Fusion is Needed Now

What is a credible and realistic plan to DELIVER?
(and not just promise)

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With much appreciation to the many scientists and engineers I have worked with over decades!

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Fusion is Needed Now

- Governments & the public want fusion now to solve the climate change crisis
- AI needs huge amounts of energy. Because fusion is not available, AI is looking for nuclear power to fulfill its energy needs. (Nuclear stocks gaining on AI optimism)
- Enormous interest in fusion energy from industry and private investors

Yet, we cannot deliver!!

- We need a credible and attractive plan to actually deliver fusion (not just a promise)
- Without serious R&D to address FNST (Fusion Nuclear Science and Technology), it is impossible to have a credible pathway to DT fusion energy
- Fusion is like a plane: to fly, it needs an engine with sufficient fuel and reliability. It needs BLANKET.

Yet, no blanket has ever been built or tested!!

Challenging FNST issues
identified in comprehensive international studies as most essential to address in defining a credible pathway

1. Lack of External T Supply to provide the large **T Startup Inventory** required for any major fusion facility
2. Technology and physics Uncertainties in achieving **Tritium Self-Sufficiency**
3. RAMI (Reliability/Availability/Maintainability/Inspectability)
   - **RAMI** is the Achilles' Heel issue for fusion
4. Complex and new **Multiple/synergistic Effects** and Interactions Phenomena
   - These phenomena cannot be synthesized from "separate effects" experiments or modelling
5. **Nuclear Heating in a large volume with steep gradients**

These FNST Issues can be adequately addressed only in the fusion nuclear environment of a DT plasma-based facility (VNS)

The Tritium supply and breeding Issues (1 & 2) mandate that the fusion power of VNS must be **small** (< 100 MW). So, it cannot be as large as in Pilot or DEMO

Issue 3 requires a very aggressive RAMI program and indicates that it is hard to predict the time in which reliability growth will be sufficient to proceed to Pilot/DEMO plant

Reliability/Availability/Maintainability/Inspectability (RAMI)

Detailed Analyses show: RAMI is a serious challenge for fusion that has major impact on engineering feasibility and economics: anticipated MTBF is hours/days (required is years), and MTTR is 3-4 months (required is days), and availability is very low < 5%

OTHER Fields of Technology take RAMI very seriously

1. Aerospace and Fission have had very extensive RAMI Programs with continuous Reliability Growth programs
2. Self-driving cars are already serving as a taxi in Los Angeles. Even if it is scary to ride the self-driving car, failure modes and rate data are constantly being taken and reliability is being improved

Fusion does not have facilities or programs for RAMI/Reliability Growth.

We urgently need them. VNS will play a central role

A clear conclusion from international studies (most led by US) over the past 30 years: There is no credible plan to build DEMO/Pilot and "deliver" fusion if it does not seriously address FNST- this requires constructing and operating VNS parallel to (or earlier than) ITER

We need a DT plasma-based device (VNS), in which we can learn behavior of Blanket/FW/Divertor in the fusion nuclear environment, discover and understand multiple/synergistic-effects phenomena, quantify the potential to attain T self-sufficiency, and understand failure modes, rates, and effects (RAMI).

- It should have a small size (R ~ 2-3 m), low fusion power (< 100 MW), ~ 0.5 MW/m^2 NWL on ~ 10 m^2 test area. Only inside the vacuum vessel (Blanket/FW/divertor) needs to be prototypical. Plasma should be highly driven, Q ~ 1 with plasma burn > 200s (VNS should be based on current plasma physics)

EU and China have recently recognized this and are acting on it in major ways:

- China decided they could not go directly to constructing CFETR (DEMO/PILOT-type), and is now constructing BEST (a version of VNS but with added physics mission) with operation expected in 2029. Intensive R&D programs are ongoing.
- EU concluded after many years of DEMO studies that **VNS should precede the DEMO**

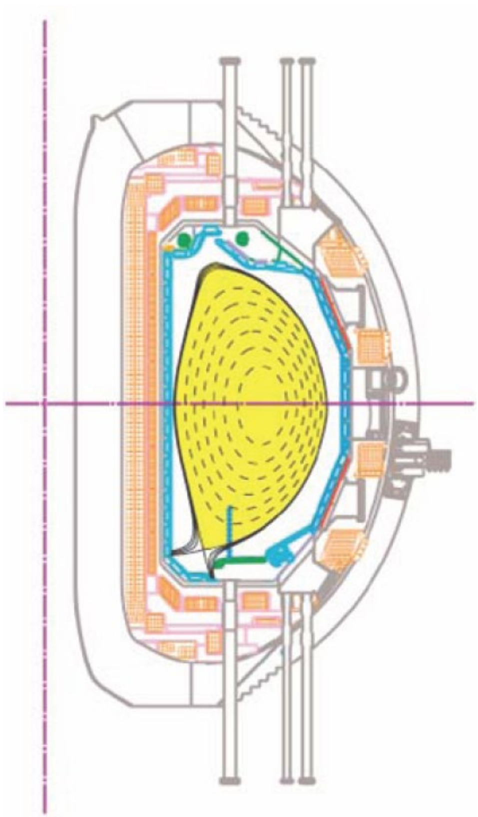
The EU Fusion Program has recently started serious and credible planning to accelerate Fusion.
It has VNS as a central element to develop Blanket and RAMI.

1. The EUROfusion program carried out over the past several years a comprehensive program with intensive physics, engineering, and technological assessments to design a DEMO that follows ITER. The study did not include VNS. Instead, it planned to operate the first stage of DEMO to qualify the blanket.
2. The conclusions of this comprehensive study are very important:
   Qualifying the blanket in 1-2 GW DEMO is very expensive and requires a blanket with TBR~1 from day 1. It is also time consuming because of the low reliability and availability.
3. A study by the EC commission in 2022/2023 showed that VNS can reduce cost and time and accelerate fusion development. This conclusion was strengthened by the long delay in ITER.
   - So, EUROfusion started in 2023 a year long VNS feasibility study that addressed Programmatic considerations, Concept Definition, and Implementation Strategy.
   - A recent review was very positive. A Conceptual Design Phase is likely to start very soon.

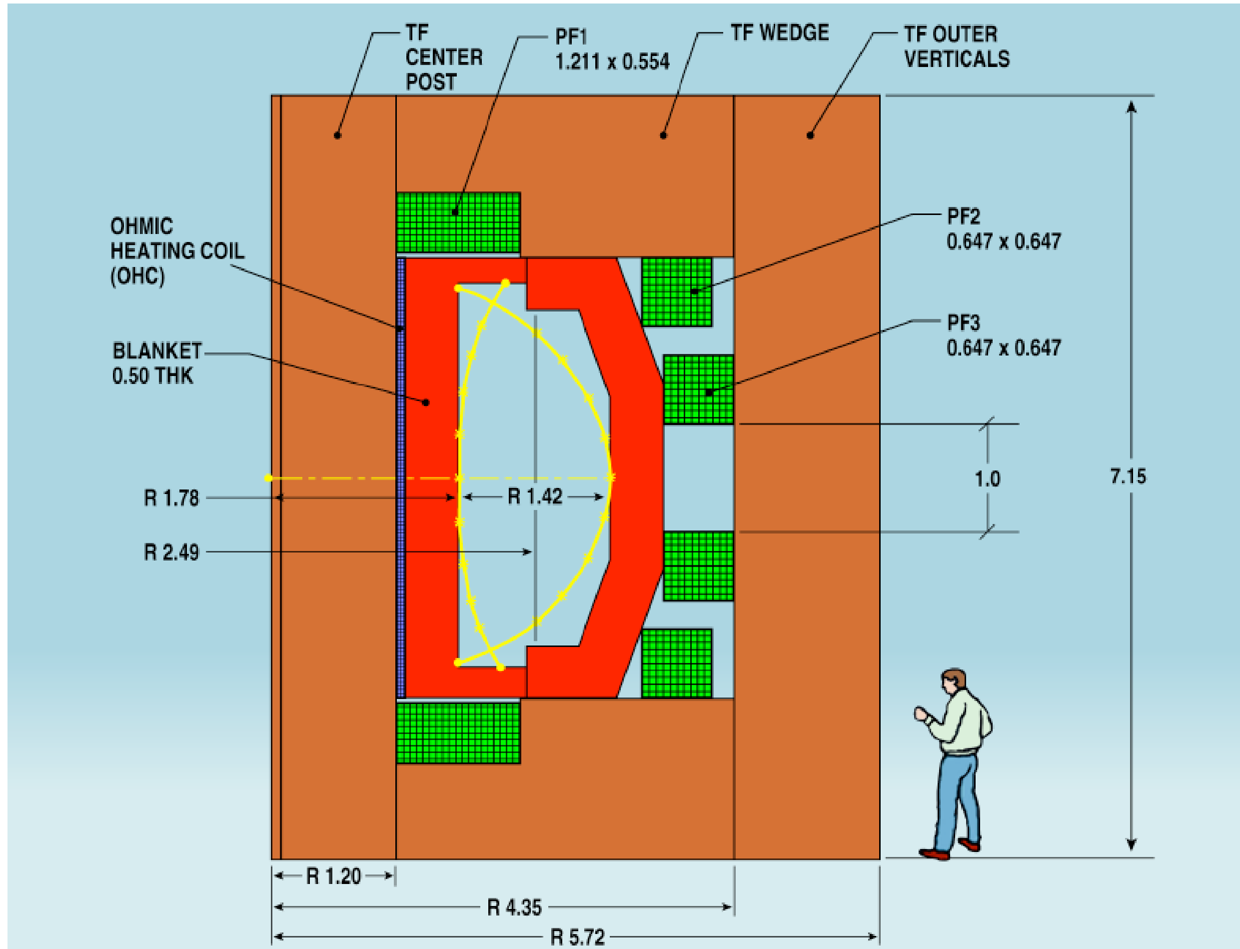
US-led studies of 30 years developed credible options for VNS. Results from the recent EUROfusion VNS Feasibility Study and Chinese BEST are consistent with US-led studies.

An example of US VNS Design Option: 2011 GA Design
Standard Aspect Ratio (A=3.5) with demountable TF Cu coils

R= 2.5 m, P_{fusion} = 125 MW, NWL = 1MW/m^2



High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation



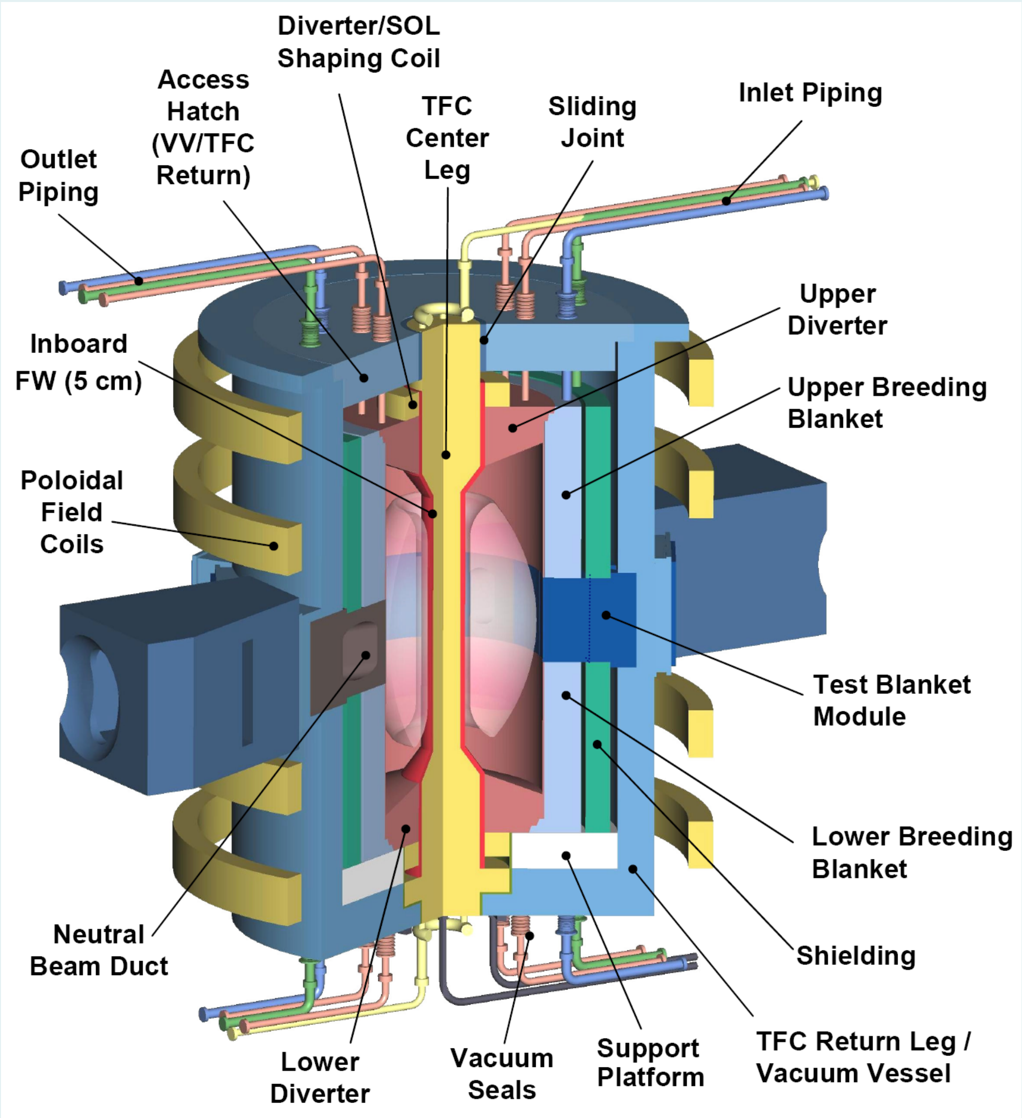
Challenges for Material/Magnet Researchers:

- **Development of practical "demountable" joint in Normal Cu Magnets**
- **Development of inorganic insulators (to reduce inboard shield and size of device)**

Another example of US VNS Design Option: 2011 ORNL, Peng et al.

(ST) Smallest power and size, Cu TF magnet, Center Post

R=1.2m, A=1.5, κ=3, P_{fusion}= 75MW, NWL = 1MW/m^2



W_L [MW/m^2]	0.1	**1.0**
R0 [m]	**1.20**	
A	**1.50**	
Kappa	**3.07**	
Bt [T]	1.13	**2.18**
Ip [MA]	3.4	**8.2**
Beta_N	**3.8**	
Beta_T	0.14	**0.18**
n_e [10^{20}/m^3]	0.43	**1.05**
f_{BS}	0.58	**0.49**
T_{avgi} [keV]	5.4	**10.3**
T_{avge} [keV]	3.1	**6.8**
HH98	**1.5**	
Q	0.50	**2.5**
P_{aux-CD} [MW]	15	**31**
E_{NB} [keV]	100	**239**
P_{Fusion} [MW]	7.5	**75**
T M height [m]	**1.64**	
T M area [m^2]	**14**	
Blanket A [m^2]	**66**	
$F_{n-capture}$	**0.76**	

Designs and Objectives of recent EU VNS and Chinese BEST are consistent with earlier US studies, but they add improvements

1. Recent advances in superconducting magnets (including HTS) enabled EU VNS and BEST to use superconducting magnets rather than the CU coils used in earlier US Studies.

2. The use of superconducting magnets enables VNS designs to be more compact and operate at less fusion power. Reducing fusion power and volume: A- further reduces the tritium consumption (further mitigates the external T supply problem) and B- further reduces the volume of radioactive waste from failed blanket modules

3. The EU VNS study and BEST project provide further advances in remote maintenance and addressing RAMI issues

4. The EU VNS study addresses in depth "Blanket Qualification" in VNS to the level required for DEMO.

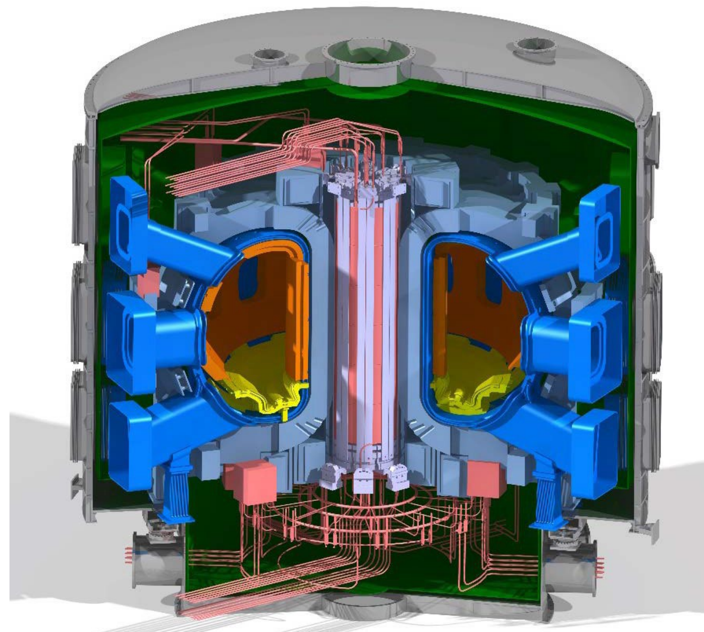
Highlights of Chinese BEST

Mission

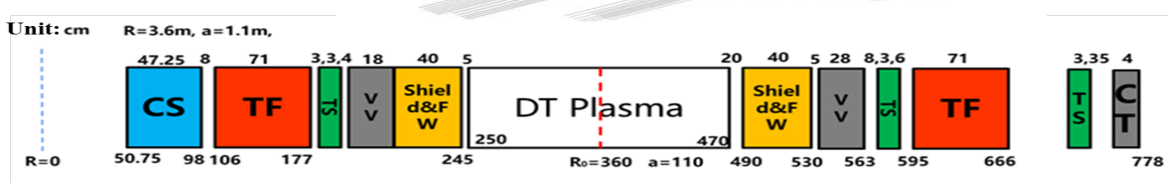
- Steady state DT plasma with Q ~ 1, together with material, blanket and fuel inventory testing (VNS-type mission): P_{fusion}~ 40 MW
- Short pulse DT plasma with Q > 5 (burning plasma physics mission): P_{fusion} = 125 MW
- Develop key technologies for CFETR (DEMO/PILOT -type)

	Q>5(100MW) GASC	Q>1(30MW) GASC
R/a(m)	3.6/1.1	3.6/1.1
Bmax/Bt(T)	12.48/6.14	12.48/6.14
Kappa/delta(q95)	1.75/0.335	1.75/0.335
A	3.27	3.27
q_{95}	4.45	5.86
Ip(MA)	6.32	4.79
H98	1.51	1.69
n_e/n_{GW}	0.68	0.40
Te/Ti	16.0	20.0
betaN	2.00	1.45
f_{BS}	0.45	0.43
f_{ohm}	0.44	0.00
Pn/Awall	0.57	0.17
P_{CD}(MW)(LH/EC)	1.4/16.1	6.2/9.5
P_{aux}(MW)	35.0	31.5
P_{fus}(MW)	124.9	37.2
Q_{plasma}	3.56	1.18
Zeff	1.96	1.96
P_LH(MW)	32.7	18.1

Features: Superconducting magnets, HTS in CS
TEST ports with blanket TBM/sectors
Notable: fast schedule: design, R&D, construction, etc.

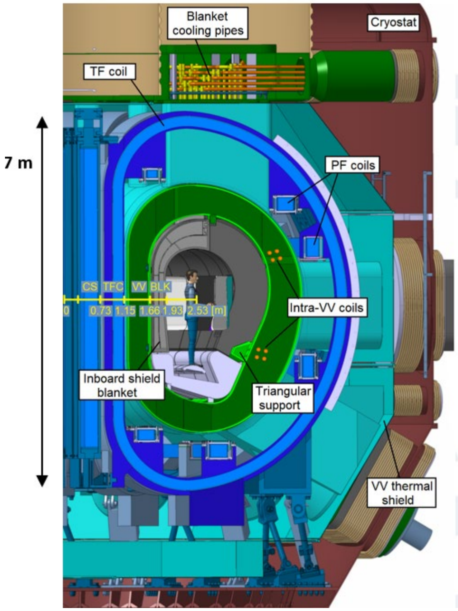


Machine size has been fixed on Jan.2022.2



Highlights of EU Study of VNS

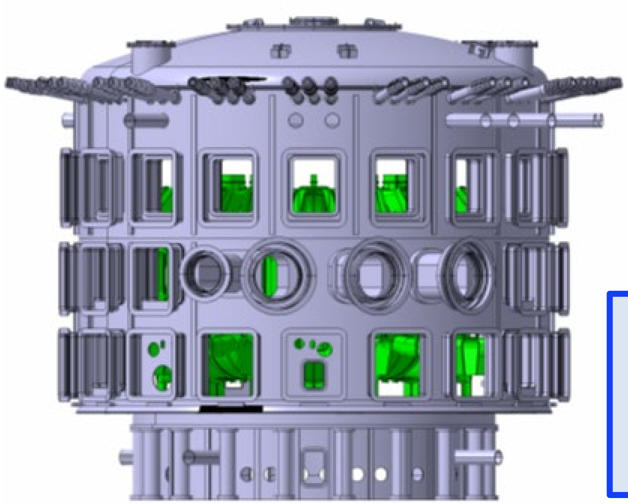
Reference: G. Federici - *Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO*, Nucl. Fusion 63 (2023) 125002.



A Q<1 beam (120 keV) driven plasma.
This approach differs considerably from other proposals made for component testing utilising highly performing plasmas that require a full physics qualification mission.

Source: EUROfusion

	VNS	ITER
Linear Size, R_o, (m)	2.5	6.2
Fusion power (MW)	<50	500
Plasma current (MA)	1.7	15
Magnetic Field (%)	5.4	5.3
Plasma fusion amplif., Q	<1	10
Beams energy (keV)	120	1000
Beams power (MW)	45	33
ECH (MW)	10	> 40
Plasma volume (m^3)	23	1300
Plasma surface (m^2)	80	900
Power consumption (MW)	170	
Neutron wall (MW/m^2)	0.5	1
Fluence (dpa)	50	0.3



„ITER“ CRYOSTAT

„VNS“ CRYOSTAT

- **VNS volume is 50 times smaller than ITER, DEMO, and PILOT**
- **VNS fusion power is < 60 times DEMO fusion Power. T consumption in VNS can be supplied from External sources, but impossible for DEMO**
- **Fluence achievable in VNS is 100 times more than ITER and sufficient to qualify blankets**

What will the US do?

The US has led in FNST studies and has been identifying and defining VNS for > 30 years. It now must consider seriously VNS – start at least a feasibility study. We can not just say we will build PILOT in 10-15 years knowing that it is impossible without constructing a VNS-type facility first.

Thank you!