Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Fusion Fission Hybrid Reactor based on High field tokamak neutron source

Francesco Paolo Orsitto[1] , N Burgio[2],M Ciotti[1],F Panza[2].

[1]ENEA Department Fusion and Technologies for Nuclear Safety C R Frascati ,via E Fermi 45 , 00044Frascati , Italy
[2]ENEA Department Fusion and Technologies for Nuclear Safety C R Casaccia ,via Anguillarese 301, 00123 S Maria di Galeria(Roma) , Italy

IAEA Technical Meeting on synergies between Nuclear Fusion Technology Developments and Advanced Fission Technologies
6-10June22 IAEA Headquarters Vienna, Austria

Fusion-Fission activity at ENEA

Activity started in 2011 with the organization of the FUNFI (Fusion Neutrons for Fission) Conference in Varenna

After few years in 2016yr FUNFI2 was organized in Frascati ENEA(Italy)

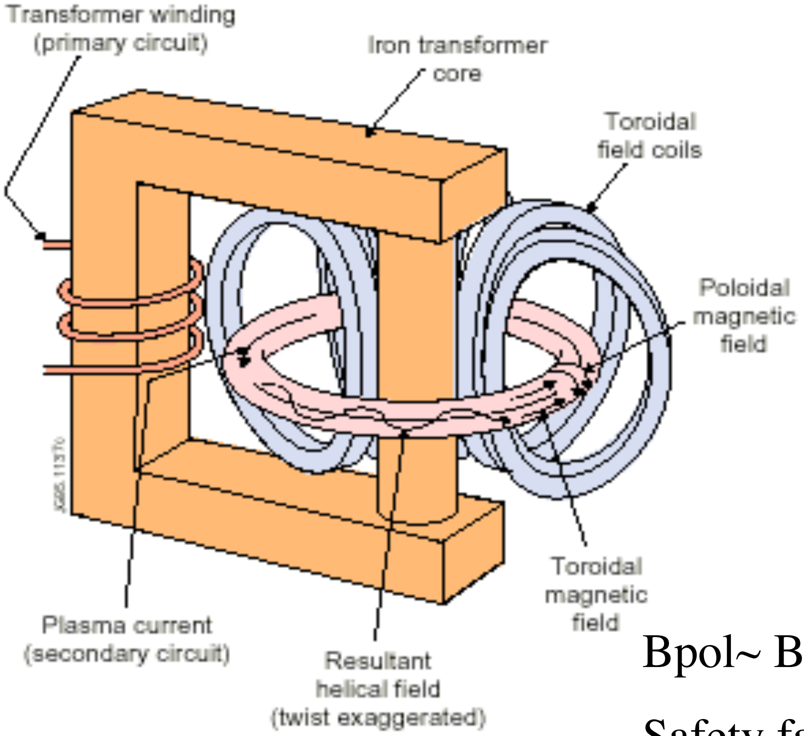
FUNFI3 (nov 2018) and FUNFI4 (nov 2020) were organized in Hefei (China) and in Moskow virtual

Main activity at ENEA :

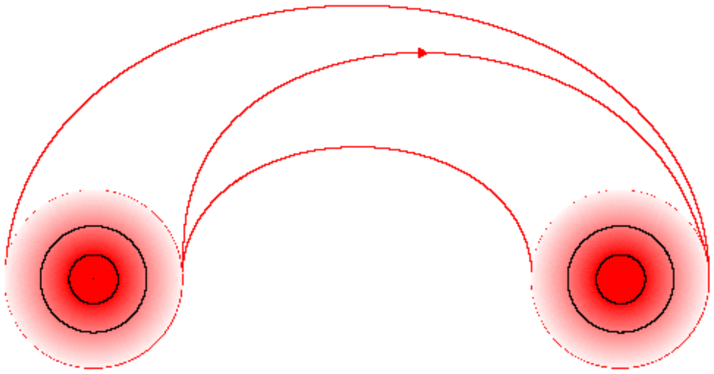
- Study models of Fusion Fission Hybrid reactor with tokamak neutron source
- In particular study of low power COMPACT (R ≈t1.5-2m) tokamak neutron sources

- Study the Validation of FFH concept through experiments on fission reactor working
- in subcritical mode using a 14MeV neutron source as external source

Scheme of a Tokamak



- In a plasma contaned in a toroidal device with axial magnetic field a current is induced by a transformer
- A magnetic field results with elical field lines which close after a certain number of turns on surfaces called ‘rationale surfaces’



JG99.321/10c

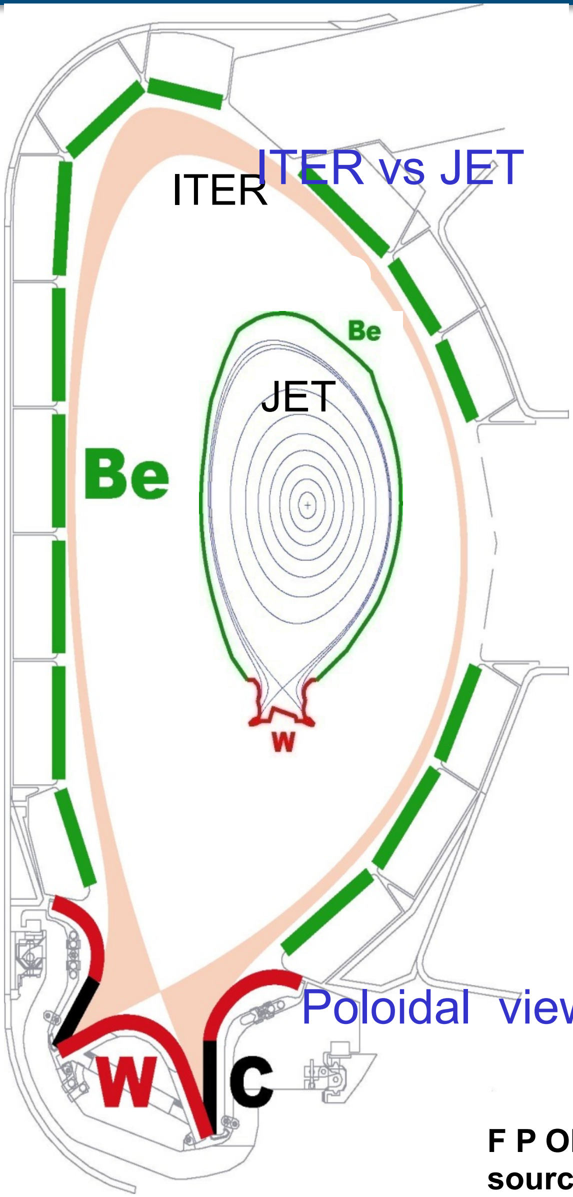
Bpol~ Btoroidal/10;

Safety factor q=(number of toroidal turns /n poloidal turns)=

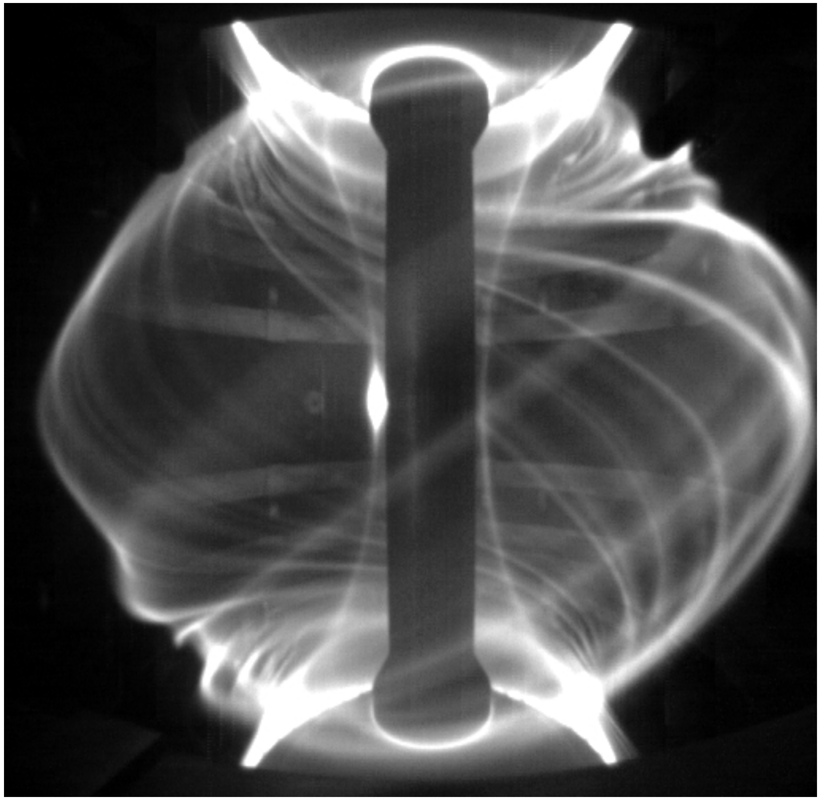
$$\boxed{q = \frac{5a^2 B}{RI}(1 + k^2 / 2)}$$

magnetic shear S= (q/r) (dq/dr)

JET / ITER A=R/a≈3, MAST A=1.67



Poloidal view of tokamak



MAST(UKAEA) spherical tokamak

F P ORSITTO Fusion Fission Hybrid Reactor based on High field tokamak neutron source- IAEA TM on Synergies between Fusion and Fission . 6-10June 2022

The following Questions on the tokamak neutron source of a FFH (Fusion-Fission Hybrid) Reactor are basic for this talk

A neutron souce with fusion gain factor in the range Q=1-3 is needed for FFH

1.Can we define the parameters of a **compact (high magnetic field (≤8T) based on High temperature superconductors) source of the order of 1m major** radius, producing 20MW fusion power , so that the FFH reactor has a power of the order of 200MW ? ➔scaling laws for tokamak fusion plasmas (M Romanelli and F P Orsitto , PPCF 63 (2021) 125004)
Which are the plasma parameters of a neutron source based on tokamak Standard aspect ratio A=R/a=3 and Spherical Tokamak with A=1.8 using **Thermal Fusion** ?
➔use of the scaling laws for determining the plasma parameters

2.At low values of gain factors , the **non-thermal tokamak fusion plasmas** is a reasonable alternative route to the FFH neutron Source: can we define plasma parameters for a device working in NON-thermal scheme?

3. **Thermal Fusion** : plasma Te_electrons=Tions (Te=8-10keV)
Non-thermal Fusion : plasma with Ti>>Te obtained
With direct interactions of Tritium ions with fast Deuterium

Outline : NEW SCALING LAWS for Tokamak plasmas with aspect ratio A=R/a=3 and 1.8

1.Plasma parameters of FFH neutron sources based on tokamaks obtained from new scaling laws for fusion reactors.

2. Parameters of plasmas working at standard aspect ratio A=2.5 and high field(B=8T) are derived based on FTU/ALC CMOD confinement data.and extrapolated to thermal fusion.

2.1. Parameters Spherical plasmas with aspect ratio A=1.8-2 and high field(B=3-4T) are derived based on NSTX /MAST confinement data and extrapolated to thermal fusion.

2.2. Parameters Spherical NON THERMAL plasmas with aspect ratio A=2 and high field (B=3-4T) are derived based on TFTR supershots

3.The study of the FFH reactor based on the tokamak neutron sources are derived from point 1. A FFH model composed by a Tokamak source surrounded by a subcritical fission blanket and by a litium blanket, is carried out showing one of the main property: tritium production

MOTIVATION

1. **Tokamaks plasma confinement properties are depending on the aspect ratio A=major radius/minor radius=R0/a . Standard tokamaks A≥2.5; Spherical tokamaks A≤2 (A=1.8).**

- 2.Data base for high field standard tokamak needs to be built as there is very less data available at high field B>6T than at B<6T for designing devices. In practice only four devices (FT , FTU , ALCATOR-C and C-MOD).

- **2.1.The advantage of high field is well known as the device size can be made more compact reducing the costs and maximizing the performance(at the fixed cost)** .The high field tokamak plasmas can be operated at higher density and with resonably good confinement properties in L-mode .The advantage of using L-mode is that the damage on first wall due to the ELMs can be avoided : **this is the reason why the H-mode producing type I ELMs is being under discussion for DEMO**. The High field route is now closer with the High Temperature Superconductors

- 3.High Field Spherical tokmaks (B=3-4T) are the parallel route explored for FFH neutron sources :For spherical tokamak we have a limited database in practice including NSTX and START and MAST . Scaling laws on spherical tokamaks are introduced and dimensions for spherical tokamak based neutron sources are given .

Design criteria for a MCF neutron source : scaling laws plasma

Scaling laws for reactor plasmas in Hmode

If we define the set of the following conditions :

1.$Q=Q_0$ fixed
2.$\tau_{SD} = \Lambda_{SD}\, \tau_E$.($\Lambda_{SD} \ll 1$) (slowing down time of alpha particles << energy confinement time) ,
3.$P_\alpha = \Lambda_{LH}\, P_{LH}$ ($\Lambda_{LH} > 1.5$) the alpha heating is sufficient to keep the plasma in H-mode

We find that **the scaling parameter linking equivalent fusion plasmas** is :

$$S_{FR} = R\ B^{4/3}\ A^{-1} * Q_0^{\ 1/3}$$

M Romanelli, F Romanelli, F Zonca – 28th EPS Funchal 2001, ECA vol 25 A(2001)697
F P Orsitto and T N Todd , Proceedings Conference FUNFI3 Hefei 2018
https://www.enea.it/it/seguici/pubblicazioni/edizioni-enea/2019/funfi3-international-conference-on-fussion-fission
M Romanelli and F P Orsitto , PPCF 63 (2021) 125004

H mode Qfus=1-2

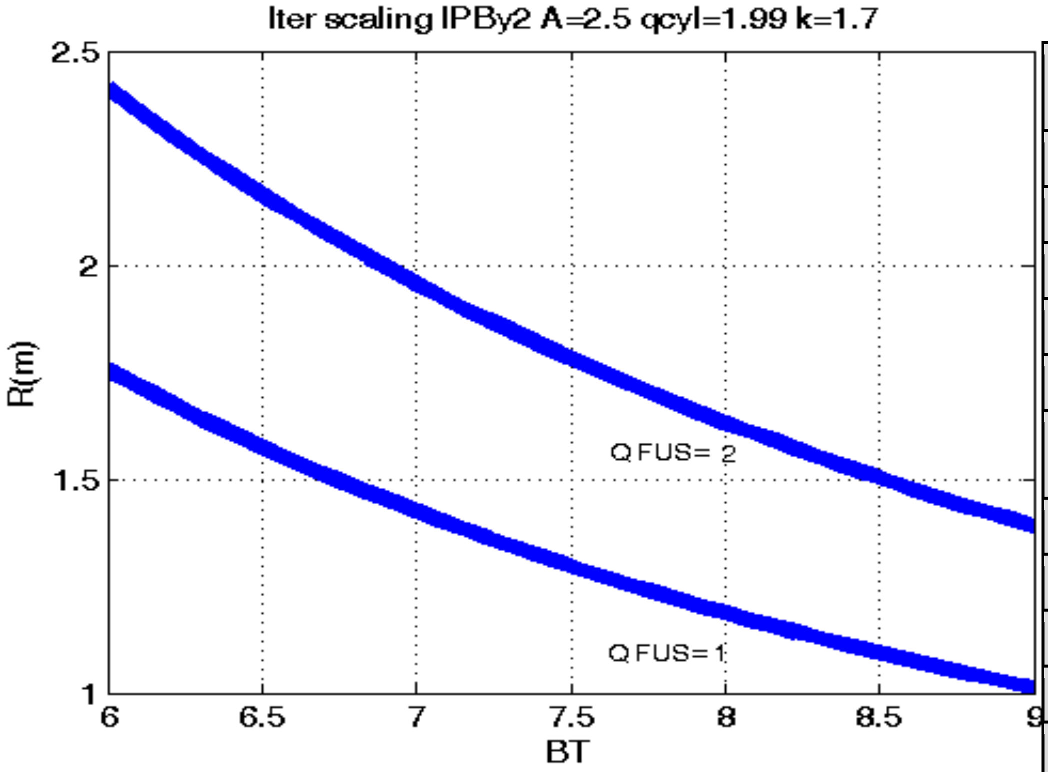


Fig.1. Major radius vs magnetic field of devices at QFus=1and 2 , aspect ratio A=2.5, qcyl=1.99, elongation k=1.7

Table II Parameters of Q=2 Tokamaks A=2.5

	Q=2	Q=2
R(m)	1,5	2,4
A	2,5	2,5
B(T)	8,5	6
Ip(MA)	10	9,84
nG(10^{20} m-3)	6,28	3,4
n (10^{20} m-3)(0.8*nG)	5	2,7
Beta(%)	3,7	5,3
betaN(%)	2,1	3,1
Pfus (MW)	44	51,4
Pinput(MW)	22	25,7
T0(keV)	7,3	9,8
fi(dilution)	0,8	0,8
Neutron flux (10^{20}n/s)	0,158	0,183

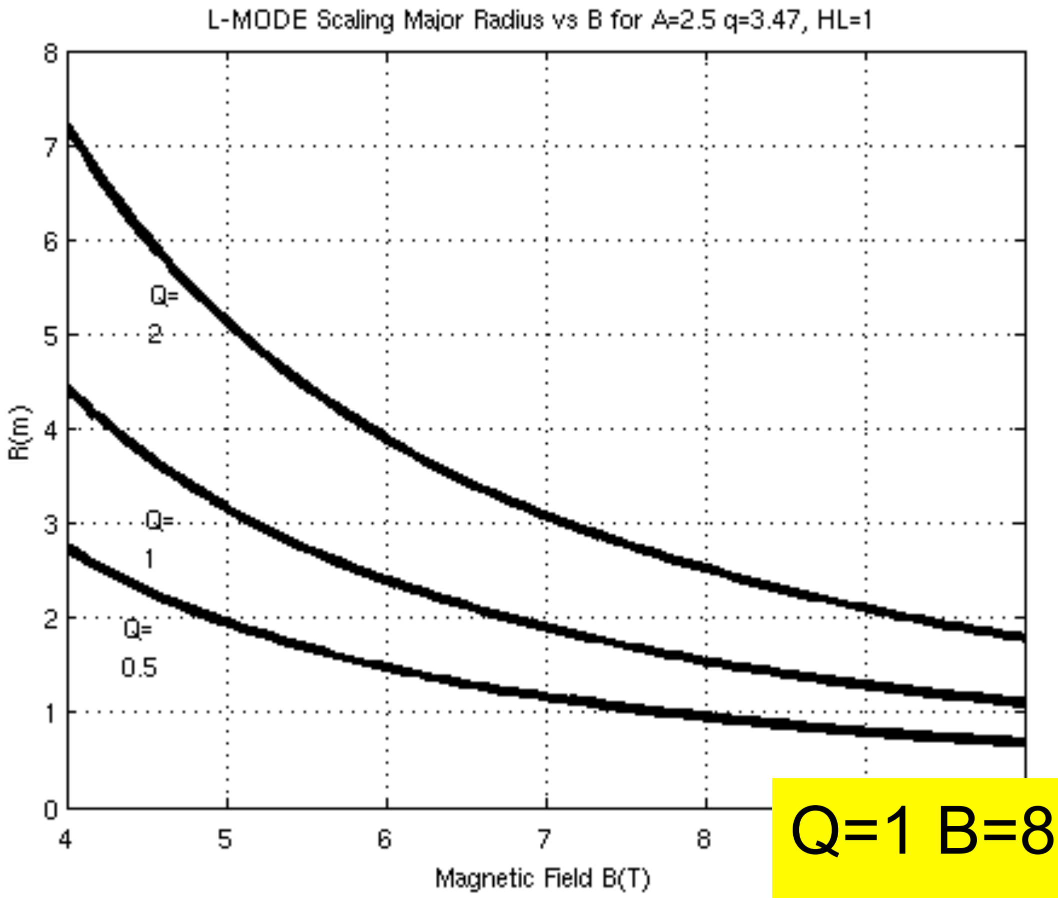
Scaling parameter for L-mode confinement

$$S_{FRL} = R\ B^{1.5}\ A^{-0.74}\ Q_0^{-0.7}$$

R = major radius
A=aspect ratio
B=magnetic field
Q0=fusion gain factor

All the other parameters are fixed equal to the reference device Taken as reference for the scaling : in particular Mass, safety factor and dilution

Parameters for Devices operating in L-mode Aspect ratio A =2.5 Major radius R0 vs magnetic field B



Q=1 B=8T R=1.5m

Q=2 B=8T R=2.5m

Scaling laws for spherical tokamaks(*)

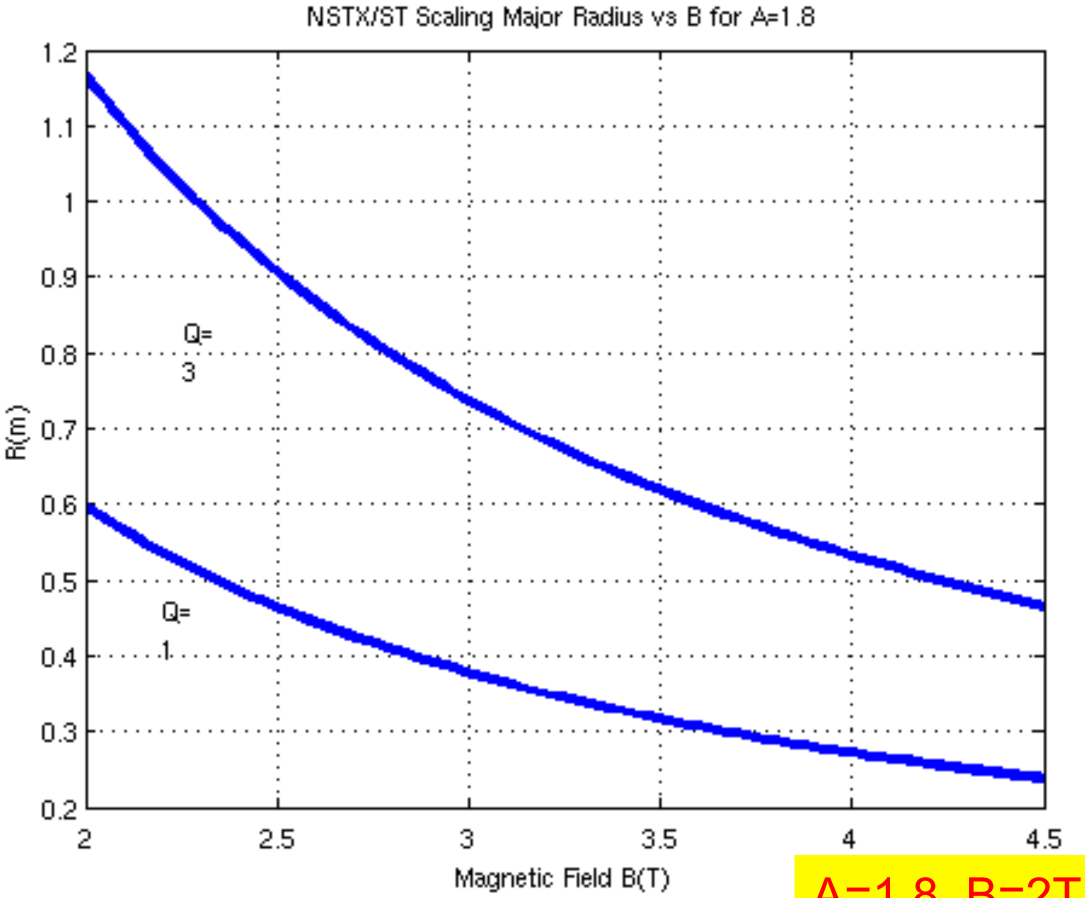
$$R_{ST} = C_{ST} \; Q_0^{0.61} \; B^{-1.13} \; A^{1.59} \; M^{0.22} \; q^{0.4}$$

$$C_{ST} = \left(\frac{\Lambda_{SD}}{A_{SD}} \right)^{-0.036} \left(\frac{\Lambda_{th} \; A_{lh}}{f_{\alpha}} \right)^{0.24}$$

This scaling law has been obtained using the same Hypothesis as the other scaling laws
Incorporating also the ST confinement time scaling law (see P F Buxton PPCF 61(2019)035006)

(*) M Romanelli and F P Orsitto PPCF 63 (2021) 125004

Parameters for Spherical Tokamak Devices R0 vs Magnetic field B



A=1.8 B=2T Q=1 R=0.8m

A=1.8 B=3T Q=3 R=0.75m

F P ORSITTO Fusion Fission Hybrid Reactor based on High field tokamak neutron source- IAEA TM on Synergies between Fusion and Fission . 6-10June 2022

NON-thermal fusion scheme :
ST Tokamaks design parameters using the TFTR Supershots confinement scaling

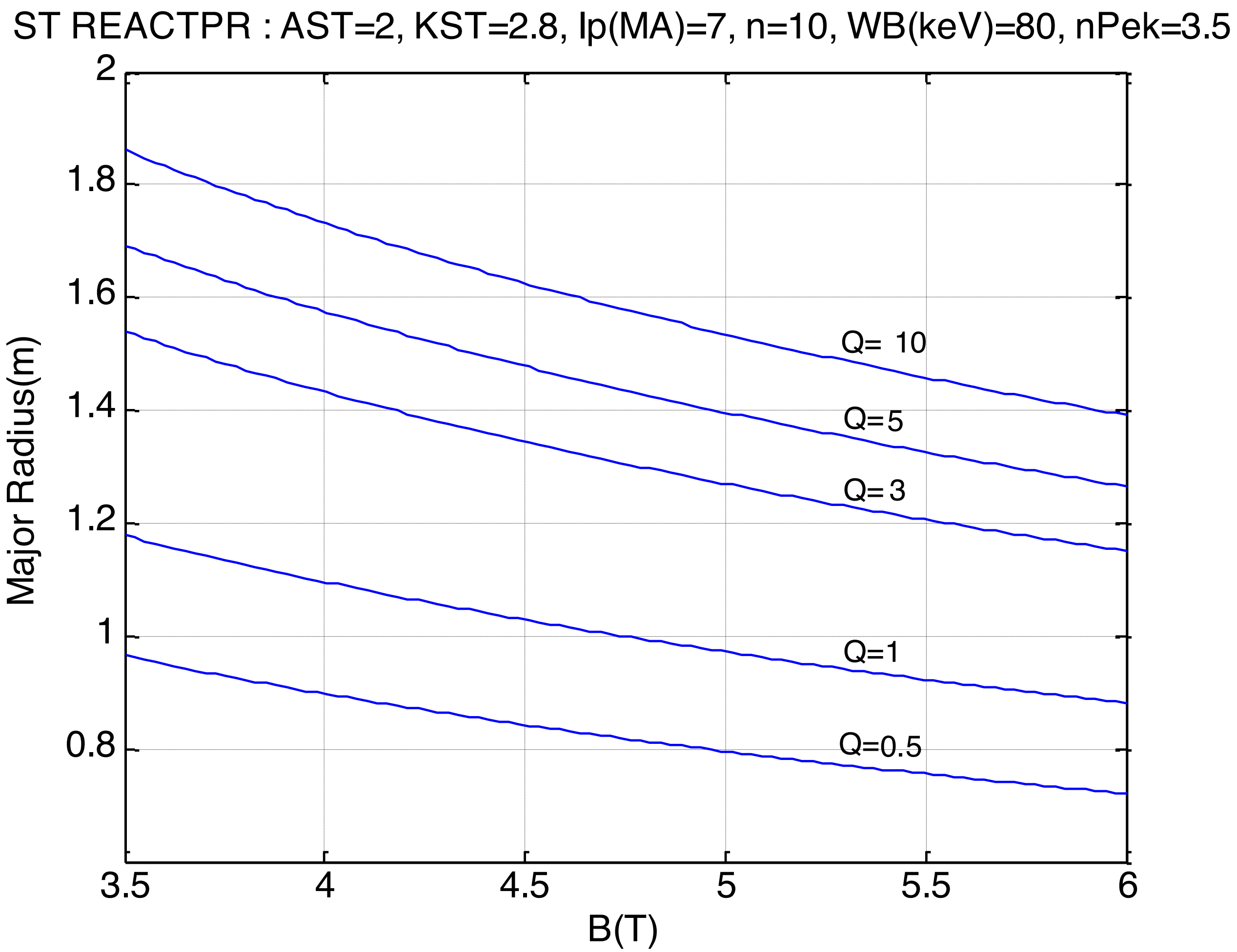
Supershot /Hot ion scaling

- The scaling law of confinement in TFTR supershots was given by J Strachan in a Nuclear Fusion paper vol.33 , 1993.
- An extension of this scaling laws to arbitrary geometry was proposed in the following form

$$\tau_{\mathrm{TFTR}} = \mathrm{Ip}^{0.22}\,\mathrm{Bt}\ \mathrm{Wbeam}^{-0.56}$$

$$\tau = \mathrm{Ip}^{0.22}\,\mathrm{Bt}\ \mathrm{Wbeam}^{-0.56}\,\mathrm{R}^{1.83}\ \mathrm{A}^{0.06}\ \mathrm{k}^{0.64}\left(\frac{\mathrm{n}}{\langle \mathrm{n} \rangle}\right)^{1.5}\mathrm{n}^{0.4}$$

Q=0.5-10 scan major radius vs B



Summary plasma parameters for tokamak neutron sources

Q	R	B	A	Plasma Scenario
1	1.5	7	2.5	Hmode
2	2	7	2.5	Hmode
2	1.5	8.5	2.5	Hmode
1	1.5	8	2.5	L-mode w pellets
2	2.5	8	2.5	L-Mode w pellets
1	0.8	2	1.8	NSTX scaling
3	0.75	3	1.8	NSTX scaling
1	1.2	3.5	2	TFTR supershots
3	1.4	4	2	TFTR supershot

Analyzing the various options of plasma scenarios it seems possible Defining the plasma parameters of a compact neutron source with major radius R0 ≈1.5m with Q≈2.

Tokamak neutron source plasma parameters

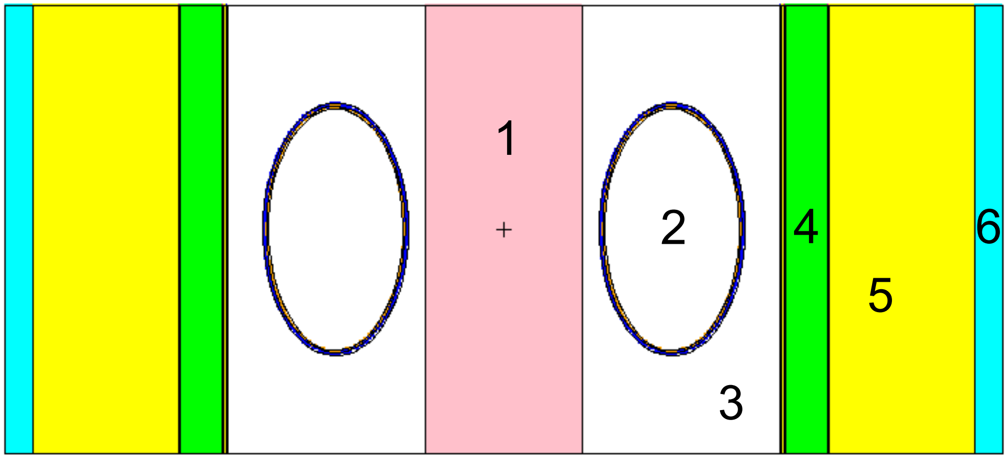
The scaling parameter linking equivalent fusion plasmas Hmode (ITER scaling) is (H-mode) :

SFR =scaling parameter for fusion reactors = $R\ B^{4/3}\ A^{-1}\ Q^{1/3}$

Q	2
R	1,5
A=R/a	2,5
B	8,5
Y (neutr/s)	1.50E+19
Pfus (MW)	40
a	0,6

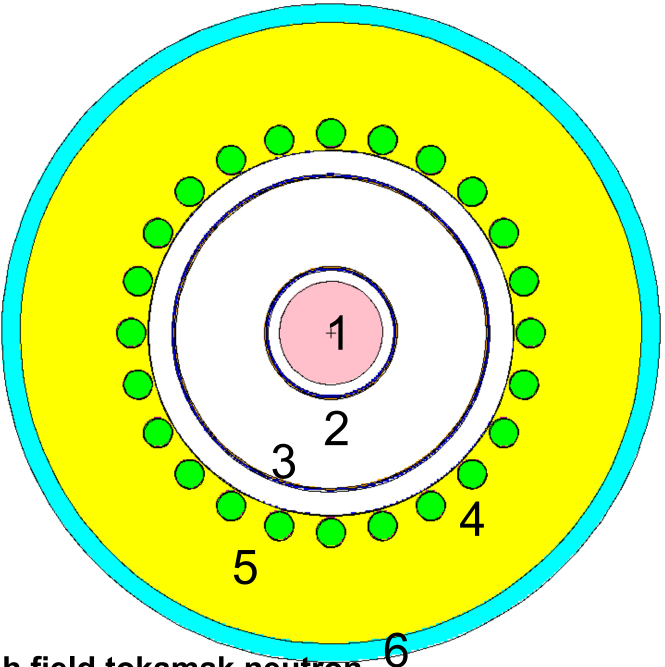
	radial Build (cm)
gap LCMS -VV	5
Vacuum Vessel(VV)	10
shield (Zr(BH4)4,W)	25
thermal insulator	5
inboard thickness	45
	Central solenoid
RTF,inboard (cm)	45
BTF(T)	28,3
ITF(MA)	6,367
Tpulse (s)	58,6

MCNP model for FFH conceptual design:
tritium production evaluation in fusion blanket



FFH's Model layout

1. Central solenoid
2. Plasma chamber
3. Torus first wall
4. Fuel
5. Fusion blanket
6. Reflector

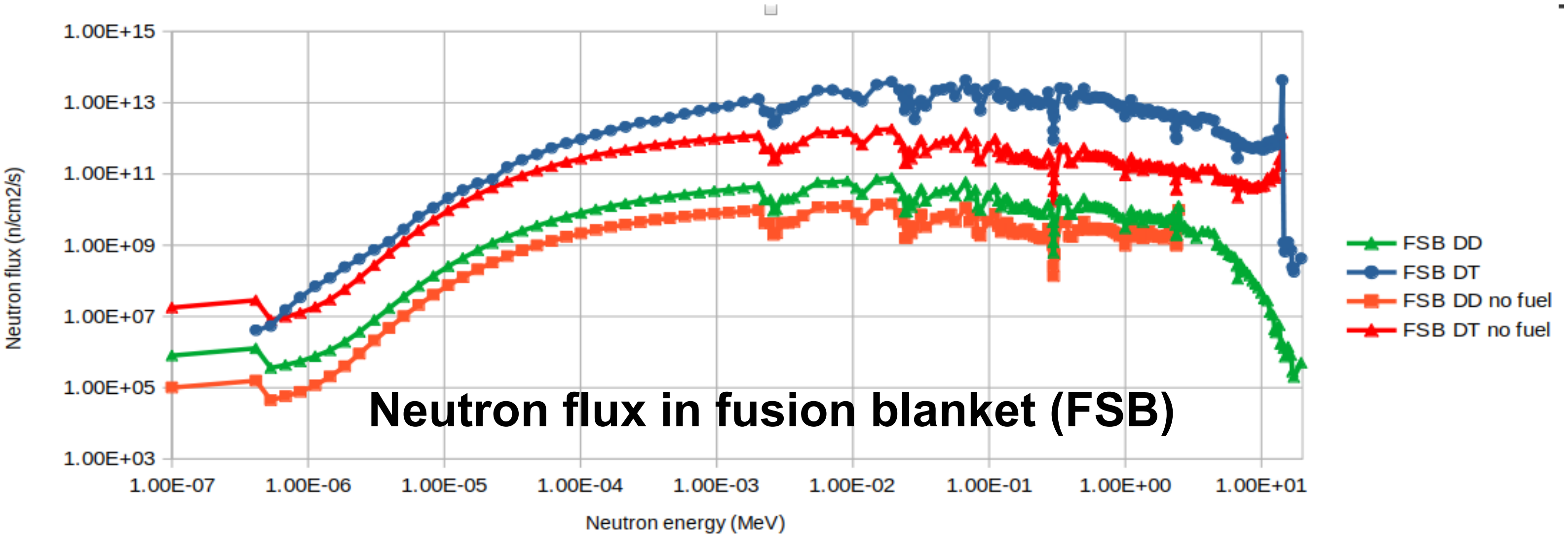


Main Design parameters

Fuel	Fresh MOX (Natural U + 5 at% 239Pu oxides, density 7.91 g/cm3) , 24 fuel rods (Height=400 cm, Radius=19 cm)
Coolant	Helium
Fusion breeder	γ lithium aluminate
Neutron yield (n/s)	1.50E+19 (DT) 1.50E+17 (DD)

F P ORSITTO Fusion Fission Hybrid Reactor based on High field tokamak neutron source- IAEA TM on Synergies between Fusion and Fission . 6-10June 2022

MCNP model for FFH conceptual design:
neutronic parameters (k_{eff} = 0.96)



Neutron flux in fusion blanket (FSB)

The tritium yielding rate estimation, calculated according to the following relation

$$\frac{dR}{dt} = \int \Phi(E)\sigma(E)\,dE$$

dR/dt =Tritium yield;
$\Phi(E)$ = Neutron spectrum;
$\sigma(E)$ = ^{6}Li(n,α)T cross- section;

shows a factor 4.33 and 5.66 gains for tritium production in DD and DT mode, respectively, using the fuel rods.

Conclusions

1. Q=1-3 plasma parameters obtained using new scaling laws for tokamak at low(A=1.8-2) and standard (A=3) aspect ratio obtained for thermal plasma in L-mode(low confinement mode) and H-mode(High Confinement mode)

1.1.NON thermal plasma are considered as well

2.Tokamak Major radius R0≈1.5-2m are reasonable plasma dimensions

3.High field B=8T for A=3 , and B=4T for A=1.8.

4.FFHR evaluated using fusion-fission blankets :
Tritium production is an important characteristic of these blankets.