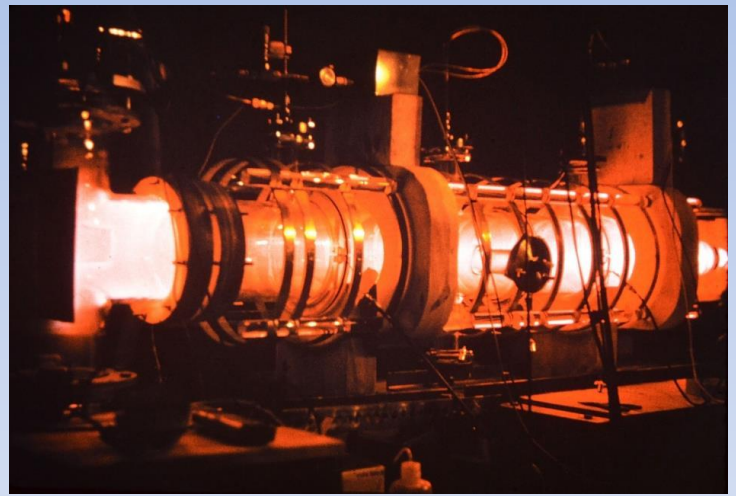
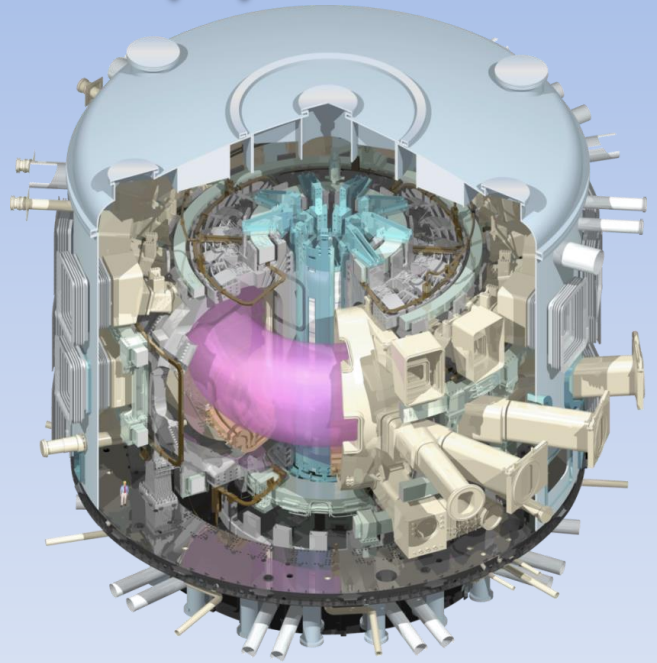
On the way to ITER via TFR, JET etc.

A inside view from a rank and file physicist



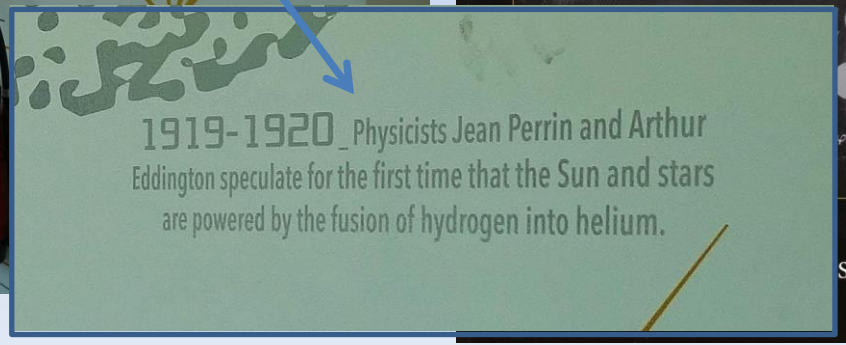
Plasma gun, Madison Wisconsin 1963

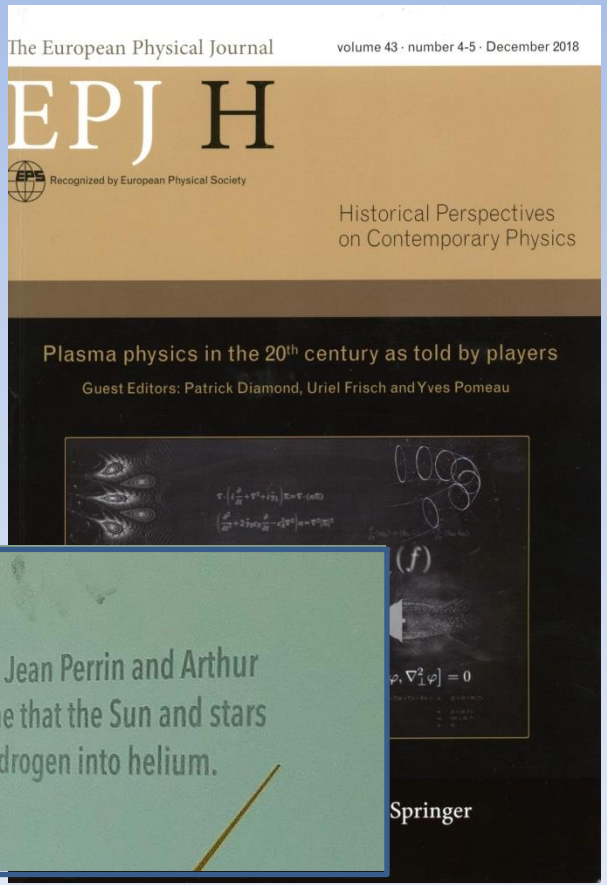


2019

Jean Jacquinot, Theory Festival 8 July 2019

Happy 100 year anniversary !

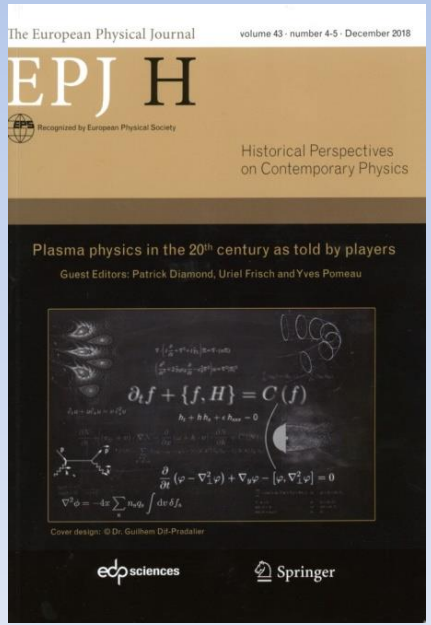




Anything to add to the *EPJ H* historical perspectives?

- **Personal memories** initiating from a small CEA French lab that produced 2 JET directors, 3 ITER directors, a host of known scientists and a new fusion world centre in Cadarache

- Starting point: the 1958 *Atom for Peace* conference in Geneva
  - CEA starts building a group on controlled fusion and signs an association contract with Euratom
  - CEA starts research on many fronts
    - **Many confinement schemes** explored: typically 1 or 2 PHD per scheme. Theory and experiments (mirrors, toroidal pinches, toroidal device with internal core etc.). Not much cohesion between the schemes;
    - CEA professional posts are all called **'ingénieurs'** embedding both PHD physicists and high level engineers ➔ well adapted to constructing fusion machines requiring integration of many concepts
    - Some success (e. g. Mercier criterion)



Some familiar faces from the French school

ITER directors, EDA phase

Right: P-H Rebut 1991 – 1994

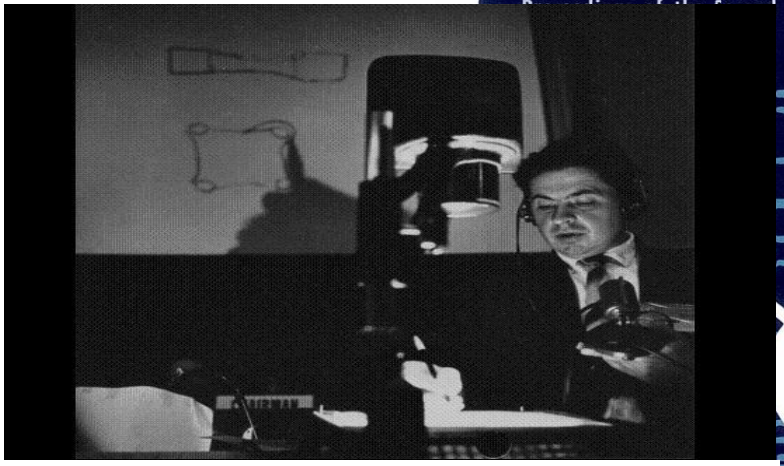
Left: R. Aymar 1994 - 2001

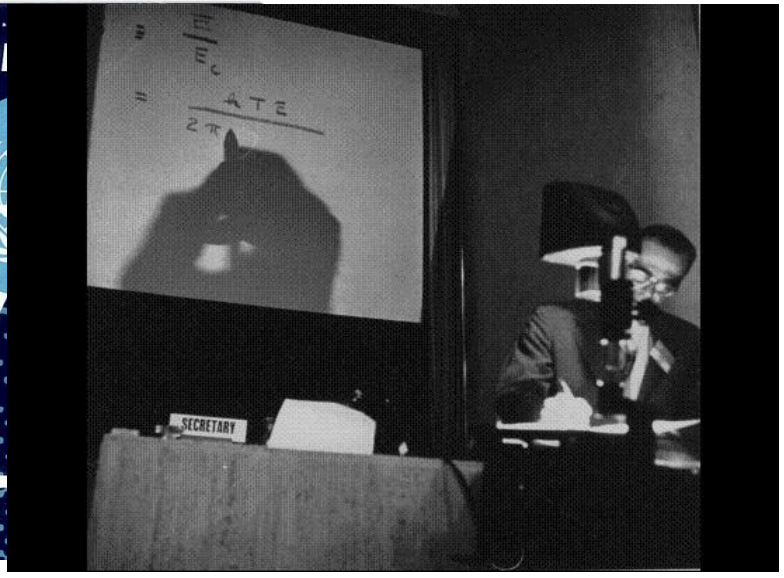
Bernard Bigot, ITER DG since 6 March 2015

Nature, June 2015

A new World centre for fusion

September 1958 “Atoms for Peace” (IAEA, Geneva)



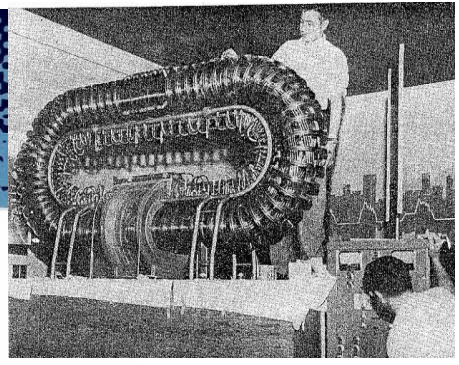


Kadomtsev et al: plasma stability

Spitzer: describes the Stellarator

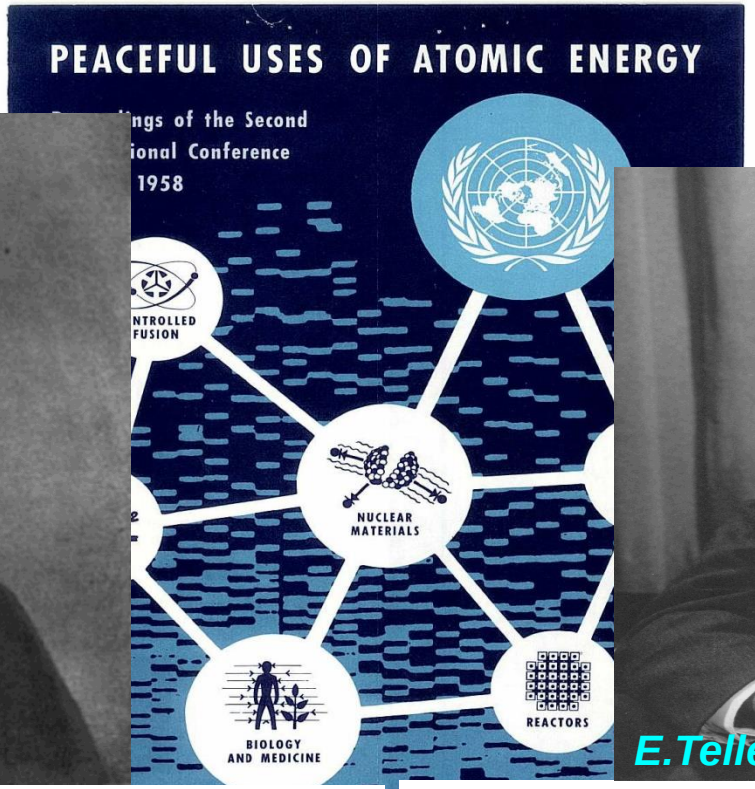
111 papers : Aymar, Braguinsky, Bierman, Dreicer, Drummond, Kerst, Lehnert, Myamoto, Rosembluth, Shafranov, Thoneman etc

Just to name a few…



September 1958 “Atoms for Peace” (IAEA, Geneva)

L.A.Artsimovich

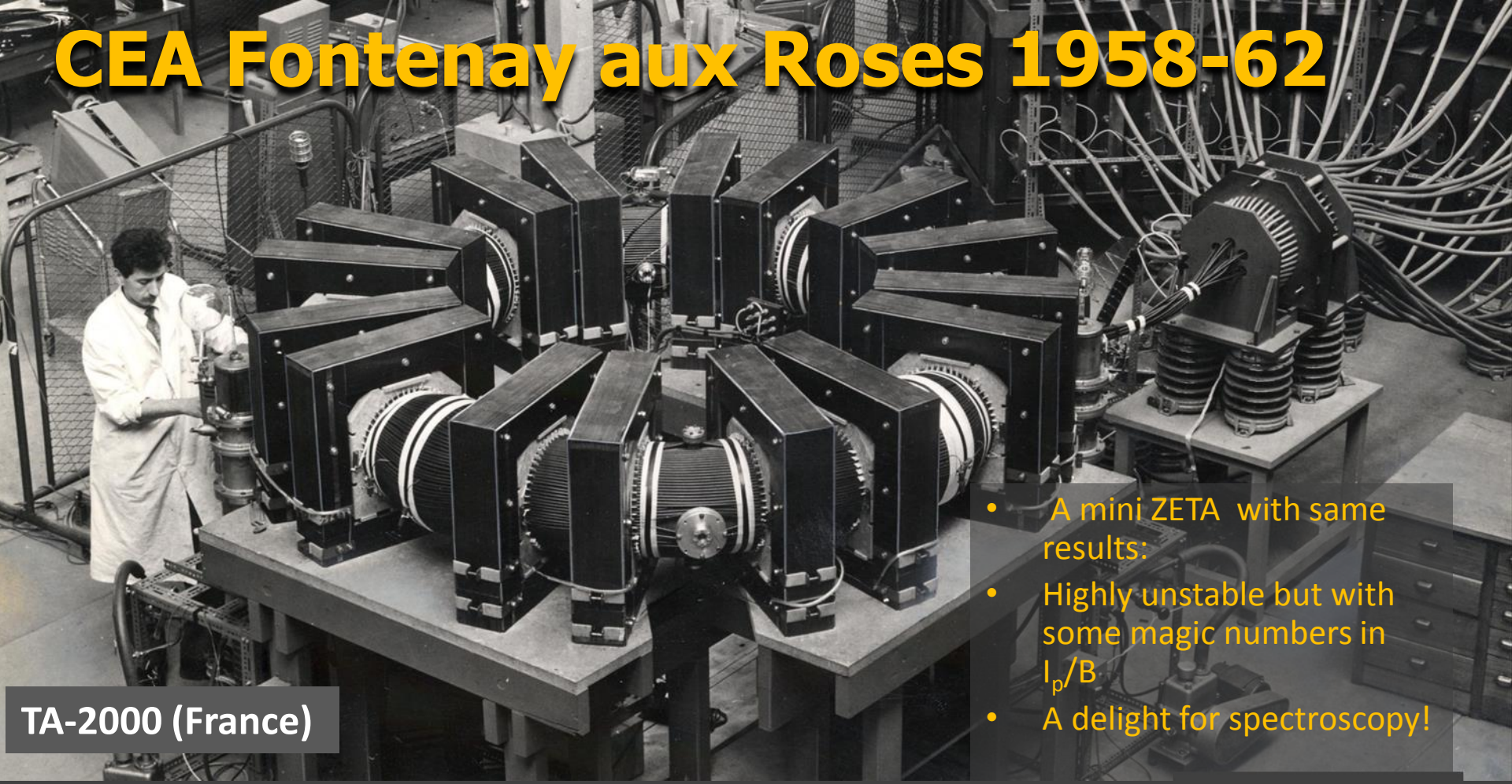


E.Teller

Plasma physics is very difficult. Worldwide collaboration is needed for progress

Fusion technology is very complex. It is almost impossible to build a fusion reactor in this century

CEA Fontenay aux Roses 1958-62



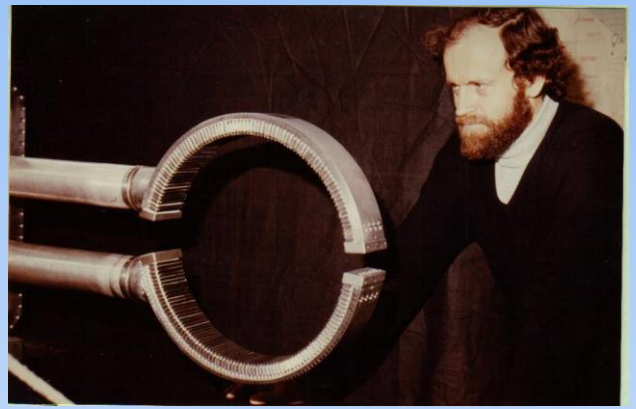
TA-2000 (France)

- A mini ZETA with same results:
- Highly unstable but with some magic numbers in I_p/B
- A delight for spectroscopy!

Times of darkness: experiments struggling with macro and micro instabilities; major theory effort needed

A long way to ITER

- ‘63-’64: Post graduate University Madison Wisconsin
  - Don Kerst; octopole; plasma gun
- ‘65 – ’81: Fusion Lab Fontenay aux Roses
  - Mirrors (diagnostics) then TFR tokamak (ICRH heating, minority schemes)
- ‘81 – ’99: JET
  - ICRH and LH heating & CD
  - Head of operation department (DT phase) then JET director
- ‘00 – ’04: Head Tore-Supra lab (now IRFM)
  - Long pulses and ITER-in-Cadarache proposal and negotiations
- ‘05 – present: retired
  - Advisor (Education, reviews, ITER action plan)



Circa 1975 ICRH antenna for TFR

1997 Just after the 16 MW shot

Physics cultures

Francis Bacon (1561-1626)
Priority to observations
Anglo-saxon?

René Descartes (1596 – 1650)
Rationalize first
Latin?

Still discernable?

Washed out by collaboration at world level?

Computer modelling invades all. Unfortunate?

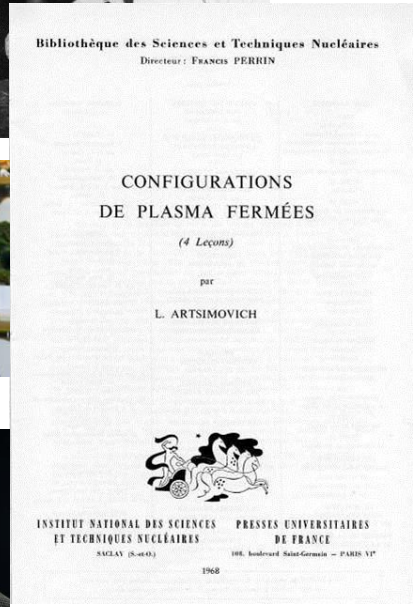
Memories of top events

By event I mean any major piece of work or event that had a deep impact, positive or negative, on the research of the group to which I belonged at the time. Again only from a personal perspective.

1 FEC 1968: the Tokamak tsunami and the French "May revolution"

- TM3/T3 results in Novosibirsk: huge gap with the results elsewhere (τ_E ~ 10 ms; ~ 50 τ_{Bohm}; Te ~ 1 keV)
- Artsimovich (and his colleagues) completely open and keen to collaborate ➔ still strong via IAEA, IEA etc.
  - Series of lecture in Saclay (I have been his occasional chauffeur!)
  - Independent measure of T_e by J. Peacock et al
- The May '68 Paris riots had a deep effect on the Fontenay lab

René Pellat



An example of turbulence leading to auto-organisation!

- Bottom up decision to concentrate on a single device

  ➔ TFR (after some debate) constructed and becoming for a couple of years the most powerful Tokamak. Rebut shines!

Paul-Henri Rebut

Robert Aymar

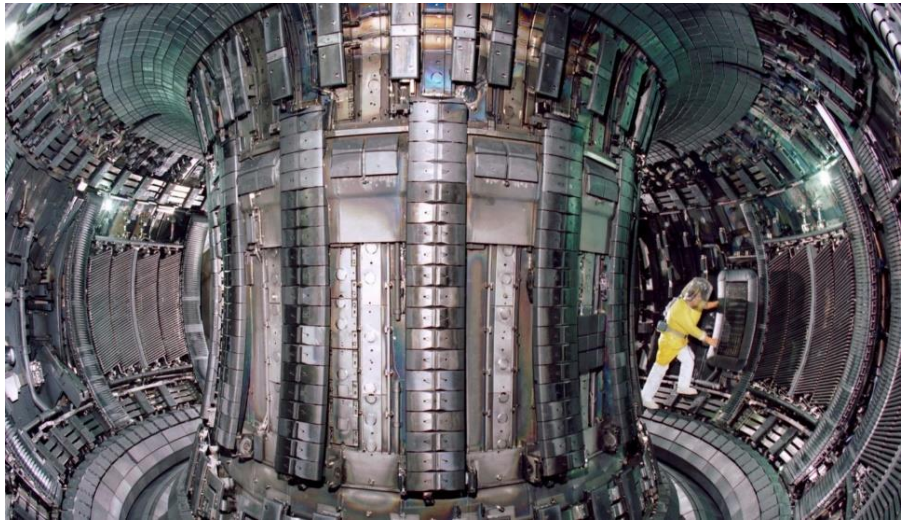
TFR in the seventies

TFR (France)

#2 Wave particle interactions

- J. Malmberg and C. Wharton, (1964) demonstration of Landau damping
- Stix's book; crystal clear
- Rip Perkin's wonderful approximations
- 1977 (re)discover minority heating (H/D) and demonstration at high power on **TFR** then on **JET**
- Fight impurity generation by sheath effects and coupling to co-axial modes

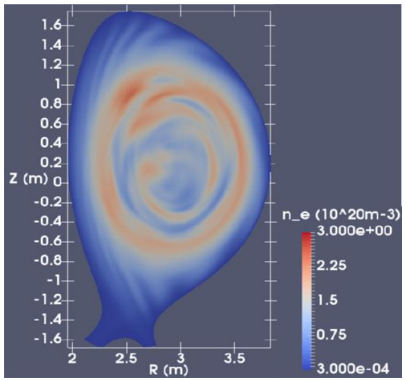
➔ Effective (and highly satisfying) synergy between theory and experiments



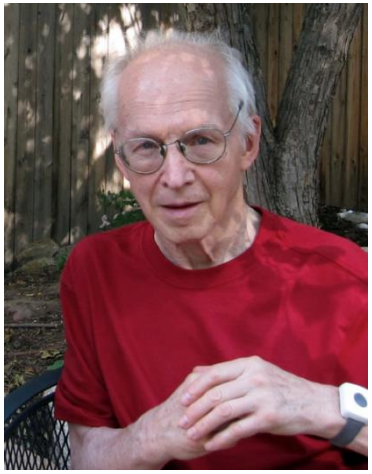
Inspecting antennas inside JET

#3 San Diego ITER Physics integration unit

- Physics Integration Unit* of the ITER EDA team in San Diego headed by Rip Perkins with Marshall Rosenbluth as a central figure
  - Led to the ITER physics basis in 1999
  - Inspired all
  - Revealed physics strength and pitfalls of ITER
    - Runaways generated by disruptions in large machine ➔ requires to dissipate both thermal and magnetic energy
    - Effect of zonal flows on transport (see next slides)



Shattered pellet injection


Rip Perkins

*** ITER Joint Central Team and Physics Integration Unit:** R. Aymar, Y. Shimomura, D. Boucher, A. Costley, N. Fujisawa, Y. Igitkhanov, G. Janeschitz, A. Kukushkin, V. Mukhovatov, F. Perkins, D. Post, S. Putvinski, M. Rosenbluth, J. Wesley

#4 Sink the Titanic syndromes

- ''**JET** will be the most expensive neon tube in the world''
  - B. Coppi circa 1976 (based on ITG instabilities) ➔ no nTτ values in JET objectives
- ''**ITER** will never ignite''
  - J. Glanz reporting in 'Science' on Dorland and Kotschenreuther 1996
    "first physics-based transport model for tokamaks"
  - The US quit ITER in 1997 ➔ but the 3 other partners continue with a smaller ITER

➔Value of peer reviewing and of multiple strong theory based groups
  ➔Complexity of physics based models integrating both core and edge physics
  ➔Predicting reactor performance:
    can we do better than the scaling based on similarity laws?

5 Titanic rescued! Thanks Marshall

VOLUME 80, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1998

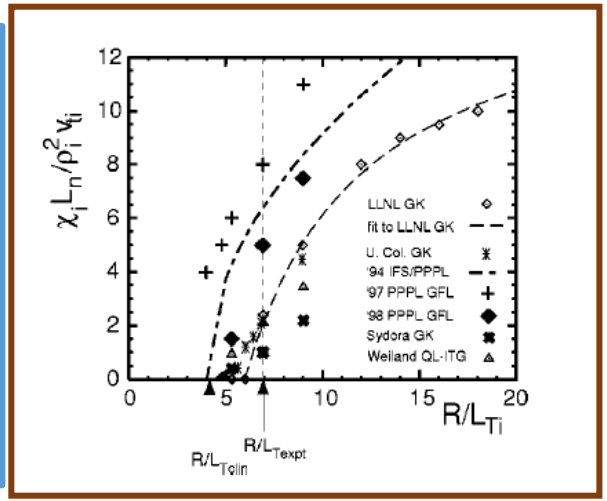
Poloidal Flow Driven by Ion-Temperature-Gradient Turbulence in Tokamaks

M. N. Rosenbluth* and F. L. Hinton
General Atomics, San Diego, California 92186-5608
(Received 27 August 1997)

We show that linear collisionless processes do not damp poloidal flows driven by ion-temperature-gradient (ITG) turbulence. Since these flows play an important role in saturating the level of the turbulence, this level, as well as the transport caused by ITG modes, may be overestimated by gyrofluid simulations, which employ linear collisionless rotation damping. [S0031-9007(97)05109-0]

PACS numbers: 52.55.Fa, 52.25.Fi, 52.35.Ra, 52.65.Tt

Beautiful transport regulating mechanism !



Comparison between GK and GFL transport codes
Dimits et al 2000

#5 Other surprises

- Transport is highly abnormal but neo-classical theory still applies for a number of phenomena
  - **Plasma resistivity; bootstrap current; current drive et.**
- Auto-organisation can work in your favour.
  - **H-mode, Internal barriers, zonal flows, sheared flows**
  - **A lot of room between collisional relaxation and present transport values.** More good surprises to come?
- Abnormal events are severe threats
  - **Disruptions, ELMs, fast particle instabilities etc.**

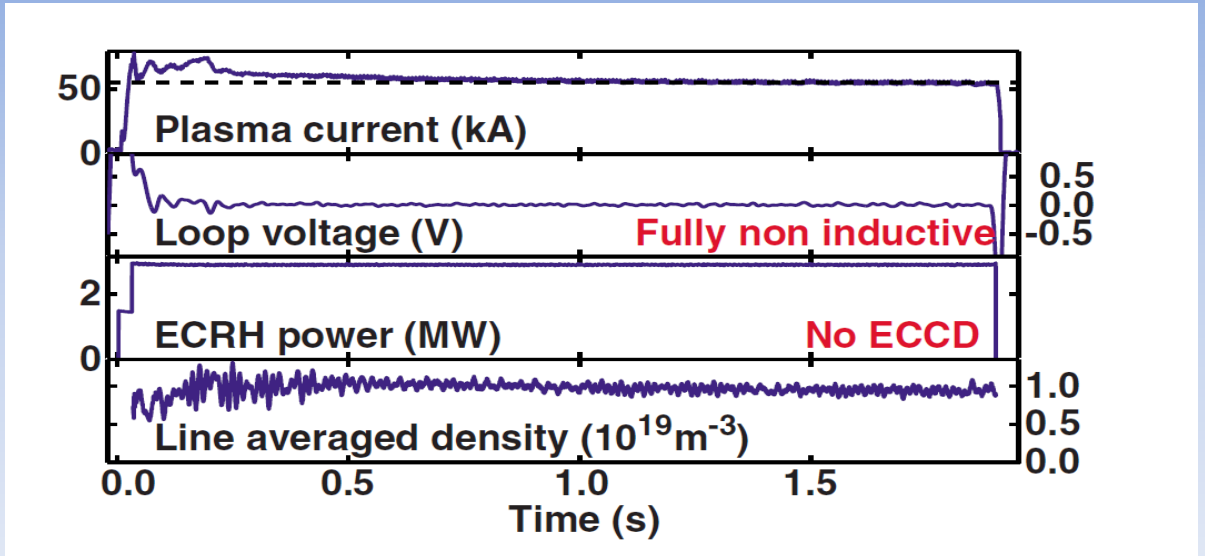
Steady State without external CD

- 100% bootstrap in TCV and JT60
  - Good confinement at high q_{95}
  - A strong e-ITB at ρ= 0.25
  - Demonstration of a stable self-consistent equilibrium state

S. Coda et al. FEC 2008

➔ The bootstrap current profile can be exactly and stably aligned with the high gradient region it engenders

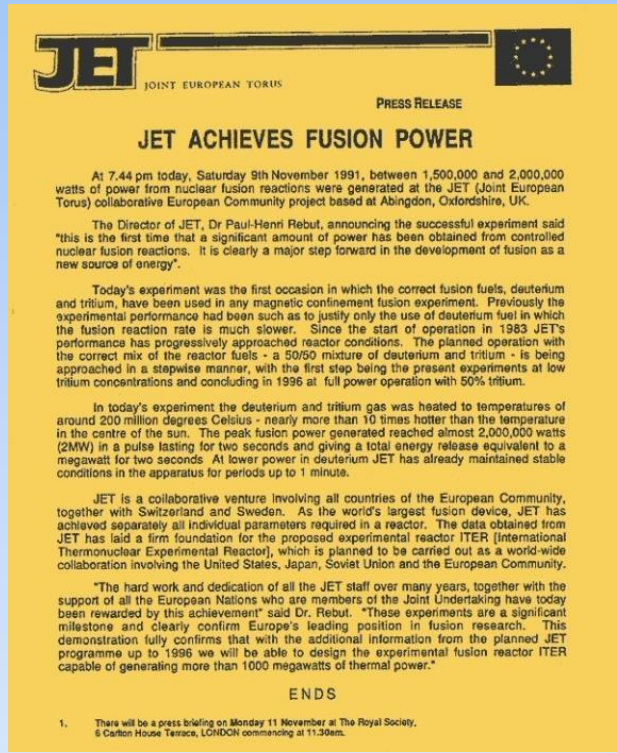
NB: in neoclassical theory no bootstrap on the magnetic axis



#6 Bold steps

- Often confronted with: “this step is far too big”
  - From T3 to TFR ➔ TFR confirmed and extended Russian results (10 ms to 30ms) then developed additional heating
  - From TFR to JET ➔ Scaling and D/T power demonstration
  - From JET to ITER ➔ Facing the nuclear constraints and …..???

➔ So far bold steps have delivered much of what we know today and I much admire the leaders and the teams with the guts for making these steps.



JET
JOINT EUROPEAN TORUS

PRESS RELEASE

JET ACHIEVES FUSION POWER

At 7.44 pm today, Saturday 9th November 1991, between 1,500,000 and 2,000,000 watts of power from nuclear fusion reactions were generated at the JET (Joint European Torus) collaborative European Community project based at Abingdon, Oxfordshire, UK.

The Director of JET, Dr Paul-Henri Rebut, announcing the successful experiment said "this is the first time that a significant amount of power has been obtained from controlled nuclear fusion reactions. It is clearly a major step forward in the development of fusion as a new source of energy".

Today's experiment was the first occasion in which the correct fusion fuels, deuterium and tritium, have been used in any magnetic confinement fusion experiment. Previously the experimental performance had been such as to justify only the use of deuterium fuel in which the fusion reaction rate is much slower. Since the start of operation in 1983 JET's performance has progressively approached reactor conditions. The planned operation with the correct mix of the reactor fuels - a 50/50 mixture of deuterium and tritium - is being approached in a stepwise manner, with the first step being the present experiments at low tritium concentrations and concluding in 1996 at full power operation with 50% tritium.

In today's experiment the deuterium and tritium gas was heated to temperatures of around 200 million degrees Celsius - nearly more than 10 times hotter than the temperature in the centre of the sun. The peak fusion power generated reached almost 2,000,000 watts (2MW) in a pulse lasting for two seconds and giving a total energy release equivalent to a megawatt for two seconds At lower power in deuterium JET has already maintained stable conditions in the apparatus for periods up to 1 minute.

JET is a collaborative venture involving all countries of the European Community, together with Switzerland and Sweden. As the world's largest fusion device, JET has achieved separately all individual parameters required in a reactor. The data obtained from JET has laid a firm foundation for the proposed experimental reactor ITER [International Thermonuclear Experimental Reactor], which is planned to be carried out as a world-wide collaboration involving the United States, Japan, Soviet Union and the European Community.

"The hard work and dedication of all the JET staff over many years, together with the support of all the European Nations who are members of the Joint Undertaking have today been rewarded by this achievement" said Dr. Rebut. "These experiments are a significant milestone and clearly confirm Europe's leading position in fusion research. This demonstration fully confirms that with the additional information from the planned JET programme up to 1996 we will be able to design the experimental fusion reactor ITER capable of generating more than 1000 megawatts of thermal power."

ENDS

1. There will be a press briefing on Monday 11 November at The Royal Society, 6 Carlton House Terrace, LONDON commencing at 11.30am.

Concluding remarks

- Huge progress were made on all fronts
  - Macroscopic stability well understood ➔ predictive theory is available
  - Micro-instabilities now understood in the linear and quasi-linear regimes
    - Largely predictive for wave heating (but spectral gap?)
  - Fully developed turbulence may still reserve good and bad surprises
    - Room for more favorable auto organized regimes?
- Internal and international **collaborations** played a major role
- 'Real' theory should remain a major tool (computer modelling and simulation having a supporting role)
  - Need more theory based predictive tools (e.g. H-mode thresholds, abnormal events etc.)

➔This was the basis of my actions in 2000 for the Cadarache theory group and for creating the festival.

➔**No regrets whatsoever and best wishes!**