EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

JET - Enhanced Performance Project ITER-like ICRF Antenna

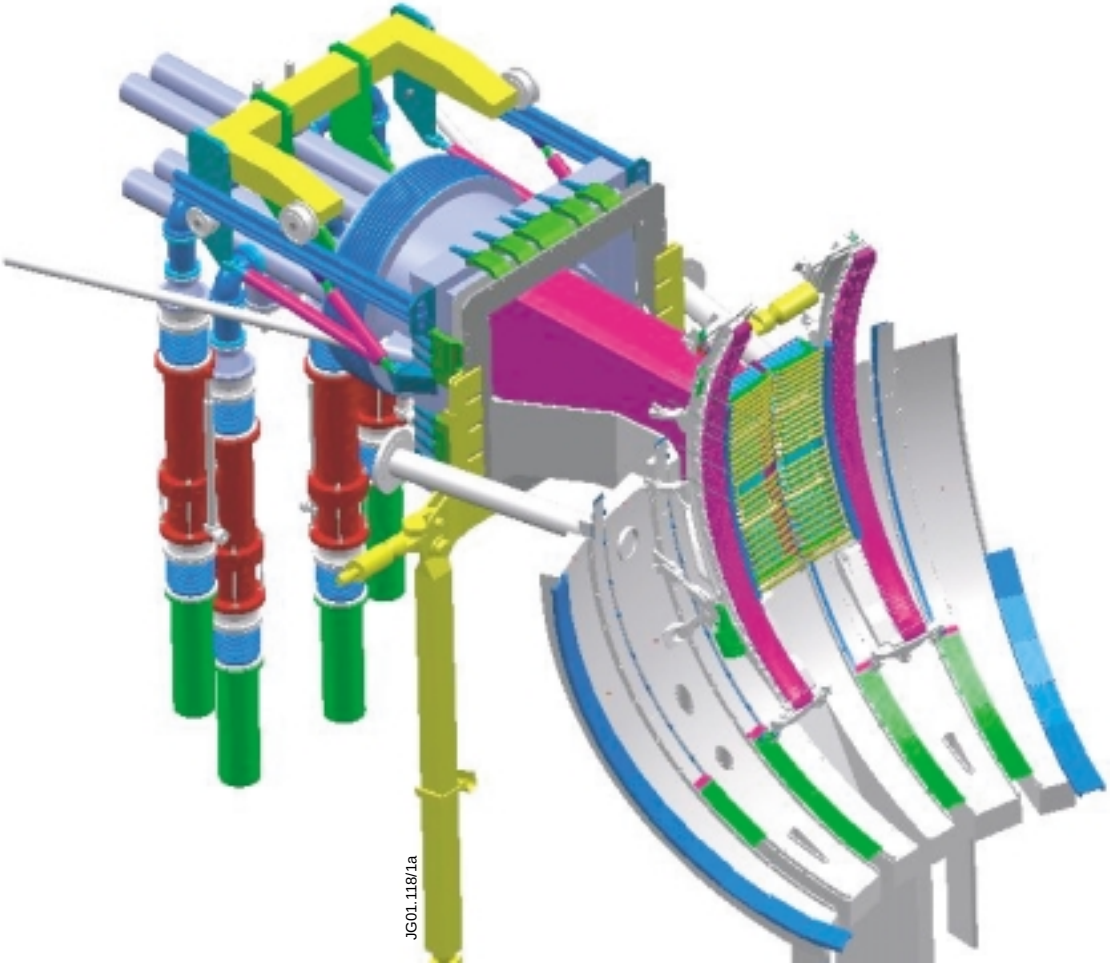
G Agarici[1], G Amarante[2], W Baity[3], B Beaumont[1], S Brémond[1], L Colas[1], F Durodié[#,2], J Fanthome[4], R Goulding[3], R Koch[2], A Kaye[4], **P Lamalle**[5,2], G Mazzone[6], J-M Noterdaeme[7], Y Pouleur[8], V Riccardo[4], M Roccella[6], C Sborchia[9], A Sibley[4], P Testoni[6], P Tigwell[4], K Vulliez[1], R Walton[4]

[1]Association EURATOM / CEA, Cadarache, France,
[2]Association EURATOM / Belgian State, LPP-ERM/KMS, Brussels,
[3]ORNL, USA,
[4]UKAEA / EURATOM Fusion Association, Culham, U.K.,
[5]EFDA-CSU Culham, U.K.,
[6]Associazione EURATOM-ENEA sulla Fusione, Frascati, Italy,
[7]Max Planck IPP-EURATOM Assoziation, Garching, Germany,
[8]CEN SCK, Belgium,
[9]EFDA-CSU Garching, Germany.
[#]Project Leader

Outline

- **Design basis, main RF features**
- **Recent design choices** (JET-EP ICRF Team meeting, Cadarache, 11-12 April 2001)
- **Ongoing R&D** At the Oxnard RF Topical Conf.:
  - Low power mockup — S Brémond ***et al***
  - Matching capacitors
  - Modelling: circuit / 3D electromagnetic simulations — R Koch ***et al***
  - Impedance transformer and vacuum window
  - Baseline and fallback design options — R Goulding's presentation

Octant 6 Layout

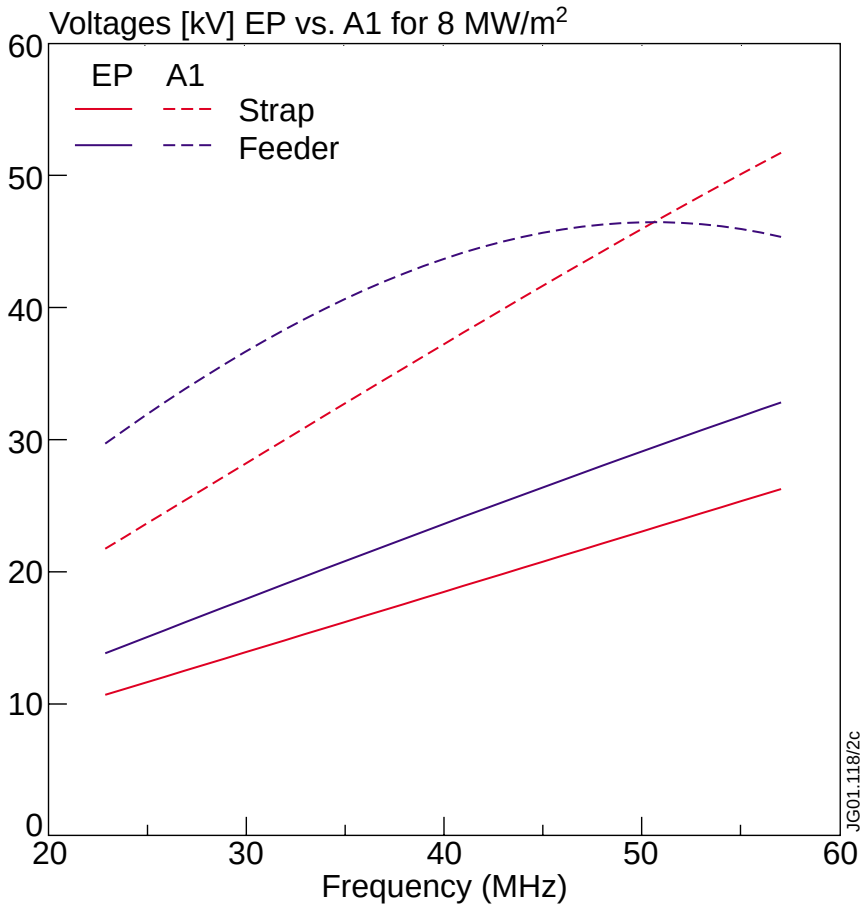


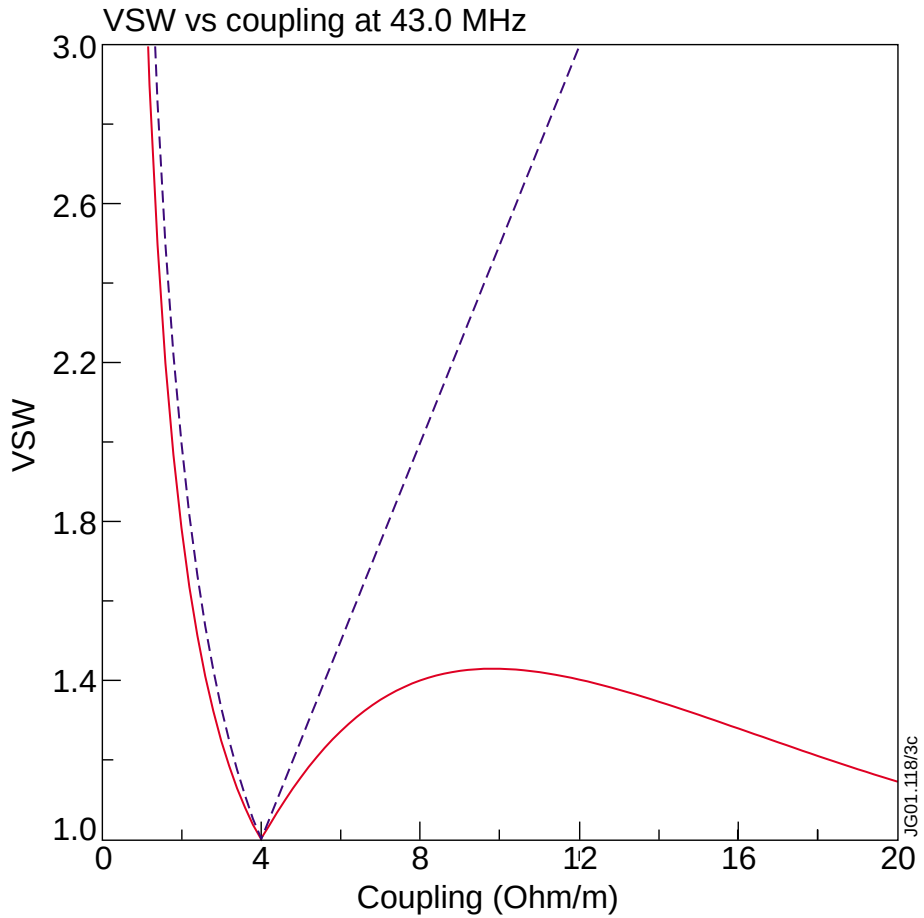
Octant 2 Strap Layout

Design Basis

Short Straps ⇒ Low Voltages

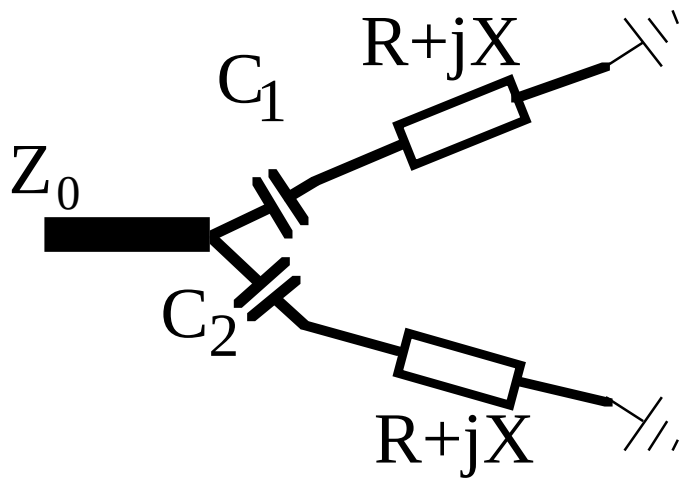
Conjugate - T Matching ⇒ Load tolerance





Load tolerance of JET-EP antenna

- **'Conjugate T' matching: 2 branches in //, input line with characteristic Z_0**



Branch impedances:

$$Z_1 = R + j\left(X - \frac{1}{\omega C_1}\right) \equiv R + jX_1$$

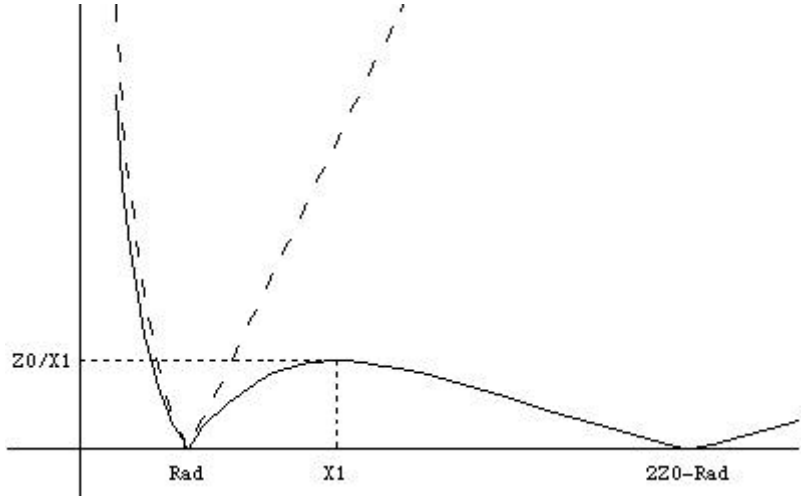
$$Z_2 = R + j\left(X - \frac{1}{\omega C_2}\right) \equiv R + jX_2$$

Input admittance at connection:

$$Y_{in} = 1/Z_1 + 1/Z_2$$

Matching to transmission line at $R=R_{ad}$ requires $Y_{in} = 1/Z_0$, leading to complex conjugate branch impedances: $X_1 = -X_2 = \sqrt{R_{ad}\,(2Z_0 - R_{ad})}$

- **Input SWR vs load resistance R (at constant reactance X):**



plain line: conjugate T matching;

dashed lines: conventional matching

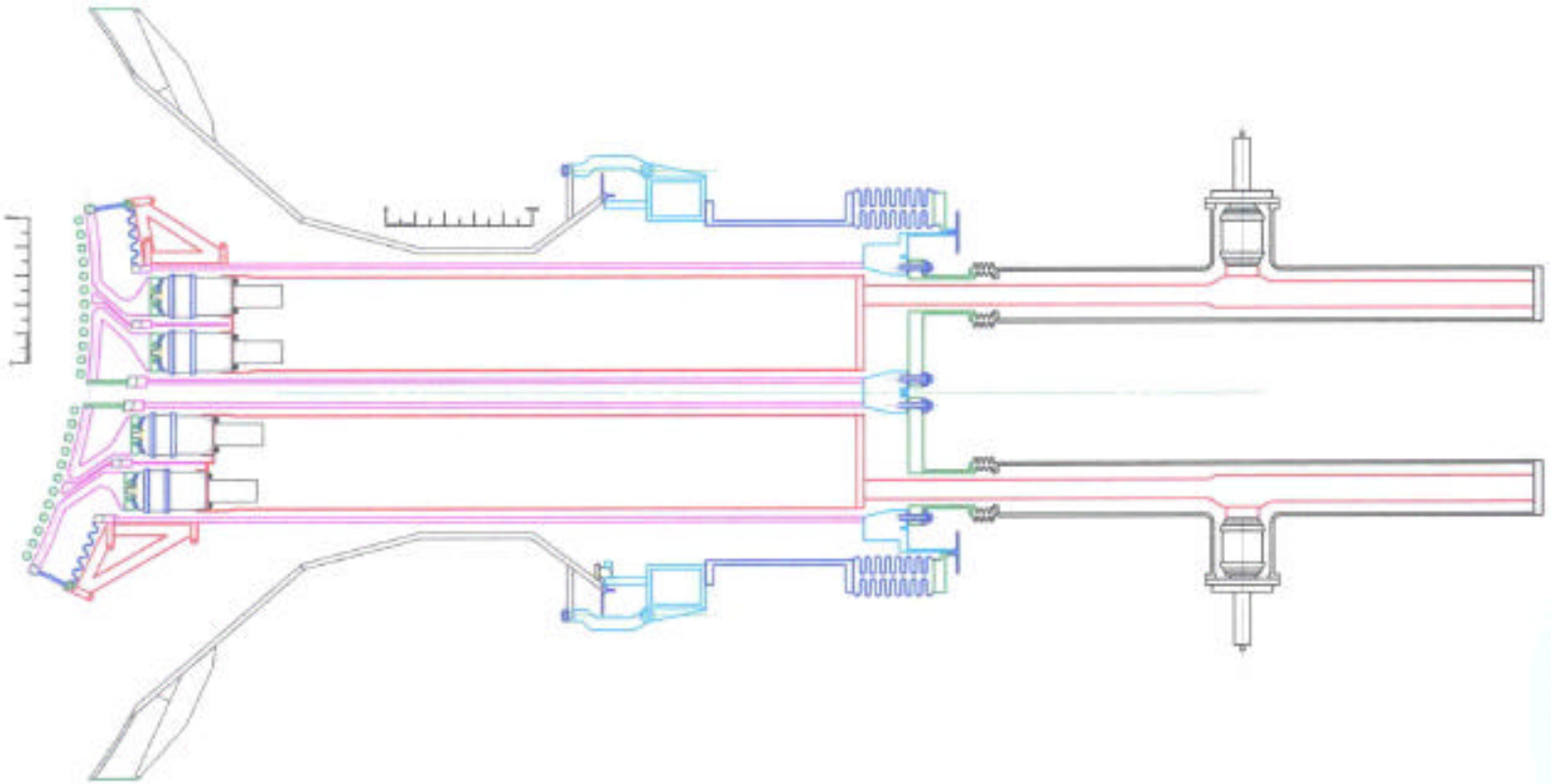
- At variable R: max.SWR= $Z_0/X_1 = 1/\sqrt{\frac{R_{ad}}{Z_0}(2-\frac{R_{ad}}{Z_0})}$ for $R=X_1$

  Hence given R_{ad}, choose smallest Z_0 consistent with acceptable electric field

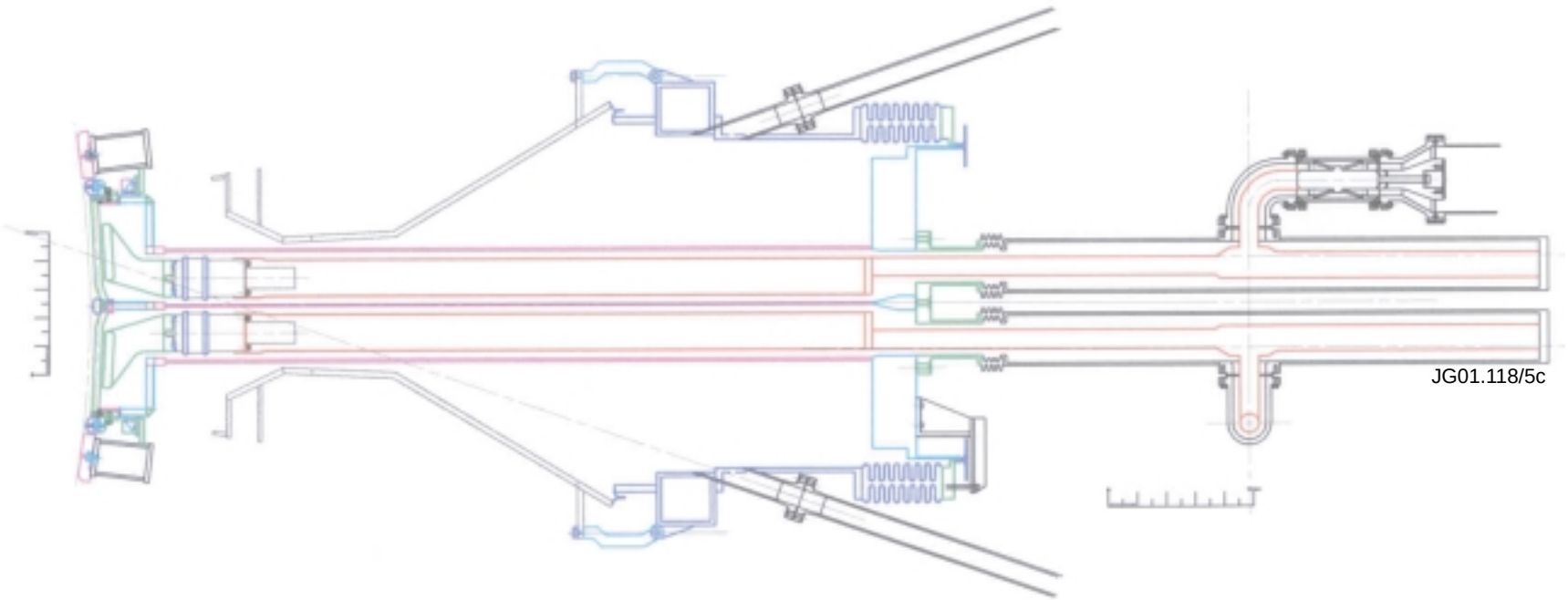
  Need impedance transformer from Z_0 to 30Ω MTL

- N.B.: reactance variations assumed negligible during load transients!

Reference design (Oct. 6 layout)



Horizontal Section – Octant 6 Layout



Antenna characteristics - Plasma-facing parts

Short straps, non-tilted feeders and short-circuits

Small private antenna limiter (behind poloidal limiters)

Avoid uncontrolled RF flux linkages: Closed antenna box

Low impedance RF connections

antenna limiter to poloidal limiters

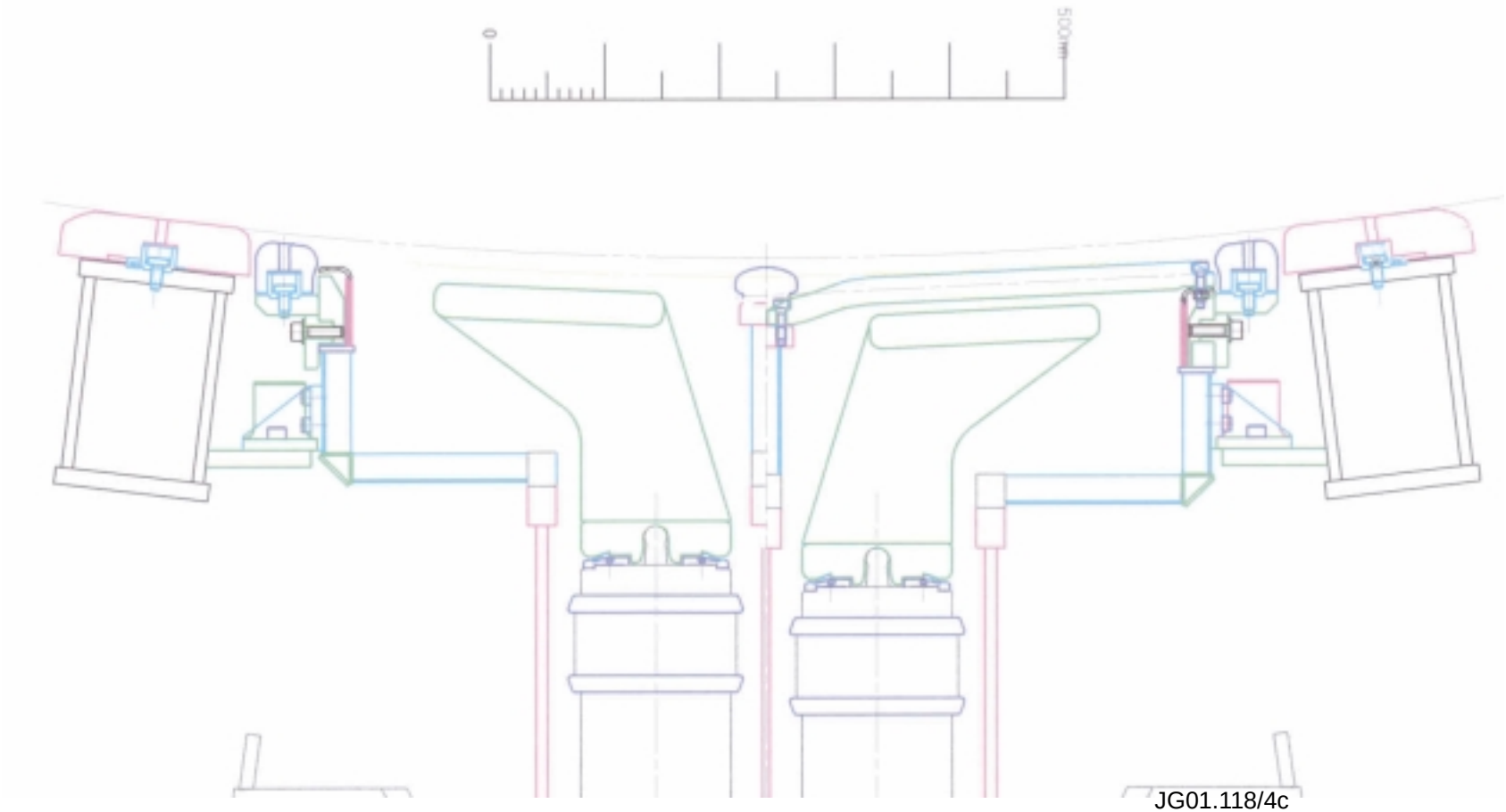
poloidal limiters to wall

Full septum

Faraday shield connected to septum

Shield elements: non-tilted rods

Antenna radial adjustment secondary to grounding requirements, but aiming at ±25mm

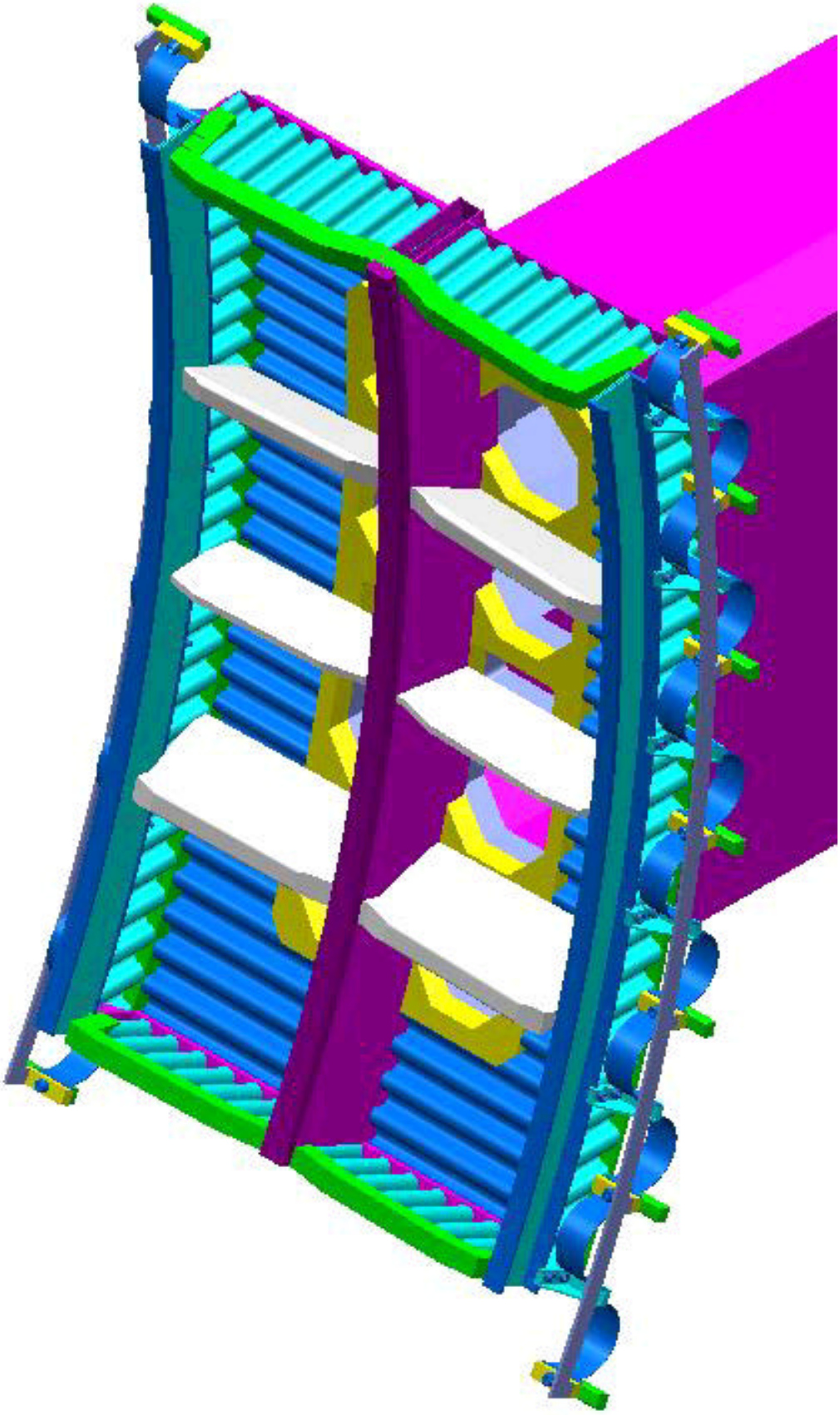


JG01.118/4c

Faraday screen removed
strap moved ~25mm inward

Standard operation with
Faraday screen

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET



JET - EP ICRH Project Workshop on Outstanding Issues in RF Technology,

Oxnard, CA, 9-10 May 2001

Recent design choices

(JET-EP ICRF Team meeting, Cadarache, April 2001)

- Strong preference of RF Team for antenna installation in JET Octant 2 rather than Oct. 6

  Allows removing diagnostic line-of-sight gap between top and bottom halves

  better strap equalization and higher symmetry

- Port allocation Meeting May 9: …
- Flexible RF connections of private limiters to main poloidal limiters:

  Move them closer to front tiles.

  More work required to determine most favorable orientation (horizontal vs vertical?)

Low power antenna mock-up

(S Brémond et al, CEA Cadarache)

- Full-scale flat model of 2 toroidally adjacent resonant loops
- Modular construction allows measurements on several layouts:
  - before / after connection of capacitors
  - with / without Faraday shield
  - asymmetric / symmetric loops
  - first tests with thin straps, then repeated with more realistic thick straps
- First estimate of strap electrical parameters / update of earlier circuit models
- Effects of loop asymmetries: **+**: can reduce capacitor range requirement;
  -: one loop at higher input voltage better to equalize the loops
- Toroidal and poloidal mutual couplings: very low in air

- **Next:**

  - load the antenna

  - assess tolerance to load variations

- **Measurements to be compared with 3D electromagnetic simulations:**

(R Koch et al., ERM-KMS / Univ. Nancy)

- ICANT code (self-consistent antenna currents, plasma slab)

- N.B. ANSYS, available at JET, has a HF finite element module

Capacitor R&D

- **Aims of R&D** (CEA, EFDA-CSU Garching, COMET)

  Improve reliability with respect to existing type used on Tore Supra

  Reduce diameter (180 to 140mm)

  If possible, reduce cooling requirements to one side of capacitor

- **New components**

  Stainless steel + Cu (electrodeposited) bellows, instead of Cu

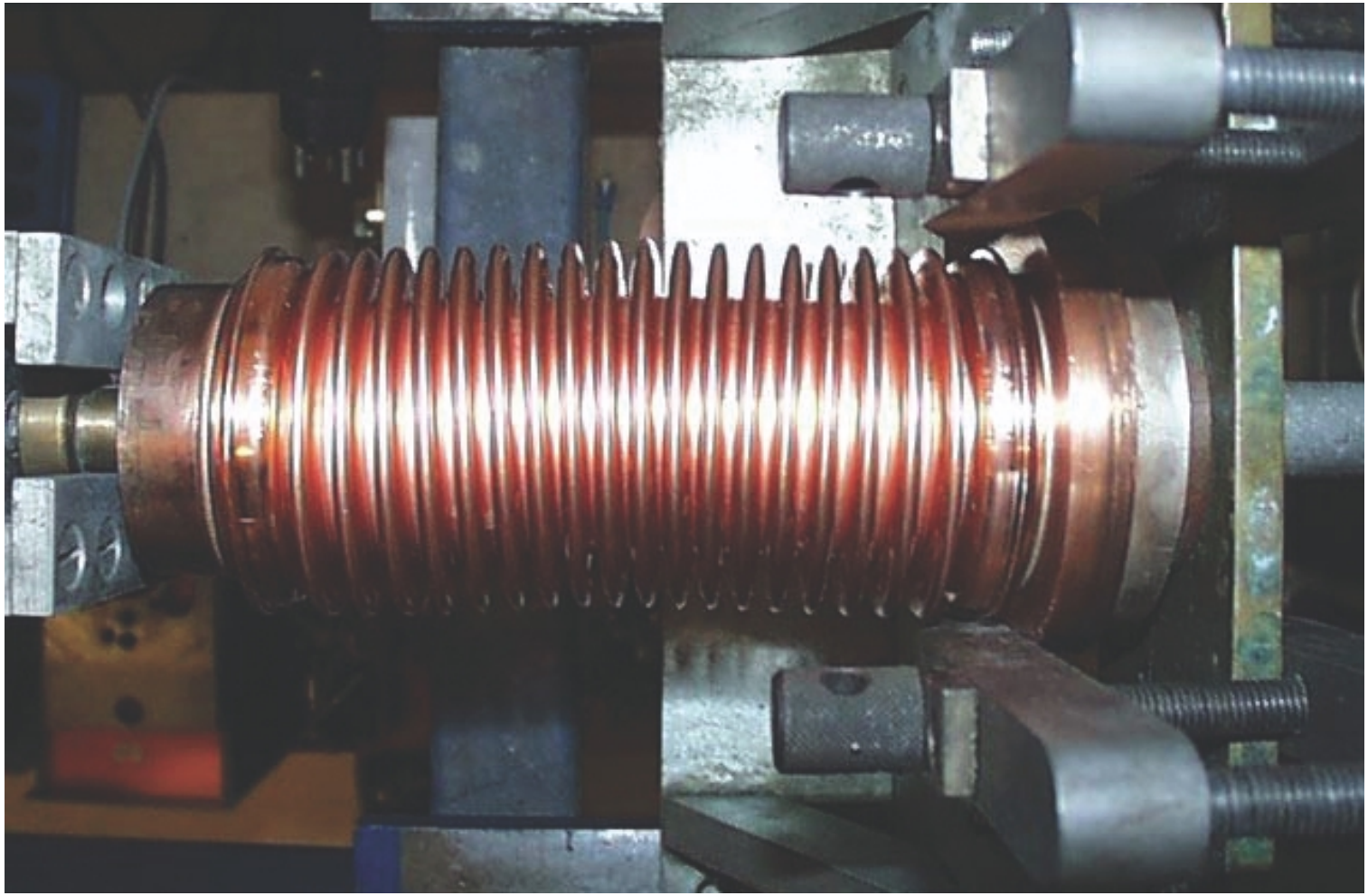
  Double bellows containment of coolant, instead of O-ring seal

- **Outline report received**

  Two bellows fatigue tested at 100% stroke: 11500 and 11504 cycles to rupture

  (Specs. require 5000 cycles)

Capacitor Bellow Fatigue Test



RF chokes

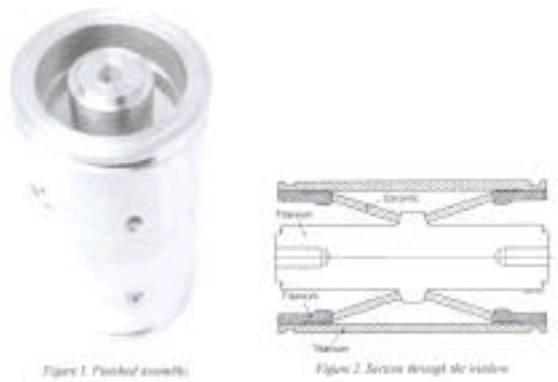
- Allow RF-free cooling circuits and capacitor actuators
- Usually implemented by λ/4 stub (i.e. here, adjustable 1.3 to 2.5m)

Choice:

- Fixed stub (~0.9m) in vacuum region + commercial variable capacitor in parallel (20-250pF)
- Instrumental in capacitor replacement procedure

Vacuum window

- Successful design by UKAEA [R Walton, A Kaye]



- Double conical window
- Tested to 48kV, 1.1kA rms for 20 s at 51MHz

- Frequency response measured: 31 to 32Ω (30 - 60 MHz)

Impedance transformer

- Low impedance reference at conjugate-T input for load tolerance:

  10Ω: SWR < 1.8; 6Ω: SWR < 1.5 over wide range of R_{in}

- Large rectangular VTL arrangement

  (cooling pipes + capacitor actuators inside; low elec. field)

- Must incorporate RF window
- Two or 3 sections? (each λ/4 at 42MHz, ~1.8m): under study

1. Keep (tested) window as is:
   a. 2-stage transformer, window ~ where it is now
   b. Move window away, use 3-stage transformer
   c. Window where it is, design specific transformer with this 'handicap'
2. Modify window to Z0=25Ω and incorporate in 3rd transformer stage

Baseline and fallback design options

a)

- **Baseline design:**

  Cooled matching capacitors inside JET

  Impedance transformers to 30Ω main transmission line (MTL)

  Keeps line voltage < 30kV (30 to 55MHz)

  Relies on successful outcome of

  - capacitor R&D
  - detailed mechanical design, including assessment of capacitor replacement procedure

  Capacitor failure would have very serious consequences

- **Fallback solution:**

  Capacitors (or stubs) ex-vessel

  Additional line stretchers

  Line voltage < 35kV, electric fields < 2kV/mm (30 to 55MHz)

b) Ongoing discussion:

Which is the best approach to demonstrating feasibility of ITER ICRH system?

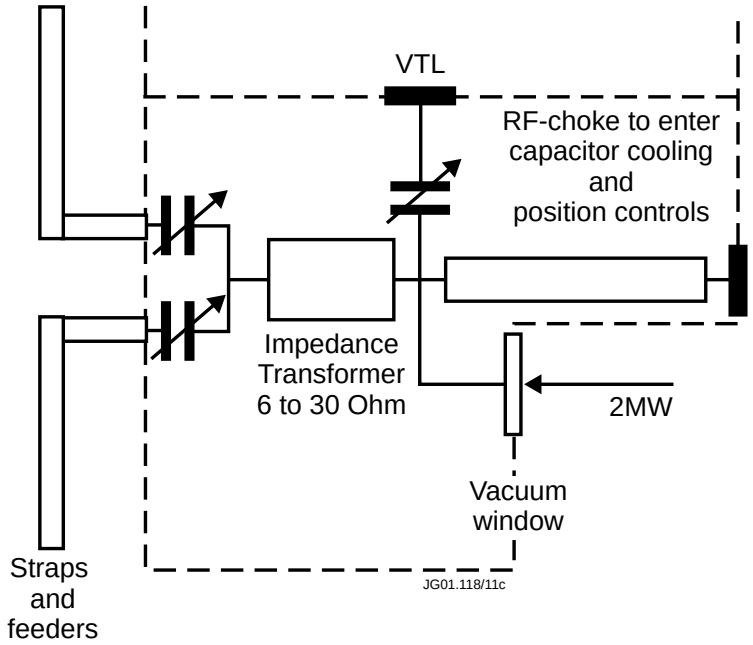
- Successful baseline design would still require

  Development of an all-metal in-vessel matching element for ITER

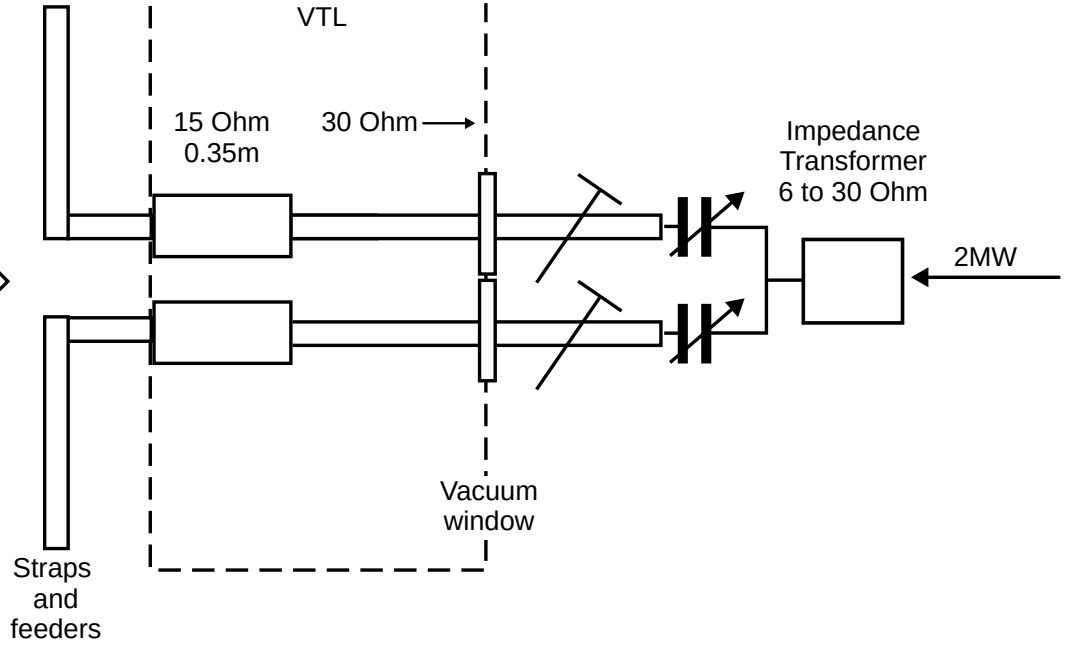
  + Its testing (e.g. on 1/4 ITER antenna, as 8 stubs wouldn't fit in a port)

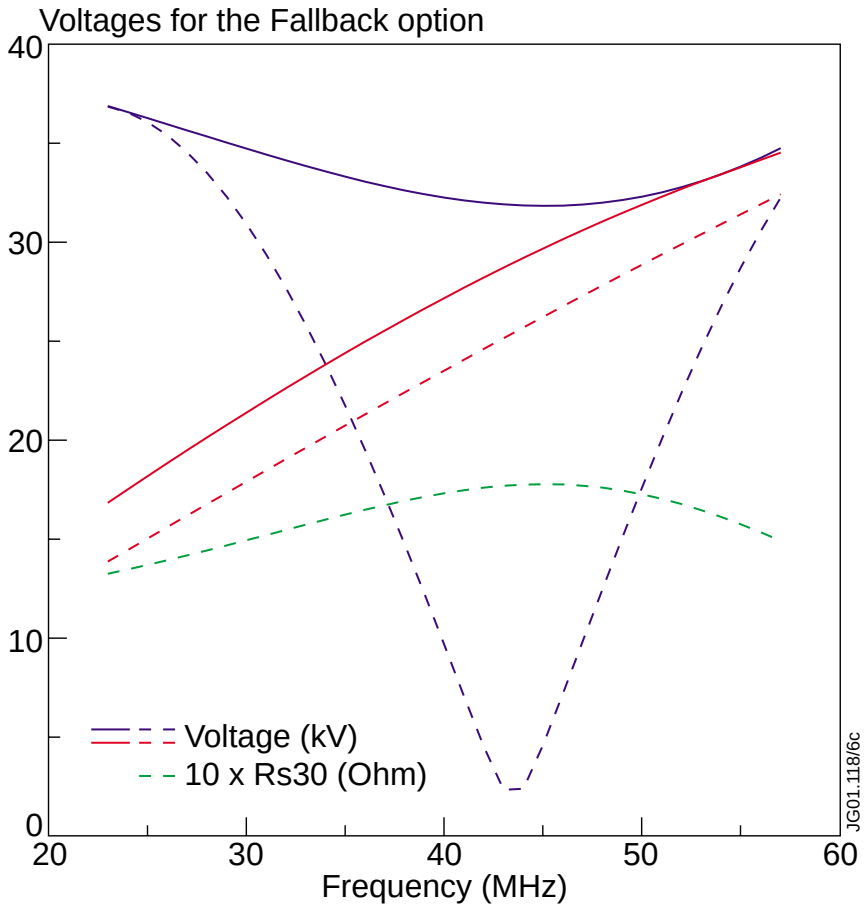
- Successful fallback solution more directly applicable to ITER?

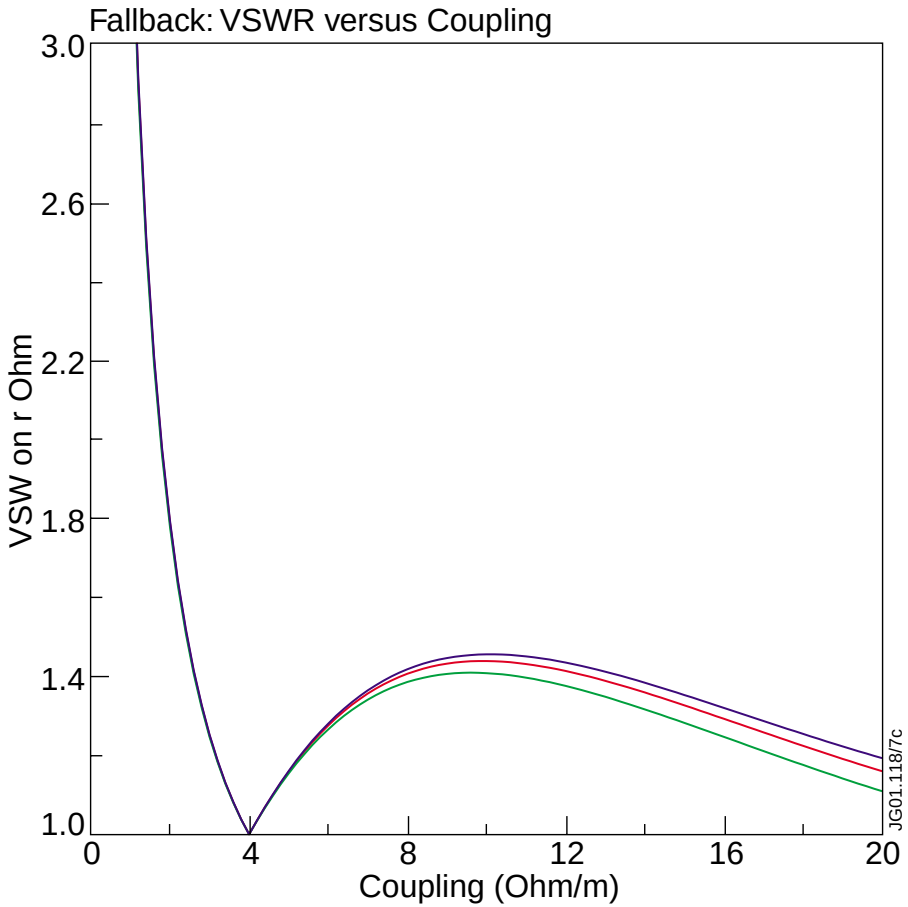
Reference Design



Fallback Option

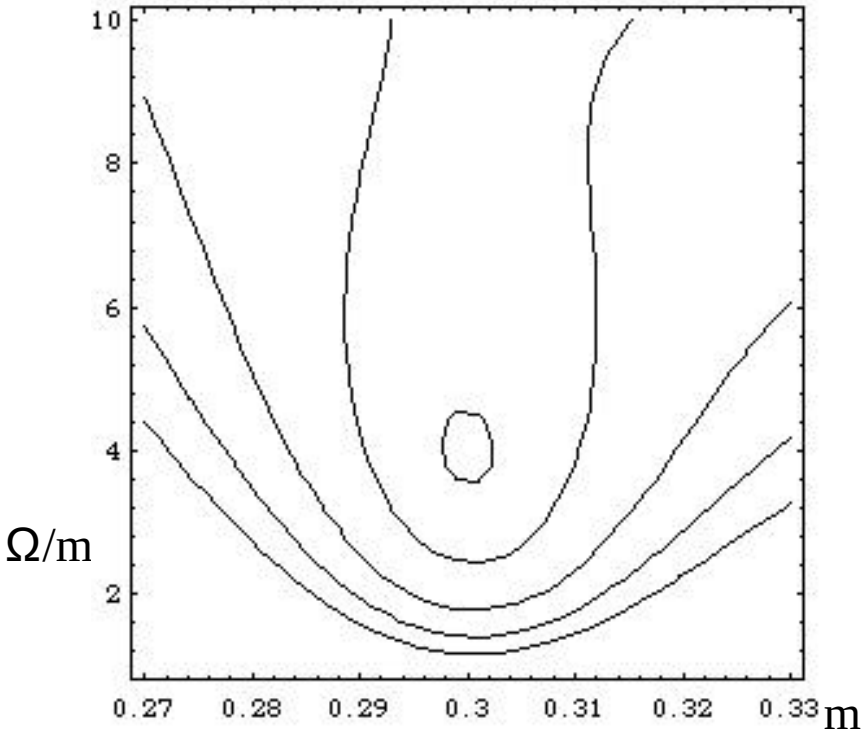



Voltages for the Fallback option
40
30
20
10
0
20
30
40
50
60
Frequency (MHz)
Voltage (kV)
10 x Rs30 (Ohm)
JG01.118/6c


Fallback: VSWR versus Coupling
3.0
2.6
2.2
1.8
1.4
1.0
VSW on r Ohm
0
4
8
12
16
20
Coupling (Ohm/m)
JG01.118/7c

Current issues / ongoing work

- **Adverse effect of reactance transients (routinely observed on JET A2) on ELM resilience?**



55MHz - simult. variations of strap lengths L (m) and lineic resistance R' (Ω/m).

Constant SWR contours on 10Ω (levels 1.1, 1.5, 2, 2.5, 3)

[Strap length variation simulates change of lineic inductance; purely resistive changes are along vertical line at L=0.3m and yield best load tolerance; we need to estimate a realistic relationship between δR' and δL during ELMs to correctly assess load tolerance]

• Capacitor R&D

Prototypes to be delivered end June (Wk 27) / to be tested at Cadarache this summer.

Thermal shield and cooling of surrounding cyl. conductor are needed

Presence of grease (max 150˚C), special tests needed if 350˚ baking required

(1 prototype without grease)

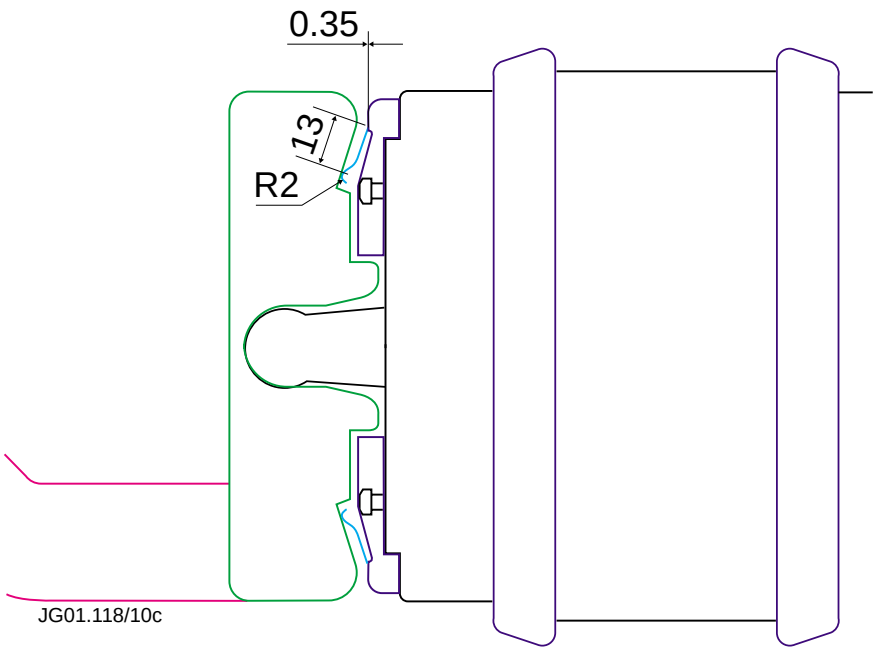
Voltage spec. of 33kV too tight. COMET to be asked implications of 40kV request.

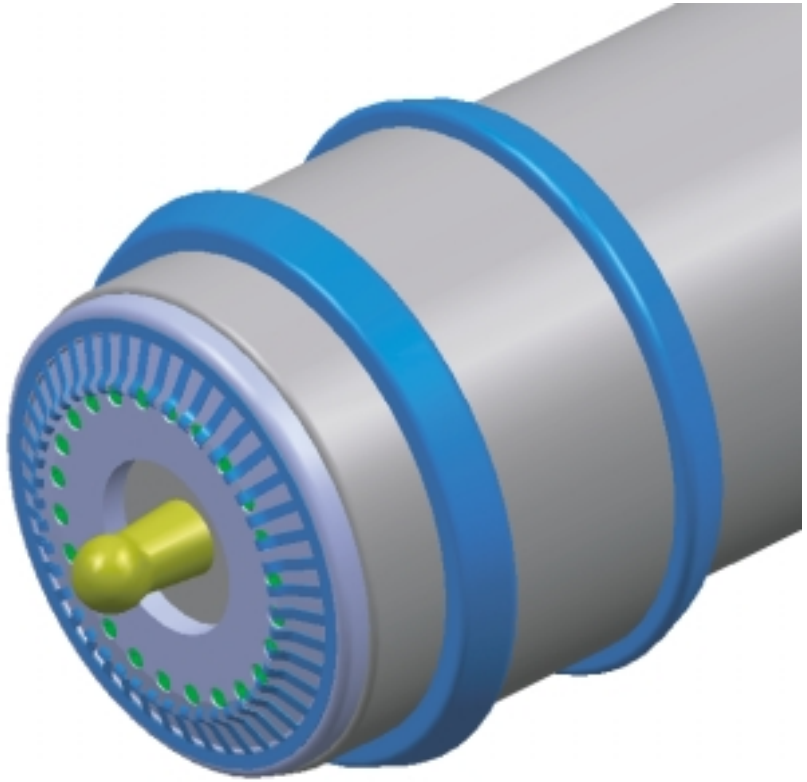
• Connection of capacitors to straps: spring vs axially oriented contacts?

• RF connection of poloidal limiter to wall: now 4 discrete links / limiter. More work required

‘Radial Contact’

Solution for Capacitor-Strap Connection





- Impedance transformer: 2 vs 3 sections (~ 1.8m each, 1st and part of 2nd in vessel)

  Two-section: easy implementation with tested DCF window, but impact on capacitor specs (37kV needed), feeder voltage & current imbalance 13% at 55MHz.

  Three-section: very good electrical characteristics. Requires either

  - Window displacement pumping issues

  or - Modify window to ~ 25ohm

  or - Nonstandard transformer design, to be investigated.

- 3dB hybrids for generator isolation:

  +: insurance policy; if combiner near generator, splitter in torus hall: two 4MW TLs.

  -: without add. hardware, imposes π/2 poloidal phasing. Impact on physics to assess

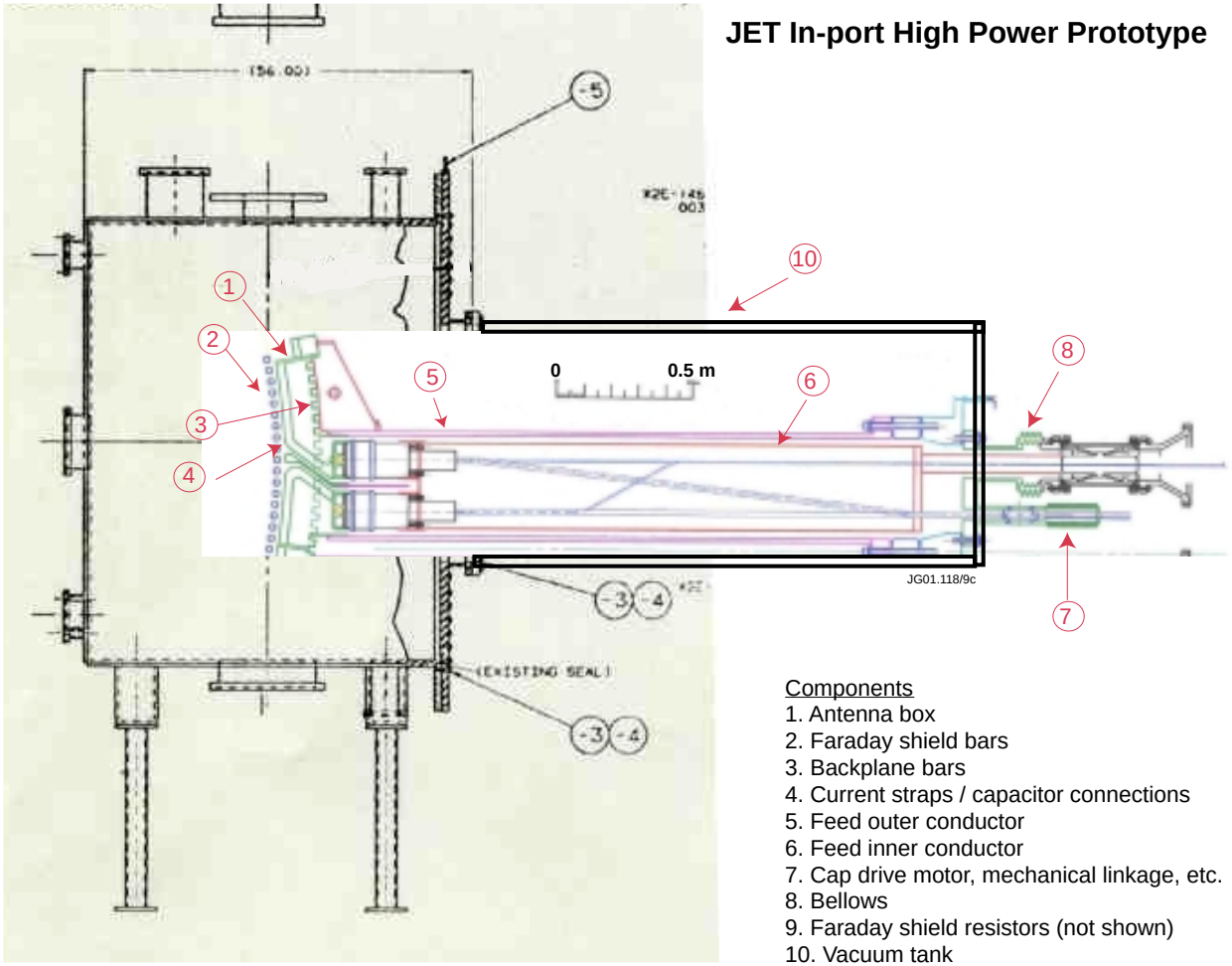
- Detailed TL layout, generator and matching controls

- Occasional arcing may occur during ELMs (although antenna voltage lower): importance of reliable arc detection system
- Antenna instrumentation (reflectometer, visible and IR cameras, voltage probes...)
- Sensitivity of max. voltage & current spectrum to matching errors
- Overall system modelling to analyze possible resonances at tetrodes
- Choose detailed design of impedance transformer, incorporating vacuum window.
- N.B. fallback option not yet at same level of analysis as baseline, study under way

ORNL-PPPL

Full-Scale Test of 1/4 Antenna

JET In-port High Power Prototype



Components
1. Antenna box
2. Faraday shield bars
3. Backplane bars
4. Current straps / capacitor connections
5. Feed outer conductor
6. Feed inner conductor
7. Cap drive motor, mechanical linkage, etc.
8. Bellows
9. Faraday shield resistors (not shown)
10. Vacuum tank
11. Stand (not shown)

References

G Bosia, B Petzold, C Sborchia, “Phase II Proposal for the JET ITER-like Ion Cyclotron Heating and Current Drive”, Presented to JET-EP Ad-Hoc Group for Phase 2 approval, Garching, June 2000

Poster presentations at 14th RF Topical Conference, Oxnard, May 7-9 2001:

Durodié et al, Brémond et al, Koch et al.

... and several memos from the team