Breeding Potential and Blanket / Materials Testing Strategy for FNSF

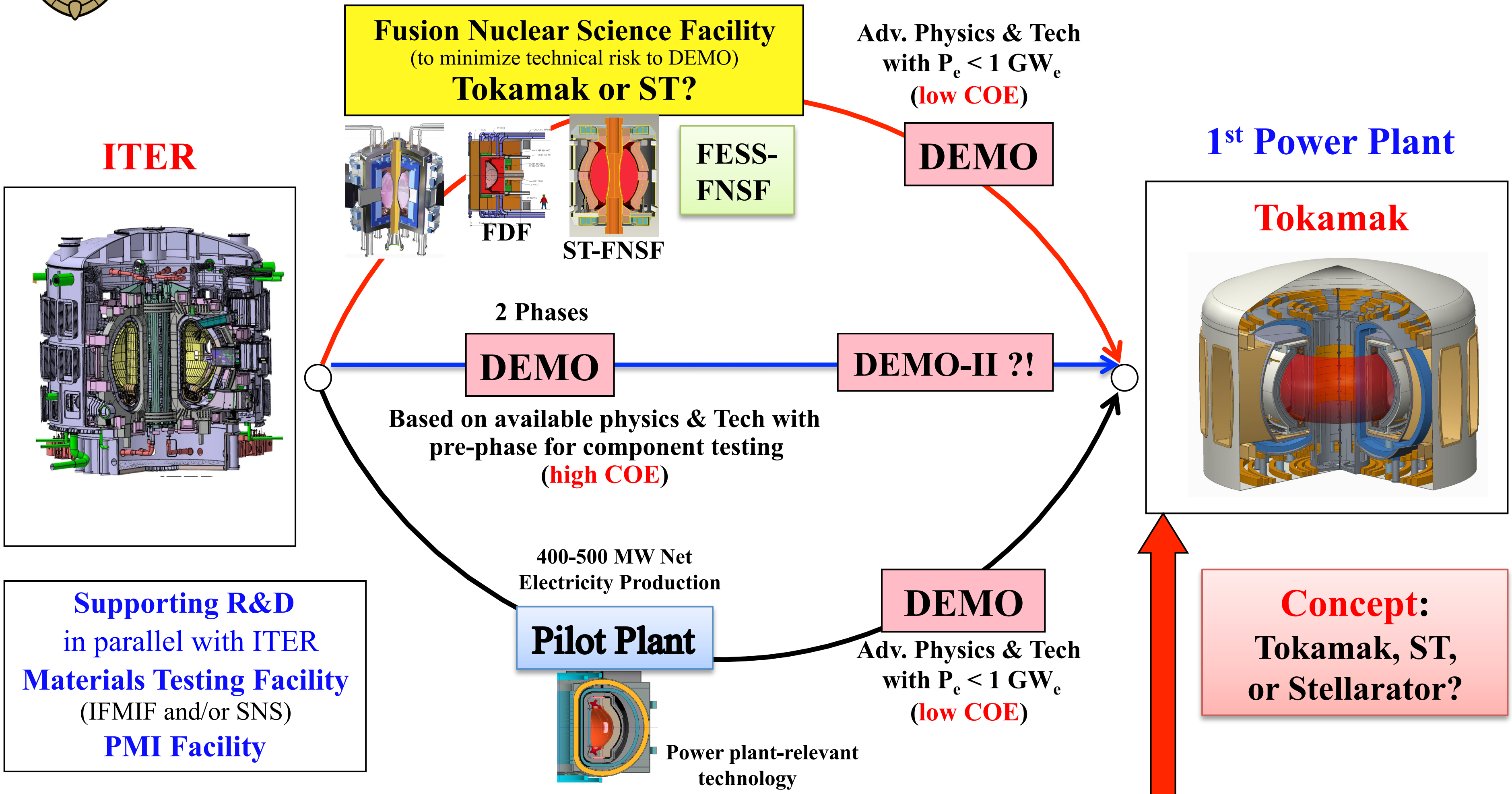
L. El-Guebaly (University of Wisconsin-Madison)
S. Malang (Consultant, Germany)
A. Rowcliffe (Oak Ridge National Laboratory)
L. Waganer (Consultant, USA)

ANS 21st Topical Meeting on the Technology of Fusion Energy
November 9 - 14, 2014
Anaheim, CA, USA

This work supported by US DOE Contract # DE-FG02-98ER 54462

Pathways to Fusion Energy

(Which Pathway offers Lowest Risk?)



ITER

Fusion Nuclear Science Facility
(to minimize technical risk to DEMO)
Tokamak or ST?

FESS-FNSF

Adv. Physics & Tech with $P_e < 1$ GW_e (low COE)

DEMO

2 Phases

DEMO → **DEMO-II ?!**

Based on available physics & Tech with pre-phase for component testing (high COE)

400-500 MW Net Electricity Production

Pilot Plant

Power plant-relevant technology

DEMO

Adv. Physics & Tech with $P_e < 1$ GW_e (low COE)

1st Power Plant

Tokamak

Concept: Tokamak, ST, or Stellarator?

Supporting R&D
in parallel with ITER
Materials Testing Facility
(IFMIF and/or SNS)
PMI Facility

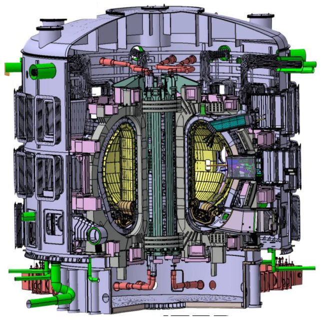
Alternative pathways indicated NO time link between DEMO and ITER

Advanced or Conservative Physics and/or Technology?

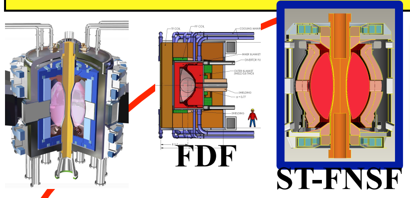
This Talk Focuses on FESS-FNSF

(DOE funded project; under development)

ITER



Fusion Nuclear Science Facility
(to minimize technical risk to DEMO)
Tokamak or ST?



FESS-FNSF

TBR

Adv. Physics & Tech with $P_e < 1$ GW_e (low COE)

DEMO

2 Phases

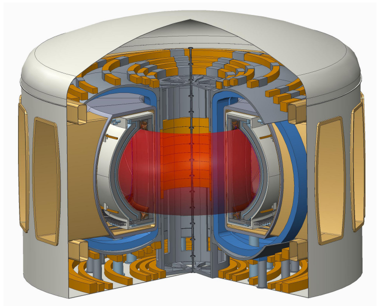
DEMO

DEMO-II ?!

Based on available physics & Tech with pre-phase for component testing (high COE)

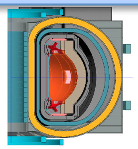
1st Power Plant

Tokamak



400-500 MW Net Electricity Production

Pilot Plant



Power plant-relevant technology

DEMO

Adv. Physics & Tech with $P_e < 1$ GW_e (low COE)

Supporting R&D
in parallel with ITER
Materials Testing Facility
(IFMIF and/or SNS)
PMI Facility

Concept:
Tokamak, ST, or Stellarator?

Alternative pathways indicated NO time link between DEMO and ITER

Advanced or Conservative Physics and/or Technology?

Outline

- FESS-FNSF radiation environment.

- Novel testing strategy to develop and qualify DCLL blankets **and** materials for DEMO and power plants.

- FNSF breeding potential.

Radiation Environment

FNSF Operating Schedule*

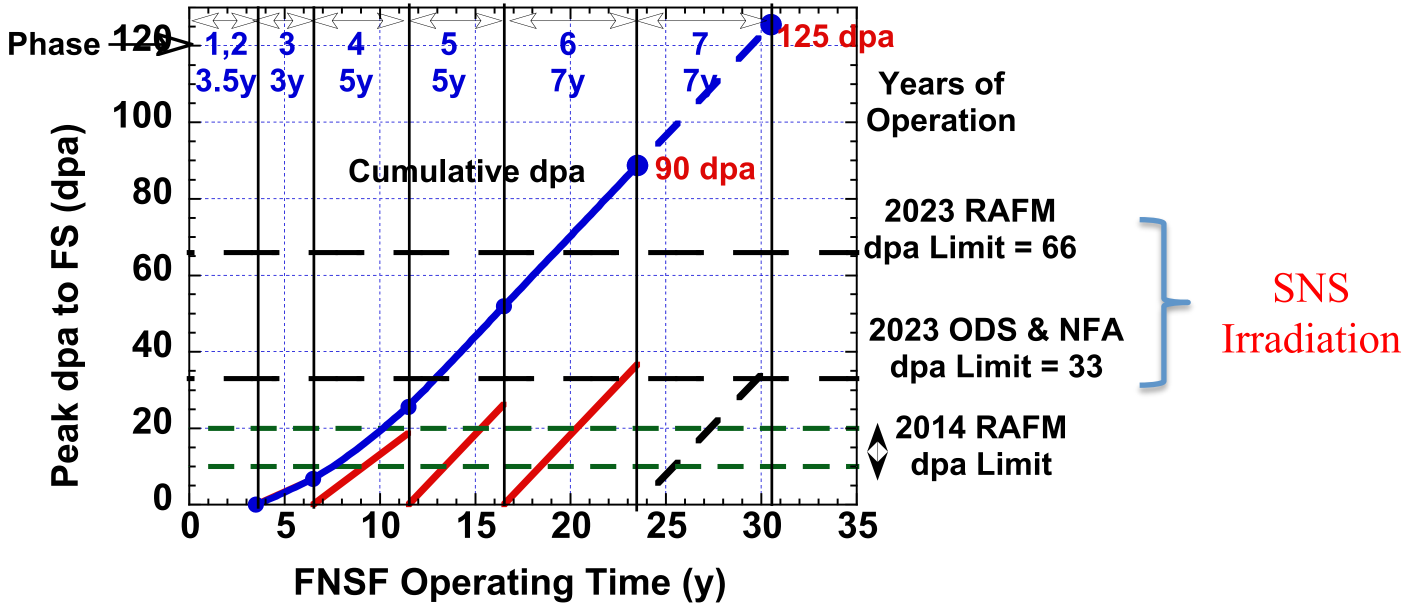
Fuel Cycle	He/H		D-D		D-T		D-T		D-T		D-T	More?
	Plasma physics				Low Fluence Fusion Nuclear Break-in				High Fluence Fusion Nuclear Operation			
Phase	1		2		3		4		5		6	7
Phase Time (y)	1.5	1	2	1	3	1	5	1	5	1	7	7
FNSF Operating Time (y)	1.5		3.5		6.5		11.5		16.5		23.5	30.5
N_w^{peak}, MW/m^2			~0.009		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)
FPY					0.3 – 0.45		1.25		1.75		2.45	2.45
Peak EOL Fluence (MWy/m^2)					0.45-0.68		1.88		2.63		3.68	3.68
Cumulative EOL Fluence					0.68		2.56		5.19		8.87	12.55
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
Peak dpa					4.5-6.8		18.8		26.3		36.8	36.8
Cumulative dpa					6.8		25.6		51.9		88.7	125.5
Total # of plasma cycles					111-165		230		130		91	91

* C.E. Kessel et al., The Fusion Nuclear Science Facility (FNSF), the Critical Step in the Pathway to Fusion Energy, presented at 21st TOFE-2014.

FNSF Assumptions

- Tokamak concept.
- 8 ports: 4 TBMs, 1 MTM, and 3 H/CD ports on OB side.
- 10 dpa/FPY per MW/m^2.
- 10-20 dpa **present** limit for RAFM FS.
- Possibility of pre-FNSF irradiation in SNS (@ 5.5 dpa/FPY) could yield:
  - 66 dpa in 12 y for RAFM FS
  - 33 dpa in 6 y for ODS-FS
  - 33 dpa in 6 y for Nano-Structured Ferritic Alloys (NFA).

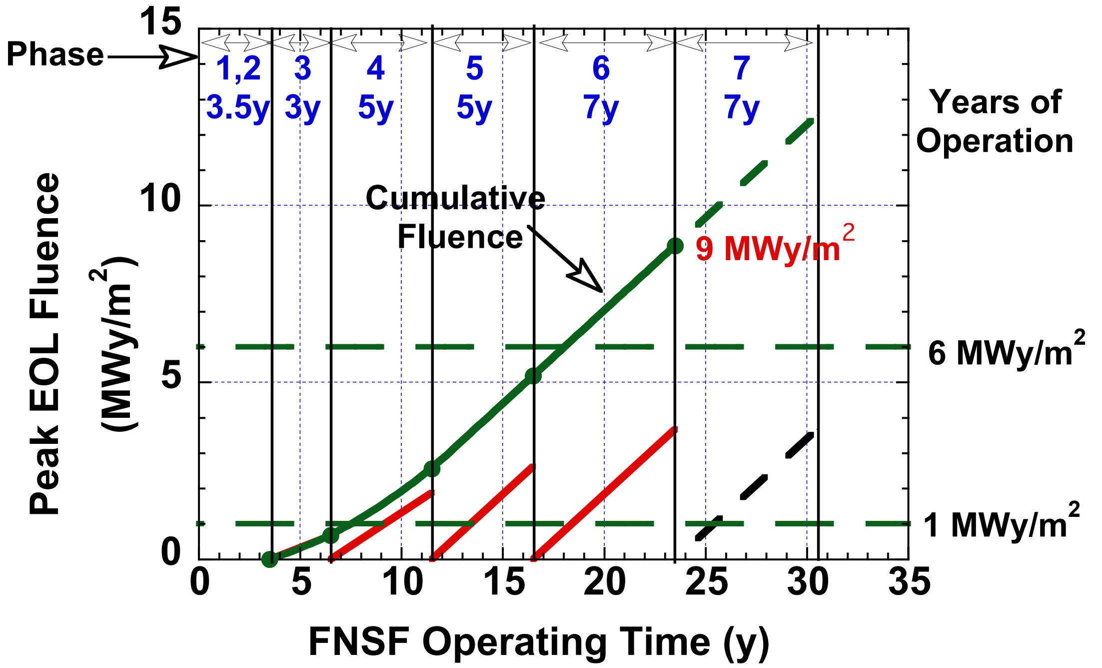
Radiation Damage and Lifetime of RAFM Structure
(OB midplane)



- Structural material replacement may coincide with end of Phase.
- Testing modules (TBM and MTM) could remain in place to achieve high fluence (66 dpa for RAFM FS, 33 dpa for ODS-FS, and 33 dpa for NFA).
- Cumulative dpa could reach 90-125 dpa max @ OB midplane.
- What other failure mechanism could limit RAFM structure lifetime?
- How long should TBM/MTM operate to provide meaningful testing? EOL fluence?

End-of-Life Fluence for Testing

(OB midplane)



- Should TBM EOL fluence coincide with end of phase (0.7 – 3.7 MWy/m^2 for 6 – 37 dpa)?
- EOL fluence could reach 9 – 12 MWy/m^2 for 90 -125 dpa @ OB midplane.
- What is the ultimate **fluence goal** for meaningful testing?
  - 1 MWy/m^2 (for reliable operation; ~0.7 FPY)?
  - 6 MWy/m^2 (for operating over long time of exposure; ~4 FPY)?

Blanket Testing Strategy

Blanket Testing, Development, and Qualification

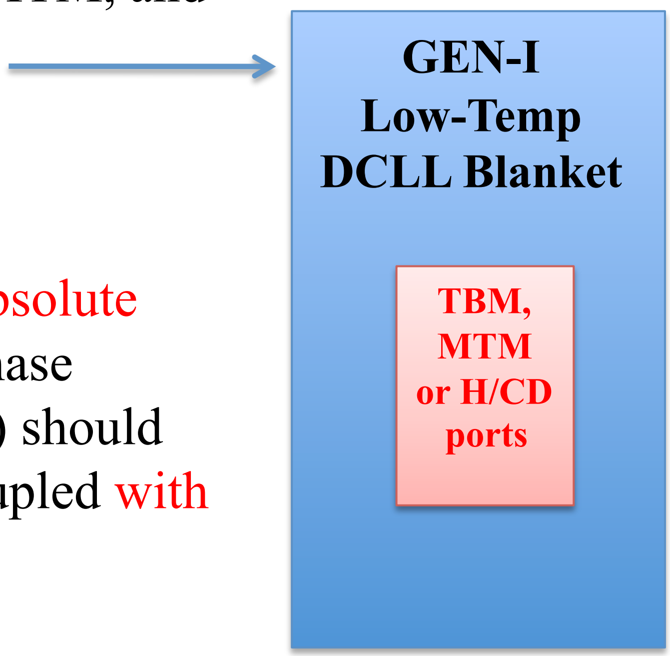
- **Goal**: Qualify preferred US blanket concept (DCLL) for DEMO (and power plants) through testing, developing, and enhancing performance during each phase of FNSF operation.
- **Novel Strategy** that reaches beyond traditional testing mission of ITER: Four generations of DCLL blanket concept tested first in test blanket modules (TBM with limited dimensions), and then converted (assuming +ve results) into full sector for qualification before use in DEMO (and power plants).
- **Requirements**:
  - TBMs located at outboard (OB) midplane (where neutron flux peaks)
  - Surrounding DCLL blanket utilized for tritium breeding, qualification, and reliability growth testing.

- **Staged blanket testing**: During operation, TBM serves as "forerunner" and develops more advanced blanket technologies for GEN-II, III, and IV DCLL blanket systems.
- **Combined results** from TBMs and blanket systems are essential to build high confidence and lower risk for successful operation of advanced blankets in DEMO (and power plants).

GEN-I DCLL Blanket Installed at Beginning of FNSF Operation

- To breed tritium, low-temperature, robust, and highly reliable blanket installed at beginning of FNSF operation and covers entire space surrounding 4 TBMs, 1 MTM, and 3 H/CD ports.

- To assure high reliability, sufficient margins to absolute limits (maximum structure temperatures, inter-phase temperatures to coolant, and mechanical stresses) should all be considered in designing GEN-I blanket coupled with extensive pre-FNSF R&D blanket program*.


GEN-I
Low-Temp
DCLL Blanket

TBM,
MTM
or H/CD
ports

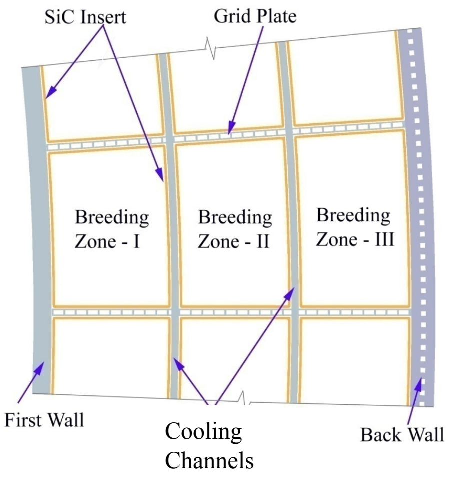
---

* S. Smolentsev et al., R&D Needs and Progress Measurement for Liquid Metal Blankets and Systems on the Pathway from Present Experimental Facilities to FNSF, presented at 21st TOFE-2014.

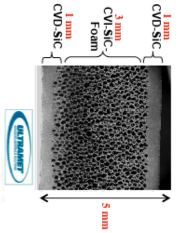
Proposed Low-Temperature GEN-I DCLL Blanket

- Operates with moderate coolant temperature (e.g., FS temperature of 400-500^{o}C and LiPb and He inlet/outlet temperature of 350/450^{o}C).
- Requires FCI to serve as electric insulator to control MHD pressure drop. (Since operating temperature is not too high, FCI does not serve as thermal insulator).
- Temperature in FW and blanket structure as uniform as possible to minimize thermal stresses.
- Since SiC FCI may not be developed and qualified before operating FNSF, sandwich-like FCI made of FS/alumina/FS multilayer could be employed for GEN-I blanket.

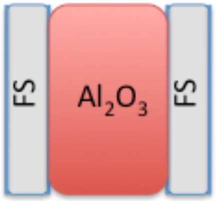
Typical DCLL Blanket Layout



SiC FCI

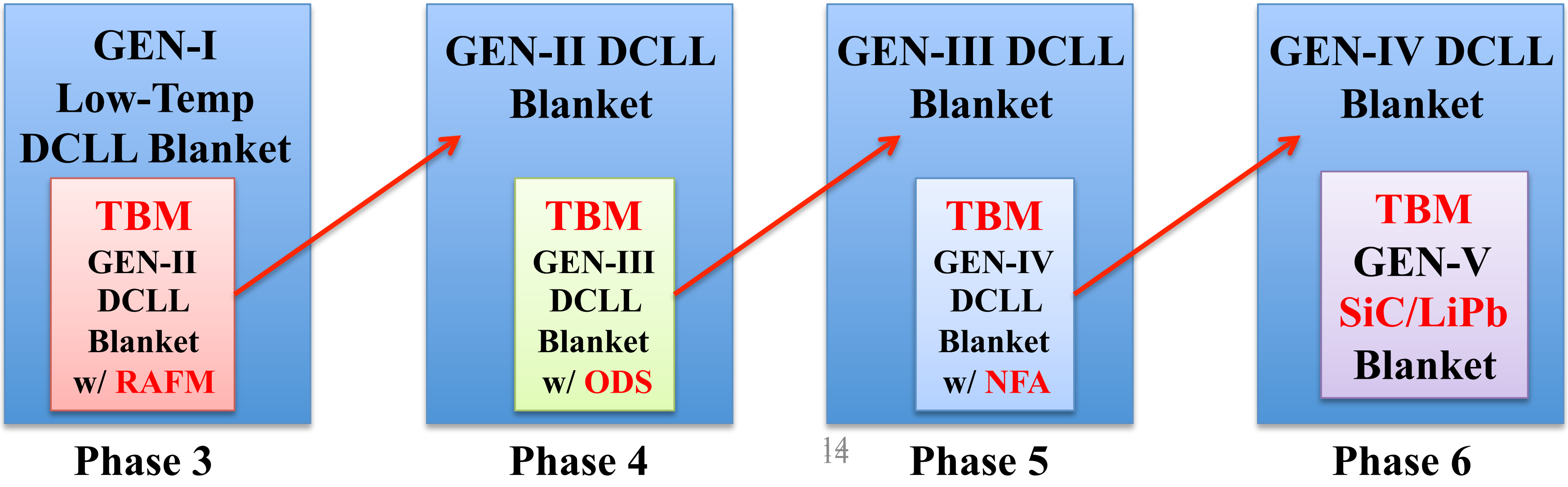


FS/Al_2O_3/FS FCI



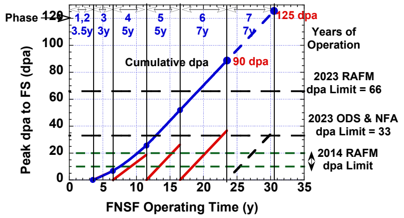
DCLL Blanket Development, Testing, and Qualification

- **Five generations of blankets will be developed for FNSF:**
  - **GEN-I** low-temperature DCLL blanket: with FS/Alumina/FS FCI, RAFM structure (F82H of EUROFER) operating at 350-550^{o}C, maximum LiPb and He exit temperature of 450^{o}C, and maximum interface steel/LiPb temperature of 450^{o}C.
  - **GEN-II** DCLL blanket first tested successfully in TBM and later installed in all sectors to qualify it if necessary for DEMO and/or power plants: DCLL blanket with SiC FCI, RAFM structure operating at 350-550^{o}C, LiPb exit temperature of 700^{o}C, He exit temperature of 500^{o}C, and maximum interface steel/LiPb temperature of 500^{o}C (for corrosion considerations) .
  - **GEN-III** DCLL blanket first tested successfully in TBM and later installed in all sectors to qualify it if necessary for DEMO and/or power plants: DCLL blanket with SiC FCI, ODS-FS structure operating at 600^{o}C, LiPb exit temperature of 750^{o}C, He exit temperature of 500^{o}C, and maximum interface steel/LiPb temperature > 500^{o}C.
  - **GEN-IV** DCLL blanket first tested successfully in TBM and later installed in all sectors to qualify it if necessary for DEMO and/or power plants: DCLL blanket with SiC FCI, NFA structure operating at 700^{o}C, LiPb exit temperature of 800^{o}C, He exit temperature of 500^{o}C, and maximum interface steel/LiPb temperature > 500^{o}C.
  - **GEN-V** SiC/LiPb blanket tested in TBM for more advanced DEMO or power plants: advanced SiC/LiPb blanket with SiC/SiC composites operating at 1000^{o}C and LiPb exit temperature of 1100^{o}C.
- For GEN III and IV blankets, it is assumed that ODS-FS and NFA (that operate at higher temperatures than 550^{o}C) are employed everywhere in FW and blanket to enhance radiation lifetime and thermal conversion efficiency. LiPb/FS corrosion solutions should be found by 2030.



Materials Testing Strategy

MTM Will Develop More Advanced Materials for Fusion



- **Goal**: Develop comprehensive multi-materials database for up to 90 dpa with possibility of extending tests to 125 dpa in Phase #7.
- Whole list of new materials could be tested in MTM:
  - New GEN of FS (as first generation of ferritic steels (F82H and EUROFER) are **not** performing well at high and low temperatures):
    - Extend max operating temp into 550-1000°C regime (for FW, blanket, SR, and divertor)
    - Develop FS variant less susceptible to DBTT in low-temp regime (for VV and LT shield)
    - Develop reusable NFA if temp exceeds 1000°C during severe accidents.
  - SiC/SiC composites for FW/blanket
  - W alloys (W-TiC, WL10, W-K, W/W composites, VMW, etc.) for divertors
  - LTS and HTS magnet materials: superconductors, jackets, insulators, etc..
- Pre-FNSF characterization and theoretical predictive modeling using advanced computing methods will define MTM testing environment.

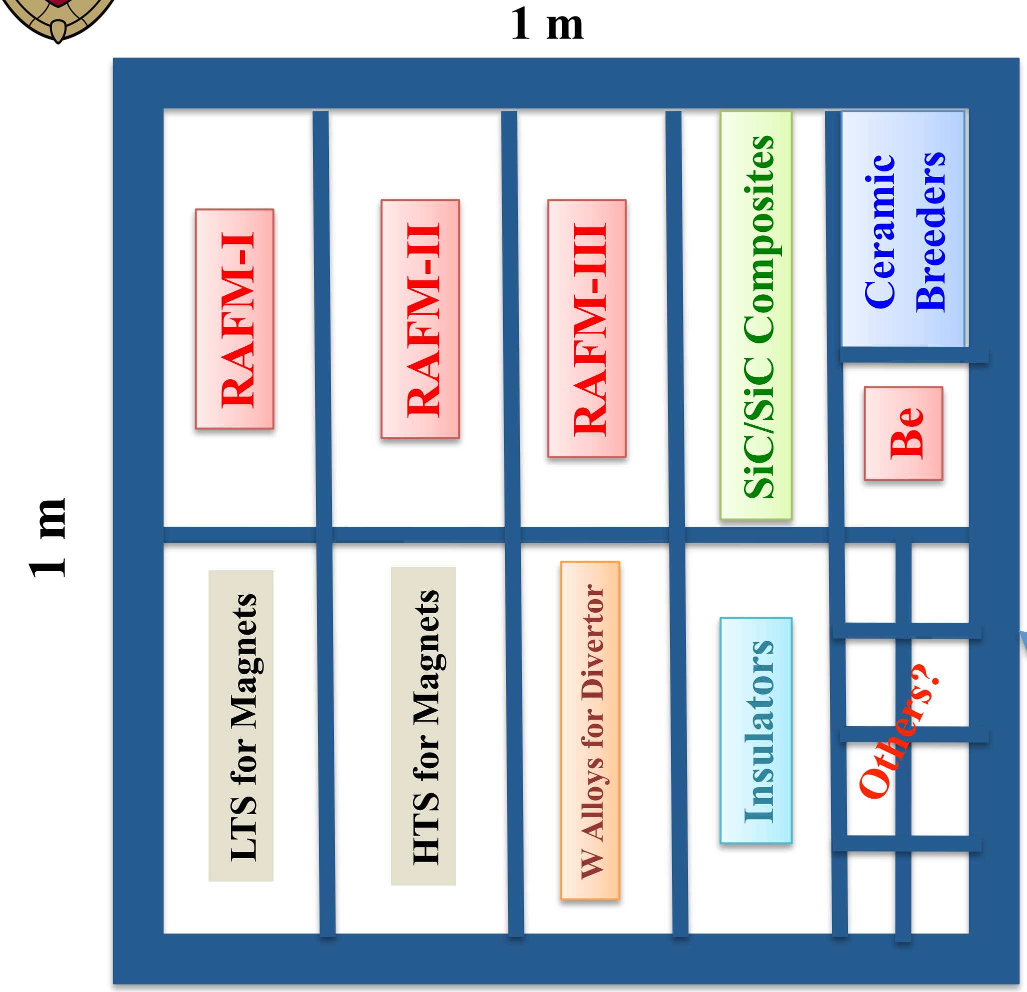
MTM Provides Critically Important Resource for Evaluation and Validation of Materials Performance in 14 MeV Neutron Environment

- Other data developed with continuous radiation sources (SNS, IFMIF or early Neutron Source):
  - Is essential for developing science-based understanding of 14 MeV neutron radiation damage phenomena that underpins development of damage-resistant materials.
  - Forms basis for developing engineering database for designing and licensing FNSF.

- MTM is **complementary resource** with advantages of:
  1. Carrying higher **multiplicity of larger specimens** compared to 10-500 ml range available in the SNS/IFMIF
  2. Providing radiation effects data in pulsed neutron environment
  3. Providing surveillance program to track performance of several materials irradiated in same 14 MeV neutron environment using range of specimen geometries
  4. Provide a means of irradiation testing of new materials variants arising from:
     - Continuing development of improved compositions/microstructures
     - Application of advances in fabrication technologies (additive manufacturing, precision casting, joining technologies, etc).

MTM Offers Testing in Real Fusion Environment

(unavailable in IFMIF, HFIR and SNS)



1 m

1 m

RAFM-I

RAFM-II

RAFM-III

SiC/SiC Composites

Ceramic Breeders

Be

LTS for Magnets

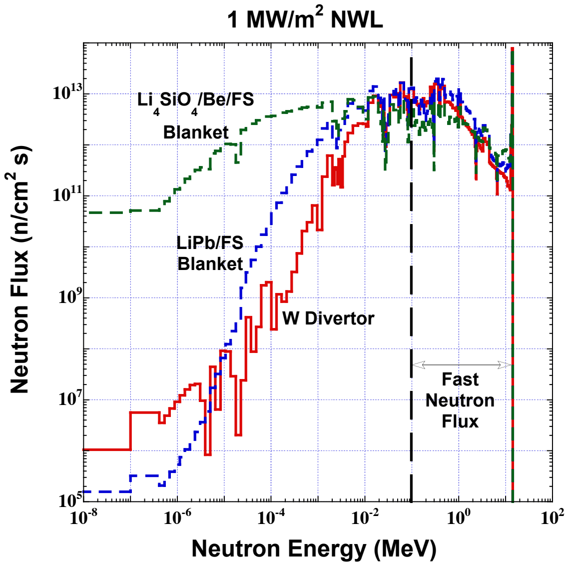
HTS for Magnets

W Alloys for Divertor

Insulators

Others?

Fusion Spectra



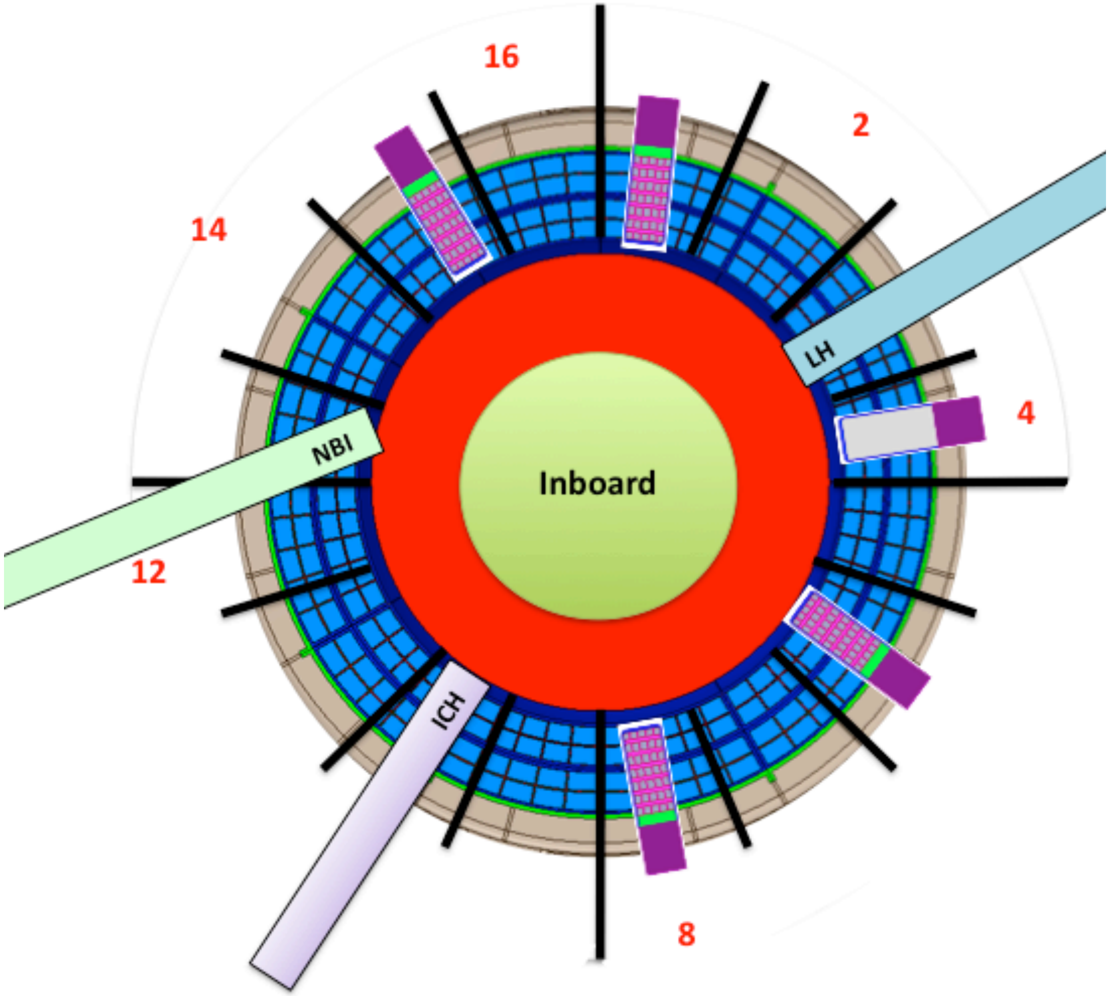
Replaceable FS structural frame upon reaching dpa limit while tested materials could be re-installed after each change out.

Layout of material samples within MTM (with varying shapes, sizes, thicknesses, etc.)

Preliminary Layout of FNSF with 8 Ports

Layout Guidelines

- **16 sectors**:
  - 8 sectors containing 8 ports
  - 8 sectors w/o ports.
- High degree of neutron flux symmetry at TBM surface is desirable in order to compare blanket concept performance under same operating conditions
- TBM ports at OB midplane should be arranged to exchange TBMs and MTM rapidly. All coolant pipes should be accessible from outside VV.

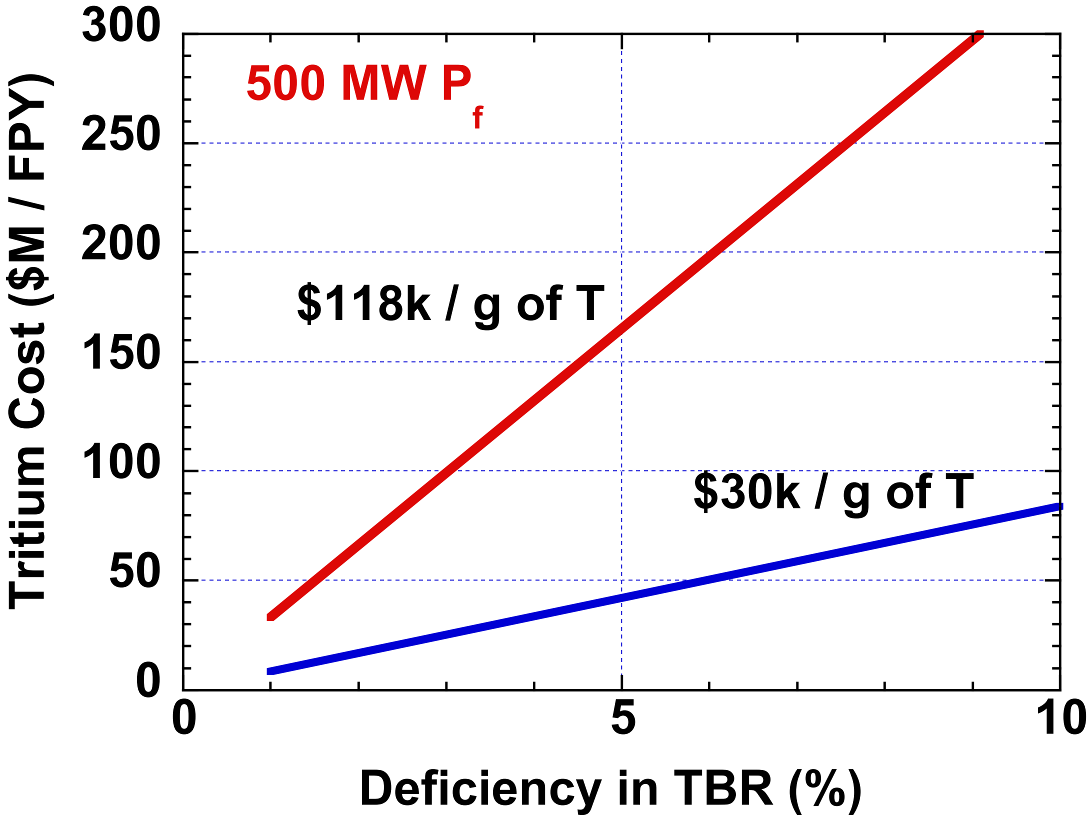


FNSF Breeding Potential

Tritium Breeding Ratio (TBR)

- TBR is a metric for T self-sufficiency ⇒ Calculated TBR > 1.
- FNSF must breed their own T needed for plasma operation as external sources of T are insufficient, impractical, and/or inaccessible. (Available T resources from CANDU reactors will all be used by ITER).
- Annual T consumption for 500 MW fusion power is high (28 kg per full power year (FPY)).
- T is extremely expensive ($30-118k per gram).

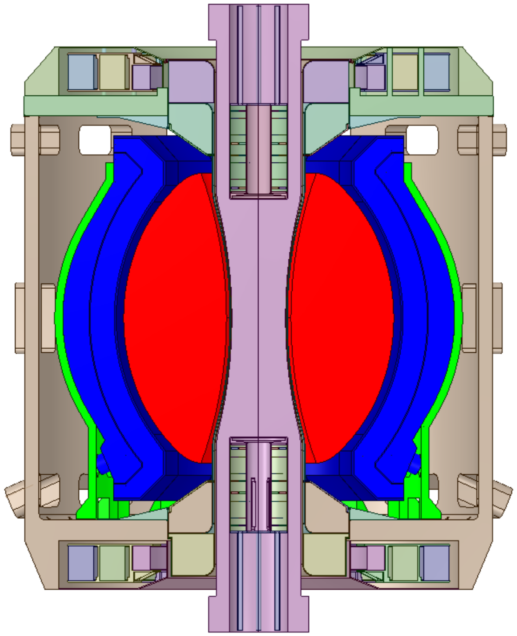
Small Deficiency in TBR Represents Significant Contribution to FNSF Operational Cost



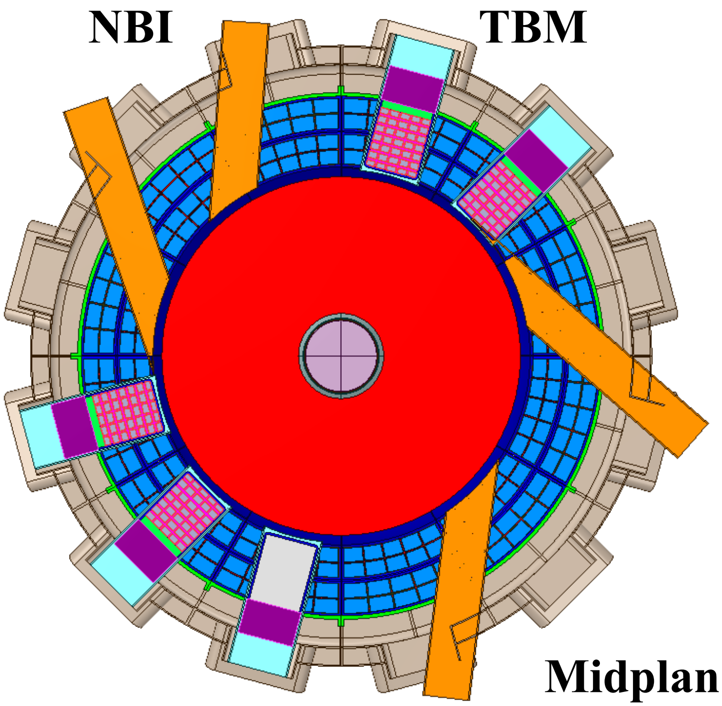
- 1% less TBR in FNSF means T shortage of ~300 g/FPY, costing $8-33M to purchase annually from *unknown* external sources.
- TBR must meet breeding requirement and should be calculated with high accuracy.

Example: TBR of ST-FNSF

(1.7 m Device)



3-D Neutronics Model
(R= 1.7 m)



Midplane Cross Section with
4 TBMs, 1 MTM, and 4 NBIs

TBR ~ 0.97

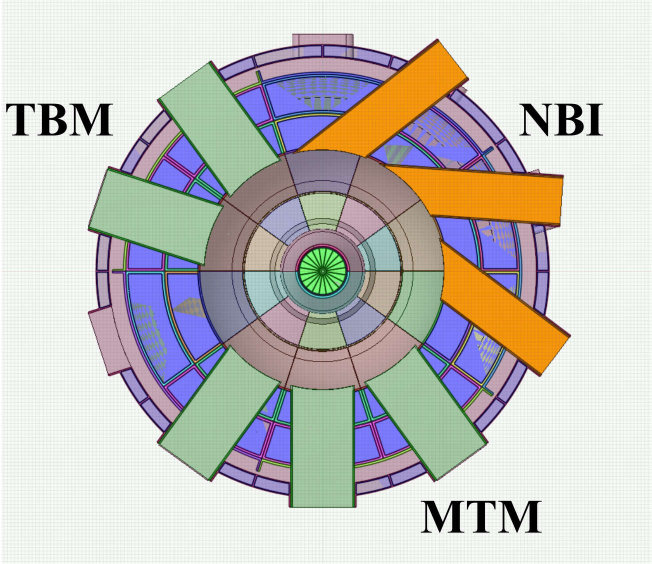
Design measures to enhance TBR:

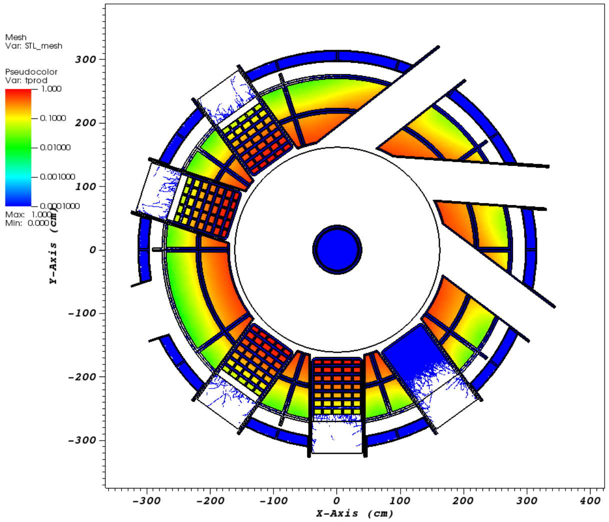
- Less cooling channels within blanket
- Replace PF coil shield by blanket (~3%)
- Smaller opening to divertor to reduce neutron leakage
- Thicker IB VV with internal breeding.

1.7 m device has potential to achieve TBR > 1 – major advantage over smaller devices

Example: TBR of ST-FNSF

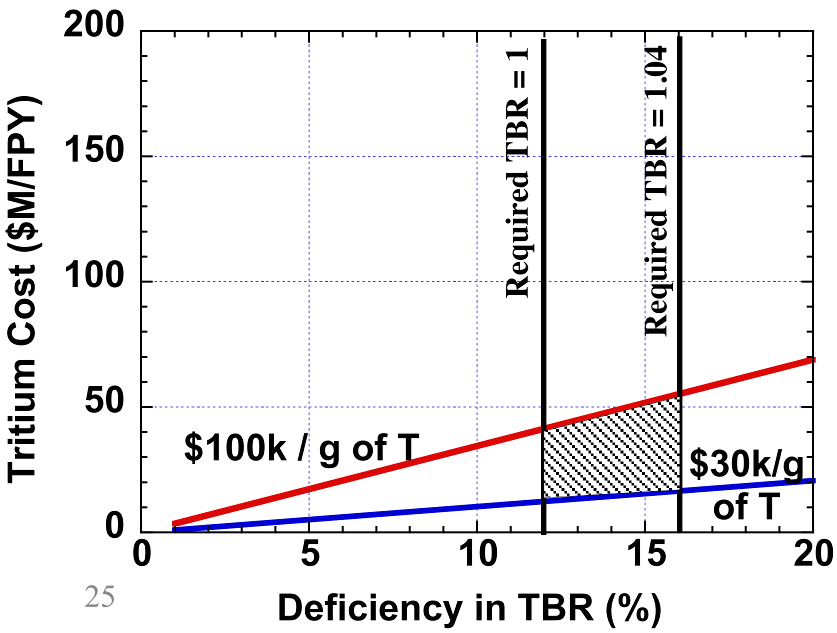
(1.0 m Device)





TBR ~ 0.88

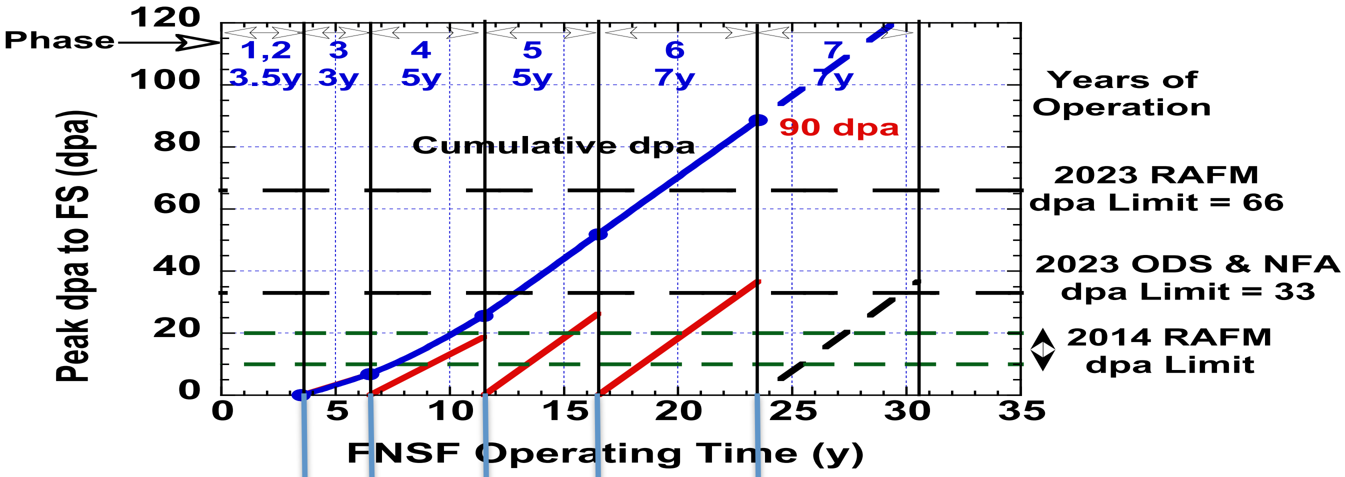
- 1 m device cannot achieve TBR > 1 even with design changes
- **Solution**: purchase ~3kg of T/FPY from outside sources at $30-100k/g of T, costing $12-55M/FPY.



Final Remarks

- T self-sufficiency and materials testing should be essential part of FNSF mission.
- **TBMs and MTM** serve as preliminary breadboard prototypes to test future generations of blankets and materials in real fusion environment (He/dpa = 10).
- **Initial blanket surrounding TBMs and MTM** must be robust and highly reliable, provide adequate tritium breeding, have adequate design margin and lifetime, and able to withstand high heat flux and disruptions during off-normal events.
- **More advanced generations of incrementally improved blanket concepts** can first be tested in TBMs, and then converted into full sectors to validate/qualify blanket for DEMO and power plants.
- **Strong pre-FNSF R&D program** combined with state-of-the-art predictive capability (extensive modeling and computer simulation) assure success of TBM testing and FNSF operation.
- **Do not limit scope of testing.** Develop flexible TBM and MTM capable of testing and validating more attractive blankets/materials than presently known.

Single Phase Testing in FNSF



TBM:

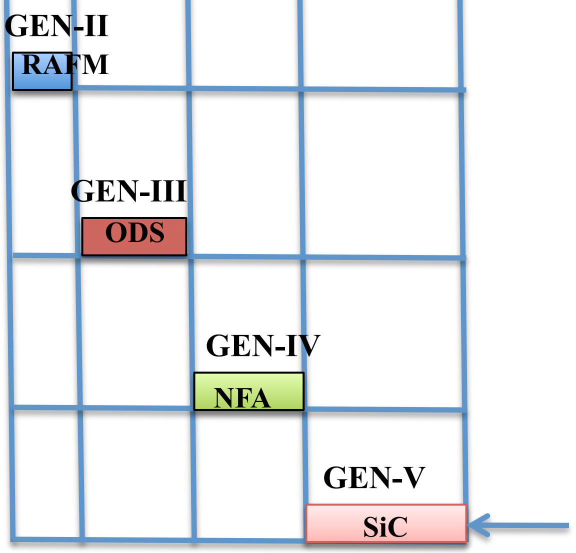
dpa MWy/m^2

Phase 3: **3 y (0.45 FPY); 7 dpa; 0.7 MWy/m^2**

Phase 4: **5 y (1.25 FPY); 20 dpa; 2 MWy/m^2**

Phase 5: **5 y (1.75 FPY); 26 dpa; 2.6 MWy/m^2**

Phase 6: **7 y (2.45 FPY); 37 dpa; 3.7 MWy/m^2**

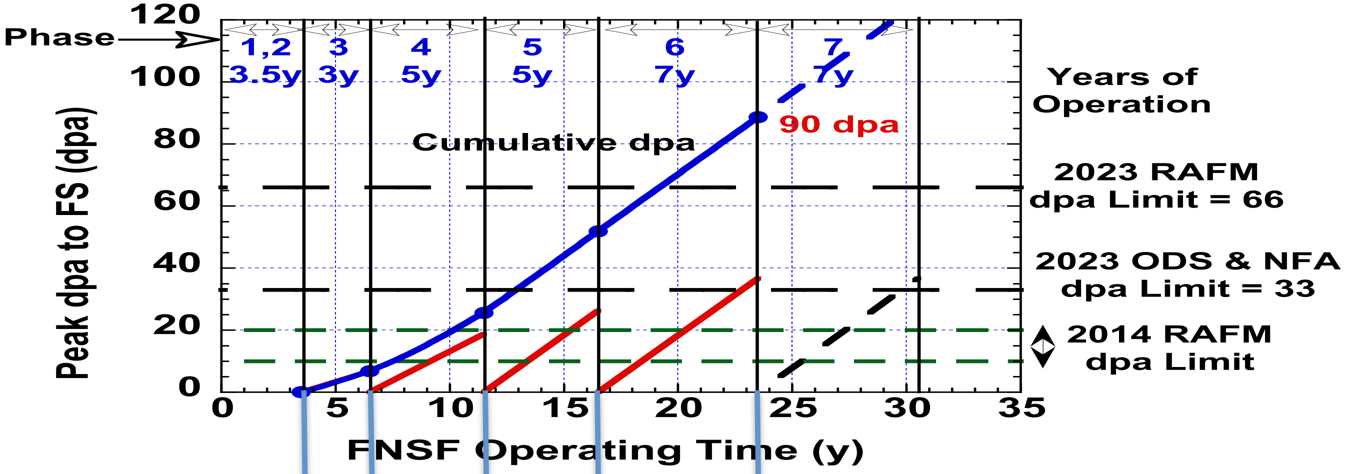


or more advanced FS

Robust DCLL Blanket (GEN-I)

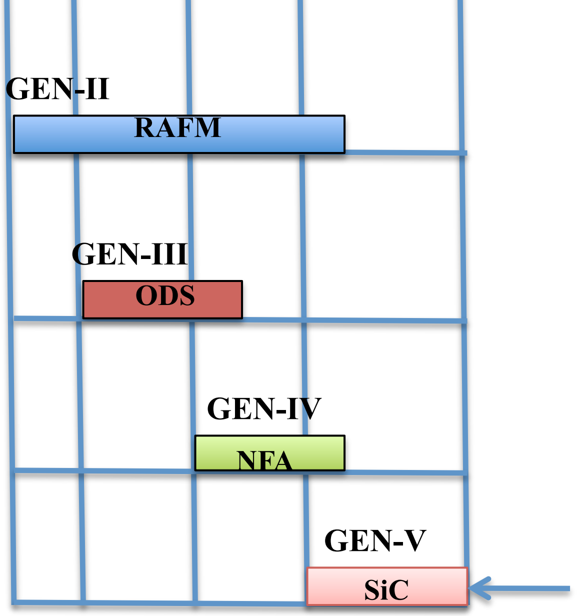
TBM

Extending TBM Testing to Maximize Fluence



Multiple phase testing:

	Max dpa	Max Fluence
15.5 y (4.4 FPY);	66 dpa;	6.5 MWy/m^2
7.5 y (2.2 FPY);	33 dpa;	3 MWy/m^2
6 y (2.1 FPY);	33 dpa;	3 MWy/m^2
7 y (2.45 FPY);	?? dpa;	3.7 MWy/m^2



or more advanced FS

R&D Needs

- Well planned R&D program for non-nuclear blanket testing[*] before FNSF operation.

- State-of-the-art predictive capability to avoid failure and assure success of testing in FNSF.

- Limited nuclear testing (small mock-ups of blanket could be tested with 14 MeV neutrons in IFMIF, GDT, etc.).

- Specific tests may continue during FNSF operation.

---

[*] S. Smolentsev et al., R&D Needs and Progress Measurement for Liquid Metal Blankets and Systems on the Pathway from Present Experimental Facilities to FNSF, presented at 21st TOFE-2014.

MTM Attributes

- Most important attribute would be the much larger specimen volumes compared to 10-500 ml range available in the SNS/IFMIF series of neutron sources.
- Provide a means of testing larger size mechanical property specimens:
  - Pressurized creep tubes and fracture toughness specimens with range of section thicknesses and crack geometries
  - Validation of data derived from highly miniaturized specimens irradiated in SNS/IFMIF.
- Provide a means of conducting critically important surveillance program using range of specimen geometries to track radiation-induced changes in mechanical properties and dimensional stability of FW/blanket materials, divertor materials, structural materials, etc.
- Provide a means of irradiation testing of new materials variants arising from:
  - Continuing development of improved compositions/microstructures
  - Application of advances in fabrication technologies (additive manufacturing, precision casting, joining technologies, etc).