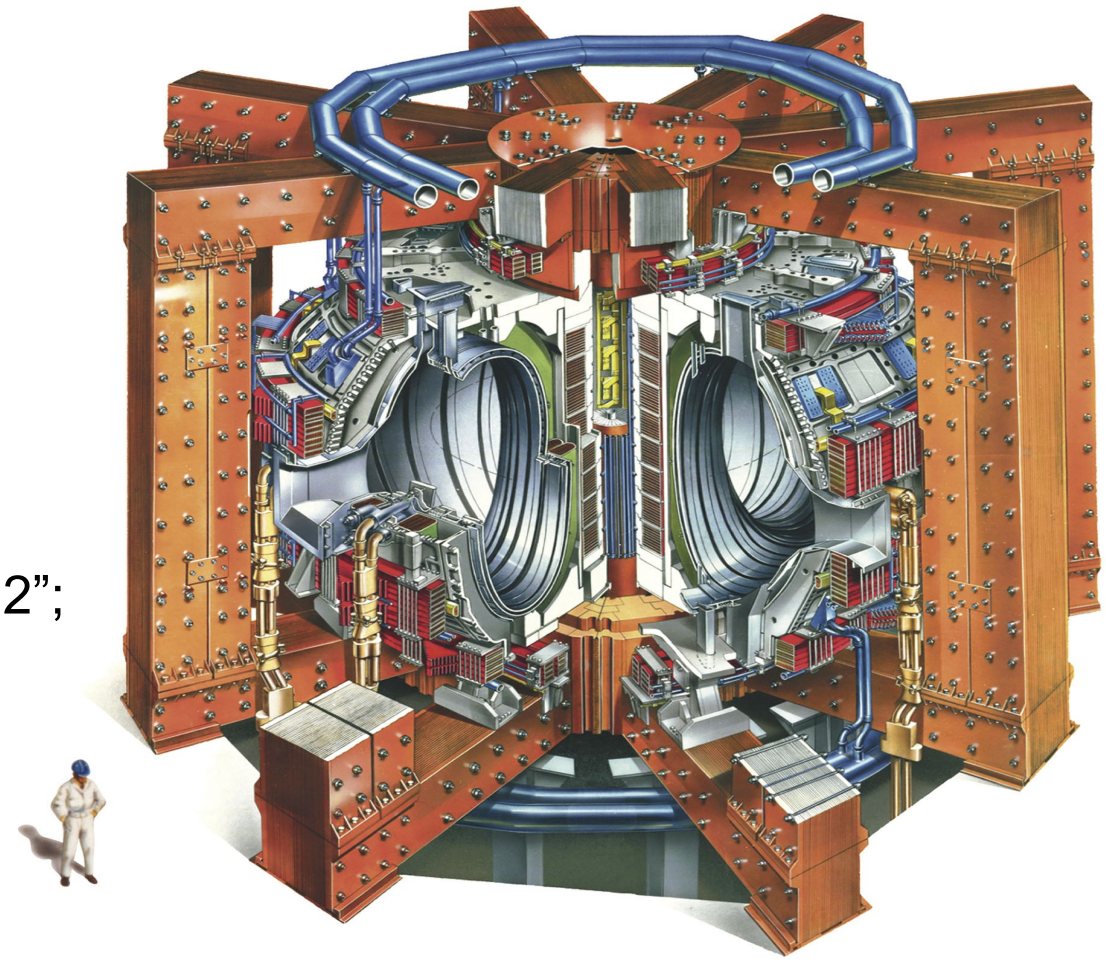
The Design of the JET Tokamak

Contents

- Key parameters
- Load assembly
- Plasma heating systems
- Power supplies
- Tritium recycling
- Remote Handling
- "Enhanced Performance 2";
  Main projects:
  - ILW
  - NBE
  - ERFA
- Summary



JET - key parameters

- Vessel: R = 3.02m a = 1.36m b = 2.14m
- Plasma: R ~ 2.90m a_p ~ 1.0m b_p ~ 1.7m

- $B_{toroidal} \leq 3.45T$ (4.0T) $I_p \leq 4.8MA$ (6MA) $\Delta\Phi \sim 37Wb$

- $P_{aux\text{-}tot} \leq 47MW$ (EP2-NBH, ICRH, LH)

- Vessel temperature = 350ºC (bake-out),
  = 200ºC (operation)

JET load assembly

Vacuum vessel

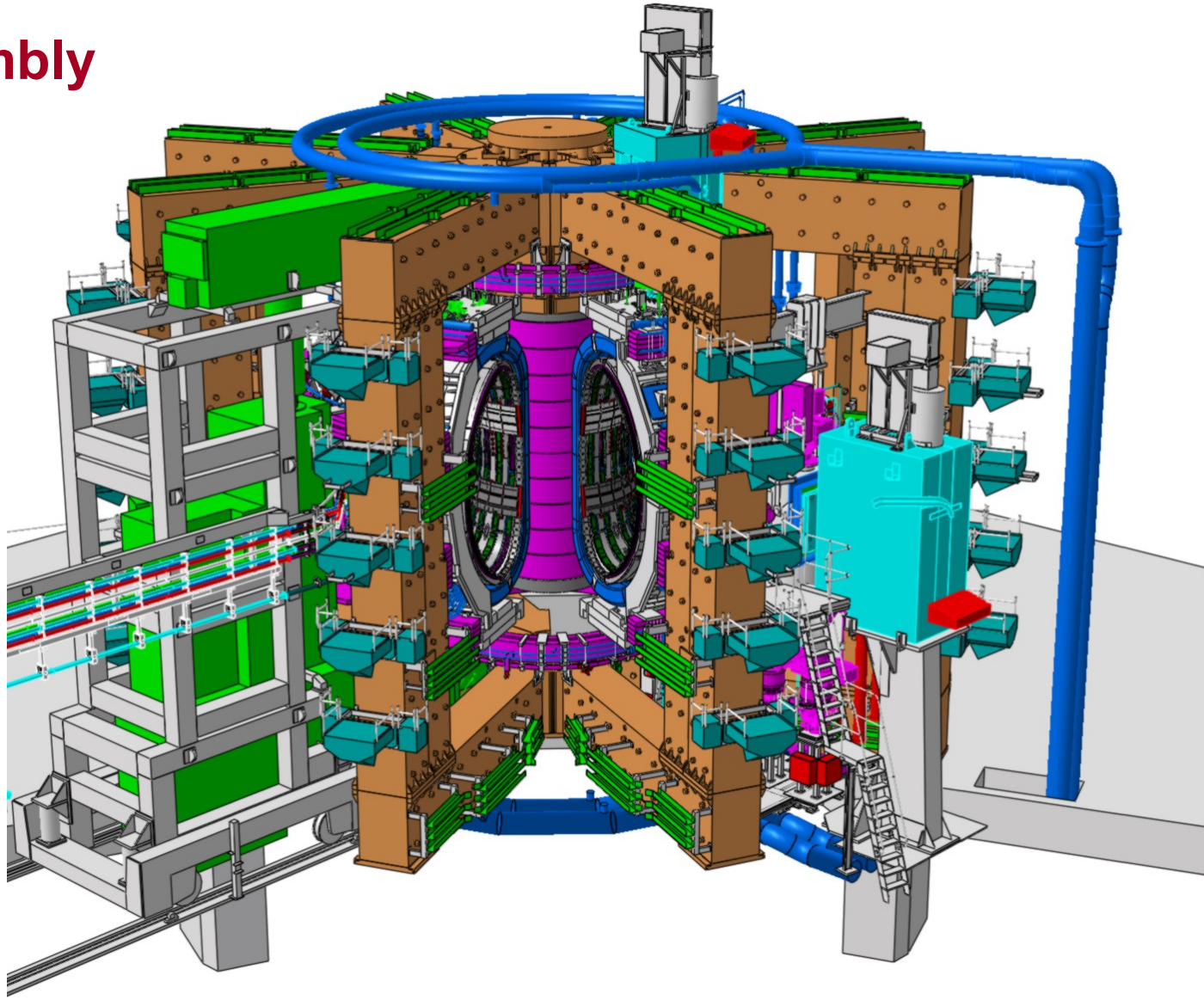
TF coils

Support structure

PF coils

Iron limbs

…etc



In the 1990s a four-coil divertor was added

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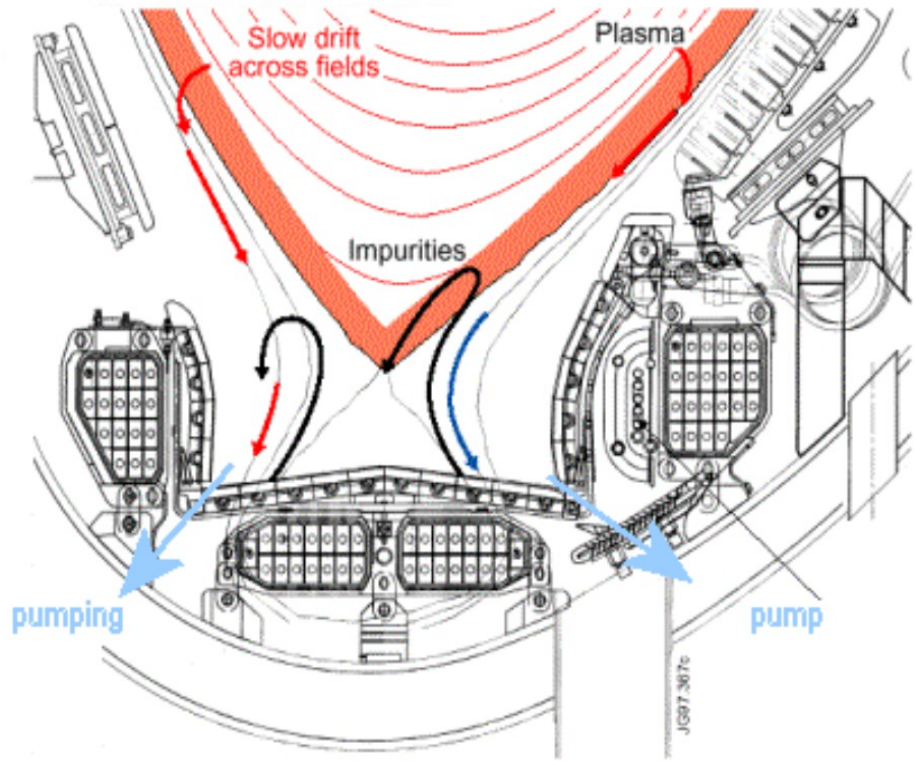
Stage 2 was for the fabrication of the four poloidal coils inside the vacuum vessel, in a very restricted space. This was a completely new experience, requiring new methods of fabrication and new procedures. In fact, the work in the factory was limited to the production of pre-formed and insulated copper hollow bars of 1800 mm^2 cross-section and 1/2 or 1/3 circumference long; to the manufacture of the tools; and to the qualification of the brazing process. The bars were inserted in the vessel through a main horizontal port and positioned (Fig. 7). Each brazed joint had to be performed on curved bars, with transportable brazing tools, and mechanically and X-ray tested to high standards. The coil impregnation took place inside the final casing, a 3 mm thick Inconel structure (Fig. 8).



Vacuum System - Over-view

- **Typical vacuum vessel parameters necessary for tokamak operation:**

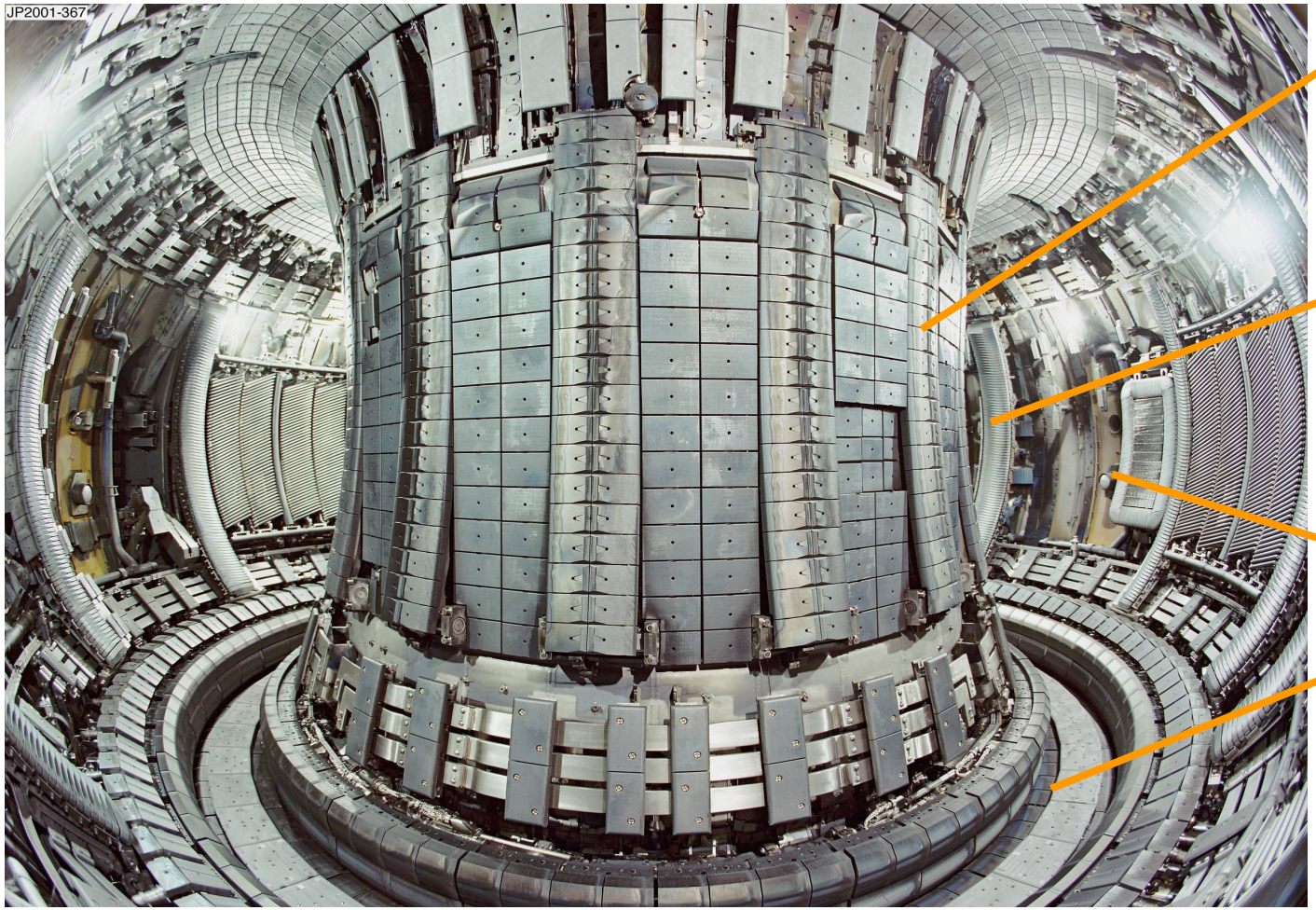
Pressure (Total)	**10^{-7} mbar (mainly D_2 or T_2)**
Pressure (Impurities)	**10^{-9} mbar**
Vessel Temperature	**200 or 320 ^{o}C to maintain clean walls**

- **The ~200m^3 torus is pumped by turbomolecular and cryopumps with effective pumping speeds:**
  - turbos ~4000 litres/sec
  - cryopumps ~100,000 litres/sec (optionally with Ar frosting to pump He)

- **Auxiliary systems have additional UHV pumps, TMP and cryo**

Vacuum System

– until the 2009-2011 shut-down, a lot of CFC to out-gas...



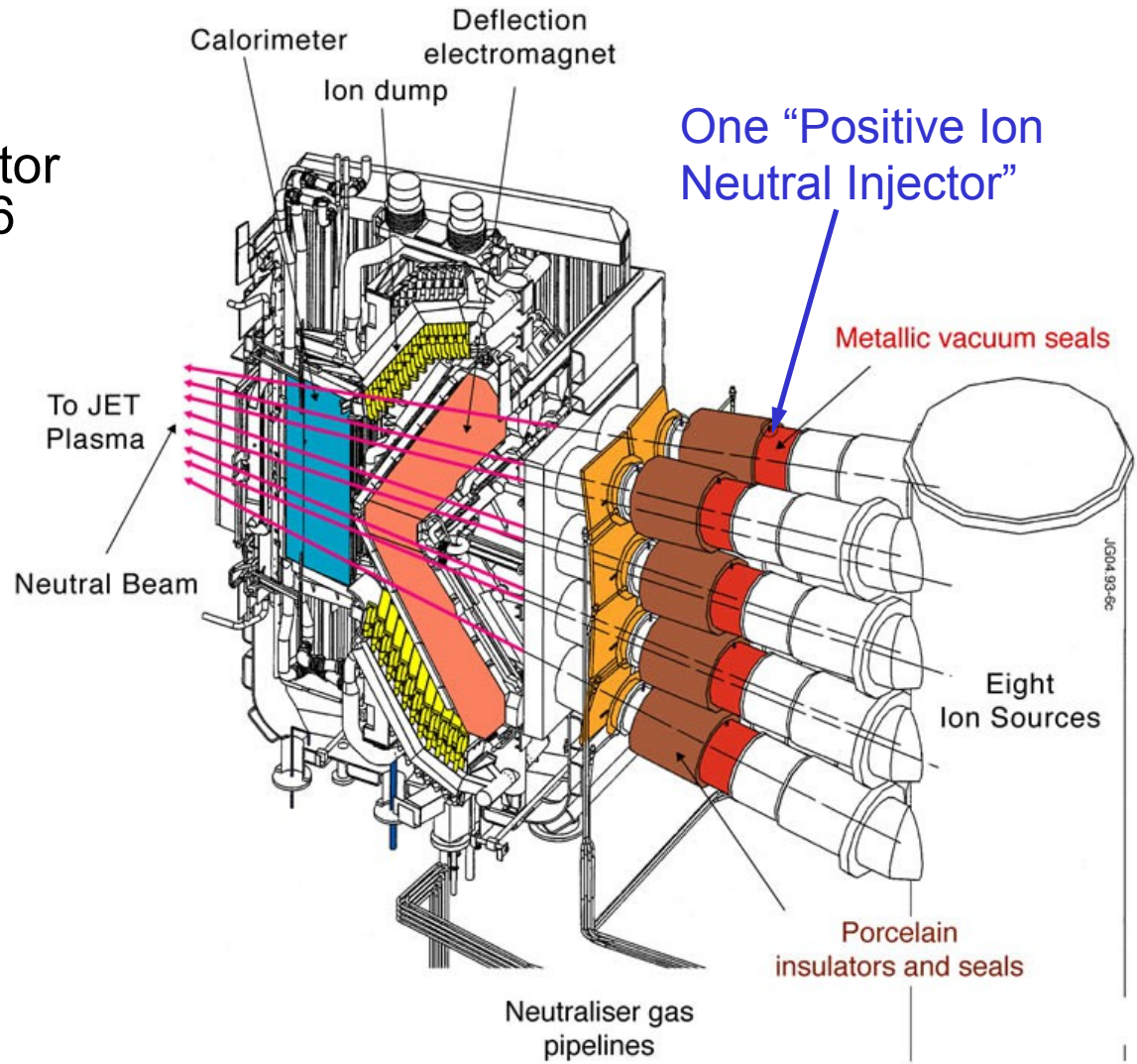
Vacuum system - Cryopumps

- High capacity cryopumps are used at JET to control the plasma fuel gases such as D, H, T and He
  - in the torus, for plasma density control by minimising gas recycling
  - in the NIBs, to inhibit neutraliser gas flowing into the duct region (to minimise beam reionisation) and the torus

- There are five cryopumps in total on JET comprising:
  - **6,000,000 ls-1** in each NIB
  - **100,000 ls-1** in the Torus Divertor (in two halves)
  - **50,000 ls-1** in the Lower Hybrid system

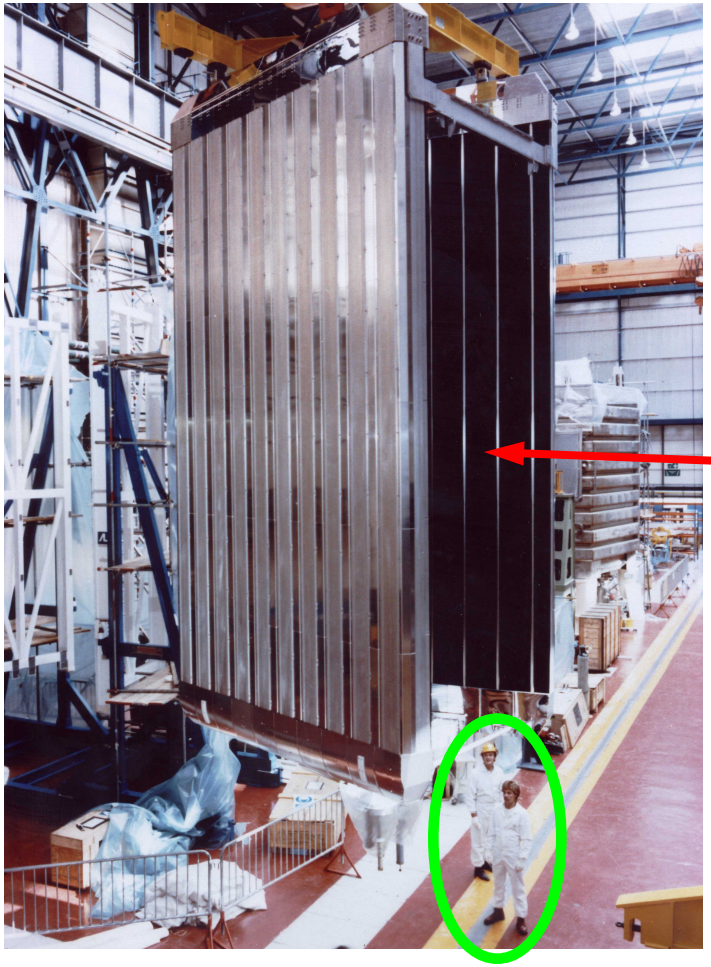
Neutral Beam Injection

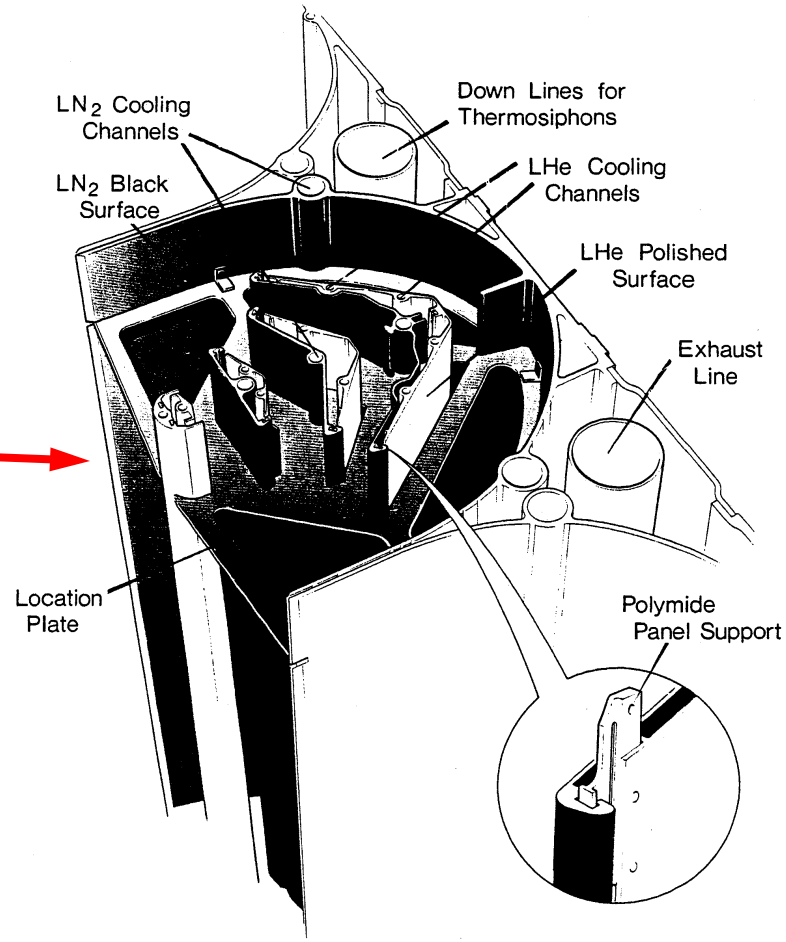
- JET has two Neutral Injector Boxes, each containing 16 PINIs.



- After the EP2 Shut-down:
  - All triode accelerators, 125kV, 65A each
  - P_{tot} = 34MW (D)
  - E_{tot} (max) = 680MJ

Neutral Injector Boxes - Cryopumps

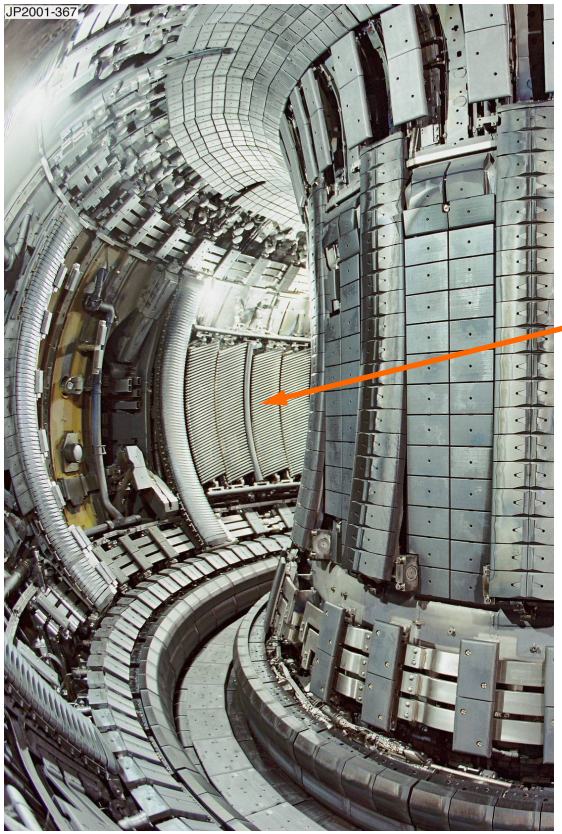




Ion Cyclotron Resonant Heating

The JET ICRH frequency is 23-57MHz, selected within 4MHz sub-bands. Power coupled to the plasma is presently restricted by antenna-plasma shape mismatch.

Sub-band central frequency, MHz	Maximum coupled power, MW
25	3.2
29	5.2
33	7.8
37	13.0
43	13.6
47	10.9
51	11.8
55	5.0



"A2" ICRH antennae, one of 3.

Lower Hybrid Wave Current Drive

24 klystrons @ 3.7GHz, total max power = 15MW

One module (4 klystron units) in J1H.

Thomson TH2103A klystron
650kW/10s or 500kW/20s

Lower Hybrid wave launcher

Stainless steel, copper plated

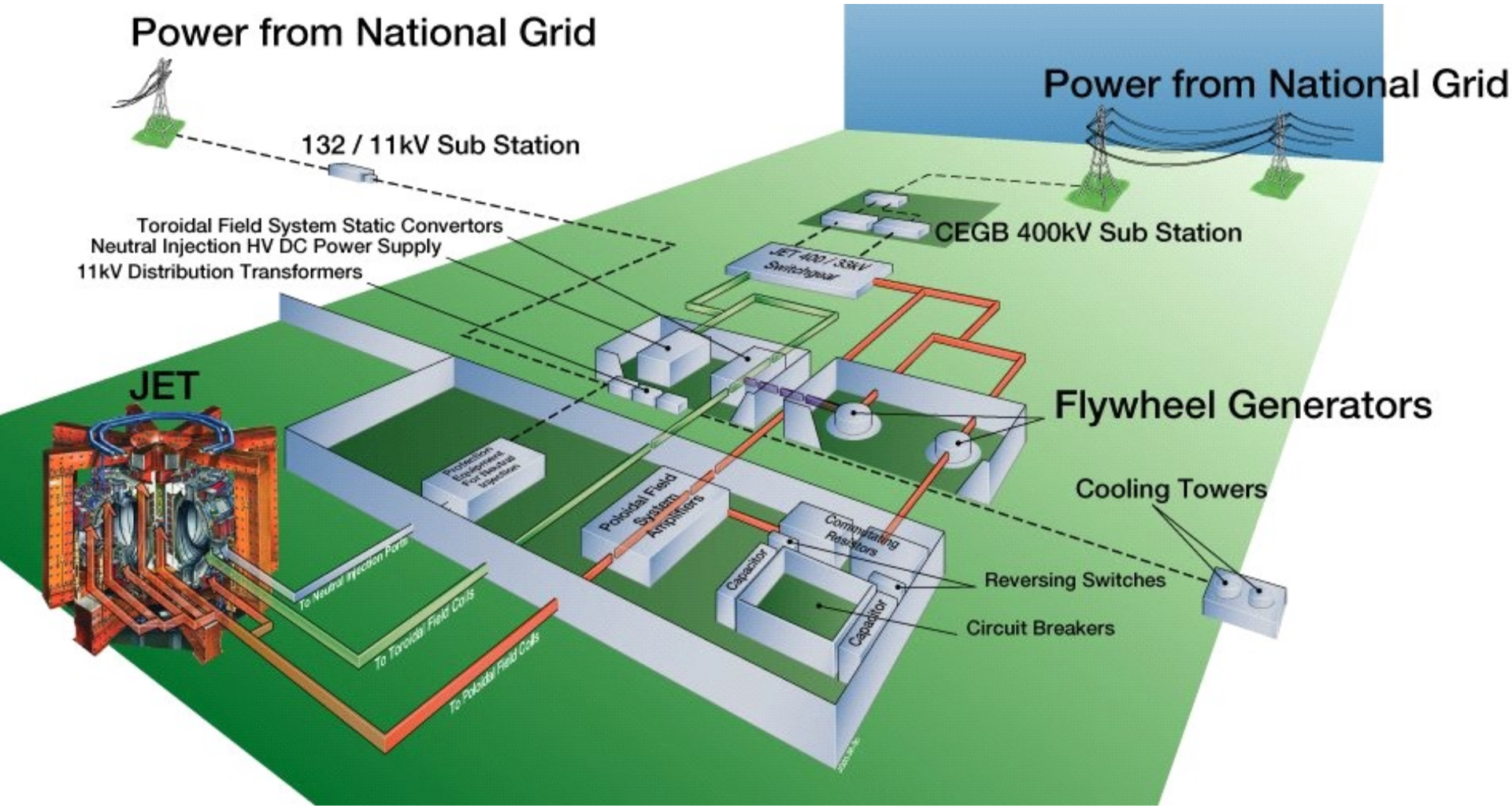
Assembly of 48 multijunctions subdivided into 384 small waveguides facing the plasma

Protection limiters surround the grill (all of castellated Be after the EP2 Shut-down)

Max power and energy ever achieved:
7.3 MW peak power
6 MW for 5s
68 MJ

Max power and energy achieved since 2000:
5.7 MW peak power
4.5 MW for 5s
24 MW/m^2 (as required for ITER) for 5s
56 MJ

Power Supplies - Over-view



JET Tokamak Power Supplies

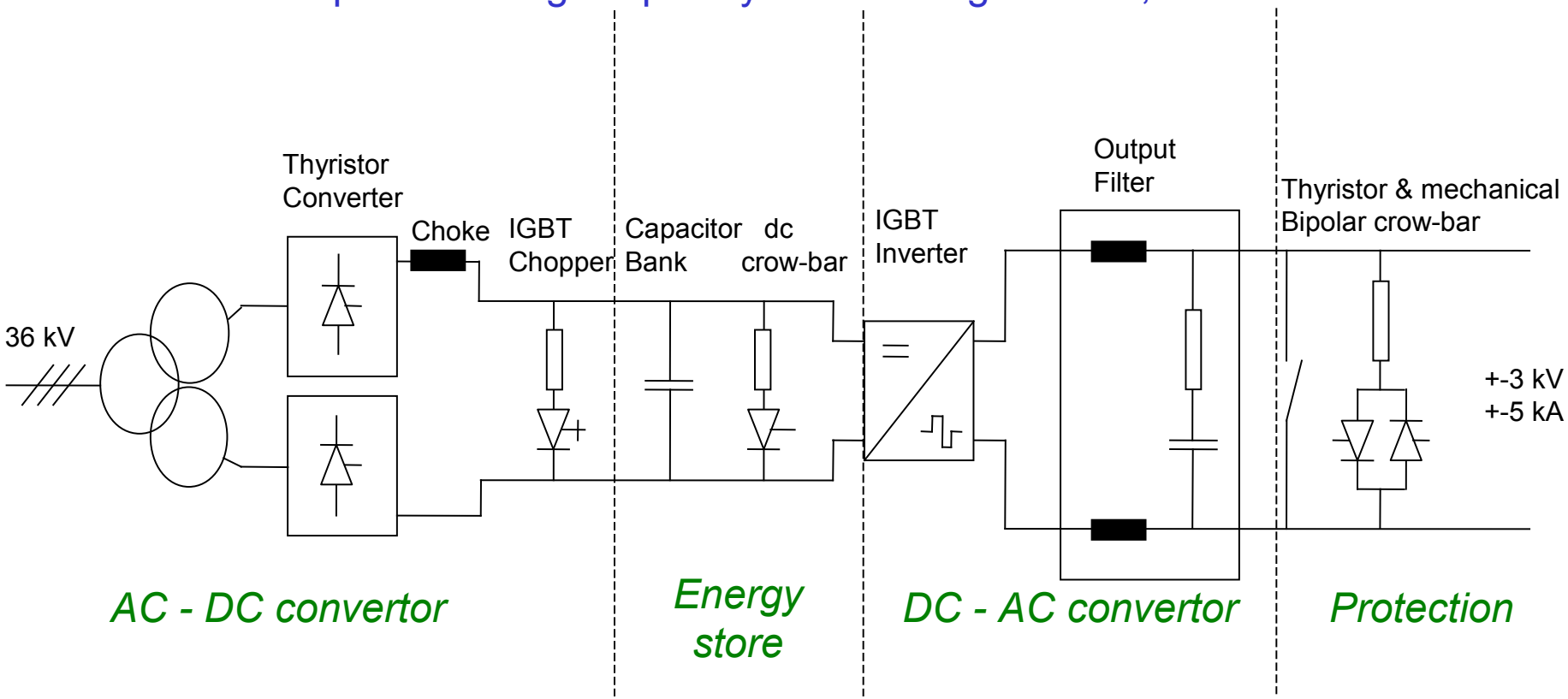
Identifier	Units	Volts	Current	Type	Year	Quadrants
ERFA	4	±3kV	±5kA #	Convertor/Invertor	2009	4
PVFA1	1	±1500V	40kA	Convertor	1985	2
PVFA2	1	±1500V	±20kA	Convertor	1985	4
PVFA3-4	2	±3000V	40kA	Convertor	1985	2
PVFA5-6	2	±3000V	40kA	Convertor	1987	2
PVFB	2	9200V	1kA	Convertor	1987	2
PDFA1-4	4	1000V	40kA #	Convertor	1991	2
PRFA*	4	1500V	6kA #	Convertor	1985	4
PF FGC	1	4kV	100kA	Flywheel Convertor	1982	1
TF FGC	1	4kV	100kA	Flywheel Convertor	1982	1
TFSU1	2	3500V	80kA	Convertor	1985	1
TFSU2	2	3500V	80kA	Convertor	1985	1

Rating is per unit

* Now resurrected to drive Resonant Magnetic Perturbation coils (EFCC), and changed from ±3kA to +6kA

Enhanced Radial Field Amplifier

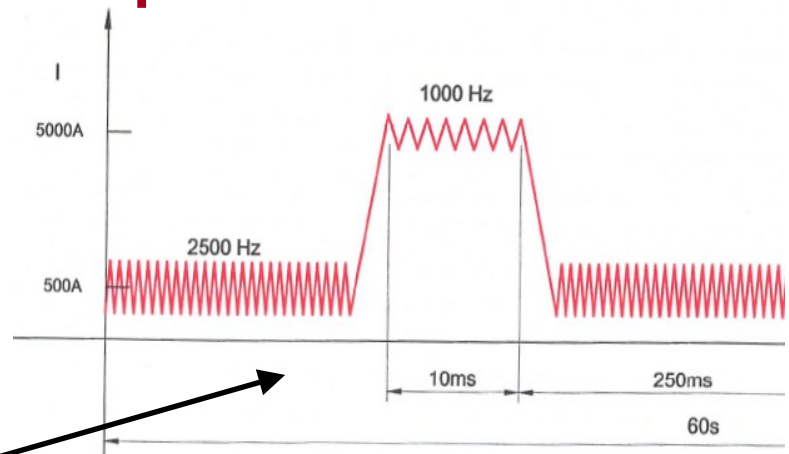
- Improves plasma vertical stability, eg to ELM energy loss from ~0.5 MJ to ~1MJ
- 4 Units, each 3kV, 5kA, 4-quadrant,
  >1kHz output switching frequency at full voltage ±12kV; >2.5kHz at ±3kV



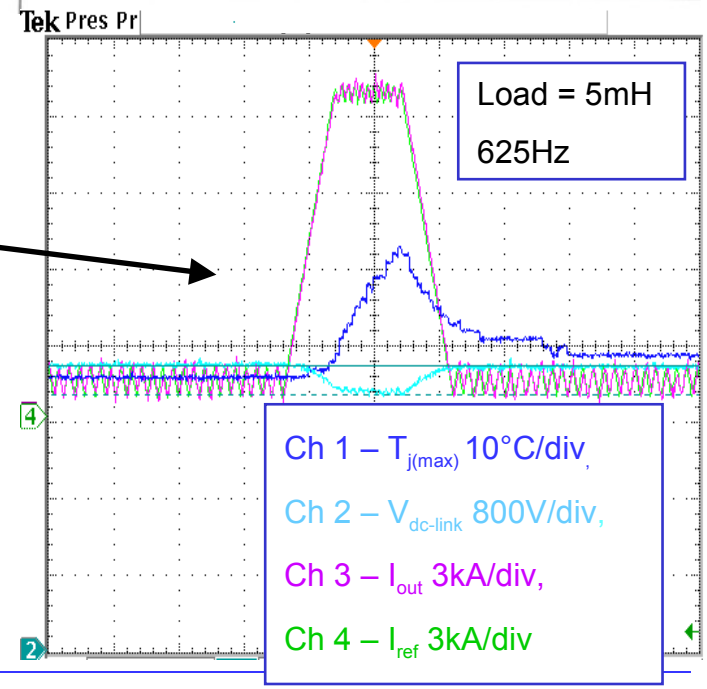
Enhanced Radial Field Amplifier

DC Link – Invertor IGBTs

Specified in contract



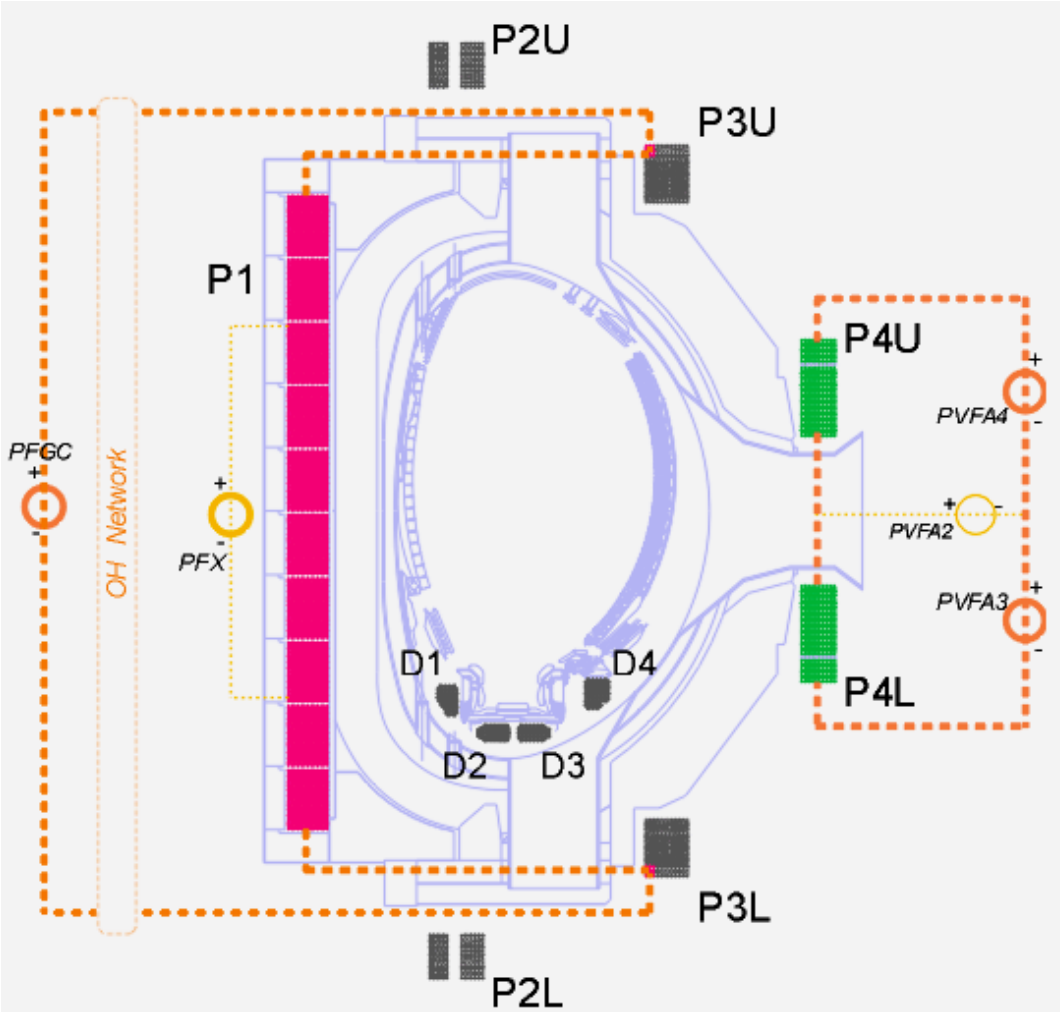
Tested in factory



JET Tokamak Power Supplies

Connection scheme for:

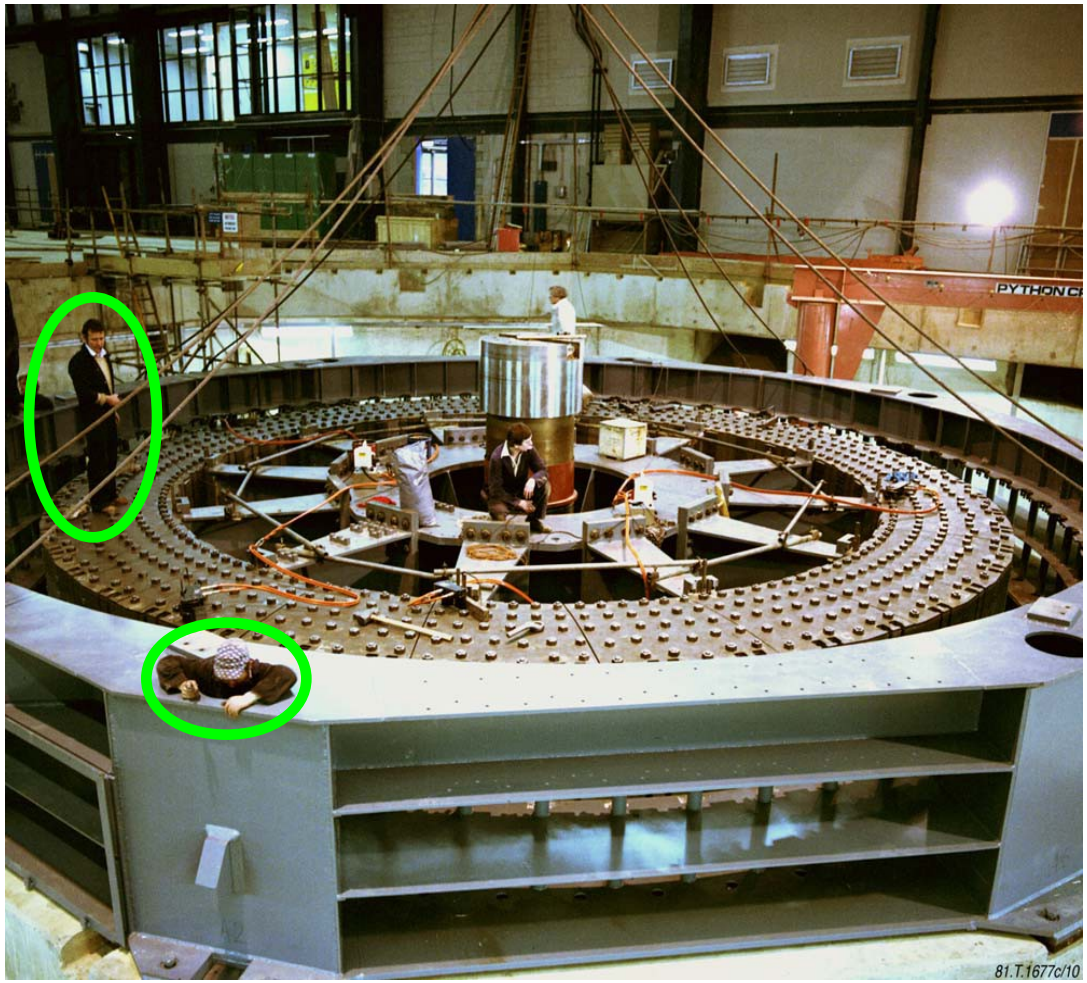
- PF FGC (primary)
- PFX (inboard pusher)
- PVFA4 (vertical field)



Tokamak Supplies - Flywheel Generator Convertors

Each:

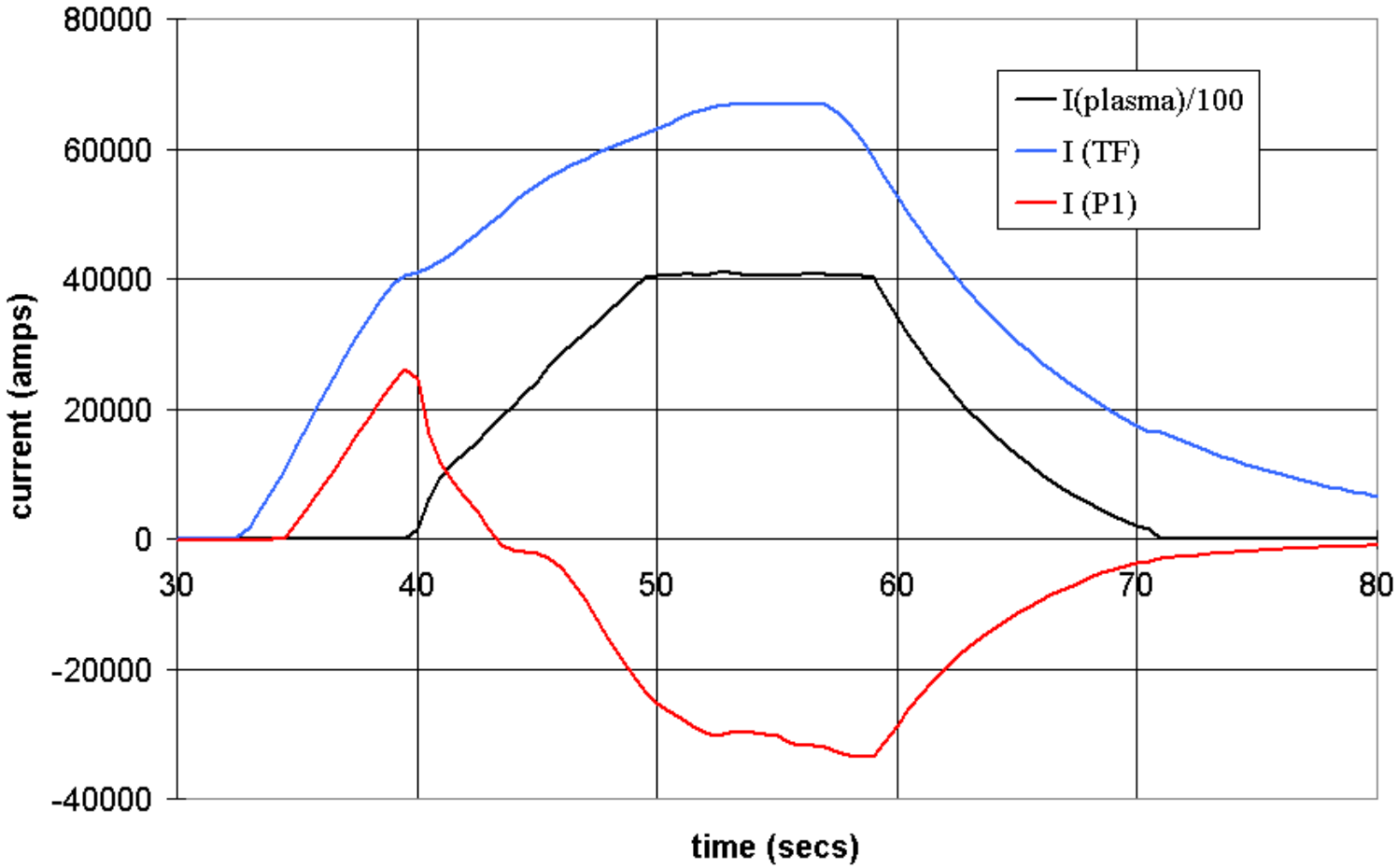
- 800 tonnes
- 112 - 225 rpm
- 8MW pony motor
- 410MVA
- 2.6GJ extractable energy



JET Plasma Heating Systems Power Supplies

System	Units	Volts	Current	Type	Year
NBH	4	160 kV	60A	SCR/Mod-reg	1984
NBH	6	130 kV	130A	Switch Mode	2003
ICRH	4	14 → 26 kV	345A	SCR	1985
LHCD	24	-40 → -65 kV	100A	SCR	1990

Tokamak Power Supplies - Typical Waveforms



Plasma discharge evolution

Torus interior lit by
D_α plasma light

Make gas break-down at bottom

Shift plasma up,
dwell on inboard limiter

Create poloidal divertor

Apply heating...

Plasma dies on inboard limiter

Plasma discharge evolution

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JET

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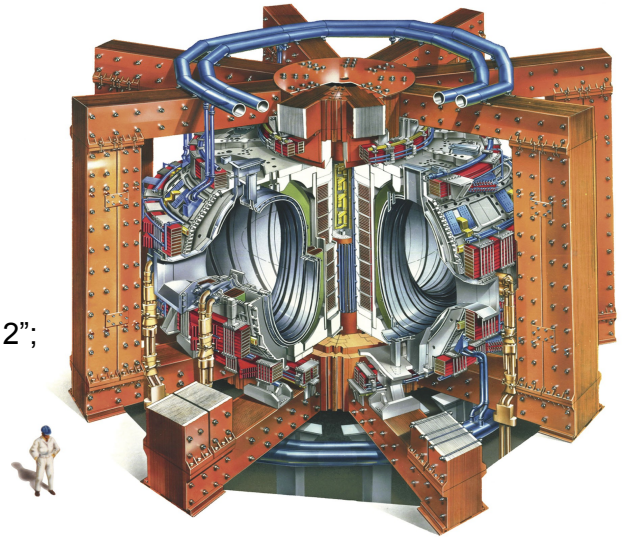

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JET is currently the largest operating tokamak in the world, and is sited at Culham in Oxfordshire, England.

It was built as a joint European project under special management and funding arrangements, which changed at the end of 1999. Since then the United Kingdom Atomic Energy Authority has operated JET for Euratom, while the various "Association" laboratories of Europe, including that of the United Kingdom Atomic Energy Authority, bid to run experiments on the machine under the management of the EFDA CSU (European Fusion Development Agreement, Close Support Unit). EFDA was replaced by the Eurofusion Consortium at the end of 2013.

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JET - key parameters

- Vessel: R = 3.02m a = 1.36m b = 2.14m
- Plasma: R ~ 2.90m a_p ~ 1.0m b_p ~ 1.7m
- $B_{toroidal} \leq$ 3.45T (4.0T) $I_p \leq$ 4.8MA (6MA) $\Delta\Phi$ ~ 37Wb
- $P_{aux\text{-}tot} \leq$ 47MW (EP2-NBH, ICRH, LH)
- Vessel temperature = 350ºC (bake-out),
  = 200ºC (operation)

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Soon JT60SA in Japan will be operating and it has key parameters essentially the same as those of JET, with the main differences being a much lower maximum toroidal field but the ability to run extremely long pulses (hundreds of seconds compared to only a few tens of seconds in JET). This is because the magnetic field coils of JET (designed in the early 1970's) are all copper whereas those of JT60SA (under construction now) are all superconducting.

Soon after JT60SA comes on line, ITER – described in another talk! - will begin operation.

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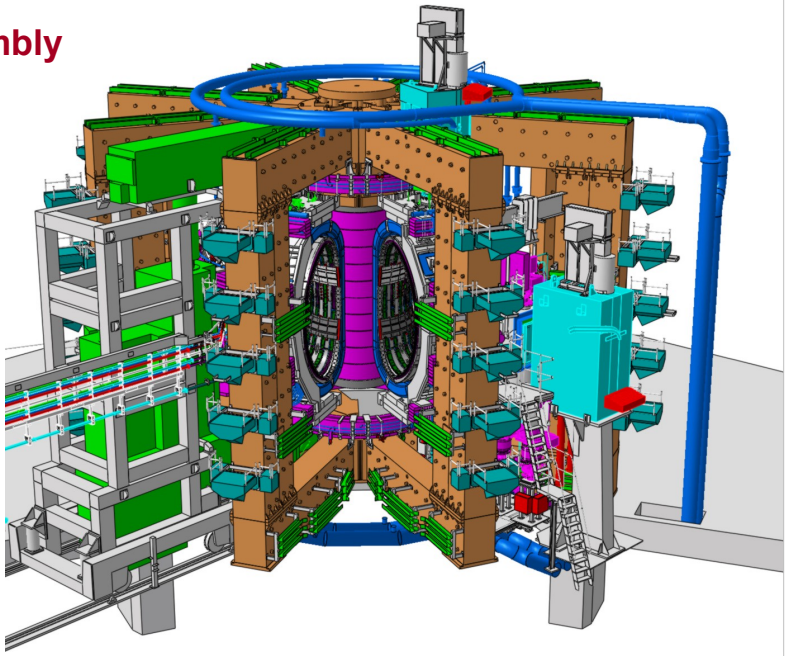
JET load assembly

- Vacuum vessel
- TF coils
- Support structure
- PF coils
- Iron limbs
- …etc



In the 1990s a four-coil divertor was added

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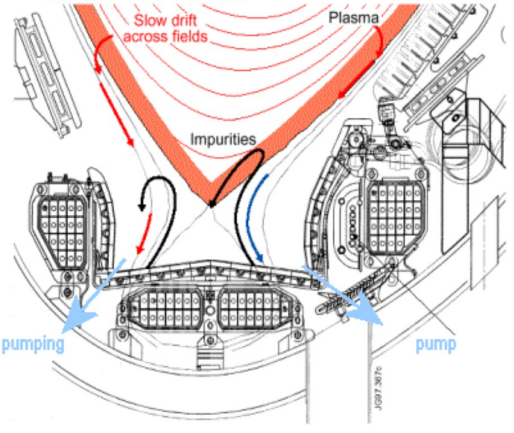
Stage 2 was for the fabrication of the four poloidal coils inside the vacuum vessel, in a very restricted space. This was a completely new experience, requiring new methods of fabrication and new procedures. In fact, the work in the factory was limited to the production of pre-formed and insulated copper hollow bars of 1800 mm^2 cross-section and 1/2 or 1/3 circumference long; to the manufacture of the tools; and to the qualification of the brazing process. The bars were inserted in the vessel through a main horizontal port and positioned (Fig. 7). Each brazed joint had to be performed on curved bars, with transportable brazing tools, and mechanically and X-ray tested to high standards. The coil impregnation took place inside the final casing, a 3 mm thick Inconel structure (Fig. 8).



Vacuum System - Over-view

- **Typical vacuum vessel parameters necessary for tokamak operation:**

Pressure (Total)	**10^{-7} mbar (mainly D_2 or T_2)**
Pressure (Impurities)	**10^{-9} mbar**
Vessel Temperature	**200 or 320 ^{o}C to maintain clean walls**

- **The ~200m^3 torus is pumped by turbomolecular and cryopumps with effective pumping speeds:**
  - turbos ~4000 litres/sec
  - cryopumps ~100,000 litres/sec (optionally with Ar frosting to pump He)

- **Auxiliary systems have additional UHV pumps, TMP and cryo**

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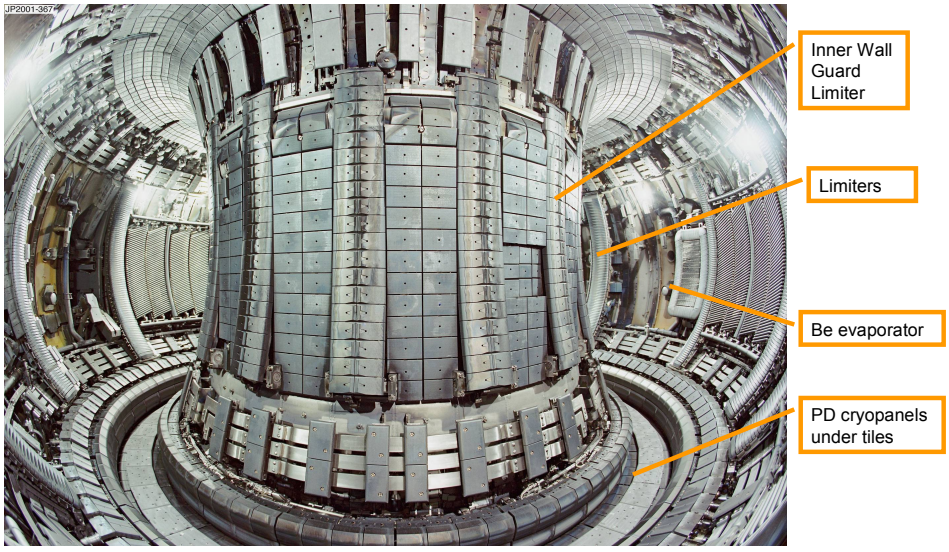
Vacuum System
– until the 2009-2011 shut-down, a lot of CFC to out-gas...



CFC = Carbon-Fibre reinforced Carbon, the same as used in airplane and sports-car brakes. Both types of application rely upon the high thermal conductivity and high sublimation temperature (with no liquid phase) of the material.

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Vacuum system - Cryopumps

- High capacity cryopumps are used at JET to control the plasma fuel gases such as D, H, T and He
  - in the torus, for plasma density control by minimising gas recycling
  - in the NIBs, to inhibit neutraliser gas flowing into the duct region (to minimise beam reionisation) and the torus
- There are five cryopumps in total on JET comprising:
  - **6,000,000 ls-1** in each NIB
  - **100,000 ls-1** in the Torus Divertor (in two halves)
  - **50,000 ls-1** in the Lower Hybrid system

If you take a cold bottle of beer out of the refrigerator and blow on it, the water vapour in your breath will condense onto it. This is how a cryopump works, only the temperature is chosen to be below the evaporation point of the liquid phase of the gas of interest and therefore much is colder than a bottle of beer!

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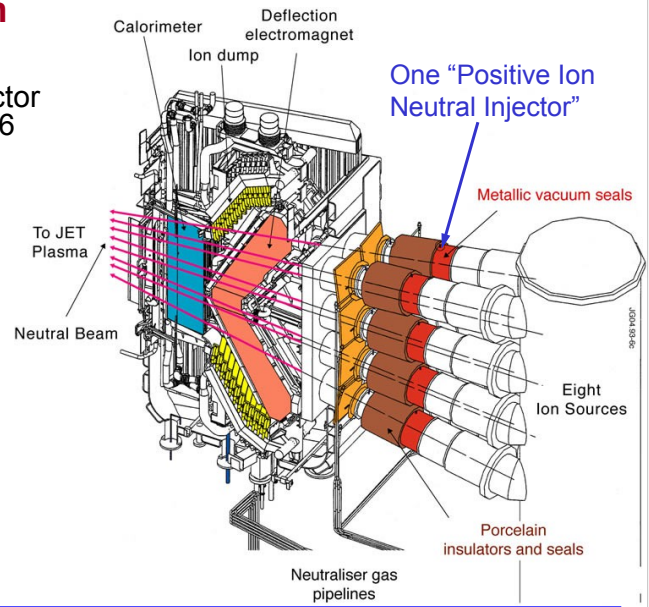
Neutral Beam Injection

- JET has two Neutral Injector Boxes, each containing 16 PINIs.



- After the EP2 Shut-down:
  - All triode accelerators, 125kV, 65A each
  - P_{tot} = 34MW (D)
  - E_{tot} (max) = 680MJ

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You cannot inject ion beams of the plasma fuel species into a tokamak because they would be deflected strongly by the toroidal magnetic field. Heavy ion beams can be injected and are used for special diagnostic purposes (such as probing the electric potential profile of the plasma) but if significant power was injected that way, there would be excessive contamination of the plasma.

So we have to neutralise the fuel ions (isotopes of hydrogen, or sometimes helium for special tests). Fortunately if the accelerated ion beam is simply shone through a region containing neutral gas, there is a tendency for charge exchange to occur – the fast ions become fast neutrals suitable for injection into the tokamak, and the neutral gas becomes very slow ions, subsequently neutralised at the walls of the neutraliser chamber.

Unfortunately this tendency to charge-exchange becomes very weak at beam energies above ~200keV for positive ions. However hydrogen and its isotopes can form a weakly bound negative ion, which is very easily stripped off the atom and accordingly high energy beams (as will be used in JT60SA and ITER) use negative ion beams as precursors.

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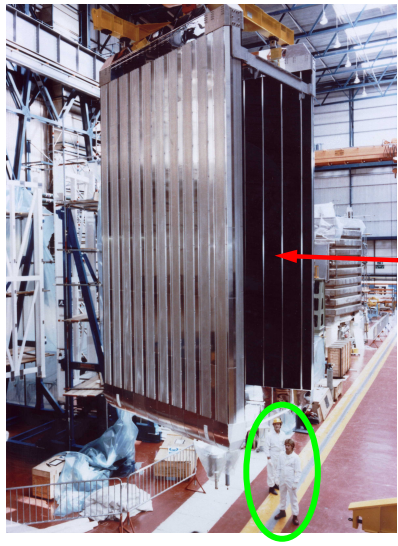
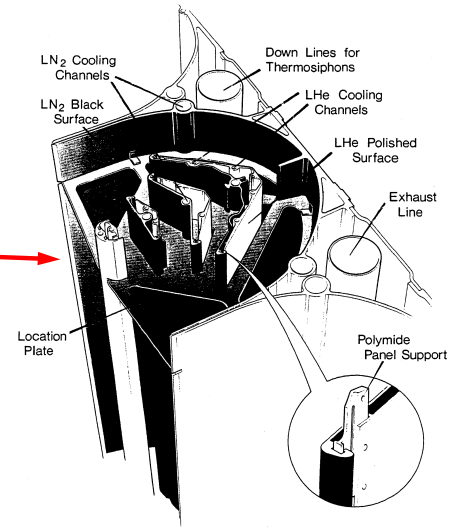
Neutral Injector Boxes - Cryopumps





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It is necessary to have a certain "gas density times length" for the neutraliser to asymptote towards the maximum neutralisation fraction it can achieve. Size constraints make that a shortish length times a high density, which has to be stopped from flooding the torus with too much gas. Hence extremely large pumping speeds are required between the neutraliser cell and the torus entry duct, most easily achieved with large area cryopumps.

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Ion Cyclotron Resonant Heating

The JET ICRH frequency is 23-57MHz, selected within 4MHz sub-bands. Power coupled to the plasma is presently restricted by antenna-plasma shape mismatch.

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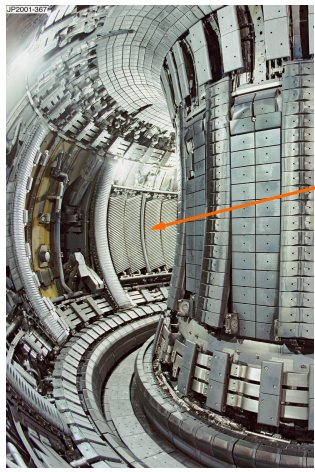

Charged particles in a magnetic field gyrate around the field lines at a characteristic frequency called the cyclotron frequency. If this (or a harmonic of it) is resonated by an alternating electric field, the charged particle gains energy (like a child being pushed cyclically on a swing – only effective if resonant*).

*Experience tells you that you can resonate the swing very well by sub-harmonically resonating with the oscillation of the swing. However that does not work for charged particles in a magnetic field, where the counter-intuitive higher frequency harmonics provide the other useful resonances.

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Lower Hybrid Wave Current Drive

24 klystrons @ 3.7GHz, total max power = 15MW

One module (4 klystron units) in J1H.

Thomson TH2103A klystron
650kW/10s or 500kW/20s

Lower hybrid waves effectively make the electrons in the plasma "surf" and can therefore be used to push the electrons in one direction around the torus, constituting current drive as well as electron heating.

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

Lower Hybrid wave launcher

Stainless steel, copper plated

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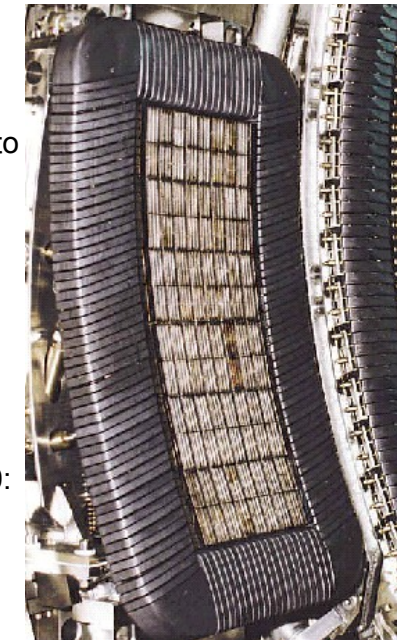

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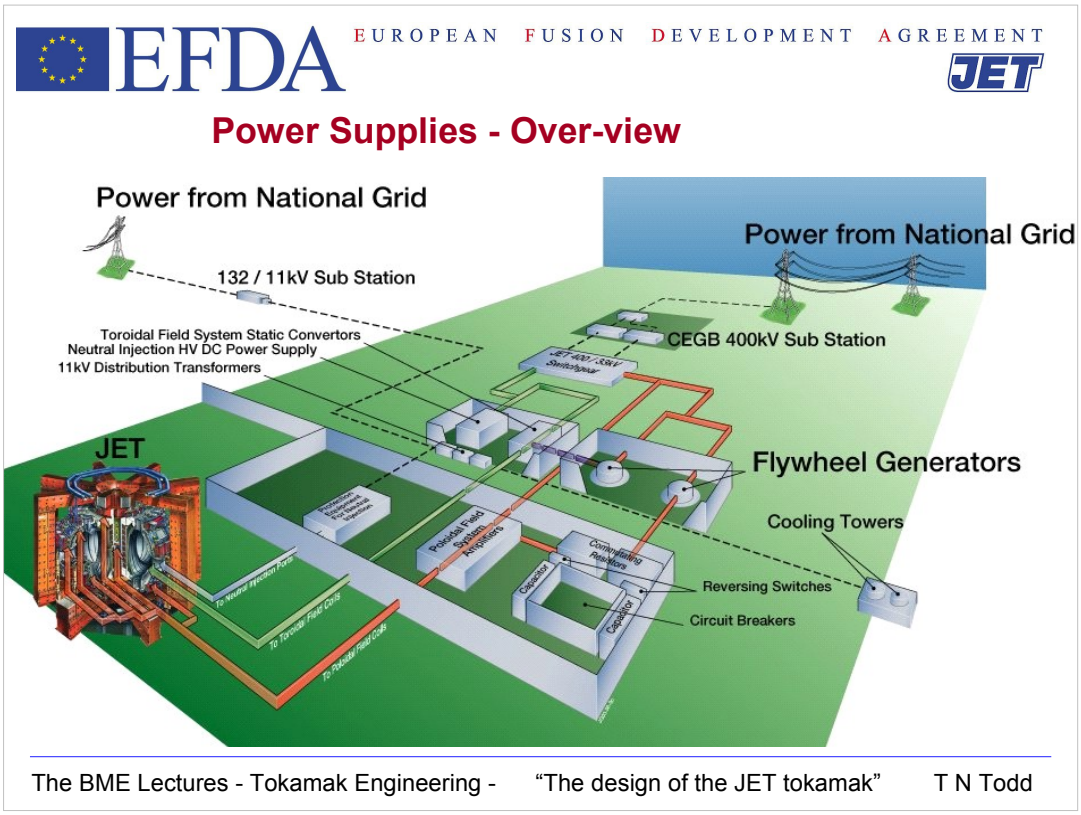
Adjacent waveguides are differentially phased by typically 45, 60 or 90 degrees to promote a wave perpendicular to the normal of the antenna array, which has a phase velocity much lower than the speed of light and somewhat above the mean thermal speed of the electrons.



The copper coils in JET consume several hundred MW, some of which comes from the flywheel generators and some from direct supplies running straight off the grid.

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

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PF FGC	1	4kV	100kA	Flywheel Convertor	1982	1
TF FGC	1	4kV	100kA	Flywheel Convertor	1982	1
TFSU1	2	3500V	80kA	Convertor	1985	1
TFSU2	2	3500V	80kA	Convertor	1985	1

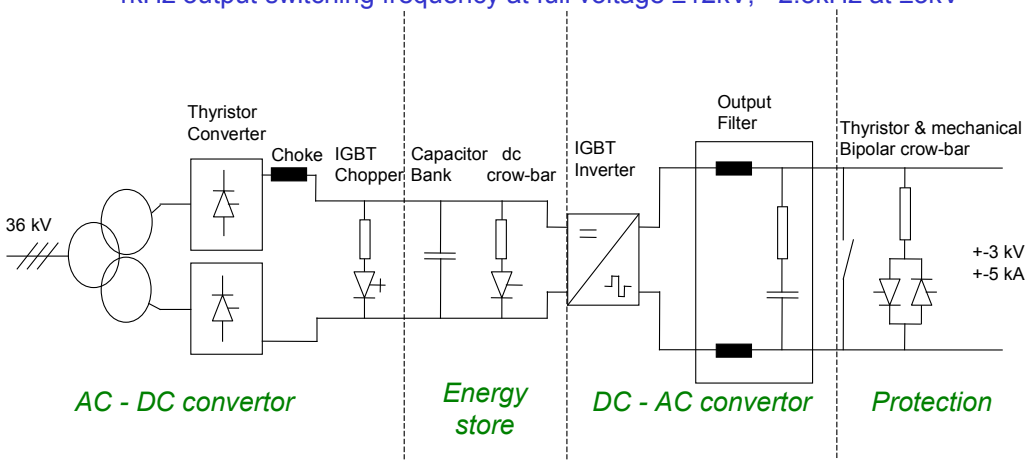
Rating is per unit
* Now resurrected to drive Resonant Magnetic Perturbation coils (EFCC), and changed from ±3kA to +6kA

"Convertor" means thyristor convertor, mostly 12-phase known as "12-pulse" in electrical engineering.

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Enhanced Radial Field Amplifier

- Improves plasma vertical stability, eg to ELM energy loss from ~0.5 MJ to ~1MJ
- 4 Units, each 3kV, 5kA, 4-quadrant,
  >1kHz output switching frequency at full voltage ±12kV; >2.5kHz at ±3kV



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"IGBT" = Insulated Gate Bipolar Transistor.

EUROPEAN FUSION DEVELOPMENT AGREEMENT

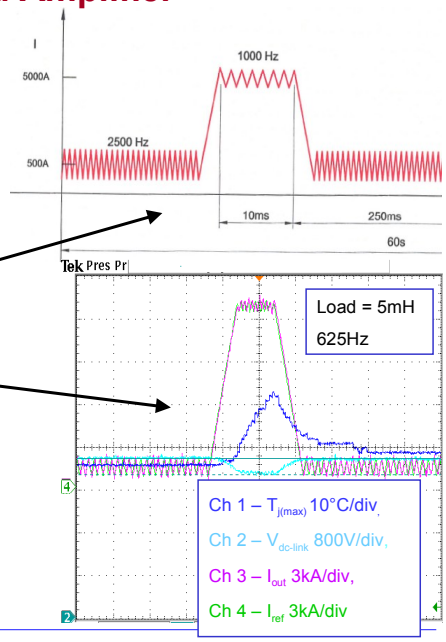
JET

Enhanced Radial Field Amplifier

DC Link – Invertor IGBTs

Specified in contract

Tested in factory



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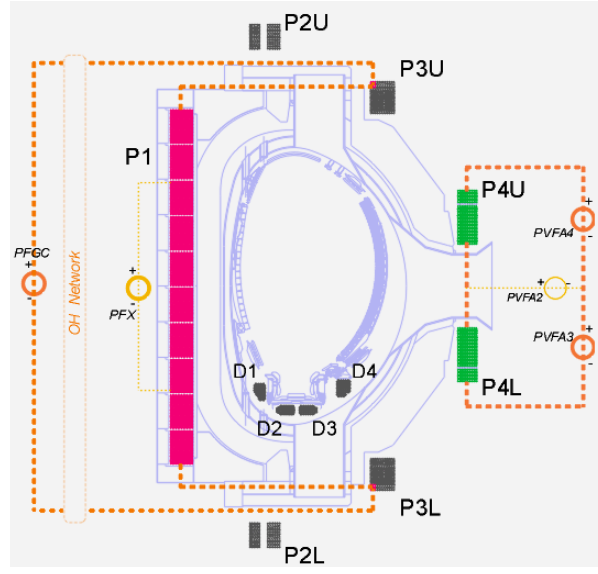
JET Tokamak Power Supplies

Connection scheme for:

- PF FGC (primary)
- PFX (inboard pusher)
- PVFA4 (vertical field)



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The turns in the P3 coils provide some compensation for the return field of the central solenoid, although in JET the large iron limbs around the outside of the machine provide most of that function.

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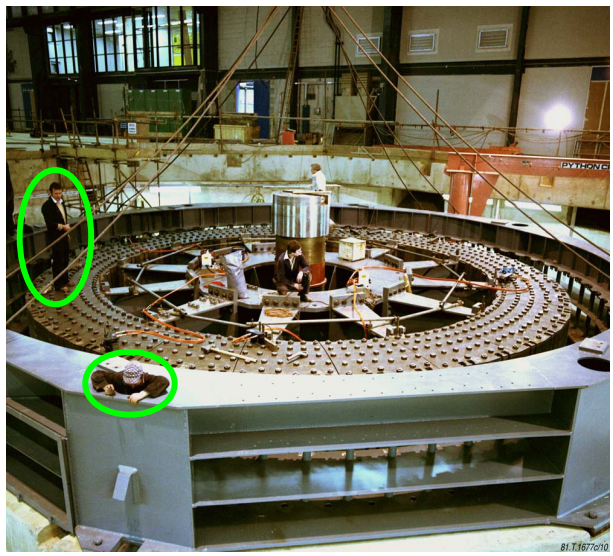
Tokamak Supplies - Flywheel Generator Convertors

Each:

- 800 tonnes
- 112 - 225 rpm
- 8MW pony motor
- 410MVA
- 2.6GJ extractable energy



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MW are related to MVA by including the cosine of the phase angle between the AC current and voltage, which in a highly reactive system can be very small, but in typical loads is ~0.8.

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JET Plasma Heating Systems Power Supplies

System	Units	Volts	Current	Type	Year
NBH	4	160 kV	60A	SCR/Mod-reg	1984
NBH	6	130 kV	130A	Switch Mode	2003
ICRH	4	14 → 26 kV	345A	SCR	1985
LHCD	24	-40 → -65 kV	100A	SCR	1990

SCR = Silicon Controlled Rectifier = thyristor.

Mod-Reg = Modulation – Regulation = HVDC supply followed by large thermionic valve.

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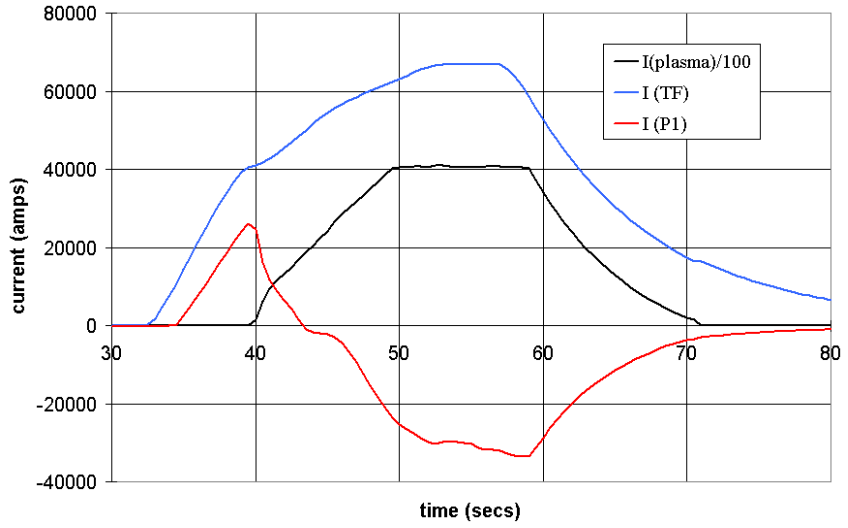
Tokamak Power Supplies - Typical Waveforms



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A copper coiled machine, remember.

The longest plasma pulses in JET have been ~60 seconds in duration, at about 2T.

Plasma discharge evolution

Torus interior lit by
D_α plasma light

Make gas break-down at bottom

Shift plasma up,
dwell on inboard limiter

Create poloidal divertor

Apply heating...

Plasma dies on inboard limiter

Plasma discharge evolution

Torus interior lit by
D_α plasma light

Make gas break-down at bottom

Shift plasma up,
dwell on inboard limiter

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