Fusion Nuclear Science Facility Study

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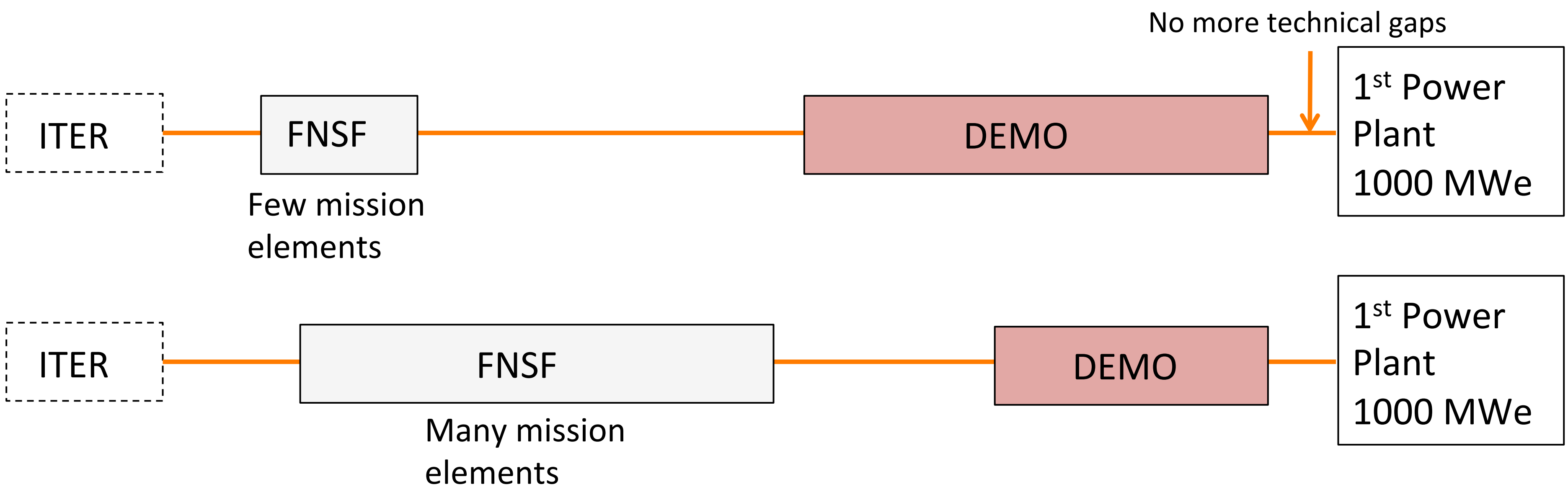
The Pathway to DEMO Completion – the FNSF Provides the Stepping Stone to Fusion Power



The outcome of DEMO is likely fixed by the need for no remaining technical gaps to a power plant

The FNSF could have some variability in its starting point since there may be different pre-requisite R&D accomplished (level of integration reached, 14 MeV neutron data on materials, plasma duration, etc.)

Otherwise, the FNSF program extent toward DEMO determines the DEMO start point

How do we Describe/Measure the Advancement to the End of DEMO

The FNSF program will move through a series of technical demonstrations:

Demonstration of technologies (tritium extraction, maintenance schemes…)

Plasma parameters (β_N, Q, plasma-on time, …)

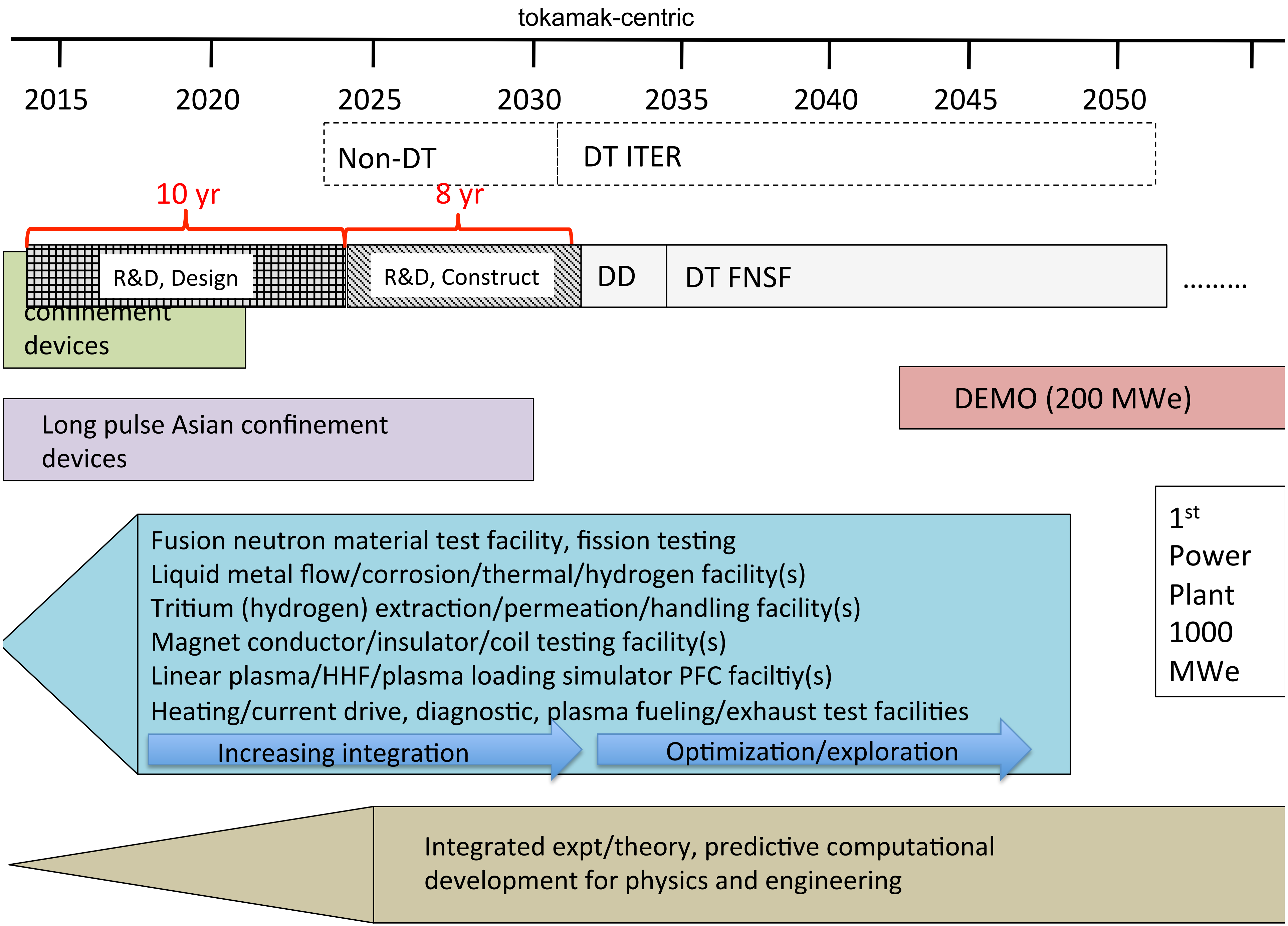
Blanket environmental parameters ($N_w\Delta t$, dpa, T, flow rates, …)

Blanket performance (TBR, lifetime to replace, ….)

Divertor environmental & performance parameters

Some particular parameters can serve as metrics:

Life of plant peak neutron fluence, MW-yr/m^2
Peak neutron fluence to replace the first wall and blanket, MW-yr/m^2 (dpa)
Average and peak (outboard midplane) neutron flux, MW/m^2
Fusion power, MW
Tritium breeding ratio (sustainment)
Net tritium consumption over plant life, kg
Plasma fusion gain (P_{fuson}/P_{inject})
Engineering gain ($P_{elec,gross}/P_{recirculating}$)
Plasma performance, $\beta_N H_{98}/q_{95}$
Peak heat flux on divertor/FW, MW/m^2
Divertor/FW lifetime to replacement, years
Plasma on time in a year, %
Life of plant, years
Plasma pulse duration (what are limits), days
Plasma duty cycle
Overall plant availability…….


tokamak-centric
2015
2020
2025
2030
2035
2040
2045
2050
Non-DT
DT ITER
10 yr
8 yr
R&D, Design
R&D, Construct
DD
DT FNSF
....
confinement devices
DEMO (200 MWe)
Long pulse Asian confinement devices
Fusion neutron material test facility, fission testing
Liquid metal flow/corrosion/thermal/hydrogen facility(s)
Tritium (hydrogen) extraction/permeation/handling facility(s)
Magnet conductor/insulator/coil testing facility(s)
Linear plasma/HHF/plasma loading simulator PFC faciltiy(s)
Heating/current drive, diagnostic, plasma fueling/exhaust test facilities
Increasing integration
Optimization/exploration
1st Power Plant 1000 MWe
Integrated expt/theory, predictive computational development for physics and engineering

There Must Be an R&D Program to Prepare for the FNSF

Fusion relevant neutron source – single materials

Fission neutron sources HFIR – small assemblies

Non-Nuclear Non-Confinement facilities

- Material testing/fabrication facilities
- Liquid metal/Solid Breeder facilities
- Tritium facilities
- ……
- Magnets development
- Measurements
- High heat flux facilities
- Linear plasma facilities
- Plasma enabling (H/CD,fuel/pump,…)

Confinement Facilities (tokamak, ST, stellarator)

ITER burning plasma operation

ITER TBM

Partial and high integration facilities, blanket component

Plasma scenario
Divertor solutions
Power/particle handling
PMI

FNSF

Why a FNSF?

The FNSF will provide the *fully integrated environment* (T, B, q'', q''', pressure/stress, chemical/corrosion, plasma-vacuum, hydrogen, flows, fusion neutrons, and gradients in these parameters) for *fully integrated components* like the FW/blanket, shield, vacuum vessel, magnets, divertor, and launchers/ diagnostics

the FNSF must provide a technical basis for DEMO by demonstrating paths to

1. tritium breeding, extraction, fueling and exhaust, and processing, reaching a tritium breeding ratio of ≥ 1, providing self-sufficiency
2. the heat extraction and electricity production
3. the integrated blanket (first wall, breeding zone, shield, and vacuum vessel) concept
4. the power and particle handling in the plasma chamber, the divertor and first wall concepts
5. the long plasma durations
6. all support technologies (magnets, pellet injector, heating and current drive, vacuum systems, remote maintenance, diagnostics, etc.)
7. reliable, safe, maintainable, and inspectible operation

Program on the FNSF

1) Very long plasma pulses, several days
2) Higher plasma duty cycles, ratio of plasma-on time to total plasma operation time
3) Progressively higher neutron fluence on components (blanket, divertor, launchers)
4) Blanket and divertor concept optimization from one session to another
5) Qualify fusion core and outside core components for the DEMO

	He/H		DD		DT		DT		DT		DT	More?
	Plasma physics				Low Fluence Fusion Nuclear Break-in				High Fluence Fusion Nuclear Operation			
Session	1		2		3		4		5		6	7
Time, yr	1.5	1	2	1	3	1	5	1	5	1	7	7
N_w^{peak}, MW/m^2			~0.009		1.5		1.5		1.5		1.5	1.5
Plasma on-time per year (days)	10-25% (37-91)		10-50% (37-183)		10-15% (37-55)		25% (91)		35% (128)		35% (128)	35% (128)
Plasma duty cycle (days on/days off)			0.33-0.95 1/2 – 10/0.5		0.33 1/2		0.67 2/1		0.91 5/0.5		0.95 10/0.5	0.95 10/0.5
Operation / Maintenance per year (days)					111-165/254-200		137 / 228		141 / 224		135 / 230	135/230
$N_w^{peak} x \Delta t_{on}$ (dpa)					0.45-0.68 (4.5-6.8)		1.88 (18.8)		2.63 (26.3)		3.68, (36.8)	3.68 (36.8)
Total # plasma cycles					111-165		230		130		91	91
Life of plant peak fluence, MW-yr/m^2											8.64-8.87 (86.4-88.7)	12.3-12.6

Primary Technical Missions

Advance fusion neutron exposure toward power plant levels

Utilize long term power plant relevant materials

Operate blanket and divertor at power plant prototypical temperatures (and other environmental parameters)

Produce tritium at levels that approach, reach or exceed consumption

Establish complete tritium cycles, breeding and fueling/pumping, with extraction from breeder, transfer through heat exchanger, and leakages through out the plant meeting all safety criteria, all approaching power plant levels

Establish long plasma durations that accommodate the FNS mission, and tend toward power plant durations between routine maintenance

Establish enabling technologies that support plasma operations at levels sufficient for plasma durations time scales, under nuclear and PMI loading, including H/CD, fueling/pumping, measurements, disruption mitigation

Develop power plant relevant subsystems for robust and high efficiency operation including H/CD, pumps, cryoplant, heat exchanger, coolant/breeder purity control….

Establish power plant relevant availability, including subsystem and component reliability, efficient maintenance operations, and accumulation of failure data

The FNSF Could Take on a Range of Mission Scopes

Minimal:
: Discard most power plant features to explore fusion neutron regime

Moderate:
: Adopts many power plant features, but defers systems that can be established elsewhere

Maximal:
: Adopt virtually all power plant features including electricity production with some reduced Q_{engr}

	Minimal	Moderate	Maximal
Peak FW fluence, life of plant, MW-yr/m^2	1.5	6.0-8.0	12.0
Peak FW fluence, replace FW/blkt, MW-yr/m^2	0.3-1.7	0.5-3.7	0.5-6.0
Ave, peak neutron wall load, MW/m^2	0.7, 1.05	1.0, 1.5	1.5, 2.25
TBR	0.5-0.7	$\gtrsim$1.0	>1.0
Fusion power, MW	150	400	800
Plasma on-time per year	5-15%	10-35%	10-50%
Plasma fusion gain	1.5	3.0	15
Engineering gain	0	0.25	1.0-1.5
Blanket concept	LT-DCLL	LT→HT DCLL	LT→HT DCLL
Divertor concept	H_2O W-alloy	He cooled W-alloy	He-cooled W-alloy
VV concept	SS	SS	Bainitic
TF Magnet	Cu	LTSC	LTSC
PF Magnets	Cu	LTSC	LTSC

Many Issues Need Some Decisions to be Made, and Justification for Those Decisions

What will be the blanket concept?

How many blanket concepts could really be qualified in non-nuclear facilities before FNSF, and then examined on the FNSF?

What would be the backup blanket concept if the primary concept fails, and how should this be identified?

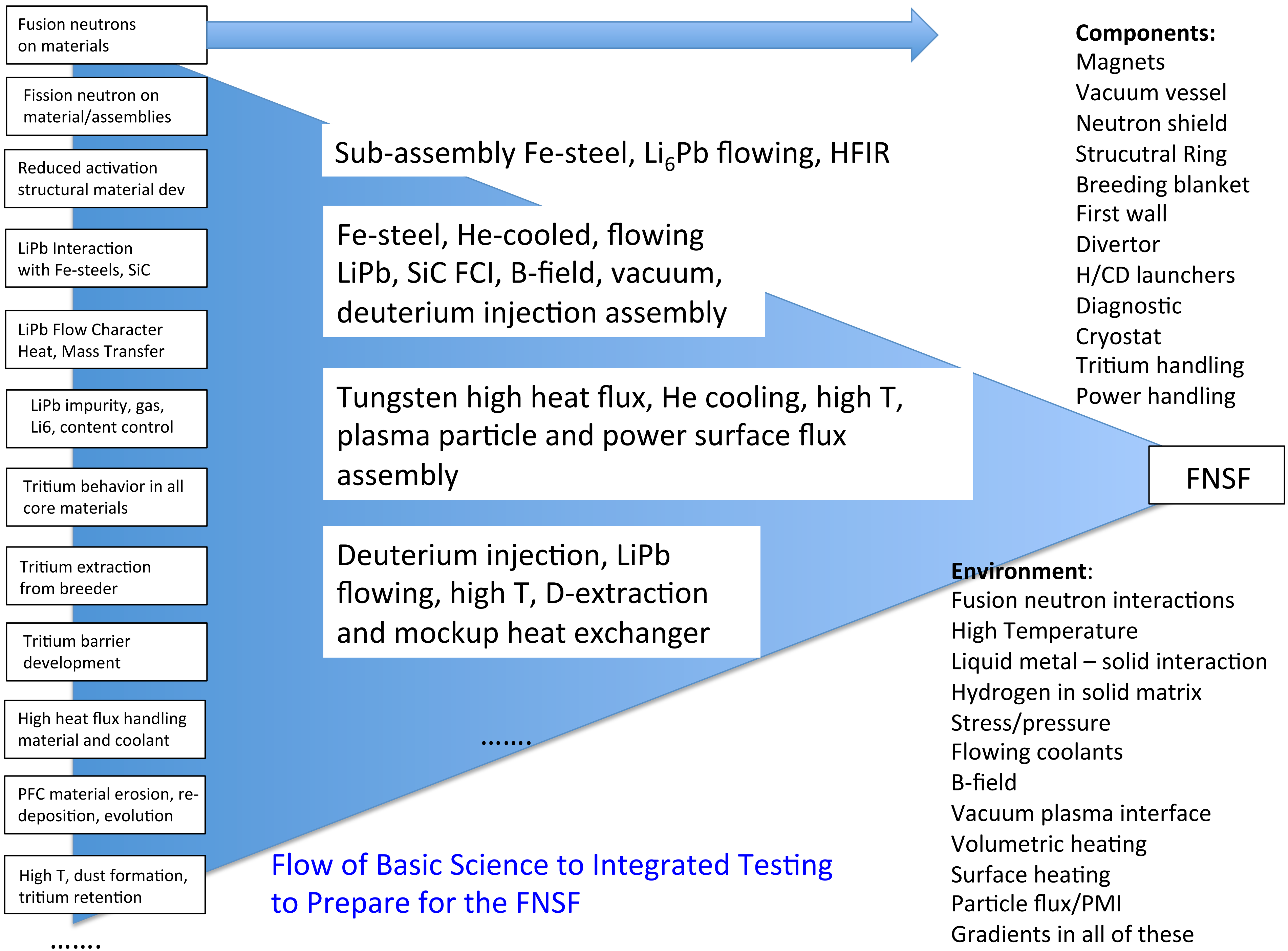
What will be the divertor concept? He-cooled W-alloy with W armor, what else is there?

Should water be eliminated from the fusion core if we expect not to use water in a power plant?

Should we pursue single null plasma or double null plasma?

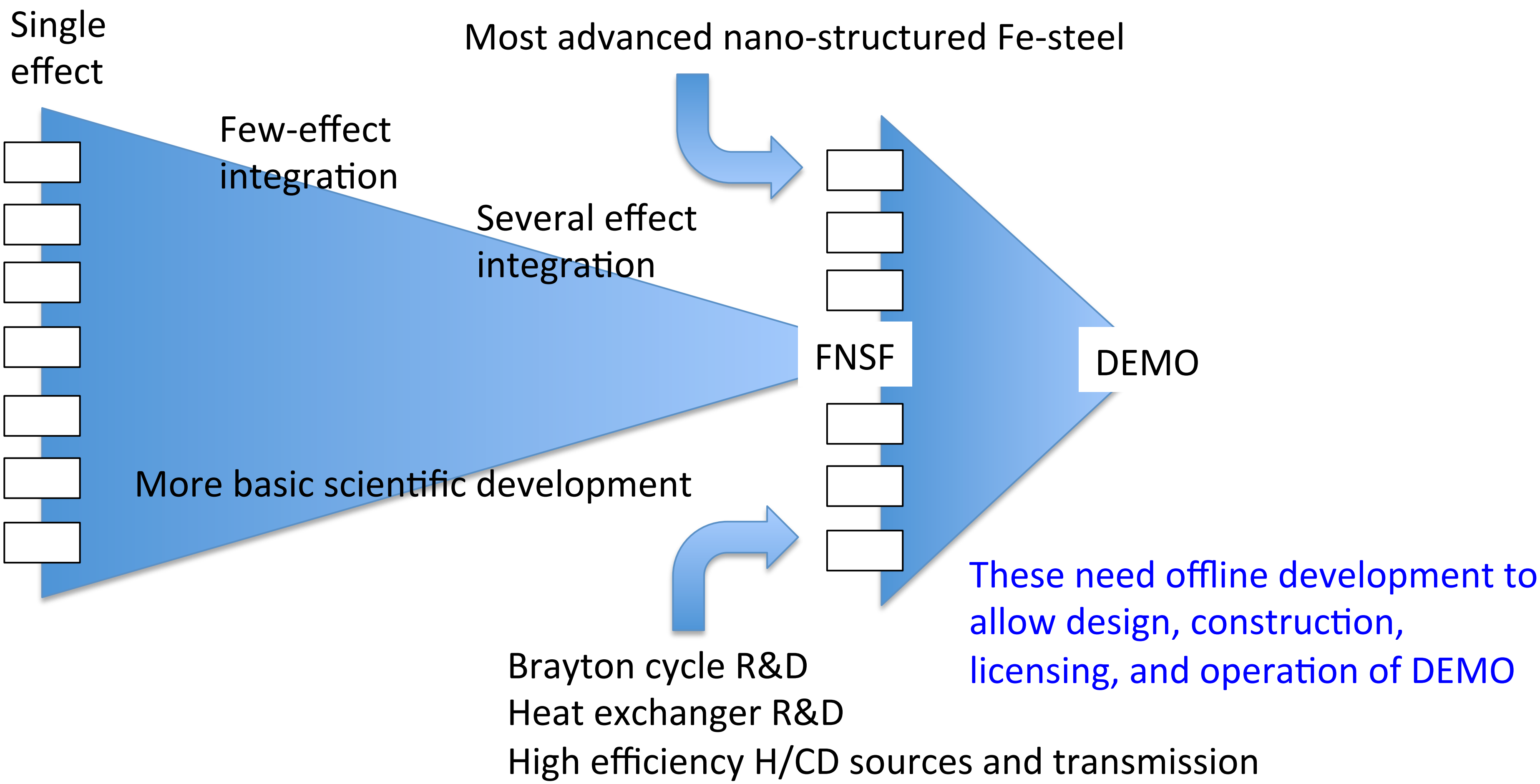
Can we take advantage of higher β_N with a stabilizing wall and rotation/feedback/kinetic effects to increase the neutron wall load?

Can higher performance (than ITER) low temperature superconducting coils be developed for FNSF?


Fusion neutrons on materials
Fission neutron on material/assemblies
Reduced activation structural material dev
LiPb Interaction with Fe-steels, SiC
LiPb Flow Character Heat, Mass Transfer
LiPb impurity, gas, Li6, content control
Tritium behavior in all core materials
Tritium extraction from breeder
Tritium barrier development
High heat flux handling material and coolant
PFC material erosion, re-deposition, evolution
High T, dust formation, tritium retention
....
Sub-assembly Fe-steel, Li_6Pb flowing, HFIR
Fe-steel, He-cooled, flowing LiPb, SiC FCI, B-field, vacuum, deuterium injection assembly
Tungsten high heat flux, He cooling, high T, plasma particle and power surface flux assembly
Deuterium injection, LiPb flowing, high T, D-extraction and mockup heat exchanger
....
FNSF
Components:
Magnets
Vacuum vessel
Neutron shield
Strucutral Ring
Breeding blanket
First wall
Divertor
H/CD launchers
Diagnostic
Cryostat
Tritium handling
Power handling
Environment:
Fusion neutron interactions
High Temperature
Liquid metal – solid interaction
Hydrogen in solid matrix
Stress/pressure
Flowing coolants
B-field
Vacuum plasma interface
Volumetric heating
Surface heating
Particle flux/PMI
Gradients in all of these
Flow of Basic Science to Integrated Testing to Prepare for the FNSF

Bringing the DEMO into the Pathway Where the FNSF is one of the R&D inputs to DEMO

What components or systems would be left by the FNSF as undone, or insufficiently developed prior to DEMO



Revisit DEMO parameters outlined in Starlite report, more technical basis for scale up, re-define minimum parameters

Guiding principles for DEMO:

- Leave no technical gaps which require R&D so that the first power plant is an experimental demonstration
- The technical differences between any DEMO subsystem and a power plant's are scalable with high confidence
- The operational aspects of DEMO and a power plant's are scalable with high confidence
- Adhere to utility advisory mandates; no evacuation plan,….

Recognize that the DEMO must bridge the gaps in metrics from the FNSF to the power plant level, and therefore there needs to be a more flexible definition of the DEMO parameters

Establish more relevant ways to measure scalability; power per unit area, power per unit volume, operating temperatures, ….

The FNSF Study will Last for 3 Years, and Will Likely Only Examine the Tokamak

Organize and prioritize the R&D activities prior to the FNSF

Establish FNSF missions, and metrics for determining the advancement toward a power plant

Establish the characteristics and detailed engineering and physics description of the "moderate" FNSF

Describe actual program on the FNSF and any associated parallel R&D activities

Establish DEMO program and minimum parameters to provide the technical basis for a commerical power plant (scale-up requirements)

Provide the pathway associated with all these features described above