Fusion hybrid reactor for nuclear waste burning and energy production

Olov Ågren, Vladimir Moiseenko, Klaus Noack, Anders Hagnestål, Jan Källne, Uppsala University

Why?

1. Transmutation of long-lived radioactivity, nuclear nonproliferation, fast fission reactor safety
2. Global energy production (> 1 000 years) without CO_2
3. Not as difficult as fusion !!

How?

A ”simple” fusion device produces fusion neutrons. Only modest requirements on plasma confinement.

Each fusion neutron gives 12 fission reactions and $Q_r \approx 150$ times more power from fission than from fusion.

Advantages with a mirror machine:

1. Steady state, large energy multiplication ($Q_r \approx 150$), short shut down time
2. Reactor safety, gross plasma stability
3. Compact (25m long apparatus for 1.5 GW thermal power)
4. Tolerable load on “divertor” plates & 1st wall
5. Diagnostics & RF heating devices outside fusion region
6. Current coils can be built with fission mantel inside

Mirror machines close to the required performance, in particular the electron temperature (T_e = 500 eV enough for mirror hybrid).

Comparison tokamaks and mirror hybrid reactor:

Tokamak (JET/ITER)		**Mirror hybrid**	
Volume:	70 / 800 m^3	12 m^3	more compact
Toroidal current:	$I_t \approx 5$ / 15 MA (no steady state)	$I_t = 0$ (not driven)	simplification
Magnetic field:	$B_t \approx$ 3-4/5.6 T	$B \approx$ 2.5-10 T	more complex coils (possible to design !)
Plasma pressure:	$\beta \approx$ 2-8 %	$\beta \approx$ 30 %	better use of magnetic field
Confinement time:	$\tau \approx 1/4$ s	$\tau \approx 0.2$ s	reduced particle confinement demands
Fusion energy gain:	Q = 0.6/10	$0.1 \le Q \le 1$	reduced plasma confinement demands
Ion temperature:	$T_i \approx 20$ keV	$T_i \approx 50$ (10-100) keV	somewhat higher ion temperature (possible with RF or NBI)
Electron temperature:	$T_e \approx$ 10/20 keV	$T_e \le$ 0.5 keV?	electron temperature requirements reduced in a hybrid! **T_e is the weak point of mirror machines!** $T_e \approx 0.5$ keV seems possible !
Plasma pulse length:	$t_{pulse} \le 30$ min	t_{pulse}=1 year?	steady state possible (no transformer action) commercial reactor requires $t_{pulse} \ge 1$ year (?)
Disruptions:	threat !	No gross instabilities	licensing of a reactor requires no disruptions (?!)
Power:	20 / 500 MW	1 500 MW$_{th}$	high energy multiplication ($\approx$ 150) by fission reactions. Only 10 MW fusion power required!

Our conceptual study: “Straight field line mirror” (SFLM) with magnetic expander

Fig. Entire coil set för an SFLM mirror machine

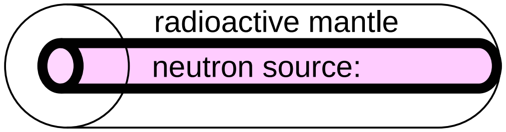


Fig. Scheme for transmutation of nuclear waste

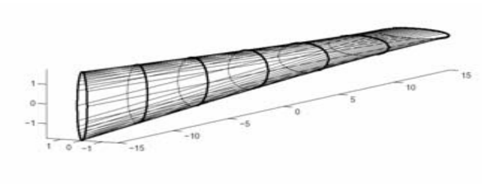


Fig. SFLM has straight nonparallel magnetic field lines

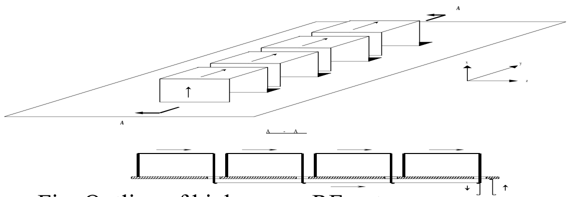


Fig. Outline of high power RF-antenna

SFLM:

1 No gross plasma instabilities
2 Kinetic instabilities controlled
3 Gyro center moves along a single flux line
4 High plasma density (beta)
5 Efficient RF-heating
6 Magnetic expander gives large T_e …..

Interests for FDS:

China: Plans for a tokamak-FDS
Russia: GDT: Mirror FDS machine
USA: Plans for an FDS program
Cost in USA for nuclear waste:
250 billion dollars
(Obama does not approve disposal at Yucca M.)

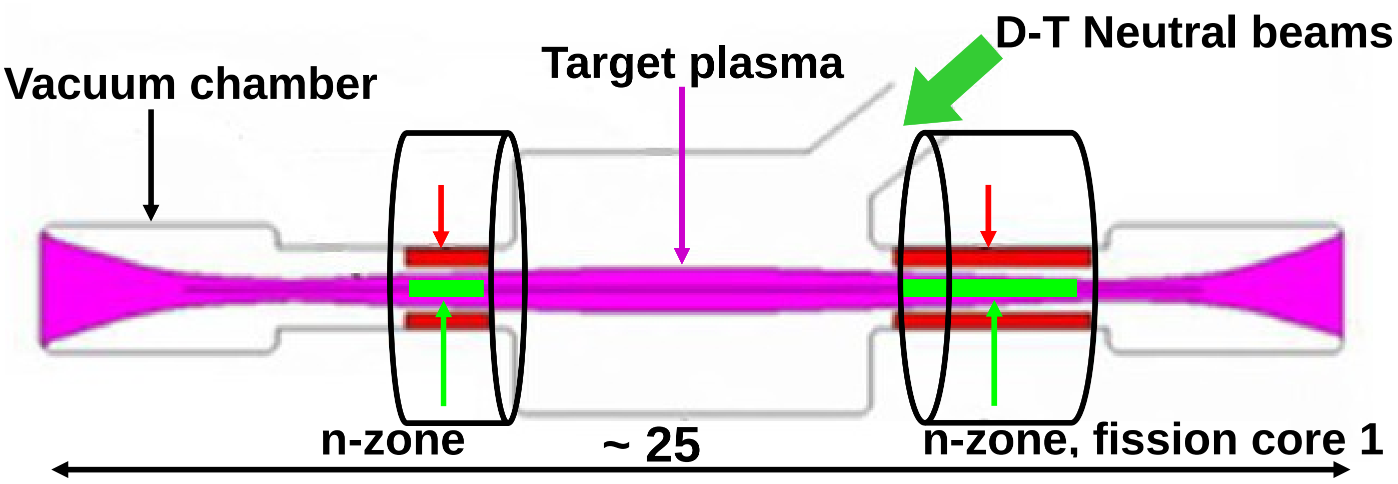
Axisymmetric mirror:

MHD stabilization with expanders
(high beta, but low T_e ?)

Non-axisymmetric mirror:

MHD stability without plasma in expander
(high T_e possible)

GDT (Novosibirsk): Axisymmetric mirror with expander

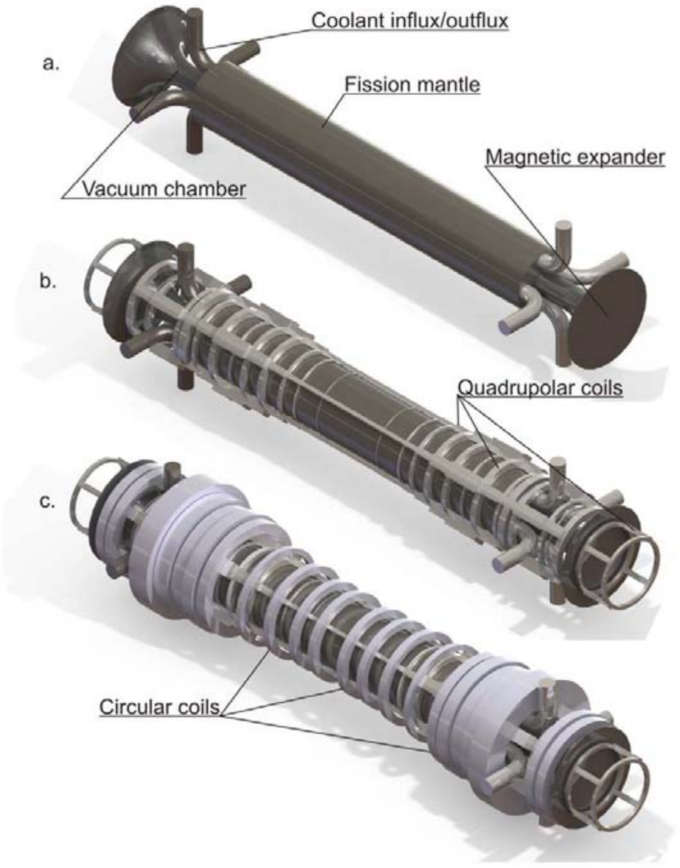


Neutron computations for GDT:
K. Noack et al, Annals of Nuclear Energy 35 (2008) 1216

Good: No plasma systems in high neutron flux zone
Simple coils, low power expected for cooling superconductors, high beta, ….
Improved T_e with rotational shear (upper limit on T_e not yet known!)

But: Two reactor cores
Low energy efficiency with low T_e

Coil system for SFLM with expander:



Concerns for non-axisymmetric mirrors: Coil construction possible!

Flux tube ellipticity tolerable!

Results for SFLM with expander:

Superconducting coils:

Mirror ratio 4, Ellipticity 17, r_{plasma} = 40 cm, L = 25 m

Enough space for fission mantle, RF feeding through mirror ends

RF (ion cyclotron) heating simulations:

Efficient heating of minority deuterium (>90%) and tritium (2nd harmonic)

Monte Carlo neutron simulations:

$Q_{r,max} = 146 \approx 150$ (with $k_{eff} = 0.97$)

99.6 % of fusion neutrons reach fission mantle (39% in the FTWR tokamak)

Reactor safety: Δkeff < 2% (LOCA, boil of coolant) ⇒ keff + Δkeff < 1

1st wall replacement: 30 years (200 dpa), tritium reproduction > 1

Fusion neutrons: 10 MW fusion power ⇔ 1.5 GW_{th} power output

Estimates on electron temperature demands: (power loss by electron drag)

$T_e >$ 350 eV: Power production (with $Q_r \approx 150$)

$T_e >$ 500 eV : $Q_{el,net} \geq 450$ MW

$T_e \approx 2$ keV a possible limit with density depletion in expander

Objectives with SFLM:

1) Optimized Q_r:

a) no holes in fission mantle, “all” fusion neutrons trigger fissions

b) $k_{eff} < 0.97$ for reactor safety

c) lead-bismuth coolant

Fission to fusion energy multiplication:

$$Q_{r,max} \approx 150$$

(the FTWR tokamak has Qr (20-40)

2) Increased Te

a) Low plasma density in expander ↔ strong electric potential for electrons

b) Impurity control

c) No ECRH (in our scenario)

3) Plasma confinement

a) MHD: Av. min B field, no instability drive from Ohmic heating

b) Warm plasma stabilization, sloshing ions

c) Zero banana widths (omnigenuity)

e) Low T_e demands with high Q_r !!! Electron drag $\Rightarrow T_{e,crit}$ [keV] $\approx 10/(Q_r)^{2/3} < 0.5$

$T_e \approx 0.5$ keV seems possible for a mirror machine!!

4) Material load minimized

- a) Tolerable load on “divertor” plates in expander
- b) No spectroscopic windows in confinement region
- c) RF antenna outside neutron producing region
- d) low load on 1st wall (30 years for 200 dpa)
- e) No large scale plasma instability foreseen

Summary:

1. No obvious weak point found (on heating, stability, refueling, material load etc)
2. Electron temperature physics should be addressed
3. Favorable predictions with $k_{eff} = 0.97$:
   - a) 450 MW net electric power production (if Te = 500 eV)
   - b) Detailed studies (coils, neutronics, plasma s$_{\Delta keff}$tability, RF heating etc)

     Neutron source: 25 m long, $r_{plasma} = 40$ cm:

     $Q_r \approx 150$ (with $k_{eff} = 0.97$)

     3.6×10^{18} fusion neutrons/sec $\Leftrightarrow$ 10 MW_{fusion} $\Leftrightarrow$ 1.5 GW_{th} power output
   - c) Low plasma fusion Q sufficient for reactor! $Q \geq 0.15$

Thank you for your attention!