History of Fusion
Personal view

V. Chuyanov
9 July 2009

Special thanks to ITER Communication Division.

Initial comments

- This is not an official history of Fusion Research
  - I selected events:
    - I consider important or
    - I have a personal knowledge as a participant or from the real participants (no second hand information) or
    - I believe, some lessons can be learned.

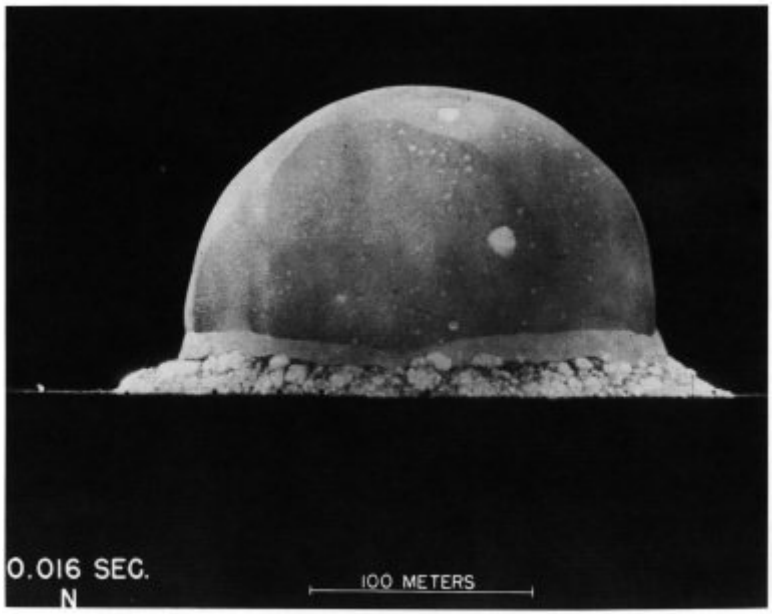
Early Fusion history can not be separated from nuclear weapon development

July 16 1945, 5:29:45 A.M. (Mountain War Time)

The Trinity Test

Trinity Site Zero, Alamogordo Test Range, Jornada del Muerto desert.

Yield: 20-22 Kilotons



29 August 1949:

The Soviet Union became the second nation in the world to detonate a nuclear device

1st November 1952: Mike-first prototype (liquid) of hydrogen bomb

12-Aug-53

First Soviet Union **thermonuclear** explosion 400kT

Big Ivan, The Tsar Bomba ("King of Bombs")

- **30 October 1961**

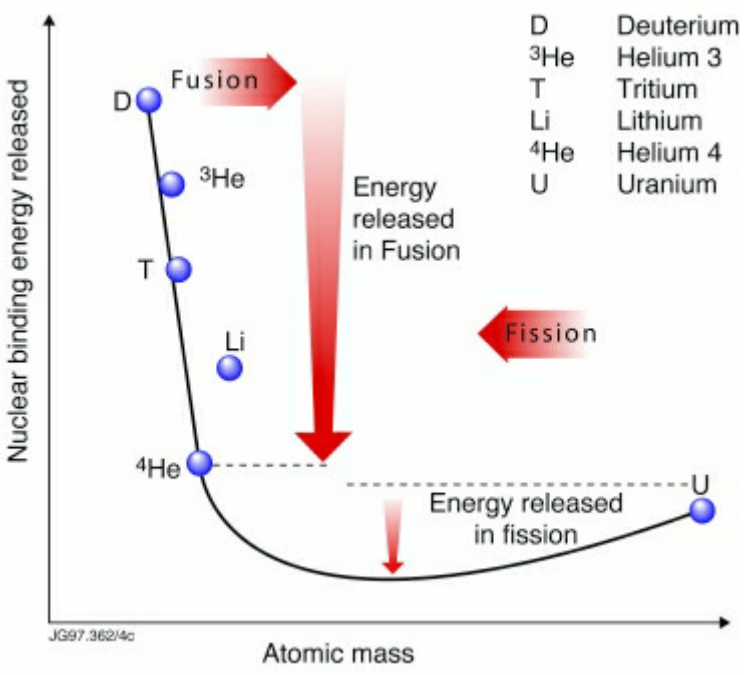
Characteristics :

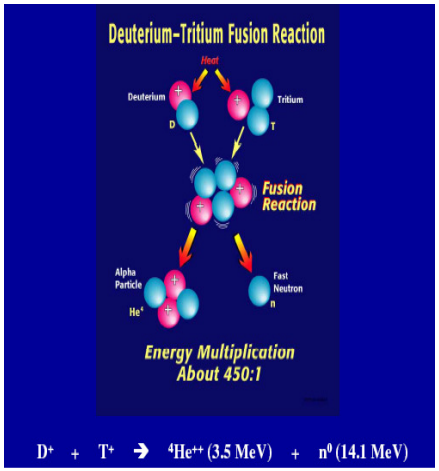
- **Maximum Design Yield** 100 Megatons
- **Weight** Approx. 27 tonnes
  [**Length** 8 meters **Diameter (body)** 2.1 meters
- **Delivery Method**
  Modified Tu-95 strategic bomber,
- Three stage radiation implosion system
- Tertiary (and probably secondary) stages tested with non-fissionable lead tampers
- **50% fusion, 50% fission at full yield**
- There were no military targets for such a bomb.
- After this test there were no questions of design
- There was a question of fission material availability

$D_2 + T_3 = He_4 + n + 17.5$ MeV

Two isotopes of hydrogen, deuterium (D) and tritium (T), have maximum reactivity at around 100 million °C

- Atomic nuclei are made of protons and neutrons held together by the strong nuclear force.
- The nuclei with moderate masses are bonded stronger then light or heavy nuclei.
- If products of nuclear fusion or fission reactions are lighter then initial nuclei , the energy will be released as kinetic energy





Why fusion became of importance in 1950?

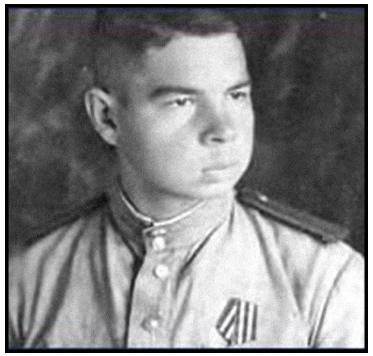
- **One fission reaction produces 1 neutron available for breeding of Pu and ~200Mev energy**
- **One fusion reaction produces 1 fast neutron which can be multiplied in n-2n reactions and one of the new neutrons may be used for plutonium breeding.**
- **The energy produced for one act of breeding ~ 17.5 Mev**
- **Fusion breeding ~10 times cheaper !**

  (Cost usually proportional to power)

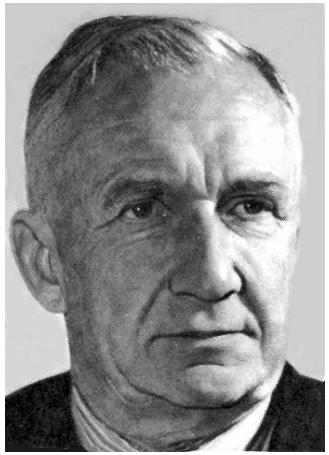
Prehistory and Secrete Time

- **1939**: Hans Bethe is awarded the Nobel Prize in physics "*for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars.*"
- **1950** (July) : Russian soldier Oleg Lavrentiev writes a letter to Stalin outlining a concept to produce energy through controlled thermonuclear reactions.
- **1951** (January) : I.E. Tamm and A.D. Sakharov's proposal on "toroidal magnetic trap is approved.
- **1951 :** Lyman Spitzer starts the Princeton Plasma Physics Laboratory.
- **1953** : The US and USSR develop "pinch devices".
- **1954** : ZETA machine (Zero Energy Thermonuclear Assembly)

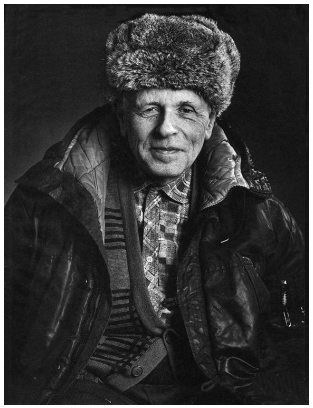
Hans Bethe



Oleg Lavrentiev

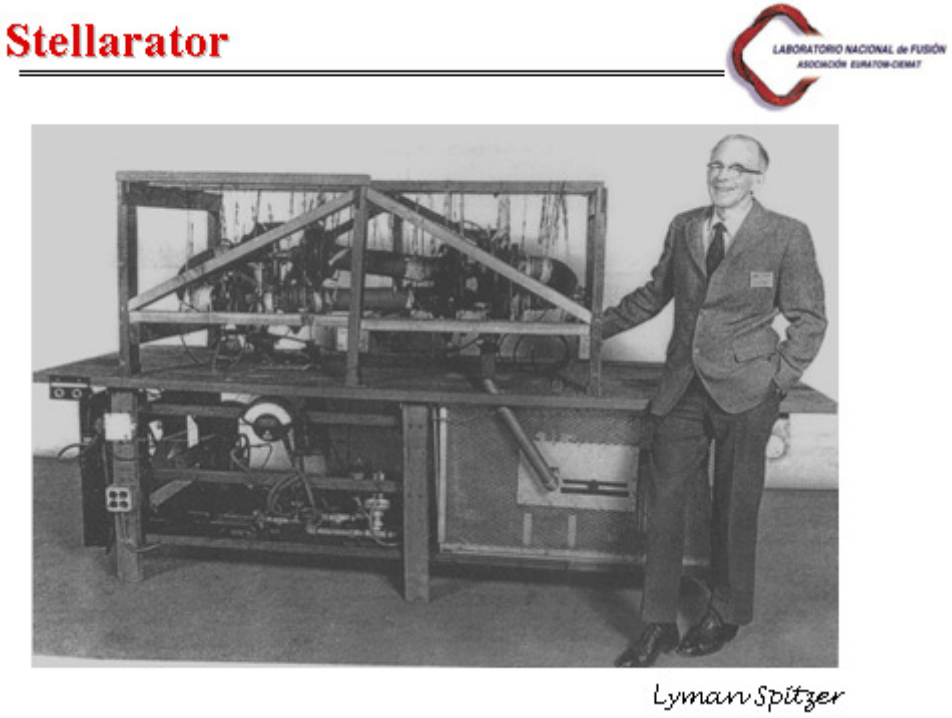


T. Igor Evgenevich Tamm

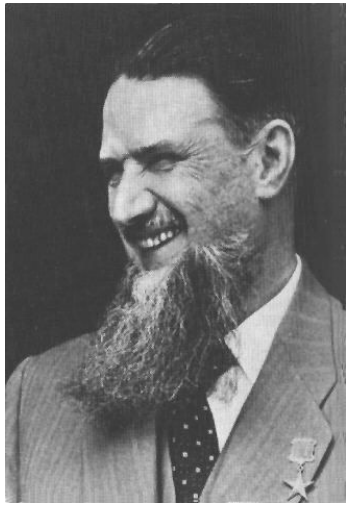


A.D. Sakharov

1951 : Lyman Spitzer starts the Princeton Plasma Physics Laboratory.



Opening of the fusion research



1956: A Soviet delegation, led by Igor Kurchatov, head of Soviet fusion research, visits Harwell and delivered the first open presentation of results of fusion research (pinches).

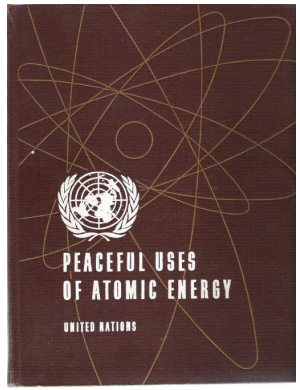
Why Kurchatov persuaded Khruschev to open fusion research ?

- To 1956 plutonium problem has been solved by other means . No military interest to fusion.
- Fusion appeared to be much more difficult then expected . Combined word effort was needed.
- Results may be of the highest importance for all the humanity – biggest source of energy is at stake.
- The best problem for international cooperation

After the Kurchatov's lecture the British government also decided to open fusion research.

1958 (September): The "Second United Nations International Conference on the Peaceful Uses of Atomic Energy", better known as the "Atoms for Peace" conference opens in Geneva.

The veil of secrecy is lifted from fusion research



Lev Artsimovitch, head of Soviet delegation:

"*A most important factor in ensuring success is the continuation and further development of the international cooperation*"

Edward Teller, director, Lawrence Livermore National Laboratory :

"*It is wonderful that over a large and important area of research we can now all talk and work together freely. I hope that this spirit of cooperation will endure, that it will be generally exercised throughout the world*

Fusion Power Terminology

Fusion power density $P_{fus}=E_{fus}\, n_d\, n_t \langle\sigma_{fus}\, v\rangle \sim n^2 T^2$

Heat loss $P_{loss}=3nT/t_E$

Fusion gain Q is determined by $\mathbf{Q= P_{fus}/P_{loss} \sim Tnt_E}$

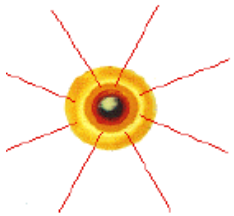
- Two isotopes of hydrogen, deuterium (D) and tritium (T), have maximum reactivity at around 100 million °C

High density (high pressure) $t_E \sim r/v$ - inertial confinement

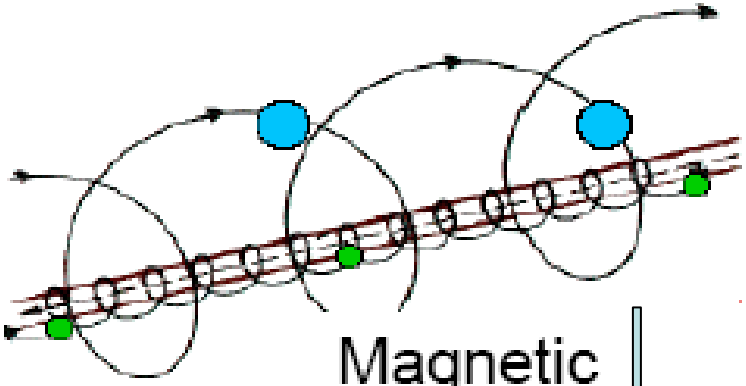
Low density (low pressure) $t_E >>> r/v$ – magnetic confinement

Different approaches to achieve fusion:

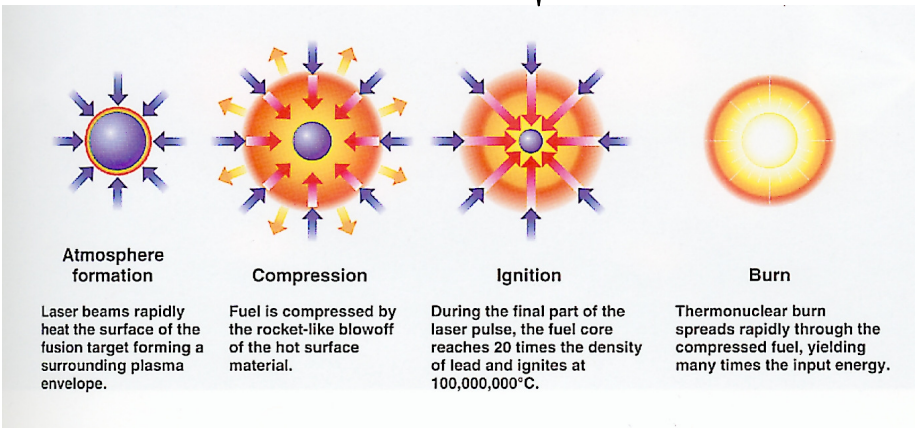
Gravitational

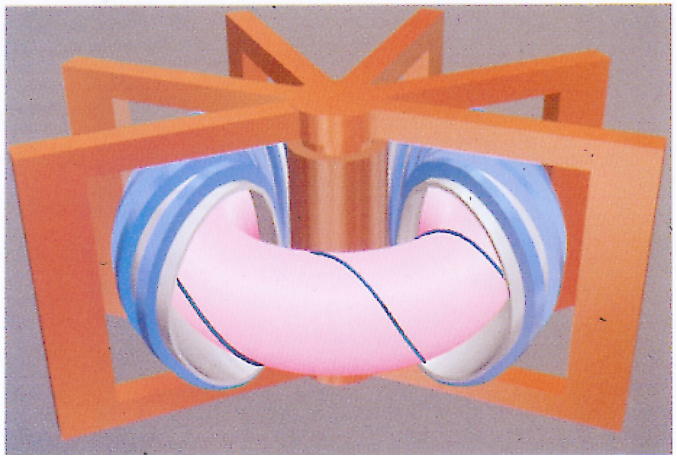


Inertial



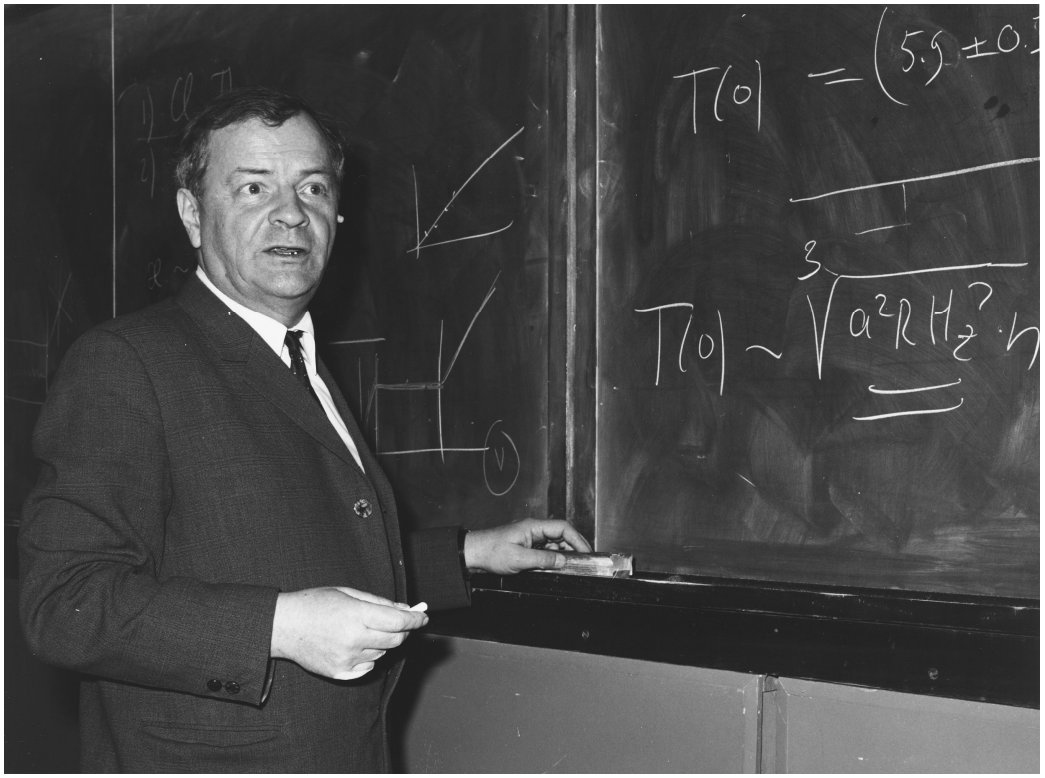
Magnetic





We are not in an finishing school for young noble ladies,
We are here to discover the truth

L.A.Artsimovich



Toroidal Pinch Hopes and disappointments

- **1958** (January) : ZETA claims fusion power.
- UK newspapers' headlines read : "British H-Men Make a Sun";
- "The Mighty Zeta: Limitless Fuel for Millions of Years

1958 – 1968: Most developed nations operate fusion machines of various shape, size and concept (mirror machines, pinch machines, stellarators, levitrons, superstators, etc.) But results are generally disappointing.

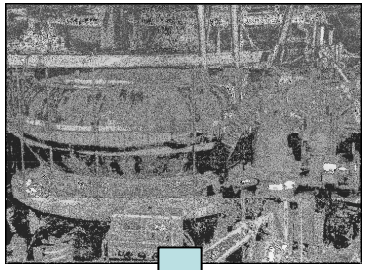
From a scientific point of view, it was a decade of doubt and frustration

Meantime a new secret Russian weapon has been prepared

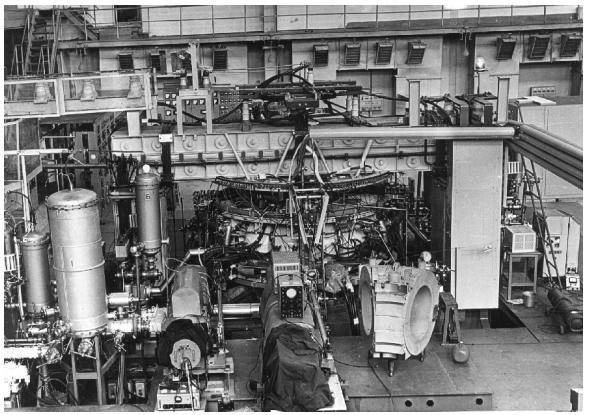
1957: T-1 toroidal device is operational at Moscow's 'Sector-44', within the Laboratory of Measuring Apparatus of Academy of Science – the future Kurchatov Institute.

Igor Golovin coins the acronym Tokamak.

TM3 and T3 have been build during the next 10 years



T-1
1957



T-3
1967

First real success in fusion

- **1968 IAEA Conference Novosibirsk**
- **Lev Artsimovitch's claims that in T-3 and TM-3 tokamaks, electron temperature of more than 10 million degrees has been attained and held into the plasma for 10 to 20 msec**
- **This is considerably better than the Princeton's stellarator, where plasmas had never been "hotter" than 1 million degrees, and confinement time never exceeded 1 thousandth of a second.**

The results were to good to believe

- **Artsimovitch offers his Western colleagues to come to Kurchatov and "check" the reality of these results**
- **A British team from Culham goes to Moscow.**
- **I am exchanged for the team and go to Culham**
- **Implementing a newly developed temperature measurement technique ("Thomson scattering") N. Peacock reaches the conclusion:**

  The reality is even better that had announced at the Novosibirsk conference a year earlier

  (As I remember almost twice better)

- **It was a "*giant leap*" in fusion research.**

Proliferation of Tokamaks

- **1973** : TFR tokamak in France.
- **1975 :** T-10 at Kurchatov Institute, Moscow,
- **1976** : Design work on JET begins
- **1978** : D-III, in San Diego,
- **1980 :** ASDEX at the Max-Planck IPP in Garching

ASDEX team will observe "H Mode" (self induced improved confinement) in 1982

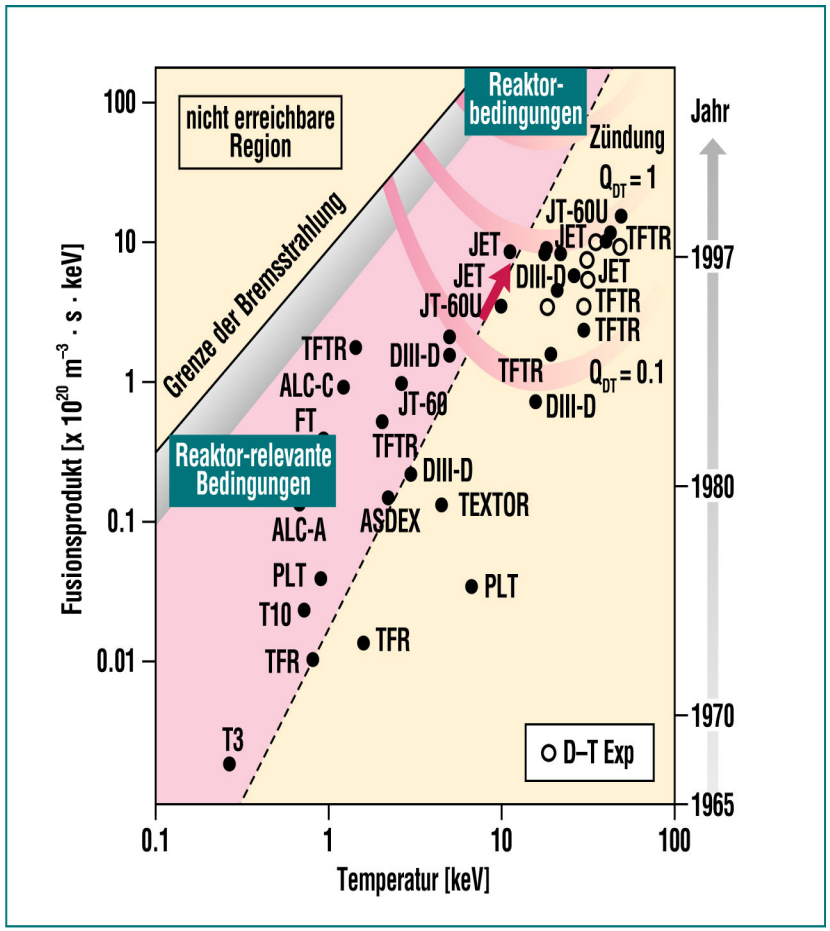
- **1982 :** TFTR (Tokamak Fusion Test Reactor) is operational at Princeton
- **1983 :** JET is completed .
- **1985 :** Japanese tokamak JT-60 starts operation at Naka
- **1991** (November 9) **:** JET achieves 1.5 to 2 MW fusion power
- **1994 :** TFTR produces 10.7 MW of controlled fusion power.
- **1997:** JET achieves a peak fusion power of 16 MW.

How to measure Fusion Performance

Fusion gain Q is determined by

$$\mathbf{Q = P_{fus}/P_{loss}} \sim \mathrm{Tnt_E} \quad \mathrm{kev^{*}sec/m^{3}}$$

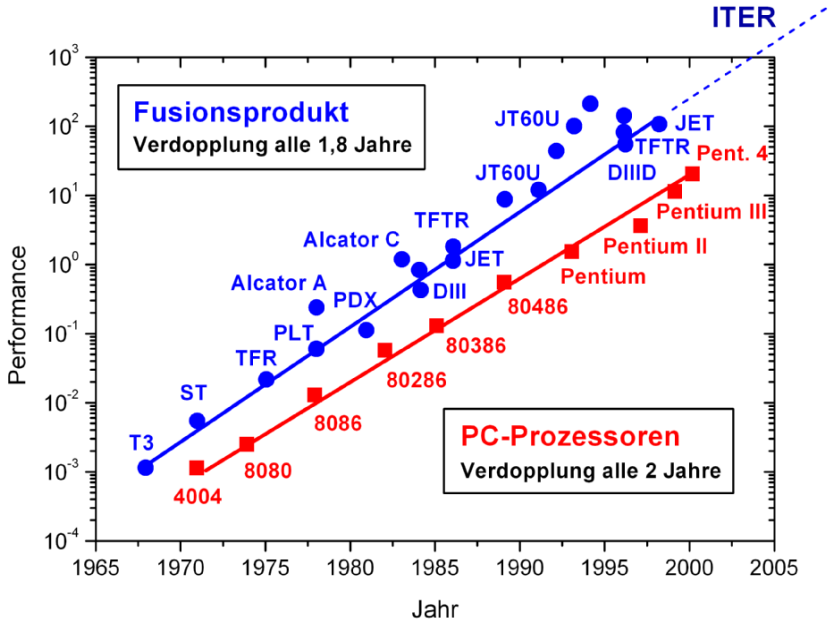
Progress of Tokamaks for 40 years of research



Speed of development of plasma physics

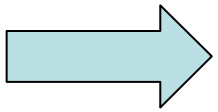
compared

to PC processors



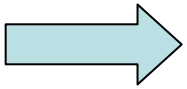
Why Tokamaks?

- Plasma must be as close to thermodynamic equilibrium as possible. Radial gradient of pressure is not possible to eliminate , all other disturbances must be eliminated.



Spherical symmetry of distribution function,
Toroidal magnetic confinement.

Toroidal equilibrium impossible without rotational transformation of toroidal magnetic fields

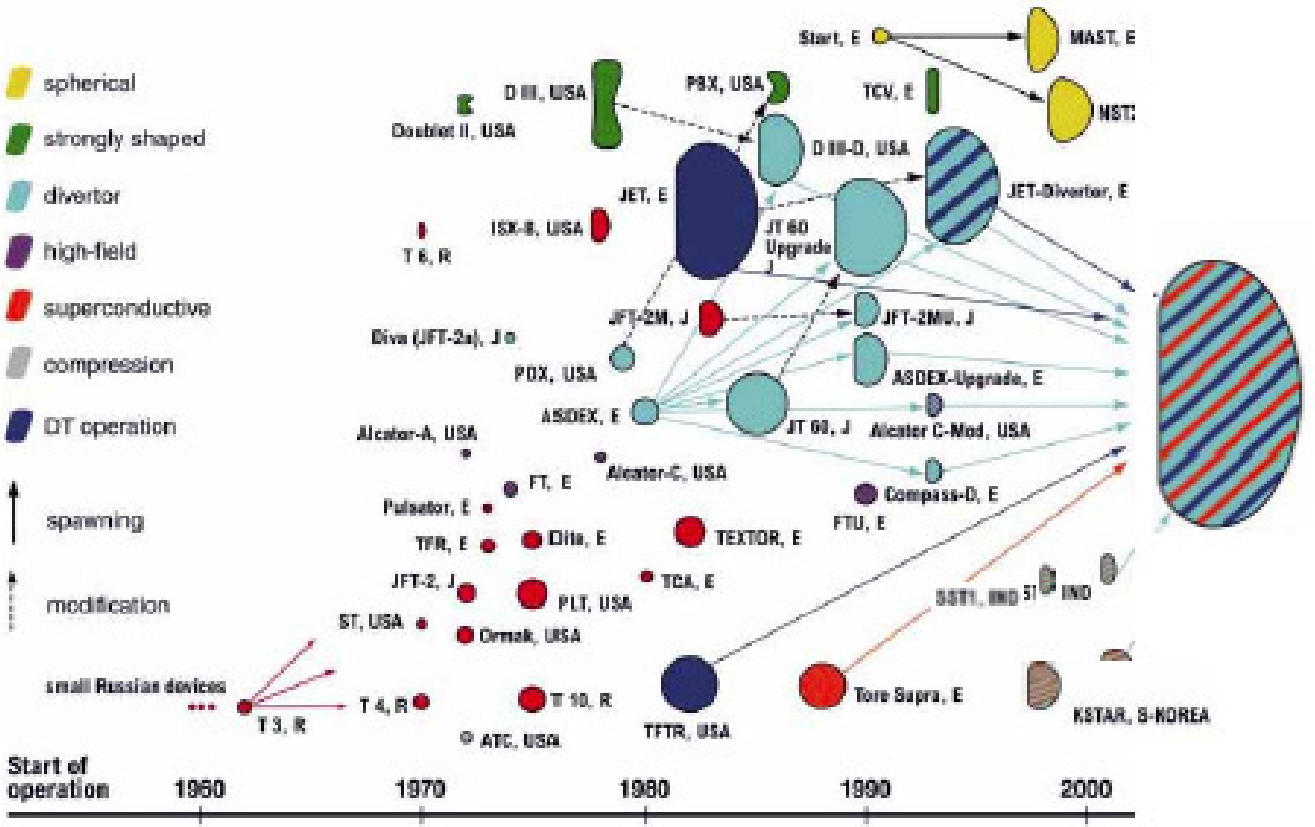


Current in plasma (tokamaks) or
External helical fields (stellarators)

Tokamaks have smaller aspect ratio R/a, they are fatter, radial gradients are smaller. Tokamaks can have smaller R to get the same results as stellarators
But Tokamaks have high toroidal current (another source of instabilities)
What is more important: smaller radial gradients or no current?

Spherical tokamaks may be even better

The range of tokamaks built worldwide have provided physics basis for the next step : ITER.



Why ITER?

- Confinement in tokamaks is improving with size and current.

→ The clear way to improve confinement leads to

big machines, high cost.

- Confinement in tokamaks degrades with higher additional heating power → Even higher size and higher cost are needed to achieve fusion temperature .
- There is no hope to build small cheap model of a fusion reactor.
- Solution: → **share cost**, international cooperation

ITER Cooperation

- **1978 (November): First "Steering Committee of the INTOR Workshop" convenes in Vienna. INTOR was the first attempt at building a truly international fusion programme. INTOR was very close to ITER in its concept.**

- **1985 (November): At Geneva Superpower Summit in 1985 US president Reagan and Secretary General Gorbatchev propose an international effort to develop fusion energy... "as an inexhaustible source of energy for the benefit of mankind". This is the first political step to the ITER programme**

ITER Cooperation

- 1988-1990 **ITER CDA (Garching)**
- 1992-1999 **ITER EDA (San Diego, Garching, Naka).**
- **USA leaves ITER cooperation .The EU ,Japan and Russia decide to continue.**
- 1999-2001 **Redesigning of ITER from Ignition to Q=10 (21MA to 15 MA)**

- 2001: **ITER Council approves design of the ITER machine. Symbolically, the meaning of ITER is changed. It is not the acronym of International Thermonuclear Experimental Reactor anymore, but the Latin word "iter" which means "the way".**
- 2005 (June): **Decision on building ITER in Cadarache is reached on 28th June at ministerial meeting in Moscow**
- 21/11/2006: **ITER Agreement is signed at Elysée Palace in Paris by the seven Parties: China, Europe, India, Japan, Korea, Russian Federation and the United States of America**

21/11/2006:

Now, let us return to work and continue making the history