聚变能源概论

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第8讲：

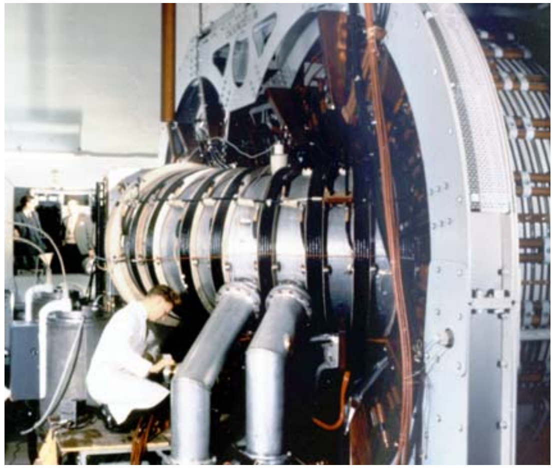
受控聚变的基本途径1–磁约束（续）

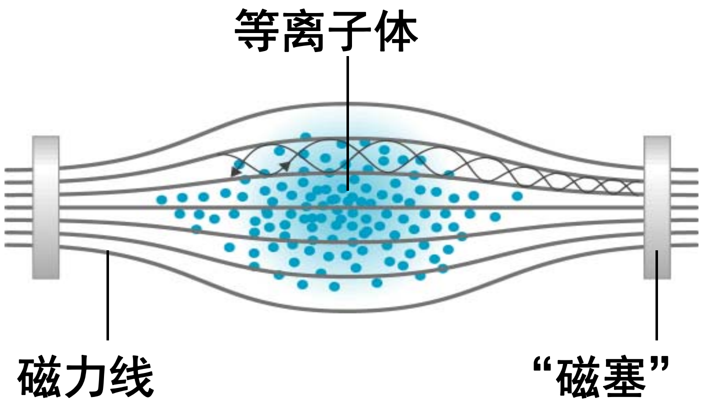
上节回顾

- 约束的图像和方式
- 磁约束聚变基本原理
- 箍缩装置：瞬态快过程
- 磁镜/最小场：开端损失

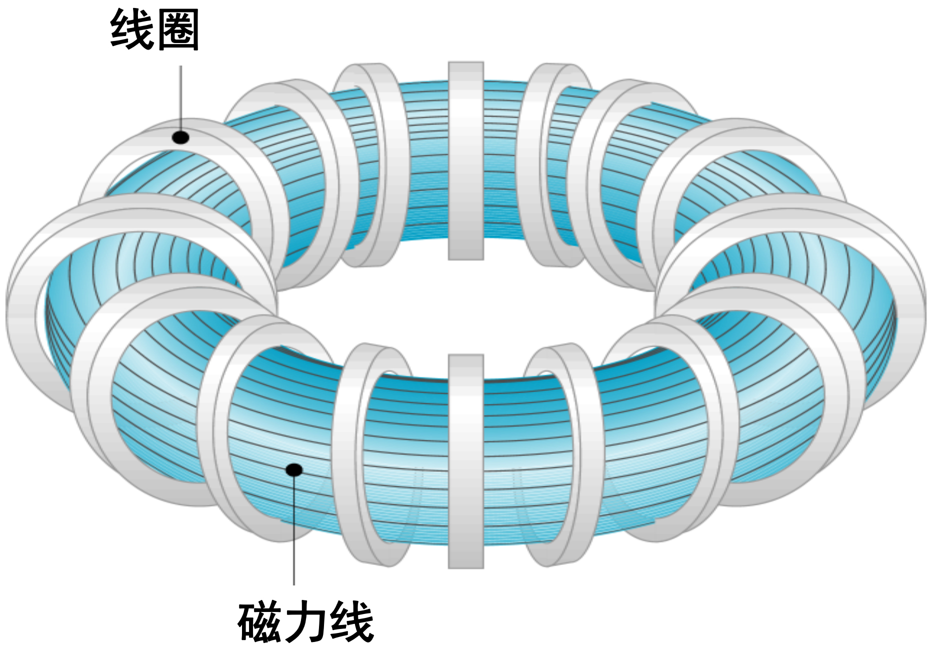
环形约束：殊途同归的选择

环向角箍缩(瞬态）→环向约束（稳态）





磁镜(开端）→ 环（闭环）

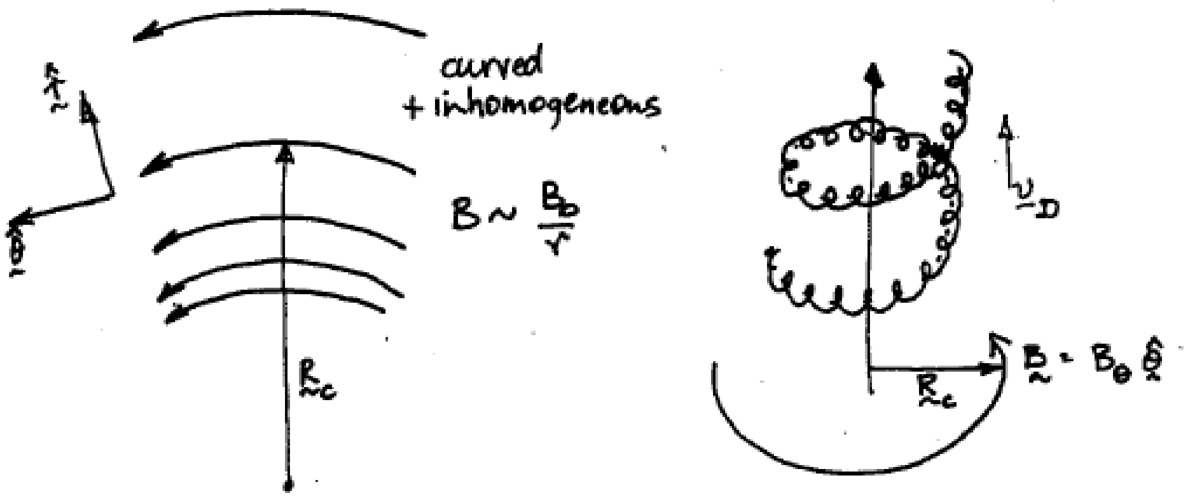


$$\mathbf{v}_{\nabla B} = \frac{(-\mu_B \nabla B) \times \mathbf{B}}{qB^2} \qquad \mathbf{v}_R = \frac{\left(-mv_{//}^2 \mathbf{R}\right) \times \mathbf{B}}{qR^2B^2} = \frac{mv_{//}^2}{qB}\frac{\mathbf{B}}{B} \times \left(\frac{\mathbf{B}}{B} \cdot \nabla\right)\frac{\mathbf{B}}{B}$$

$$B\nabla B = (\mathbf{B} \cdot \nabla)\mathbf{B} - (\nabla \times \mathbf{B}) \times \mathbf{B}$$

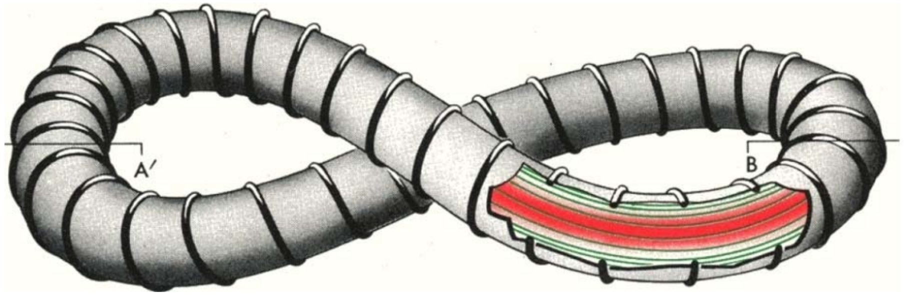
环漂移

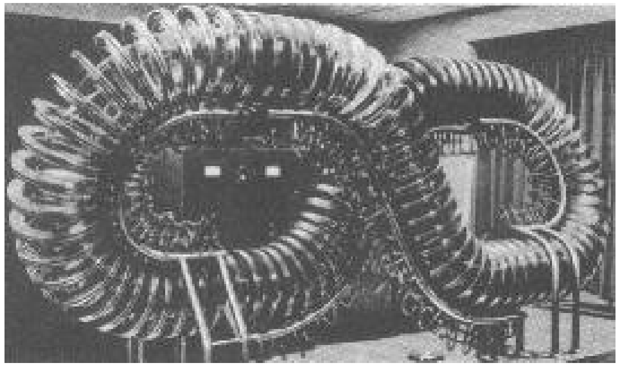
$$v_T = v_{\nabla B} + v_R = \frac{m}{q}\left(\frac{R_c \times B}{R_c^2 B^2}\right)\left(v_\parallel^2 + \frac{1}{2}v_\perp^2\right).$$

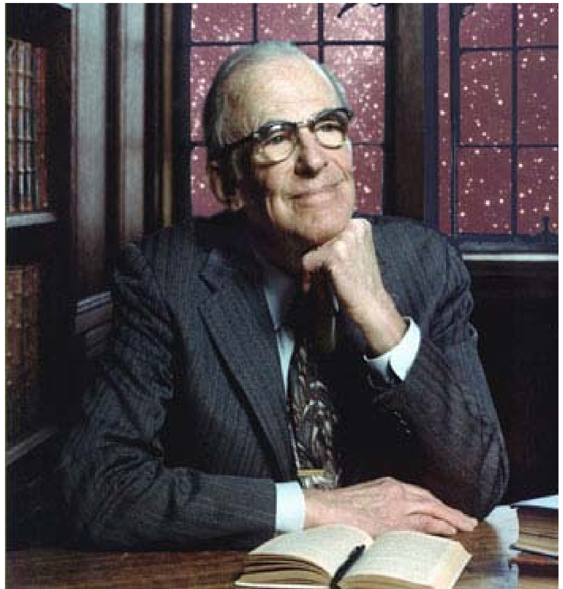


no confinement !

仿星器

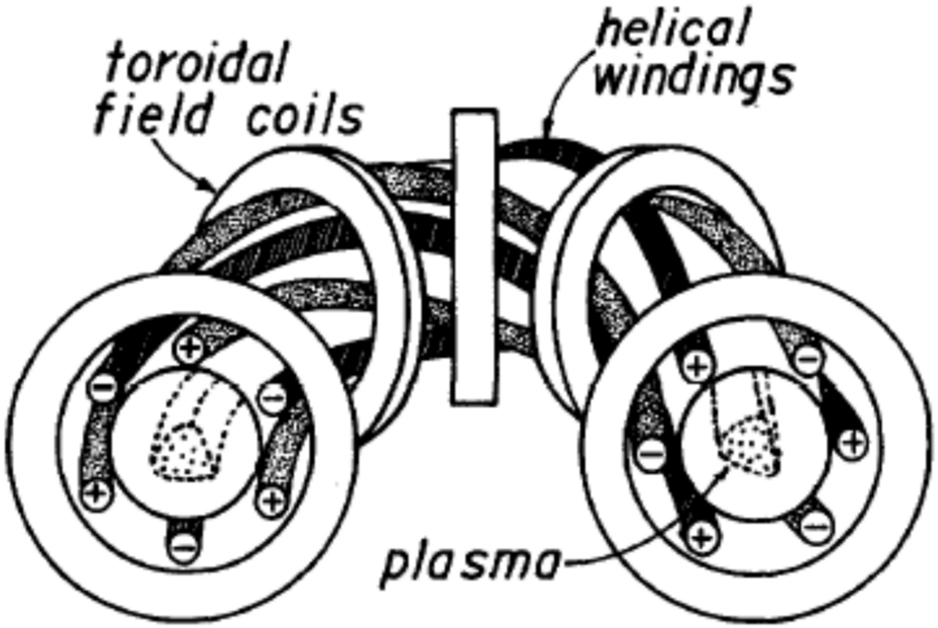




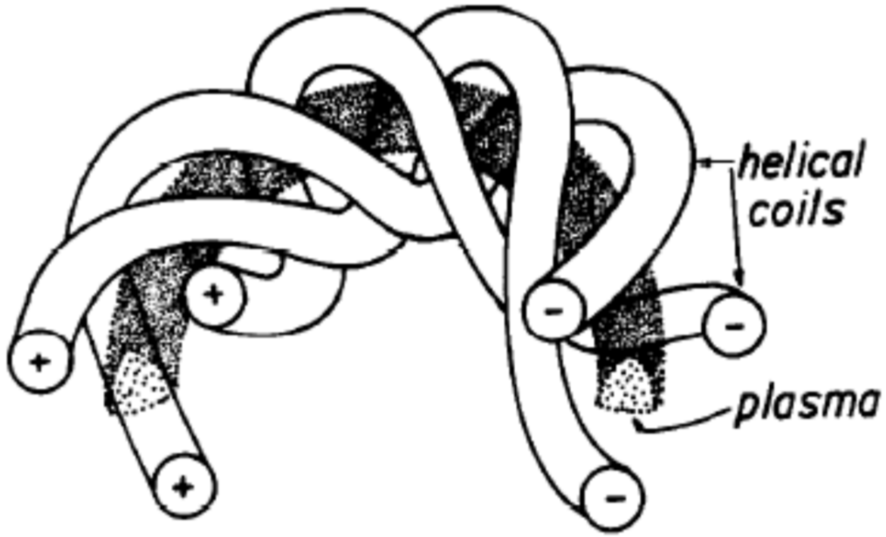


Lyman Spitzer, Jr.
(1914—1997)

Model B-3 stellarator @US



Original stellarators

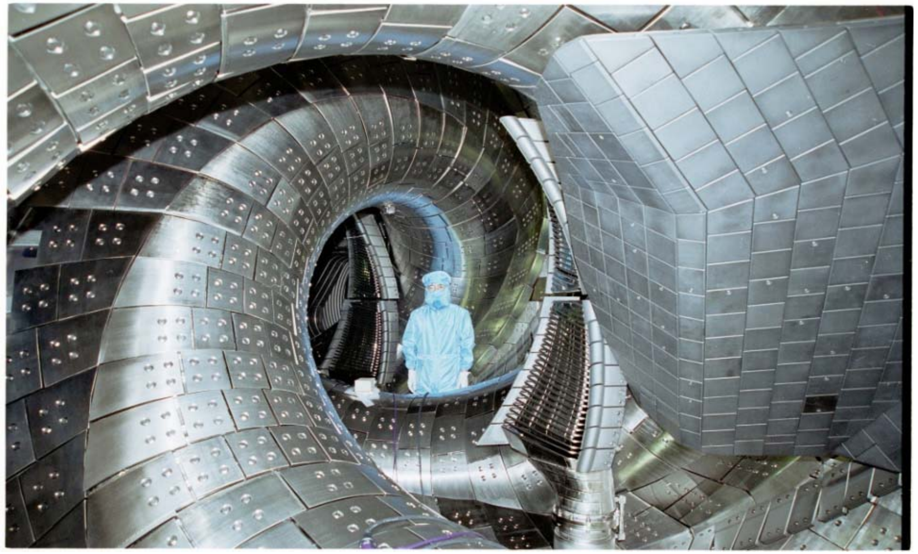


Torsatron or Heliotron

Large Helical Device (LHD) in Toki, Japan

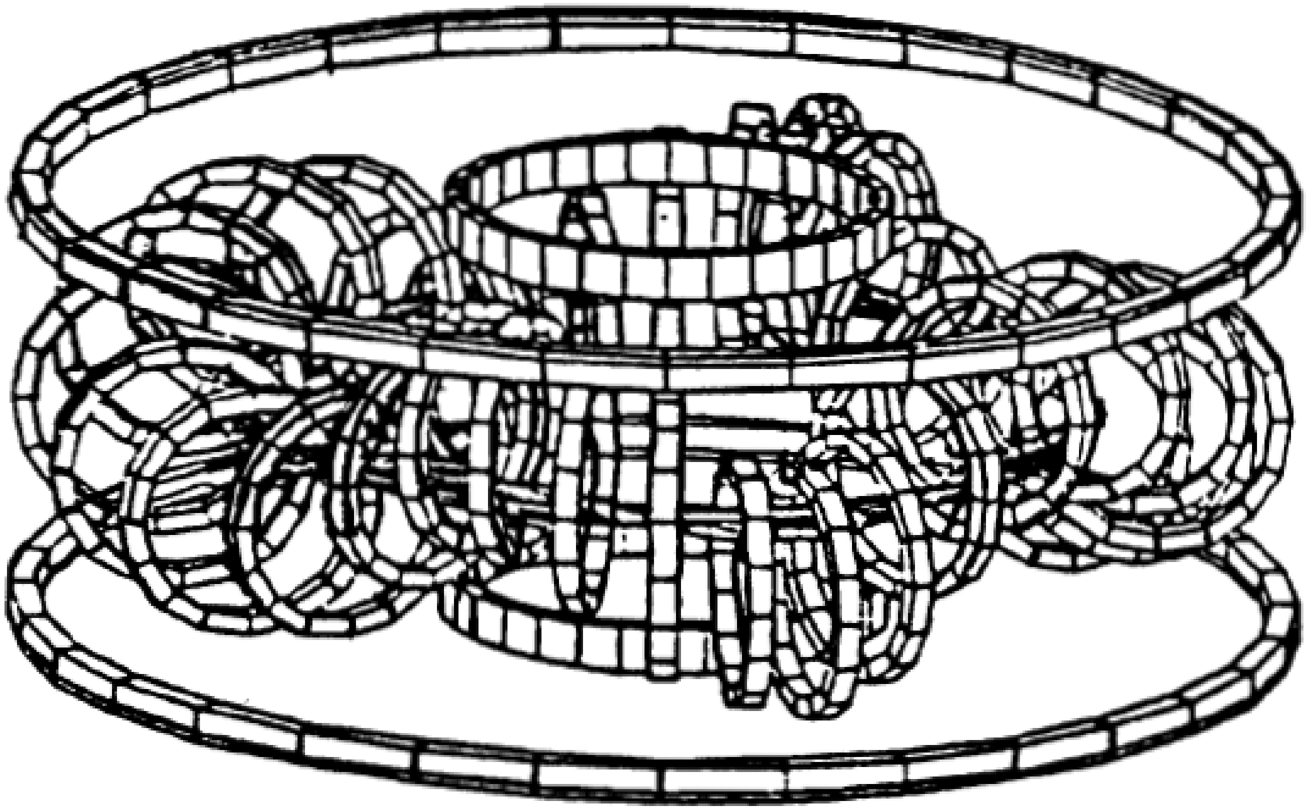
$T_i(0)$ = 8 keV, $T_e(0)$ = 10 keV,
β = 4.1%
48 min operation at 1.2 MW,
2 keV

2017 upgrades of NBI, ECH,
ICRF,
Deuterium



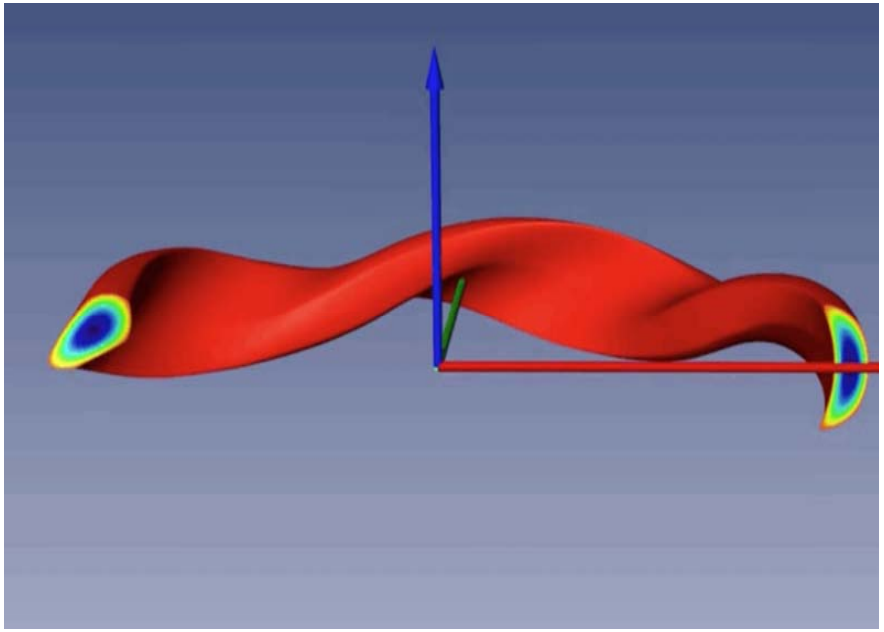
LHD @ Japan

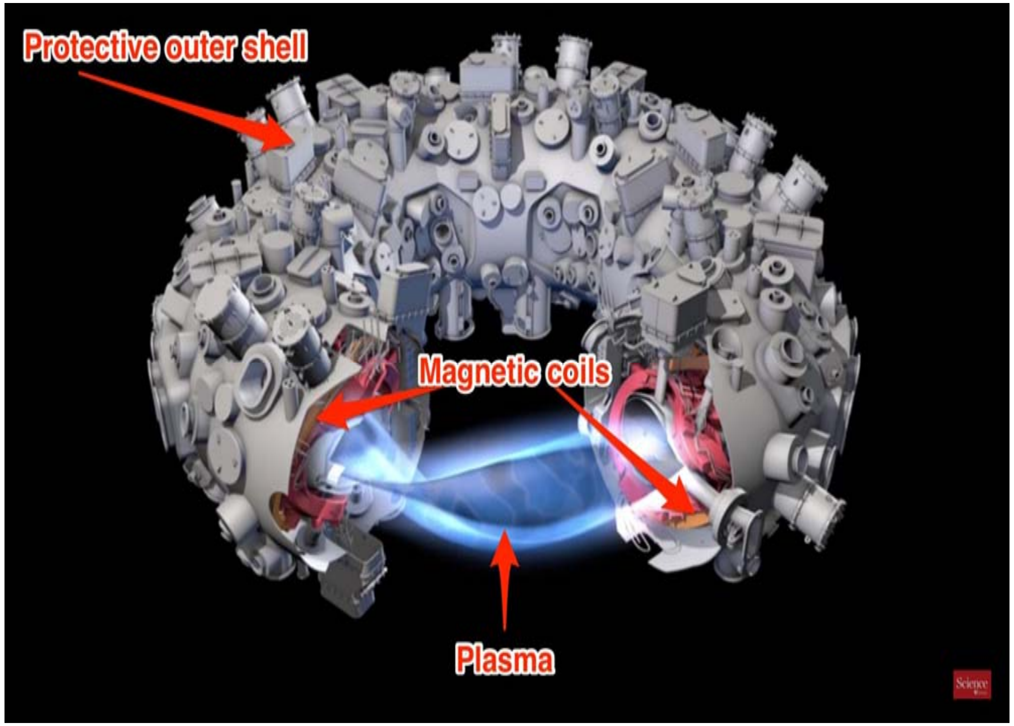
Heliac/Helias



空间磁轴仿星器 Tj-II Heliac 的线圈布设

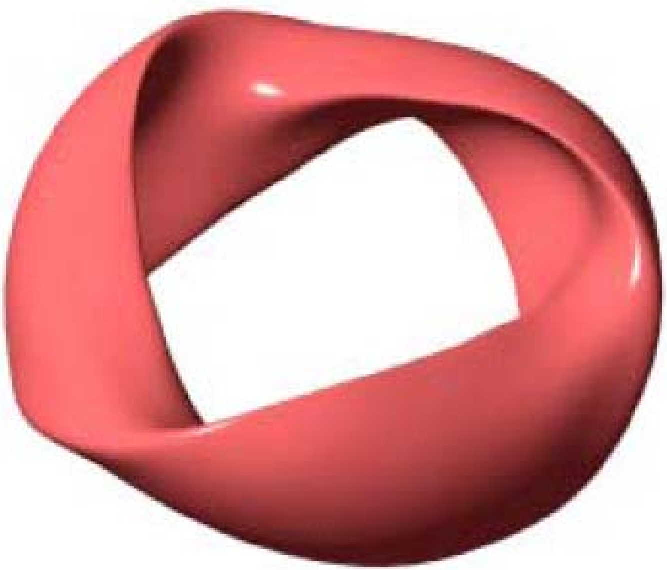
Wendelstein 7-X Modular Stellarator

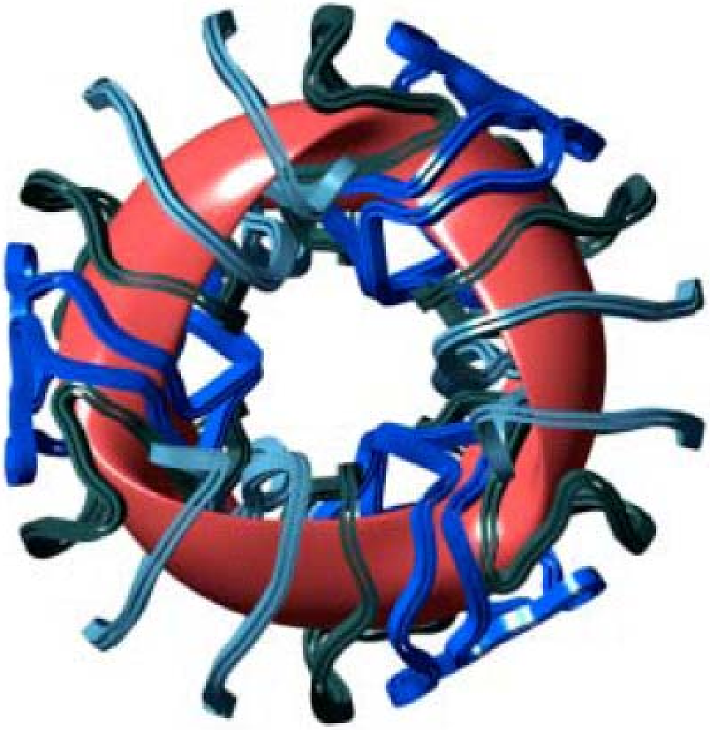




W7-X originally expected in 2006, finally completed in Oct. 2015

NCSX

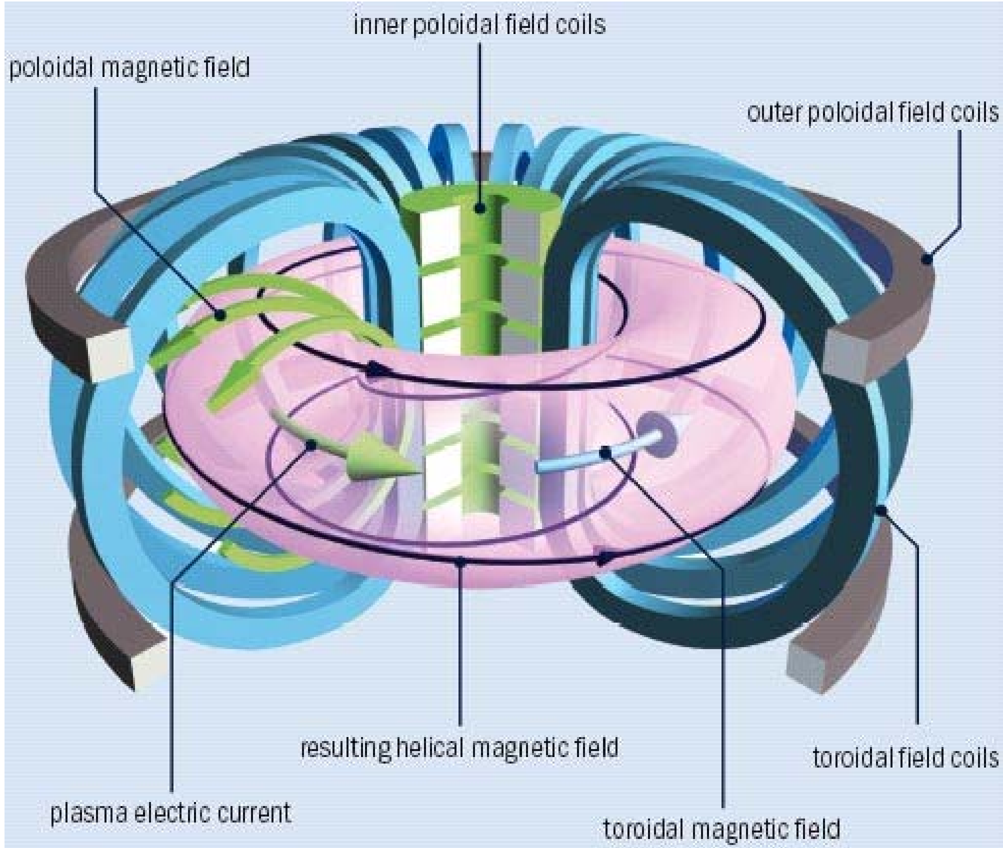




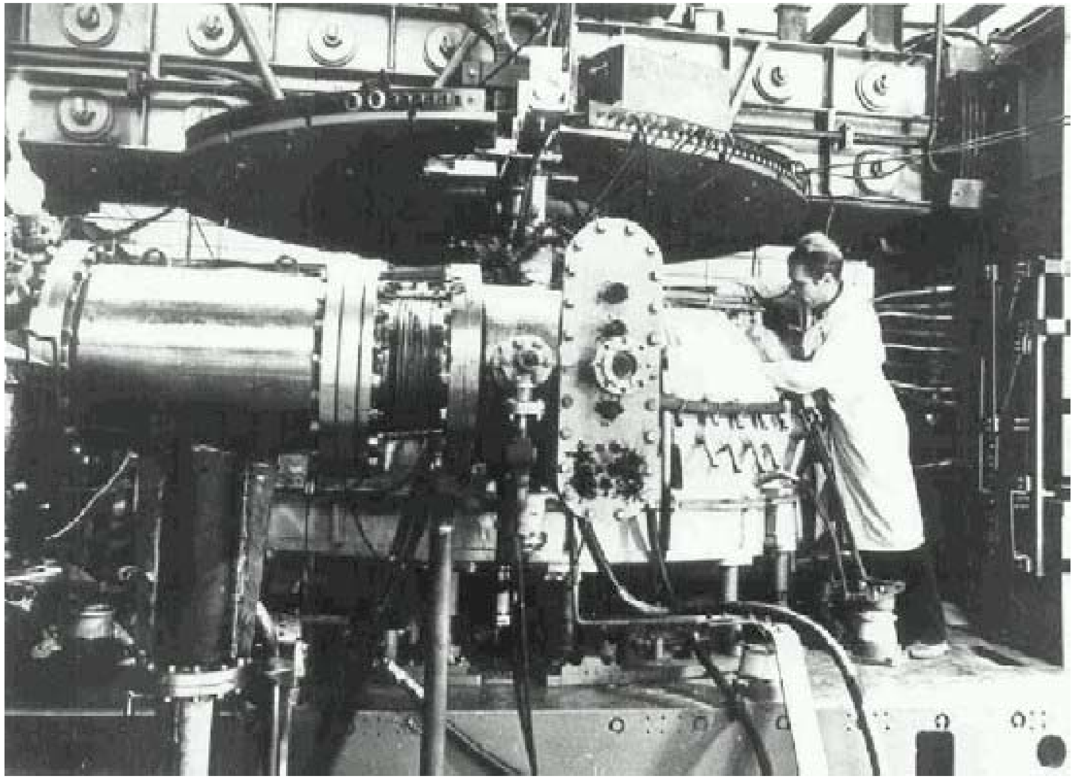
NCSX (expected in 07 but shutdown in 08)

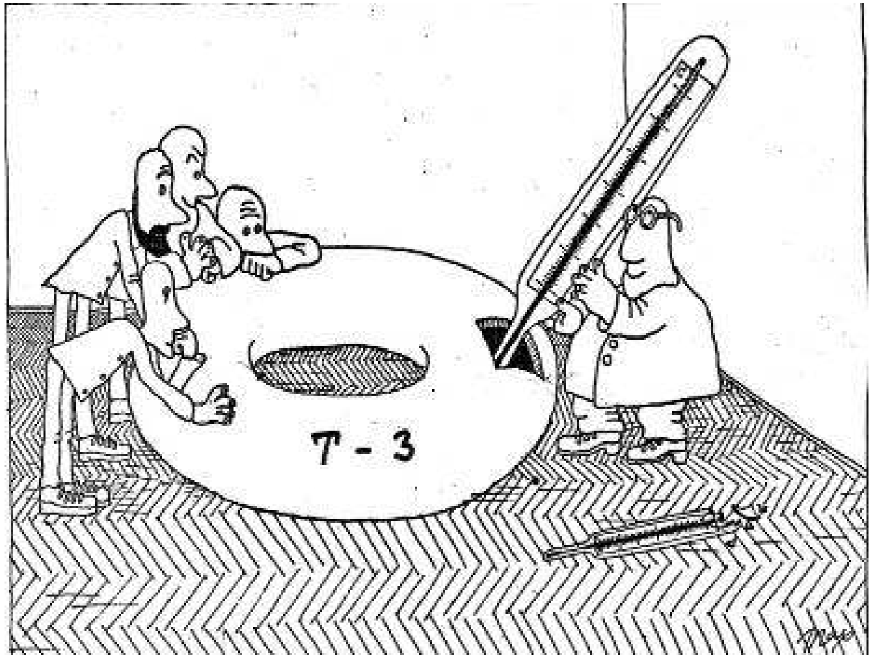
托卡马克Tokamak（领跑者）

Lev Artsimovich
(1909-1973)



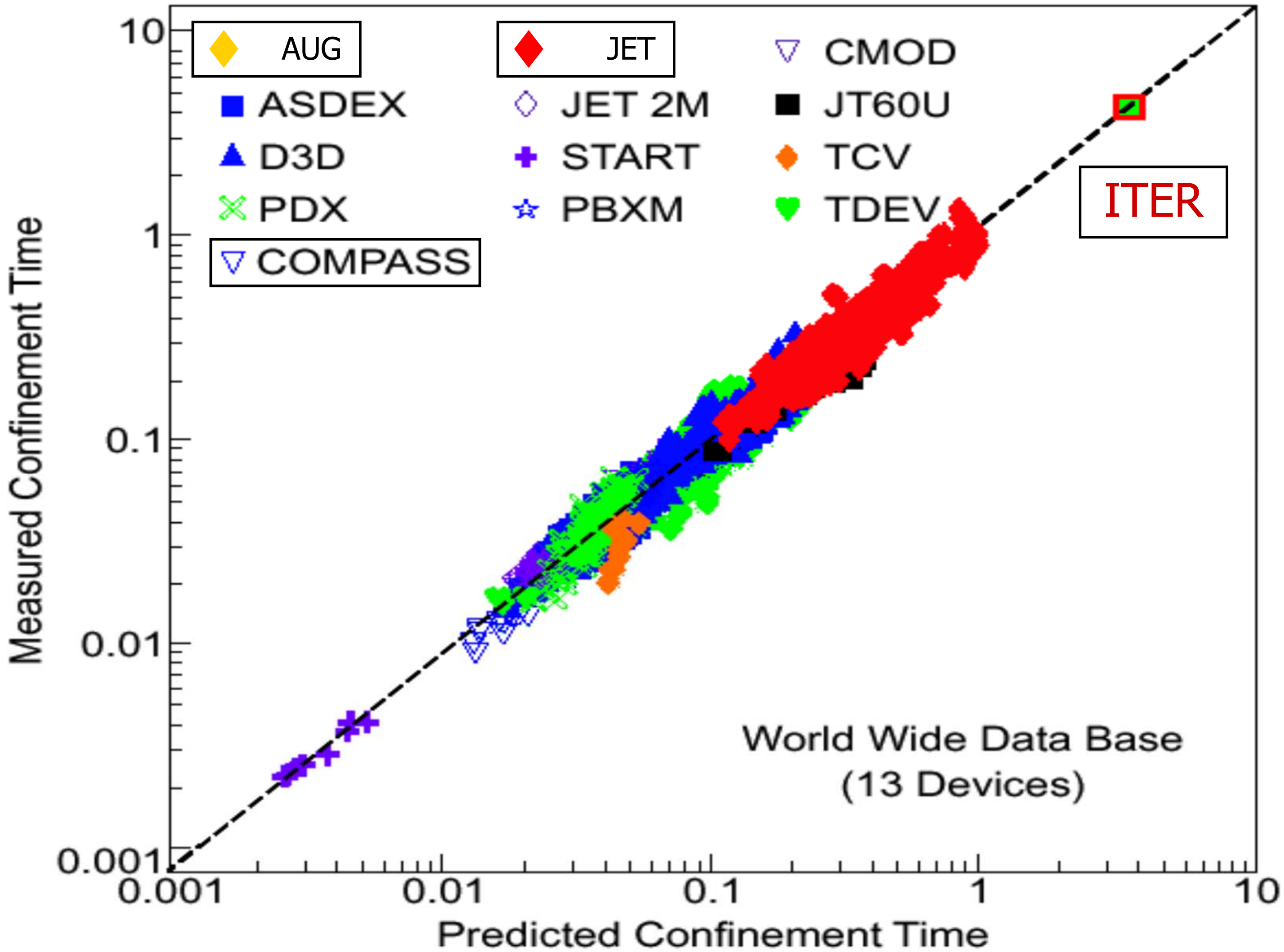
- 托卡马克（TOKAMAK）在俄语中是“环形”、“真空”、“磁”、“线圈”几个词的组合，即环流磁真空室的缩写





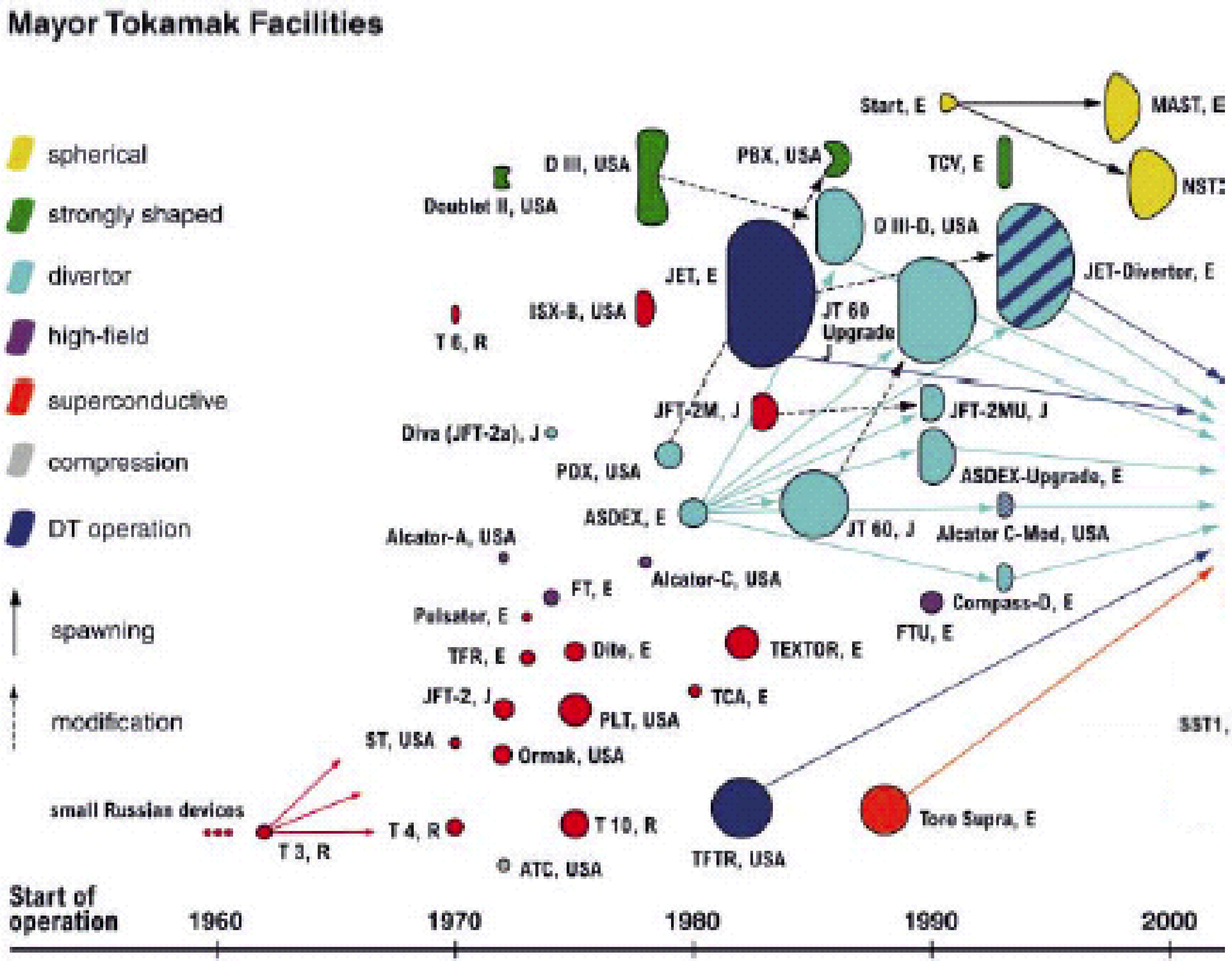
T-3 Tokamak @ USSR

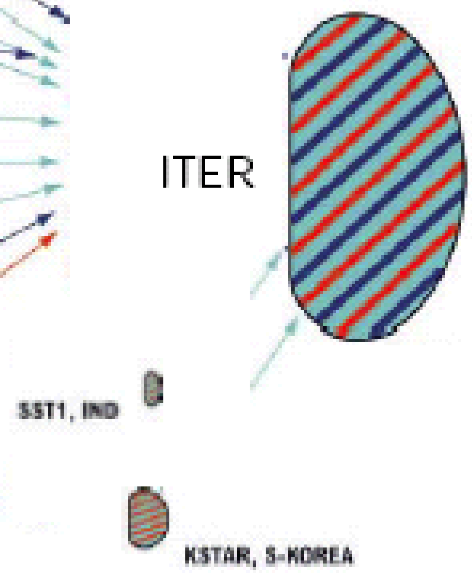
Tokamak能量约束



$$\tau_{th,98y2} = 0.0562 I_p^{0.93} B_t^{0.15} n_{19}^{0.41} P_L^{-0.69} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} M^{0.19}$$

tokamak research is mature for the step to a burning plasma - (1)

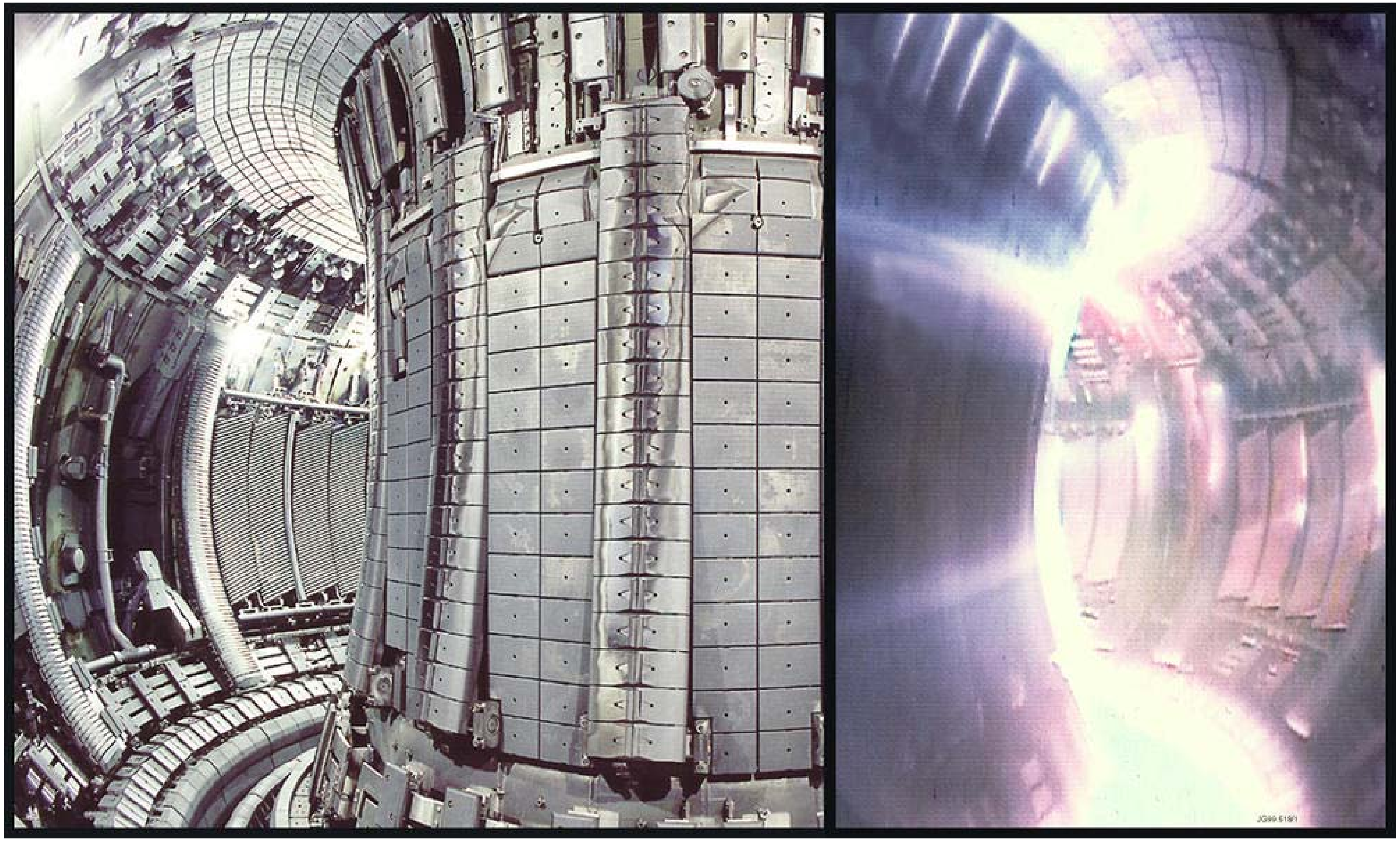




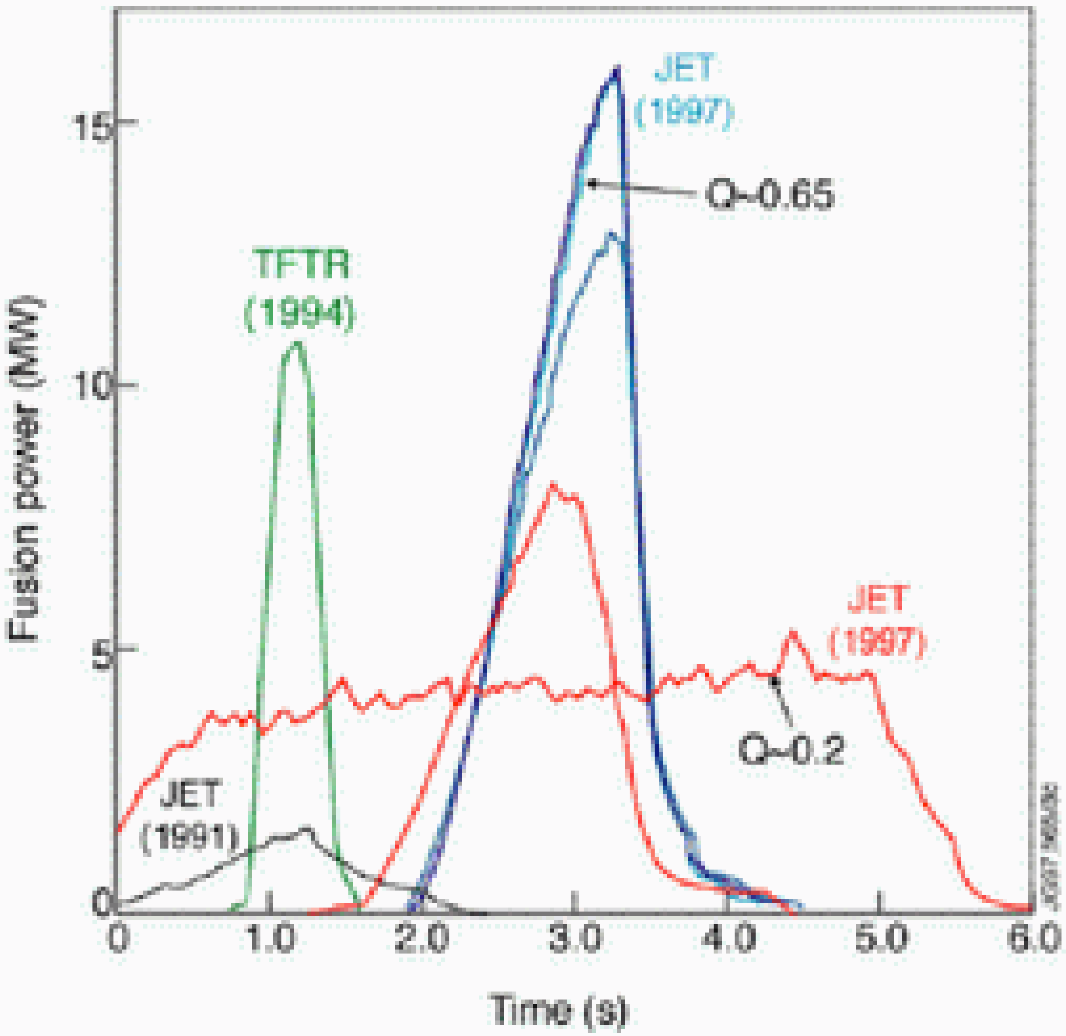
tokamak research has converged

ITER incorporates all successfull developments:

- elongated (D-shaped) cross-section
- divertor
- superconducting coils
- DT operation



Joint Europe Torus



JET 1991 (EU) : **1.7 MW**
First controlled DT fusion experiments on earth

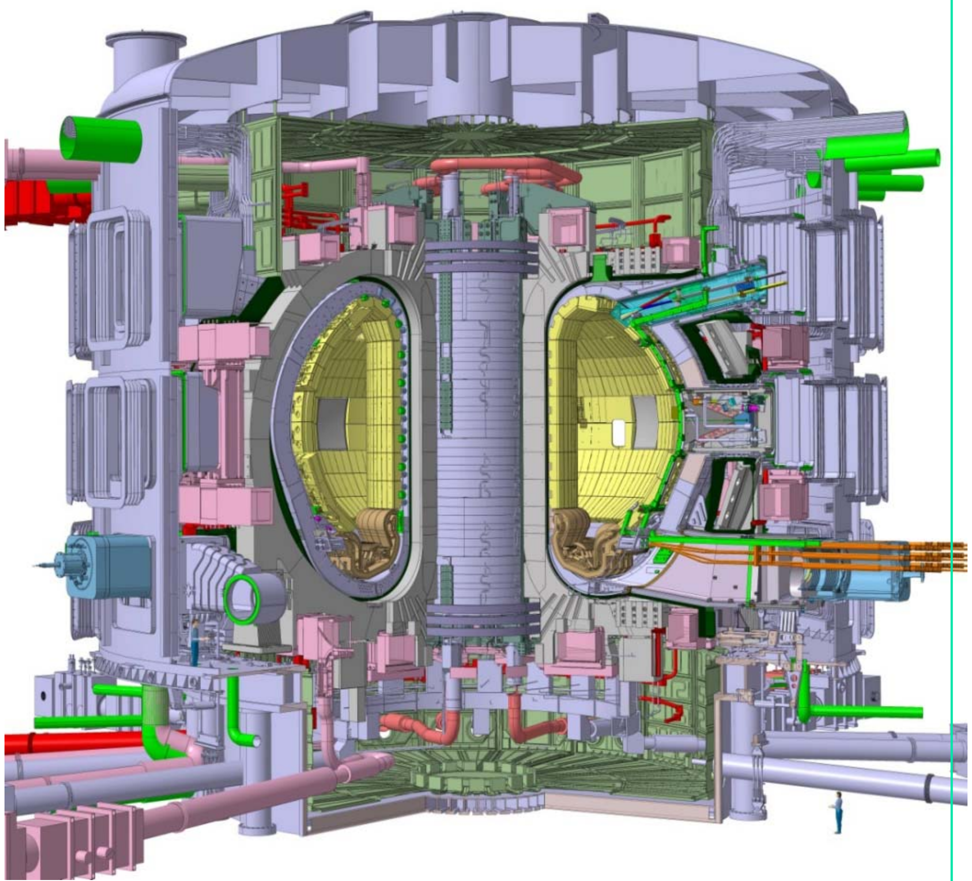
TFTR 1994 (US) : **11.5 MW**

JET 1997 (EU) : **16 MW**
energy amplification Q~0.65
Alpha particle heating clearly observed and consistent with theory

ITER 2015-2020: ***500-700 MW***
energy amplification Q>10

Power plant : ***1500-2000 MW (thermal)***
Q~30-40

International Thermonuclear Experimental Reactor



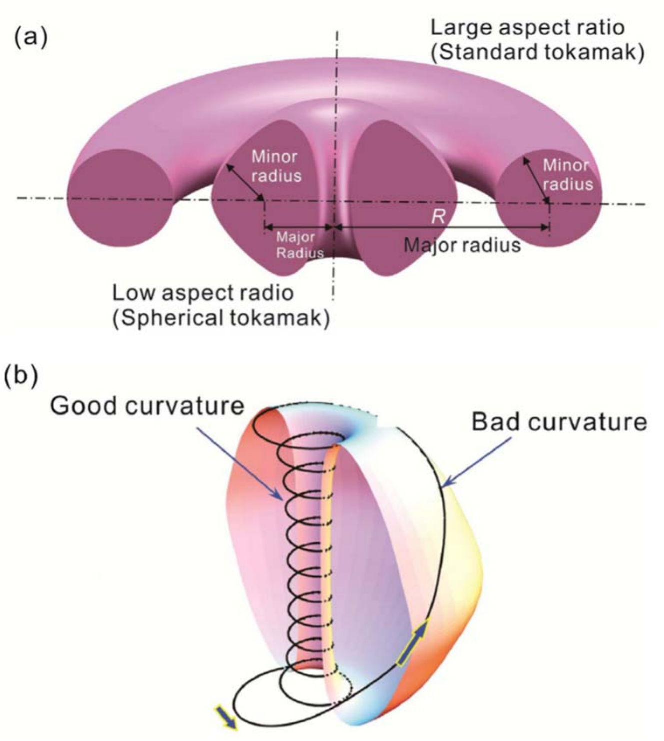
Physics:

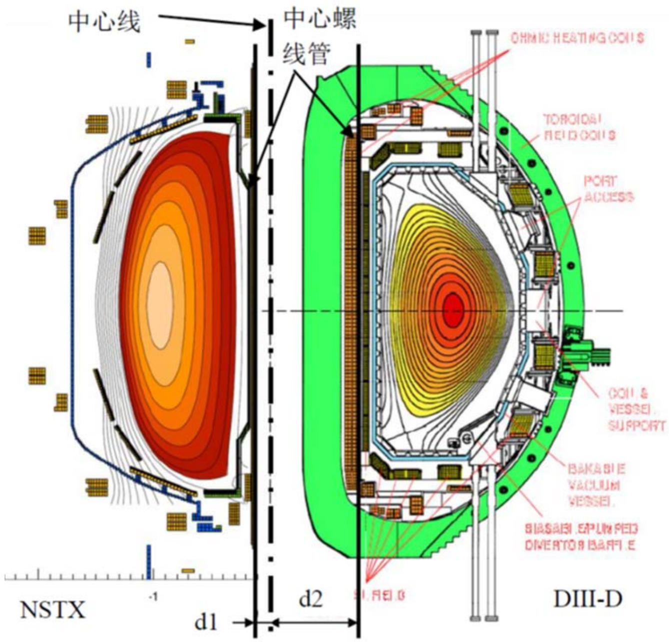
- produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor (Q $\geq$10) in long-pulse operation (300 - 500s)
- aim to achieve steady-state operation of a tokamak (Q=5
- retain the possibility of exploring 'controlled ignition'(Q$\geq$30)

Technology:

- demonstrate integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding module

球形托卡马克/紧凑环





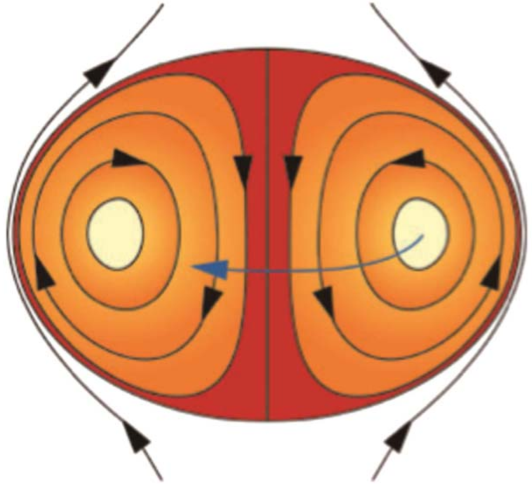


Fig. 2. Spheromak configuration. (Courtesy of Lawrence Livermore National Laboratory).

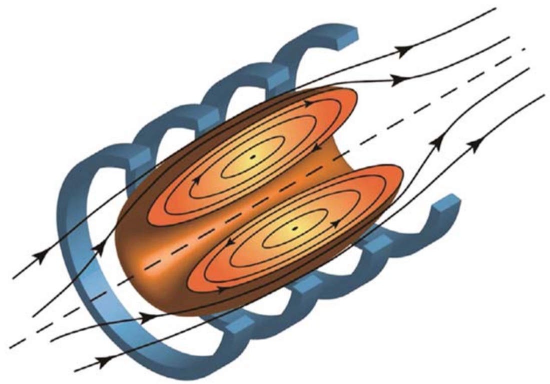


Fig. 3. Field reversed configuration (Reprint from Figs. 2–5 of Ref. [50])

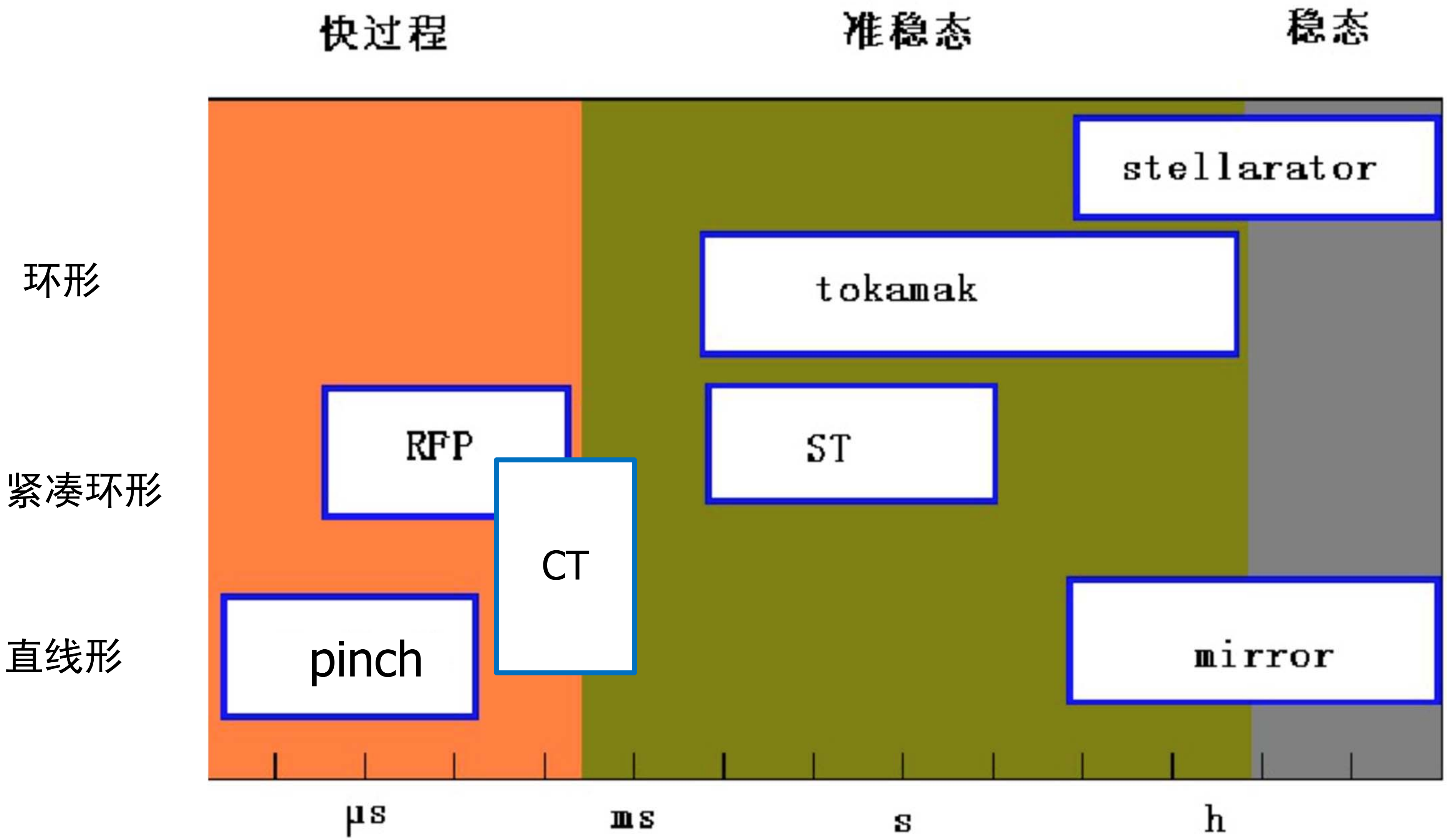
Matter and Radiation at Extremes 1 (2016) 153–162
www.journals.elsevier.com/matter-and-radiation-at-extremes

Review article

Compact magnetic confinement fusion: Spherical torus and compact torus

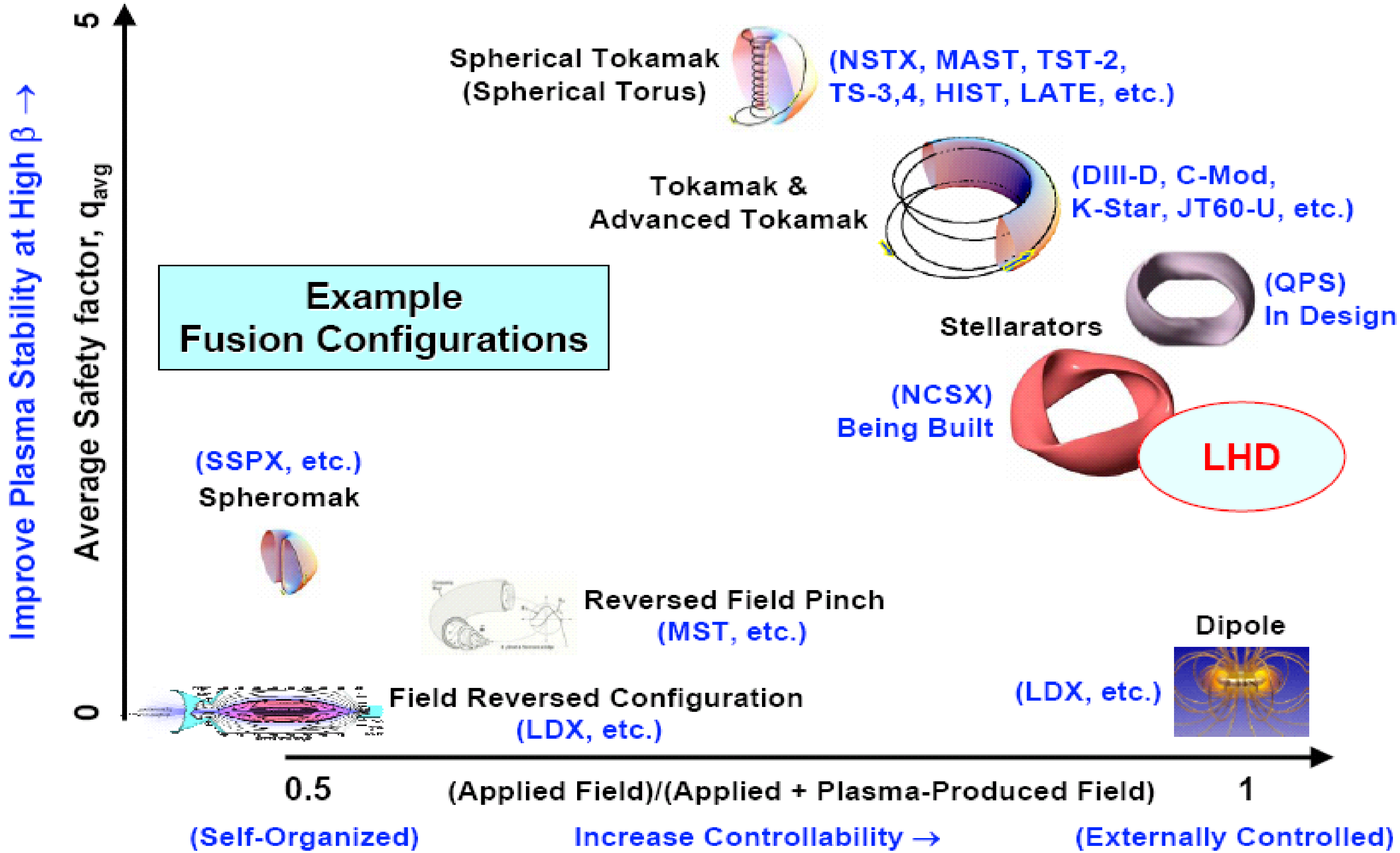
Zhe Gao

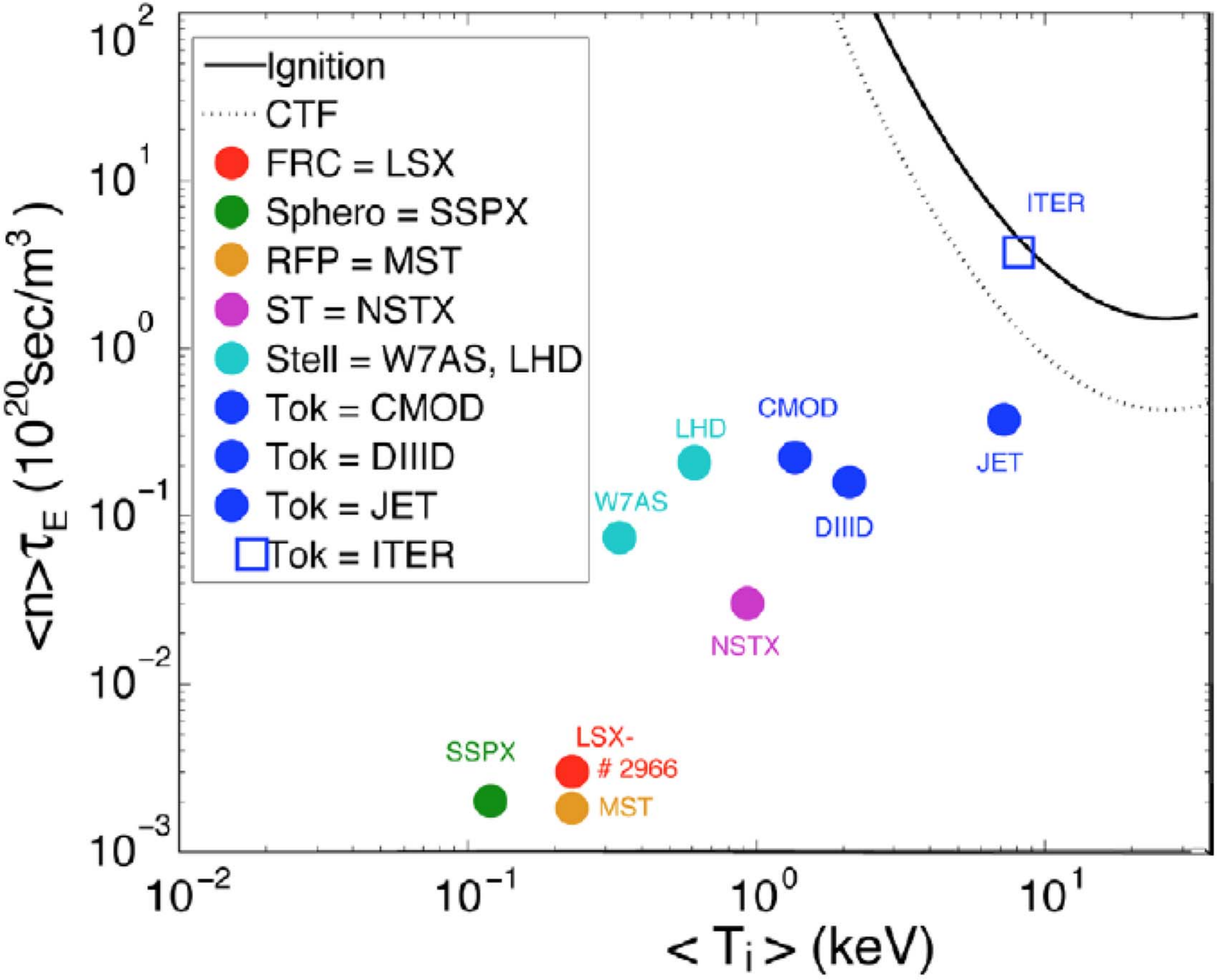
磁约束聚变类型在位形-时间平面上的分类



修改自王龙《磁约束等离子体实验物理》

从所加磁场和等离子体稳定性所做的分类

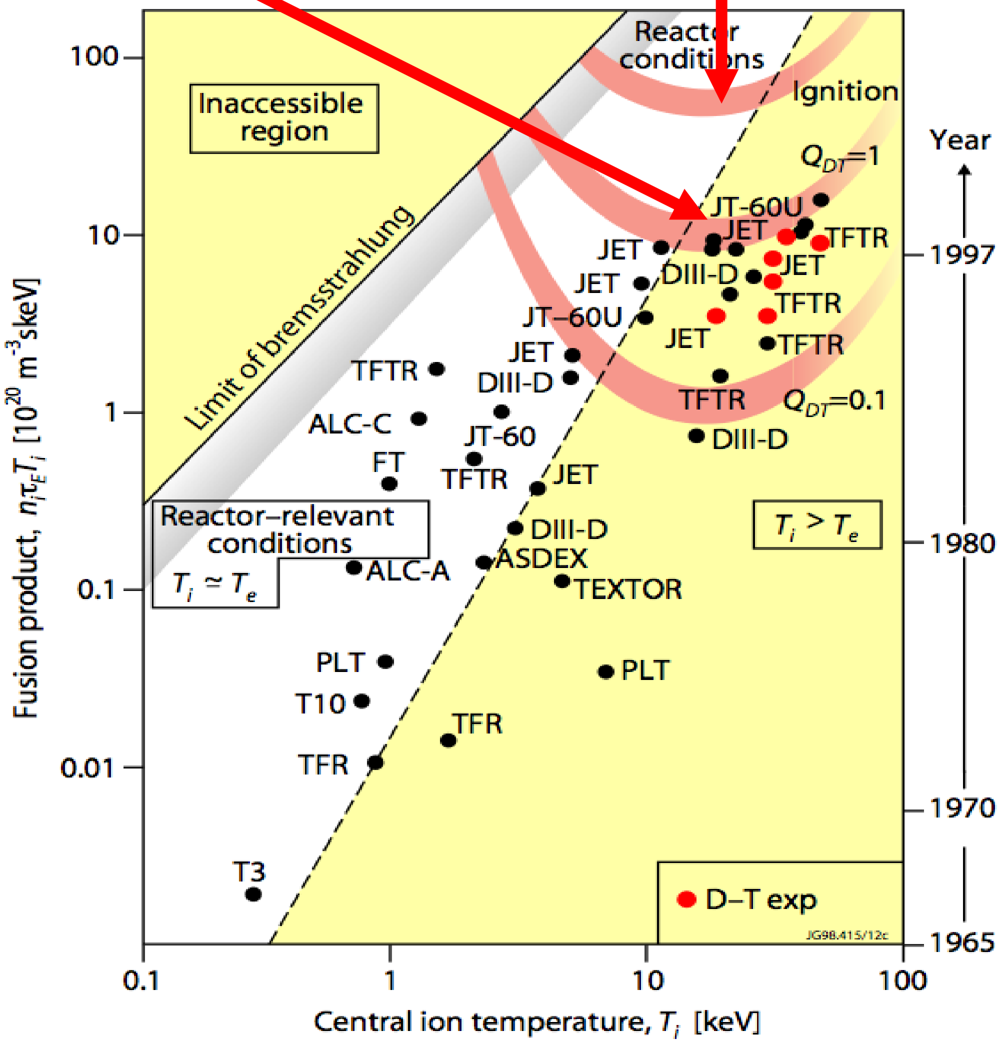




Ignition
CTF
FRC = LSX
Sphero = SSPX
RFP = MST
ST = NSTX
Stell = W7AS, LHD
Tok = CMOD
Tok = DIIID
Tok = JET
Tok = ITER
ITER
CMOD
LHD
JET
W7AS
DIIID
NSTX
SSPX
LSX-
2966
MST
$\langle n \rangle \tau_E$ (10^{20}sec/m^3)
$\langle T_i \rangle$ (keV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1

ITER Ignition

Break Even



作业（网络学堂）

- 1. 大环径比（r/R_0<<1）圆截面托卡马克的磁场可以表示成

$$\vec{B}(r,\theta)=\frac{rB_0}{q(r)R_0}\vec{e}_\theta+\frac{B_0}{1+r\cos\theta/R_0}\vec{e}_\varphi$$

  从直圆柱扭曲模不稳定性条件给出安全因子q应满足的条件。
- 2. 简述托卡马克和环箍缩的异同点
- 3. 选作：
  - 阅读文章【Y Xu, A general comparison between tokamak and stellarator plasmas, Matter and Radiation at Extremes 1,192-200 (2016)】，比较托卡马克和仿星器的异同点，分析它们各自的优缺点。
  - 阅读文章【Z Gao，Compact magnetic confinement fusion：Spherical torus and compact torus, Matter and Radiation at Extremes 1,153-162 (2016)】，比较球形环和紧凑环的异同点，分析它们各自的优缺点

雨课堂期中测验

- 30分钟答题时间
- 闭卷，雨课堂会监视切屏
- 注意单选和多选，多选题少选可得部分得分