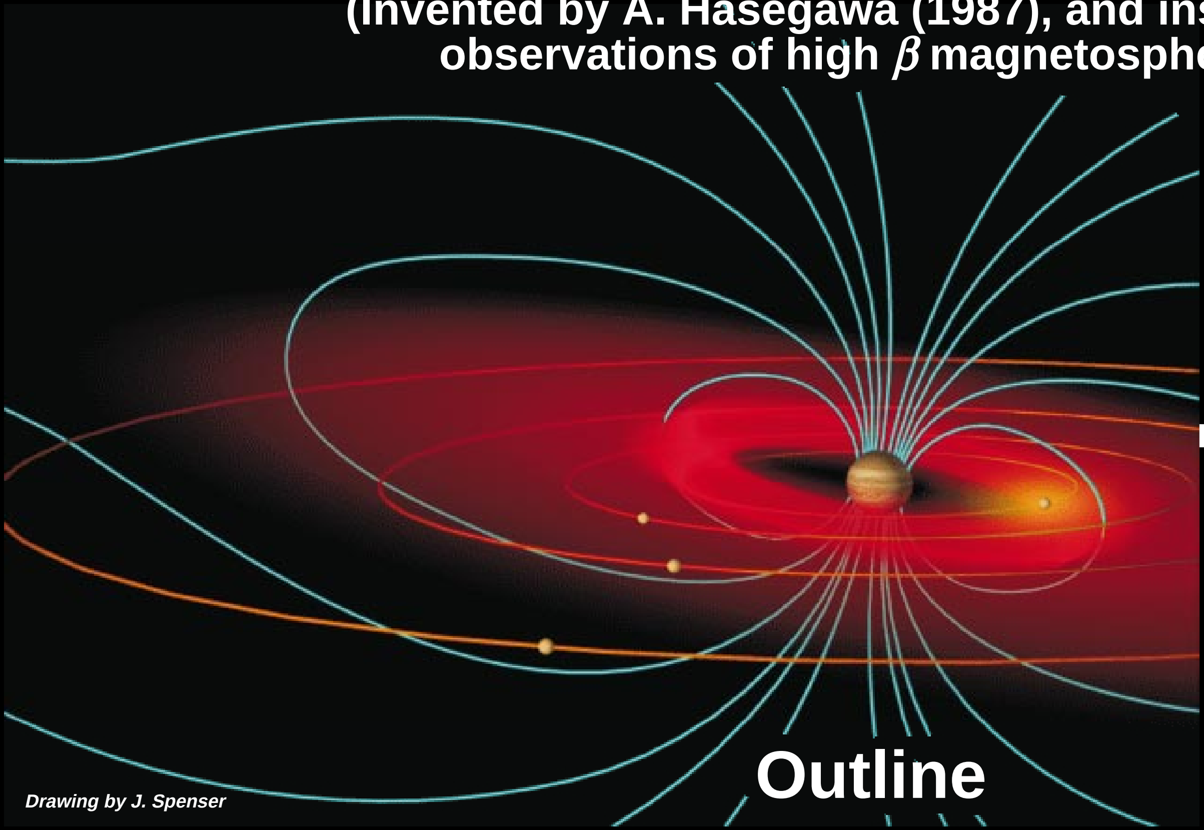
The Dipole Fusion Concept

(Invented by A. Hasegawa (1987), and inspired by observations of high β magnetospheres)


Drawing by J. Spenser

M. E. Mauel

for the LDX Group:
Darren Garnier, Jay Kesner, J. Minervini,
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B. Smith, P. Thomas, A. Zhukovsky

Outline

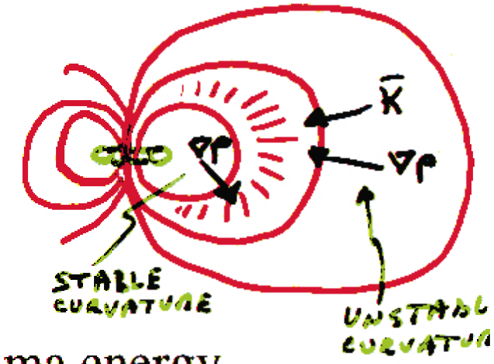
- **Introduction & the physics basis for the dipole concept**
- **Differences between a dipole fusion power source and traditional magnetic fusion concepts**
- **Development paths for dipole fusion power**

Physics Basis for Dipole Confinement was long "Understood" but still Untested in the Laboratory

- Dipole concept derives from the thermodynamic arguments of Rosenbluth and Longmire, *Ann. Phys.* (1957). The work required to exchange tubes of equal magnetic flux is

$$\Delta E_p = \delta V \left(\delta p + p\gamma \frac{\delta V}{V} \right) = \delta\left(pV^\gamma\right) \frac{\delta V}{V^\gamma}$$

where $V \propto \int dl/B$.

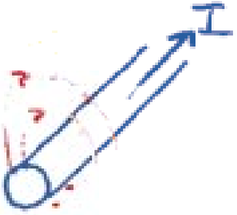


- For $\delta(pV^\gamma) > 0$, any exchange of flux tubes will increase plasma energy.

- Stability by compressibility defines a critical pressure gradient. When $\nabla p < (\nabla p)_{crit} = p\gamma \nabla \ln V$, MHD perturbations do not grow.

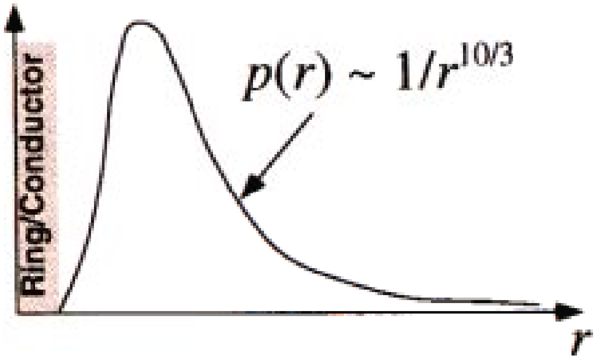
  In the magnetosphere, $\delta(pV^\gamma) \sim 0$ is called Southwood's fourth adiabatic invariant. (First used to describe magnetospheric plasma by Gold, 1959.)

  Low-aspect ratio tokamaks, with $A \leq \gamma = 1.7$, may gain substantial stabilization from compressibility.



A "STRAIGHT" DIPOLE

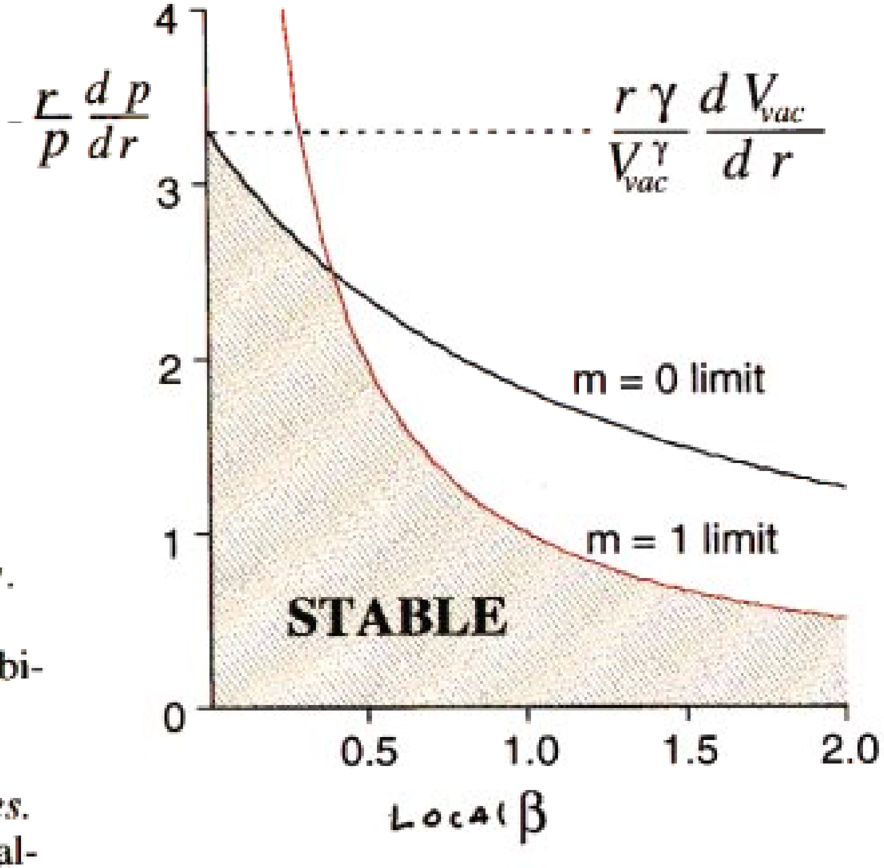
Example: A hard-core z-pinch…



$$V_{vac}(r) \propto r^2 \propto \oint \frac{dl}{B}$$

- m = 0 interchange mode (no field-line bending) is stabilized by compressibility.
- m ≥ 1 kink-ballooning modes can be stabilized by bending energy.
- For a dipole, Chan and Chen, *J. Geo. Res.* (1994) have shown that for $p' < p'_{crit}$, ballooning is stable up to β < 2.

$V_{vac}(r) \propto r^4$ in Dipole



From Freidberg, *Ideal MHD*, Plenum (1987).

Interchange stability of an axisymmetric, average minimum-B magnetic mirror

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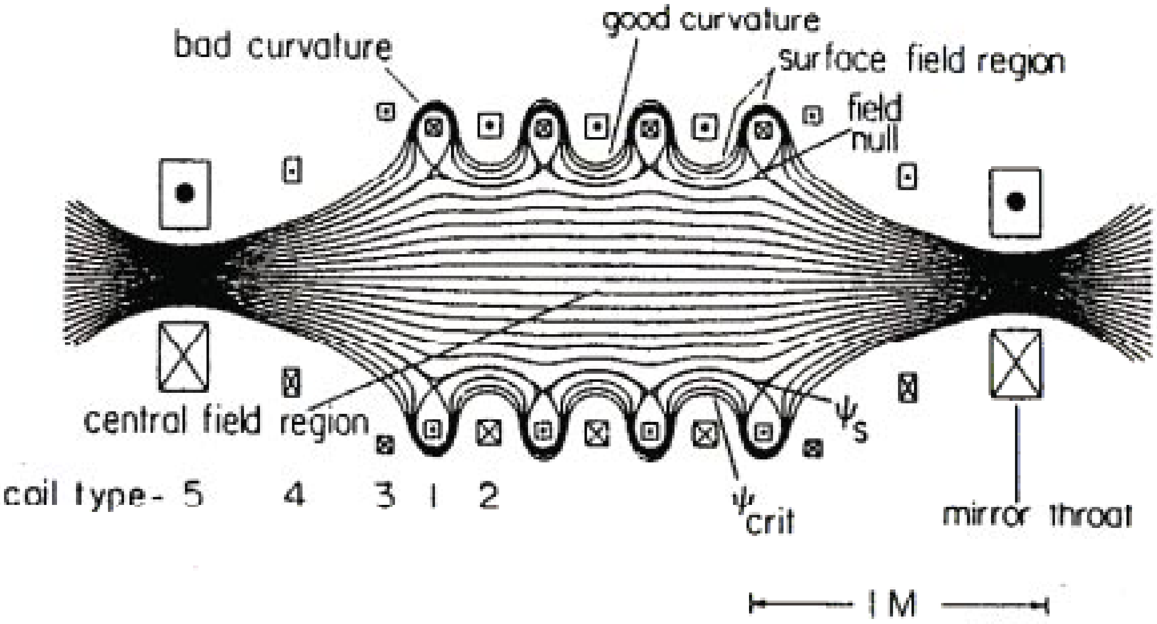
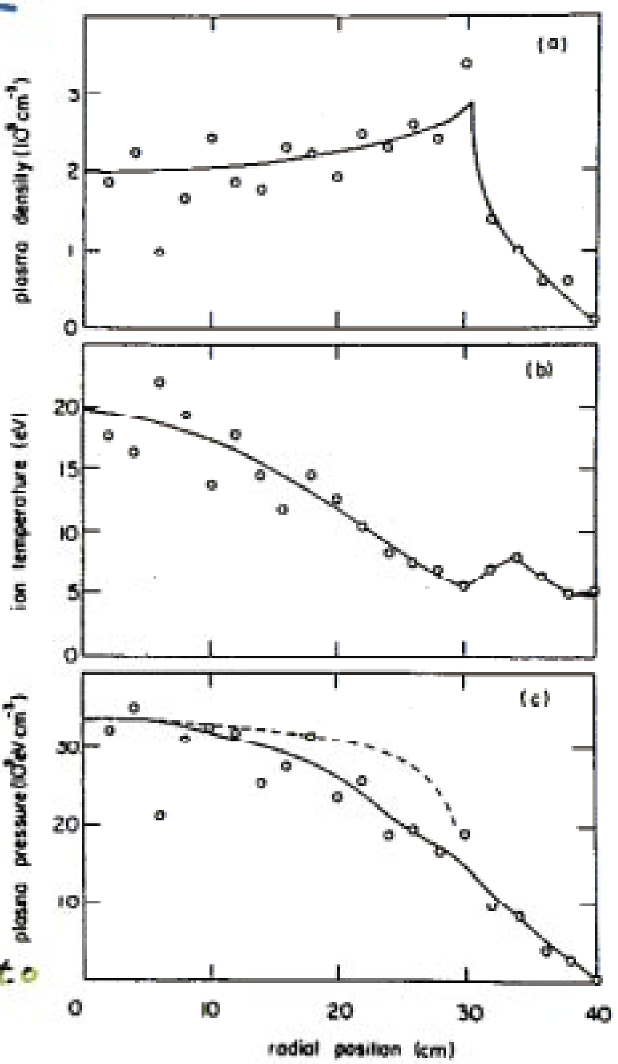
(Received 14 January 1983; accepted 8 April 1983)

An axisymmetric magnetic mirror with large diameter and easily variable mirror ratio is described. The magnetic field configuration is a simple mirror with an average minimum-B field region on the outer surface. Experimental results are given which demonstrate that the surface field region ensures interchange stability. Stability can be maintained with both positive and negative radial plasma pressure gradients provided that the product of the pressure gradient and specific flux volume gradient is positive.

$\delta(pV^{\gamma}) > 0$





FACTOR OF TWO DUE TO COMPRESSIBILITY

A Dipole is Not a Spherator!

- A dipole field is purely poloidal. Levitrons add toroidal field → neoclassical degradation.

- A dipole is stabilized by flux expansion allowing $\beta > 1$. A levitron is stabilized by an average well, $\beta < 0.1$.

- A dipole requires $R_{wall} > 5\, R_{coil}$. The wall of a levitron is near the coil since the toroidal field prevents large flux expansion.

- A dipole may be stable to low-frequency perturbations → classical confinement. Levitrons exhibited intense turbulence.

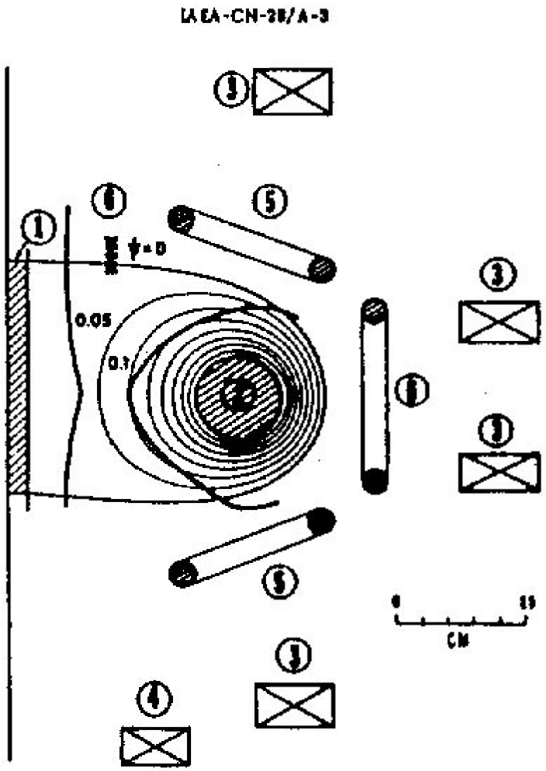
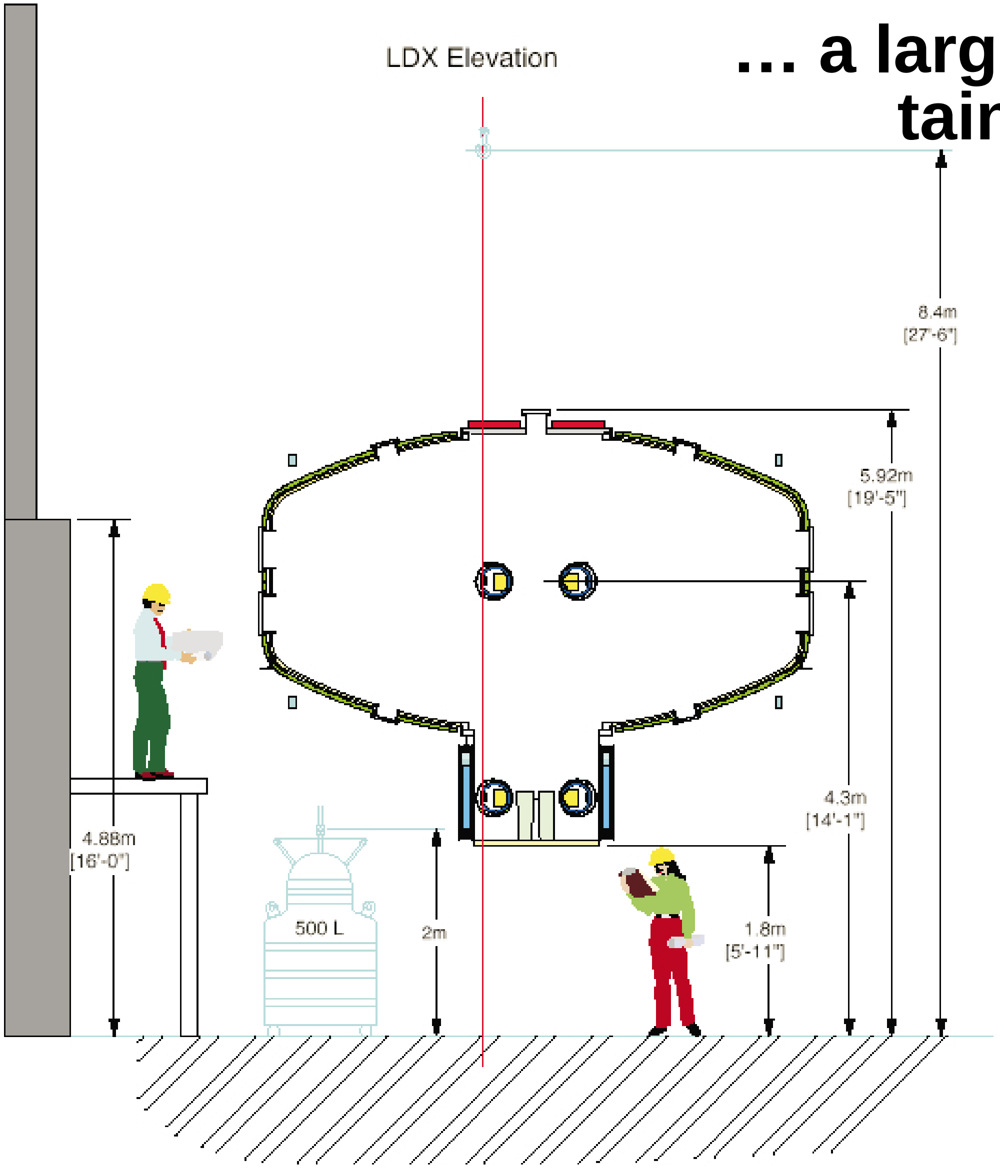
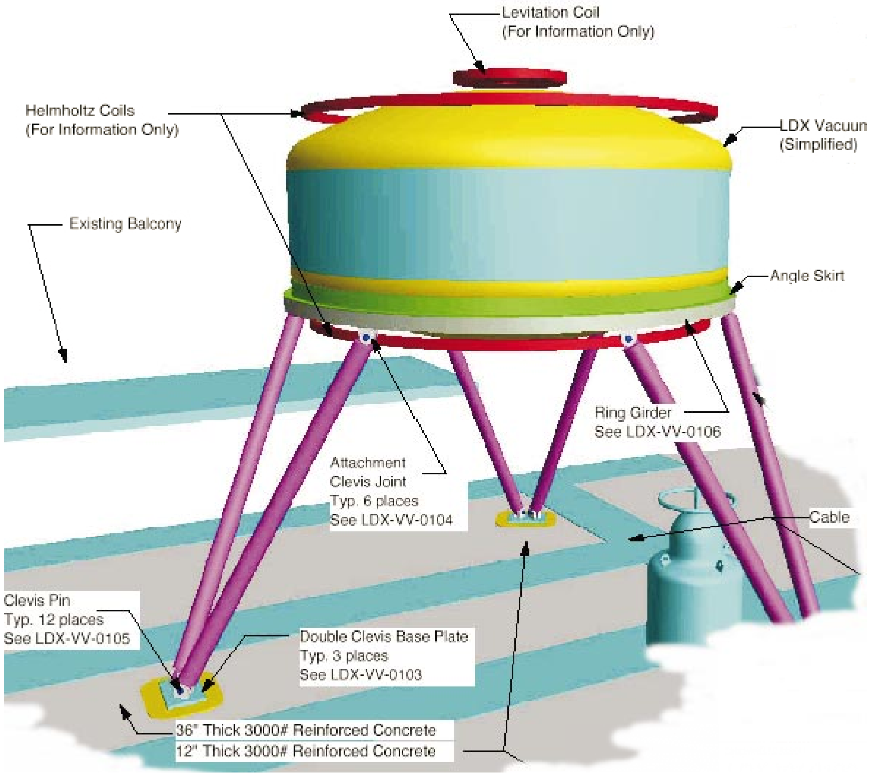


FIG. 1. Cross-sectional view of the levitated spherator: (1) TF coil, (2) levitated superconducting ring, (3) external coils, (4) coil for levitating the ring, (5) stabilizing field coils, and (6) limiter. The poloidal flux surfaces (ψ) are shown along with the surfaces of electron cyclotron resonance at 9.45 GHz.

LDX, a joint Columbia/MIT research device, now under construction at MIT, will provide the first glimpse of a dipole plasma confinement device:



… a large (cheap!) vacuum tank containing a high-performance, but very small, floating magnet



Vacuum Chamber Installed: Summer, '99 Magnet Testing: Winter, '99 First Plasma: Spring, '00

(1991)

Goals of First D-^{3}He Dipole Reactor Design

Goals:

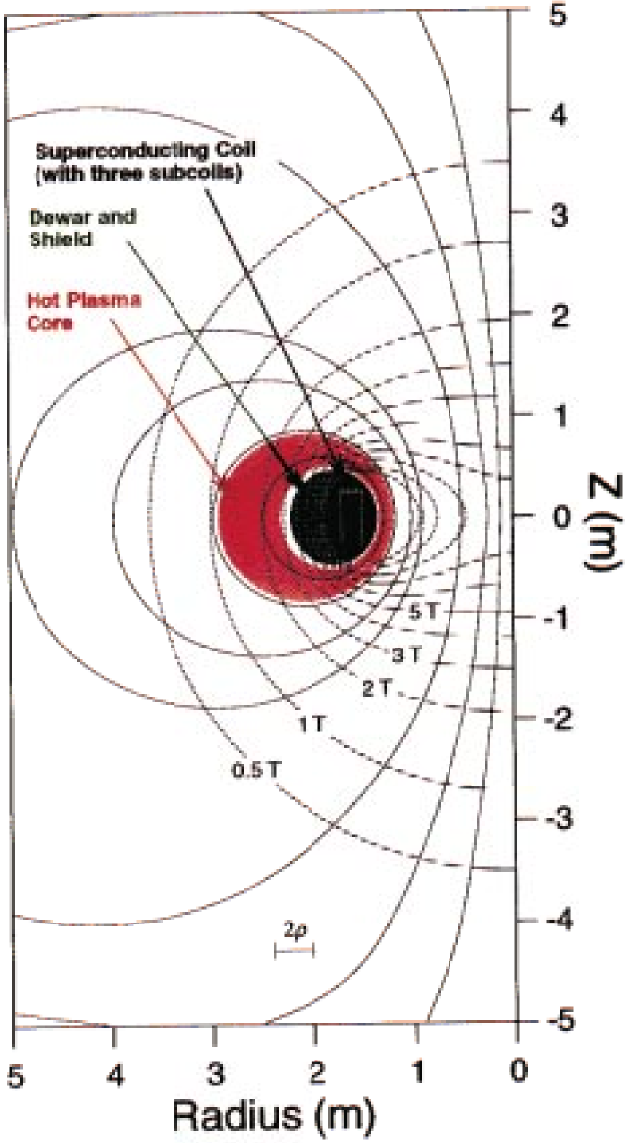
Nb_3Sn conductor as presented in ESECOM (1989) reactor stufy.

Confine fusion protons.

Reduced edge plasma temperature to ≤ 150 eV with core temperature of 75 keV.

Peak plasma $\beta \leq 3$.

Maintain dipole surface temperature below 1400 °C.



Design values:

20 MA dipole current; 800 MJ stored magnetic energy.

Dimensions of dewar and shield are 1.8 m radius, 0.8 m diameter.

Required ignition confinement time ≥ 2.4 sec.

170 MJ stored plasma energy.

70 MW fusion power.

SPACE PROPULSION BY FUSION IN A MAGNETIC DIPOLE

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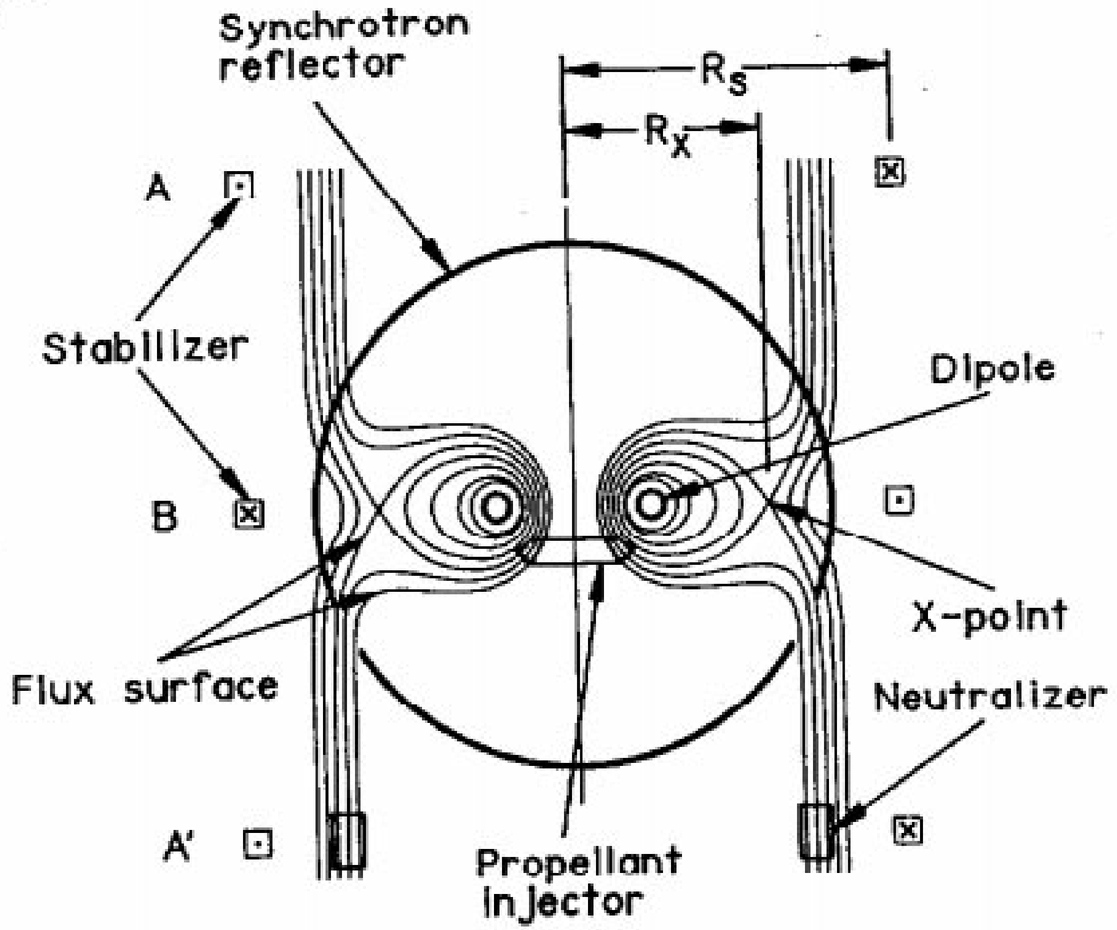
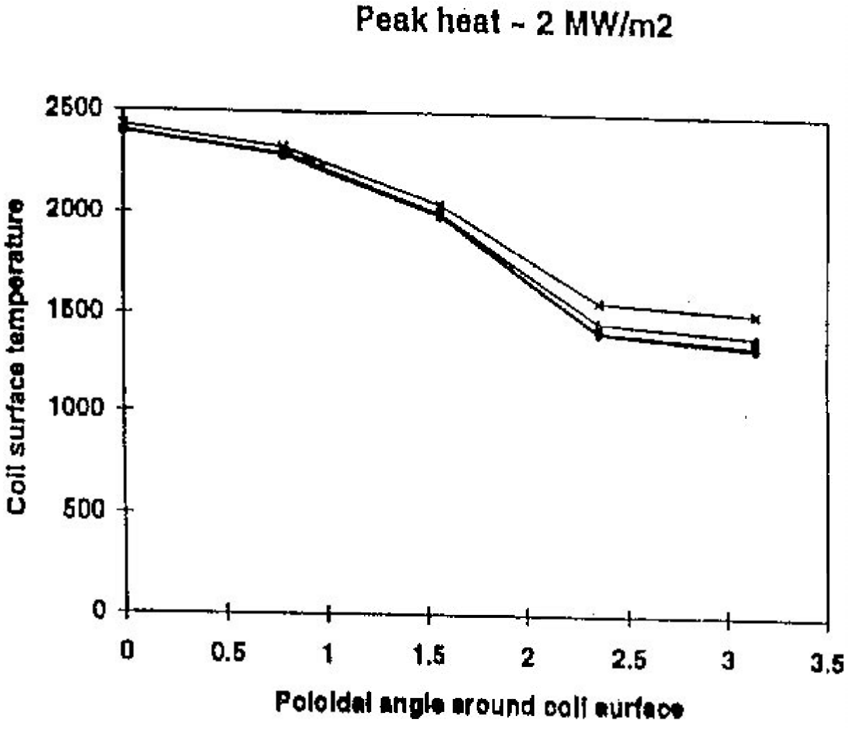


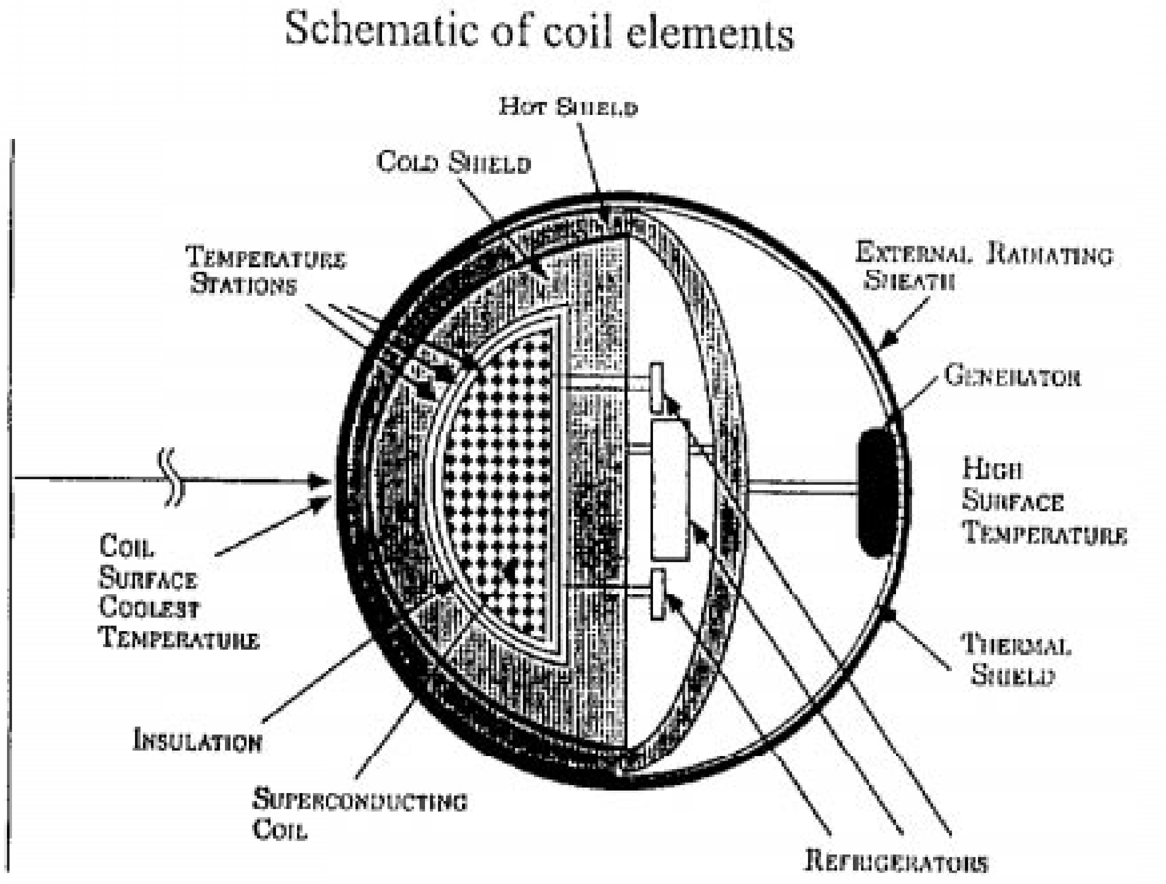
(1992)

LDX has motivated renewed interest in dipole-based fusion reactors…

For example, L. Bromberg has examined…

- The impact of high-T_C superconductors
- Realistic onboard power sources and refrigerators
- First wall issues and improvements in thermal power generation efficiency





The Levitated Dipole Fusion Concept Differs Significantly from Traditional MFE Concepts

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❶ The physics basis for dipole fusion is relatively well-developed, but it is untested in the laboratory.

❷ The dipole confinement devices are toroidal without toroidal magnetic fields…

- Achievable β depends on size; and β can be arbitrarily high provided $p' < p'_{crit}$ (B_t in tokamaks, stellarators, RFP's produce average stability; $\beta_p \sim 1$, but $\beta << 1$.)
- Classical (instead of neoclassical) confinement
- Convective cells may improve ash removal without degrading energy confinement
- Very large flux expansion simplifies first wall problem. (With B_t, TF coil prevents flux expansion generating first wall problems.)

❸ The dipole concept is steady-state without the need for current drive.

❹ The dipole concept is free from disruptions.

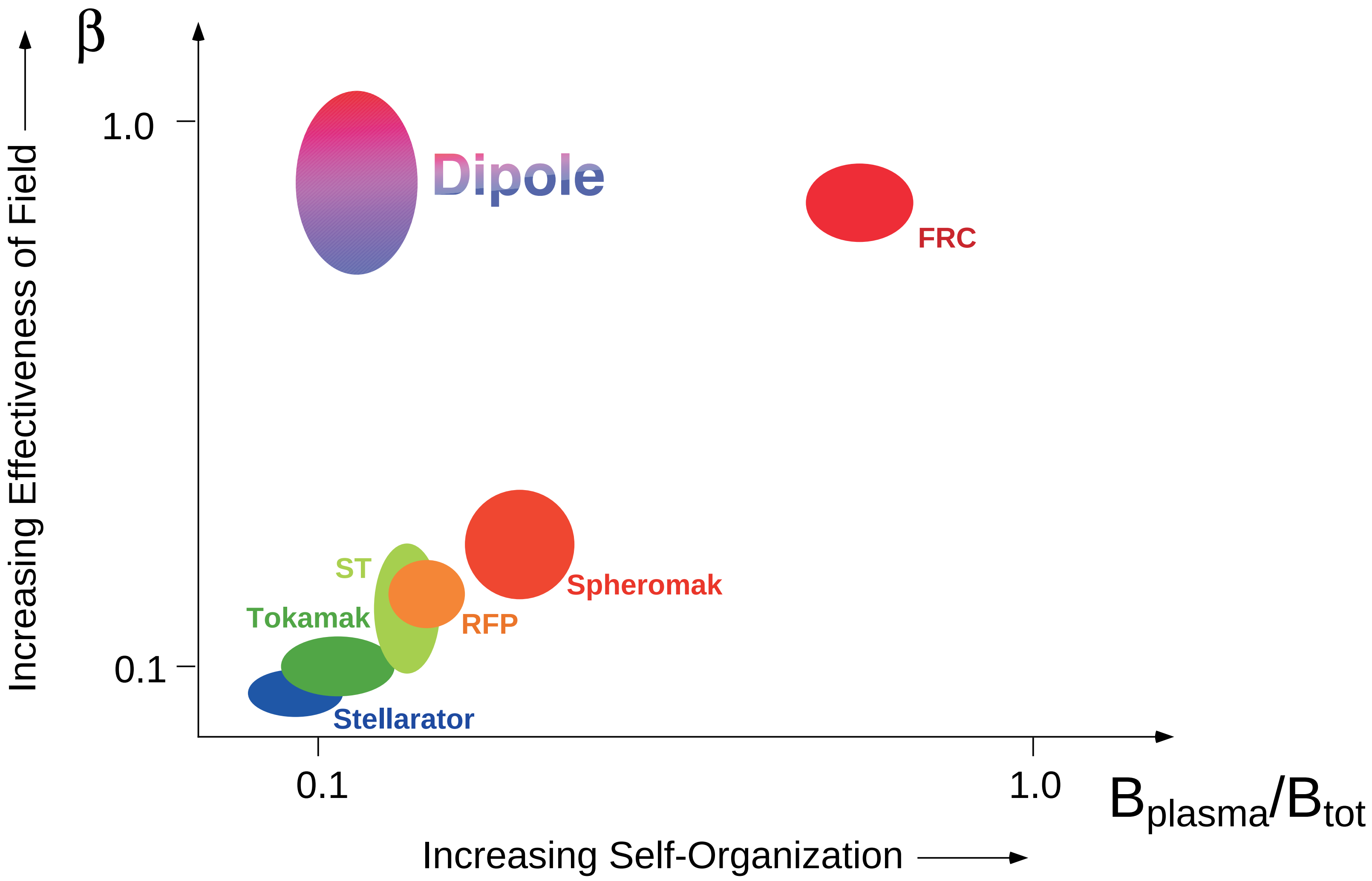
❺ The dipole fusion concept is based (primarily) on D-^{3}He fuel instead of D-Li fuel…

- Dipole fusion does not require the development breeding blankets
- EM radiation transfer (not neutron transport) is used for energy extraction
- Fast triton removal (via drift-resonance “pump-out”) have been suggested

❻ The dipole fusion concept is linked to space exploration…

- A dipole power source has a thin, low-weight outer wall and a small floating magnet. This is makes the dipole concept ideally suited for large, space-based power sources and space propulsion systems.
- ^{3}He fuel is plentiful in space.

MFE Fusion Concepts



Dipole concept broadens our fusion development pathways, and it has the potential of expanding our vision of fusion applications

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➊ D-^{3}He vs. D-Li

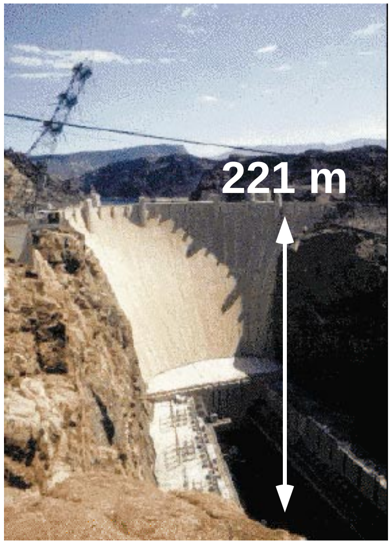
➋ Small, highest-possible field magnets needed

➌ Large size is not so bad…
If the outer wall is “low-tech”, highly reliable, and does not contain high-field magnets or complex breeding systems.

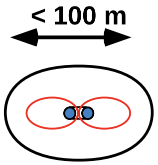
➍ In addition to fusion’s goal to produce safe, carbon-free electricity, …
Fusion (and plasma science) are natural partners with the space program.

Big is not necessarily bad, if it is reliable, available, maintainable, and low-cost…

The Itaipu Dam, completed in 1982 on the Parana River between Brazil and Paraguay, will eventually generate 12,600 MW, making it the largest power complex on Earth. The Itaipu Dam is 8 km long and cost $20B.



Hoover Dam, located on the Colorado River in southeastern Nevada, was opened in 1936. The impounded waters formed Lake Mead, 185-km-long, one of largest artificial lakes in the world. The dam, 221 m high, is used for flood control, irrigation, and power.

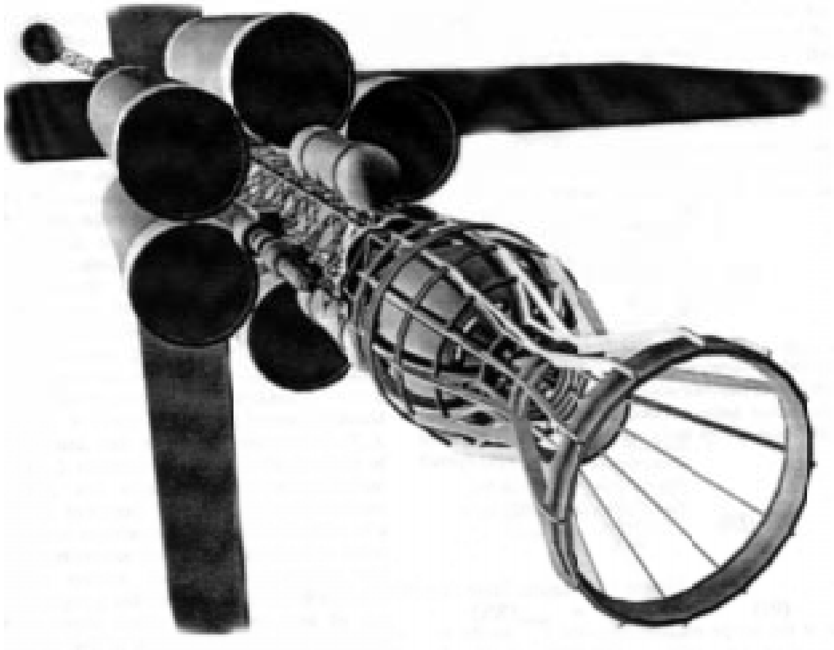


A Large Dipole Power Source

Fusion (and Plasmas!) have no Competitors for Some Space Applications

D-^{3}He ST-Based Fusion Rocket to the Outer Planets

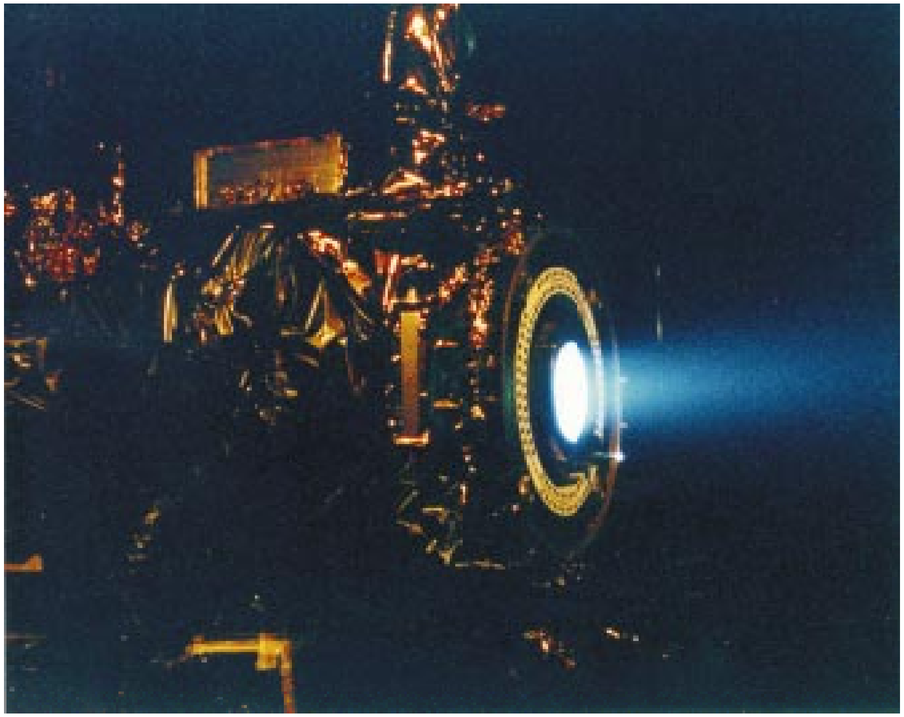
(NASA/Lewis, Dec. 1998)



(…and the dipole has even lower weight/watt than the ST!)

Deep Space 1 Xe Ion Engine

(Launched Oct. 1998)



“Although contestable…only a single propulsion technology exists at this time that can reasonably be expected to offer [manned outer-planet] capability: nuclear fusion, either magnetic or inertial.”
C. Williams, et al., NASA/Lewis, AIAA-98-3591

(See also, “Reaching for the Stars,” *Scientific American*, February, 1999.)