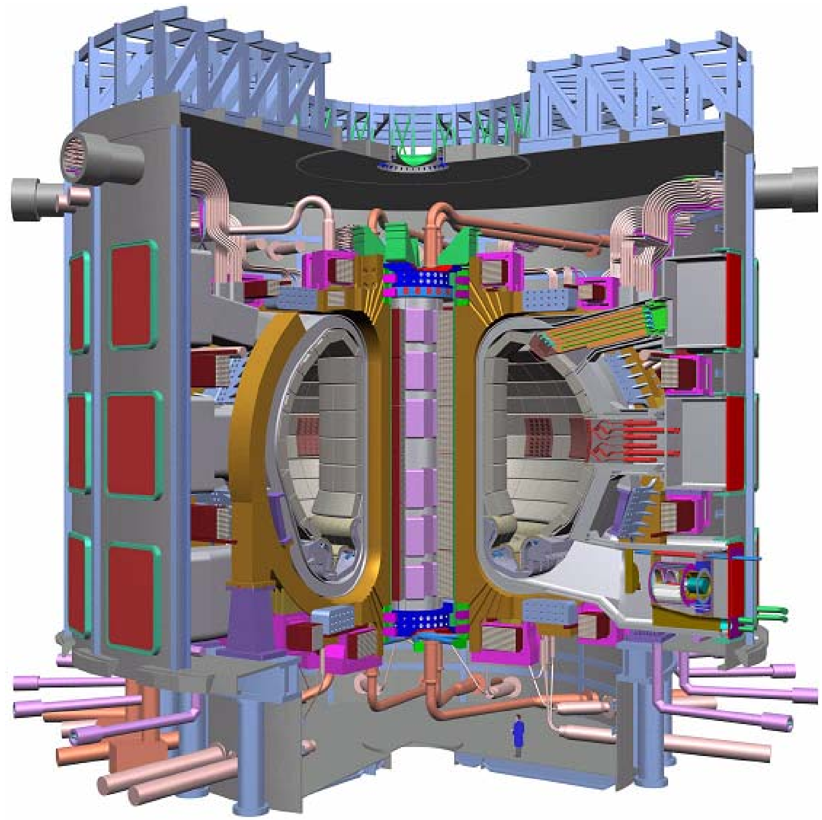
CERN course on Power Converters for Particle Accelerators
Warrington, UK, 12-18 May 2004

ITER and the Power Converters

I. Benfatto



OUTLINE

- **Part 1:**
  - **Role of ITER in Fusion Development**
  - **The ITER Design**
- **Part 2:**
  - **Electrical characteristics of the European site**
  - **The ITER power supplies**
  - **The ITER power converters**

Part 1

The ITER experiment and the main design parameters

with contributions from the ITER International Team

Role of ITER in Fusion Development

- New large energy sources will have to be developed before ~2050 to prevent an environmental crisis.
- With a successful demonstration of controlled fusion and key technologies fusion power plants could contribute to the world electricity needs for the second half of this century.
- **ITER will demonstrate the scientific and technological feasibility of fusion energy.**

Tentative Roadmap of Achievements

Main Achievements Required

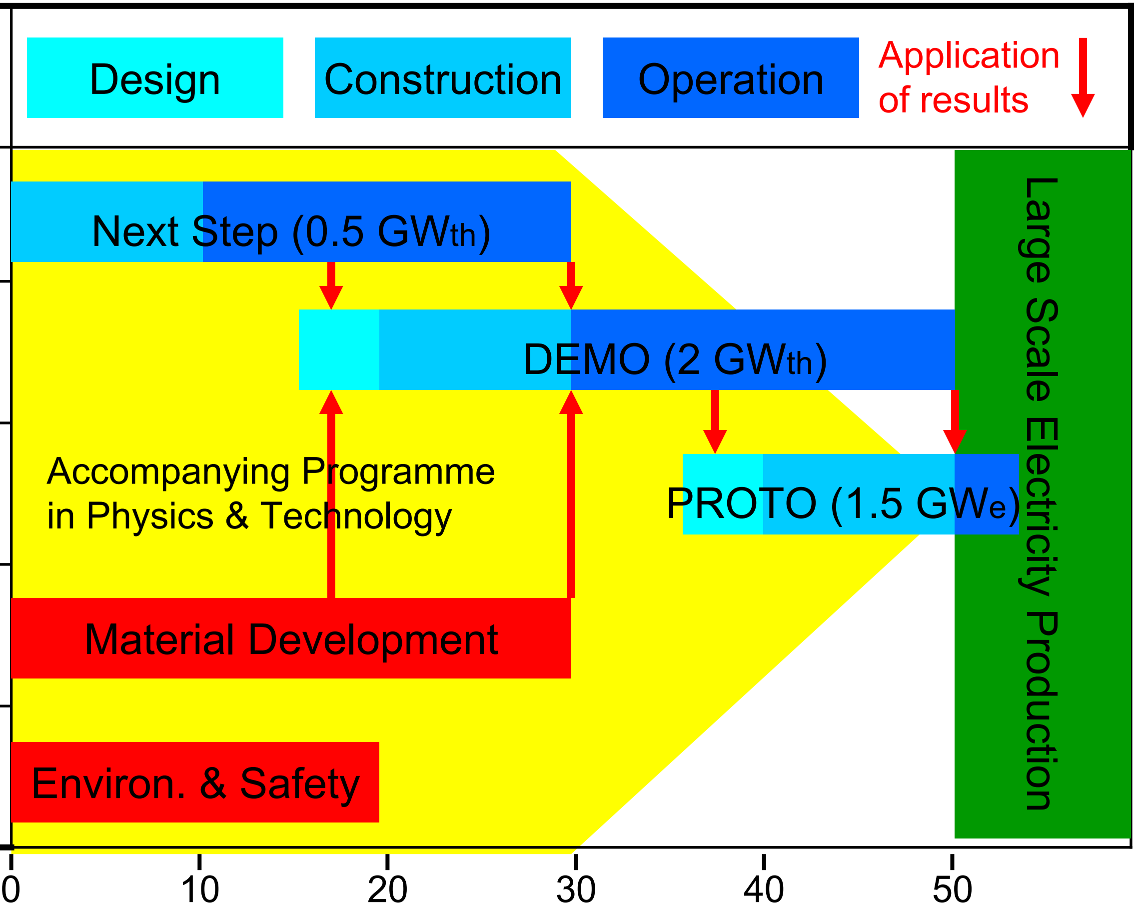
- Production and control of long pulse-burning plasma
- Heat and particles exhaust (plasma facing compon.)
- Test of breeding blanket modules for DEMO

- Net electricity production (full hot breeding blanket)
- High reliability of operations
- Qualification of lower activation material for PROTO

- Improved economy in electricity production
- Improved low activation materials

- Demonstr. of a reference low activation steel for DEMO
- Search for higher performance materials for PROTO

- Demonstration of waste management and recycling
- Demonstration of safety management
- Demonstration of low environmental impact potential



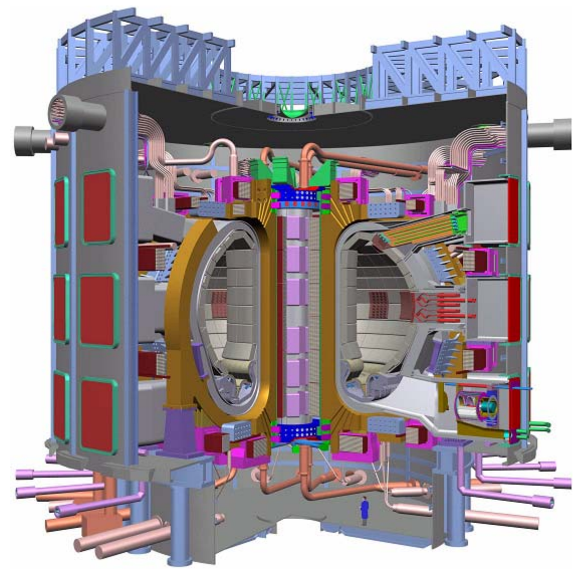
Years after decision on Next Step

Extracted from:
"Five Year Assessment report related to the specific programme: Nuclear energy covering the period 1995-1999", June 2000

What is ITER?

Overall programmatic objective:"demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes".

- **ITER is a burning plasma experiment:** designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating
- Long pulse burning plasma with Q>10 (Q = Pfusion/Pheat).
  - *Study alpha particle physics*
  - *Study controllability of fusion reaction*
  - *Study advanced regimes aiming at steady state operation*
  - *Study divertor operation (impurity control) in reactor conditions*
  - **……In an integrated way**
- Designed to make functional tests of DEMO-relevant breeding blanket modules.
- Device operation ~20 years.



ITER Engineering Design Activities History

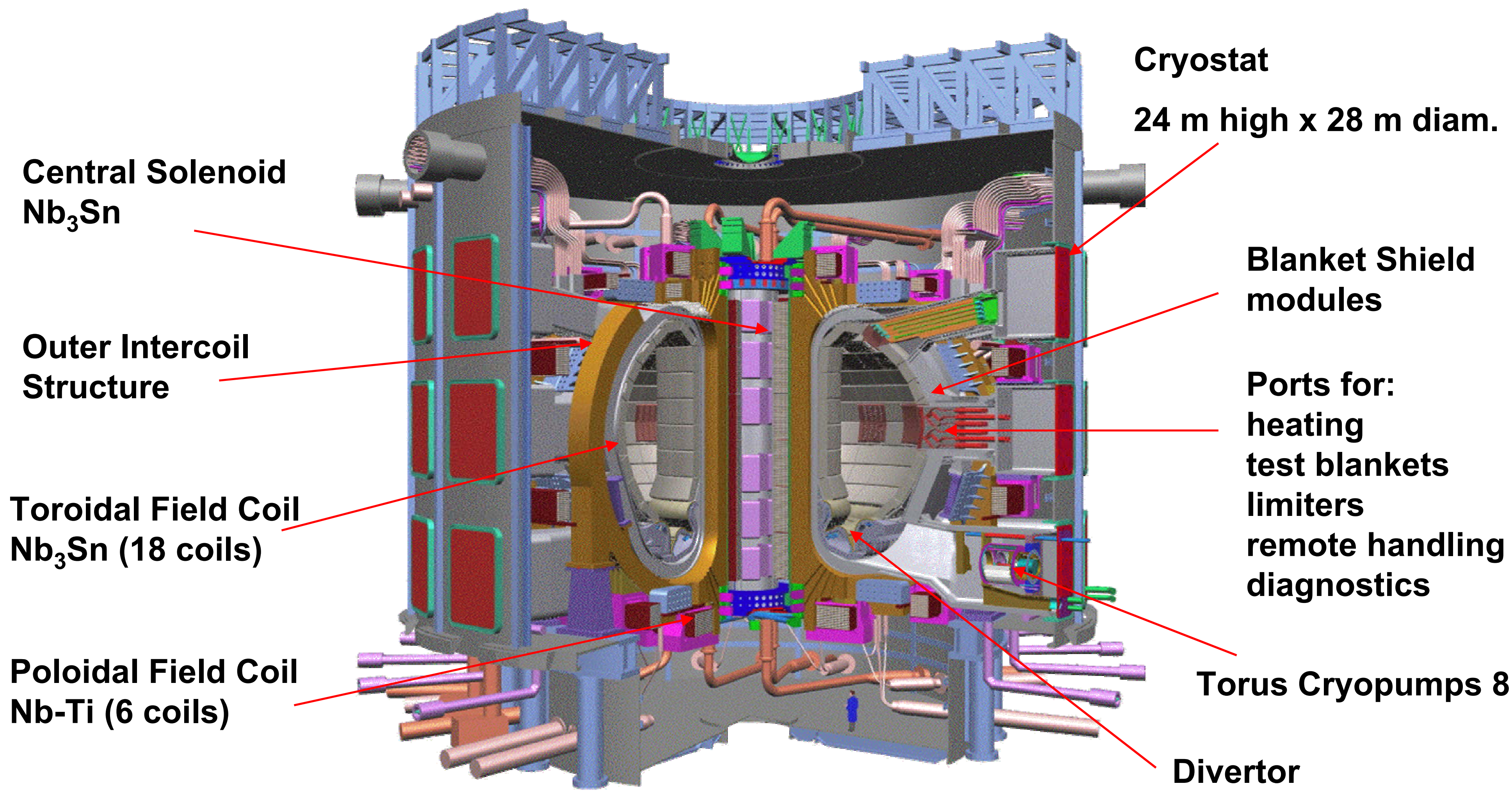
- **1988-1991 - (CDA) Conceptual Design Phase**
  - Start of common activities among EU,RF, USA and JA.
  - Selection of machine parameters and objectives.
- **1992-1998 - (EDA) Engineering Design Phase**
  - Developed design capable of ignition ($Q = \infty$) - large and expensive.
  - The Parties (EU, JA, RF, US) endorsed design but could not afford to build it.
- **1999 - 2001**
  - US withdrew from project.
  - Remaining Parties searched for less ambitious goal.
  - New design: moderate plasma power amplification ($Q = 10$) at about half the cost.
- **2001 - now**
  - Start of negotiations on construction and operation.
  - Sites offered by Canada, Europe (Cadarache and Vandellòs) and Japan.
  - US re-joins, China and South Korea are accepted as full partners.
  - EU Research Ministers select Cadarache as EU candidate site.

ITER Main Design Parameters

• Total fusion power	500 MW (* 700 MW)
• Q = fusion power/auxiliary heating power	≥10
• Average neutron wall loading	0.57 MW/m^2 (* 0.8 MW/m^2)
• Plasma inductive burn time	≥ 300 s
• Plasma major radius	6.2 m
• Plasma minor radius	2.0 m
• Plasma vertical elongation	1.7
• Plasma current	15 MA
• Toroidal field @ 6.2 m radius (axis)	5.3 T
• Max. field in the superconductor (Toroidal coils)	12 T
• Plasma volume and surface	837 m^3 3,678 m^2
• Installed auxiliary heating/current drive power	73 MW (*110-130 MW)

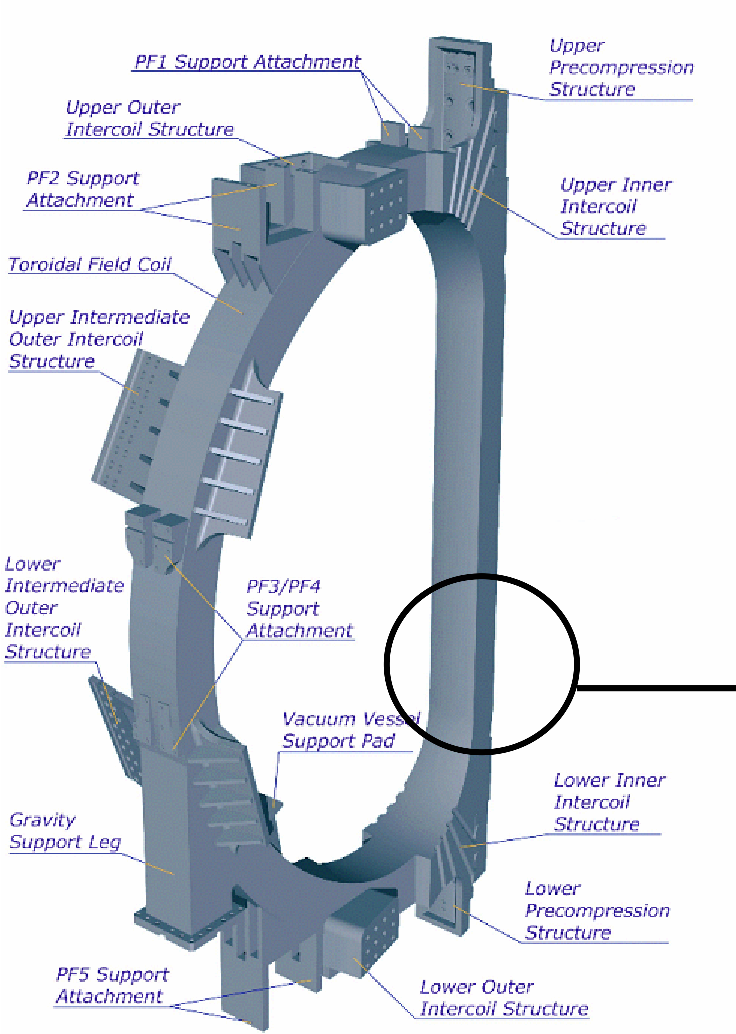
(*) During the extended phase

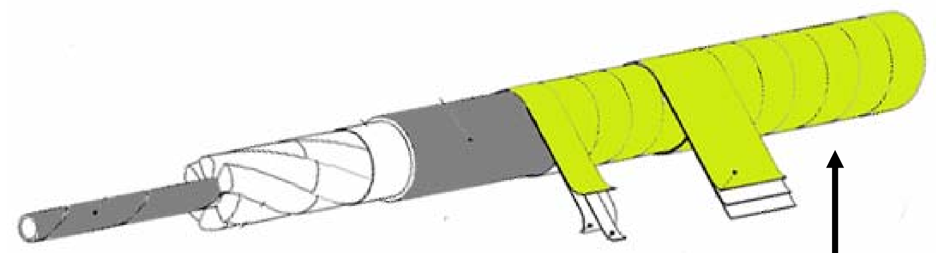
Main Design Features



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

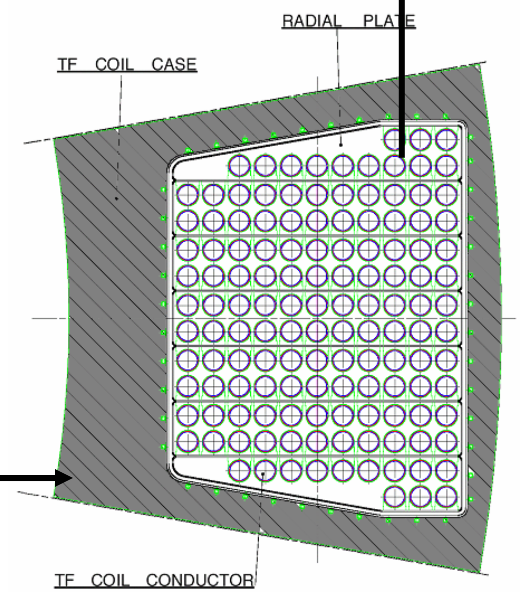
Toroidal Field Coils



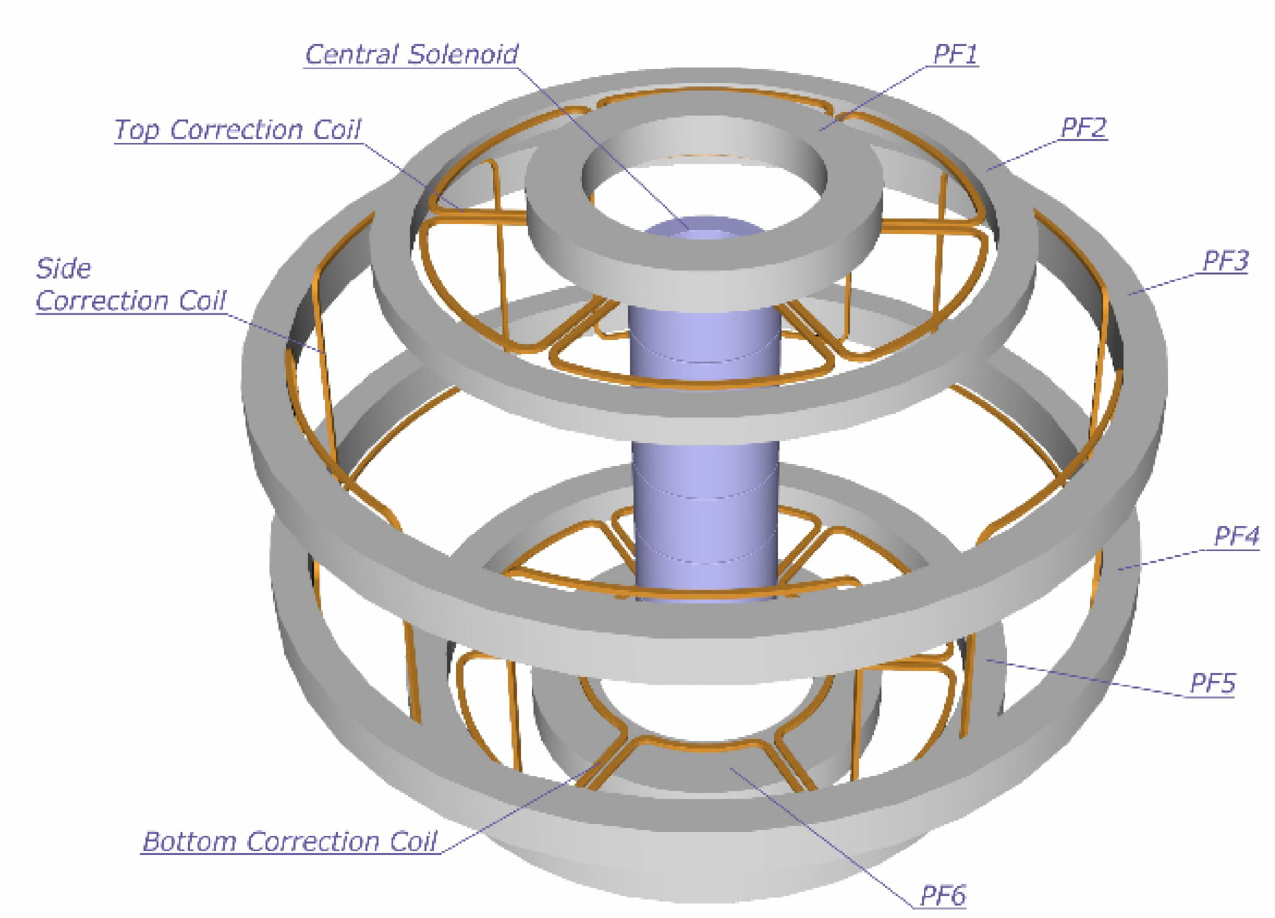


18 Nb_3Sn toroidal field coils producing a toroidal field of

5.3 T axis, max. ≤12 T



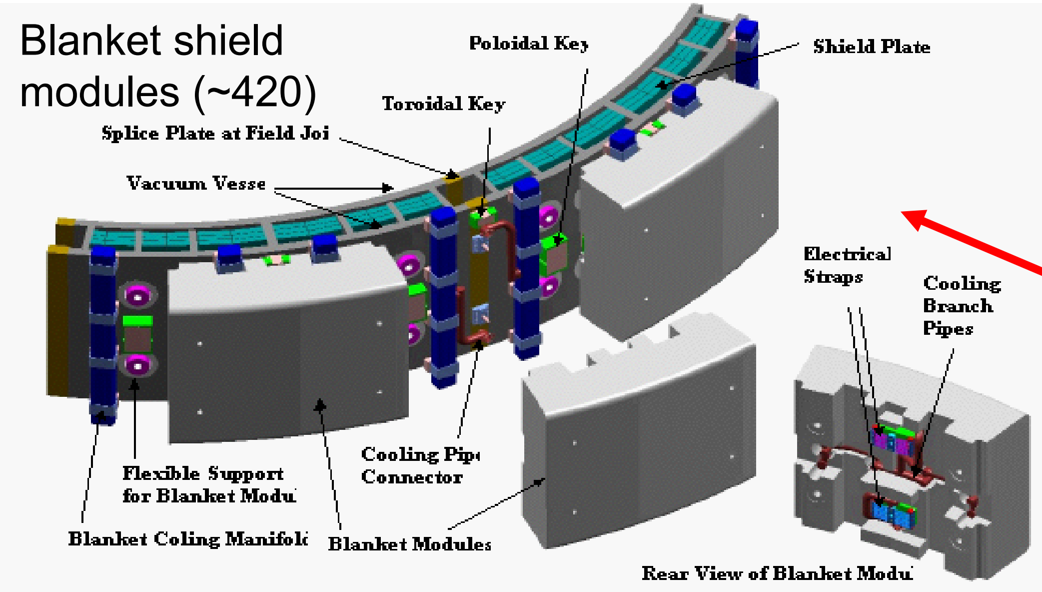
Poloidal Field Coils



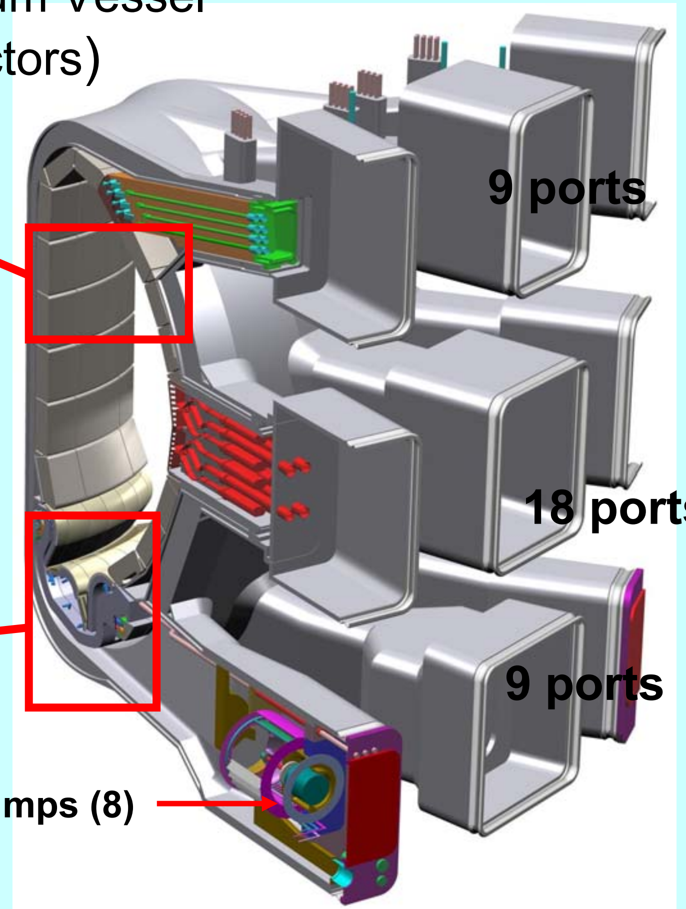
- **Modular Nb_3Sn central solenoid coil induces current in the plasma (+13.5 T to -12 T);**
- **6 NbTi poloidal field coils position and plasma shape control (max. 6 T);**
- **Correction coils:** correct error fields due to manufacturing or assembly imperfections and stabilize the plasma.
- **The magnet system (TF, CS and PF) weighs ~ 8,700 t.**

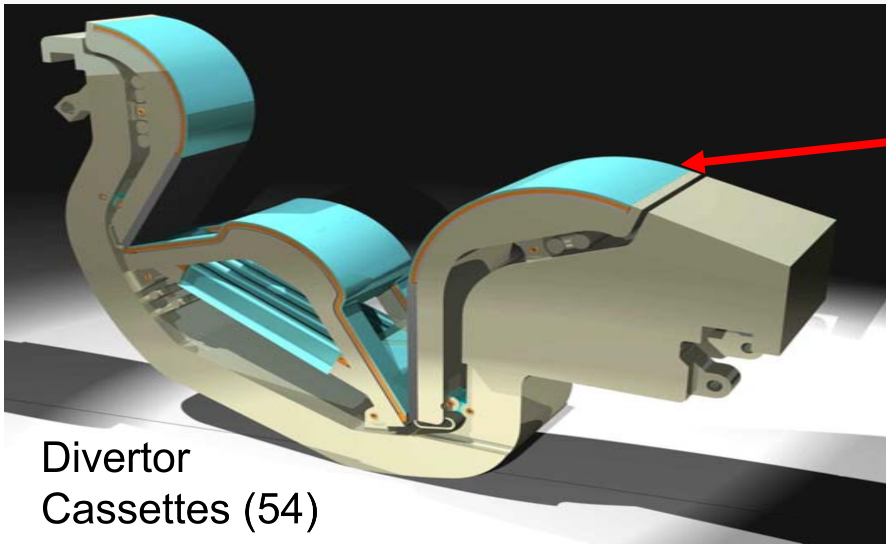
Vessel and In-vessel Components

Blanket shield modules (~420)



Vacuum Vessel (9 sectors)





Divertor Cassettes (54)

The total vessel/in-vessel mass is ~10,000 t.

The Seven Large R&D Projects

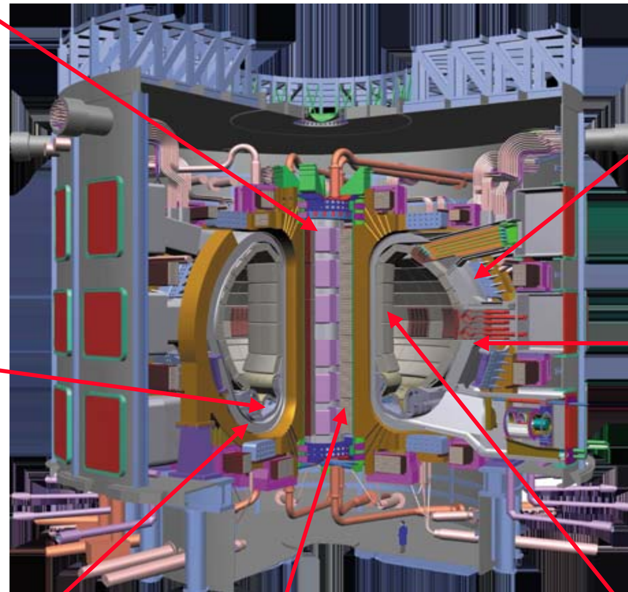
Completed R&D Activities by July 2001.

CENTRAL SOLENOID MODEL COIL

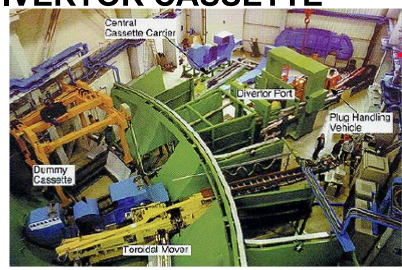
Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm



REMOTE MAINTENANCE OF DIVERTOR CASSETTE



Attachment Tolerance ± 2 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

DIVERTOR CASSETTE

Heat Flux >15 MW/m^2, CFC/W

TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
B_{max}=7.8 T
I_{max} = 80kA

REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

The ITER Potential Sites

Joint assessment concluded that all the candidate sites meet the ITER site requirements.

Direct Construction Cost:

~ 4.6 billion Euro

Licensing/Construction:

9 years

Operation:

20 years

~ 250 million Euro/year

International Organization:

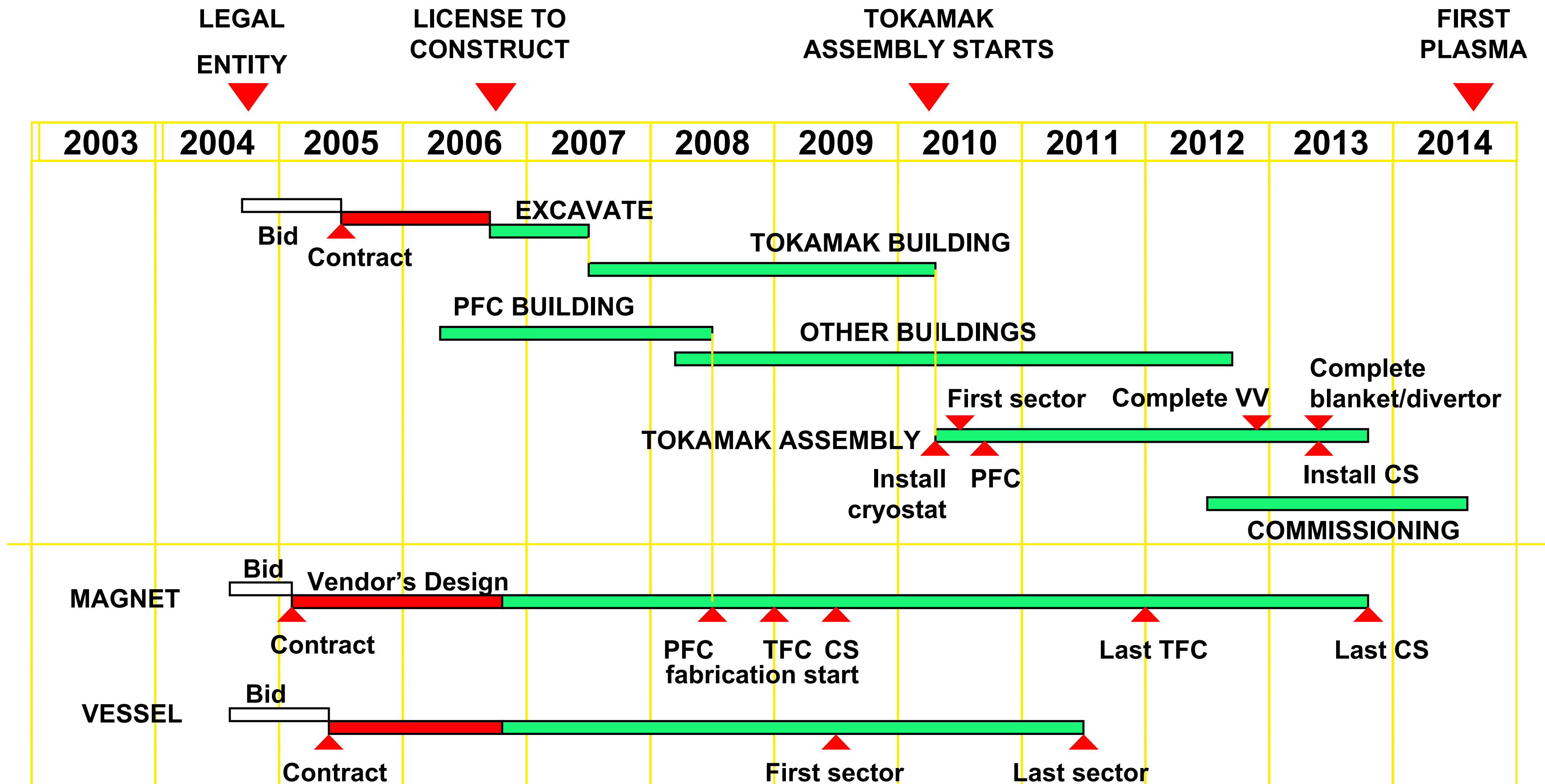
600 staff

Visiting scientists

France - Cadarache

Japan - Rokkasho

Construction schedule



Summary of the part 1

- ITER is the essential step needed for fusion research towards an energy source.
- Technical preparations are advanced to turn the design of ITER into technical reality.
- The ITER project offers a wide variety of fusion development activities for the worldwide scientific community.
- During operation, scientists will participate remotely in experiments (e.g testing breeding blankets, operating diagnostics, analysing data, making proposals for the experimental programme) from many locations in the world.

Part 2

The electrical characteristics of the European site

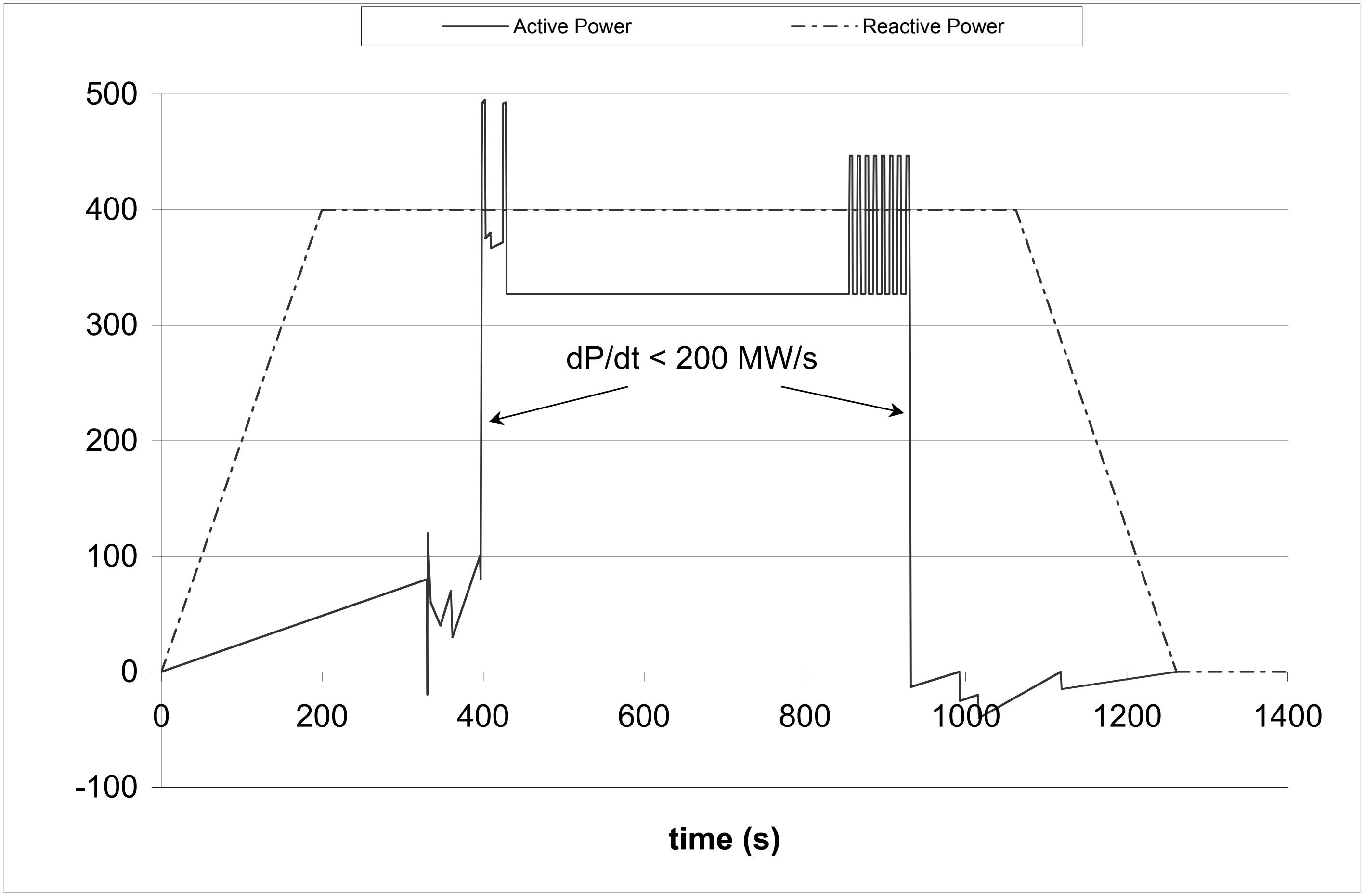
and the ITER power converters

Cadarache: the ITER European Site (1)

Cadarache: the ITER European Site (2)

ITER Pulsed Power Demand (*)

assumed for the joint assessment of the European candidate sites

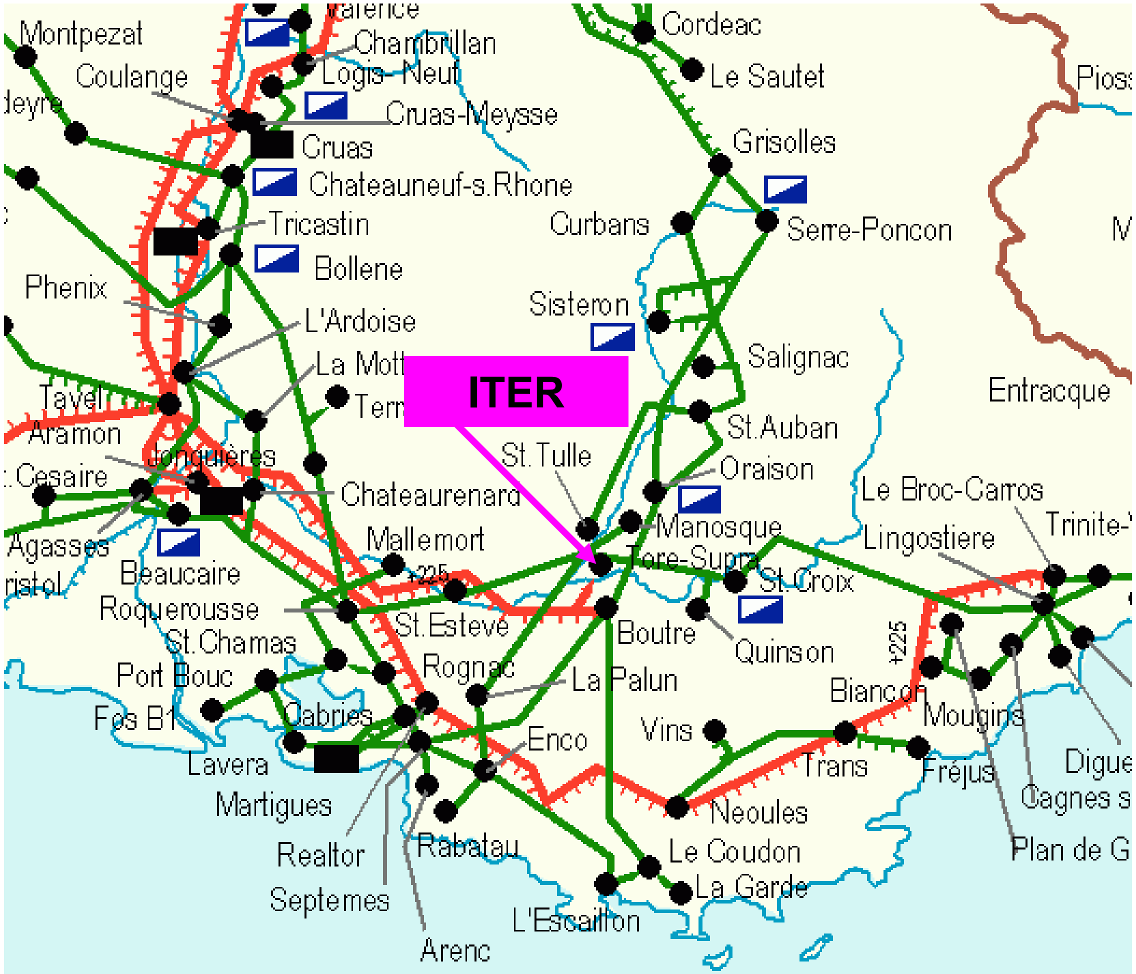


(*) +120 MW, steady state power, for the auxiliaries

400kV grid capability at Cadarache (1)

	Grid capability	ITER site requirements
Max. active pulsed power	± 510 MW +120 MW, steady state, for the auxiliaries	± 500 MW (+ 120 MW)
Max. reactive power	**180 Mvar**	**400 Mvar**
Max. active power step	power steps are acceptable up to ± 510 MW	± 60 MW
Max. active power rate (dP/dt)	power steps are acceptable up to ± 510 MW	200 MW/s
Short Circuit Power	10 – 12 GVA	> 10 GVA
Power-frequency characteristic "stiffness"	18 GW/Hz	
Permissible frequency variation	50 mHz	
Max. expected frequency variation	28 mHz	

400kV grid capability at Cadarache (2)



- Good capability to provide active pulsed power
- Requires reactive power compensation

Transmission grid in the Cadarache area

Lines:

400 kV, 2 circuits — 1 circuit

220 kV, 2 circuits — 1 circuit

Power plants: Thermal — Hydro

Source: "Union for the Co-ordination of Transmission of Electricity" http://www.ucte.org

Design strategy of the ITER Power Supplies

- The main design work on power converters has been carried out by the ITER Joint Central Team between 1994 and 1998, with the collaboration of the Home Teams, EU in particular (industries and national laboratories).
- The design strategy for the ITER power converters has been:
  - to demonstrate the feasibility of the basic components;
  - to limit, as much as possible, the development of new components/technologies;
  - to adopt the cheapest solutions.
- Therefore the use of GTO, IGCT or IGBT was limited to the power converters of loads requiring fast switch-off protection.
- The procurement is expected to be based on functional specifications accompanied by a reference design, which demonstrates the feasibility of the components. The supplier may propose other solutions.

The ITER Power Supplies

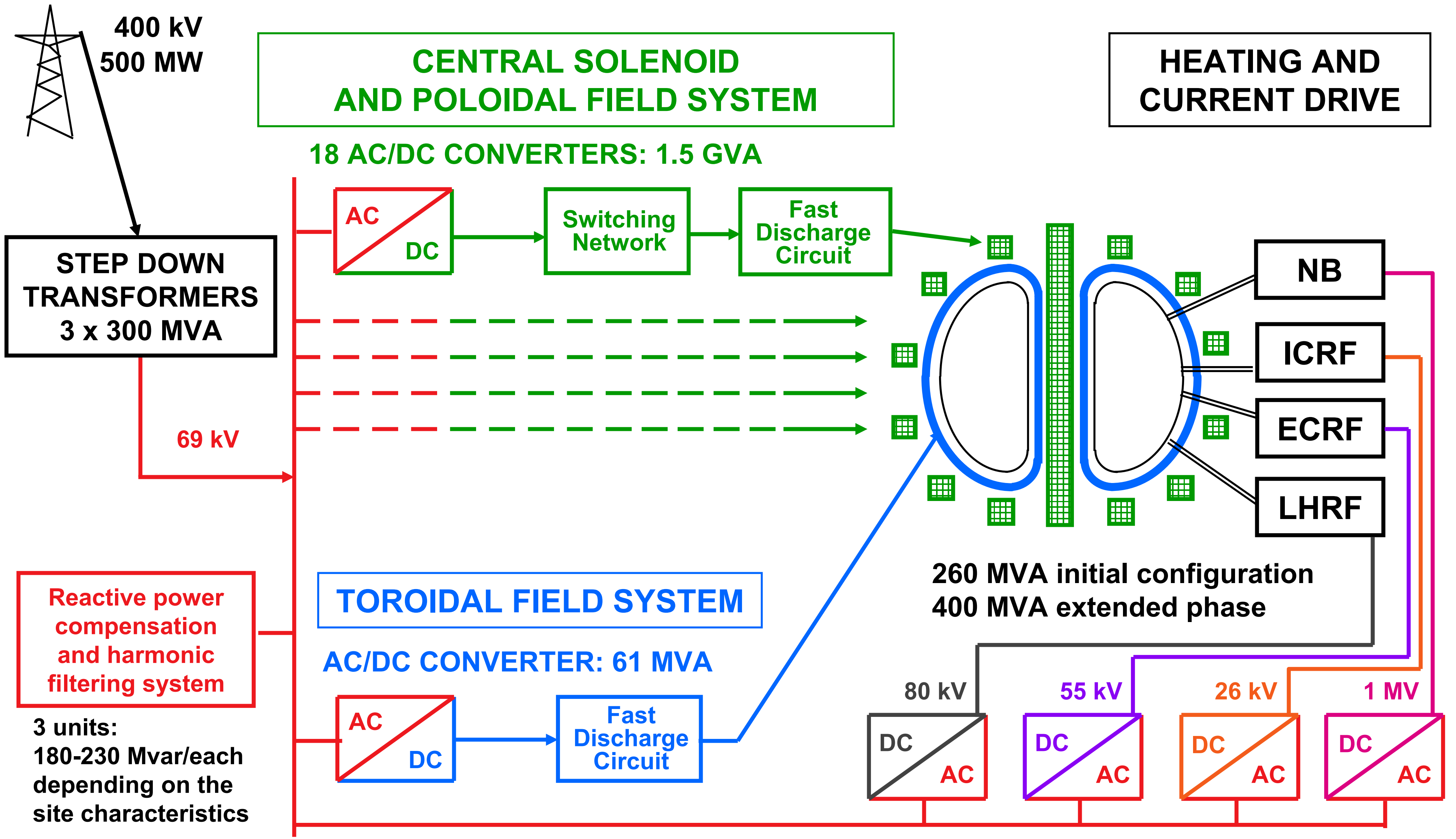
- The ITER Power Supplies consist of two independent systems:
  - the Steady State Electrical Power Network (SSEPN);
  - the Pulsed Power Supply System (PPSS).

The Pulsed Power Supply System (PPSS)

MAIN DESIGN FEATURES AND FUNCTIONS OF THE ITER PPSS:

- The PPSS provides controlled DC power to:
  - the superconductive magnets;
  - the Heating and Current Drive (H&CD) systems.
- Rated voltages in the range:
  - from about 1 kV (supeconductive magnets);
  - to 1 MV (Neutral Beam H&CD).
- Rated DC currents up to 68 kA (TF coil Power Supplies).
- Controls (both amplitude and accuracy) the DC supply voltage of the individual loads.
- Protects the superconductive magnets by fast discharge in case of a quench.
- Protects the H&CD systems:
  - fast switch off (10-200 μs, depending on the load);
  - fault energy limitation (10-50 J, depending on the load).

PPSS block diagram



Coil Power Converters: design ratings

Load	Quantity	DC current (kA)	No load output voltage (kV)	Rated unit power (MVA/unit)	Operational quadrants	Duty cycle (s/s)	Response time of the voltage control (ms)
TF converter	1	68	0.9	61	2	1:1	15
Main PF converters	12	45	2.0	90	4	1:1	15
Vertical Stabilization Converters	2	22.5	4.0	90	4	1:1	7.5
Booster PF converters	4	10	5.6	56	4	30:1800	15
Correction coil converters	9	7.5	0.8	6	4	1:1	15

- Total installed power: 1.6 GVA

H&CD Power supplies: design ratings

Load name	Quantity		Rated on load output voltage (kV)	Rated active power/unit (MW/unit)	Switch off time (μs)	Max fault energy (J)
	Initial configuration	Possible later upgrade				
NB	2	+ 1	1000	55	200	50
IC	8	+8 (*)	26	3.9	10	10
EC	2	+2 (*)	50	30	10	10
LH	0	4	80	24	10	10

(*) one system only, between IC and EC, will be upgraded.

All power supplies are designed for continuous duty.

NB = Neutral Beam injection source

IC = Ion Cyclotron radio frequency generators **40-55 MHz from Tetrodes**

EC = Electron Cyclotron radio frequency generators **(120) 170 GHz from Gyrotrons**

LH = Lower Hybrid radio frequency generators **5 GHz from Klystron**

ITER Power converter technologies

Technology	Conventional industrial application	ITER application	Main enhancements required for ITER
High current (up to 68 kA) thyristor converters	Electrochemical plants	Coil power supplies	Fault Suppression Capability Internal bypass Output voltage up to 5 kV
High voltage rectifiers • diode rect. up to 200 kV • thyristor rect. up to 80 kV	Special DC applications	H&CD power supplies	Diode rectifiers with very high ground insulation level, up to 1 MV DC for the NB power supplies
Pulse Step Modulators	Broadcasting Transmitters	Radio Frequency H&CD power supplies	--
GTO, IGCT and IGBT DC/AC inverters	Drives	Neutral Beam H&CD power supplies	--
Thyristor Controlled Reactors	Static var Compensators	Reactive Power compensation and Harmonic Filtering	--

Design Criteria of the Coil Power Converters

- **Main aims:**
  1. Increase the availability of the conversion plant.
  2. To reduce the overall system cost
- **Design solutions:**
  - aim 1 - "Fault Suppression Capability" (FSC).
  - aim 1 - One redundant thyristor per arm.
  - aim 2 - 12 pulse operation (reduces the cost of the AC filters).
  - aim 2 - Modular approach (simplifies design, construction and maintenance).
  - aim 2 - Increase as much as possible the size of the basic units (reduces the cost/MVA).

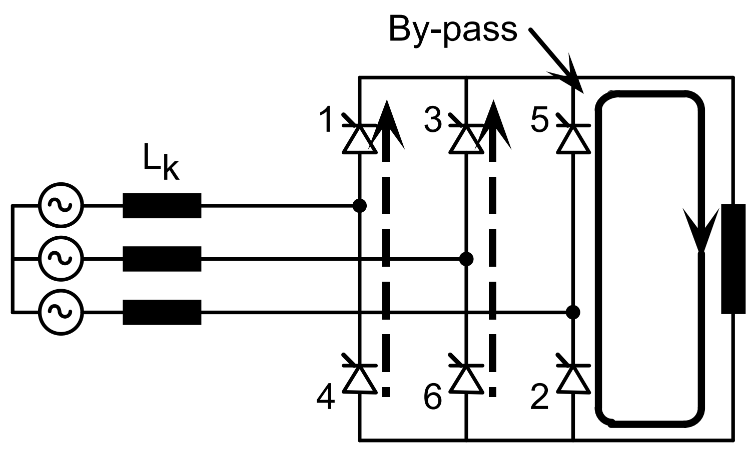
Fault Suppression Capability

- **The FSC is the capability of the converter to clear (electronically) the overcurrents, due to the most frequent faults**.
- A fuse, in series with each thyristor, operates only in the case of one thyristor failure.
- The operation can be restarted immediately after the fault clearance.

Fault type	Protective Actions
Circulation current between anti-parallel bridges.	Electronic protection shutdown and backup AC breaker opening.
Short circuit on the DC side (downstream of the DC reactor).	Electronic protection shutdown and backup AC breaker opening.
Short circuit on the converter DC terminals.	Electronic protection shutdown and backup AC breaker opening.
Thyristor failure. (thyristor short circuit)	Melting of the thyristor fuse, backup electronic protection, shutdown and AC breaker opening.

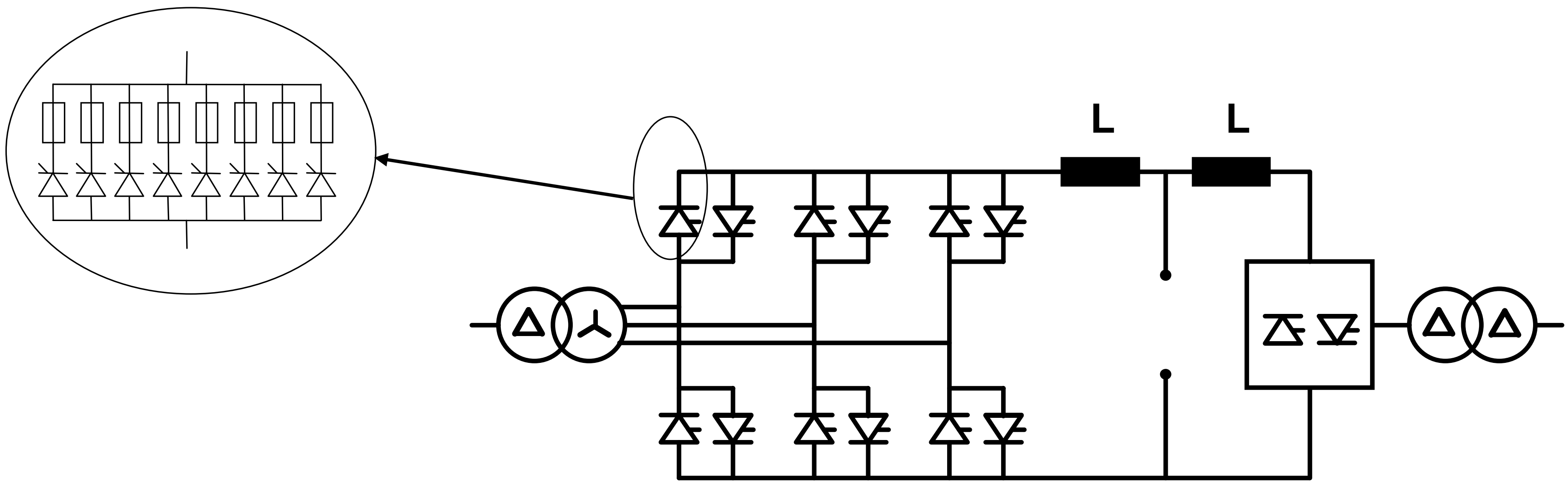
Internal bypass

- Internal, non cycling, freewheeling **in each arm.**
- Approximately requires the same number of thyristors in parallel as the FSC design criteria (no cost increase).
- Provides the freewheeling path.



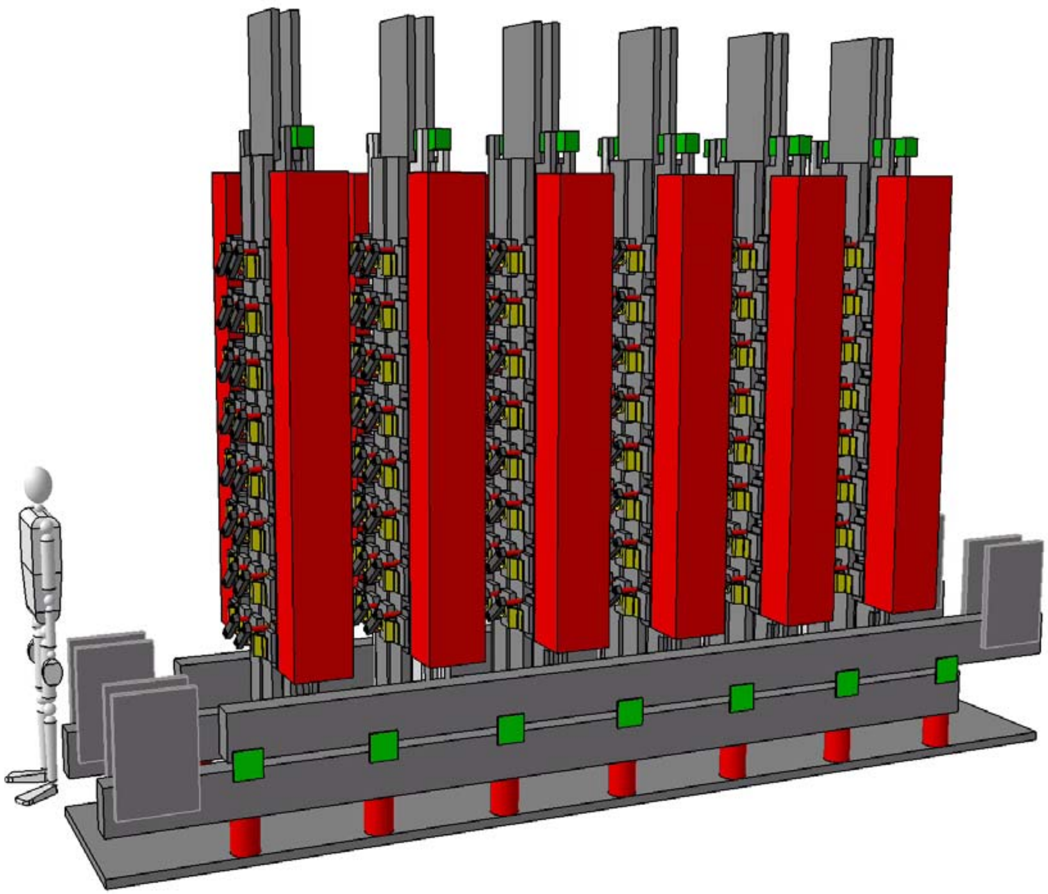
Design features of the largest basic unit

- 12 pulse operation via parallel connection of two, 6 pulse, phase shifted, sub-units.
- two 6-pulse, 4-quadrant bridges in one mechanical assembly (external inductors).
- eight 125 mm devices per arm, directly connected in parallel,
- 45 kA, 2 kV **(90 MVA continuous duty, 4-quadrants, FSC, in a single unit).**



The largest basic unit

“6-leg assembly”

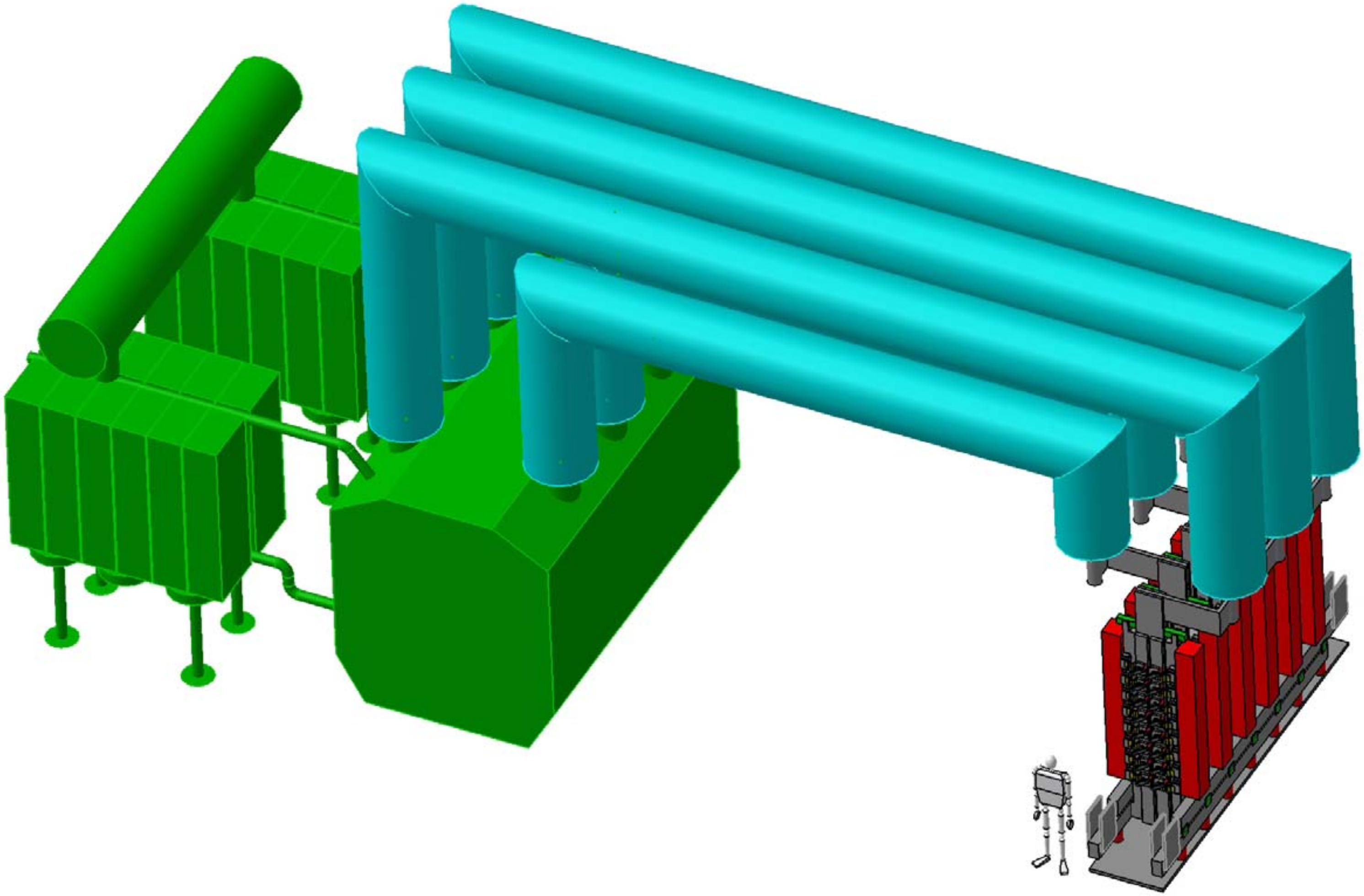


Advantages of the six leg structure:

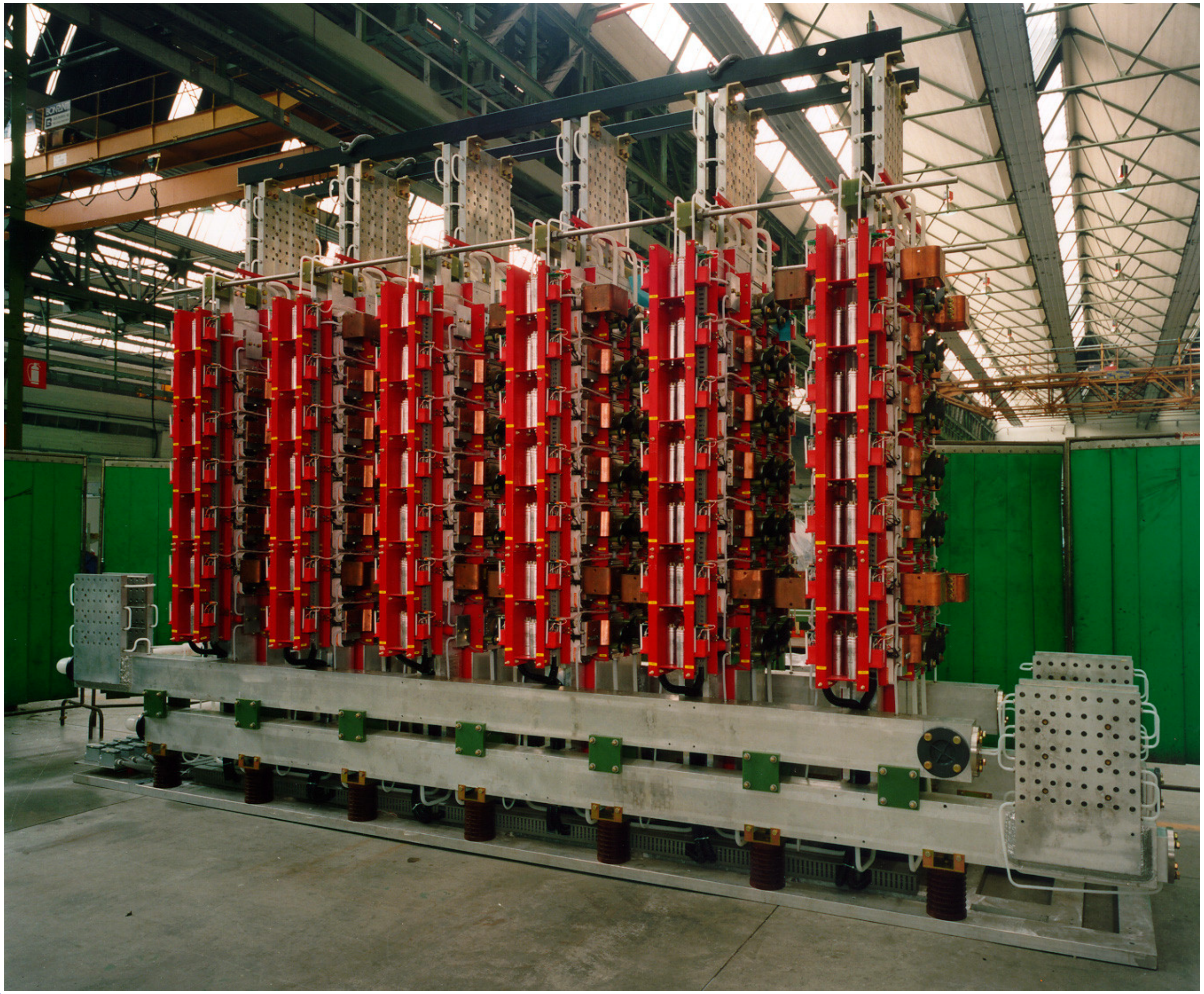
– **better current sharing among the thyristors in parallel** (due to the greater distance between the arms of the same commutating group);

– **the converter has a power density of 3 MVA/m^3** (high value for a 4 quadrants, 12 pulse converter, designed to meet the FSC requirements).

The largest basic unit converter and its transformer

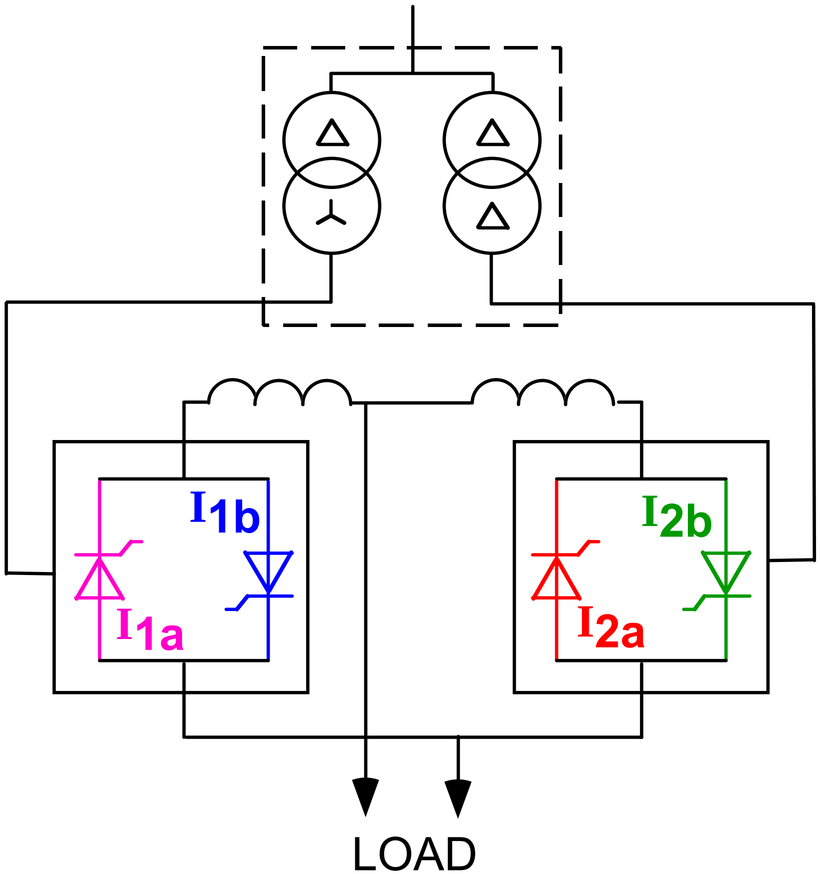


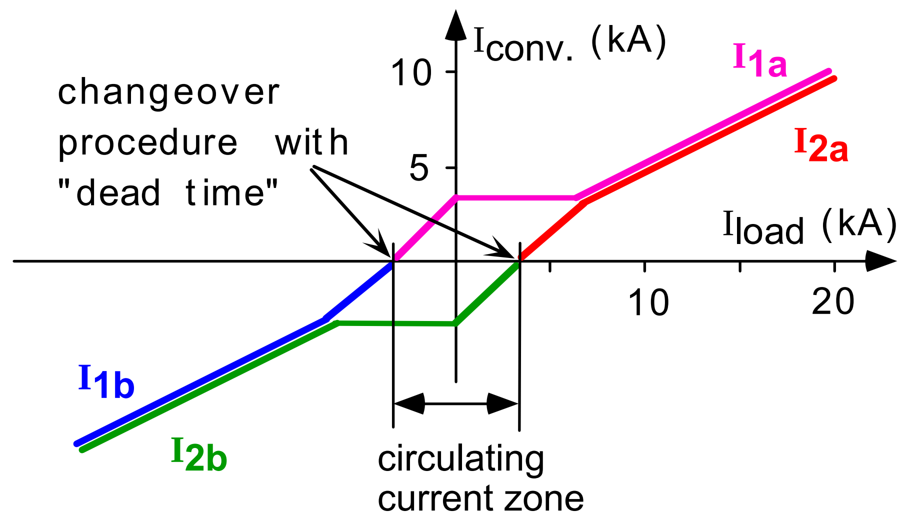
The converter prototype tested in 1998



- The FSC concept was already used in fuse-less, one thyristor per arm converters (as those installed in the HVDC plants).
- FSC had to be demonstrated for converters with many thyristors in parallel.
- In 1998 FSC was successfully demonstrated with 10 x 100 mm, thyristors
  in parallel (8 x 125 **in the 1998 ITER design**).
- A current imbalance factor <1.4 was achieved, **without "selected" thyristors,**
  not only in case of normal operation, but also under fault conditions.

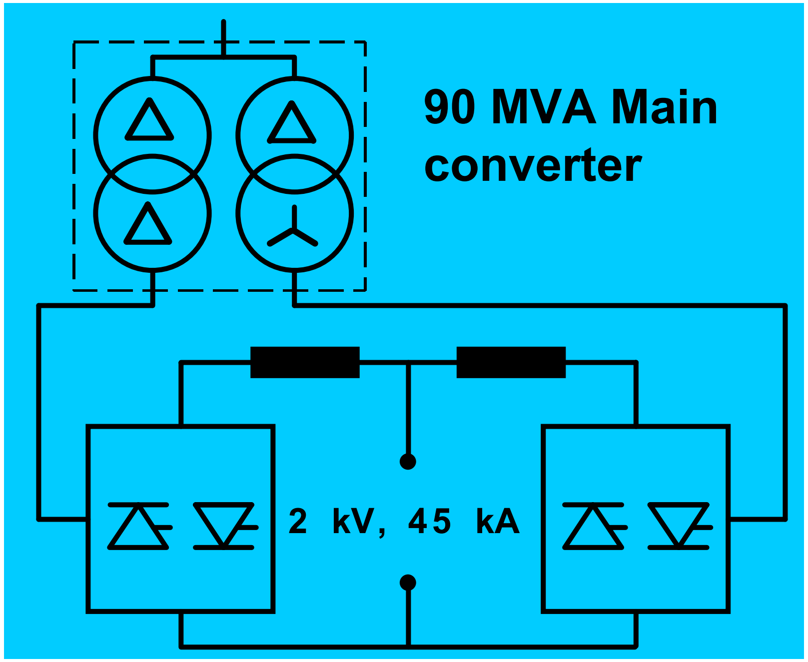
Polarity change

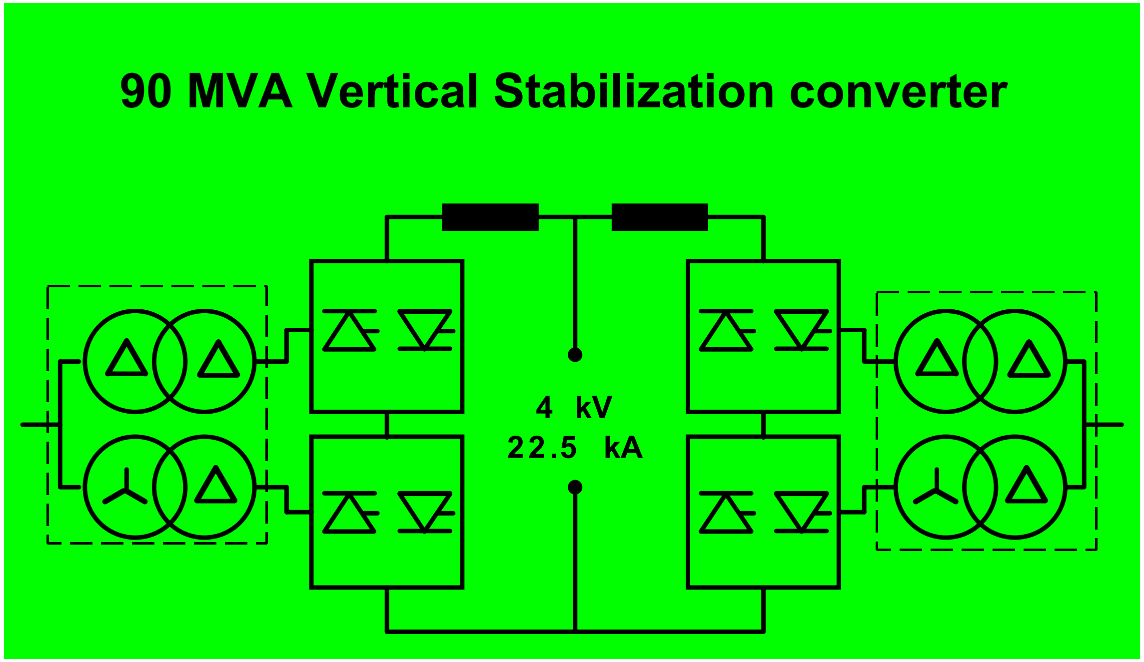




The thyristor converter unit with 7.5 ms response time

The ITER main converter unit cannot achieve 7.5 ms response time because of the parallel connection of phase shifted 6 pulse sub-units.	**To achieve the 7.5 ms response time,** in the Vertical Stabilization converter, **the 12 pulse operation is obtained via the series connection (instead of parallel) of the 6 pulse sub-units.**





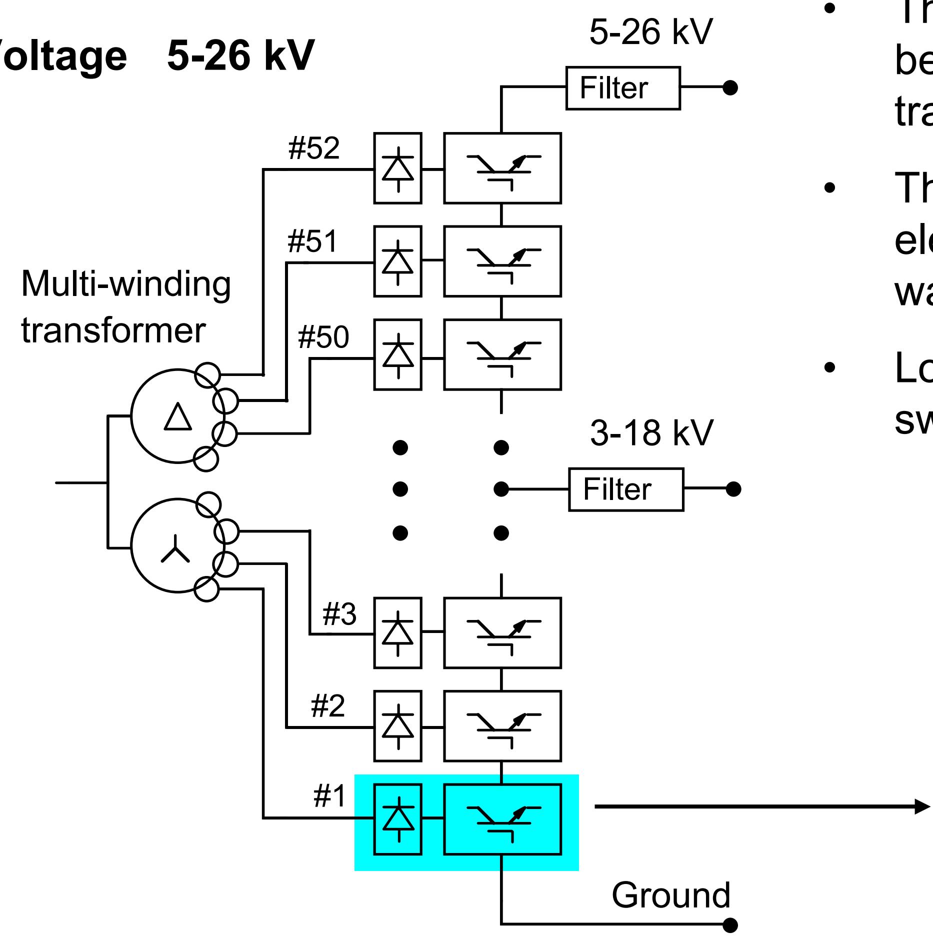
The Pulse Step Modulator Technology

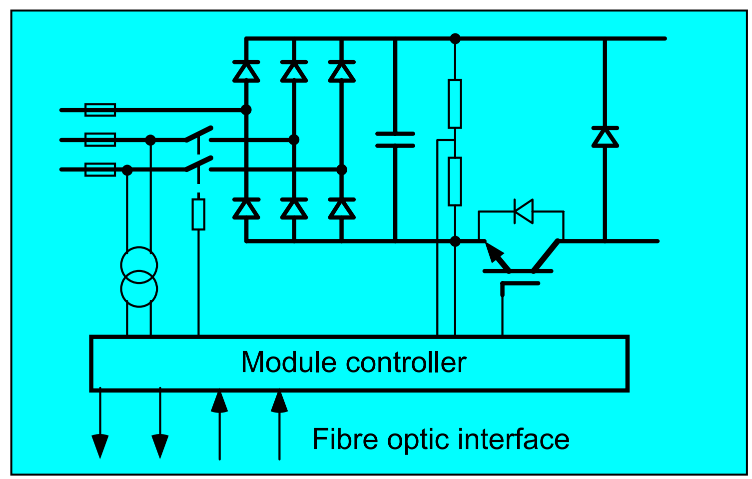
BASIC ITER IC UNIT

Power 3.9 MW

Voltage 5-26 kV

- Reference design for the IC H&CD power supplies.
- The Pulse Step Modulator (PSM) technology has been developed during the ‘80s for broadcasting transmitters.
- The PSM uses several modules, which can be electronically switched in and out of the circuit. In this way the output voltage can be rapidly controlled.
- Load protection is accomplished by fast (< 10 μs) switching off all modules.



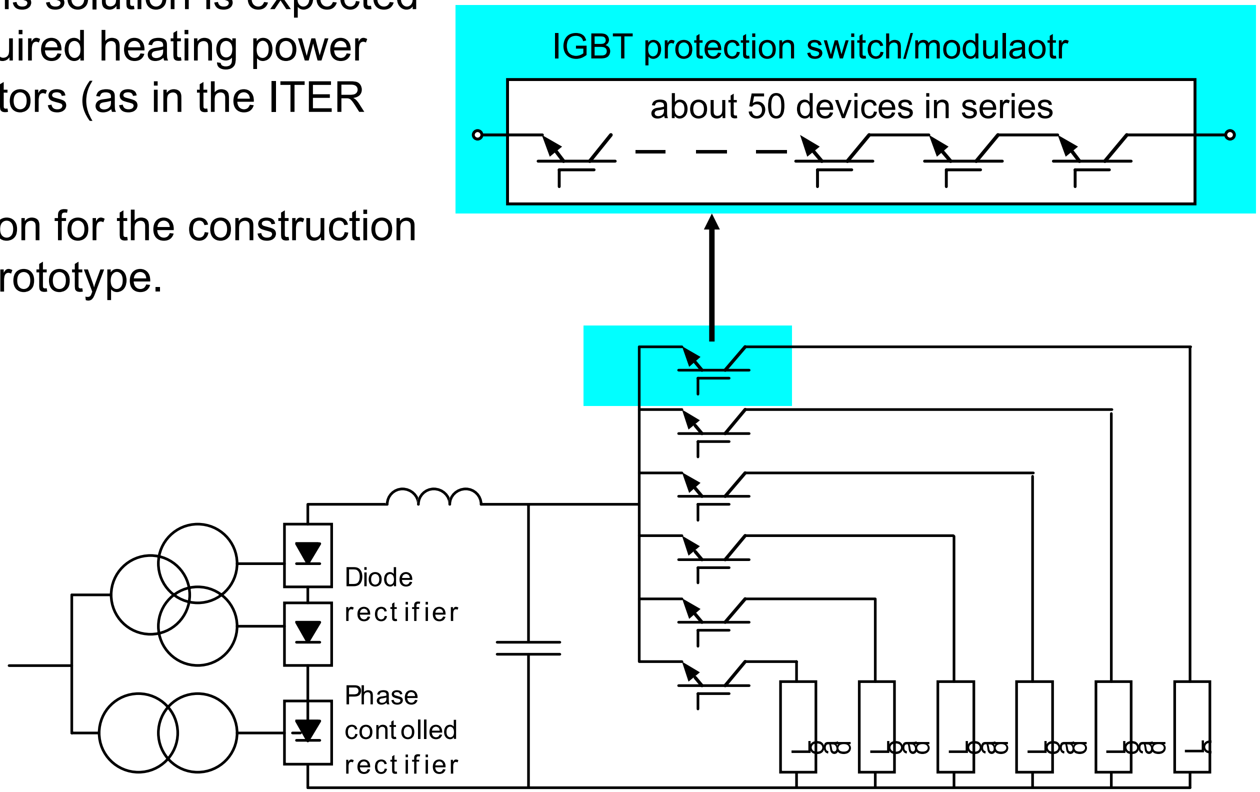


Thyristor converter with series IGBT switch/modulator

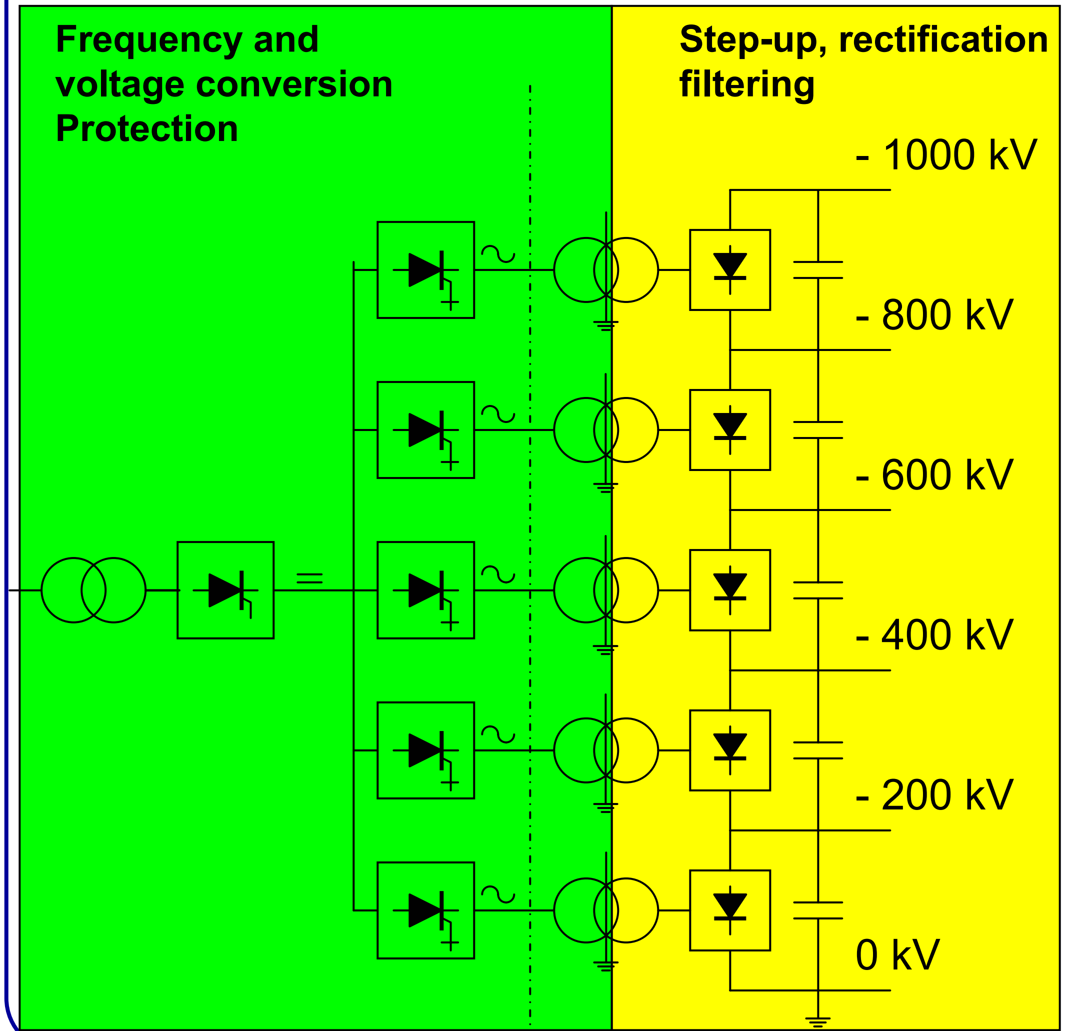
- Reference design concept for EC and LH H&CD power supplies.
- In comparison with the PSM, this solution is expected to be competitive when the required heating power requires several EC/LH generators (as in the ITER design).
- EFDA has started a tender action for the construction of the IGBT modulator/switch prototype.

<u>BASIC ITER EC UNIT</u>

Max output power	**22.5 MW**
Output voltage	**50 kV**
Voltage regulation	**±5%**
Total output current	**450 A**

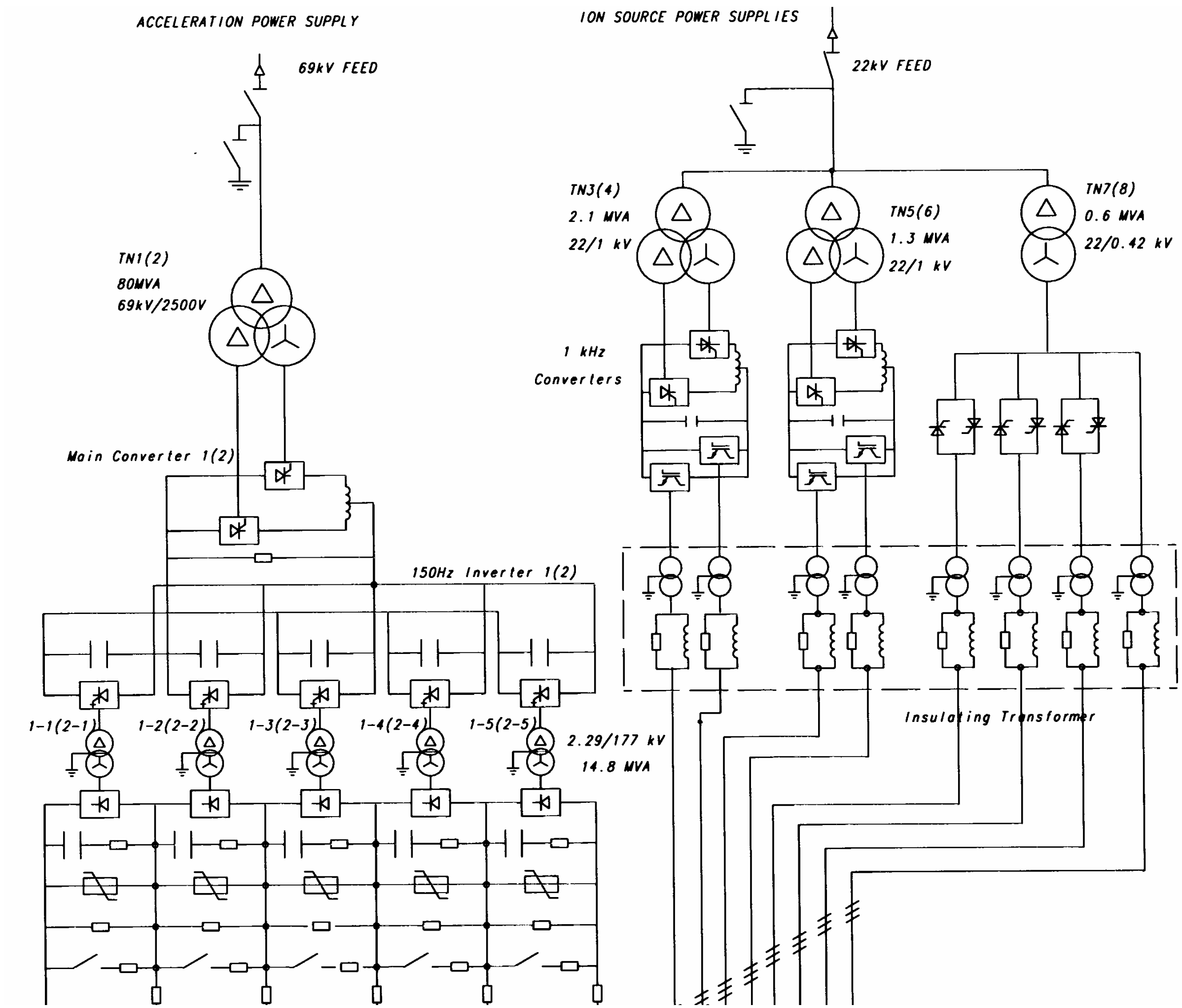


1 MV Main Power Supplies for the NB system

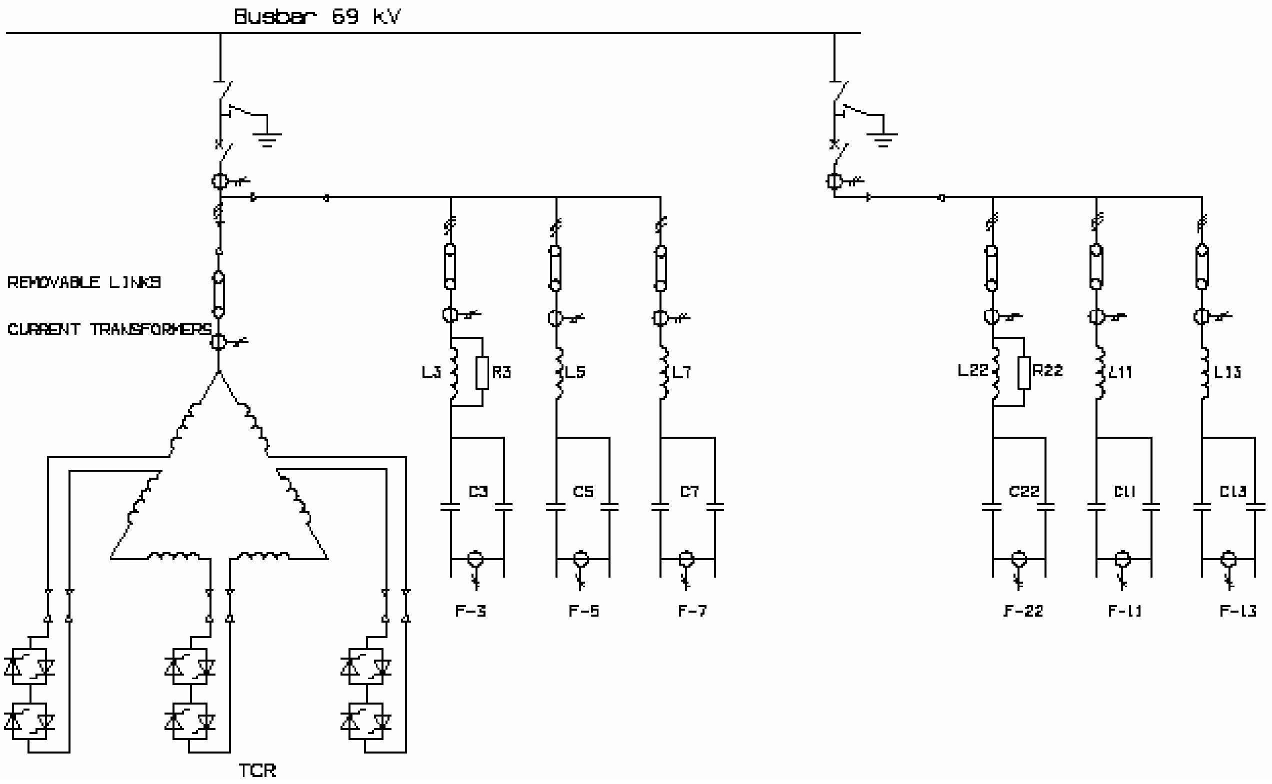


- **The challenge is the development of the following 1 MV components:**
  - **Step up transformers**
  - **Gas insulates transmission lines**
  - **Bushings: air to pressurized gas, oil to air, oil to pressurized gas.**
- Conventional GTO or IGCT converters, at ground potential.
- Diode rectifiers, on the secondary side (high potential) of the step up transformers.

1 MV NB Power Converters



The Reactive Power Compensation and Harmonic Filtering System



- Based on the conventional Static Var Compensation technology.
- Without the Thyristor Switched Capacitor.
- Design without step-down transformer for the Thyristor Controller Reactor (TCR). Requires high voltage TCRs.

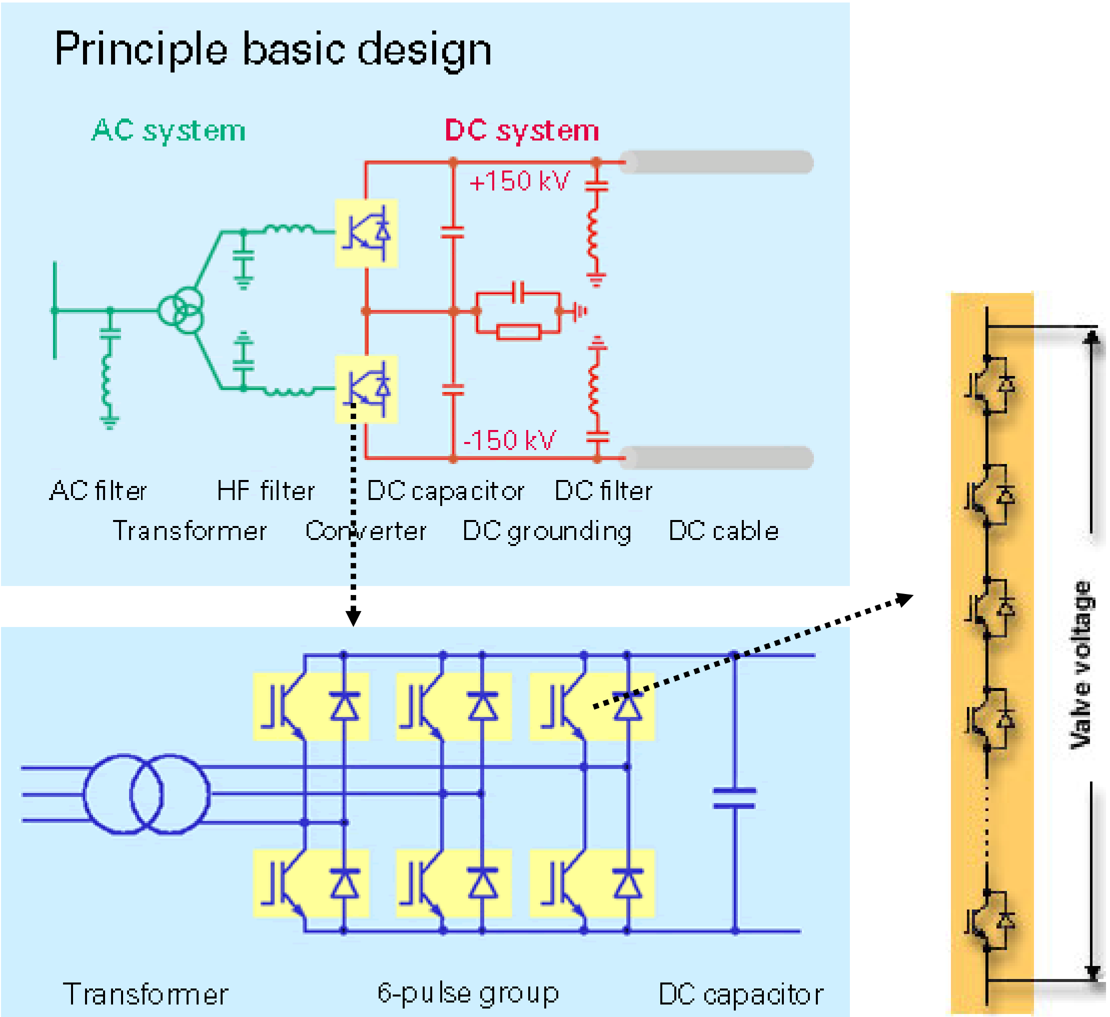
Summary of the part 2 - Conclusions

- The design ITER power converters started in 1994 with the following strategy:
  - to demonstrate the feasibility of the basic components;
  - limiting as much as possible the development of new components/technologies;
  - using the cheapest solutions.
- Between 1994 and 1998, the design work carried out by the ITER Joint Central Team, in collaboration with the Home Teams, has demonstrated the feasibility of all basic components.
- The use of GTO, IGCT, or IGBT was limited to the power supplies of loads requiring fast switch-off protection (H&CD power supplies).
- The FSC in thyristor bridges, with several thyristor directly in parallel, was successfully demonstrated in a full scale prototype built in 1998. A current imbalance factor <1.4 was achieved, without “selected” thyristors, not only in case of normal operation, but also under fault conditions.
- After 1998, design changes and improvements have been applied to the configuration of the overall power supply system. Almost no changes on the design of the individual basic components.

Challenges of the future work

- **Development of the following 1 MV DC components for the NB H&CD system:**
  - **Step up transformers**
  - **Gas insulated transmission lines**
  - **Bushings: air / pressurized gas, oil / air, oil / pressurized gas.**
- The fabrication and testing of an IGBT valve, which combines the function of protective switch and modulator for the EC and LH H&CD systems.
- Revise the component design taking into account emerging new technologies (example: application of HVDC light® - HVDC plus® to the H&CD power supplies).

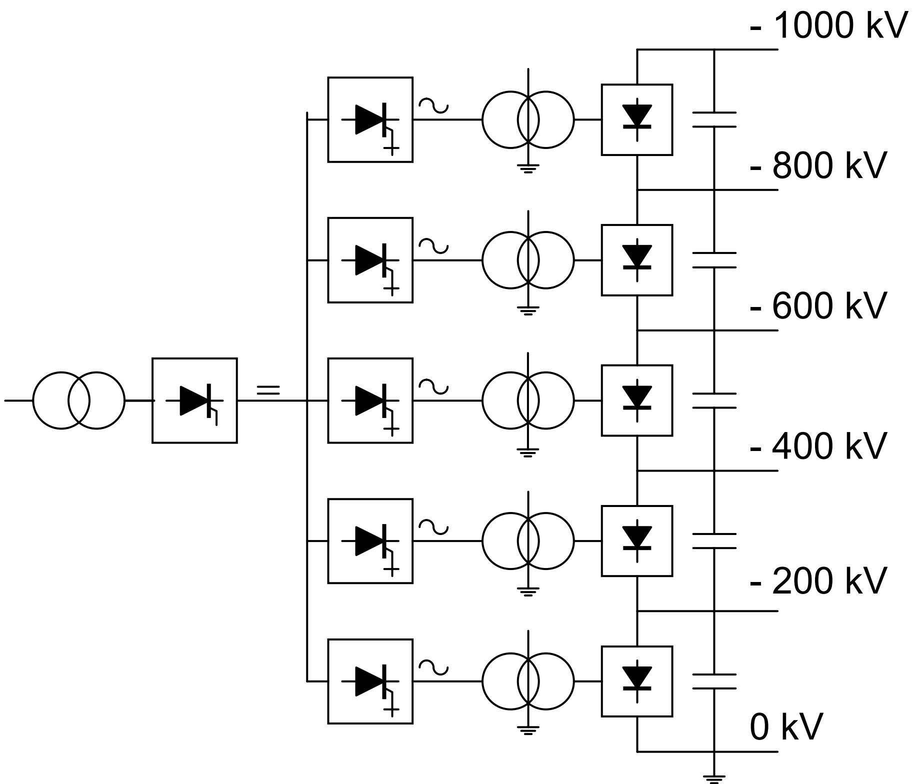
HVDC light® - HVDC plus®



- HVDC light® (ABB) - HVDC plus® (Siemens) is a relatively new technology for advanced power transmission systems.
- More info on the WWW sites of ABB and Siemens.
- It could be attractive for the ITER H&CD power supplies (IC, EC, LH and NB),
- <u>If the price is competitive.</u>

Possible application of the HVDC light®/plus® technology.

Present 1 MV design concept



Alternative option to be studied, costed, assessed…