Fusion-Fission Research Facility (FFRF) as a practical step toward FFH

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Abstract

Introduction is given to a project, called FFRF (R/a=4/1 m/m, Ipl=5 MA, Btor=4 T, $P_{DT} = 50-100$ MW, $P_{fission} = 80-4000$ MW) with launching the fusion phase of the machine in China in 12-15 years and in 20 years to proceed with fusion-fission research.

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1 Mission and the reference design parameters *(to ToC)*

FFRF is a project of ASIPP, an institution working on the development of fusion applications to nuclear energy.

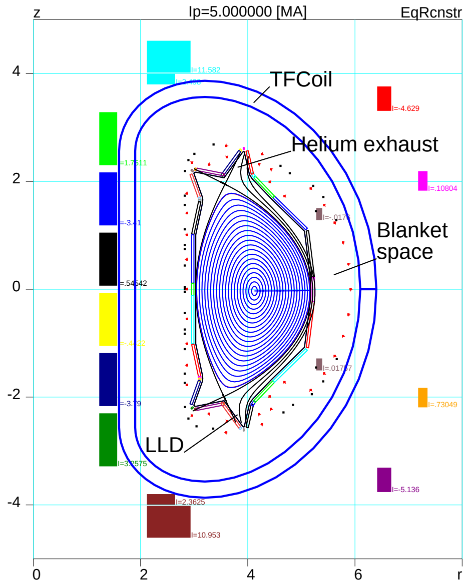
The mission of FFRF is to advance fusion to the level of a stationary neutron source and to create a technical, scientific, and technology basis for the utilization of high-energy fusion neutrons for the needs of nuclear energy and technology.

Within a year, a team, now formed in ASIPP for the pre-conceptual design phase, will make the final determination of the major design parameters of FFRF, such as the size of toroidal filed coils (TFC), plasma current, total fusion power and space for the blanket based on its anticipated regimes.

The design of FFRF will rely as much as possible on ITER design. Thus, the magnetic system, especially TFC, will take advantage of ITER experience. TFC will use the same superconductor as ITER. The plasma regimes, on the other hand, will represent an extension of the stationary plasma regimes on HT-7 and EAST tokamaks at ASIPP. Both pulsed inductive discharges and stationary non-inductive Lower Hybrid Current Drive (LHCD) will be possible. FFRF strongly relies on the new, Lithium Wall Fusion (LiWF) plasma regimes, the development of which has already started and is anticipated to be completed within the next 5-7 years. This development will eliminate a number of uncertainties, which still remain unresolved in the ITER project.

The reference plasma parameters of FFRF are listed in the Table

Parameter	FFRF
$D_{blanket,m}$	1
a_m, R_m	1.0, 4.0
$V^{pl}_{m^3}, S^{pl}_{m^2}$	150, 235
n_{20}	0.4
E^{NBI}_{keV}	120
$\frac{T_i+T_e}{2}\|_{keV}$	24
$B_{t,T}$	4
$I_{pl,MA}$	5.16
P^{DT}_{MW}	50
$W_{th,MJ}$	42
$\tau^{IND}_{E,sec}, \tau^{LHCD}_{E,sec}$	21.4-8.5, 2.0
$P^{NBI}_{MW}, P^{LHCD}_{MW}$	2-5, 20
$Q^{DT}_{IND}, Q^{DT}_{LHCD}$	25-10, 2



Active core power is 80-4000 MW. Only thermal neutron regimes have been analyzed so far.

The magnetic system, based on the ITER superconductor, would be capable of a toroidal magnetic field of up to 6-7 T, higher than the reference one of 4 T. In parallel with progress in ITER plasma performance, advanced plasma regimes of FFRF with a higher plasma density and fusion power of up to 100 MW could be possible at a later stage of FFRF without enhancement in the total plasma current. The increased magnetic field could be used also in the reference regime for enhancing cyclotron radiation and cooling the electrons in order to enhance the fusion producing fraction of the beta parameter.

2 Fusion Mission of FFRF *(to ToC)*

Even with reduction in requirements on plasma performance for FFH purposes, it is still necessary to make significant progress in fusion plasma R&D. Analysis of ITER experience with its anticipated, but never realized, reliance on "well-established data and understanding" of plasma physics and fusion technology, has led to a different approach adopted in FFRF.

While the technology and engineering design decisions will follow existing experience, including ITER, FFRH relies on LiWF plasma regimes which will be developed within 5-7 years in parallel with the conceptual and technical design phases.

So far, magnetic fusion relied on the highest possible heating power (including alpha particle in ITER) for compensation losses due to plasma edge cooling by recycled neutrals from the wall. In contrast to this, LiWF regimes implement prevention of plasma cooling by pumping all plasma particles by the lithium covered surfaces and elimination of recycling.

Prevention of cooling is much more efficient than reliance on extra heating. It makes LiWF regimes consistent with stringent requirements on plasma control in a fusion device with a fission blanket core. These regimes should exhibit high edge plasma temperature, absence of temperature gradient driven turbulence, reduced energy losses from the plasma, enhanced core and edge stability (absence of Edge Localized Modes and associated peaked in time thermal loads on the plasma facing components, absence of sawtooth oscillations, etc). They also permit the use of the entire volume for fusion power production, stationary regime in terms of non-inductive current drive and plasma-wall interaction. High plasma temperature and reduced density are consistent with the non-inductive LHCD. Because of this, FFRF has a very appealing fusion mission.

So far, there were no single failure of LiWF theory in prediction of relevant experimental results on CDX-U, NSTX (PPPL), DIII-D (GA), FTU (Frascatti).

Fusion mission and milestones:

1. Achieve ignition level performance in DD plasma $\langle p\rangle \tau_E \geq 1$ (which would be the ignition condition in the α-heated plasma) in both inductive and lower hybrid current drive regime.

2. Achieve the rate of low-density He pumping consistent with the LiWall Fusion regime.

3. Demonstrate a short (about 1min) ignition and long lasting (fraction of an hour) $Q_{DT} > 20$ in an inductively driven current regime.

4. Obtain long lasting (hours), or stationary, externally controlled, stable plasma regime with non-inductive (LHCD) current drive and $P_{DT} = 50$ MW.

With its fusion mission, FFRH will represent a substantial step in non-Fission Fusion (nFF) development, parallel and complementary to ITER, consistent with the on-going world fusion program.

3 Fusion-Fission mission *(to ToC)*

At this time, it is not possible to specify realistically a definite mission (waste transmutation, fuel production, control of a sub-critical active fission core, etc) for a fusion-fission hybrid, which would lead either to a solution of some problems in nuclear energy, or to a better approach to these compared to existing approaches not involving fusion. Neither fusion, nor related blanket technology and tritium cycle are ready to offer this kind of certainty.

In this regard the FFRF, as a research facility, represents a necessary step for discovering the means of merging the energetic neutron spectrum from fusion plasma with a variety of fission blanket compositions and regimes.

Fusion driven nuclear blanket mission and milestones:

1. Integrate toroidal plasma with a full size (1-1.5 m) fission blanket.

2. Develop remote handling of blanket modules situated inside the toroidal magnetic field.

3. Operate safely blankets with different content of fissile/(nuclear waste) materials at nuclear power in the range 80-4000 MW and $k_{eff} < 0.95$.

4. Operate different kinds of blankets in toroidal sectors of FFRF simultaneously.

5. Breed tritium with the use of both fusion and fission neutrons.

6. Determine practical limits on the He-cooled version of blanket.

7. Partially perform functions of a component testing facility (CTF) for the purpose of nFF development by utilizing both fusion and fission neutrons.

Utilization of a fast fission neutron spectrum regime would be a significant enhancement in the mission of FFRF.

4 Timetable for FFRF *(to ToC)*

The development of a timetable for the implementation of the FFRF project is one of the goals of the one year pre-conceptual design phase. The reference timetable assumes close collaboration between the US and Chinese fusion programs and is presented in the table below. In many aspects the fusion part of the FFRF mission is consistent with the on-going fusion program in the US and in China.

The timetable assumes a gradual development of FFRF plasma regimes on existing devices, including LTX, NSTX, HT-7, EAST. In particular, the NSTX device in PPPL is a front runner in developing the LiWF plasma regimes. The FFRF project makes NSTX program synchronous with the strategic goal of developing advanced regimes for both an ST-based neutron source for nFF and for stationary plasma in the EAST device. While US devices can determine all the necessary conditions for the LiWF regimes, the Chinese devices HT-7 and EAST can implement the stationary version of these with the flowing liquid lithium plasma facing target plates. Demonstration of LiWF plasma on EAST will be the final step to FFRF.
The reference timetable, assuming equal partner participation of the US in the FFRF project is given below.

Project	2010	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
FFRF	pre-CD	CD,TD				Go ahead			Assembly			DD, $p\tau_E = 1$				DT, Ignition					FFH
TFCoils	CD	TD				Manuf			Assembly			4-6 T									FFH
VVessel	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
PFC	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
Control	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
Blanket	CD										TD				Manuf			Assmbl			FFH
NSTX	LLD1	LLD2,τ_E=0.25			Upgrade		LiWF														
HT-7	Li tray	LLL		graduate implementation of Flowing LLL																	
EAST	0.5 MA	1 MA		NBI			Flowing LLL			HeP			Simulation of FFRF								
ST1				CD		TD		Manuf		Assmbl		LLD		LiWF		$p\tau_E = 1$					
NBI	CD long pulse 120 keV				TD stationary 120 keV						stationary 120 keV										
FLLL	Demo FLLL		FLLL for HT-7				FLLL for EAST				FLLL for FFRF										
HeP		CD		TD			HeP for EAST				HeP for FFRF										

Abbreviations used in the TimeTable

CD	Conceptual design
TD	Tecnhical Design
DD	Deuterium phase
DD	Deuterium-Tritium phase
PFC	Plasma facing components
HeP	Pumping low density helium ash
αP	Handling α-particle losses from the plasma
LLL	Liquid Lithium Limiter
FLLL	Flowing Liquid Lithium Limiter
LLD	Liquid Lithium Divertor
FLLD	Flowing Liquid Lithium Divertor

While the design of the tokamak core itself does not represent significant challenges, substantial R&D is necessary for Li technology, stationary NBI compatible with the neutron flux, low density helium pumping, α-particle handling technology, and all technologies, associated with remote blanket handling inside the toroidal magnetic field of a tokamak.

5 US-China cooperation *(to ToC)*

FFRF is uniquely consistent with the current nFF program in the US and China as well as with FFH ideas:

1. During the first two decades of design and operation, FFRF represents essentially a fusion facility, which can be considered as a backup for ITER. Being complementary in mission to ITER and parallel in time, FFRF relies on LiWF regime which promises much more reliable plasma operation, relevant to both controlled magnetic fusion and FFH.
2. At the same time, if progress will be achieved with core fueling at enhanced plasma densities, FFRF can implement the advanced scenarios with $B_t = 6 - 7$ T and $P_{DT} = 100$ MW. In this capacity it will be able to reproduce the "sub-critical reactor" suggested in FFH discussion.
3. FFRF stimulates the development of LiWF plasma regimes on NSTX facility in the PPPL. Besides FFRF needs, this serves automatically two additional purposes: (a) development of a Spherical Tokamak (ST) based neutron source as CTF for nFF, and (b) development of Compact Fusion Neutron Source, suggested earlier for nuclear waste transmutation.
4. During its operation as a research facility for fusion-fission, FFRF will provide the basic data for variety of possible technologies utilizing high-energy fusion neutrons for nuclear energy, as well as fission neutrons for testing fusion reactor blanket components.
5. For both non-fission fusion and fusion-fission, FFRF will be the first device which will develop the tritium cycle technology.

Potentially, the entire FFRF project can be realized as a national Chinese program. Nevertheless, with strong collaboration with the US in both design and operation phases, FFRF could be launched on schedule and would serve interests of both countries.