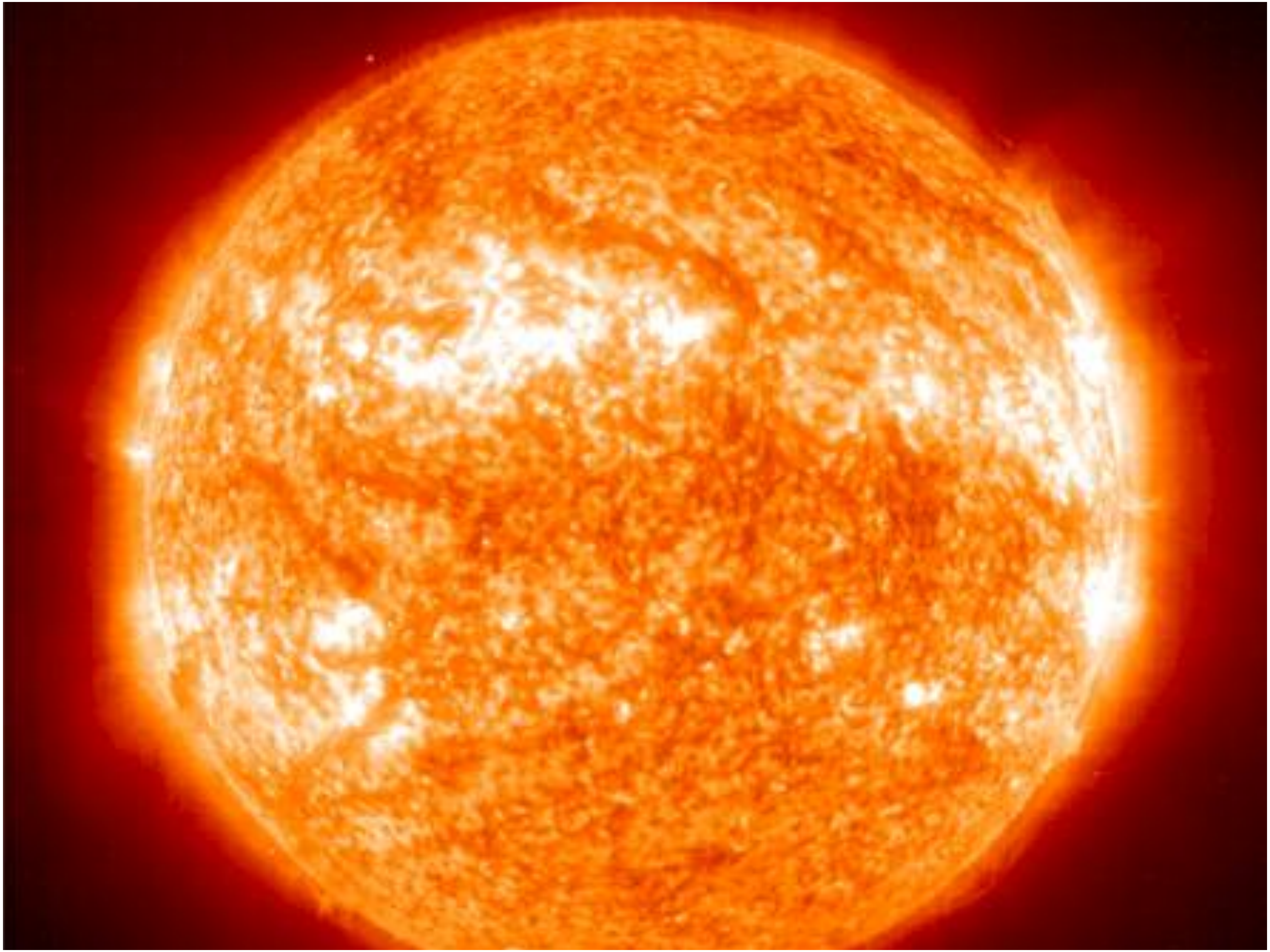
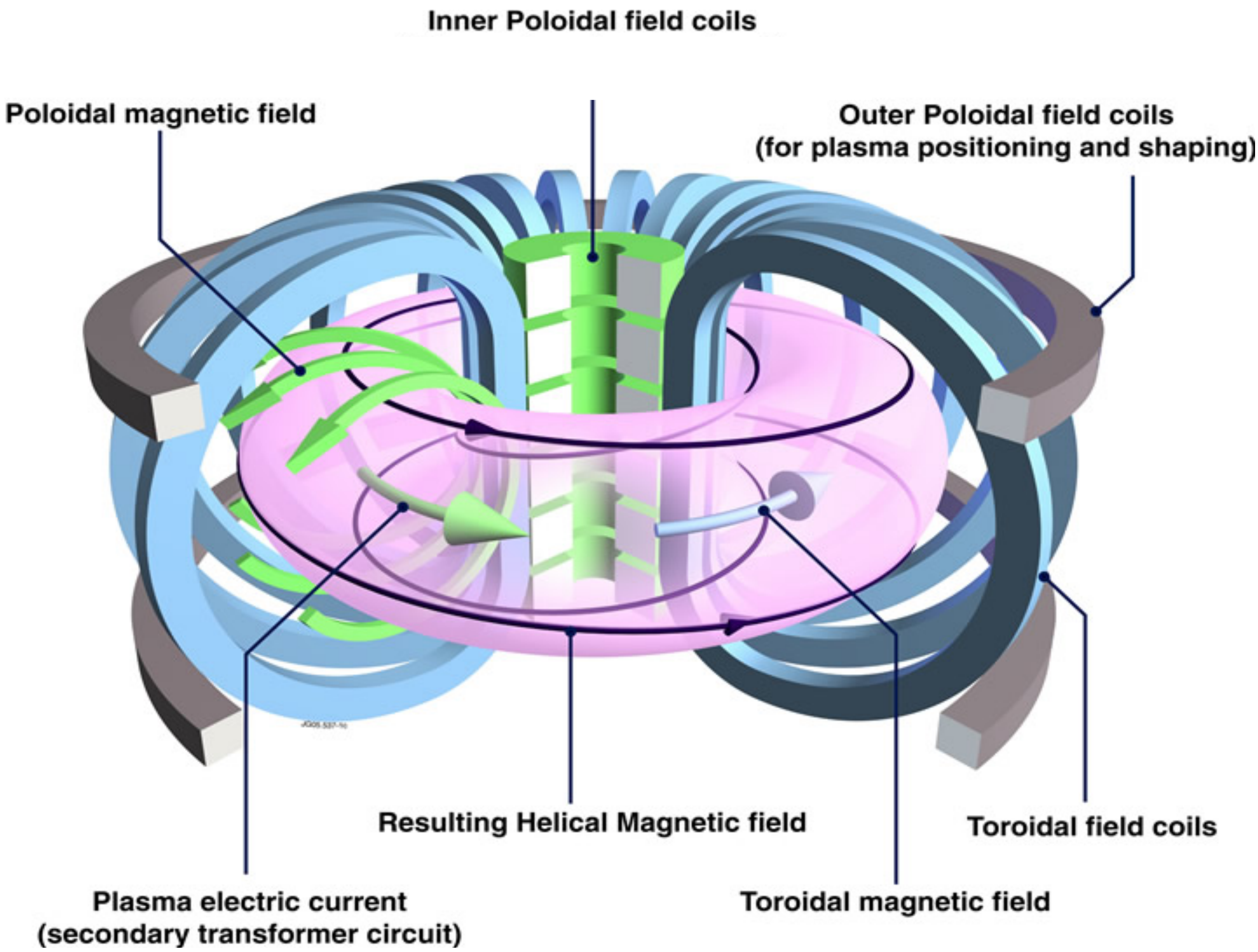
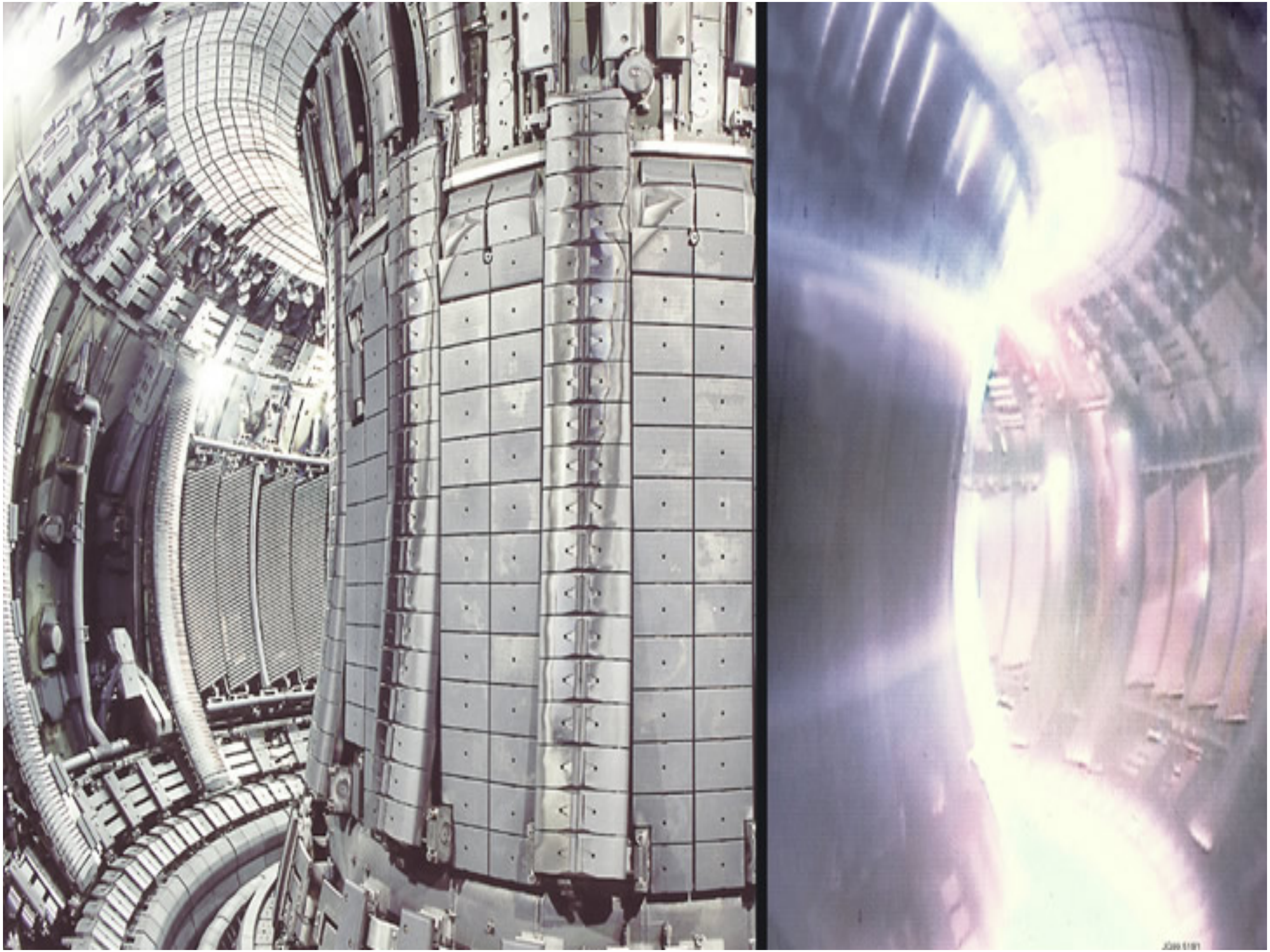
Power Plant

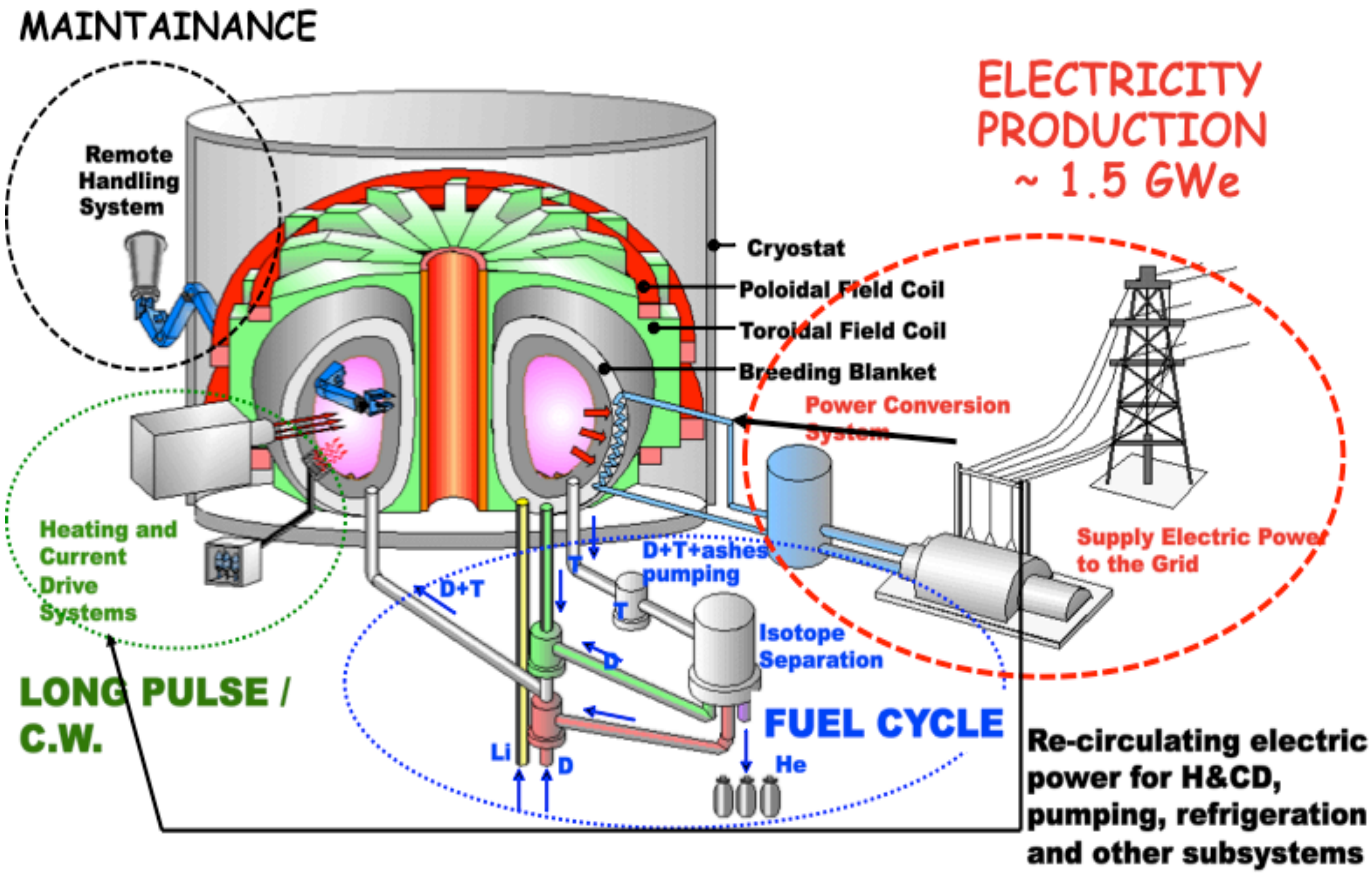
The real breakthrough was the invention of the Toroidal Ring of stones to contain the fire. Chemistry Review. Volume 16, 2006/07, p.18.




Inner Poloidal field coils
Poloidal magnetic field
Outer Poloidal field coils
(for plasma positioning and shaping)
Resulting Helical Magnetic field
Toroidal field coils
Plasma electric current
(secondary transformer circuit)
Toroidal magnetic field



Power Plant


MAINTAINANCE
Remote Handling System
ELECTRICITY PRODUCTION ~ 1.5 GWe
Cryostat
Poloidal Field Coil
Toroidal Field Coil
Breeding Blanket
Power Conversion System
Supply Electric Power to the Grid
Heating and Current Drive Systems
D+T+ashes pumping
T
D+T
T
D
Isotope Separation
FUEL CYCLE
Li
D
He
LONG PULSE / C.W.
Re-circulating electric power for H&CD, pumping, refrigeration and other subsystems

Italian Fusion Association = ENEA-Euratom

Born in 1960, formed by 3 coordinated Research Groups each with scientific autonomy and associated partners: is the second largest after Germany (~17% as France)

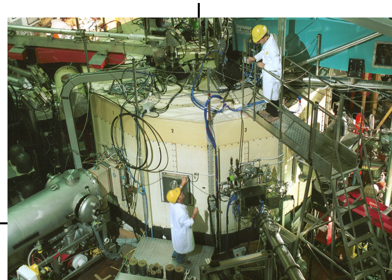
Euratom-ENEA Association

CNR IFP Milano
CNR Fi, Politecnico Mi
Univ. Mi, Univ. Bicocca

Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

ENEA-Frascati and Brasimone

ENEA



Consorzio RFX
Univ. Pd, INFN Legnaro
CNR, ENEA, Acc.Venete

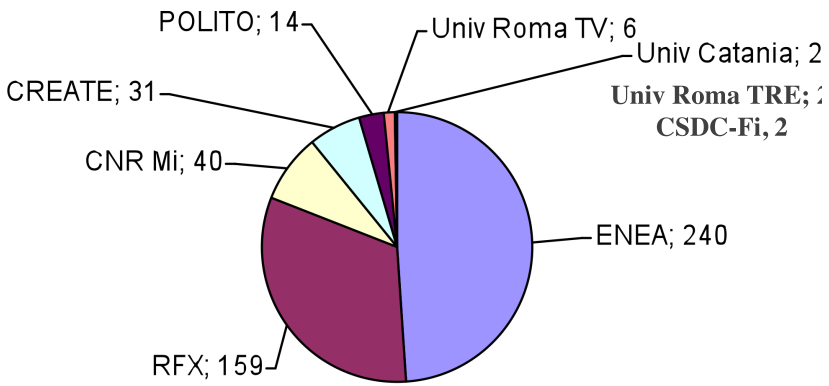
CONSORZIO RFX
Ricerca Formazione Innovazione

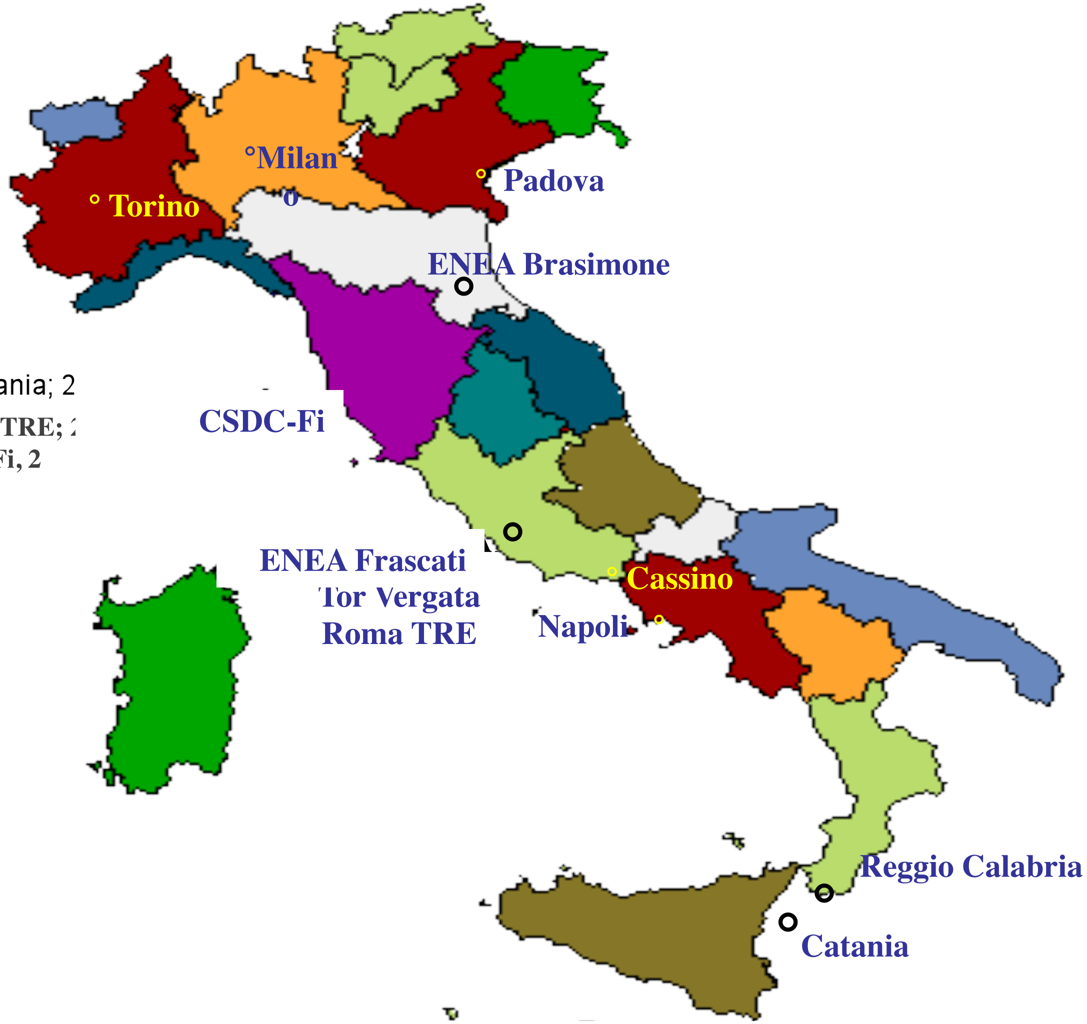
CREATE | **PoliTo** | **Univ. Catania** | **Univ. Firenze** | **Univ. Roma Tor Vergata** | **Univ. Roma TRE**

CSDC
CENTRO STUDI DINAMICHE COMPLESSE

Distribuzione Geografica dei laboratori Italiani sulla fusione e relative risorse umane

~540 PPY





High power RF in Fusion Plasmas:
from 10s of MHz to 100s of GHz

Presented by

ENEA C.R. Frascati
Ente per le Nuove Tecnologie, l'Energia e l'Ambiente

Angelo A. Tuccillo

With Special Thanks to:

IFP Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

Daniela Farina

And Many RF Colleagues from:

ENEA-FRASCATI, IFP.CNR-Milano, IGI.CNR-Padova, CREATE-Napoli
CEA-F, IPP-D, CCFE-UK, ERM-B, PPPL+GA+MIT-USA, JAEA-J,
TEKES-FI, IOFFE-RF, IPP.CR-CZ, Pohang University-KR

OUTLINE

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Some notion, result and future experiments/developments on

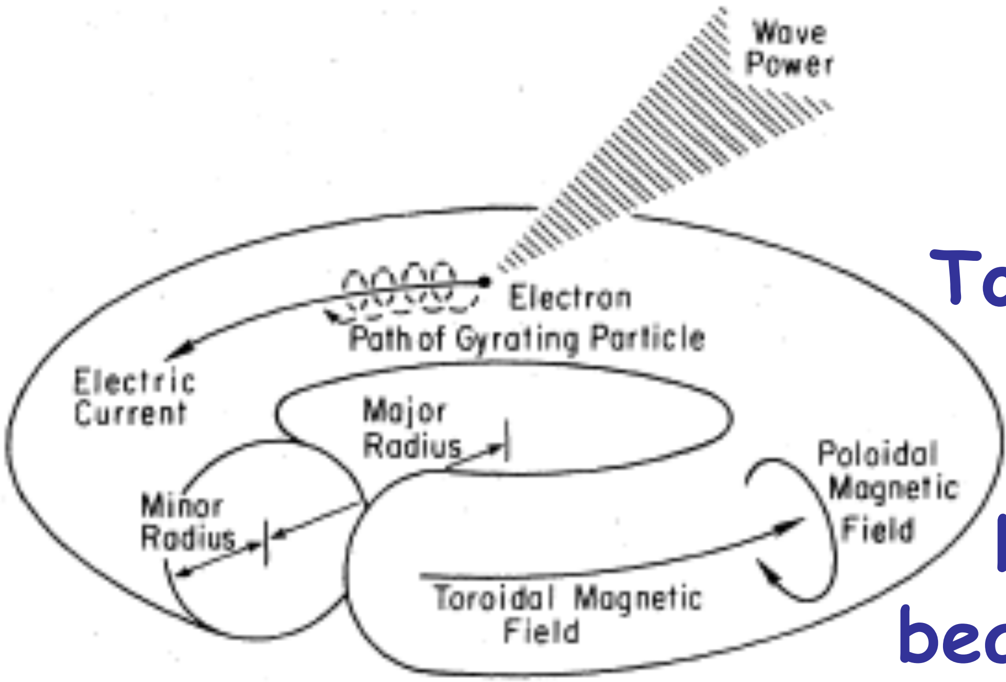
- Ion Cyclotron Radio Frequency

- Electron Cyclotron Resonant Heating and Current Drive

- Lower Hybrid Heating and Current Drive

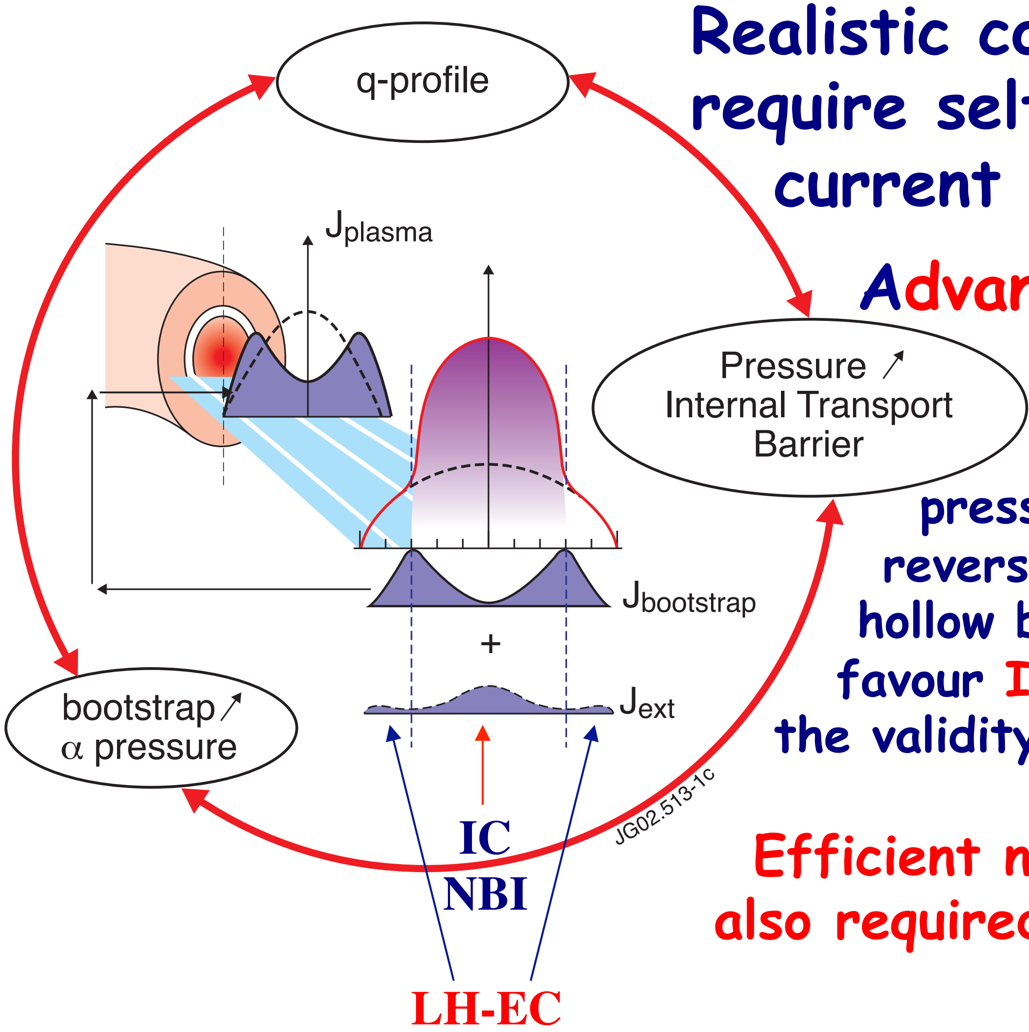
- Summary and a word on the future

Fusion could be an answer to the Planet Energetic Demand. A Steady State Fusion Reactor would be the most economically advantageous solution (no downtimes)



To have a CW Tokamak non-inductive current must be driven, i.e. by injecting neutral beams or travelling waves

Steady State Fusion Operations



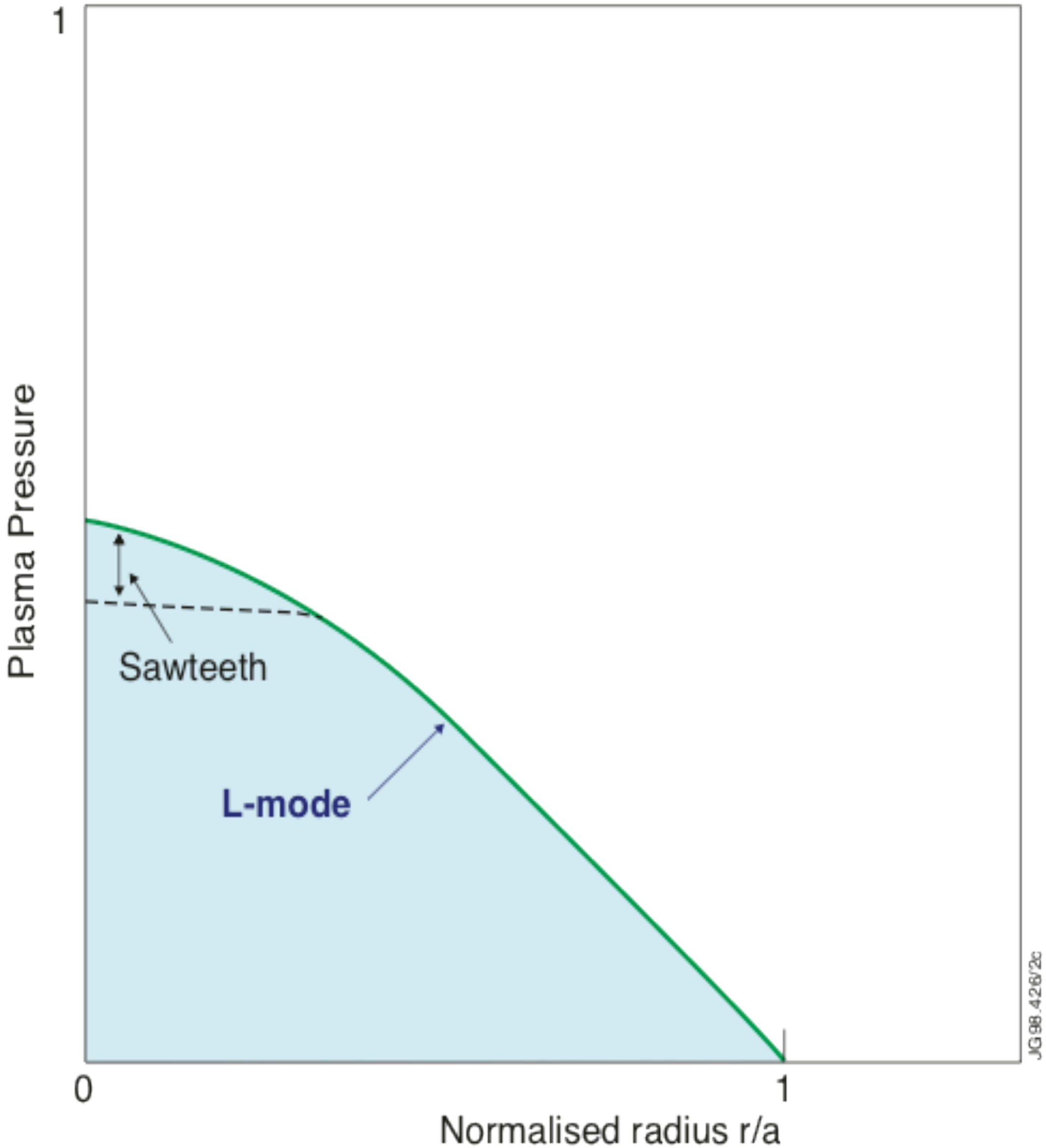
Realistic continuous operations require self-generated bootstrap current I_{Boot}/I_P>60-70%

Advanced Regime plasmas with Internal Transport Barrier best candidates: steep pressure gradients, associated with reversed/flat q-profiles, favour large hollow bootstrap current that in turn favour ITB formation. ITER could test the validity of this approach

Efficient non inductive off-axis CD is also required for profile and MHD control

Plasma Regimes: till early 80s

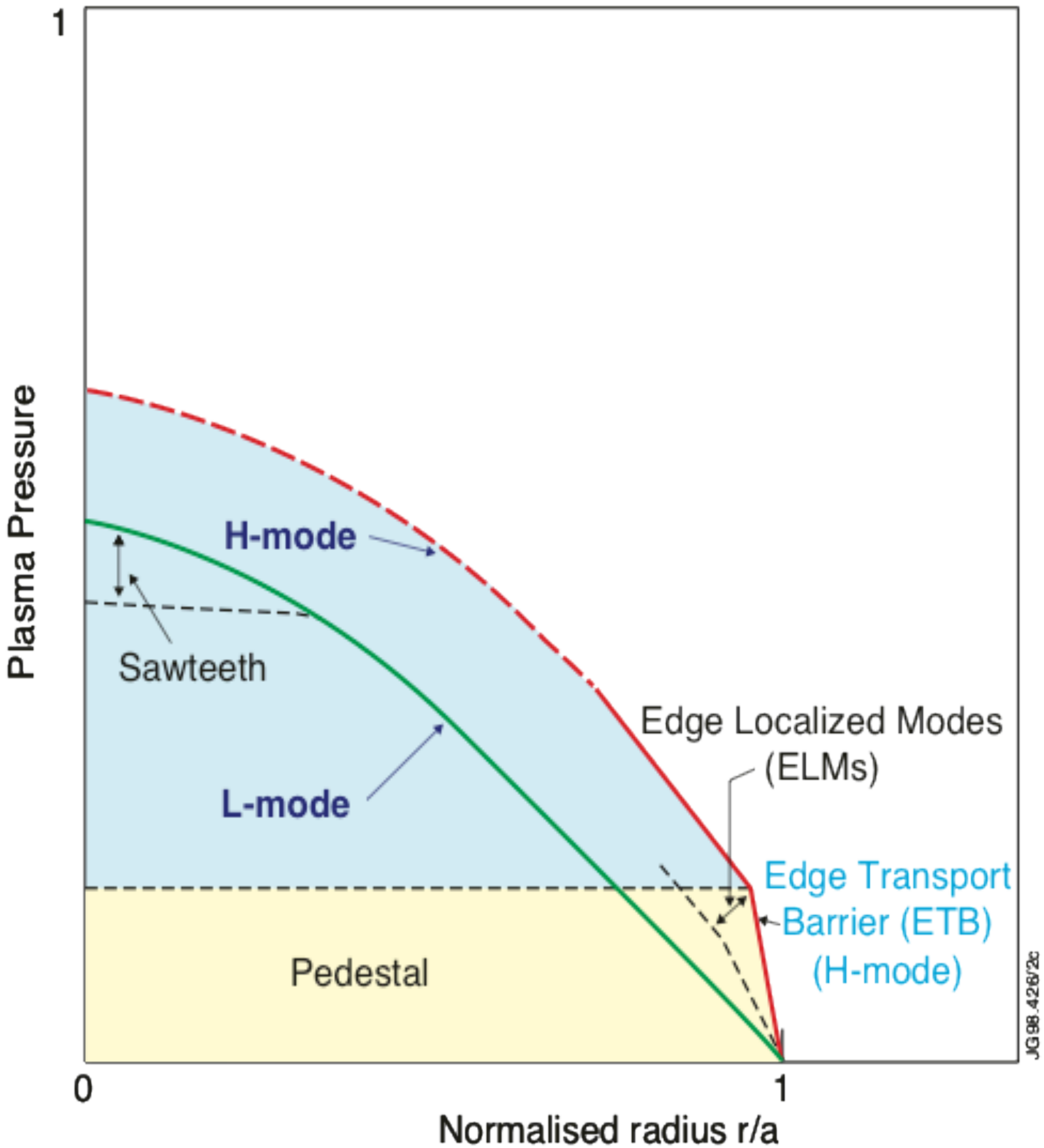
Basic Confinement: L-mode



Plasma Regimes: from mid 80s up to now

Basic Confinement: L-mode

Improved Confinement: H-mode ➔ Higher Performance = More Compact Reactor ➔ ITER

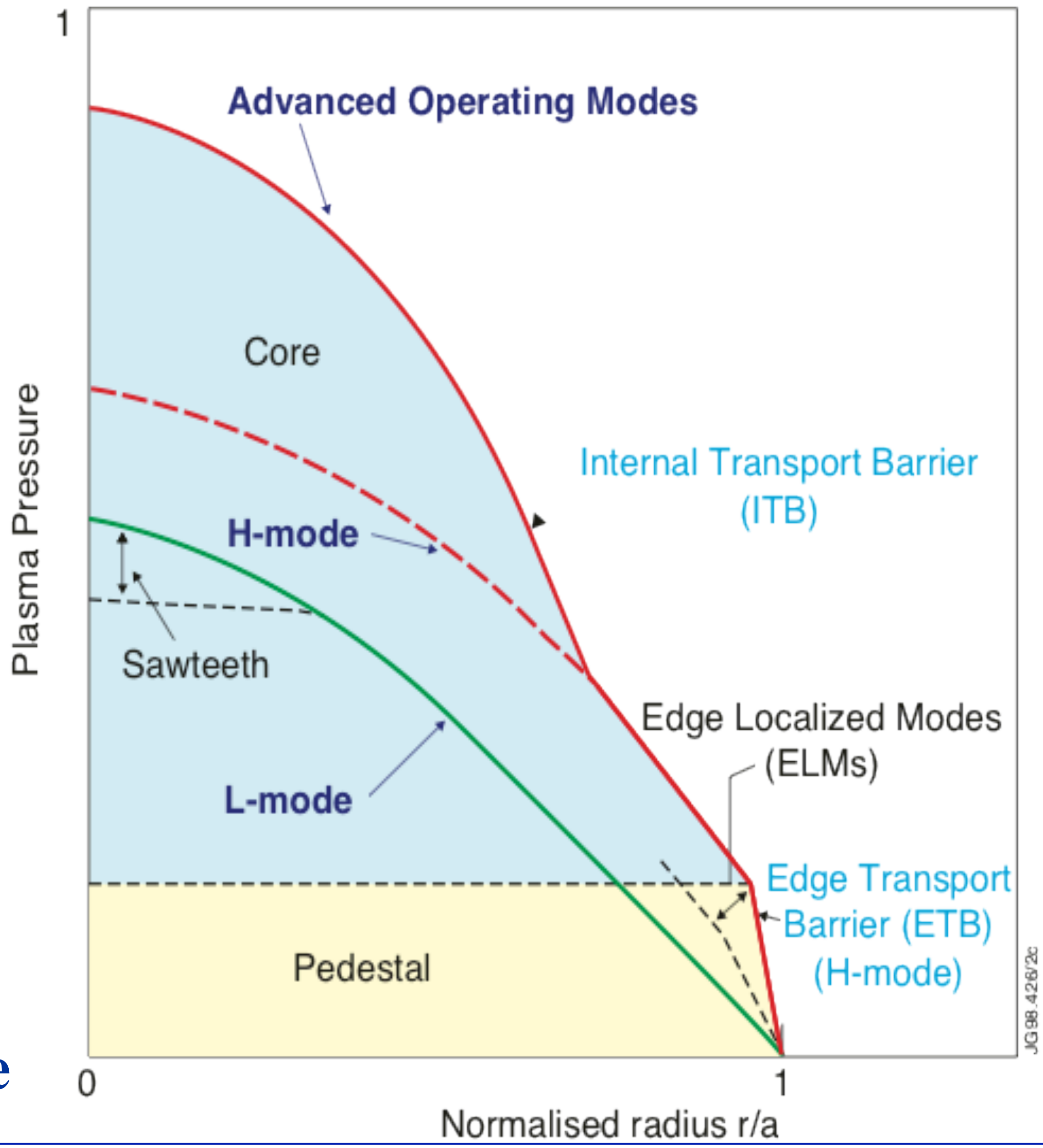


Plasma Regimes: from early 2000 onward

Basic Confinement:
L-mode

Improved Confinement:
H-mode ➔
Higher Performance =
More Compact Reactor ➔
ITER

Further improvement:
(ITB) Internal Transport
Barriers ➔ better central
confinement ➔ Stady State



Plasma Waves Interaction

- **Waves interact with plasma through resonance processes:**

$$\omega = n\omega_c + k_{||}v_{||} \qquad n = 0, \pm 1, \pm 2, .. \qquad \omega_c = \frac{\text{charge} \times \text{magnetic field}}{\text{mass}}$$

- **Selecting particle species:**

$$\omega \approx n\omega_{ce} \quad \text{or} \quad \omega \approx n\omega_{ci} \qquad e, i = \text{electron}, \text{ion}$$

- **Localising in space:**

At location where: $\omega \approx n\omega_c(R)$

- **Localising in velocity space:**

$$\omega \approx k_{||}v_{||} \quad (n = 0)$$ *(// , ⊥ with respect to the magnetic field)*

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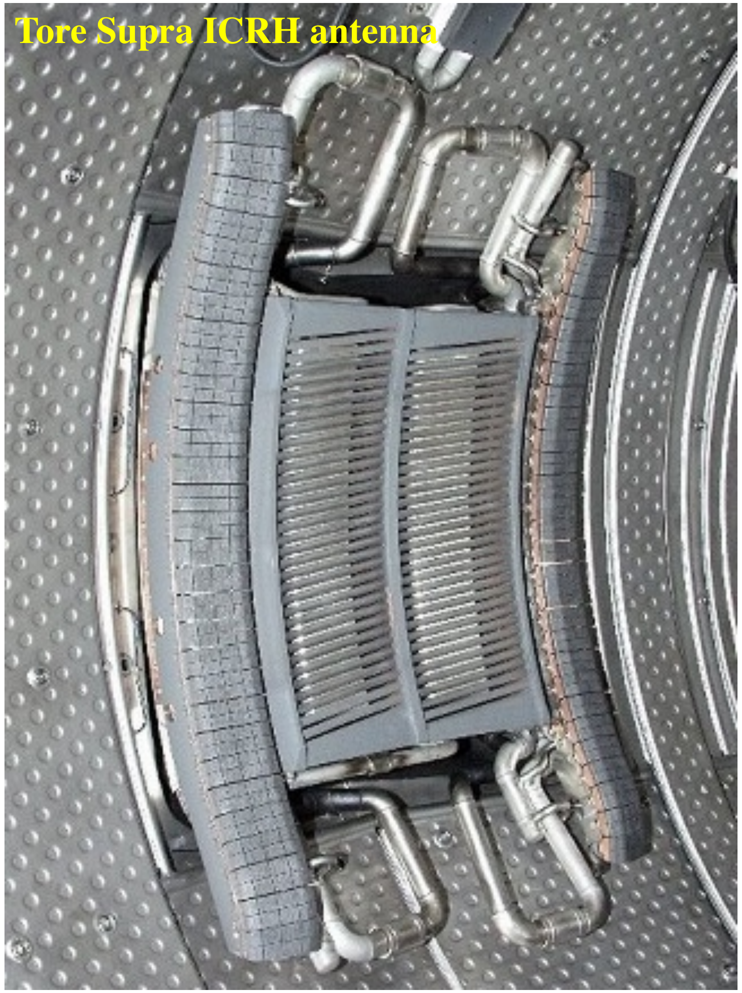
Ion Cyclotron Resonance Heating

$$\omega - n_h\omega_{ci} - k_{//}v_{//} = 0 \quad \Rightarrow \quad \omega = \omega_{ci} + k_{//}v_{//} \quad \Rightarrow \quad \boxed{\omega \approx \omega_{ci}}$$



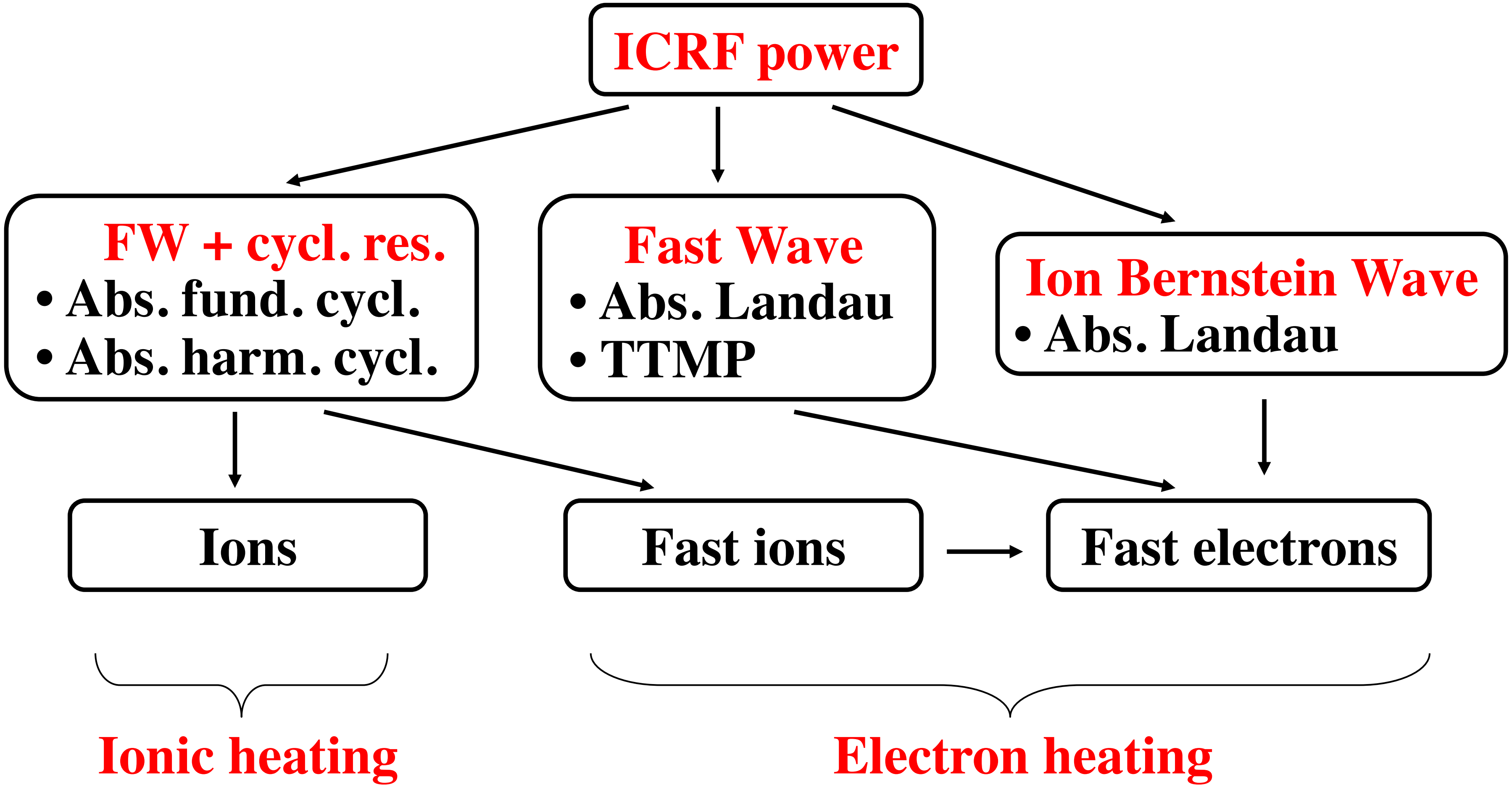
$$\nu_{ci} = \frac{q_i B}{2\pi m_i} \approx 15.2\left(\frac{Z_i}{A_i}\right) B_T\,[MHz] \approx \textbf{30-120 MHz}$$

Minority Scheme most used
Propagation and polarization are determined by the majority ions

Absorption determined by minority ions, higher their concentration lower the resulting tail energy

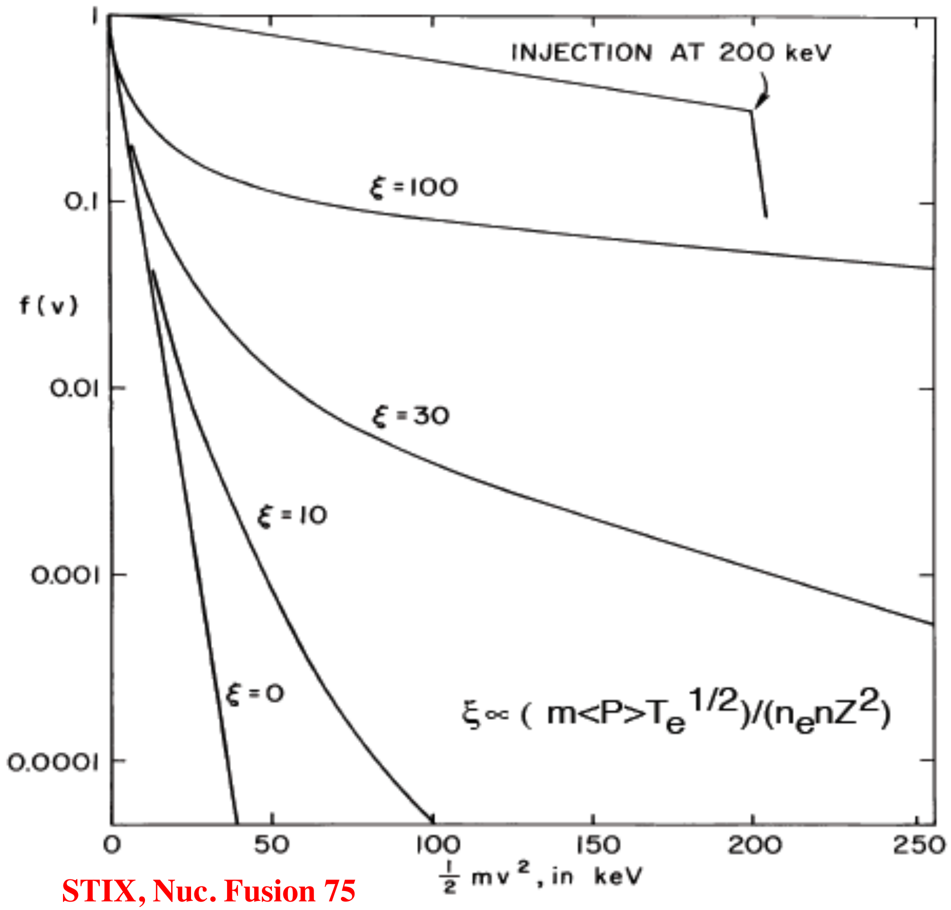
But further increasing minority concentration ➔ Mode Conversion to Ion Bernstein Waves (IBW) CD (?)

ICRF Power Scheme



PLT early results: Minority Heating H Tail

Fokker-Planck Energy Distribution Calculated for RF Excitation at the Minority Ion Cyclotron Frequency

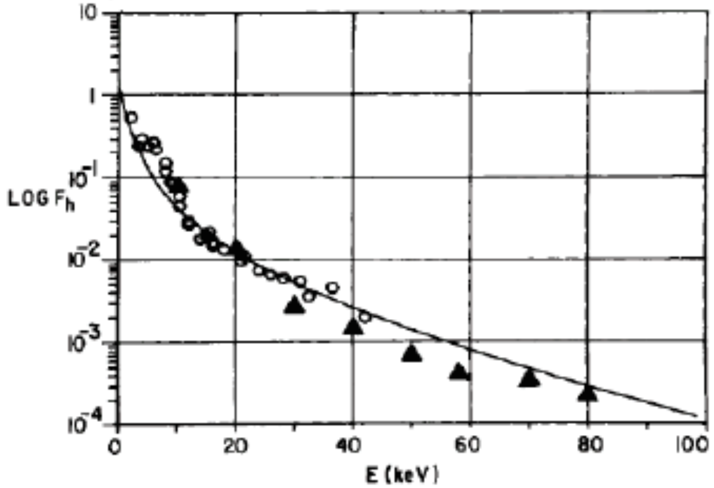


STIX, Nuc. Fusion 75

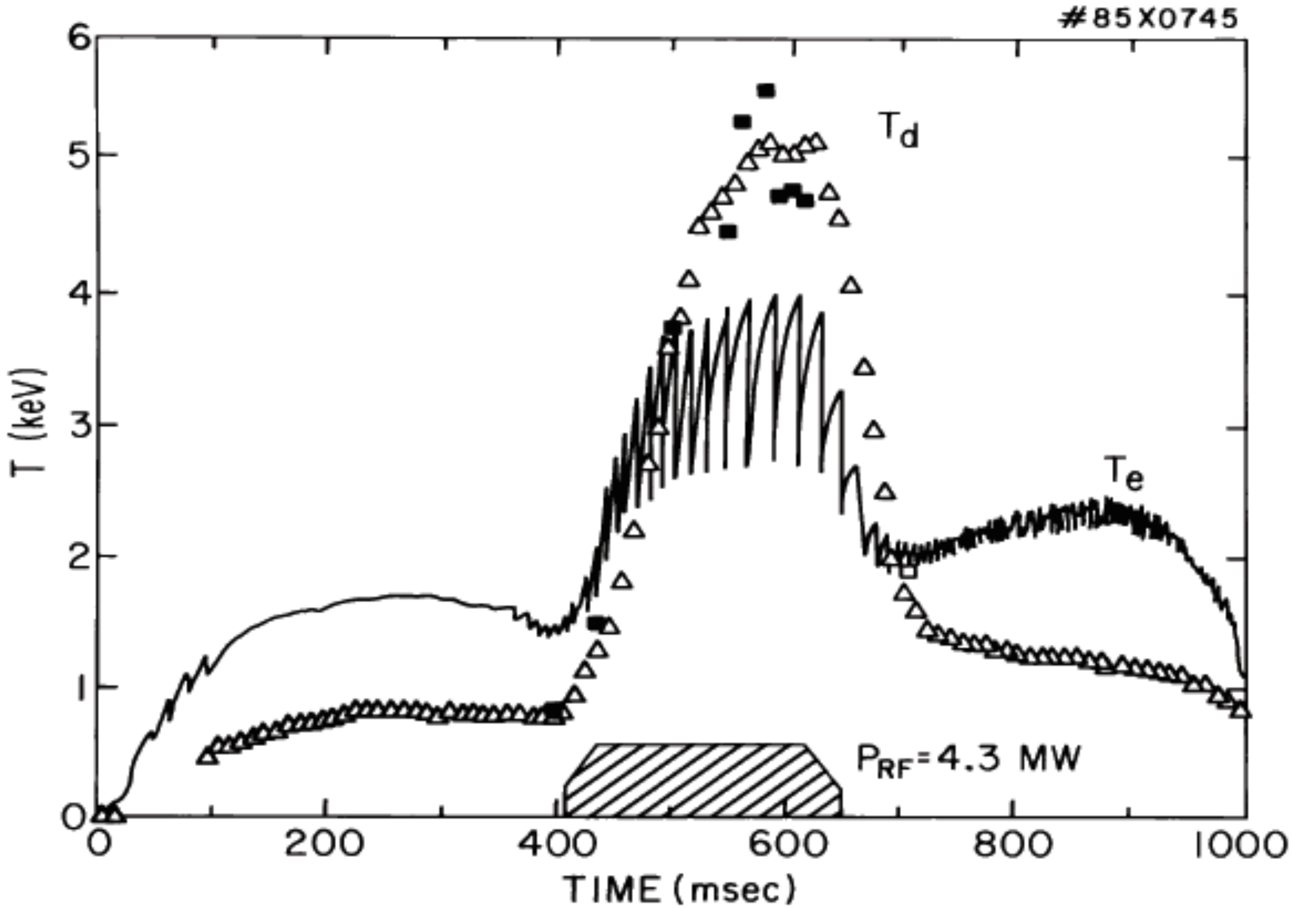
Hosea et al, 1982

PLT Hydrogen Ion Energy Distribution Compared with Theory

P_{RF} = 350 kW, D-H Plasma, $n_e = 2\times10^{13}$ cm^{-3}, I_P = 300 kA



PLT early results: High T with IC FW-^3H_e



Deuterium plasma with ^{3}He minority cycloton damping

$n_e = 3.7 \times 10^{13}$ cm^{-3}

I_P = 600 kA

B_Φ = 32.5 kG

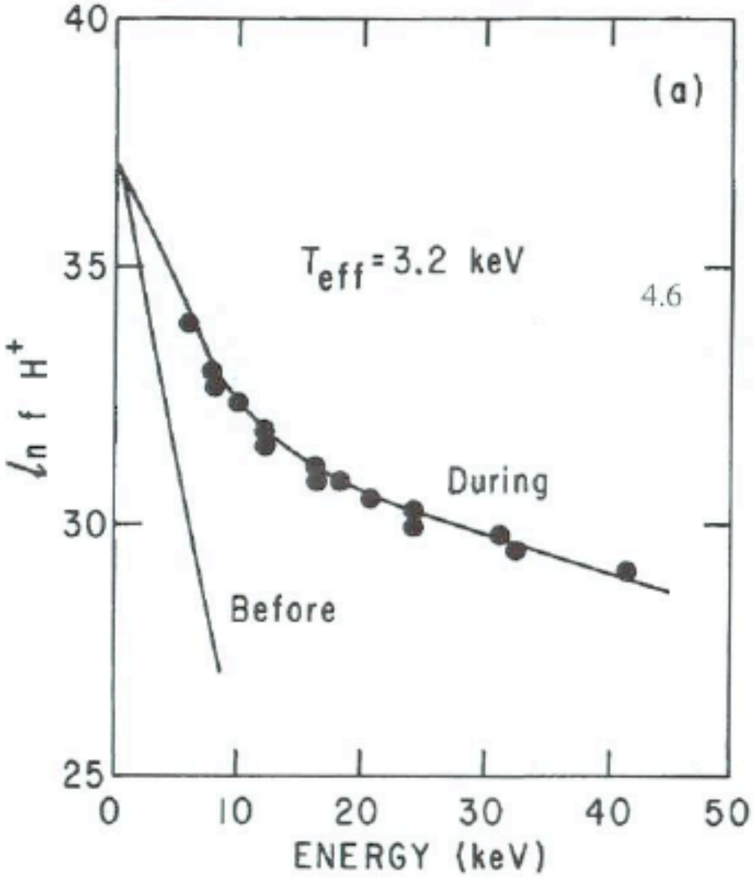
High heating efficiencies (80% or more) established for *minority* heating

Wilson et al, 6th AIP-RF, GA 1985

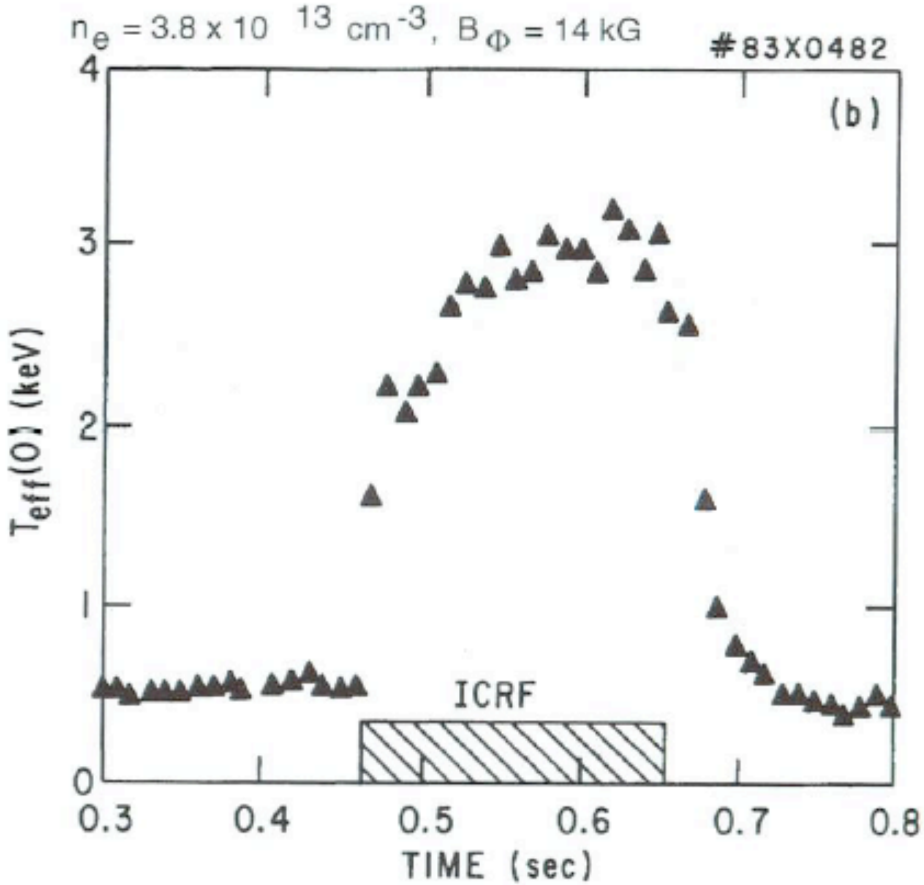
Hosea et al, EPS Budapest 1985

Second Harmonic Hydrogen heating

- $2\ \Omega_H$ with $P_{RF} = 2.8$ MW



Charge-exchange distribution



T_{eff} versus time

Hwang et al, PRL 1983

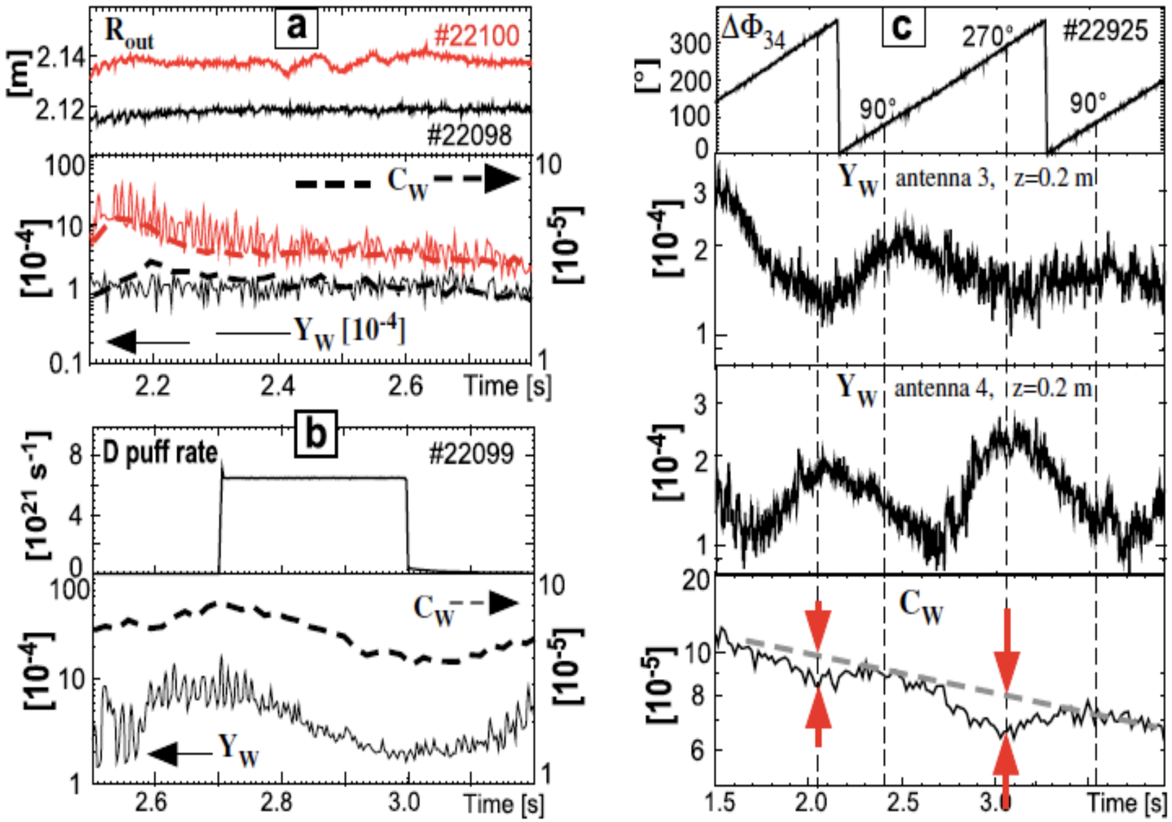
ICRF side effect: Rectified fields ➔ Z_{eff}

Main problem for next generation machine:

High exhaust power P ≥ 50MW/m2 ➔ High Z material "W"

➔ Low sputtering threshold ➔ Plasma Contamination……

Control of W contamination on AUG



Vl. Bobkov et al, J. Nuc. Mat. **390-391** 2009 900-903

RF induced sheaths strongly enhances sputtering and Self-sputtering of high z PFs

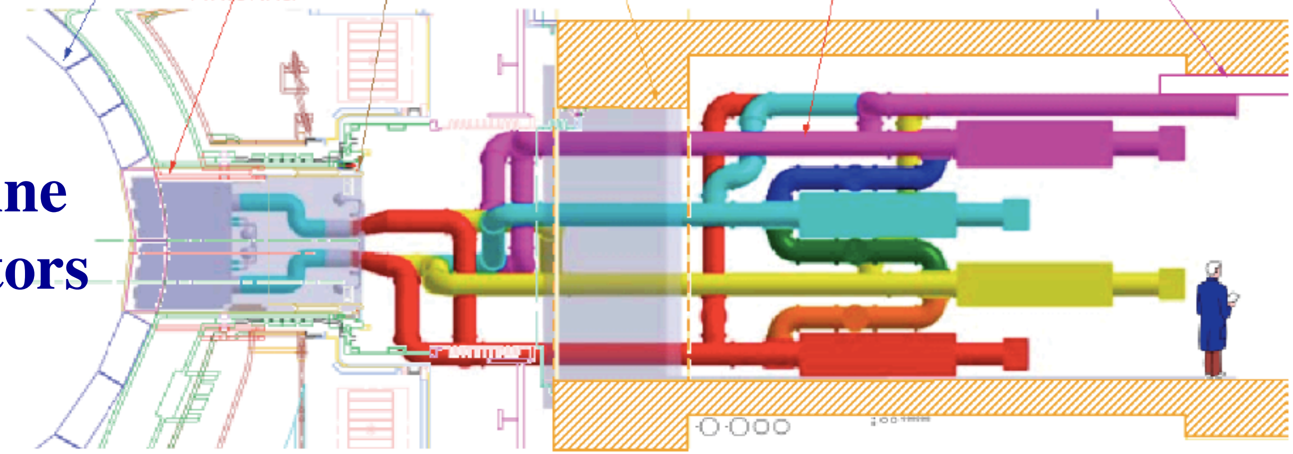
~300 eV E threshold for D sputtering on W, $E_{//}$ can be kVs on present antennae, not foget antennae cross talk

Integrated design is needed (RF in real antenna and torus Geometry) minimising unwanted Effect

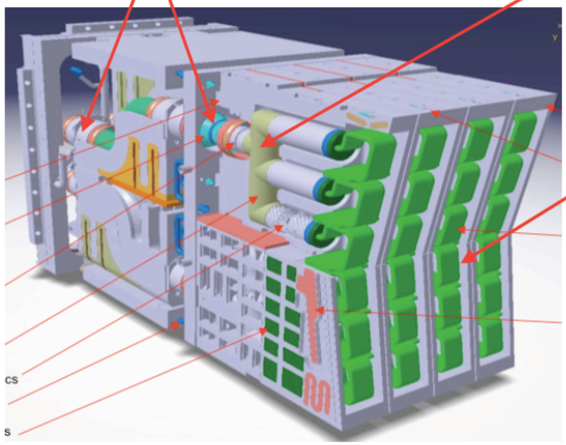
AUG good candidate for testing (comparing) ITER extrapolable solution, including reliable arc detections

ITER: ICRF antenna Design

EU **Antenna**
US **Transmission line**
India **PS and generators**



No moving parts in antenna
"4-port junction" - drives 3 current straps from 1 input
- Junction is at high-voltage point



1 antenna x 20 MW coupled
4 columns x 6 rows straps
External matching, but inside Bioshield
All external components must be removed to extract the antenna

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Main properties of EC waves

- **Quasi-optical propagation:**

  $f \leq 170$ GHz $\Rightarrow$ $\lambda \leq 6$ mm

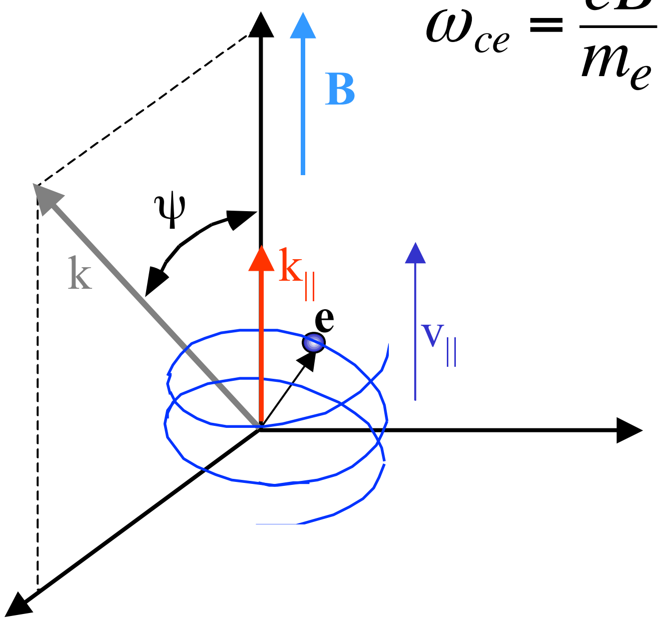
- **Resonance at the harmonics of the electron Larmor frequency**

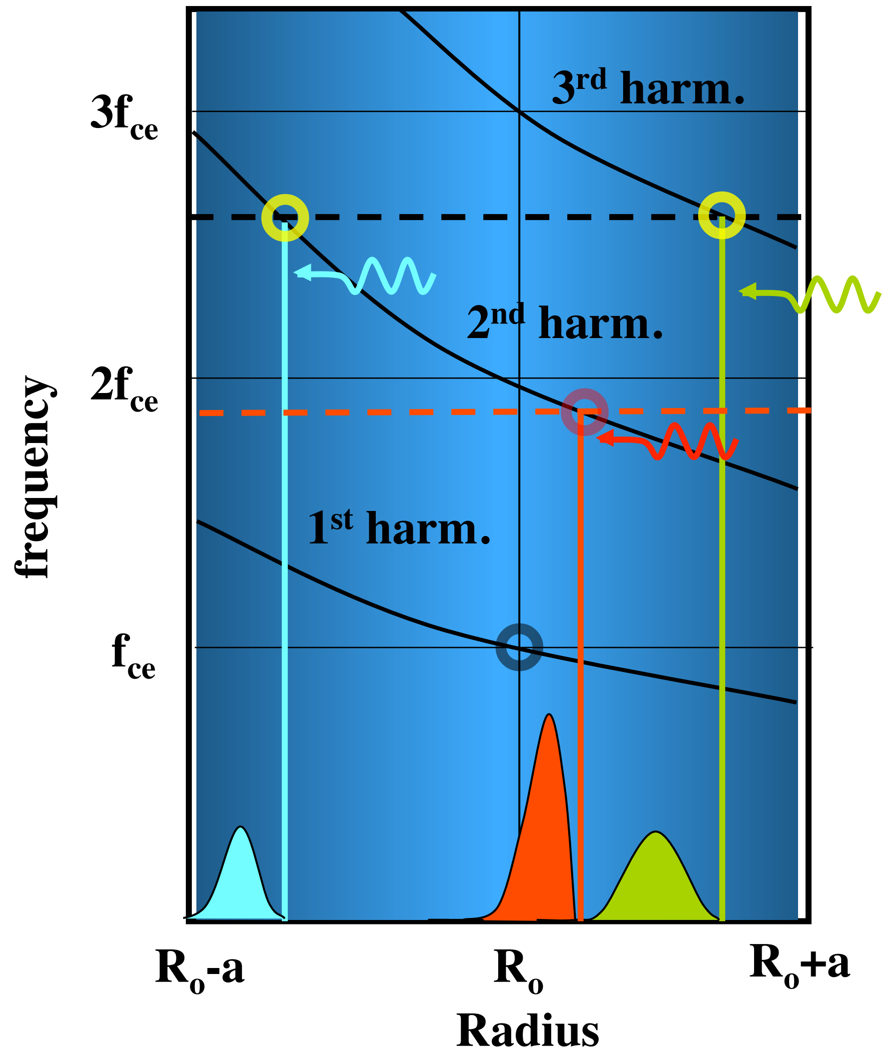
  $$\omega_{ce} = 2\pi f_{ce} = eB/m_e$$

- **Spatially localised absorption**

  $\rightarrow$ a few cm

$$\omega_{ce} = \frac{eB}{m_e}$$





Cyclotron absorption

RESONANCE CONDITION

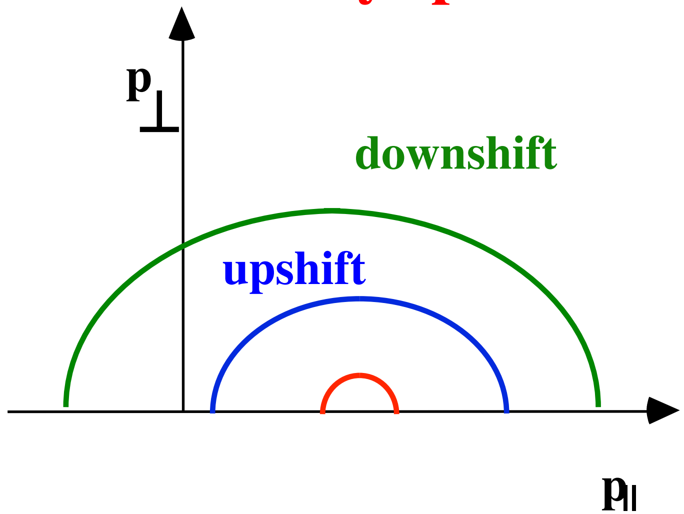
$$\boxed{\omega - k_{\|} v_{\|} = l\,|\omega_{ce}|/\gamma}$$

Doppler shift **Harmonic** **Relativistic factor**

$$\nu_c = \frac{ZeB}{m} \approx 28\left(\frac{Z}{A}\right) B_T\,[GHz]$$

Wave absorption only arises as a result of full kinetic treatment ('hot' plasma theory)

Resonance is an ellipse in velocity space



Relativistic effects must be included even for moderate T_e

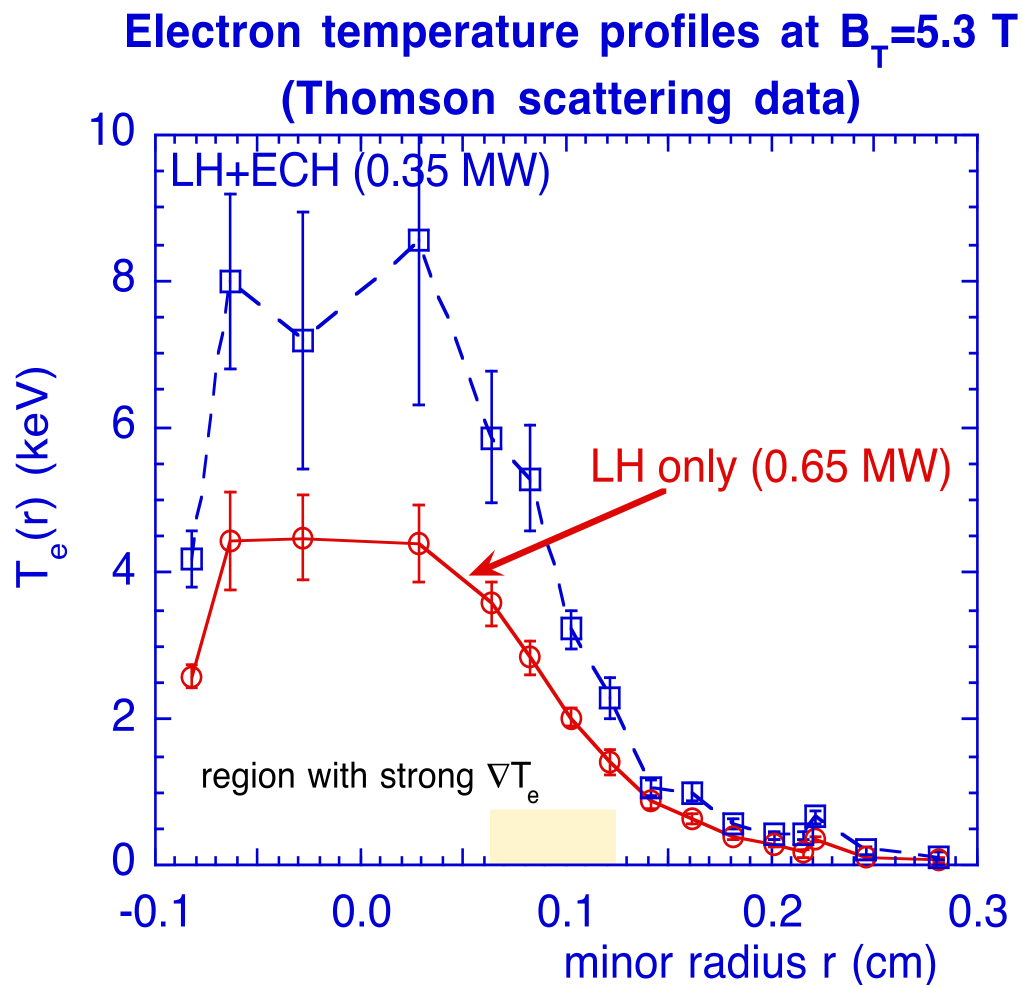
X1 mode damping complicated ⇒ absorbed even for $T_e = 0$ (effective for pre-ionisation)

O1, X2 mode strongly absorbed for $T_e \geq 1$keV

Absorption of succeeding harmonics decreases by a factor T_e/mc^2

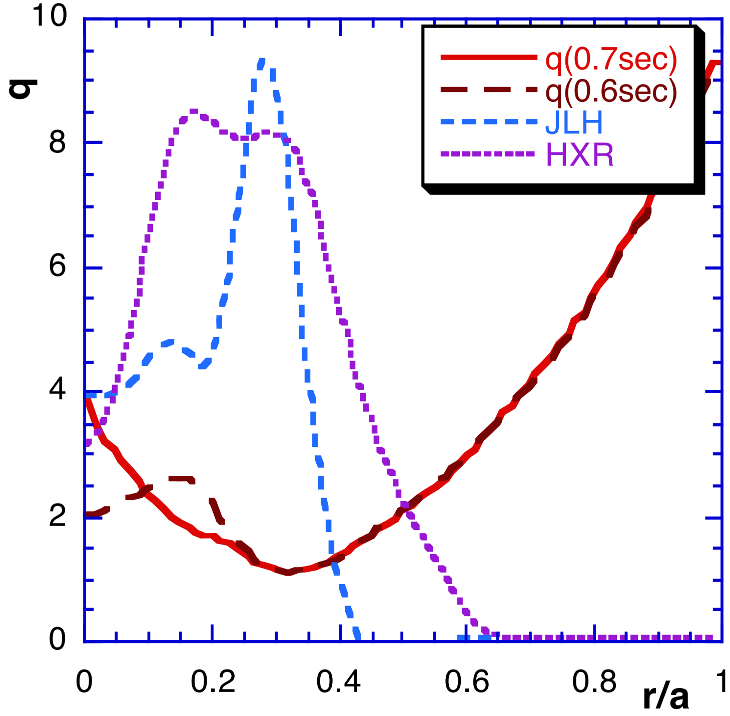
Note that poloidal beam steering allows control of absorption location at fixed B_ϕ

ECRH applied at plasma centre in full LHCD FTU plasma, MHD stable. Magnetic shear appears reversed at centre



Ip= 350 kA full LHCD

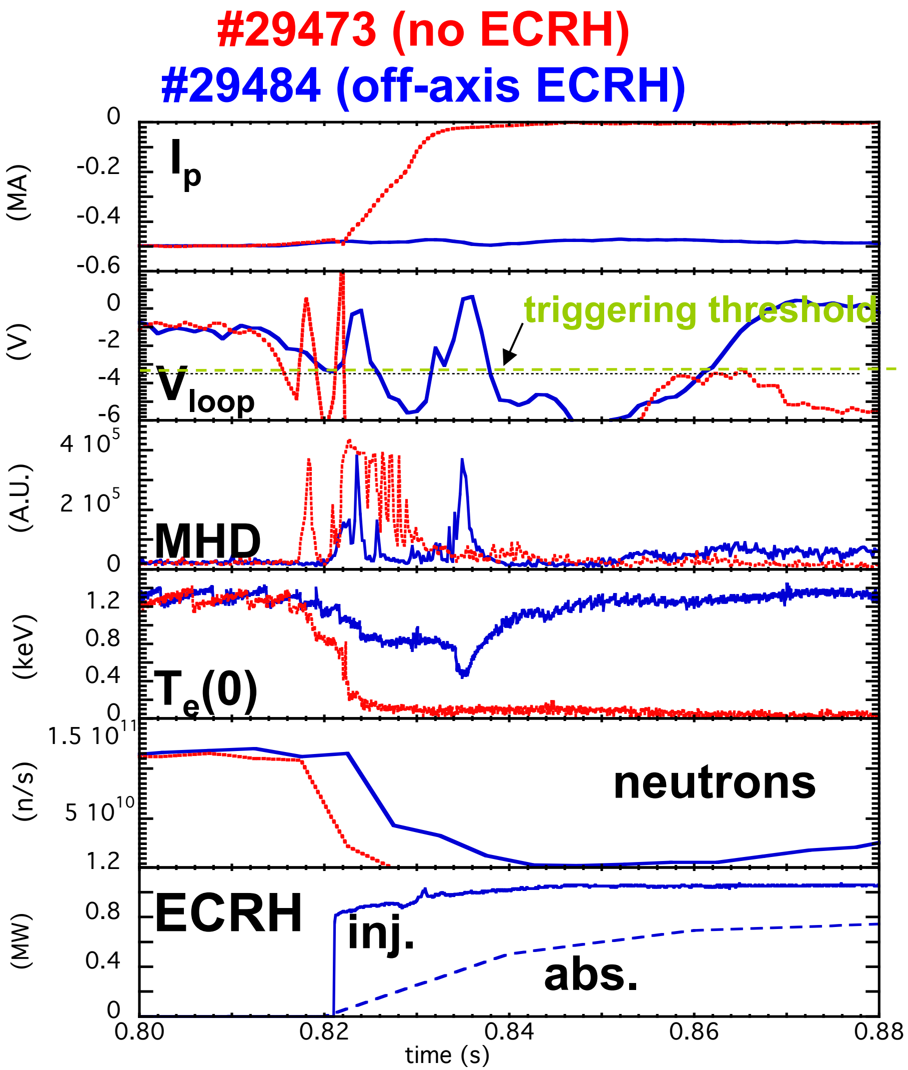
$\langle ne \rangle = 0.35\ 10^{20}\ m^{-3}$



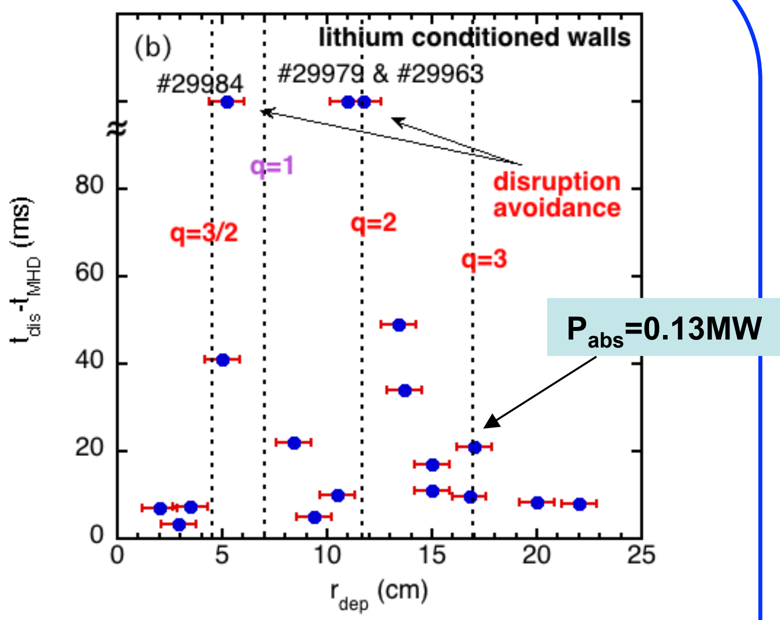
Te increase on a region (15 cm) much wider than EC resonance (~2 cm

Effective e- ITBs produced in these conditions

Avoidance in LBO disruptions with ECRH



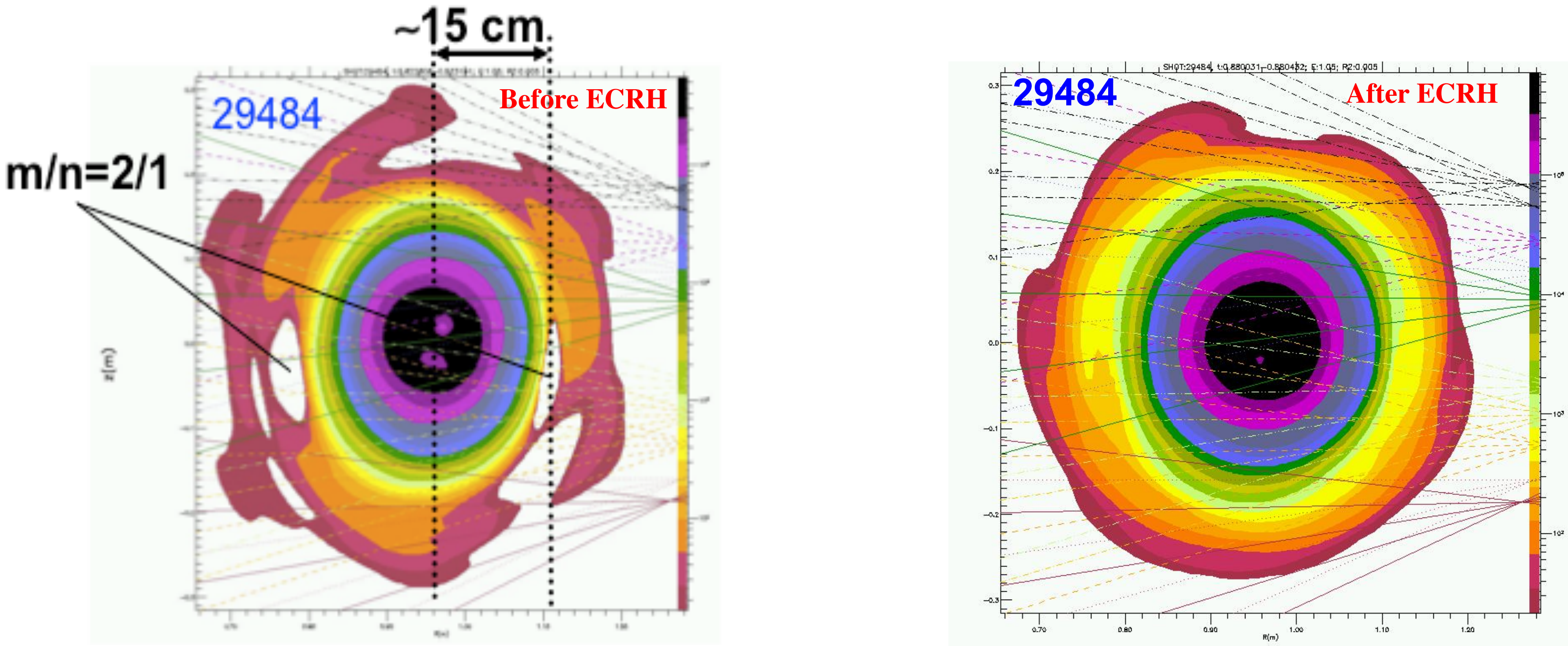
Power Deposition Scan



Delay between MHD onset and I_p quench versus r_{dep} indicate that ECRH produces avoidance when $r_{dep} = r_{q=m}$

Modes are coupled also in stabilizing phase

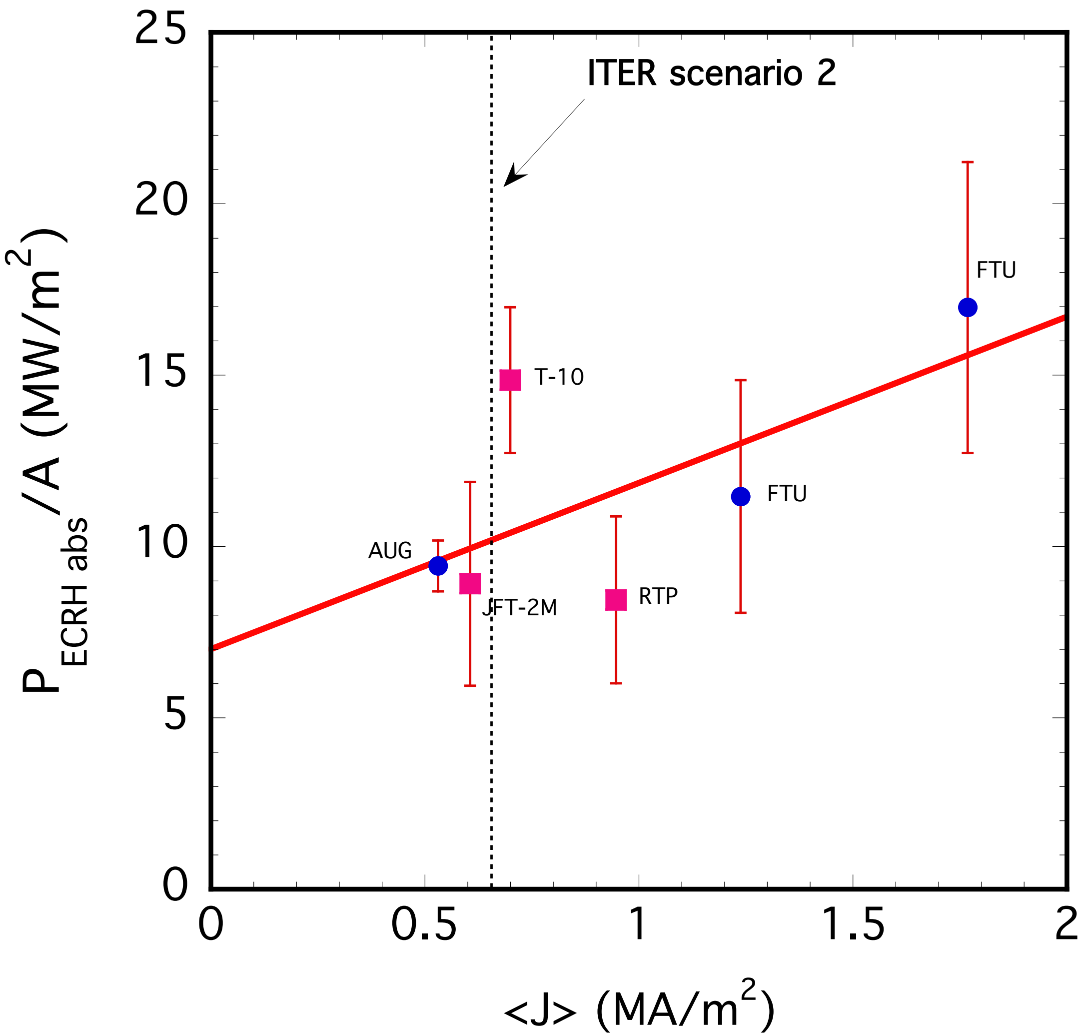
Disruption Avoidance with ECRH-I



Disruption avoidance: when ECRH (no CD) is deposited (ECWGB 3D code, *S. Nowak et al., PoP 1 1242 1994)* at resonant surface (q=3/2, q=2, q=3 in LBO induced disruptions) by poloidally steering 1-3 beams in constant magnetic field plasmas

However current quench delayed when deposition radius is close to the MHD resonant surface

Power Threshold Analysis



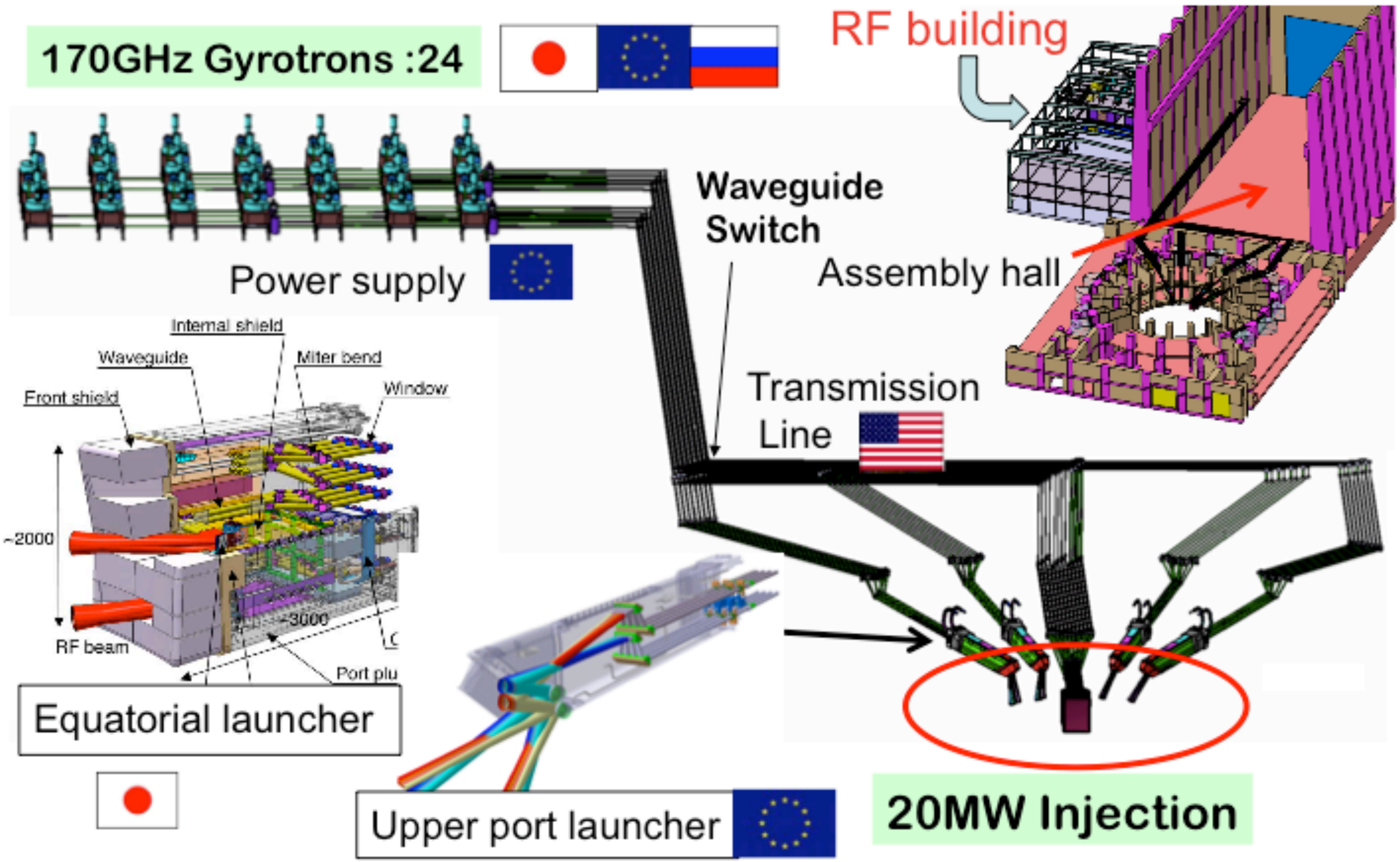
Data considered are for q=2 stabilization

Error bars indicate the range between the saved case and unsaved case

The EC power density is taken from the absorbed power divided by the q=2 corona (width=hwhm)

The minimum required absorbed power in ITER is 4 MW (assuming hwhm~3.75 cm)

ITER ECRH system: Technical and Logistic Complexity



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LH wave absorption

- $\omega \approx \omega_{LH}$: resonant absorption by ions
  - requires very high densities
  - scheme abandoned in modern applications
- $\omega > \omega_{LH}$: absorption by electrons
  - via **Cerenkov resonance**: $\omega = k_{\|} v_{\|} \quad \left(n_{\|} = \frac{c}{v_{\|}} \right)$
  - mechanism: **Landau damping**

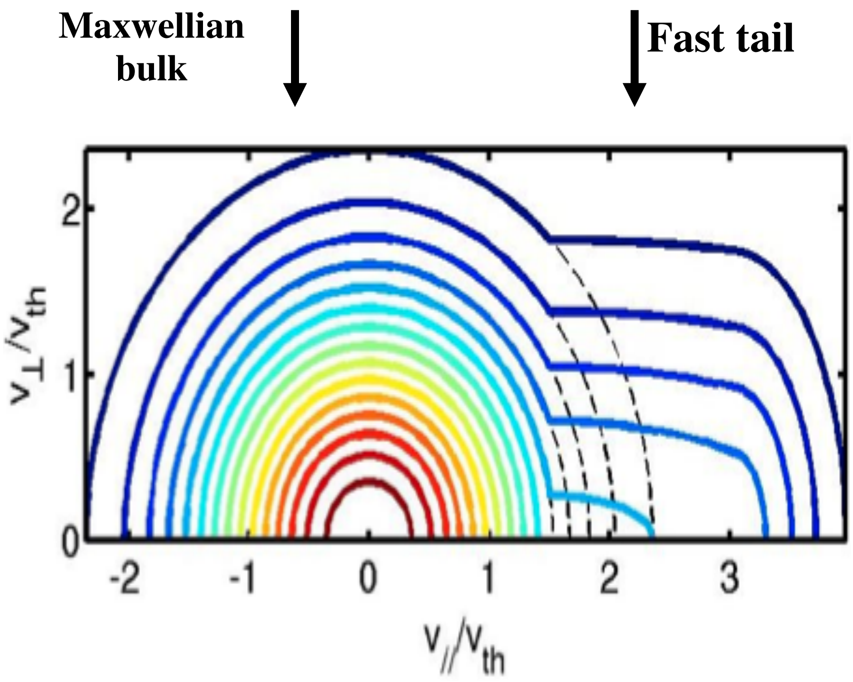
$$\text{power absorbed per particle} \propto \left. \frac{\partial f}{\partial v_{\|}} \right|_{v_{\|} = \frac{\omega}{k_{\|}}}$$

  - main application: non-inductive current drive

LH waves drive fast electron tail

$$\omega_{ci} \ll \omega \ll \omega_{ce}$$

$$f \approx 10^7 \quad 10^9 \quad 10^{11} \text{ Hz} \qquad (\lambda \sim 3\text{-}10 \text{ cm})$$

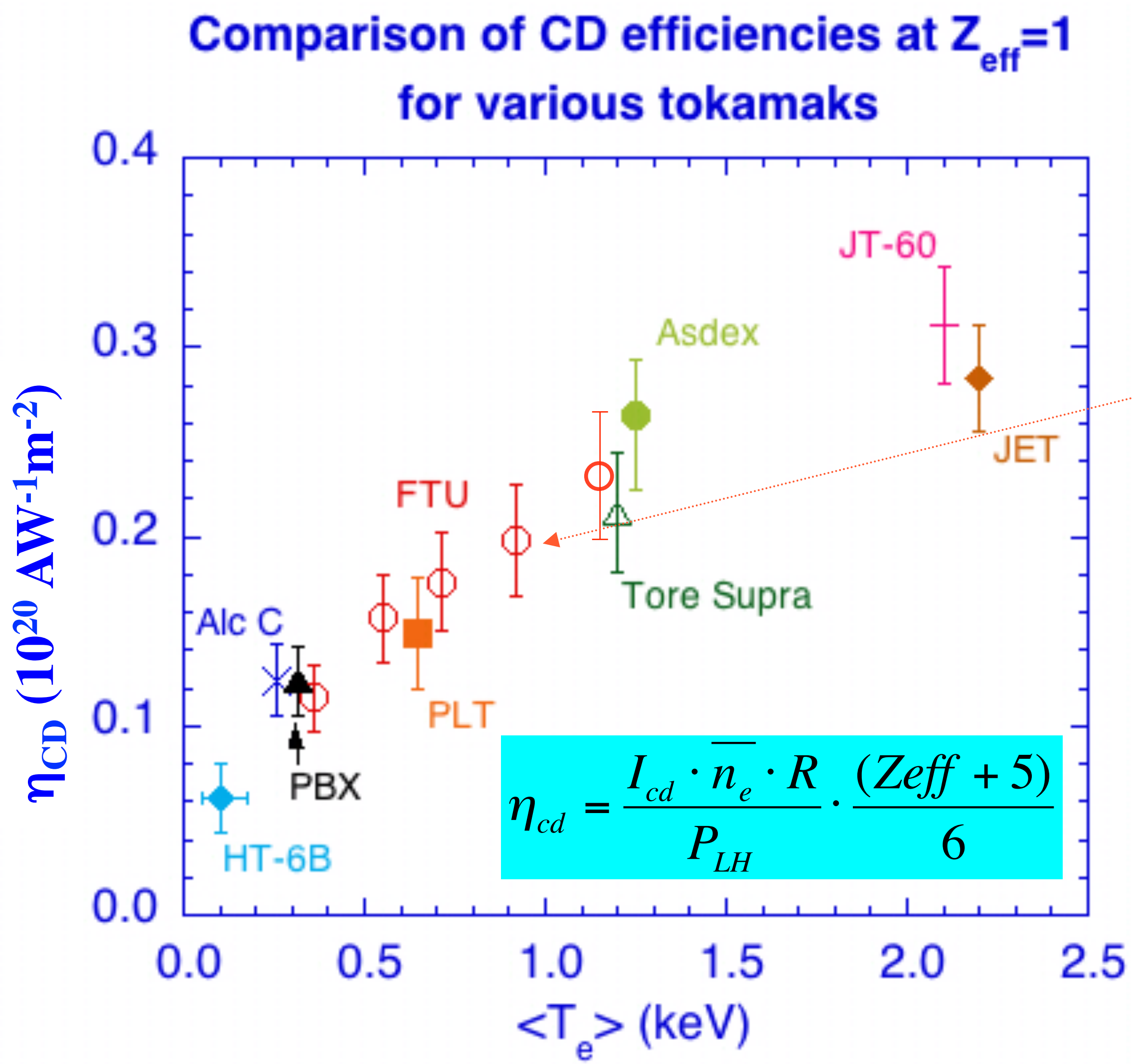


Electron absorption via Landau damping $v_{||} = c/n_{||}$ ➔ tail electrons ➔high n_{CD} at given Te➔Off Axis CD

Cannot penetrate plasma centre at high n_e (accessibility) or strongly absorbed at high Te (cannot penetrate in ITER plasmas r/a≥0.8)

Wave evanescent in vacuum ⇒ coupling requires finite density at antenna mouth ➔ antenna-plasma interaction

LH CD: Highest experimental efficiency



V. Pericoli-Ridolfini et al, Phys. Rev. Lett. 82, 1, 93 (1999)

CD Efficiency at values foreseen for ITER:

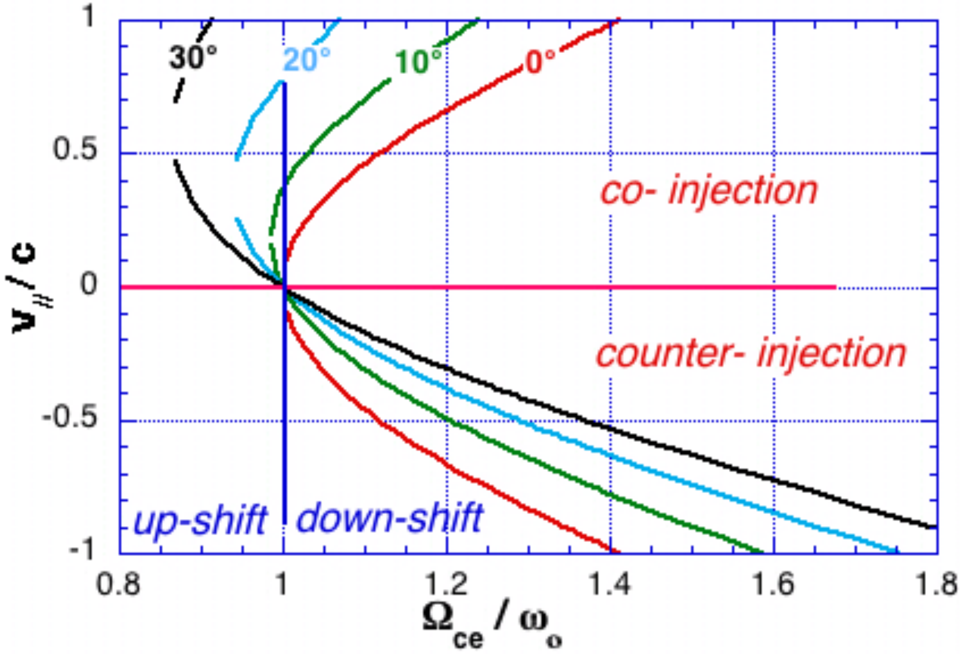
- at ITER density $n_{e0}/n_{el} = 1.3/0.75 \cdot 10^{20} m^{-3}$
- at $T_e \leq T_e$ ITER off-axis
- with different launchers
- and frequencies

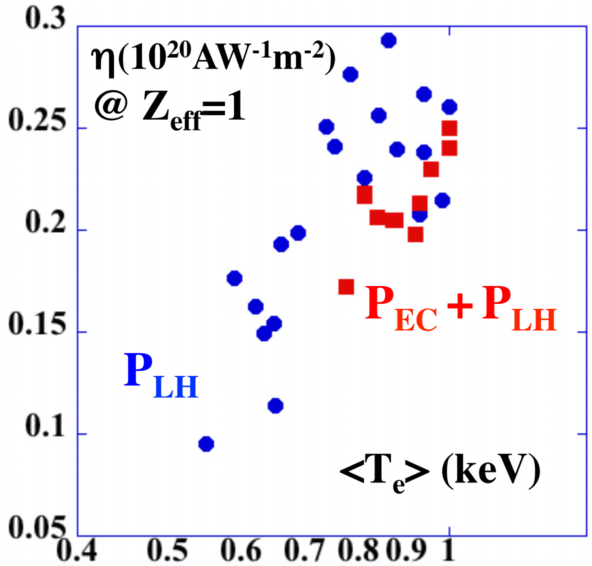
$$\nu_{exm} \leq \nu_{ITER} < \nu_{exM}$$

0.8-4.6GHz 8GHz

LH+EC Synergy Scenarii

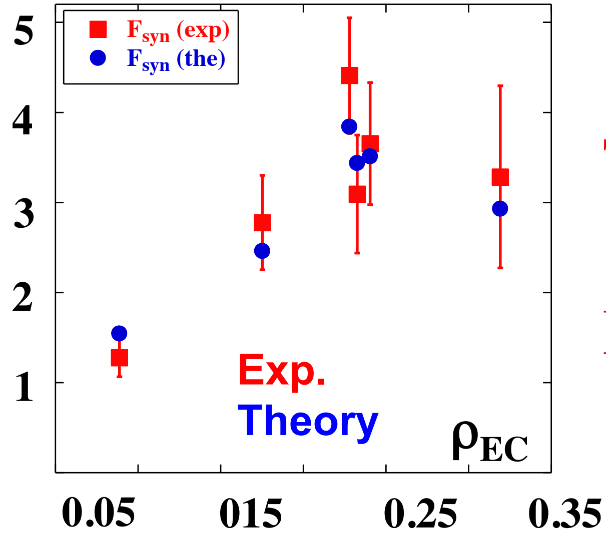
$$\frac{\Omega_{ec}}{\omega_0} = \frac{n_{\parallel}^{\mathrm{LH}}}{\sqrt{n_{\parallel}^{\mathrm{LH}\,2} - 1}} \left(1 - \frac{N_{\parallel}^{\mathrm{EC}}}{n_{\parallel}^{\mathrm{LH}}} \right)$$





FTU
Down Shifted

$\eta_{EC} \sim \eta_{LH}$

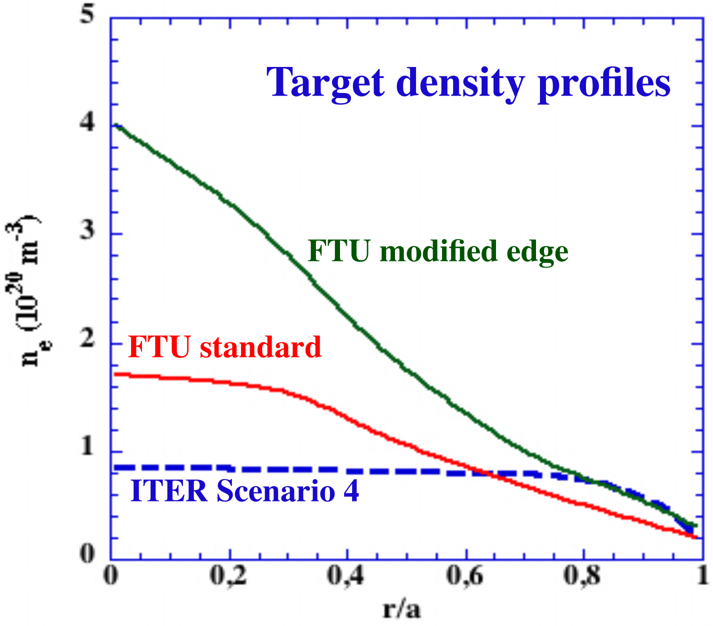


Tore Supra
UP Shifted

$I_{syn} > 4 * I_{lin}$

Down-Shifted: $B > B_{Res}$
Up-Shifted : $B < B_{Res}$ only co-cd injection
Driven current always co-direction

LHCD in FTU at ITER relevant n_e

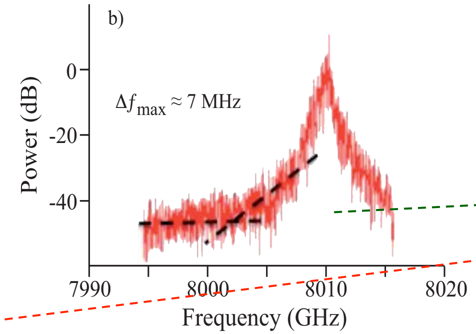


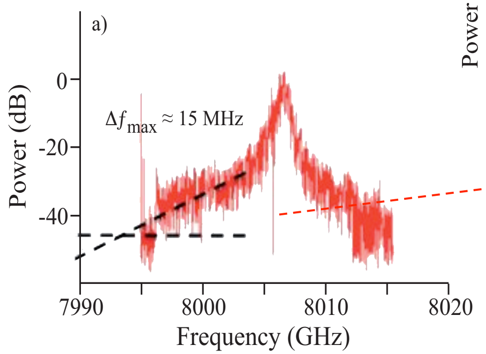
Regime high T_{e_Out} ($Te \approx 250eV$ @ $r/a \approx 0.8$):

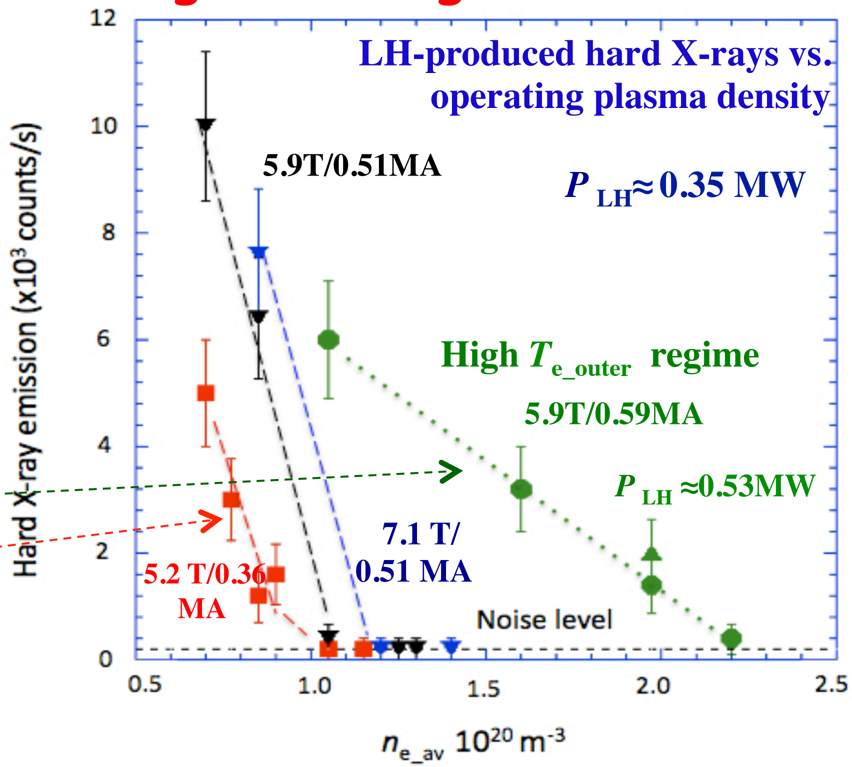
Lithizated vessel, pol. limiter ops, gas fuelling + pellet

Standard regime ($Te \approx 100$ eV @ $r/a \approx 0.8$):

Boronized vessel, toroidal limiter ops, gas fuelling

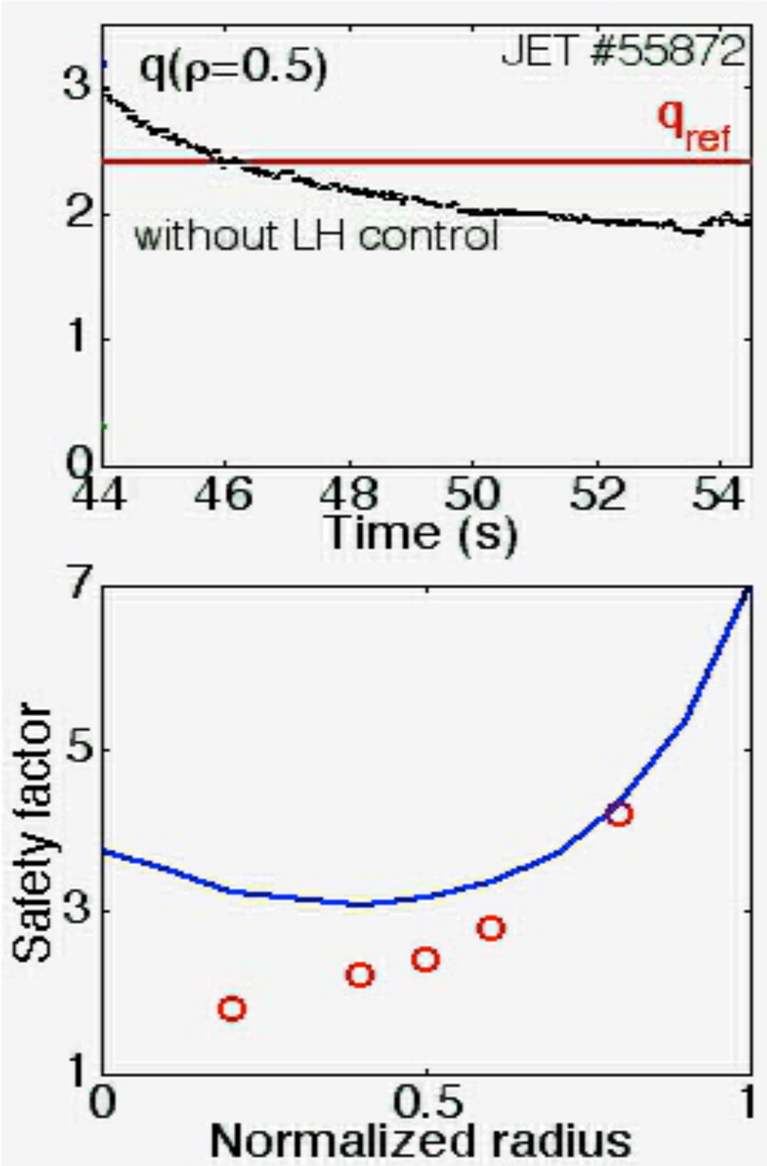






R Cesario et al., Nature coms1052, Aug 2010

LHCD in Advanced Regimes: Real Time Control

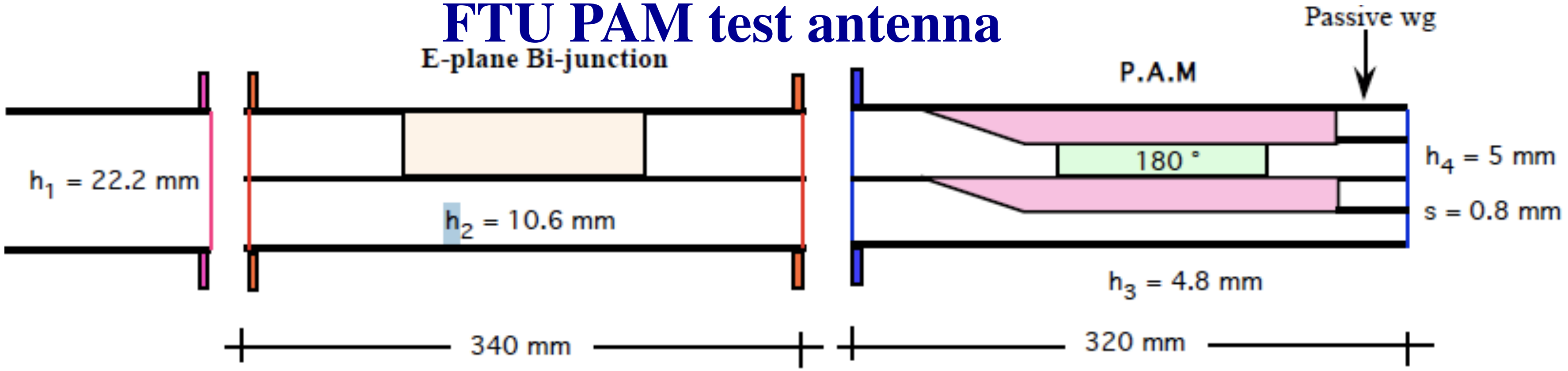


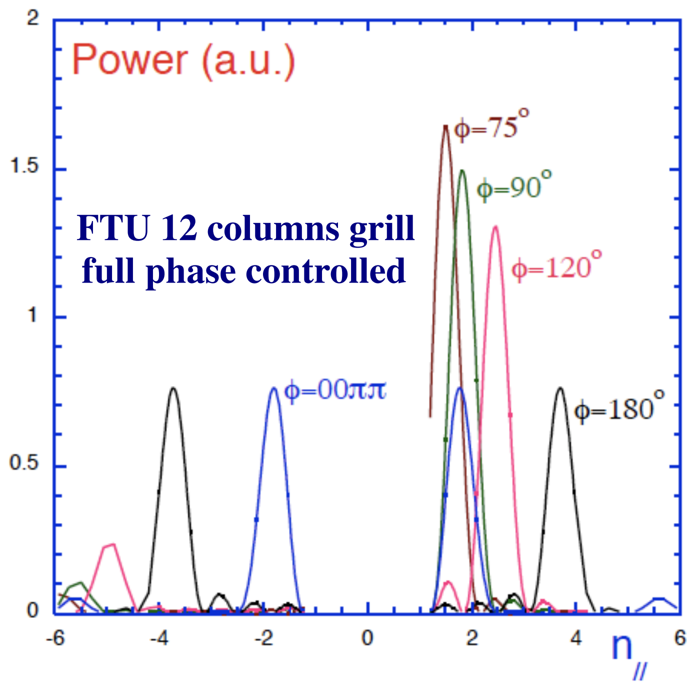
Successful RTC experiments in JET and JT-60U have shown the essential & unique role of LH CD for reaching and maintain a reference, monotonic or reversed q-profile

LH power under real time feedback to control the desired q-profile in a long prelude phase at JET

LH Launchers: Phased Array, MJ, PAM

FTU PAM test antenna





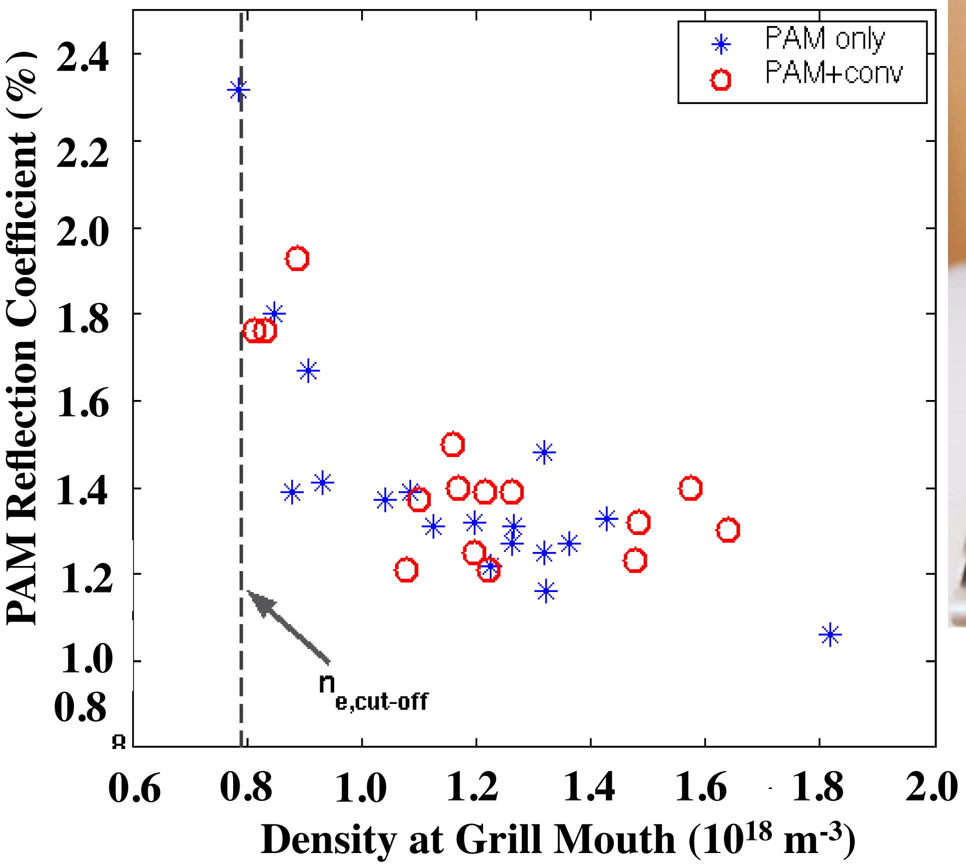
Only **PA** can continuously adjust $n_{//}$ spectrum from symmetric to very directive $n_{//0}=\lambda_0\phi/2\pi\Delta$, but need $n_g \sim n^2_{//} n_{CutOff}$ ($\sim f^2$) for coupling with $R \leq 5\%$

MJ (Nguyen and Moreau SOFT 1982) is designed for re-circulating reflected power at splitting section ($R_{gen} \sim R^2_{grill}$)
Better coupling at low density, less flexibility

PAM (*Bibet et al., NF 35 1995*) has half guides not radiating: more the reflection more they contribute ➔ coupling at very low density, efficient cooling, half surface, lower directivity.

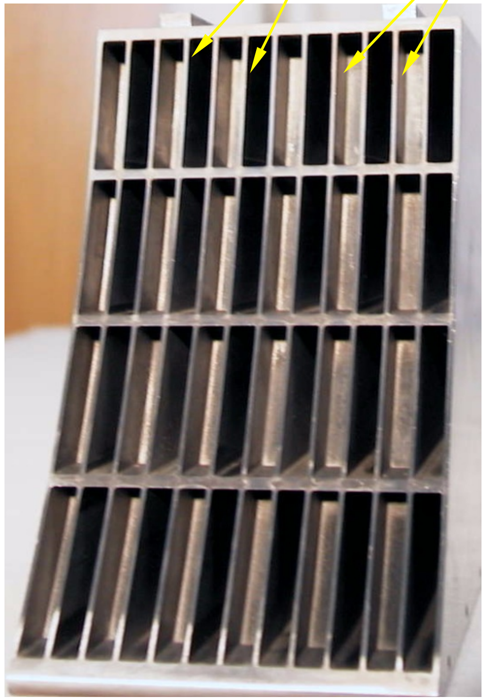
LH Coupling: PAM Test on FTU (2003)

Very good coupling even at density close to the slow-wave cut-off: PAM flush to FTU wall



Pericoli et al, PPCF 28 2004

FTU PAM: 6 active/6 passive wgs



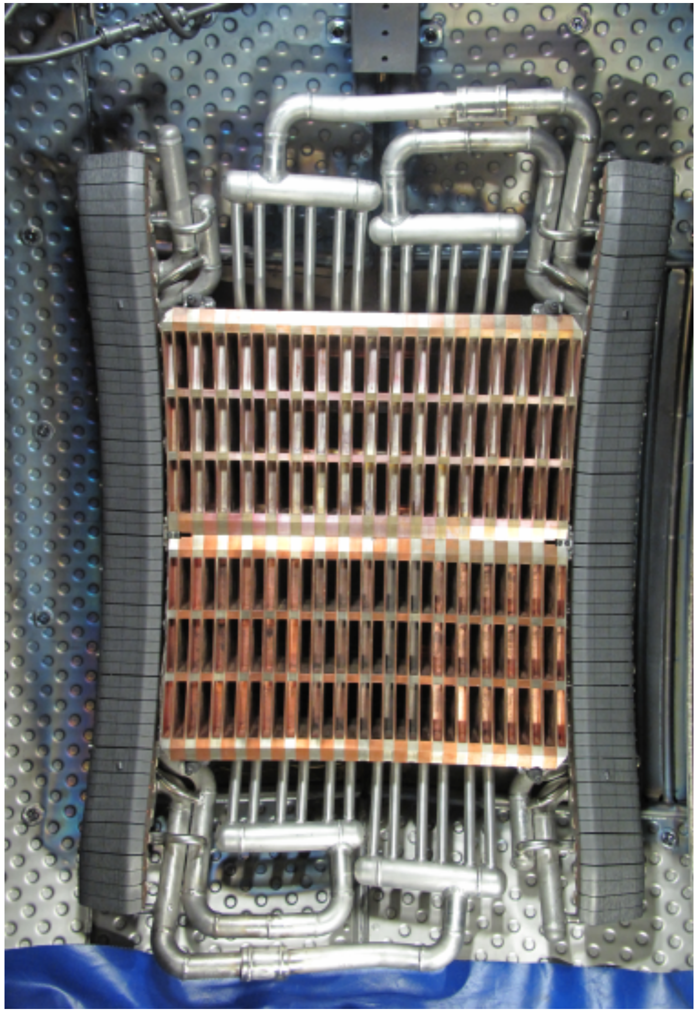
1) FTU:
PAM Concept demonstrated

2) Tore Supra:
To test PAM Technological performance

3) (??):
PAM test on ITER relevant coupling Conditions

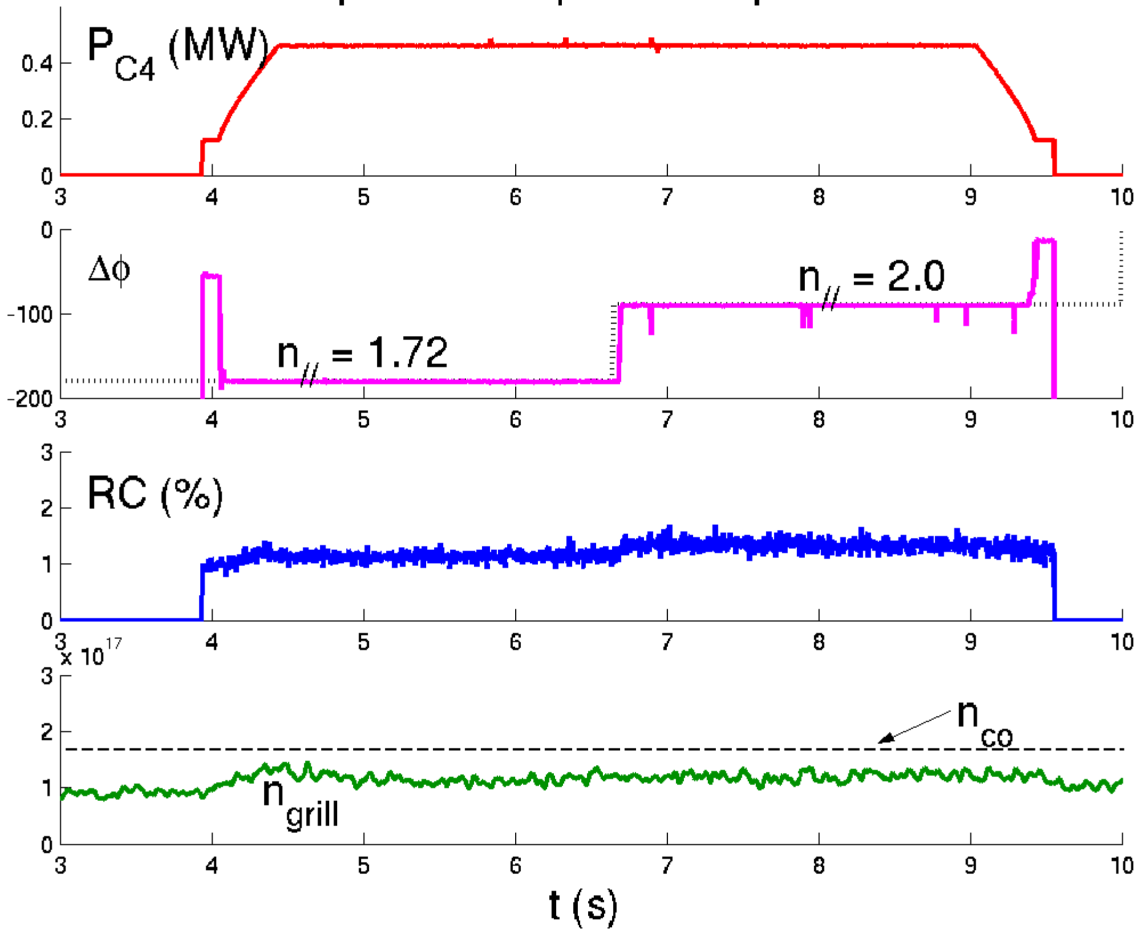
Next Step in China
➔ EAST?

First PAM launcher results on Tore Supra - 28/10/2009



$\bar{n}_e \sim 2.6*10^{19} m^{-3}$, $\Delta V/V \leq 20\%$

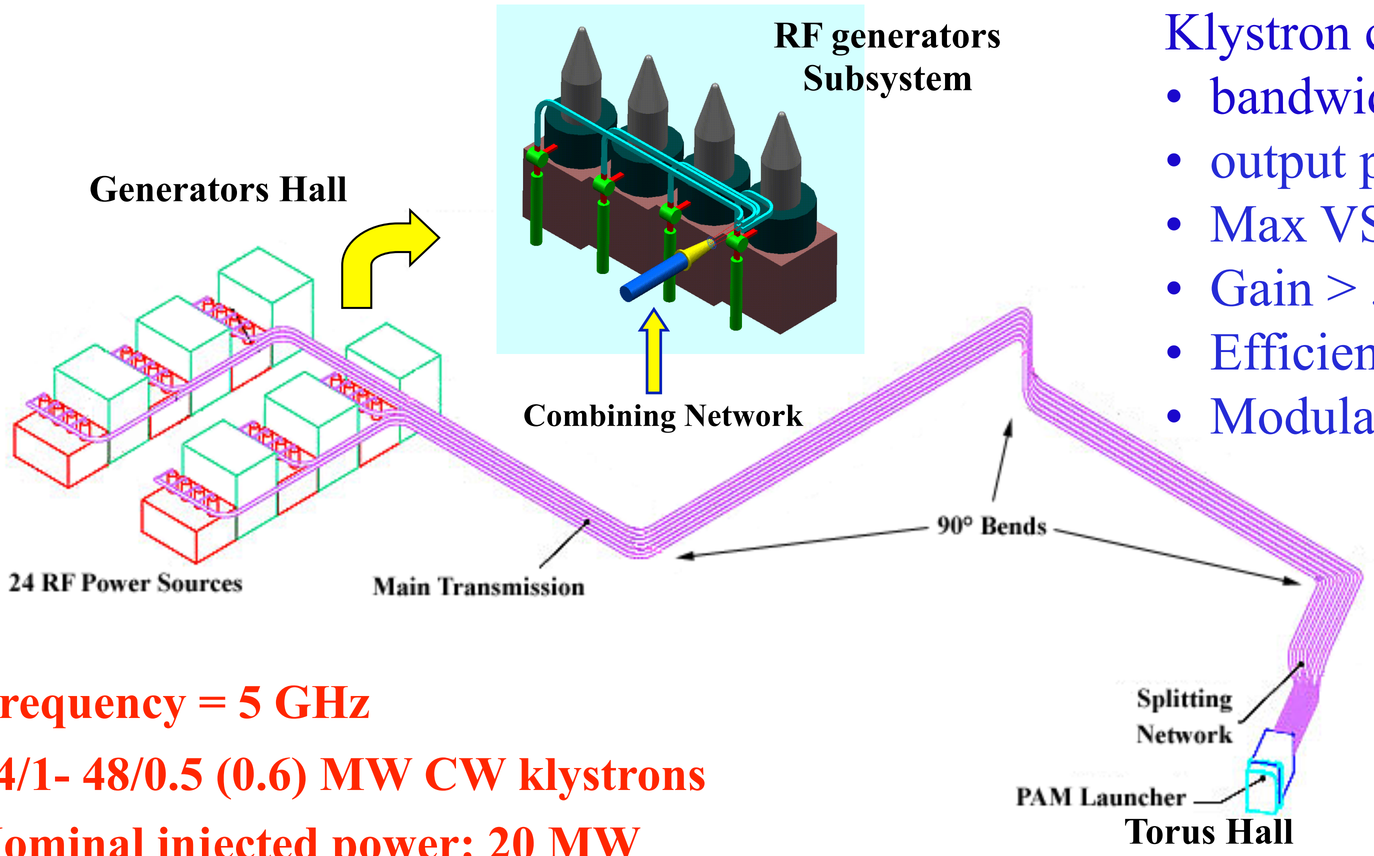
#43788 (I_P = 1MA, B_T = 3.8T, $n_l = 4*10^{19}$ m^{-2})



TS-Team 28/10/2009

PAM performance best in once feared conditions

ITER LH (TBD): System overview



Klystron characteristics:

- bandwidth: ± 10 MHz
- output power: >500 kW
- Max VSWR all phase: 1.4
- Gain > 50 dB
- Efficiency > 45%
- Modulating anode

- **Frequency = 5 GHz**
- **24/1- 48/0.5 (0.6) MW CW klystrons**
- **Nominal injected power: 20 MW**
- **Power combination by hybrid junction**
- **4 klystrons powered in parallel**
- **No circulator considered**

MTL Average Length ≈ 70 m

Transmission mode TE^{o}_{01}

Estimated cost: 24 klystron ~3 €/W
48 klystron ~5 €/W

P. Bibet et al - CEA
F. Mirizzi et al-ENEA

OUTLINE

Introduction (RFs in fusion plasmas)

IC

Some Physics notion
Some result
New and future experiments/References

EC

Some Physics notion
Some result
New and future experiments/References

LH

Some Physics notion
Some result and Coupling
New and future experiments/References

Summary and a word on the future

RFs: Summary of capabilities, pro & cons

- IC (ITER frequency 55 MHz)

Generators: Tetrode(10-120 MHz), Dycrode higher frequency

Transmission: Coaxial cable; Launcher: antennae

Pros: ion H, localised H&CD, broad B, flexible and cheap

Cons: edge plasma → Coupling, Sheat rectification → Impurity → PFCs

- EC (ITER frequency 170 GHz)

Generators: gyrotron (28, 60-84, 110, 118, 140, 170 GHz)

Transmission: wg, optical; Launcher: open wg, steerable mirrors

Pros: propagate in vacuum, physics understood, very localised → surgical tool

Cons: B dependent, Mirrors close to plasma, expensive, high f generators

- LH (ITER frequency 5 GHz, not approved yet)

Generators: Klystron (0.8, 1.2,2-2.45, 3.7, 4.6 GHz), Gyrotron (8 GHz)

Transmission: wg; Launcher: Phased array, Multjunction, Passive Active Mj

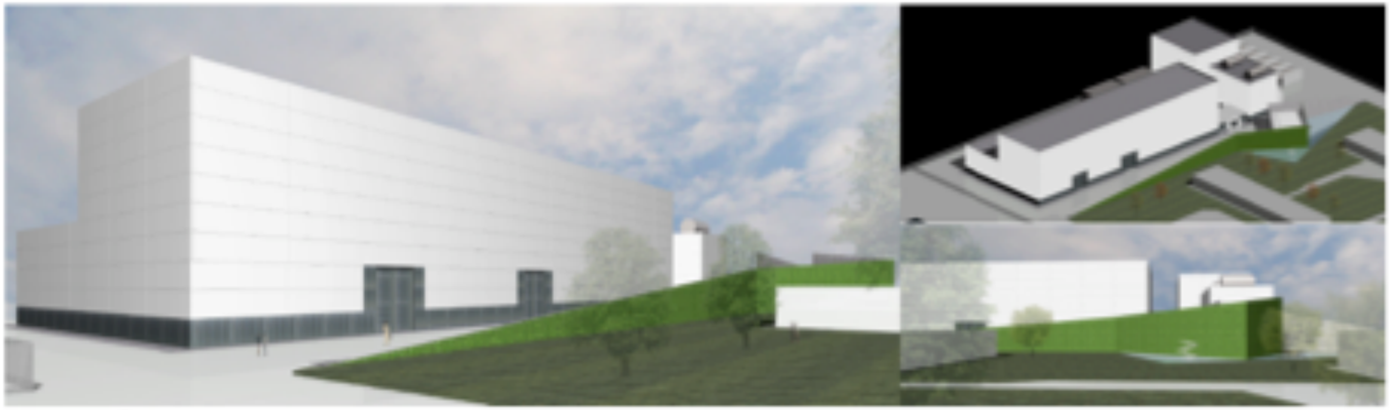
Pros: off Axis CD, no B dependence, HW sound

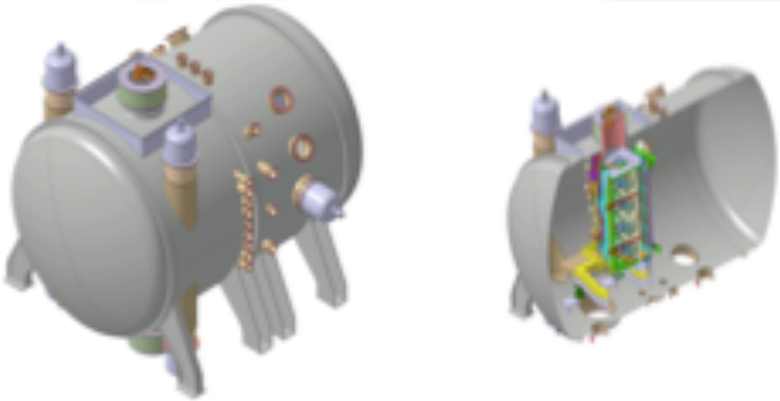
Cons: vacuum evanescent → PFC, α's absorption, High freq klystrons

- Negative Neutral Beam (ITER E=1MeV)

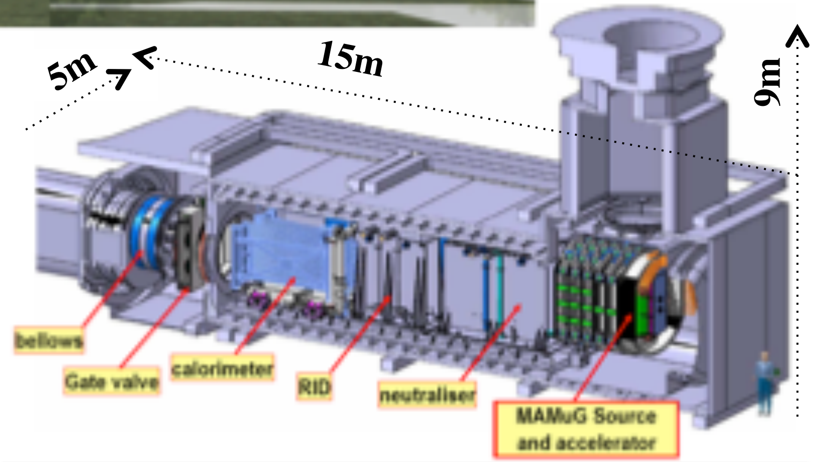
RFX Consortium: ITER Neutral Beam Test Facility

PRIMA
Padova **R**esearch on **I**njector **M**egavolt **A**ccelerated



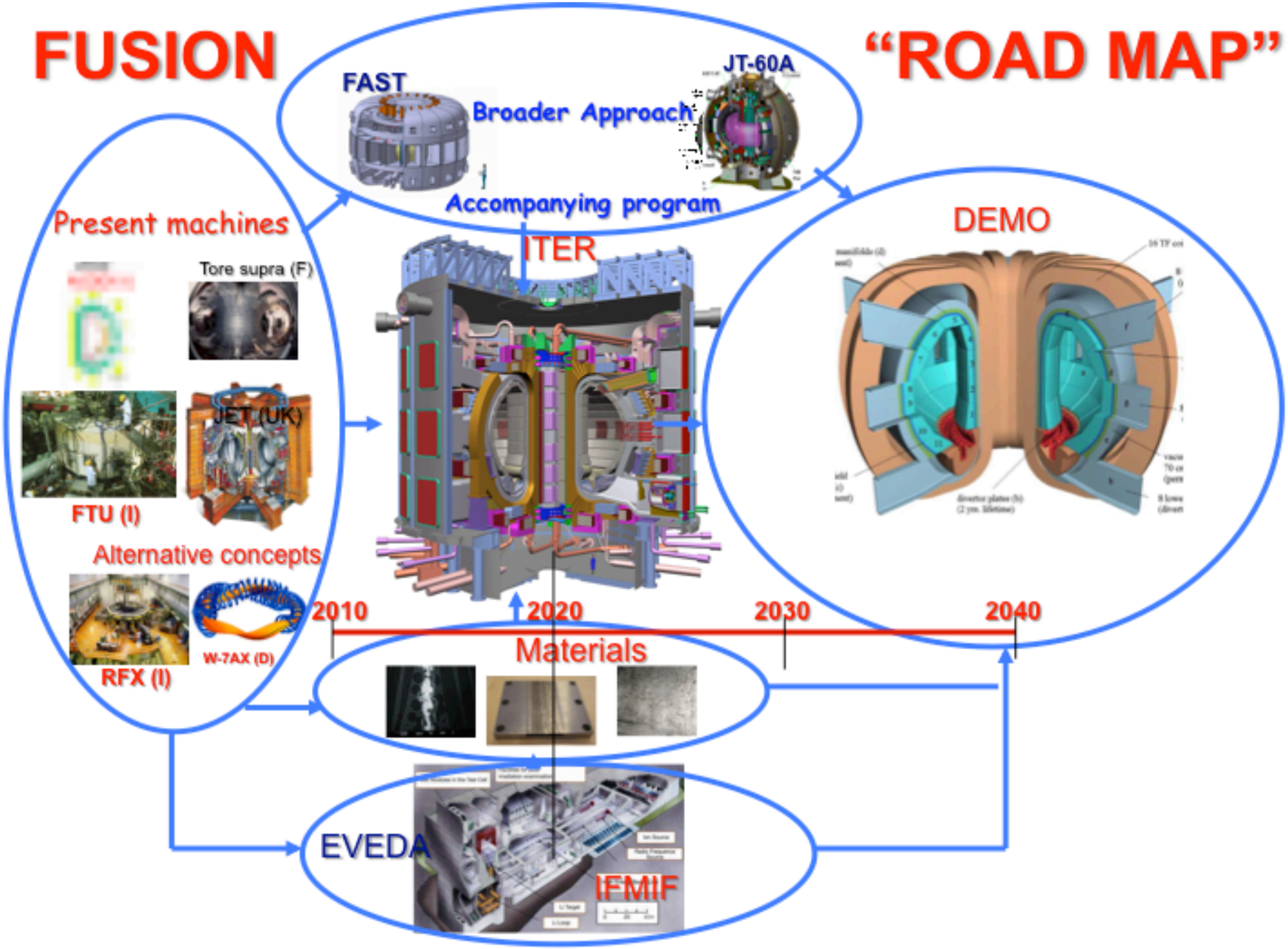


SPIDER
Source for **P**roduction of **I**on of **D**euterium **E**xtracted from **R**f plasma



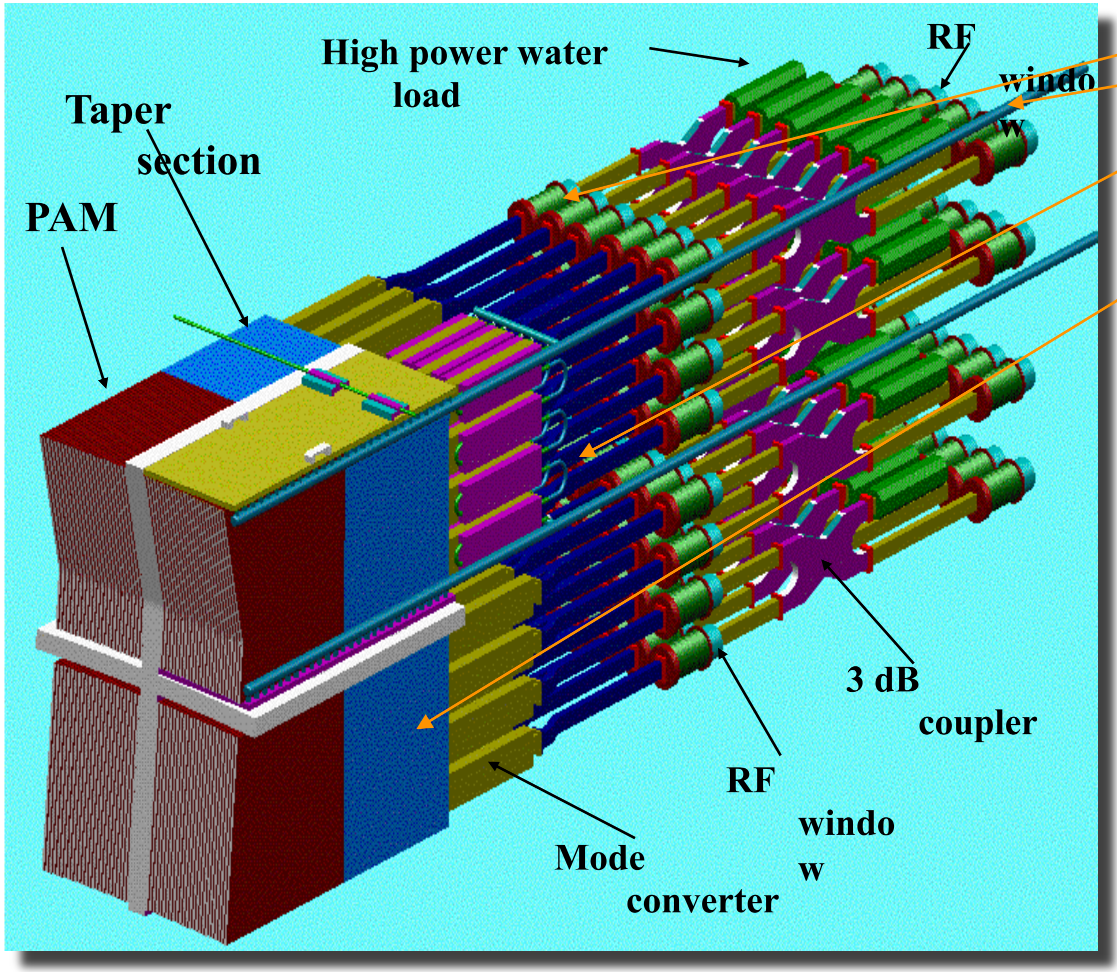
MITICA
Megavolt **IT**ER **I**njector & **C**oncept **A**dvancement

FUSION "ROAD MAP"



ITER LH: Launcher design

- PAM Grill Efficiently water cooled
- Power density: 33 MW/m² at 5 GHz
- 4 blocks (4 x 12 x 24a/25p waveguides) Each block:



-3x4+3x2 RF windows

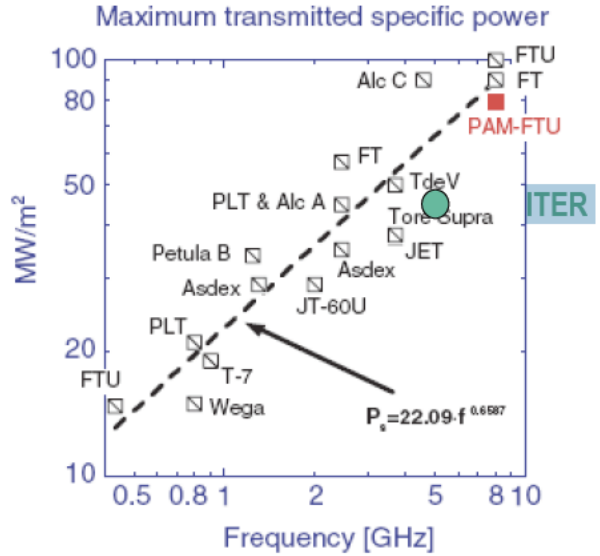
-3x4TE$_{10}$toTE$_{30}$ mode converter

-E plane 270°- 8 waveguides MJ

$n_{//}$ = 1.9 to 2.1

directivity ~0.7 (lowest density)

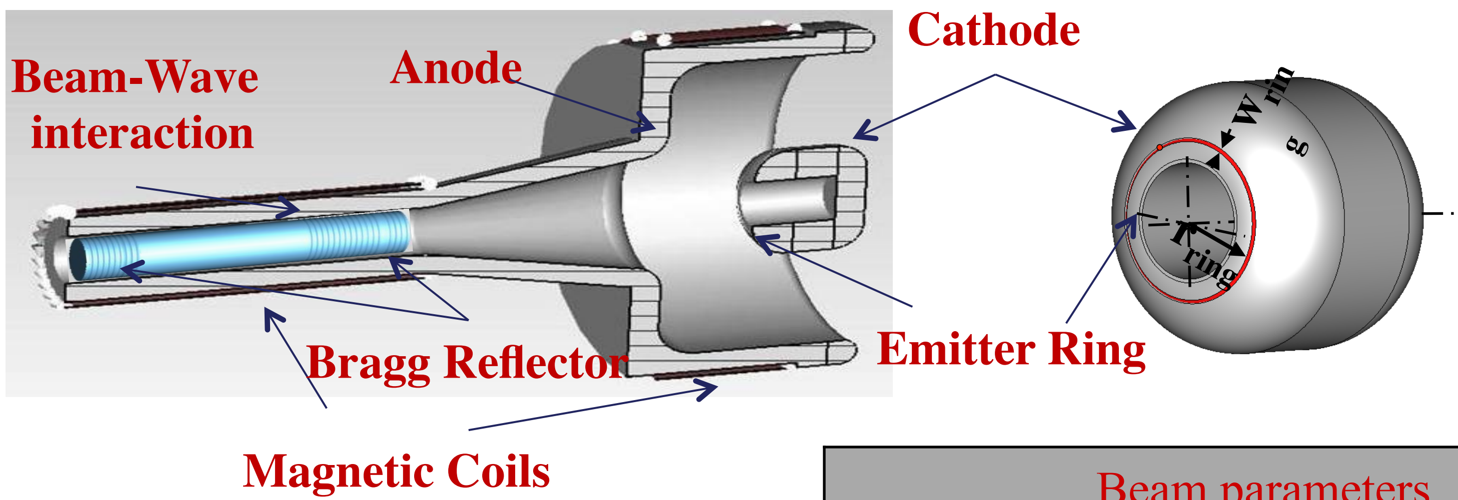
R <3% even near the cut of



Next step in Electron Cyclotron high frequency generator

Demonstrative Tokamak "DEMO" will have so high electron temperature T_e > 50 keV that Electron Cyclotron absorption will be shifted outward by tail resonance. Heating plasma core will require frequency in excess of 250 GHz: New sources need to be developed

To this purpose ENEA Colleagues of FEL Team in Frascati are developing a generator based on the CARM (Cyclotron Auto-Resonance-Maser) concept

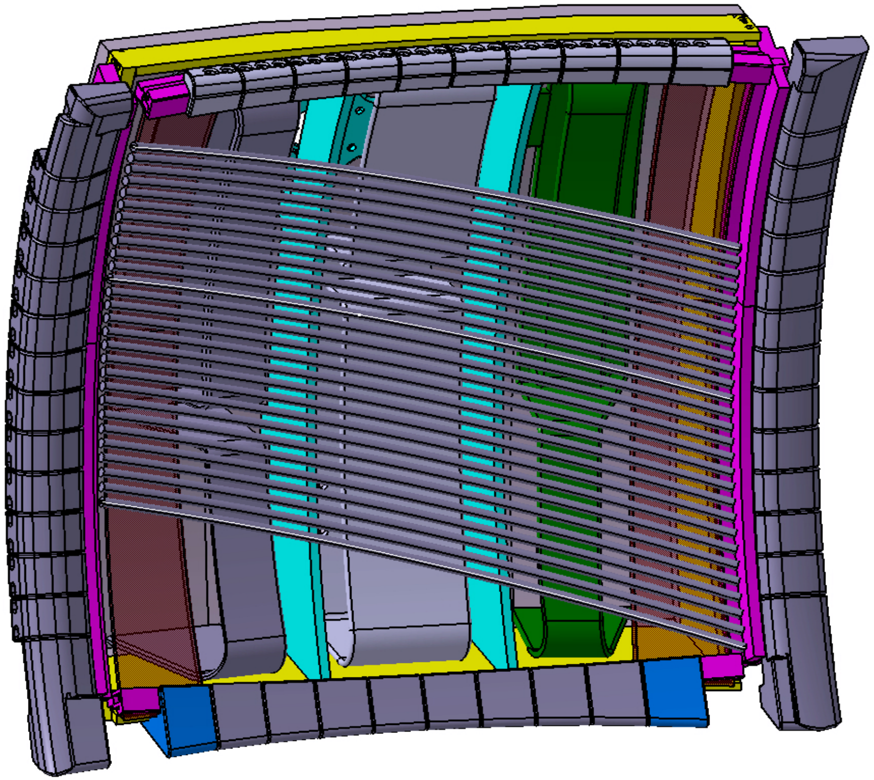


Device Efficency	
Beam – Wave interaction efficency	30 %
Efficency due to energy recovery	20 ÷ 30 %
Total projected efficency	50 ÷ 60 %

Beam parameters	
Beam Current	3 ÷ 10 A
Pitch ratio $\alpha = v_{\perp}/v_{ll}$	<0.5
Axial and transverse velocity spread	<0.1÷0.3 %
Beam Energy Recovery	20 ÷ 40 %

New ICRF Antenna 3 Straps Antenna

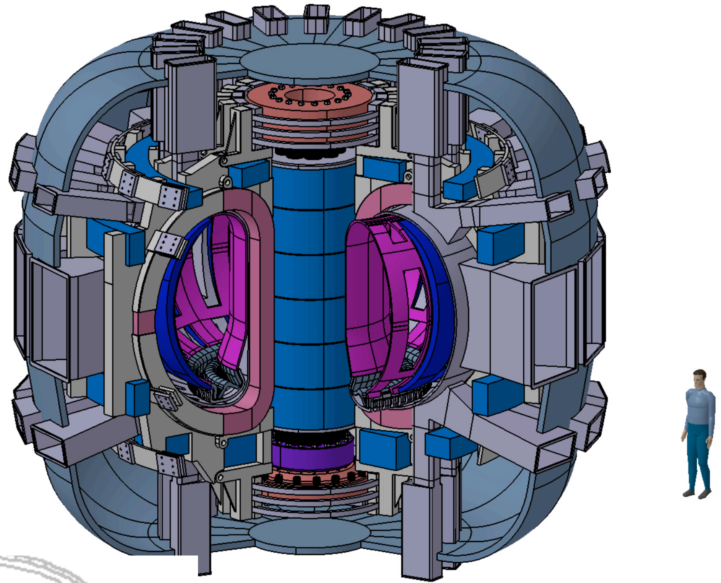
A collaboration between ENEA-I, ASIPP-Cn, IPP-D to test a low parallel electric field ICRF antenna on Asdex-UpGrade

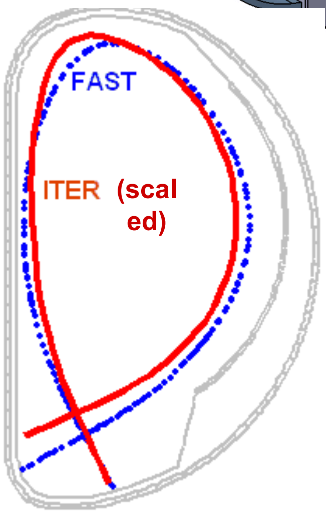


Designed with 3D RF code TOPICA developed at PoliTo, antenna matching computed with real plasma load (HFSS, Microwave studio use dielectrics)

The collaboration aims at finding solution for next generation high power ICRF experiments in presence of high Z material (W, Mo)

FAST: an Integrated Experiment Also testing high RF power issues





The ITER magnetic Topology (plasma shape) is guaranteed, for any Plasma Scenarios, by using the Extreme Shape Controller

Plasma Current (MA)	≤ 8 (*10*)
B_T (T)	≤ 8.5
Major Radius (m)	1.82
Minor Radius (m)	0.64
Elongation k_{95}	1.7
Triangularity δ_{95}	0.4
Safety Factor q_{95}	~ 3 (*2.3*)
V_p (m^3)	23
<n>(m^{-3})	≤ 5.5×10^{20}
Flat-top B_T (s)	15 -> 170
H&CD power (MW)	40 (->50)
ICRH	30 (->15)
ECRH	4 (->15)
LH	6 (->10)
NNBI	10 (tbd)
P/R (MW/m)	22
Q	~ 1.5 (*3*)