All you need to know about Magnetic Fusion Energy, from Mitchell Street to Provence in 25 minutes or less

Cornell LPS@50: an ANNIVERSARY SYMPOSIUM

Los Alamos NATIONAL LABORATORY EST. 1943

Don Rej

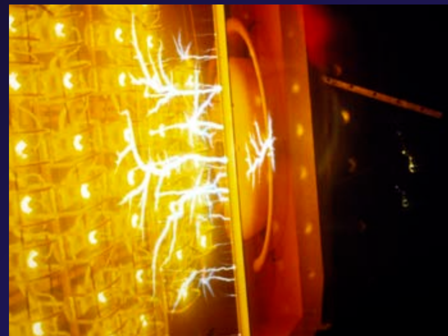
Director, Office of Science Programs at LANL

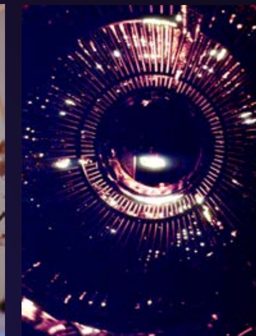
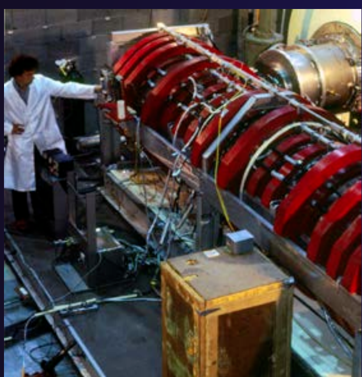
October 6, 2017

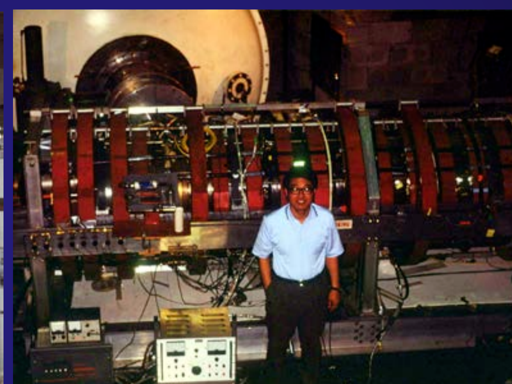
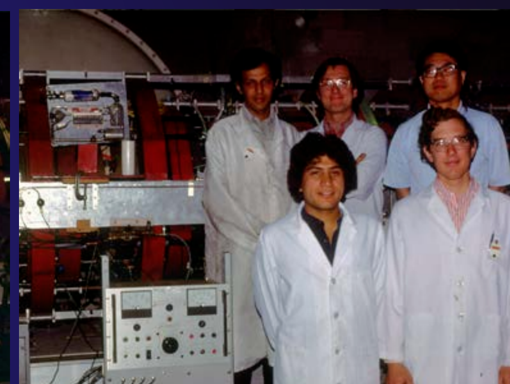
NNSA National Nuclear Security Administration

LA-UR-17-28978

Has it really been 40 years?

Career Highlights

- **Magnetic Fusion Energy (MFE)***
  - Electron Rings for MFE
  - Field Reversed Configurations
  - Fusion Diagnostics
  - Stellarators
- **Plasma Materials Science**
  - Plasma Source Ion Implantation
  - Materials Surface Modification with Intense Ion Beams
- **Particle Accelerators**
  - RF LINACS
- **Private – Public Partnerships**
- **Line, Program, & Project Management**
- **Government Advisor**

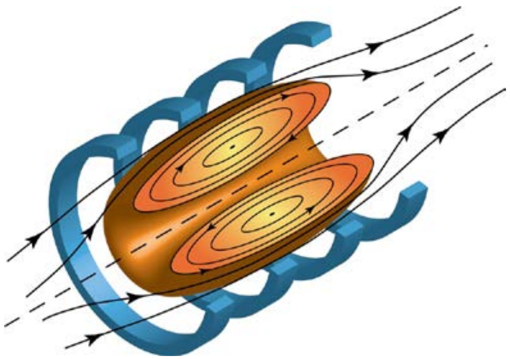
While my talk will focus on MFE, I want to recognize Cornell alumni who, unlike me, have devoted their entire distinguished careers in MFE

- ***Paul Bonoli (MIT)***
- ***Stan Luckhardt (MIT, UCSD)***
- ***Stewart Zweben (PPPL)***

Also, exceptional Cornell postdoc and visiting faculty mentors during my tenure involved in MFE:

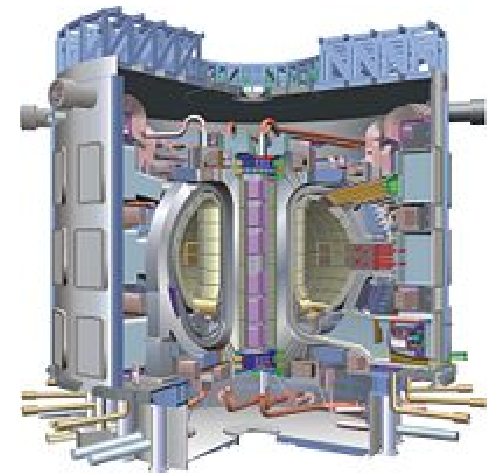
- ***Hal Davis (LANL)***
- ***John Finn (NRL, LANL, Tibbar)***
- ***Raghavan ("Jay") Jayakumar (MIT, LLNL, GA)***
- ***Clark Swannack (LANL)***
- ***Dan Taggart (NRL, LANL)***
- ***Alan Turnbull (GA)***
- ***Michel Tuszewski (UC Berkeley, LANL, Tri Alpha Energy)***
- ***Prof. Kiyoshi Yatsui (Nagaoaka University of Technology)***

Of the plethora of Magnetic Fusion Energy (MFE) ideas over 70 years, we will focus on three very different MFE configurations



Field Reversed Configurations: A fusion reactor engineer’s dream but far from physics proof-of-concept

Stellarators: A fusion reactor engineer’s nightmare but on the threshold for a major physics proof-of-concept



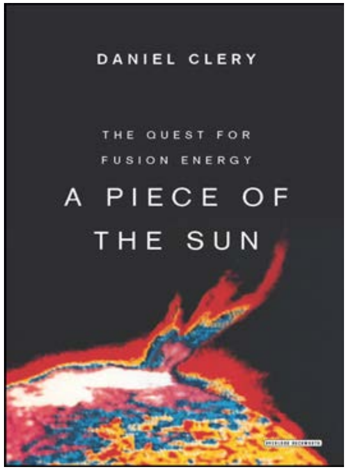
Tokamaks: A fusion reactor engineer’s challenge but has the most promising performance to date

V·T·E **Fusion experimental devices by confinement method** [hide]

Magnetic	Tokamak	International	ITER · DEMO · PROTO
		Americas	STOR-M · MEDUSA-CR · Alcator C-Mod · DIII-D · UCLA ET · LTX · NSTX-U · Pegasus · PBX-M · TEXT · TFTR · ETE
		Asia and Australia	LT-1 · CT-6 · CFETR · EAST · HL-1(M) · HL-2A · HT-6(B, M) · HT-7(U) · KT-5 · SUNIST · ADITYA · SST-1 · IR-T1 · JT-60 · QUEST · KTM · GLAST · KSTAR · KDEMO
		Europe	JET · COMPASS · GOLEM · TJ-I · Tore Supra · TFR · ASDEX Upgrade · TEXTOR · FTU · IGNITOR · RTP · ISTTOK · T-3 · T-4 · T-10 · T-15 · TCV · START · MAST · MAST-U
	Stellarator	Americas	ATF · CAT · HSX · NCSX · QPS · SCR-1
		Asia and Australia	H-1NF · Lingyun · CHS · Heliotron J · LHD · TU-Heliac
		Europe	UST-1 · UST-2 · TJ-IU · TJ-II · TJ-K · WEGA · Wendelstein 7-AS · Wendelstein 7-X · Uragan-1 · Uragan-2 (Uragan-2M) · Uragan-3 (Uragan-3M) · L-2M
	RFP		RFX · TPE-RX · EXTRAP T2R · MST
	Other		MTF · LDX · SSPX · MFTF · MCX · Polywell · Dense plasma focus · ZETA
Inertial	Laser	Americas	NIF · OMEGA · Nova · Nike · Shiva · Argus · Cyclops · Janus · Long path · Laser Inertial Fusion Energy
		Asia	SG-I · SG-II · SG-III · SG-IV · GEKKO XII
		Europe	HiPER · Asterix IV (PALS) · LMJ · LULI2000 · ISKRA · Vulcan
	Non-laser		Qiangguang-1 · PTS · Z machine · PACER

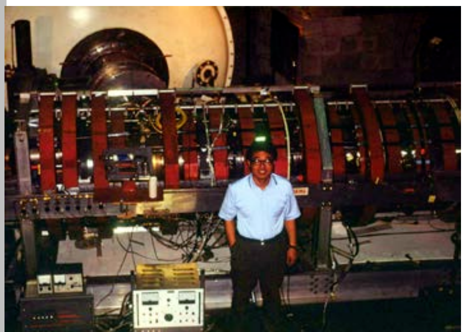
International Fusion Materials Irradiation Facility

More inclusive, albeit incomplete, list of MFE, Inertial Confinement, and Magneto-Inertial concepts (https://en.wikipedia.org/wiki/List_of_fusion_experiments)

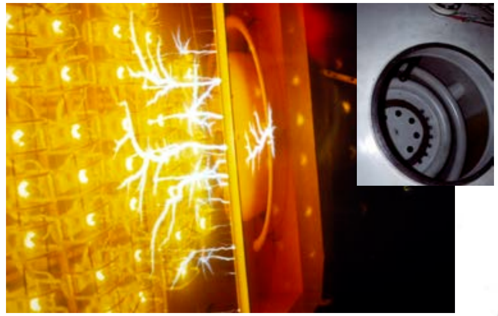


A good summary of fusion energy history from 1930’s to 2012

Cornell Relativistic Electron Coil Experiments (RECE): Field Reversed Configuration research at the Mitchell Street High Voltage Lab



RECE-Christa magnetic trap



5 MeV Marx generator and blumlein to drive a diode electron beam injector

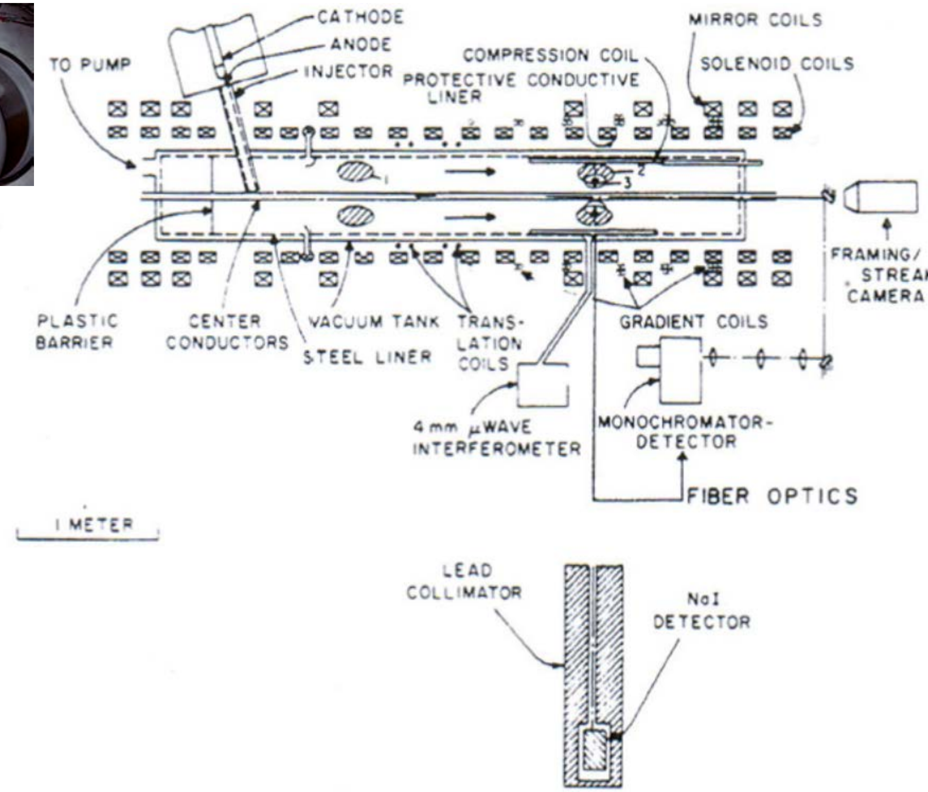


FIG. 4. Schematic diagram of the RECE–Christa device and associated diagnostics.

Jay Jaykunar, Kiyoshi Yatsui, Abe Ghambari , Mark Parker

Topnotch engineers, technologists and machinists were "hands-on mentors": Jim Ivers, Jim Milks, Mark Newall, Frank Redder, Cornell machine shop

Manipulating electron rings: trapping, stacking, and adiabatic compression

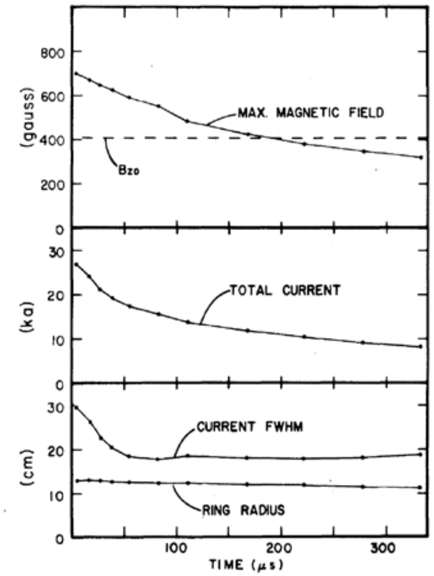


FIG. 3. Typical time dependence of ring parameters over first 350 μsec.

VOLUME 37, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1976

Generation of Field-Reversing E Layers with Millisecond Lifetimes*

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Laboratory of Plasma Studies and School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

(Received 8 June 1976)

Field-reversing electron rings, exhibiting initial axial field changes $\delta B/B_{z0} \leq 170\%$, and having overall lifetimes of greater than 1300 μsec, have been generated by injection of 2.1-MeV, 30-kA electron-beam pulses into the relativistic-electron-coil-experiment (RECE)–Christa mirror field, $B_{z0}(z)$. These lifetimes, which are comparable with those expected from collisional diffusion of the fast electrons, constitute an improvement of more than a factor of 40 over the earlier results from RECE–Berta.

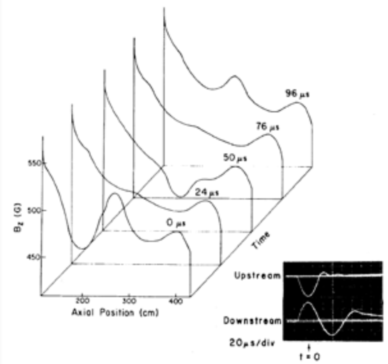

FIG. 2. Magnetic-field profile at different times, and pulse driving current wave forms. Injector position is 115 cm, upstream and downstream pulse coil positions are 202 and 269 cm, respectively.

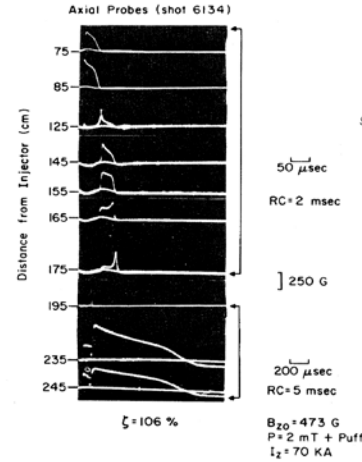

FIG. 3. Oscilloscope recordings, from a set of on-axis probes, showing ring translation and stacking to field reversal.

VOLUME 39, NUMBER 12 PHYSICAL REVIEW LETTERS 19 SEPTEMBER 1977

Production of Field-Reversing Electron Rings by Ring Stacking

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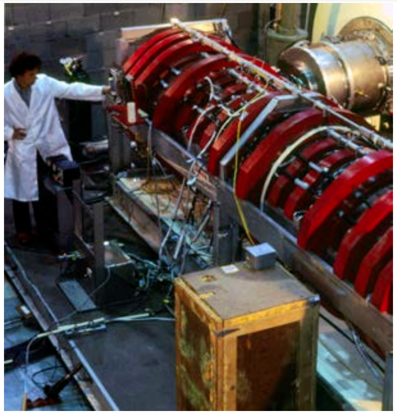
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

(Received 2 June 1977)

In the relativistic-electron-coil–Christa experiment two separate, strong E layers are generated from a single beam pulse, and then combined by moving one of the layers along the tank axis. The "stacking" of two layers with about half of the field-reversal strength each leads to the generation of single E layers with field-reversal strength.



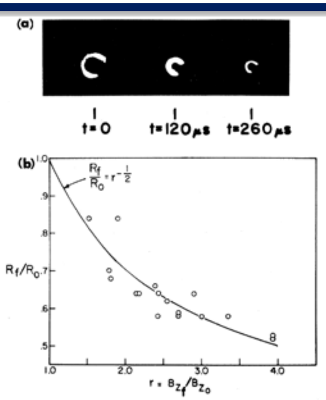


FIG. 4. Measurements of ring radius with end-on framing photography. (a) typical recording ($r = 3$) showing electron ring with axial conductor before, during, and at peak compression. (b) Compression-induced fractional changes in major ring radius for various compression ratios and rings.

VOLUME 43, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1979

Adiabatic Magnetic Compression of Field-Reversing E Layers

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(Received 24 January 1979)

In the RECE-Christa device, electron rings were adiabatically compressed in low-density background gas with axial magnetic field compression ratios $B_{zf}/B_{zi} \lesssim 4$, without encountering any gross instabilities or other anomalous losses. In agreement with a simplified theoretical model, the field-reversal factor, δ, remains constant, and the major radius and the axial length of the rings scale with $B_z^{-1/2}$ while the ring current increases with $B_z^{1/2}$. Furthermore, field-reversal times have been extended to 1.1 msec.

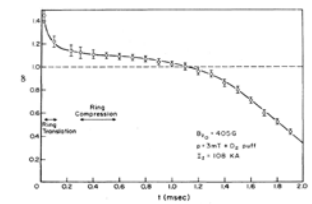


FIG. 5. Full time dependence of field-reversal factor for long-lived ring.

Minimizing electron ring energy loss during translations

Axial translation of field-reversing E layers[a)]

D. J. Rej, M. Tuszewski, H. A. Davis, and H. H. Fleischmann

School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853
(Received 23 August 1978; accepted for publication 25 September 1978)

Experiments are described in which field-reversing E layers were transported axially in RECE-Christa over a distance of up to 10 ring radii using time-varying magnetic fields. When properly executed, this process does not lead to anomalous fast-electron losses. The translation speed appears consistent with that expected from the interaction of the rings with the axial B_z-field gradients and the resistive tank wall. No significant difference is observed between moving the rings in a homogeneous H_2 fill and moving them from a transient gas cloud into a low-gas-density region.

910 Appl. Phys. Lett. 33(11), 1 December 1978 0003-6951/78/3311-0910$00.50 © 1978 American Institute of Physics 910

Resistive wall interaction of axially moving field-reversed E layers or plasma rings

D. J. Rej, D. A. Larrabee, and H. H. Fleischmann

School of Applied and Engineering Physics, Cornell University, Ithaca, N.Y. 14853
(Received 25 February 1980; accepted for publication 6 June 1980)

Calculations are performed of the interaction force between an axially moving current carrying plasma ring or E layer with a resistive wall for a variety of parameters relevant to various moving-ring fusion schemes and experiments. Various wall configurations are considered: (i) For a thin resistive wall, the interaction force $F_r(v_z)$ is found to be proportional to the axial speed v_z or to $(1/v_z)$ for small or large velocities, respectively, and to be strongly dependent on the ratio of the effective ring radius R to wall radius R_w. In contrast, the force dependence on the ring thickness δR is found small when rings with similar external field distributions are compared. For fusion-relevant ratios $R/R_w \leq 0.7$, and $L/R = 1$–2 (L = ring length), the energy losses for moving the rings an axial distance equal to L may amount to 25% of the rings' magnetic self-energy. However, this energy can be strongly reduced by proper choice of parameters. (ii) The addition of a fully flux-conserving wall at a radius $R_c > R_w$ is also found to lead to significant reductions of $F_r(v)$ in the low-velocity regime, dependent in size on the ratio $\alpha = R_c/R_w$. (iii) A finite wall thickness mainly will lead to increases in $F_r(v)$ at large v_z, where the transit time of the rings $t_r \simeq (R_w^2 + L^2)^{1/2}/v_z$ becomes shorter than skin-depth time of the wall. In this case, $F_r(v) \sim v_z^{-1/2}$ is obtained.

5285 J. Appl. Phys. 51(10), October 1980 0021-8979/80/105285-07$01.10 © 1980 American Institute of Physics 5285

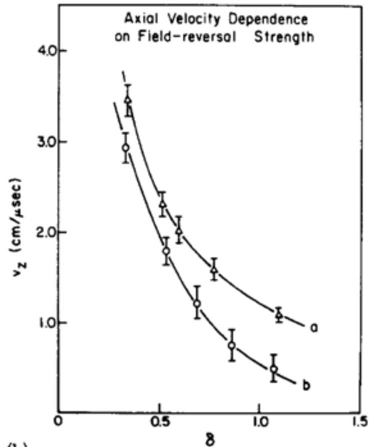
Measurements of resistive wall and plasma drag on the axial translation of field-reversing E layers

D. J. Rej,[a)] M. R. Parker, and H. H. Fleischmann

School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853
(Received 28 September 1981; accepted 16 September 1982)

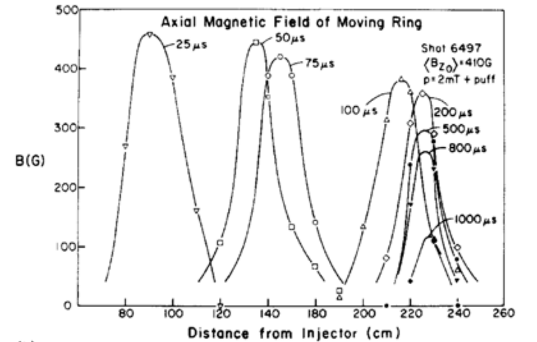
Results from detailed measurements and related analyses of the axial translation of strong E layers in the RECE–Christa experiment testing the interaction of the rings with resistive image currents in the wall and in the ring plasma are presented. The experiments were performed under a variety of experimental conditions including cases with (i) $F_w > F_p$, (ii) $F_w < F_p$, and (iii) $F_w \simeq F_p$ (F_w and F_p denoting the retarding image forces due to interaction with wall currents and plasma currents, respectively). In the respective analyses, theoretical ring velocities are calculated from simultaneously measured ring, wall, and plasma parameters. In all cases, good qualitative and quantitative agreement [10%–20% for case (i), and 30%–50% for (ii) and (iii)] between the observed and the theoretically calculated velocities is found.

323 Phys. Fluids 26 (1), January 1983 0031-9171/83/010323-14$01.90 © 1983 American Institute of Physics 323



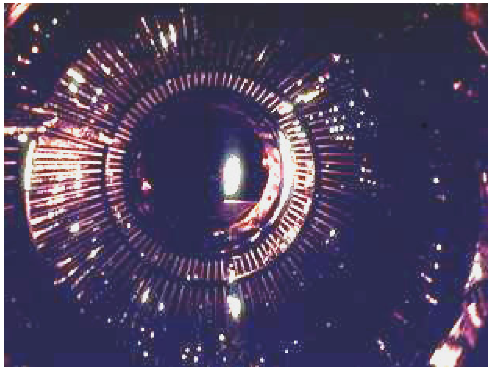
(b)

FIG. 4. Measurements of ring velocity in approximately uniform field gradient. (a) Probe recordings for dB_z/dz = 0.5 G/cm; (b) observed velocities with dB_z/dz = 0.5 and 0.35 G/cm for curves (a) and (b), respectively.



(b)

FIG. 3. Typical ring propagation in the puffed-gas shot. (a) Recordings from various probes positioned along the tank axis; (b) corresponding magnetic ring profiles at various times.



Ethane condensation with a LN2 cryopump

Exceptional classmates: David Larrabee and Mark Parker, and undergraduate interns Karl Bromer and Von Walters

Field Reversed Theta Pinches at Los Alamos

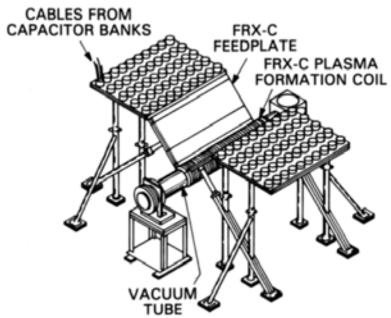
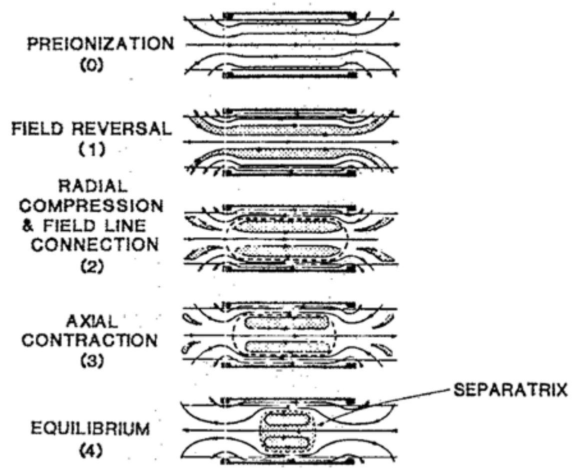


Fig. 3. Schematic of the FRX-C field-reversed theta pinch.



Phases of FRC formation in a field-reversed theta pinch

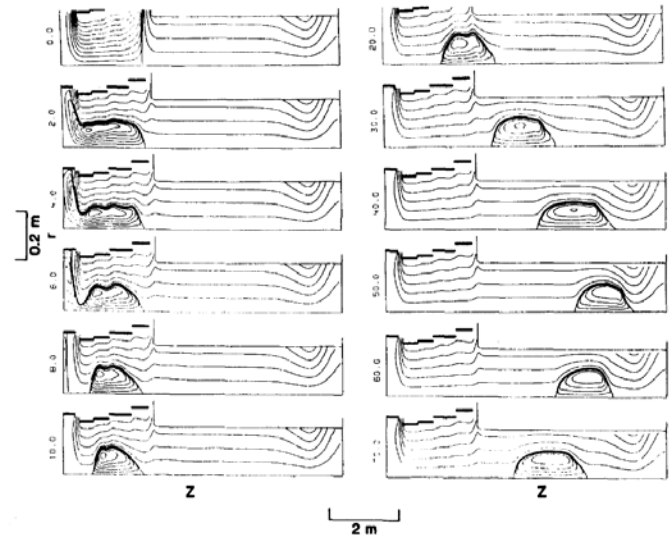
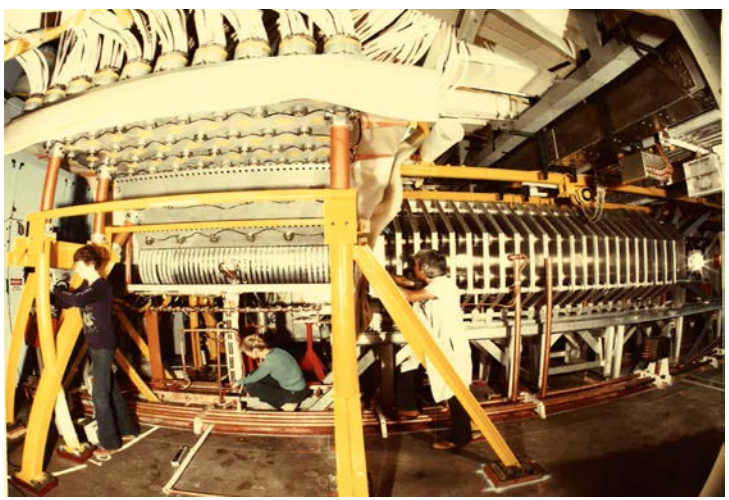


FIG. 11. Time evolution of the poloidal flux contours as predicted from 2-D MHD simulations of FRC translation in FRX-C/T for the low-compression, 5 mTorr puff mode with $B_0 = 2.5$ kG and $R_M = 2.5$.

MHD simulation of poloidal flux for FRC translation



LANL FRX-C/T theta pinch (left) and dc magnet coils surrounding the translation chamber (right)

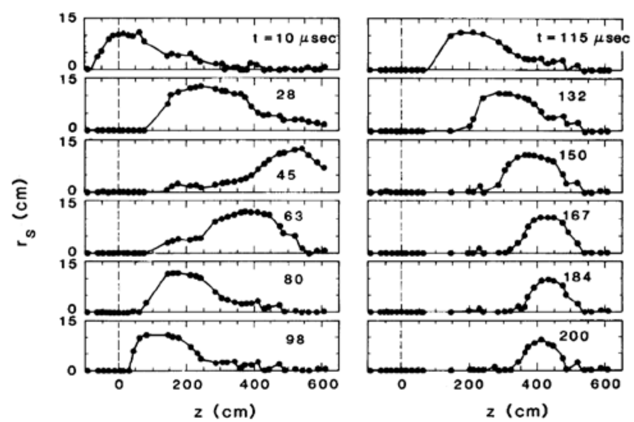
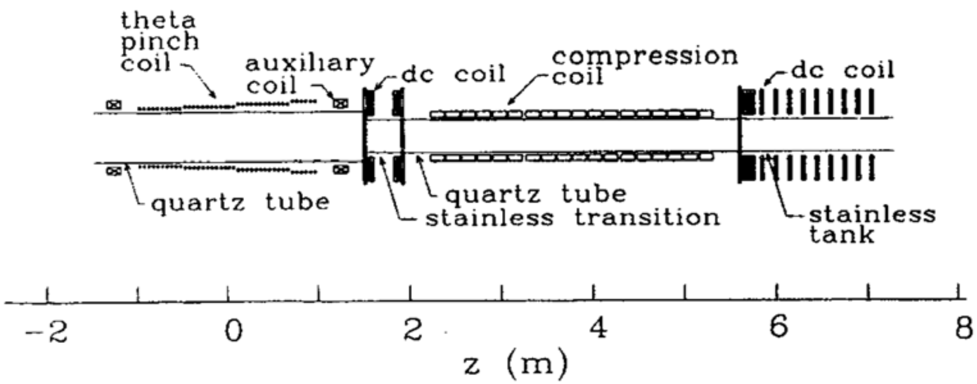


FIG. 2. Time evolution of the FRC separatrix radius profile $r_s(z)$, as inferred from excluded magnetic flux measurements. These data are from a single FRX-C/T discharge at the low-compression, 5 mTorr puff mode with $B_0 = 2.5$ kG and $R_M = 2.5$.

Experimental measurements of excluded magnetic flux for FRC translation

1 GW magnetic-compression heating of translated FRCs



Schematic diagram of the FRX-C/LSM compression experiment.

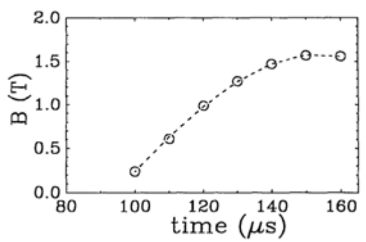


FIG. 6. Time dependence of the external B field during compression. Data represent averages of eight 10 kV compression bank discharges.

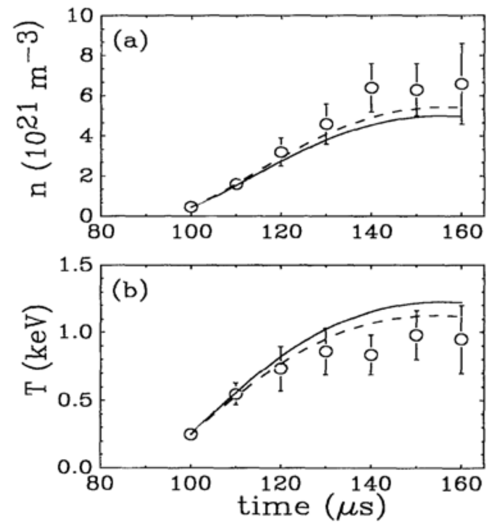


FIG. 8. Time dependence of (a) the average density n and (b) the total temperature, $T = T_e + T_i$, during compression. Data points represent averages measured in 10 kV discharges, while solid and dashed lines are the expectations of adiabatic compression theory for high- and low-flux sharp-boundary FRC equilibria, respectively.

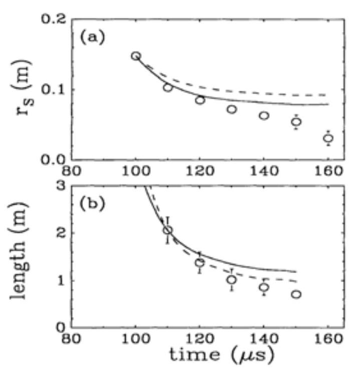


TABLE I. FRX-C/LSM data.

Parameters	Units	θ-pinch source[a]	Before compression	Near peak compression
Time	μsec	30	100	150
B	T	0.41±0.02	0.23±0.01	1.56±0.04
r_s	mm	152±11	145±5	54±6
$\langle n \rangle$	10^{21} m^{-3}	0.7±0.0	0.6±0.1	6.4±1.5
T_e+T_i	eV	516±34	189±49	970±23
$T_e(r \simeq 0)$	eV	132±26	80±15	340±40
ϕ_p	mWb	3.4±0.8	2.7±0.3	0.7±0.3
s		1.2±0.2	1.9±0.3	0.7±0.2
$e = L_s/2r_s$		4.7±0.4	5.7±0.5	4.3±0.8
τ_ϕ	μsec	210±67	147±46	33±16
τ_N	μsec	175±48	129±66	33±21
τ_E	μsec	79±15	51±20	21±7

[a]Data from source are for nontranslated FRC's from *in-situ* experiments.[24]

Significant electron and ion heating consistent with the expected $B^{4/5}$ adiabatic scaling was observed, despite significant particle diffusion, which is enhanced during compression.

High-power magnetic-compression heating of field-reversed configurations

D. J. Rej, D. P. Taggart, M. H. Baron, R. E. Chrien, R. J. Gribble, M. Tuszewski, W. J. Waganaar, and B. L. Wright
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 21 January 1992; accepted 27 February 1992)

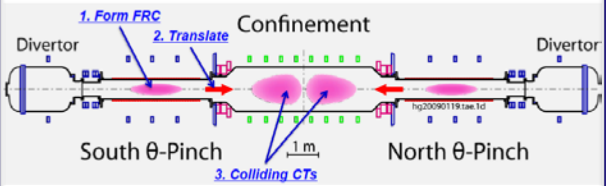
Magnetic compression heating experiments at the 1 GW level on field-reversed configuration (FRC) compact toroid plasmas are reported. FRC's formed in a tapered theta-pinch coil have been translated into a single-turn compression coil, where the external magnetic field is slowly raised up to seven times its initial value. Significant electron and ion heating consistent with the expected $B^{4/5}$ adiabatic scaling is observed, despite significant particle diffusion, which is enhanced during compression. The $n=2$ rotational instability is enhanced during compression, but has been controlled to an extent by the application of an external quadrupole field. The particle and flux confinement times, τ_N and τ_ϕ, remain approximately equal and decrease roughly with the square of the plasma radius R during compression, implying a constant nonclassical field-null resistivity. The observed τ_N and τ_ϕ magnitudes and scalings are compared with classical and anomalous transport theories, and existing empirical models. Particle diffusion dominates the energy confinement, accounting for three-fourths of the total losses. Upper bounds on the electron thermal diffusivities are estimated.

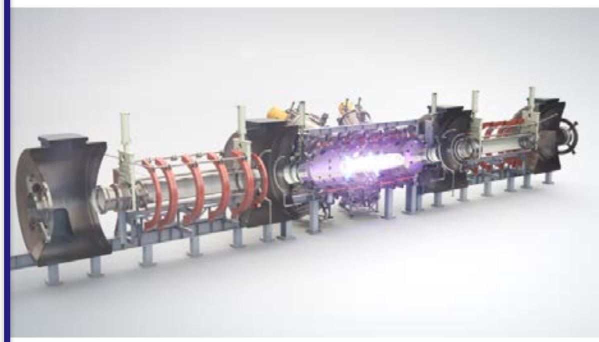
1909 Phys. Fluids B 4 (7), July 1992 0899-8213/92/071909-11$04.00

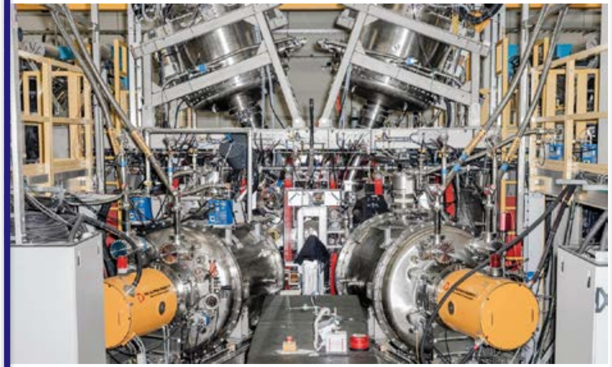
1909

Fast forward to 21st Century:
Resurgence of FRCs through private investments

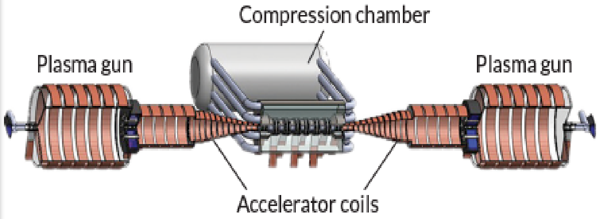
Tri-Alpha Energy, Inc
Foothill Ranch, CA

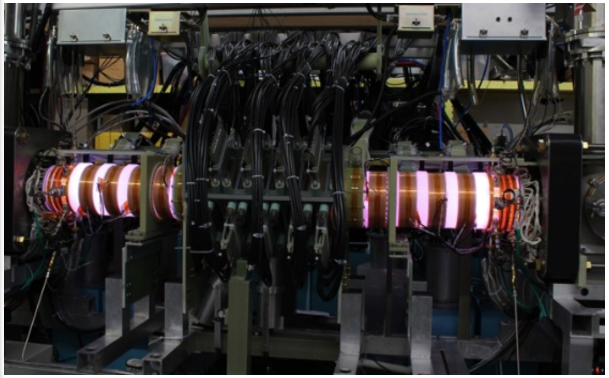




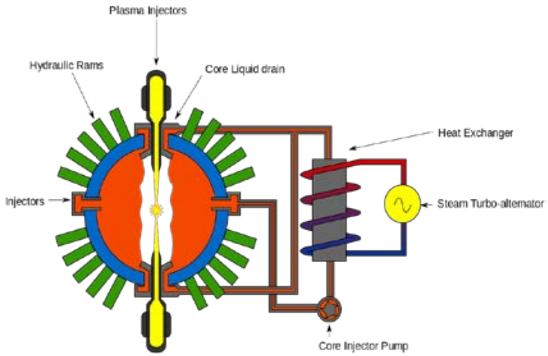


Helion Energy
Redman, WA

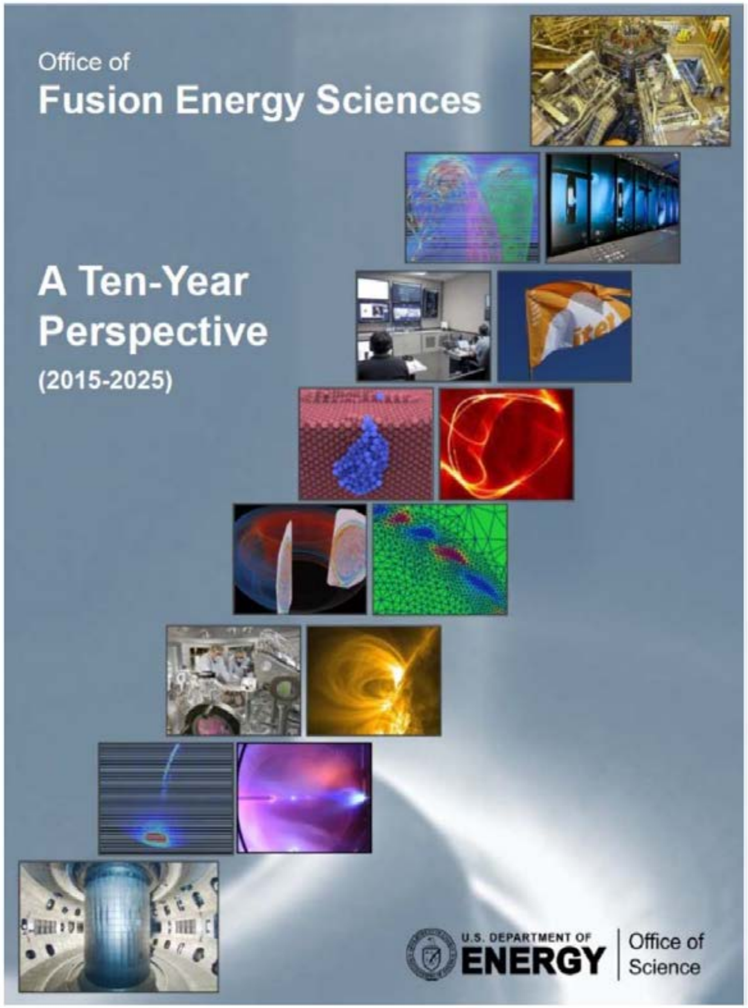




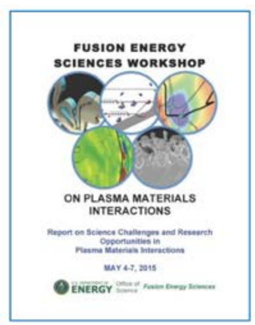
General Fusion
Burnaby, BC

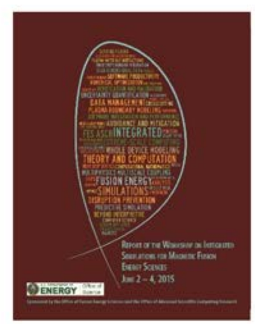


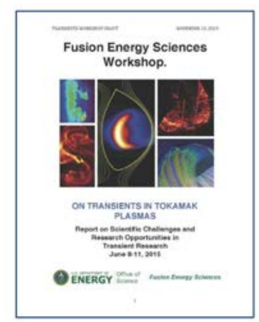
U.S. Department of Energy MFE Program Today

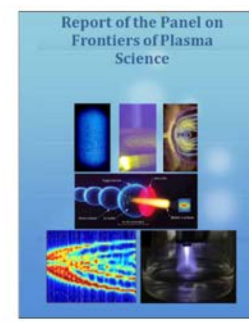


The FES program mission is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished by studying plasma and its interactions with its surroundings across wide ranges of temperature and density, developing advanced diagnostics to make detailed measurements of its properties and dynamics, and creating theoretical and computational models to resolve essential physics principles.



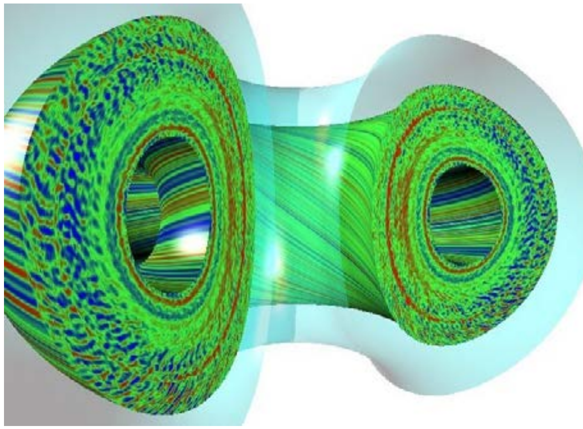




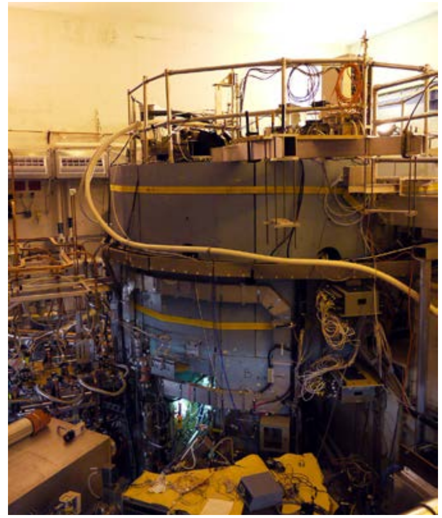


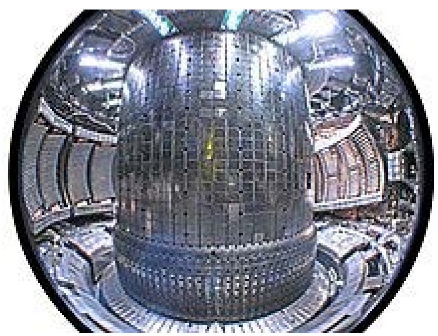
Strategies influenced by community workshops on priority research areas

For over the last 25 years, Tokamak configurations have dominated the world MFE research, including the U.S.

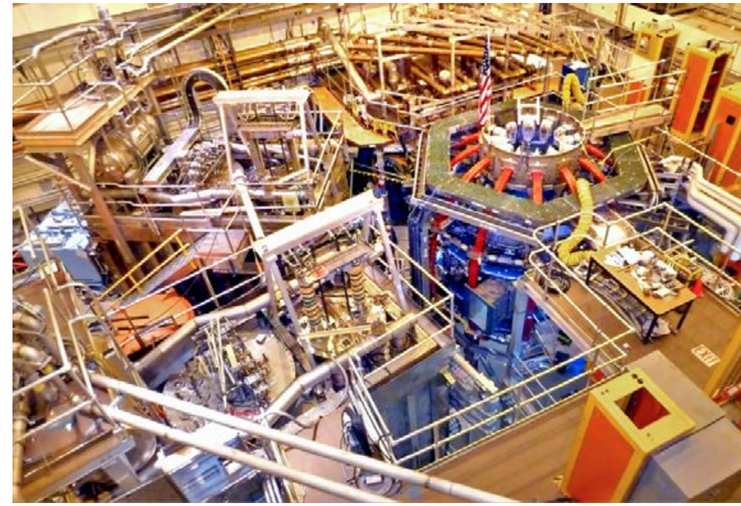


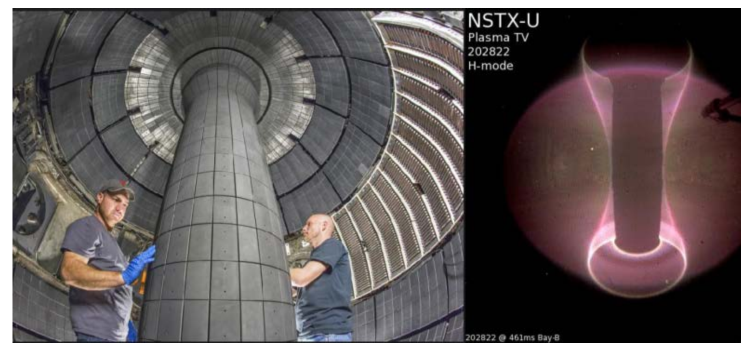
DIII-D
General Atomics





C-Mod
MIT





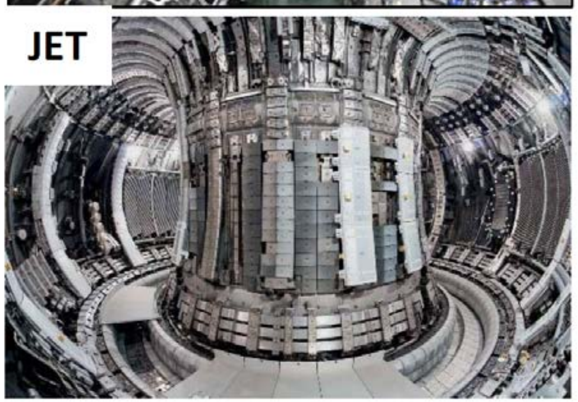
NSTX-U
Princeton

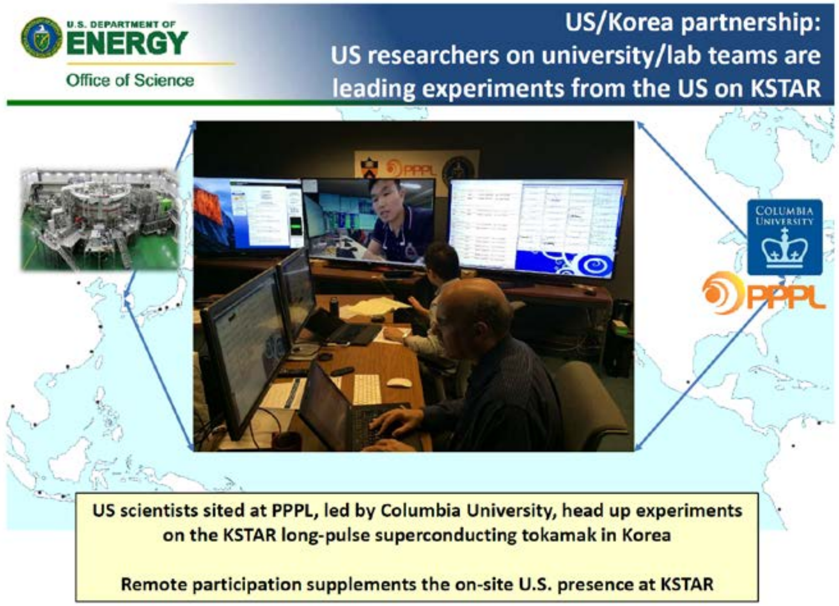
U.S. is a major partner with international tokamak programs

EAST

KSTAR

JET

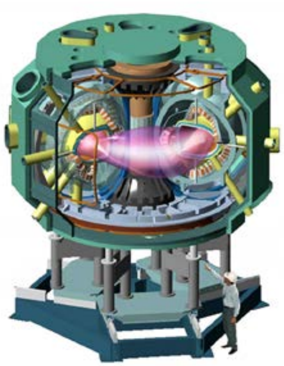




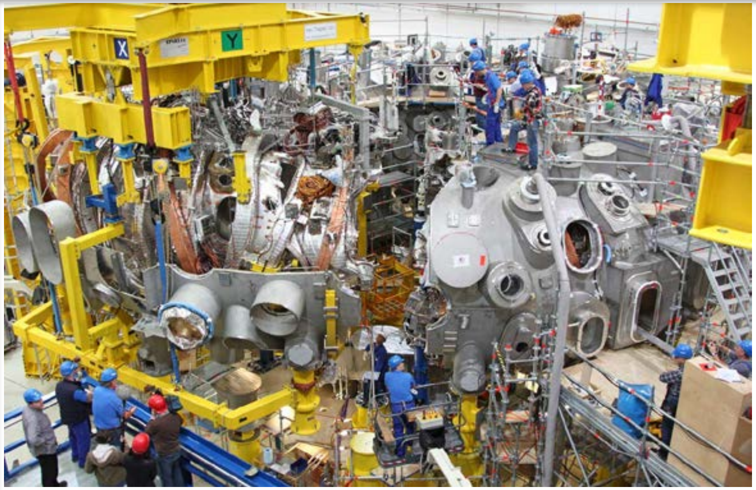
Stellarators

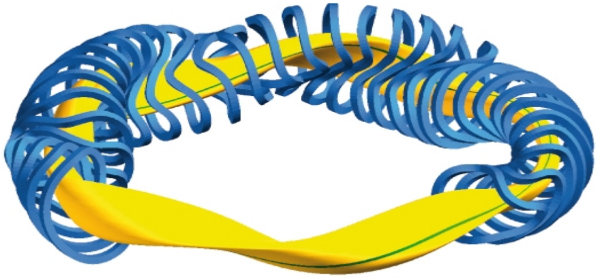
Spitzer Princeton
1951

Large Helical Device
Toki 1998



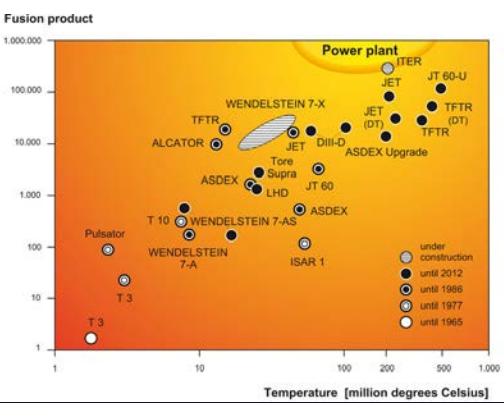
National Compact
Stellarator
Experiment
Princeton 2008

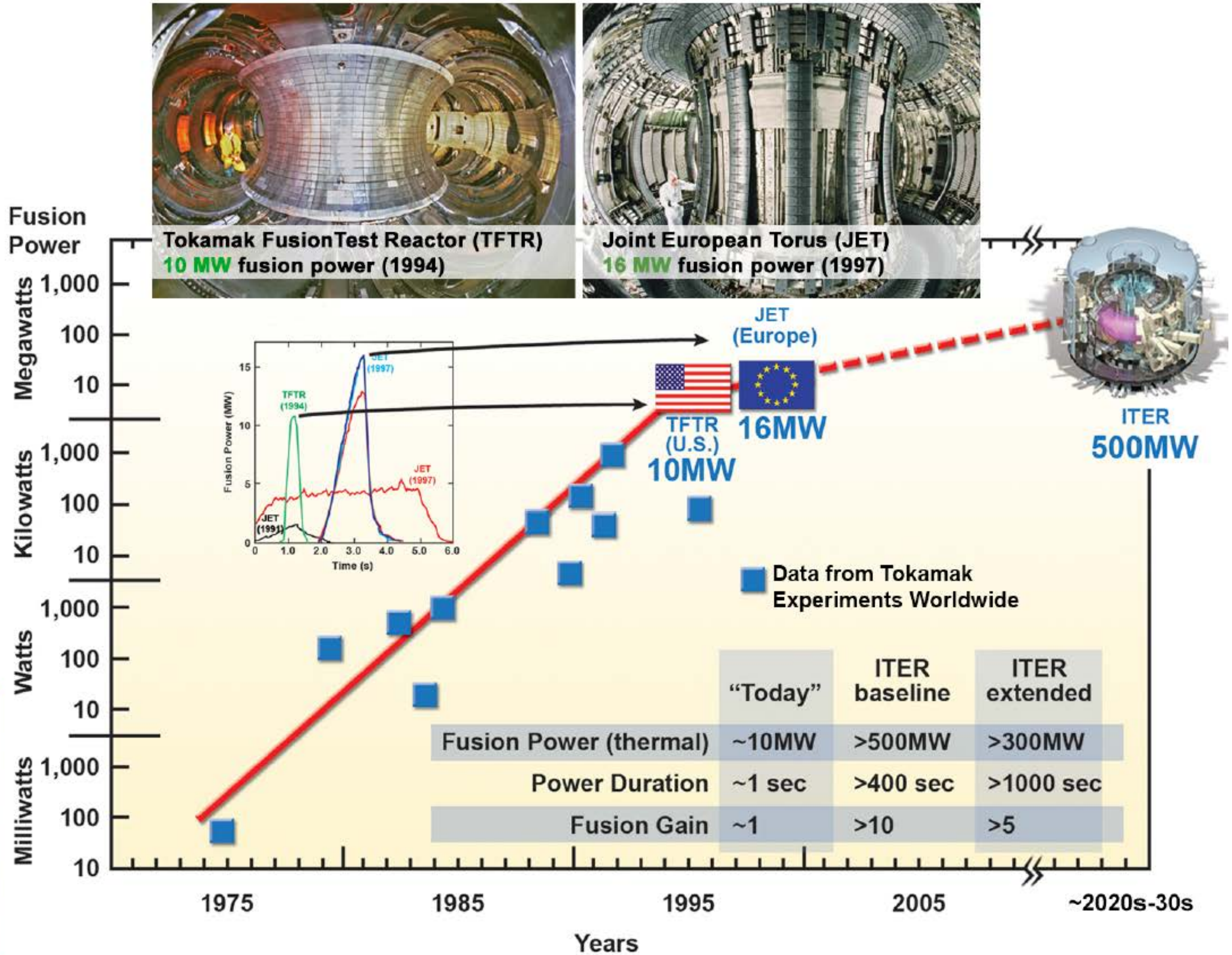




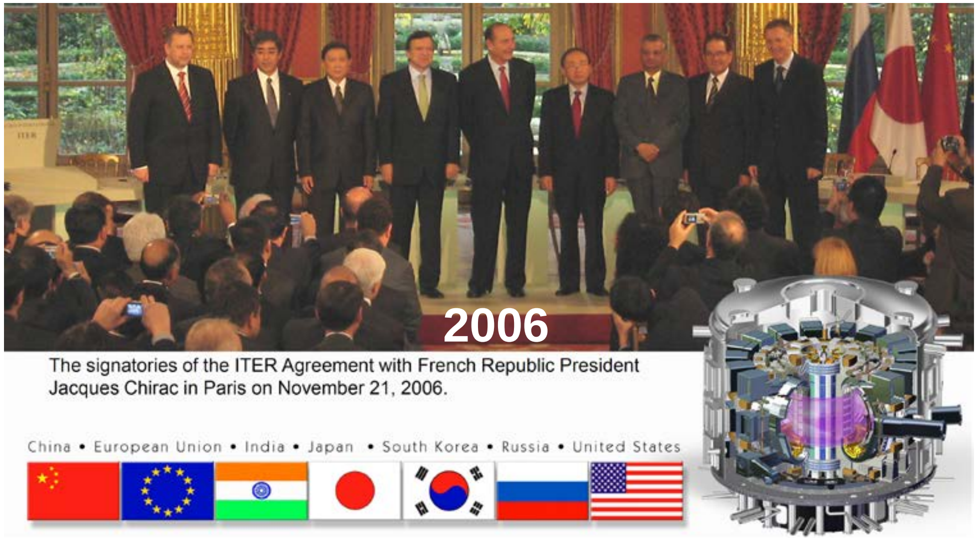
W7-X Stellarator
Max Planck Inst.,
Greifswald, 2015

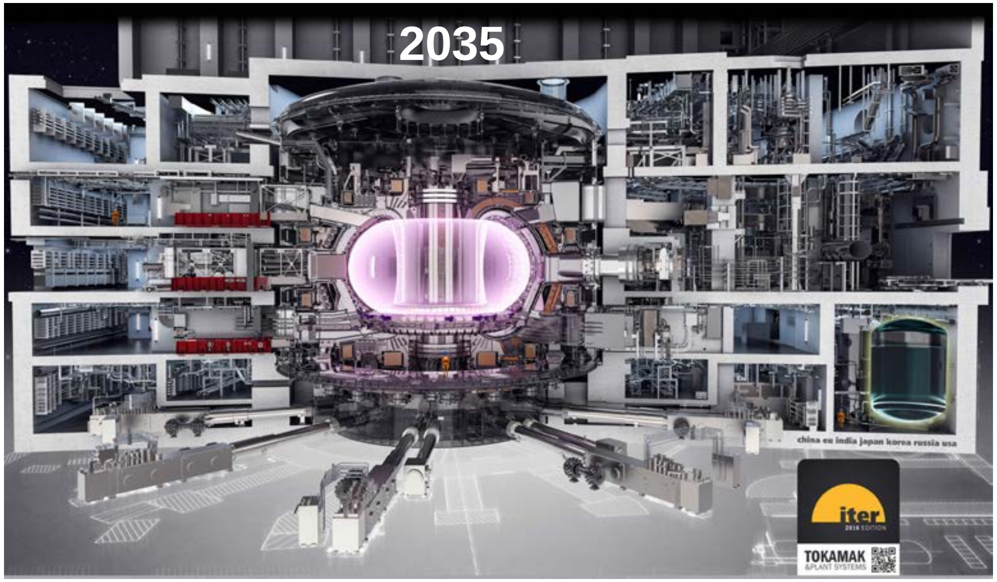
Fusion power from Tokamaks were demonstrated as a scientific proof-of-principle over 20 years ago





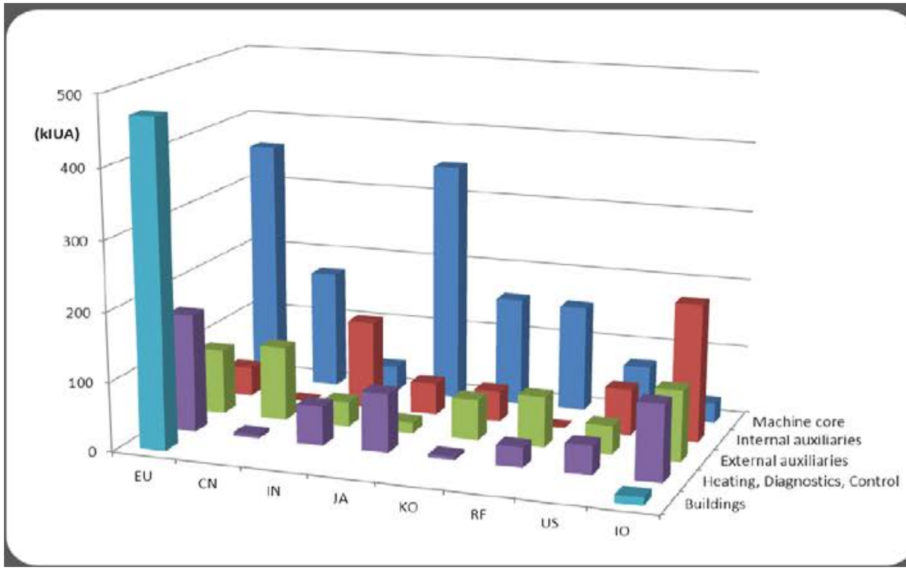
Then there is ITER





While creating the first burning MFE plasma, ITER could be the most complex and expensive civilian scientific facility in history

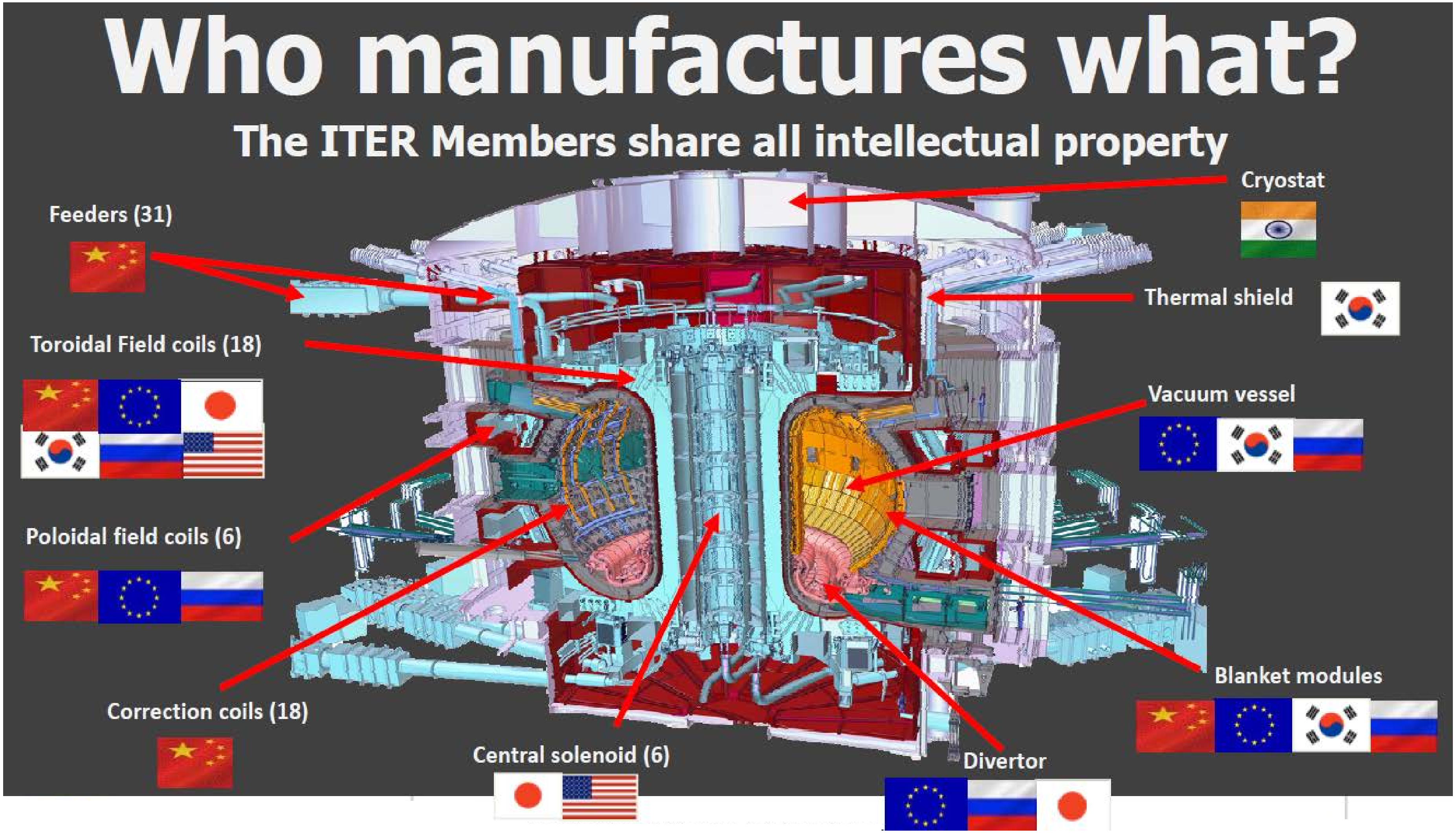
ITER is being built through the in-kind contributions of the seven members of the ITER Organization



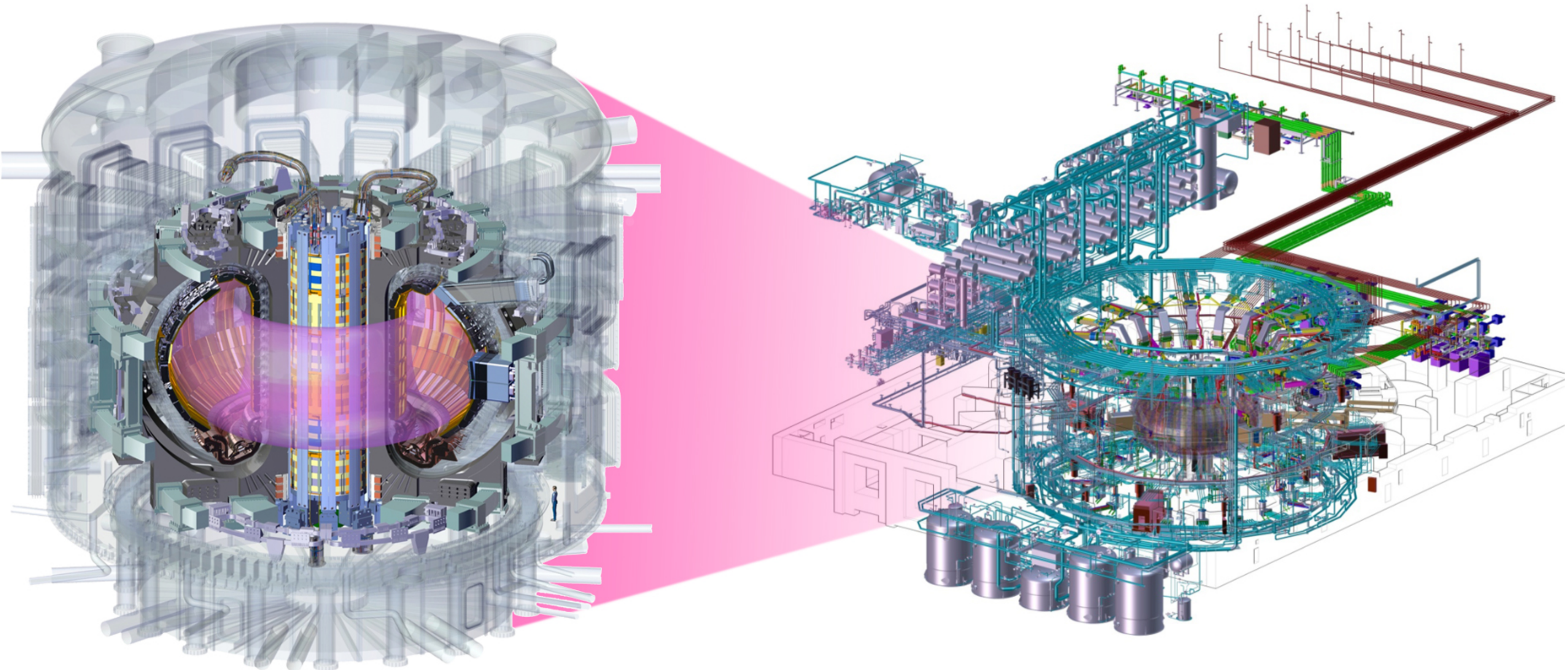
China, India, Japan, Korea, Russia and the United States each have responsibility for ~ 9% of procurement packages.

Europe’s share, as Host Member, is ~ 45% (construction and manufacturing).

ITER is supported by the governments of more than one-half of the World's population



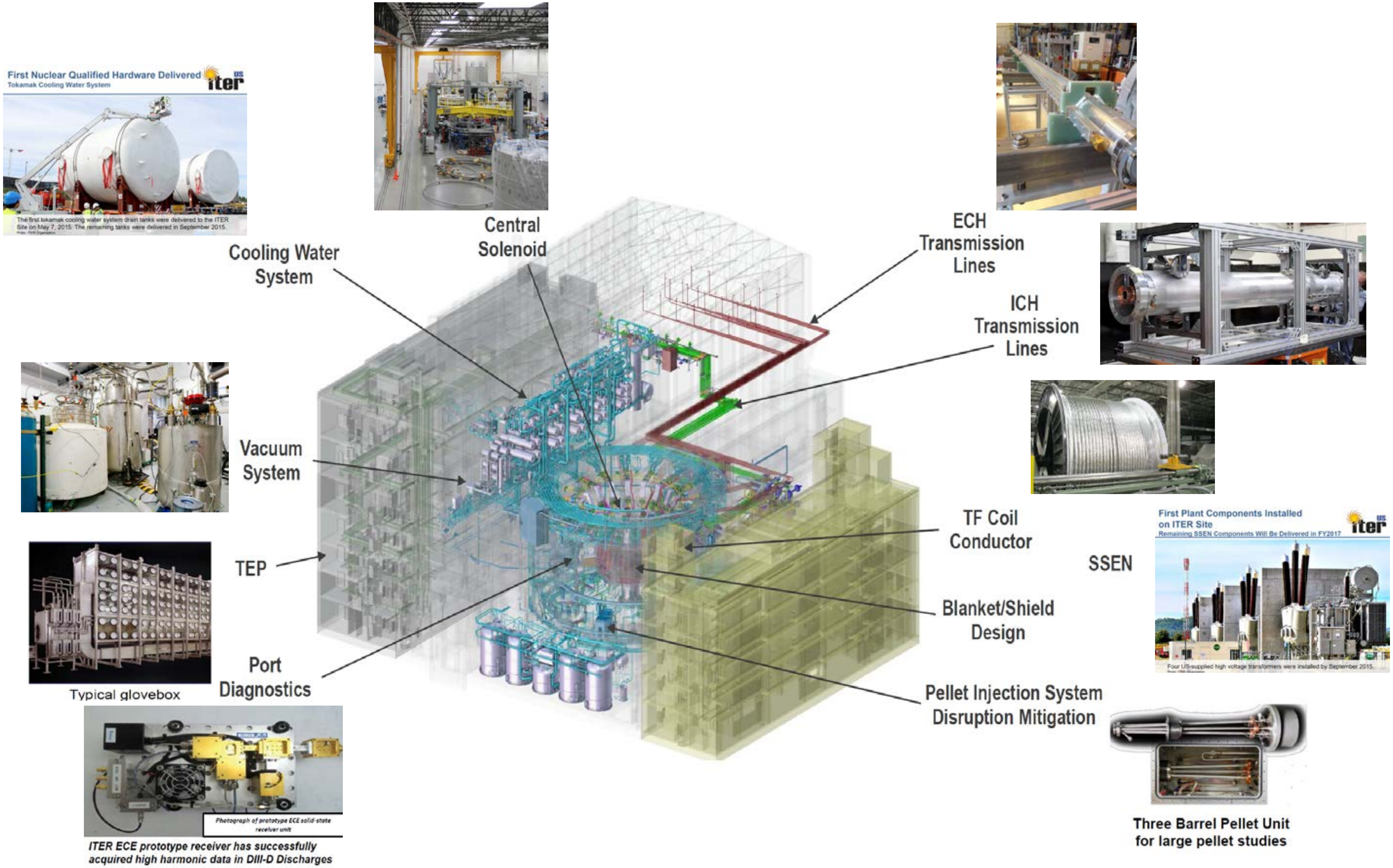
US ITER Project



ITER tokamak
(full global scope)

US ITER Contributions

US ITER Project



ITER Time Line

1985: At the Geneva Summit Gorbachev suggested to Reagan that the two countries jointly undertake construction of a tokamak

1988: Conceptual design

1992: Engineering design begins

1998: 1st final engineering design

1999: USA pulls out

2001: “Cost-cutting" design was agreed

2003: U.S. rejoins; China and South Korea join

2005: Southern France announced as ITER site; special compromise between EU & Japan.

2005: India joins

2006: Project agrees to and funded with a cost estimate of €10 billion ($12.8 billion) projecting the start of construction in 2008 and completion a decade later

2007: 14 major design changes

2013: Project had run into many delays and budget overruns. The facility is not expected to begin operations at the schedule initially anticipated

2014: Scathing project review by the “Madia” committee leaks to the press

2015: Project review concludes that the schedule may need extending by at least six years; (first plasma in 2026, first D-T in 2035)

2016: Secretary of Energy report to Congress that U.S. remain a partner in the ITER project through FY 2018 and focus on efforts related to First Plasma

Management crises, change, & encouragement

Independent schedule review by experts appointed by the seven domestic agencies 2014 – 2015

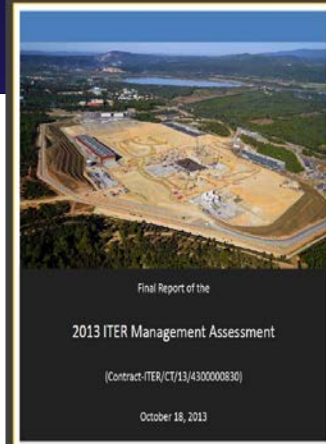
ITER Council Working Group on the Independent Review of the Updated Long-Term Schedule and Human Resources (ICRG)

Report

15 April 2016

Second external independent expert review of cost & schedule 2016

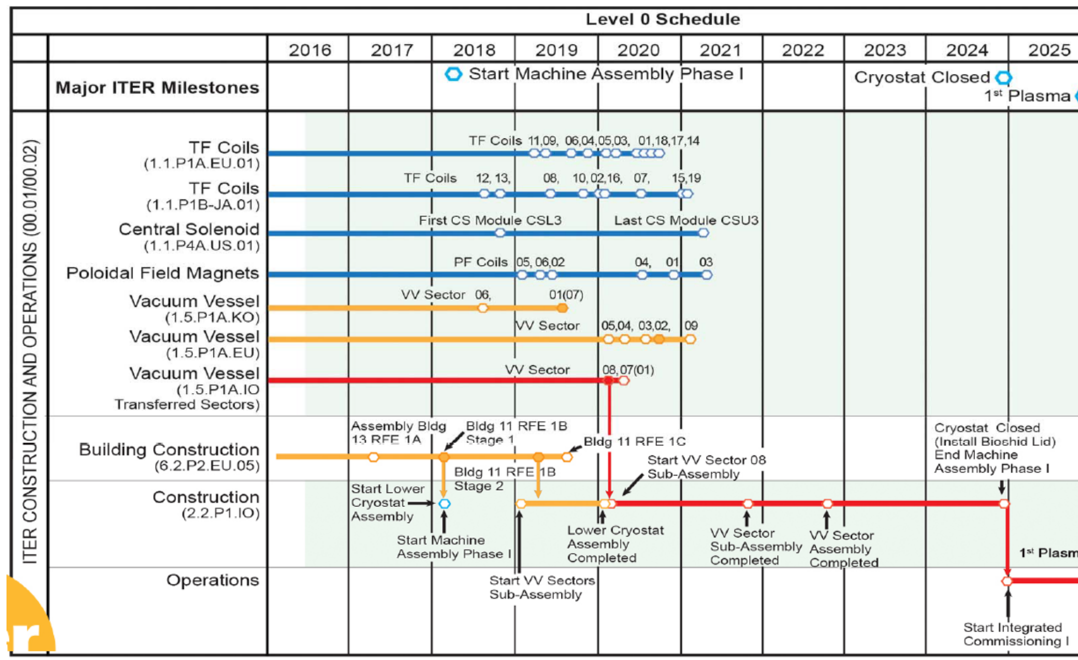
2015: managing the need for change



Action Plan 2015

Set clear priorities and timeline for reform

- ✓ Reorganized, integrated ITER Central Team with Domestic Agencies
  - ✓ Clear decision processes and accountability
  - ✓ Executive Project Board, Reserve Fund, Project Teams
- ✓ Finalized and stabilized ITER critical component design
- ✓ Comprehensive integrated bottom-up review of all activities, systems, structures, and components to build the ITER machine
  - ✓ Developed an optimized resource-loaded schedule for timely, cost-effective construction and operation through D-T plasma. Updated the 2010 Baseline.
- ✓ Developed and promoted a strong, organization-wide nuclear project culture

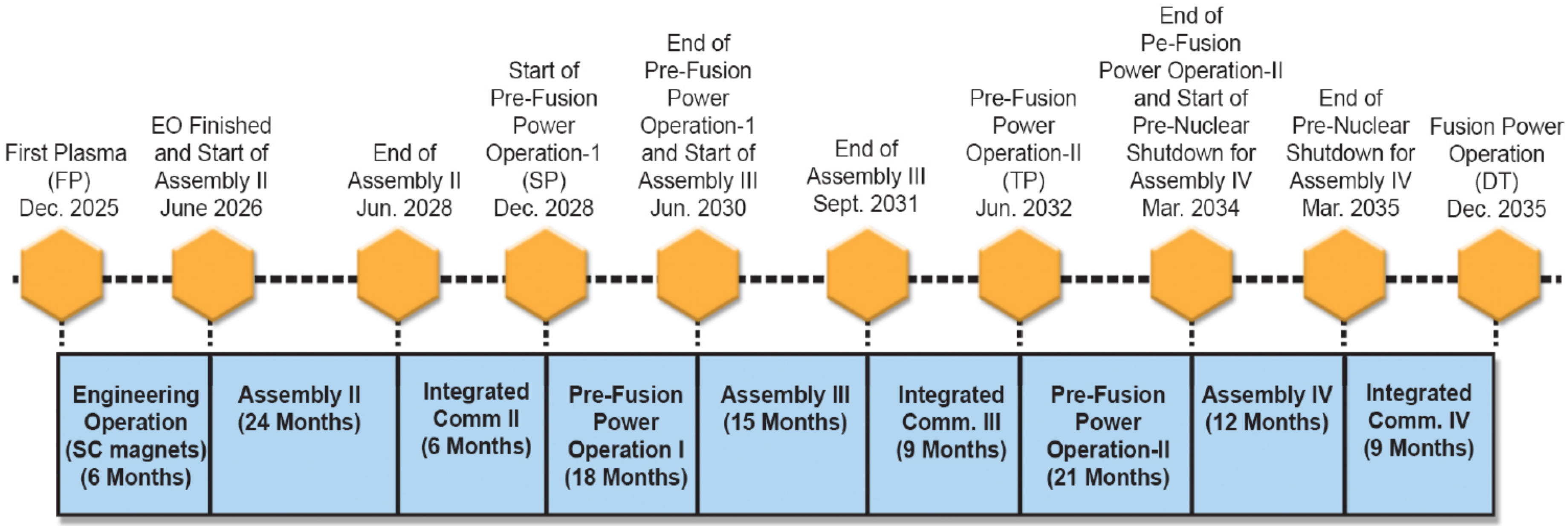


Revised resourced loaded schedule to first plasma in 2015

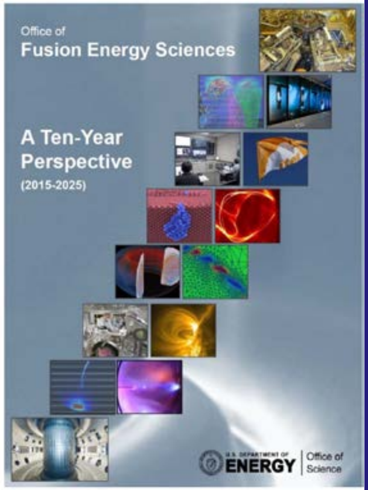
Staged approach from ITER first plasma to DT

Extensive interactions among IO and Das to finalize revised baseline schedule proposal

- ✓ Schedule and resource estimates through First Plasma (2025) consistent with Members' budget constraints
- ✓ Proposed use of 4-stage approach through Deuterium-Tritium (2035) consistent with Members' financial and technical constaints



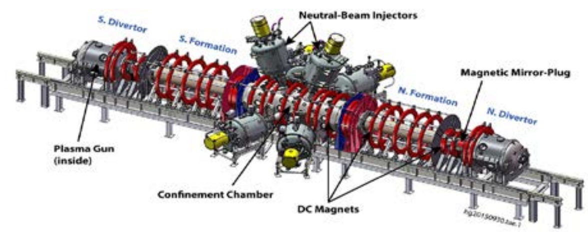
So what's in the future for MFE?



National Research Council (2004)

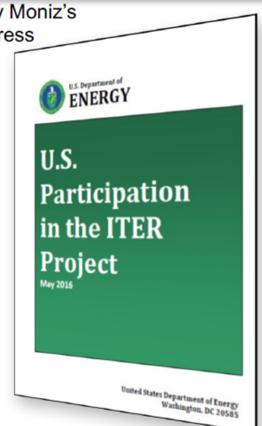
From the "Executive Summary":

"…A burning plasma…is an essential step to reach the goal of fusion power generation….The committee concluded that there is high confidence in the readiness to proceed with the burning plasma step. The International Thermonuclear Experimental Reactor (ITER), with the United States as a significant partner, was the best choice. Once a commitment to ITER is made, fulfilling it should become the highest priority of the U.S. fusion research program."



Venture capital longshots

DOE Secretary Moniz's report to Congress (May, 2016)



From the "Message from the Secretary ":

"ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power."

U.S. DEPARTMENT OF ENERGY
Office of Science

The Secretary's report to Congress also states that DOE will seek an NAS study

From the body of the report:

- The DOE will request that the National Academies perform a study of how to best advance the fusion energy sciences in the U.S., given the developments in the field since the last Academy studies in 2004, the specific international investments in fusion science and technology, and the priorities for the next ten years developed by the community and FES that were recently reported to Congress.
- This study will address the scientific justification and needs for strengthening the foundations for realizing fusion energy given a potential choice of U.S. participation or not in the ITER project, and will develop future scenarios in either case.

Thank you again for the opportunity to return to LPS after all these years and evoking many fond memories