80 YEARS OF FUSION

E.Velikhov
Kurchatov Institute, Moscow,
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

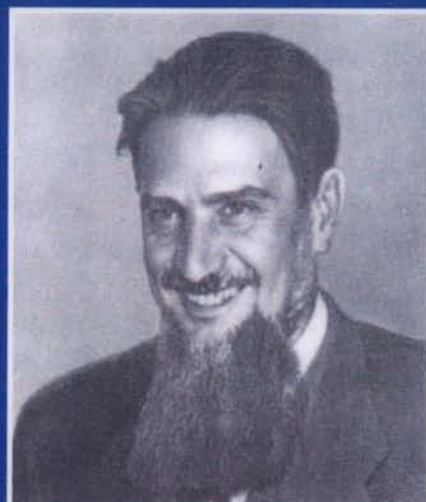
- 1946 J.Tompson,M.Blecman - DD, 9MWthermal, torus , 500 kA.
- 1944-46 Los Alamos E.Fermi, E. Teller, J.Tac, C.Ulam
- 1948 P.Tonemann exp.J=27 kA.
- 1951 X.Peron (March 21)
- 1951 L.Spitzer Stellarator B=2T, beta=50% (april)
- 1957 ZETA

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 it's own fusion research program. The final objective of which is to obtain the controlled fusion reaction and to create on it's 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. Харуэл, 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

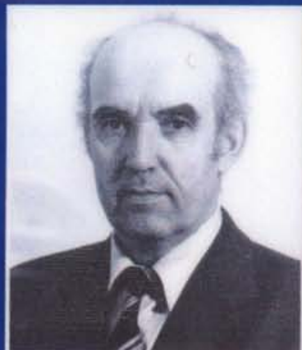
Академик
Леонтович М.А.
(1903-1983 гг.)
Academician
M.A. Leontovich

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

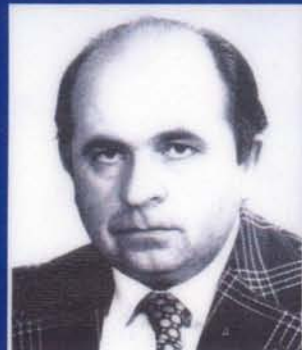
Всемирно признанные выдающие российские ученые, заложившие теоретический базис исследований по управляемому термоядерному синтезу и физике плазмы.

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

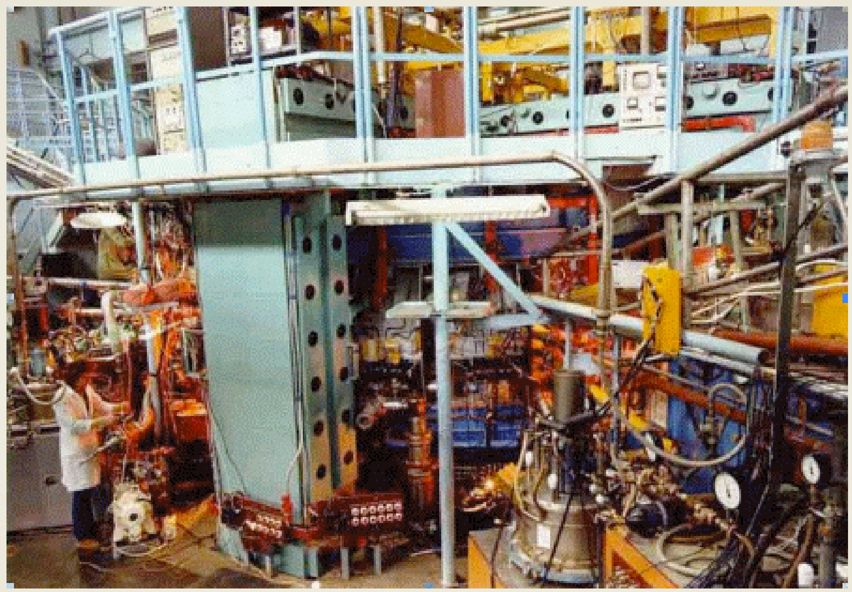
- 1956 Harwell April
- 1956 Stockholm L.Artsimovich,I.Golovin
- 1957 Venice "Ionized Phenomena in Gases"
- 1958 Geneva Stellarator,but Bohm diffusion!
-

1960s- Emergence of Tokamaks

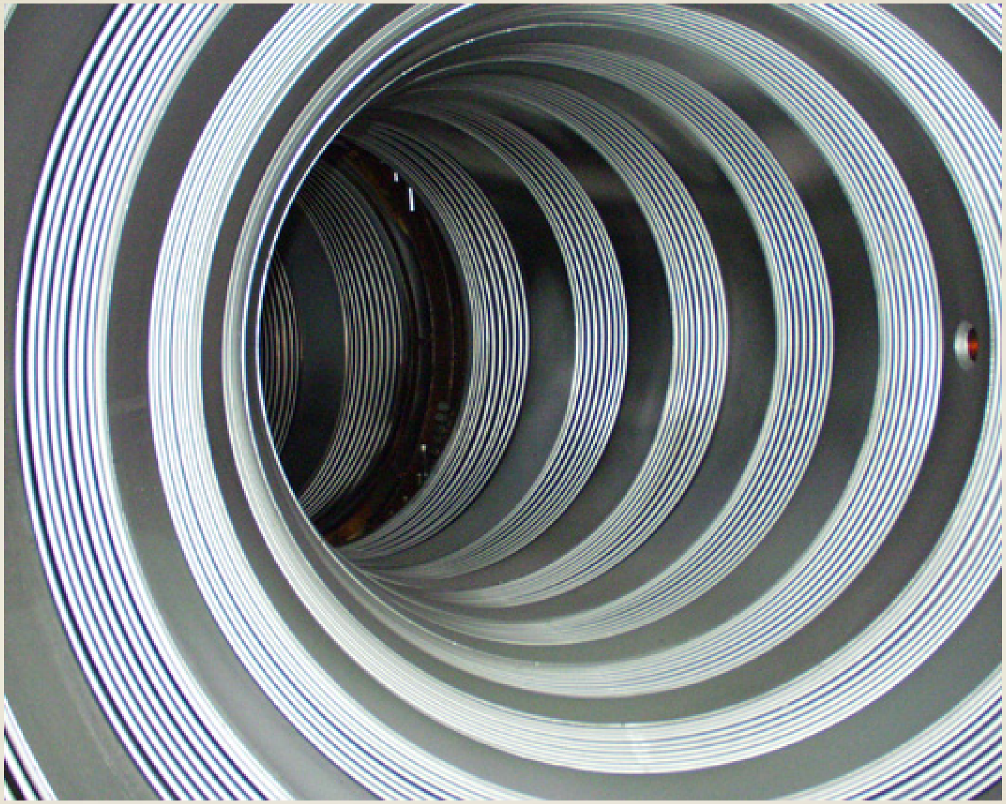
- 1961 Ioffe bars
- 1965 Culham Artsimovitch: Our confinment 10 tims better! Spitzer: It is not principal.
- 1968 Novosibirsk T-3 Tel=1kev No Bohm!
- 1969 The 2nd Workshop on thoroidal systems in Dubna.D.Robinson reports on measurment of the Tel on Tokamak T-3. TRIUMPH OF TOKAMAKS.
- 1975 T-10 and PLT

*

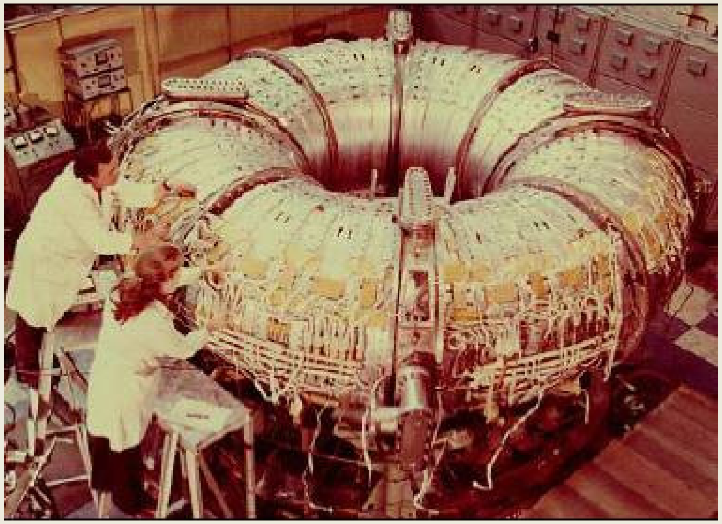
* Tio



* Tio

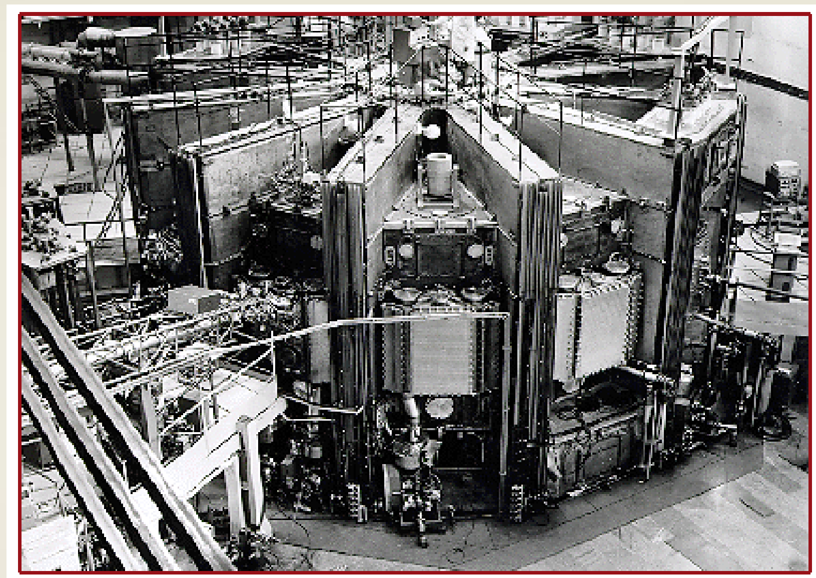


* T_7



* Tuman

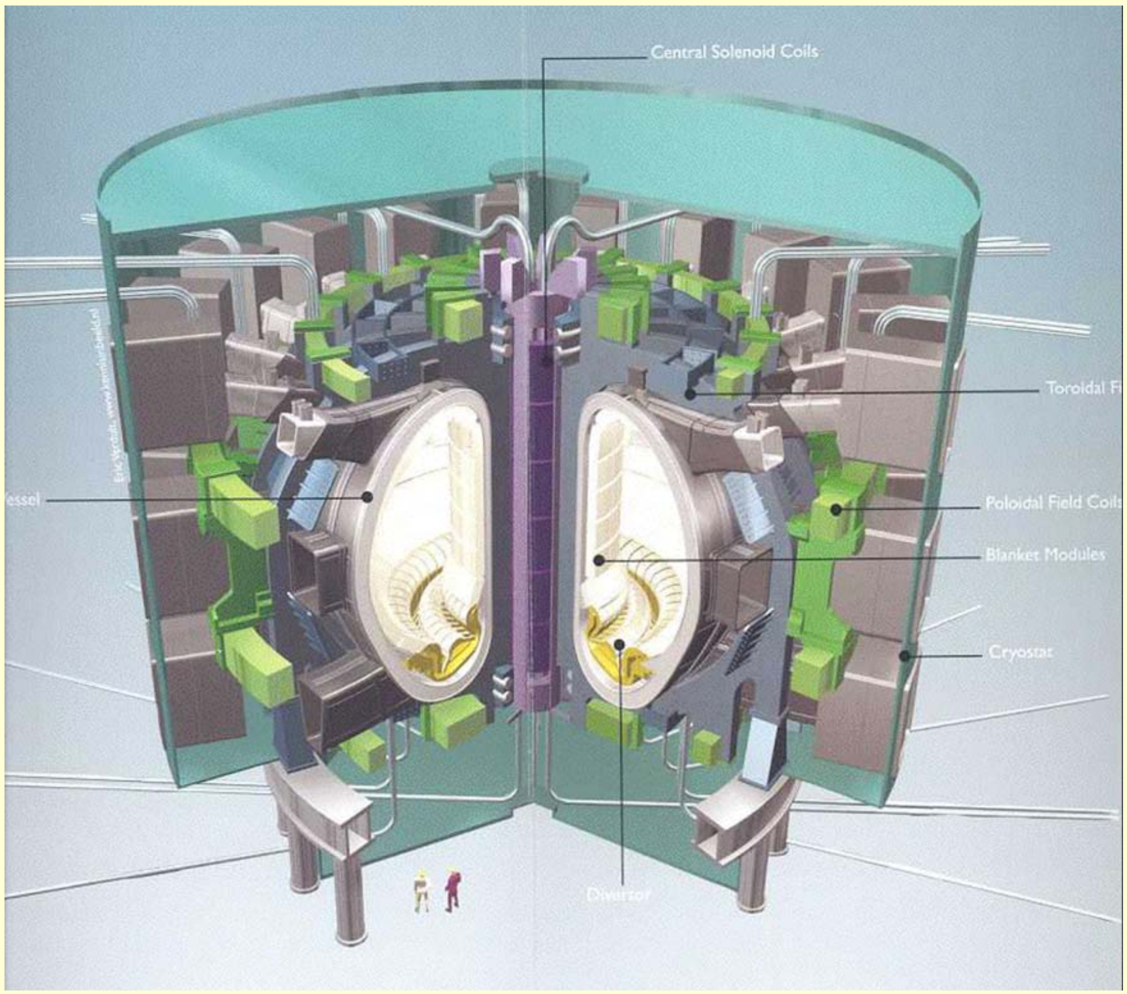
* T15



Global Energy
The International energy prize

ITER

____ ITER



The Birth of ITER

* 1978   INTOR agreement
* 1985   Paris meeting may
* 1985 Geneva Sammit november
* 1988 ITER conceptual desing (april)
* 1990 CDA succesefuly 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

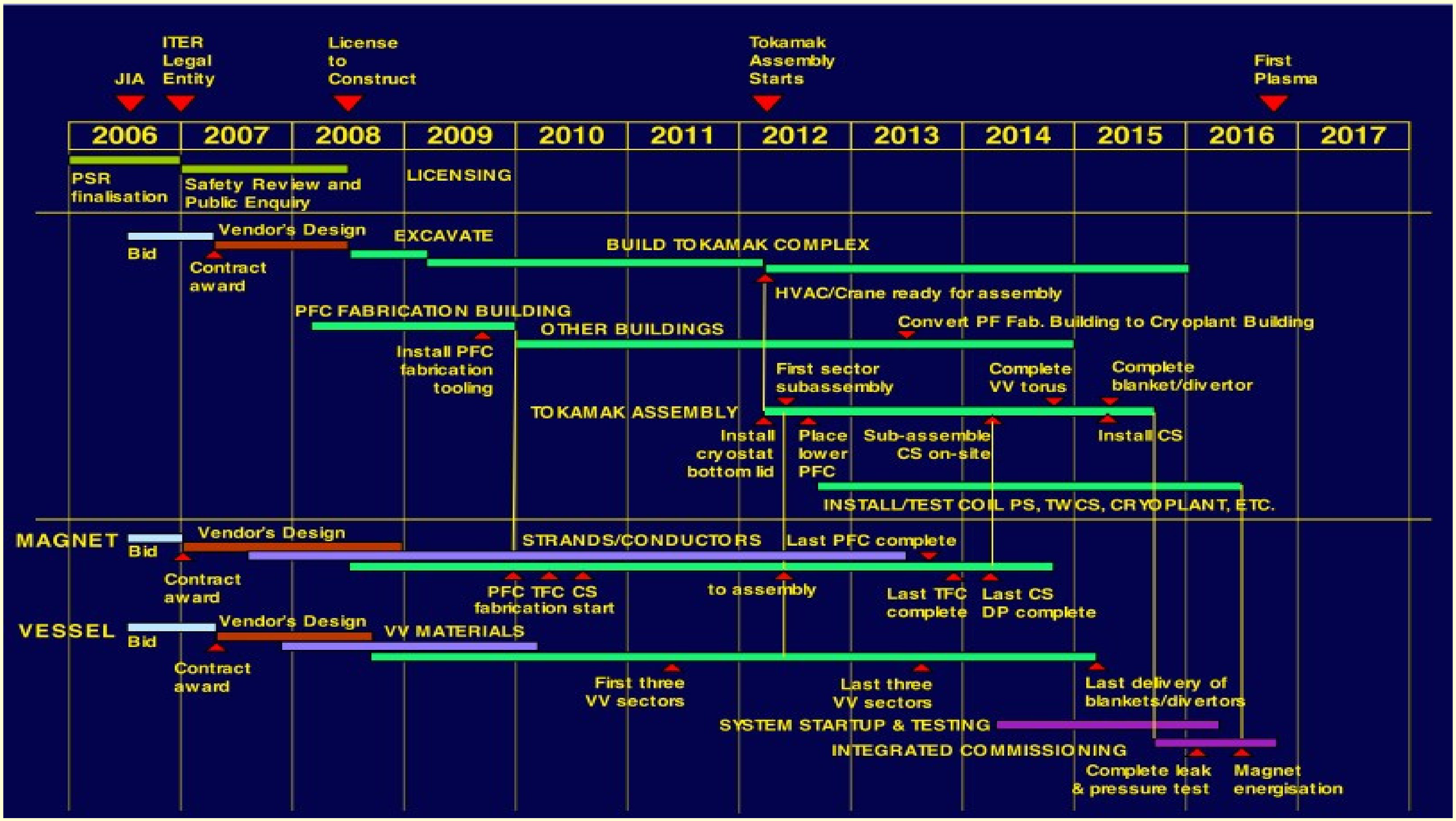
The signatories of the ITER Agreement

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

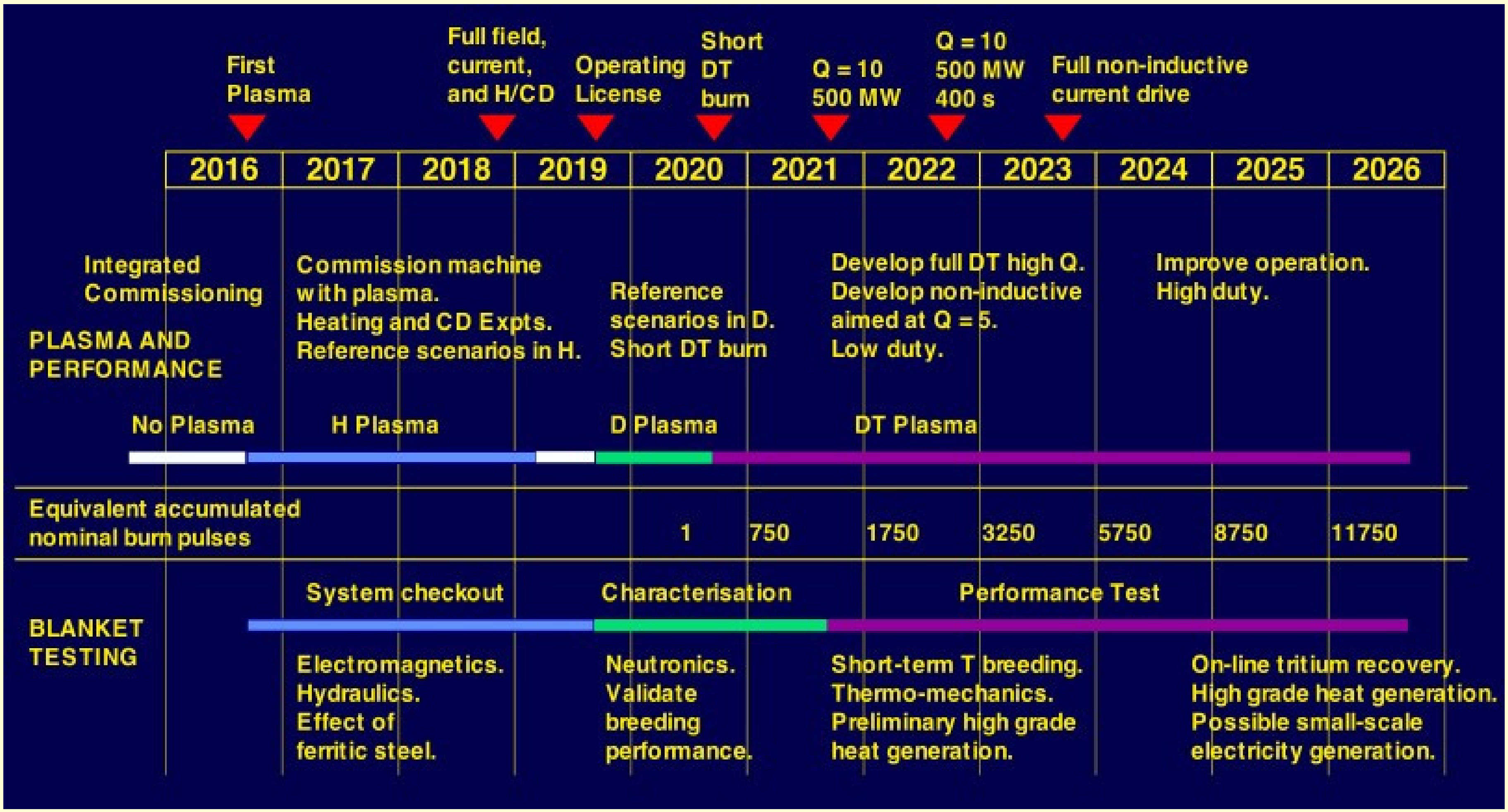
____ __________ _ _________, ________

ITER is constructed in Cadarache, France

ITER construction Schedule



ITER operation and research Schedule



Global Energy
The International energy prize

ITER

Требуемые достижения

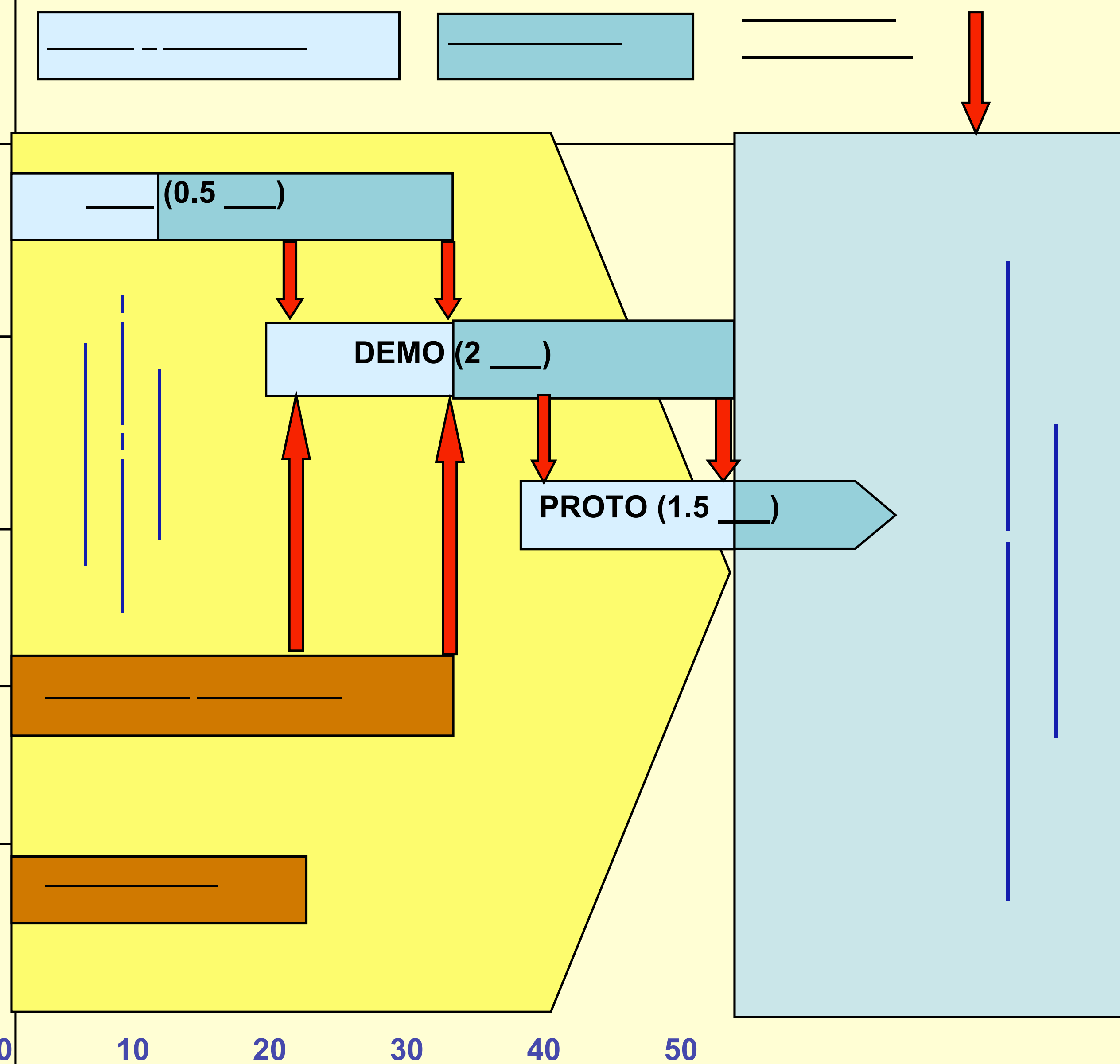
- Длинный импульс горения плазмы
- Отвод тепла и частиц (дивертор)
- Испытание бридинговых модулей для DEMO

- Получение электрической энергии
- Достижение высокой надежности
- Испытание малоактивированных материалов для PROTO

- Улучшение экономичности при производстве электроэнергии
- Улучшение малоактивированных материалов

- Демонстрация малоактивированных сталей для DEMO
- Поиск материалов для PROTO

- Демонстрация утилизации радиоактивных отходов и их переработки
- Демонстрация безопасности обслуживания реактора
- Демонстрация малого влияния на окружающую среду



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First ITER Council Meeting held in the Castle of Cadarache

____ __ _____ 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 — **С током** — **Без тока**

1976: $T_e = 150$ эВ

1978: $T_e = 700$ эВ, $T_i = 400$ эВ

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

WVII-AS (с 1988 г.) **Без тока**

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

1992: H-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	$a_p = 1.8$	$B = 5$ T	$N_{coil} = 50$	$\iota = 0.8 - 1$
	HSR4/18	$a_p = 2.0$	$B = 5$ T	$N_{coil} = 40$	$\iota = 0.8 - 1$

ЯПОНИЯ

Киото

Heliotron-E (1982 – 1997)

1982: $T_{e\,0} = T_{i\,0} = 600$ эВ; 1984: $T_{i\,0} > 1$ кэВ

$\beta = 1\%$ $\beta_0 > 3\%$

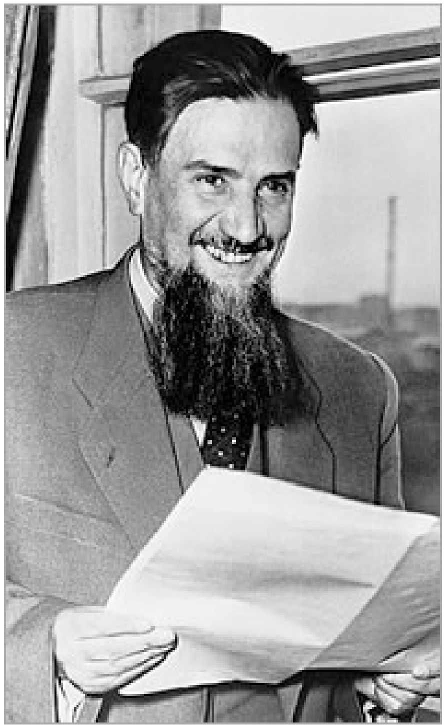
Toki – NIFS

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

1992: $\beta = 3\%$, H-мода

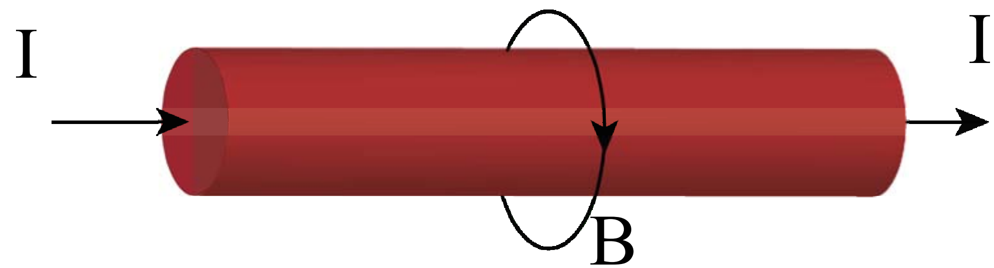
LHD с 1998 $R = 3.9$ $A = 6.5$ $N_{fp} = 10$

2001: $T_{e\,0} = 10$ кэВ $T_{i\,0} > 3.5$ кэВ $\tau_E = 0.3$ с $\beta = 2.4\%$



Z-pinch as a Pioneer of Controlled Nuclear Fusion

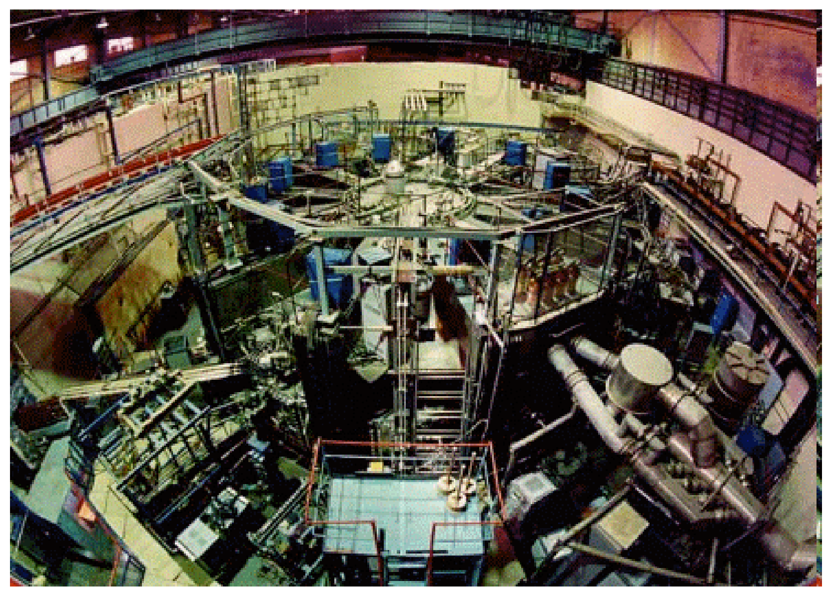
Harwell, 1956. Igor Kurchatov opens the Soviet Fusion Program



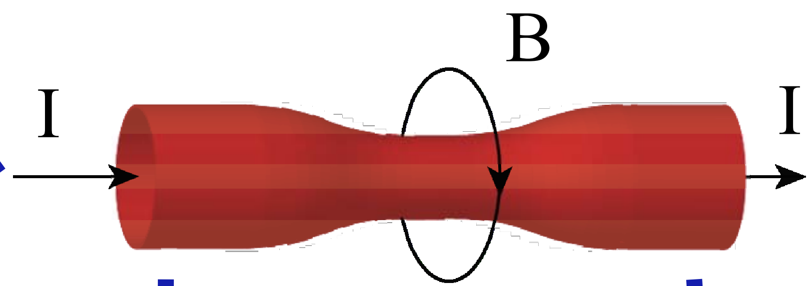
This program at that moment was based, in particular, on Z-pinches.

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.



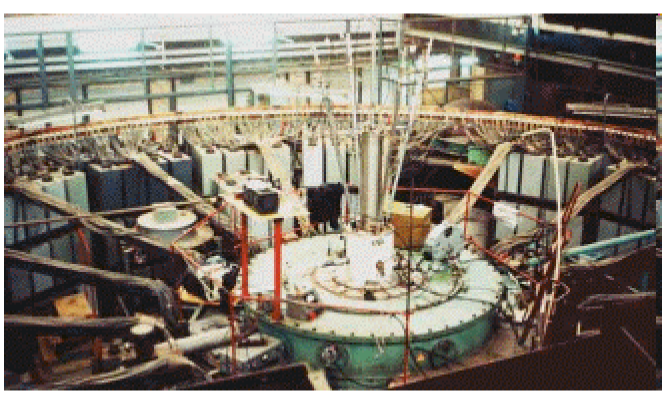
Dynamics
Leontovich
Imshennik
Bodin
Kvartskhava

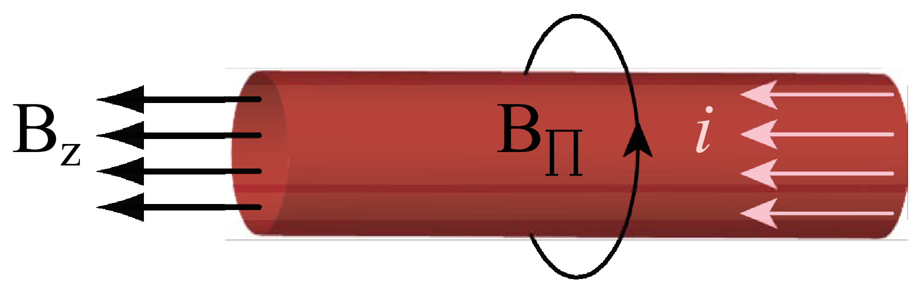


Stability
Shafranov
Krall
Rosenbluth
Rostoker

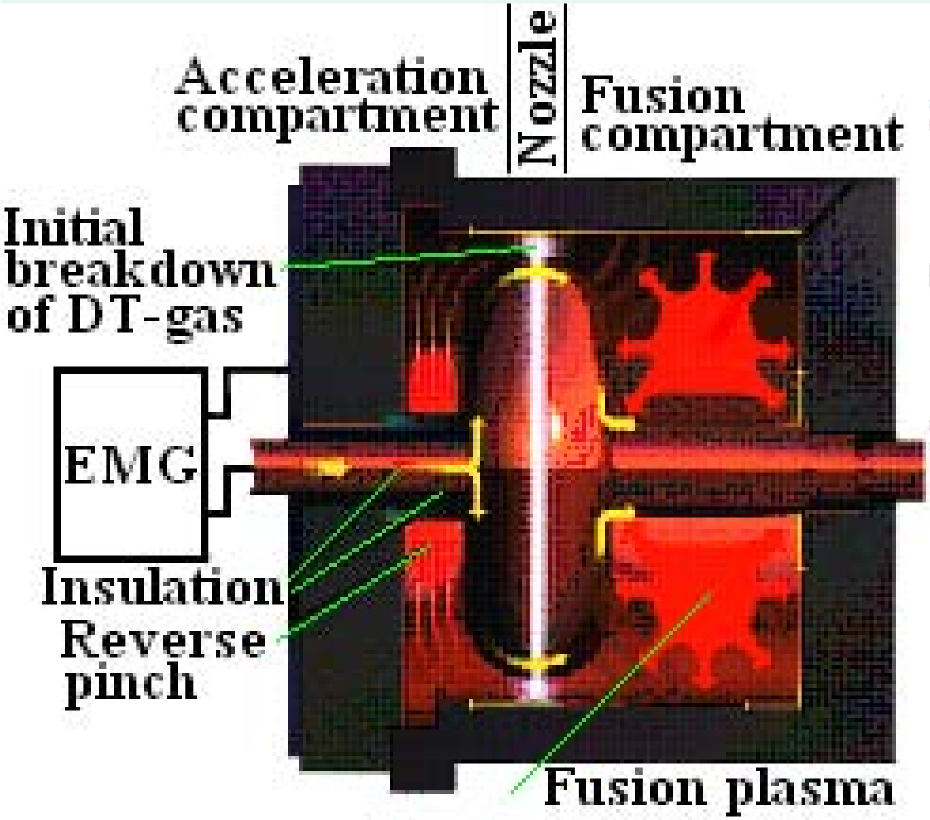
Plasma Focus
Filippov
Maiser
Maisonnier
Sadovski
Krauz

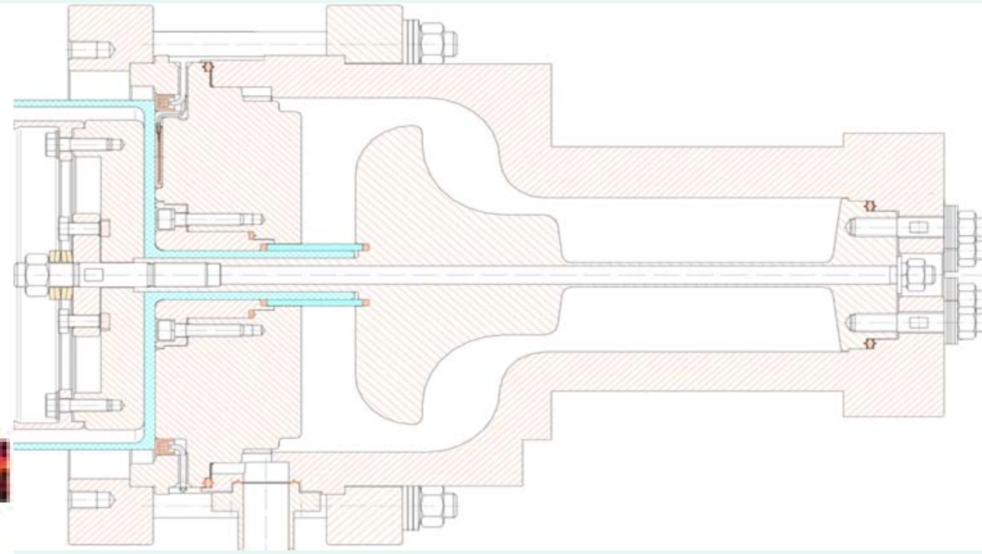
Liner
Sakharov
Pavlovski
Alikhanov
Velikhov





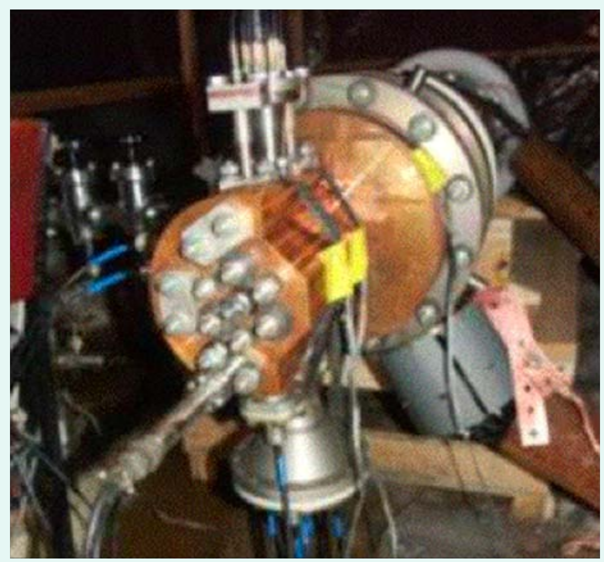
EXPERIMENTS ON THE PROLONGED PLASMA CONFINEMENT WITH THE FUSION CHAMBER MAGO



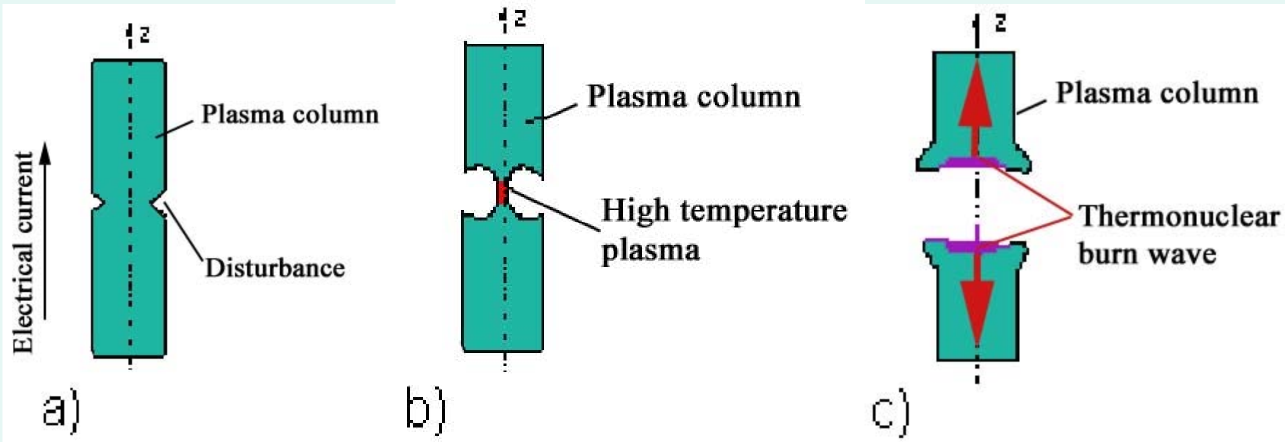


Physical scheme of MAGO chamber operation

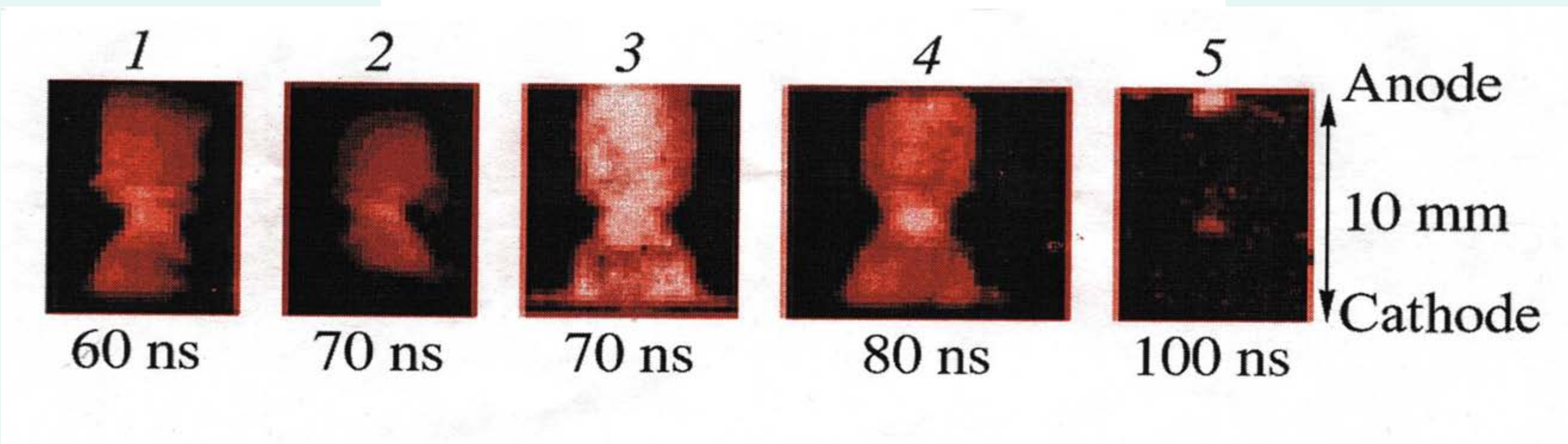
Plasma chamber MAGO-IX



Prospect of ignition in the Z-pinch neck



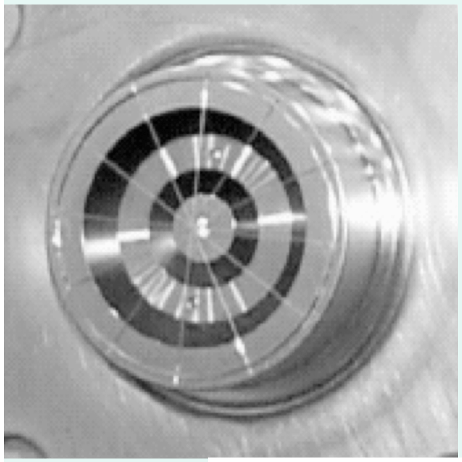
Agar-agar foam, $\rho_0 = 0.1$ g/cm^3.



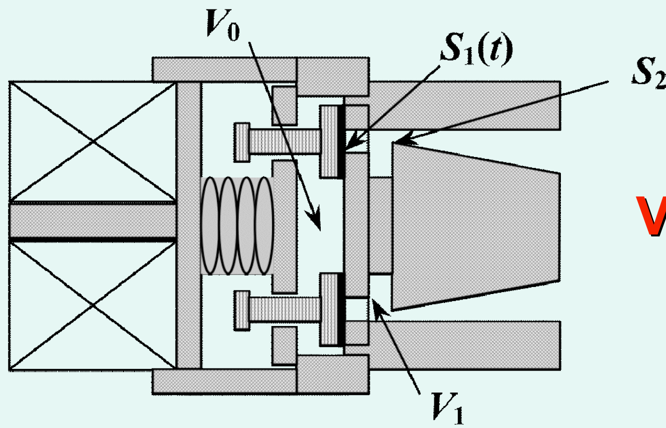
ICT photographs in the optical range (1,2) and VUV-SXR range (3,4,5)

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

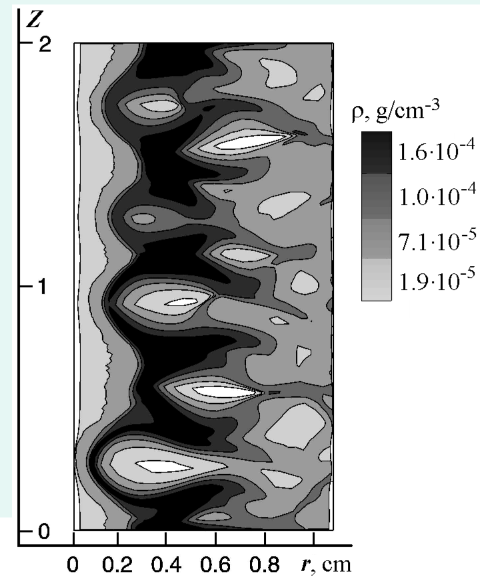
Nozzle



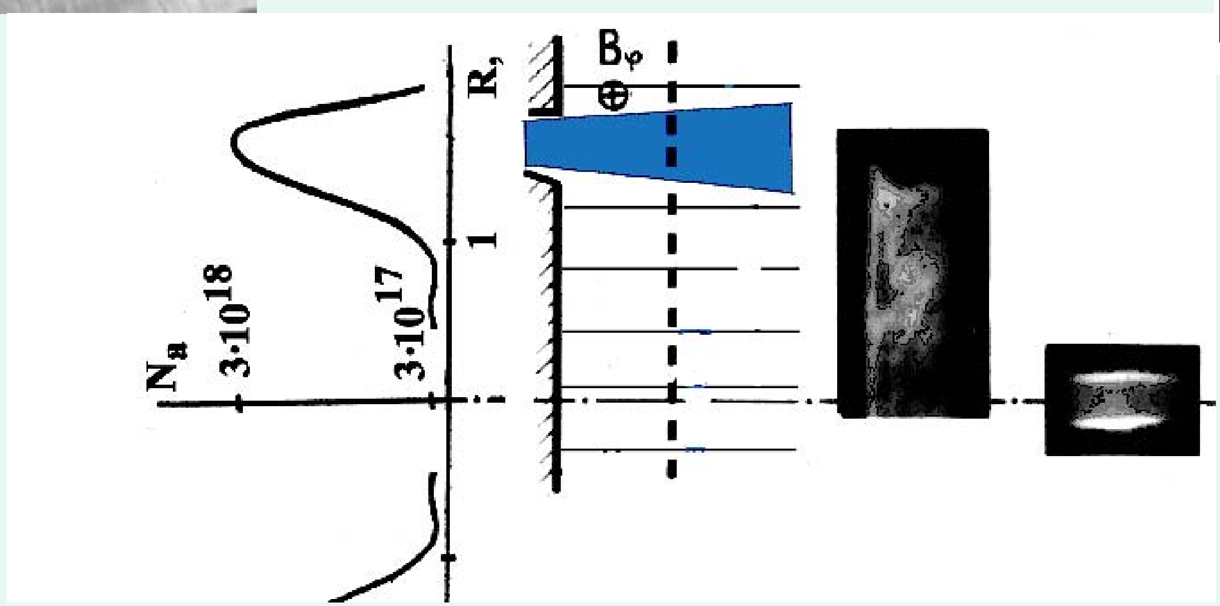
1. Gas-Puff Liners



Valve

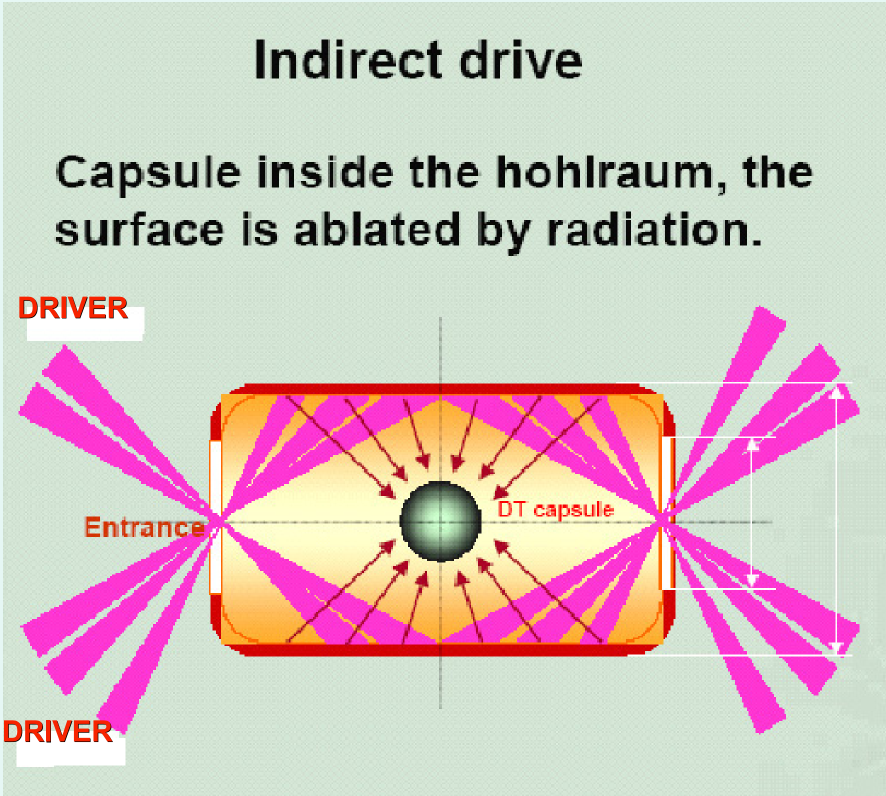


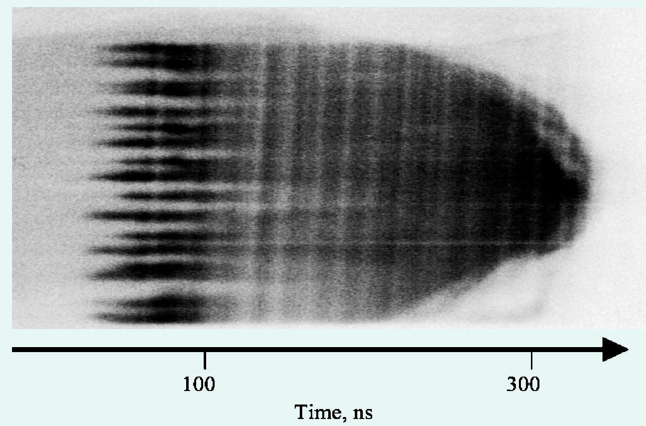
Instability

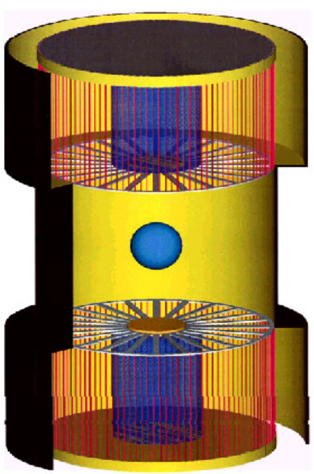


Stabilization by the applied longitudinal magnetic field

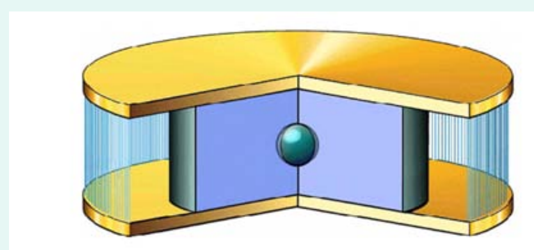
2. HOHLRAUM. HIGH-CURRENT WIRE ARRAYS







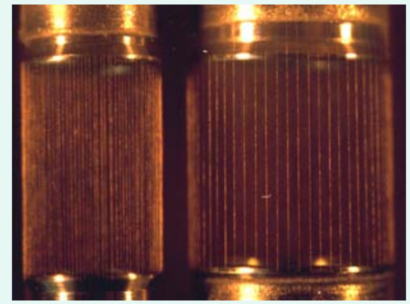
Double-ended vacuum Hohlraum (SANDIA)



Dynamic Hohlraum (TRINITI)

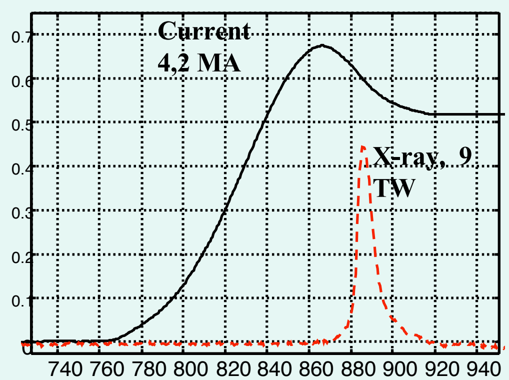
FAST INTENSIVELY RADIATING Z PINCHES DRIVEN BY PULSED POWER GENERATOR ANGARA-5-1

SRC RF TRINITI, TROITSK



W wire liners, N=120

d=6um D_1=12 mm D_2=20 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

ANGARA-5-1, TRINITI

Double Liner Implosion Dynamics

V_{max} δ (5 |7) $\cdot 10^7$ cm/s

R_{out} = 16 mm m_{out} = 100 …g/cm (Xe)

r_{in} = 2 mm m_{in} = 200 …g/cm (foam)

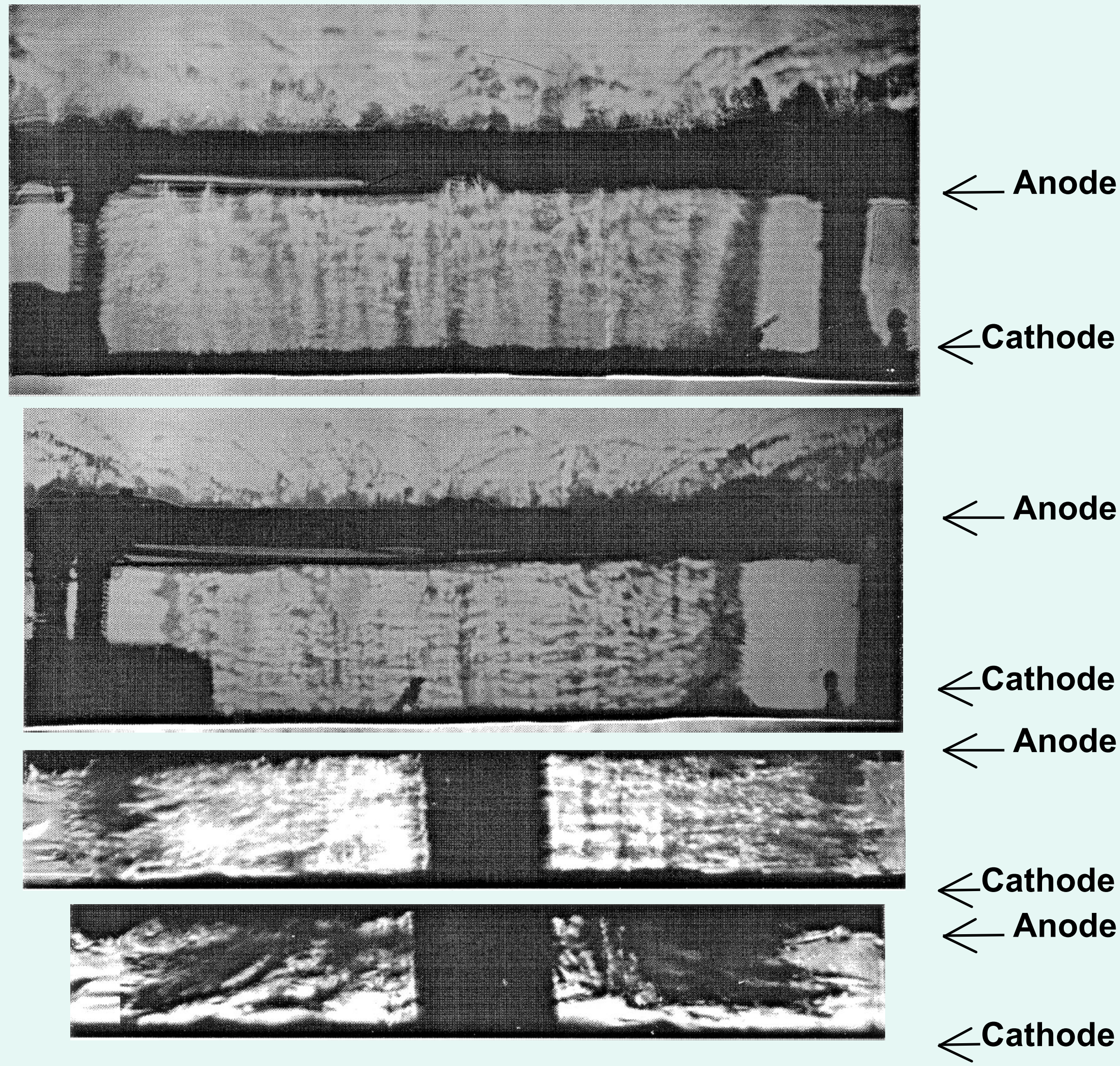
Laser shadow pictures

60 ns before pinch

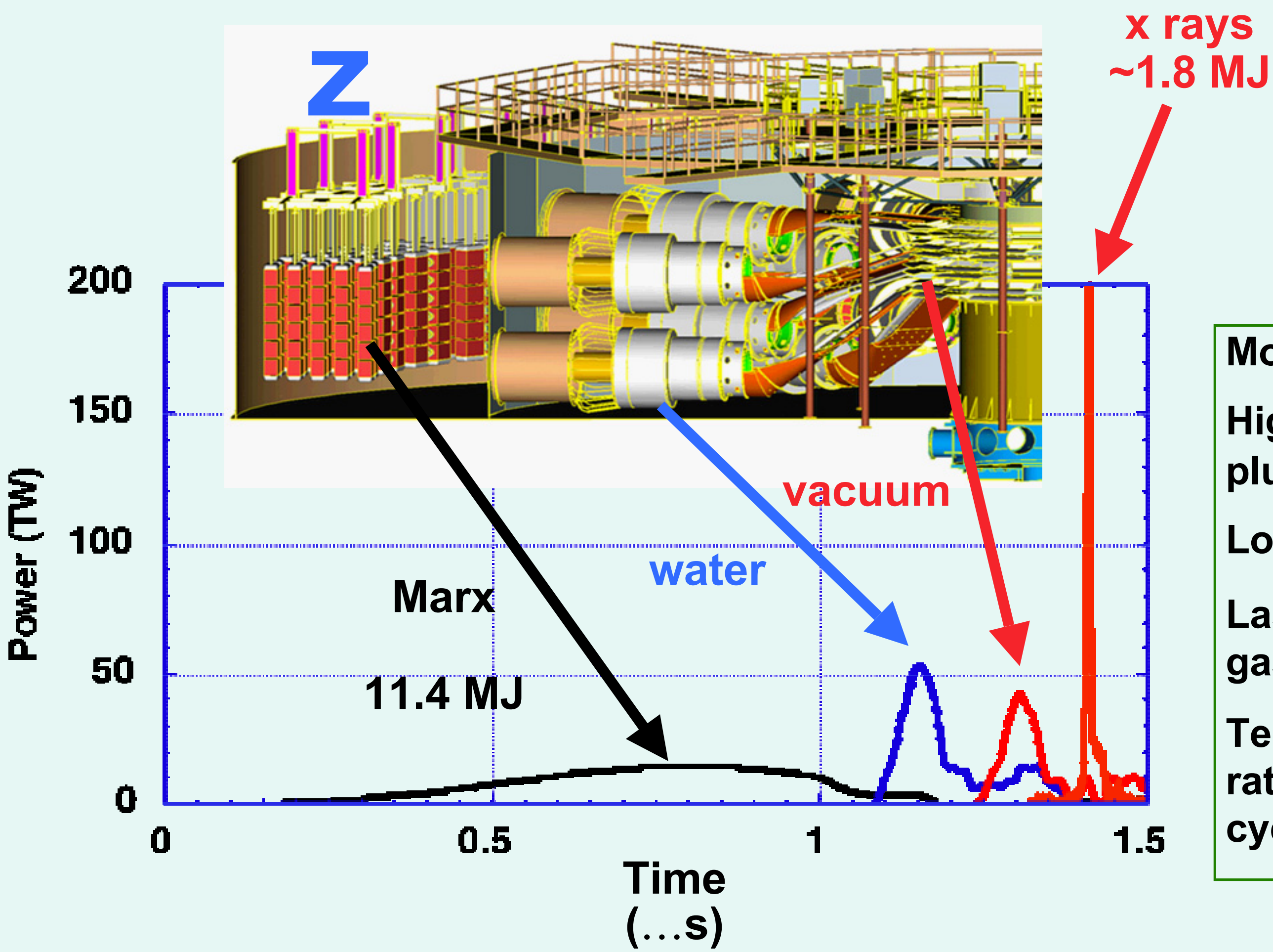
45 ns before pinch

15 ns before strike

1 ns after strike



Z/ZR Pulsed Power Machine



Modular

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

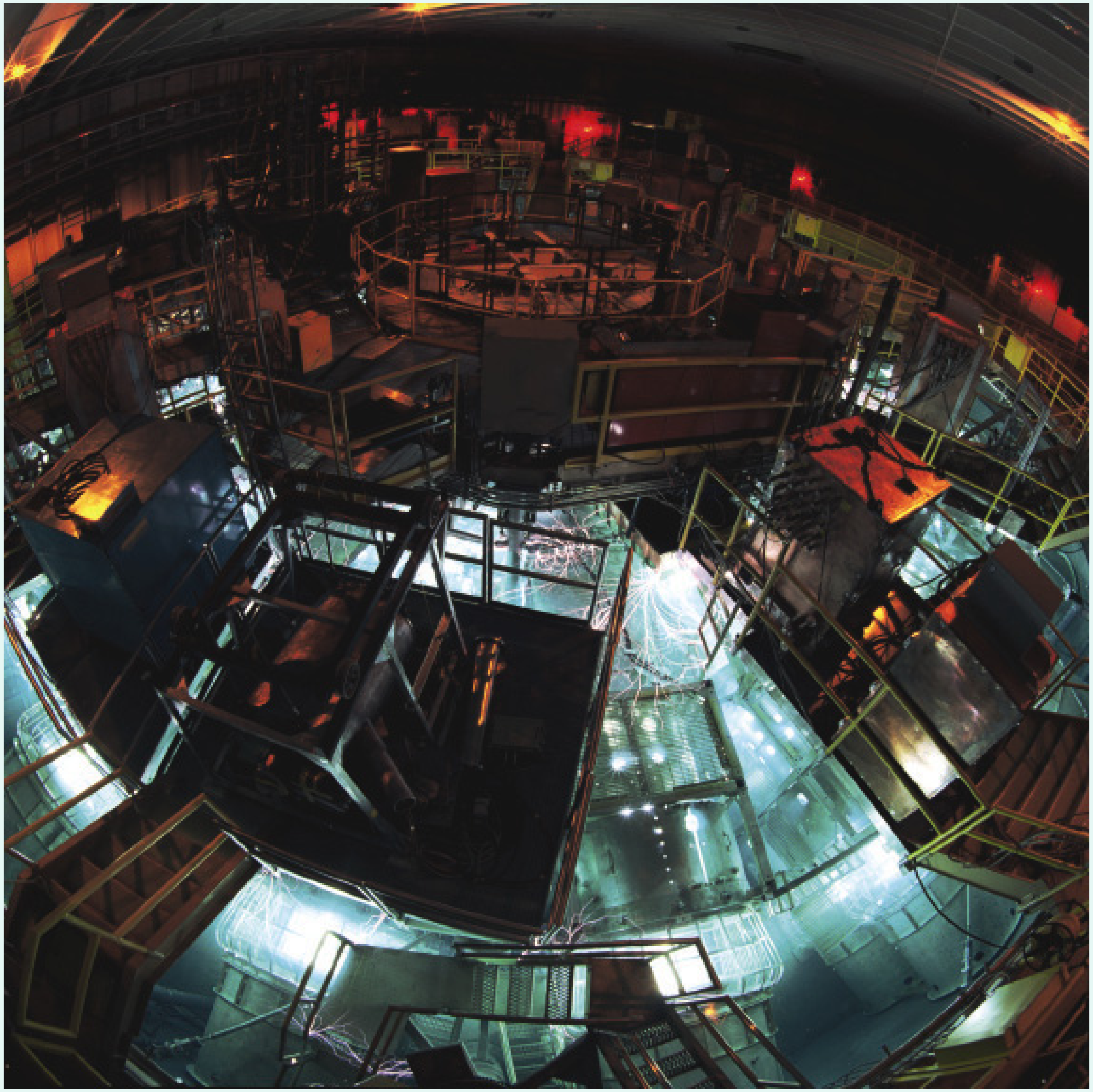
Low cost (< $30/J)

Laser-triggered pressurized gas switches

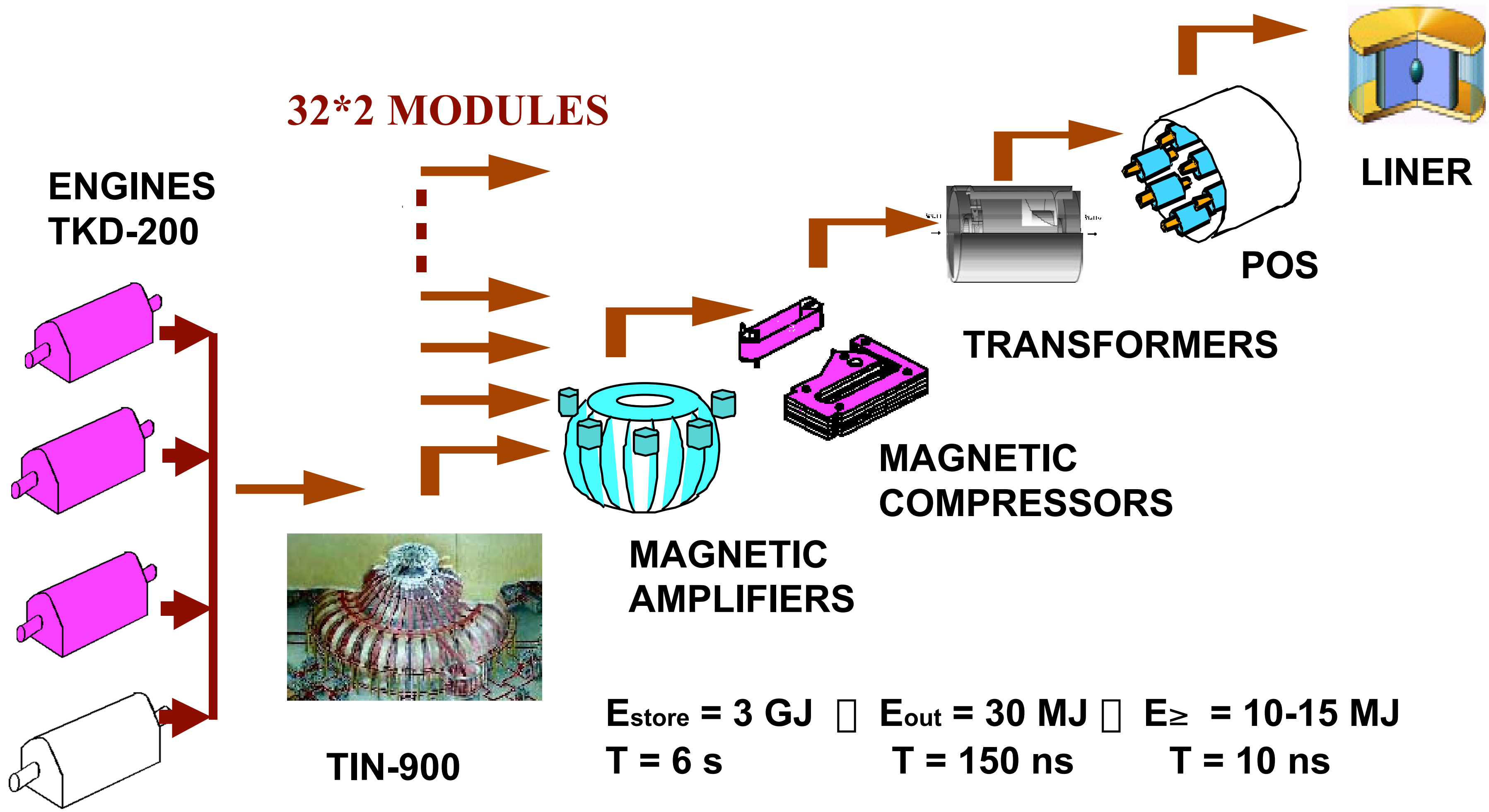
Technology is possibly rep-rateable at 0.1 Hz with fast-cycling Marx

“Z” ,SANDIA National Laboratories

1.8 MJ in SXR range; 200 TW

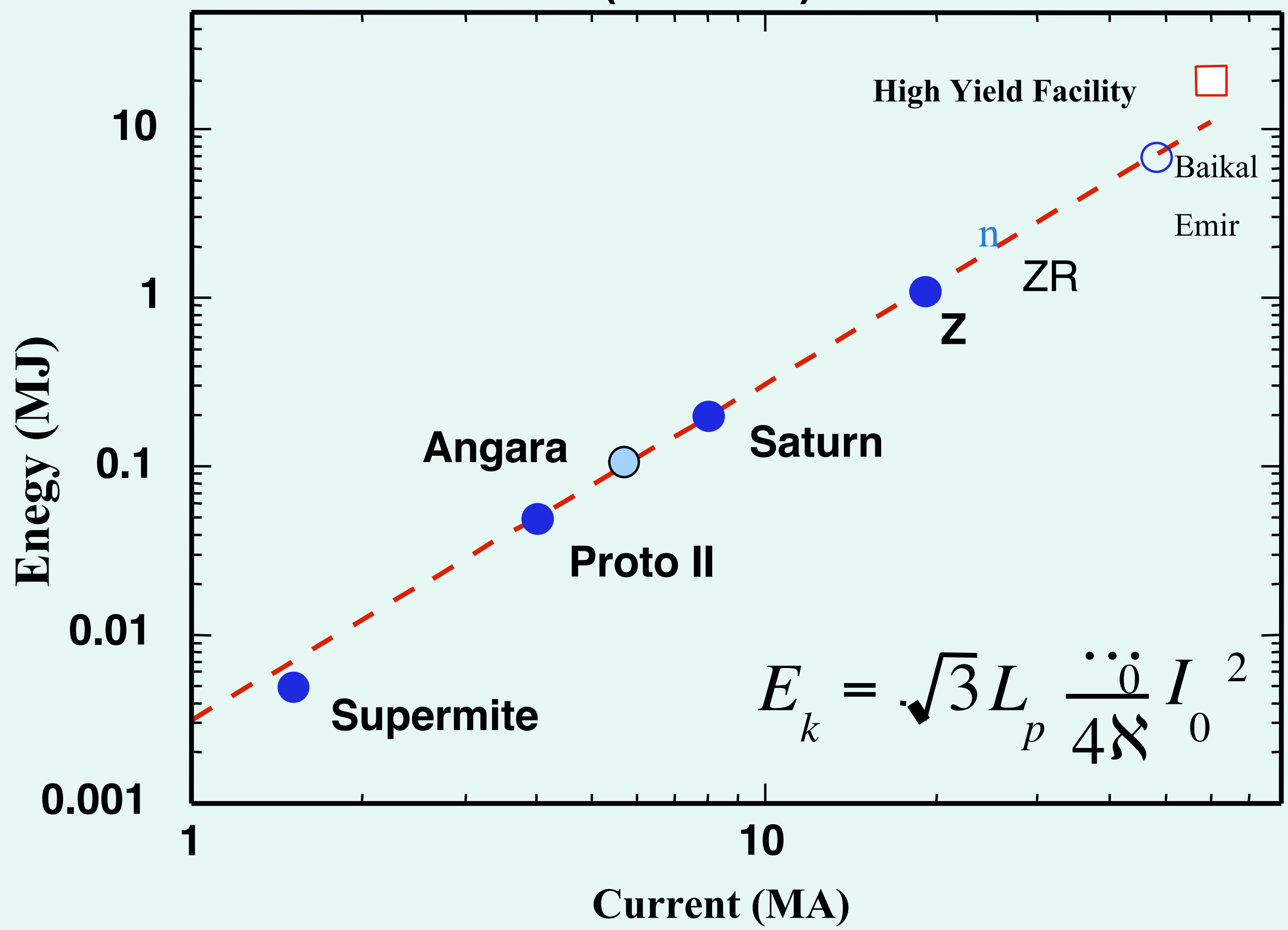


BAIKAL, THE NEW GENERATION OF PULSED POWER MACHINES

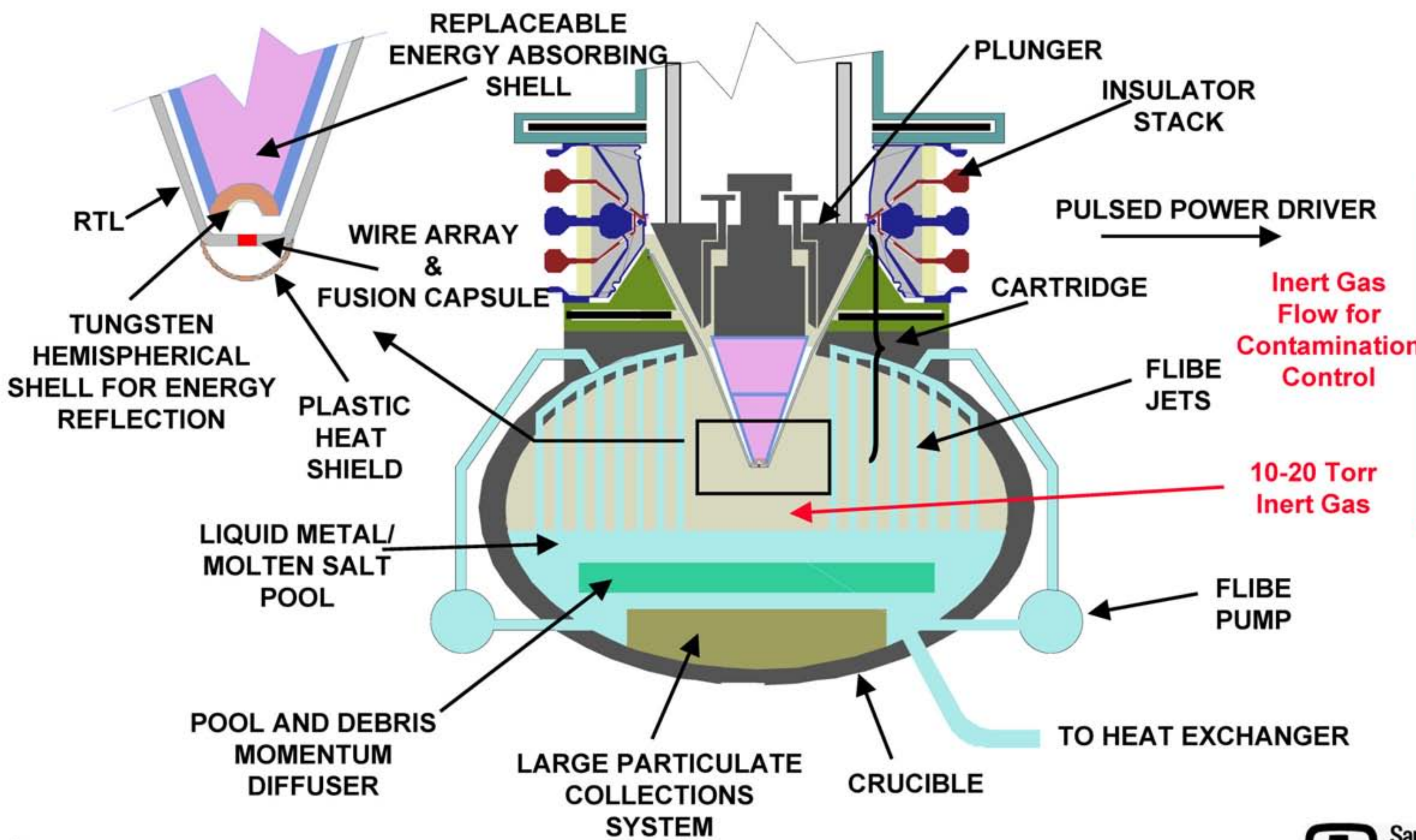


AT PRESENT MOMENT, Z-PINCH PROVIDES MAXIMAL ENERGY OF X-RAY PULSE

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



Z-Pinch Power Plant
Crucible Details



GER 9/15/04

Sandia National Laboratories

The basic functional elements of ZP-3 reactor chamber

I = 60 MA - for ignition.

I = 90 MA - for IFE power plant.