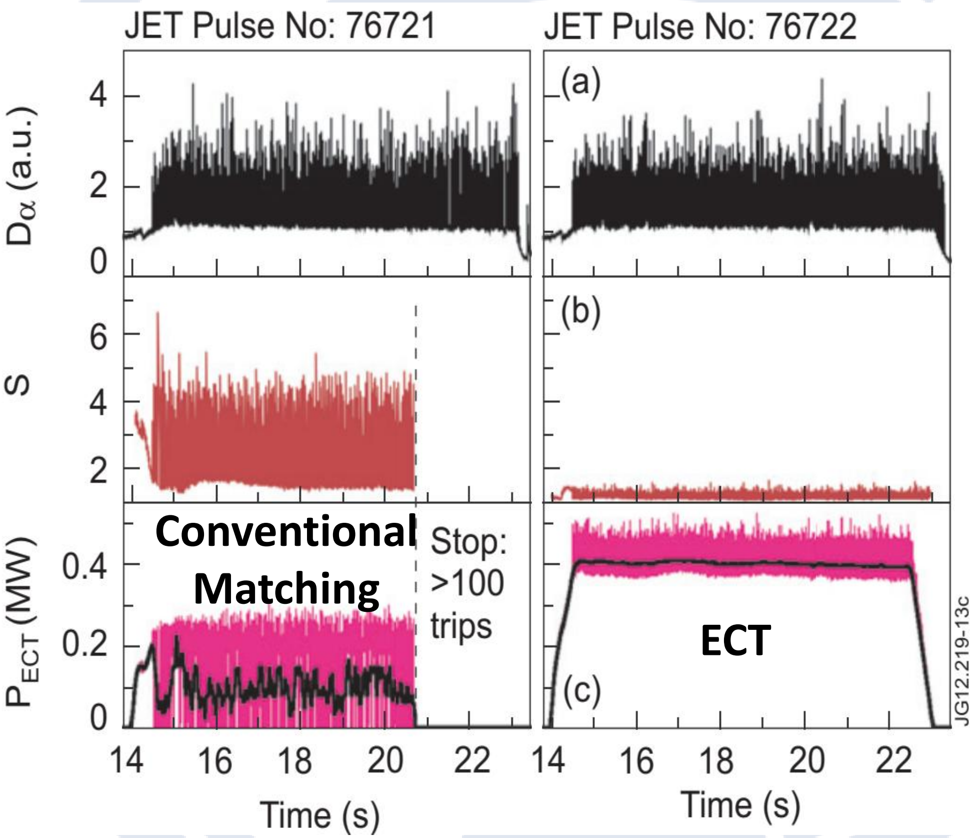
- **Load-tolerant schemes successfully implemented**

3dB hybrid couplers



Graham, 2012

External Conjugate-T



Monakhov, 2013

- Need **revised arc detection strategy** (e.g. AWACS for ECT)

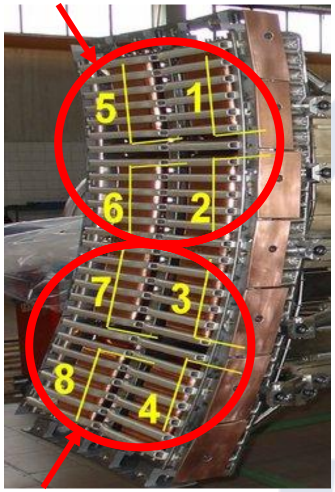
Towards High Power Density – the ILA

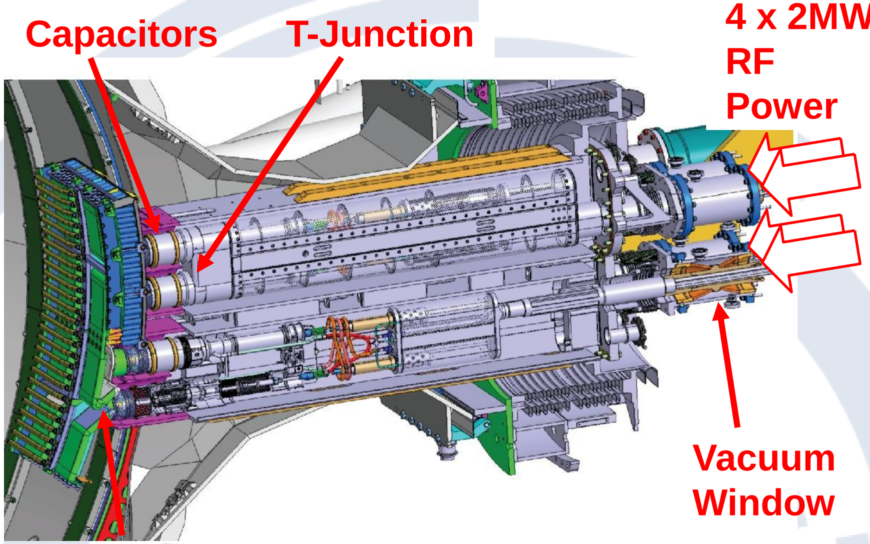
KEY FEATURES

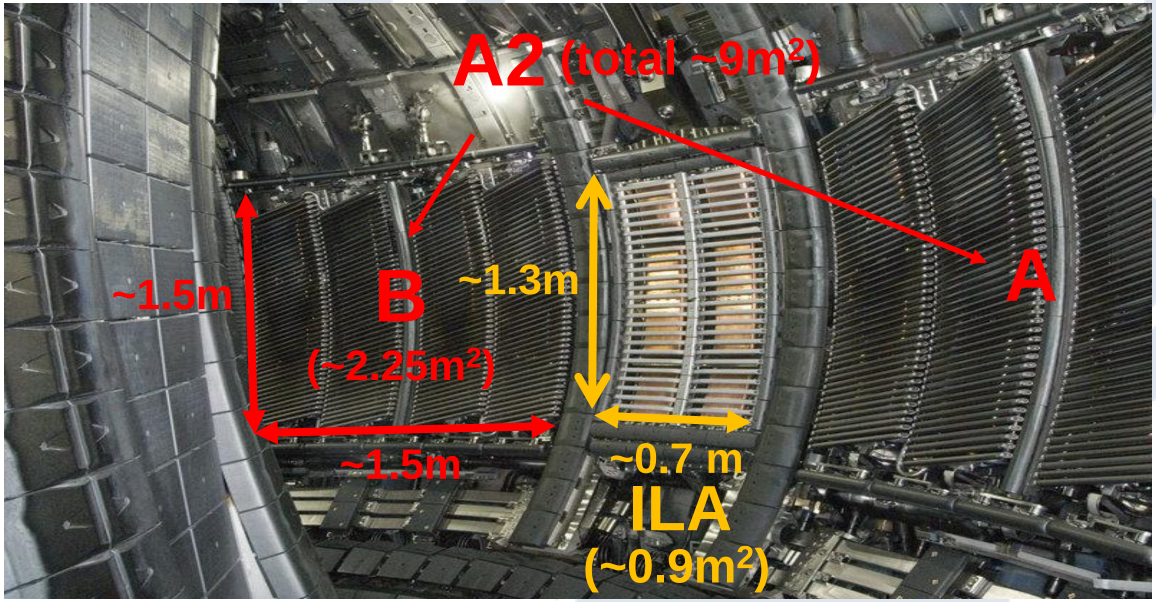
- **4 x 2 short low-inductance straps** Resonant Double Loops (**RDLs**) **In-vessel matching capacitors**
- **Conjugate-T** with typically $Re(Z_T)$=3...10Ω and $Im(Z_T)$=-5...0Ω
- $\lambda_{42.5MHz/4}$ Z-transformer + **second matching stage**
- **Port plug** antenna
- All components **tested** up to specs

ACHIEVEMENTS

- ✓ **High power density** operation **~4MW/m²** on ELMy H-mode (A2: ~1MW/m²)
- ✓ **Similar levels of impurities as A2s**
- ✓ Operation at high voltages – **40kV**
- ✓ **Control** of close-packed array
- ✓ **Load resilience**
- ✓ **Arc detection** : SMAD, SHAD
- ✓ **Validation of RF modeling** and coupling predictions
- ✓ **Capacitor failures validate the external matching choice for ITER**

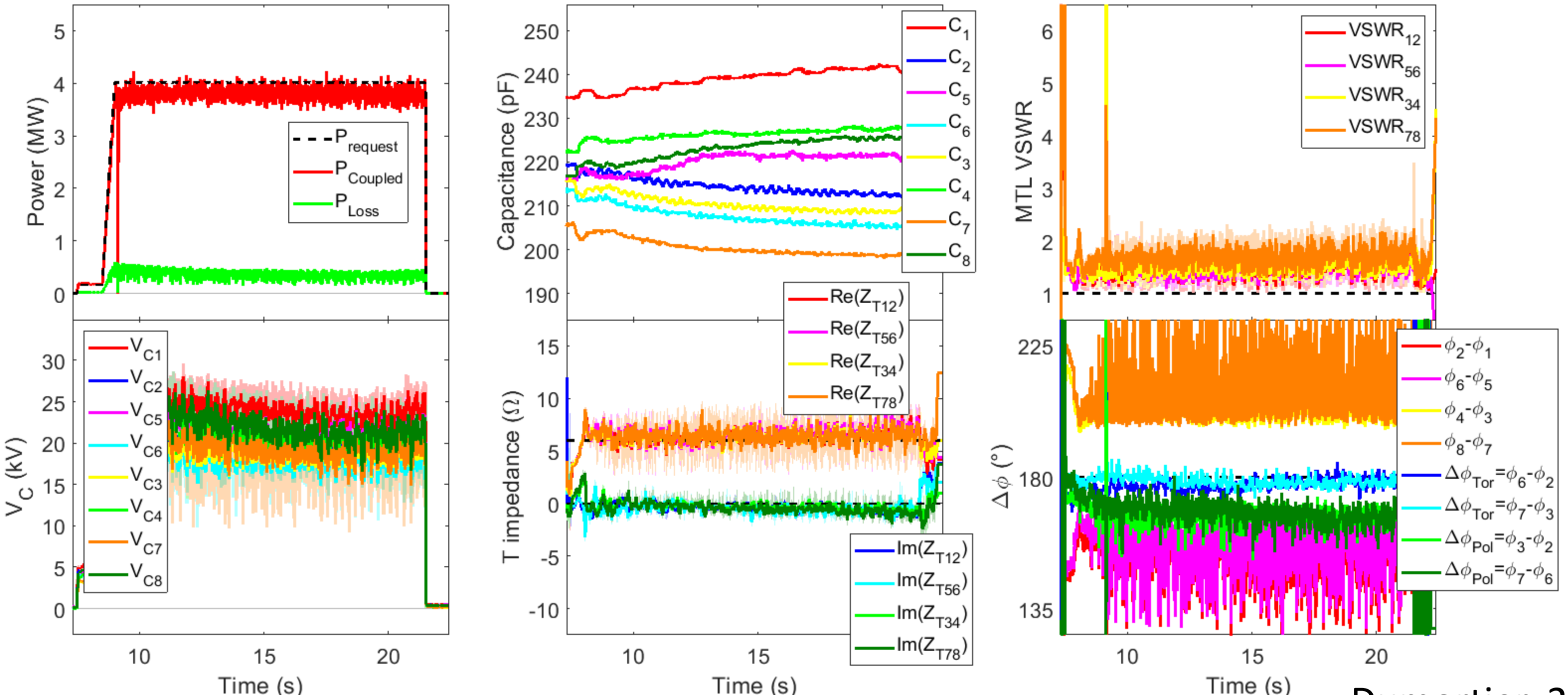






ILA Full Array Control

JET Pulse No : 95098 – 33MHz



Dumortier, 2021

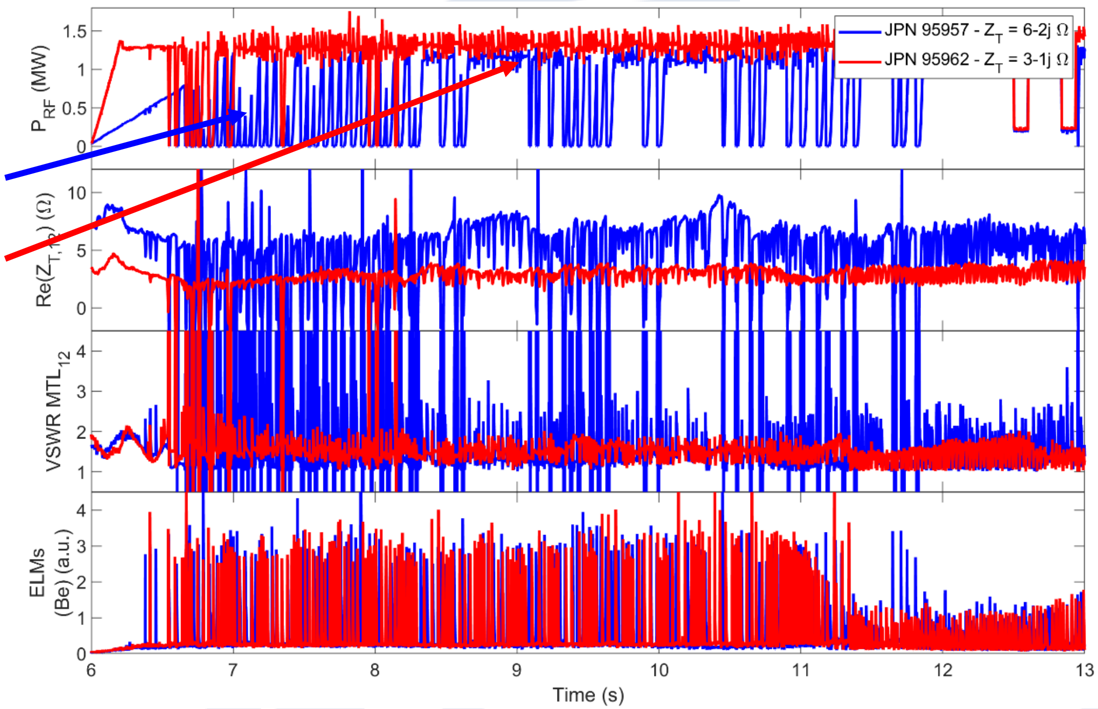
- Full array control **successful** at 33, 37 and 42MHz
- Up to **4MW** at 33 and 42MHz
- **Poloidal phase scan** achieved at 37MHz (500kW)
- Some **control instabilities** observed during campaigns
- → Test of **polychromatic operation** (Power upper and lower halves of ILA at f_0±250kHz)
  - Decoupling of control → **no control instability issues**
  - V_{max} **will limit operation** (Large cross-talk : $|V_{C,f1}| \sim |V_{C,f2}| \rightarrow |V_C| \sim 2\,|V_{C,f1}|$)
    → lower power than monochromatic full array operation

The ILA : S-Matrix Arc Detection

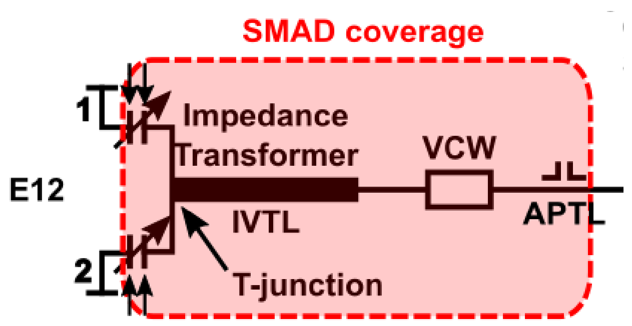
- **Better ELM-resilience at low Z_T**

$Re(Z_T)$ = 6Ω – Tripping on VSWR

$Re(Z_T)$ = 3Ω – Much less trips



- Low Z_T section not protected by VSWR against arcs → **S-Matrix Arc Detection (SMAD)**

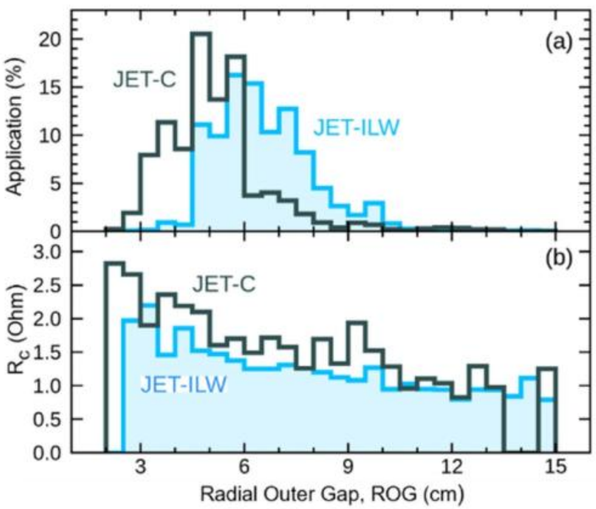


RF consistency check of the section of interest using:

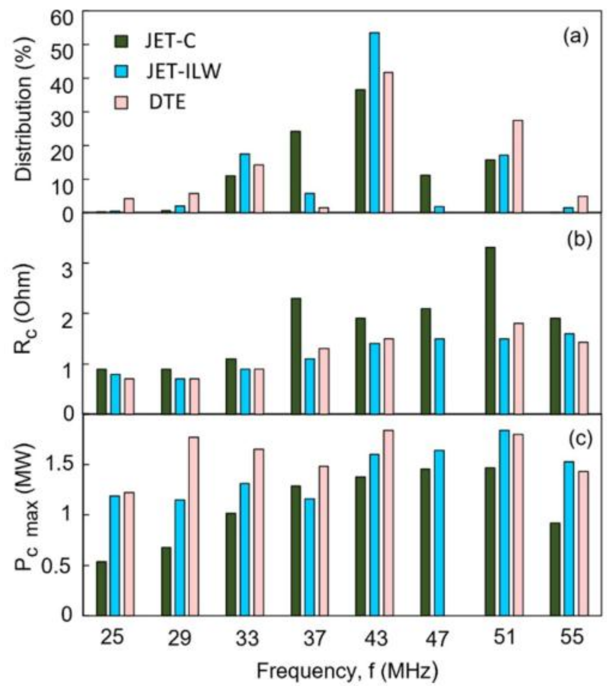
- **RF model** of the section
- Calibrated **RF signals** around the section
- SMAD error calculation by FPGA every ***2μs***

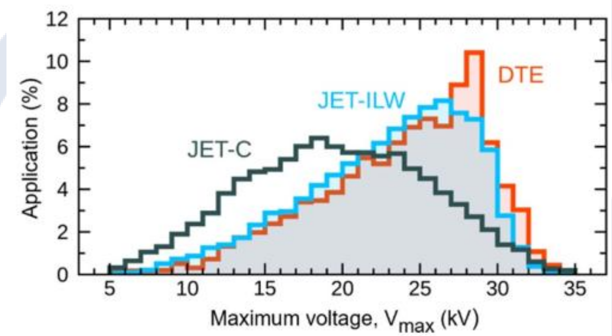
Change from JET-C to JET-ILW (Be/W) metallic wall

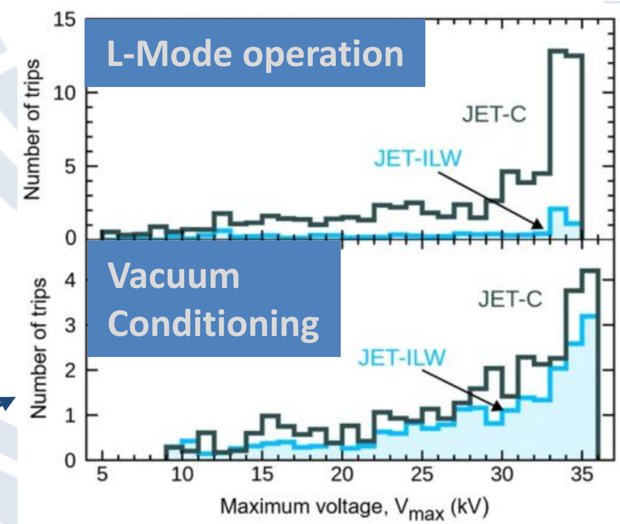
- 2009/11: installation of the **Be wall and W divertor** : modified recycling and far-SOL conditions and enhanced wall protection requirements
- Increasingly difficult matching conditions: ROG ↑, $\mathbf{R_C}$ ↓ and stronger ELMs ($\mathbf{\delta R_C}$ ↑)
- More operation at band edges in DTE
- System **maintenance**, **diagnostics** and **optimisation** allowed to keep performance up



Monakhov, 2025



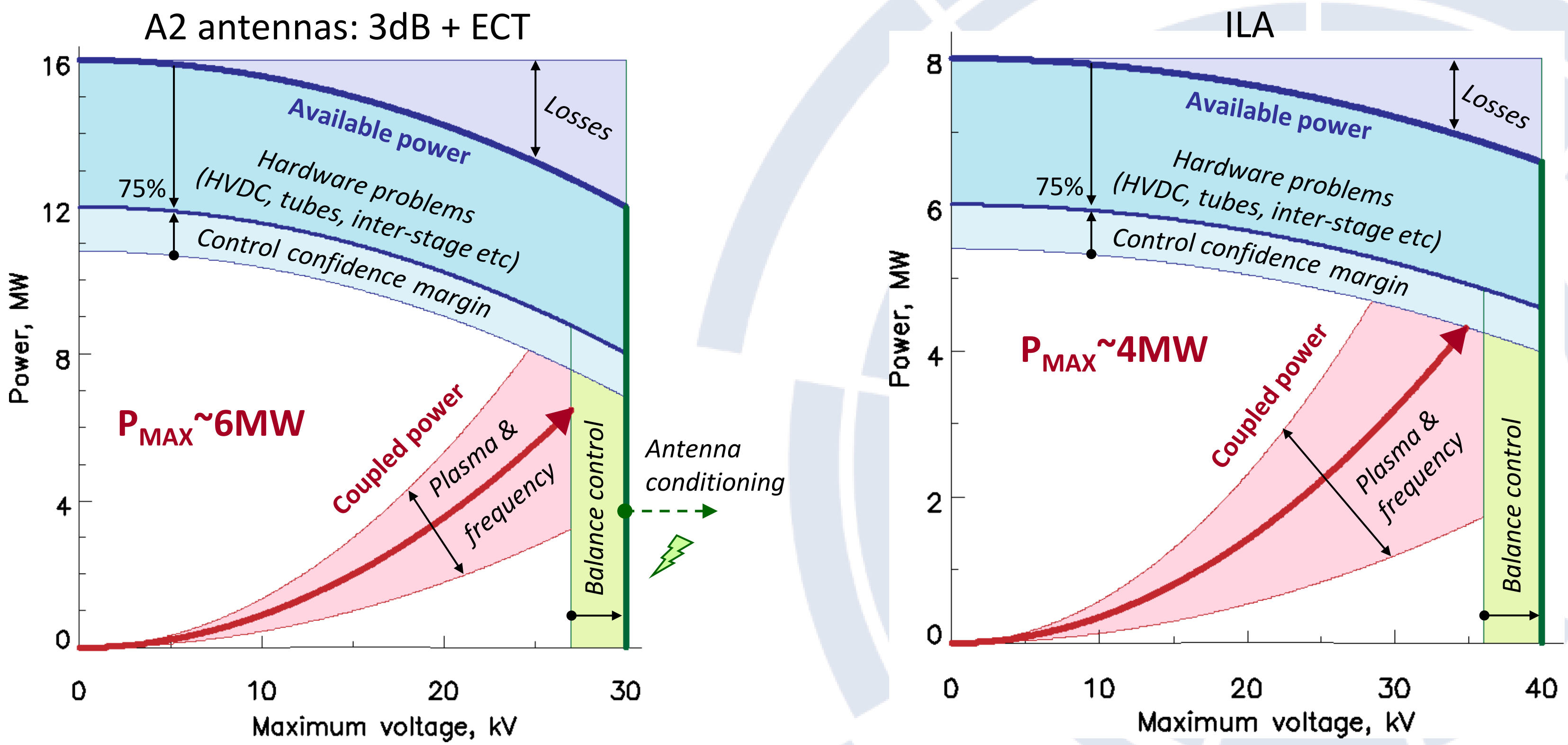




- Evidence of **easier conditioning** and **improved voltage stand-off** (dust level reduction ?)

Maximising Power and Reliability

- Expected performance at 42MHz in H-mode plasmas

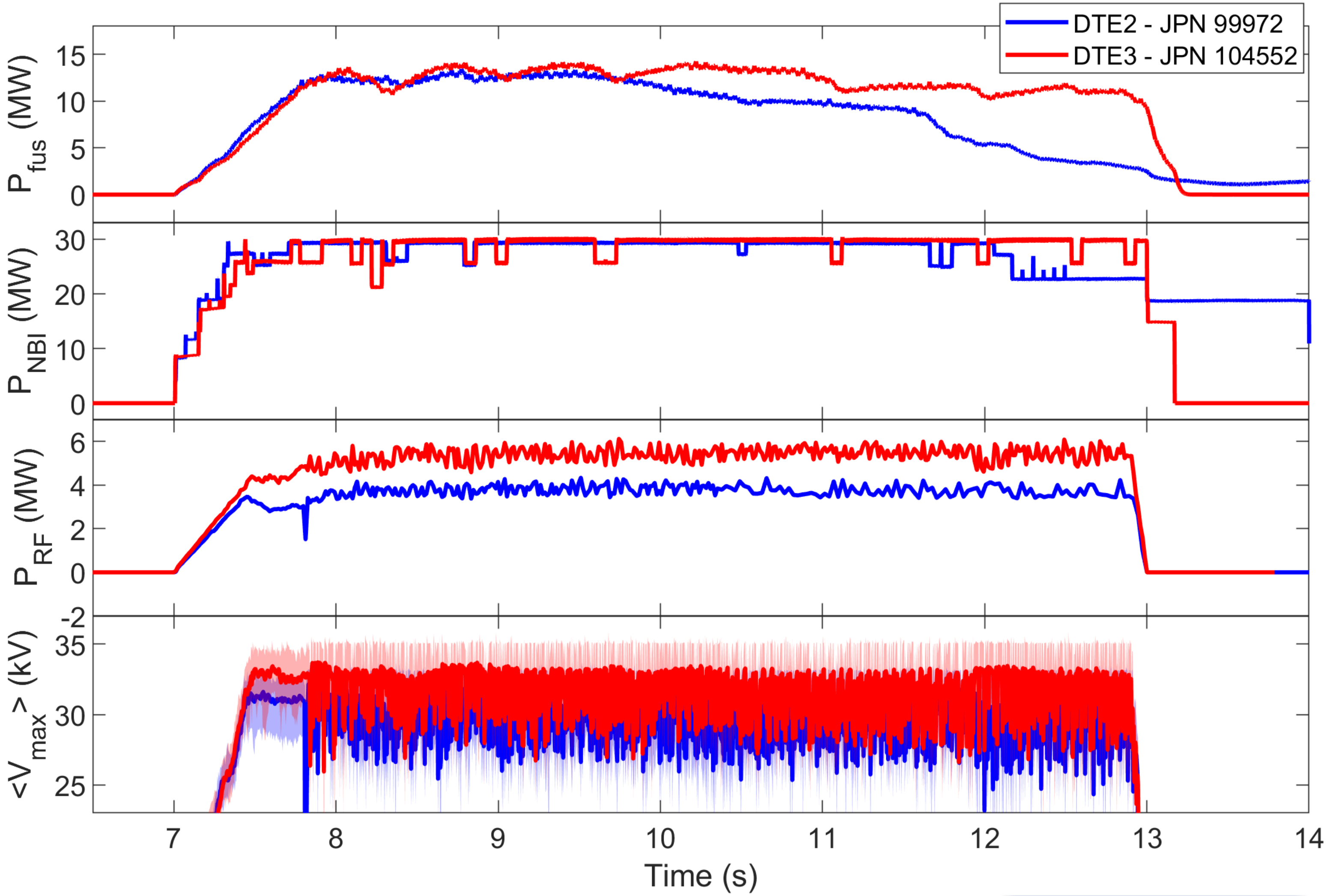


Courtesy I. Monakhov

- Importance of **maintenance** of the whole system (from HV PS to antenna), accurate **diagnostics** and high voltage **conditioning**
- **Improve coupling conditions** (e.g. ROG, gas puff optimisation)
- Strategy to improve **balance control** (RFLM upgrade)

How to improve your record

- **Antennas conditioned further for DTE3 : V_{max} set to 35kV** (vs 33kV for DTE2)
- **~1.5MW increase in coupled RF power and more stationary conditions !**



Some key ingredients for success

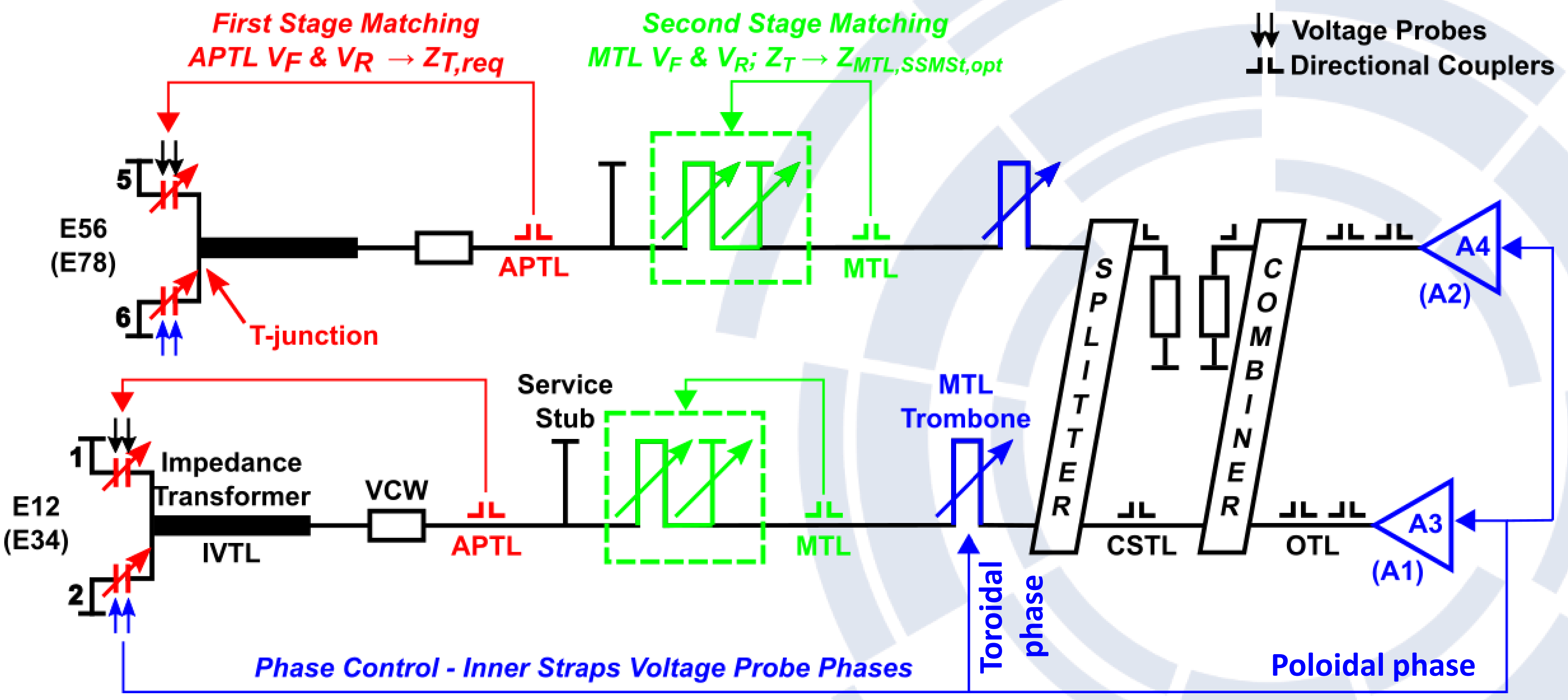
- **Design phase :**
  - Go for a **flexible** and **versatile** system for key physics (see talk by M. Mantsinen)
  - Take **DT** operation and **remote handling** on board from start of design
  - **Test** extensively all components and antenna assemblies before installation
  - **Avoid movable/critical parts inside the torus vacuum**
  - **Minimise** the **RF-induced impurity release**
  - Develop and **simulate** the **control** (including cross-talk) and the **arc detection** systems
  - Build the system to be able to quickly **identify** and **safely isolate any fault**
  - **Accessibility** for maintenance and repairs
  - Take some safety **margin** (nominal installed power)
- **Operation phase :**
  - Plan for accurate RF measurements and extensive **calibration** of all measurement points
  - Have a proper **maintenance** and **test schedule** of the whole system (amplifiers, HVDC, TL…)
  - Allow for **amplifier** tests and **optimisation during shutdowns** (HVDC not available on JET during shutdowns)
  - **Condition** as much as possible (even during breaks in ops pulses if possible)
  - **Coupling** is the **most important parameter** for system performance → **improve coupling by all possible means** (design, gas puff, plasma conditions…)

Nothing could be done without them !

Importance of team work towards a common goal !

Thank you for your attention

ILA Full Array Control



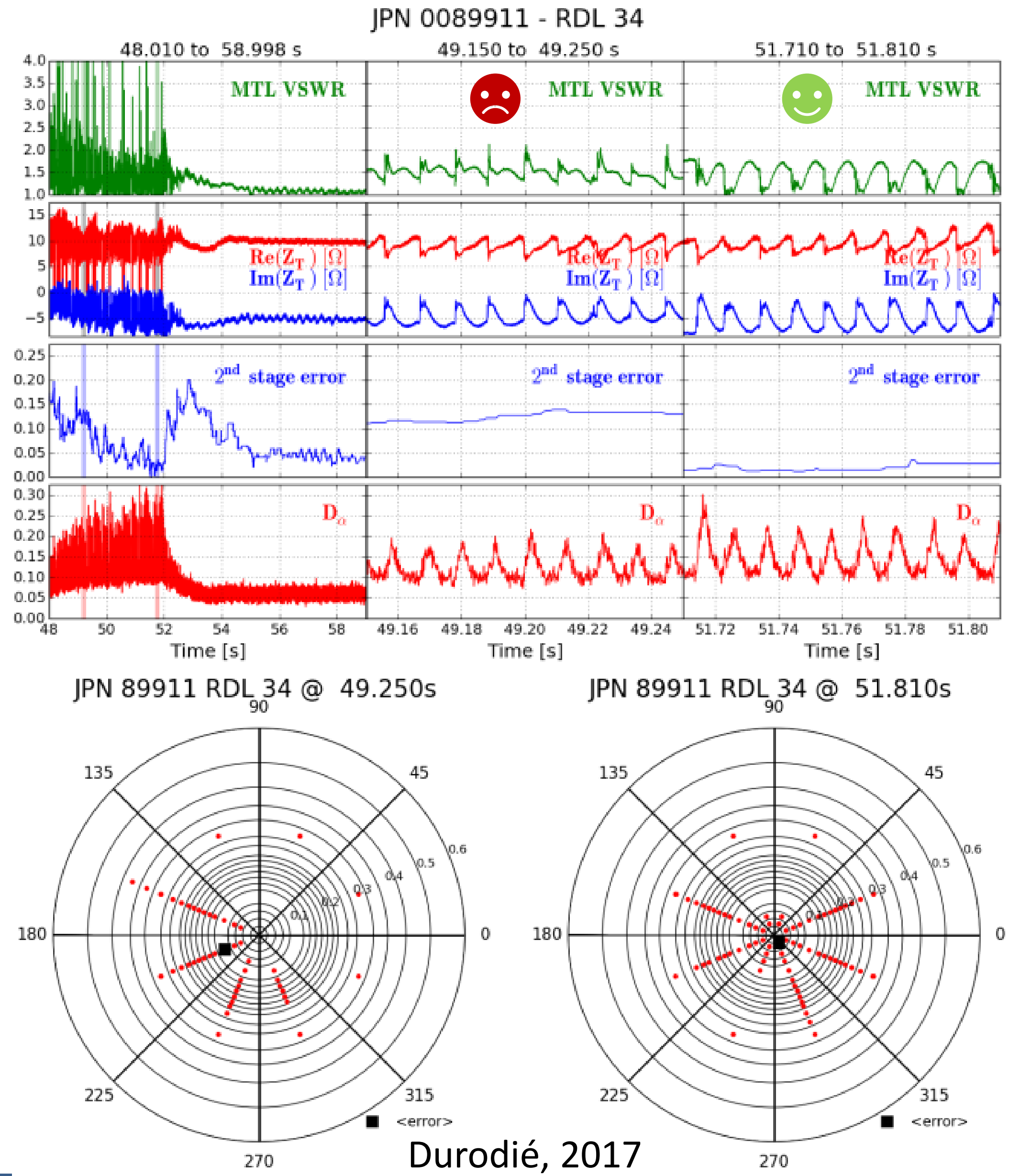
Full array: 12 feedback loops controlling 22 actuators

Half array: 5 feedback loops controlling 10 actuators

The ILA : Second Stage Offset Matching

- Asymmetric RDL straps (antenna geometry) restricts the load resilience
  → need to **offset match** in presence of ELMs to improve ELM tolerance

- Γ_{MTL} estimated on fast enough time scale to resolve ELM load variations (**2µs**) and stored in **polar map bins** (8 phase + 15-20 amplitude bins) during a chosen tracking time
- Γ_{MTL} averaged on slow time scale (**2000 points/pulse**) → error signals to drive **SSM components** (move, direction, slow/fast)



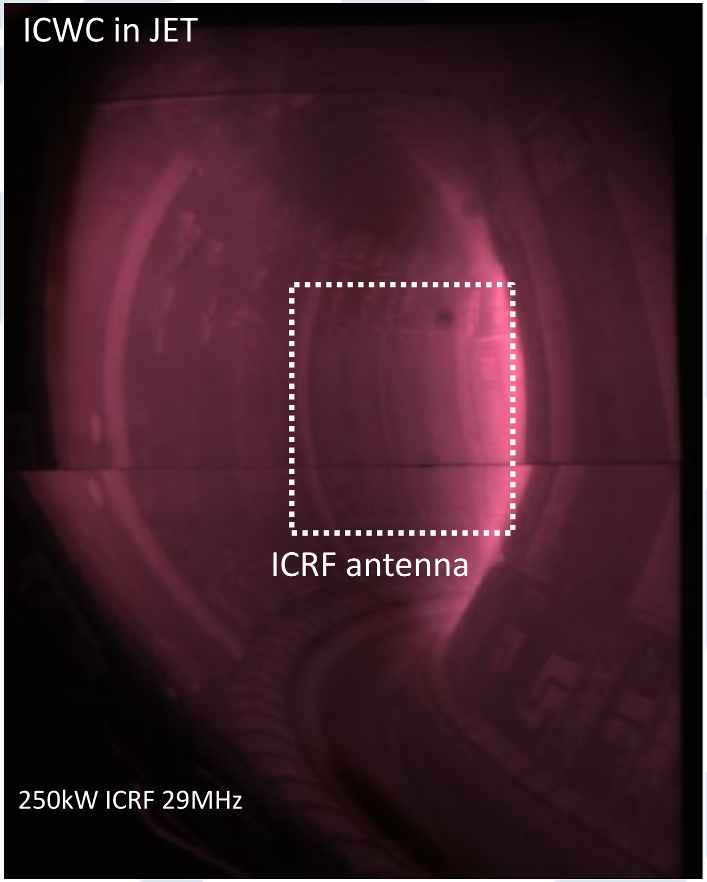
Durodié, 2017

ICWC and RF-assisted start-up

- Dedicated **protection** set-up for **ICWC** and **RF-assisted breakdown** experiments

  ✓Frequency **< 33MHz** to prevent VTL voltage node (multipactoring)
  ✓Install more restrictive **3:1 VSWR cards**
  ✓Trip counters set to **10 trips** maximum (↔25-100 trips)
  ✓VTL trip soft limit set to **5 10^{-5}** mbar (↔ 1x10-4 mbar)
  ✓PEWS interlocks overridden for zero kA
  ✓Set Local MTL limits to **20kV** (↔ 30kV)
  ✓Fast data acquisition enabled
  ✓Check trips after each pulse

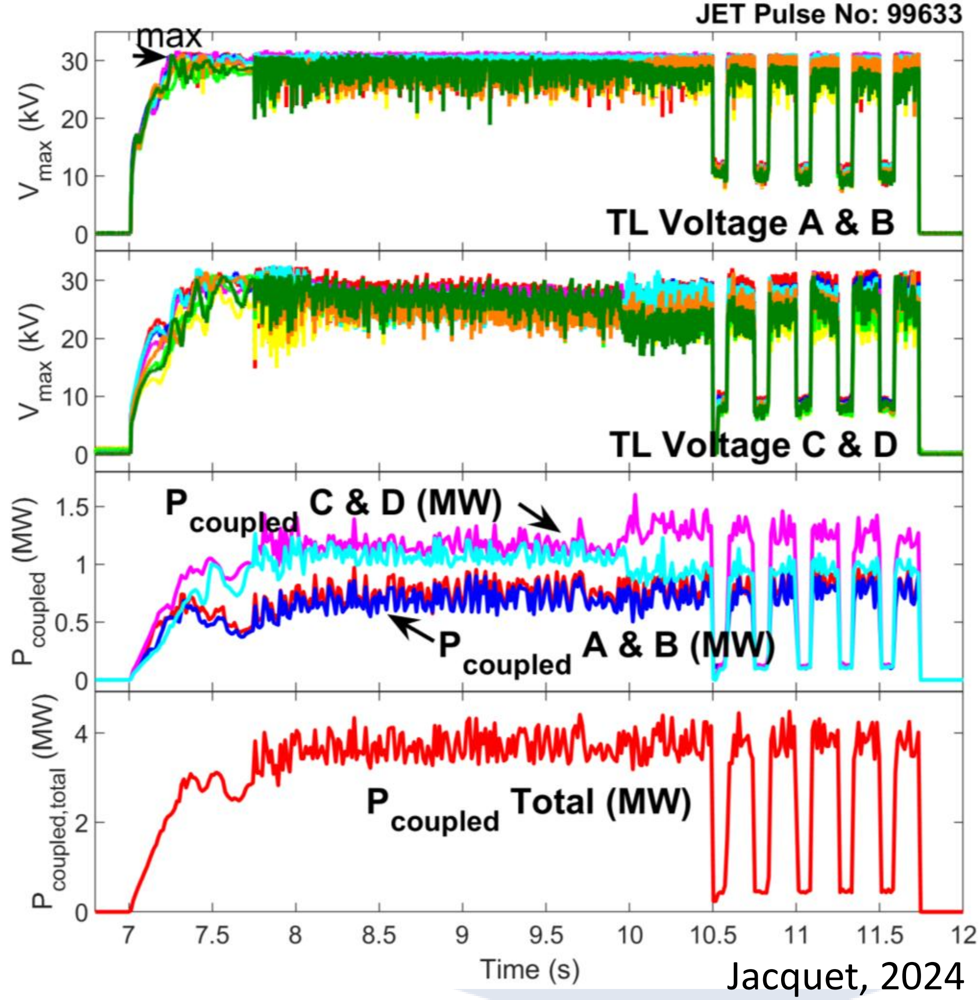
- Mostly **monopole** operation
- RF power generally applied before gas injection to avoid arcing in the antenna box
- Requires to establish **vacuum reference pulses**



Wauters, 2021

DT Operation

- **D-T** operation **planned from start** (remote handling, double vacuum window, etc)
- **Containment of Tritium** (air flow in transmission lines handled by Active Handling Gas System, reduce extent of 3-bar pressurized transmission line air leaks, monitoring of the DCF interspace, check isolation valves…)
- **'Expensive' pulses** → need careful preparation, no spare pulses
  - Improve system **reliability, availability** and **repairability**
  - **Conditioning** as much as possible prior to the experiment
  - **Test load pulses** to identify issues and know the plant limit
  - Target is to deliver **full power on first pulse**
  - **Reference pulses** for every scenario in same coupling conditions
  - RFLM upgrade to **equalize voltages** taking the plant limits into account



Jacquet, 2024