

# 80 YEARS OF FUSION

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Russian Federation

AAAS 2008 Annual Meeting

## 1930s The Beginning

1928. G. Gamov - the theory

1930. Olifant, Kurchatov, Sinelnikov

exp. - proton beam, Li target

1932. Bucharin proposals to Gamov.

Gamov left USSR

20 years pausa

# Mid-1940s to Mid-1950s

- \* 1946 J.Tompson,M.Blecman - DD, 9MW thermal, torus , 500 kA.
- \* 1944-46 Los Alamos E.Fermi, E. Teller, J.Tac, C.Ulam
- \* 1948 P.Tonemann exp.J=27 kA.
- \* 1951 X.Peron (March 21)
- \* 1951 L.Spitzer Stellarator B=2T, beta=50% (april)
- \* 1957 ZETA

# 1950s-Fusion in the Soviet Union

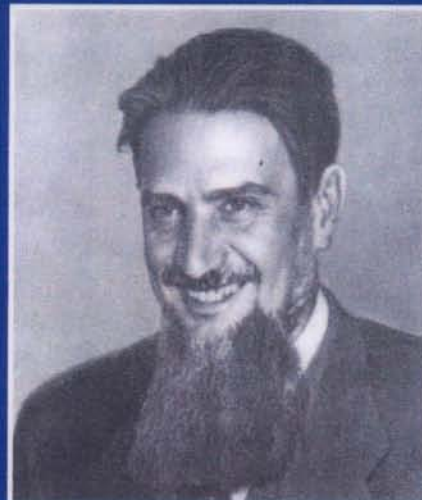
- \* 1950 O.Lavrentiev (July)
- \* 1950 A.Sacharov, E.Tamm Linear  $B=5T$ ,  $\beta=1$  (aug)
- \* 1951 Stalin sign Order for MTR (may 5)
- \*  $R=12m, a=2m, B=5T, n=10^{14}, T=100keV, W=880 Mw$ .
- \* 1952 Neutrons from pinch!
- \* 1955 First tokamak - TMP
- \* 1952





# 1956

For the first time in the world at the International Conference (Harwell, UK) I.V. Kurchatov openly declared on behalf of the Soviet Government that the Soviet Union has its own fusion research program. The final objective of which is to obtain the controlled fusion reaction and to create on its basis an inexhaustible energy source to the benefit of the mankind.



Академик Курчатов И.В.  
(1902-1960 гг.)  
Academician I.V. Kurchatov

Впервые в мире на международной конференции (г. Харуэлл, Англия) И.В. Курчатов открыто объявил от имени Советского Правительства о том, что Советский Союз имеет собственную программу термоядерных исследований, конечной целью которых является осуществление управляемой термоядерной реакции и создание на этой основе неиссякаемого источника энергии на благо всего человечества.



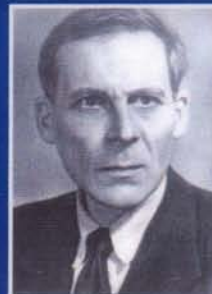
# ОСНОВОПОЛОЖНИКИ ТЕРМОЯДЕРНЫХ ИССЛЕДОВАНИЙ В СССР INITIATORS OF THE FUSION RESEARCH IN THE USSR

## 1950-1954

Worldwide acknowledged outstanding Russian scientists who laid theoretical foundation of fusion and plasma physics research.



Академик  
Тамм И.Е.  
(1895-1971 гг.)  
Academician  
I.E. Tamm



Академик  
Леонтович М.А.  
(1903-1983 гг.)  
Academician  
M.A. Leontovich



Академик  
Сахаров А.Д.  
(1921-1989 гг.)  
Academician  
A.D. Sakharov

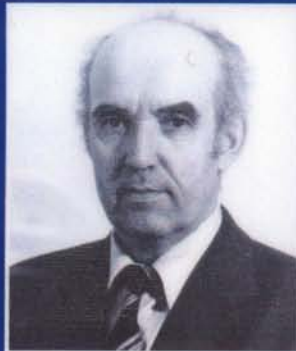
Всемирно признанные выдающие российские ученые, заложившие теоретический базис исследований по управляемому термоядерному синтезу и физике плазмы.



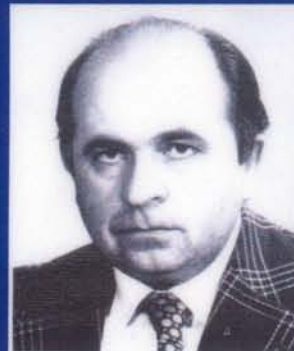
## 1951-1954



Академик  
Арцимович Л.А.  
(1909-1973 гг.)  
Academician  
L.A. Artsimovich



Академик  
Шафранов В.Д.  
(1929 г.р.)  
Academician  
V.D. Shafranov



Академик  
Кадомцев Б.Б.  
(1928-1998 гг.)  
Academician  
B.B. Kadomtsev



Профессор  
Головин И.Н.  
(1913-1997 гг.)  
Professor  
I.N. Golovin



Доктор физ.-мат. наук  
Явлинский Н.А.  
(1912-1962 гг.)  
Dr. of phys. and mathem. sci  
N.A. Yavlinsky

The leading Russian scientists, who worked and implemented under the supervision of L.A. Artsimovich the concept of the fusion facility consisting of the toroidal vacuum discharge vessel and external magnetic system that meets the criteria of the plasma column stability in the magnetic field (Shafranov-Kruskal criteria). Tokamak facility is the world acknowledged leader in fusion research. For the first time in the world, the facility of this type (TFTR, USA, 1997) a breakeven was reached (the parity of the supplied and released energy) as a result of D-T reaction.

Выдающиеся российские ученые, разработавшие и реализовавшие под руководством академика Арцимовича Л.А. концепцию термоядерной установки, состоящей из тороидальной вакуумной разрядной камеры и внешней магнитной системы и удовлетворяющей критерию устойчивости плазменного шнура в магнитном поле (критерий Шафранова – Крускала) – ТОКАМАК (ТОроидальная КАмера МАгнитная Катушка). Установки ТОКАМАК ныне признанный мировой лидер в термоядерных исследованиях, впервые в мире на установке данного типа было получено равенство вложенной и высвободившейся в результате D-T реакции синтеза энергий (установка TFTR, США, 1997 г.).

# Opening Soviet Fusion to the West

- \* 1956 Harwell April
- \* 1956 Stockholm L.Artsimovich,I.Golovin
- \* 1957 Venice “Ionized Phenomena in Gases”
- \* 1958 Geneva Stellarator,but Bohm diffusion!
- \*

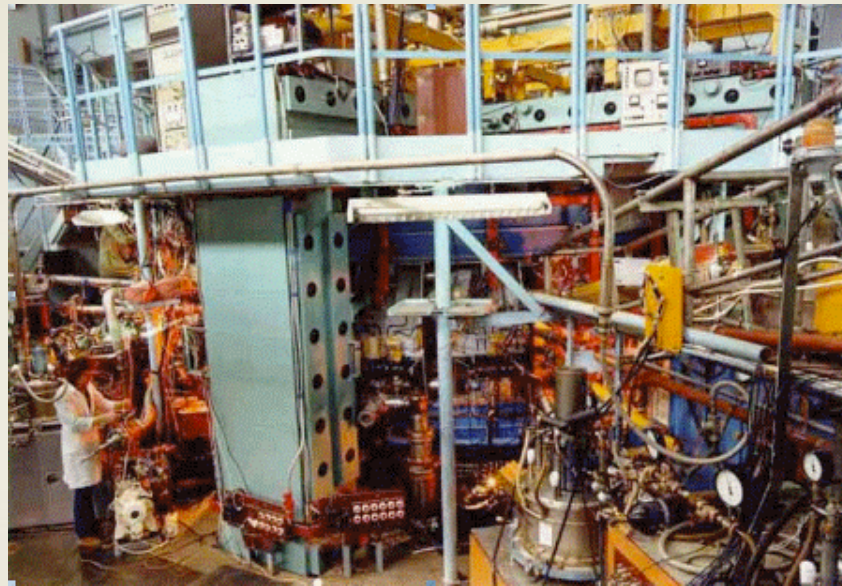
# 1960s- Emergence of Tokamaks

- \* 1961 Ioffe bars
- \* 1965 Culham Artsimovitch: Our confinement 10 times better!  
Spitzer: It is not principal.
- \* 1968 Novosibirsk T-3  $T_e=1\text{keV}$  No Bohm!
- \* 1969 The 2nd Workshop on toroidal systems in Dubna. D. Robinson reports on measurement of the  $T_e$  on Tokamak T-3. TRIUMPH OF TOKAMAKS.
- \* 1975 T-10 and PLT

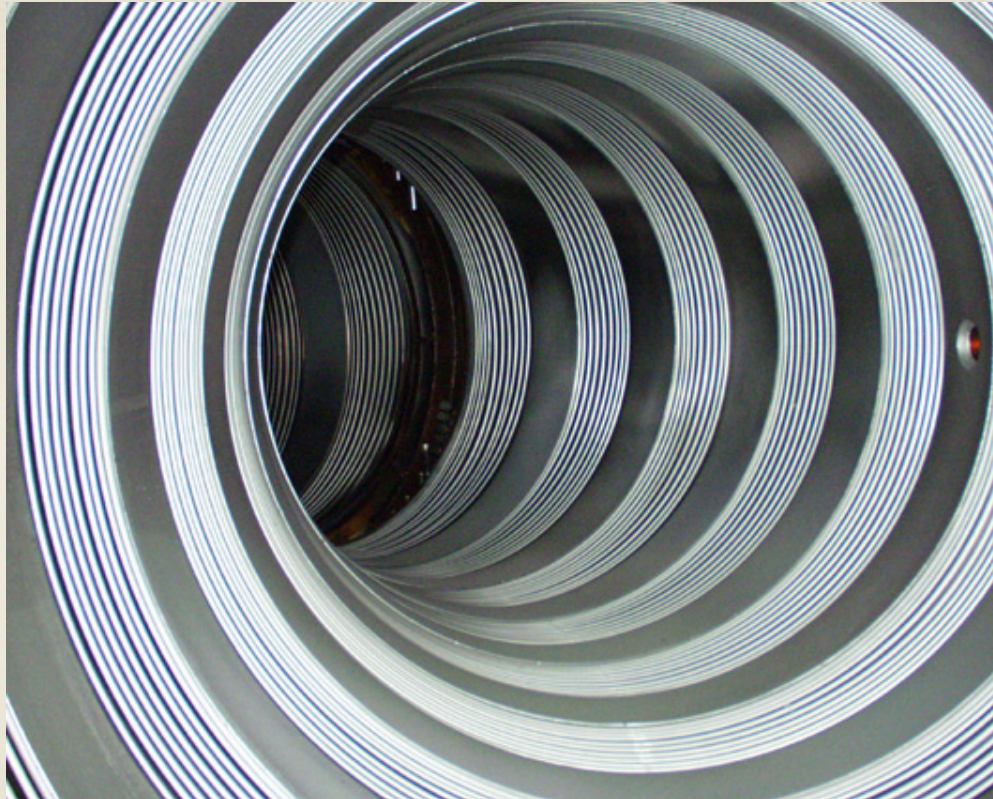


\*

\* T<sub>10</sub>

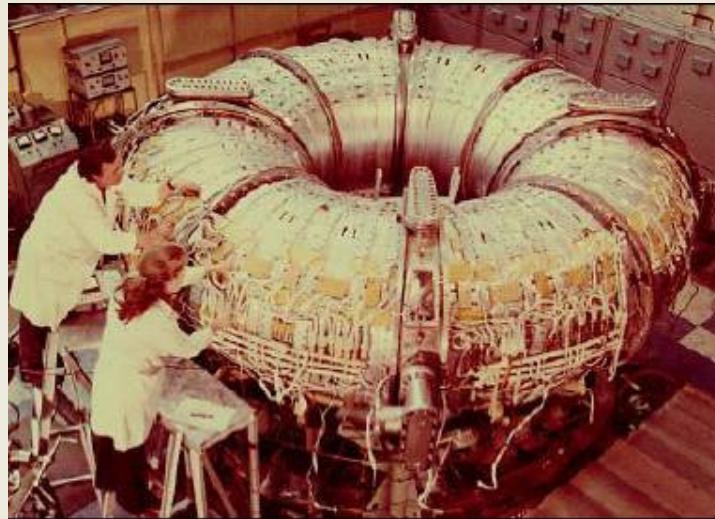


\* TIO





\* T7

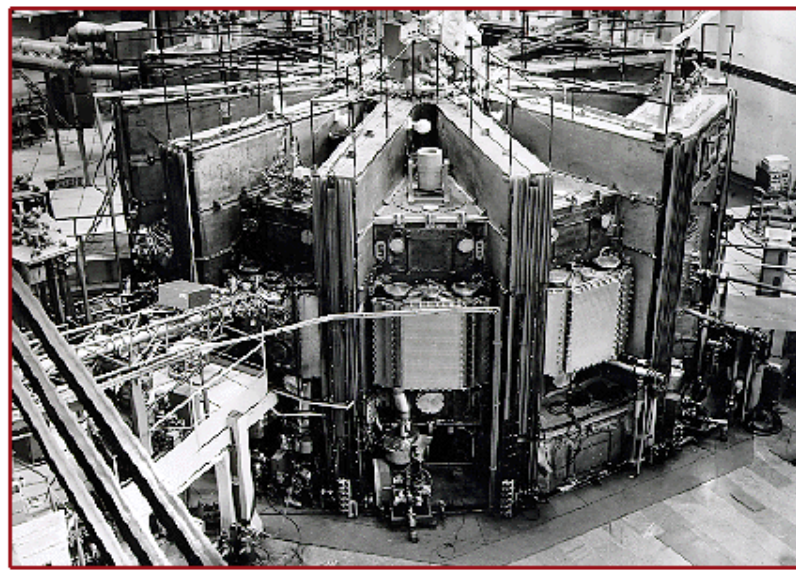


\* Tuman



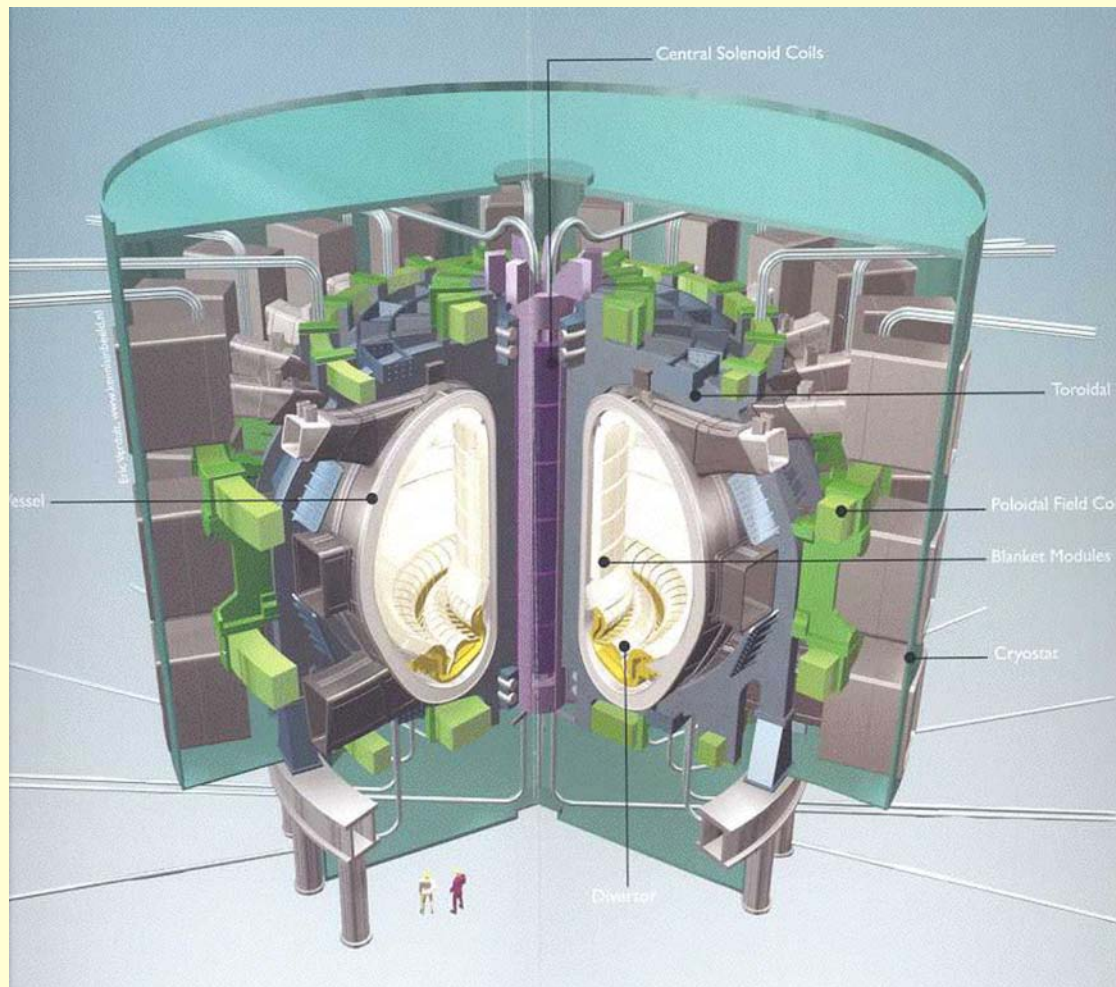


\* T15





# \_\_\_ ITER



# The Birth of ITER

- \* 1978 INTOR agreement
- \* 1985 Paris meeting may
- \* 1985 Geneva Summit november
- \* 1988 ITER conceptual desing (april)
- \* 1990 CDA succesefully concluded (december)
- \* 1992 EDA start,Canada @ Kasachstan join in association

- \* 1988 EDA end, but party decided cut prize by half.  
EDA continues up to 2001
- \* 1999 US leave projec
- \* 2001 ITER FEAT project finish.
- \* 2005 Cadarache site decigion.





21.11.2006

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## The signatories of the ITER Agreement







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More than a half of the world population lives in “ITER countries”





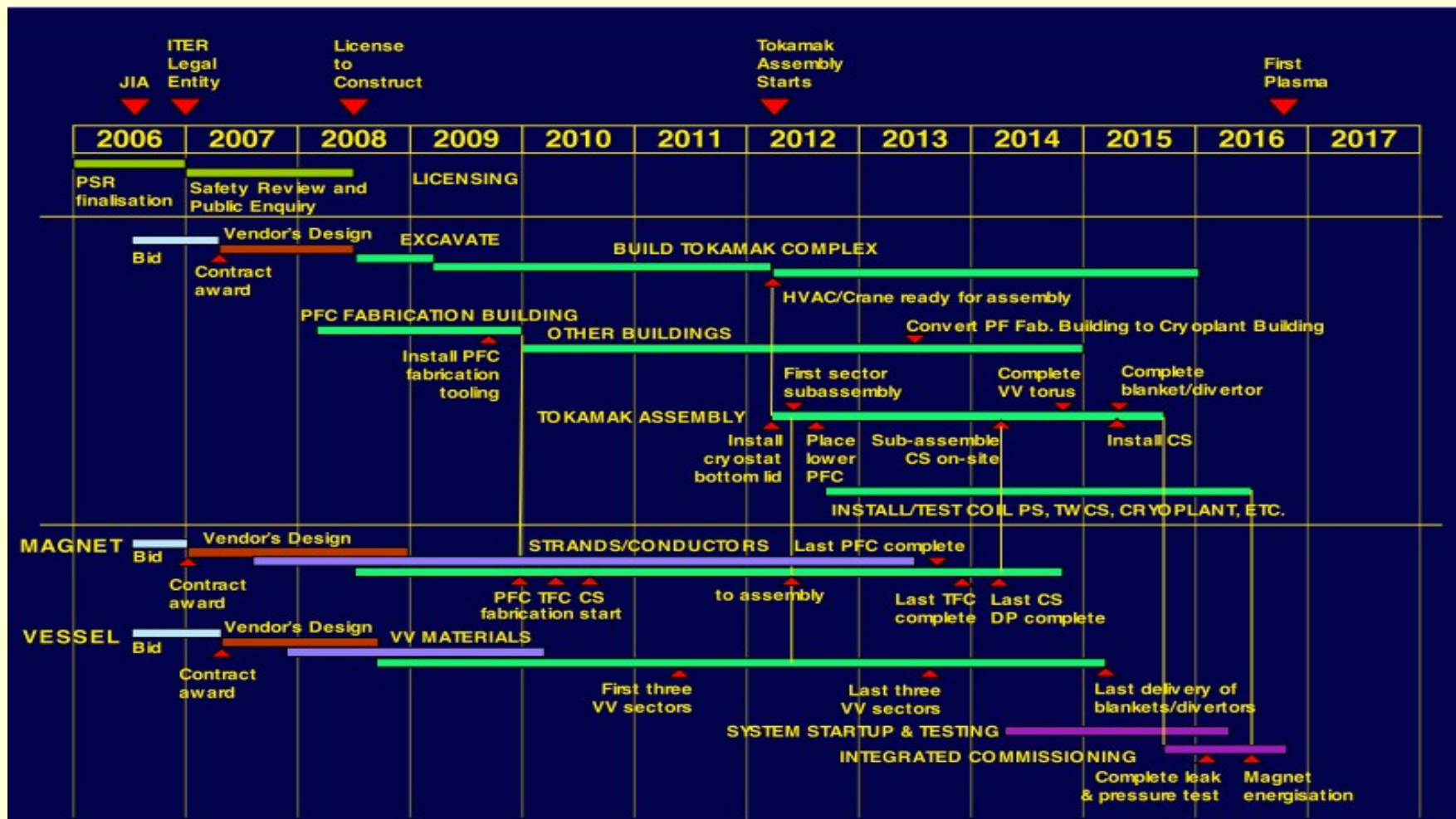
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ITER is constructed in Cadarache, France



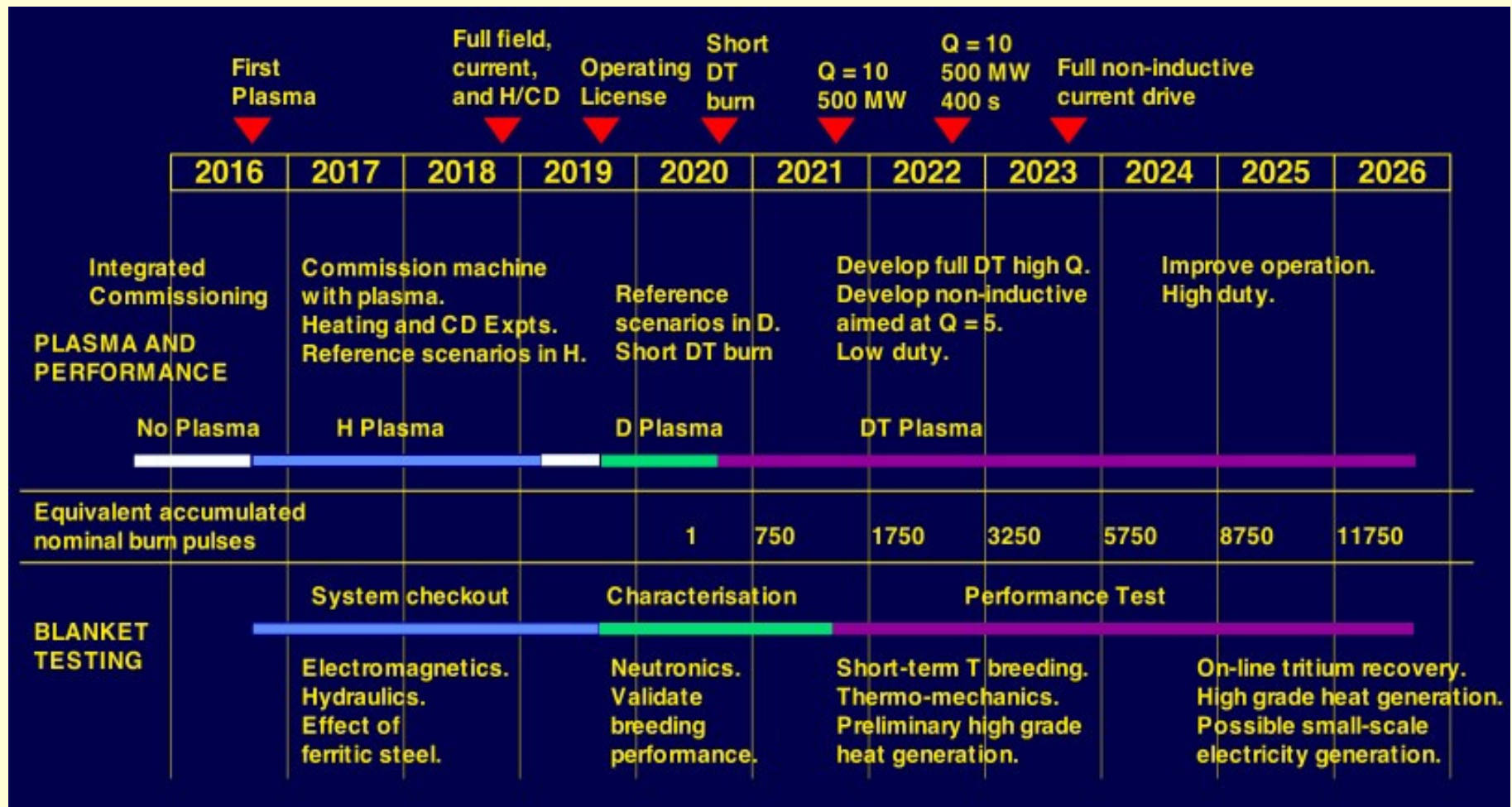


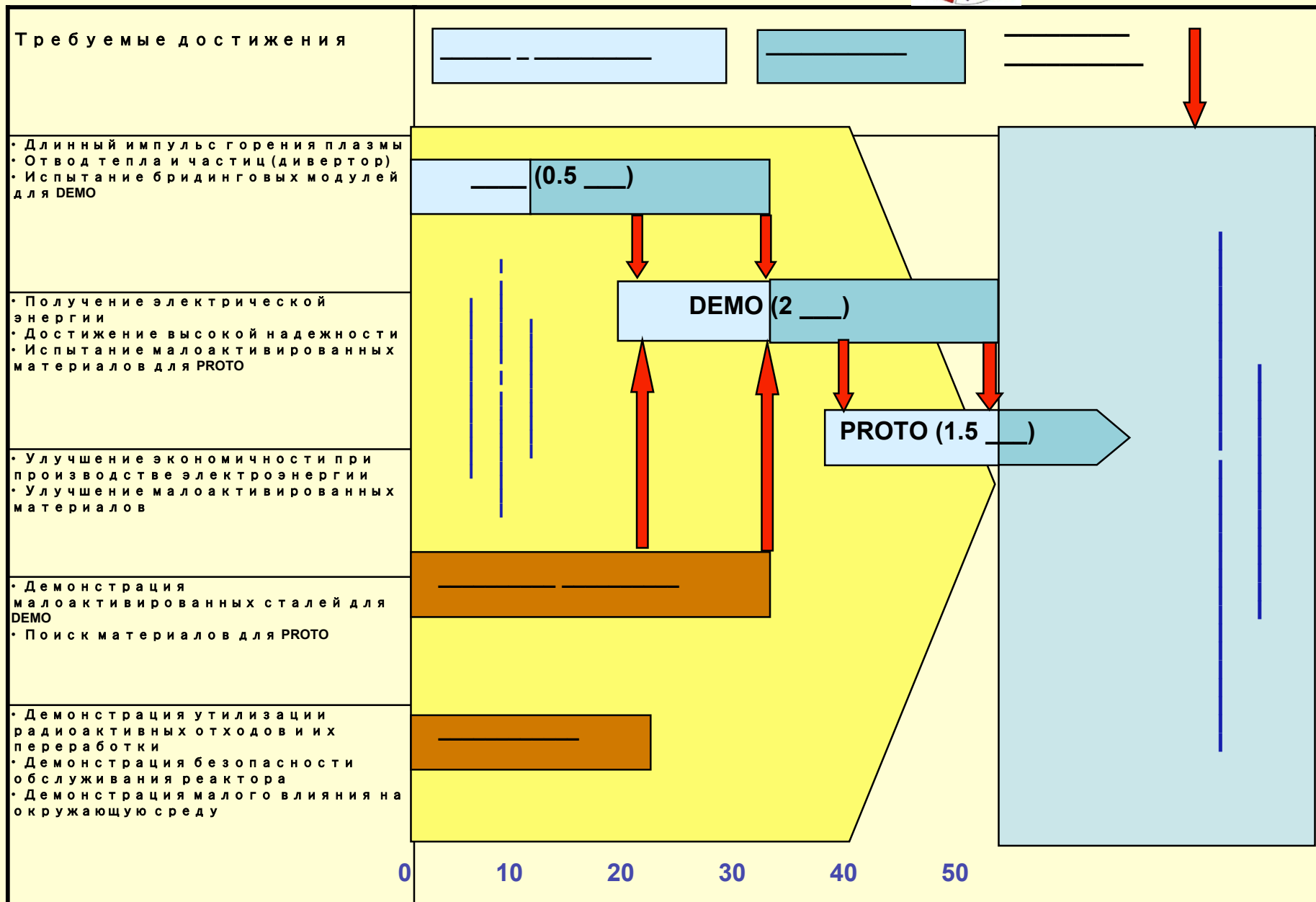
## ITER construction Schedule





## ITER operation and research Schedule





0 10 20 30 40 50



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## First ITER Council Meeting held in the Castle of Cadarache



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Memory photo

### 13. Стеллараторный путь к УТС

The history of the helical magnetic systems is not less dramatic than the tokamak one. Both the PPPL first **figure-eight stellarator** (circular magnetic coils and plasma cross-section, no shear) and the next type **the racetrack stellarator C** ( $l=2$  and  $l=3$  helical windings on U-bend sections, **noncircular plasma cross-section**) had enhanced Bohm diffusion. The same time there were no explicit evidence of Bohm diffusion in stellarators with periodic structure of the magnetic field (**Garching's  $l=2$  stellarators** as well as stellarators of Lebedev Institute in Moscow and of Khar'kov's stellarators). In spite of this the PPPL closed the stellarator program in 70-th in favor of the tokamak one.

The optimization of the magnetic surface boundary (**Garching**) instead of the magnetic field winding position has become the key for the followed improvement the stellarator systems. The use of Hirshman code VMEC without fixing magnetic axis has led to striking favorable results. There was discovered the well optimized helical axis stellarators (**Helias**) with good properties which differs from the **Heliac-system** by the quite moderate excursion of the helical magnetic axis (**см. след. рис.**).



## Стеллараторы с малым широм (длиннопериодные системы)

### ГЕРМАНИЯ

#### WVII-A

1976:  $T_e = 150$  эВ

#### С током

1978:  $T_e = 700$  эВ,  
 $T_i = 400$  эВ

#### Без тока

1984:  $T_e = T_i = 1$  кэВ  
 $\beta = 1\%$

#### WVII-AS (с 1988 г.)

1990:  $T_e = 600$  эВ,  
 $\tau_E = 10$  мс,

#### Без тока

1992: Н-мода  
 $\beta \cong 1\%$

2001:  $T_e = 3$  кэВ  
 $\beta = 2\%$

#### 2006: **WVII-X**

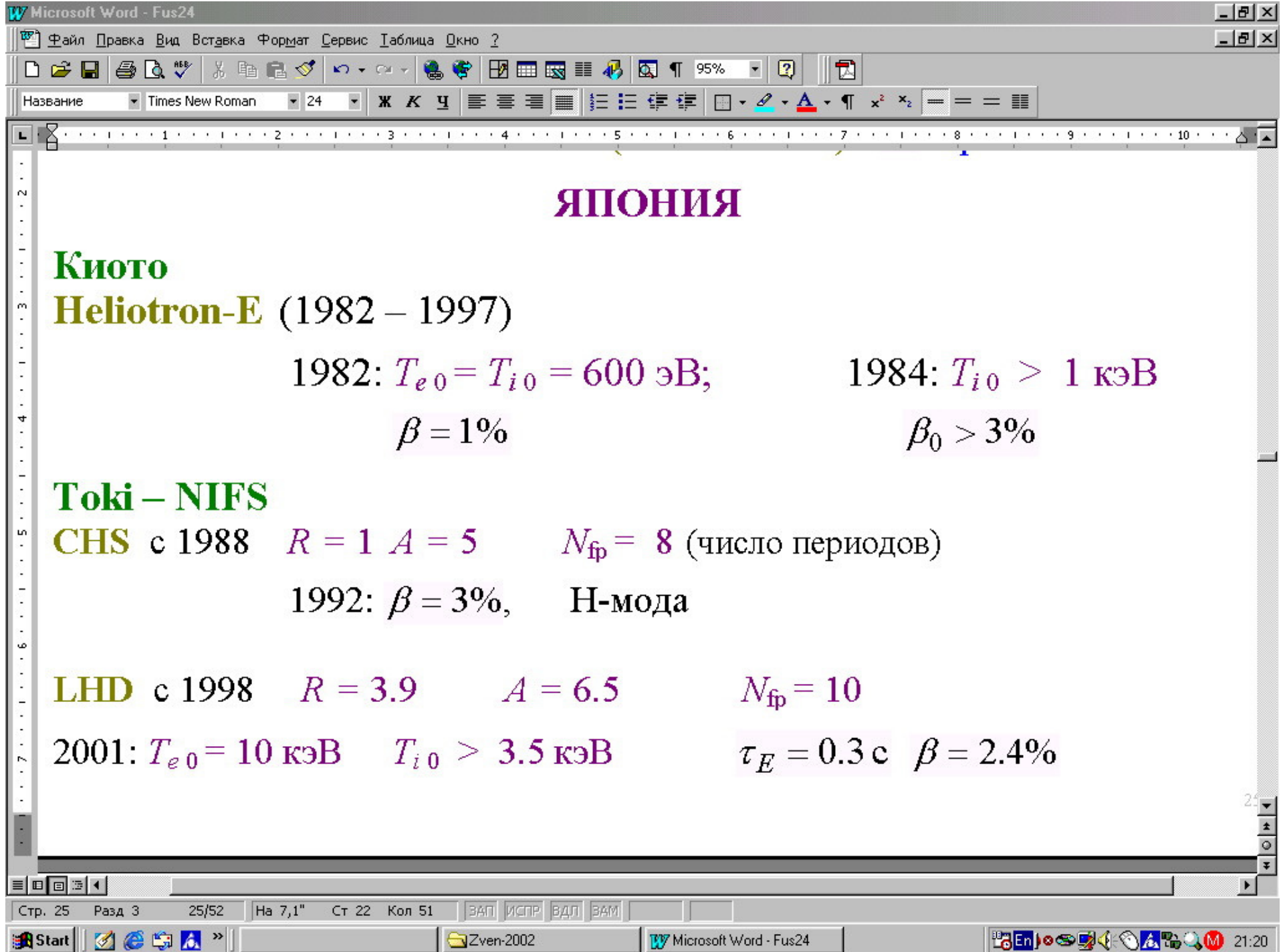
$R = 5,5$

$a_p = 0.55$

$\beta = 4,5\%$

РЕАКТОР: HSR5/22  $a_p = 1.8$   $B = 5$  Т  $N_{\text{coil}} = 50$   $\iota = 0.8 - 1$

HSR4/18  $a_p = 2.0$   $B = 5$  Т  $N_{\text{coil}} = 40$   $\iota = 0.8 - 1$



# ЯПОНИЯ

## Киото

**Heliotron-E** (1982 – 1997)

$$1982: T_{e0} = T_{i0} = 600 \text{ эВ};$$

$$\beta = 1\%$$

$$1984: T_{i0} > 1 \text{ кэВ}$$

$$\beta_0 > 3\%$$

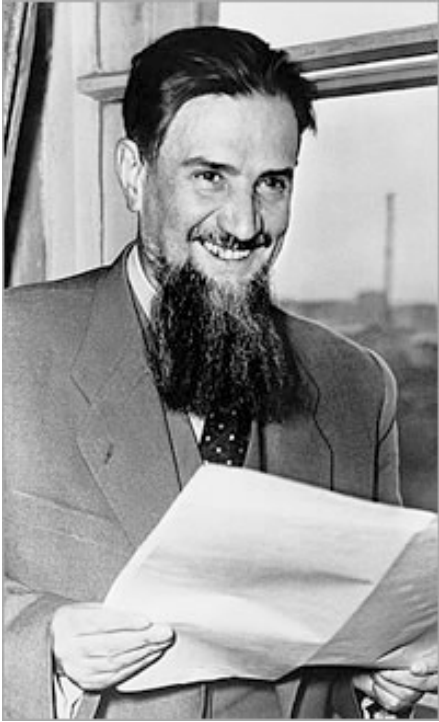
## Токі – NIFS

**CHS** с 1988  $R = 1$   $A = 5$   $N_{fp} = 8$  (число периодов)

$$1992: \beta = 3\%, \quad \text{H-мода}$$

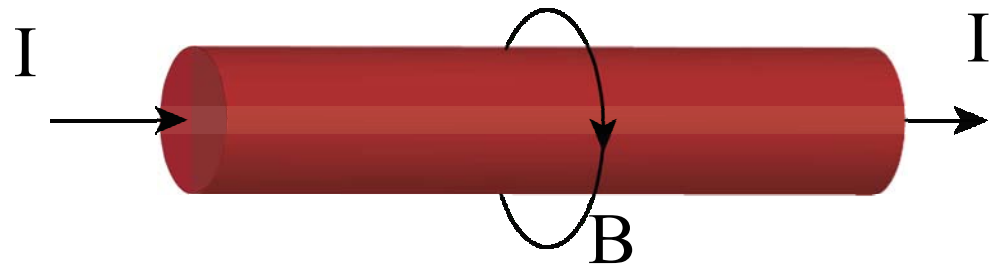
**LHD** с 1998  $R = 3.9$   $A = 6.5$   $N_{fp} = 10$

$$2001: T_{e0} = 10 \text{ кэВ} \quad T_{i0} > 3.5 \text{ кэВ} \quad \tau_E = 0.3 \text{ с} \quad \beta = 2.4\%$$



# Z-pinch as a Pioneer of Controlled Nuclear Fusion

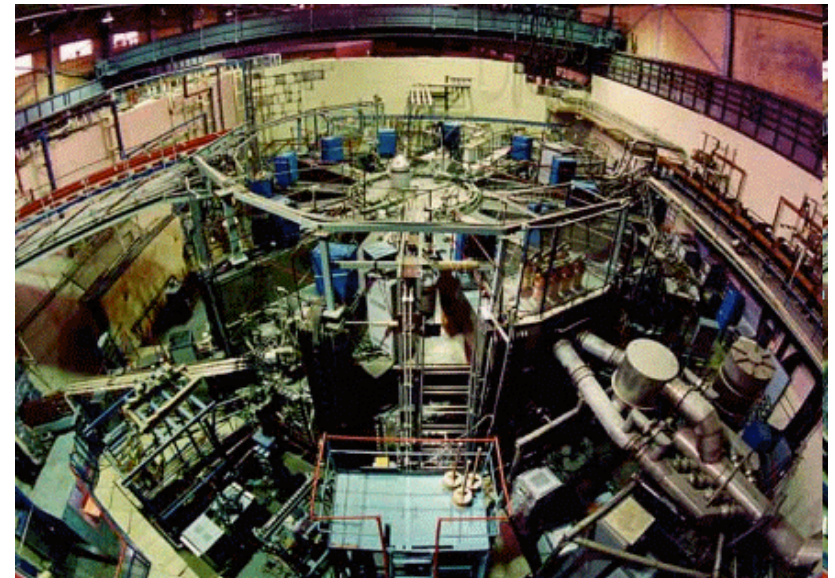
Harwell, 1956. Igor Kurchatov opens the Soviet Fusion Program



This program at that moment was based, in particular, on Z-pinches.

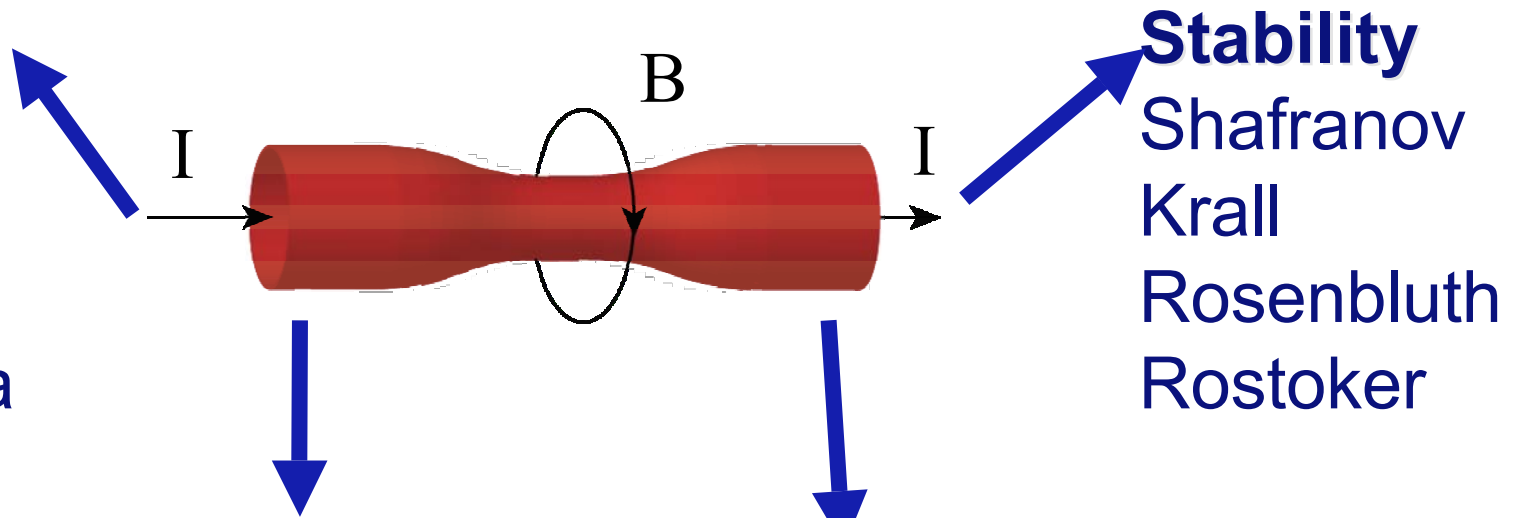
Z-pinch, compared to magnetic traps, is to more extent dynamical system.

Nevertheless, it has provided the base to develop the toroidal quasi-steady traps, to wit, tokamaks.



## Dynamics

Leontovich  
Imshennik  
Bodin  
Kvartskhava



## Stability

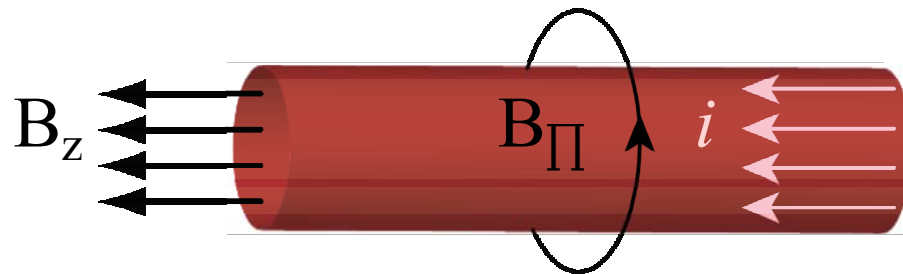
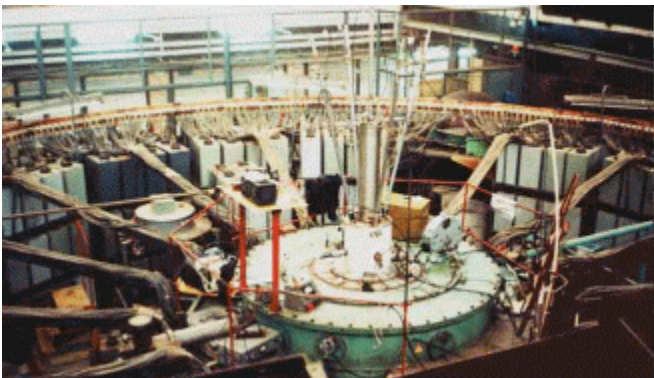
Shafranov  
Krall  
Rosenbluth  
Rostoker

## Plasma Focus

Filippov  
Maiser  
Maisonnier  
Sadovski  
Krauz

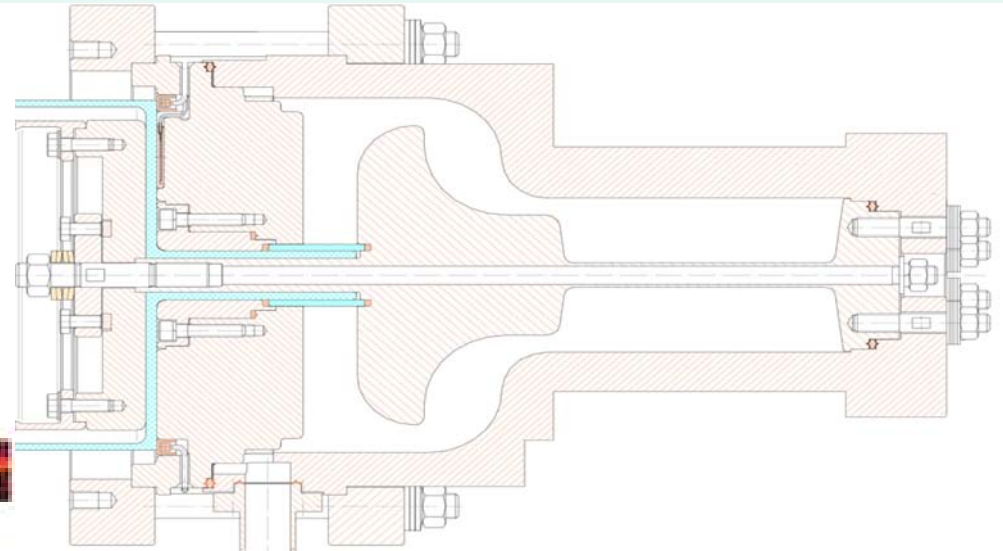
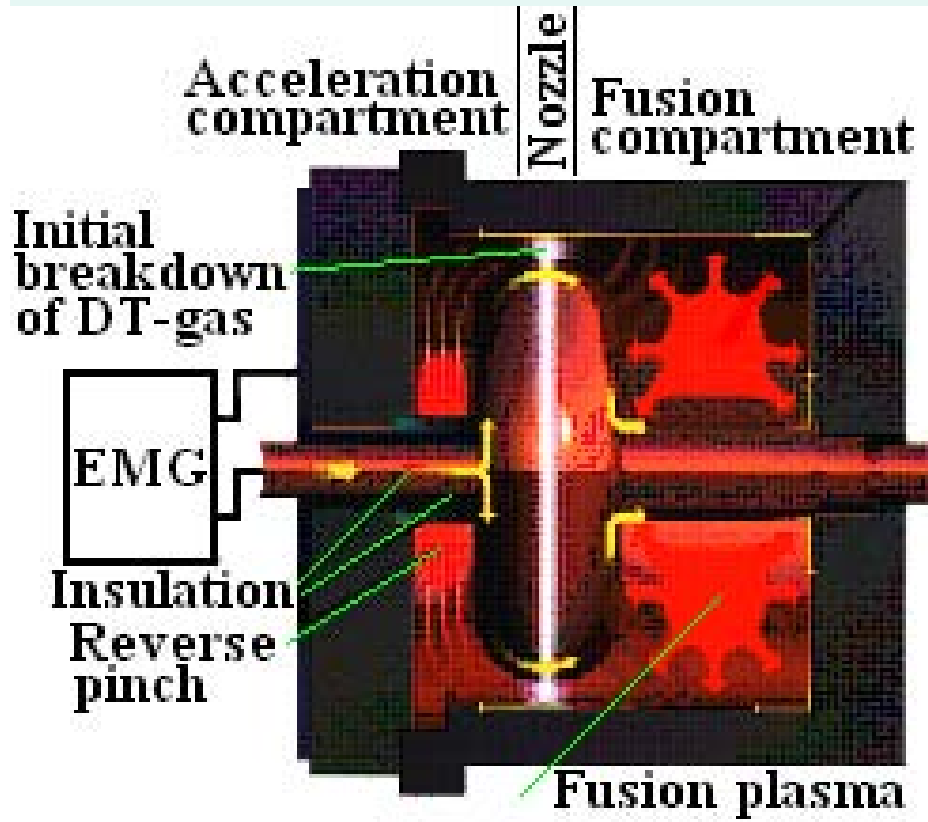
## Liner

Sakharov  
Pavlovski  
Alikhanov  
Velikhov





# EXPERIMENTS ON THE PROLONGED PLASMA CONFINEMENT WITH THE FUSION CHAMBER MAGO

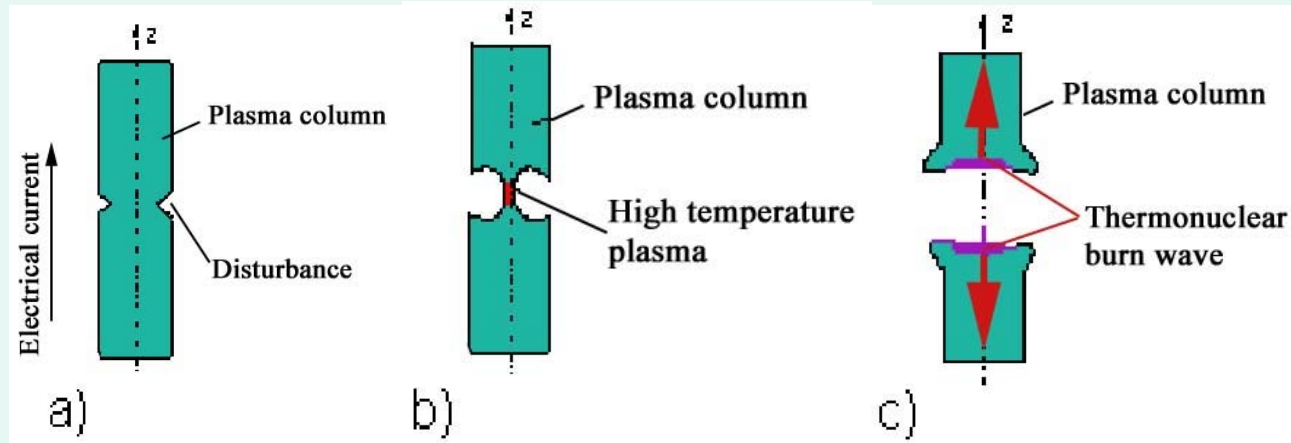


Plasma chamber MAGO-IX

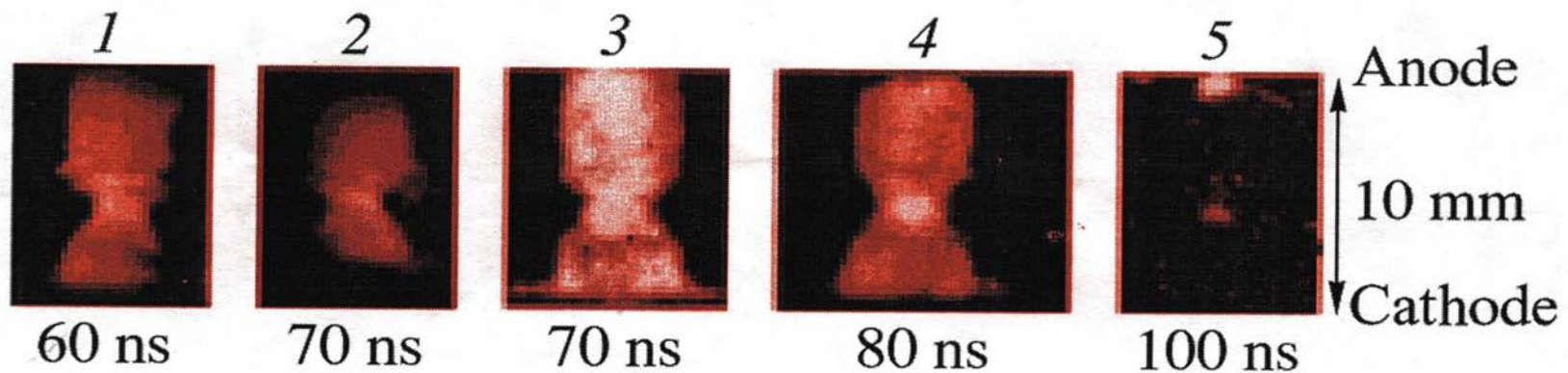


Physical scheme of MAGO chamber operation

# Prospect of ignition in the Z-pinch neck



Agar-agar foam,  $\rho_0 = 0.1 \text{ g/cm}^3$ .

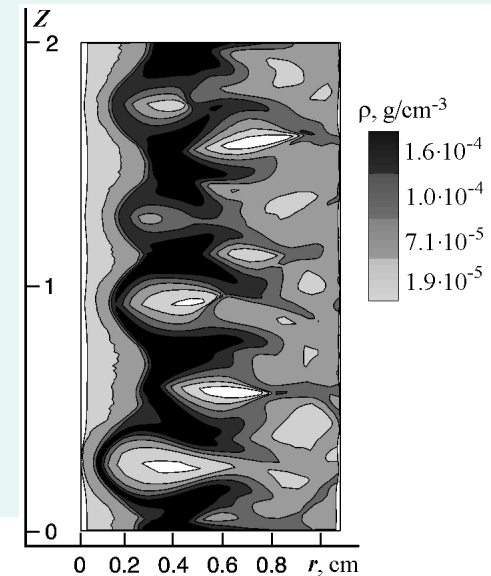
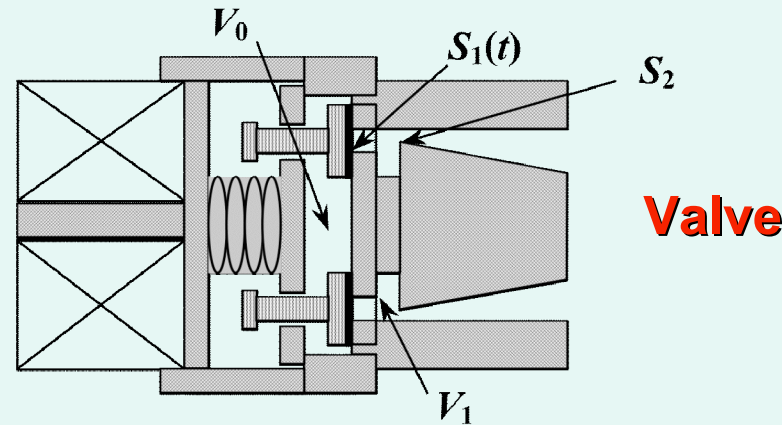
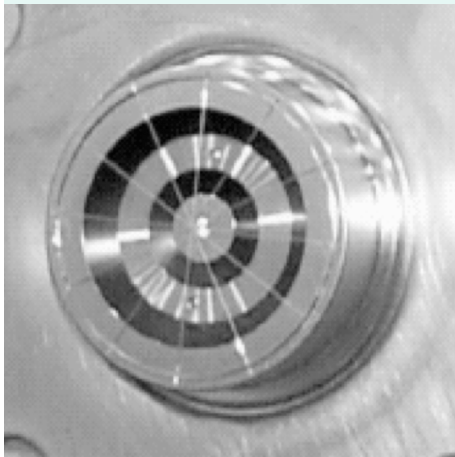


ICT photographs in the optical range (1,2)  
and VUV-SXR range (3,4,5)

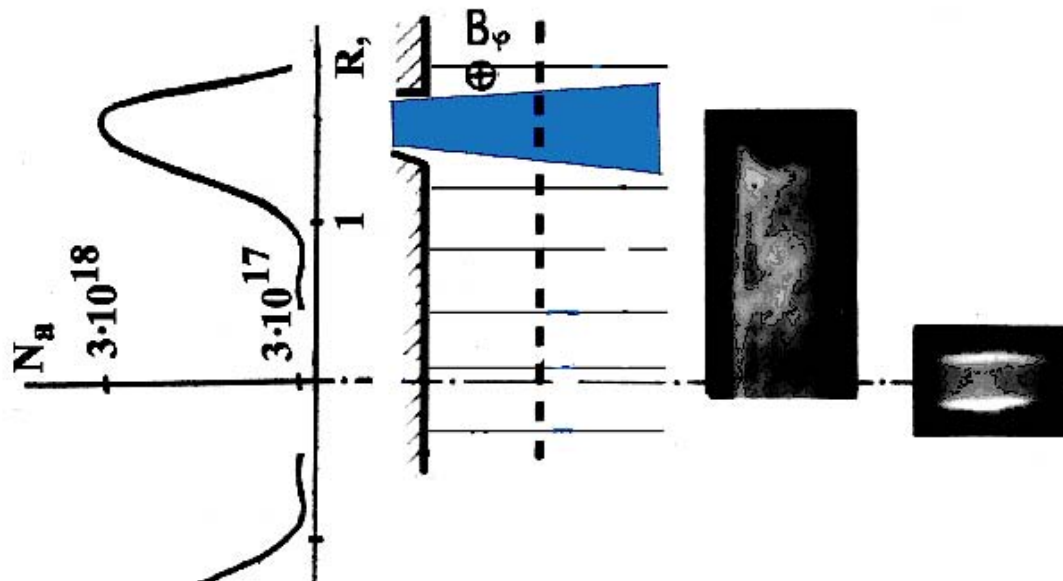
# FAST Z-PINCHES (Smirnov, Rudakov, Quintenz, Cuneo, Deeney, Matzen, McDaniel, Mehlhorn, Olson...)

## Nozzle

### 1. Gas-Puff Liners



**Instability**



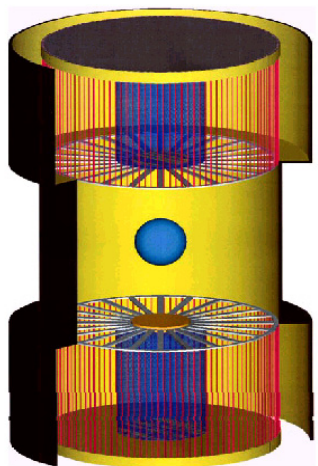
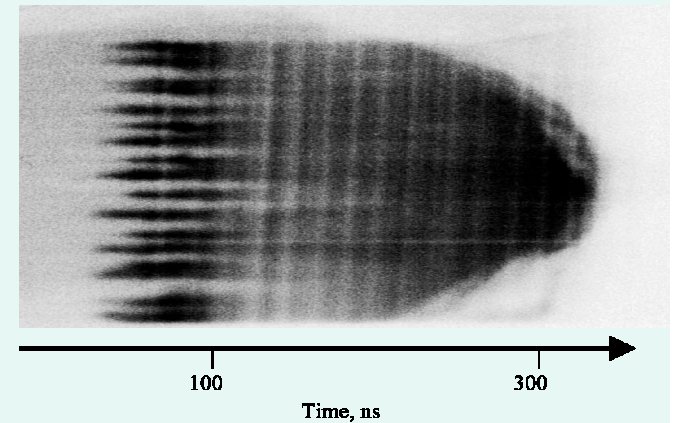
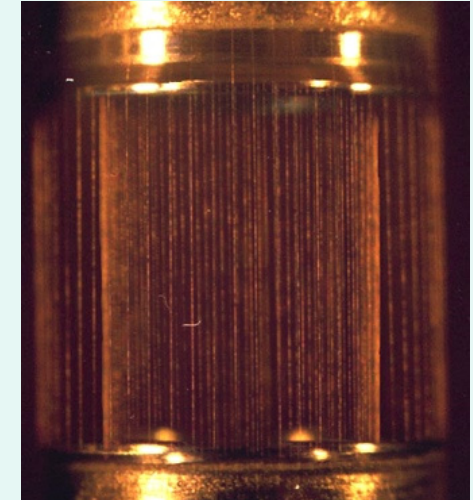
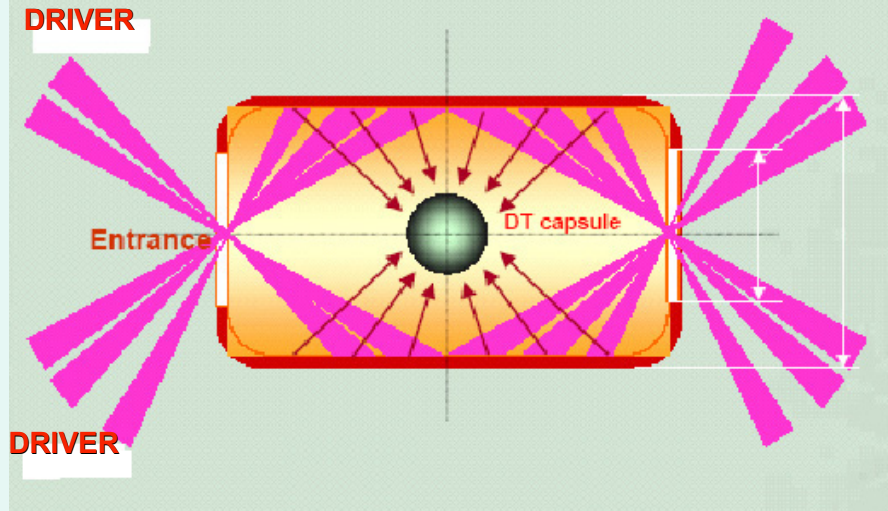
**Stabilization by the applied longitudinal magnetic field**



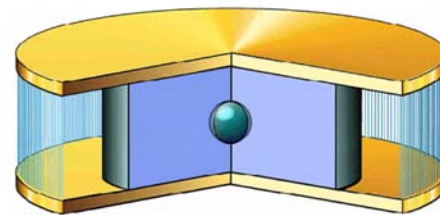
## 2. HOHLRAUM. HIGH-CURRENT WIRE ARRAYS

Indirect drive

Capsule inside the hohlraum, the surface is ablated by radiation.



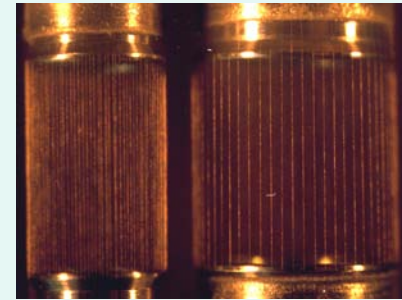
Double-ended  
vacuum Hohlraum  
(SANDIA)



Dynamic Hohlraum  
(TRINITY)

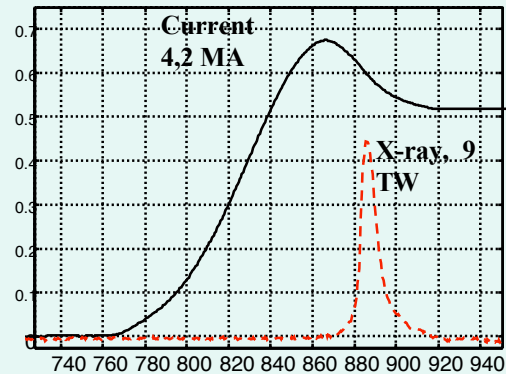
# FAST INTENSIVELY RADIATING Z PINCHES DRIVEN BY PULSED POWER GENERATOR ANGARA-5-1

SRC RF TRINITI, TROITSK



W wire liners,  $N=120$   
 $d=6\mu\text{m}$   $D_1=12\text{ mm}$   $D_2=20\text{ mm}$

NUMBER OF UNITS: 8  
CURRENT PULSE: 4 \_\_, 90 ns  
Load- WIRE ARRAYS:  
ENERGY 100 kJ  
PULSE DURATION 6-10 ns



Intensively radiating Z pinches of the matter with high atomic number is a driver for ICF on base of the indirect ICF targets compression



# Double Liner Implosion Dynamics

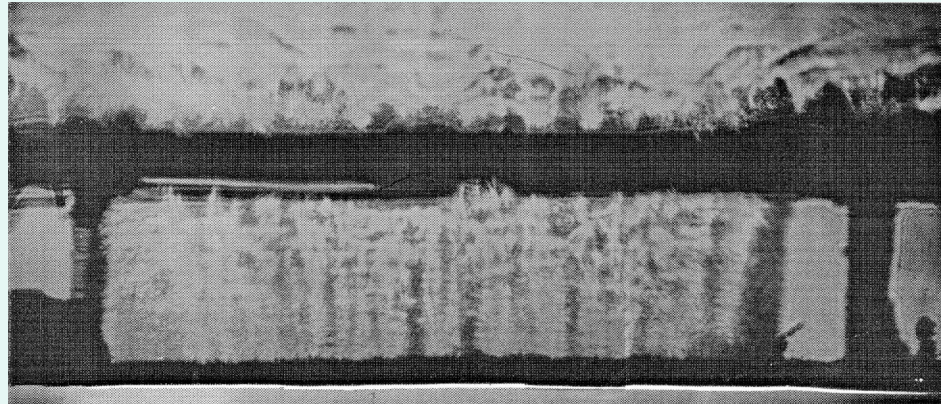
$$V_{\max} \approx (5-7) \cdot 10^7 \text{ cm/s}$$

$$R_{\text{out}} = 16 \text{ mm} \quad m_{\text{out}} = 100 \dots \text{g/cm (Xe)}$$

$$r_{\text{in}} = 2 \text{ mm} \quad m_{\text{in}} = 200 \dots \text{g/cm (foam)}$$

*Laser shadow pictures*

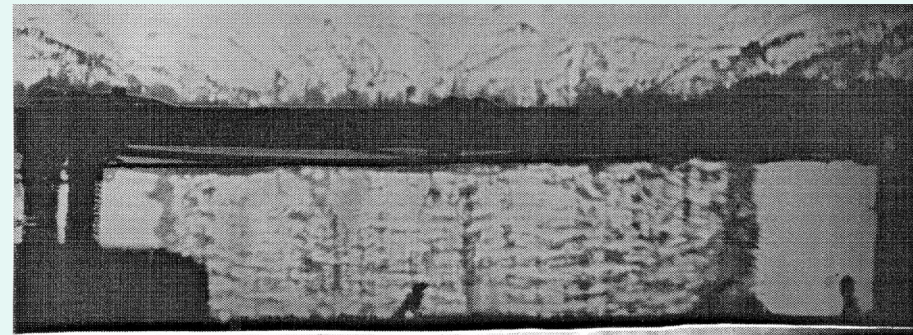
*60 ns before pinch*



← Anode

← Cathode

*45 ns before pinch*

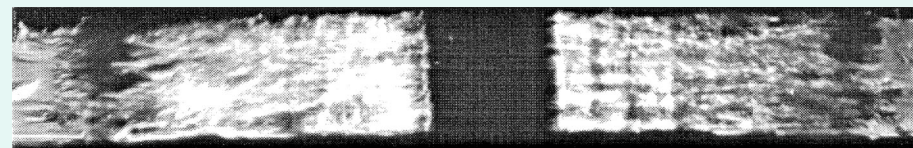


← Anode

← Cathode

← Anode

*15 ns before strike*



← Cathode

← Anode

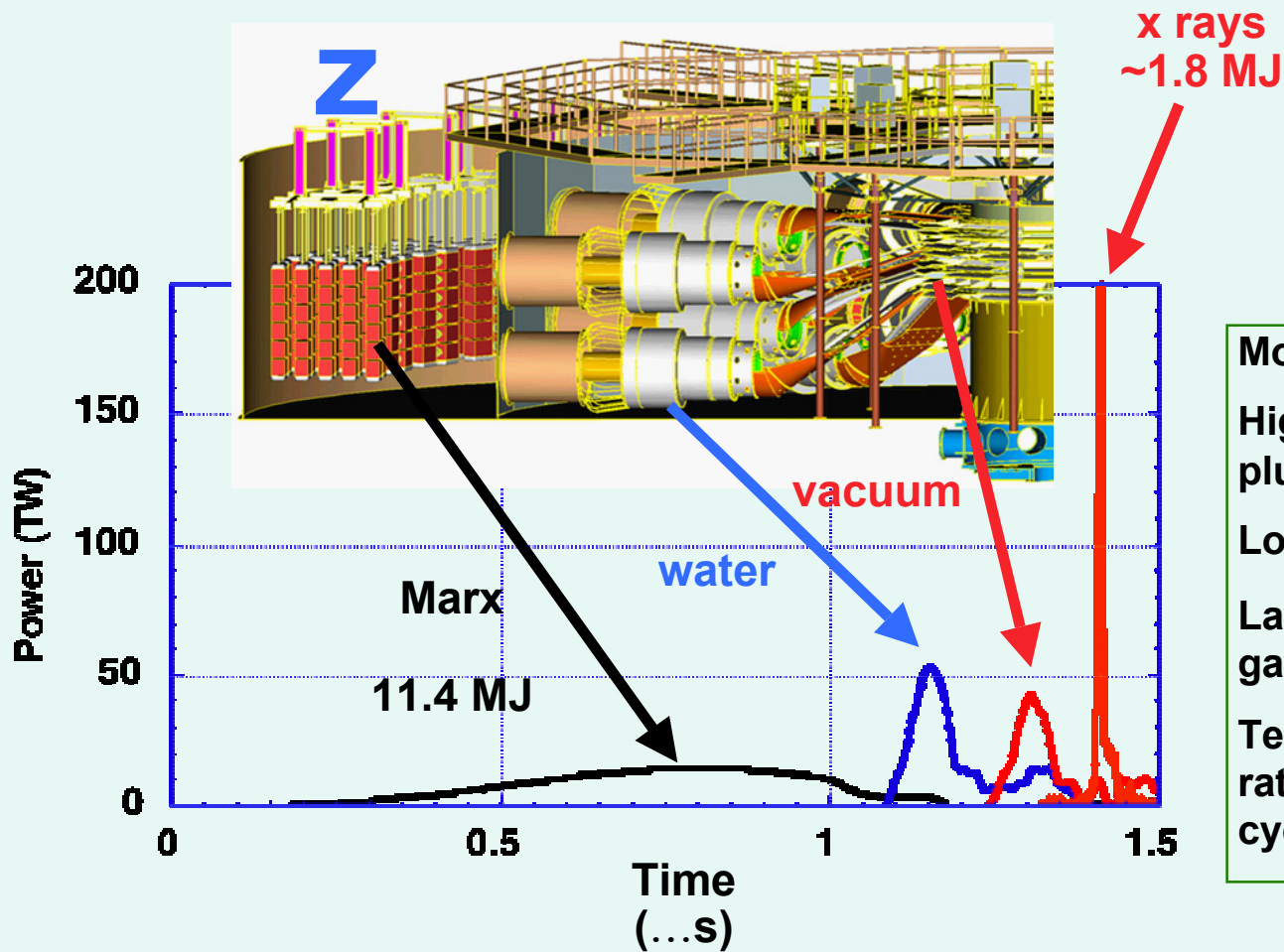
*1 ns after strike*



← Cathode



# Z/ZR Pulsed Power Machine



**Modular**

**High Efficiency (> 15% wall-plug to x-rays)**

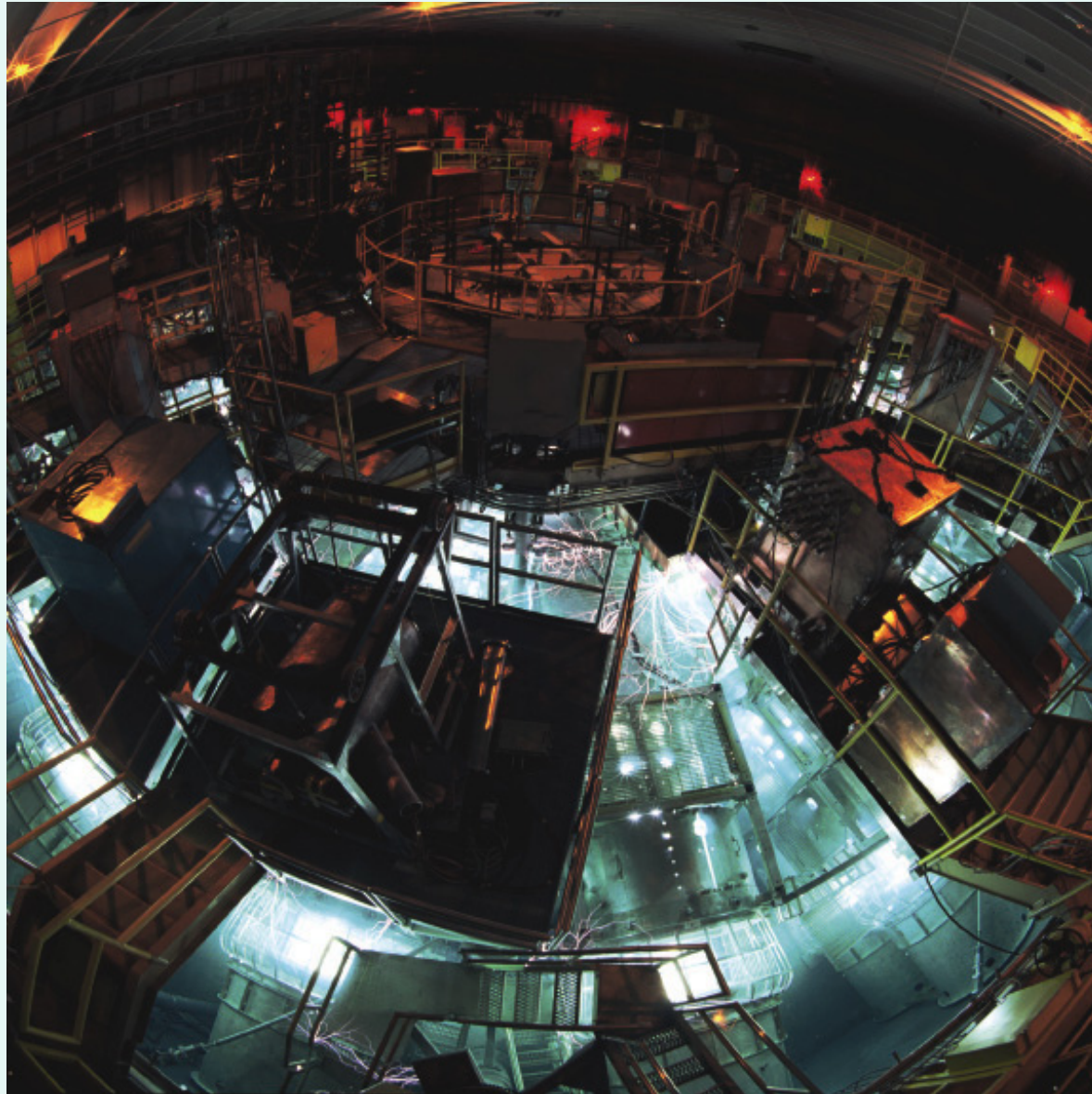
**Low cost (< \$30/J)**

**Laser-triggered pressurized gas switches**

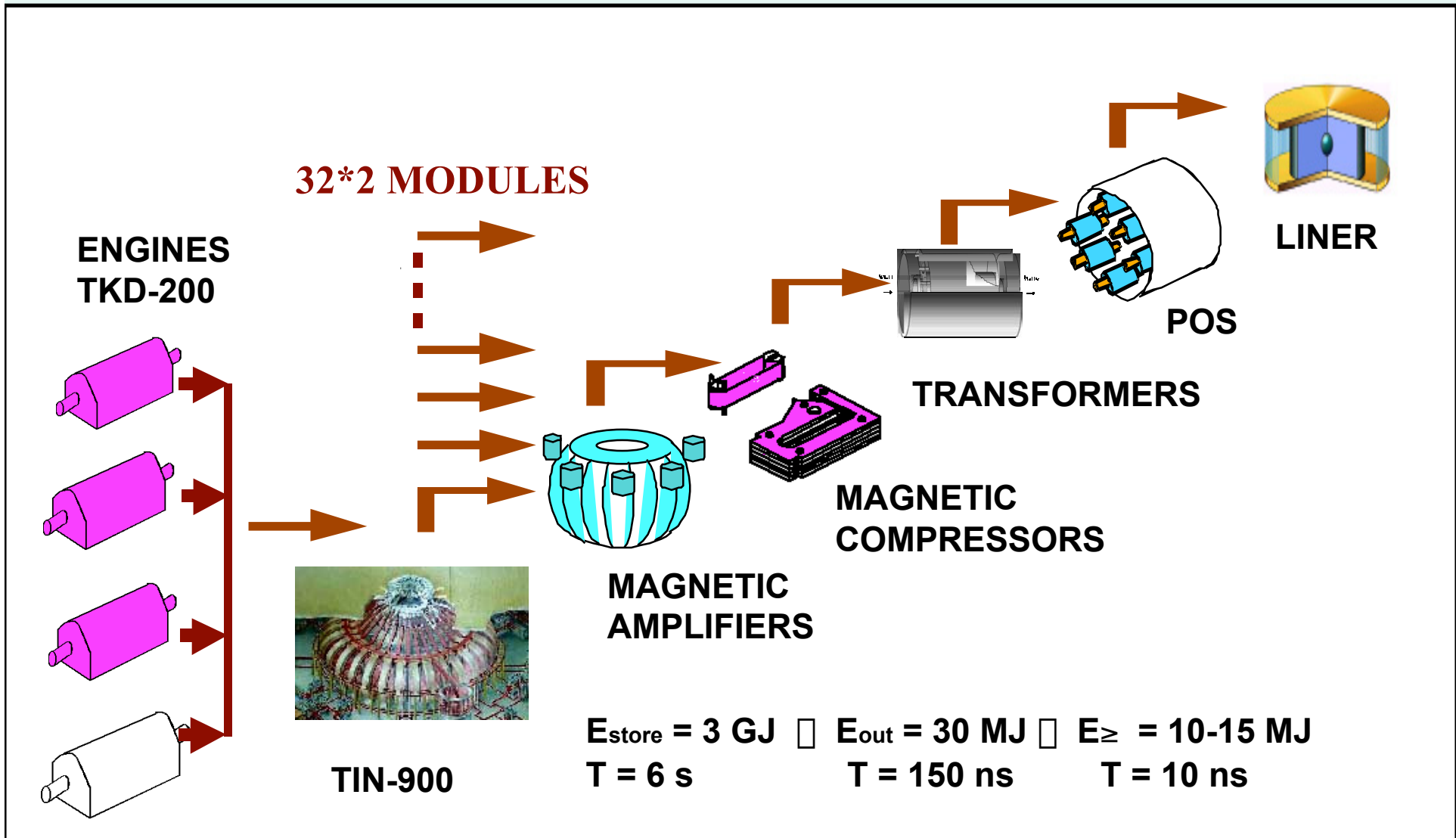
**Technology is possibly repeatable at 0.1 Hz with fast-cycling Marx**

# “Z” ,SANDIA National Laboratories

1.8 MJ in SXR range; 200 TW



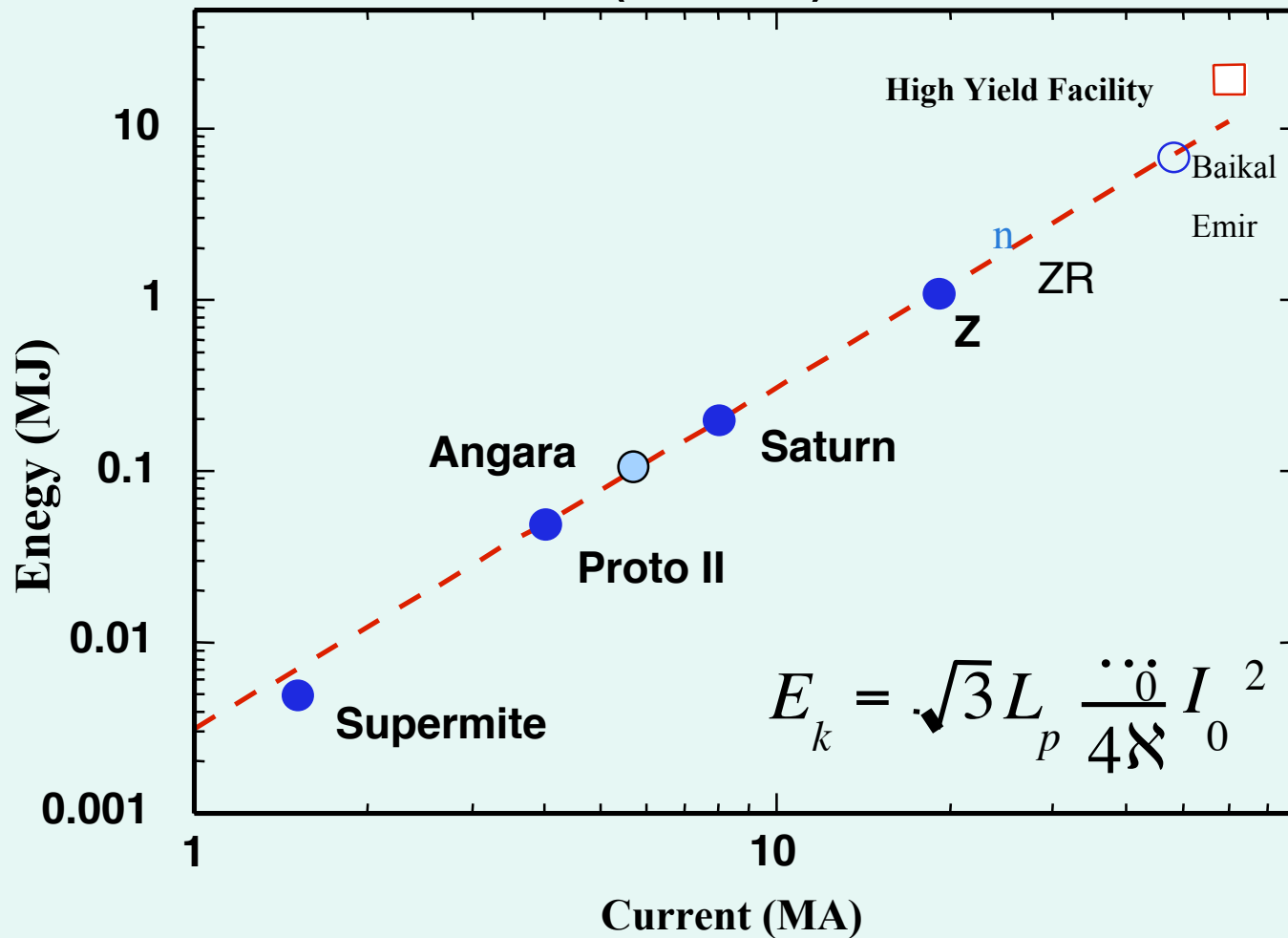
# BAIKAL, THE NEW GENERATION OF PULSED POWER MACHINES



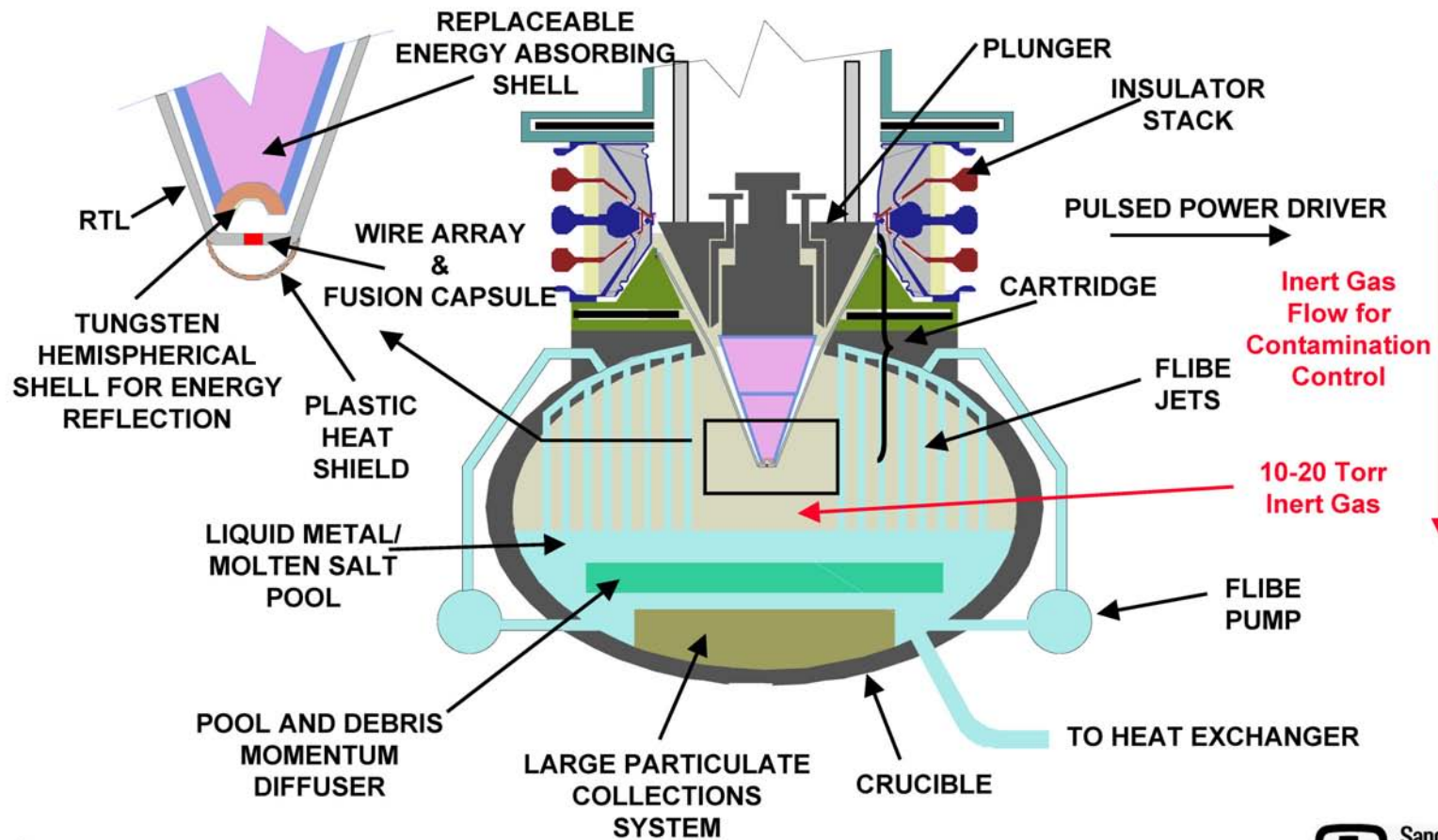


# AT PRESENT MOMENT, Z-PINCH PROVIDES MAXIMAL ENERGY OF X-RAY PULSE

The level of energy achieved is close to that necessary for ignition  
(~ 10 MJ)



# Z-Pinch Power Plant Crucible Details



9

GER 9/15/04



The basic functional elements  
of ZP-3 reactor chamber

$I = 60$  MA - for ignition.

$I = 90$  MA - for IFE power plant.