Latest Results from the IAEA Fusion Energy Conference

ICTP, Italy

Guenter Mank

NAPC, Physics Section

IAEA

International Atomic Energy Agency

8 March 2005, Trieste

Outline

1. Basic Remarks
2. Status

3.1. Long Pulse Operation

3.2. Confinement Scenarios

3.3. Transport

4. ITER
5. Materials Research and Safety
6. Inertial Fusion Energy (IFE)
7. Summary

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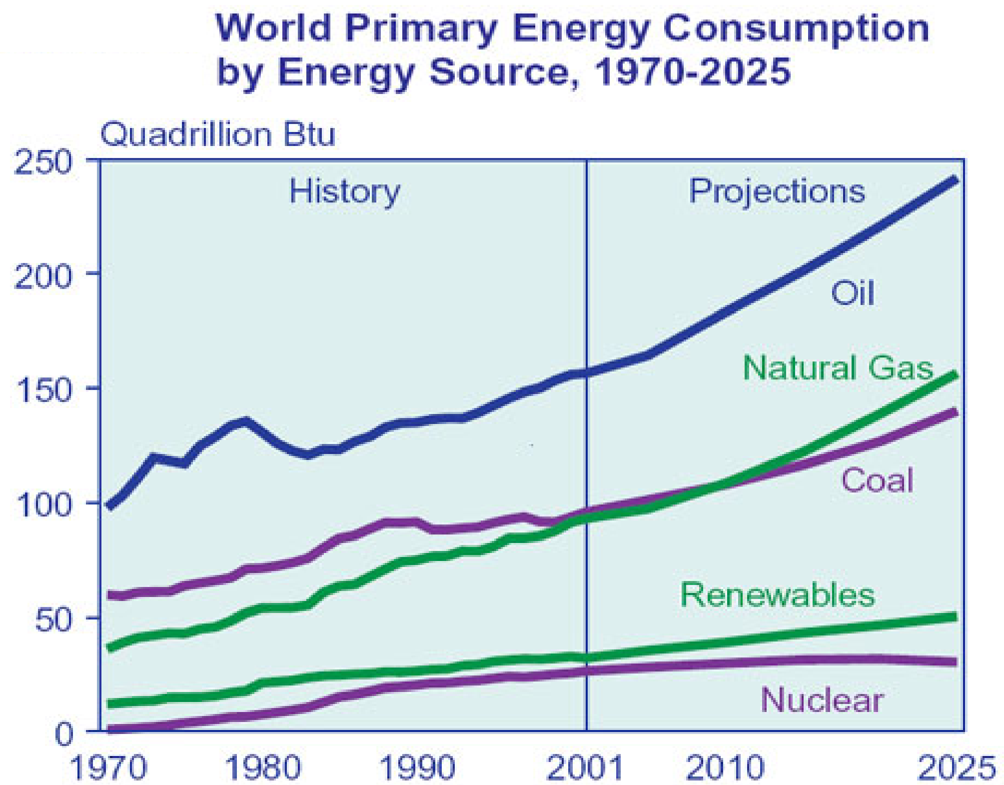
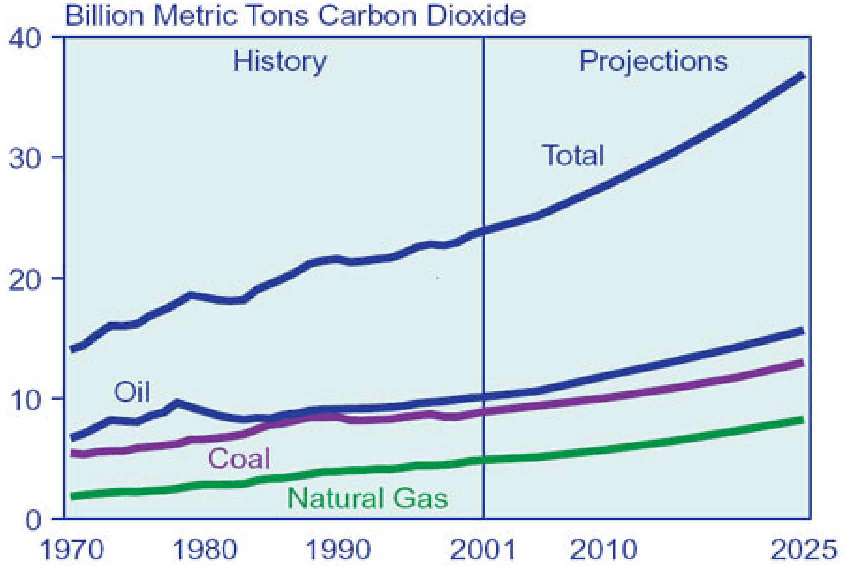
Energy Sources - Trends



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

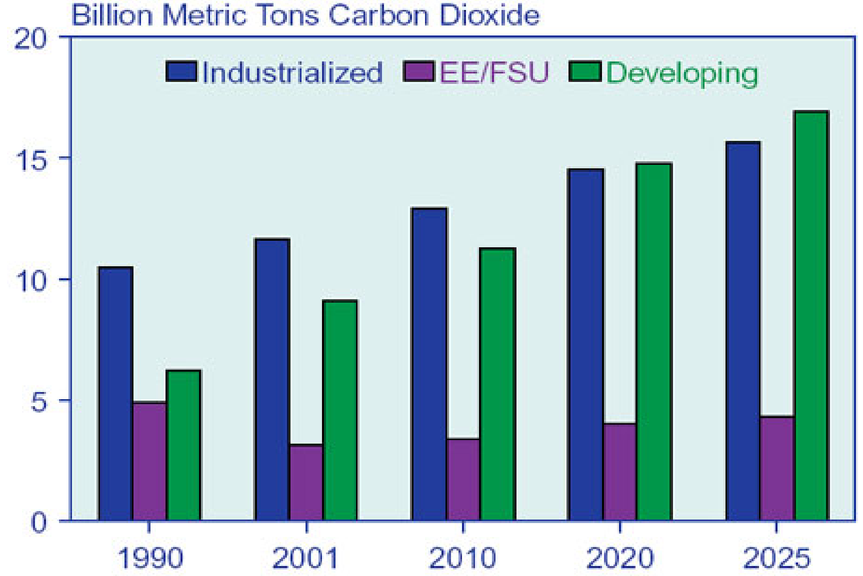
Energy Sources – CO_2 Problem

World Energy-Related Carbon Dioxide Emissions by Fuel Type, 1970-2025



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

World Energy-Related Carbon Dioxide Emissions by Region, 1990-2025



Sources: **1990 and 2001:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219 (2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

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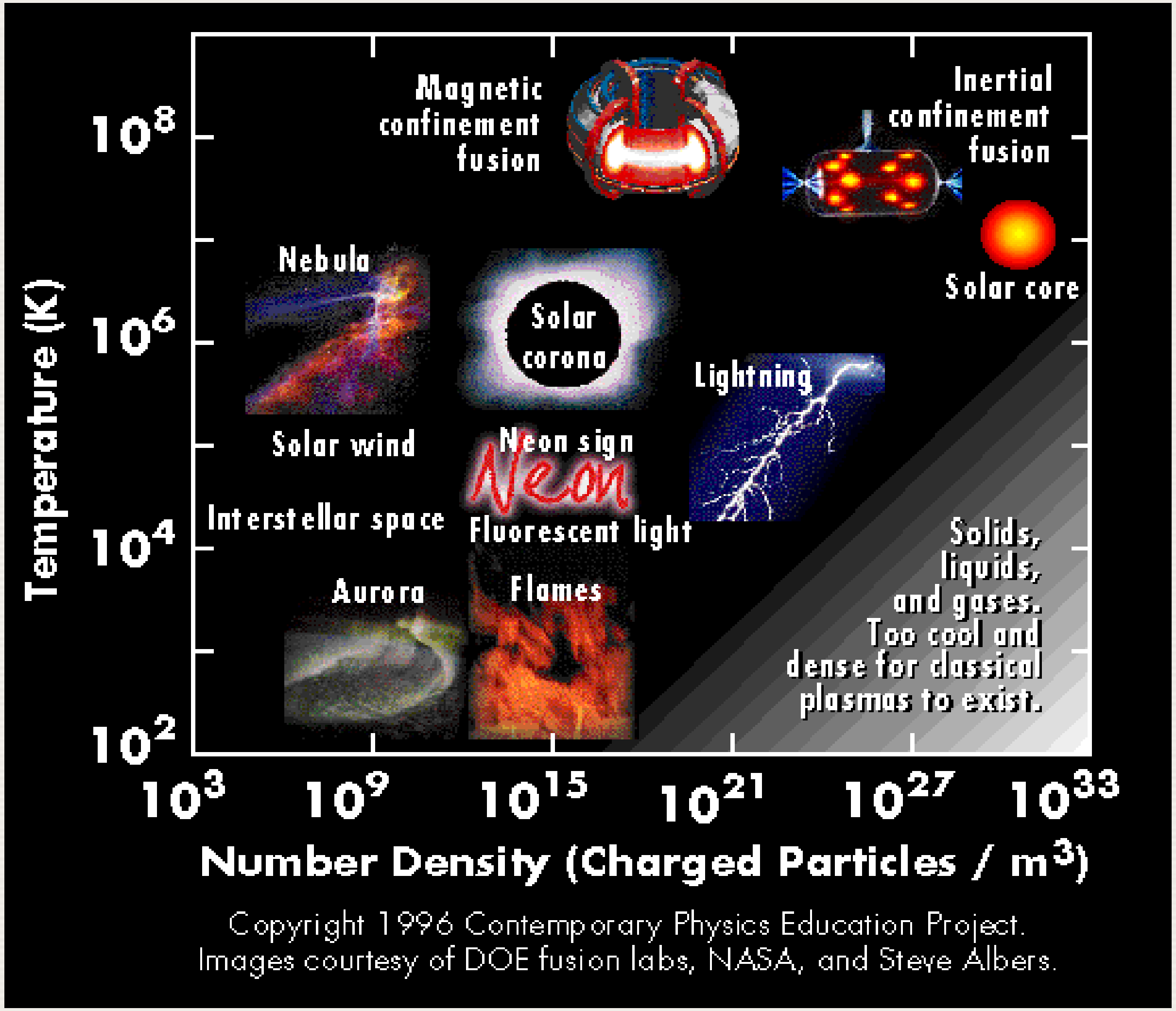
4th State of Matter



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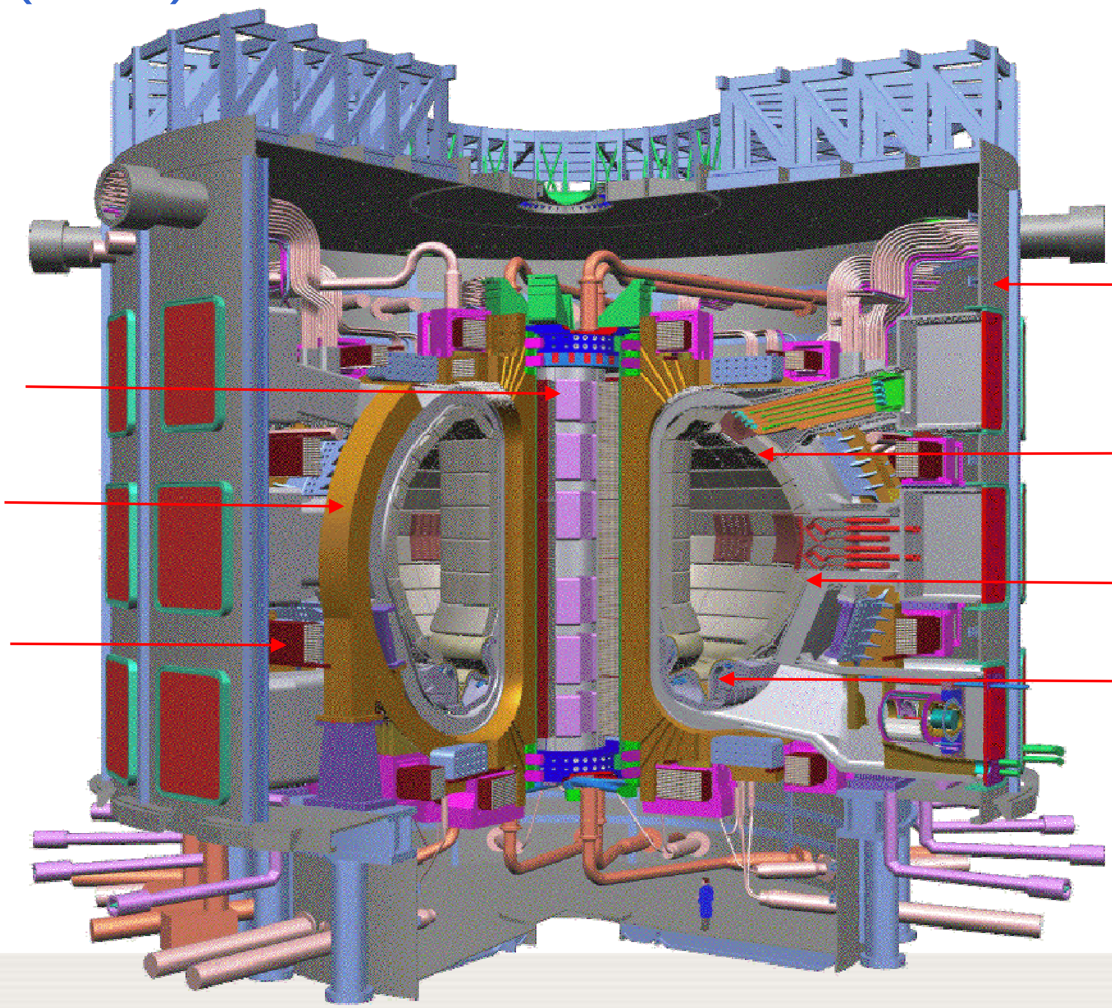
ITER: Intl. Toroidal Experimental Reactor

Iter: The way (Latin)



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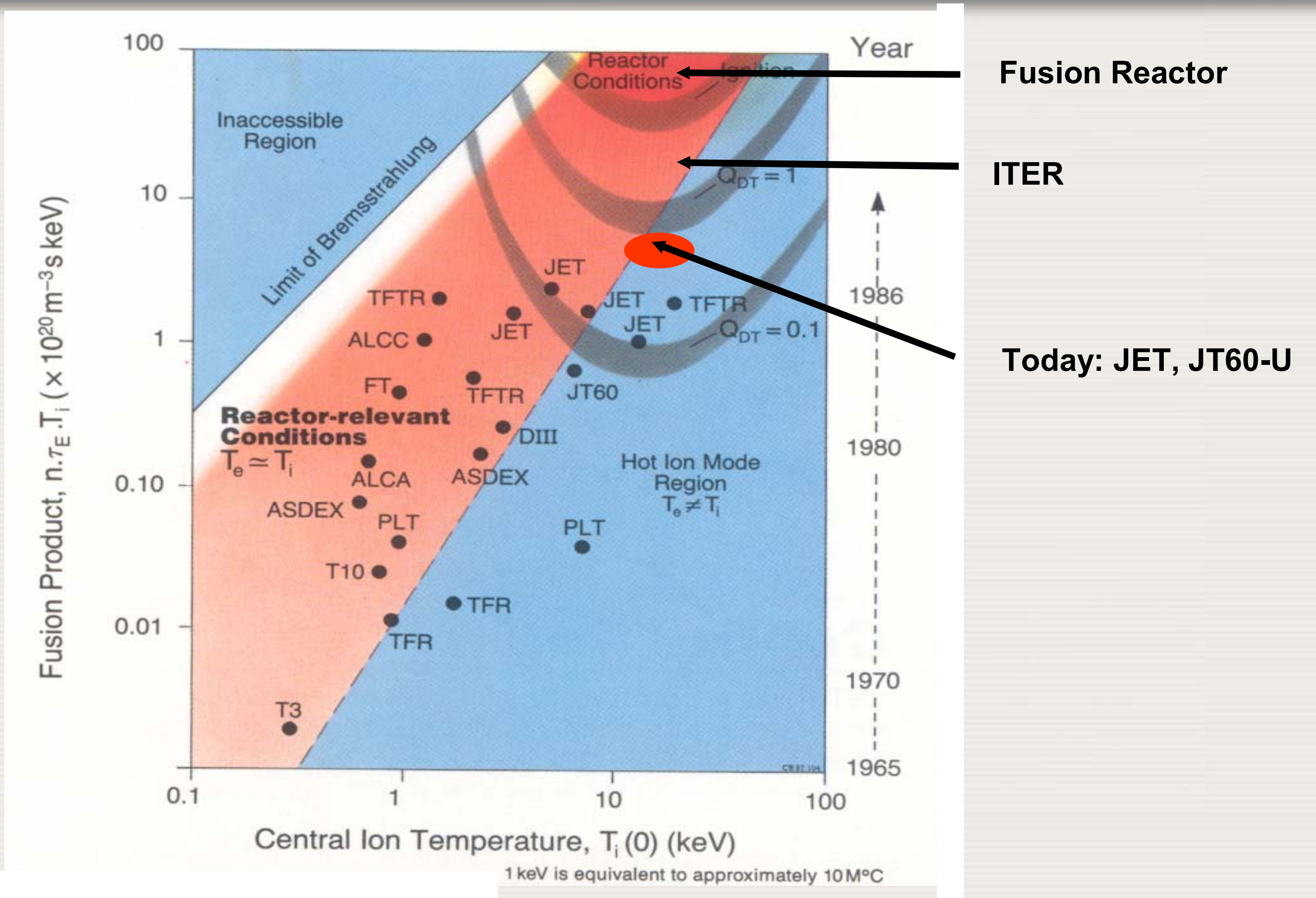
Status Magnetic Confinement



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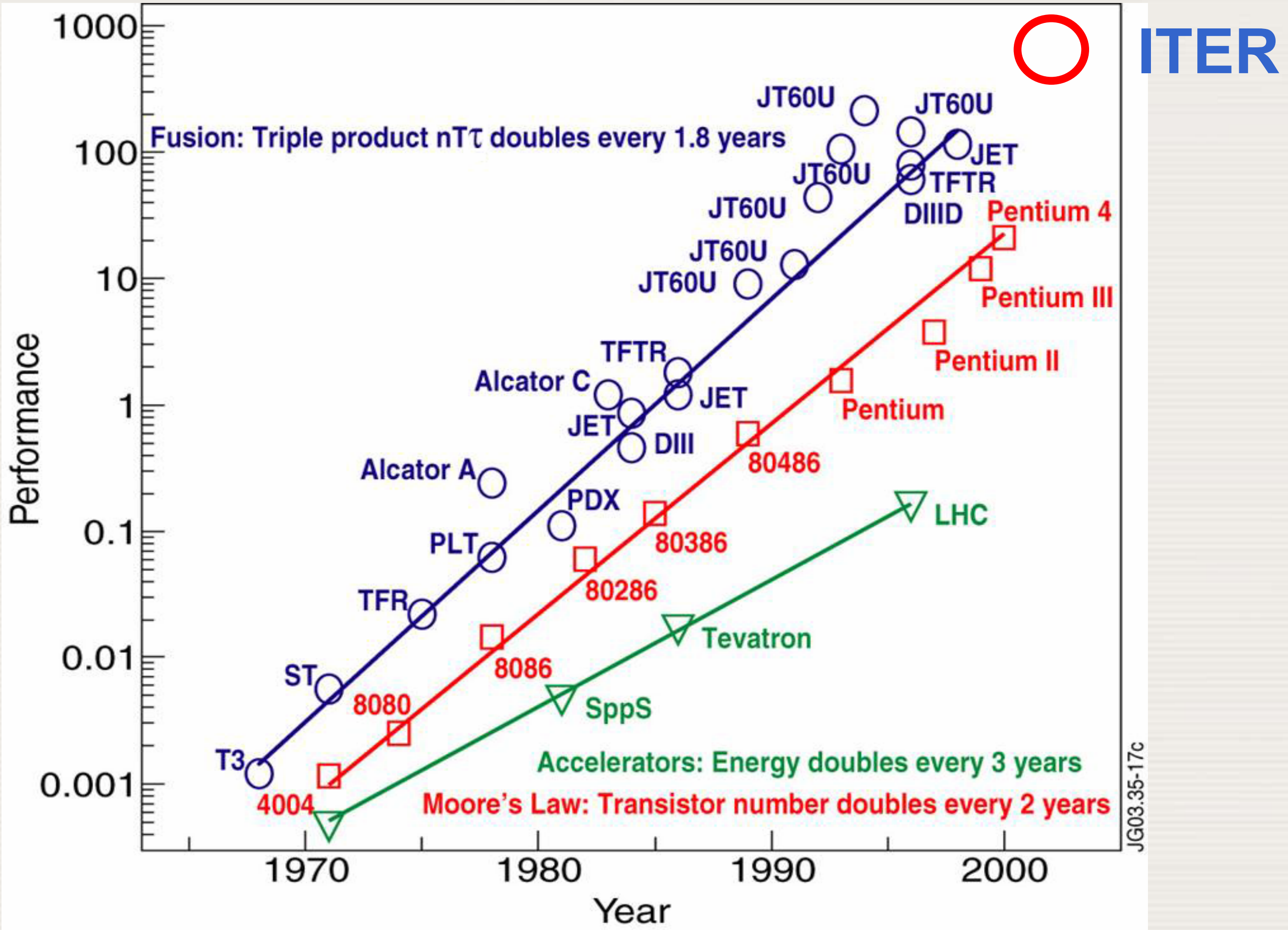
The goal



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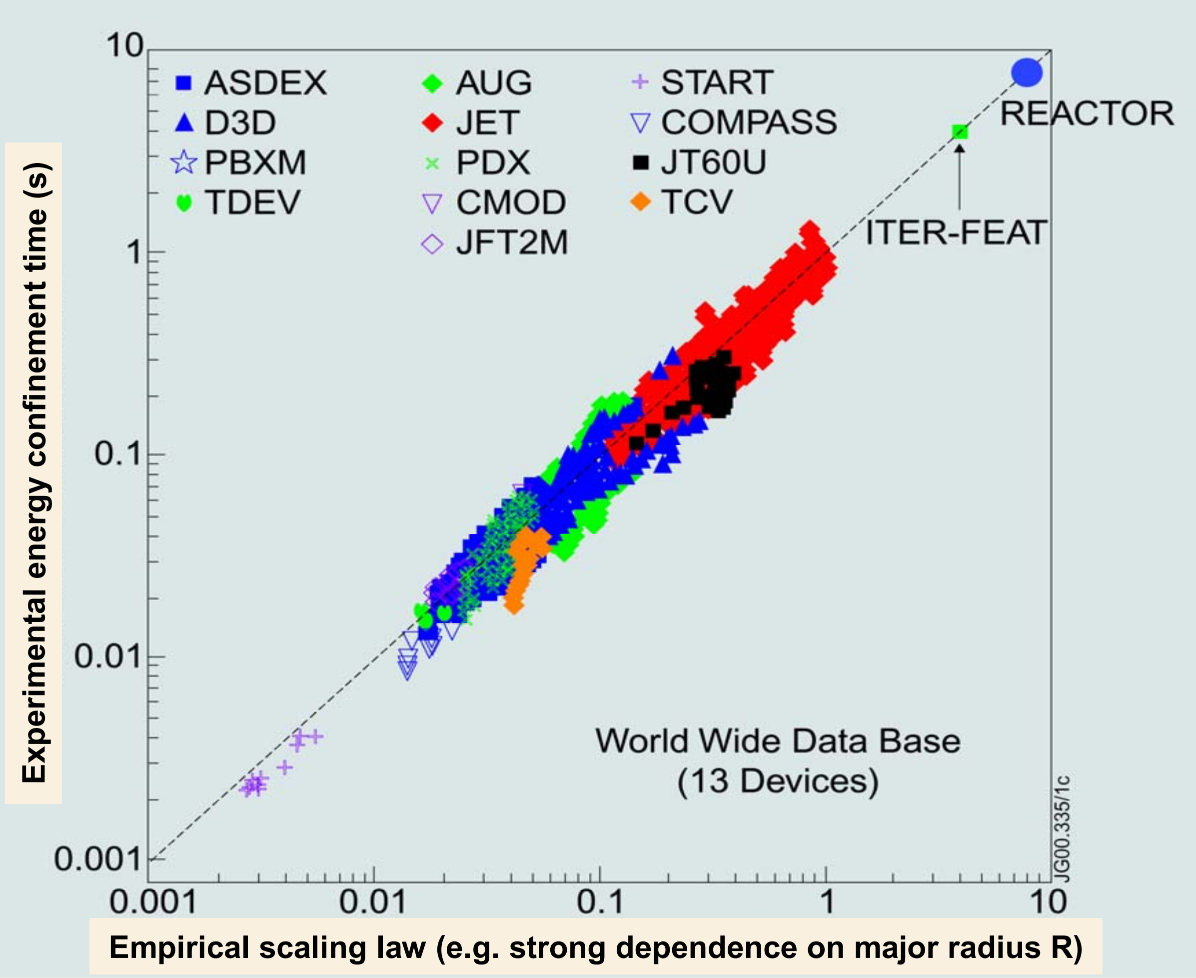
Energy Confinement - Tokamaks



Source: IEA

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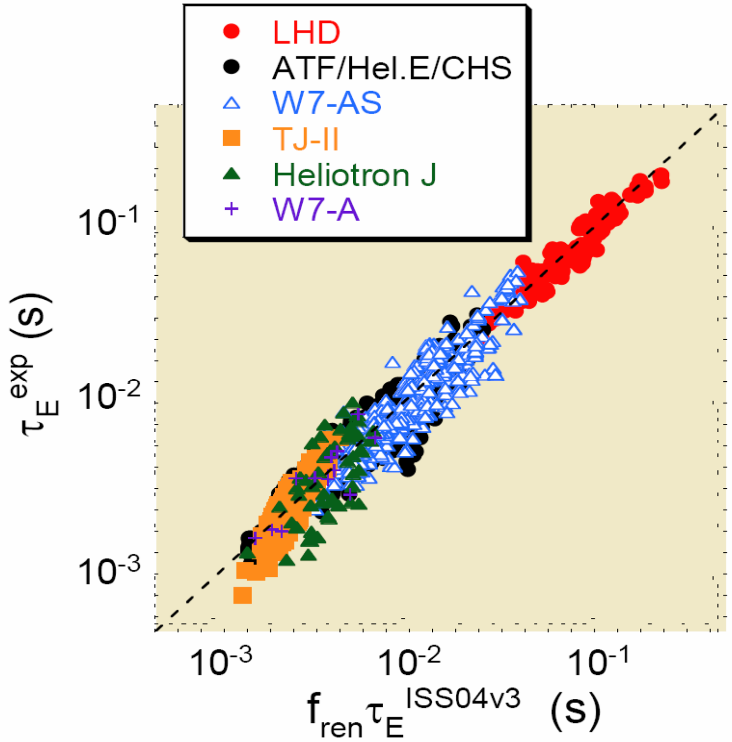
Energy Confinement - Stellarators

International stellarator database has been extended and new gyro-Bohm scaling has been extracted.



$$\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \bar{n}_e^{0.55} B^{0.85} \iota_{2/3}^{0.41}$$

$$\propto \tau_{Bohm} \rho^{*-0.90} \beta^{-0.14} \nu_b^{*-0.01} a^{0.04}$$

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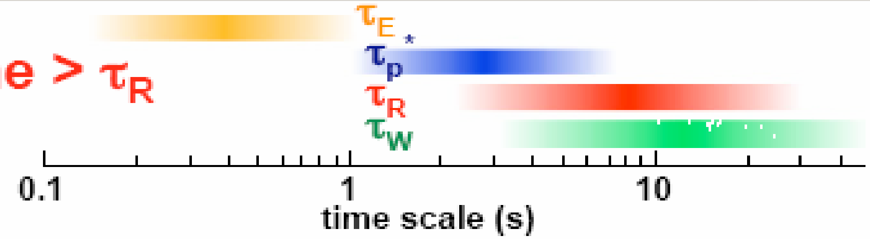
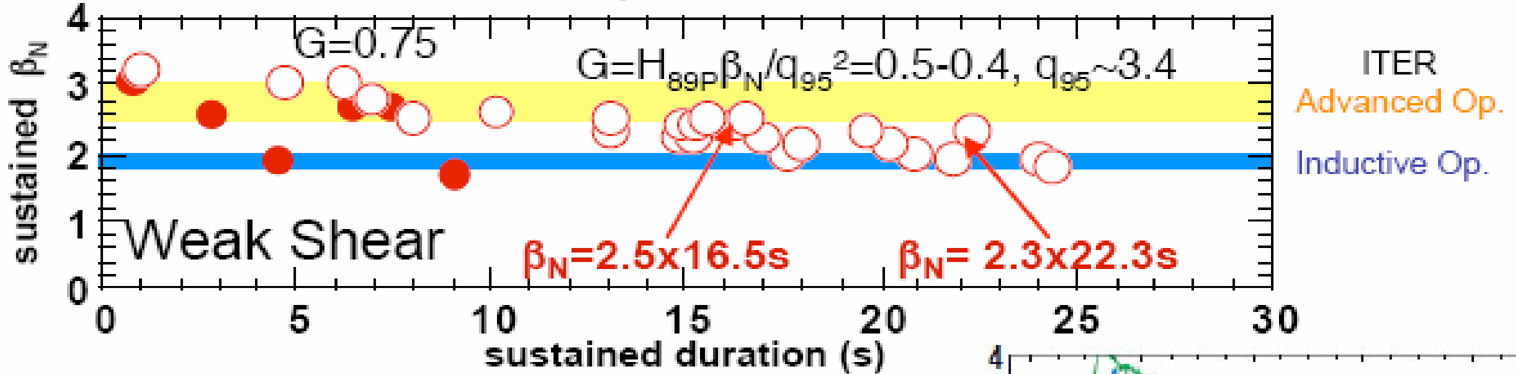
Long Pulse Operation

High β & AT (self regulating) regime > τ_R

Particle control > τ_W



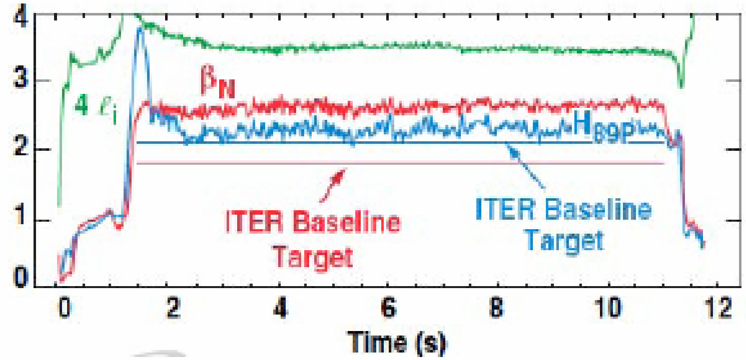
*JT-60U: extended high-β duration =13τ_R



*DIII-D: 9.5s ITER baseline scenario

~ 9τ_R, <β>=4%, G~0.55

*JET: 20s reversed shear



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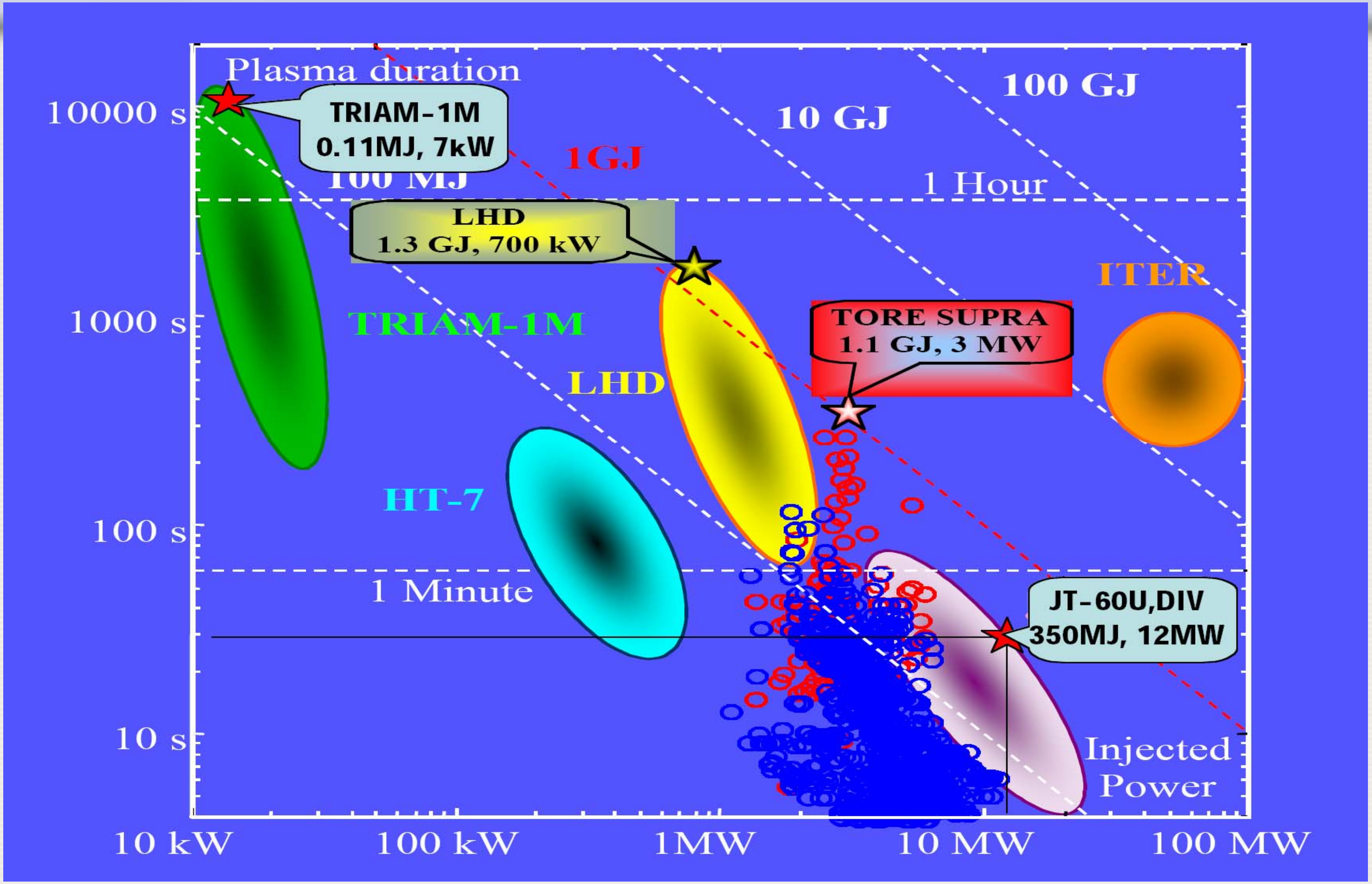
Heat Removal

Plasma Duration



Injected Power

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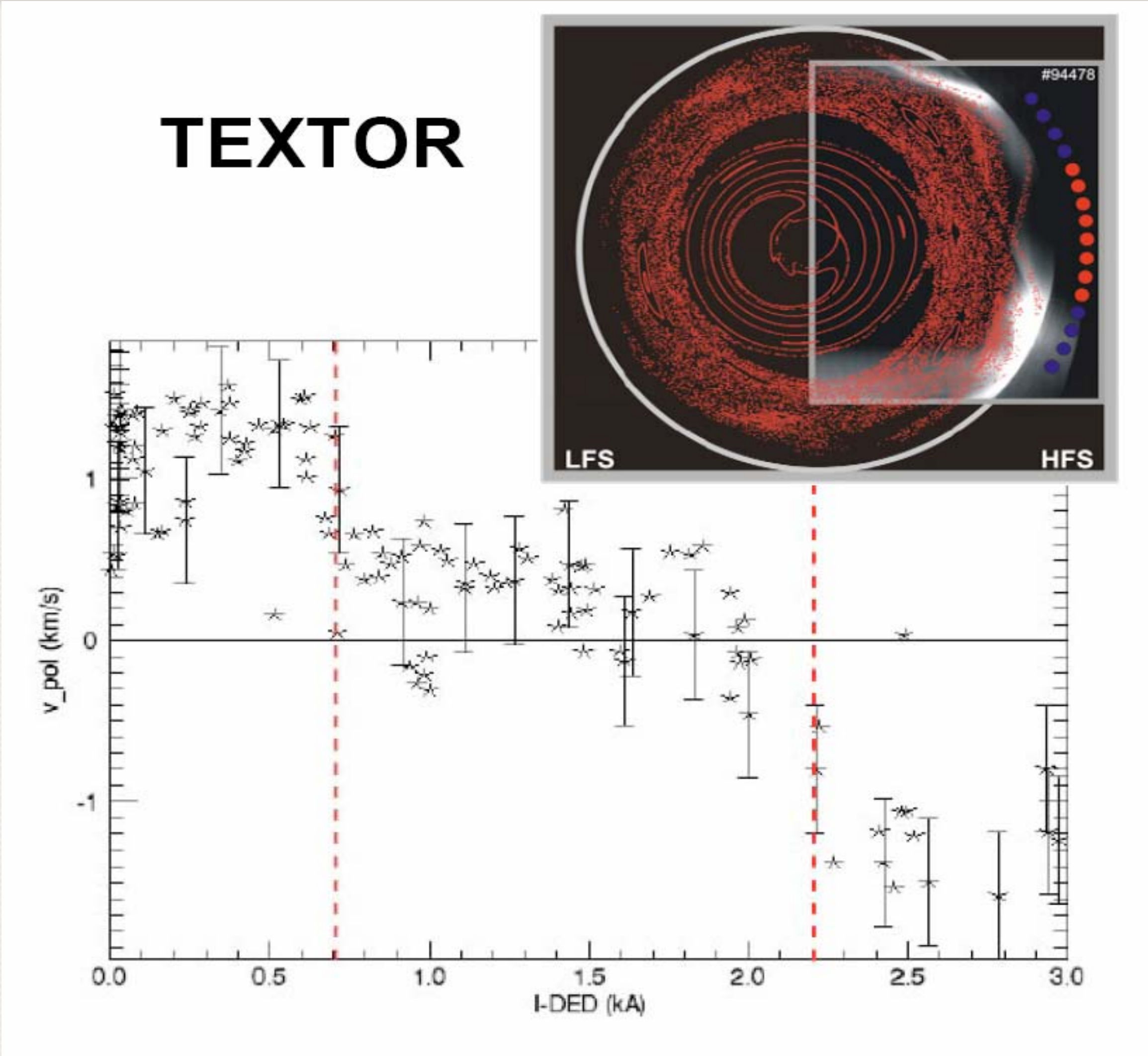
Heat Removal, Edge Poloidal Rot.



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Demands I

Demands:

Long Pulse Operation

IAEA activities:

TM on Steady State Operation of Magnetic Fusion Devices and MHD of Advanced Scenarios

TM on Energetic particles in magnetic confinement systems

TM on H-mode physics and transport barriers

TM on 1st Generation of Fusion Power Plant: Design and Technology

TM on Control, data acquisition and remote participation for fusion research.

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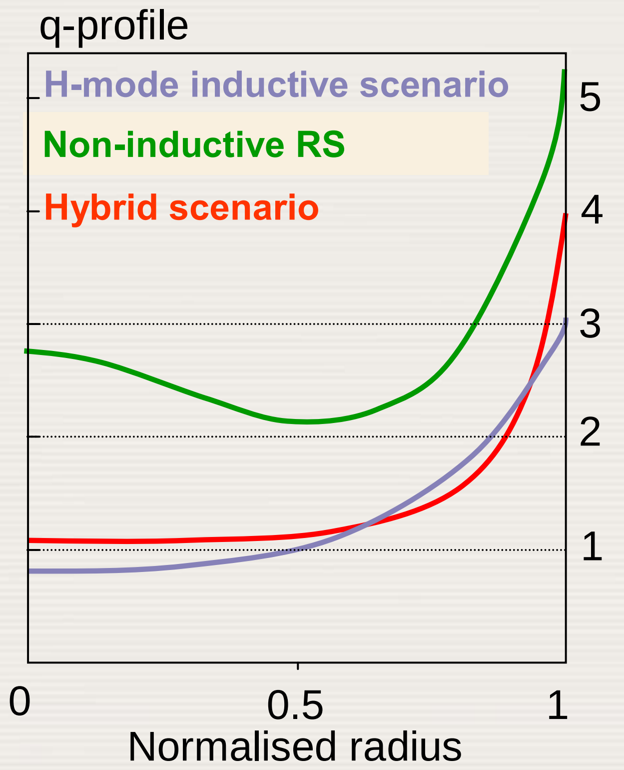
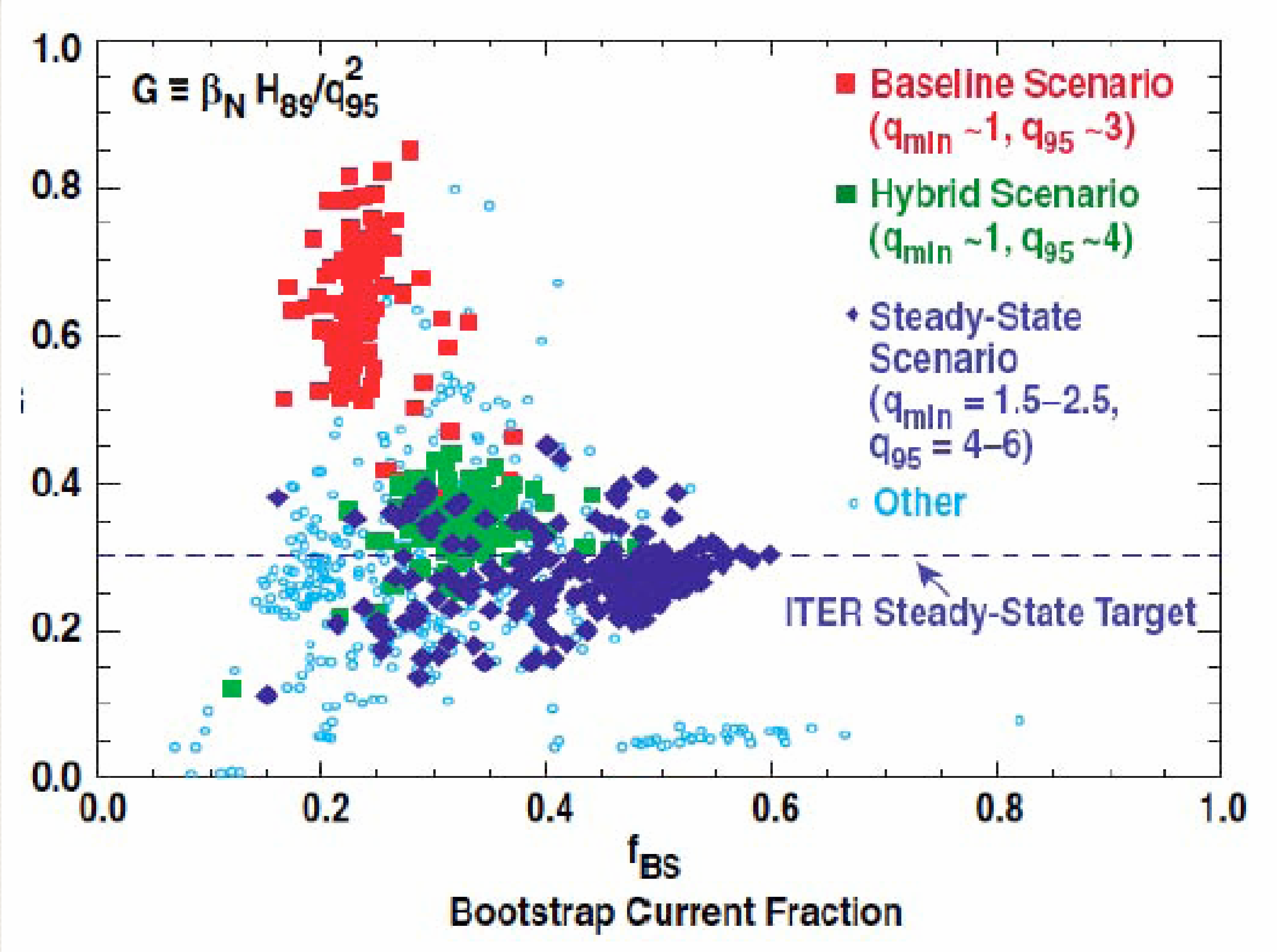
Scenarios

Maximise: ◆ $G = \beta_N . H / q_{95}^2$ ◆ $I_{boot} / I_p \sim \beta_N . q_{95}$ ◆ $n \sim 0.85\ n_{Greenwald}$



Ip	q_{95}	$\beta_N . H_{98\ y2}$	Burn time	Q	
15MA	3	1.8 x 1.0	400s	10	NTM with sawteeth High Ip disruptions
9MA	5.3	2.95x1.6	>3000s	6	Current control High β MHD
12MA	~4	~3 x 1.0	~2000s	~10	

DIII-D Scenarios



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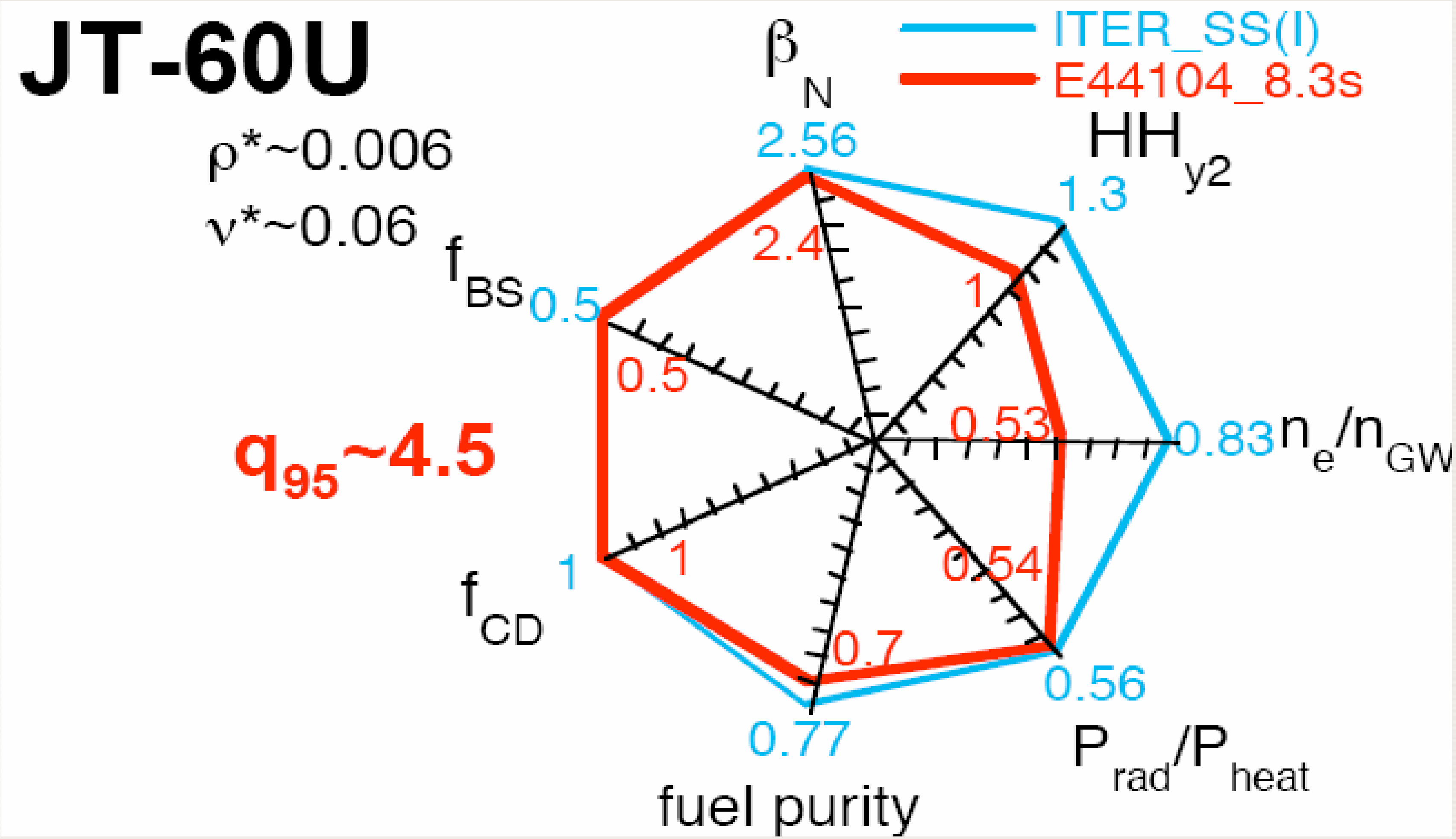
ITER Requirements



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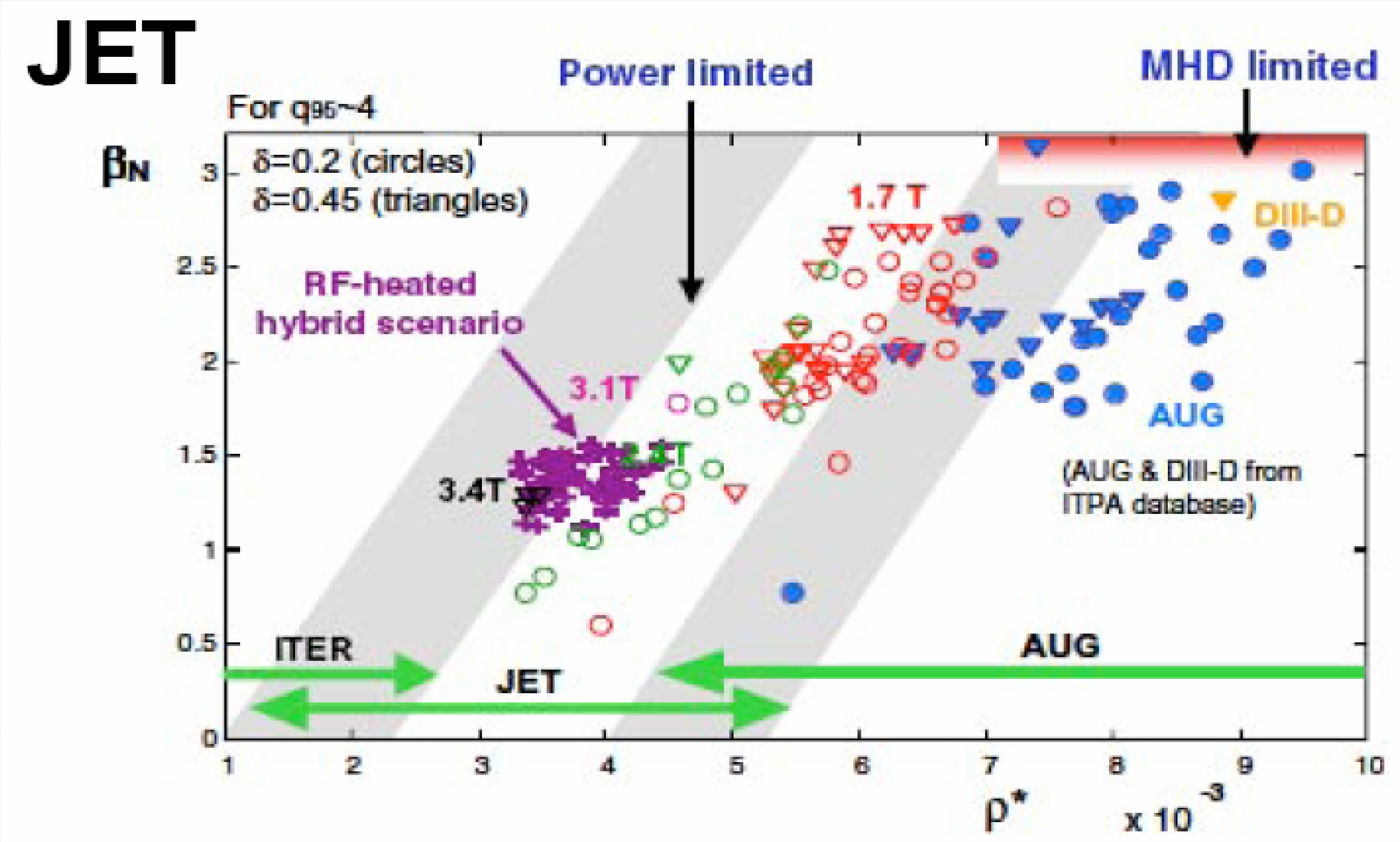
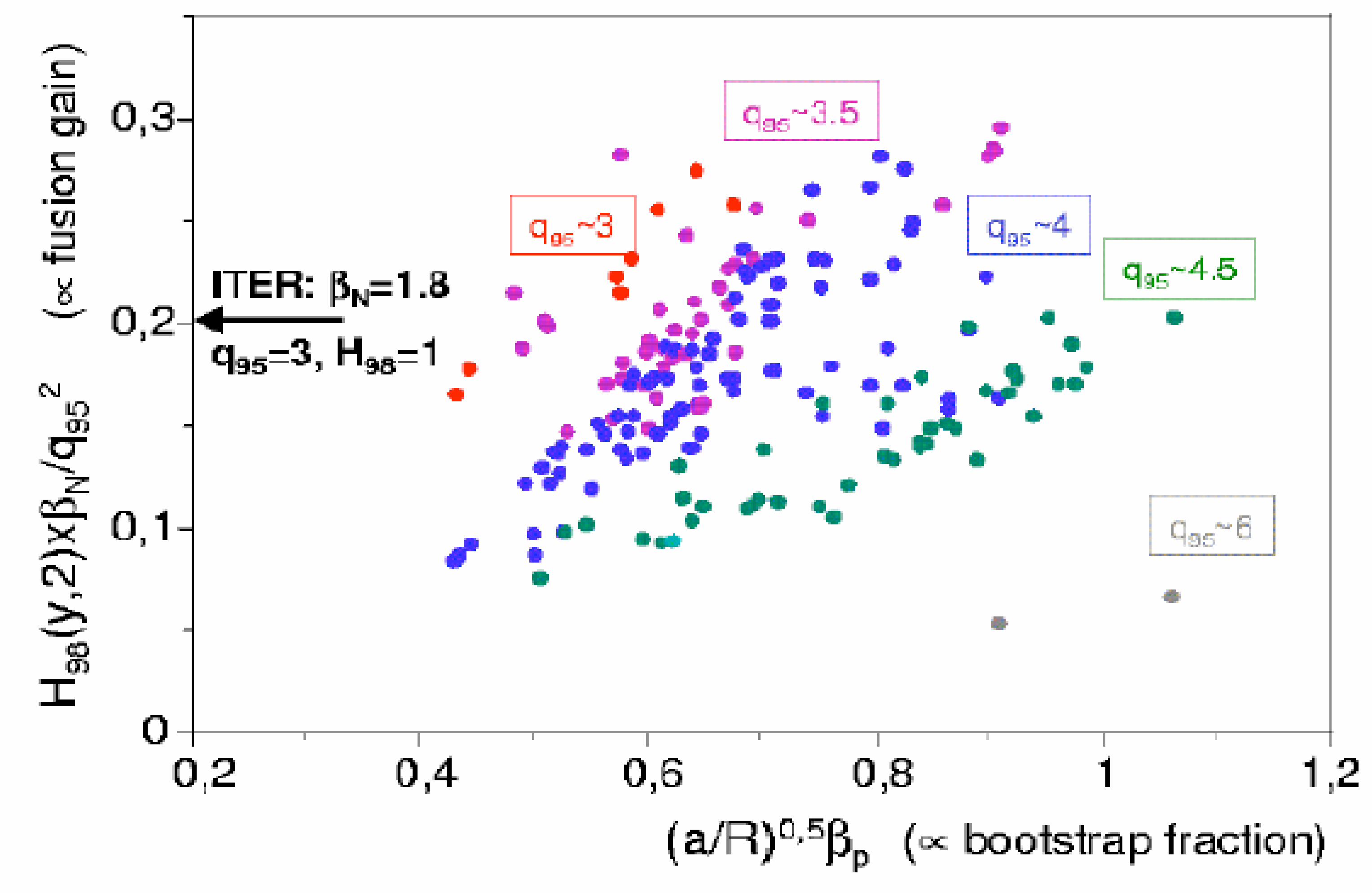
Hybrid Scenarios



ASDEX-U



$H_{98}(y,2) x \beta_N / q_{95}^2$ (∝ fusion gain)
0,3
0,2
0,1
0
0,2
0,4
0,6
0,8
1
1,2
$(a/R)^{0,5}\beta_p$ (∝ bootstrap fraction)
ITER: β_N=1.8
q_{95}=3, H_{98}=1
q_{95}~3
q_{95}~3.5
q_{95}~4
q_{95}~4.5
q_{95}~6

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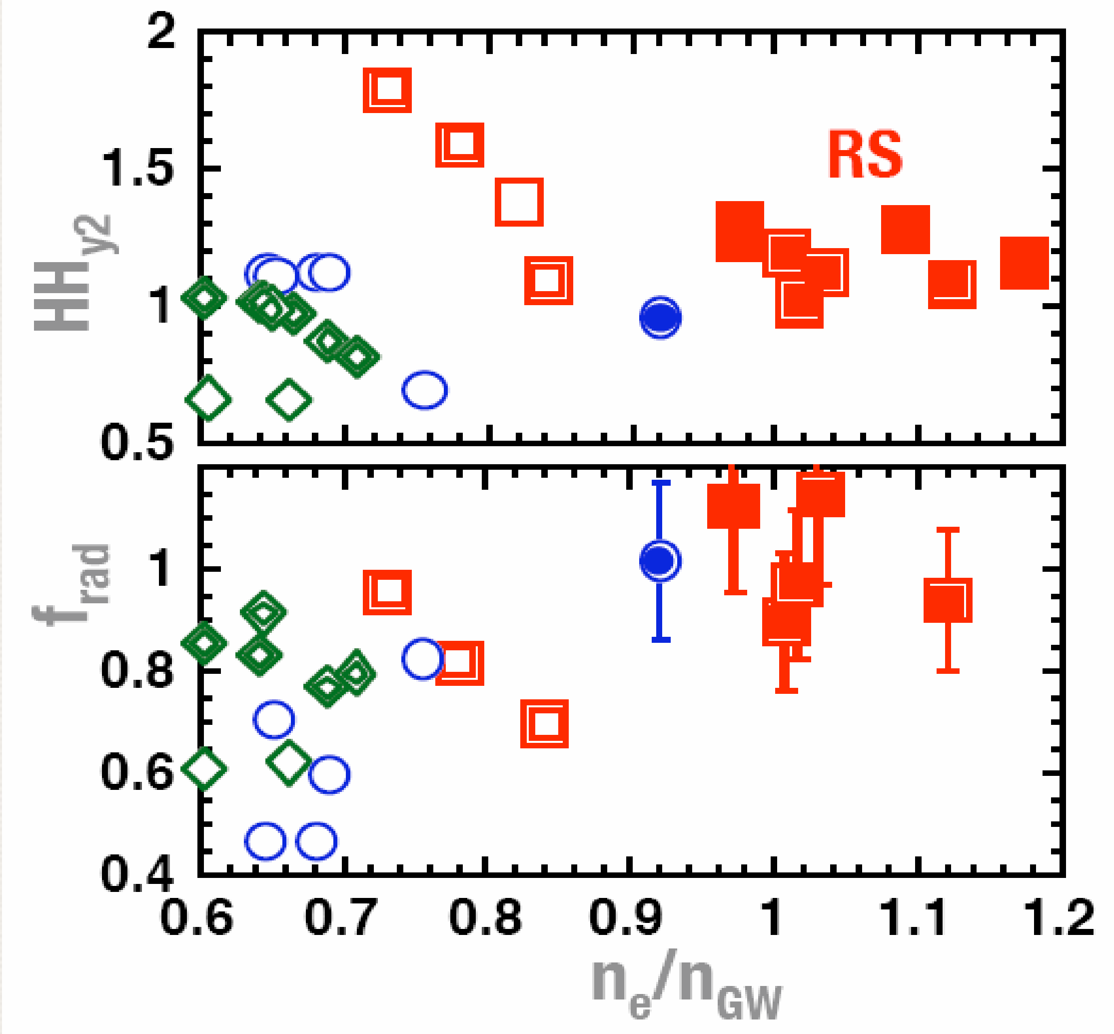
Combined Methods

JT-60U: $n_e/n_{GW}>1$,

$n_e(0)/n_{GW}$ ~1.5

Ne , Ar, D-pellet



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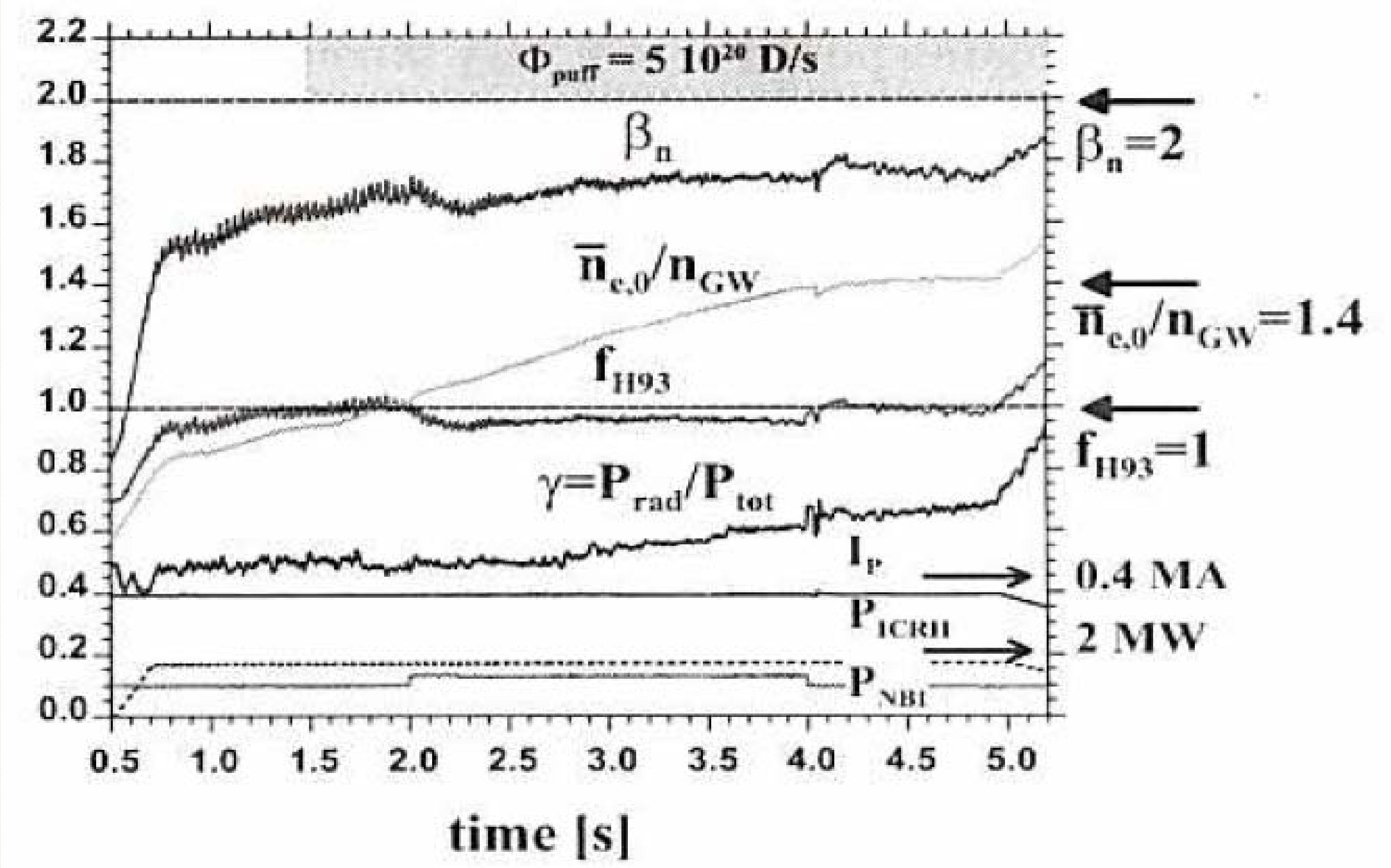
Edge Radiation and Fueling



TEXTOR, PRL 85, 11 (2000) 2312 pp

Demands II

Demands:

IAEA activities:

School on Plasma Physics and Integrated Modelling and Plasma Instability

Confinement Regimes

TM on H-mode physics and transport barriers

TM on Energetic particles in magnetic confinement systems

TM on Theory of plasma instabilities: Transport, Stability and their Interaction

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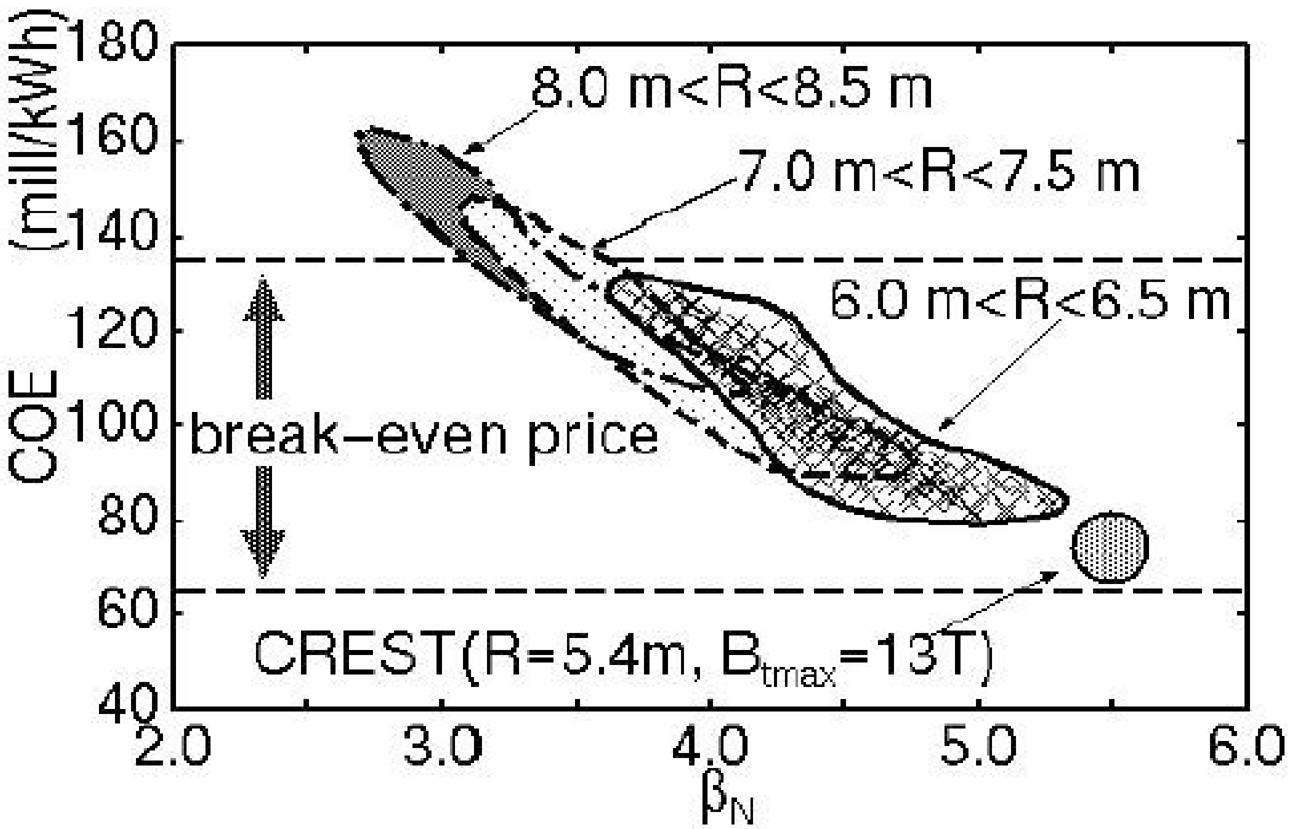
Cost of Electricity



The COE will decrease with increasing of the β_N

SE-P3/40 by R.Hiwatari et al.

Transport Physics

No.	Topics	Device/paper No.
1	**Zonal flow** Reynolds stress, GAM, Zonal flow	HT-7, Extrap-T2R JFT-2M, CHS, T-10
2	**Electron transport** Critical ∇T_e, non-linear $\chi_e \sim (\nabla T_e)^{\beta} T_e^{\alpha}$	AUG, JET, JT-60, DIII-D, LHD. TCV
3	**Particle transport** $G \sim -D[c_q \nabla q/q - c_T \nabla T_e/T_e]$, n_e^* dep.	Tore-Supra, FTU, AUG, JET, LHD, MAST, ET
4	**Momentum transport** Rotation without torque	Tore-Supra, C-Mod, FTU, DIII-D, TEXTOR
5	**Radial electric field** E_r control, Flow damping	LHD, GAMMA-10, TJ-II, HSX ISTTOK

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Transport Studies

IAEA Co-ordinated Research Project:

Joint Research Using Small Tokamaks

Aim:

1. Basic Studies (Transport, Wall, Instrumentation, Heating, etc.)
2. Exchange of knowledge and manpower
3. Strengthening efforts of small tokamaks
4. New research “beyond” ITER

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Diagnostic

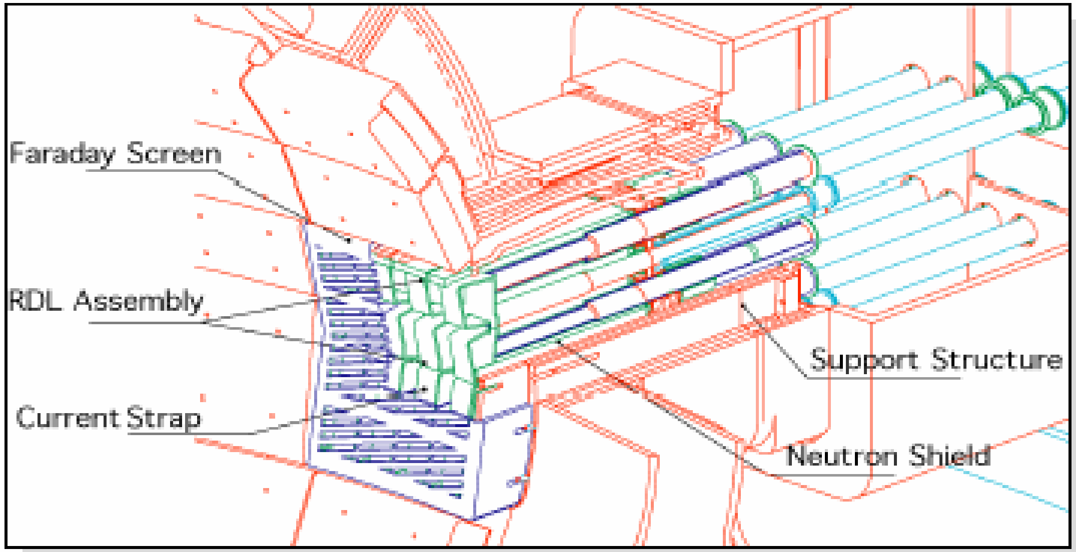
SELECTED DIAGNOSTICS for ITER

Magnetic Diagnostics	**Spectroscopic and NPA Systems**
Vessel Magnetics	CXRS Active Spectr. (based on DNB)
In-Vessel Magnetics	H Alpha Spectroscopy
Divertor Coils	VUV Impurity Monitoring (Main Plasma)
Continuous Rogowski Coils	Visible & UV Impurity Monitoring (Div)
Diamagnetic Loop	X-Ray Crystal Spectrometers
Halo Current Sensors	Visible Continuum Array
Neutron Diagnostics	Soft X-Ray Array
Radial Neutron Camera	Neutral Particle Analysers
Vertical Neutron Camera	Laser Induced Fluorescence (N/C)
Microfission Chambers (In-Vessel) (N/C)	MSE based on heating beam
Neutron Flux Monitors (Ex-Vessel)	**Microwave Diagnostics**
Gamma-Ray Spectrometers	ECE Diagnostics for Main Plasma
Neutron Activation System	Reflectometers for Main Plasma
Lost Alpha Detectors (N/C)	Reflectometers for Plasma Position
Knock-on Tail Neutron Spectrom. (N/C)	Reflectometers for Divertor Plasma
Optical Systems	Fast Wave Reflectometry (N/C)
Thomson Scattering (Core)	**Plasma-Facing Comps and Operational Diag**
Thomson Scattering (Edge)	IR Cameras, visible/IR TV
Thomson Scattering (Divertor region)	Thermocouples
Toroidal Interferom./Polarimetric System	Pressure Gauges
Polarimetric System (Pol. Field Meas)	Residual Gas Analyzers
Collective Scattering System	IR Thermography Divertor
Bolometric System	Langmuir Probes
Bolometric Array For Main Plasma	**Diagnostic Neutral Beam**
Bolometric Array For Divertor	

IT-P3/19 by A.Donne et al.

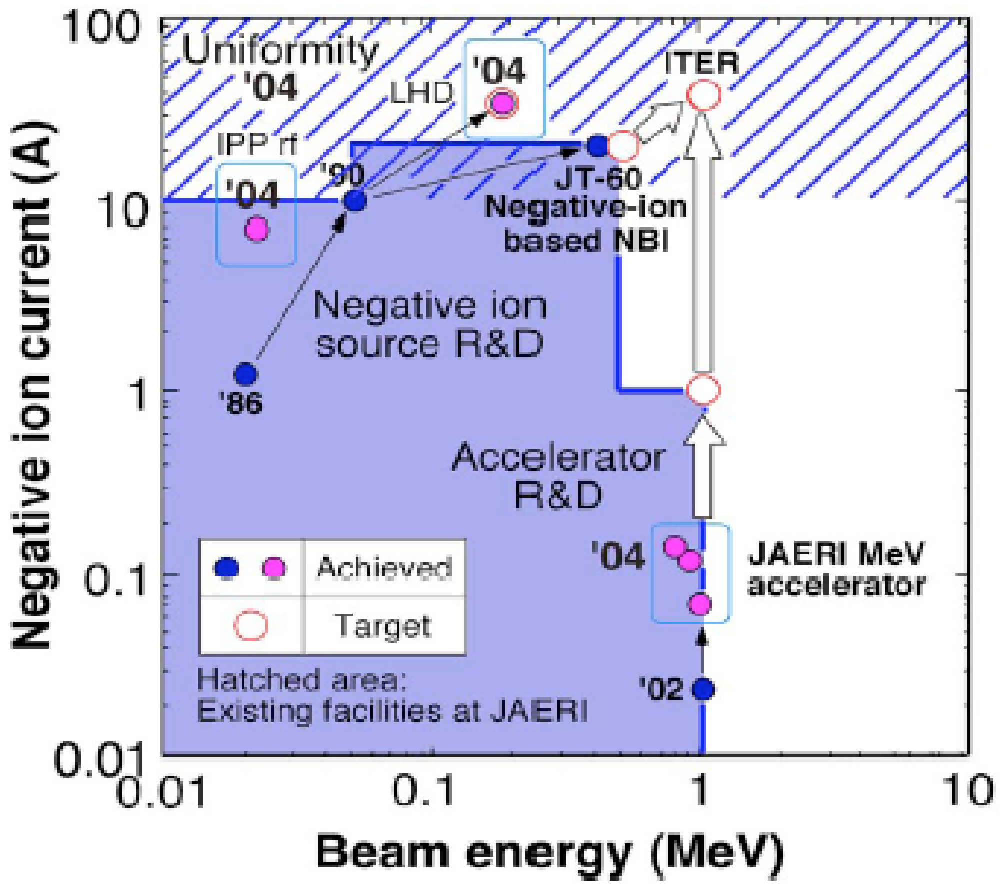
ICRH

ITER ICRF Launcher (Baseline Design)



Design goal:
– 20 MW through single port, 40-55 MHz
– produce launcher with input impedance insensitive to changes in loading
– minimize electric fields in antenna structure for a given level of current on radiating elements

Plasma Heating



- The world wide NB R&D is getting close to the ITER requirement.
- The R&D status is reaching almost on the envelope of the existing facilities.
    - Ion source R&D: ≤ 20 A, 500 keV,
    - Accelerator R&D: ≤ 1 A, 1 MeV.
- However, integration test at 40 A, 1 MeV would be necessary for ITER.

- Discussion on the full-scale testbed for the ITER NB system has been started among interested parties.

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Demands III

Demands:

Transport and Heating

IAEA activities:

School on Plasma Physics and Integrated Modelling and Plasma Instability

TM on Theory of plasma instabilities: Transport, Stability and their Interaction

TM on ECRH physics and technology for ITER

TM on Negative Ion Based Neutral Beam Injectors

TM on Research use of small fusion devices

TM on H-mode physics and transport barriers

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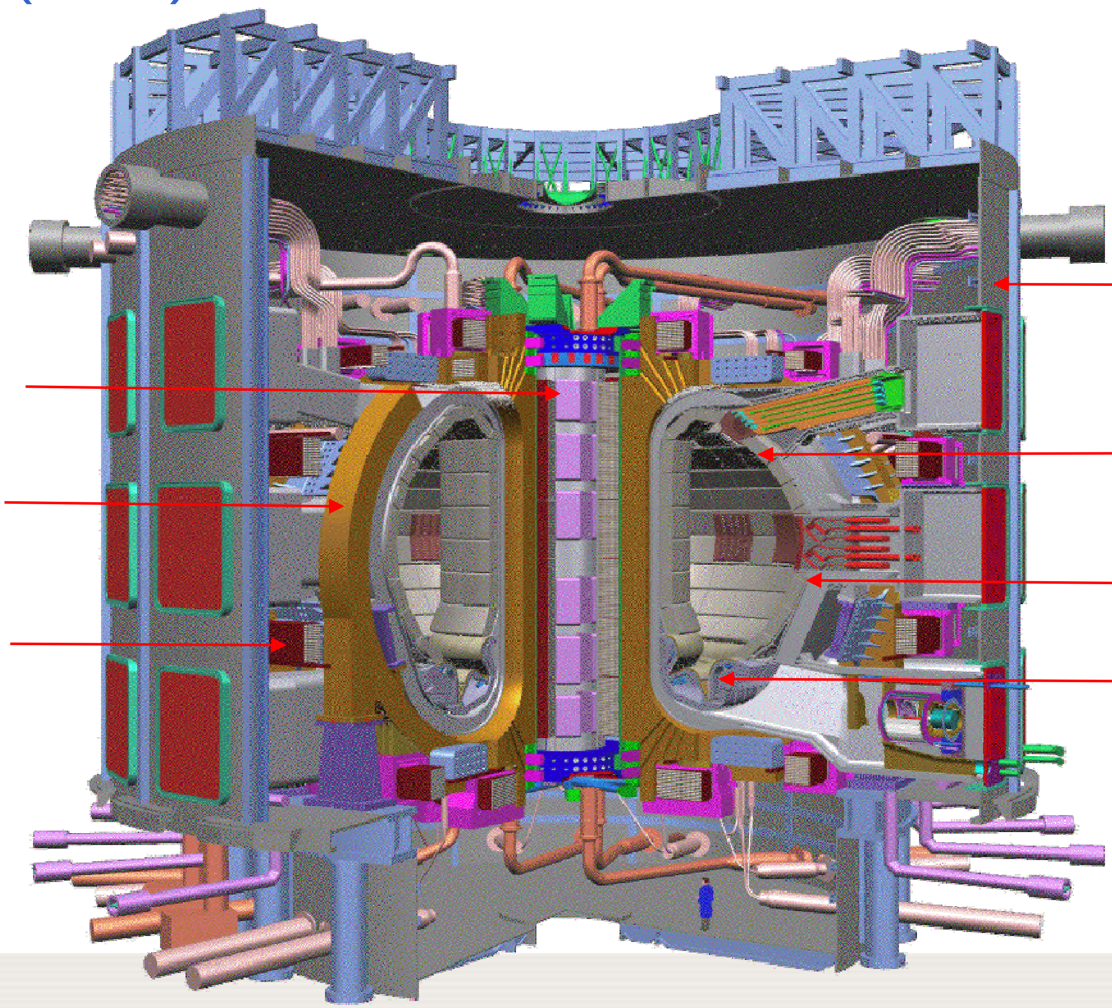
ITER: Intl. Toroidal Experimental Reactor

Iter: The way (Latin)



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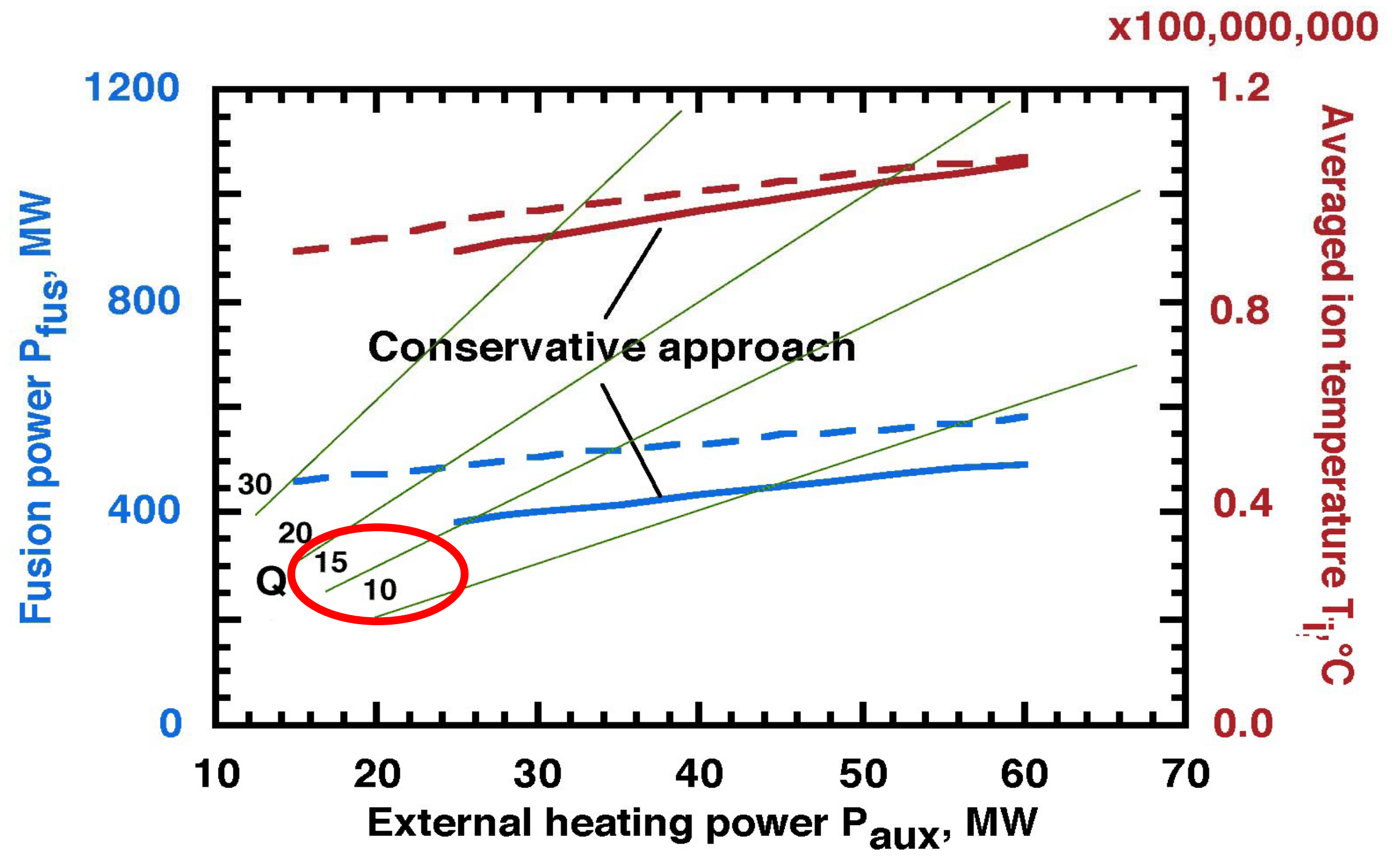
ITER Performance



B. Spears, FPA 2003, Washington

ITER Parameters

Total fusion power	500 MW (700MW)
Q = fusion power/auxiliary heating power	≥10 (inductive)
Average neutron wall loading	0.57 MW/m^2 (0.8 MW/m^2)
Plasma inductive burn time	≥ 300 s
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Plasma current (inductive, I_p)	15 MA (17.4 MA)
Toroidal field @ 6.2 m radius	5.3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Auxiliary heating/current drive power	73 MW (100 MW)

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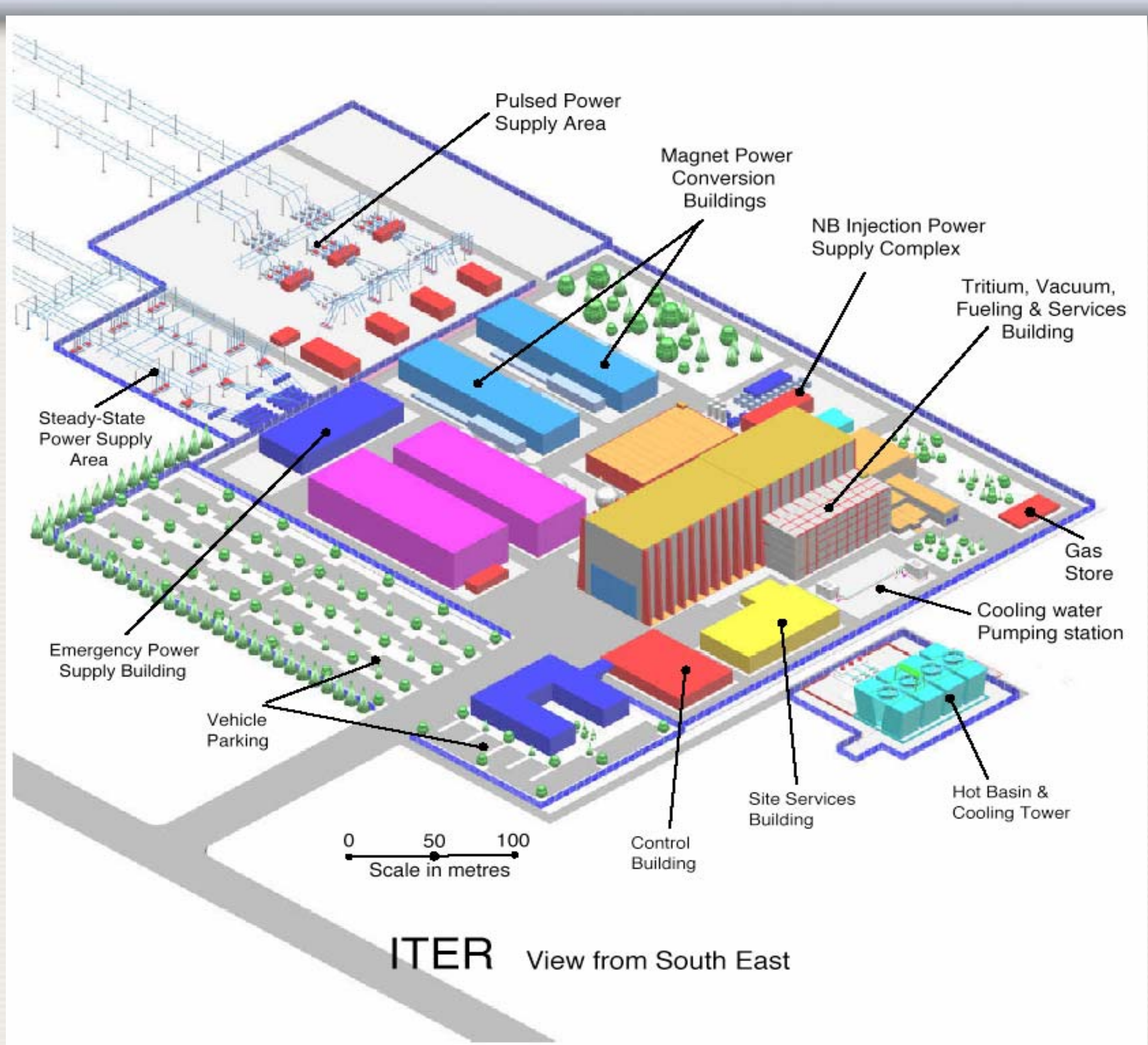
ITER Site Lay-out



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ITER Cost

	kIUA
Construction Costs	
Direct Capital	3012
Management & Support	477
R&D During Construction	~70
Operation Costs	
Permanent Personnel	60
Energy	~30
Fuel	~8
Maintenance Improvements	~90
Decommissioning	335

1 kIUA = $\$_{1998}$1M = $\$_{2000}$1.392M = €$_{2000}$1.279M = ¥$_{2000}$148M = C$\$_{2000}$1.509M

B. Spears, FPA 2003, Washington

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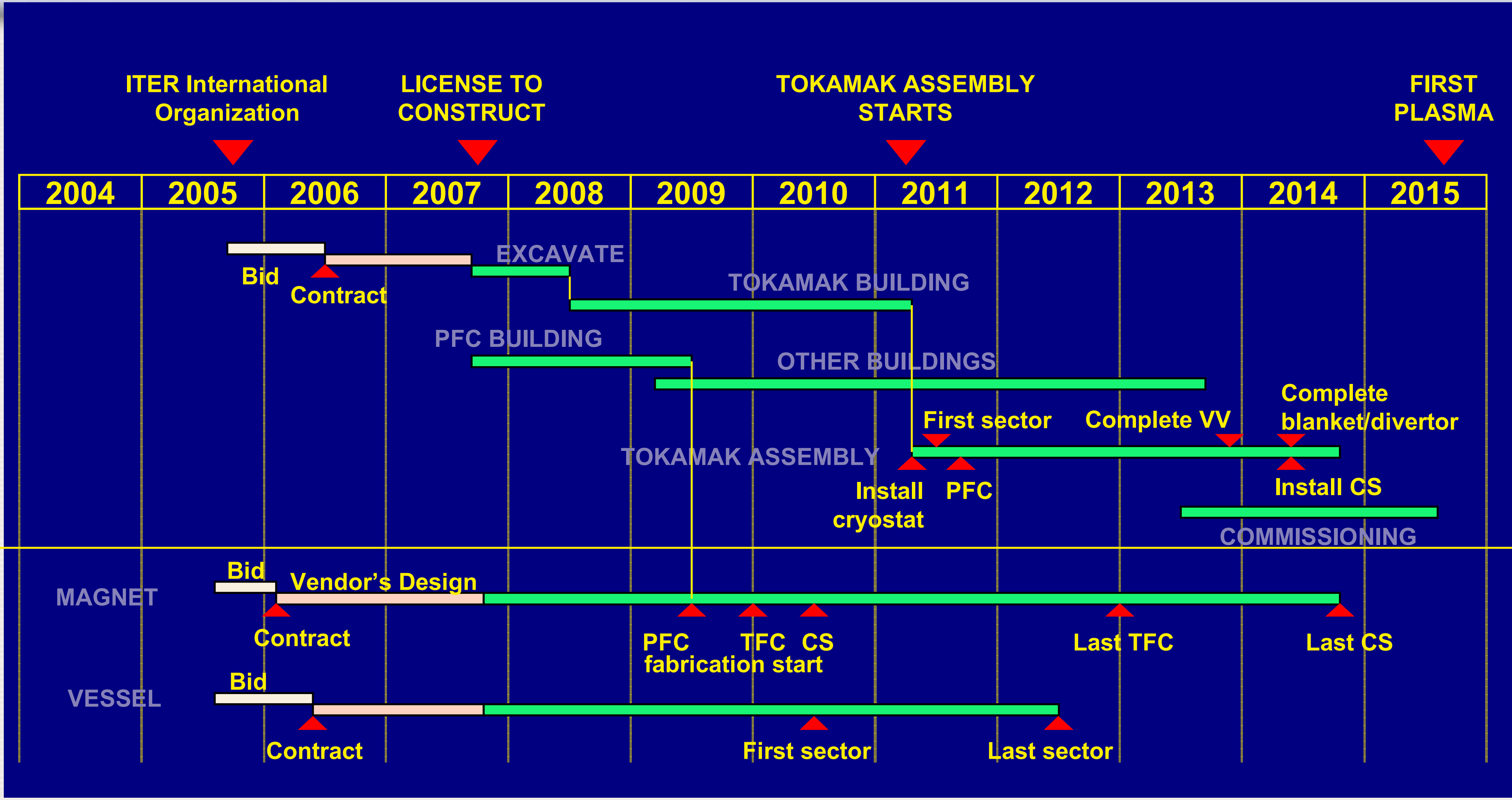
Construction schedule



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ITER

ITER site

France
(Cadarache)

Japan
(Rokkasho)

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New Devices

New devices under construction

Name	Country&Institution	Status	First plasma	Reference
SST-1	India IPP	Assembled	2005	FT-3/4
EAST	China ASIPP	Under Construction	2005	FT-3/3
KSTAR	Korea. Rep. KBSI	In fabrication and testing	2007	FT-3/2
Wendelstein 7-X	Germany IPP	In fabrication and testing	2010	FT-3/5
NCSX	USA PPPL	Production will begin soon	?	FT-P7/22

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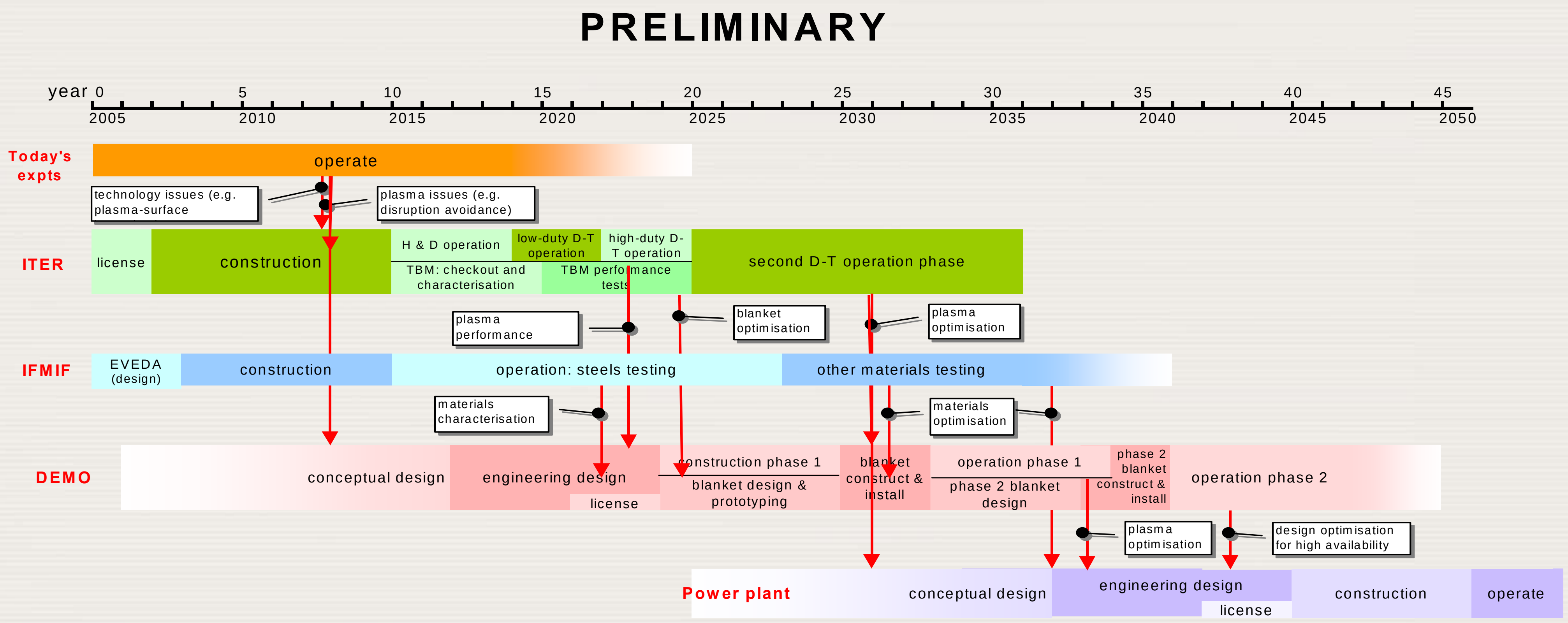
Fast Track to Fusion



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Issues and their resolution: pillars only

Issue	Today's expts	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Disruption avoidance	2	3		3	R	R
Steady-state operation	1	3		3	r	r
Divertor performance	2	3		r	R	R
Burning plasma Q>10		3		R	R	R
Power plant plasma performance	1	3		3	R	R
T self-sufficiency		1		3	R	R
Materials characterisation			3	R	R	R
Plasma-facing surface lifetime	1	1		2	3	R
FW/blanket materials lifetime		1	2	2	3	R
FW/blanket components lifetime		1		1	3	R
Divertor materials lifetime		1	2	2	3	R
NB/RF heating systems performance	1	3		R	R	R
Electricity generation at high availability				1	3	R
Superconducting machine	1	3		R	R	R
Tritium issues	1	3		R	R	R

Key:

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
r	Solution is desirable
R	Solution is essential

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C. Llewellyn Smith

Radiation Damage

Progress of Radiation Damage Evaluation for DEMO and ITER blankets

Target and accomplised damage level in "displacement per atom (dpa)"

	2002		2004		Traget level	
	ITER TBM	DEMO	ITER TBM	DEMO	ITER TBM	DEMO
Short Term Mechanical Properties						
Tensile					>3dpa	>150dpa
Fracture Toughness				20dpa	>3dpa	>150dpa
Fatigue			4dpa		>3dpa	>150dpa
Creep					>3dpa	>150dpa
Compatibility						
Cracking (EAC)			2dpa		>3dpa	>150dpa
Corrosion					>3dpa	>150dpa
Materials Engineering	100%					
Joining	75%				>3dpa	>150dpa
Condition Change	50%		2dpa		>3dpa	>150dpa
Plasticity/Ductility			5dpa		>3dpa	>150dpa
Codes	25%					
Design						
Maintenance						

IFMIF

High Damage Levels

A large progress in materials property evaluation for ITER TBM application has been accomplished

Fission reactor irradiation produces too small level of He atoms. For evaluation with high enough accuracy, facility like IFMIF is needed.

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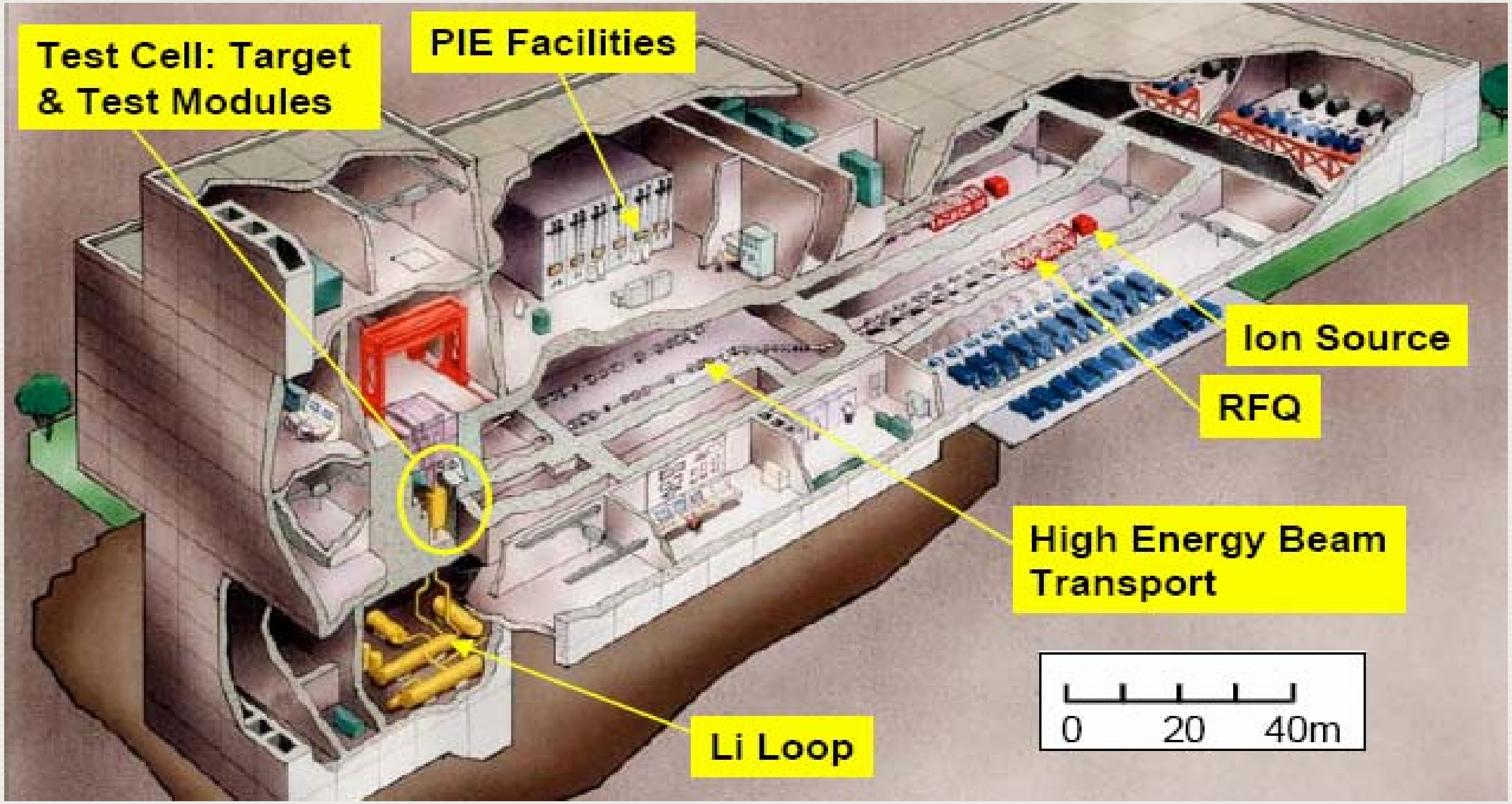
IFMIF



International Fusion Materials Irradiation Facility

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Safety Event Analysis

Event Family	Events
Plasma events	Loss of plasma control/exceptional plasma behaviour (i,a)
Loss of electrical power	Loss of off-site power for up to 1 h (i)
	Loss of off-site power for up to 32 h (a)
	Loss of off-site power and on-site class III power for up to 1 h (a)
In-vessel events	In-vess[illegible]
	Multip[illegible]
	Loss o[illegible]ne (a)
Ex-vessel HTS events	Loss o[illegible]
	Pump trip/loss of flow in divertor HTS (i)
	Pump seizure in divertor HTS (a)
	Vacuum vessel HTS break (a)
	Large ex-vessel divertor HTS break (a)
	Heat exchanger leakage (i)
	Heat exchanger tube rupture (a)
Tritium plant and fuel cycle events	Tritium process line leakage (i)
	Transport hydride bed mishandling (a)
	Isotope separation system failure (a)
	Fuelling line with impaired confinement (a)
Maintenance events	Stuck divertor cassette in transport cask (a)
	Maintenance accident on vacuum vessel (a)
Magnet events	TF short (a)
	Magnet arc (a)
Cryostat event	Air ingress (a)
	Water/air/helium ingress (a)
Hot cell events	Failure of confinement (a)

Disruptions

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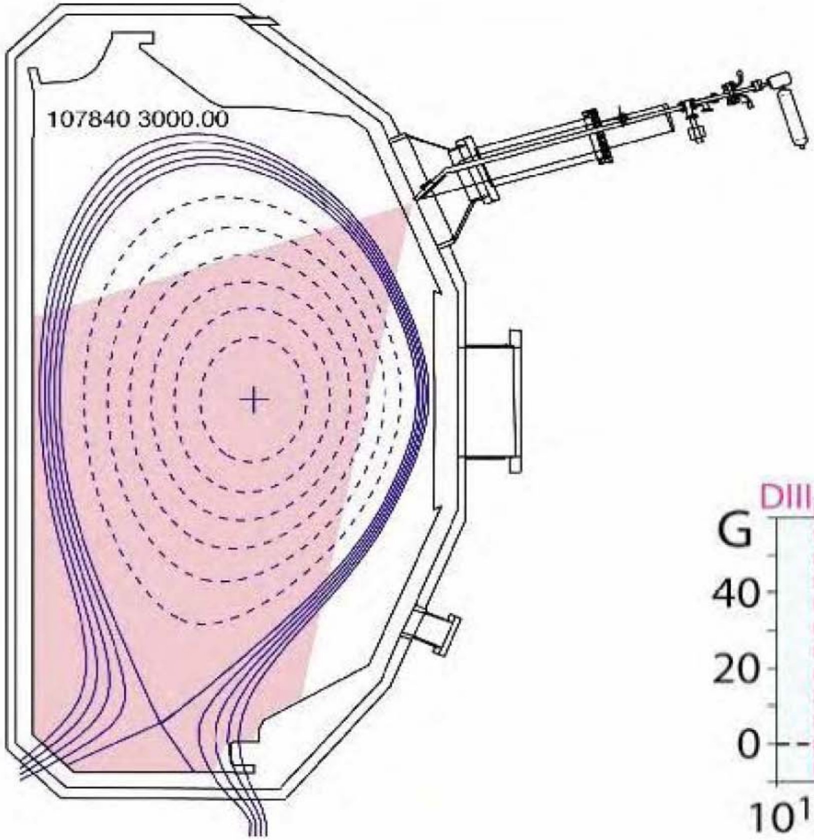
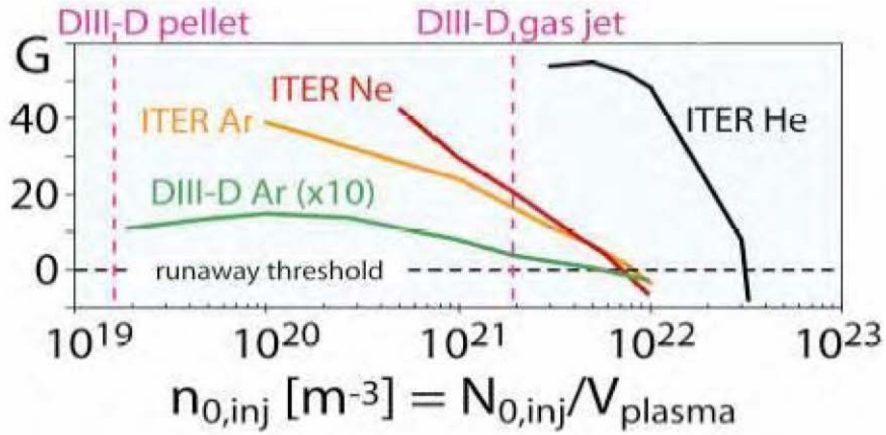
Disruption Mitigation



Runaway avalanche suppressed with sufficient electron injection.

Machine	Gas	$\frac{N_e}{V_{plasma}}$ [/m³]	$\frac{N_{0,inj}}{V_{plasma}}$ [/m³]
DIII-D	Ne,Ar	3e19	2e21
Tore Supra	He	3e19	3e21
JT-60U	Ar,Kr, Xe,H_2	1e19	6e19



Demands IV

Demands:	IAEA activities:
	TM on the Atomic and Molecular Data Centres and ALADDIN Network
Materials and Wall	School on pulsed neutron sources: Enhancing the capacity for material science
	CRP on Joint Research Using Small Tokamaks

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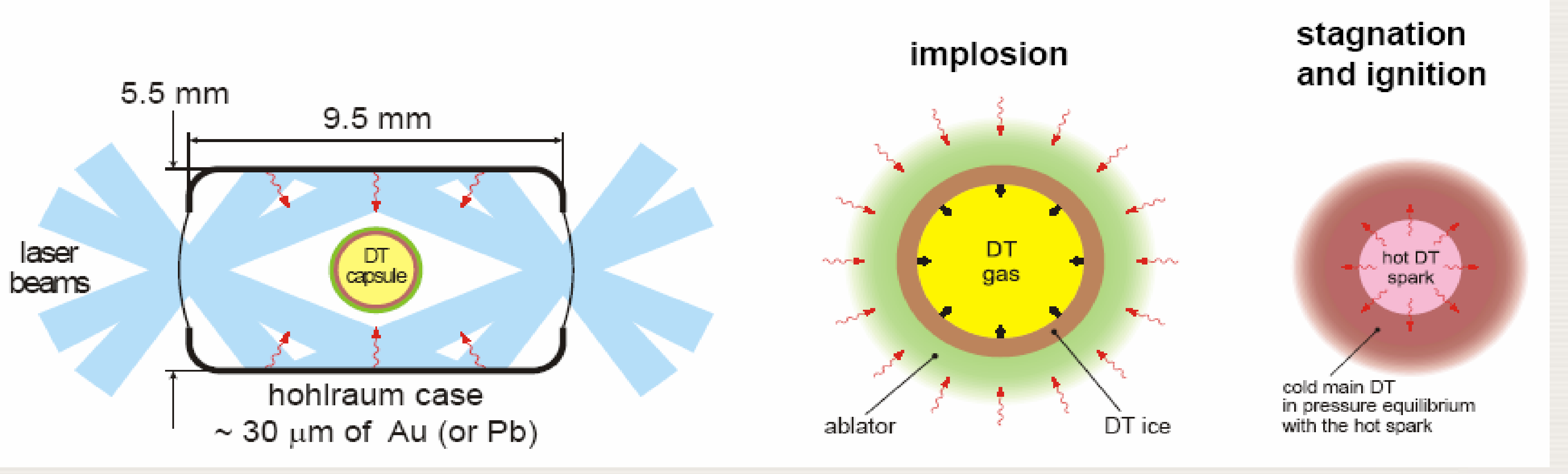
Inertial Fusion Energy

Main route to ignition: indirect laser drive with central hot-spot ignition

Baseline target and driver designs for NIF have been worked out more than 10 years ago.



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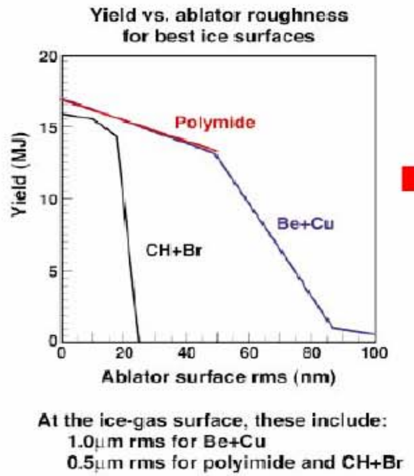
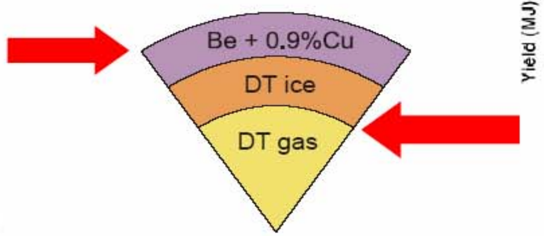
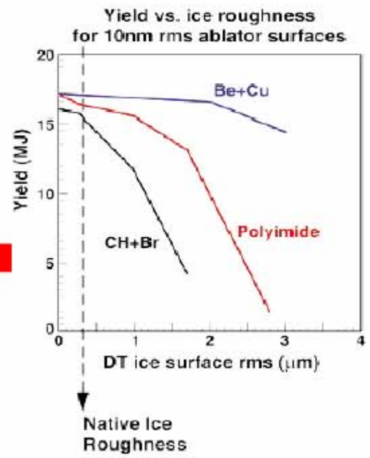
Pellet Improvement







3-D simulations for T_x = 300 eV

(J.Lindl *et al.*, PhP **11**, 339,2004)

Latest discovery: **with graded Cu doping of the Be ablator, the ablator surface roughness ⇒ 60 x NIF standard (~ 500 μm); ice roughness 1 μm ⇒ 5 μm !** (J.Lindl, OV-3/1)

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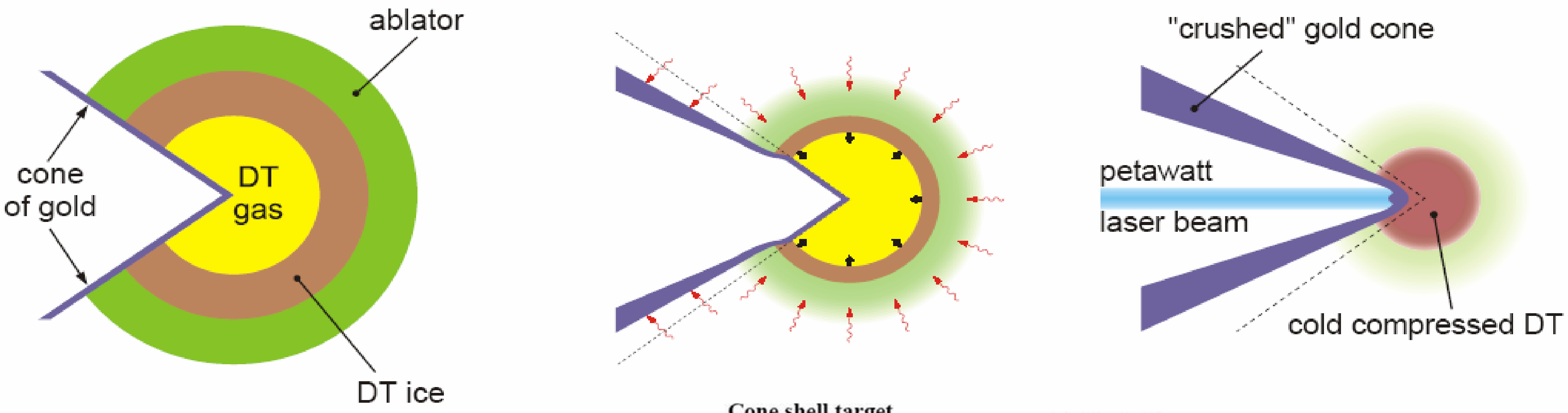
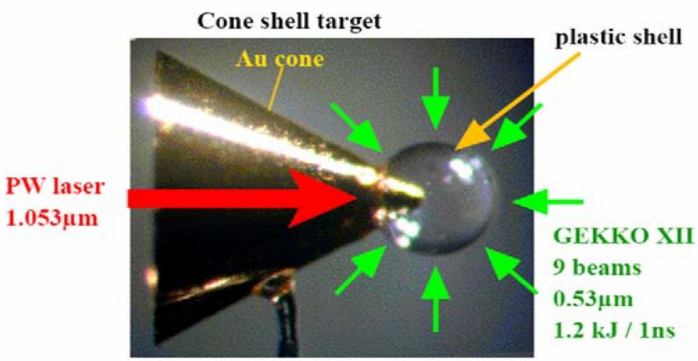
Fast Ignition

Fast ignition offers an alternate, potentially more efficient, route to ICF.

Principal option: **a cone-guide implosion of the cold fuel is followed by a fast ignition pulse.**

The FI approach to ICF does not have the highest priority, but is also making a steady progress.





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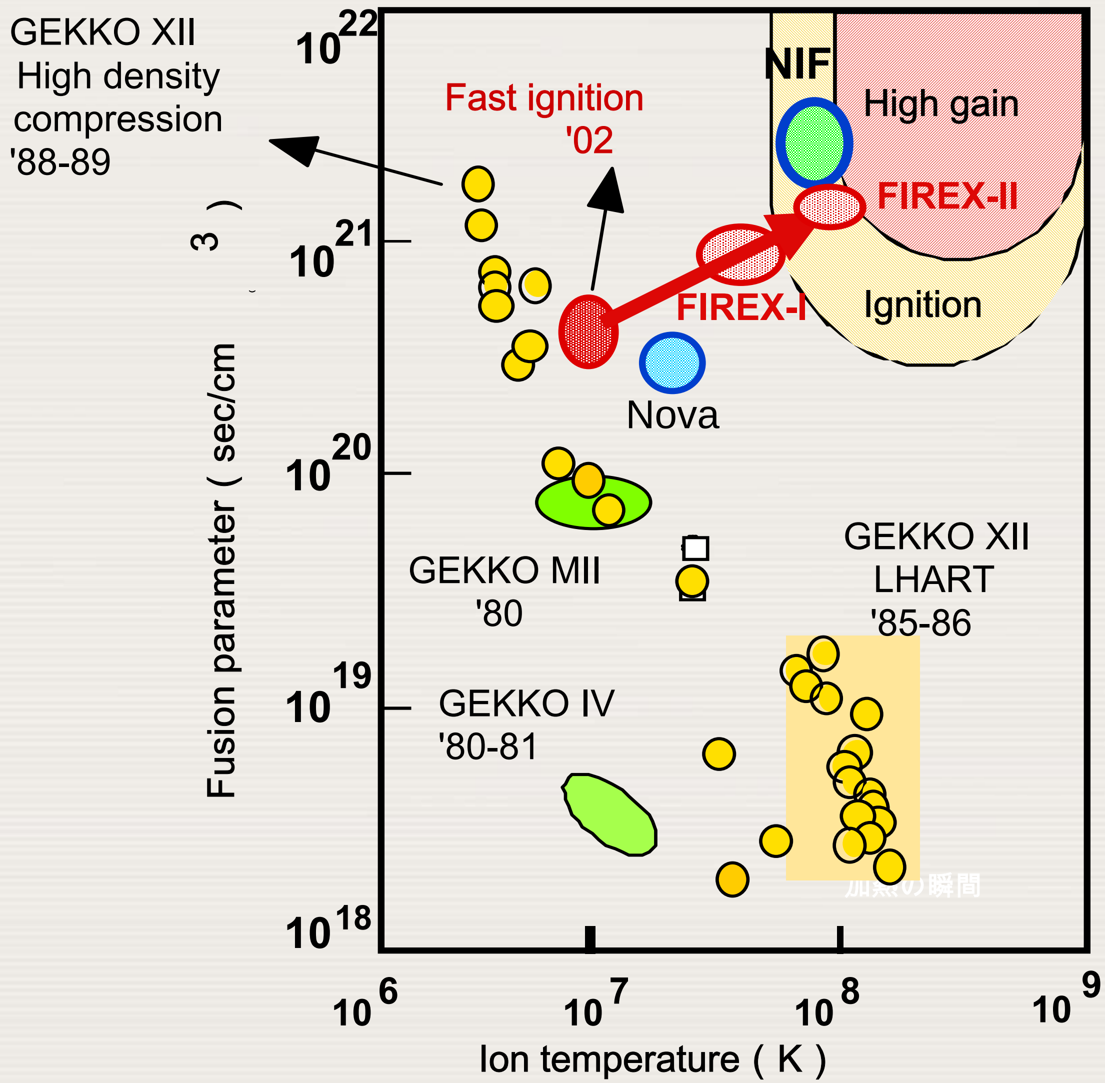
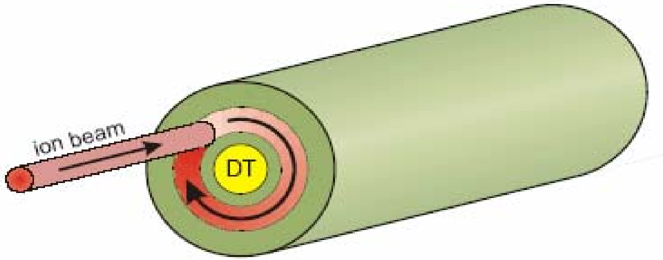
Fast Ignition - Status

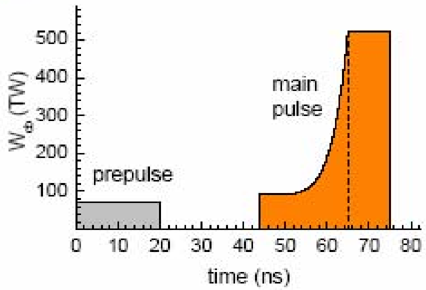


Heavy Ion Fast Ignition

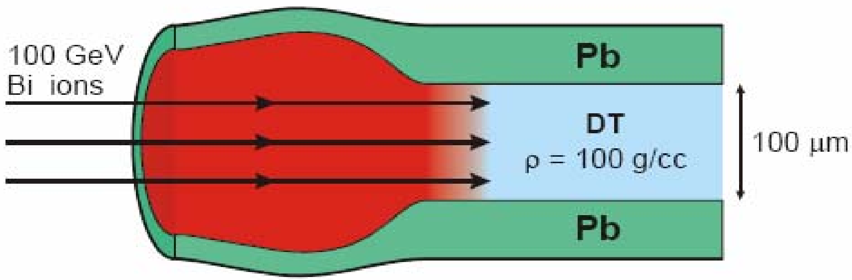
Direct drive cylindrical target: compression stage



Compression pulse:



Ignition and burn propagation



Ignition pulse:

beam energy:	E_{igb} = 400 kJ
pulse duration:	t_{igp} = 200 ps
beam power:	W_{igb} = 2 PW
focal radius:	r_{foc} = 50 μm
irradiation intensity:	$I_{igb} = 2.5\times10^{19}$ W/cm^2

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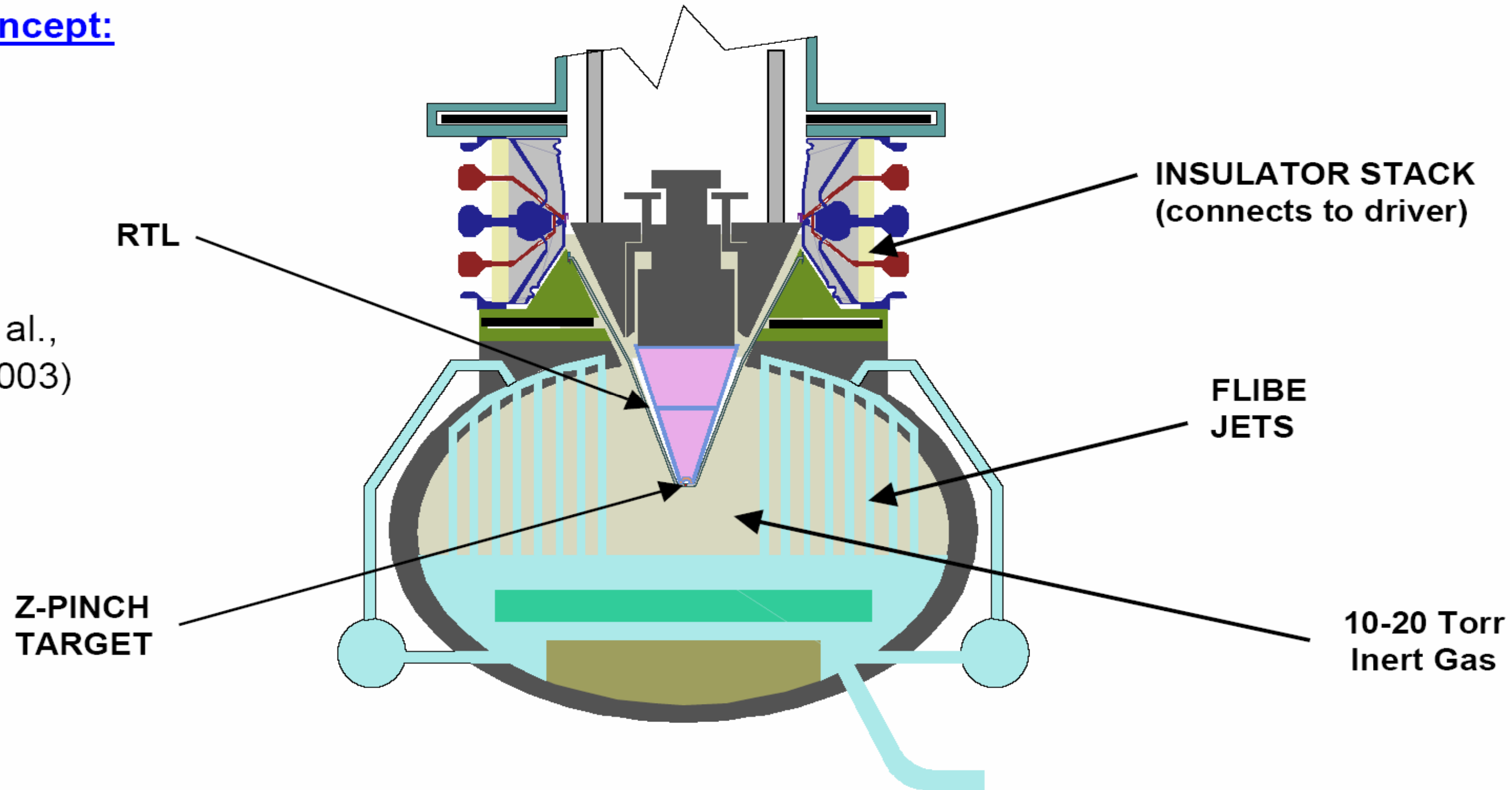
Z-pinch Wire Array

Power plant concept:

(G.E.Rochau et al., FST, **43**, 447, 2003)



Demands V

Demands:

New Concepts and IFE

IAEA activities:

TM on Innovative concepts and theory of stellarators

TM on Negative Ion Based Neutral Beam Injectors

TM on Spherical Tori.

RCM on Dense magnetised plasmas

RCM on Inertial Fusion Energy

TC support

IAEA

Summary

Future Option of Energy Production

Controlled Nuclear Fusion

Acknowledgement to participants of the FEC2004 and IAEA meetings

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