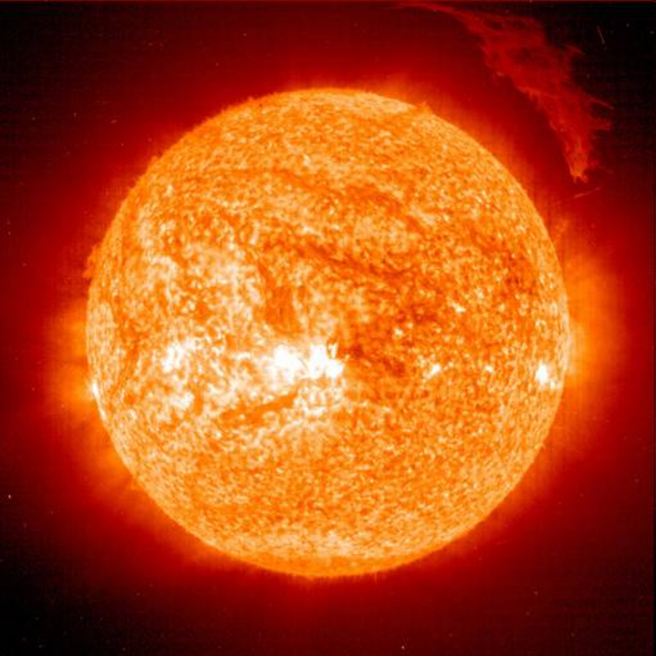
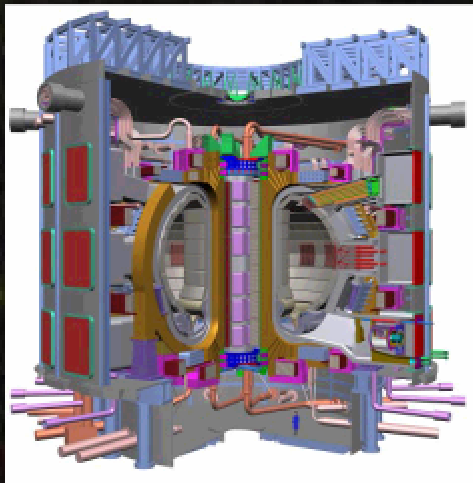


# R&D around the ITER-NBI heating system

Dr A. Simonin
CEA Cadarache
Institut de Recherche sur la Fusion Magnétique
Service Chauffage et Confinement du Plasma



# Summary of lecture

2) The ITER mains parameters and the heating systems

4) Principle of the ITER-NBI heating system; issues, planning of the developments

6) R&D around the ITER-NBI

8) Conclusion

# ITER Design Goals

Investigate the basic Physics of Fusion reactors

- Iter size in the range of the future reactor

- ITER  is designed to produce a plasma dominated by α-particle heating (Q>10)

- Long-pulse operation

**Technology**

- test components required for a fusion power plant

divertor, first wall, magnets, etc..

# Plasma Fusion Performance

Fusion power amplification:

$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

**Temperature ($T_i$):** $1\text{-}2 \times 10^8$ °C (10-20 keV)

Rq: ~10 × temperature of sun's core

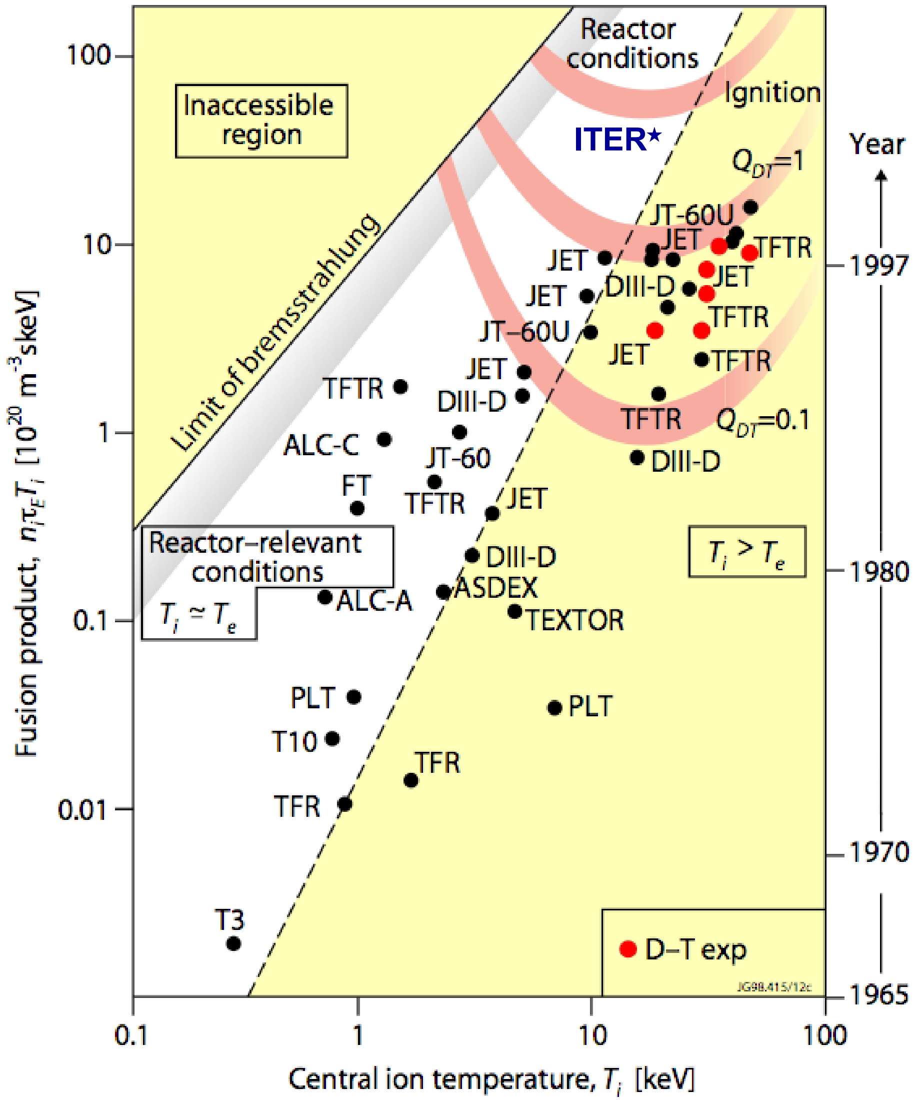
**Density ($n_i$):** $1 \times 10^{20}$ $m^{-3}$

Rq: ~$10^{-6}$ of atmospheric particle density; limitation by the magnetic field intensity ($B_T$~5T)

**Energy confinement time ($\tau_E$):** few seconds: limited by plasma instabilities

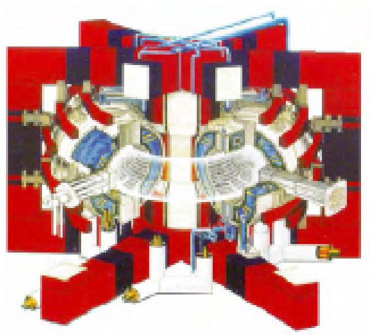
# Fusion Triple Product

- Existing experiments have achieved nTτ values ~ 1×10[21] m[-3]skeV ~ $Q_{DT}$ = 1
- JET (98) and TFTR have produced DT fusion powers of >10MW for ~1s
- ITER is designed to a scale which should yield $Q_{DT}$ > 10 at a fusion power of 400 - 500MW for ~400s



Present Fusion machines (Tokamak)

And ITER

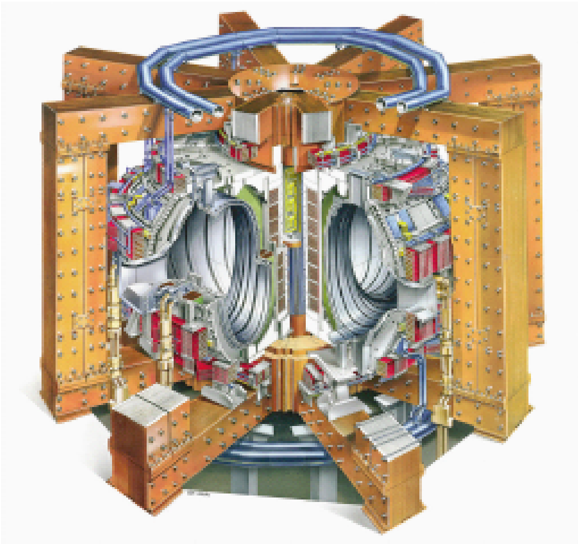


Tore Supra

$V_{plasma}$ 25 $m^3$

$P_{fusion}$ ~0

$t_{plasma}$ ~400 s

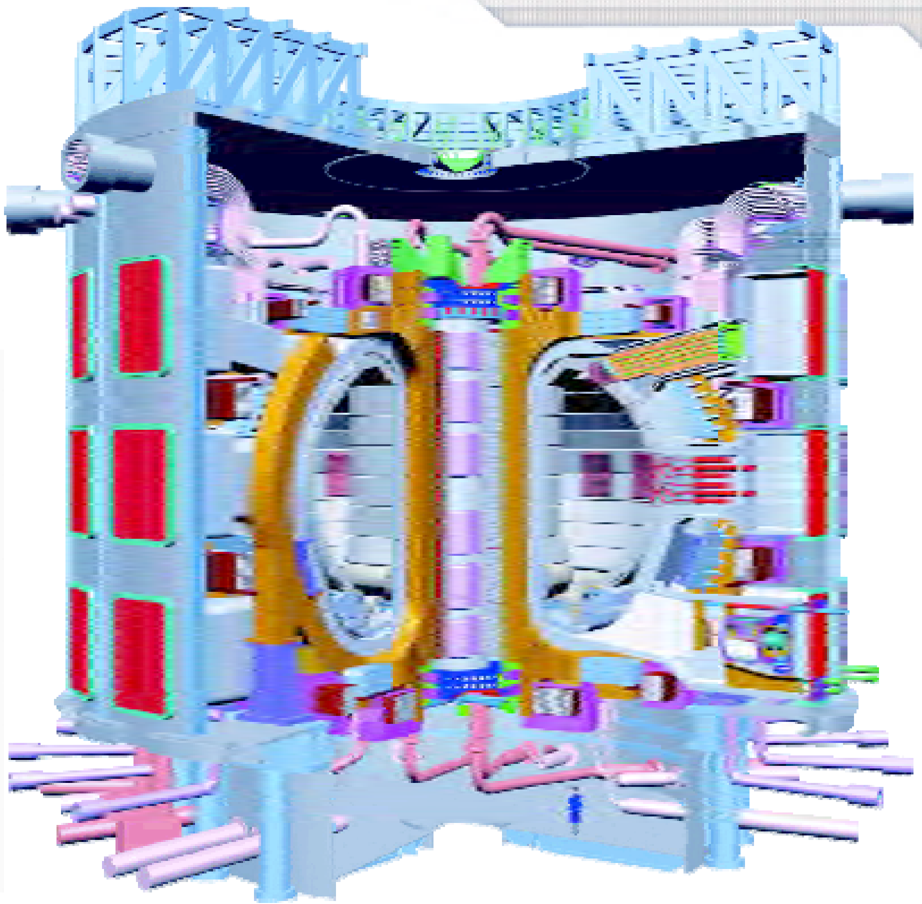


JET

$V_{plasma}$ 80 $m^3$

$P_{fusion}$ ~16 MW 2s

$t_{plasma}$ ~30 s



ITER

$V_{plasma}$ 830 $m^3$

$P_{fusion}$ ~500 MW

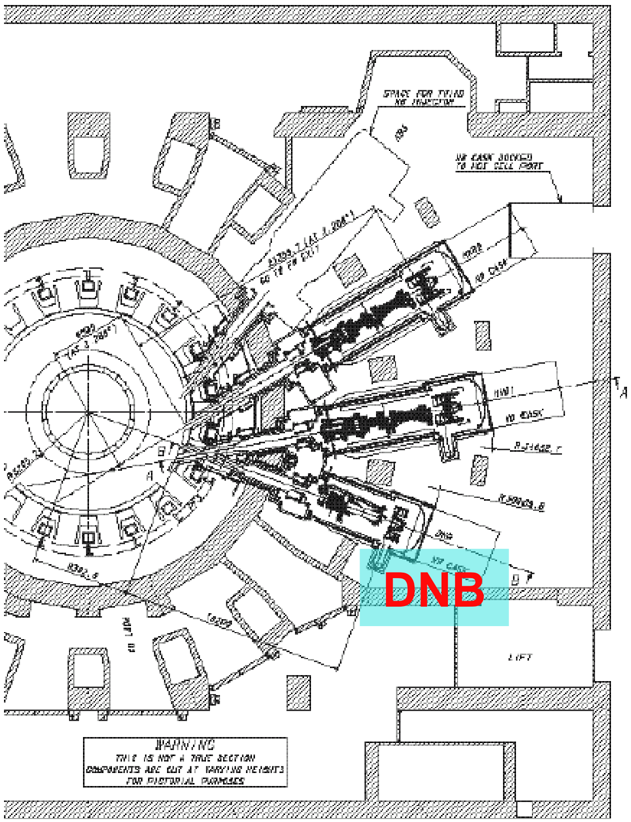
$t_{plasma}$ ~400 s

# Plasma Heating & Additional heating

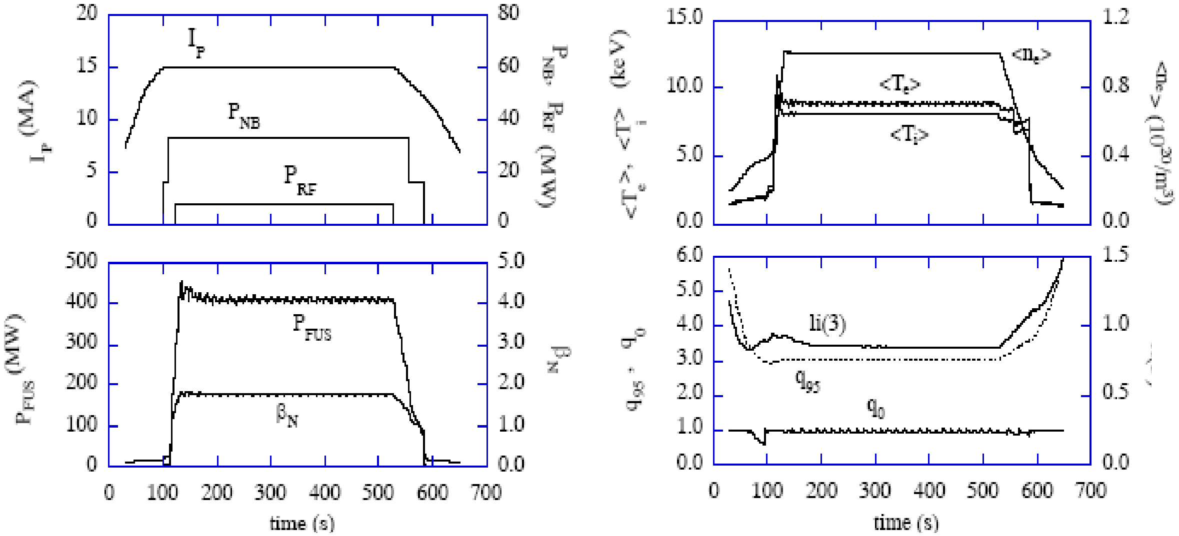
Ohmic heating of the plasma limited : $P_\Omega \propto \dfrac{(B_\Theta / R)^2}{T_e^{3/2}}$

| Heating System | Stage 1 MW | Possible Upgrade | Remarks |
|---|---|---|---|
| **NBI** (1MeV $D^\circ$) | 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 | $1.8<n_{par}<2.2$ |
| **Total** | 73 | 130 (110 simultan) | |
| ECRH Startup | 2 | | |
| Diagnostic Beam (100keV, $H^-$) | >2 | | |

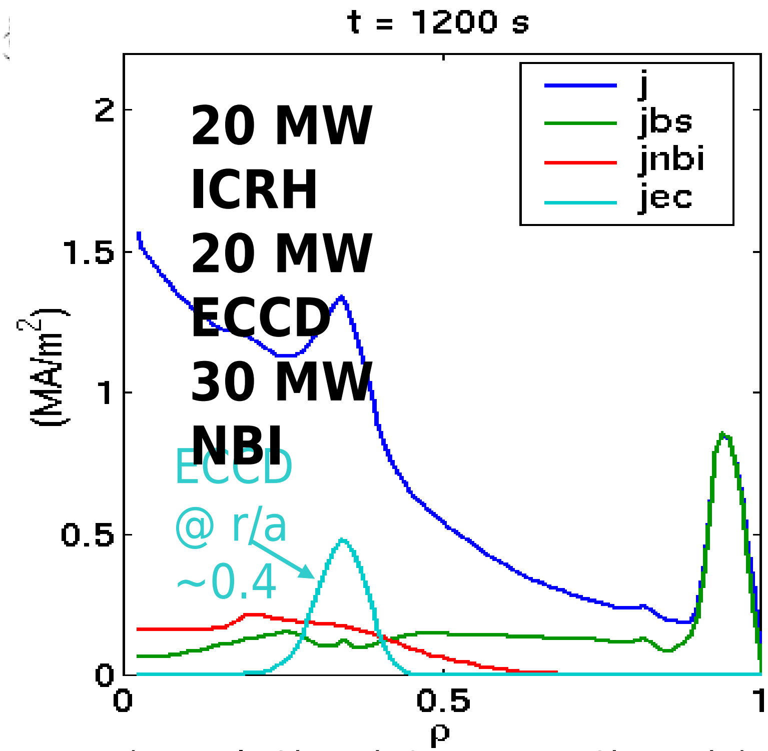
**NBI Layout**



# Heating in ITER reference scenario

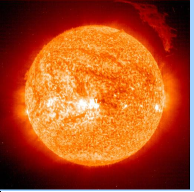



35MW of 1MeV D° beam to initiate the ITER plasma




(Kessel, Giruzzi, 21st IAEA, Chengdu)

Profile of the generated current in the ITER Plasma



# Pros and Cons for the Heating systems

## NBI

Pros: Simple physics (energy transfer in the plasma); insensitivity to B, plasma and instabilities
Substantial Plasma Fuelling
No plasma facing components

Cons: System faced to several issues for ITER (Negative Ions, high voltage (1MeV))
Real estate and cost

## ECR

Pros: Insensitivity to plasma position
Good physics predictability
Excellent localization for energy coupling ➔ a surgery tool!
Achievement of a ITER relevant Gyrotron: 170Ghz, 1MW, 800s

Cons: Mirror in plasma/neutron sight, moving parts in the vacuum vessel(in ITER)
Dependence on B (but ITER single B?)

## ICR

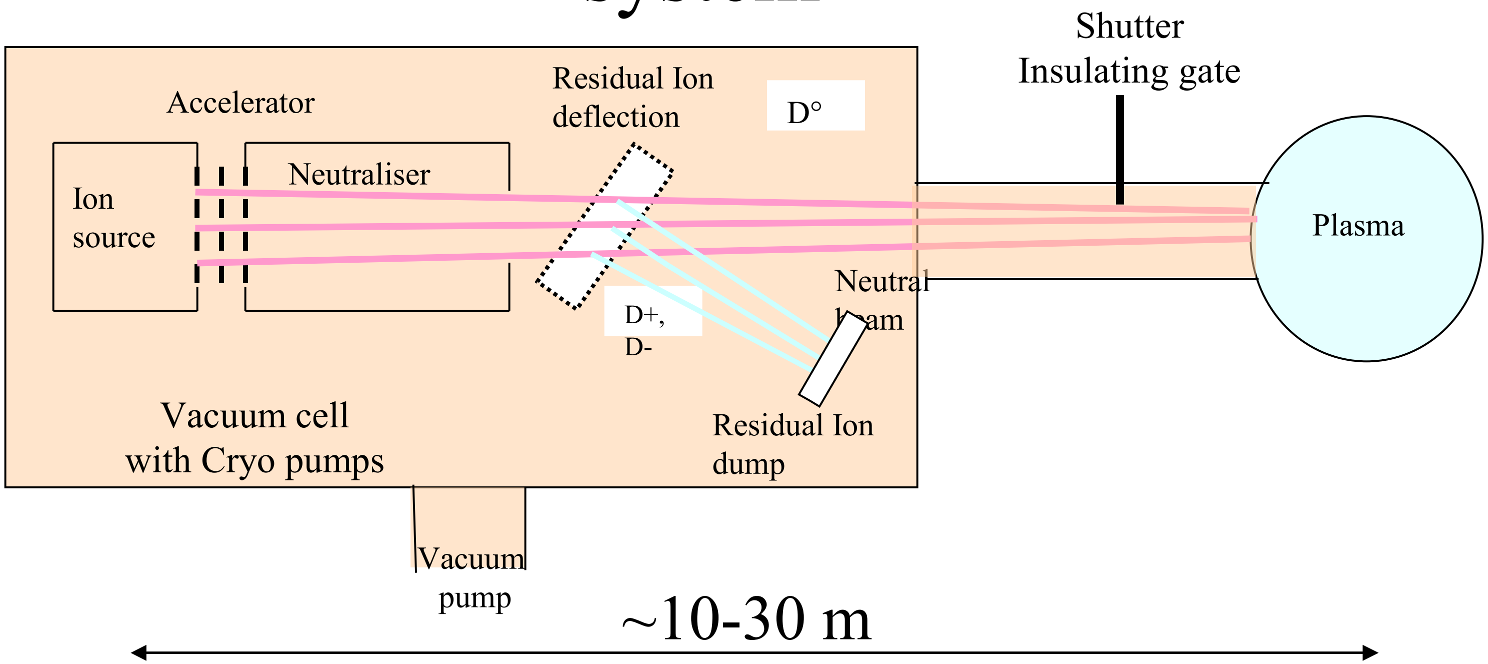
Pros: Ion heating and CD, Low Cost

Cons: Coupling wave-plasma: Dependence on plasma edge( & instabilities)
Plasma facing components (antenna localised a few mm from the plasma edge) => hot spots

An ITER-like antenna under test at JET: not very promising results !!

# 2) Description of the NBI heating system

# Principle of a Neutral Beam Injector (NBI) system




**<u>Present NBI systems:</u>**

-) are based on hydrogen positive Ions (D+, H+), in the 100keV energy range

-) main heating system for present advanced Tokamaks (JET, JT60 SA) : ~20– 30MW of D° or H°

-) Beamlines are composed of several sources with only 1.5MW of D°/source

**<u>For ITER:</u>**

energy range : 1MeV and 17MW of D°/source => **<u>factor 10</u>** in neutral power and energy

# The ITER NBI system

**Requires important R&D:**

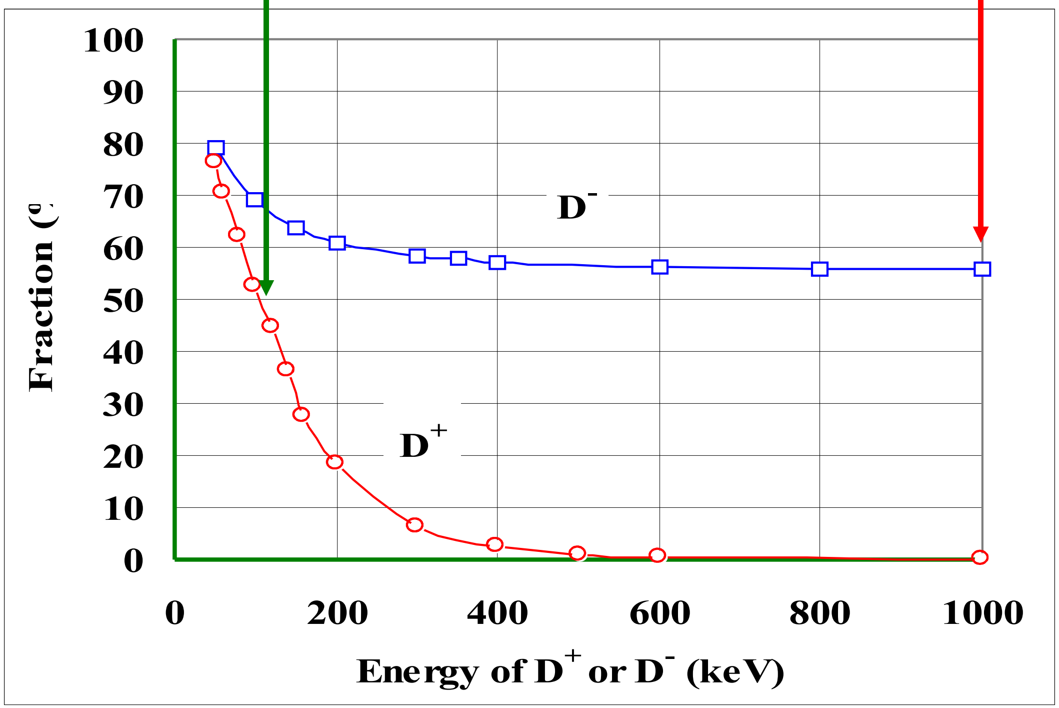
-) Based on negative Ions (D-)
-) High energy beams (1MeV)
-) High power beams : 40MW at the accelerator exit
-) Long shot operations (100-1000s)

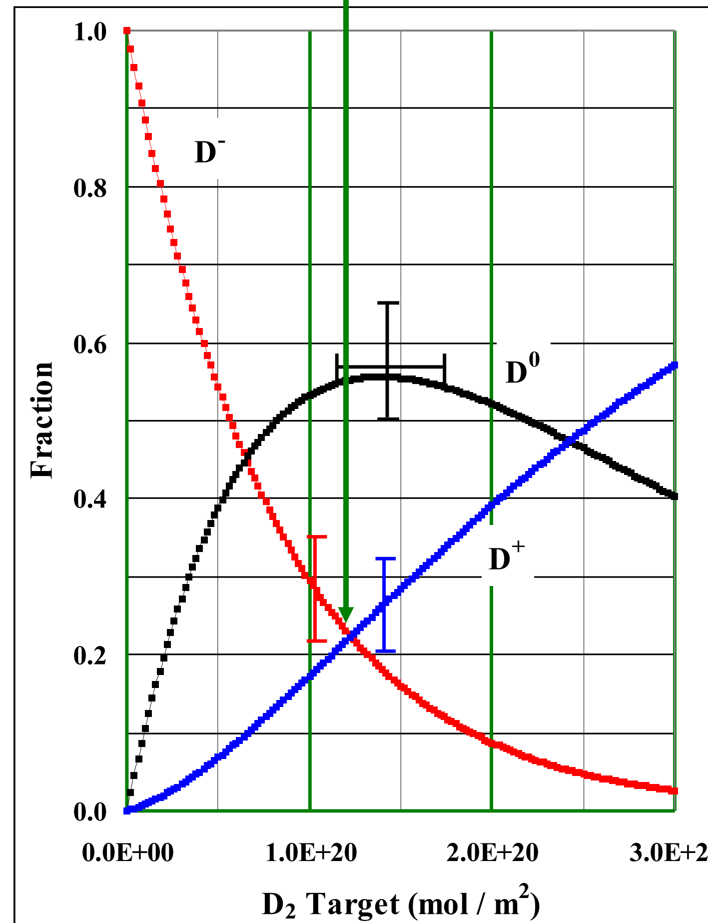
# Neutralisation rate on Gas target ($D_2$)

Present NBI system based on positive Ions

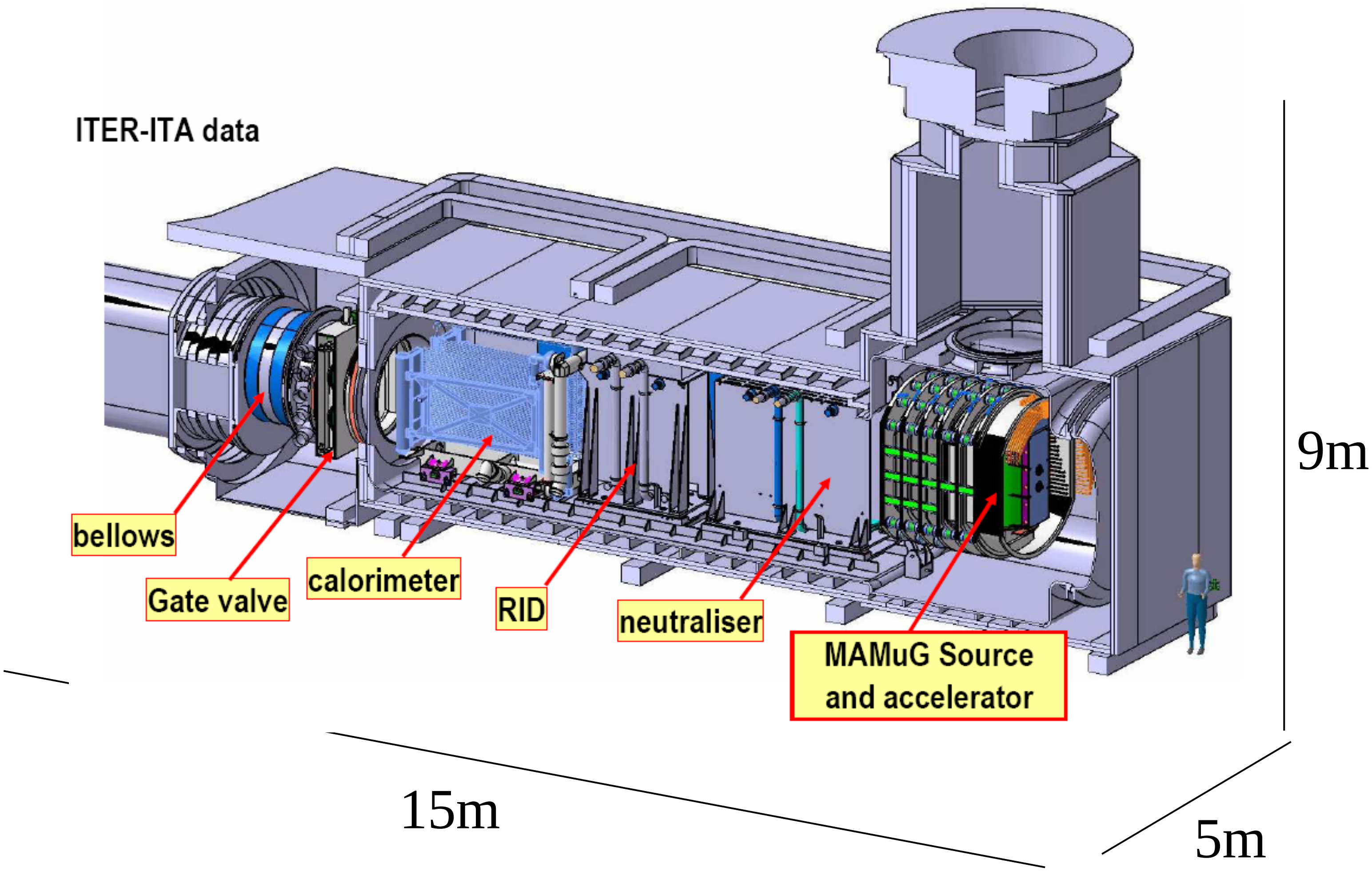
ITER

Gas target foreseen for ITER



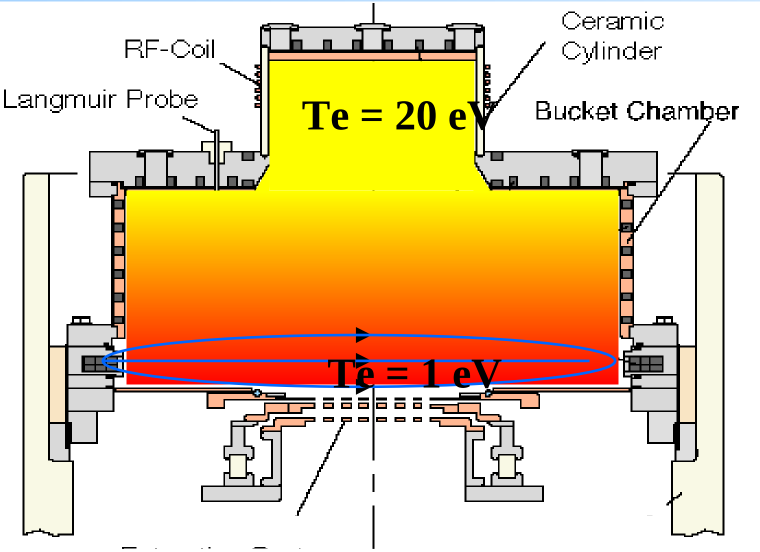



# The ITER beam line: 1MeV, 17MW D°

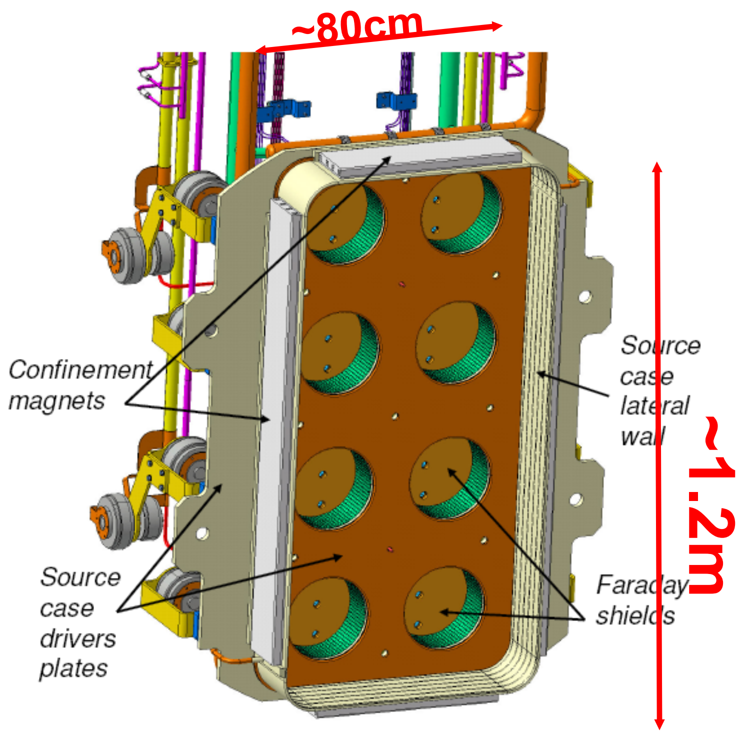



Weight >250 tons

# The ITER negative Ion source




**Principle of the negative ion source**




## Main source specifications:

Homogenous production of D- over the whole surface: **$J_{D-}$ ~ 250 A/m² ±10%**

Co-extracted electrons with the D- : **< 1 e- / D-**

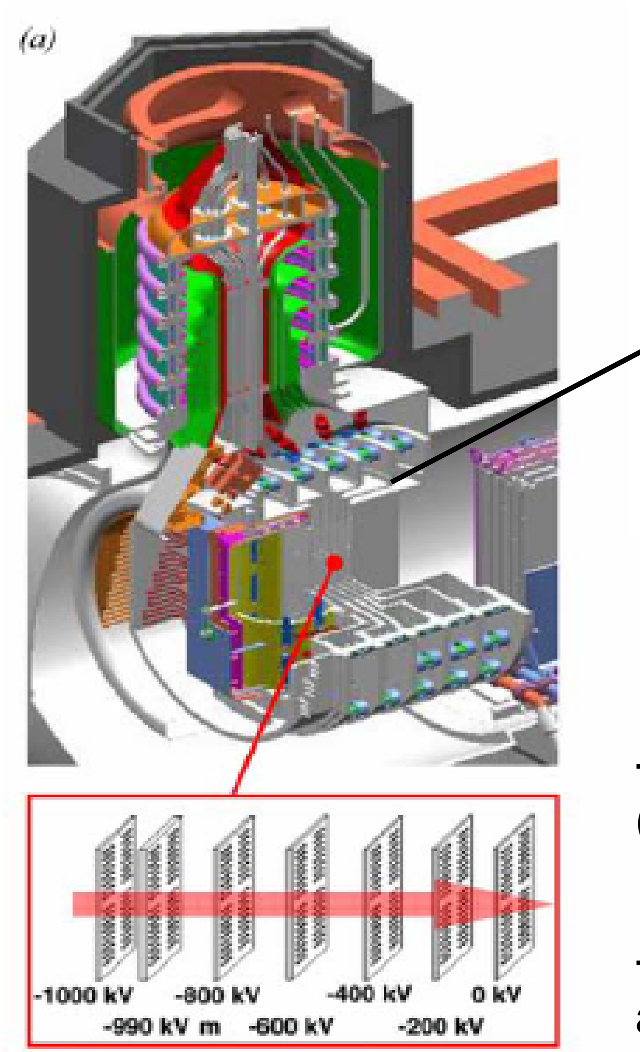
Low source pressure : **$P_S$< 0.3 Pa** (~30% of stripping losses in the accelerator)

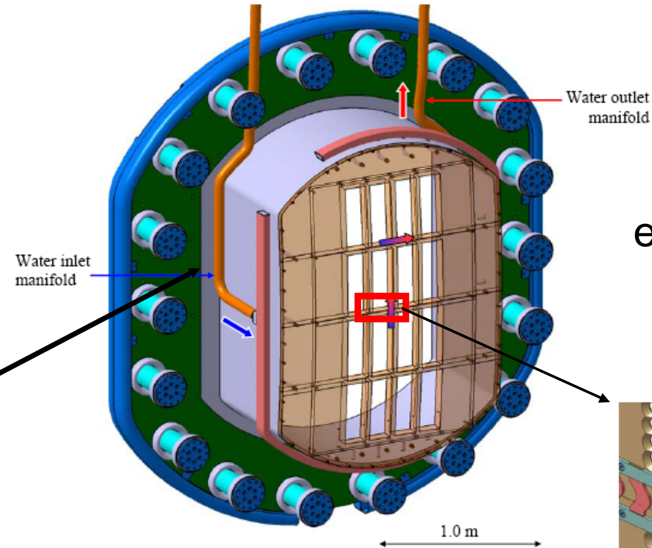
Long shot (**100 à 3600s**), low maintenance and high reliability (reactor environment)

Expected Rf power: **800kW** at 1Mhz (~100kW / Driver)

**Conclusion:** Modeling, R&D and source optimization required

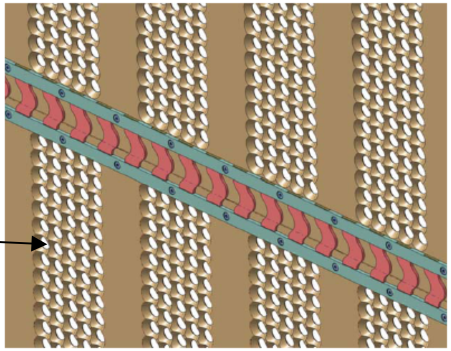
# The 1MeV 40A D- Accelerator
# Multi-Aperture Multi Grid (Mamug) Concept



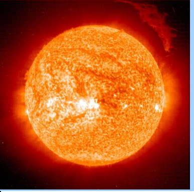

One accelerating electrode composed of 16 grids segments

80 beamlets/grid



-) The 40A D- beam is subdivided in 1280 beamlets (electrostatically indepedents)

-) Beamlet alignment constraint: ~0.4mm on the 6 accelerating gaps

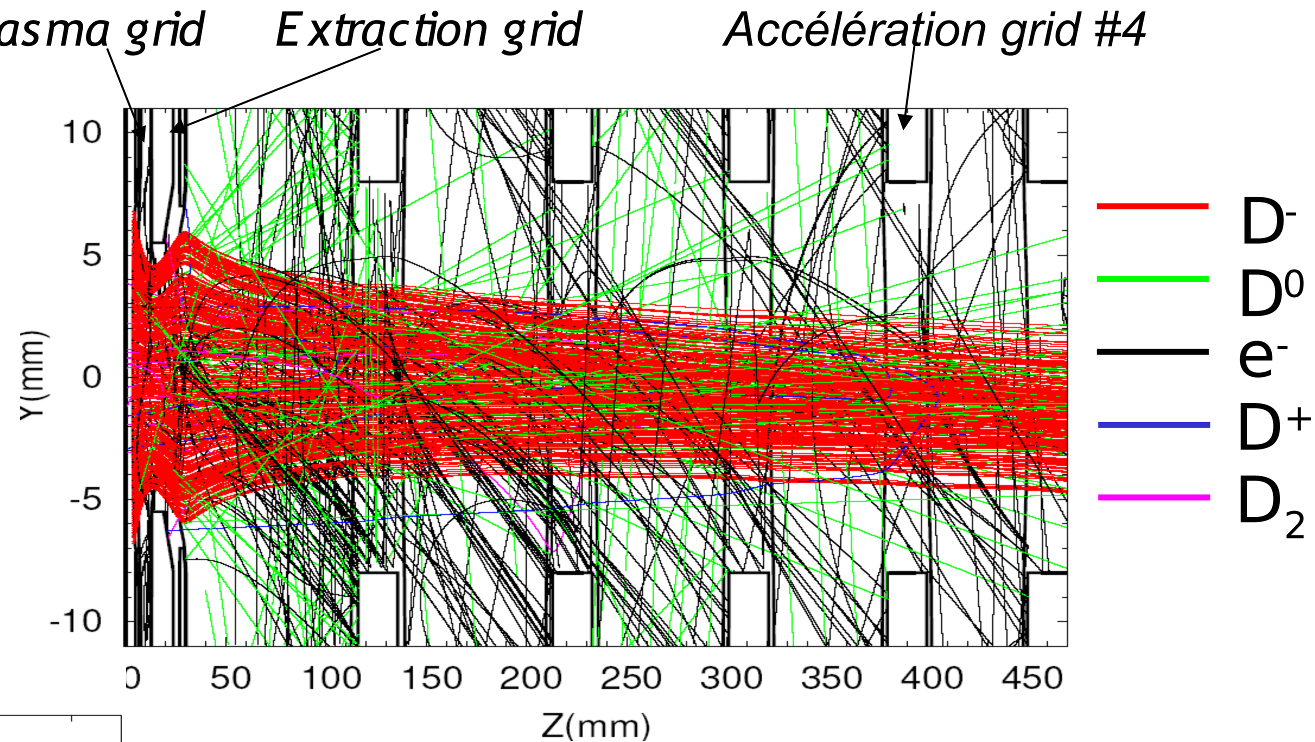


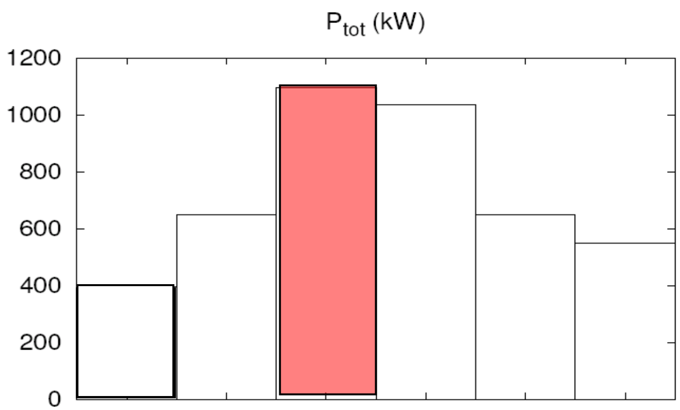
# Simulation of the stray particles in one ITER accelerator channel (beamlet)

Simulation with the EAMCC code

G. Fubiani, IRFM 2006

Stripping rate: **~28%** with 0.3 Pa of source pressure




**Power loads on the accelerating electrodes**

## Conclusion:

**Necessity to decrease the Gas injection !**

=> $P_{Source}$ ~ 0.1 Pa required …

=> Minimization of the gas in the neutralizer

# Neutralisor and E-RID

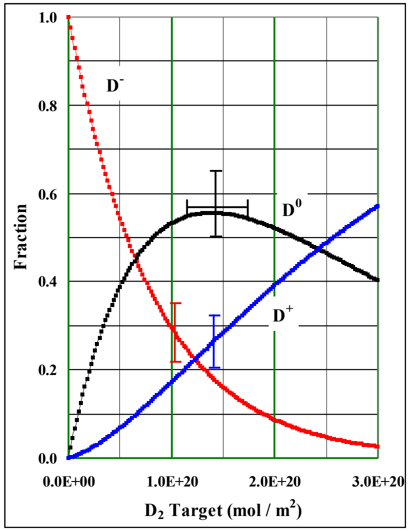
D- Neutralization by a Stripping process on gas target:

$$D^{-} + D_2 \rightarrow D° + e^{-} + D_2$$

About 58% of neutralization rate

=> 17MW of D° coupled to the ITER Plasma

=> 20% of $D^+$ and $D^-$ at 1MeV to deflect and collect out from the D° beam



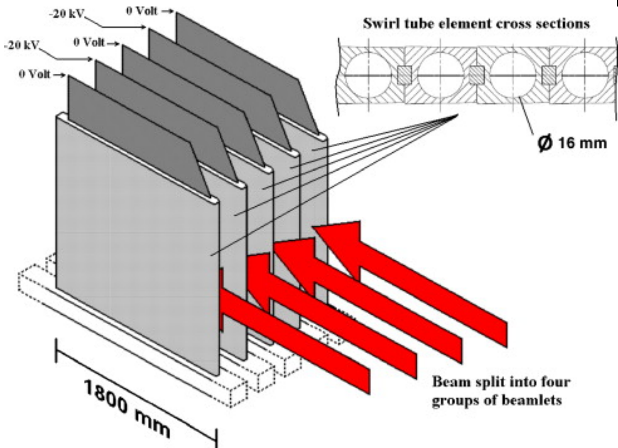

**Neutralizer issues:**

-) Minimization of the gas injection: 4 beam columns

-) Diffusion of particles from the plasma neutralizer:

**E-RID :**

-) High heat flux (1MeV D+ and D- beams): about 2MW/pannel




E-Residual Ion Dump

## Conclusion:

-) Modeling of the plasma neutralizer required

-) Study of other neutralization processes

# Main priorities in the R&D

1) Reduction of the gas injection by a factor 3 (~10% of stripping)

=> Modeling of the Ion source for higher efficiency (with additional magnetic confinement)

=> Modeling of the gas neutralizer for optimization

=> Study (modeling) of other neutralization concept (Lithium Jet, photo-neutralizer

2) Study of the Negative ion formation with Ceasium seeding to reduce the Cs consumption _

-) To get a better understanding of the process (plasma-wall interaction, Cs chemistry)

-) Conditioning protocol for the large size Ion source (~1.2m$^2$)

**Study of other NI formation concepts (without Ceasium)**

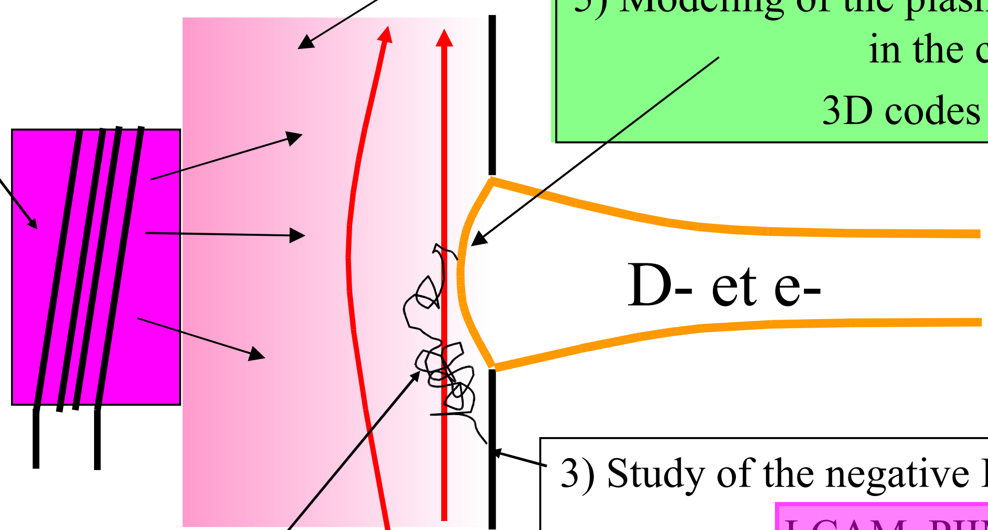
# The R&D in France around the ITER-NBI system

# Modeling and R&D around the ITER negative Ion source

1) Modeling of the ICP discharge (DRIVER)
2D code (LAPLACE)

2) Modeling of the plasma transport in the magnetized source chamber : 3D code (LAPLACE)

5) Modeling of the plasma-beam interface (meniscus) in the crossed E-B fields
3D codes (LPGP-PIIM)

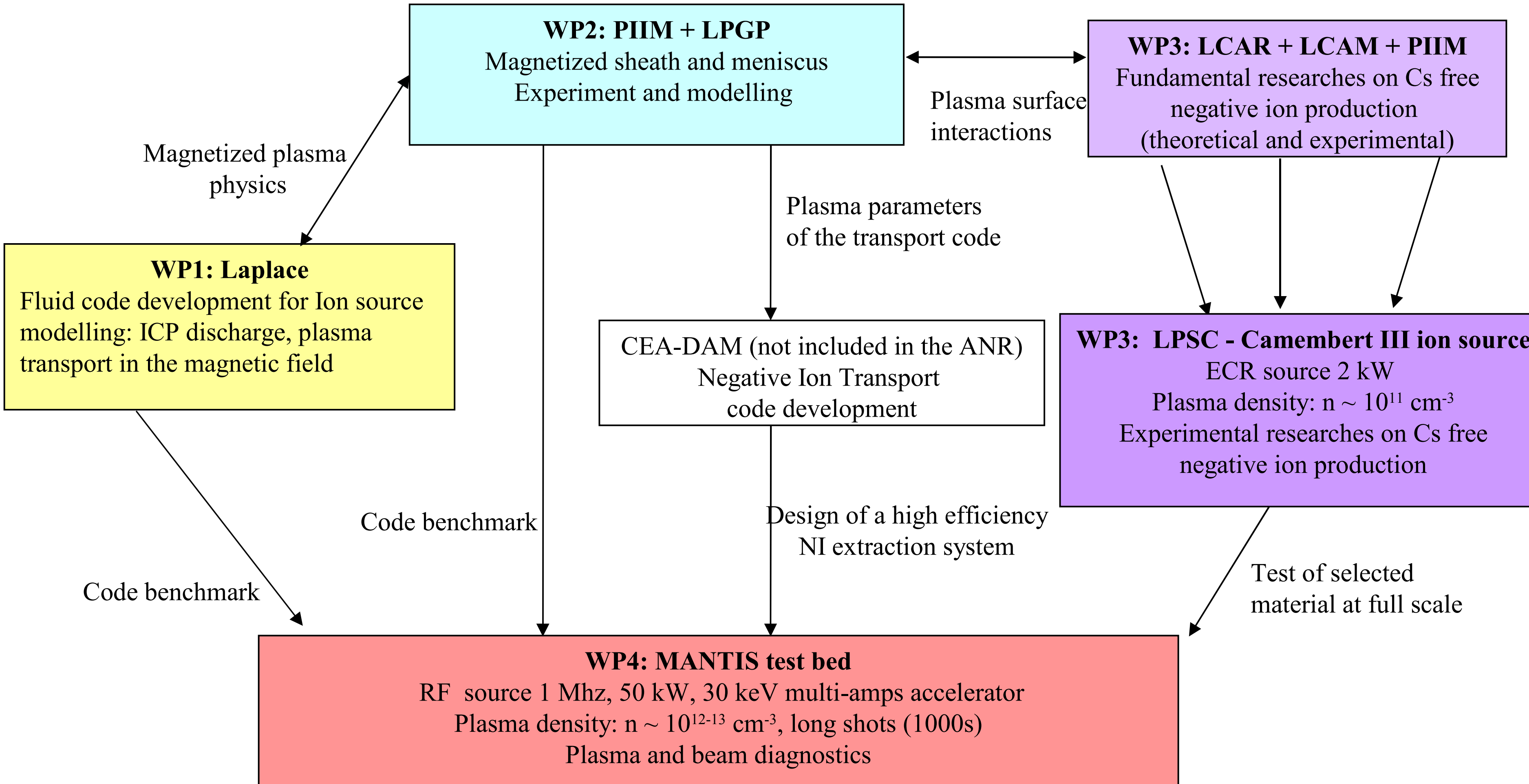



3) Study of the negative Ion formation by surface effect
LCAM, PIIM LCAR, LPSC

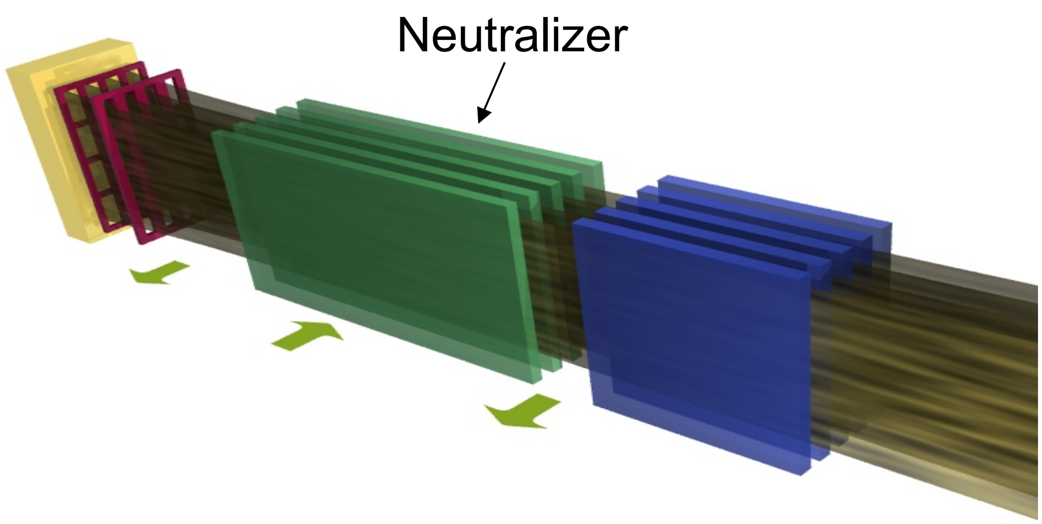
4) Transport of theNegative Ions in the plasma
(3D code) CEA-DAM

# The ITER-Negative Ion Source research project ITER-NIS

-) Grant of 800k€ from the French National Research Agency (ANR) for the next three years (2009-2011)
-) Seven Laboraories involved; Strong synergies (collaboration) between physic models and experiments



# Modeling and R&D for the 1MeV 40A D- beam neutralization




Modeling of the 1MeV D- beam neutralization by gas target
LPGP

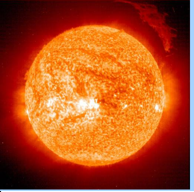
R&D for a photo-neutralization system
LAC and Artemis

# Conclusion

- The ITER-NBI is faced to important issues
  - The NI Ion source is a real challenge with stringent constraints
    - specifications far from the present knowledge
  - Too much gas released along the injector (stray particles)
    - Optimization of source and neutraliser
    - Study of other neutralizer concepts
  - Very high thermal loads on the accelerators components

- Special effort on modeling and R&D necessary
  - Modeling: First results from Heavy plasma models (3D) expected 2011
  - R&D:
    - NI formation (w/wo Cs) : Special effort is required: European coordination of the research (basic physics, modeling, experience) ??

    - Photo-neutralization: interesting but very speculative (first results 2011)



# Organization of the European Research around the ITER-NBI

- **Italy (RFX Padova) :**
  - Construction of a testbed scale 1 for one ITER beam line (1MeV, 17MW of D°) (Scheduled on 2015)
  - Construction of a testbed scale 1 for the Negative Ion source (scheduled on 2012)

- **Germany (IPP Garching)**
  - Development of a RF Ion source 1/2 scale (RADI under progress) with 50keV 20A D- accelerator (Elise project); (scheduled on 2010)

- **England (UKAEA Oxford)**
  - Thermomecanical studies of the high heat flux components (neutralizer, E-RID, Target)

- **France (IRFM, CNRS)**
  - Singap testbed (IRFM) : Study of the high voltage conditionning (1MV) and HV breakdowns
  - Mantis testbed (IRFM) : benchmark of the physics models under development in Universities (ITER-NIS)
  - Modeling and R&D in Universities: ITER-NIS, Photo-neutralizer project