Georgia Tech

Confinement

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CREATING THE NEXT®

Overview

- Confinement in theory
  - Figures of Merit
  - H-mode vs. L-mode
  - Empirical correlations
- Confinement in practice
  - DIII-D
  - ITER
  - GLOBUS

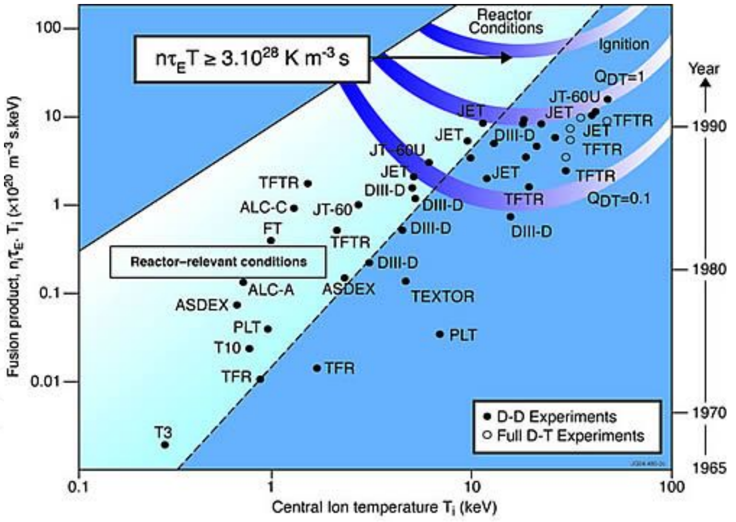
Confinement

- Different methods to trap particles and thermal energy within a volume
  - Gravitational
  - Inertial
  - Electrostatic
  - Magnetic
    - Simple mirrors
    - Tandem mirrors
    - Minimum-B mirrors
    - Stellarators
    - Tokamaks

Confinement Figures of Merit

- Lawson Criterion
  - 1955, classified British fusion research
  - Net Power > 0, inequality on n * tau
- Fusion Triple product
  - Extension of Lawson Criterion

$$nT\tau_E \geq \frac{12k_b}{E_{ch}} \frac{T^2}{\langle \sigma v \rangle}$$



https://www.euro-fusion.org/news/detail/detail/News/50-years-of-lawson-criteria/
Lawson, John D. "Some criteria for a power producing thermonuclear reactor." Proceedings of the physical society.
Stacey Weston, “Fusion Plasma Physics”

Magnetic Confinement in Tokamaks

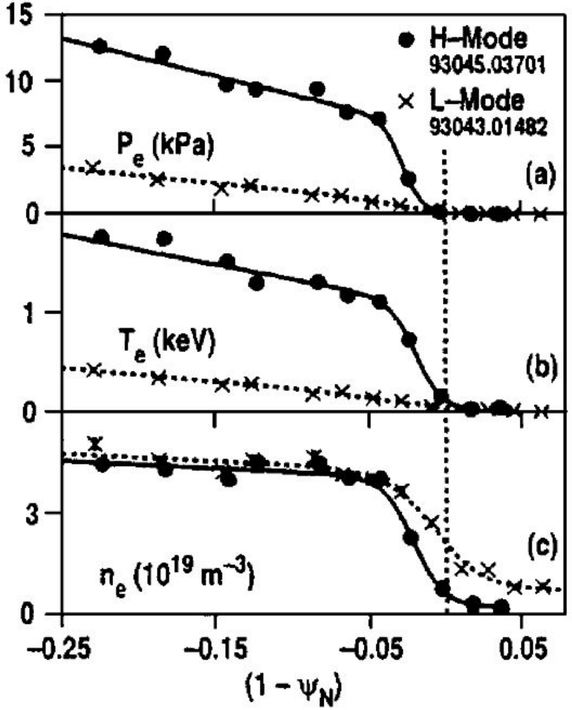
- Take advantage of the fact that particles spiral about field lines
- Poloidal field superimposed to counter drifts
- Guard against various instabilities
  - Discussed in other presentations
- H-mode vs. L-mode confinement

H-Mode Confinement

- Discovered mid-80’s
- “Tightening” of plasma edge past power threshold
- Increases confinement time 2x-3x

$$P_{\mathrm{LH}}^{(\mathrm{MW})} = (2.84/A_{\mathrm{i}})\bar{n}_{20}^{0.58} B^{0.82} R a^{0.81}$$

Fusion Plasma Physics, 425



Fusion Plasma Physics, 426

H-Mode Confinement Research

- Understanding of phenomenon still advancing
  - “H-mode confinement in tokamaks” M Keilhacker 1987 *Plasma Phys. Control. Fusion* **29** 1401
  - “Enhanced Confinement and Stability in DIII-D Discharges with Reversed Magnetic Shear” E. J. Strait, et al. 1995 *Phys. Rev. Lett.* **75** 4421
  - “A quarter-century of H-mode studies” F Wagner 2007 *Plasma Phys. Control. Fusion* **49** B1

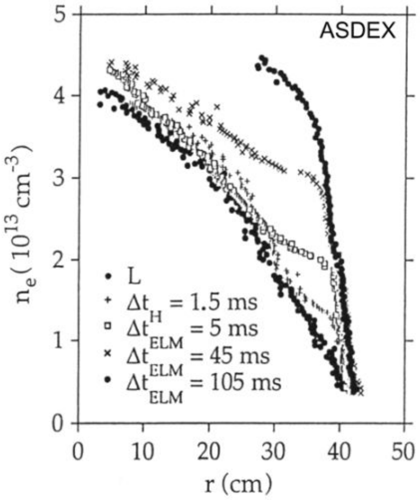


Figure 6. Development of the density profile after H-transition [33].

A quarter-century of H-mode studies, B8

H-Mode Cont.

- Mechanisms behind E x B Shear Stabilization effect on edge turbulence
  - E.g. radial electric field on polodial flow
- Achievements using this high-confinement mode
  - JET 16.1 MW fusion power discharge (Q=0.67)
  - Tore Supra 6m30s plasma duration
  - Equivalent Q=10 discharge DIII-d
  - ITER
  - Demo designs
- Crucial to achieving a burning plasma state

Empirical Correlations

- Characterization of confinement times based on a set of operation parameters

Table 5. Exponents of the several empirical log-linear scalings based on ITERH.DB3

Scaling	C (10^{-2})	I	B	n	P	R	$\kappa_a^{(1)}$	a/R	M	N	RMSE (%)	ITER τ_E (s)
IPB98(y)	3.65	0.97	0.08	0.41	−0.63	1.93	0.67	0.23	0.20	1398	15.8	6.0
IPB98(y,1)	5.03	0.91	0.15	0.44	−0.65	2.05	0.72	0.57	0.13	1398	15.3	5.9
IPB98(y,2)	5.62	0.93	0.15	0.41	−0.69	1.97	0.78	0.58	0.19	1310	14.5	4.9
IPB98(y,3)	5.64	0.88	0.07	0.40	−0.69	2.15	0.78	0.64	0.20	1273	14.2	5.0
IPB98(y,4)	5.87	0.85	0.29	0.39	−0.70	2.08	<u>0.76</u>	0.69	0.17	714	14.1	5.1

"ITER Physics Basis Chapter 2" ITER Physics Expert Group on Confinement and Transport et al 1999 *Nucl. Fusion* **39** 2175

L-Mode
$$\tau_E^{\text{ITER89-P}}(s) = 0.048\frac{I^{0.85}R^{1.2}a^{0.3}\kappa^{0.5}\left(n/10^{20}\right)^{0.1}B^{0.2}M^{0.5}}{P^{0.5}}$$

H-Mode
$$\tau_E^{\text{IPB98}(y,2)}(s) = \frac{0.056I^{0.93}B^{0.15}\left(n/10^{20}\right)^{0.41}M^{0.19}R^{1.97}\kappa^{0.78}A^{-0.58}}{P^{0.69}}$$

DIII-D Tokamak

- Operated by General Atomics for the Department of Energy in San Diego.
- Confines high temperature plasma with electromagnets.
- DIII-D National Fusion Facility conducts fusion experiments to understand fusion and plasma science.
- 3rd tokamak built with this type of doublet configuration (elongated hourglass)
- Upgraded to contain the D configuration of the cross-section

https://science.energy.gov/fes/facilities/user-facilities/diii-d/

DIII-D Tokamak Mission

- Find solutions for the tokamak disruption problem
- Solve the divertor challenge for FNSF and a future demonstration power plant (DEMO)
- Develop the governing physics laws for the burning plasma state
- Research steady-state conditions of the tokamak
- Maximize tokamak stability with three-dimensional optimization

Reference: https://science.energy.gov/fes/facilities/user-facilities/diii-d/

DIII-D Capabilities

- Field-shaping coil system to produce different 3D plasma geometries
- Variety of auxiliary heating and current drive systems
- Interior and exterior coils with respect to the vacuum vessel
- Carbon surfaces facing the plasma
- Diagnostic systems to record plasma parameters
- Advanced digital control system to maintain plasma control

https://science.energy.gov/fes/facilities/user-facilities/diii-d/

DIII-D Design Parameters

Major Radius (R): 1.67 meters

Minor Radius (a): 0.67 meters

Magnetic Field (B): 5.3 Tesla

Power (P): 23 Megawatts

Plasma Current (I): 9.39 Mega-amperes

Elongation at the Plasma Boundary (κ): 2.5

Line-averaged density (n): 6.29 x 10^{19} m^{-3}

Atomic Mass of the Ions (M): 2.515 for D-T reactions

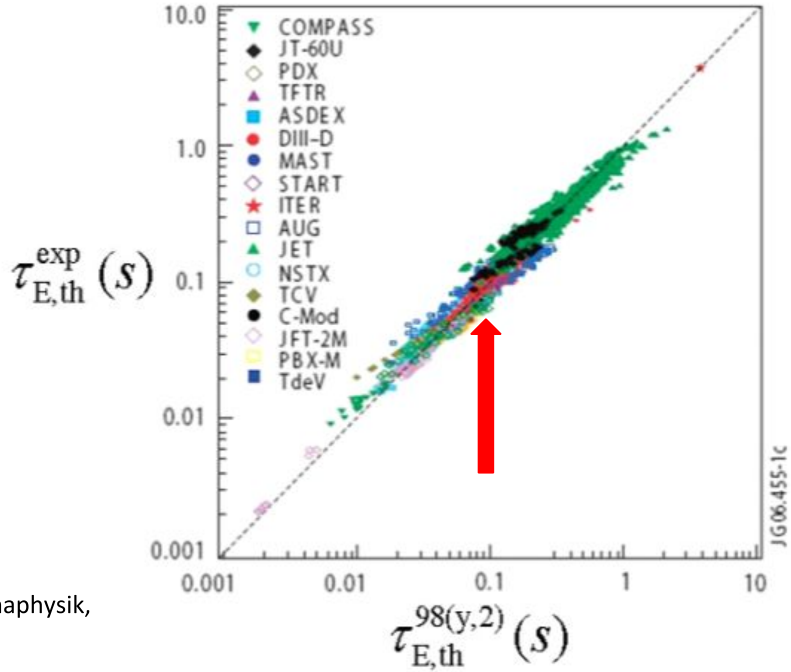
Major Radius/Minor Radius Ratio (A): 2.5

Development of Steady-State Advanced Tokamak Research in the DIII-D Tokamak. T. C. Luce. Fusion Science and Technology.

DIII-D Global Energy Confinement Time

The calculated global energy confinement time in H-mode for the DIII-D design parameters using the IPB98 (y,2) equation is:

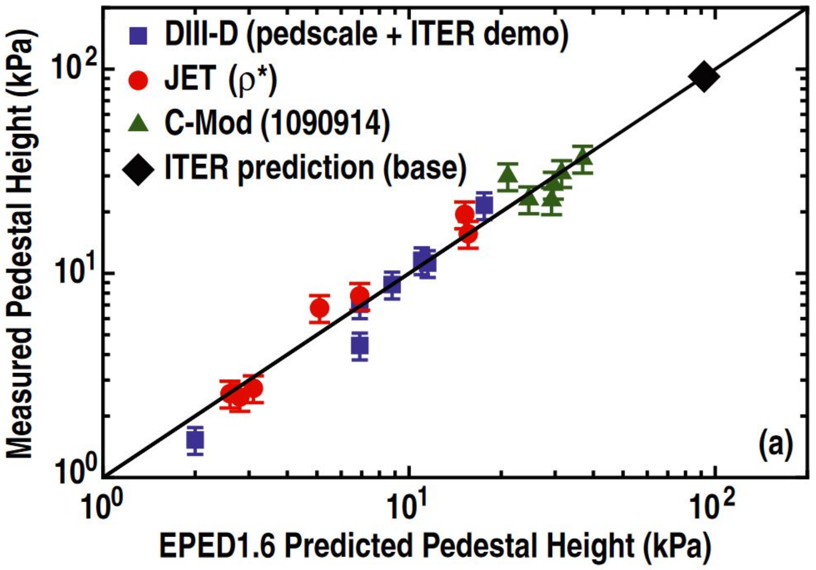
τ = 0.216 s



"The Physics Basis of ITER Confinement", F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

DIII-D Contributions to Confinement Research

- Long running experiment with numerous contributions
- Example: Predicting the H-Mode edge pedestal height
  - Model for predicting height (EPED 1.6) needs verification of parameters
  - DIII-D (and JET) experiments help verify these constants



"DIII-D contributions towards the scientific basis for sustained burning plasmas" C.M. Greenfield and the DIII-D Team 2011 *Nucl. Fusion* **51** 094009

ITER (International Thermonuclear Experimental Reactor)

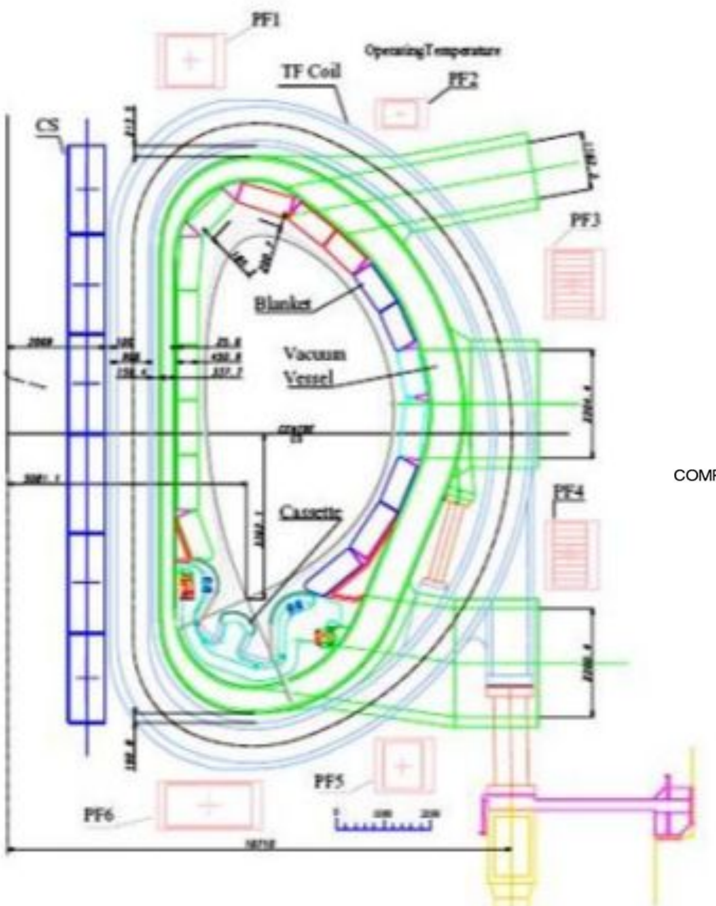
Goals:

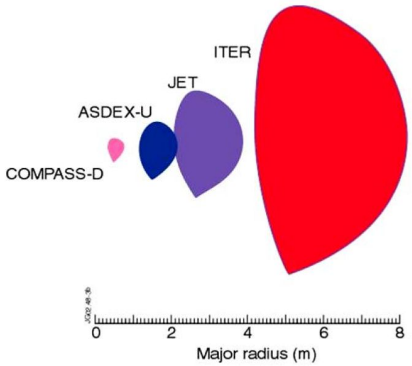
1) To produce fusion power and provide α-particle heating at a level which surpasses the external heating power
2) To develop the means to control the fusion burn
3) To study instabilities and specifically ones created by the slowing-down spectrum of α-particles
4) To develop long-pulse scenarios and techniques to qualify the tokamak for steady-state operation
5) To test a blanket module and confirm the necessary tritium breeding ratio of ~ 1.1

"The Physics Basis of ITER Confinement", F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

ITER Design

Design Parameter	Value [units]
Major Radius	6.2 [m]
Minor Radius	2.0 [m]
Toroidal Field	5.3 [T]
Elongation (k)	1.85
Plasma Current	15 [MA]
Fusion Power	500 [MW]
Q	~10
Burn Duration	~400 [s]





“The Physics Basis of ITER Confinement”, F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

ITER Operational Range

K (Elongation) → Safety Factor → I_p

Higher K values allow for higher I_p values to be operated safely

Operation Range is expanded with higher I_p values

Greenwald Limit

$$n_{GW} \leq I_p / a^2$$

Troyon Limit

$$\beta \leq \beta_N \, I_p / a$$

β

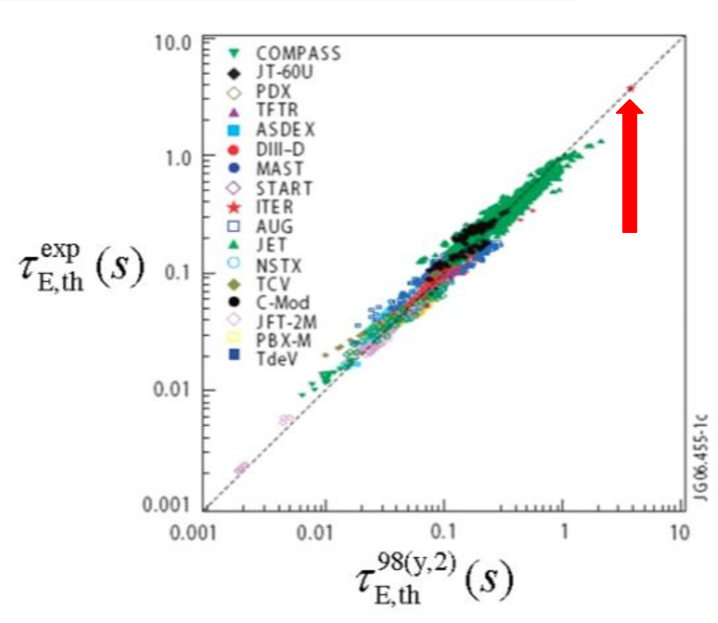
ITER will operate at $n_e/n_{GW} = 0.85$

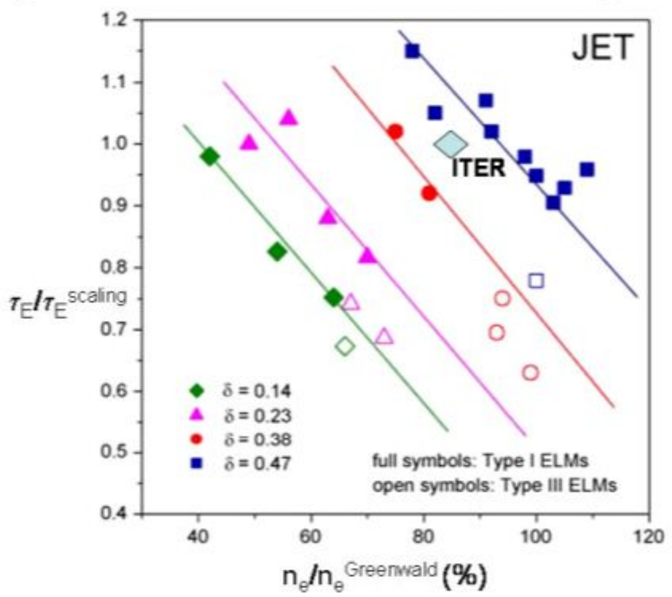
Both Limits Scale with current

"The Physics Basis of ITER Confinement", F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

Confinement Times Predictions by Scaling

According to IPB scaling, τ = 3.7 s





"The Physics Basis of ITER Confinement", F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

Summary on ITER Performance

- Large Advancements have been made in the computational modeling of ITER

- Transport modelling/simulation indicate that ITER will meet its baseline design confinement requirements (MM, IFS/PPPL, Weiland and GLF23)

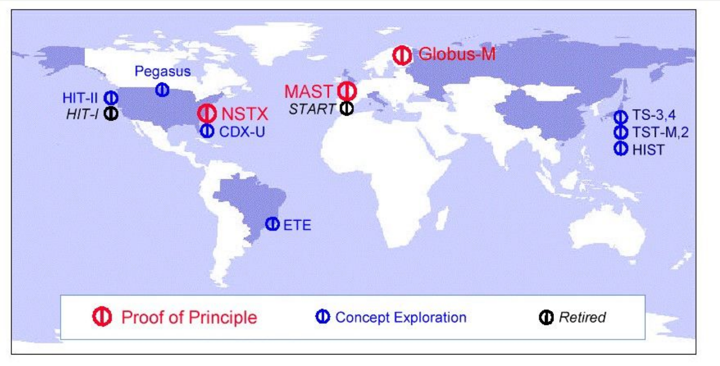
- Fully integrated (core and edge) predictive capability is still some way in the future

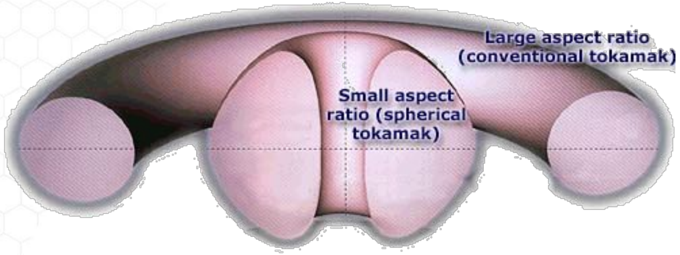
ITER Physics Expert Groups on Confinement and Transport and Confinement Modelling and Database, ITER Physics Basis Editors and ITER EDA 1999 Nucl. Fusion 39 2175

ITER Physics Basis, Chapter 2: Plasma confinement and transport, E.J. Doyle (Chair Transport Physics) et al 2007 Nucl. Fusion 47 S18

Spherical Tokamak Introduction

- Defined by low aspect ratio (R/a)
- START in the UK was first ST for hot plasma (1991)
- Developed to reduce capital costs of experiments
- Shown to produce greater pressure at lower field strengths (10x)
- Better overall economics and efficiency than conventional Tokamak





Gryaznevich, M. “Achievement of Record β in the START Spherical Tokamak” Physical Review Letters.
Gusev, Vasiliy. “Globus-M tokamak experiment.” Website.

Features of a Spherical Torus Plasma

- Magnetically similar to Spheromak
- Topologically similar to conventional Tokamak
- High edge safety factor (q > 2)
- High toroidal beta ($\beta_t > 0.2$)
- Low poloidal beta ($\beta_p < 0.3$)
- Naturally large elongation (k = 2)
- Strong paramagnetism ($B_t/B_{t0} > 1.5$)
- Large plasma current ($I_t/aB_{t0} \sim$ 7 MA/mT)
- Near omnigenous region at plasma edge

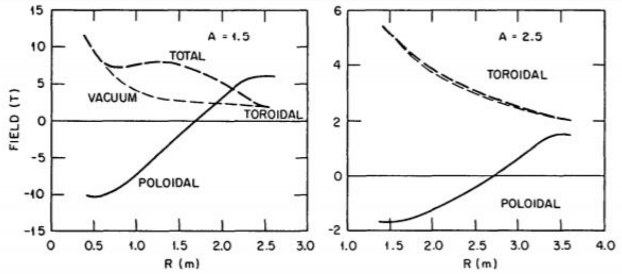
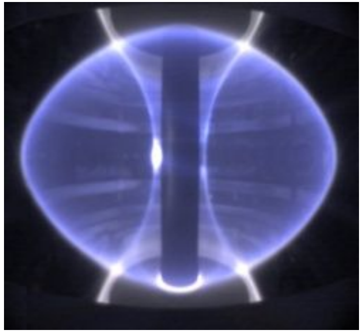


FIG. 5. Distribution of poloidal and toroidal fields on the plasma midplane of a spherical torus ($A = 1.5$, $\kappa = 3$) and a conventional tokamak ($A = 2.5$, $\kappa = 1.8$) with $q_a = 2.4$.



Peng, Y-K M. "Features of spherical torus plasmas" Nuclear Fusion.

The Globus-M Design

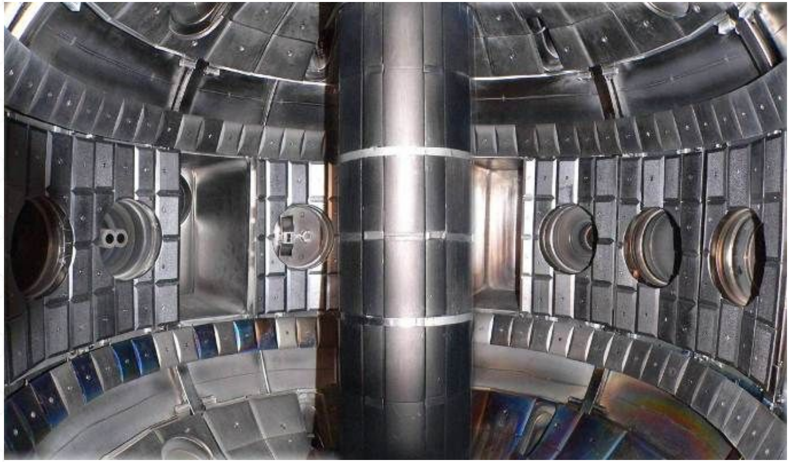
GOAL: Experimental proof of the basic spherical tokamak advantages as well as basic physics research of plasma in spherical tokamak geometry.

2 Step Process

- Optimization with Ohmic Heating
- Optimization with Auxiliary Heating

Major radius
$R = 0.36$ m
Minor radius
$a = 0.24$ m
Aspect ratio
$A=R/a=1.5$
Beta toroidal
<15%

Magnetic field
$B_{tor} < 0.62$ T
Current
$I_p < 0.5$ kA
Pulse time
$t_{pulse} < 0.3$ sec
Fuel
D-D



Gusev, Vasiliy. “Globus-M tokamak experiment.” Website.
Gusev, Vasiliy. “status of spherical tokamak Globus-M”

Globus-M Magnetic Design- Toroidal Field

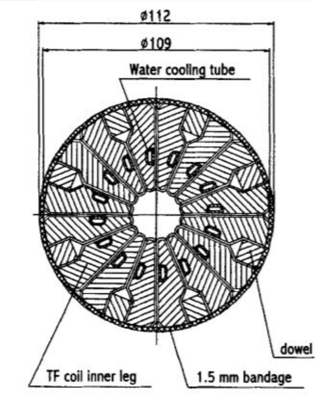
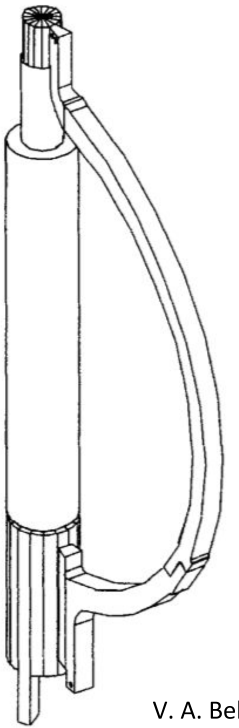


TABLE II TF-coils main parameters

Number of coils	16
Number of turns per coil	1
Axial toroidal field at $R = 0.36$ m, T	0.5
Coil current, kA	54.7
Field ripple at $R = 0.36$ m, %	1.6×10^{-4}
Field ripple at $R = 0.6$ m, %	0.785



V. A. Belyakov. "Design and assembly of the globus-m tokamak magnets," Plasma Devices and Operations

Globus-M Magnetic Design- Central Solenoid

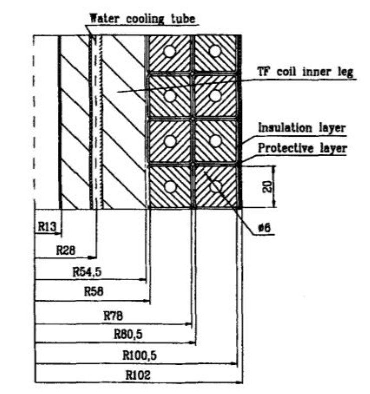
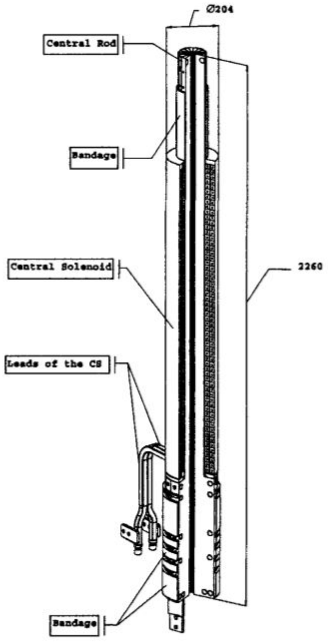


TABLE III Central solenoid main parameters

Number of layers	2
Number of turns per layer	60
Conductor cross section, mm	20 × 20
Water cooling hole diameter, mm	6
Inner diameter, mm	114
Outer diameter, mm	204
Length of the conductor, m	~ 66
Current in the conductor, kA	± 70
Axial magnetic field, T	8.3
Magnetic flux (double swing), Wb	0.31
Design number of cycles	8×10^4



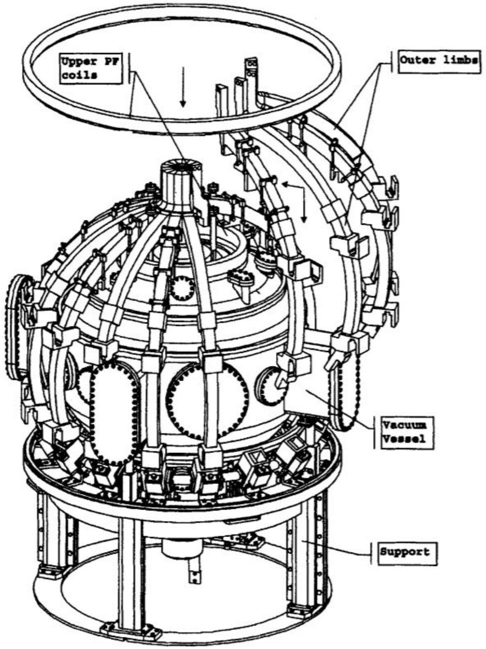
V. A. Belyakov. “Design and assembly of the globus-m tokamak magnets,” Plasma Devices and Operations

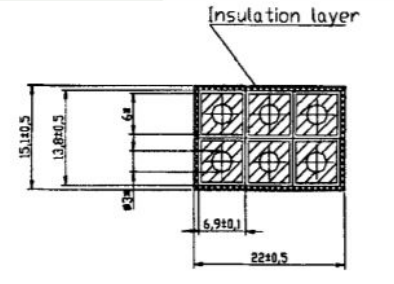
Globus-M Magnetic Design- Poloidal Field

Primary Confinement Method

9 Total Coils

- 3 for Plasma Shaping
- 3 for Vertical and Horizontal Control
- 3 to Compensate for the Central Solenoid





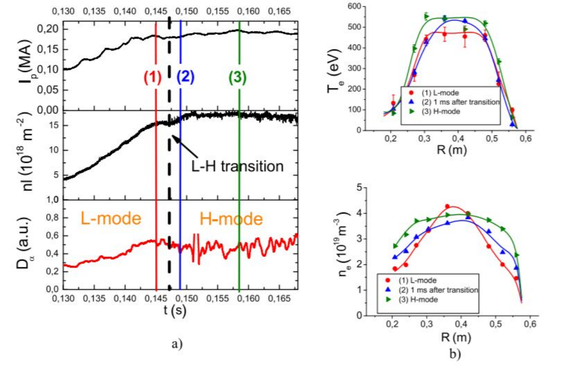
V. A. Belyakov. "Design and assembly of the globus-m tokamak magnets," Plasma Devices and Operations

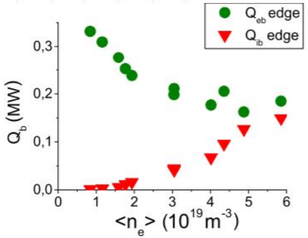
Globus-M Specific Confinement Formula

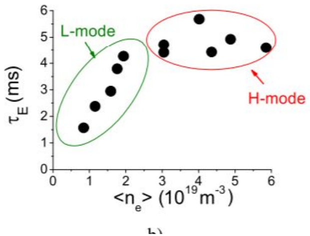
The IPB98 H-mode formula overpredicts the importance of the plasma current and underpredicts the importance of the toroidal field.

$$\tau_E^{GLB} = 6.08 \cdot I_p^{0.48\pm0.21} \cdot B_T^{1.28\pm0.12} \cdot P_{abs}^{-0.54\pm0.26} \cdot n_e^{0.77\pm0.04}$$

$$\tau_E^{\mathrm{IPB98}(y,2)}(s) = \frac{0.056 I^{0.93} B^{0.15} \left(n/10^{20}\right)^{0.41} M^{0.19} R^{1.97} \kappa^{0.78} A^{-0.58}}{P^{0.69}} \qquad (17.18)$$







Kurskiev, G S., "Scaling of energy confinement time in the Globus-M spherical tokamak" Plasma Physics and Controlled Fusion.
Kurskiev, G S., "Thermal energy confinement at the Globus-M spherical tokamak" Nuclear Fusion.

Questions?