Mirror Based Hybrids of Recent Design

Presentation to

FUNFI

Workshop on

FUSION FOR NEUTRONS AND SUB-CRITICAL NUCLEAR FISSION

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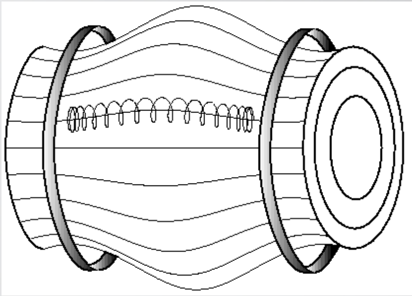
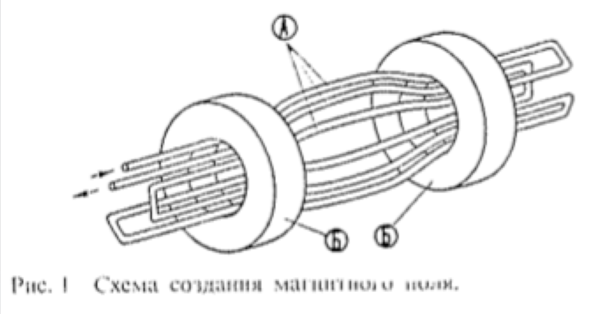
Evolution of mirror confinement fusion

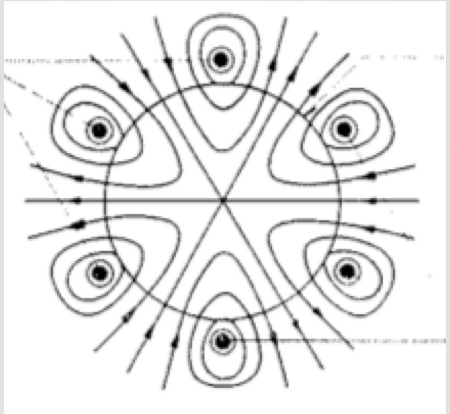


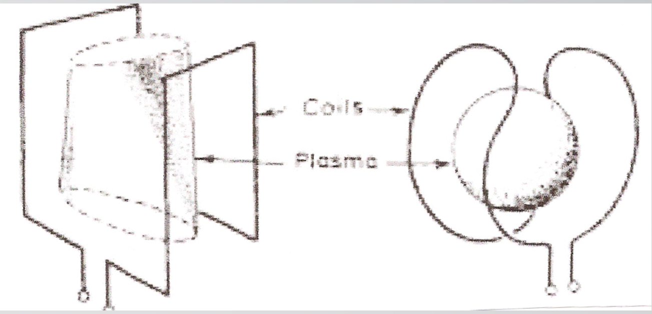
- **Simple mirror-axisymmetry**

  But MHD unstable and Q~1

- **Magnetic well—MHD stable**

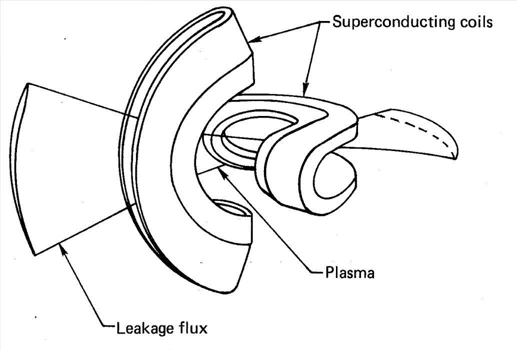






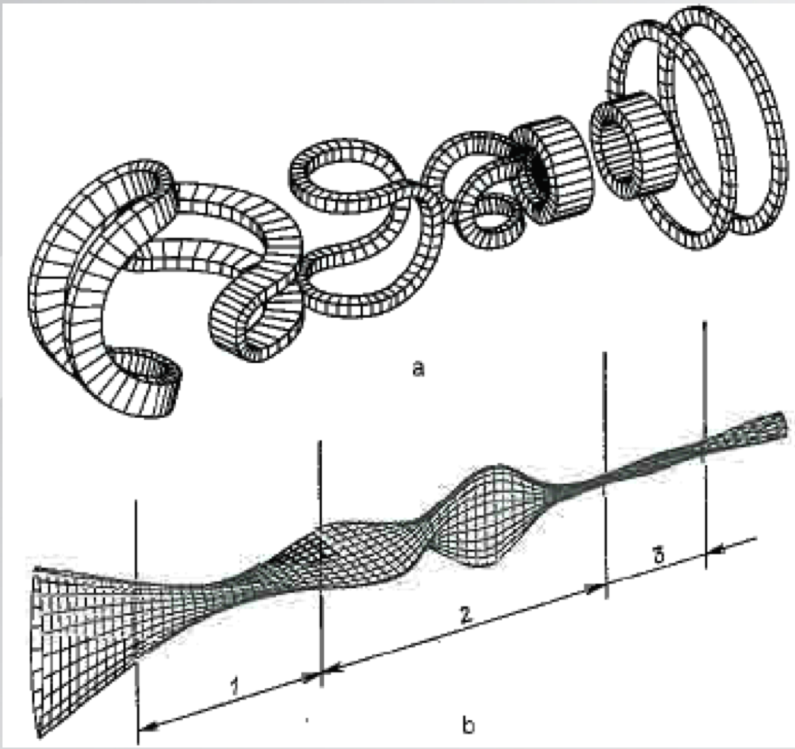
Ioffe bars **------->** **Tennis Ball coils**

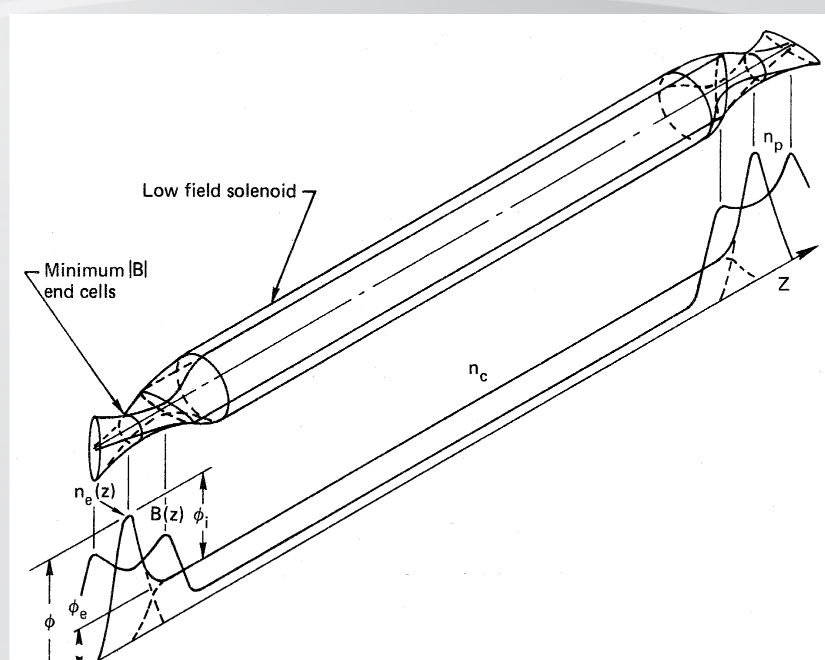
---->Yin-Yang coils



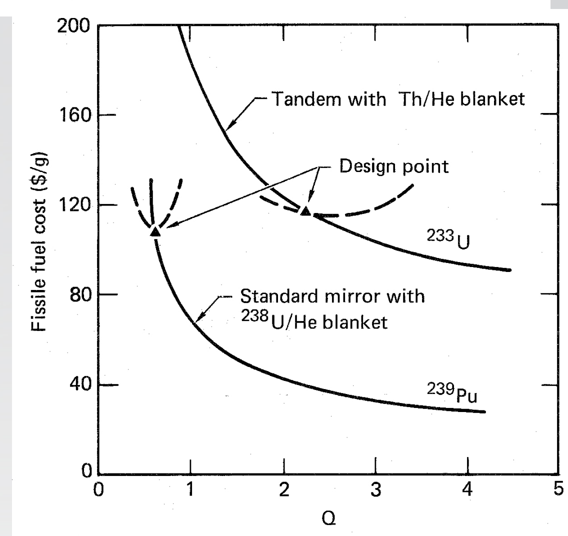
But axisymmetry lost! Still Q~1

Tandem mirror boosts Q>>1 needed for pure fusion





Moir et al. UCID-18808

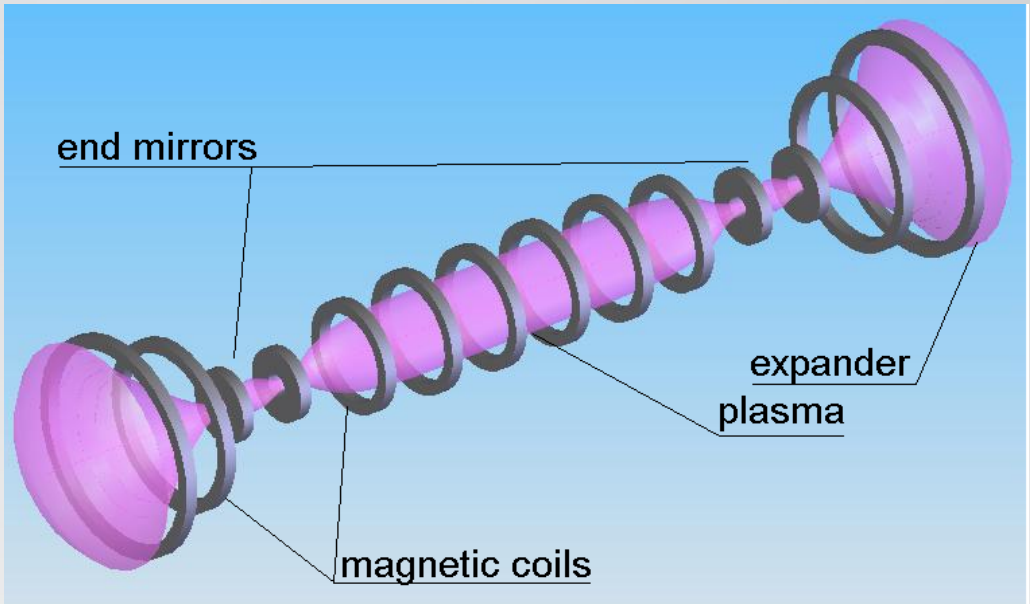


But axisymmetry lost

Q should be >1
for good economics
for fuel production

Back to axisymmetry for Hybrids

- Gas Dynamic Trap demonstrated several MHD stability mechanisms, warm plasma outflow---->Q<<1
- Can we base a low Q~1 hybrid on the simple axisymmetric mirror?
  - Sloshing ions ($V_{\perp} = V_{II}$) for microstability
  - MHD stable (?)
  - 80-100 keV D^o,T^o injection
  - 15 T mirrors



A simple axisymmetric mirror as a driver for fusion-fission hybrid

Natural divertor to handle heat with large end tanks

No externally driven currents

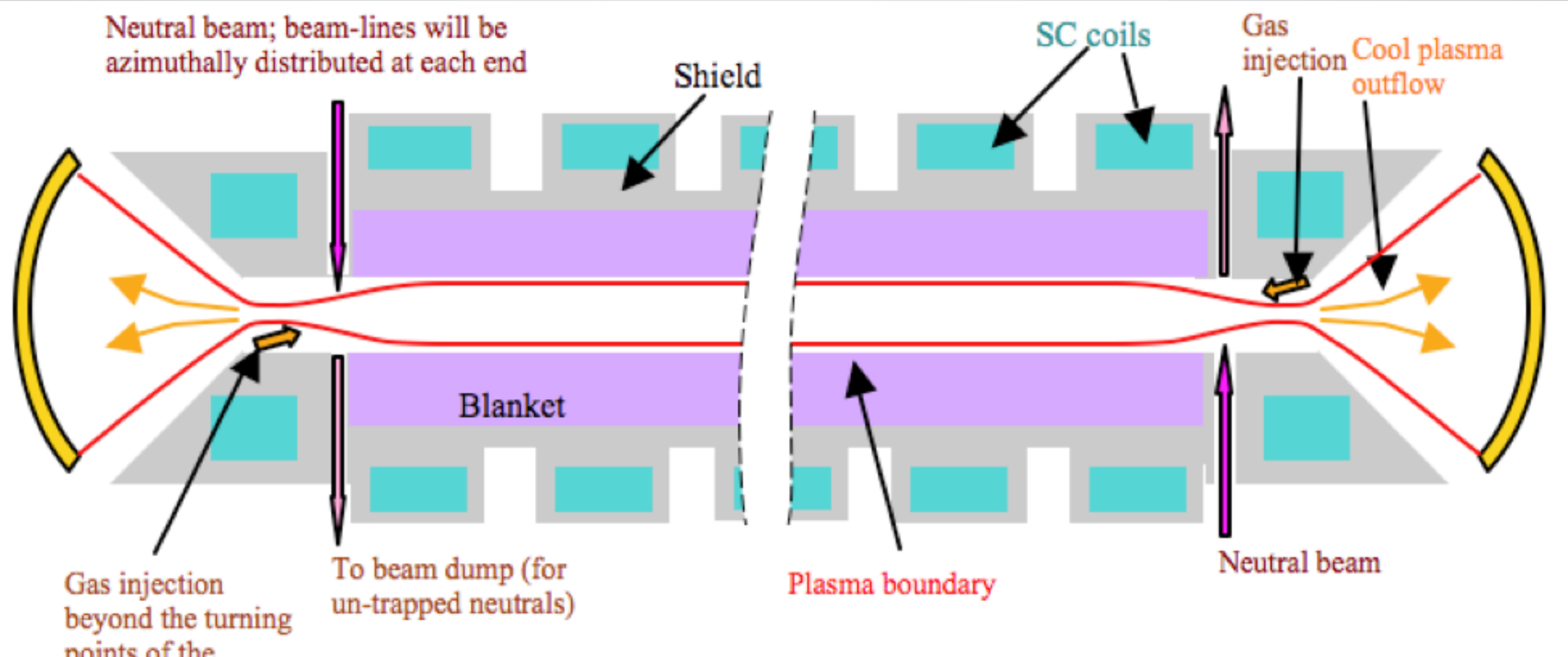
Linear geometry and simple circular magnets,

Near term mirror physics can meet near term hybrid missions: burn actinide wastes especially minor actinides

Modular blankets

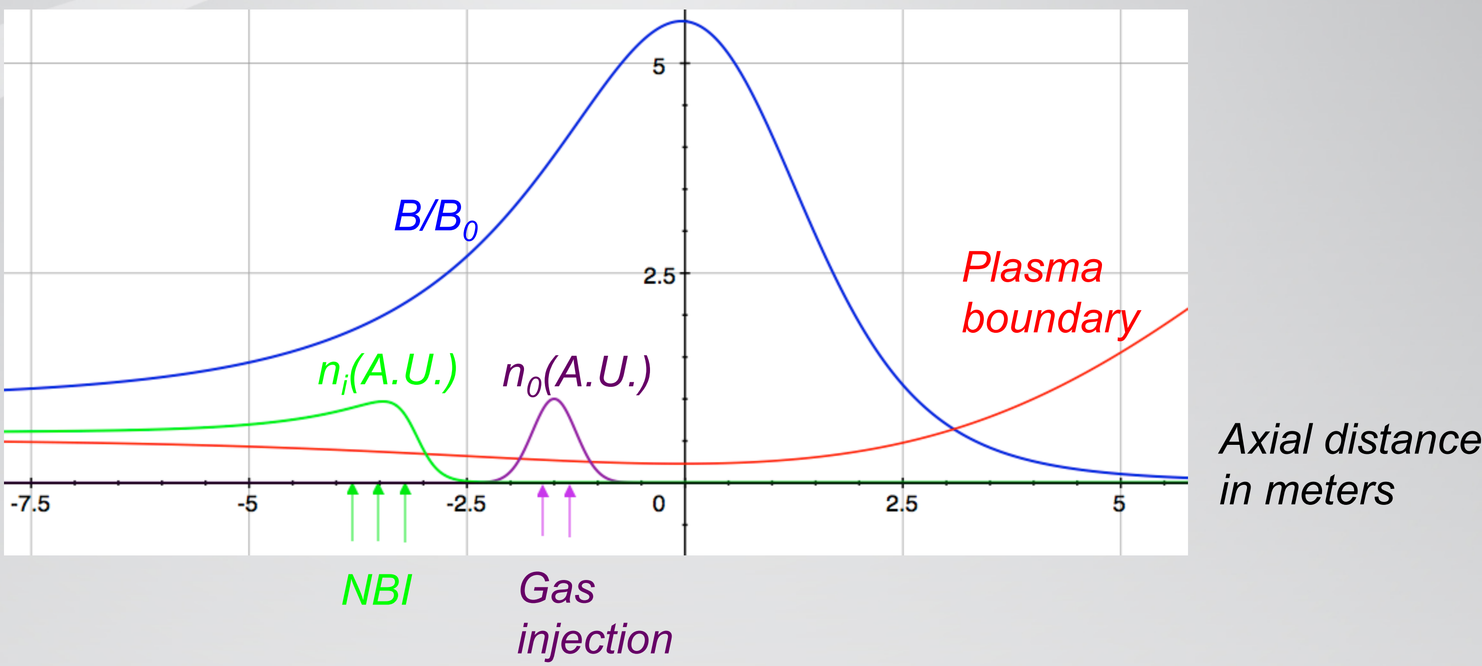
Plasma beta=0.25

Several techniques for stability



Moir et al., LLNL-PROC-484033 (2011).

80 keV neutral beam injection at B=5 T gives sloshing ions in 2.5 T solenoid. Gas injection inside the 15 T peak field lowers Te to 3 keV.

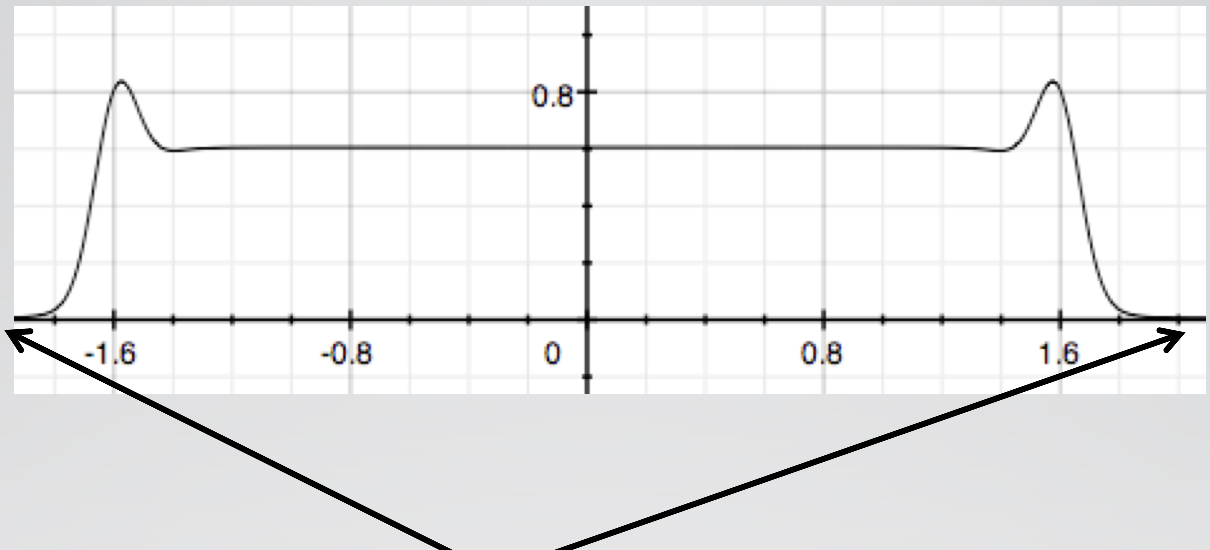


The sloshing ion distribution is much more stable with respect to velocity-space microinstabilities than the distribution peaked near the 90-degree pitch-angle. Note that the gas is injected at the distance of 2 m from the ion turning points, thereby eliminating overlapping with the hot ion distribution (and CX losses)

Moir et al., LLNL-PROC-484033 (2011).

The rest of this talk assumes a line neutron source with the axial distribution of neutrons almost uniform

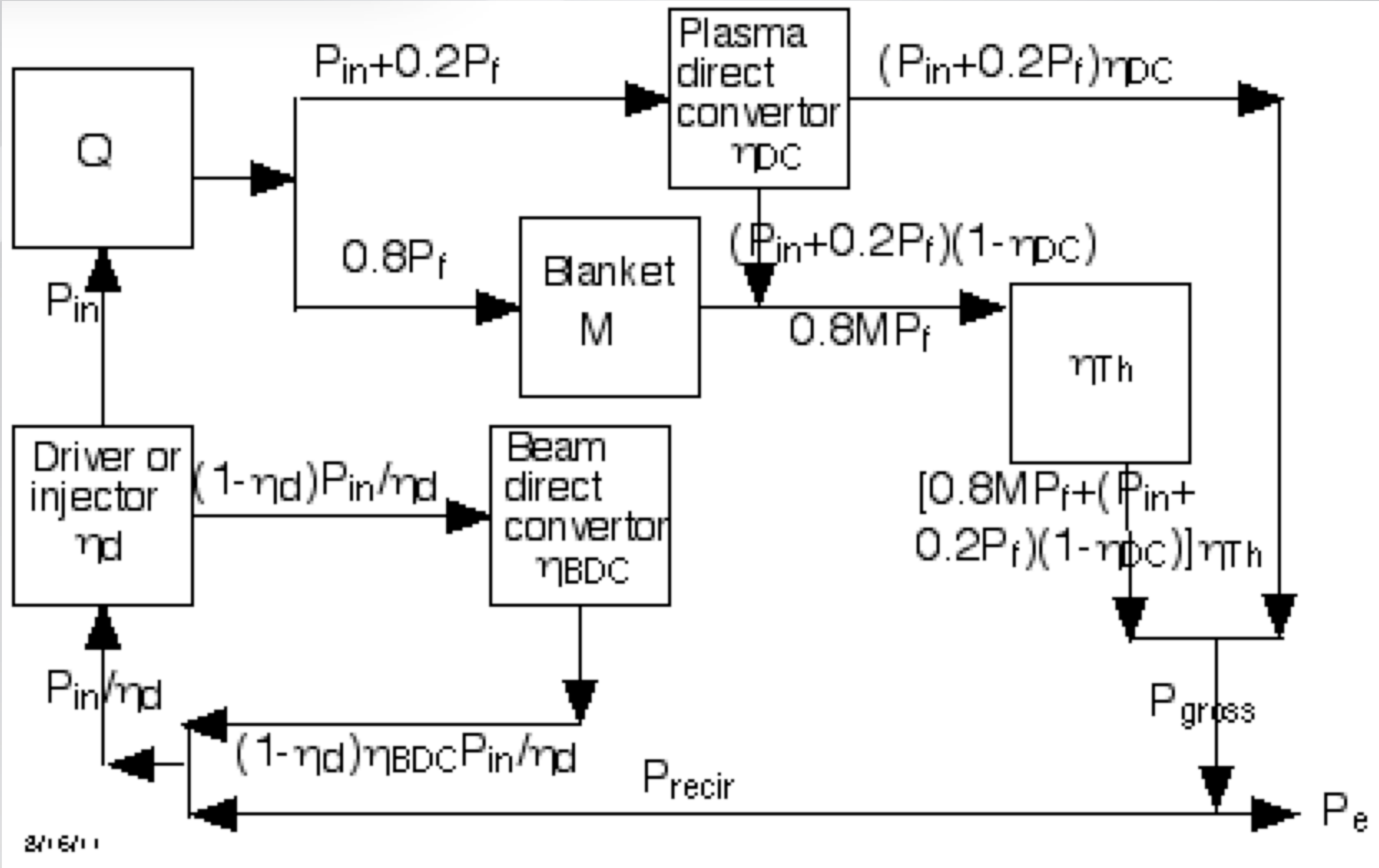
Neutron power per unit length, a.u. The mirrors are situated at z=-2 and z=2 (A.U.)



Note that in the mirror throats the neutron production is very small. The neutron flux there is dominated by the scattered neutrons.

Calculation of recirculating power fraction
$F_{recir} = P_{recir}/P_{gross}$ .. >0.4

F_{recir}>0.4 bad econ
<0.2 good econ



η_{Th} =thermal conversion efficiency, typically = 0.4

H_d =efficiency of converting electrical energy into neutral beam energy and trapping the beam=0.5

η_{BDC}=efficiency of conversion of unneutralized beam, i.e., beam direct conversion =0.5

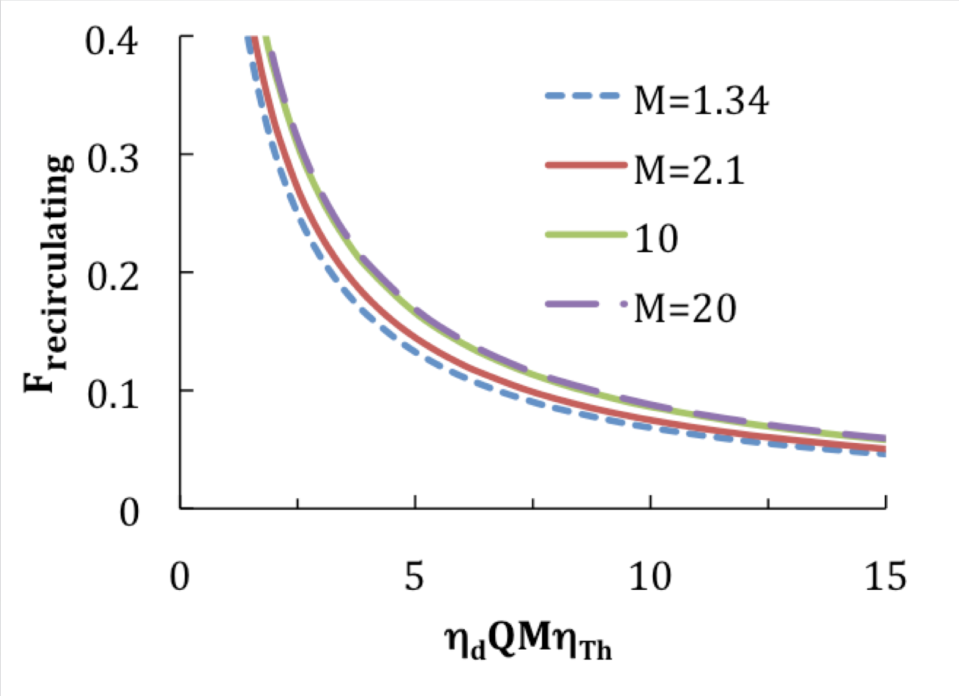
η_{DC} =efficiency of plasma direct conversion of end losses, typically 0.5

$Q=P_{fusion}/P_{in}$

M=Blanket energy/14 MeV

For favorable economics the hybrid must make power for sale and use neutrons effectively to “burn” actinide wastes, produce fissile fuel or make extra power.

The F_{recir} should be low, <0.2.



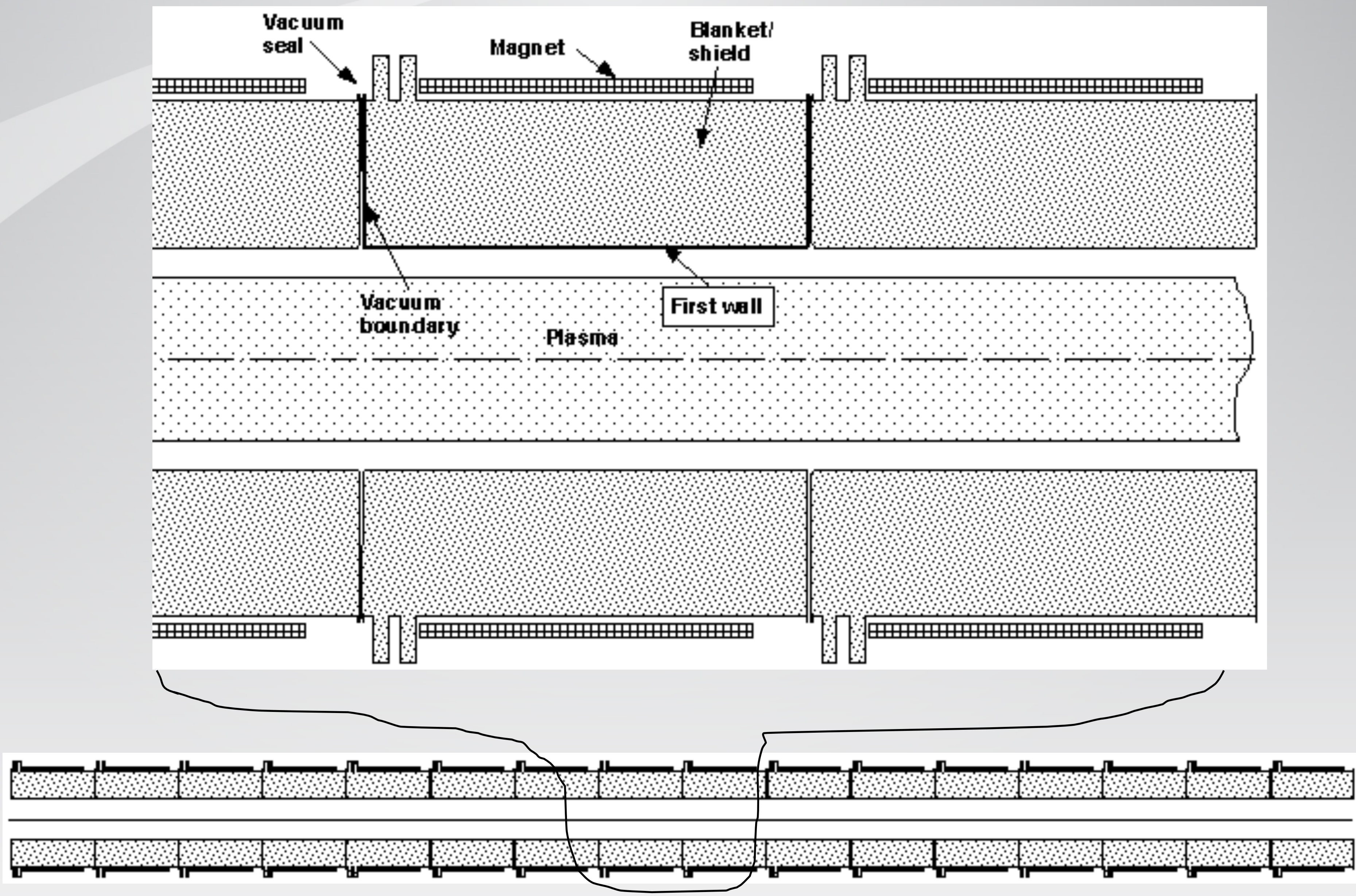
$$\eta_d Q M \eta_{th}$$

>3 with direct conversion

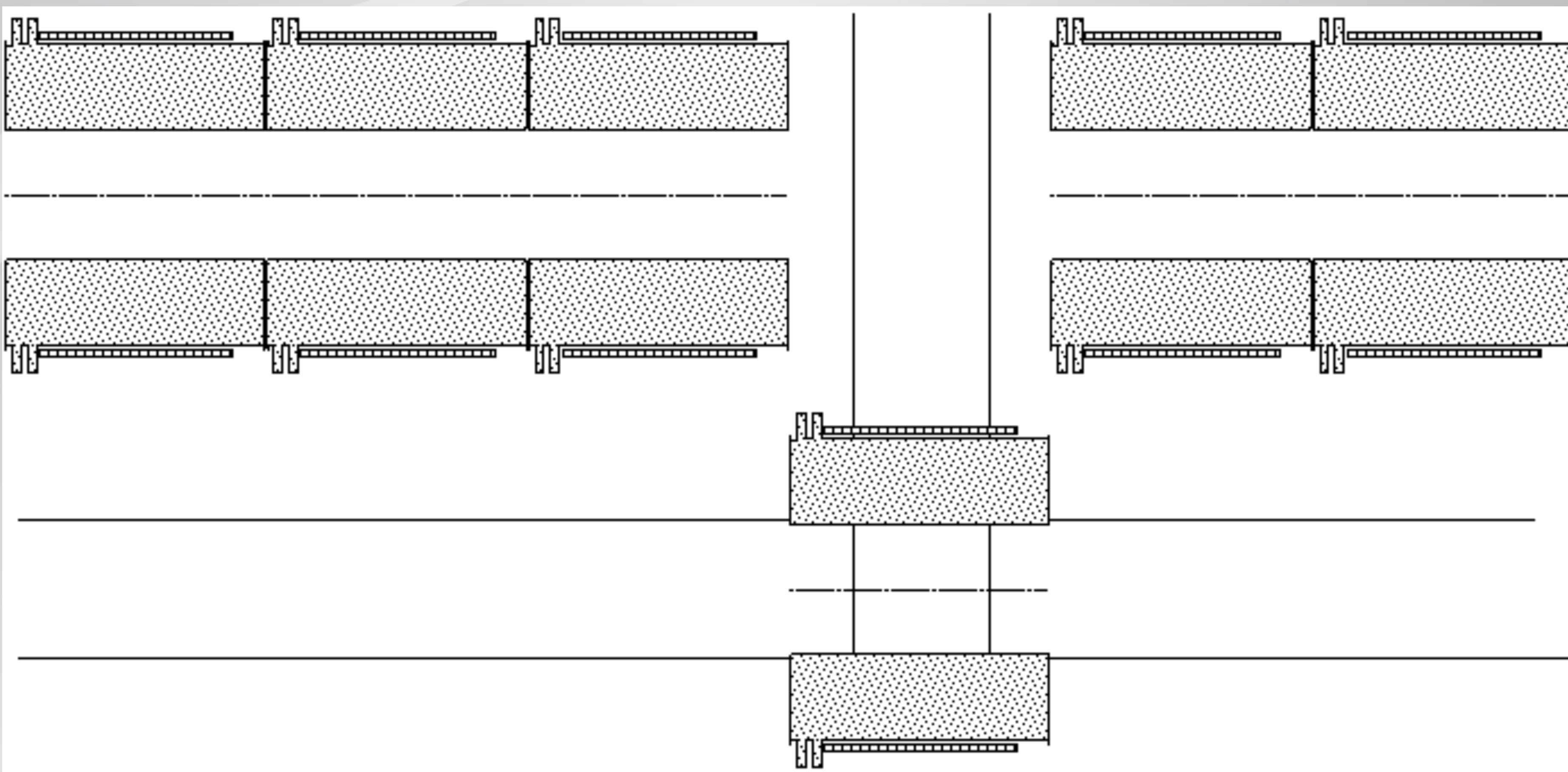
or

>6 without direct conversion

The blanket/magnet system for the axisymmetric mirror is made up of many identical modules



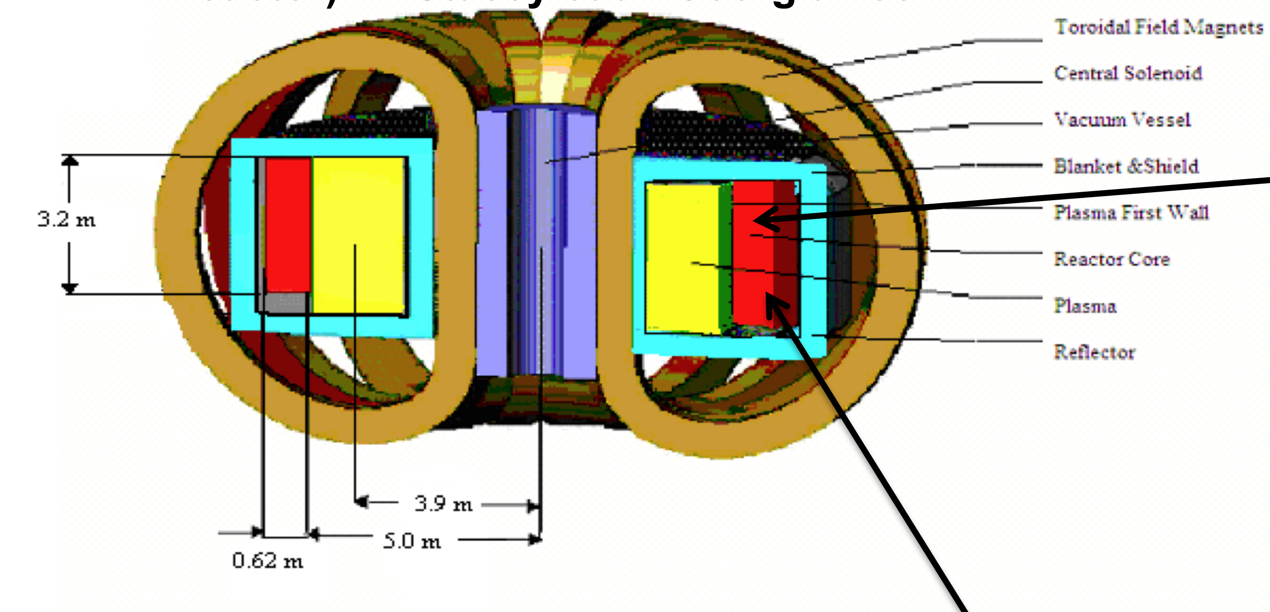
An entire module is replaced by rolling on rails

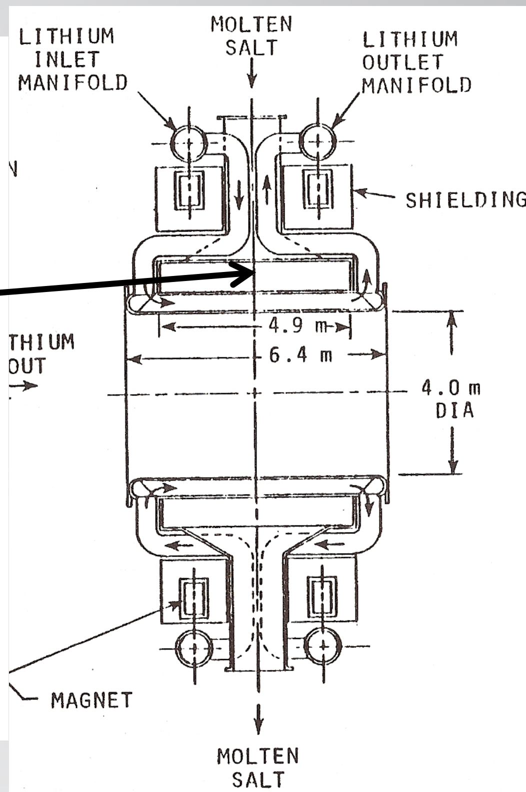


Tokamak blanket works on a magnetic mirror

Transuranic fissioning (“burning”) hybrid blanket design; M=19; Q>0.5 for F_{recir}<0.4

SABR-(Subcritical Advanced Burner Reactor) W. Stacey et al. Georgia Tech





Lee et al. UCID-19327

Active or engineered cooling needed for afterheat in case of accident.

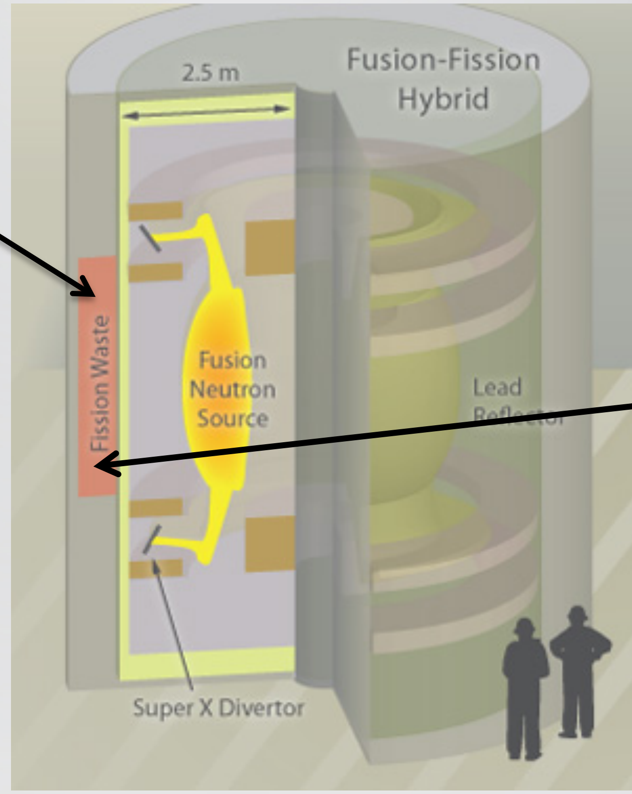
Molten salt version by E. T. Cheng, M=13, passive safety.

Sodium cooled rods made up of Transuranics (Pu, Np, Am, Cm …..) from processed LWR spent fuel

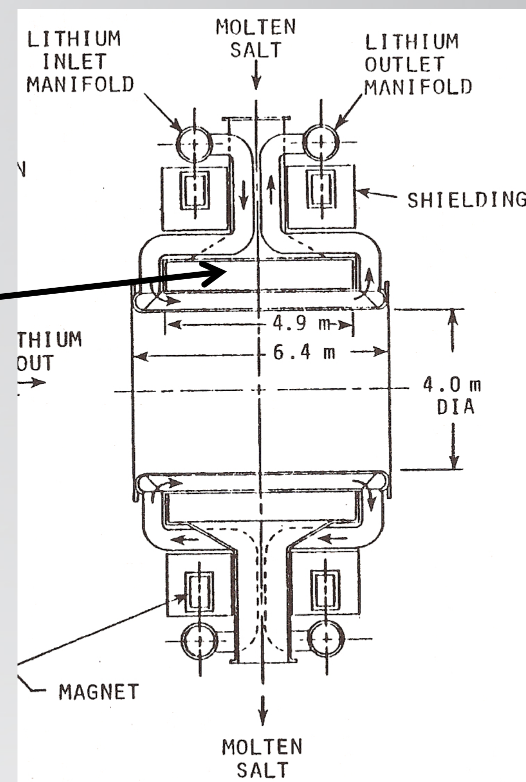
Tokamak blanket works on a magnetic mirror

Minor actinide fissioning ("burning") hybrid blanket design; M=50; Q>0.2 for F_{recir}<0.4

Sodium cooled rods made up of minor actinides (Np, Am, Cm ..) from processed LWR spent fuel



Kotschenreuther et al.
U. Texas



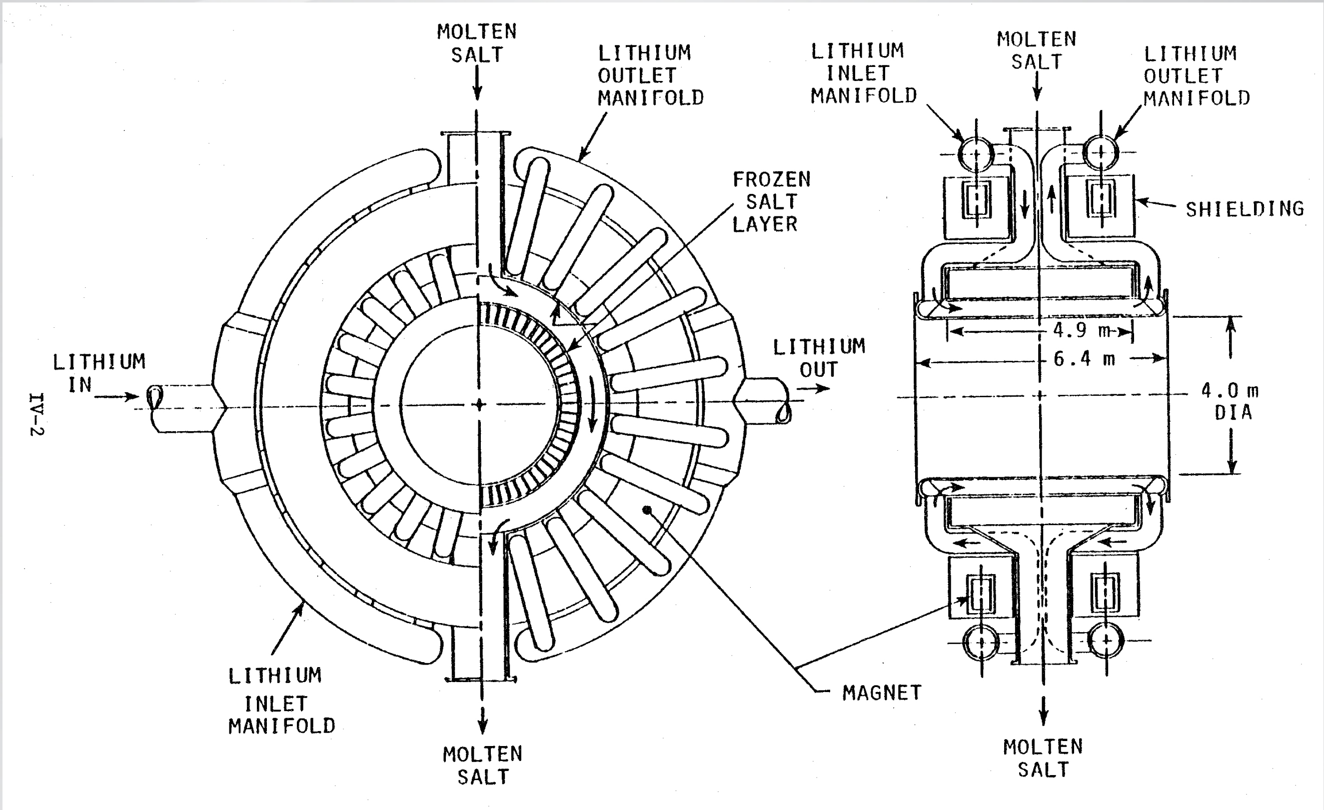
Lee et al. UCID-19327

Active or engineered cooling needed for afterheat in case of accident. → Safety! → Keff~0.99 !

Molten salt versions with passive safety possible.

Fission-suppressed fissile fuel production

Blanket/magnet module



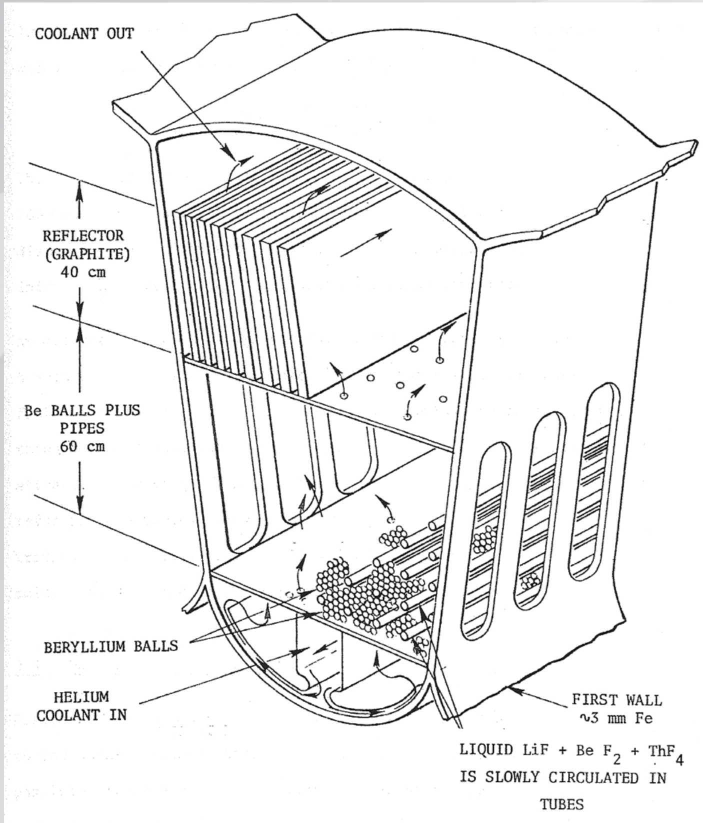
See Moir lecture 016 Thur AM

Lee et al. UCID-19327

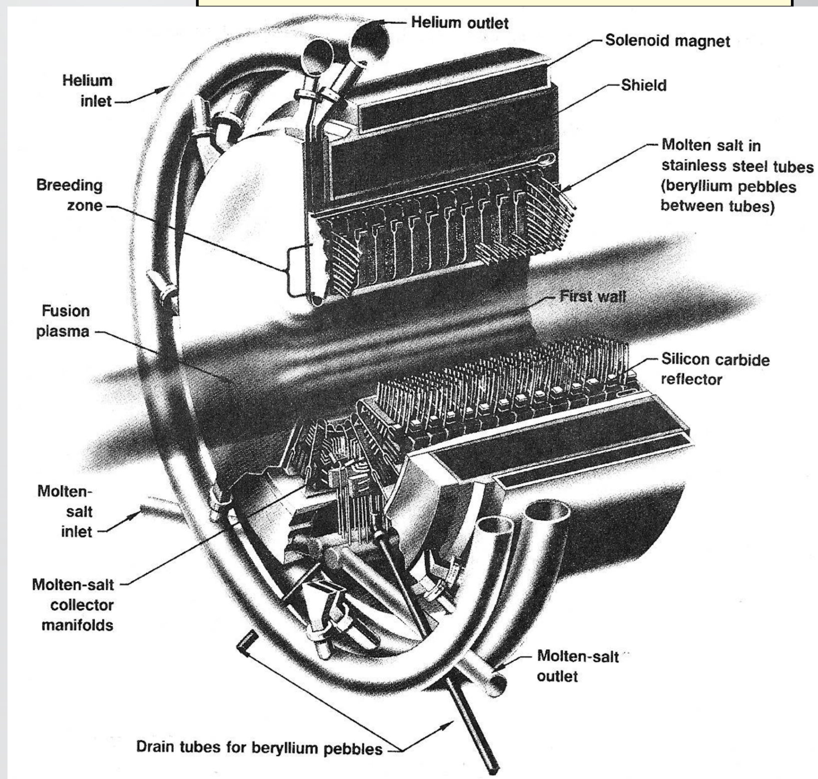
Lithium-7 to multiply neutrons and breed tritium
Molten salt facilitates draining for passive safety and easy removal of U-233 made from thorium; M=1.4, F=0.5 ^{233}U/fusion, Q>4

Fission-suppressed fissile fuel production

Submodule



Blanket/magnet module

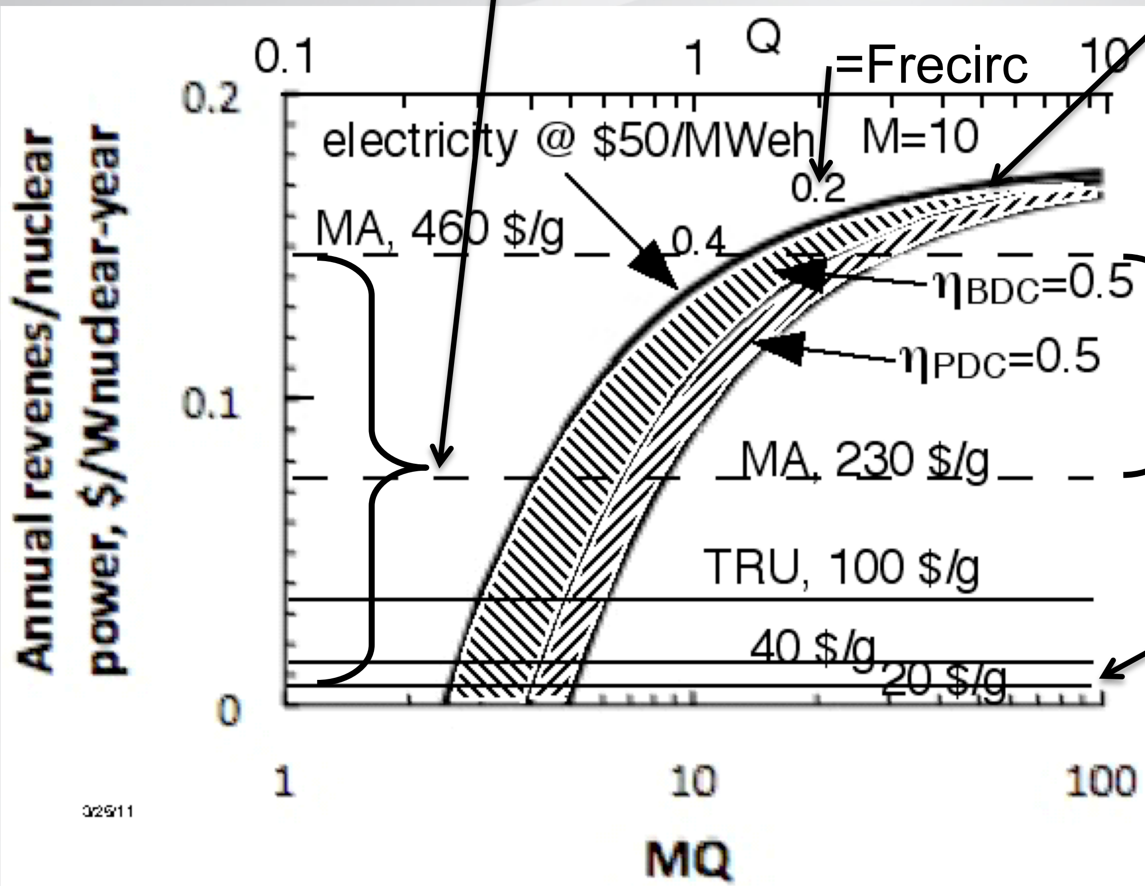


See Moir lecture 016 Thur AM

Moir, et al., *Fusion Technology*, **8**, (1985), 465-473.

Beryllium to multiply neutrons
Helium cooling
Molten salt facilitates draining for passive safety and easy removal of U233 made from thorium; M=2.1, F=0.5 ^{233}U/fusion, Q>4

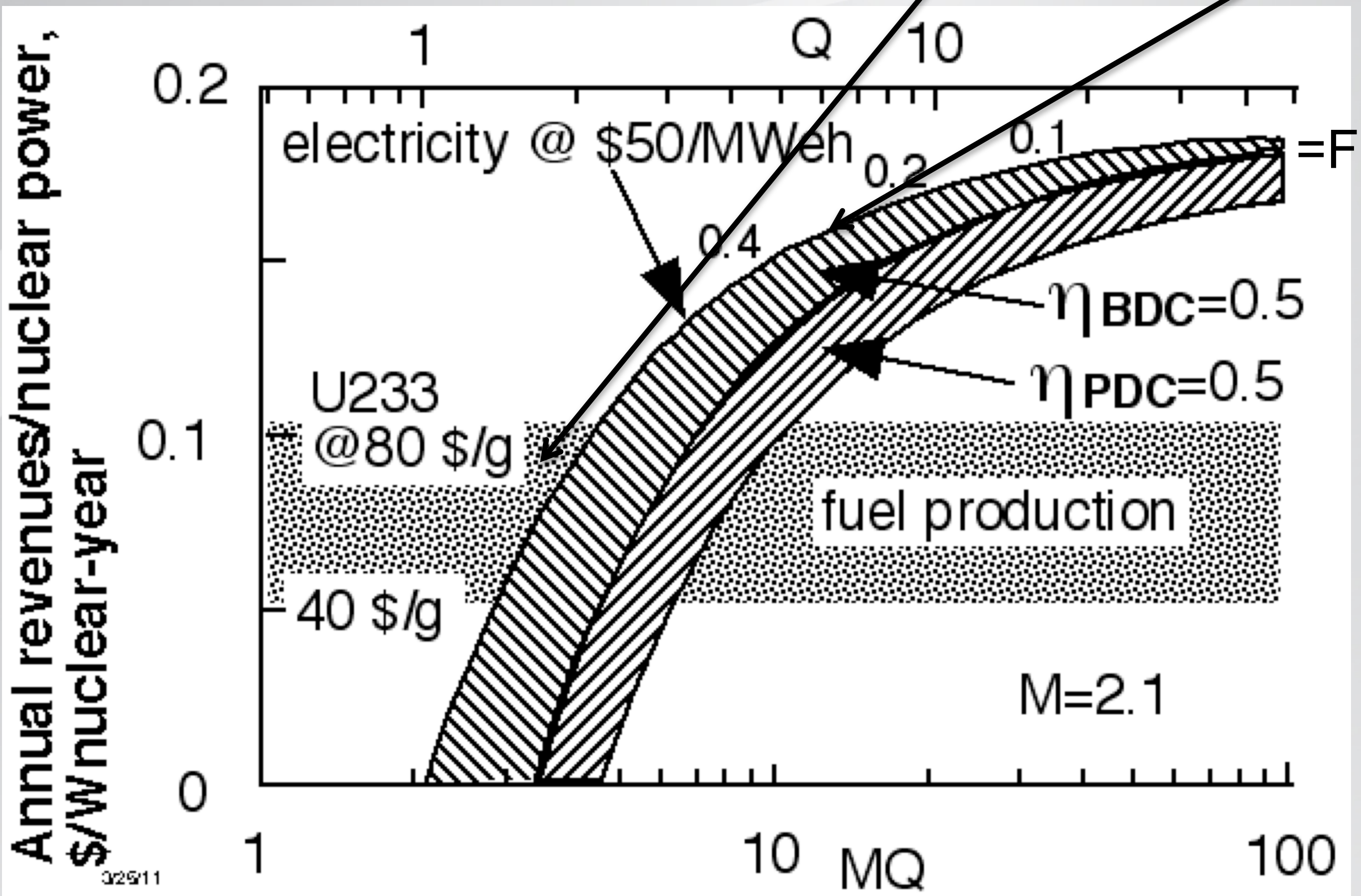
Actinide waste burning hybrid has revenues for fissioning actinides and sale of electrical power

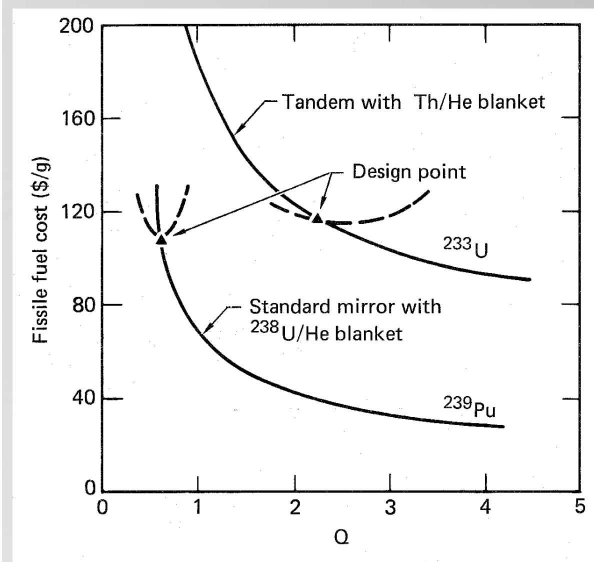


Yucca Mt economics values burning minor actinides at 230 to 460 $/g and transuranics at 20 to 40$/g.

Revenues are ~0.01 for transuranics and for minor actinides are 0.08 to 0.15 $/Watt-nuclear-year and electrical sales are 0.15 $/Watt-nuclear-year for Q=1 and M=10 or Q=0.2 and M=50 (F_{recir}=0.4)

Fission-suppressed fuel producing hybrid has revenues from sales of fuel and electrical power





$/g of ^{233}U versus Q (old studies)

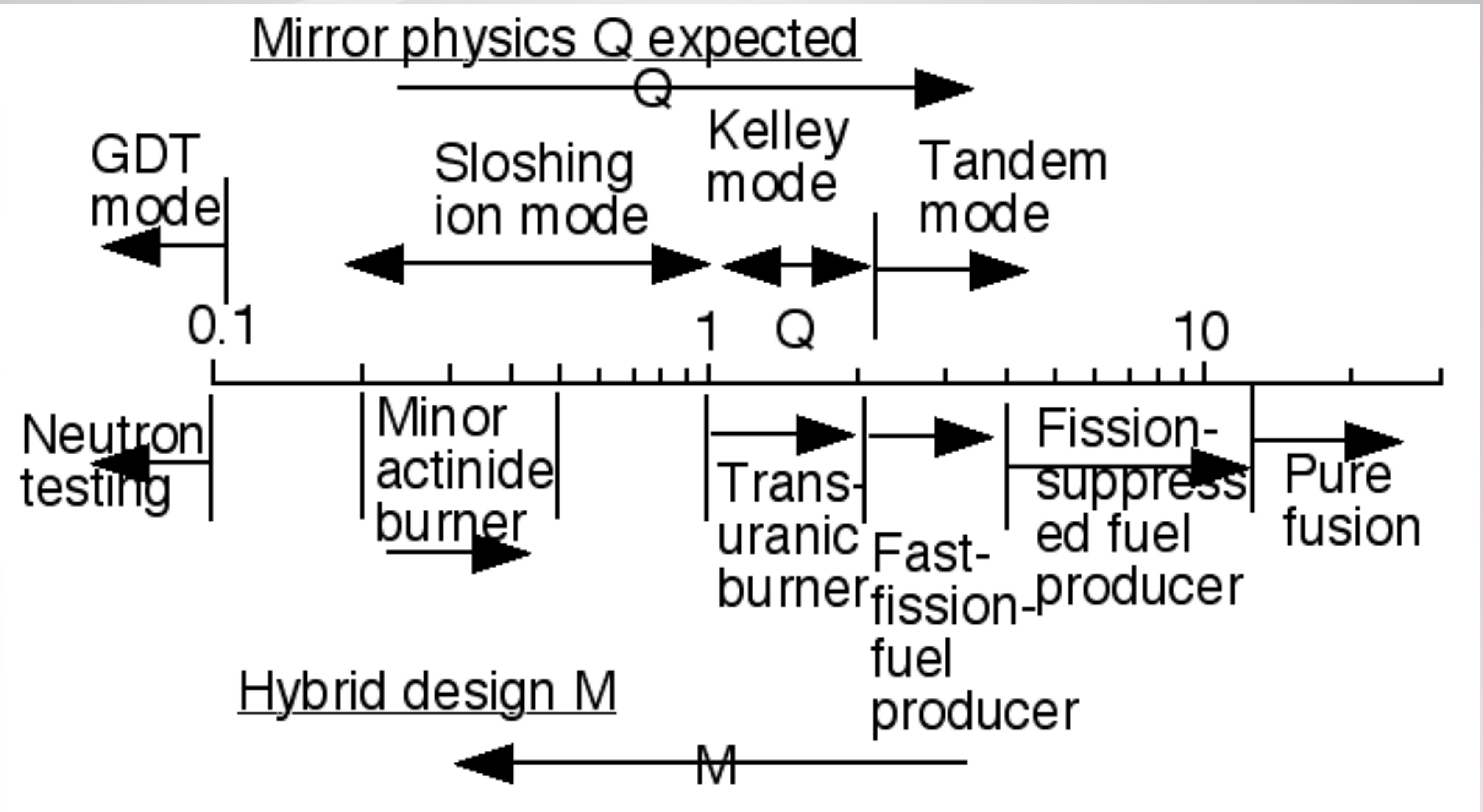
Fuel sales bring 0.1 $/Watt-nuclear-year at 80 $/g U233 and electrical sales brings 0.15 $/Watt-nuclear-year at Q=4 (F_{recir}=0.4)

Required Q for hybrids versus M

Recirculating power fraction = 0.2, $P_{nuclear}$=3000MW

Actinide burner			
Blanket multiplication, M	Minimum Q required	P_{fusion}, MW	Comments
Transuranics, M=19	1	200	solid fuel, engineered or active safety
Minor actinides, M=38 to 150	1 to 0.5 0.2 av.	25 to 100 50 av.	solid fuel, engineered or active safety
Transuranics, Molten salt, M=13	1.5	280	passive safety
Fuel producer			
Fission-suppressed, M=2.1, ^{233}U	8	1600	passive safety
Fast-fission, M=10, ^{239}Pu	2	370	engineered safety
Power producer			
M=10	2	370	molten salt-passive safety solid fuel-engineered safety
Pure fusion			
M=1.34	11	2300	passive safety

Summary: Hybrid options with larger M allows corresponding mirror operating regimes with lower Q.



Conclusions

- The sloshing ion mode (Q~0.7) meets the mission of burning minor actinides.
- Small improvements (Q>1) meets the mission of burning transuranics.
- Fuel production with fissioning needs Q>2 with some tandem physics
- Fuel production with fission-suppression needs Q~>4.
- Pure fusion requires Q>11 with lots of tandem physics

Tokamak blankets work on a magnetic mirror

simpler geometry
modular blankets
steady 2.5 T field
15 T mirrors

Detailed report is available

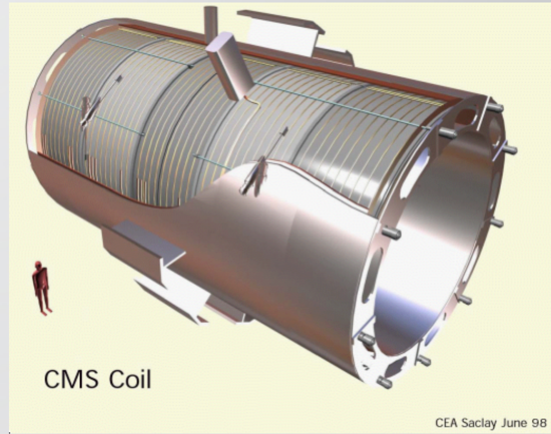
Parameters of a mirror driver

Plasma radius[1], m	0.5
Mirror-to-mirror length, m	40
Length of a reacting plasma[2], m	35
Volume of a reacting plasma[2], m^3	25
Plasma surface area[2], m^2	100
Injected ion energy[3], keV	80
Average ion energy[3], keV	40
Average ion density, m^{-3}	10^{20}
Electron temperature, keV	3
Peak ion density, m^{-3}	1.3×10^{20}
Z_{eff}[4]	1.2
Magnetic field, T	2.5
Mirror field, T	15
Volume-averaged beta	0.25
s = plasma radius/ average ion gyroradius	30
NBI trapped power, MW	65
Plasma Q	0.7
Fusion power, MW	45
Neutron power, MW	36
Neutron wall load, MW/m^2 @ 0.6 m	0.27
Power to end tanks, MW	75

[1]In the midplane
[2]Between the turning points of the sloshing ions
[3]Ignoring ½ and 1/3 energies
[4]Based on the previous experience with large-scale mirror facilities and composition of the injected particle beams

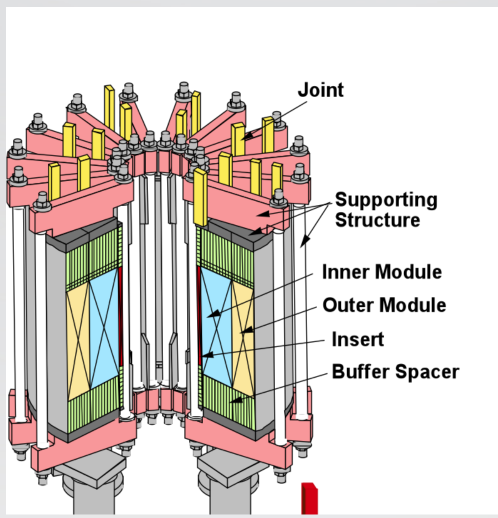
All magnets are circular, steady-state superconducting at 2.5 T and 15 T

The 2.5 T magnets with a 2.3 m inside radius based on NbTi conductor. CMS magnet 6 m ID, 4 T at CERN (courtesy of CEA Saclay)

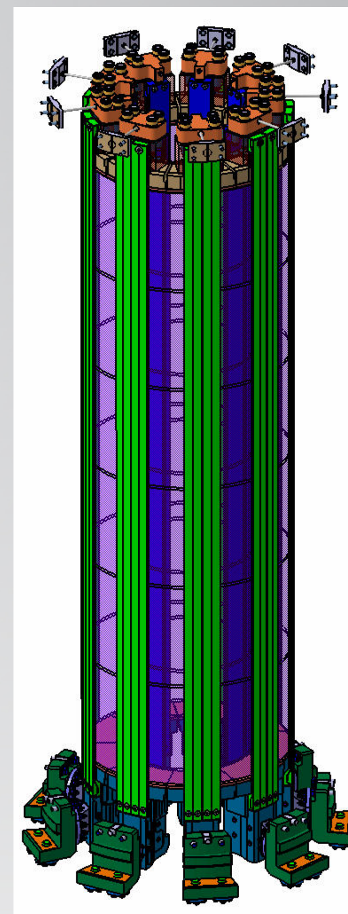


The 15 T magnet with a 1-m inside radius is similar to the ITER central solenoid (CS) magnet using Nb_3Sn

Cable in Conduit Conductor 50x50 mm^2



CS Model Coil (13 T in 1.6 m ID)



ITER CS 13 T in 2.6 m ID

Plasma fueling and heating systems

- 80 keV steady-state neutral beams, will be developed for tokamak neutron sources (FNSFs)
- Direct conversion of ions at 50-70% efficiency.
  - – neutral beams
  - – end losses (issue – charge exchange)
- Gas input lowers electron temperature to 3 keV
- Large end tanks reduce power density of leakage plasma
- Recycling cryopumps keep charge exchange losses manageable.