An Alcator Chronicle

or

What happened to Alcator B?

Ron Parker

Thanks to Paul Rivenberg, Jason Thomas, Mary Pat McNally
Tom Hrycaj and David Pace

In the beginning...........

In the late 1960's,

Experimental plasma/fusion research at MIT was done on "table top" experiments

The stellarator was being developed at Princeton

The tokamak was being developed in the Soviet Union

Bruno Coppi was at Princeton and in 1967 went to the Soviet Union and discussed neoclassical plasma confinement theory with and Albert Galeev and Raold Sagdeev.

Bruno, along with Ernesto Mazzucato, was also interested in the problem of plasma resistivity at high values of the streaming parameter

He was also intrigued with an idea of John Dawson to build a 10 T linear device and heat it with a laser.

The idea for Alcator begins to jell

In 1968, Bruno attends an IAEA conference in Novosibirsk and was impressed by the results from T-3 tokamak – 1 keV electron temperature, confinement 50X Bohm!

In 1969 T-3 results confirmed by Thomson scattering carried out by visiting scientists from the UK.

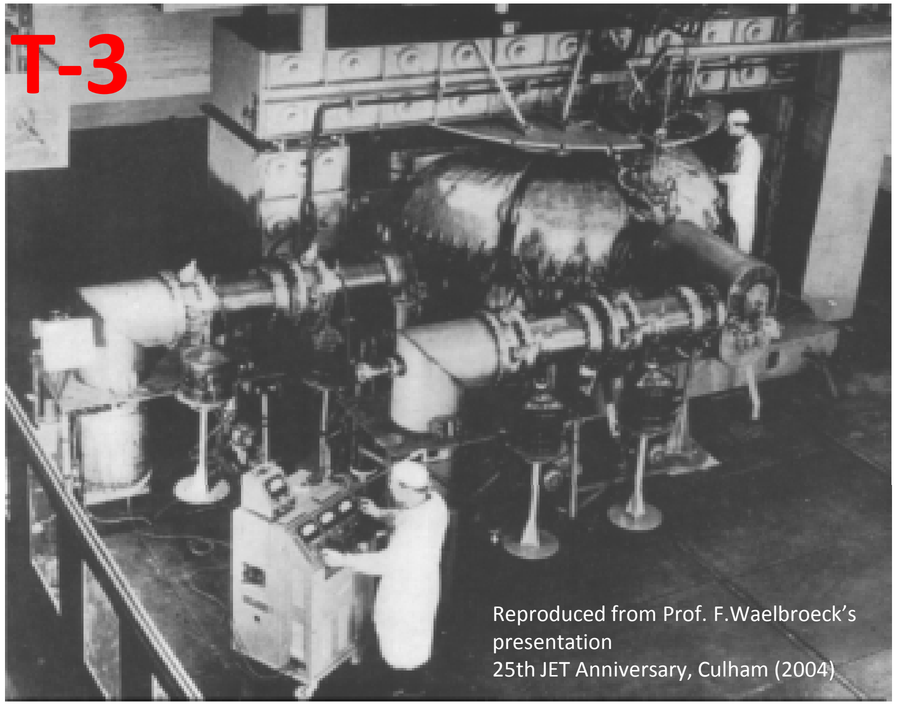
Also in 1969, Bruno accepts faculty position at MIT and collaborates with engineers at the Francis Bitter National Magnet Laboratory led by Bruce Montgomery to design a high-field, compact Tokamak – 10 T toroidal field!

Later that year, in a pivotal meeting in Albuquerque, the Atomic Energy Commission approves the MIT proposal, along with machines at Texas, General Atomics and Princeton, the latter being the conversion of a stellarator to a tokamak.

Officially authorized by AEC in January, 1970, Coppi calls it "Alcator", an acronym for ALto CAmpo TORus, Italian for High Field Torus.

The tokamak was to be powered by the FBNML's 32 MW DC generators

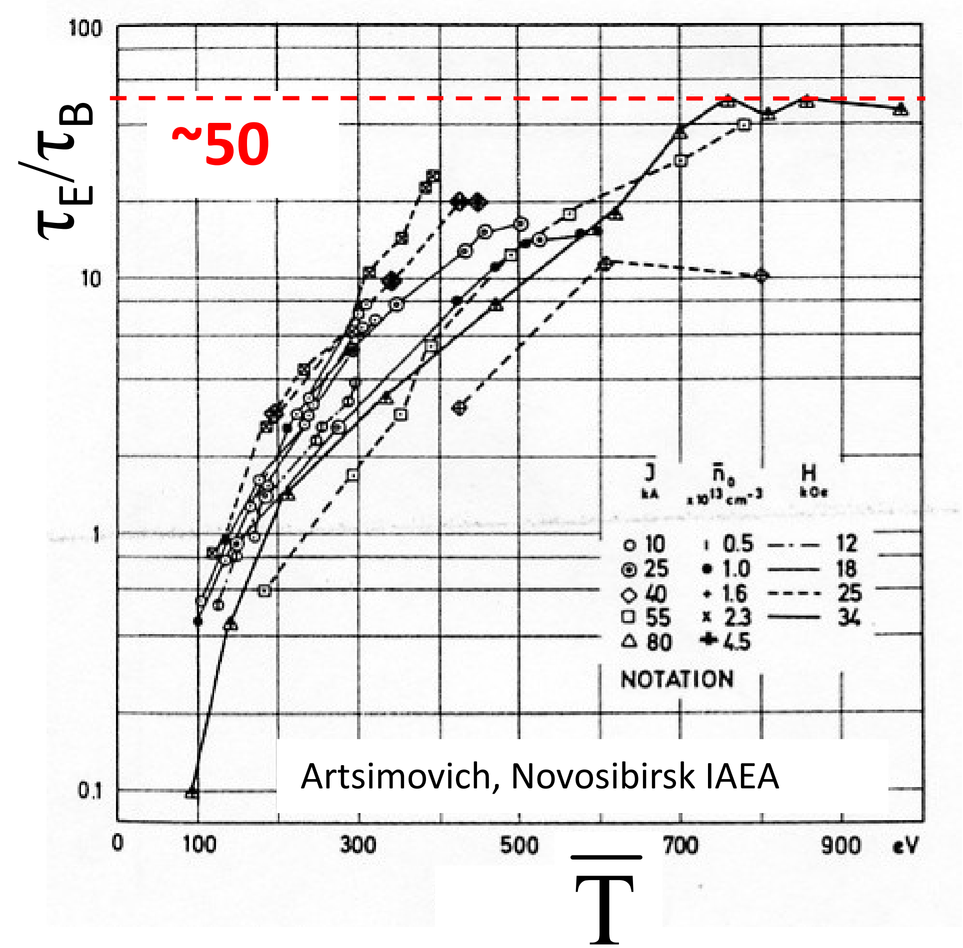
Tokamaks: Plasma confinement overcomes Bohm diffusion [1960s]



Progress of T-series experiments in Kurchatov

Novosibirsk IAEA (1968)

T-3: Te>1 keV, τ_E~50τ_{Bohm}



Culham team confirmed 1 keV-Te in T-3 by Thomson scattering (1969)

(Reprinted from Nature, Vol. 224, No. 5218, pp. 488–490, November 1, 1969)

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

Electron temperatures of 100 eV up to 1 keV and densities in the range 1–3 × 10¹³ cm⁻³ have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible

by

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Why high field, compact?

The energy confinement time: $\tau_E \sim \frac{a^2}{\chi_E} \sim \frac{a^2}{\nu_{ii}\rho_\theta^2} \sim \frac{a^2}{\nu_{ii}T} B^2$

$\Rightarrow$ Good energy confinement

The central current density: $j(0) \sim \frac{B}{R}$

$\Rightarrow$ High Ohmic heating power density and high temperature

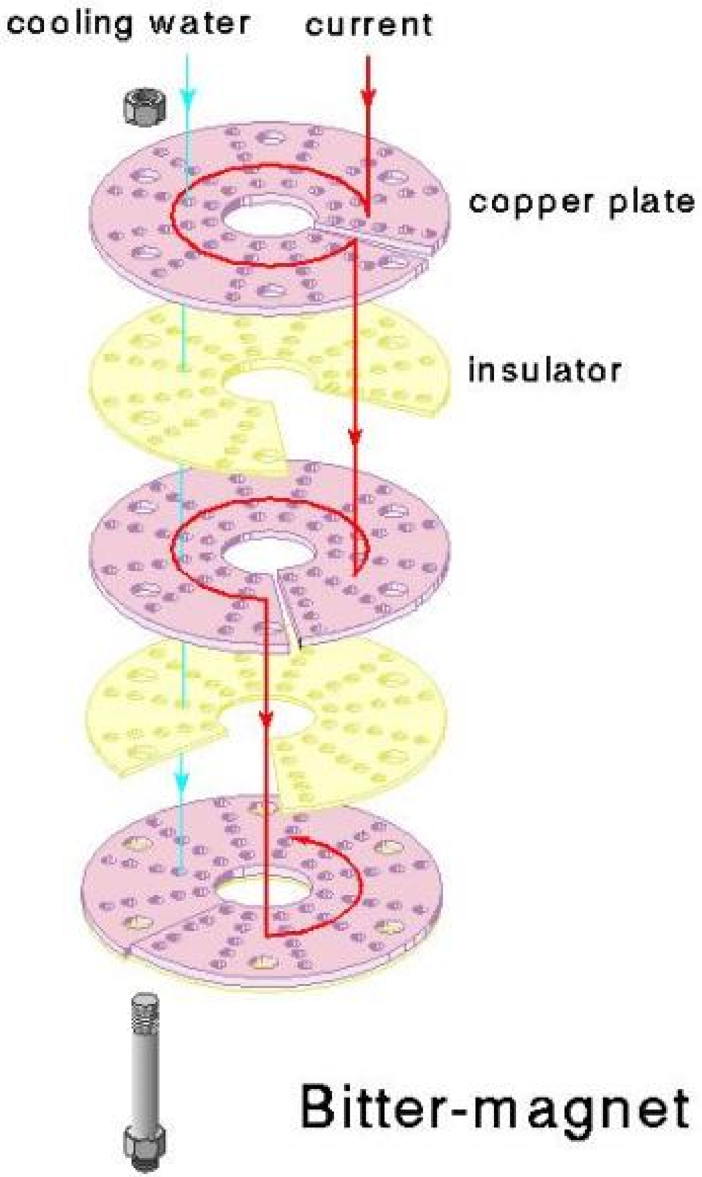
The particle density: $n \sim \frac{I}{\pi a^2} \sim \frac{B_T}{R}$

$\Rightarrow$ High particle density

All good for high $Tn\tau_E$!

The relation of field to particle density turned out to be the most important, but that was not known at the time -- serendipity!

Extending Bitter magnet technolgy to toroidal geometry enabled design of a 10 Tesla TF magnet



Schematic of a single turn of the Alcator C TF magnet

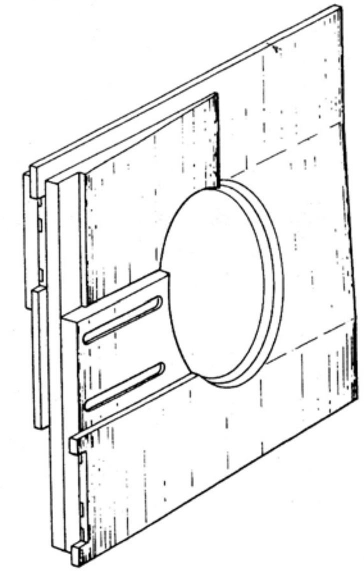
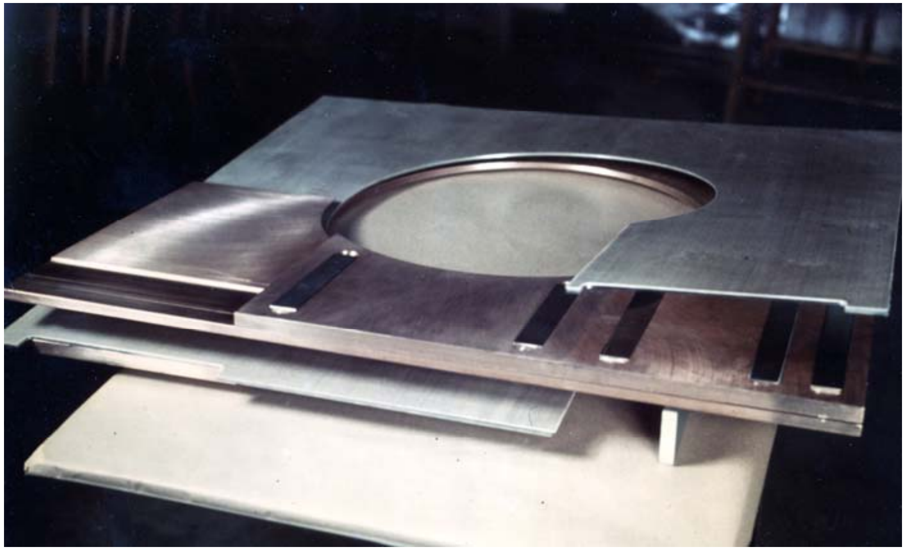


Photo of an actual turn



Insufficient space for an iron core in the bore of the TF magnet required an air core transformer

The flux swing necessary to drive and sustain the current (design = 300 kA) required development of a 20 T solenoid

The design solution was again based on an extension of Bitter magnet technology, this time to a multi turn, LN2-cooled solenoid.

Alcator was the first tokamak in the world to use an air core transformer

First assembly was completed in late 1972, followed by initial operation

First plasmas in late 1972, but there were problems!

The vacuum chamber was “dirty” -- internal coils, kapton insulation, diffusion pump, low-tech seals -- plasmas were “flourescent light” quality

Arcing in toroidal magnet between adjacent turns and first and last turn

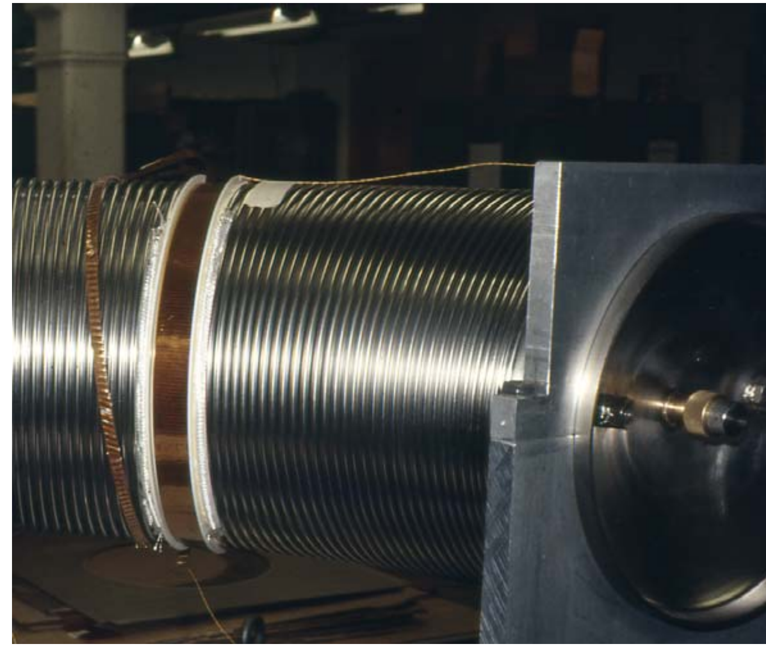
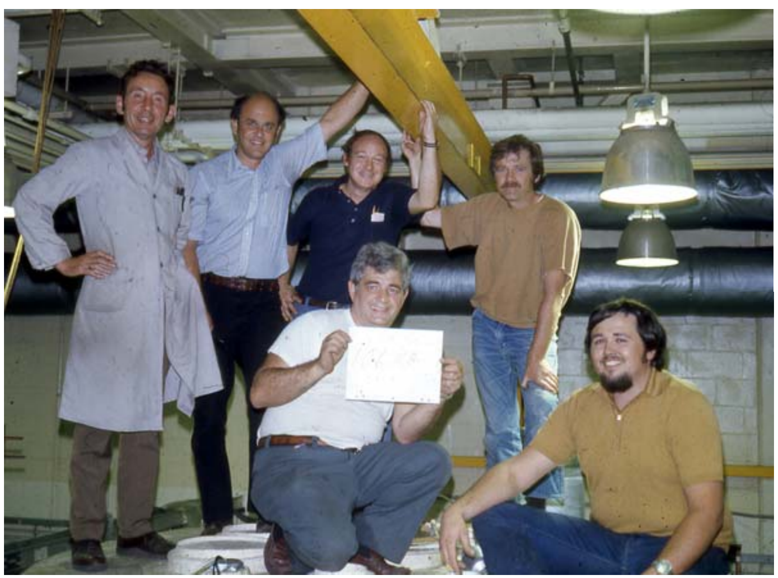
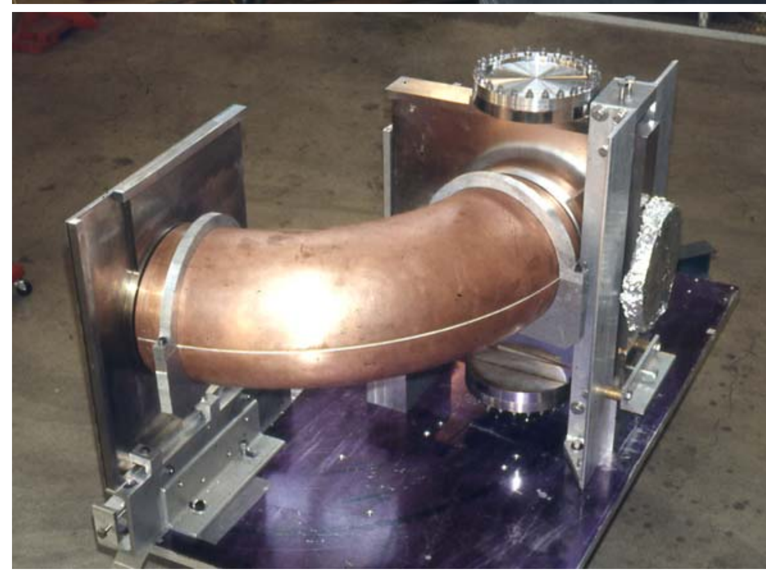
As a result, DOE (then AEC) threatened to cancel the program

At a key meeting with DOE in mid-1973, it was agreed that a necessary condition for continuing the program was to demonstrate the high field performance of the TF magnet

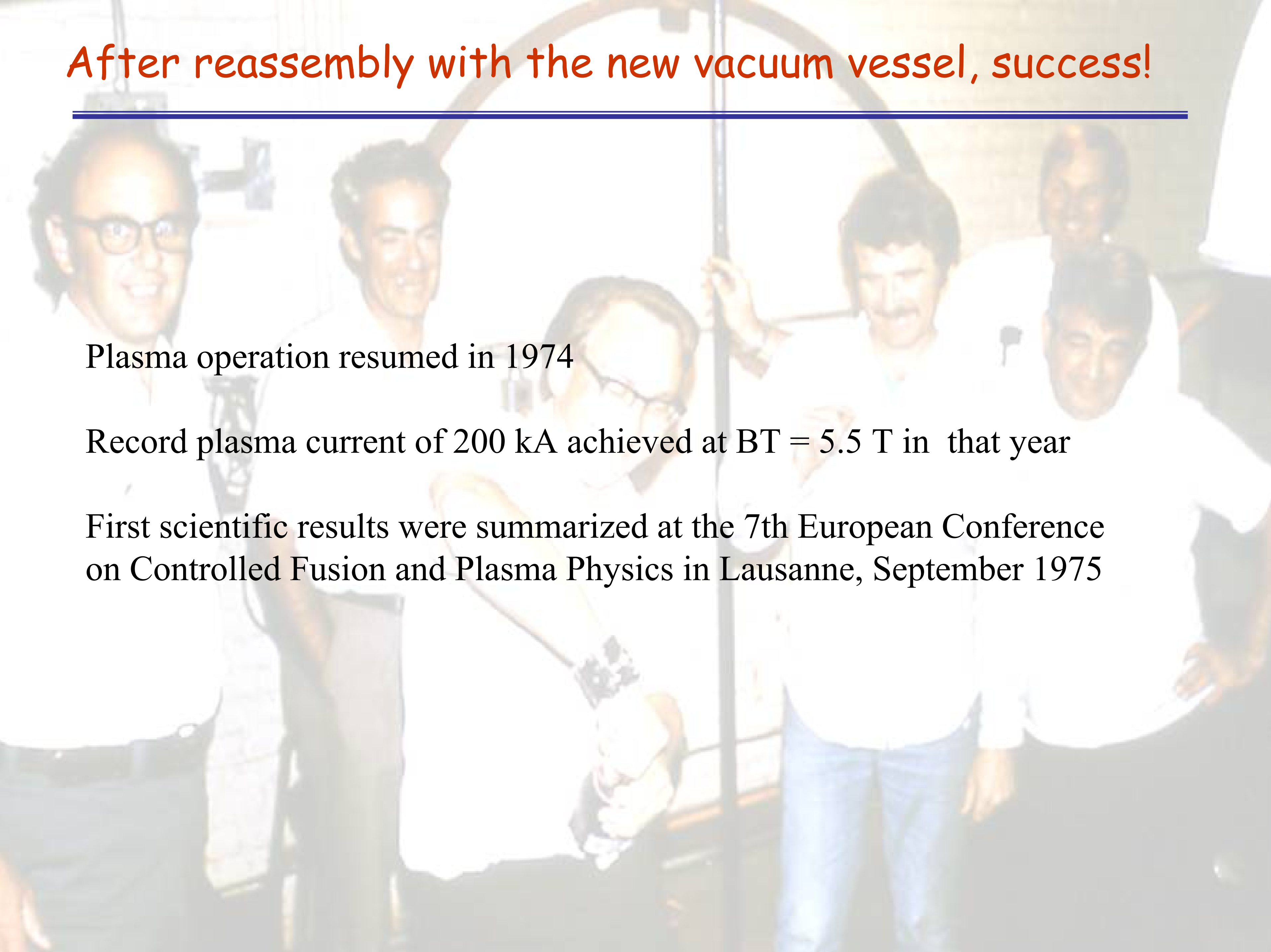
The device was then disassembled, the TF plates cleaned and reassembled with improved insulation (without the vacuum chamber, transformer) and operated at high field – thus proving the design concept.

Meanwhile, a new vacuum vessel had been fabricated, consisting of 4 “massive” flanges connected by bellows and pumped with turbomolecular pumps. Internal coils were eliminated.

The TF magnet was disassembled, Bitter plates cleaned, reassembled and tested to 5.5 Tesla

After reassembly with the new vacuum vessel, success!



Plasma operation resumed in 1974

Record plasma current of 200 kA achieved at BT = 5.5 T in that year

First scientific results were summarized at the 7th European Conference on Controlled Fusion and Plasma Physics in Lausanne, September 1975

The Lausanne paper was the result of efforts by an international team

LOW AND HIGH DENSITY OPERATION OF ALCATOR

G.J. Boxman[o], B. Coppi[*], L.C.J.M. de Kock[o], B.J.H. Meddens[o], A.A.M. Oomens[o], L.Th.M. Ornstein[o], D.S. Pappas[*], R.R. Parker[*], L. Pieroni[†], S.E. Segre[†], F.C. Schüller[o], and R.J. Taylor[*].

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The results were spectacular, foretelling the future of the Alcator program

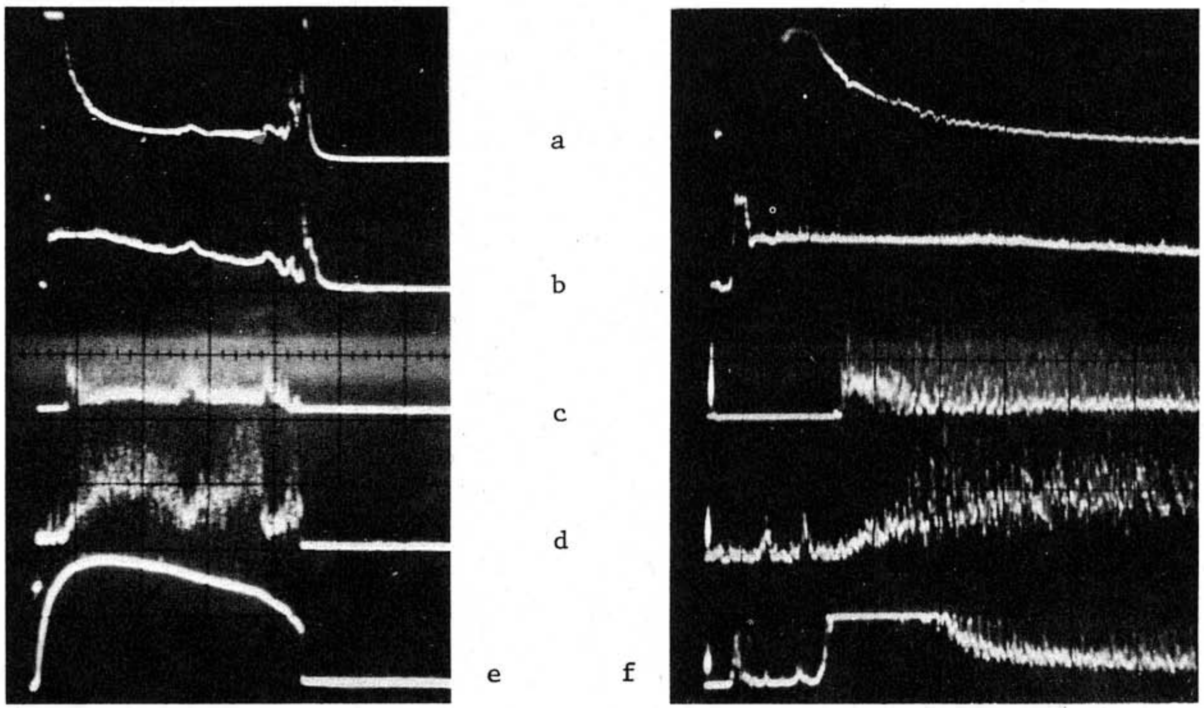
1. Discovery of a "slide-away" and the "Alcator confinement ($\tau_E \; \alpha \; n$)" regimes.

The transition between these regimes was separated by a critical value of the "streaming parameter", $\xi \equiv \left\langle \frac{v_{De}}{v_{The}} \right\rangle = \left\langle \frac{J}{nev_{The}} \right\rangle$. For deuterium, $\xi_{crit} \approx 0.2$.

2. Development of methods of discharge control and chamber preparation leading to first tokamak operation with Zeff $\approx$ 1.

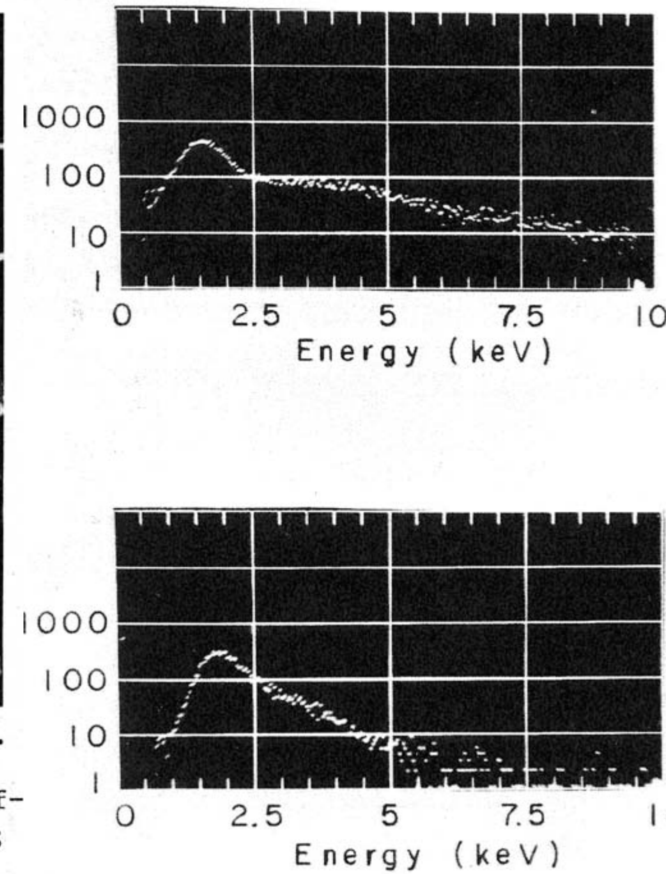
3. First RF heating experiments using waveguide coupling of lower hybrid waves.

The slide away regime featured nonthermal ion and electron tails, but few runaways



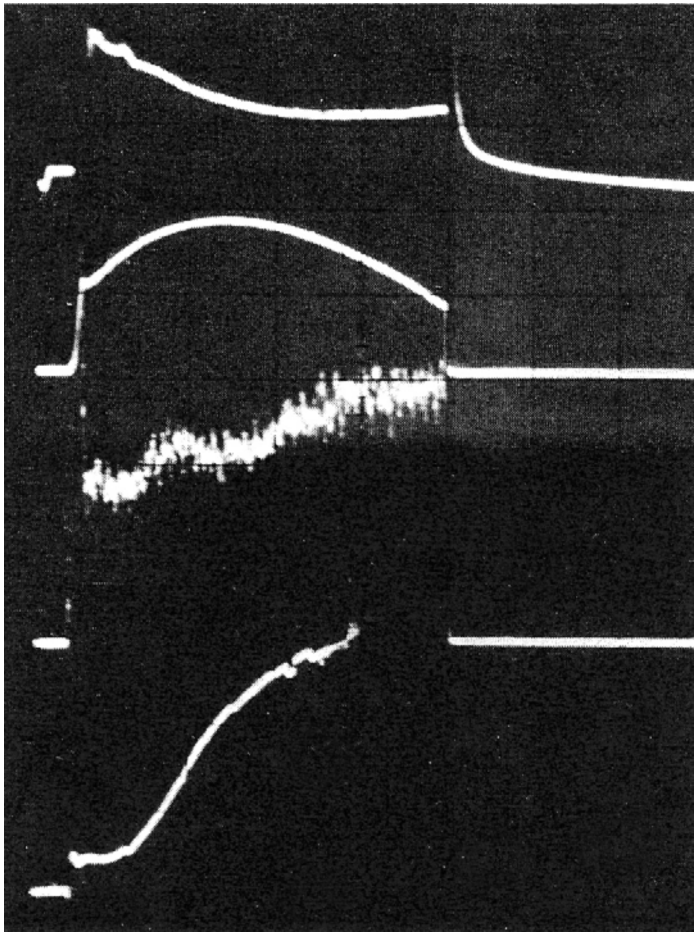
1. 2.

Fig. 4. Example of slide-away phenomena
a. loop voltage 1 V/div; b. electron density 1.2×10^{13} cm^{-3}/div; c. total rf-emission (arbitrary units); d. charge exchange neutrals: energy ∿ 2.5 keV; e. discharge current 65 kA/div; f. x-ray emission energy > 200 keV.
Sweep speed: 1. 50 msec/div; 2. 10 msec/div.



1. Soft x-ray spectra obtained in slide-away (top) and Coulomb (bottom) regime.

In the "Alcator confinement regime" the energy confinement time increased linearly with density



From top to bottom: Loop voltage, 2 V/div; Current, 65 kA/div; OVI emission, λ = 1032Å, 6.8×10^{15} photons/sec/cm^2·sterad/div; Density 4.6×10^{13} cm^{-3}/div.

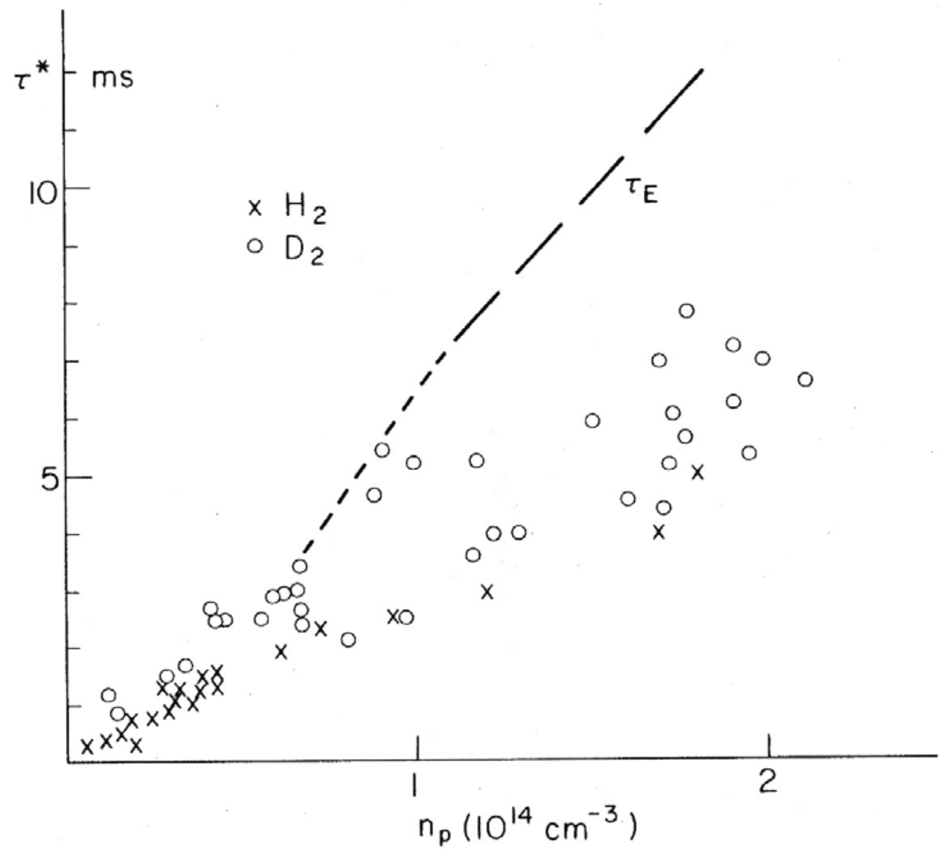


Fig. 9. Energy replacement time vs density.

Optimization of high density plasmas led to world record values of $n_0\tau_E$

$n_0\tau_E$ = 1X 10^{19} s·m^{-3} reached by Thanksgiving 1975*

$n_0\tau_E$ = 3 X 10^{19} s·m^{-3} was ultimately achieved in 1978.

In spite of huge advances in turbulent transport theory and simulation, the physics of "Alcator transport" is still not understood today!

* In a meeting in July, 1975 at "DOE", Bob Hirsch asked me what would be the best nτ and when would it be achieved. I guessed 10^{13} by Christmas. He said: "Make it by Thanksgiving and there would be a new machine at MIT."

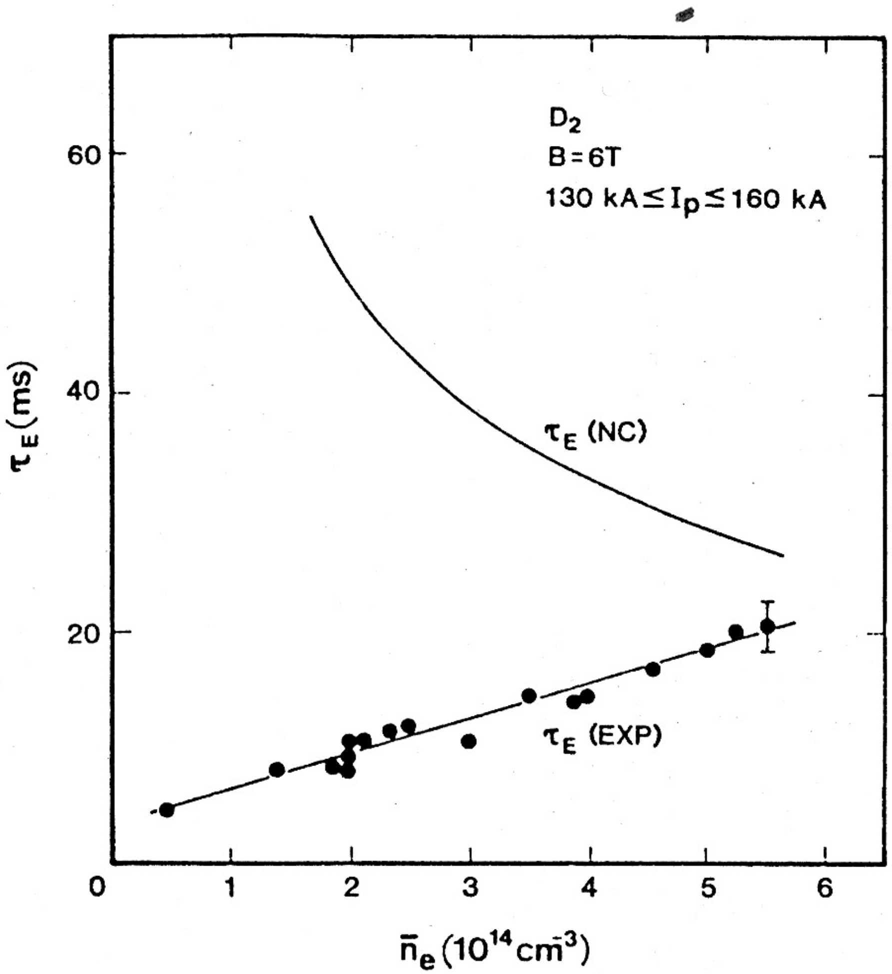
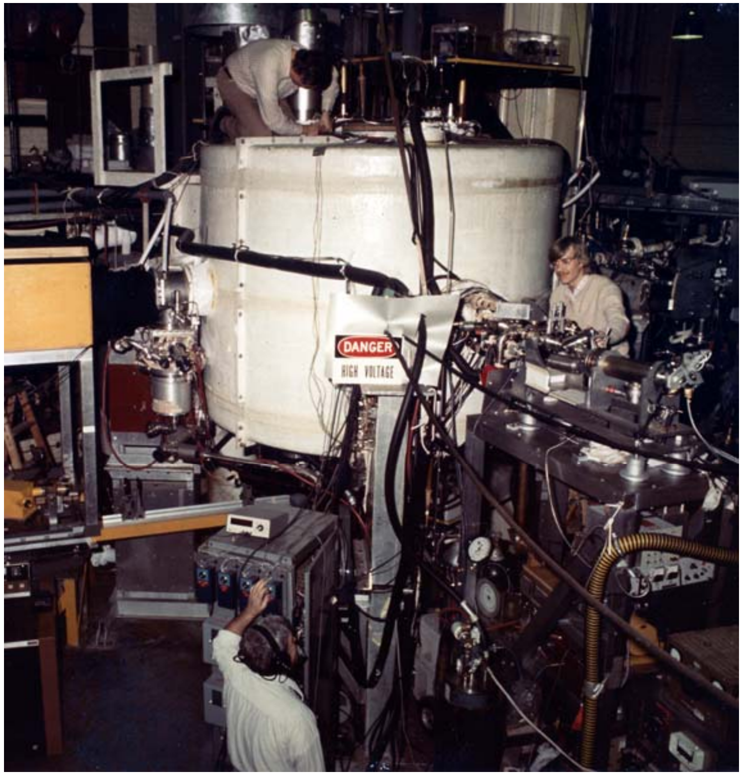
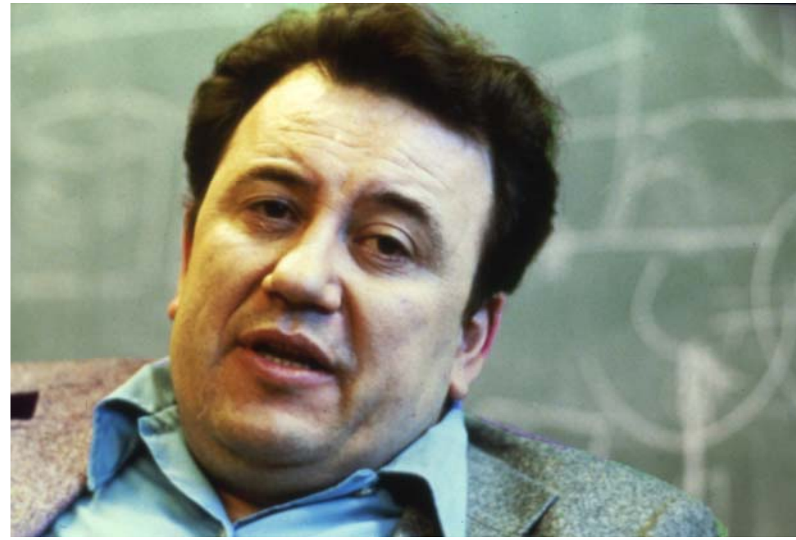
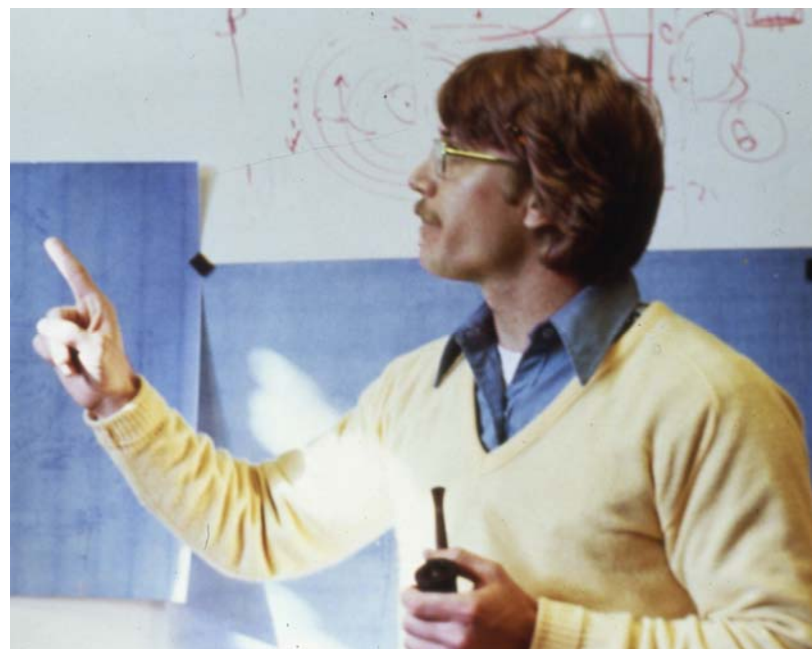


FIG.1. Energy confinement time versus line-averaged density for Alcator A. Neoclassical prediction decreases with $\bar{n}_e$, contrary to experimental data.


DANGER
HIGH VOLTAGE





Meanwhile, a new machine was being designed and built

The rapid success of Alcator prompted the conceptualization of a new machine in 1975. Since it was presumed that $\tau_E \sim na^2$ (diffusive process) the emphasis was on enlarging the minor radius as well as increasing the plasma density through an increase of the toroidal field.

The machine was proposed and authorized in 1976 with first operation scheduled for the end of 1977. It was dedicated in April, 1978 and scientific operations began in September of that year.

It was to be powered by a 225 MW alternator donated to MIT by Consolidated Edison of New York. Initial operation at BT = 6-7.5 T and Ip = 450 kA was powered by the 30 MW DC machines in the Magnet Laboratory, where it was located.

The ConEd alternator arrived at MIT in the winter of 1978 (Remember that winter?) and was incorporated into the “Alcator C” system in late summer, 1979.

What happened to Alcator B?

The initial design for an upgrade to Alcator assumed that the new machine would have to be powered by the Magnet Lab's DC machines.

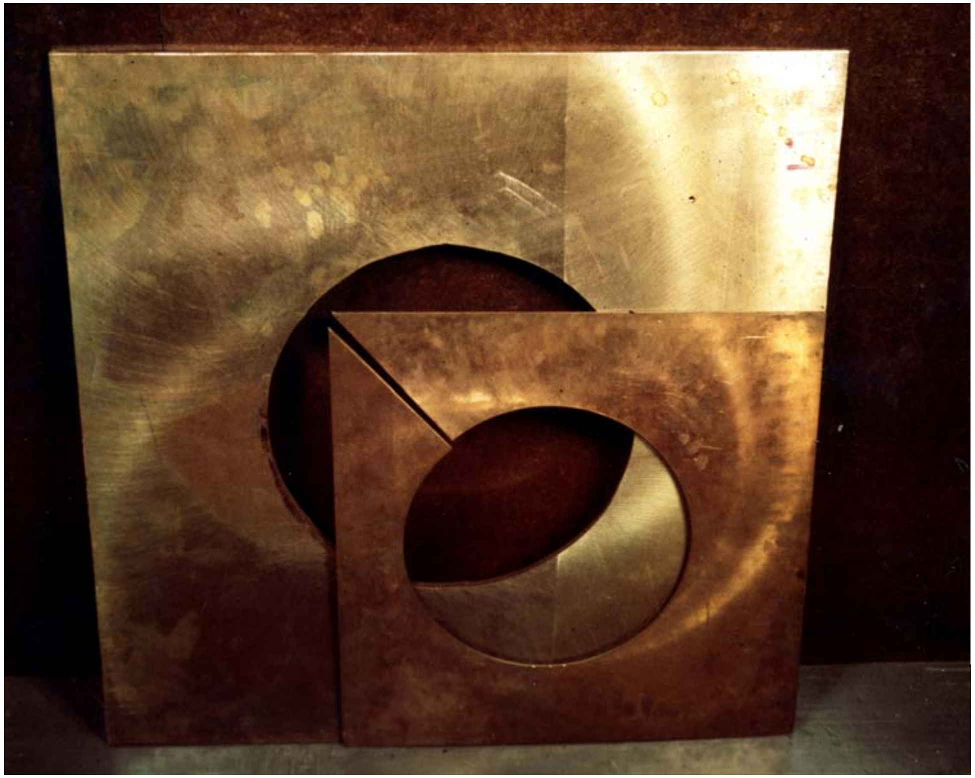
Alcator B, as it was called, would be somewhat larger and perhaps higher field, but not as substantial an upgrade as was wanted. That would require much more power and energy than was available from the Magnet Lab's generators. The problem in upgrading the power supply was cost.

I was at a meeting at Culham in 1976 and received a call from "DOE". Ed Kintner, who had taken over from Bob Hirsch, felt that "there must be a way to build the machine that we want at the price that we can afford."

There was: a surplus alternator that could be moved to MIT was located. It was in a power station on the East River operated by Consolidated Edison. ConEd donated the machine to MIT, which enabled the design of Alcator C.

Relative to Alcator A, Alcator C had a larger minor radius, increased toroidal field and plasma current

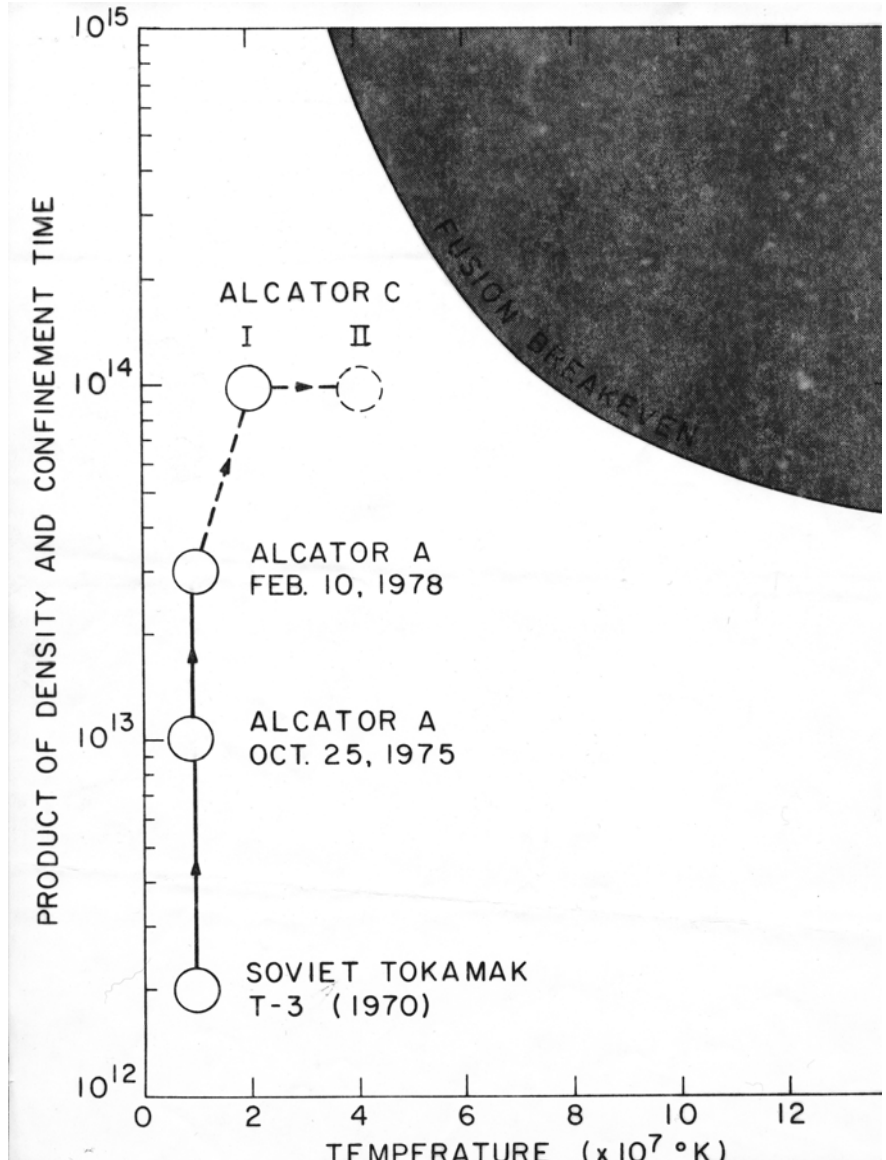
Quantity	Alcator A	Alcator C
a(m)	0.10	0.17
R(m)	0.54	0.64
B_T(T)	9	13
I_p(kA)	300	800



The main objective of Alcator C was to reach $n_0\tau_E = 1 \times 10^{20}\ \mathrm{s{\cdot}m^{-3}}$, above the minimum value required for breakeven and close to the minimum value required for ignition (at higher temperature).

In a 1st phase, $n_0\tau_E \sim 1 \times 10^{20}$ s·m^{-3} would be reached by Ohmic heating at T~ 2 keV; in a 2nd phase, T would be increased to ~ 4 keV.

This projection of Alcator C performance was shown at the dedication in April, 1978.



Oops, this time the physics didn't cooperate

Confinement time didn't scale as a^2 , nor was it simply proportional to n as in Alcator A.

To better understand the lack of a^2 scaling, the minor radius was reduced to 0.1 m and the major radius was scanned from 0.58 m to 0.71 m.

Steve Wolfe found that $\tau_E \sim R^2$! By comparing Alcator A and other machines a new confinement scaling relation was obtained:

$$\tau_E = 1.9 \times 10^{-21}\, nR^2 a$$

This was called "NeoAlcator Scaling"

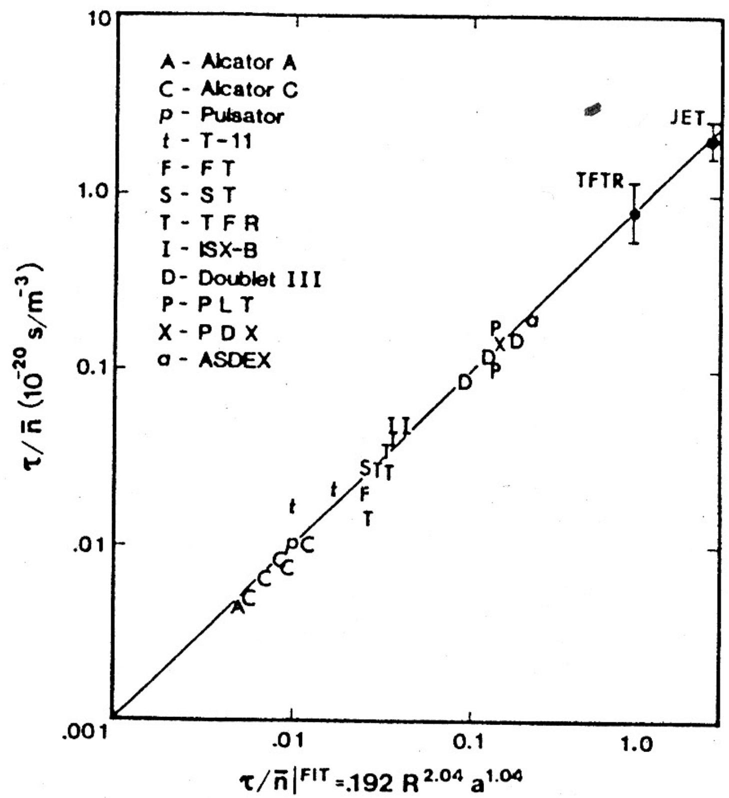
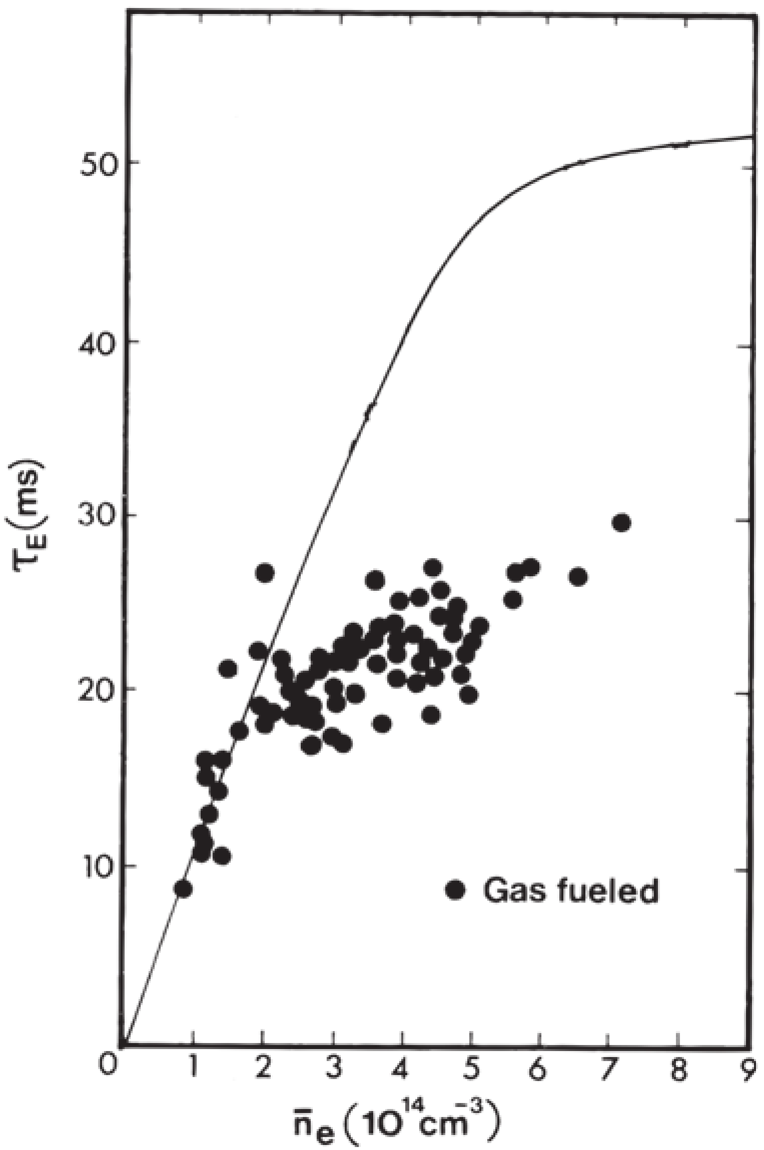


FIG.6. Confinement data from a number of ohmically heated tokamaks plotted against neo-Alcator regression parameter. Fit was done for devices in legend at upper left. Points from TFTR and JET agree well with extrapolated line.

The other problem was the “saturation with density”



Neoclassical Alcator scaling limited by neoclassical theory didn’t resolve the observed saturation with density.

DOE (then ERDA) became impatient with the MIT results – why didn’t they follow the scaling with n found in Alcator A and the Frascati tokamak?

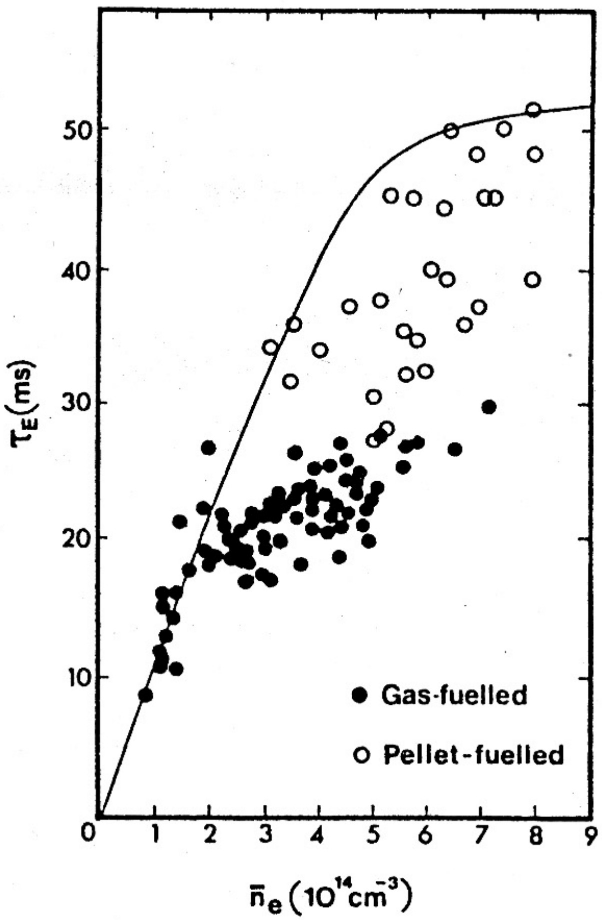
Bruno Coppi proposed that ITG turbulence was responsible. At high densities, the density profile becomes relatively flat causing $\eta = d \ln T / d \ln n$ to increase above unity and destabilize ITG modes.

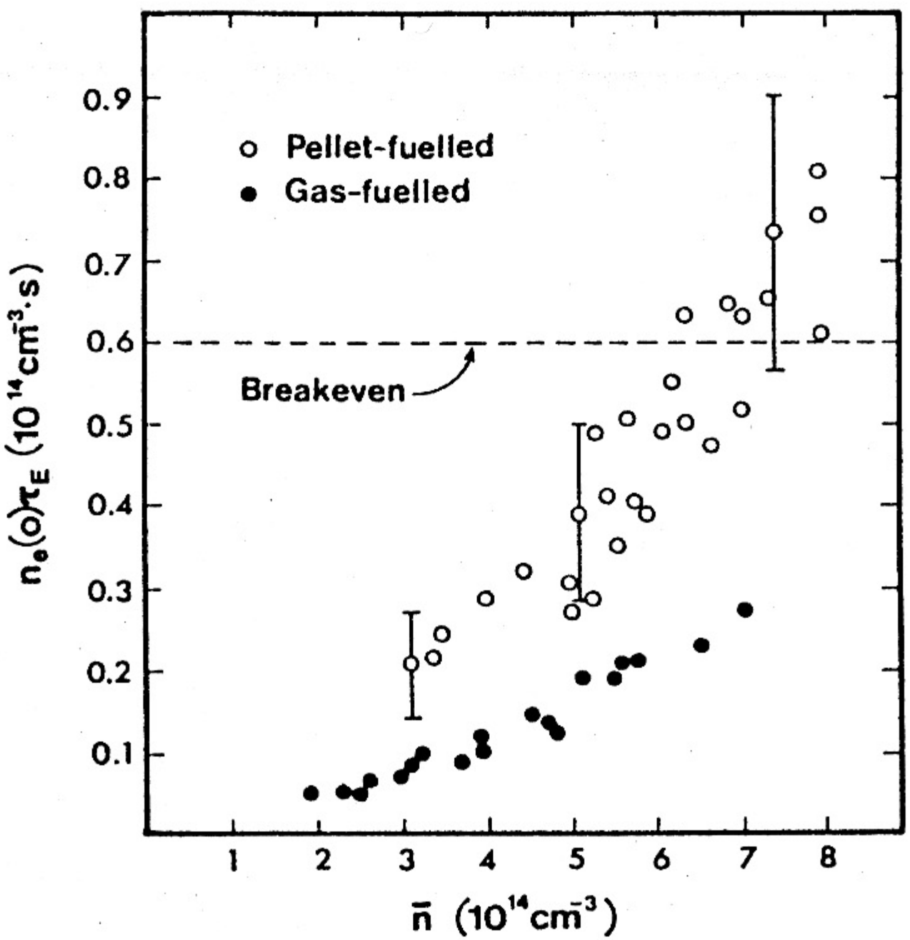
ITG turbulence consistent with subsequent CO_2 scattering measurements by C. Surko and R. Slusher.

Injecting pellets of frozen Deuterium peaked the density profile *and* raised the central density

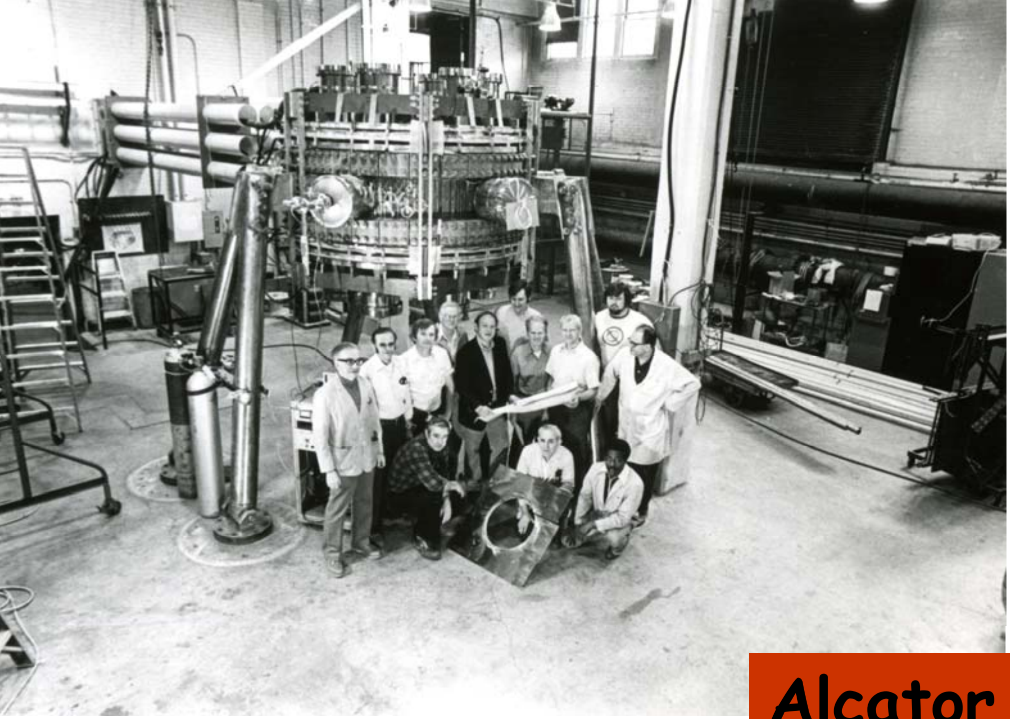
Pellet injection, a collaboration with ORNL led by Martin Greenwald, was a "win-win" solution, increasing τ_E by decreasing η, while increasing n_0.

Values of $n_0\tau_E$ approaching 1 x 10^{20} s·m^{-3} were achieved in 1983.





The Alcator C Control Room

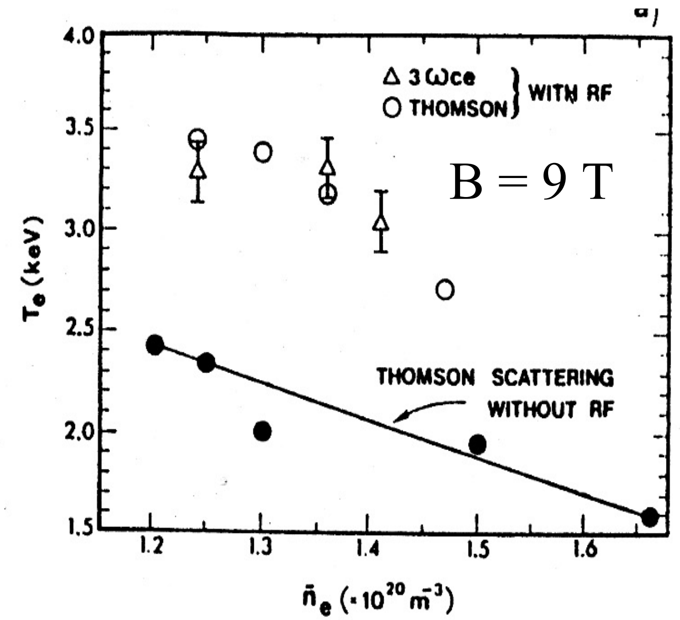


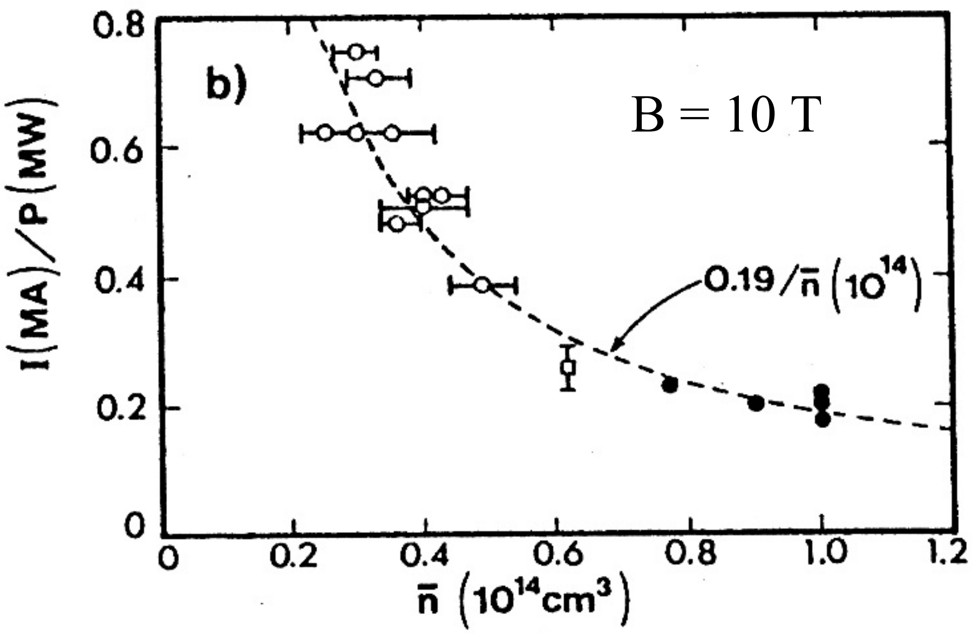
Alcator C Heros!

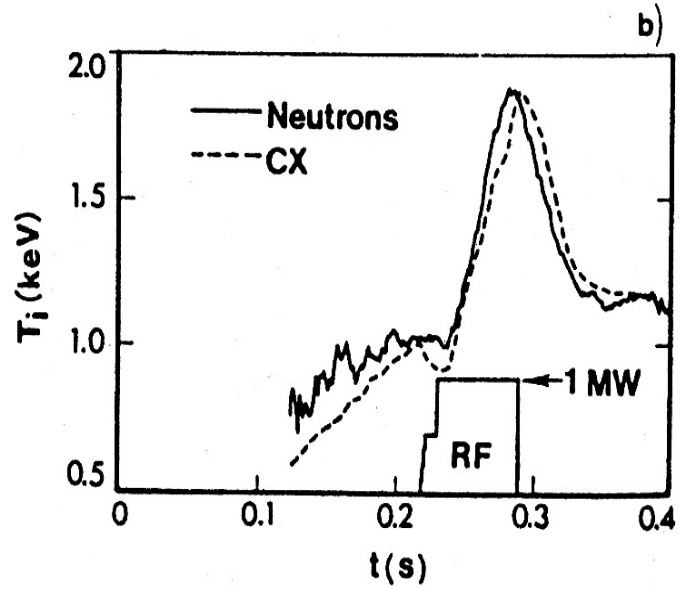
A proposal to raise the temperature in Alcator C by Lower Hybrid Heating was approved in 1978

The 6 M$ proposal for 4 MW of (source) power at 4.6 GHz applied by 4 waveguide arrays was led by Miklos Porkolab in collaboration with Raytheon.

It was a winner in the DOE sponsored "Gong Show". Electron and ion heating, and important current drive results were obtained in the period 1982-1985.







Based on the successes of the Alcator program, several new machines were conceptualized or designed (but not funded)

A torsatron design was developed by Larry Lidsky and Peter Polizer during 1977-1978 as an alternative to the tokamak

A design activity was carried out from 1978-1980 on Alcator D, a larger version of Alcator C which could accommodate more heating and possibly D-T.

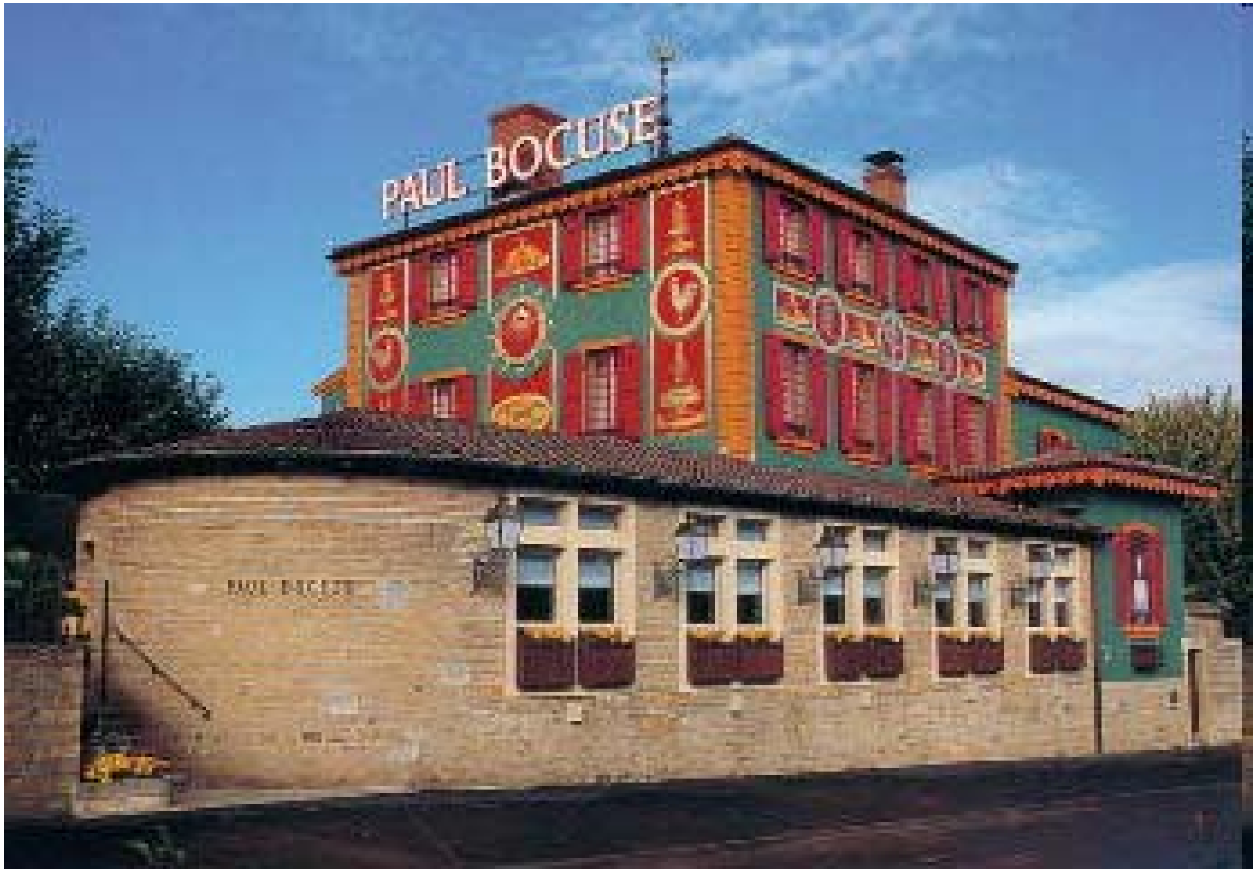
An intermediate scale device known as Alcator A-Mod, which would be a tokamak-stellarator hybrid, was conceptualized during 1979-1981

A study of an all superconducting steady-state device, Alcator DCT, was initiated in 1982. A US-France workshop was held in Cadarache in mid 1983 to compare DCT with Tore Supra.

A formal proposal was submitted to the DOE in late 1983.

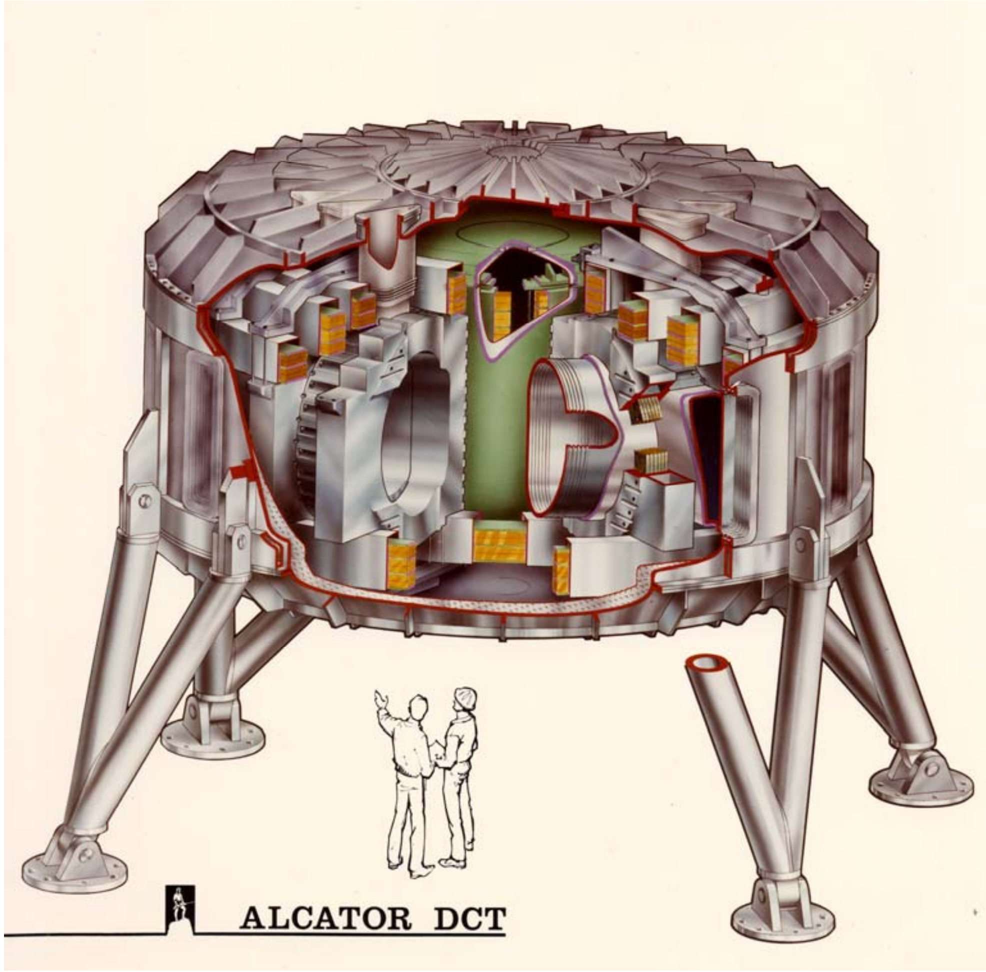
It was tough duty getting to Cadarache, but we managed to find an inn (Auberge des Templiers) in the Val de Loire

We couldn't find a McDonalds, so we had to eat at a greasy spoon



Alcator DCT was an advanced design for its time!

Major radius	2.0 m
Minor radius	0.4 m
Elongation	1.4 at 1.0 MA
Triangularity	0.2
Toroidal field	7 T
Current	1.4 MA at q = 2, κ = 1
Heating and	5 MW ICRH
Current Drive	4 MW LHCD
Edge Control	External coil divertor
Density	0.5-2.5 x 10^{20} m^{-3}
Temperature (peak)	9 keV

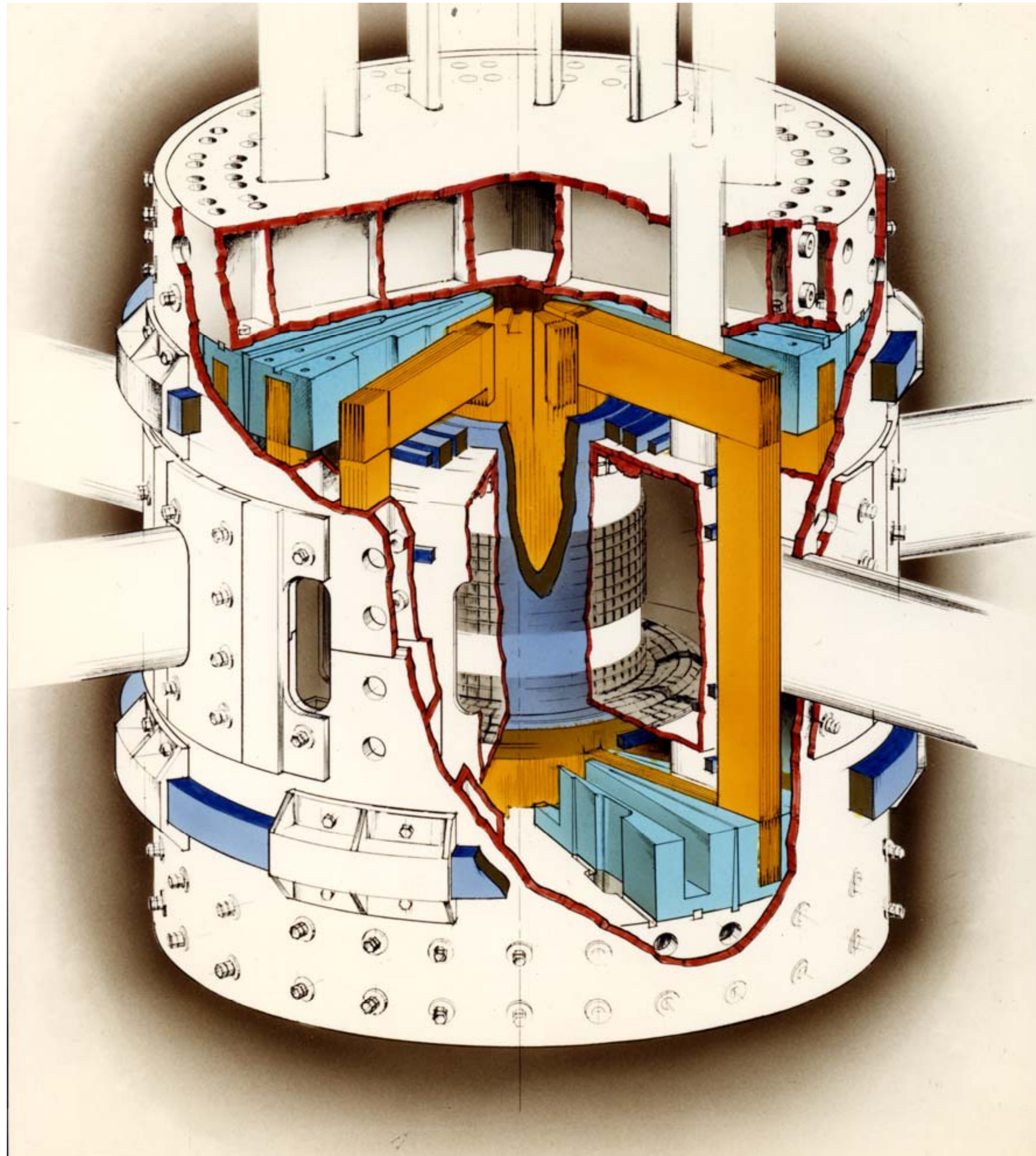


Finally, a proposal was funded!

Design work on a copper magnet version of Alcator DCT, called Alcator C-Mod began in 1984. A proposal was submitted to DOE in late 1985.

C-Mod construction was authorized in 1986.

Operation of C-Mod began in late 1991 and continues today.



Evolution of the Plasma Fusion Center

The Plasma Fusion Center was spun off from the FBNML in September 1976. Albert G. Hill was the acting director.

Ron Davidson became the first full time director in August, 1978. He served for 10 years, stepping down in 1988.

The National Biscuit Company (Nabisco) announced that it was donating its warehouse building on 184-190 Albany Street to MIT. It was conveyed to MIT in April, 1980. MIT designated it for use by the PFC.

Alcator "A" and "C" continued operation in the Magnet Laboratory until 1979 and 1987, respectively.