

# Il progetto ITER

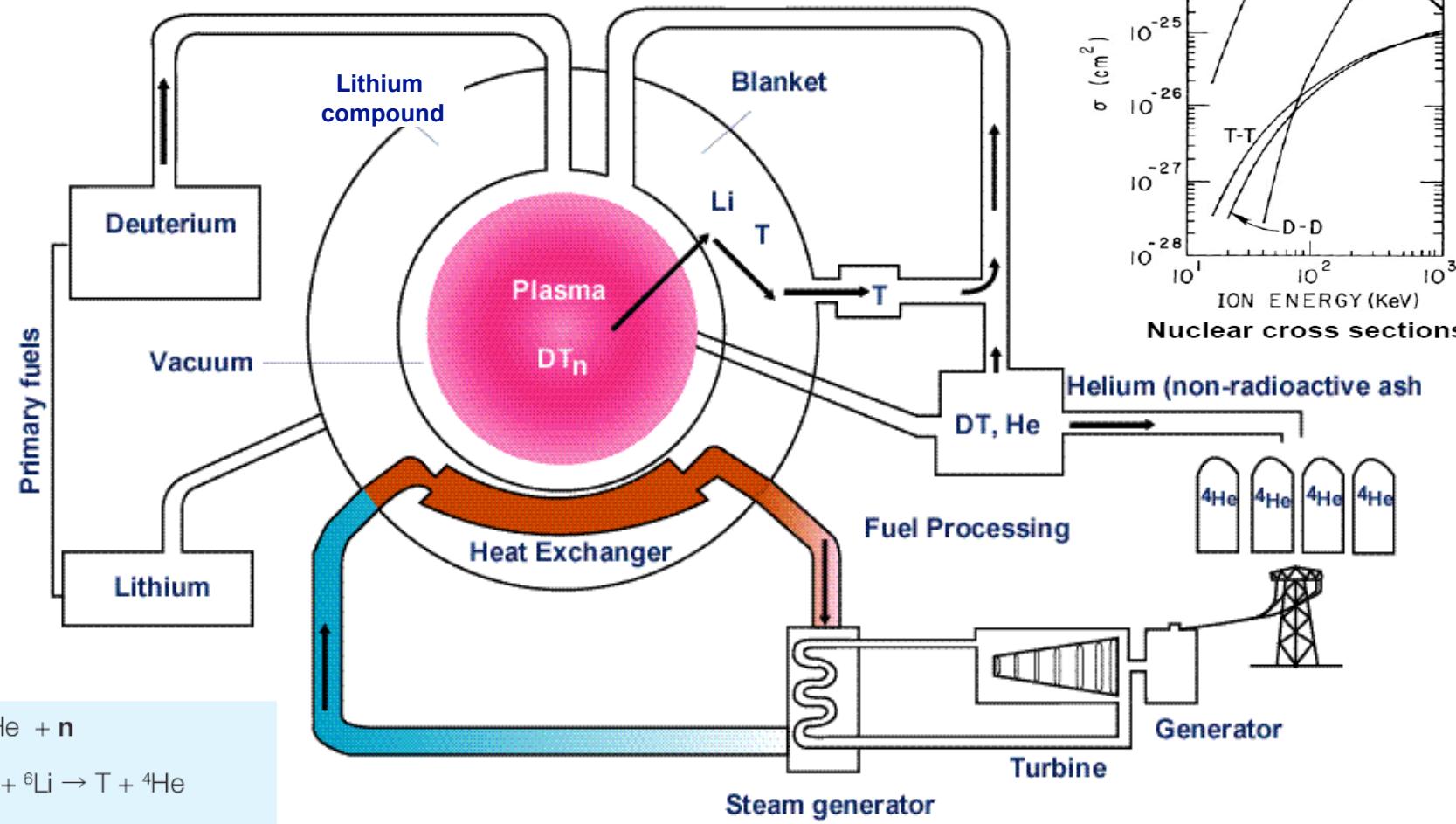
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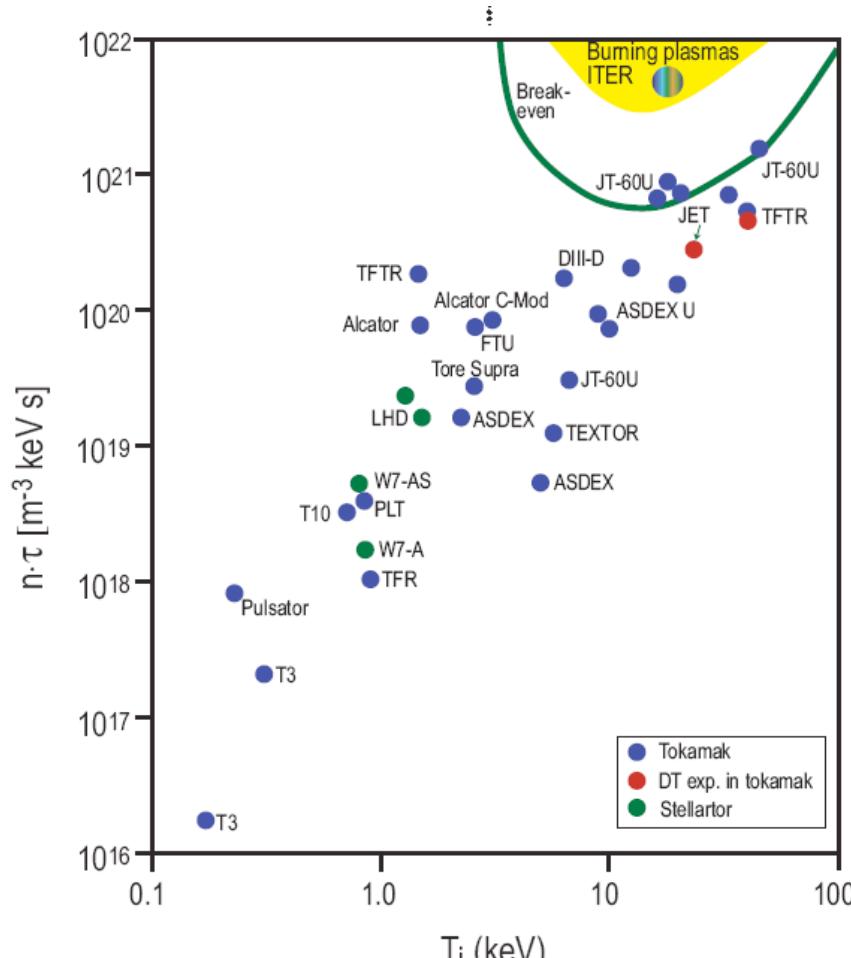
*CNR*

*Dipartimento Energia e Trasporti (DET)*

# Schema di un reattore a fusione



# Parametri per ottenere energia da fusione

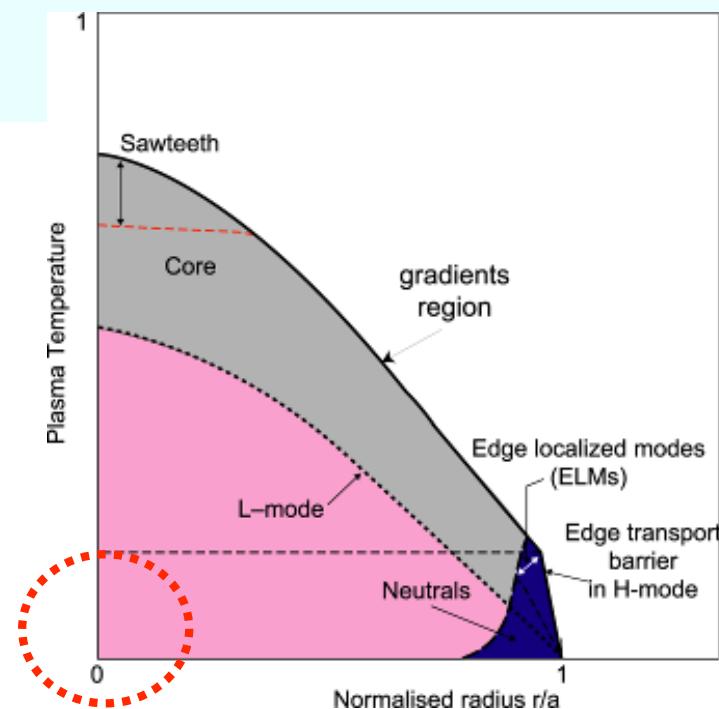


Riscaldamento

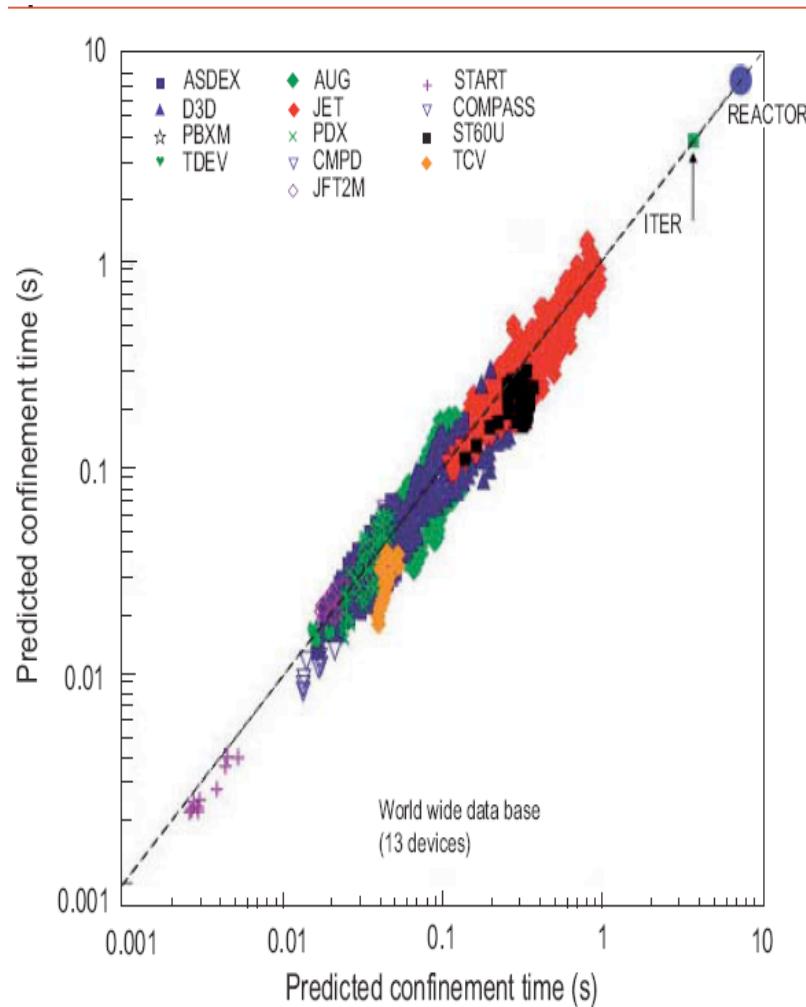
Confinamento Energia e Particelle

# Confinamento in ITER

- Conventionally, plasma confinement regimes denoted **L-mode** and **H-mode**
  - The difference between these modes is caused by the formation of an **edge pedestal** in which transport is significantly reduced - **edge transport barrier**
  - **edge localized modes** maintain plasma in quasi-stationary state



# Scaling del tempo di confinamento



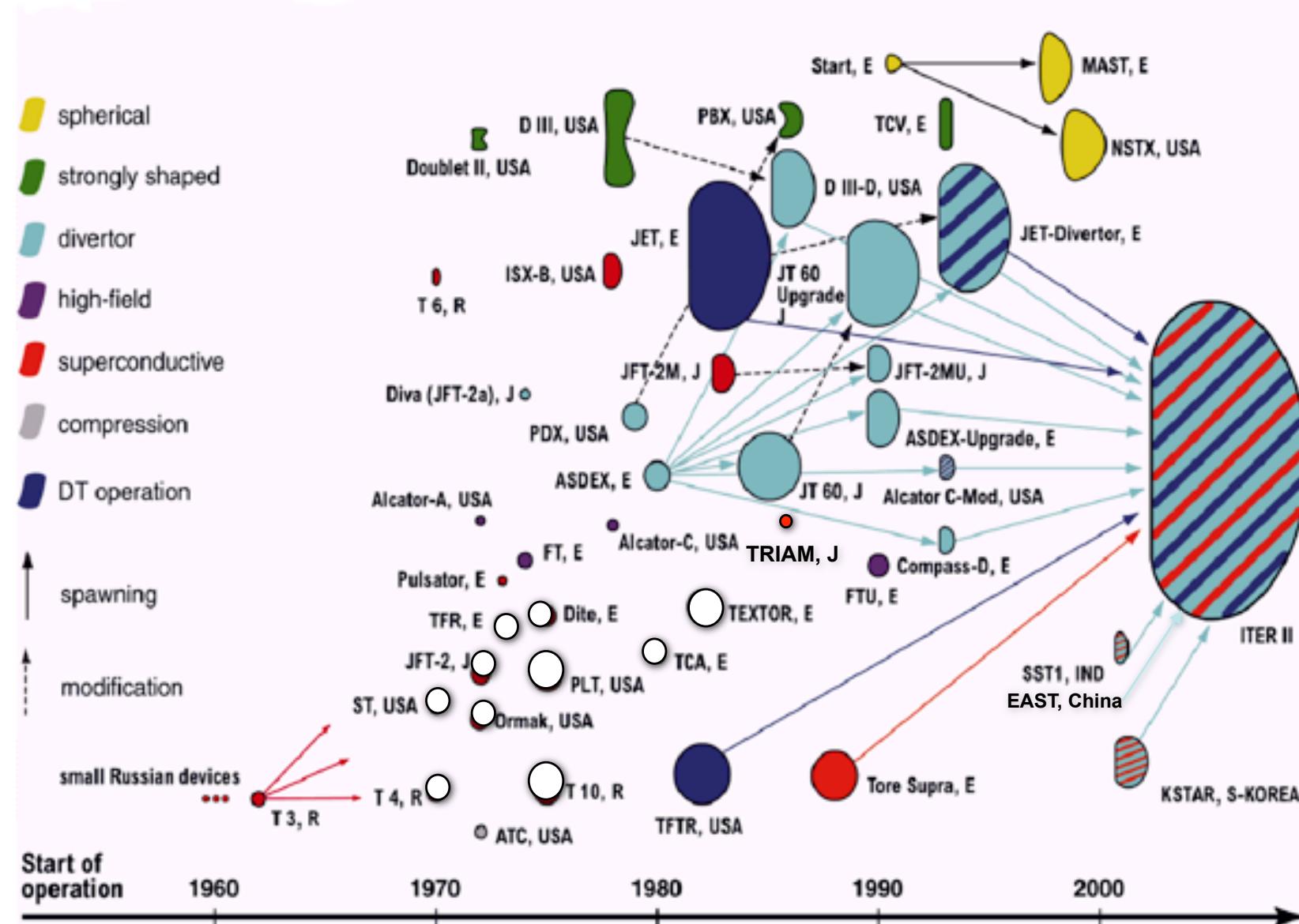
*Scaling in termini di parametri fisici*

$$\tau_{E,th}^{ELMy} \propto \tau_B \rho_*^{-0.83} \beta^{-0.50} \nu_*^{-0.10} \\ \times M^{0.97} q^{-2.52} \varepsilon^{-0.55} \kappa^{2.72}.$$

*Scaling in termini di parametri ingegneristici*

$$\tau_{E,th}^{ELMy} = 0.0365 I^{0.97} B^{0.08} P^{-0.63} n^{0.41} \\ \times M^{0.20} R^{1.93} \varepsilon^{0.23} \kappa^{0.67}$$

# History of Tokamaks



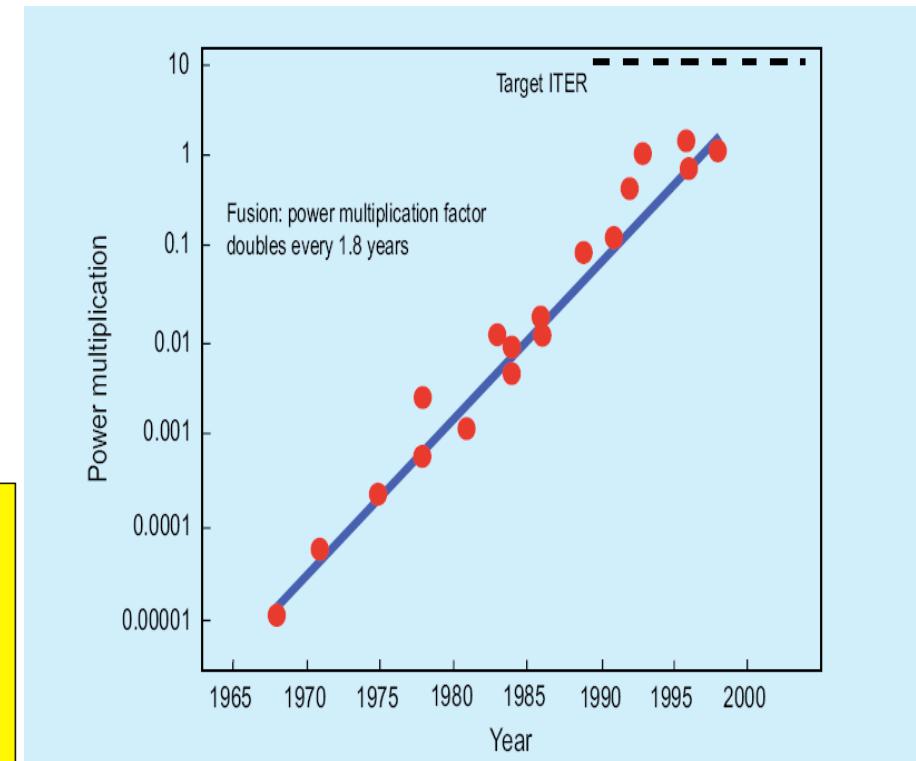
# Definition of Burning Plasma

$$\frac{dW}{dt} \rightarrow 0 \implies P_\alpha + P_{heat} = \frac{W}{\tau_E}$$

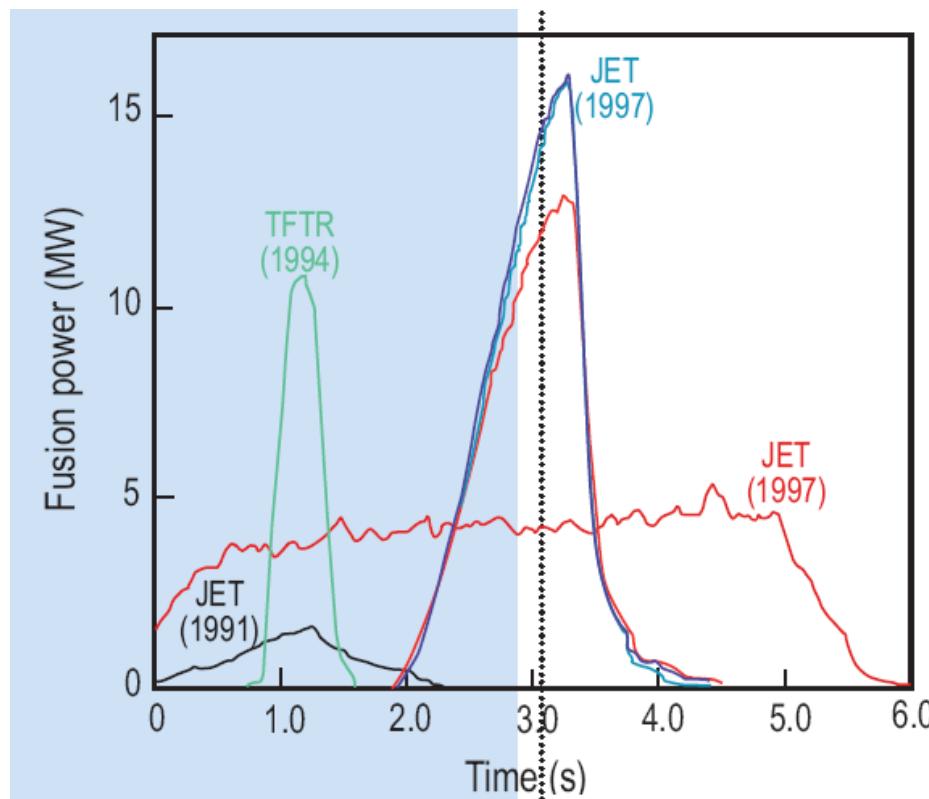
Define fusion energy gain,  $Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5 P_\alpha}{P_{heat}}$

Define  $\alpha$ -heating fraction,  $f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{heat}} = \frac{Q}{Q+5}$

<b>Breakeven</b>	$Q = 1$	$f_\alpha = 17\%$
<hr/>		
<b>Burning plasma regime</b>	$Q = 5$	$f_\alpha = 50\%$
	$Q = 10$ (ITER)	$f_\alpha = 60\%$
	$Q = 20$	$f_\alpha = 80\%$
	$Q = \infty$ (ignition)	$f_\alpha = 100\%$



# Produzione di energia D-T finora ottenuta



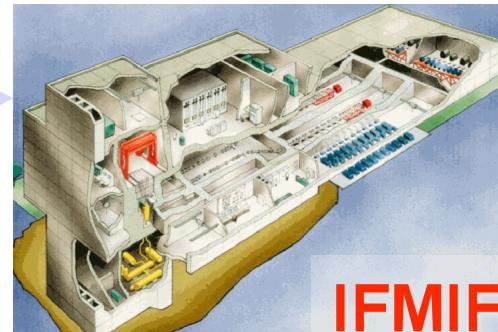
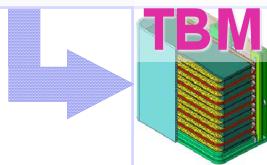
Produzione di energia da fusione dimostrata in JET e TFTR

Massimo Q ottenuto in miscela D-T  **$Q > 0.6$**

Massimo Q ottenuto in miscela D-D ( equivalente D-T)  **$Q = 1$**

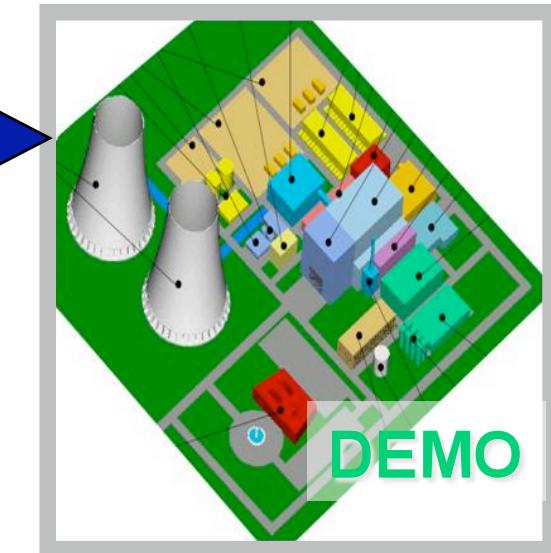
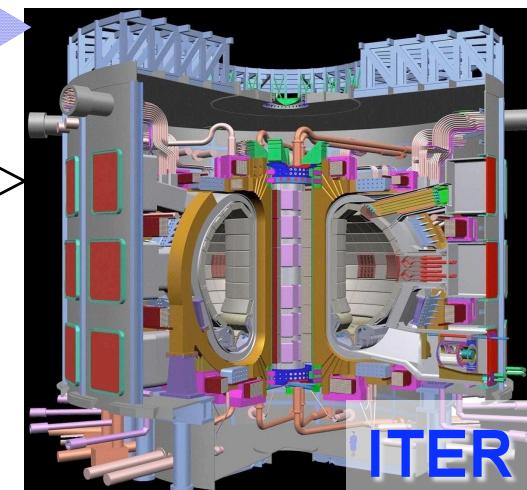
# Programma internazionale per realizzare reattore a fusione dimostrativo

**Materiali strutturali  
e moduli mantello**



**Sistema integrato:**

- Magneti superconduttori
- Sistema per trizio
- Comp. nti interno camera
- Manipolazione remota
- Sistema riscaldamento
- Sicurezza
- Moduli prova mantello



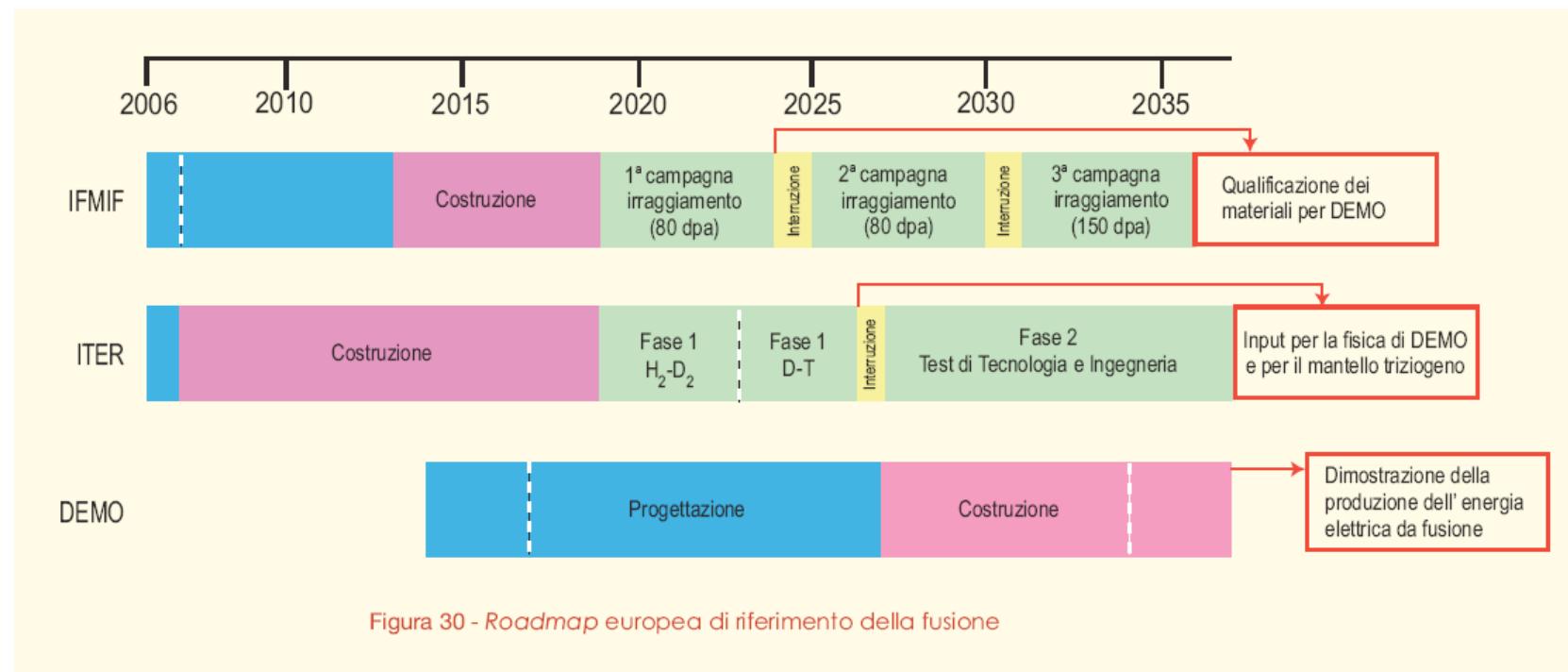
**Impianti per R&S**

- Confinamento
- Controllo impurezze
- Stabilità del plasma
- Fisica per ITER/DEMO

**JET, JT60-SA, FAST  
altre macchine**

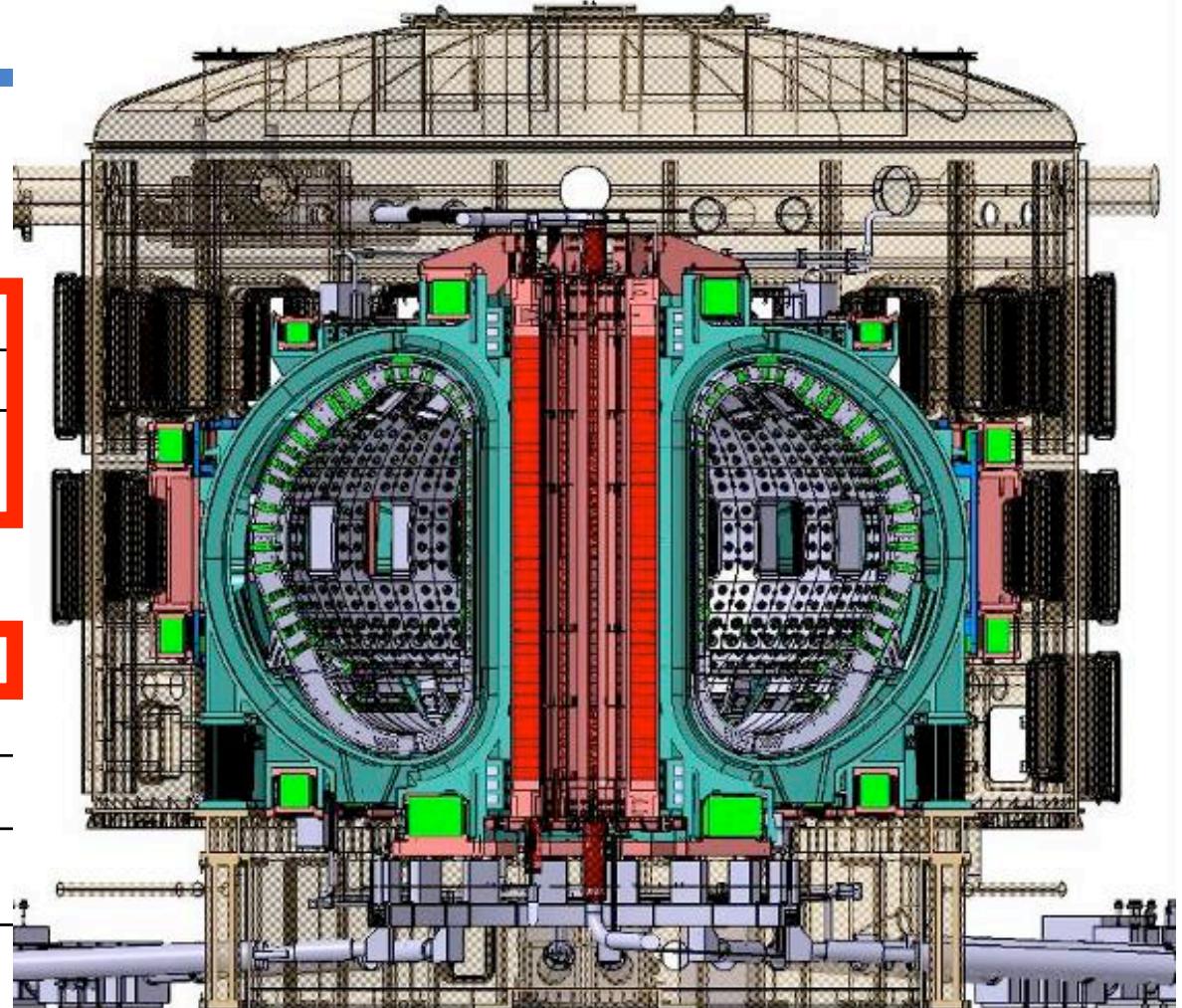


# Tempi

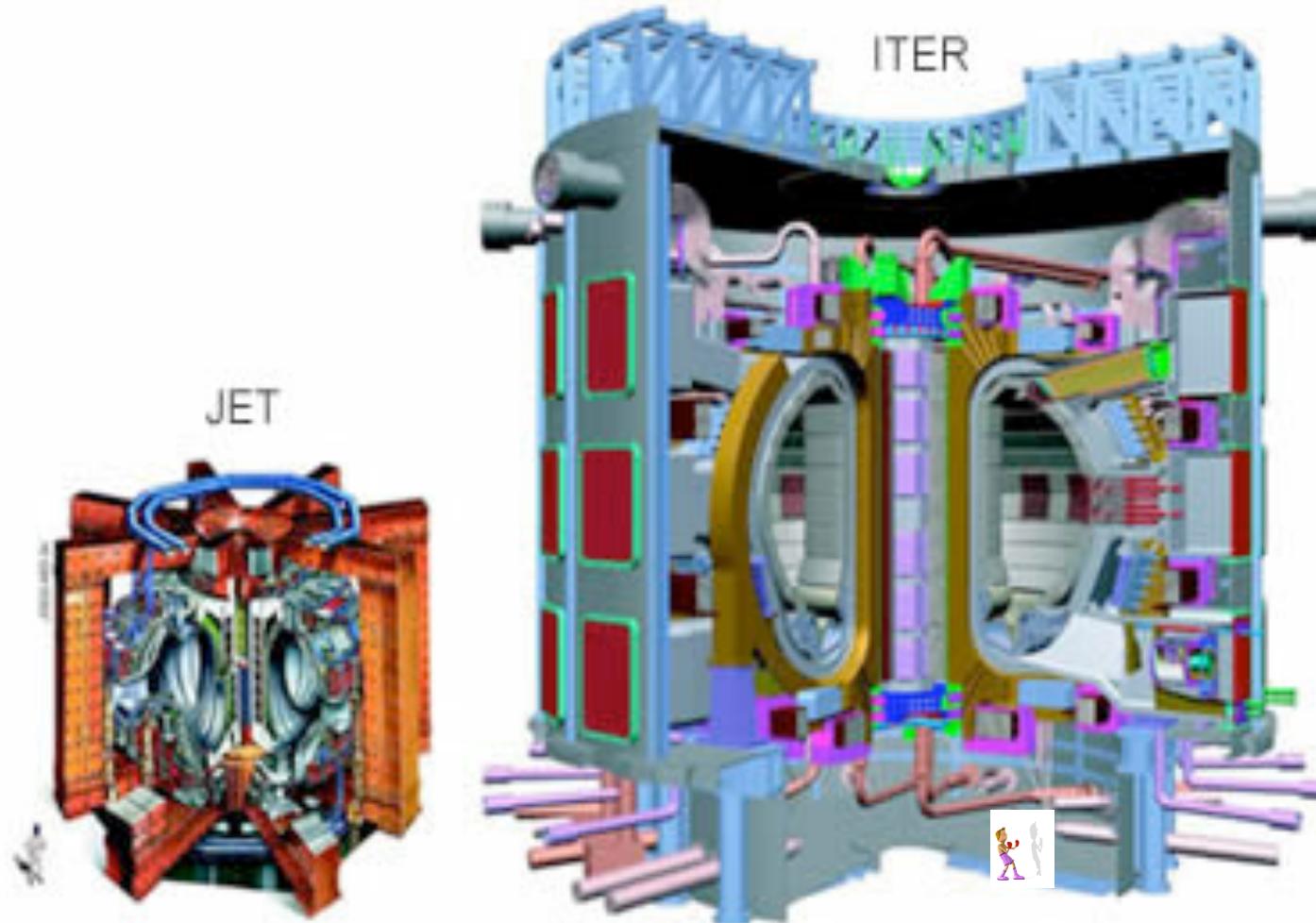


# The Core of ITER

Total fusion power	500 MW
Additional heating power	50 MW
Q - fusion power/ additional heating power	$\geq 10$
Average 14MeV neutron wall loading	$\geq 0.5 \text{ MW/m}^2$
Plasma inductive burn time	300-500 s *
Plasma major radius ( $R$ )	6.2 m
Plasma minor radius ( $a$ )	2.0 m
Plasma current ( $I_p$ )	15 MA
Toroidal field at 6.2 m radius ( $B_T$ )	5.3 T



# JET → ITER

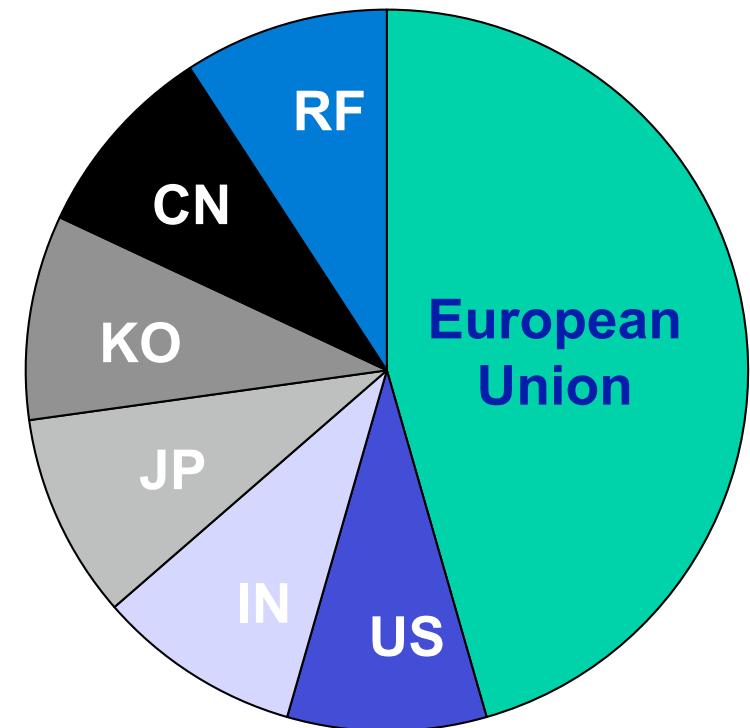


# ITER : costi e ripartizione

Overall sharing:

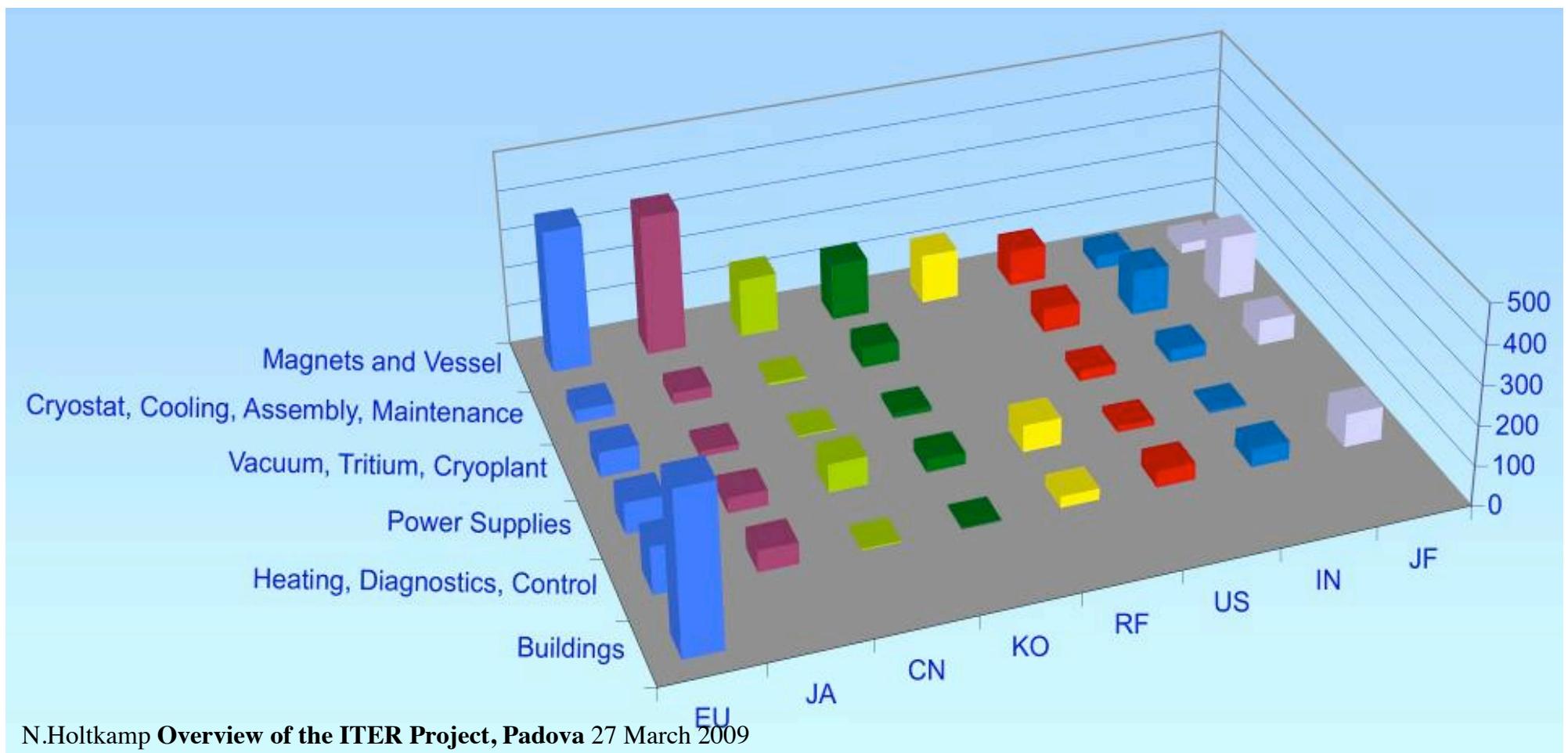
EU 5/11, other six parties 1/11 each. Overall contingency of 10% of total. Total amount: 3577 kIUA (5365 M€)

**Cost: ~5.5 billion Euros for construction, and ~5 billion for operation and decommissioning**



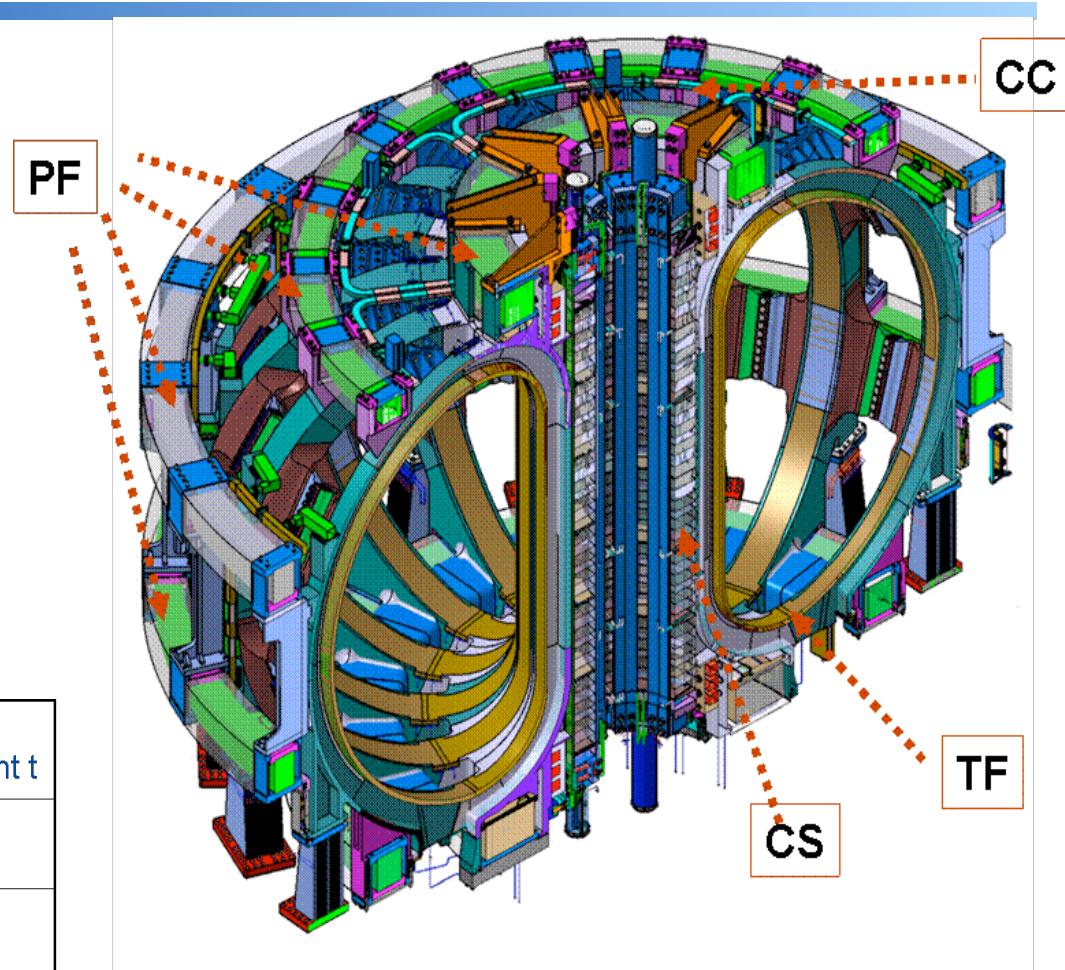
# ITER : costi e ripartizione

- A unique feature of ITER is that almost all of the machine will be constructed through *in kind* procurement from the Parties



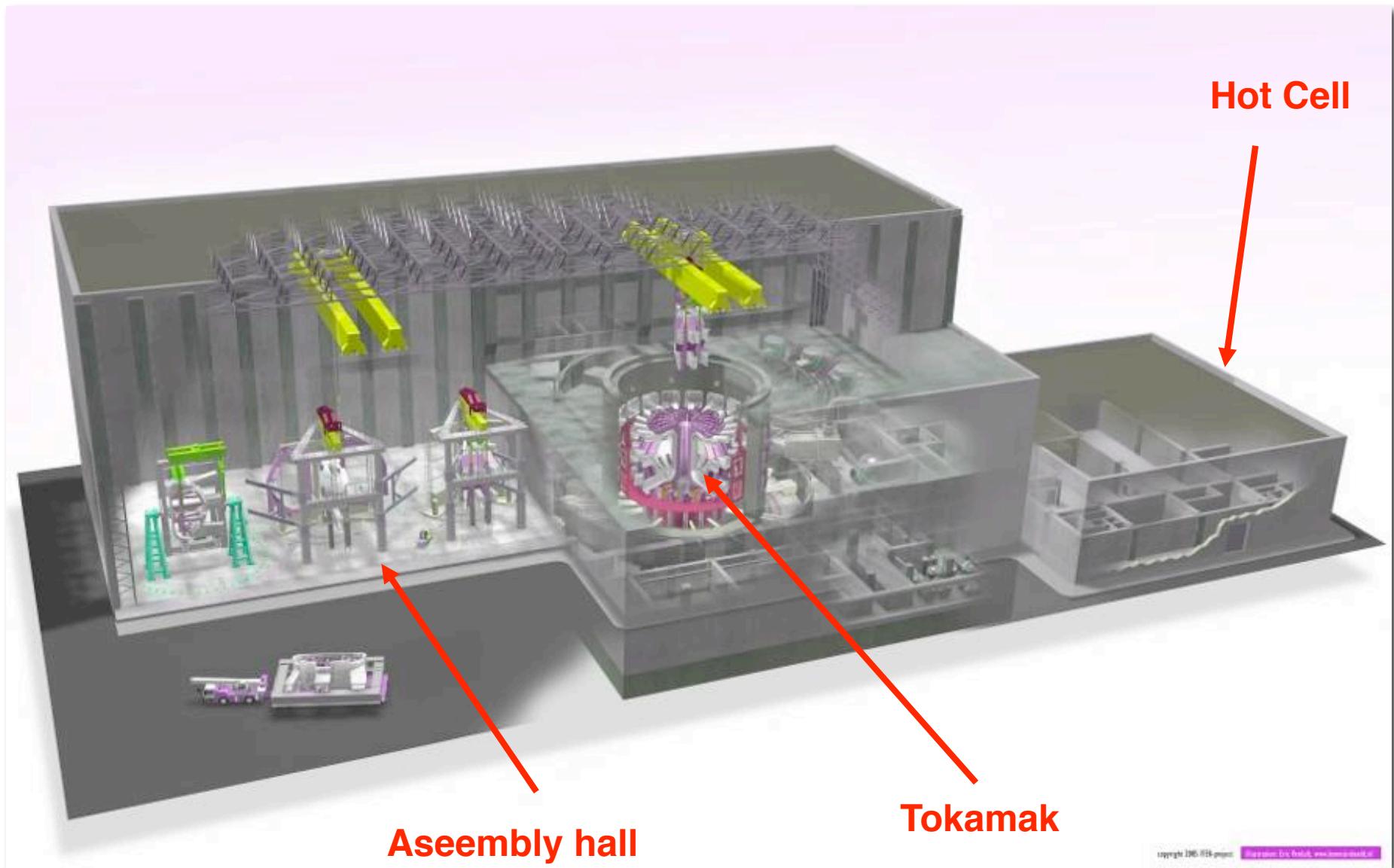
# Overview of the Magnet System

- 48 superconducting coils
  - 18 TF coils
  - 6 CS modules
  - 6 PF coils
  - 9 pairs of CC

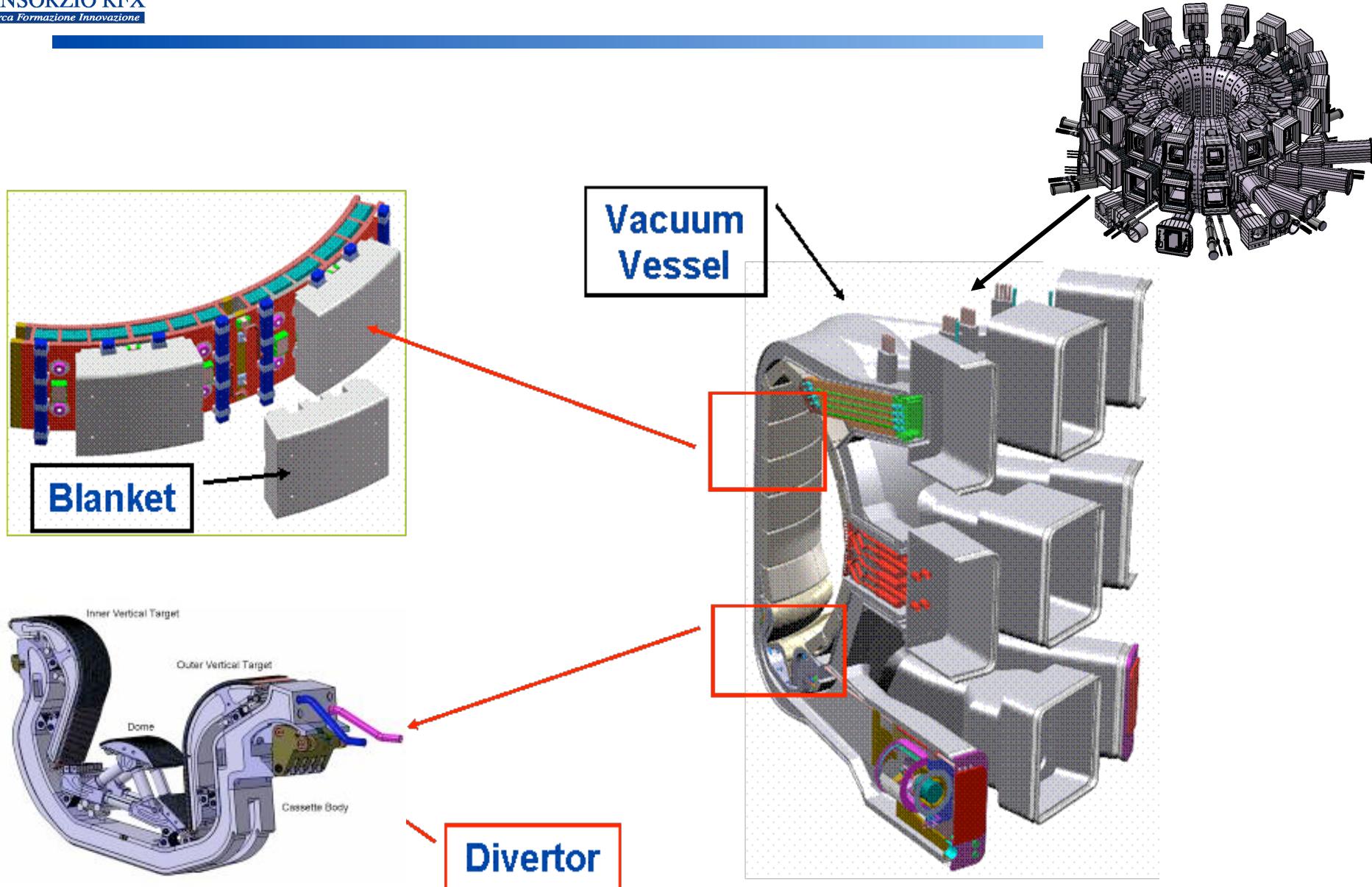


System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

# Tokamak Building



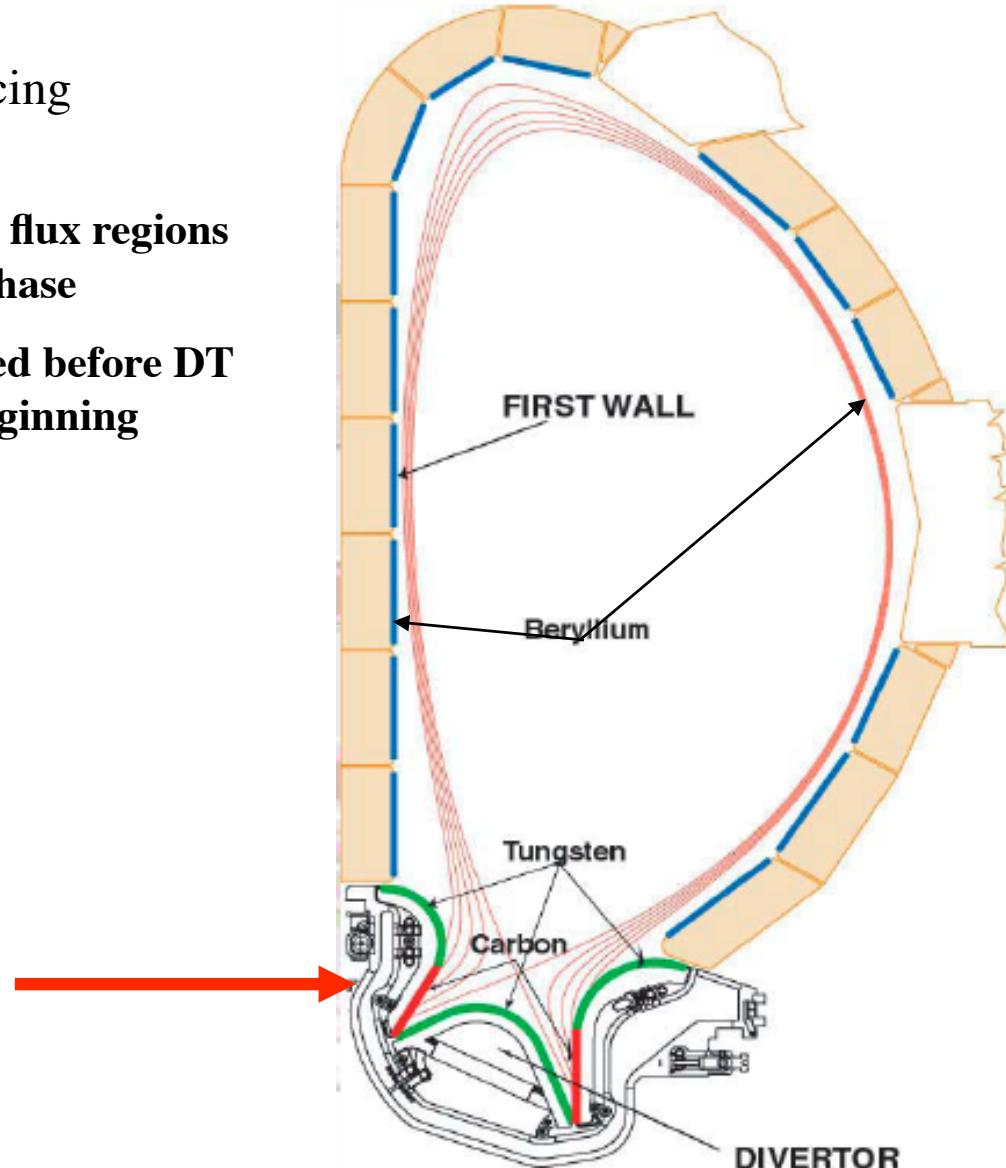
# VV and In-Vessel Components



**Disruptions and mechanical stress**

# Plasma Facing Material Strategy

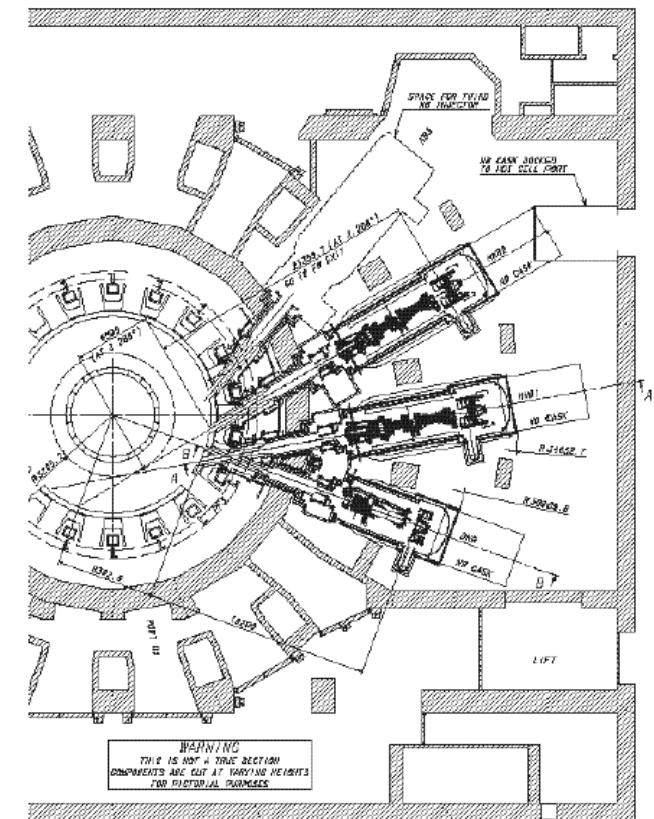
- Strategy for the use of plasma facing materials in ITER :
  - CFC will be used for high heat flux regions of divertor in advance of DT phase
  - tungsten targets will be installed before DT operation. May be from the beginning



# **ITER : sistema di riscaldamento ausiliario**

Heating System	Stage 1	Possible Upgrade	Remarks
NBI (1MeV D <sup>-</sup> ive ion)	33	16.5	Vertically steerable (z at Rtan -0.42m to +0.16m)
ECH&CD (170GHz)	20	20	Equatorial and upper port launchers steerable
ICH&CD (40-55MHz)	20		$2\Omega_T$ (50% power to ions $\Omega_{He3}$ (70% power to ions, FWCD)
LHH&CD (5GHz)		20	$1.8 < n_{par} < 2.2$
<b>Total</b>	73	130 (110 simultan)	Upgrade in different RF combinations possible
ECRH Startup	2		126 or 170GHz
Diagnostic Beam (100keV, H <sup>-</sup> )	>2		

# NBI Layout



## P<sub>aux</sub> for Q=10 nominal scenario: 40-50MW

# Programma nazionale e ruolo del CNR

- Enti coinvolti: ENEA, **CNR**, INFN, Università, nel quadro delle attività europee coordinate da EURATOM
- Attività
- 1) **Studi di Fisica e tecnologia negli esperimenti nazionali RFX e FTU ed europei (JET e altri)**
- 2) Realizzazione di ITER : **riscaldamenti ausiliari (EC , NBI)** e sviluppo Materiali
- 3) *Realizzazione di IFMIF\**
- 4) **Programma di supporto a ITER : partecipazione alla realizzazione di JT60SA\*** e proposta esperimento FAST
- \*nel quadro dell'accordo *Broader Approach* tra EU e J

# Progetto fusione del CNR

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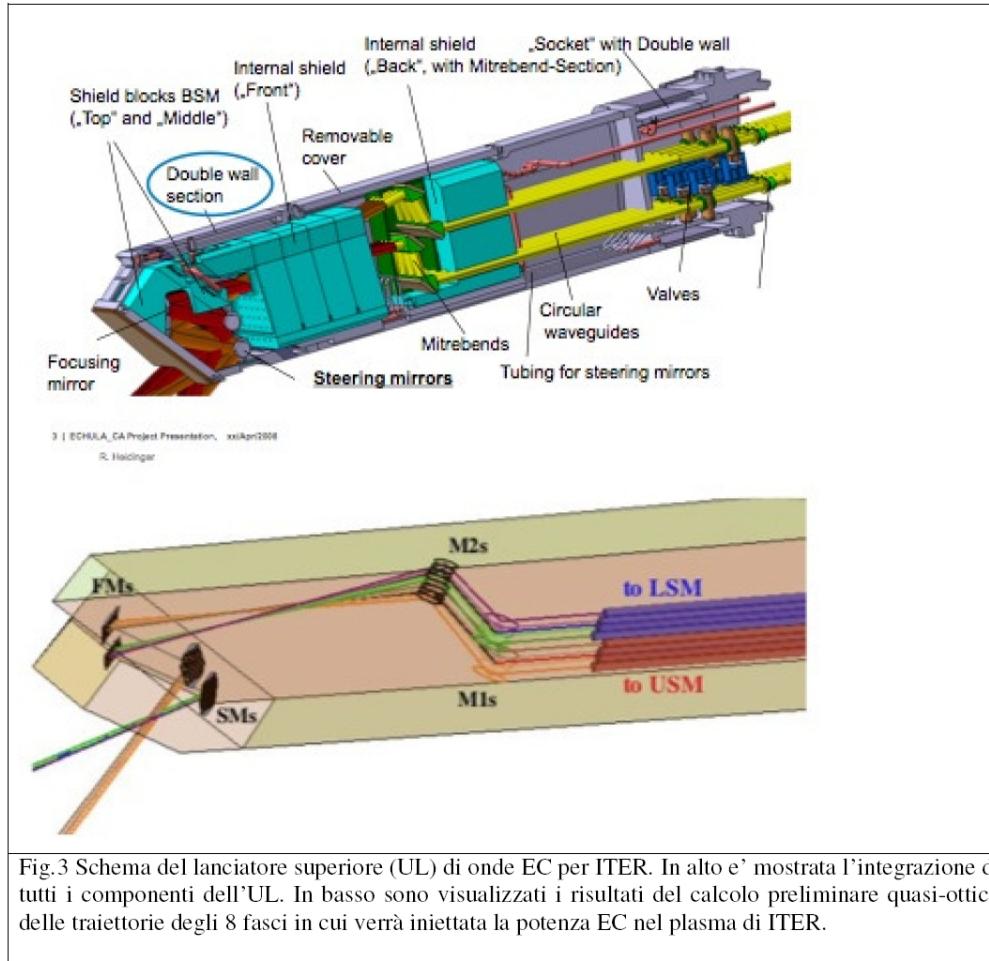
- Il CNR opera tramite gli Istituti di Fisica del Plasma (IFP) di Milano e Gas Ionizzati (IGI) di Padova e tramite il Consorzio RFX di Padova di cui è socio e in cui sono integrate le attività dell'IGI
- Complessivamente il personale coinvolto è pari a circa 190 operatori tra ricercatori e supporto tecnico e amministrativo di cui circa 40 IFP e circa 55 IGI . Inoltre presso le strutture CNR sono in formazione una ventina di studenti di dottorato e quasi altrettanti studenti in tesi

# Progetto fusione del CNR

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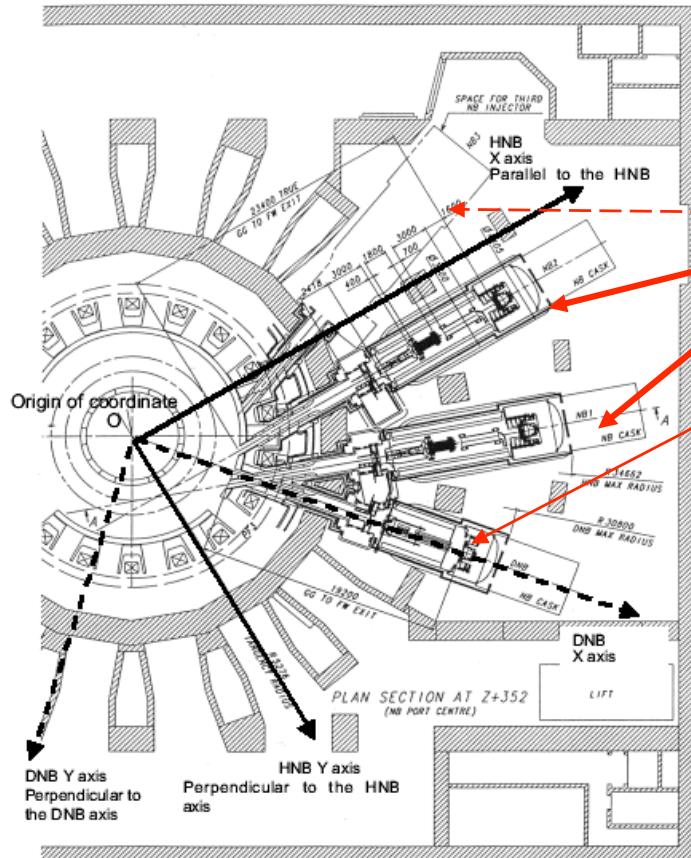
- Il DET ha costituito un progetto “Partecipazione ai programmi nazionali e internazionali sulla Fusione “ per coordinare le attività di ricerca in questo settore. Il progetto si articola in quattro commesse che fanno capo ai due istituti esecutori:
- *Fisica e Tecnologia del Plasma e della Fusione Termonucleare* (IFP) G. Ramponi
- *Strumenti e tecnologie dei processi al plasma* (IFP) G. Grossi
- *Esperimento RFX ed attività collegate* (IGI) F. Gnesotto
- *Esperimenti e modelli di processi innovativi in scala* (IFP) G Granucci.

# Realizzazioni per ITER: riscaldamento ausiliario EC



Simulazione dell'ottica del fascio e la logica del controllo per controllo in tempo reale (100ms ) di instabilità di plasma per ITER

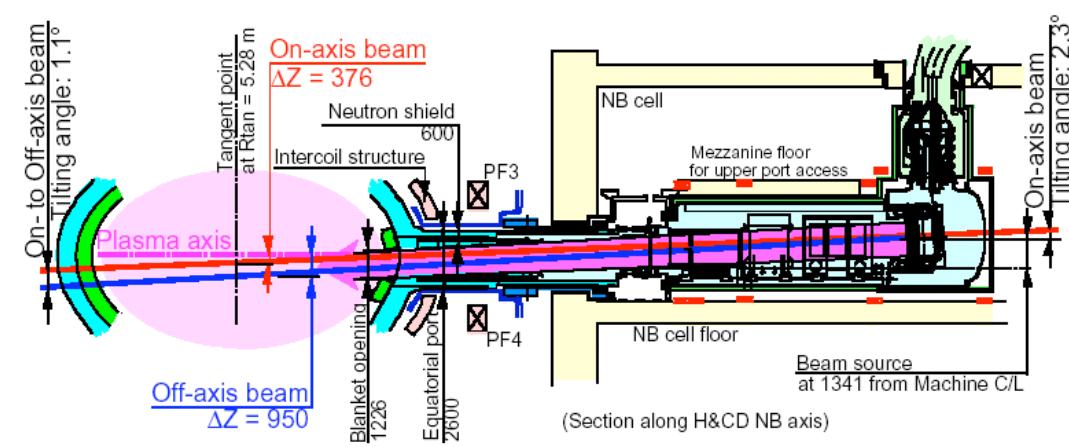
## NBI in ITER



## Plan view

2+1 NBI  
DNB

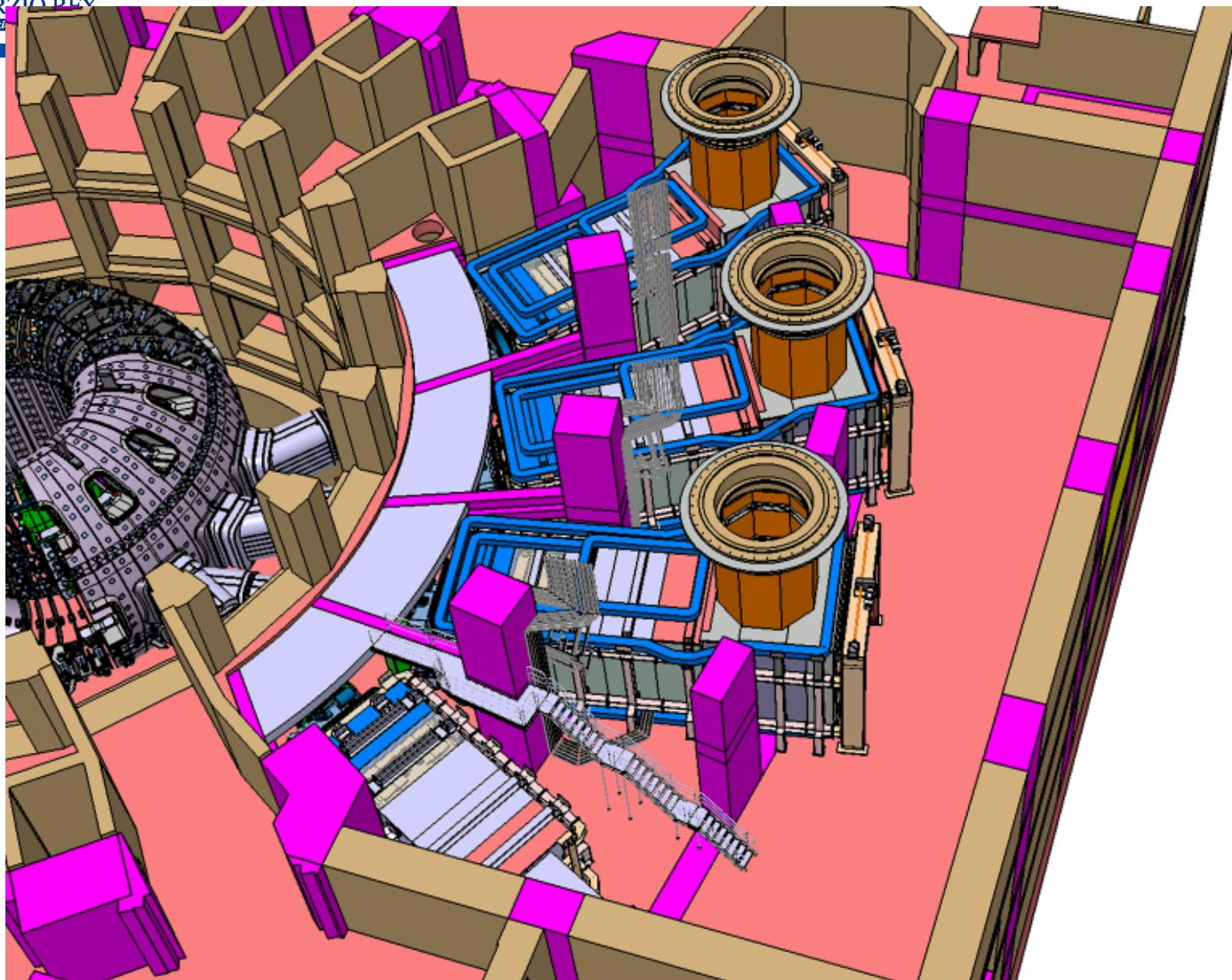
## tangential injection



## Vertical cross section view

## On/off axis injection by tilting the beam axis vertically

# L1 LEVEL NB CELL



# Realizzazioni per ITER: sistema NBI

2 (+1) NBI Neutral Beam Injectors based on negative ions are foreseen in ITER

Each beam must provide:

$P=16.5\text{MW}$

$I=40\text{A}$

$V=1\text{MV}$

$t_{\text{pulse}}=3600\text{s}$

**Effective power deposition in the plasma core implies 1MV acceleration**

**1MV efficient neutralization by charge exchange implies negative ions**

## Main functionalities:

Plasma Heating

Plasma Rotation

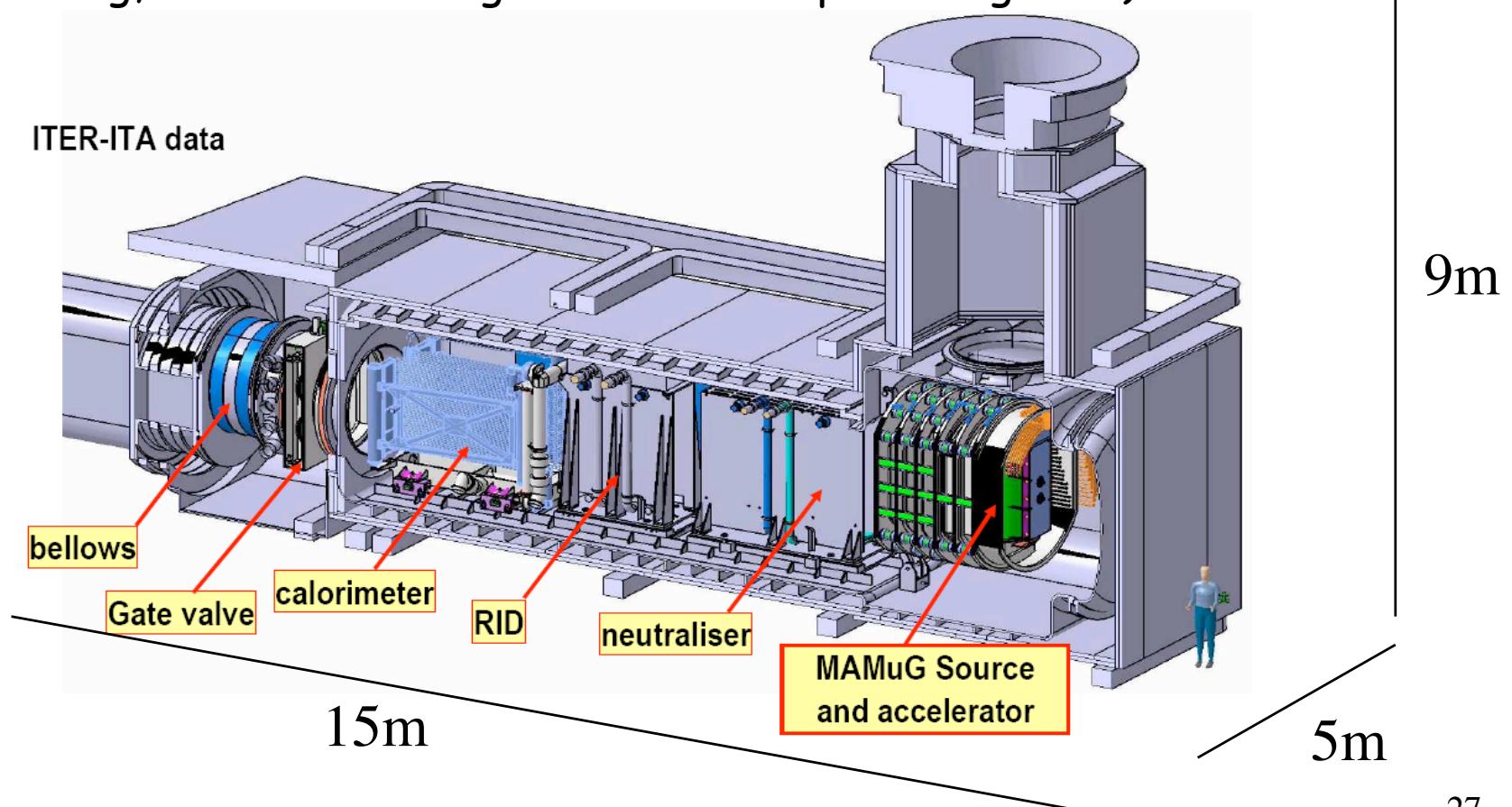
Current drive

Plasma parameter profile control

Burn phase control

## The injector

The Injector can be separated in beam components (**Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter**) other components (**cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils**)



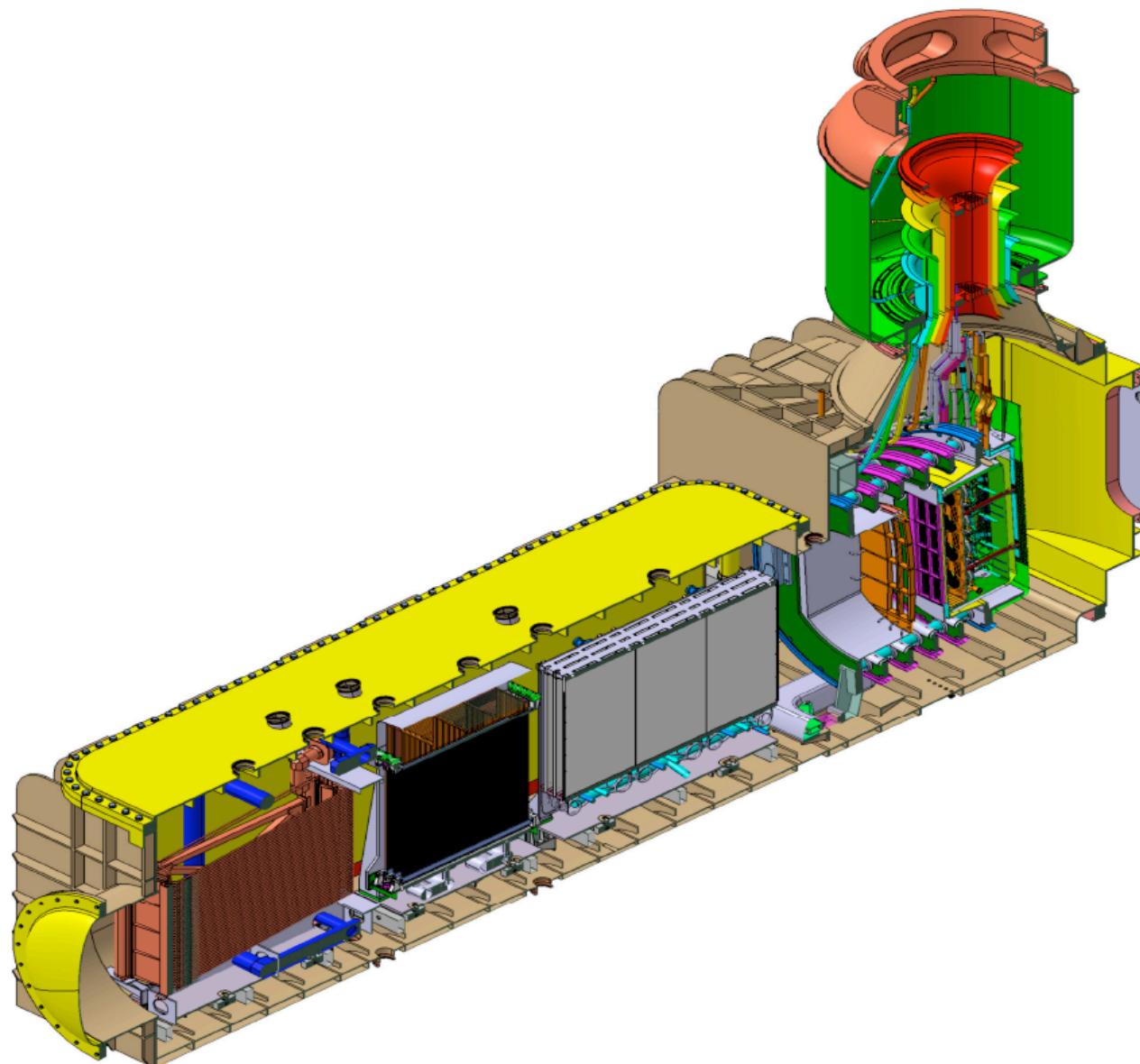
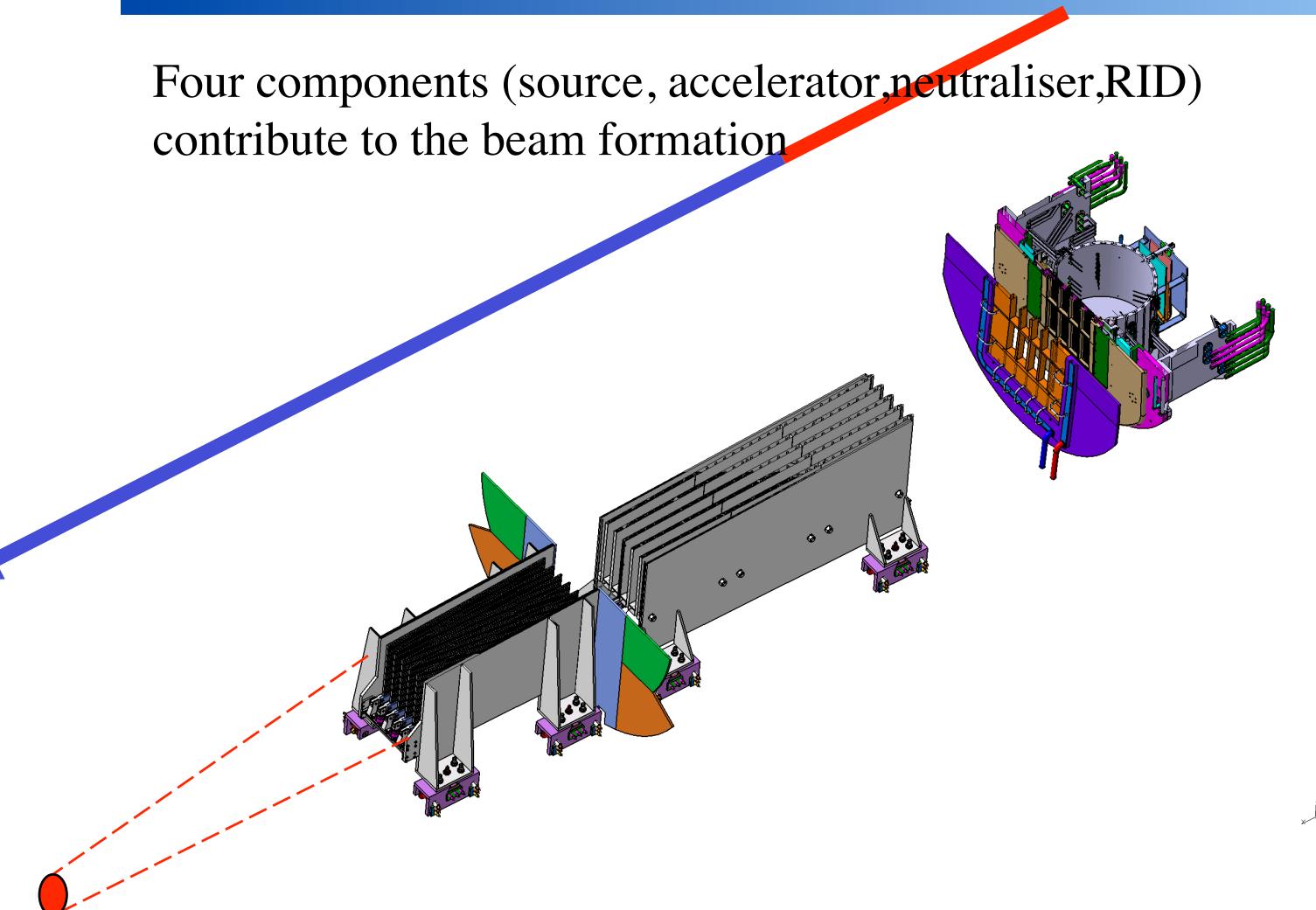


Fig. 9 Progetto del vessel per NBI di ITER

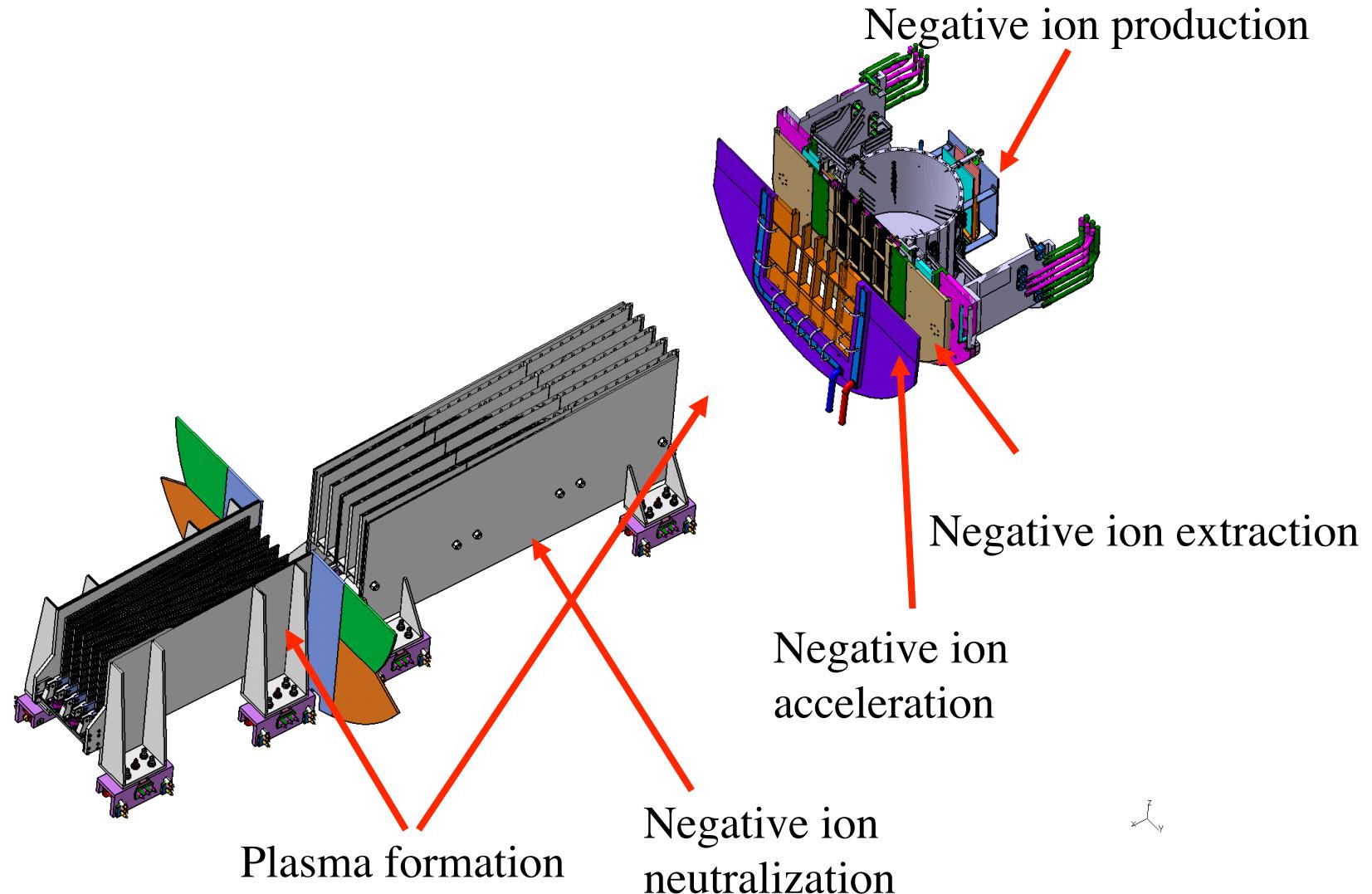
# Beam formation

Four components (source, accelerator, neutraliser, RID) contribute to the beam formation

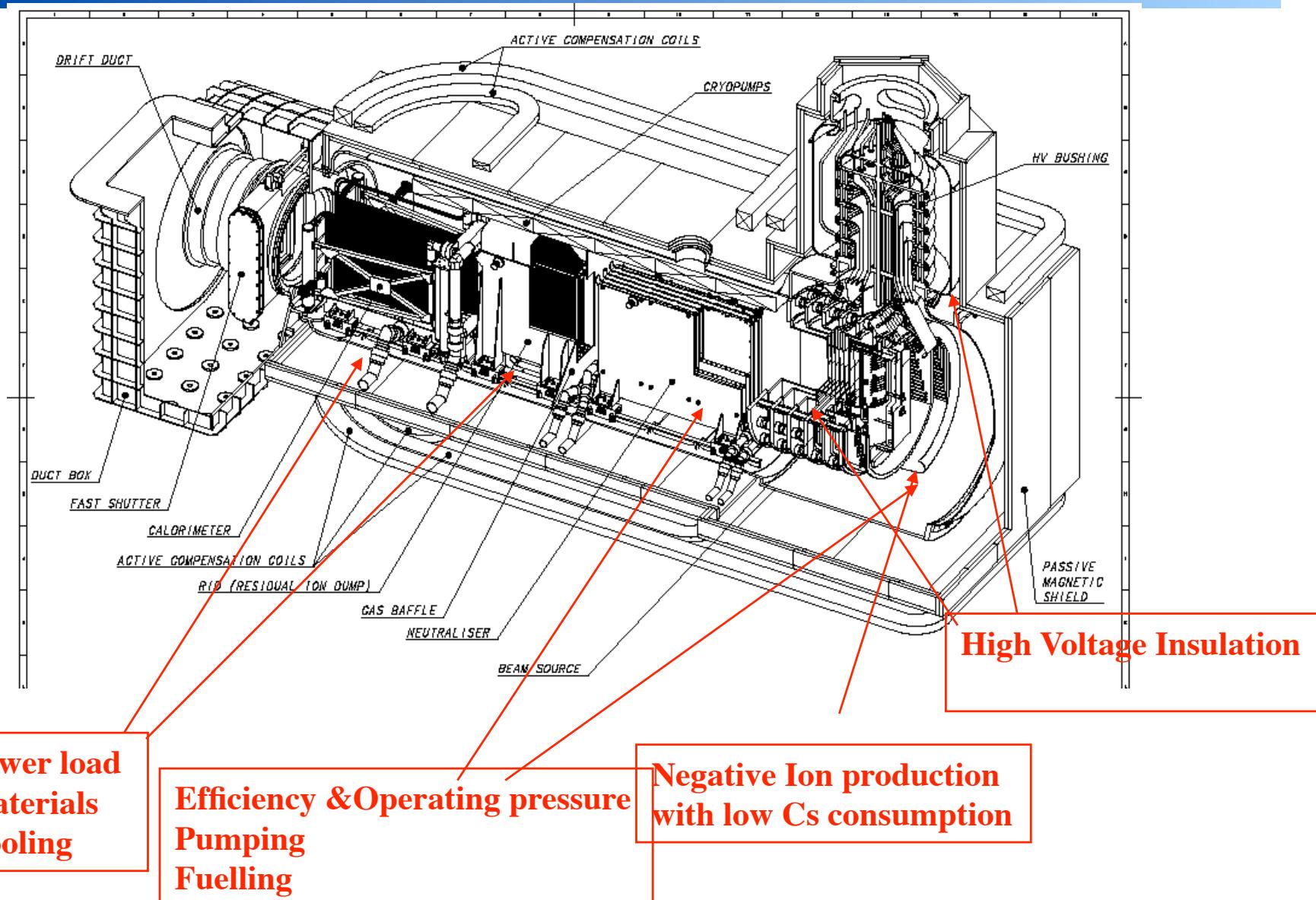


Elliptic beam size 0.6x0.8m

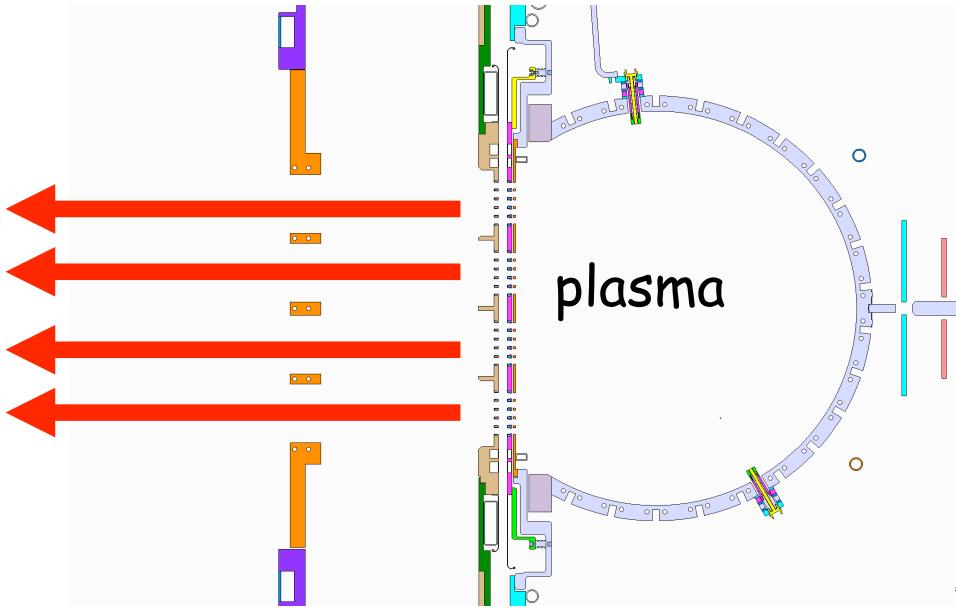
# Physics issues



# NBI main engineering issues



# Beam formation: negative ion production



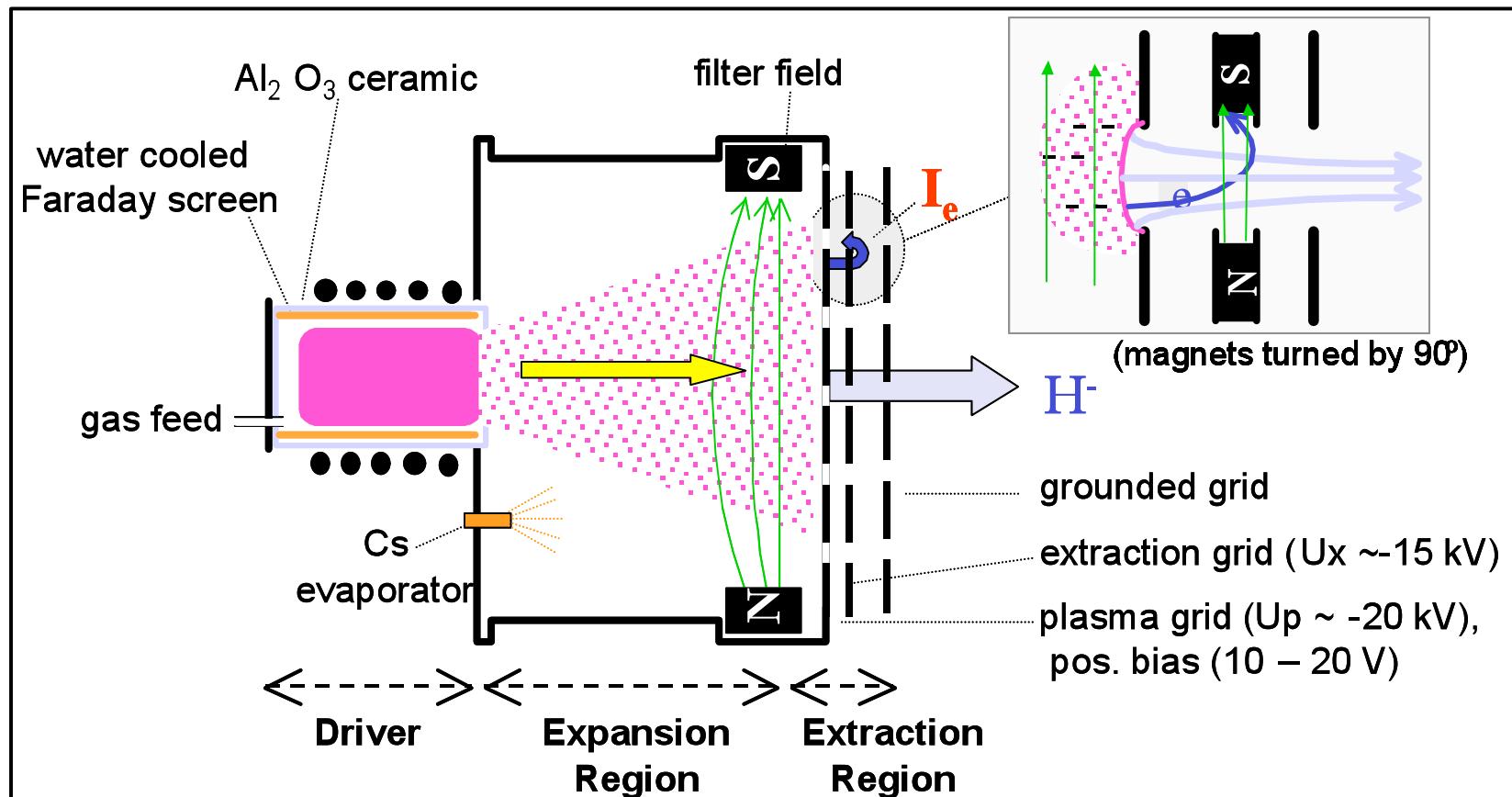
Negative Ion production

Volume production (attachment of low energy electrons to excited molecules)

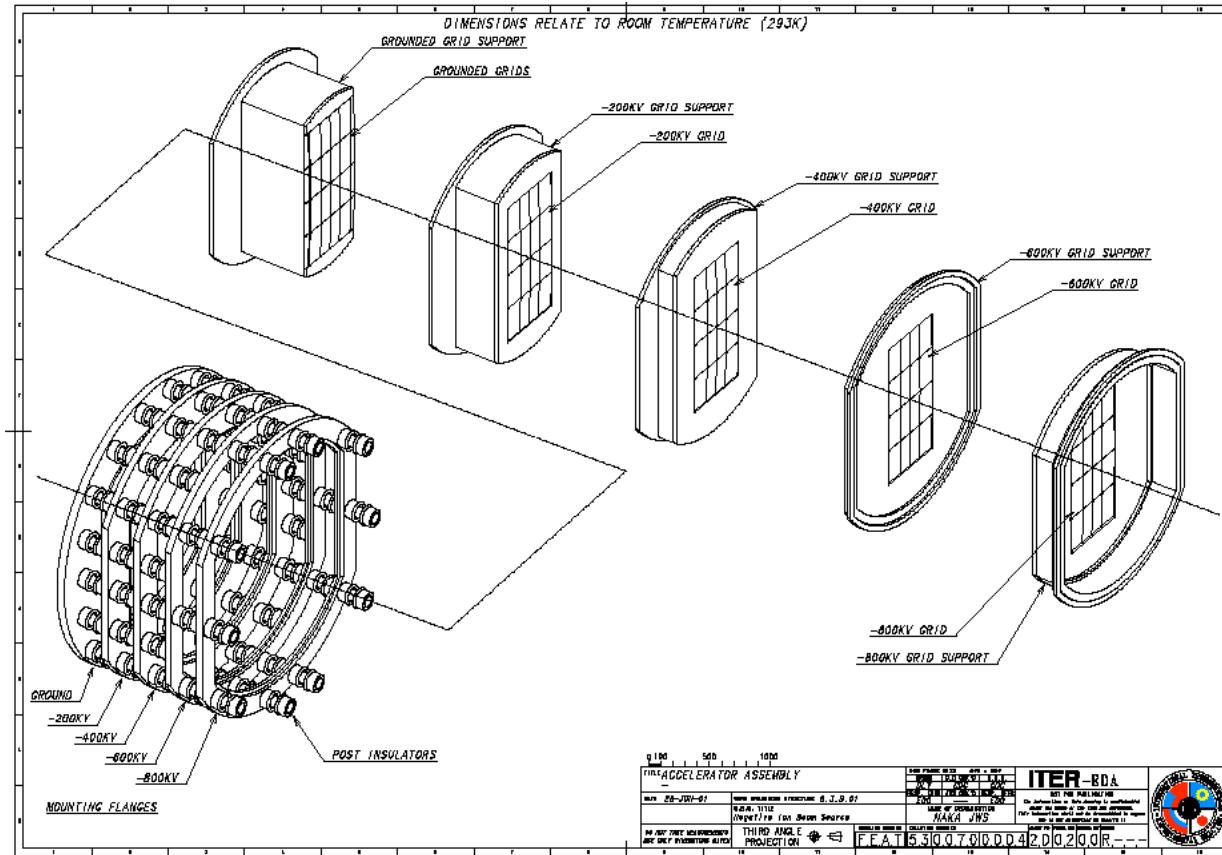
Surface production (attachment of surface electrons to incident atoms)

Cs injection greatly increases negative ion yield as it decreases surface material working function

# RF Ion Source



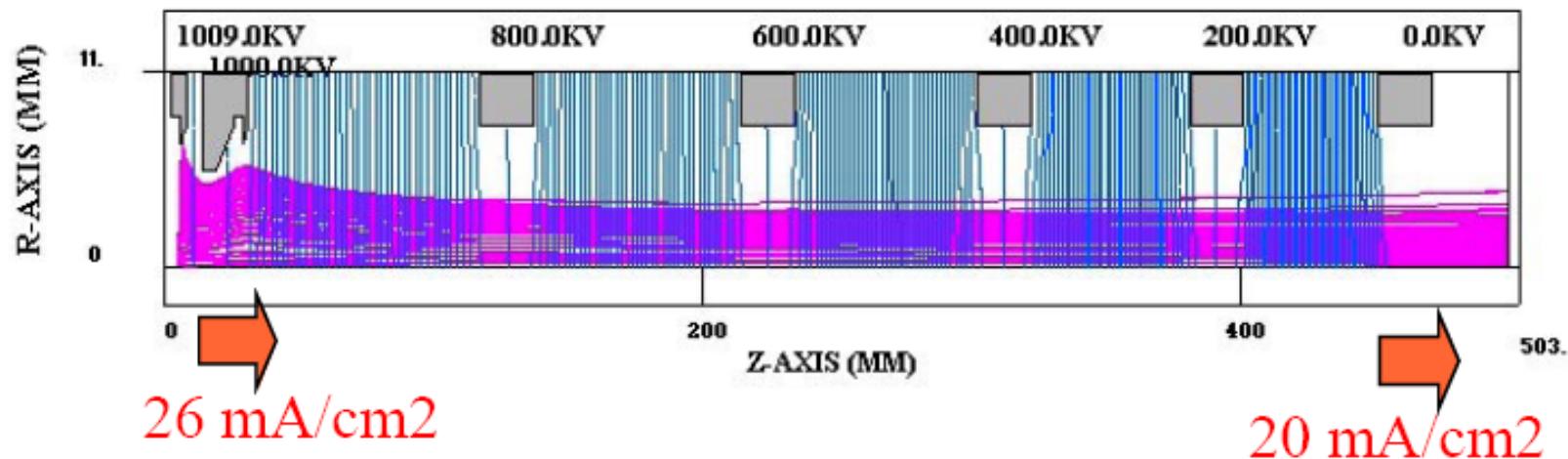
# NBI in ITER: accelerator



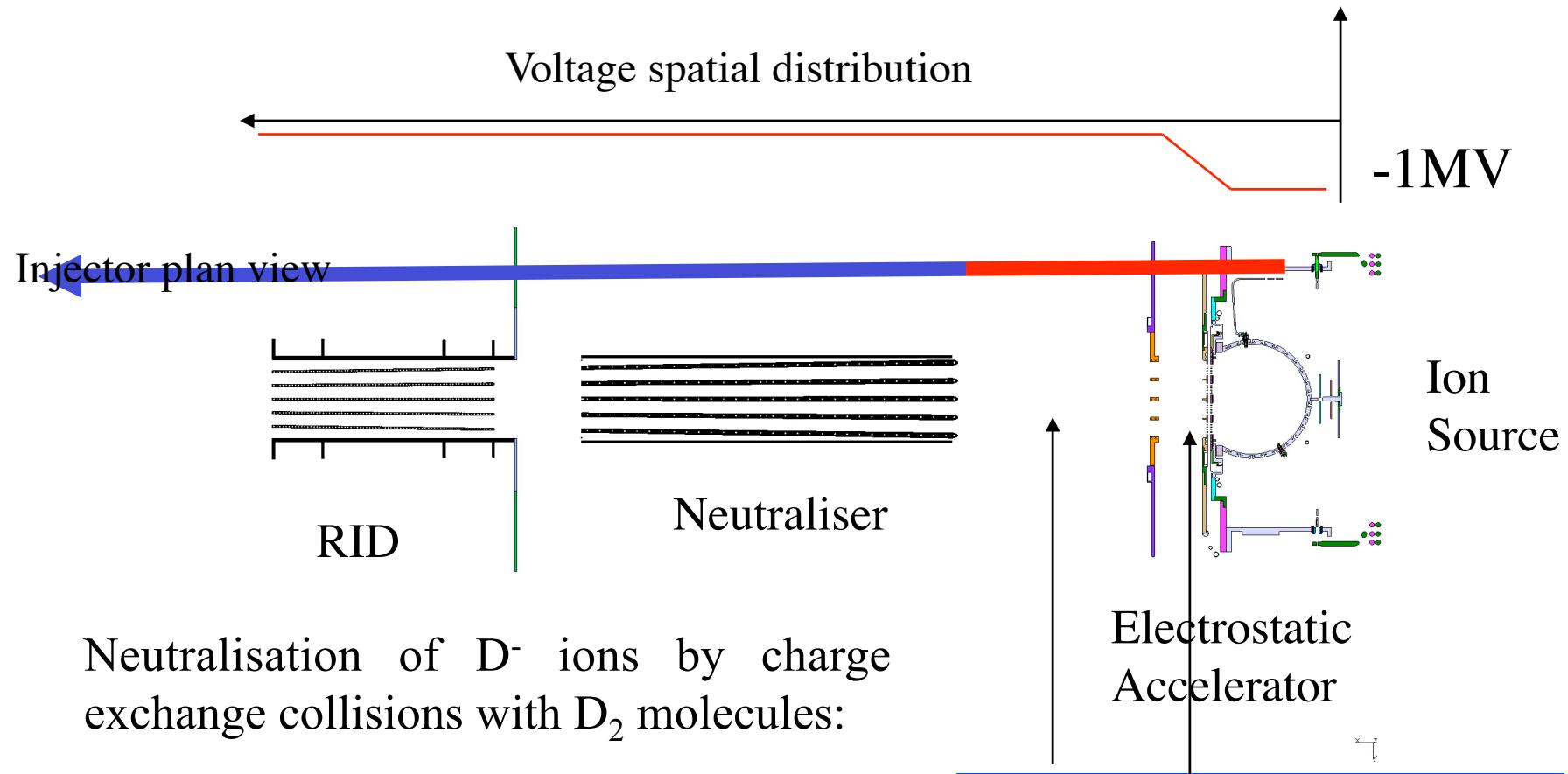
# Beam Optics

\*MeV V<sub>acc</sub>=1 MV V<sub>ext</sub>=9.0 kV 26.3mA/cm<sup>2</sup>

CURRENT DENSITY = 2.6300E+01 (MA/CM<sup>2</sup>)  
TOTAL CURRENT = 4.0343E-02 (A)  
PERVEANCE = 3.9804E-11 (A/V<sup>\*\*1.5</sup>)  
MINIMUM POTENTIAL = 0.0000E+00 (V) AT Z = 5.0332E-01 (M)  
DIVERGENCE (RMS) = 1.5686E-01 (DEG)  
ELECTRON TEMPERATURE = 0.0000E+00 (EV)  
ION TEMPERATURE = 0.0000E+00 (EV)



# Beam formation (acceleration and neutralisation)



## neutralisation



## re-ionisation (competing reaction)



Additional electrons from

- a) Stripping losses (  $p < 0.3\text{Pa}$  )
- b) Secondary electrons