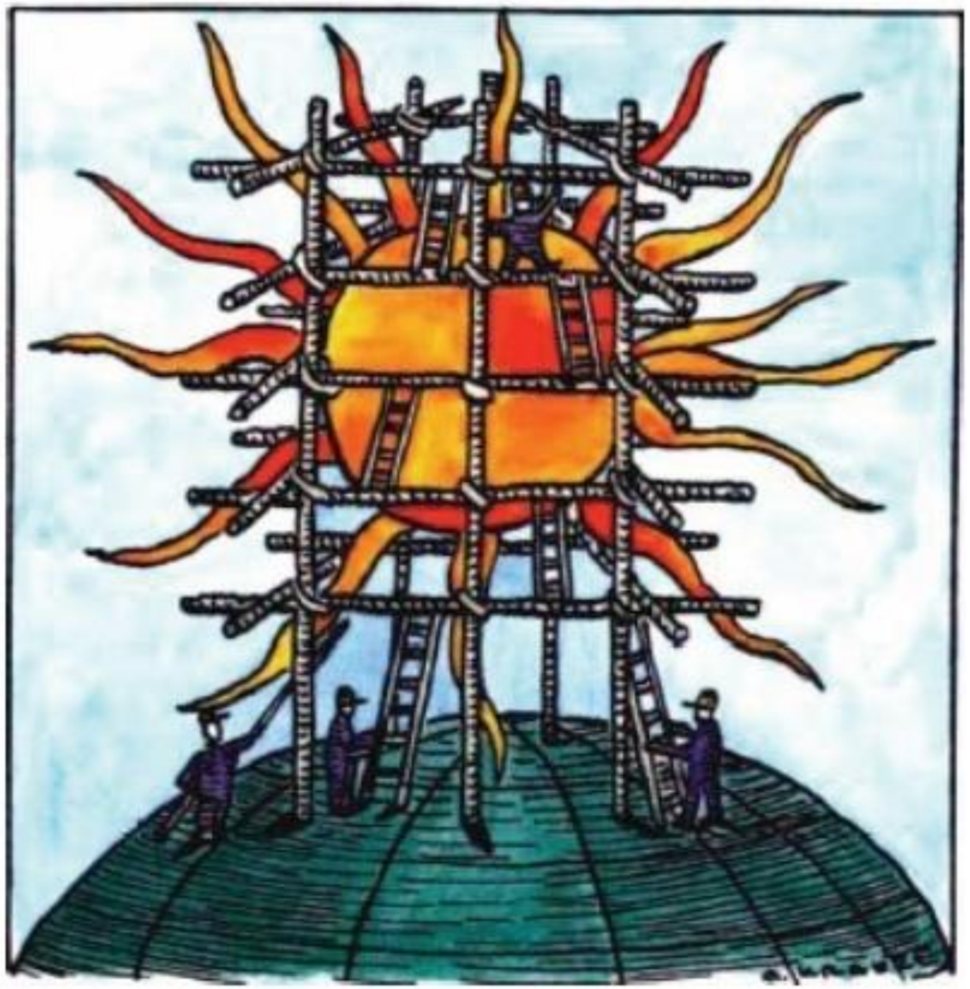
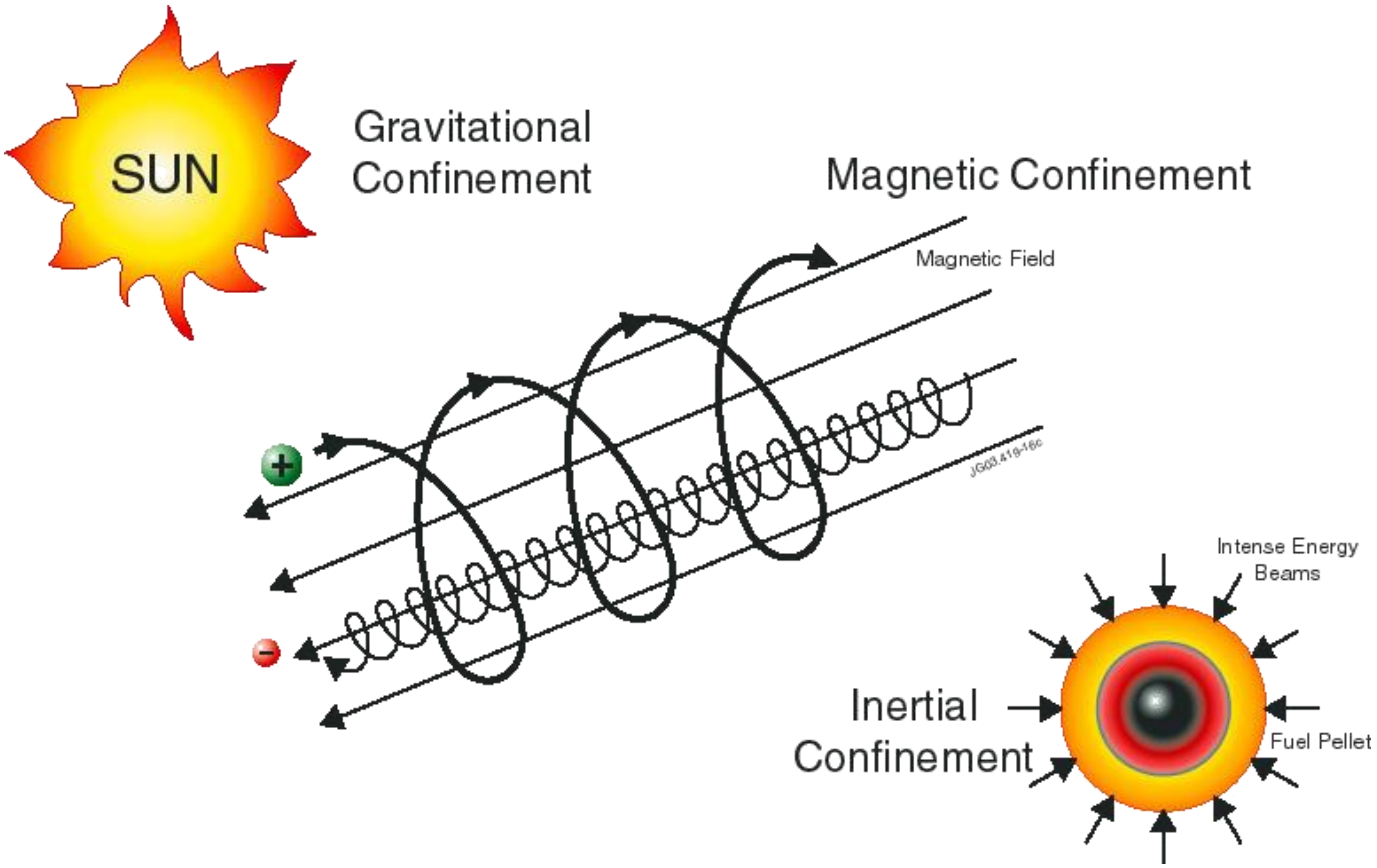
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

To build a sun on earth



To build a sun on earth



Magnetic Confinement

"To keep the ions from hitting the wall, some type of force is required that will act at a distance. A magnetic field seems to offer the only promise."

L. Spitzer, Jr.

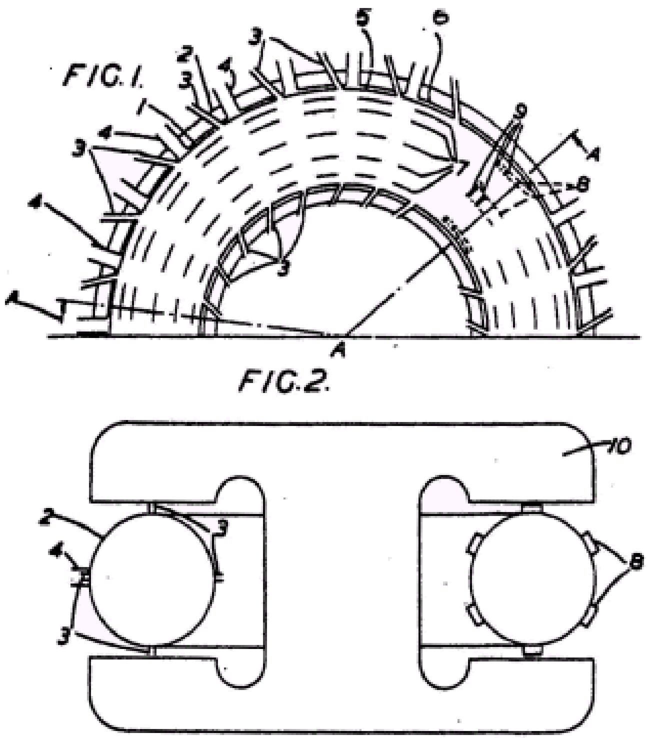
Inspecting the torus at John Jay Hopkins Laboratory's fusion research building are, from left to right:
Richard Courant, Hideki Yukawa, Marshall N. Rosenbluth, Marcus Oliphant, Niels Bohr, Edward C. Creutz, and Donald W. Kerst,
General Atomic, Division of General Dynamics Corporation
Courtesy of AIP's Emilio Segrè Visual Archives

http://pop.aip.org/article_archive_2009/09_16_09_selected_highly_cited_papers_from_50_years_of_plasma_physics

1946: Fusion Reactor Patent

- **Fusion Reactor Patent**

- G. P. Thomson and M. Blackman, of the University of London, filed a patent for a fusion reactor in 1946.
- Although the scale of this device was overly optimistic, the device already featured a vacuum chamber in a torus shape and current generation by radio-frequency waves, two important aspects found on today's tokamaks!



- Major radius R_0 = 1.3 m
- Minor radius a = 0.3 m
- Plasma current 0.5 MA, created by 3 GHz radiofrequency waves

G. P. Thompson and M. Blackman
1946 British Patent 817681

1946: Fusion Reactor Patent

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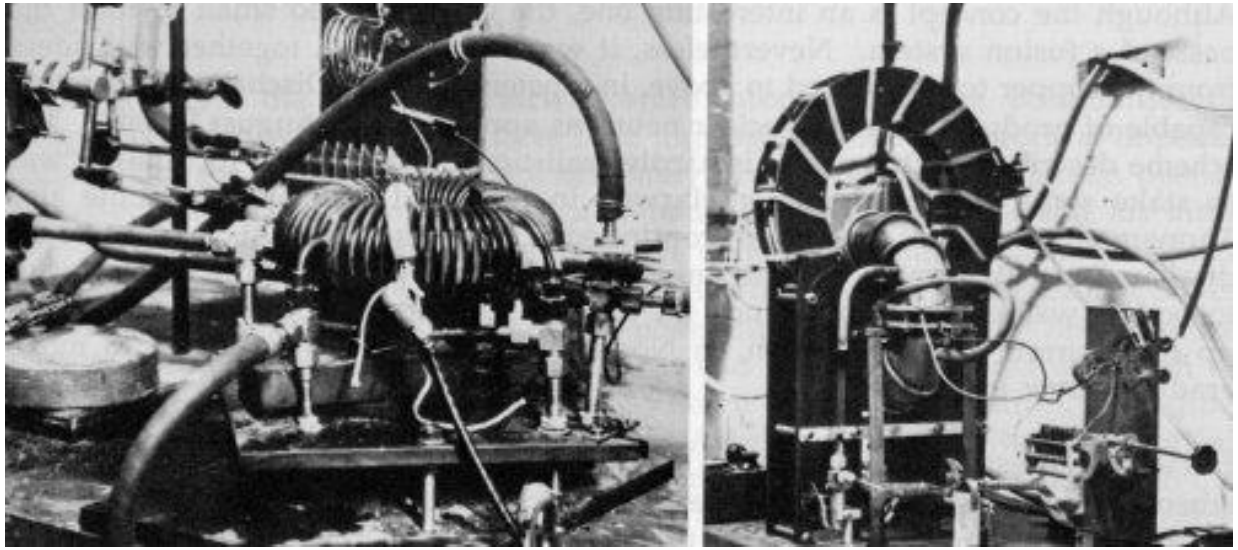


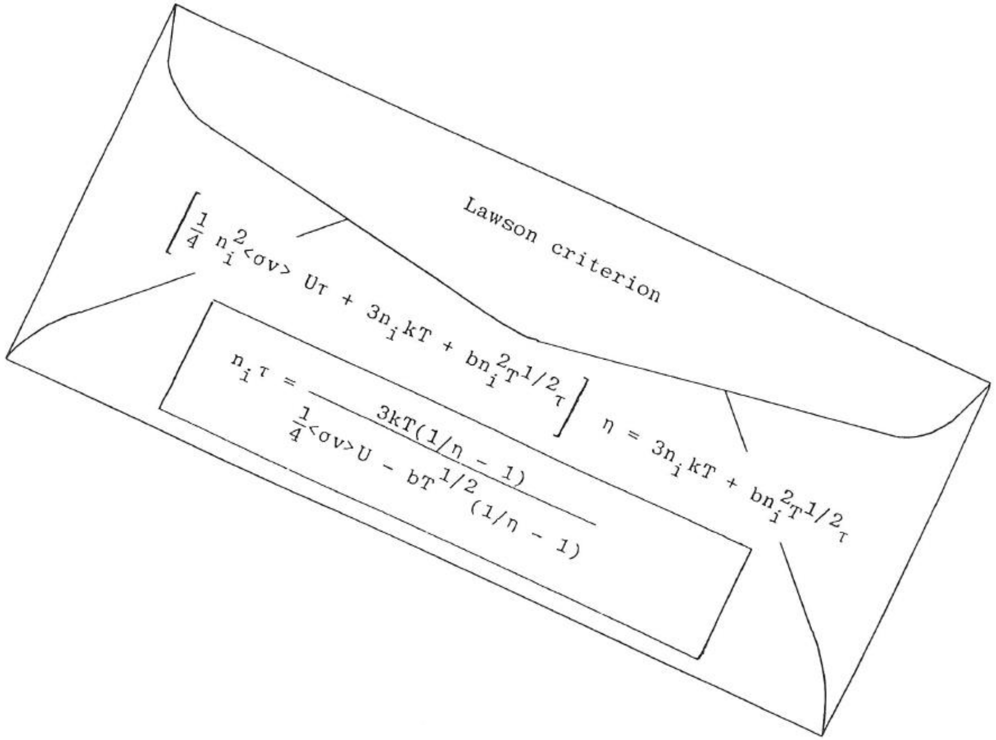
1946: the magnetic confinement devices tested by Thoneman (tori made of glass and metal), in the Clarendon laboratory (Oxford, United Kingdom)

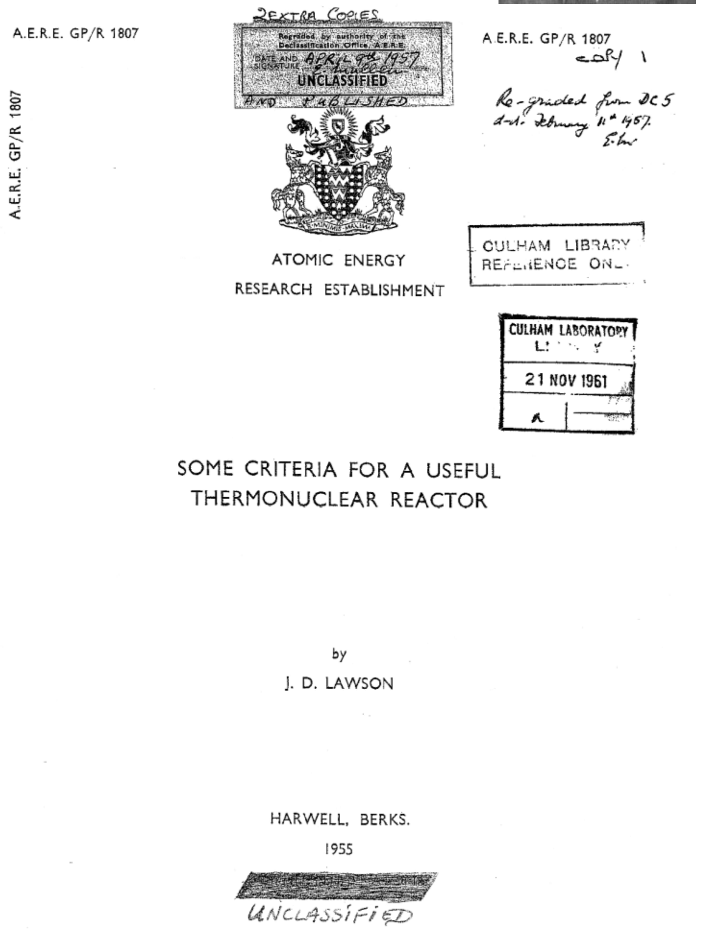
1955: Lawson Criterion

- **Lawson Criterion**

- Building a fusion reactor is a very challenging task.

- Simple criterion found by Lawson





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AND PUBLISHED

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ATOMIC ENERGY RESEARCH ESTABLISHMENT

SOME CRITERIA FOR A USEFUL THERMONUCLEAR REACTOR

by

J. D. LAWSON

HARWELL, BERKS.

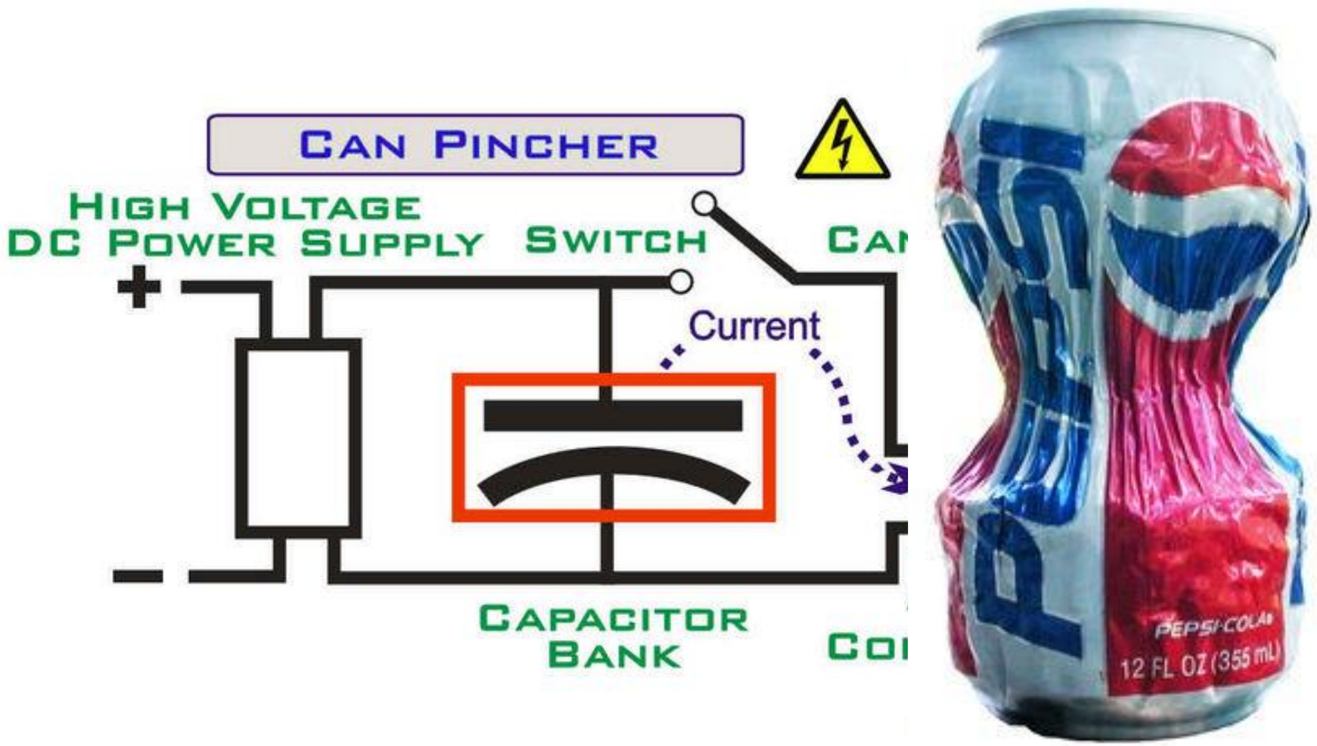
1955

[redacted]

UNCLASSIFIED

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Pinches**



A theta pinch capable of crushing an aluminium soft drink can

http://www.plasma-universe.com/Pinch

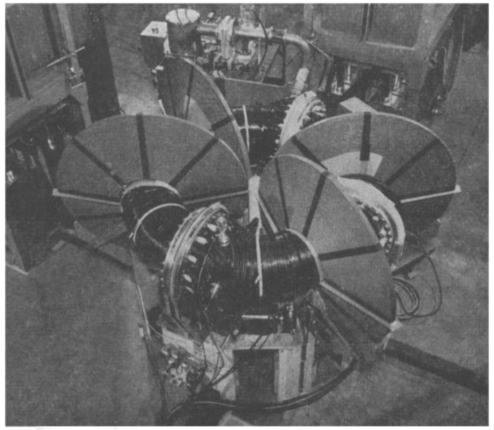
1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Toroidal Pinches, e.g.**

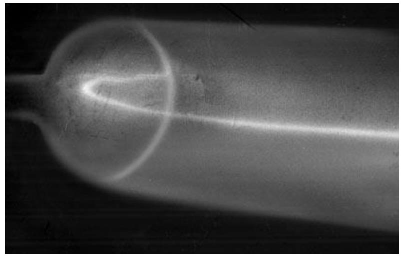
- Z-pinch: ZETA (Culham, UK), Perhapsatron S-3/S-4/S-5 (Los Alamos, USA), …
- Confinement properties and reactor prospects disappointing

"Zero Energy" refers to the aim of producing copious numbers of fusion reactions, but releasing no net energy.

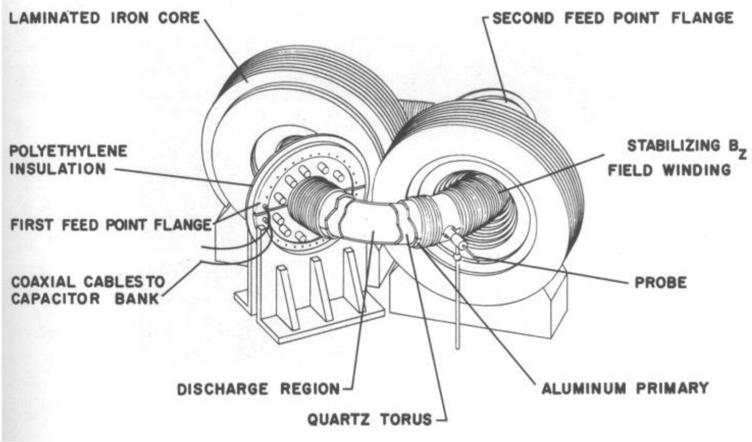
ZETA (Zero Energy Thermonuclear Assembly) (1954-58, UK)



Perhapsatron (1952-1961, USA)



Xenon pinched discharge

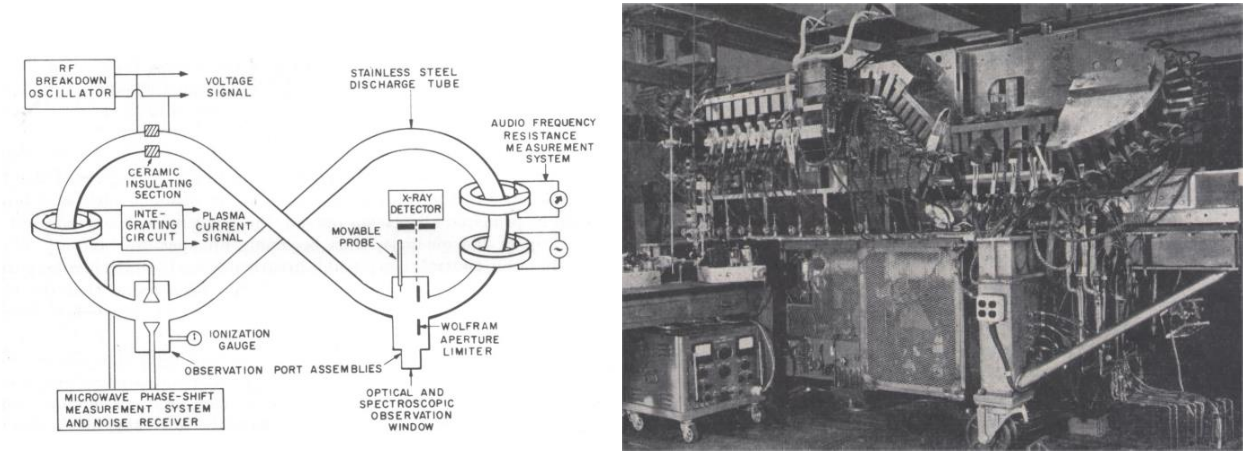


1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Stellarators, e.g.**

- C-Stellarator (Spitzer, Princeton, USA - later converted into the ST tokamak), Sirius (USSR), Initial Wendelsteins (IPP-Garching), ….
- Initial results very disappointing

Mattherhorn project
(1951, USA)

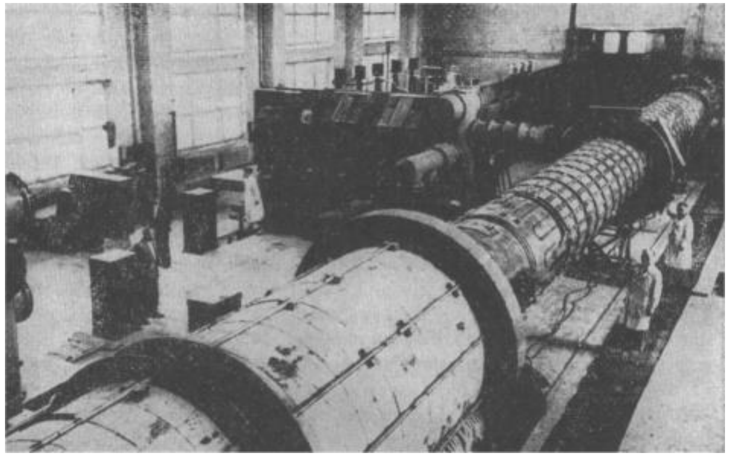


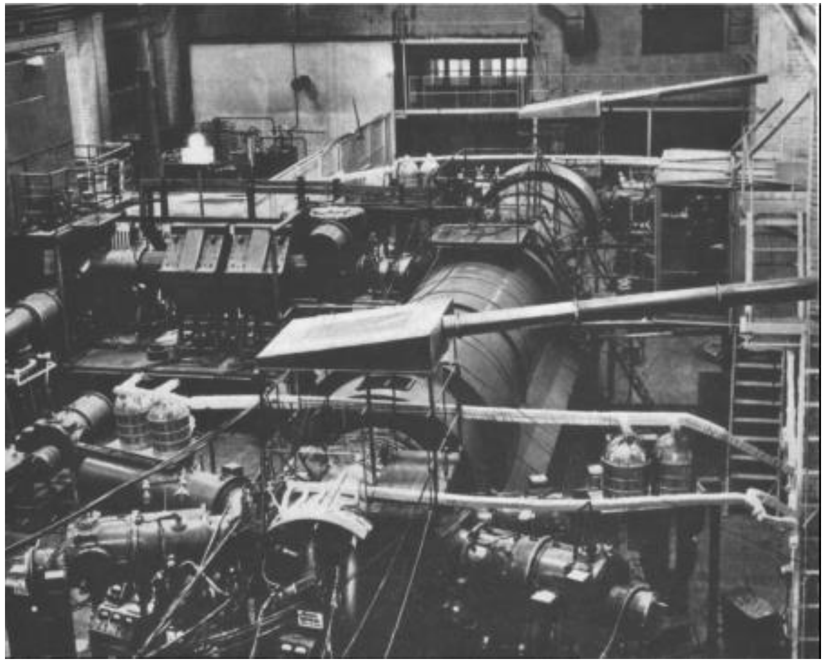
The Model B-3 stellarator (the last figure-8 stellarator)
(USA)

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Mirror Machines, e.g.**

- USSR: OGRA fitted with Ioffe's magnetic wells (Institute of Physics of Moscow)
  France: DECA I, II, III (later withdrawn) and MMII (CEA)
  USA: Table Top and Toy Top, MFTF-B (abandoned) (Livermore)





The OGRA Device (1957, USSR)

1950-1965: Configurations under Study in the Early Years of Fusion Research

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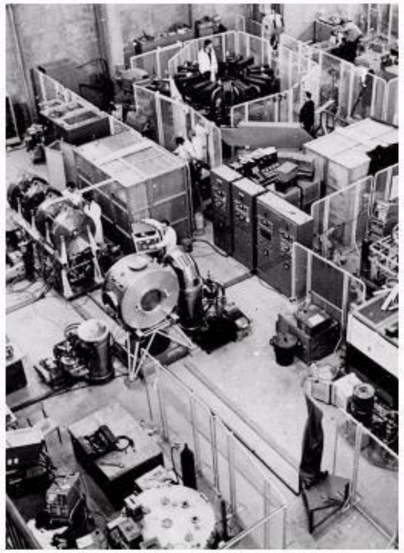
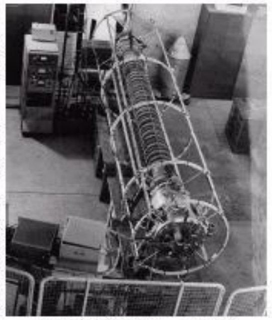
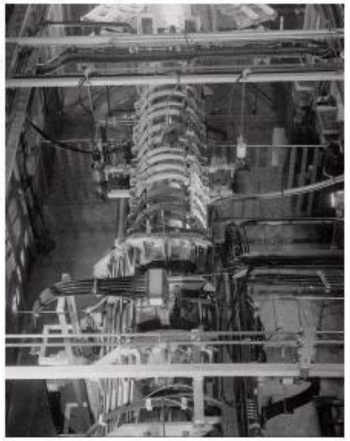


Fusion research laboratory (CEA-1962)



Capel B (CEA - 1966)



DECA 2B (CEA - 1966)

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Fundamental Difficulties**

- Several instabilities discovered reducing confinement:
  Kink instabilities, flute instabilities, …
  M. D. Kruskal and Schwarzchild "Some Instabilities of a Completely Ionized Plasma" 1954 Proc. R. Soc. Lond. A 223 348
  M. N. Rosenbluth and C. L. Longmire "Stability of Plasmas Confined by Magnetic Fields", Ann. Phys. **1** 120 (1957)

- Most toroidal machines followed the so-called Bohm scaling for the confinement time:

$$\tau \propto \frac{BR^2}{T}$$

Very low confinement times predicted by this formula (for JET this would predict 10-40 μs)

Bohm diffusion (1946):

$$D_\perp = \frac{1}{16}\frac{kT_e}{eB}$$

- Need for better machine configurations

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **1958**

- By mid-1958 nuclear fusion research had been virtually freed from all security restrictions.

No. 4604 January 25, 1958 NATURE

PRODUCTION OF HIGH TEMPERATURES AND NUCLEAR REACTIONS IN A GAS DISCHARGE

By Dr. P. C. THCNEMANN, E. P. BUTT, R. CARRUTHERS, Dr. A. N. DELLIS, D. W. FRY, Dr. A. GIBSON, G. N. HARDING, D. J. LEES, R. W. P. McWHIRTER, R. S. PEASE, Dr. S. A. RAMSDEN and S. WARD

Atomic Energy Research Establishment, Harwell

Conclusion

These preliminary results demonstrate that it is possible to produce a stable highly ionized plasma isolated from the walls of a toroidal tube. Hydrogen gas has been maintained in a state of virtually complete ionization with a particle density lying between 10^{13} and 10^{14} per cm.^{3}, for times of milli-seconds. The mean energy of the ions in the plasma is certainly of the order of 300 eV., and there are many indications that the electron temperature is of the same order. The containment time and the high electrical conductivity are both adequate for the detailed study of magnetohydrodynamical processes.

To identify a thermonuclear process it is necessary to show that random collisions in the gas between deuterium ions are responsible for the nuclear reactions. In principle, this can be done by calculating the velocity distribution of the reacting deuterium ions from an exact determination of both the energy and direction of emission of the neutrons. The neutron flux so far obtained is insufficient to attain the desired accuracy of measurement.

1950-1965: Configurations under Study in the Early Years of Fusion Research

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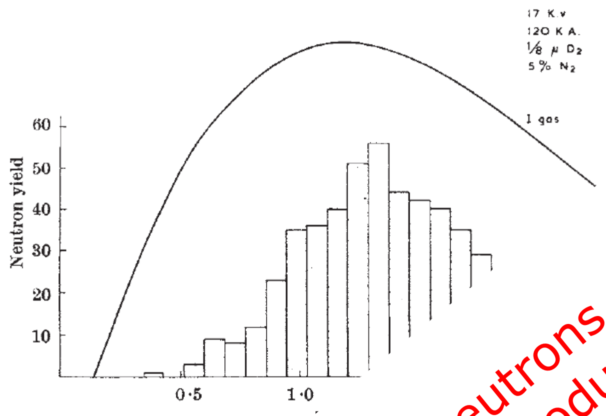


Fig. 4. Histogram show
times

The neutrons were later explained as the byproduct of instabilities in the fuel!

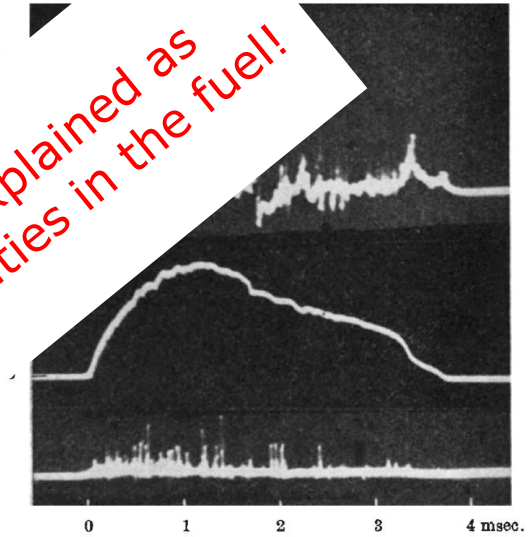


Fig. 2. Oscillograph recordings of the voltage per turn of the transformer, and the secondary current I_2. The lower trace shows the pulses produced by proton recoil in a scintillation neutron counter. Conditions: gas, deuterium + 5 per cent nitrogen + 10 per cent oxygen; pressure, $0{\cdot}13 \times 10^{-3}$ mm. mercury; axial field, 160 gauss

P. C. Thonemann et al, Nature ***181*** *217 (1958)*

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **September 1958 "Atoms for Peace" (IAEA, Geneva)**

- 1957 Eisenhower's UN speech
- IAEA established in 1957

"to make of the atom a peaceful servant of humanity, I shortly shall ask the Congress to authorize full United States participation in the International Atomic Energy Agency."

Dwight D. Eisenhower 1957

IAEA
International Atomic Energy Agency

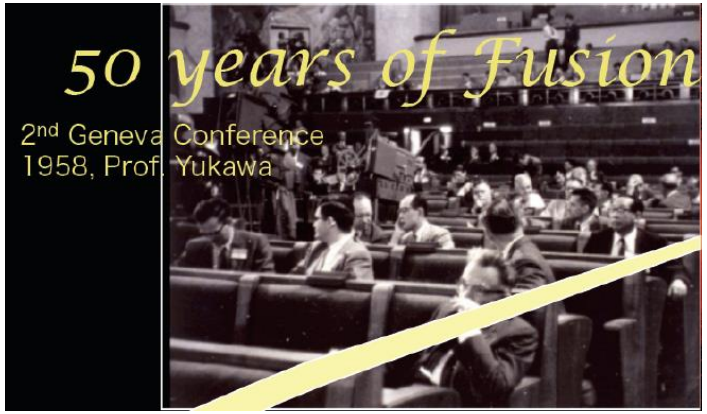
1950-1965: Configurations under Study in the Early Years of Fusion Research

- **September 1958 "Atoms for Peace" (IAEA, Geneva)**

Proceedings of the Second
United Nations International Conference
on the Peaceful Uses of Atomic Energy

Held in Geneva
1 September - 13 September 1958

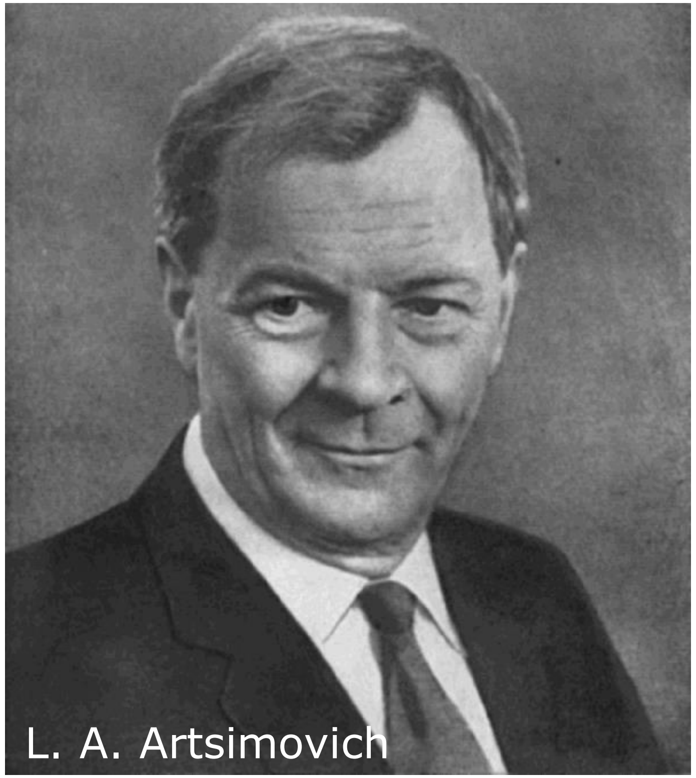
Volume 32
Controlled Fusion Devices



UNITED NATIONS
Geneva
1958

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **September 1958 "Atoms for Peace" (IAEA, Geneva)**



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

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

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

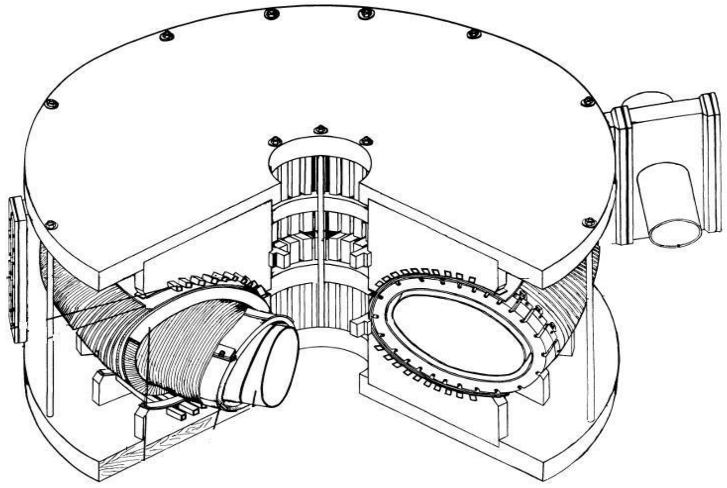
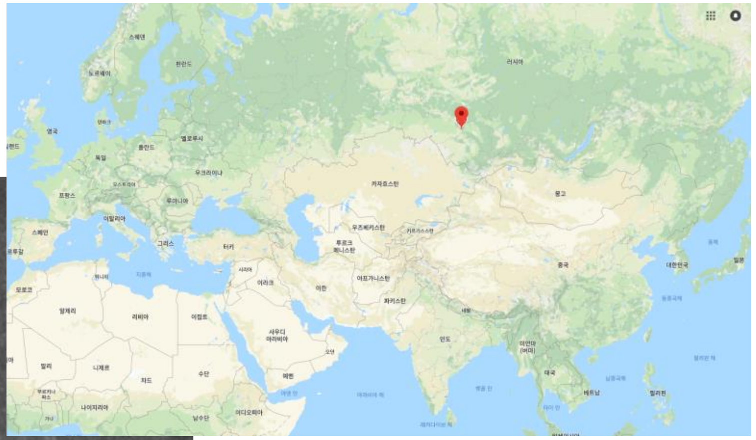


Diagram of the Kurchatov Institute's
T1 tokamak in Moscow



IAEA Novosibirsk
(August 1968)
T3 reaches 1 keV

1968: A Turning Point for Fusion Physics Emergence of the Tokamak

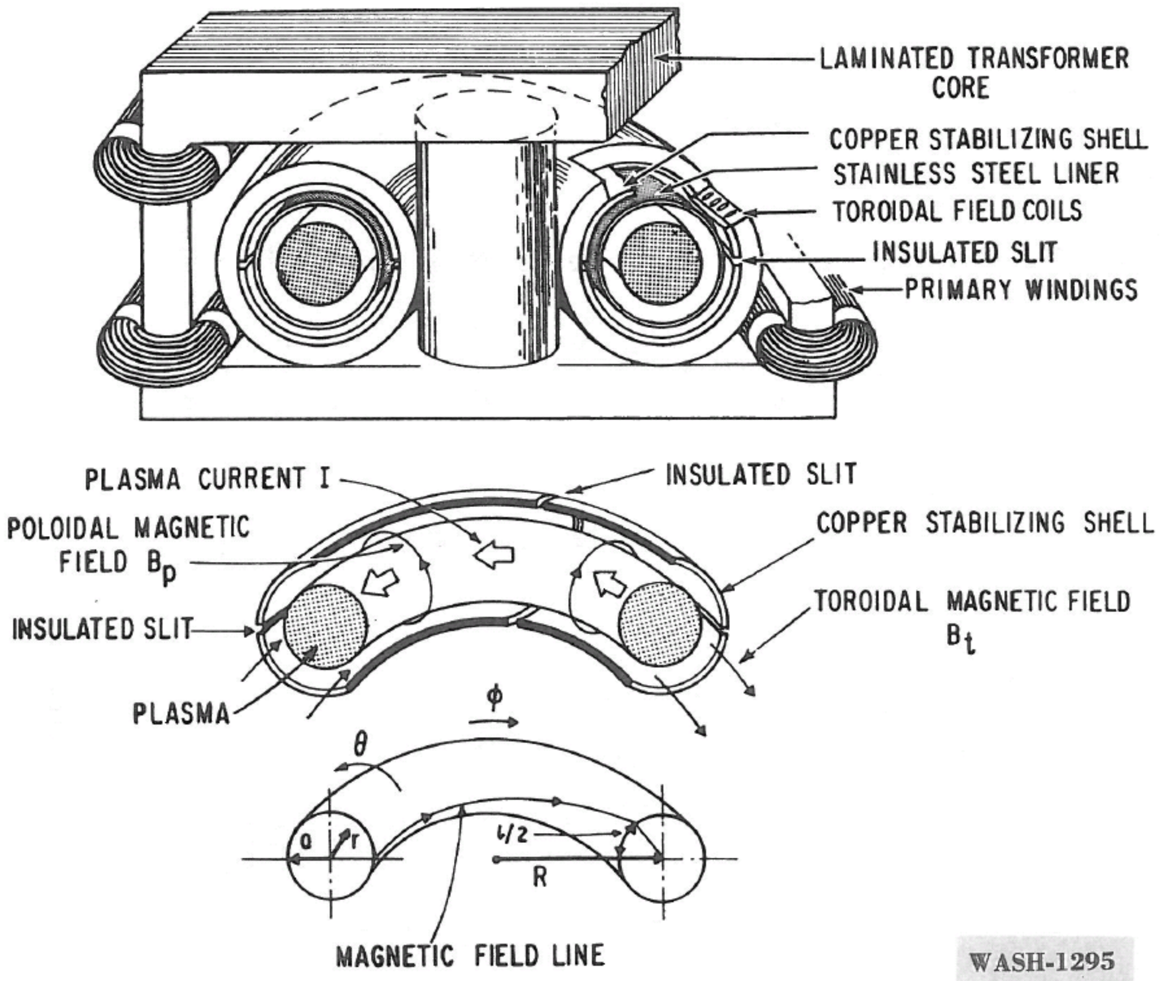
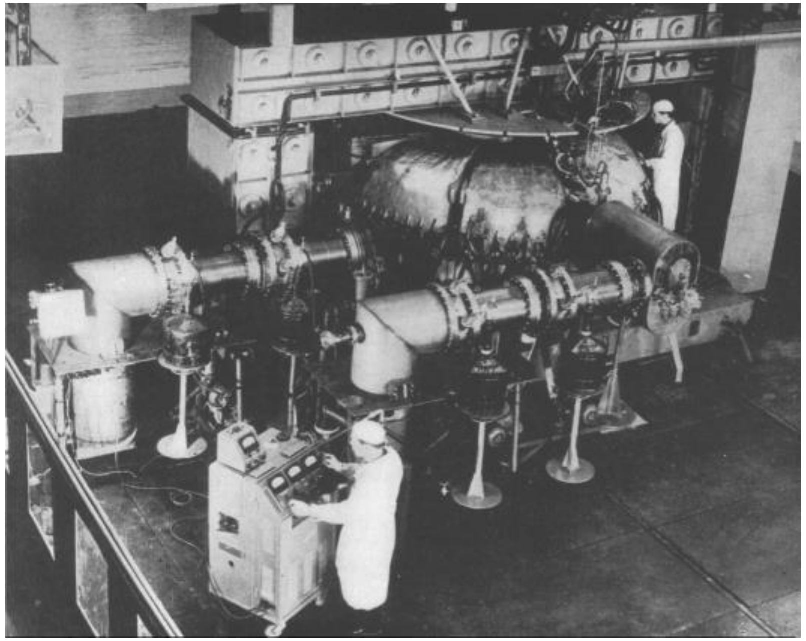
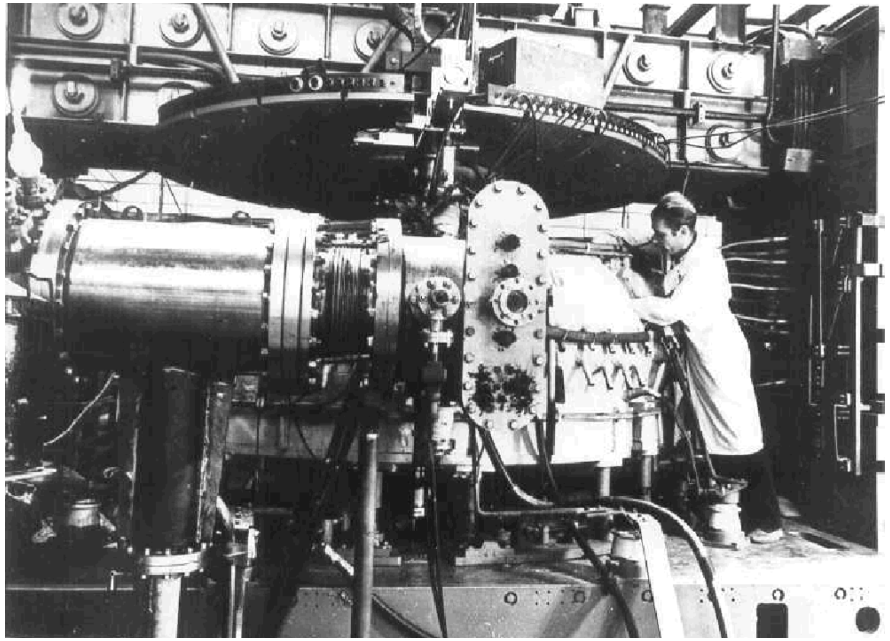


Figure 1. Basic tokamak apparatus: a toroidal plasma confined in a helical magnetic field created by the superposition of a strong, externally generated toroidal field and the poloidal field generated by the plasma current. The plasma current, induced by transformer action, resistively heats the plasma.

WASH-1295

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

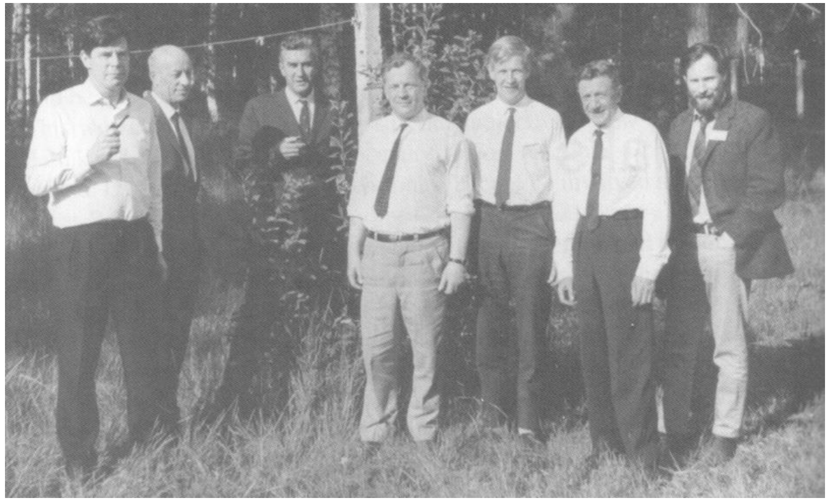




Tokamak T-3
(USSR)

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

- Confirmed by 1969 Culham mission to Moscow



A group of Soviet and British scientists during the Novosibirsk conference (1968)

(*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 $1\text{–}3 \times 10^{13}$ 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

N. J. PEACOCK, D. C. ROBINSON, M. J. FORREST

and

P. D. WILCOCK

UKAEA Research Group, Culham Laboratory, Abingdon, Berkshire

and

V. V. SANNIKOV

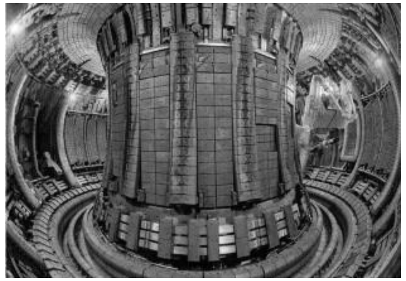
I. V. Kurchatov Institute, Moscow

1969- Success of Tokamak

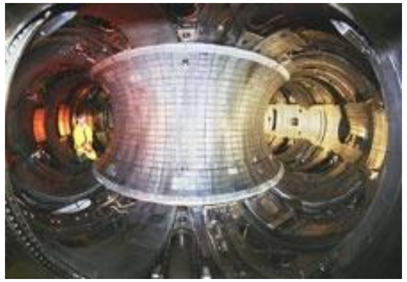
- **Tokamaks**

- Showing much better confinement than all other configurations
- T-3 (Kurchatov Institute, USSR):
  First device with temperatures in the keV range
  Confinement time (70 ms) more than 30 times higher than predicted by Bohm scaling
- 1969: General redirection towards the tokamak (‘Tokamakitis’)
- Diagnostic development on smaller devices
- Data acquisition, feedback, and heating techniques had become available.
- It appeared then that a large device could and had to be build to make further progress: JET, TFTR, JT-60U

JET



TFTR

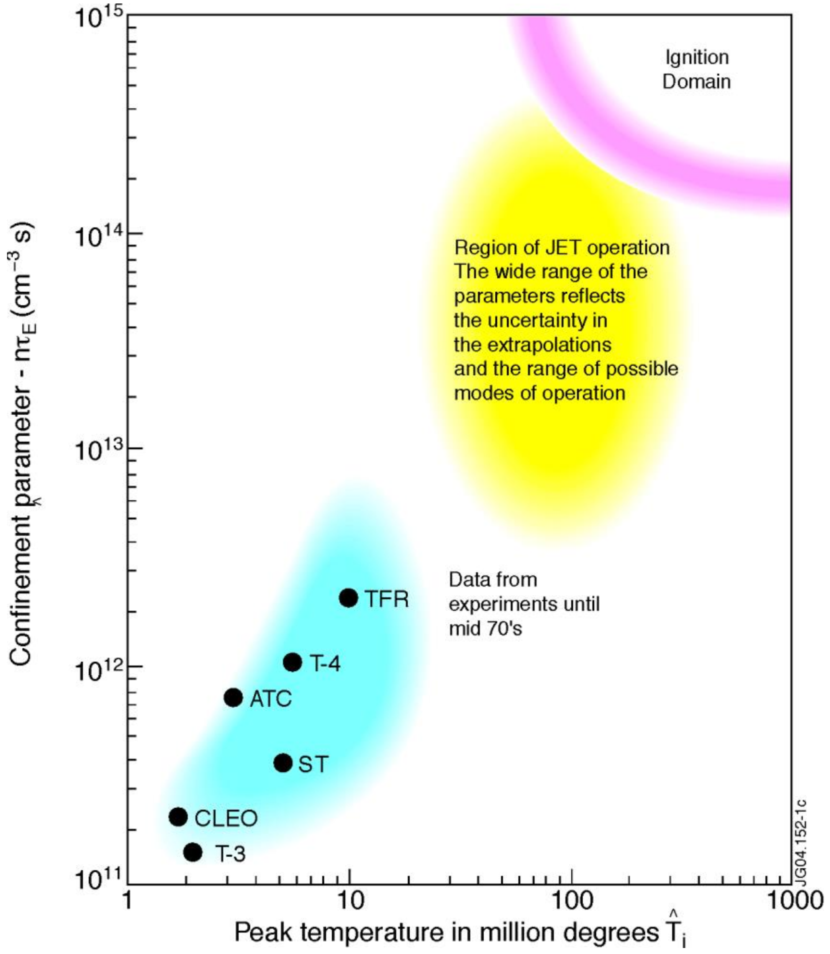


JT-60U

1969- Success of Tokamak

- **Lawson Diagram in mid 1970 s**

- Parameter domain foreseen for JET

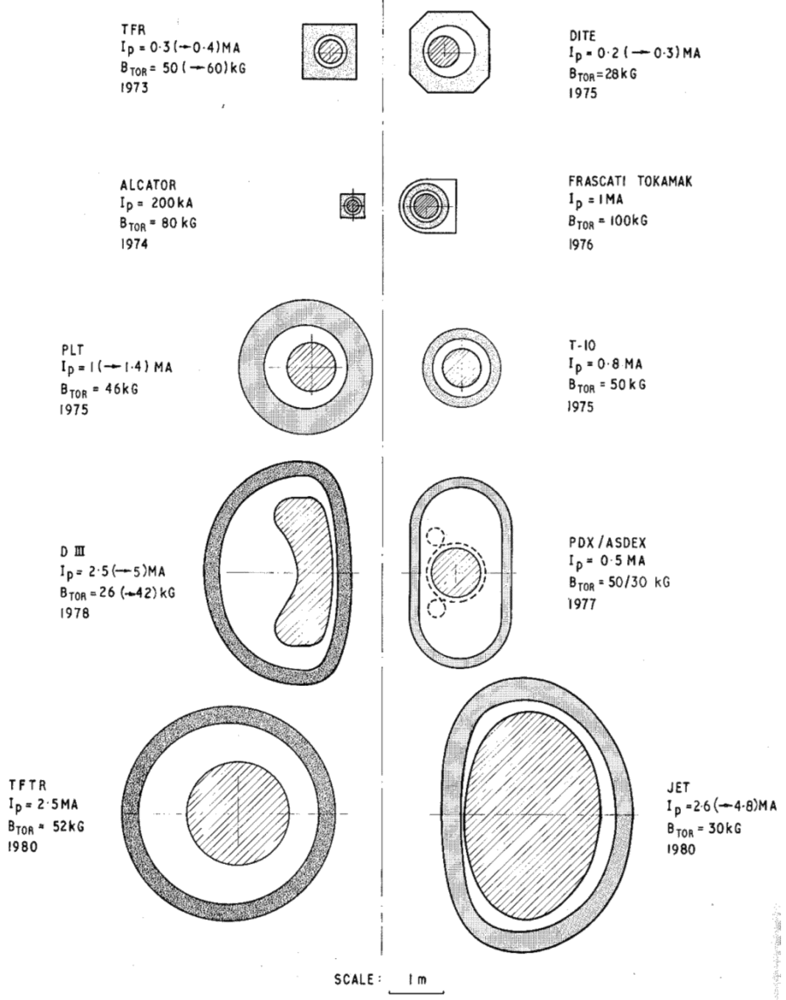


1969- Success of Tokamak

- **JET**

- Much larger plasma compared to existing or planned tokamak plasma at that time
- D-shaped plasma

Design Phase of JET (1973-1975)



1991- DT Operation

- First D-T experiments: JET (Nov. 1991)

PRÉSIDENCE
DE LA
RÉPUBLIQUE

Le Conseiller Technique

1er janvier 1992

Cher Monsieur,

Monsieur le Président a été très sensible à votre lettre du 15 novembre 1991 lui annonçant la réussite de la première fusion thermonucléaire obtenue avec la machine JET que vous dirigez. Il me demande de vous transmettre ses félicitations pour vous et l'ensemble du personnel impliqué dans ce beau succès.

Je profite de cette lettre pour vous adresser tous mes voeux personnels pour la nouvelle année et pour vous dire que je ne désespère pas de trouver un créneau dans mon emploi du temps pour visiter vos installations.

Veuillez agréer, cher Monsieur, l'expression de mes sentiments les meilleurs.

Jean AUDOUZE

Monsieur Paul-Henri REBUT
JET Joint Undertaking
ABINGDON
Oxfordshire OX14 3EA
ANGLETERRE

BUCKINGHAM PALACE

22nd November, 1991

Dear Dr. Rebut,

I am commanded by The Queen to thank you for your letter of 15th November. Her Majesty remembers with pleasure her visit to the Joint European Torus in April 1984 and appreciated your thoughtfulness in letting her know of the controlled experiment which took place recently at your headquarters which produced a quantity of fusion power. The Queen sends her congratulations and best wishes to you and all members of your team.

Yours sincerely,

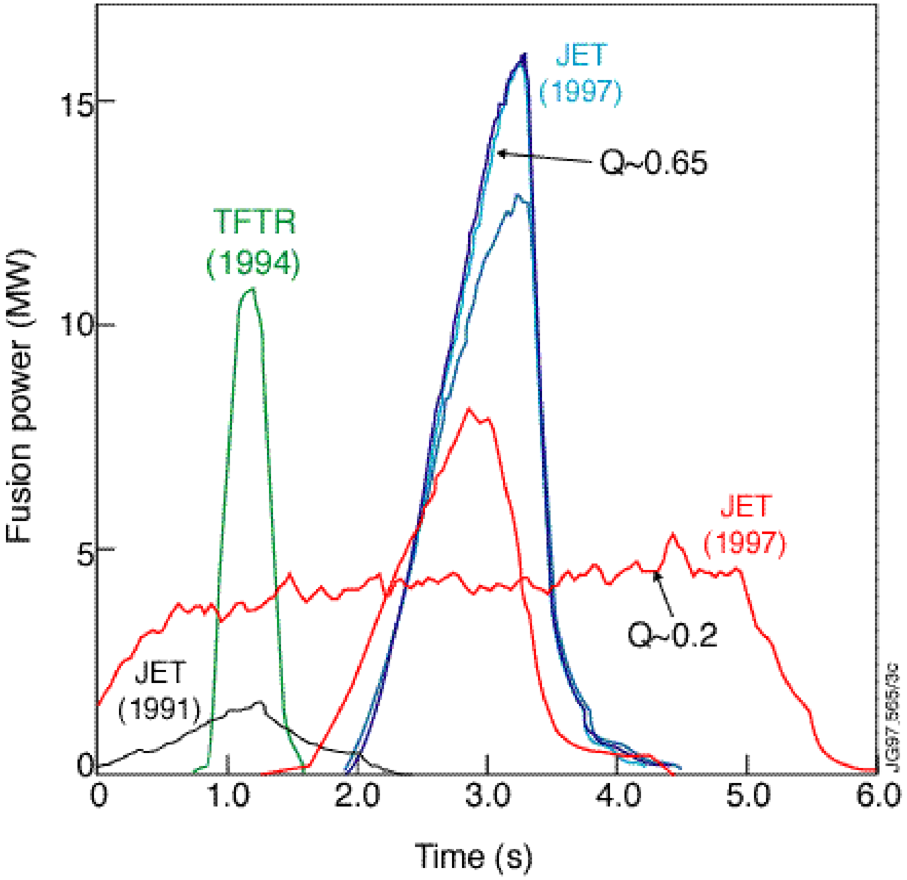
(KENNETH SCOTT)

Dr. P-H Rebut.

- Congratulations from HRH (Her Royal Highness) Queen Elisabeth II and President Mitterand for pioneering and successful D-T experiments

1991- DT Operation

- First D-T experiments: JET (Nov. 1991)



JET 1991 (EU): 1.7 MW

First controlled DT fusion experiments on earth

TFTR 1994 (US): 11.5 MW

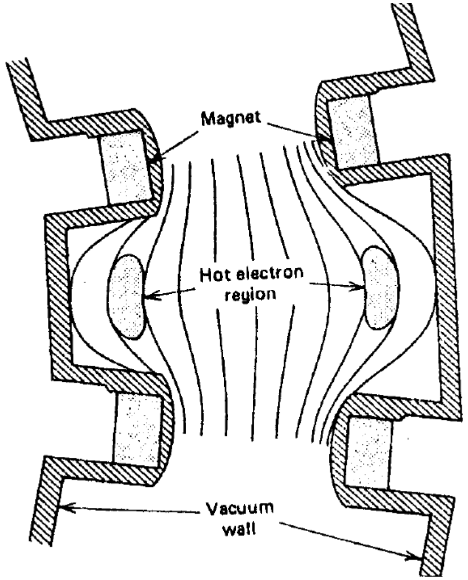
JET 1997 (EU): 16 MW

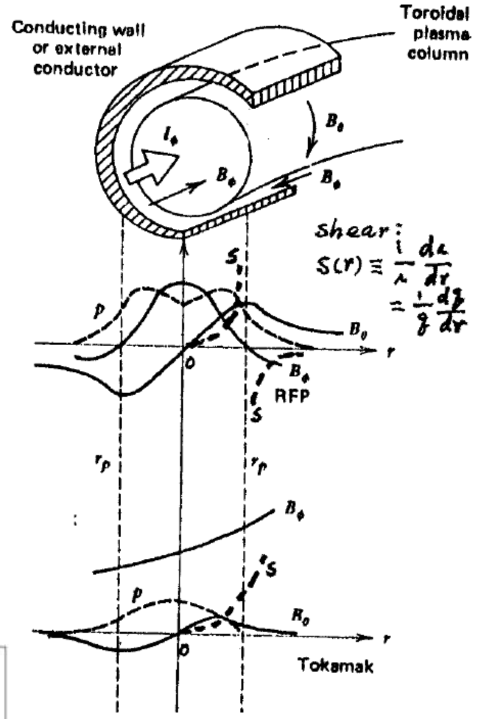
energy amplification $Q \sim 0.65$

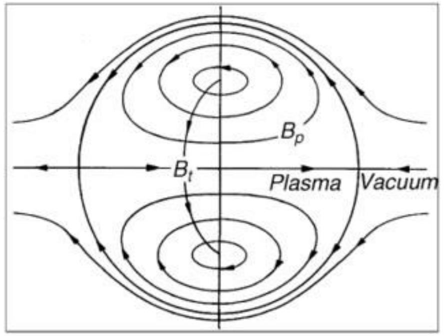
Alpha particle heating clearly observed consistent with theory

Alternative Concepts

- **Bumpy Torus**
- **Reversed Field Pinch**
- **Spherical Tokamak**
- **Spheromak**

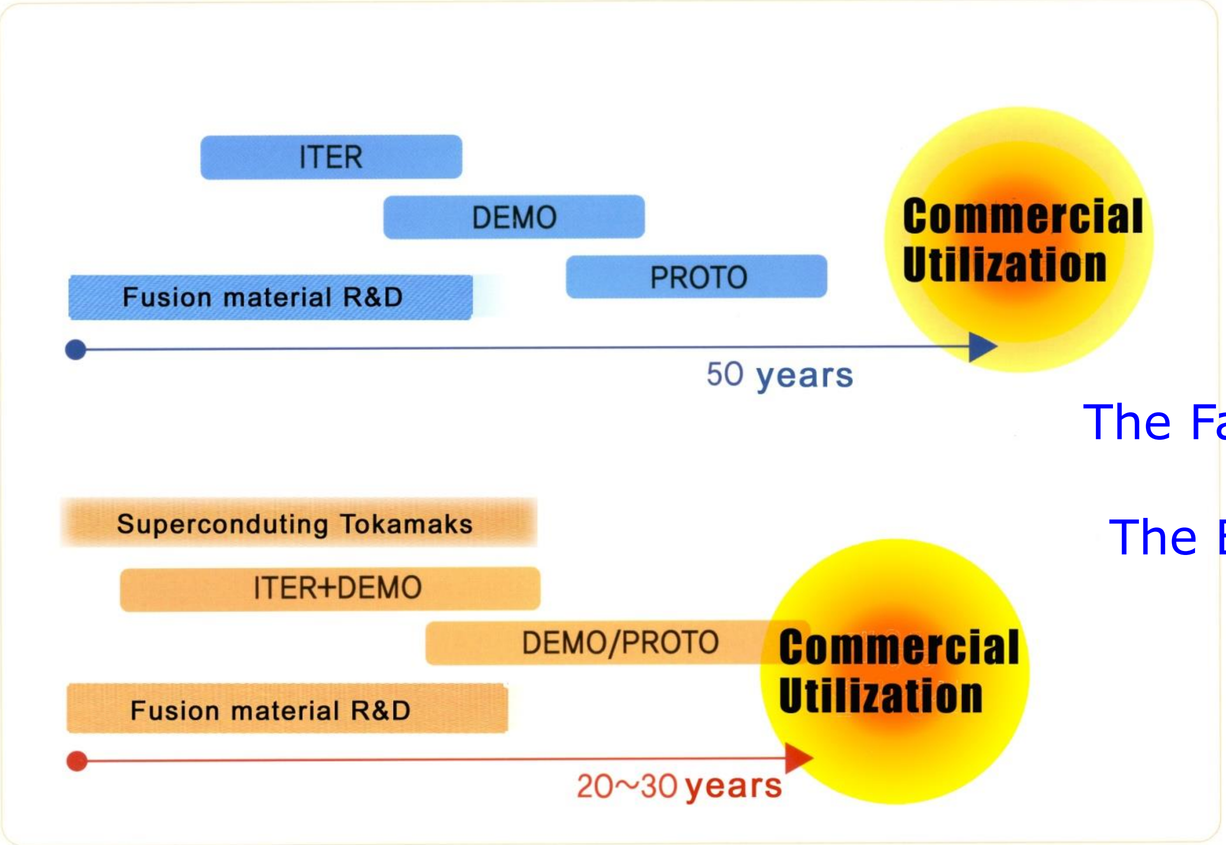






Fusion Energy Development Roadmap

Phased integration of reactor technology development

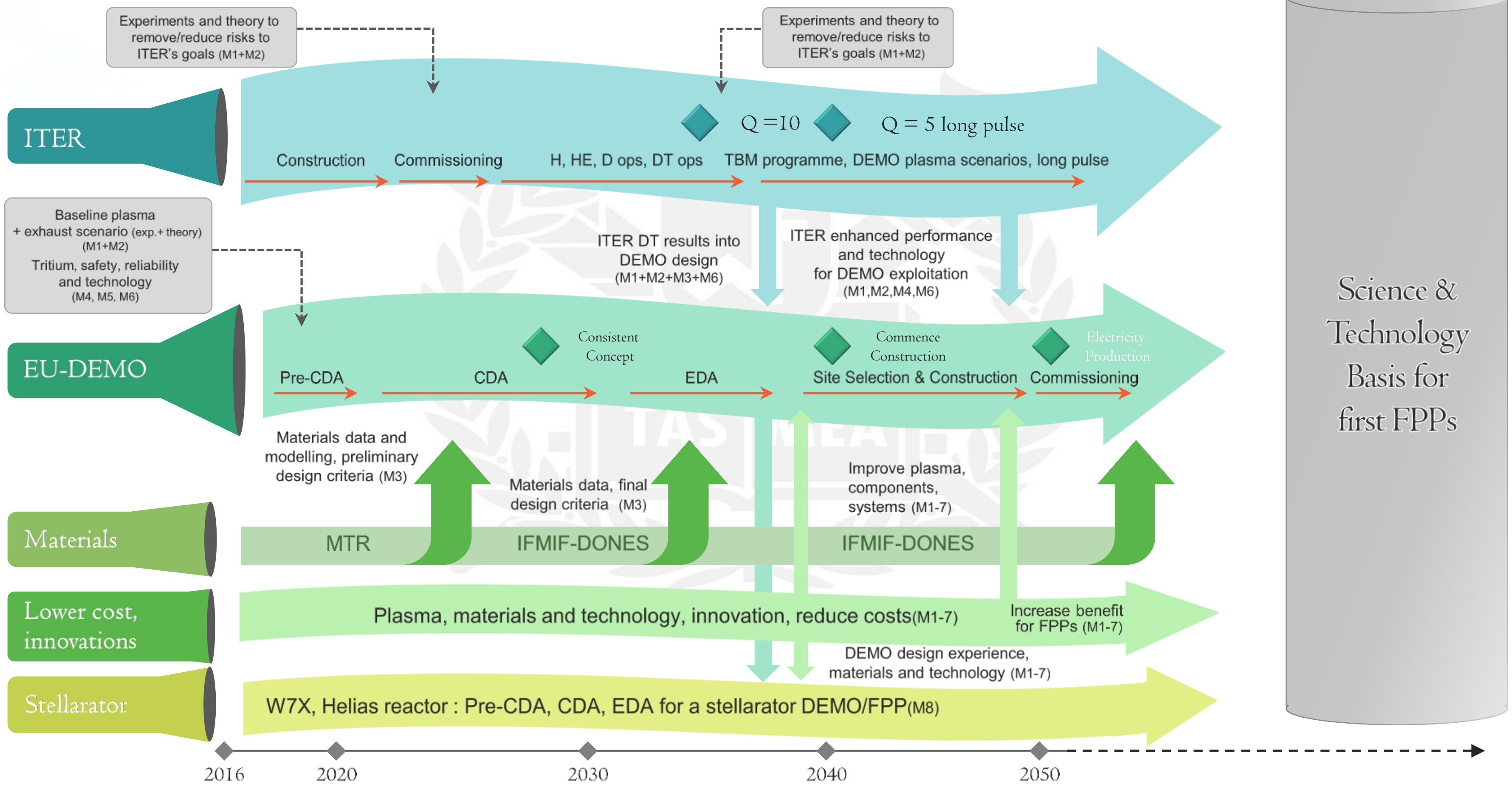


The Fast Track Approach
&
The Broader Approach

EU의 핵융합 전기생산 로드맵 (안)

EU의 핵융합 전기생산 로드맵 Fusion Electricity by 2050!

’20년대 개념설계, ’30년대 공학설계, ’40년대 DEMO 건설 및 ’50년대 운전 계획 (수정안 기준)



EU의 핵융합에너지개발 추진 현황

- EUROfusion을 중심으로 '12년 말에 수립한 핵융합에너지 전기 생산 로드맵에 따라 8대 미션 수립 및 추진 중
  - Horizon 2020을 통해 '14 ~ '18년 동안 핵융합에 총 30.7억 유로(ITER 23.6억 유로, EUROfusion 7.1억 유로) 투자 진행 중

8대 미션

Eight Programmatic Mission

1	Plasma Operation	5	Safety
2	Tritium-self sufficiency	6	Neutron resistant Materials
3	Competitive Cost of Electricity	7	Integrated DEMO Design
4	Heat Exhaust	8	Stellarator

DEMO

- 2050년까지 DEMO를 통한 전기 생산 실증을 위한 주요 마일스톤 정립 ('16년 말 수정보완 완료) 및 추진

일본의 핵융합에너지 개발 추진 현황

EU와 BA(Broader Approach) 협정 체결, JT-60SA 건설, IFMIF/EVEDA 수행, DEMO 개념설계 및 기반 R&D 3대 과제를 2007년부터 추진 중

- ITER 운영 및 DEMO 실험연구를 위한 선행연구장치로 초전도 토카막 JT-60SA 공동건설 중('19 완공 후 공동 운영)
- ITER 원격실험 준비 및 핵융합에너지 조기 상용화 DEMO R&D를 위한 국제핵융합에너지연구센터(IFERC) 운영
- IFMIF* 공학설계검증 가속기(EU) 및 액체리튬타겟(JA)을 로카쇼에 설치 운전 준비 중

  * International Fusion Materials Irradiation Facility : 국제핵융합재료조사시설

국가 차원의 공식적인 DEMO 계획 수립('15. 1) 및 세부실천과제 도출('16. 2)

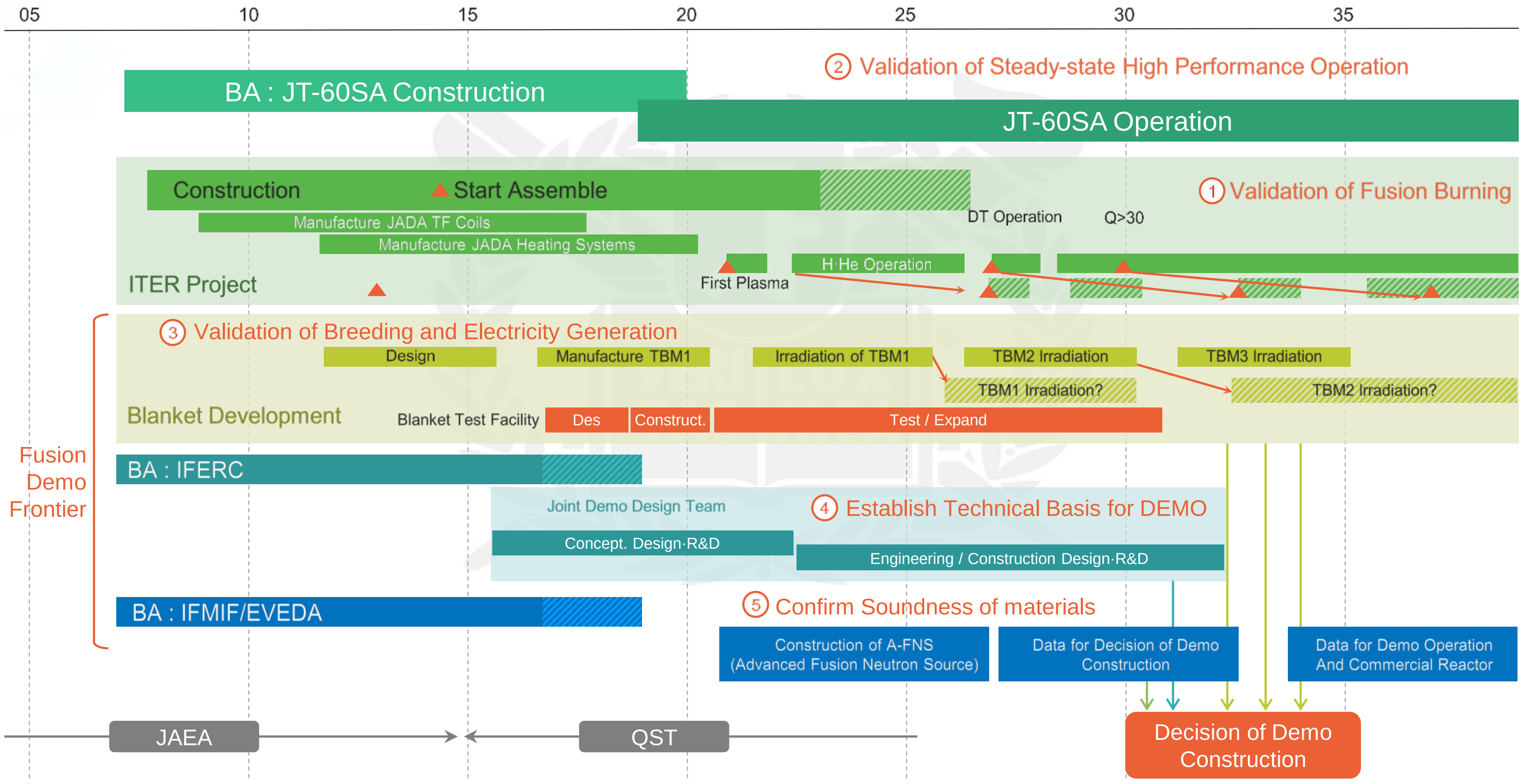
- 문부과학성 산하 핵융합과학기술위원회('15. 4) 및 DEMO개발 종합전략('15. 6) 설치
- DEMO 설계를 위한 공동특별설계팀 구성 및 운영
  ('16년 새롭게 분리 독립된 QST(35%), 대학(35%), 산업체(30%)에서 78명으로 구성)

고효율 에너지 | 풍부한 에너지 | 깨끗한 에너지 | 안전한 에너지 | 평화적 에너지

일본의 DEMO 개발 계획

일본의 DEMO 개발 일정(ITER 지연 때문에 리스케줄링 진행 중)

Key Issues : ① ITER Burning ② Steady State Operation ③ Blanket : Tritium Breeding, Electricity Gen. ④ DEMO Design & R&D : Establish Tech. Basis ⑤ Material: Confirm Soundness against Fusion Neutron



일본의 핵융합 전기 생산 실현 로드맵

실험장치 단계

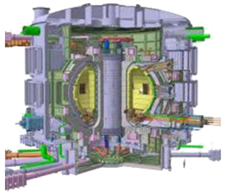
초고온
플라스마 실현

세계최고온도
5.2억도

JT-60

실험로 단계 (현재)

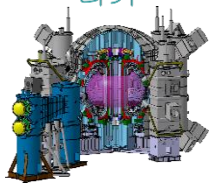
ITER
50만 kW 핵융합출력



ITER를 지원

BA(Broader Approach) 활동

나카



위성토카막
(JT-60SA)

로카쇼

IFMIF/EVEDA,
국제핵융합에너지연구센터

원형로 단계

발전실증

실용화

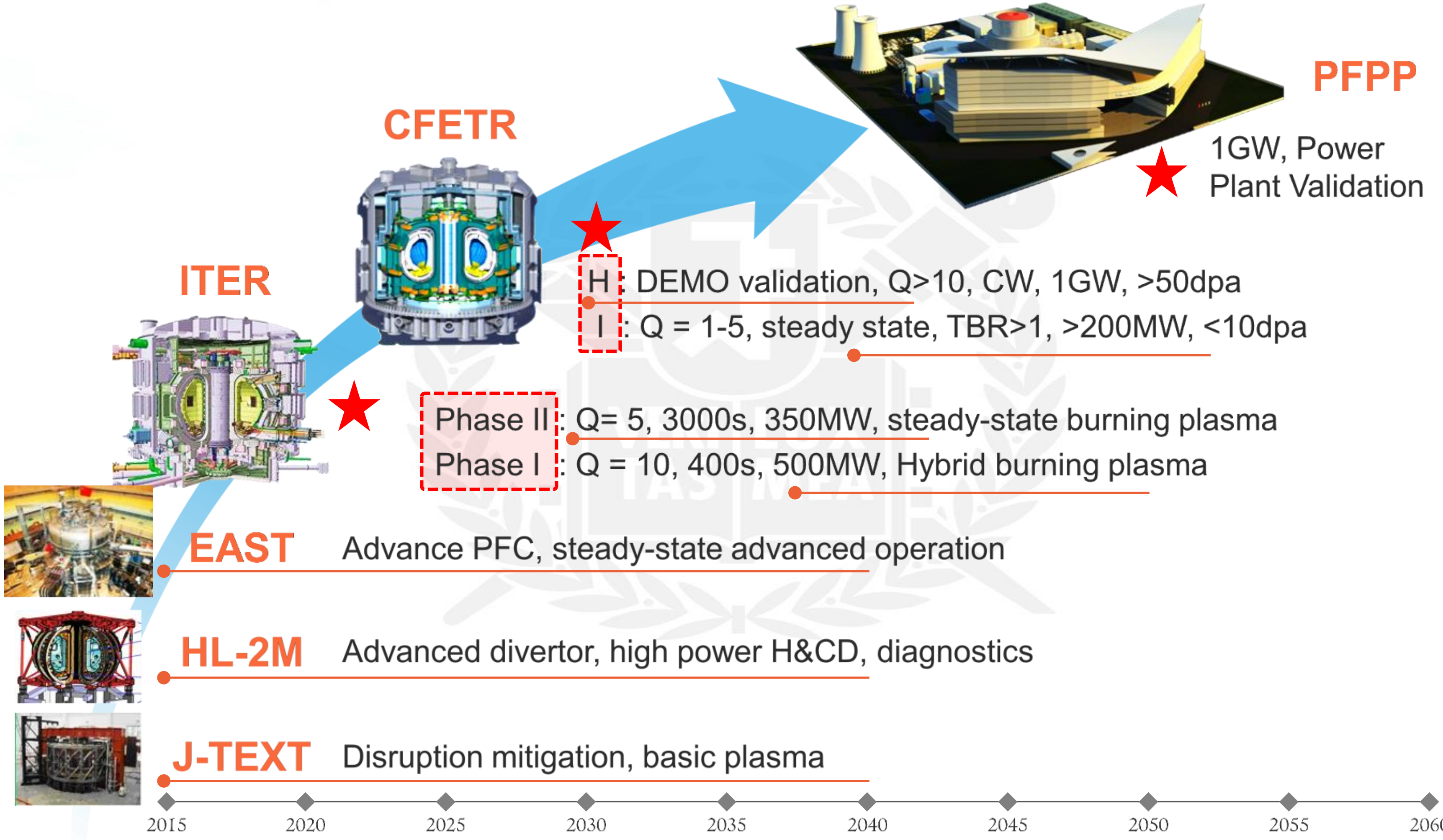
ITER
미수행 영역
보완

원형로를 위한
기술기반 구축

ITER (연소 플라즈마, TBM 시험) 및
BA (JT-60SA : 운전모드, IFERC: DEMO 설계, IFMIF/EVEDA : 재료시험) 병행 추진

중국의 핵융합에너지개발 로드맵

CFETR 건설 제안서가 향후 5년 내 정부에 의해 승인 검토 예정



글로벌 연구 동향 주요 시사점

수정된 ITER 일정을 반영한 핵융합 에너지개발 로드맵 재편 중

- 2050년 핵융합 전기 생산을 목표로 설정 (EU, 일본, 중국)

국가차원의 DEMO 계획 수립 및 세부실천과제(Action Plan) 도출

- 유럽 : Horizon 2020을 통한 8대 미션 수립 추진
- 일본 : DEMO개발 종합전략 TF 설치, BA를 통한 DEMO 기반 기술 연구 병행

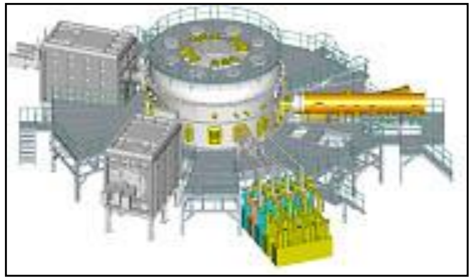
통합적 DEMO 추진 체계 수립

- 유럽 : Fusion for Energy (F4E) EUROfusion에 위탁 (유럽 연구소 참여)
- 일본 : 핵융합개발 체계 재편(QST) 및 NIFS+대학 들과 함께 DEMO 개발 추진

Phased integration of reactor technology development

2007-
KSTAR

- Long-pulse advanced tokamak operation



2025-
ITER

- Burning plasma
- Blanket technology
- Material technology

2040s
DEMO

- Demonstrating electricity generation
- System optimisation
- Economically competitiveness

2050s
FPP

- Massive electricity generation

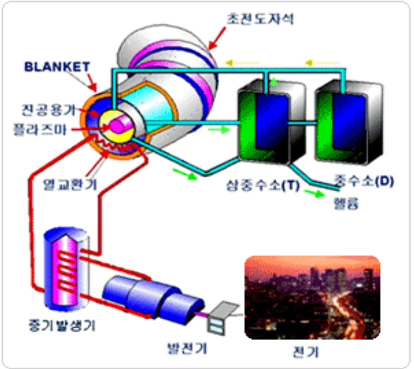


그림 15. 핵융합발전의 원리

Contents

- Introduction (2 lectures)
- Fundamentals of Nuclear Fusion (2 lectures)
- Fusion Reactor Energetics (1 lecture)
- Reviews of Plasma Physics (3 lectures)
- Plasma Confinement Concept
  - Inertial Confinement (1 lecture)
  - Open Magnetic Confinement: Pinch, Mirror (2 lectures)
  - Closed Magnetic Confinement: Tokamak, Stellarator (8 lectures)
- Plasma Heating and Current Drive (2 lectures)
- Plasma Wall Interaction (1 lecture)
- Fusion Nuclear Technology (4 lecture)
- Past and Future of Fusion Energy Development (1 lecture)

References

- *26th JET Anniversay 20 May 2004*

- D. Palumbo, “Setting JET on track” Prof. D.Palumbo
- P.H. Rebut, “JET : A step in fusion Concept and Objectives“
- François Waelbroeck, “Scientific Raison d’Etre for JET”