Fusion Reactor Technology I
(459.760, 3 Credits)

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Gap Analysis for Fusion Development

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma physics/ Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady-state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Heating, current drive and fuelling	1	2		r	R	R
	Remote handling	1	2		R	R	R
Materials & Component Nuclear performance & lifetime	Materials characterisation			3	R	R	R
	Plasma-facing surface	1	2		3	4	R
	Vessel/First Wall /blanket/divertor materials		1	1	3	4	R
	Vessel/ First Wall /blanket/divertor components		1	1	2	4	R
	T self sufficiency		1		3	R	R
Final System	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Outputs:		
	1	Will **help to resolve** the issue
	2	**May resolve** the issue
	3	**Should resolve** the issue
	4	**Must resolve** the issue

Inputs:		
	r	**Pre-existing Solution is desirable**
	R	**Pre-existing Solution is a requirement**

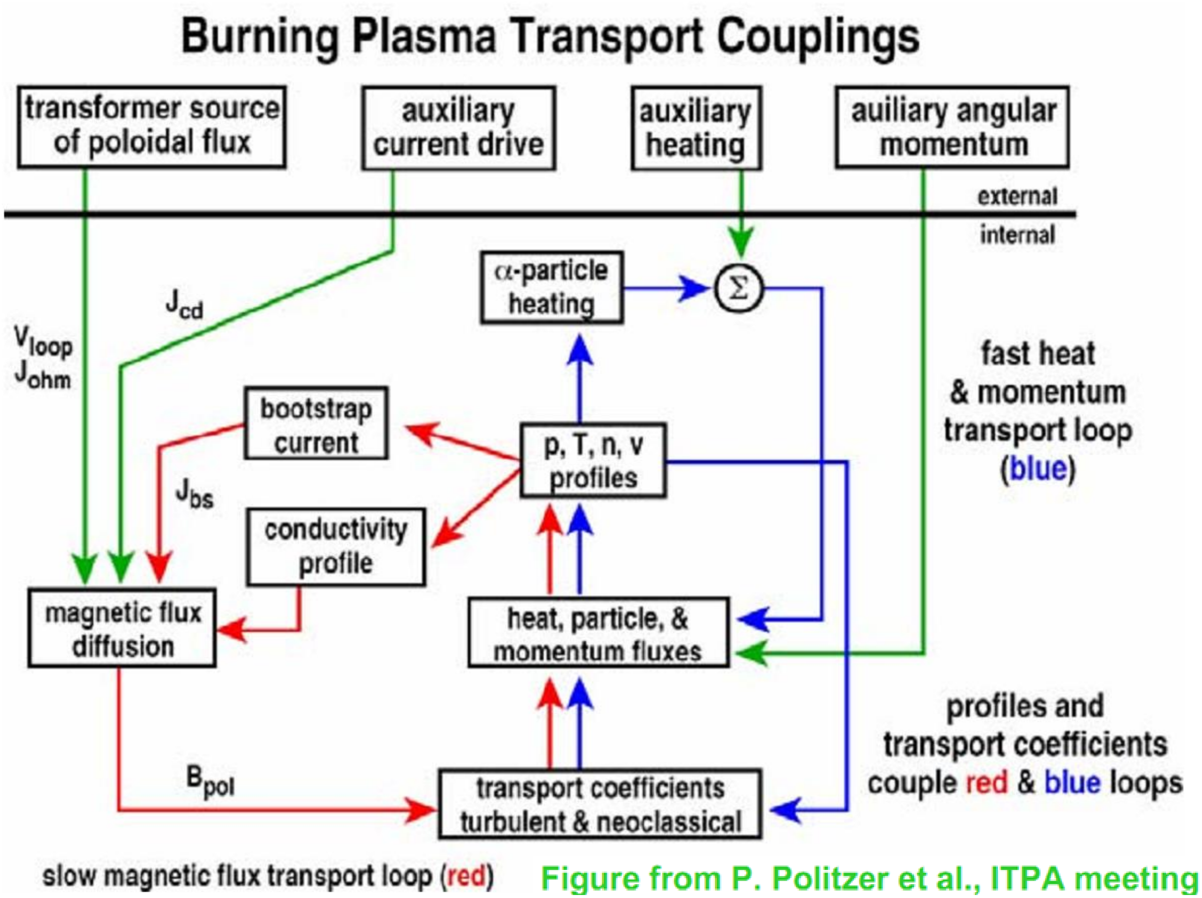
UKAEA October 2007 (revised/improved version of original table in **UKAEA FUS 521, 2005**).

I. Cook, D. Ward, L. Baker and T. Hender, "Accelerated Development of Fusion", UKAEA FUS521, February 2005

Self-Generated and Linked Control

Alpha heating dominant, $Q=P_f/P_{H\&CD}$ > 20-30
Bootstrap current fraction, f_b> 70%

← Reduce H&CD power for high Q



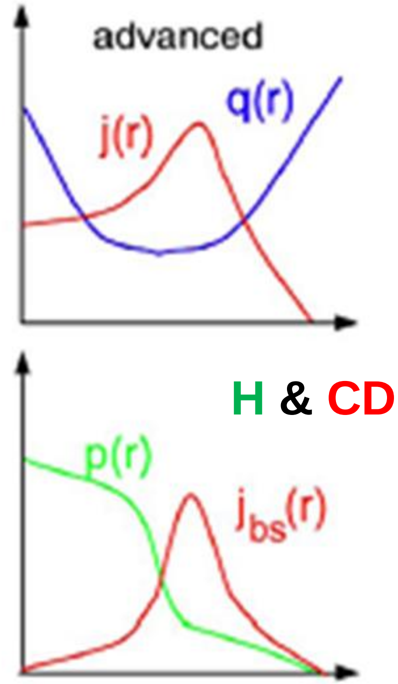
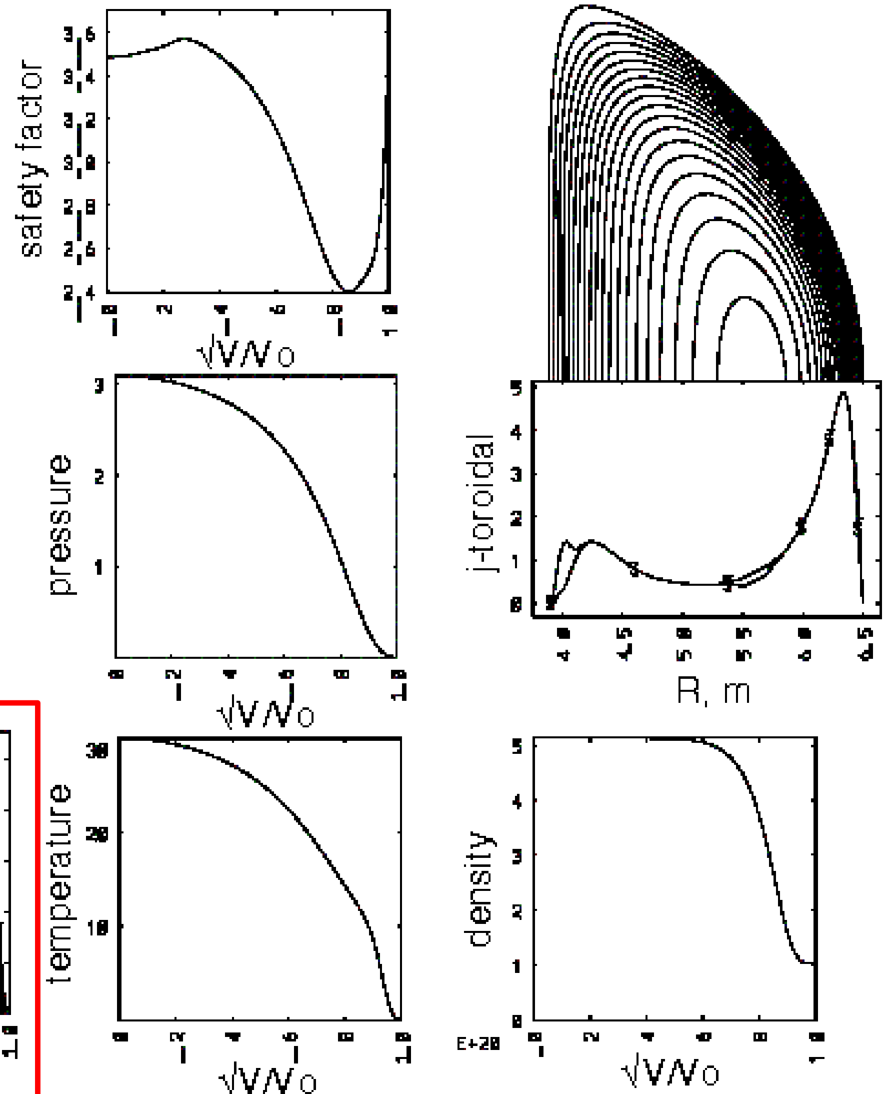


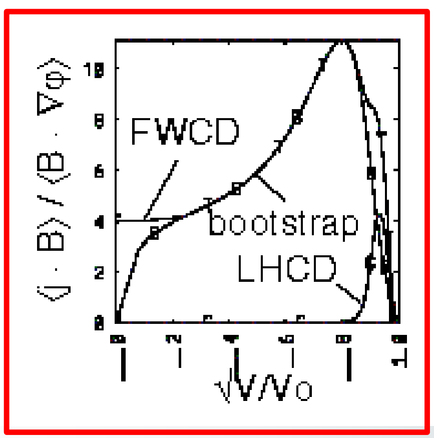
Figure from P. Politzer et al., ITPA meeting Lisbon 2004

→ Physics Issue: Transport Control for AT regime operation

ARIES-AT Equilibrium

I_p = 12.8 MA
B_t = 5.86 T
R = 5.20 m
a = 1.30 m
κ_x = 2.20
δ_x = 0.90
β = 9.15%
β_N = 5.40
I_{bs} = 11.4 MA
I_{self}/I_p = 0.91
I_{CD} = 1.25 MA
li(3) = 0.29
q_{cyl} = 1.85



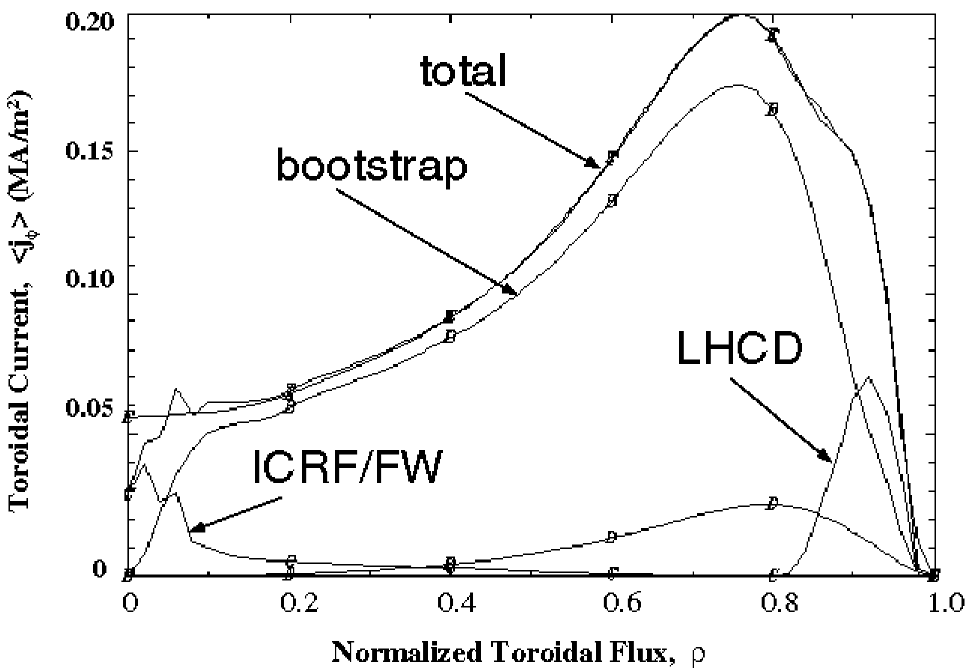


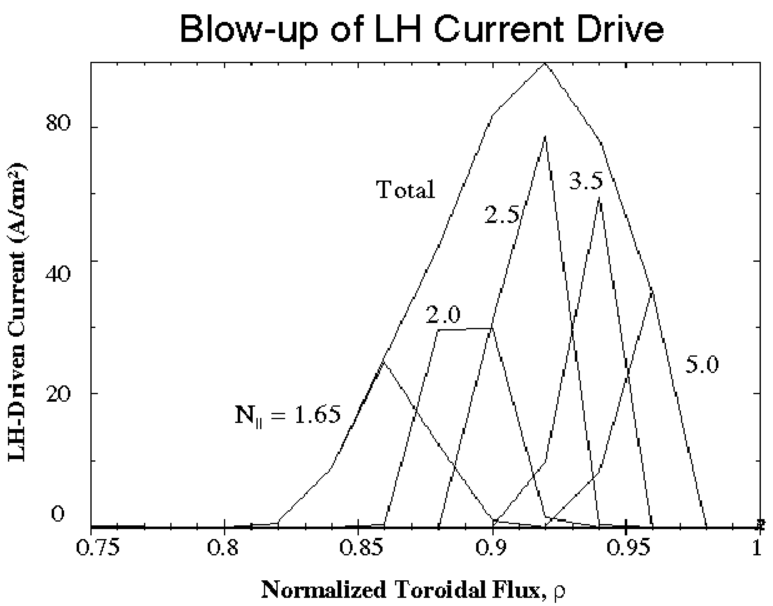
ARIES-AT External Current Drive

ICRF/FW on-axis CD; 96 MHz, $N_{||}$=2, P_{CD}=5 MW, h=0.032 A/W

LHCD off-axis CD; 3.6 GHz , $N_{||}$=1.65-3.5, P_{CD}=24.5 MW, h=0.024-0.053 A/W;

2.5 GHz, $N_{||}$=5.0, P_{CD}=12.5 MW, h=0.013 A/W



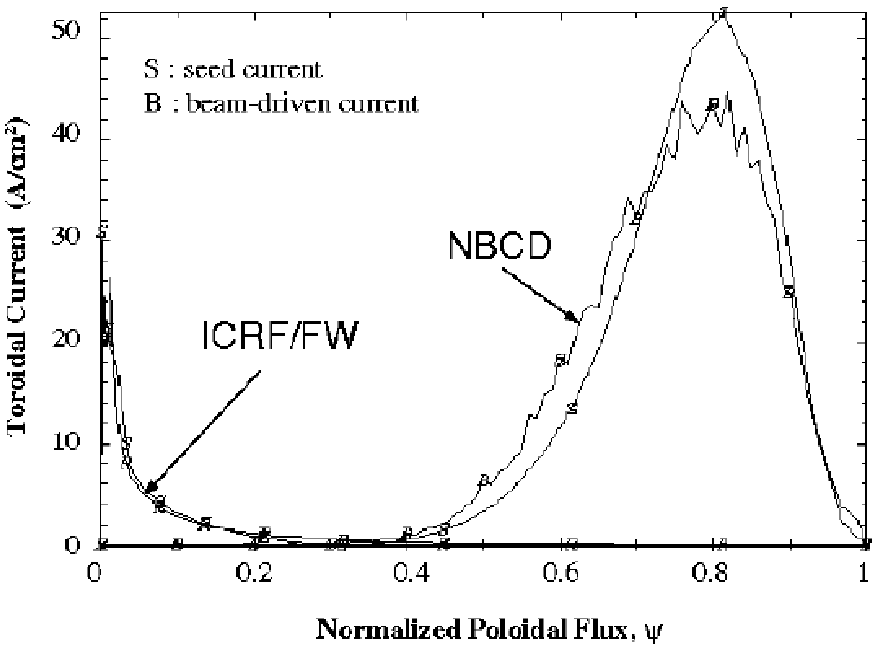


ARIES-AT Alternative Current Drive

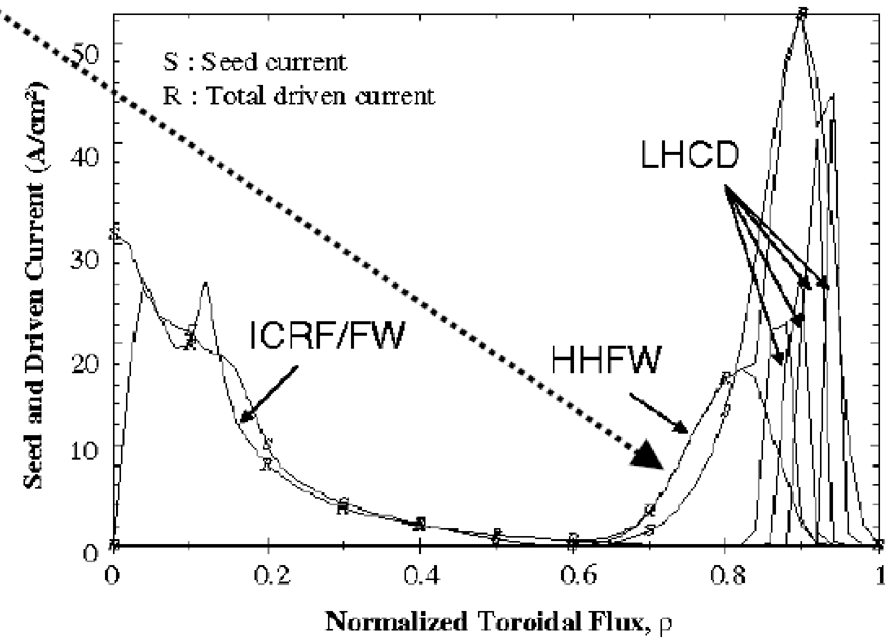
120 keV NBI provides plasma rotation and CD for $\rho > 0.6$, $P_{NB} = 44$ MW, $P_{FW} = 5$ MW (NFREYA)

HHFW at $20\omega_{ci}$ provides current at $\rho > 0.7 - 0.9$, $P_{LH} = 20$ MW, $P_{HHFW} = 20$ MW, $P_{FW} = 5$ MW

ARIES-AT



ARIES-AT



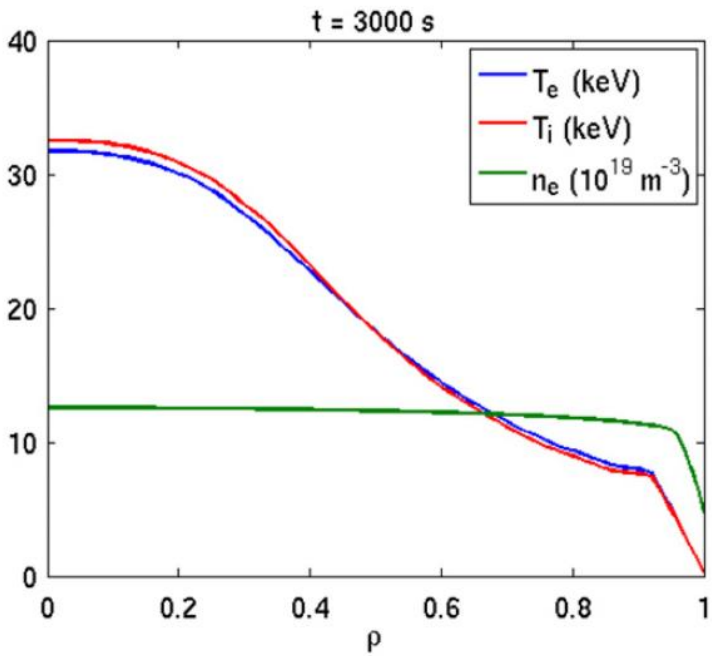
EU DEMO CD Scenarios Based on PPCS-C

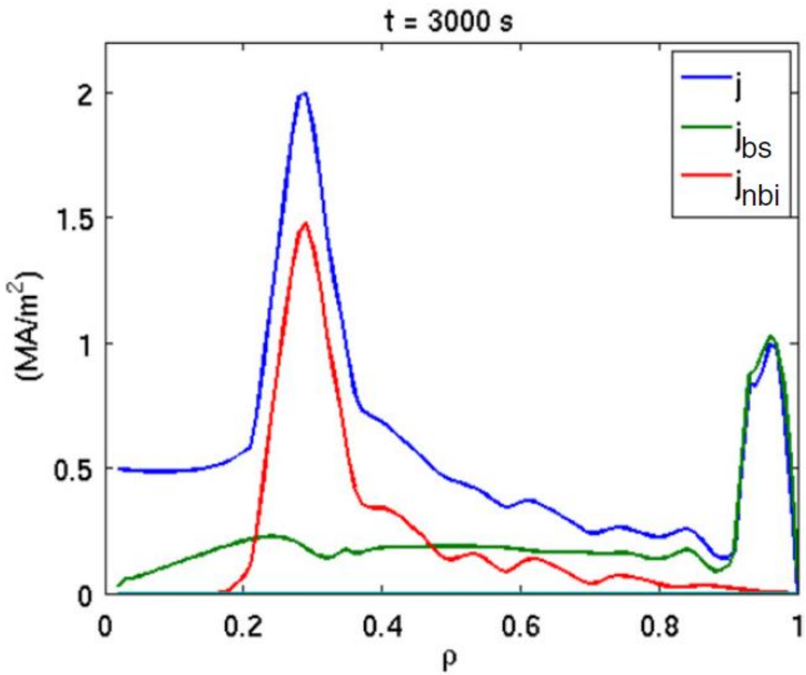
Global characteristics of the DEMO operation scen

Parameter	Value
Major radius R (m)	7.5
Minor radius a (m)	2.5
Elongation/Triangularity	1.9/0.47
B_t(T)	6.0
I (MA)	19.0
$n_{e,0}/\langle n_e \rangle$ (10^{19} m^{-3})	11.0/10.1
n_e/n_{gw}	1.20

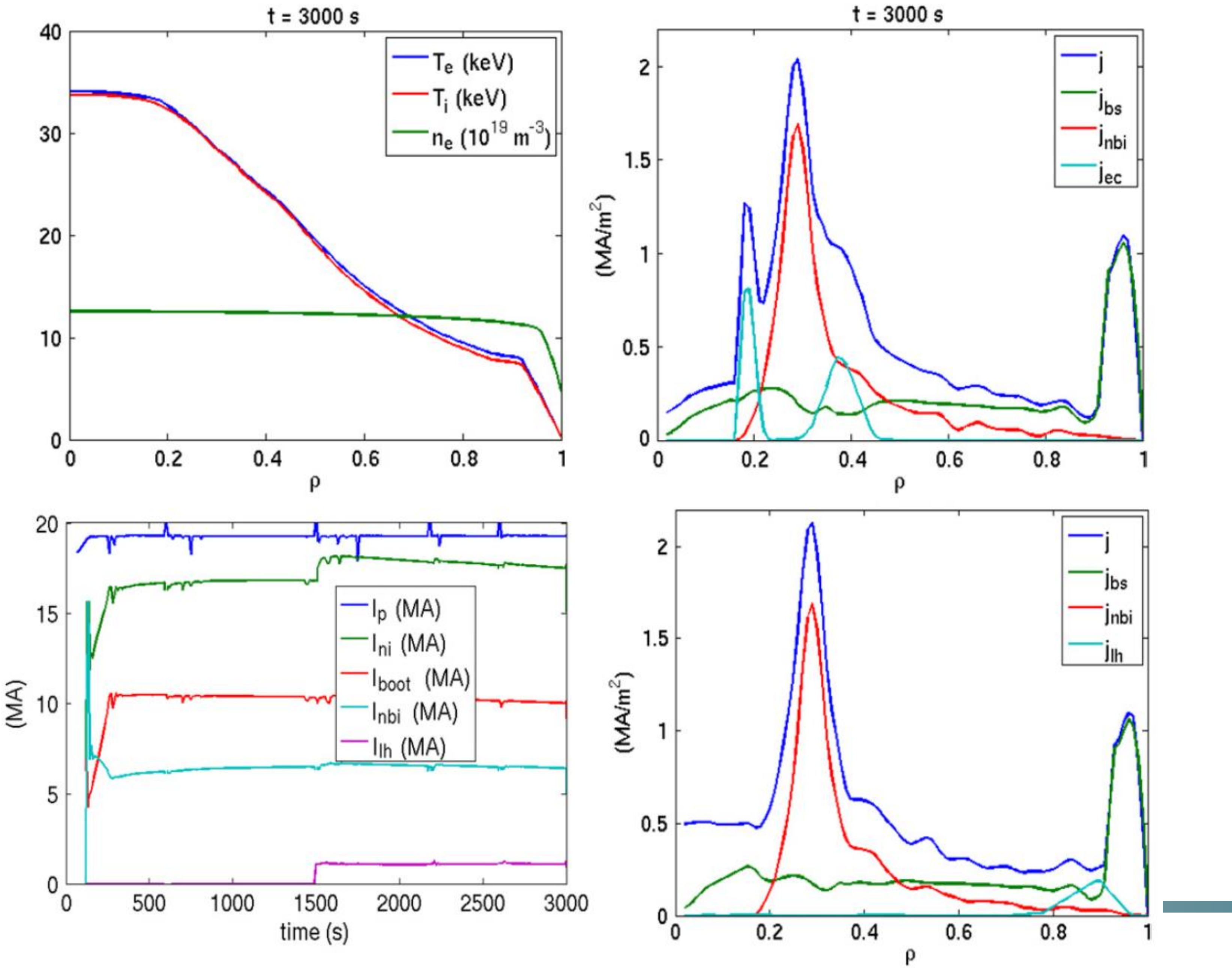
Table 3. Global results of the DEMO operation scenarios.

Parameter	Scenario 1	Scenario 2	Scenario 3
$T_{e,0}$ (keV)/$\langle T_e \rangle$ (keV)	31.7/14.6	34.5/15.4	31.7/14.5
$T_{i,0}$ (keV)/$\langle T_i \rangle$ (keV)	32.5/14.5	34.3/15.0	32.0/14.4
P_{fus}/P_{add} (MW)	2600/98.0	2820/164	2600/164
P_{ES}/P_{brems} (MW)	28.0/104	34.0/107	28.0/104
f_{BS} (%)/Q	52.6/26.5	55.8/17.2	52.1/16.4
q_0/q_{95}	2.6/6.0	10.0/6.0	2.7/6.0





EU DEMO CD Scenarios Based on PPCS-C



H & CD Efficiency for DEMO

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Three steps

1. conversion of electric power into power launched in plasma: conversion efficiency η_{conv}
2. coupling of launched power to plasma: coupling efficiency η_{coupl}
3. current drive efficiency (current driven per power unit coupled to plasma ε_{CD})

$$P_{enet} = P_{egross} - P_{eHCD} - P_{eBoP} = P_{egross} - I_{CD}/\eta_{conv}\,\eta_{coupl}\,\varepsilon_{CD} - P_{eBoP}$$

	Wall-plug to coupled power efficiency		CD efficiency (DEMO-like plasmas)
	CONVERSION (Technology)	COUPLING (Physics) (Technology)	PHYSICS
NNBI	Low (20-30%)	high	high
ICRH	Medium (40-50%)	low-medium	medium
LHCD	Medium (40-50%)	medium	high
ECRH	Low-Medium (20-40%)	high	low-medium

→ Physics Issues: coupling and CD efficiency at high density plasmas

→ Technology Issues: power source efficiency, launcher compatibility

H & CD Efficiency for DEMO

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- DEMO assumptions:
  $\eta_{WP} \bullet \gamma_{CD} = 0.24 - 0.27$
- Negative NBI $\eta_{WP} \bullet \gamma_{CD} \sim 0.12 - 0.14$
- ECCD $\eta_{WP} \bullet \gamma_{CD} \sim 0.08$
- ICRF $\eta_{WP} \bullet \gamma_{CD} \sim [0.18 - 0.24] \bullet f_{coupled}$
  (where $f_{coupled}$ = fraction of generator power coupled at edge of plasma ~ 0.4 max H-mode – note no experiment has ever coupled >12MW ICRF power into an H-mode) ~0.07 – 0.095 for H-mode
- Lower Hybrid CD $\eta_{WP} \bullet \gamma_{CD} \sim [0.15 - 0.18] \bullet f_{coupled}$
  (LH klystrons are ~ 50% efficient – again $f_{coupled}$ is fraction of generator power coupled by grill to plasma – note, no experiment has ever coupled more than 4MW LH power into an H-mode)
- With these levels the installed CD powers on PPCS power plants go up considerably

→ Physics Issues: coupling and CD efficiency at high density plasmas
→ Technology Issues: power source efficiency, launcher compatibility

H & CD Efficiency for DEMO

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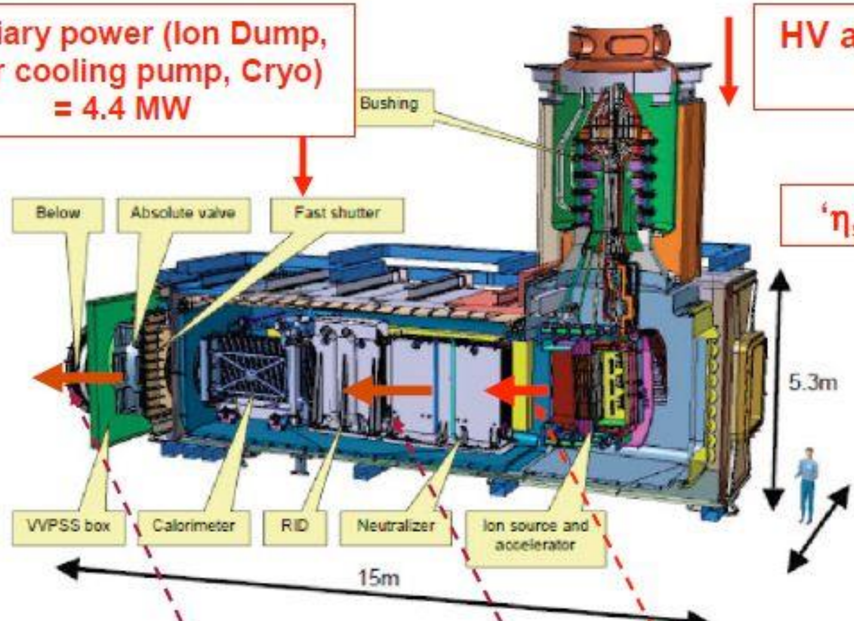
assumptions vs reality (III) - NBI system efficiency: ITER System

Auxiliary power (Ion Dump, water cooling pump, Cryo) = 4.4 MW

HV and Source power = 58.2 MW



'η_{source}' ~ 40.8/(58.2+4.4) ~ 0.66

Source – courtesy R S Hemsworth - ITER

NB to plasma = 18.8 MW

Neutralised Beam = 23.2 MW

Accelerated beam =40.8 MW

η_{TR} ~ 18.8/40.8 ~ 0.46

Overall heating efficiency

For NBI η_{WP} ~ 0.66x0.46 ~ 0.30

Predicted current drive efficiencies extrapolated to DEMO temperatures:

Neutral Beam (1.5 MeV)	γ ~ 0.4 - 0.45
Electron Cyclotron CD	γ ~ 0.15
Ion Cyclotron	γ ~ 0.3 - 0.4
Lower Hybrid CD	γ ~ 0.3 - 0.35

NB Technical Issues for DEMO

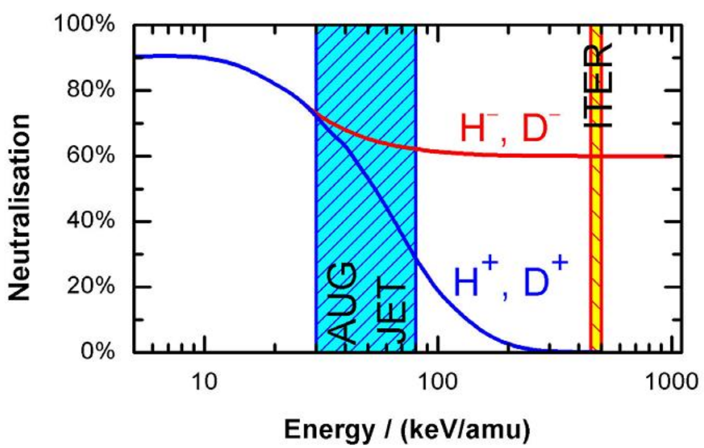
◆ Negative-Ion Neutral Beam Injector

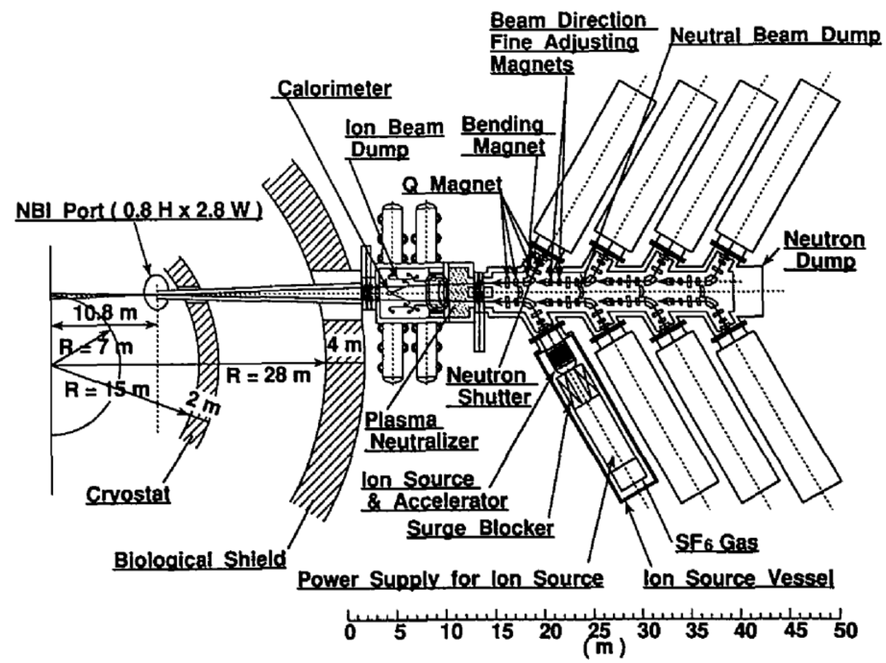
- ➢ RF negative ion source: Cesium free ?
- ➢ Neutron shielding: slit extraction and beam bending
- ➢ Advanced neutralizer: photo or plasma neutralizer
- ➢ High energy acceleration: RFQ ?

Fusion Engineering and Design 23 (1993) 49-55
North-Holland 49

Conceptual design of a 2 MeV neutral beam injection system for the Steady State Tokamak Reactor

M. Mizuno [a], M. Hanada [a], T. Inoue [a], Y. Ohara [a], Y. Okumura [a], S. Tanaka [a], K. Watanabe [a], M. Asahara [b], K. Konishi [b], H. Nakazato [c] and A. Ozaki [d]
[a] Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken, 311-01, Japan
[b] Sumitomo Heavy Industries Ltd., Japan
[c] Nissin Electric Co. Ltd., Japan
[d] Toshiba Corporation, Japan





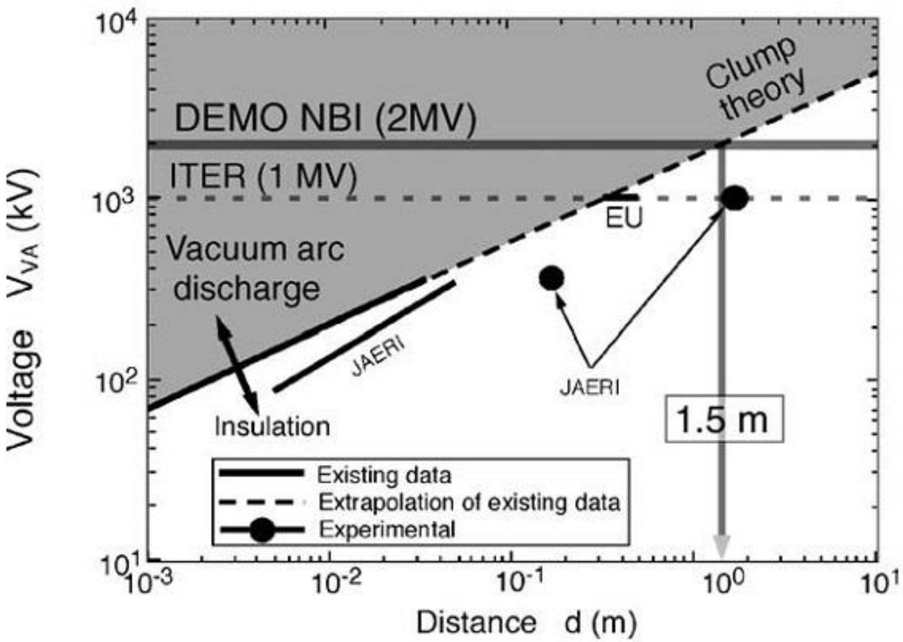
A comparison of accelerator types for NB system of fusion DEMO plant

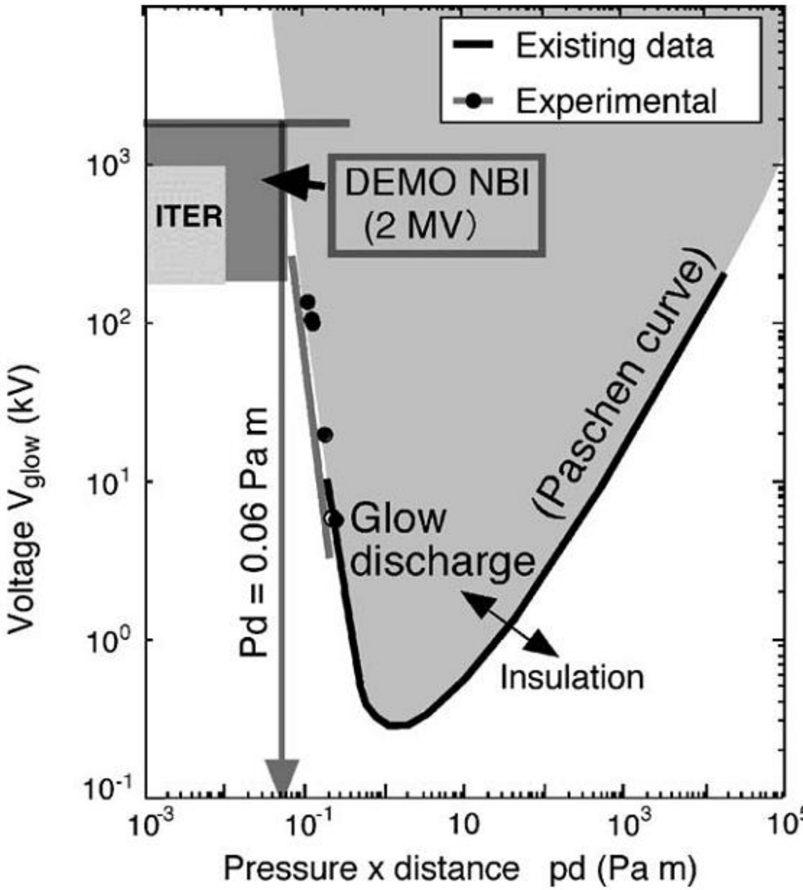
	Electrostatic accelerator	RFQ accelerator
Beam energy	1.5–2.0 MeV, limited by vacuum insulation	>2 MeV
Current	Up to several tens ampere	In the order of 100 mA
Acceleration efficiency	≥90%	~25%
Technology basis	Extrapolation of existing technology	New development required

HW. RFQ?

NB Design for J-DEMO

Inoue, FED2006





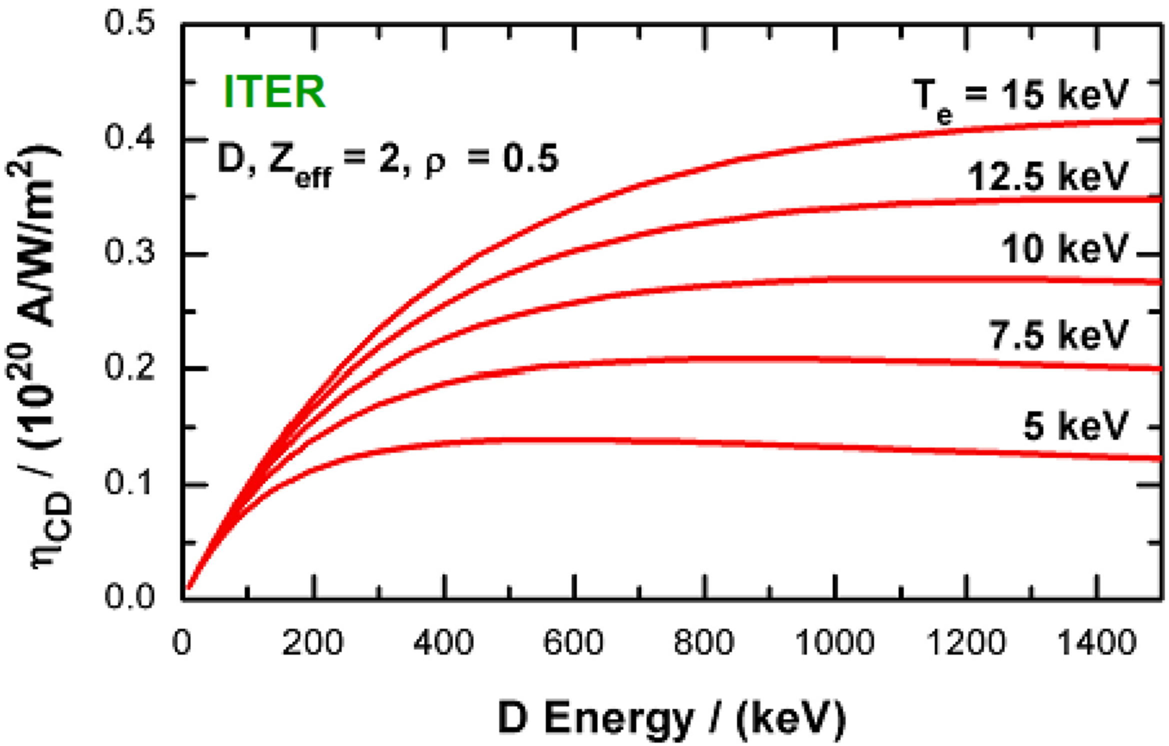
From Fig. 1, necessary insulation distance to avoid vacuum arc discharge is estimated to be 0.8–1.5 m for 1.5–2 MeV. From Fig. 2, it is found that the threshold *Pd* value for the glow discharge is 0.06 Pa m. One of the crucial positions for the glow discharge would be along the accelerator exterior: The vacuum insulation distance is 1.5 m for 2 MV, and the pressure is assumed to be 0.02 Pa from the ITER design (*Pd* = 0.03 Pa m).

NB Current Drive Efficiency

$$\eta_{CD} = \frac{I_{NBCD} n_e R}{P_{dep}}$$

$$I_{NBCD} = I_{NB} + I_R = I_{NB}\left(1 - G \cdot \frac{Z_b}{Z_{eff}}\right)$$

deposition power of the beam P_{dep}



ITER: 2 MA current drive! (33 MW heating power)

EC for DEMO

- **functions of EC waves in DEMO: same as in ITER ?**
  - plasma startup
  - heating for access to H-mode
  - q-profile control (mid-radius CD)
  - MHD control (NTM, other ?)
  - CD for steady-state ?
  - Bootstrap control ?
  - Impurity control ?
  - Disruption control ?

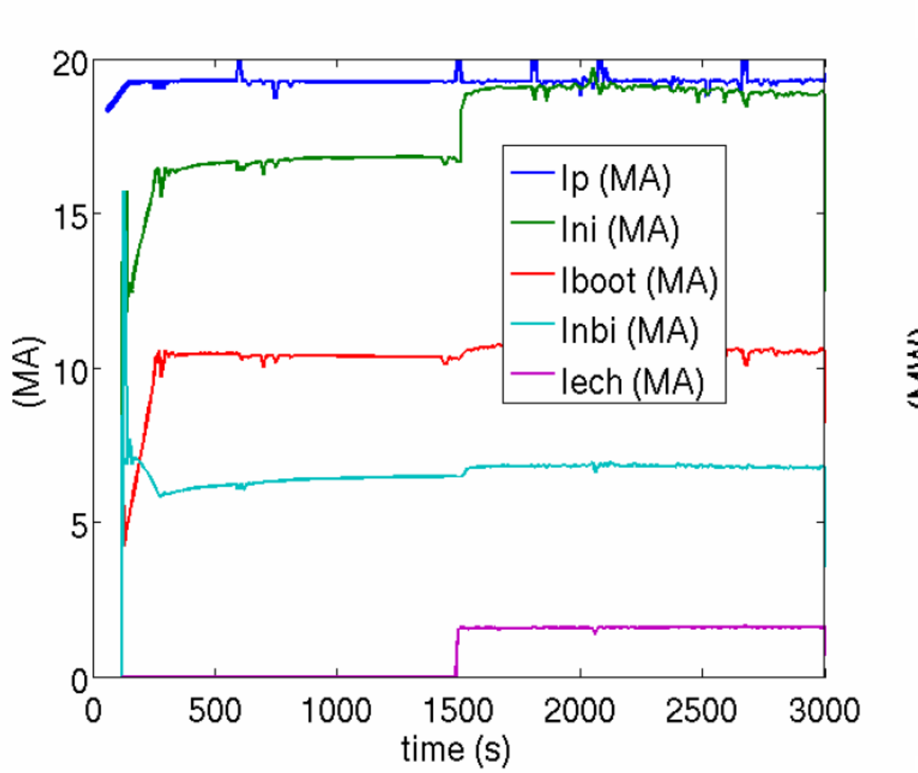
- **likely system requirements:**
  - frequency ~ 200 GHz, cw, power ~ 50 – 100 MW
  - full control of absorption location
  - efficiency / availability / reliability

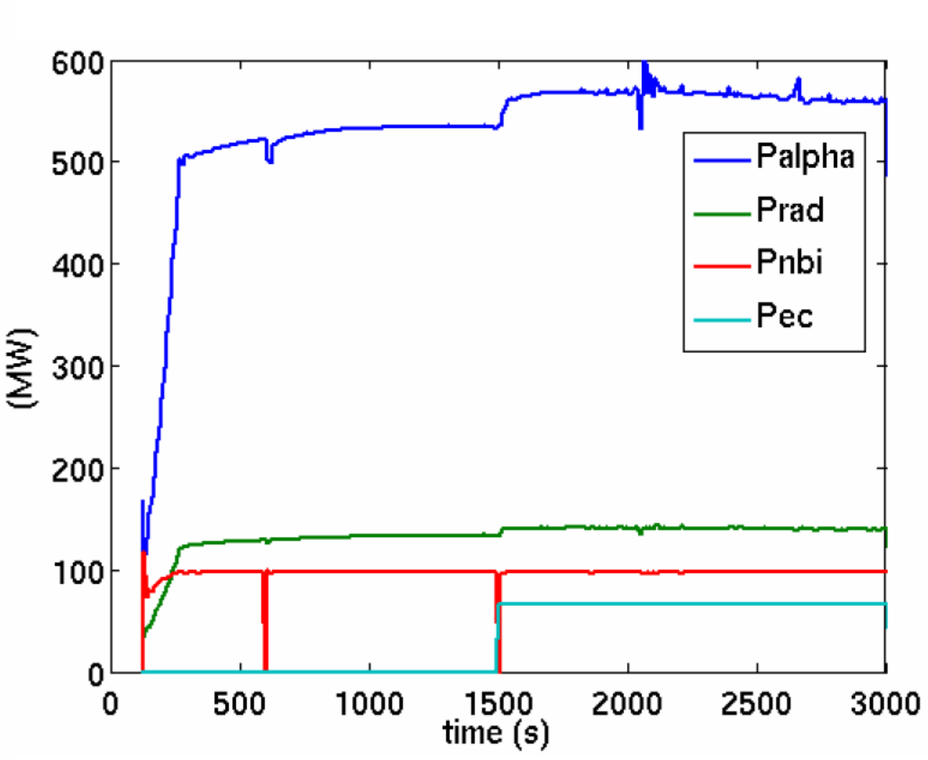
    (to be quantified in function of the missions of DEMO …)

Steady-State Scenario with ECCD Global Parameters

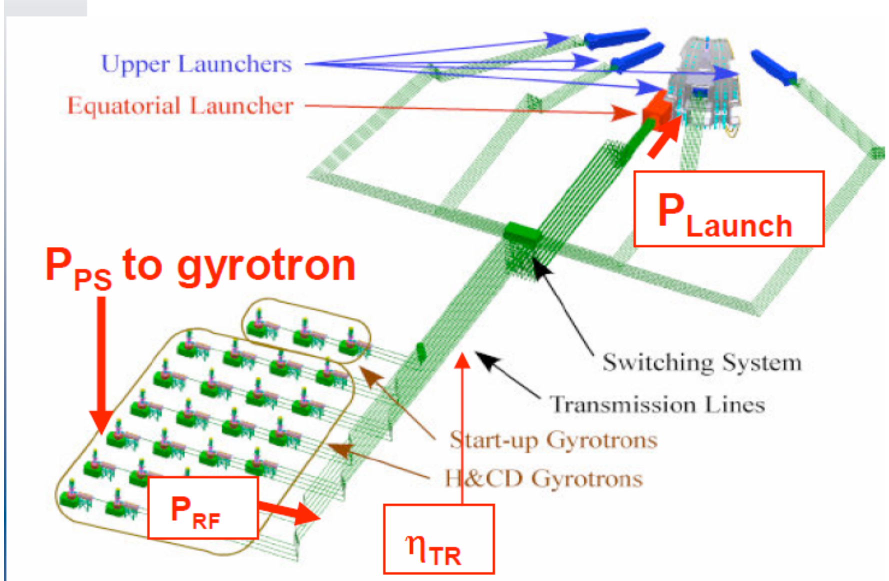
G. Giruzzi

- I_p = 19 MA, $\mathbf{B_T = 6\ T}$, $n_{e0} = 1.25\ 10^{20}\ m^{-3}$
- $f_D/(f_D+f_T)$ = 50%, f_{Be} = 3%, f_{Ar} = 0.12%, $\tau_{He}^*/\tau_E = 5$ ($Z_{eff} \sim 1.9$)
- P_{NBI} = 98 MW (2 MeV, **off-axis**), P_{EC} = 66 MW (**200 GHz**, t > 1500 s)
- **transport model: GLF23** $T_{ped} \approx 7.8$ keV

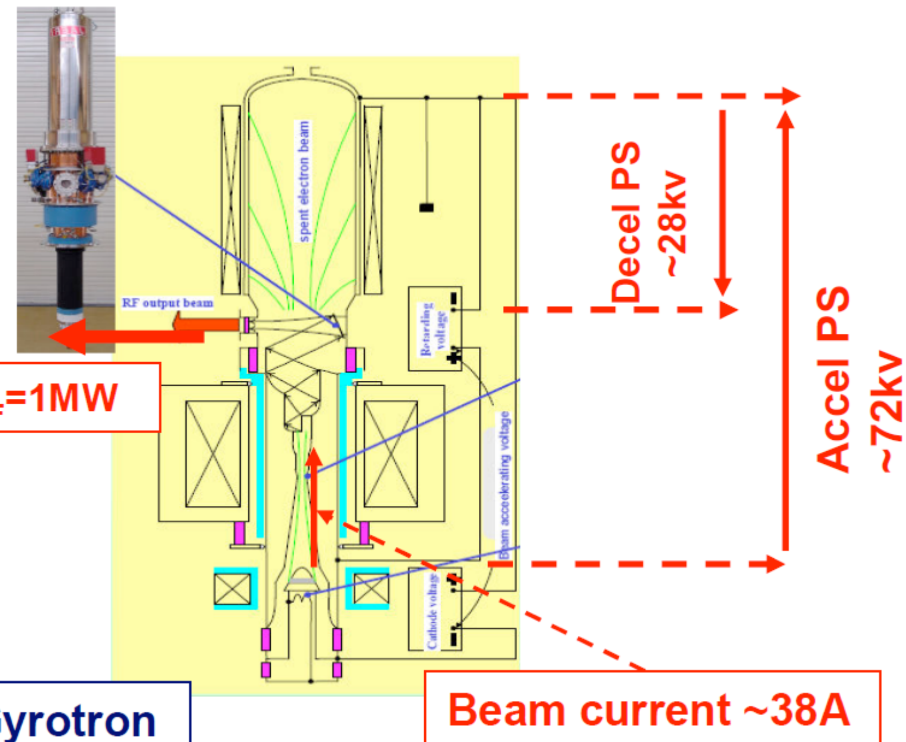


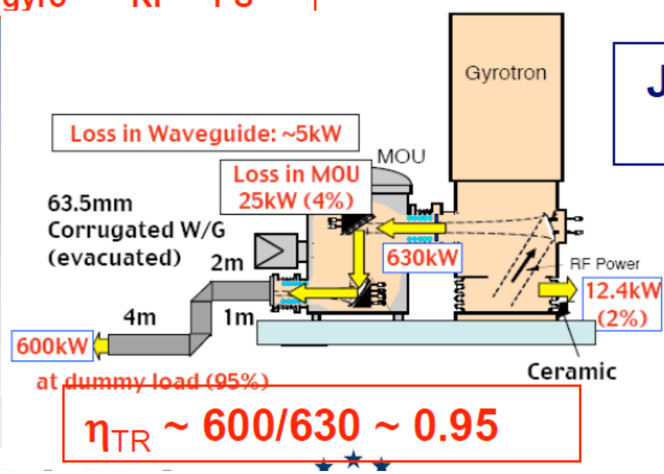


ECH for DEMO



$\eta_{gyro} = P_{RF}/P_{PS}$





η_{TR} ~ 600/630 ~ 0.95

Japanese Gyrotron
η_{gyro}= 55%

For ECRH η_{WP} ~ 0.55x0.95 ~ 0.52

See eg. Ref [22] Kasugai et al., and refs therein

EC Technical Issues for DEMO

- **Launcher**
  - Steering mirror at high heat and neutron irradiation
  - Remote wave launcher
- **Power sources : Gyrotron or FEM (Free Electron Maser) ?**
  - High frequency(>200GHz), high power(>1MW), CW sources
  - Efficient(>50%): multi-stage depressed collector
  - High power window: synthetic diamond
  - Multi-frequency source

Comparison of Gyrotron and FEM Oscillators

Table XXXIV lists a comparison of the main performance parameters and features of gyrotron oscillators and FEMs for ECRH of plasmas in nuclear fusion research. The important advantage of the FEM is its fast and continuous frequency tunability and the possibility of very high peak power but the gyrotron is a much simpler device [4]. Up to now, the cylindrical cavity gyrotron is the only millimeter wave source which has had an extensive on-the-field experience during fusion plasma heating experiments over a wide range of frequencies and power levels (8-170 GHz, 0.1-1.0 MW) [5].

	Gyrotron Oscillator (cyclotron resonance maser axial magnetic field)	Free Electron Maser Oscillator (periodic transverse magnetic field)
1. Beam voltage	low (70 - 95 kV)	high (0.2 - 2 MV)
2. Magnetic field (140 GHz)	high (5.5, 1 st harmonic)	low (0.2 T, wiggler)
3. Frequencies	8 - 650 GHz	270 MHz - visible
4. Frequency tunability	$\Delta U_{beam}+\Delta U_{mod}$: fast step tuning (5%) ΔB: slow step tuning (35%)	ΔU_{beam}: fast continous tuning (10%) slow mechanincal tuning (50%)
5. Electron beam	magnetron injection gun	Pierce elctron gun, acceleration and deceleration tubes, beam optics
6. Ohmic losses in cavity	cutoff cavity 2 kW/cm^2	oversized circuit far away from cutoff
7. Power density in cavity	high	low
8. Longitudinal mode competition in cavity	single mode operation	nonlinear temporal dynamics can bring broad frequency spectrum
9. Linearly polarized output mode	generated by internal quasi-optical mode converter	linearly polarized, low-order resonator mode
10. Number of internal quasi-optical mirrors	2-4 on ground potential 0.9% ohmic losses	15 - 25 phase coherence required mostly on 2 MW potential 6% ohmic losses
11. Absorbed power on first mirror (1 MW, 140 GHz)	3 kW	12 kW
12. Internal microwave diagnostics	not required	required
13. Output power (140 GHz) present status	high average power 1 MW / 12 s 0.92 MW / 1800 s (coax. 2.2 MW / 17 ms)	2 GW/20ns but very low duty cycle (LLNL amplifier)
14. Exp. system efficiency without energy recovery	45% 32%	low 5 - 10%
15. Collector loading	relatively low	high
16. Theor. system efficiency with depressed collector	60% (exp. 50%)	60% (exp. 14%)
17. Physical size	3 m x 3 m x 3 m	12 m x 3 m x 3 m
18. Power per unit (140 GHz)	1 MW (coax., 4 MW)	5 MW

Tunable Free Electron Maser (FEM) Source

Electron beam line (with multi-stage depressed collector)

electron beam current :	12 A
body current :	< 20 mA
gun voltage :	80 kV
type of gun	triode gun, cathode operated in space-charge limited regime
normalized beam emittance	6 p mm mrad (before interaction)
electron beam energy :	1.35 - 2.0 MeV (130 - 250 GHz operation)
acceleration / deceleration :	electrostatic
focusing system	solenoids in period focusing arrays
pulse length	2 ms - 100 ms

Undulator

period	40 mm
pole gap	25 mm
number of periods	34
peak field strength section 1	0.20 T, 20 cells
section 2	0.16 T, 14 cells
drift gap	35 - 60 mm length, adjustable
focusing scheme	equal focusing in x- and y-direction
matching scheme	1/2 cell 1/4 strength, 1/2 cell 3/4 strength

mm-wave system

primary waveguide :	rectangular corrugated
waveguide dimensions :	15 x 20 mm^2
waveguide mode :	HE_{11}
feedback and outcoupling :	via optical beam multiplication in stepped waveguides
feedback coefficient :	adjustable : 0 - 100 %
output window :	Brewster-angle boron-nitride window

mm-wave output power

mm-wave frequency[1)] :	130 - 260 GHz
on-line tunability[2)] :	5 % on ms time-scale
output power :	1 MW
electronic efficiency :	5 %
system efficiency :	> 50 %

1) Slow frequency tuning by changing the electron beam energy from 1.35 to 2.0 MeV, and adjusting the height of the stepped waveguides (mechanical adjustment).

2) Frequency adjustable on ms-time scale, via a sweep of the electron beam energy. The bandwidth of the stepped waveguides is sufficient to sweep over 5%.

Table XXXIII: Design parameters of the FOM-FEM [145-155,750]. The project was terminated in The Netherlands in the autumn of 2001 and is being rebuilt in Israel.

Window Materials for High Power Gyrotron

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Using the available material parameters and employing various beam profiles, finite element computations revealed the options for 170 GHz, 1 MW, CW operation given in Table XII [38-42,45,423]. The diamond options 2 and 3 being water cooled, are preferred for their simplicity, in particular for use as torus window.

	Material	Type	RF-Profile	Cross-Section	Cooling
①	Sapphire/Metal	distributed	flattened Gaussian	rectangular (100 mm x 100 mm)	internally water cooled (300 K) $\tan\delta = 2\text{-}5 \cdot 10^{-4}$, $k = 40$ W/mK
②	Diamond	single-disk	Gaussian	circular ($\varnothing = 80$ mm)	water edge cooled (300 K) $\tan\delta = 2 \cdot 10^{-5}$, $k = 1900$ W/mK
③	Diamond	single-disk Brewster	Gaussian	elliptical (152 mm x 63.5 mm)	water edge cooled (300 K) $\tan\delta = 2 \cdot 10^{-5}$, $k = 1900$ W/mK
④	Silicon Au-doped	single-disk	Gaussian	circular ($\varnothing = 80$ mm)	edge cooled (230 K), refrigerator $\tan\delta = 2.5 \cdot 10^{-6}$, $k = 300$ W/mK
⑤	Silicon Au-doped	single-disk	Gaussian	circular ($\varnothing = 80$ mm)	LN_2 edge cooled (77 K) $\tan\delta = 4 \cdot 10^{-6}$, $k = 1500$ W/mK
⑥	Sapphire	single disk	flattened Gaussian	elliptical (285 mm x 35 mm)	LN_2 edge cooled (77 K) $\tan\delta = 6.7 \cdot 10^{-6}$, $k = 1000$ W/mK
⑦	Sapphire	single disk	Gaussian	circular ($\varnothing = 80$ mm)	LNe or LHe edge cooled (27 K) $\tan\delta = 1.9 \cdot 10^{-6}$, $k = 2000$ W/mK

Note that the power capability of options ②,③,⑤ and ⑦ is even 2 MW.

Table XII: Options for 1 MW, CW, 170 GHz gyrotron windows [38-42,45,423].

High Frequency Gyrotron at 1st Harmonic

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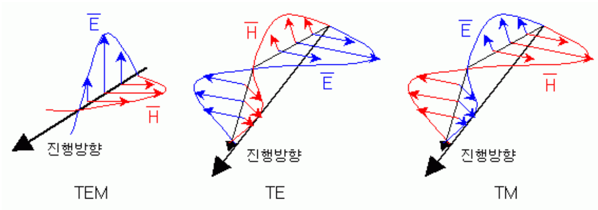
Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [μs]	
IAP, Nizhny Novgorod [65,66]	250	$TE_{20,2}$	0.3	31	30 - 80	
	350		0.13	17	30 - 80	
	430		0.08	10	30 - 80	
	500	$TE_{28,3}$	0.1	8.2	30 - 80	
	540		0.06	6	30 - 80	
	600	$TE_{38,2}$	0.05	5	30 - 80	
	650		0.04	4	40	
MIT, Cambridge [48,217,393,396-401, 468-475]	107.1	$TE_{21,6}$	0.94	24	3	
	110	$TE_{22,6}$	1.67	42	3	
		TEM_{00}	1.5	48 (SDC)	3	
	113.2	$TE_{23,6}$	1.18	30	3	
	140	TE_{04}	0.025	7.4	3	PBG resonator BW = 35%
	140	$TE_{15,2}$	1.33	40	3	
	148	$TE_{16,2}$	1.3	39	3	
	166.6	$TE_{27,8}$	1.50	34	3	
	170.0	$TE_{28,8}$	1.50	35	3	
	173.4	$TE_{29,8}$	0.72	29	3	
	188	$TE_{18,3}$	0.6		3	
	225	$TE_{23,3}$	0.37		3	
	231	$TE_{38,5}$	1.2	20	3	
	236	$TE_{21,4}$	0.4		3	
	267	$TE_{28,4}$	0.2		3	
	280	$TE_{25,13}$	0.78	17	3	
	287	$TE_{22,5}$	0.537	19	3	
	320	$TE_{29,5}$	0.4	20	3	
	327	$TE_{27,6}$	0.375	13	3	
UNIVERSITY, Fukui [450,455]	278	TE_{33}	0.001	5	1000	
	290	TE_{62}	0.001	4	1000	
	314	TE_{43}	0.001	4	1000	

Table XIV: Capabilities and performance parameters of pulsed millimeter- and submillimeter-wave gyrotron oscillators operating at the fundamental electron cyclotron resonance.



Mode란대체무엇일까? (rfdh.com)

High Frequency Gyrotron at 2nd Harmonic

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Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
CPI[1], Palo Alto [445]	250	$TE_{11,1}/TE_{11,2}$	10	3.4	0.1
IAP, N. Novgorod [65,66,446]	157	TE_{03}	2.4	9.5	CW
	250	TE_{02}	4.3	18	CW
	250	TE_{65}	1	5	CW
	326	TE_{23}	1.5	6.2	CW
MIT, Cambridge [447,448]	209	TE_{92}	15	3.5	0.001
	241	$TE_{11,2}$	25	6.5	0.001
	302	TE_{34}	4	1.5	0.0015
	339	$TE_{10,2}$	4	3	0.0015
	363	$TE_{11,2}$	7	2.5	0.0015
	417	$TE_{10,3}$	15	6	0.0015
	457	$TE_{15,2}$	7	2	0.0015
	467	$TE_{12,3}$	22	3.5	0.0015
	503	$TE_{17,2}$	10	5.5	0.0015
UNIVERSITY, Fukui [67-70,449-461]	383	TE_{26}	3	3.7	1
	402	TE_{55}	2	3	1
	576	TE_{26}	1	2.5	0.5

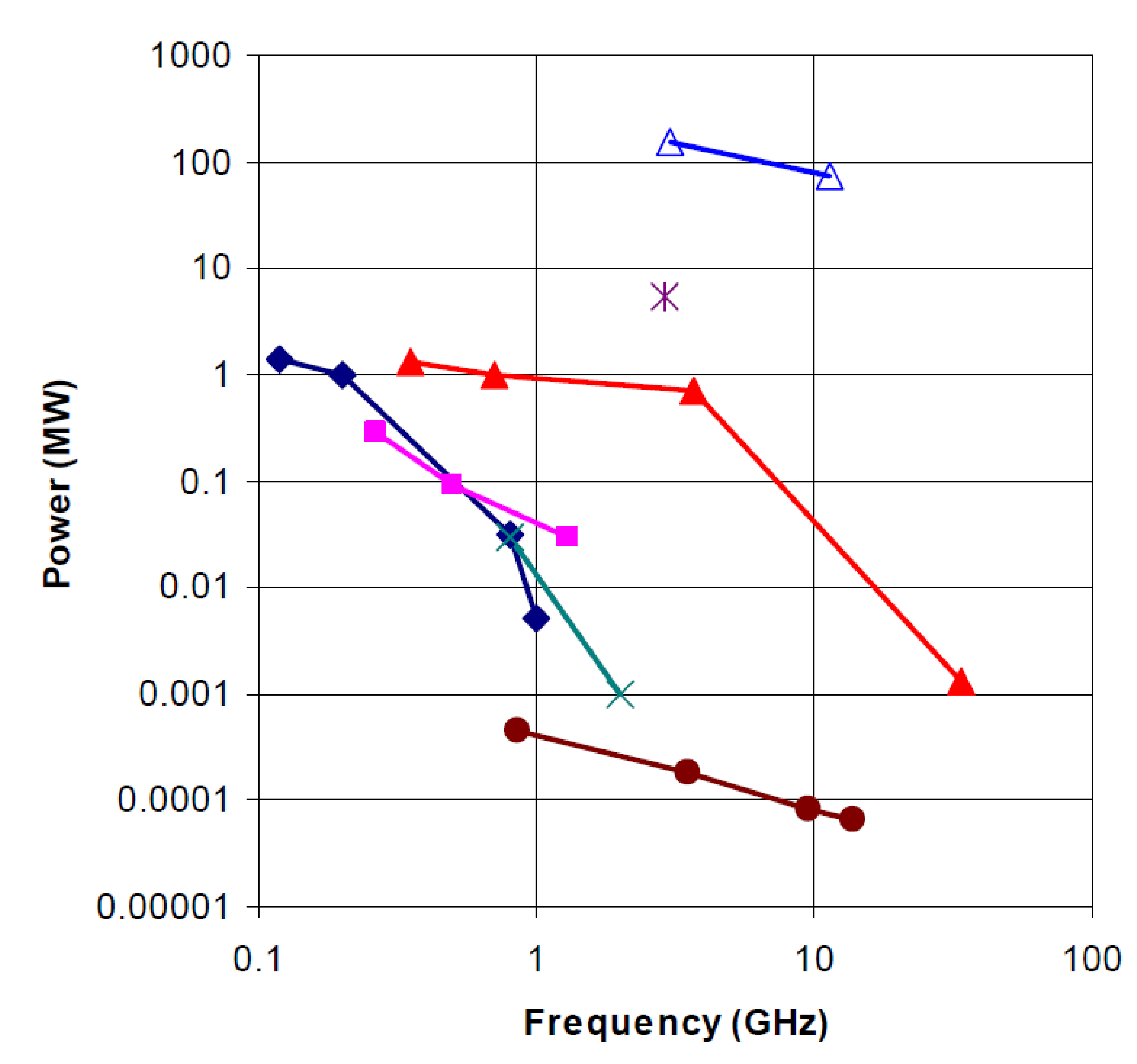
[1] Communications & Power Industries; formerly VARIAN

Table XIII a: Capabilities and performance parameters of mm- and submillimeter-wave gyrotrons operating at the second harmonic of the electron cyclotron frequency, with output power $\geq$ 1 kW.

IC/LH Technical Issues for DEMO

- **Launcher : coupling with minimal plasma material interactions**
  - High heat and neutron irradiation
  - Folded waveguide, PAM(passive active multi-junction), etc
- **Power sources : Klystron**

RF Power Sources : State of the Art



IOT: Inductive Output Tube

Klystron : State of the Art

핵융합로공학 선행연구센터 CARFRE Center for Advance Research in Fusion Reactor Engineering

CW Klystrons

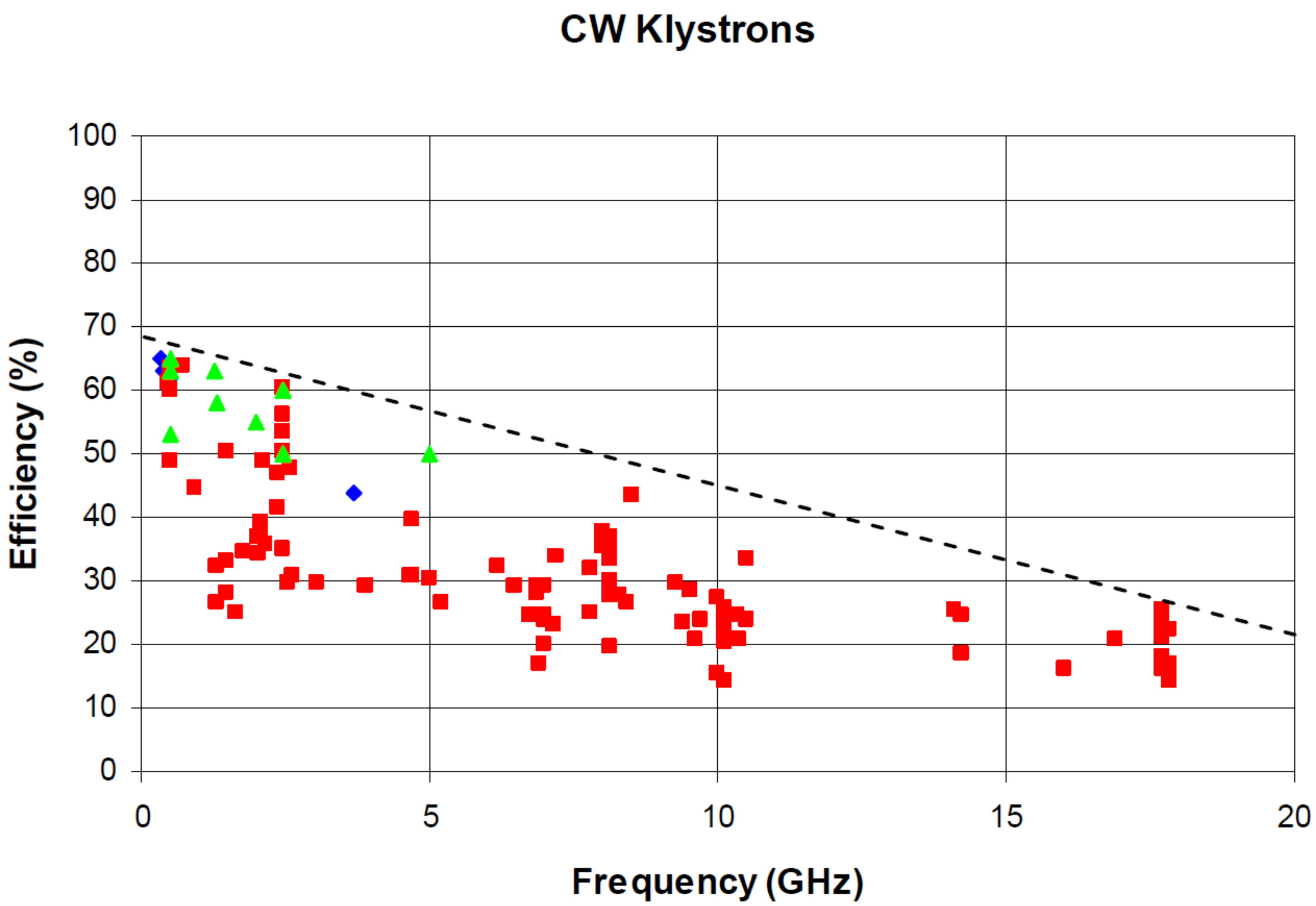
Frequency	352	700	3700	MHz
Beam voltage	100	92	60	kV
Beam current	19	17	20	A
RF output power	1.3	1.0	0.7	MW
Efficiency	67	65	44	%

Pulsed Klystrons

Frequency	2.87	3.0	11.4	GHz
Beam voltage	475	590	506	kV
Beam current	620	610	296	A
RF output power	150	150	75	MW
Efficiency	51	42	50	%

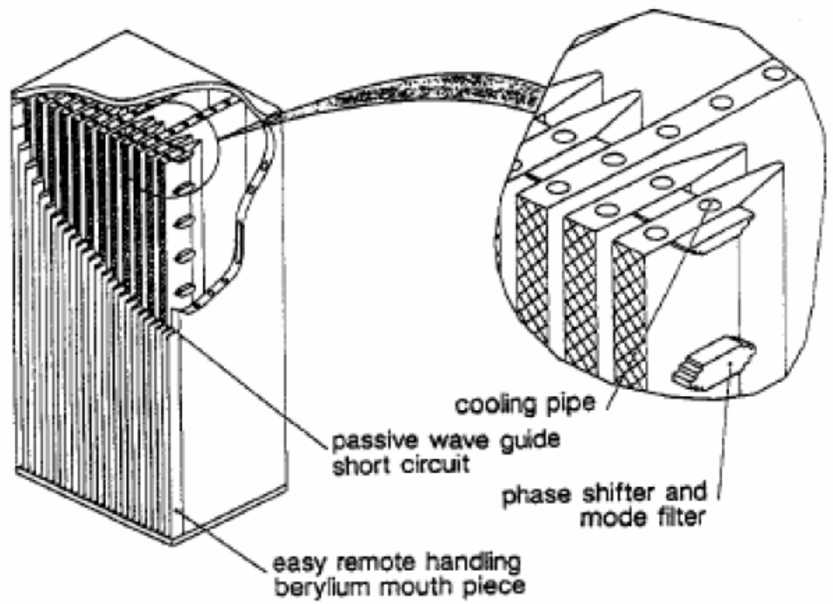
Note: Breakdown voltage is higher for short pulses than for DC

CW Klystron Power Efficiency



Launcher Development for LHCD

Center for Advance Research in Fusion Reactor Engineering



P. Bibet et al., Nucl. Fusion, 35, No. 10, (1995) 1213.

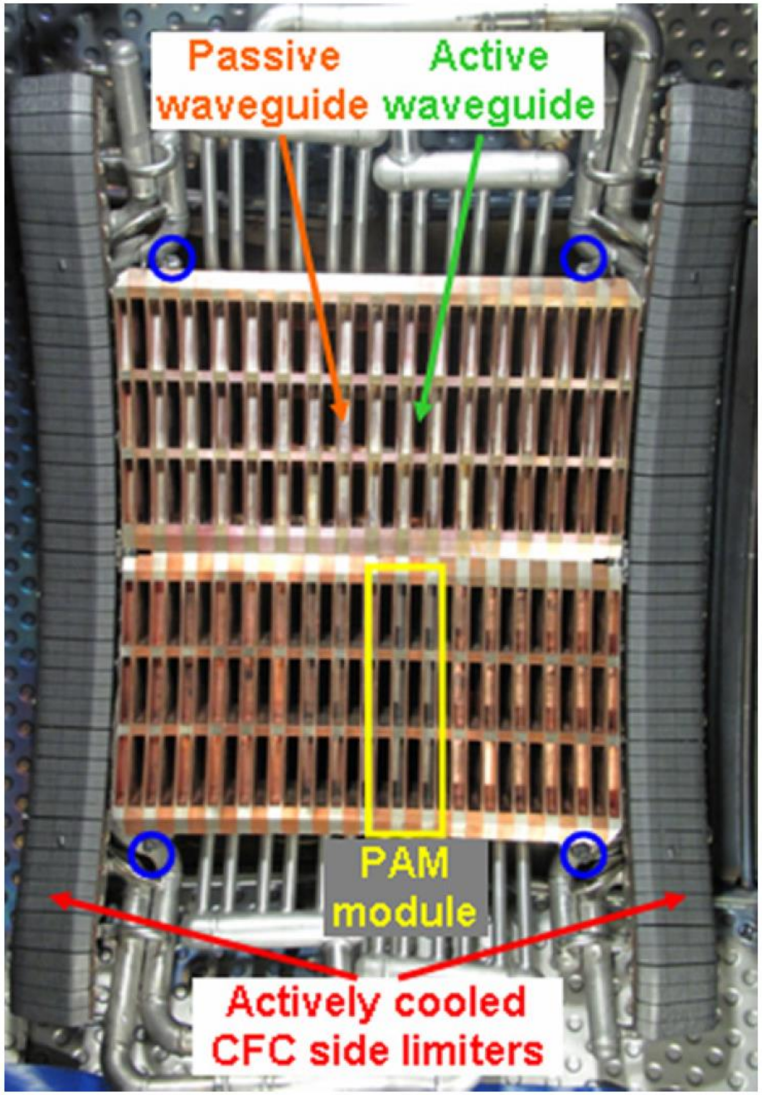
- Robust LH launchers are required to face the harsh plasma environment of ITER:
  - Electromechanical stresses (~ 100 MPa)
  - Strong thermal loads (heat flux = 0.5 MW/m2, neutron flux = 0.5 MW/m2)
- Thick vertical walls between ***active*** waveguides (e.g. 13.25 mm for ITER)
  - mechanical stiffness, effective neutron shielding, cooling system in the walls

PAM: Passive Active Multi-junction

- Advantages deriving from the self–matching properties of the multijunction.
- ***Passive*** (short-circuited) waveguides (depth $\simeq \lambda/4$) at the mouth (within the thick walls) that act as reflectors radiating back toward the plasma part of the reflected RF power
  - enhance the coupling properties of the launcher by increasing its periodicity.
  - allows significant reduction of the height of all the odd order peaks in power spectrum with the help of optimized depth of the passive waveguides and the E-plane bi-junction phase shift.
- Best performances of the PAM expected at low plasma density (close to cut–off) due to the effect of passive waveguides:
  - the launcher could be positioned far from the plasma where, in addition, the thermal loads are smaller.

Launcher Development for LHCD

Tore Supra



Nucl. Fusion **50** (2010) 112002 (5pp)

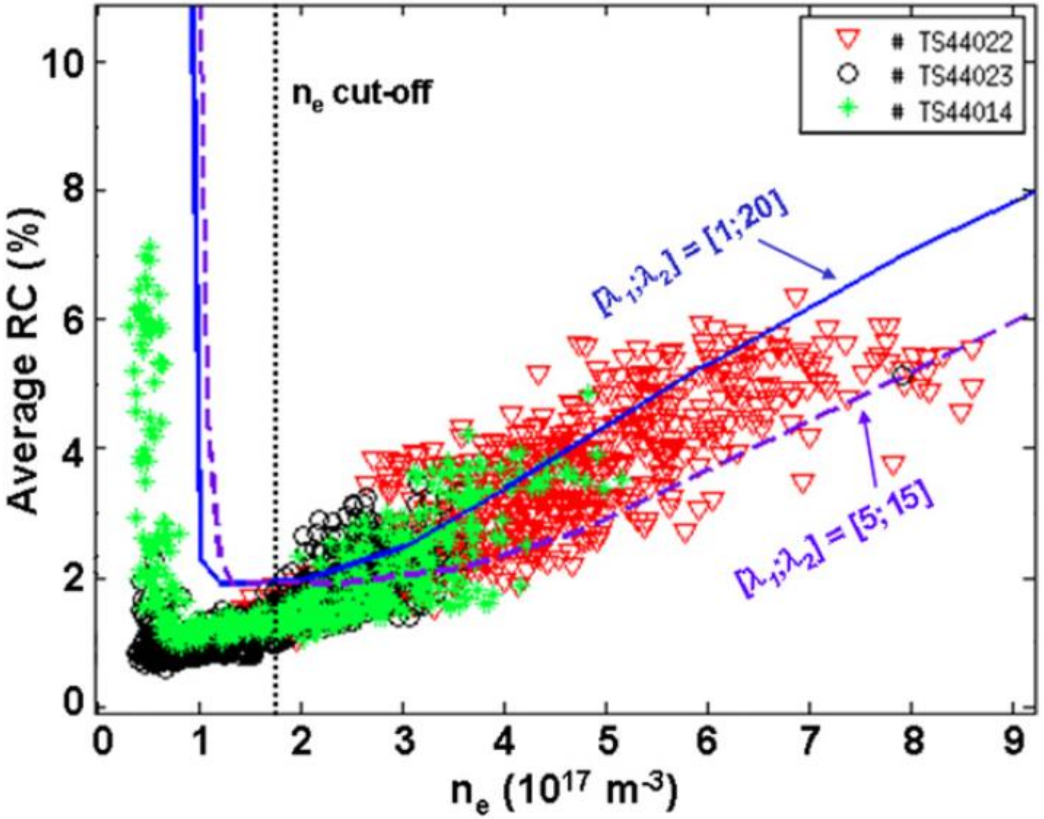


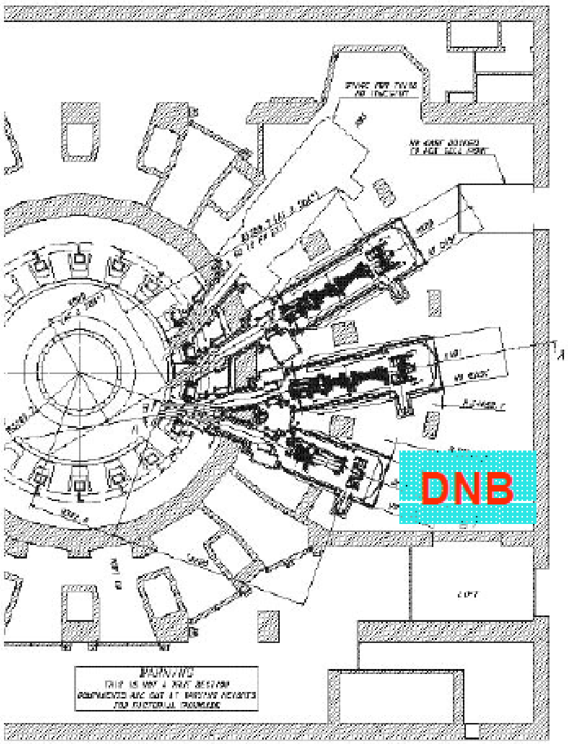
Figure 2. Average reflection coefficient (RC) on the PAM launcher versus electron density at the launcher mouth, as measured by a Langmuir probe on the launcher. The two lines correspond to the ALOHA code calculations, using $\lambda_{n1} = 1$ mm and $\lambda_{n2} = 20$ mm (solid line), and $\lambda_{n1} = 5$ mm and $\lambda_{n2} = 15$ mm (dashed line). Good agreement with the ALOHA code is obtained.

ITER Heating and Current Drive System

P_{aux} for Q=10 nominal scenario: 40-50MW

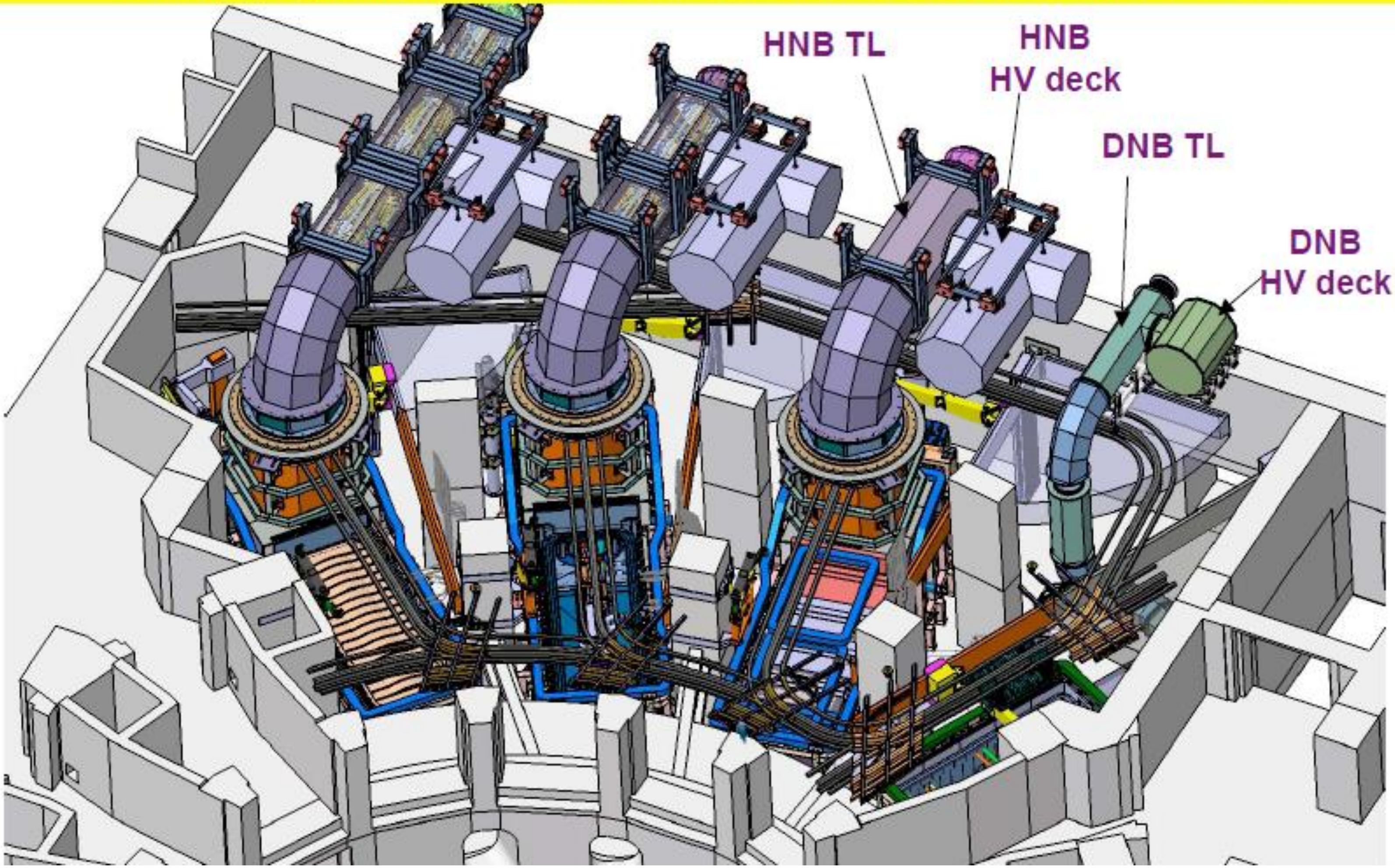
Heating System	Stage 1	Possible Upgrade	Remarks
NBI (1MeV –ive ion)	33	16.5	Vertically steerable (z at Rtan -0.42m to +0.16m)
ECH&CD (170GHz)	20	20	Equatorial and upper port launchers steerable
ICH&CD (40-55MHz)	20		$2\Omega_T$ (50% power to ions Ω_{He3} (70% power to ions, FWCD)
LHH&CD (5GHz)		20	$1.8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

NBI Layout



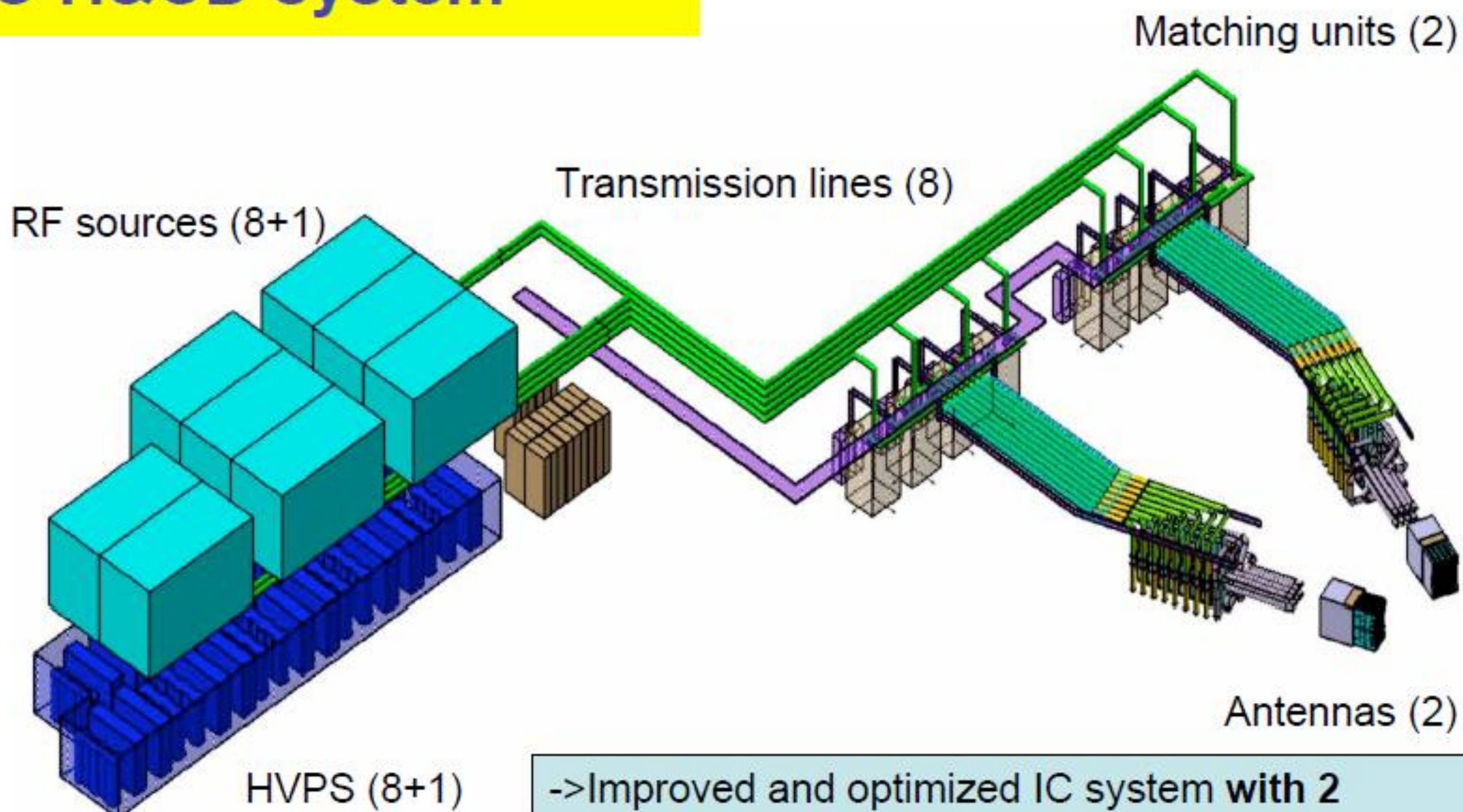
ITER NBI System

NBI: 1 MeV beams – 16 MW power deposited in the plasma by each
Development is a challenge – test bed under construction in Padua
first heating and the diagnostic beam installed in 2020 second in 2022



ITER IC H & CD System

IC H&CD system



Challenge is antenna design and coupling to the plasma - TBD

->Improved and optimized IC system **with 2 antennas** allows to secure the **coupling of 20 MW** in all envisaged scenarios (large scrape off, short decay length, 40 to 55 MHz, dipole phasing) with 40 kV max in the circuits
->Efficient resilient matching limit ELM effect: reflected power is kept below 1% of forward power

SOFE- June 1

ITER ECH Gyrotron Development

2 MW gyrotrons from EU, 1 MW from JA and RF.
• Diode type gun gyrotrons from EU and RF, triode type from JA (requiring an additional PS for the anode).

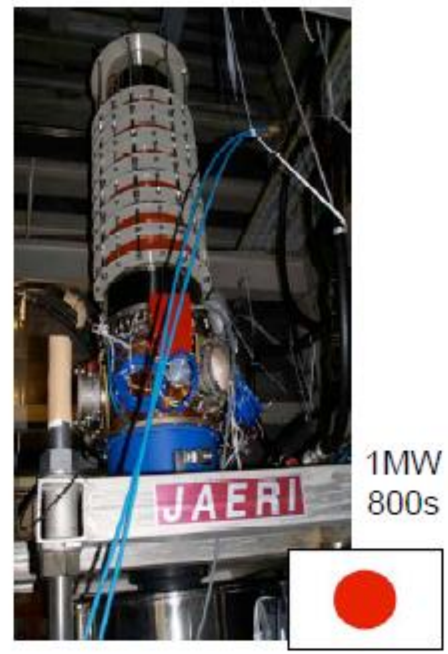
Challenge is the development of the sources – good progress

And the development of the louncher s – very good progress

Short pulse prototype

2MW short pulses

1MW ~300s



1MW 800s

Diagnostics for DEMO

DEMO cannot have as extensive an array of diagnostics as ITER. However, *DEMO* must operate reliably and effectively from the beginning. Hence, the latter phase of operation in ITER must be used to determine and optimize the minimal set of diagnostic measurements for operating and controlling *DEMO*'s plasmas.

In some cases, the loss of key measurements could be compensated by the development of validated theories and modeling, filling the gaps between measurements available from a reduced diagnostic set. In other cases, there will be a serious need for the development of new and/or alternate techniques which would be compatible with the environment found in a reactor. The development of these techniques will require a long and dedicated process ranging from the laboratory test to a full implementation on ITER or equivalent burning plasma experiment.

R&D required (non-exhaustive)

- New diagnostic development for replacing standard systems for T_e , n_e (Thomson scattering), T_i, rotation, (CXRS), q profile (MSE), radiated power (bolometers), etc.
- Dedicated program for radiation hardening of components to withstand high fluence while operating in high neutron flux.
- Development of easily withdrawn and replaced, modular 'front-end' components.
- A new emphasis on the reliability and robustness of operation and calibration of diagnostic systems.
- A strong program in microwave technology, which could provide many of the solutions for the issues raised.

Diagnostics for DEMO

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Device Protection

Measurements required:

Parameter to be controlled	*Contributing plasma measurement*
Disruptive instabilities	Disruption precursors, large ELMs
Intense local heat load	High local first wall/divertor plate temperatures
Plasma beta	Magnetic or sum of kinetic measurements
Start-up initial conditions	Pressure and partial pressures
Start-up localization	Magnetic equilibria
Profile control (auxiliary heating, fuelling)	Density, temperature, rotation profiles
Development of excess alpha-particle loss	Lost- alphas, high local wall temperature
Significant loss of plasma (disruption, etc.)	Many measurements

Issues: Unlikely to have beams and x-ray measurements, as they may fail in radiation, so measurements such as those of T_i and rotation will require development. Magnetic diagnostics are likely to fail for very long pulses. Optical/IR systems will suffer from first-mirror degradation. Monitoring of the first wall will be severely limited.

Control

Measurements required:

Parameter to be controlled	*Contributing plasma measurement*
Plasma equilibrium	Magnetic configuration, kinetic measurements
Separatrix to wall gap	Edge density profile
Growth/control of instabilities	Fluctuations over frequency range ~ 1 kHz - ~ 2 MHz
Burn onset and control	Neutron flux and beta
Plasma rotation profile	Toroidal rotation speed
Fuel species, impurity density	Density measurements of D, T, H and low-Z and high-Z impurities
Excess growth of helium in core	Helium density
Fuel and fuel ratio control	Exhaust neutral densities
Auxiliary power input performance	Many measurements to be determined
Density control at start-up, auxiliary heating permissives	Density (probably profile)

Issues: Same issue with beams but additional difficulty of measuring core helium. Difficult to gain spatial information about fluctuations.

Diagnostics and Control for DEMO

- Diagnostics:
  - survivability of windows in high radiation environment (ITER systems will only see <1dpa – DEMO up to 5-10 dpa per fpy);
  - availability of lines-of-sight through blankets (spectroscopic and optically-based measurements of plasma temperature, density, current profile etc).

⟶

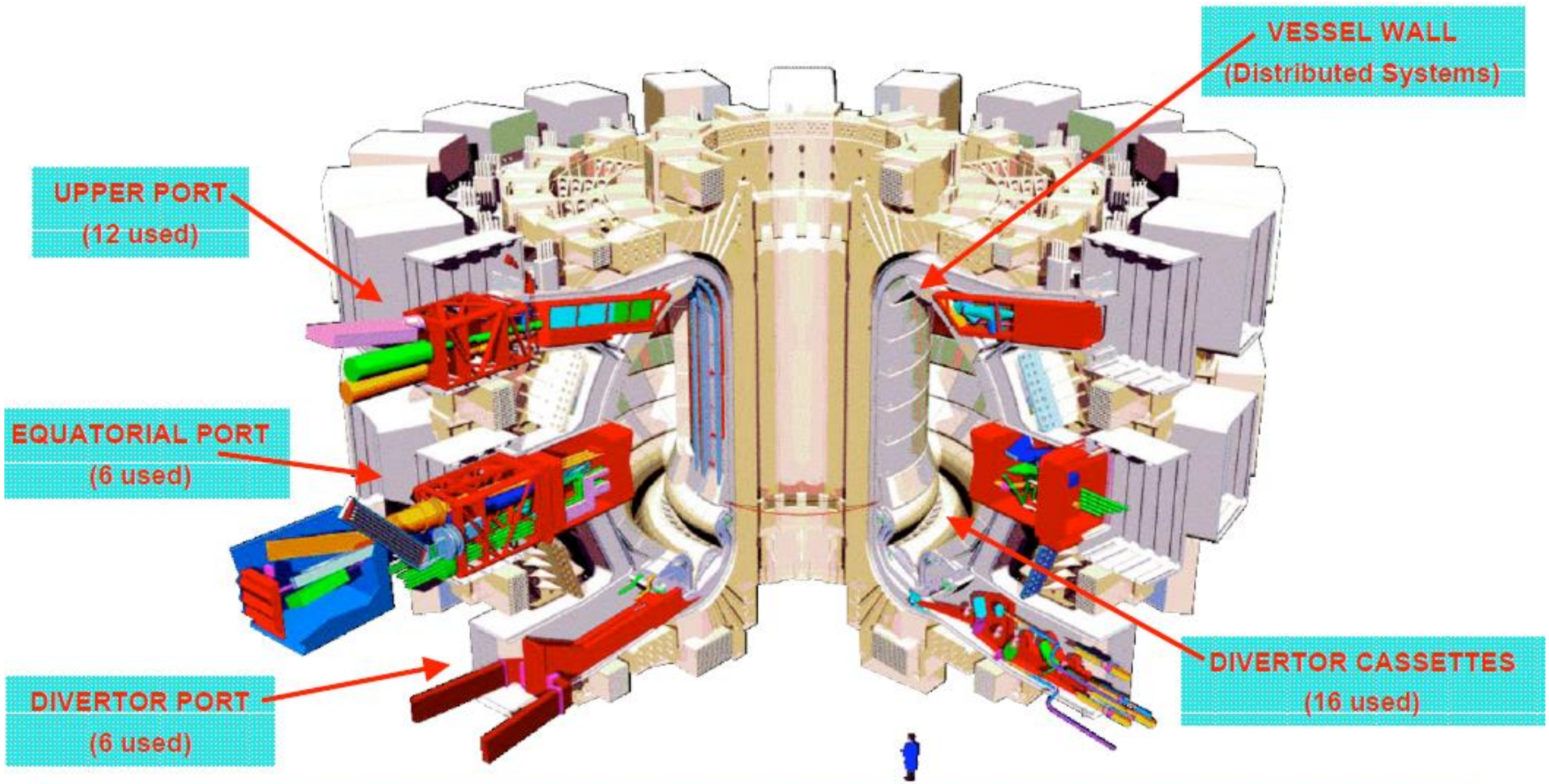
- ➢ Improve survivability of major diagnostic systems
- ➢ New diagnostic development for replacing standard diagnostic systems

- Control systems:
  - Inability of control coils to survive in-vessel radiation doses – poor controllability/response time using coils placed far from plasma;
  - Restriction of lines-of-sight, and limits to numbers of magnetic-coil measurements in-vessel (system complexity optimisation) → sparse dataset available → development of control algorithms based on sparse data.

⟶

- ➢ Develop control system with sparse data and remote actuators

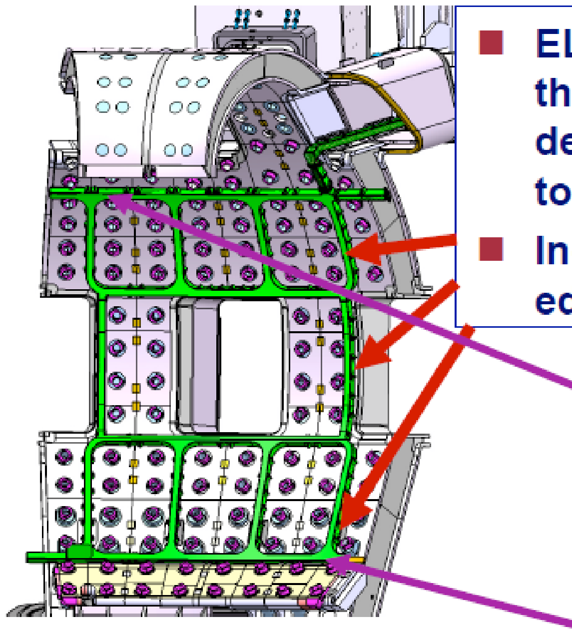
ITER Diagnostics



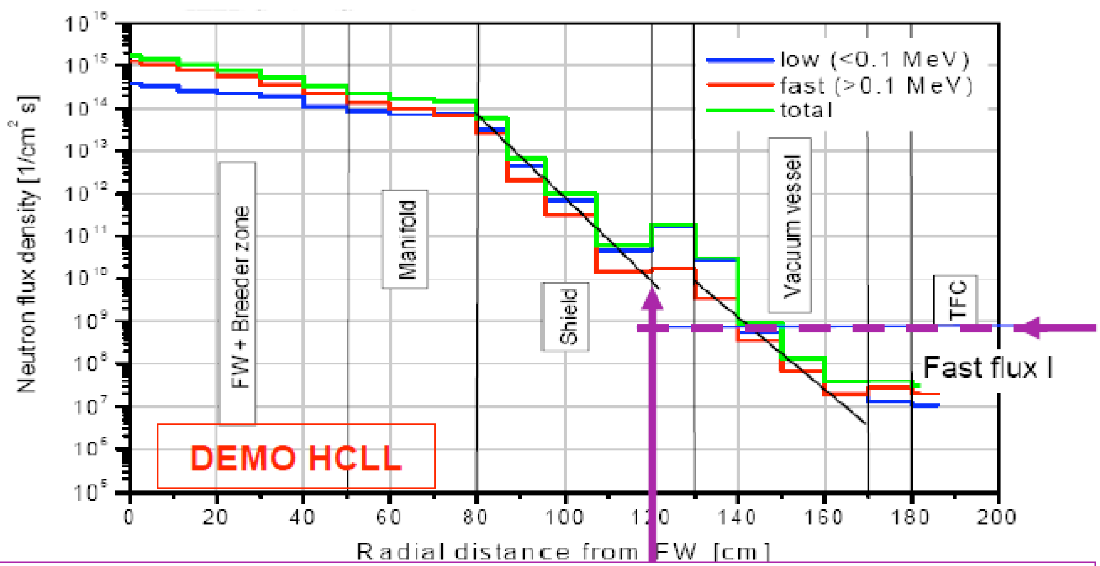
- **About 40 large scale diagnostic systems are foreseen:**
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)

ITER In-vessel coils for vertical stability/ELM control/Resistive Wall Mode control:

coils are behind the Blanket modules



- ELMs (edge modes expelling particles and energy) are thermal pulses of 500μs duration, the peak energy density must be < $0.5 MJ.m^{-2}$ to avoid excessive damage to walls and divertor.
- In-vessel coils → magnetic perturbations → destabilise edge modes whilst still small → small energy deposition



- Other fast response coils correct vertical instabilities
- ..ex-vessel stabilisation systems not fast enough

Equivalent position in DEMO – coil insulation sees ~ 100x lifetime limit.

Current and Current Profile Relationships in a Reactor-sized experimental device

All Current Drive systems rely on creating or injecting a fast particle population in the plasma