Fusion Energy Technology Development
Collaboration opportunities

PSFC

CDTI presentation, Sept. 6, 2022

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Director, Plasma Science and Fusion Center
Professor, Nuclear Science and Engineering
MIT

Why fusion energy

- No polluting emissions
- Freely available and inexhaustible fuel supply
- Flexible generation anywhere
- No meltdown or long-lived nuclear waste in fuel cycle
- No fissile material proliferation
- Civilization-scale energy

A unique tool to tackle climate change…
but too slow

We understand the physics of fusion plasmas:
High magnetic field is key to confining and stabilizing plasma

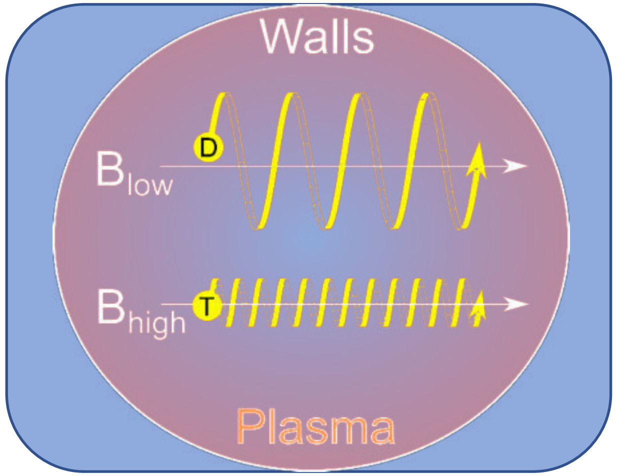
How well a plasma is insulated:

Make many of these fit inside the device size R

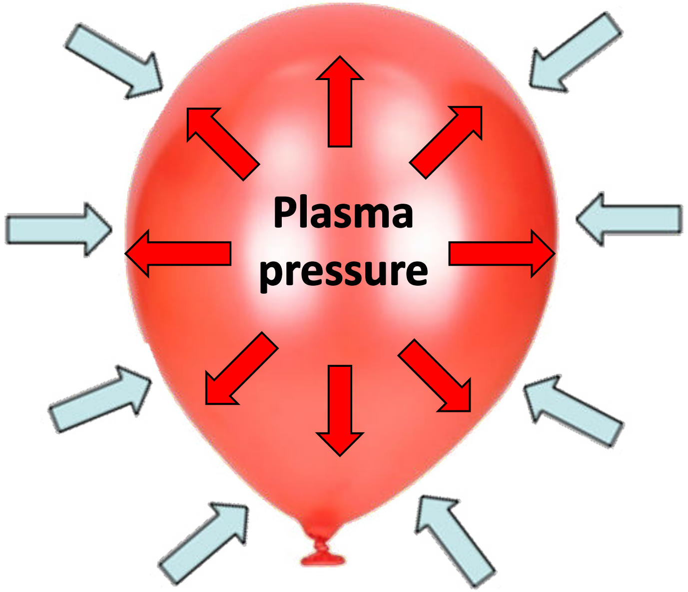
$$r_{ion} \approx \frac{\sqrt{T}}{B}$$

Plasma temperature, Set by fusion nuclear cross-section

Magnetic field, set by superconductor



How stable the plasma is:



Magnetic pressure ~ B^2

Cost ~ Volume ∝ R^3 ∝ $1/B^3 - 1/B^6$

Fusion power density ∝ (plasma pressure)^2 ∝ B^4

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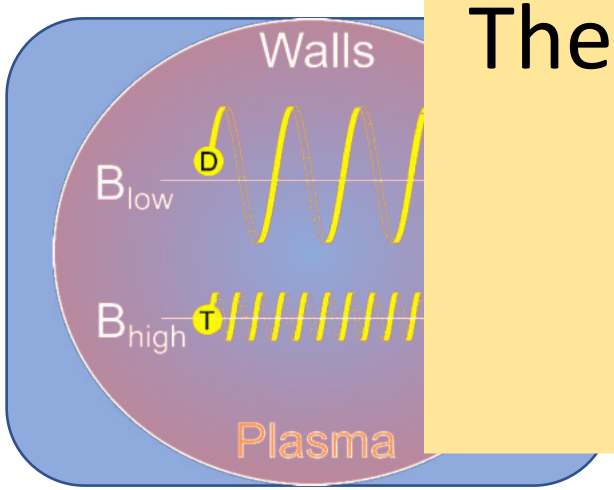
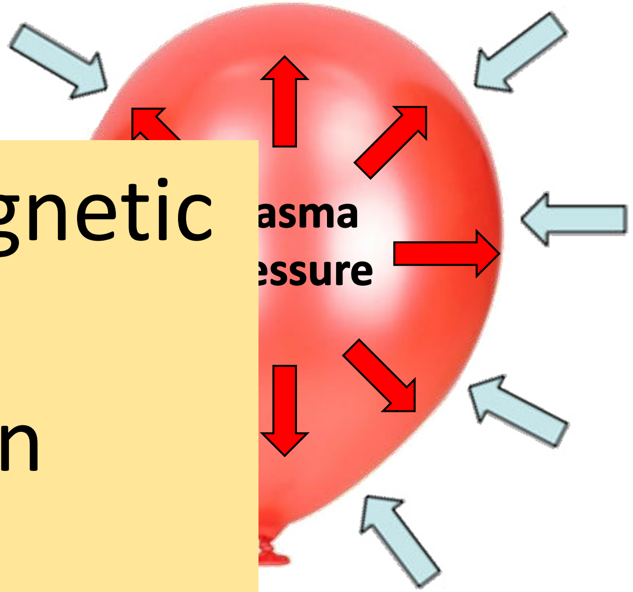


Therefore a doubling of magnetic field B provides ~20-40x improvement in Cost per Watt

How stable the plasma is:



Cost ~ Volume ∝ R^3 ∝ $1/B^3$ - $1/B^6$

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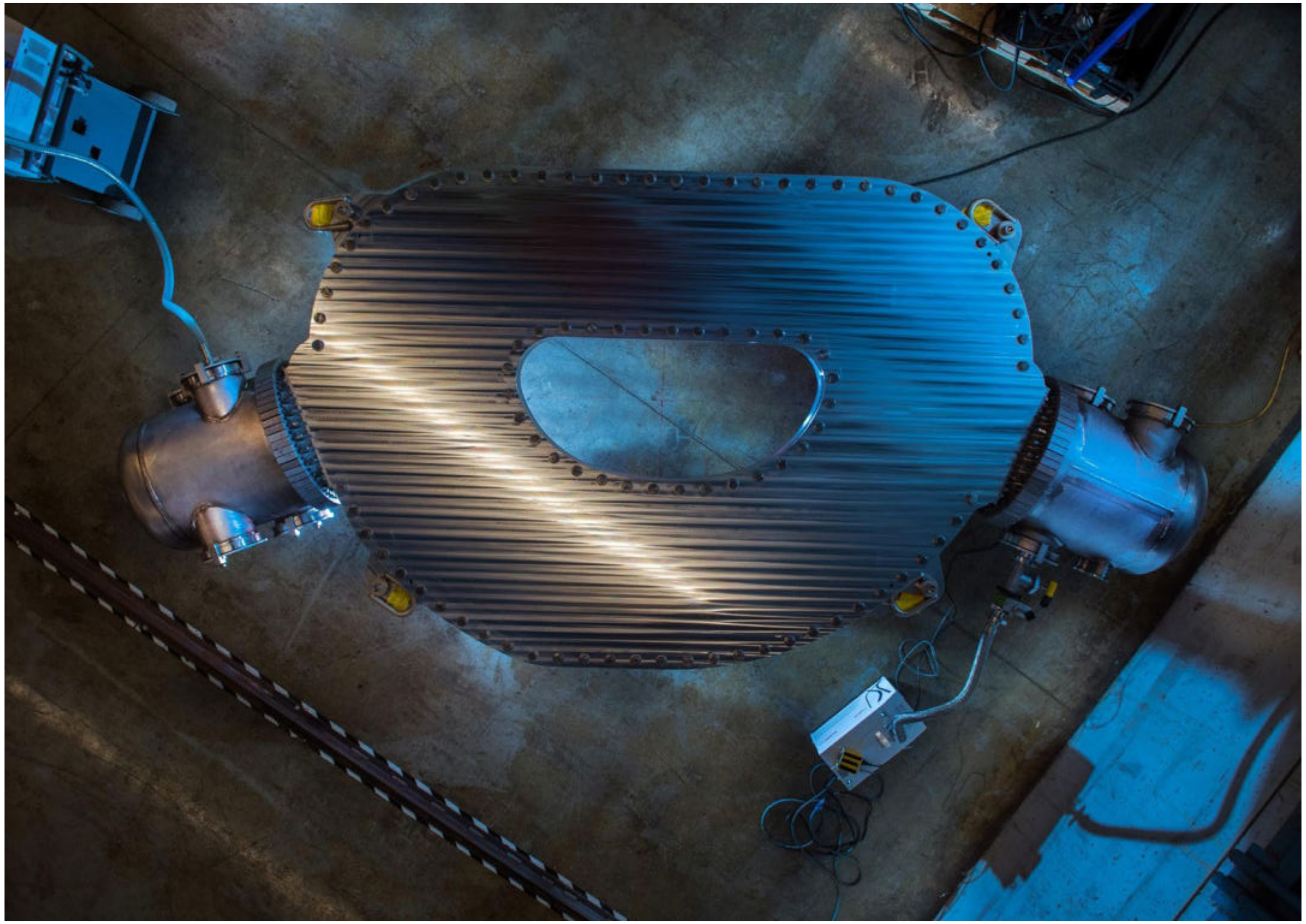
We built and tested the needed high-field magnet



- Fully representative of SPARC coil operation
- >20T on coil, doubling the B field!
- Modular: Each of 16 pancake is world’s largest HTS magnet
- **Successfully tested: September 5, 2021**

Pathway to developing and deploying fusion energy based on REBCO high-field magnets

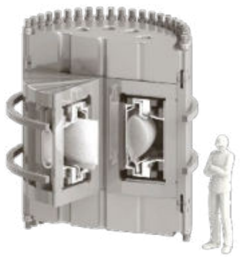
COMPLETED:
Alcator C-Mod

COMPLETED
TFMC demonstrated
September 5, 2021

FUNDED at 1.8 B$
December 1, 2021

CONSTRUCTION PLANNING UNDERWAY for 2025 LAUNCH
SPARC achieves net energy

Early 2030s
ARC fusion power on the grid



Net energy

Carbon-free scalable commercial power

SPARC under construction outside Boston. Fusion power > 100 MW
Plasma energy gain > 10. Highly compact (~20 m^3).

If SPARC is working mid-decade, how do we accelerate now to economic ARC?

COMPLETED:
Alcator C-Mod

COMPLETED
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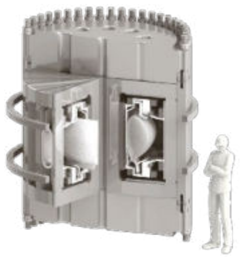
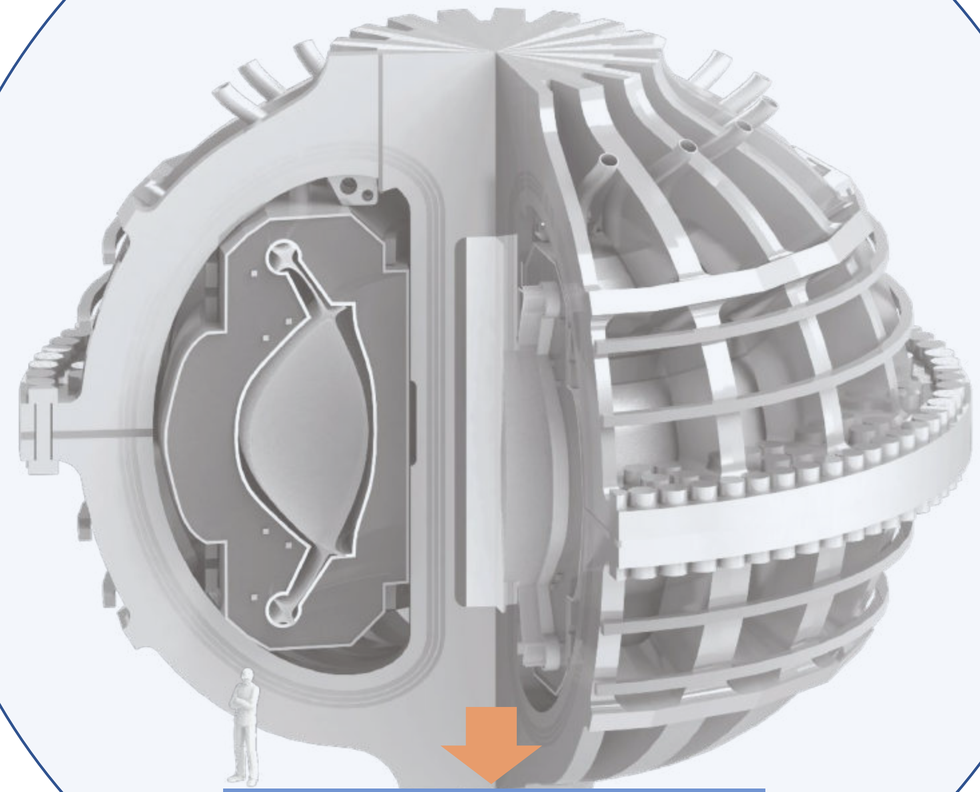


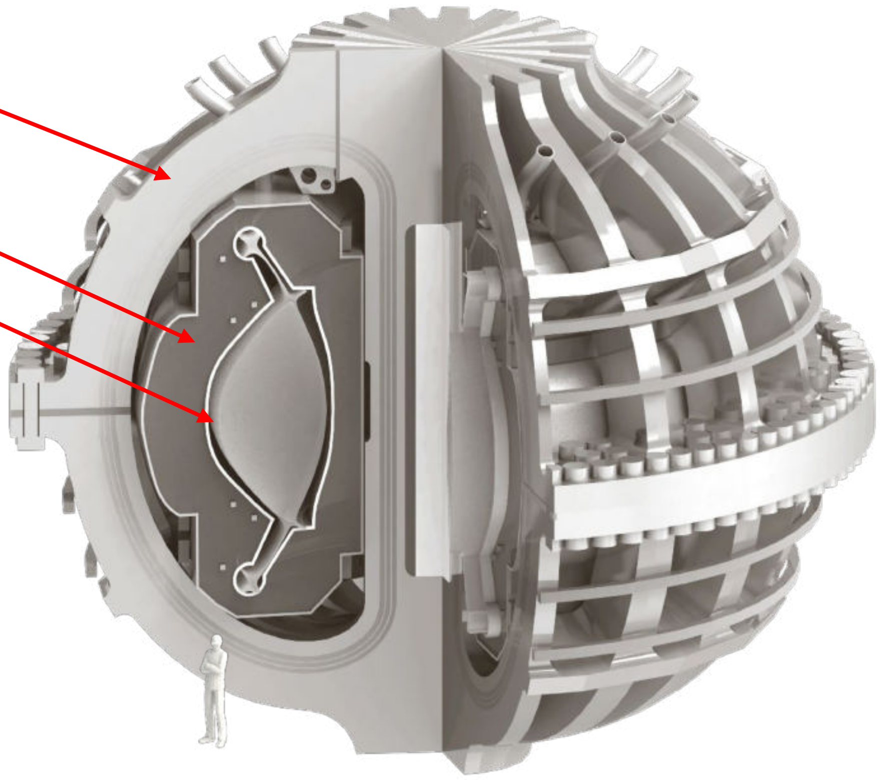
Net energy



Carbon-free scalable commercial power

ARC – a platform for fusion energy development..NOT a fixed design

- Only a few set boundary conditions
  - REBCO-based high B magnets → ~JET size tokamak
  - Liquid immersion blanket → neutron physics
  - Modular design → replaceable thin VV/first wall



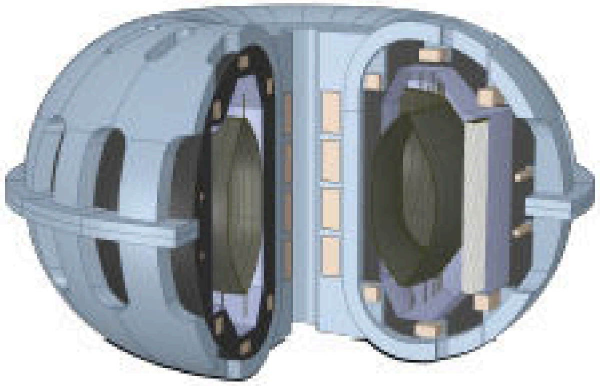
- Set by market
  - economics require driving down ($/W)…size more or less set by magnet B field, put power can be increased?
  - need to have a flexible platform that can provide integrated answers to plant availability

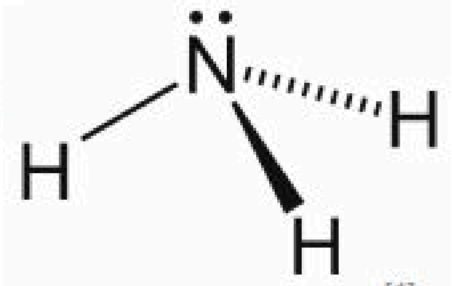
Background and outline

- CFS does commercialization, MIT does research
- SPARC and its REBCO magnets answer key question: will ARC overall strategy of high B, high gain, compact size ”work”
  - Our present estimate is that there are only a few places like tritium breeding where the “fundamental” science of ARC has not been demonstrated
- But there is enormous R&D required to improve the economic prospects of ARC, particularly if we collectively want to develop this quickly. This leads to the subjects I will touch on today
  - Example integrated plant design (ARC-H) → how technology → economics
  - Efficient RF sources for heating and control
  - Liquid immersion blanket: heat transfer, SiC, tritium extraction
  - Materials development and down-selection

ARCH: Affordable, Robust, Compact, *Hammoniacum*

1. Use fusion's heat: make H_2, then NH_3 🌊 + 🔥 → ⛽
2. Shipyards: serial production of fusion-to-NH_3 platforms 🏗️
3. Sell NH_3 as shipping fuel, for \$280/ton
4. Decarbonize shipping with cost-effective ammonia





[1]

Artwork by Simon Clements

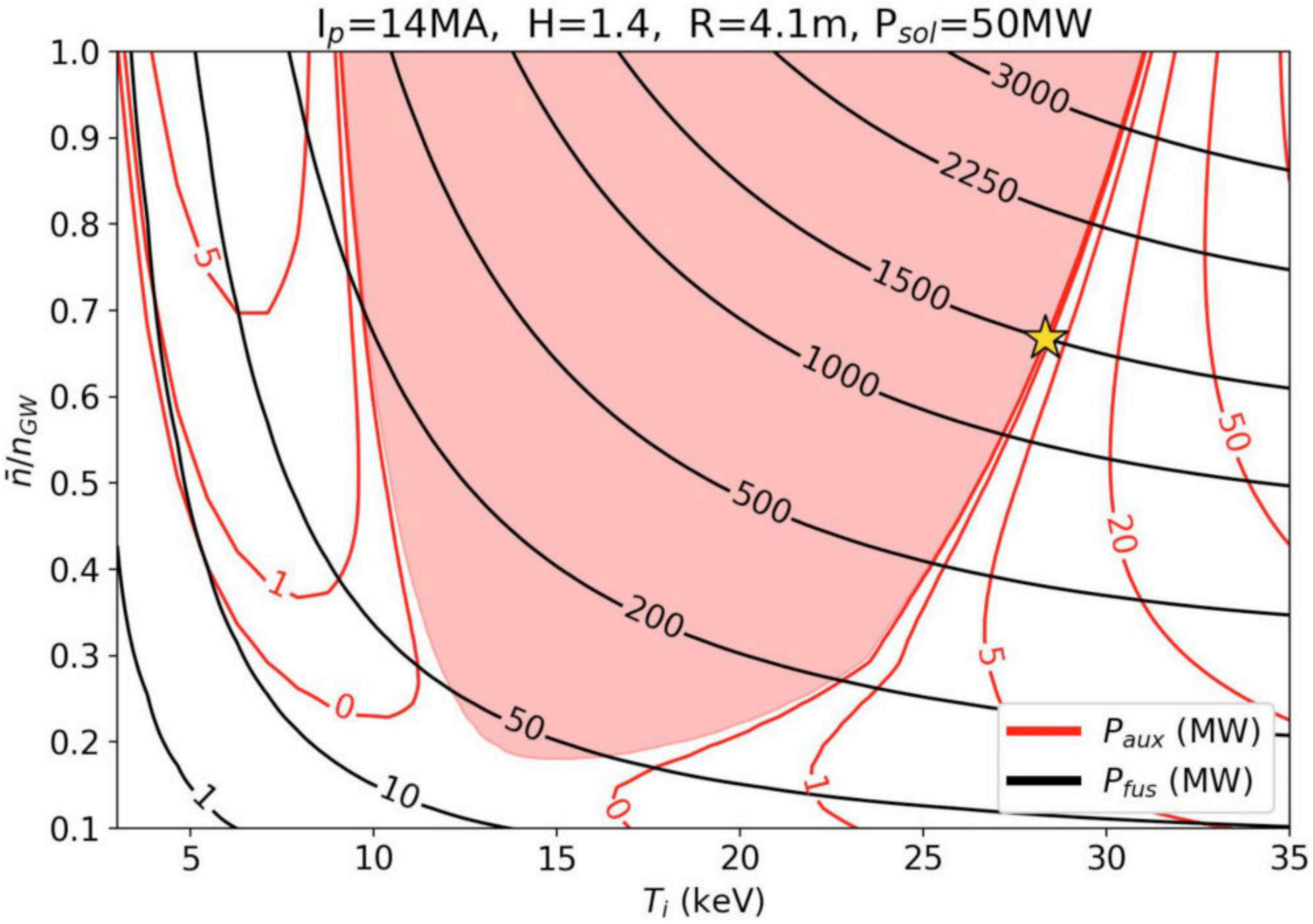
The image is to scale and highlights the size difference between the two ships.

© LucidCatalyst

[1] "Ammonia-2D.svg". Image by "Radio89", distributed under a CC-BY-SA 3.0 license, https://en.wikipedia.org/wiki/Ammonia#media/File:Ammonia-2D.svg

Operating point chosen for ARCH

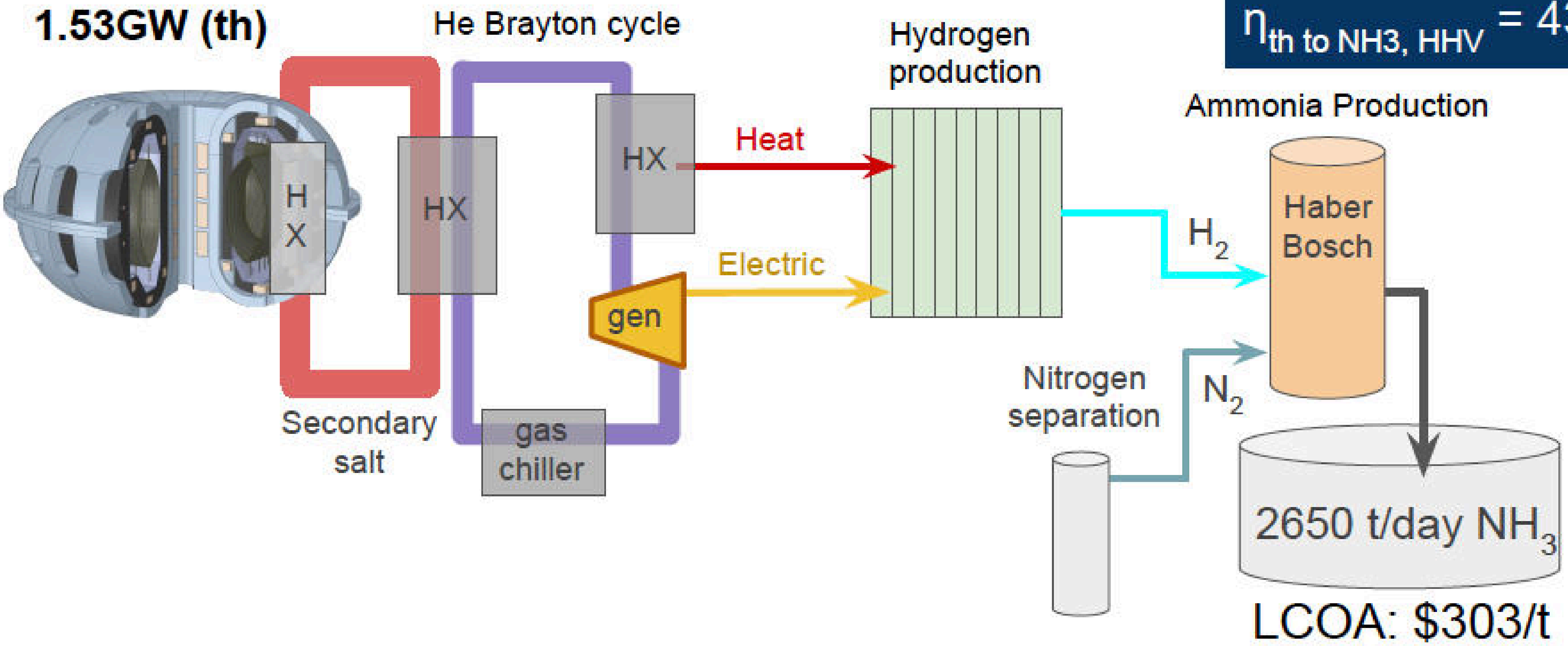
	ARC	ARCH
P_{fus} [MW]	525	1500
P_{aux} [MW]	**38.6**	**15**
$f_{rad} = P_{rad/}P_{heat}$	0.35	0.84
I_p [MA]	**7.8**	**14**
B_{T0} [T]	**9.2**	**11.5**
R [m]	**3.3**	**4.1**
a [m]	1.13	1.15
κ	1.84	1.9
f_G	0.67	0.7375
H_{89}	**2.8**	**1.4***



High magnetic field greatly expand physics capability to produce much more power fundamentally improving fusion economics!

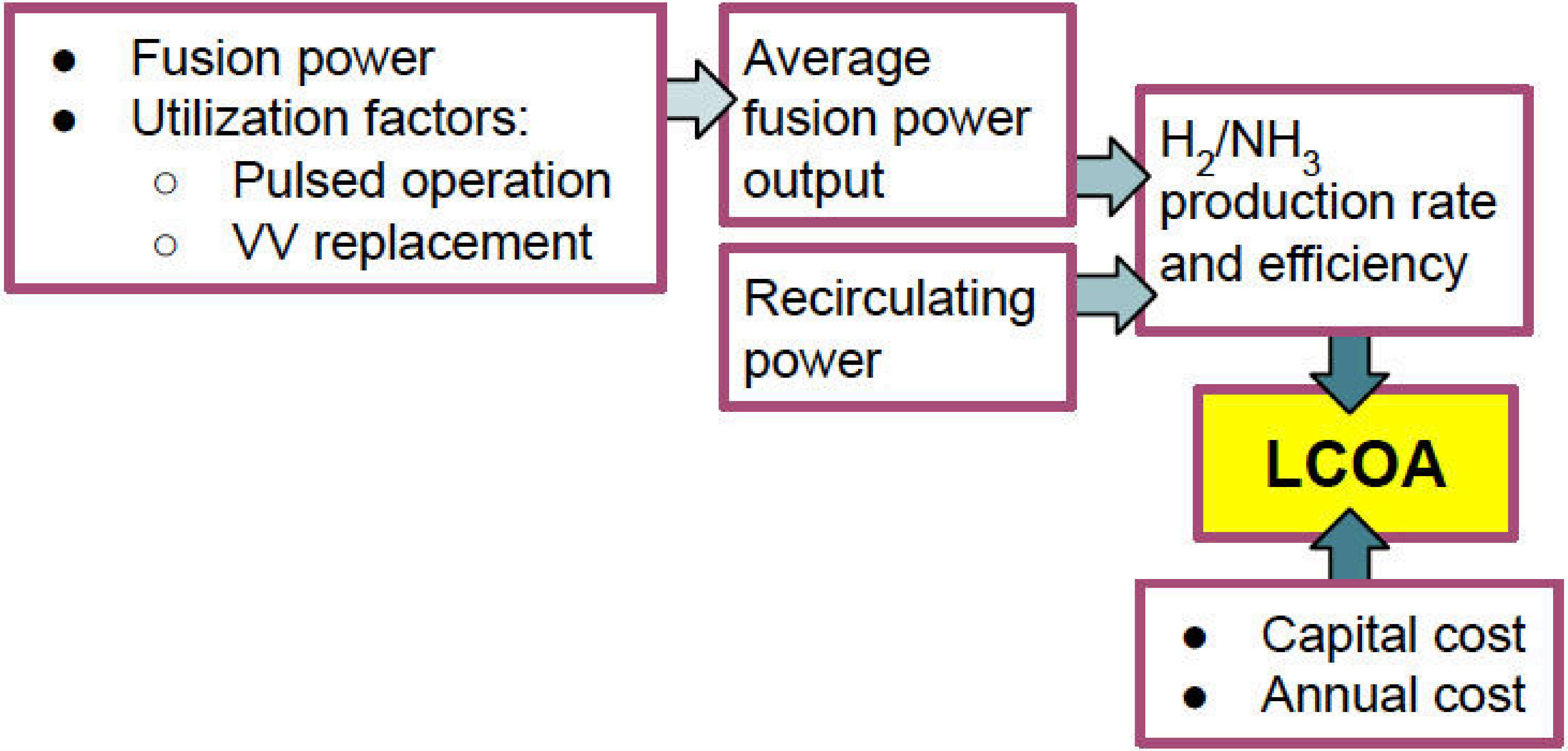
Plant produces hydrogen, then ammonia

$\eta_{th\ to\ NH3,\ HHV} = 43\%$

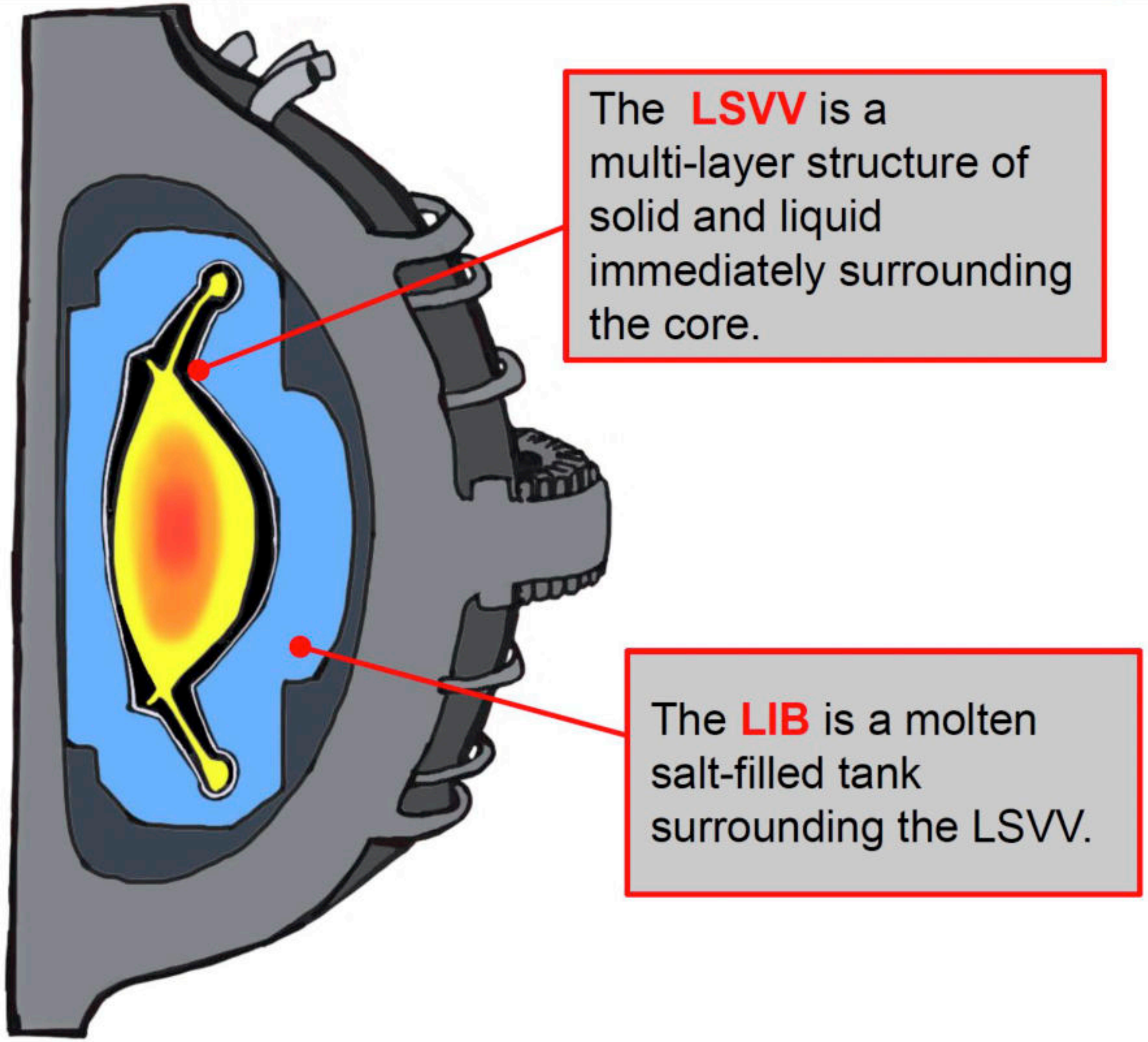


Overview of operations and costing model

Goal: Achieve Levelized Cost of Ammonia (LCOA) of $280/ton

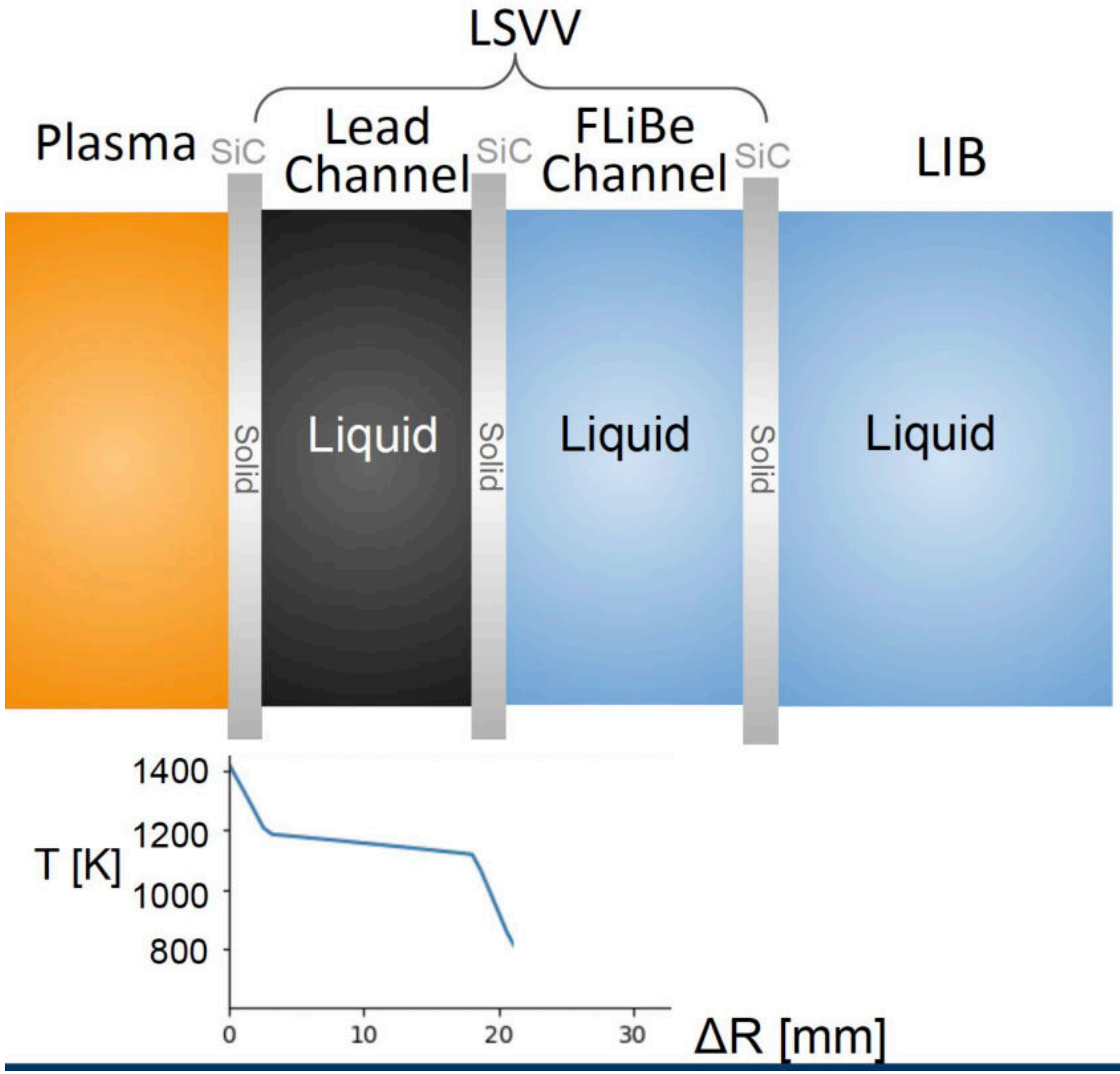


An integrated system is required to solve the major challenge of heat transfer and shielding



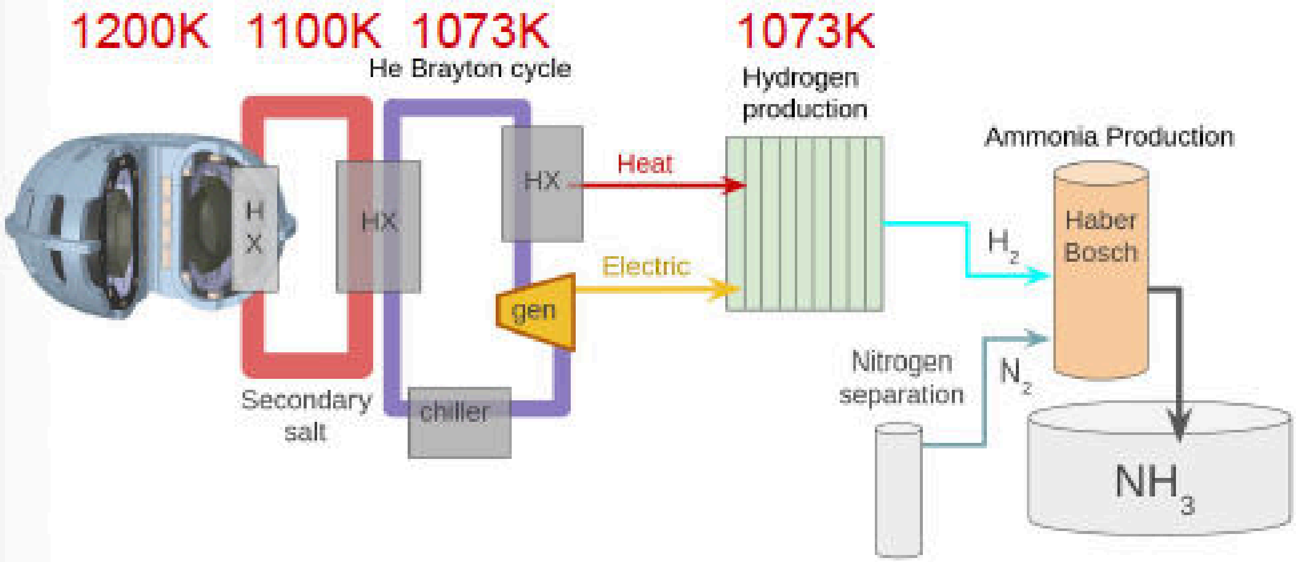
- 1.5 GW of power over 290 m^2 first wall surface area ≈ **5 MW/m^2**
  - 0.3 GW from radiative photons → surface heating
  - 1.2 GW from 14.1 MeV neutrons → volumetric heating
- The Liquid Sandwich Vacuum Vessel (**LSVV**) and Liquid Immersion Blanket (**LIB**) comprise ARCH's solution to this challenge.

The LSVV incorporates alternating layers of solids and fluids to achieve multiple design objectives



- Tritium Breeding Ratio (TBR) > 1
  - Neutron economy improved by neutron multiplication in lead and thin solid walls.
- Optimizing heat transfer to the large volume of FLiBe molten salt in the LIB
  - Uses induced convection and thin solid materials.
- Tolerant to disruption forces
  - To be presented by next team.

High temperature allows efficient power generation and electrolysis processes



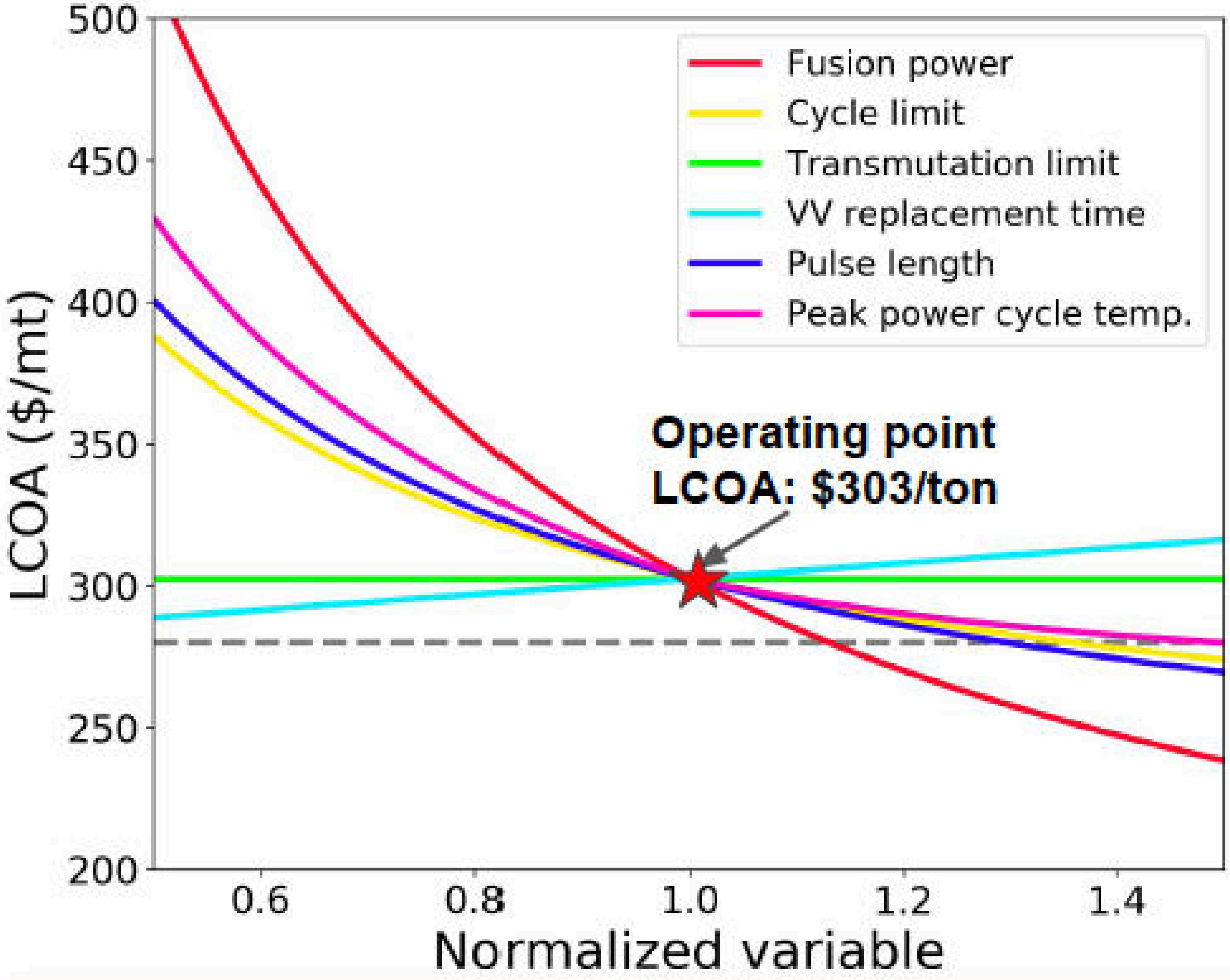
- FLiBe at 1200 K
- Secondary salt 1100 K
- He Brayton cycle at 1073 K
  - 48% efficiency

- High temperature steam electrolysis for H_2 production
  - 1073 K
  - 95% electrical efficiency, after heating

LCOA is most sensitive to integrated energy output

- ➔ **Fusion power 1.5 GW**
- ➔ **VV fatigue limit: 10,000 cycles**
- ➔ **Transmutation limit: 0.5% He**
- ➔ **VV replacement time: 1 month**
- ➔ **Pulse length: 30 min**
- ➔ **Peak power cycle temp: 800 °C**

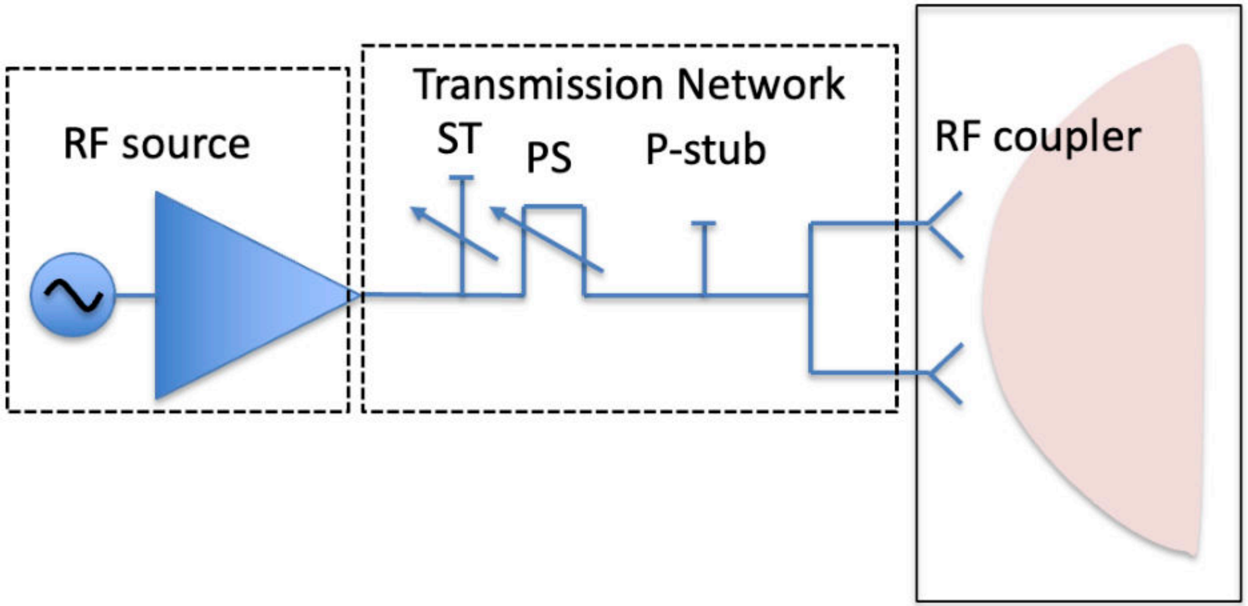
- Options to achieve goal LCOA:
  - **Increase fusion power**
  - Increase pulse length (CS design)
  - Increase peak power cycle temperature
  - Explore materials with higher cycle limits



RF Systems are Enabling Technology for Fusion Development

Radiofrequency (RF) systems can be designed to perform a variety of functions:

- Heat the plasma to thermal nuclear temperatures.
- Drive current to sustain plasma.
- Instability and disruption suppression/control.



RF systems consist of:

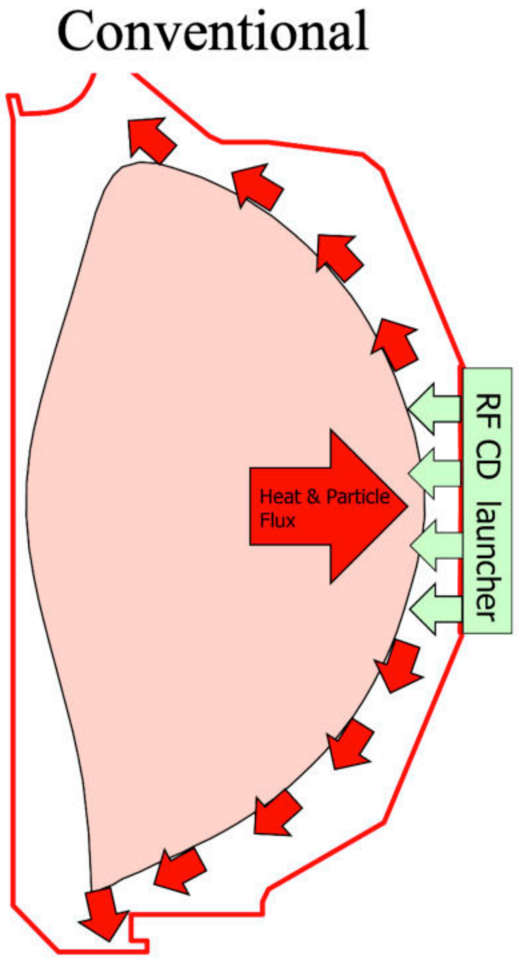
- RF source – converts AC or DC power to RF range of frequencies (>MHz)
- Transmission network conveys power to device and transforms coupler impedance to RF source impedance
- RF coupler is plasma facing and couples RF power to plasma

Presentation from Steve Wukitch PSFC

Significant Challenges Remain for Effective RF Systems

1) Reliable, robust coupling – Coupling limits system efficiency and is greatest risk to system reliability.
    - Coupling = transfer of RF power from coupler to desired absorption scenario and location.
2) RF associated impurity contamination – want to eliminate it completely
3) In a reactor environment, plasma material interaction (PMI) issues associated with coupling structures are similar to the first wall with the additional challenge that it needs to couple high power to the plasma.
    - Identified as a potential show-stopper
    - RF launchers near the plasma edge lack credible solutions.
4) High heating and current drive efficiency with proper profile.
    - Determined by physics
5) RF source efficiency and availability
    - high wall plug efficiency (~90%) with “off the shelf” sources
    - ~100 MHz ~70%, 5 GHz ~40%, 100 GHz ~30%

High Field Side (HFS) Launch Offers Integrated Physics and Technological Solution



HFS launch avoids turbulent, high heat and particle flux region.

Expect reliable, robust coupling.

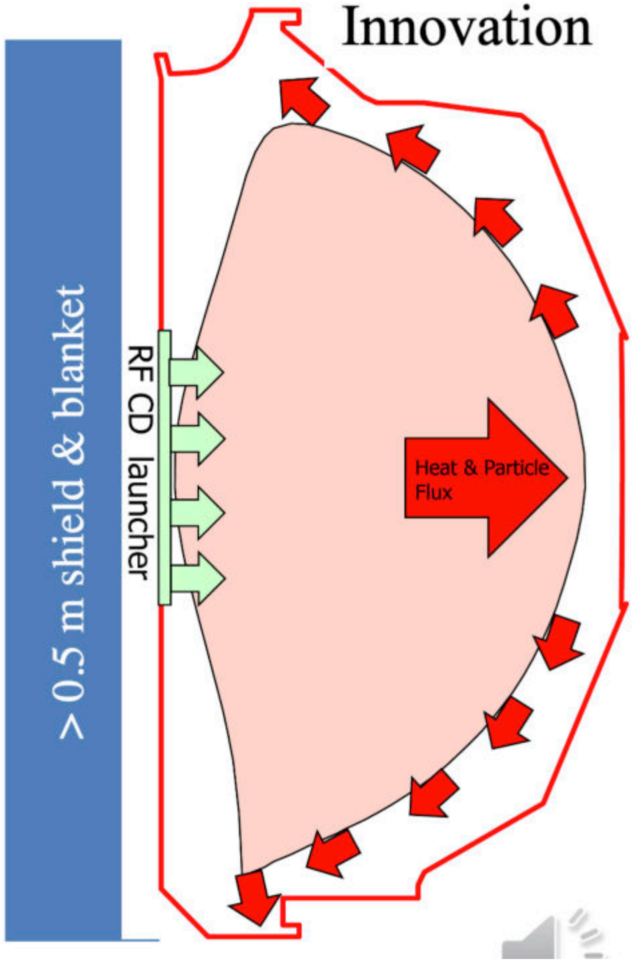
- HFS edge is quiescent.

Impurity penetration is significantly lower.

- Whatever impurities are generated, many fewer penetrate into the plasma.

PMI issues are greatly reduced due to reduced heat and particle flux.

Improved RF wave physics leads to higher effectiveness.



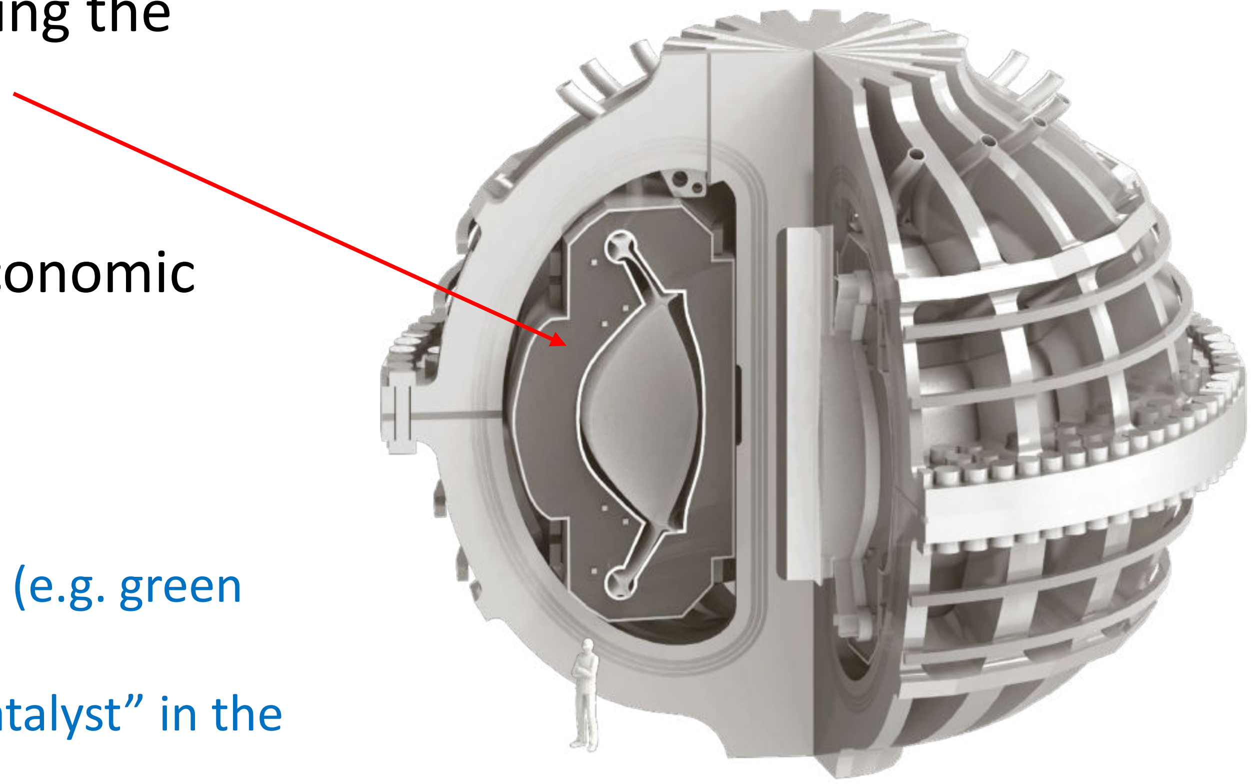
Required R&D: 3-D printing of antennae and waveguides, active cooling, duration of dielectric materials w/ radiation

Synergistic needs and opportunities

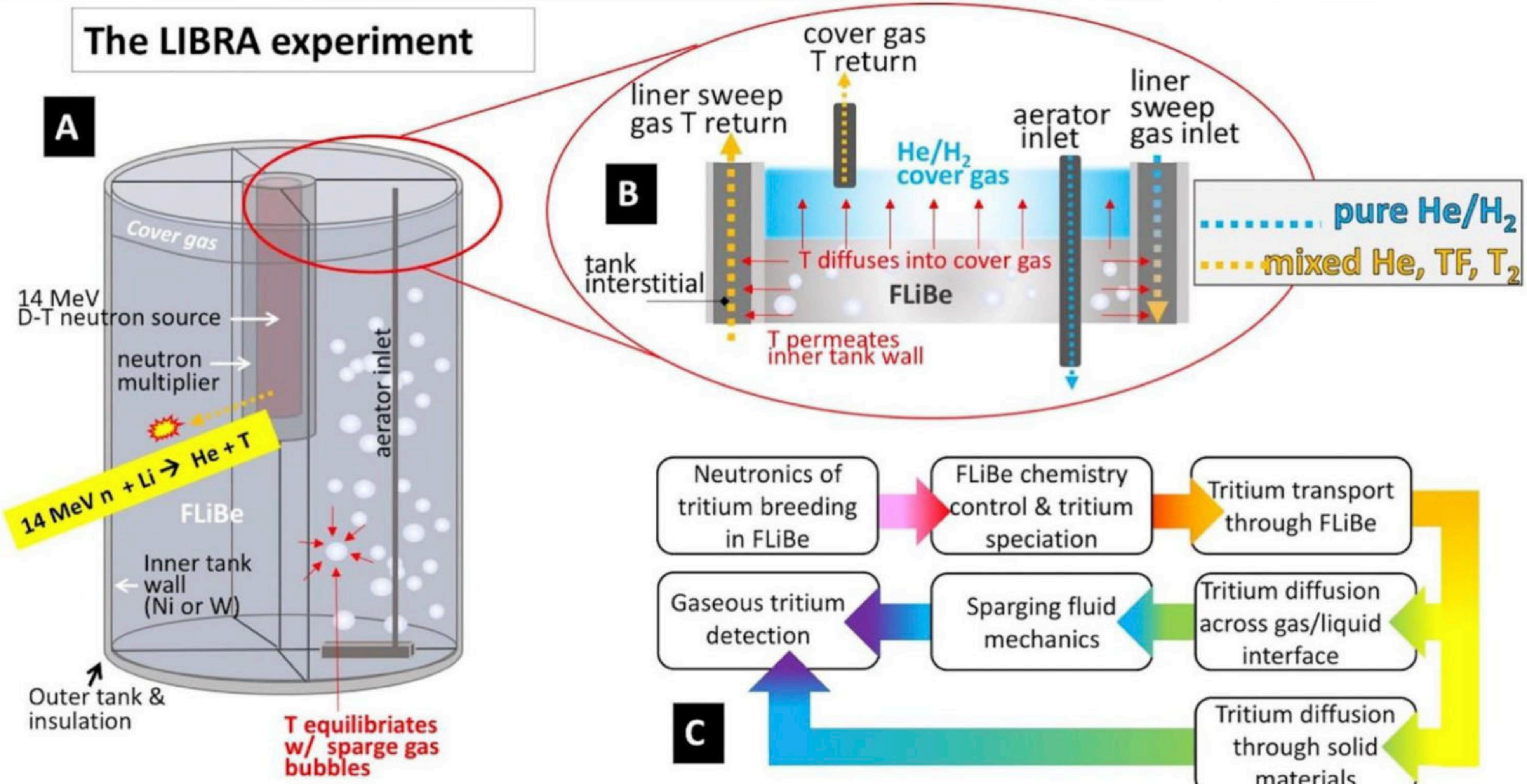
- Efficient RF sources at range of frequencies ~GHz…want to boost from ~30-40 % to 80-90% wall plug efficiency
- New generation at electron resonance in ARC > 300 GHz
  - Will have other industrial impact
  - Feasible now with advent of REBCO magnets
- Internal power handling in sources and transmission is ubiquitous design requirement.
- Advanced Manufacturing for launchers

Liquid Immersion Blanket is critical to economics

- This captures the fusion energy and converts to heat in the liquid, a high-T molten salt surrounding the fusion plasma
- And produces tritium from lithium
- This “heat” of the blanket is the primary economic output of a fusion power plant
- Technological R&D focus
  - High-T for plant efficiency
  - High-T for opening up direct energy conversion (e.g. green fuels)
  - Efficient production and recycling of tritium “catalyst” in the lithium containing salt
  - Corrosion and purity control → no activation blanket!
  - Heat exchangers
  - Salt ”tanks”



LIBRA Overview



The LIB work is starting in earnest and is open for multiple collaboration pathways
Now funded by ARPA-E and internal PSFC funds

CORE LIBRA TEAM at MIT PSFC

Dennis Whyte
- ★ PSFC director / head PI of LIBRA

Sara Ferry
- RS / materials, salt radiochemistry, fuel cycle modeling

Ethan Peterson
- RS / neutronics of LIBRA and the LIB

Kevin Woller
- RS / experimental design, neutron and T detection

Facility Development

MIT Environmental Health and Safety
- Ed Lamere (lead EHS contact)
- Jim Doughty, Andrew Kalil

Architecture/Lab Design
- E4H Architecture
- MIT Campus Construction office

PSFC Facilities
- Matt Fulton

Additional PSFC team members

Engineering team
- Rui Vieira
- Rick Leccacorvi
- Lihua Zhou

Faculty
- Zach Hartwig
- Bilge Yildiz
- Mike Short

Postdoctoral associates
- Remi Delaporte-Mathurin (Oct 2022; CEA-IRFM, France; T modeling)

Graduate students
- Samuele Meschini (Y3/visiting student, U. Politecnico di Torino, Italy)
- Andrew Lanzrath (Y1/June 2022; Wentworth Inst. of Tech.)
- Nikola Sobeš (Y1/Sept 2022; U. of Novi Sad, Serbia)
- Collin Dunn (Y1/Sept 2022; Georgia Tech/Helion)
- Jack Fletcher (Y1/Sept 2022; Missouri U. of Sci. and Tech.)

External Team Members

Idaho National Laboratory
- Chase Taylor
- Tommy Fuerst
- Adriaan Riet
- Matthew Eklund
- Masashi Shimada

Advisory Board
- Raluca Scarlat (UC Berkeley)
- Brenda Garcia-Diaz (SRNL)
- Mark Johnson (Clemson)
- Christian Day (Karlsruhe IT)
- Bruce Pint (ORNL)

Interested collaborators

UKAEA
- H3AT team
- STEP fuel cycle team

Commonwealth Fusion Systems
- Caroline Sorenson (ARC blanket lead & co-author of the LIBRA proposal)

Kyoto Fusioneering

Key metrics for LIBRA

Technology Summary

- Validate Tritium (T) breeding in Liquid Immersion Blanket (LIB) technology directly from representative volume of molten FLiBe salt irradiated with 14 MeV D-T fusion neutrons
- Show unprecedented T breeding ratios possible with 70% lower cost LIB technology

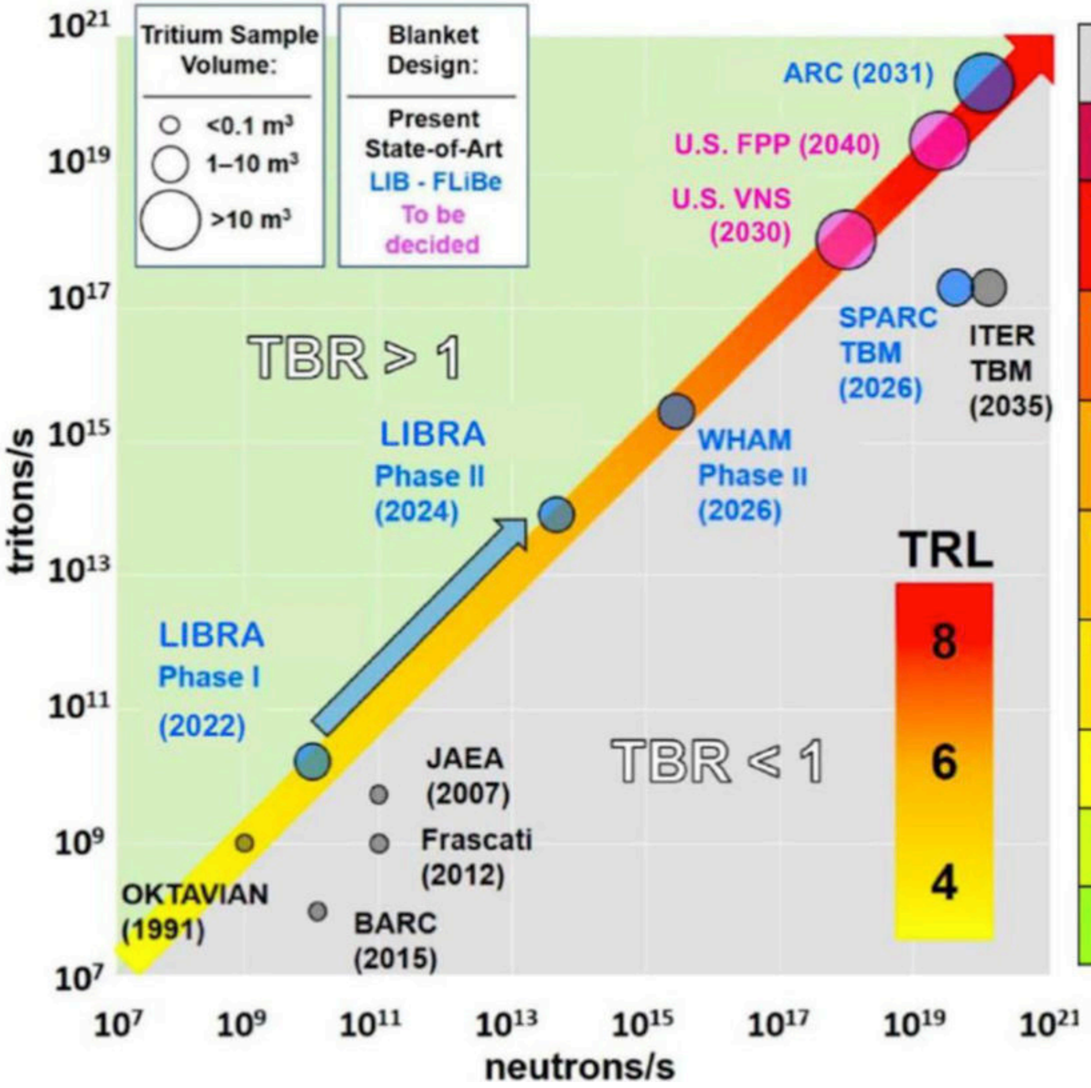
Technical Targets	SoA FLiBe breeder tests	LIBRA Experiment
Neutron energy	arbitrary	14 MeV D-T fusion
T equilibration time	~7 days	< 1 day
Validated true TBR	N/A	> 1
Breeder Volume	0.001 m^3	0.5 m^3

Technology Impact

- More efficient (W/$, W/kg) Fusion power plants
- Exponential growth in commercial fusion power capacity
- Simplified maintenance leading to lower cost over life of the fusion power plant.

Economic impacts	SoA FPP design	LIBRA-enabled
Starting T inventory	> 5 kg	< 1 kg
T doubling time	>5 years	<2 years
Fusion share of World's capacity in 2050	<0.006%	~6%

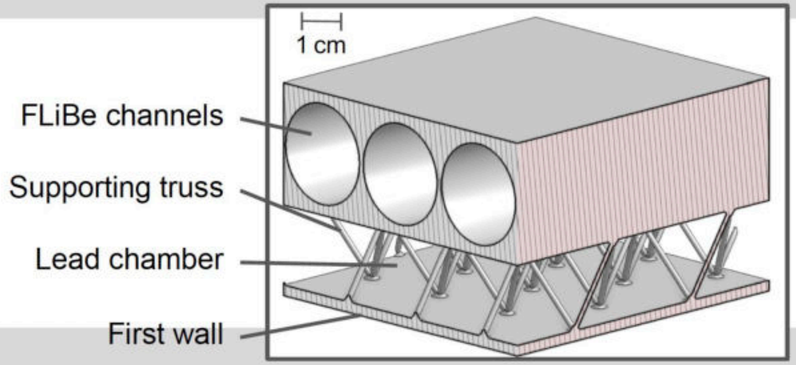
LIBRA is a TRL accelerator for the LIB.



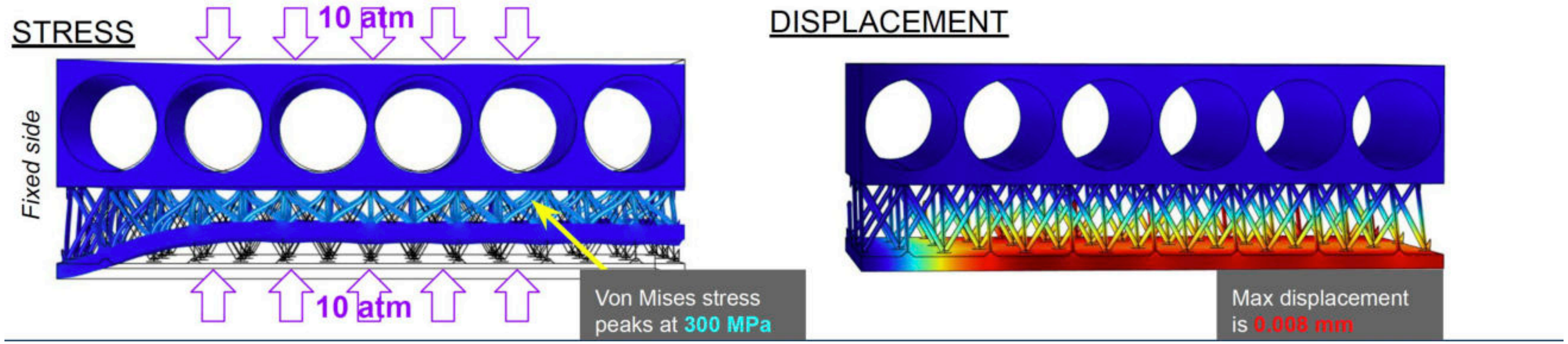
Level	NASA TRL definition for spaceflight technologies	Applying the TRL framework to the LIB
TRL 9	System "flight proven" through successful mission operations	Many LIB-equipped FPPs are operating successfully
TRL 8	Actual system completed and "flight qualified" through demonstration	T breeding and extraction demonstrated on an FPP with the first full-scale LIB
TRL 7	System prototype demonstration in a space environment	LIB test blanket module is deployed and tested on a DT-tokamak with Q>1
TRL 6	System prototype demonstration in a relevant environment	LIBRA PHASE II: scale up the system
TRL 5	Component/breadboard validation in a relevant environment	LIBRA PHASE I : demonstrate global TBR > 1 in a radiochemically relevant environment
TRL 4	Component/breadboard validation in a laboratory environment	T successfully extracted from FLiBe following neutron irradiation (INTREXFLIBE, JUPITER-II, etc.)
TRL 3	Proof-of-concept demonstrated	Analysis demonstrates validity of LIB concept (LIB/ARC introduced in 2015 (Sorbom et al.))
TRL 2	Technology concept formulated	The LIB concept is created
TRL 1	Basic principles observed and reported	Interactions between neutrons and the lithium in FLiBe create tritium

Less than a centimeter of solid SiC with 1mm truss members is sufficient for LSVV structure

- Structural analysis from COMSOL.
- The truss members concentrate stress, but not beyond reasonable limits during normal operating conditions



Example: high compression test on wall segment

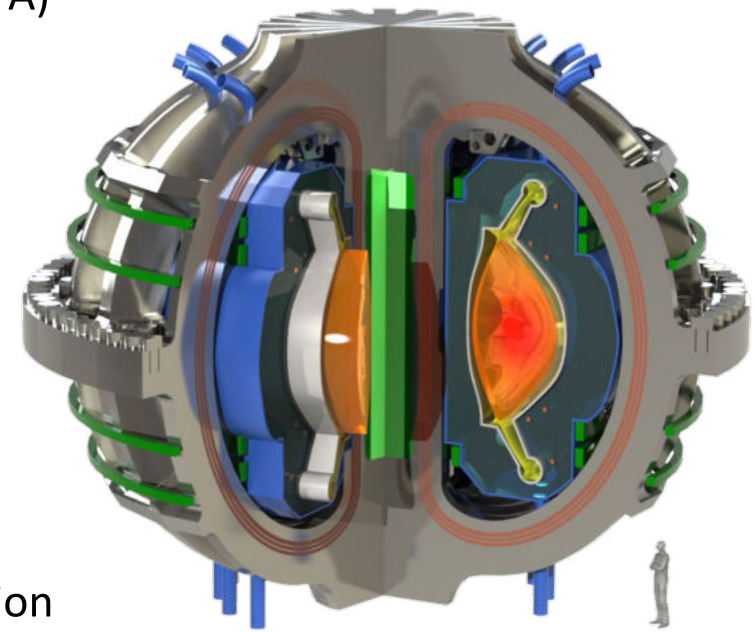


The development of LSVV is now underway but needs significant help / collaboration in manufacturing and assembly

Key needs: SiC-SiC composites, additive manufacturing, joining technologies, component testing at T>600 C

Implementation of fusion energy on 15 year timescales requires solutions for radiation damaged materials

Structural Materials
- High damage rates (10s of DPA) with bulk helium generation (100-1000 appm) at high temperatures (<800 K)
- Chemical compatibility with molten salt under simultaneous irradiation



Common challenges:
- D-T fusion generates 14.1 MeV neutrons, which cause high-levels of bulk H and He generation in addition to cascade damage
- Neutron energy spectrum varies widely depending on subsystem of interest, and material response will vary accordingly
- Relevant neutron spectra and fluences are not possible to produce with existing sources.

Plasma-facing materials
- Tritium retention and migration in bulk damaged materials
- Radiation damage changes to material properties required for high heat flux handling (10 MW/m^2)

Functional materials
- Degradation of the critical current of superconductor while irradiated at cryogenic temperatures (<20 K)
- Browning of optical glass and mirrors required for plasma diagnostics

MIT's Fusion Power Plant Concept: ARC

[0] B. N. Sorbom *et al*, FED **100** (2015) 378-405
[1] A Q. Kuang *et al,* FED **137** (2018) 221-242

Present approaches to fusion materials are limited, resulting in long schedules, high costs, and uncertain results

Materials irradiation in nuclear reactors

Disadvantages / limitations:

- Low material damage rates
- High cost at rare facilities
- Long and few learning cycles
- Low fidelity for most fusion materials

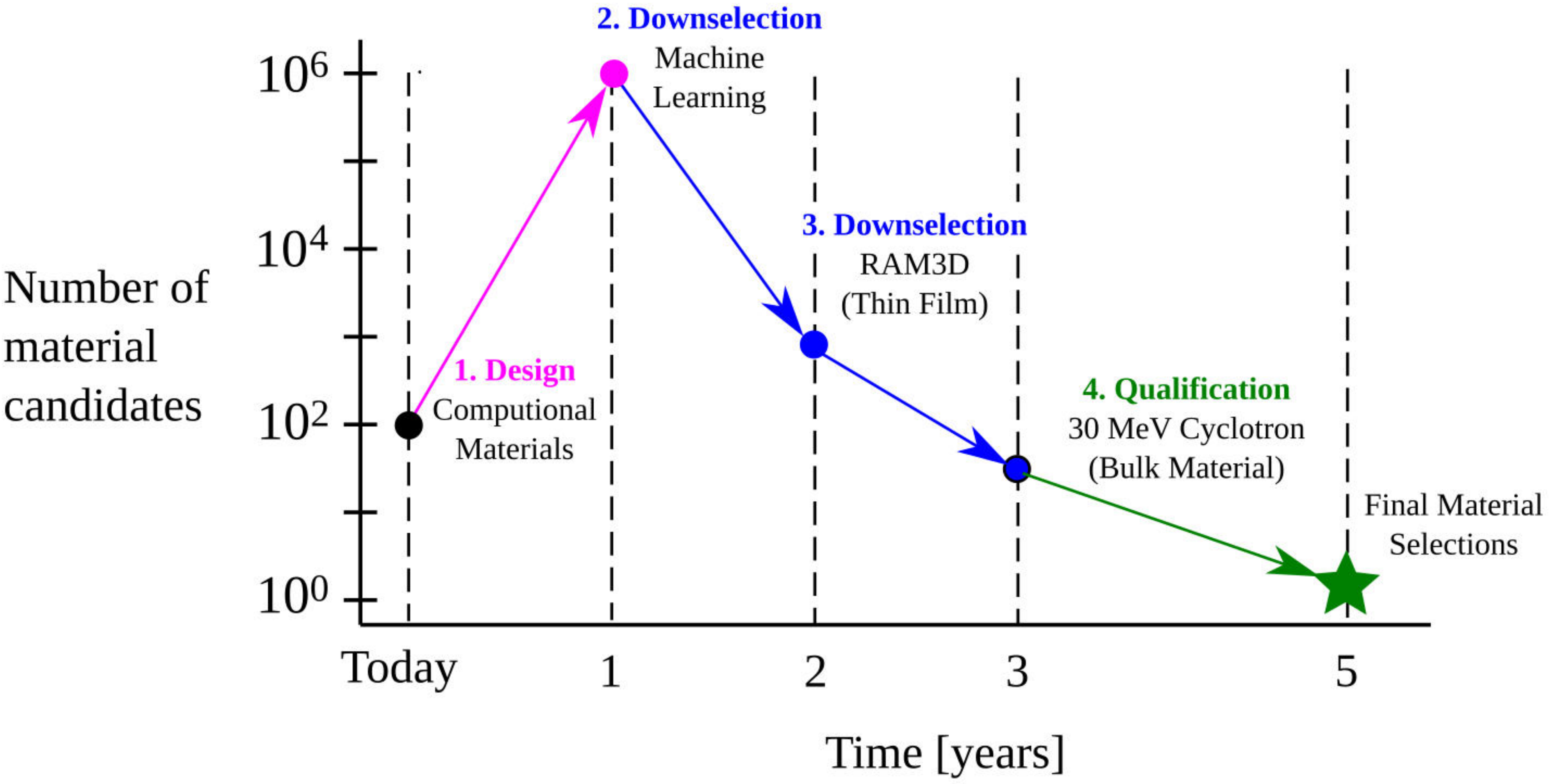
Low energy proton / self-ion beams

Disadvantages / limitations:

- Damages surface layers not bulk
- Inability to extrapolate to bulk properties
- Low fidelity for most fusion materials

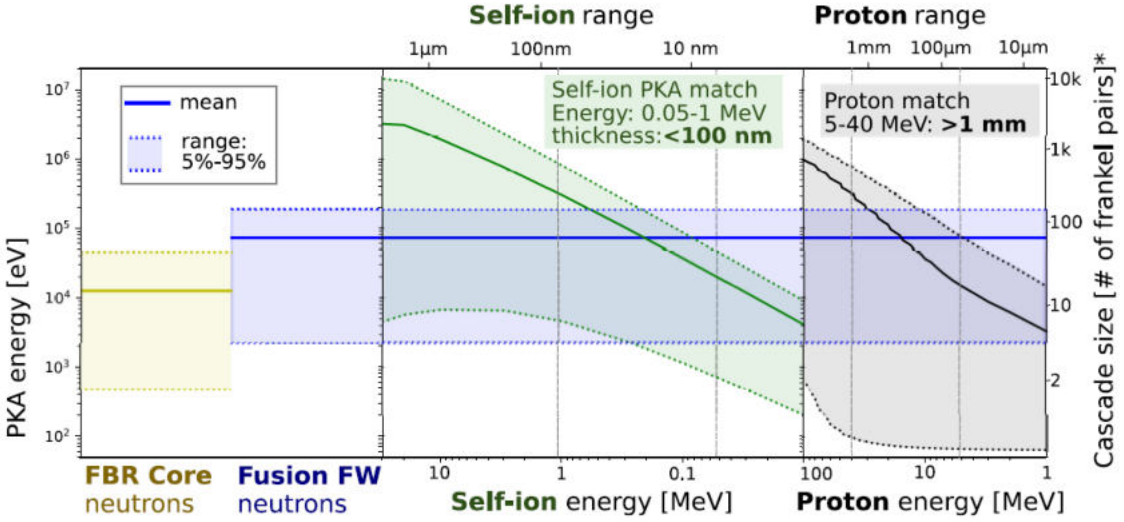
Other approaches proposed remain decade away (e.g. IFMIF), or unlikely to be funded on required timelines in US (e.g. FPNS), and/or suffer from many of the same problems as above.

MIT PSFC is proposing a coupled, multi-step process that would accelerate material solutions for fusion energy in 5 years

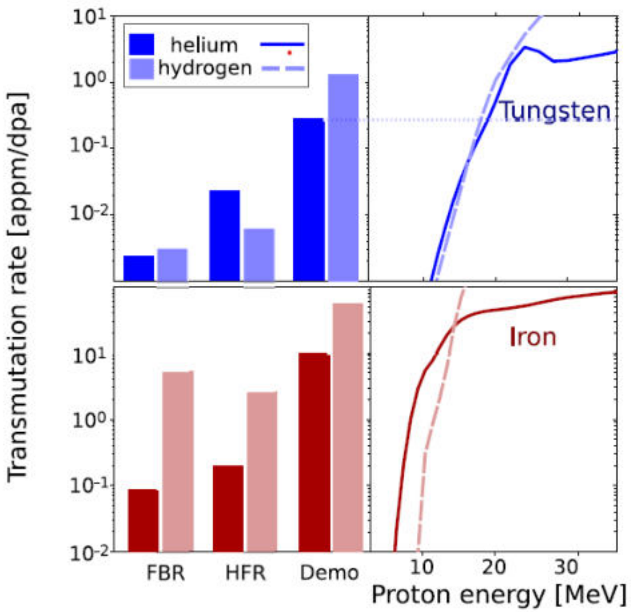


10 – 30 MeV proton/alpha irradiation offers high throughput, high fidelity radiation damage testing in bulk materials

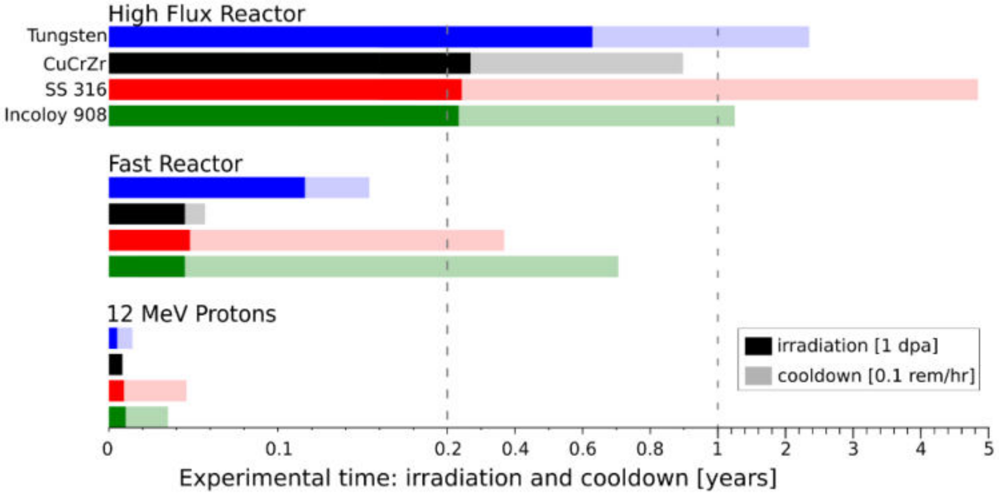
Superior emulation of fusion radiation damage in materials



Successfully emulates critical fusion-specific effects, such as bulk production of H/He gases in materials



Bulk materials irradiation at high throughput and low cost



Provides a strategy to qualify fusion materials in a short time under realistic conditions.
Order (10) materials → Final material selections

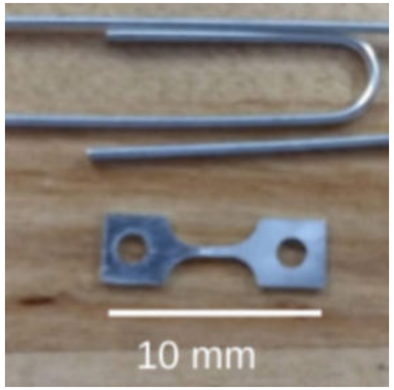
[1] S. J. Jepeal, L. Snead, Z. S. Hartwig. *Mat. Design* **200** (2021) 109445.
https://arxiv.org/abs/2009.00048

Experimental validation and demonstration of the technique confirms ability to replicate bulk property changes

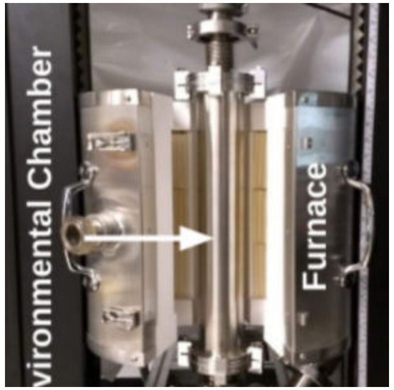
A proof-of-principle facility has been built at MIT PSFC [1] and has experimentally validated the technique

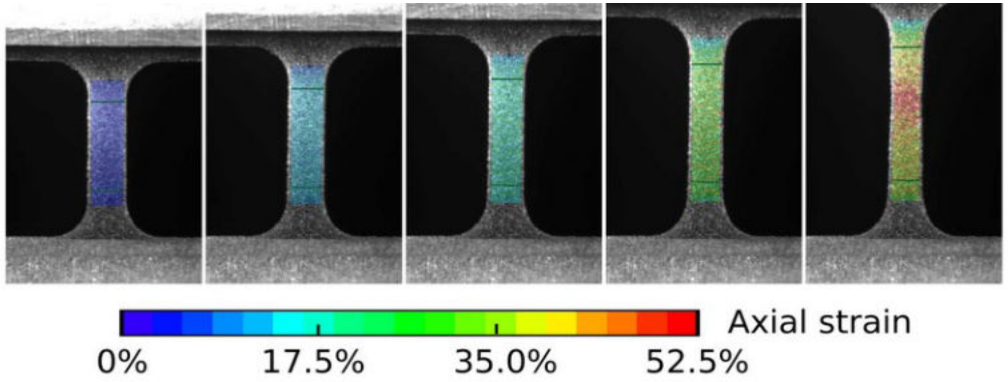
12 MeV proton cyclotron

Irradiation tensile target

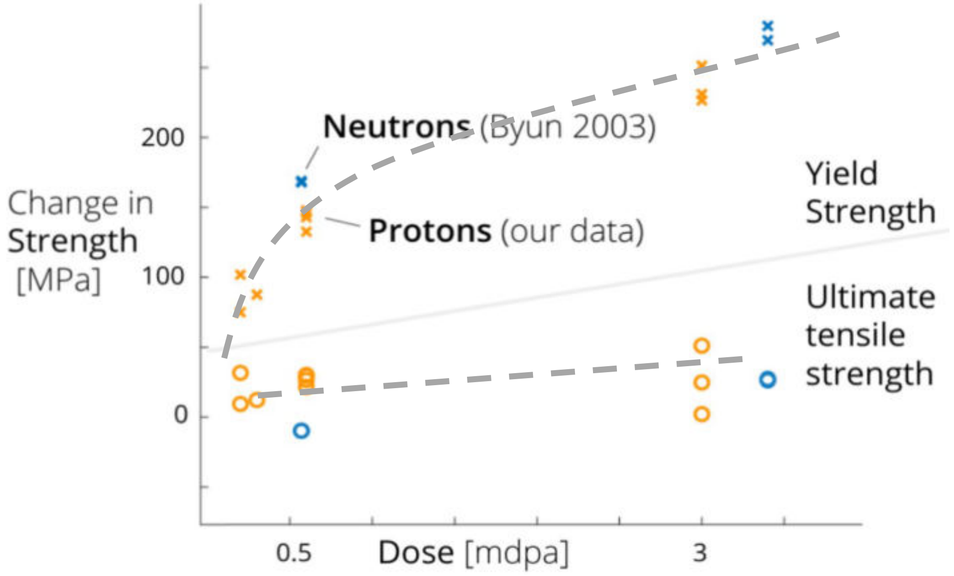


Custom tensile test machine



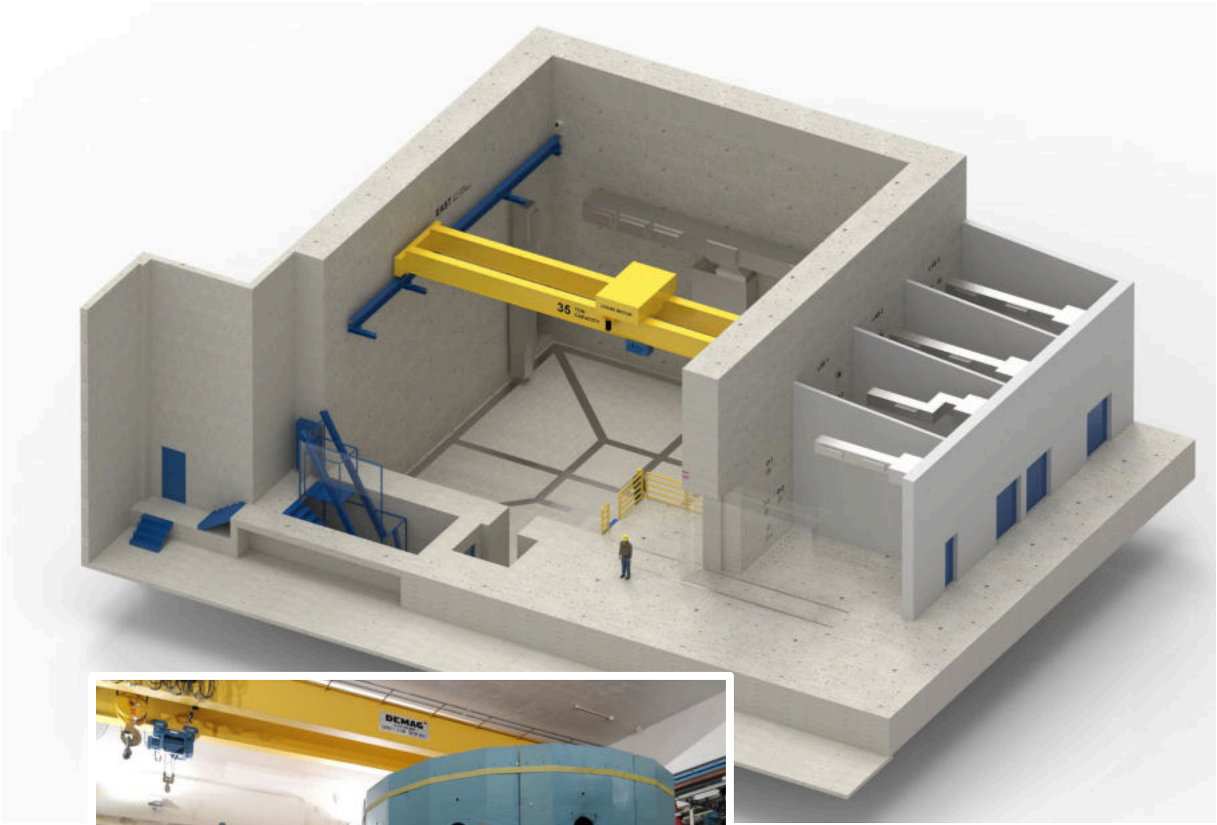


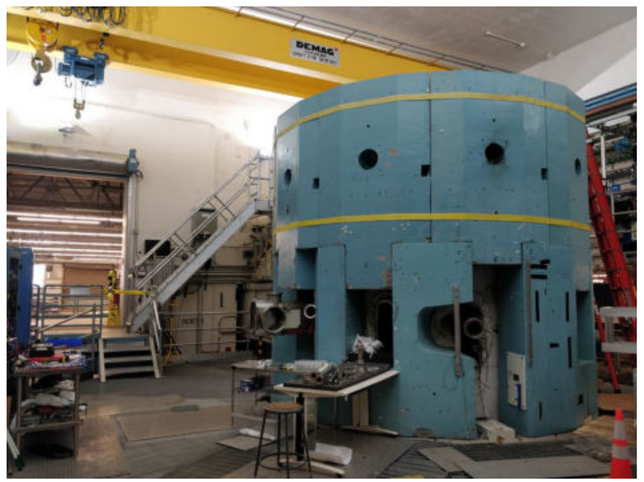
Protons replicated expected Inconel 718 irradiated structural material changes



[1] S. J. Jepeal, …, Z.S. Hartwig. *Nucl. Instr. and Meth. B* **489** (2021) 41-49. https://arxiv.org/abs/2010.06044

A large experimental space is being prepared as the potential site for the cyclotron facility at PSFC





CAD rendering of the vault (above) and picture of the Alcator C-Mod tokamak being dismantled (left)

- PSFC is now clearing out the large vault that hosted the Alcator C-Mod tokamak

- This is a fully equipped, well-suited experimental facility valued at ~$40M (if built from green field)
  - 18m x 18m x 18m internal space
  - High density 1.8m thick walls and shield door
  - Power, chilled water, cryogenics, etc.
  - 35 ton bridge crane

- Located on MIT’s main campus in Cambridge at the heart of the PSFC
  - Easy access for faculty, scientists, students, and visiting users
  - Supported by PSFC engineering staff and technical shops (e.g. welding, machining, etc.)
  - Connection to extensive materials science capabilities across MIT

A large experimental space is being prepared as the potential site for the cyclotron facility at PSFC

- PSFC is now clearing out the large vault that

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nd shield door
, etc.

ambridge

s, students, and
visiting users

- Supported by PSFC engineering staff and technical shops (e.g. welding, machining, etc.)
- Connection to extensive materials science capabilities across MIT

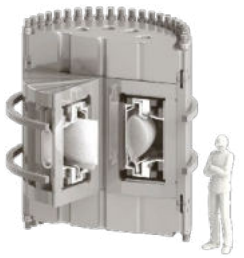
- We are developing a "consortium" model to support this critical area for fusion development.
- Welcoming both industrial, laboratory and academic participation, both for operating this device at MIT, but also seeing its multiplication
- Will be key R&D in design and fabrication of this facility
  - Adapting commercial cyclotrons
  - Beam dynamics, extraction and control
  - Heat management in target stations.

- Welcome direct conversations with CDTI+partners on joining this endeavor
- Highly synergistic with DONES as a rapid screening tool to make it much more effective (we are making the same arguments to US DOE)

(above) and picture of the Alcator C-Mod tokamak being dismantled (left)

If SPARC is working mid-decade, how do we accelerate now to economic ARC?

COMPLETED:
Alcator C-Mod



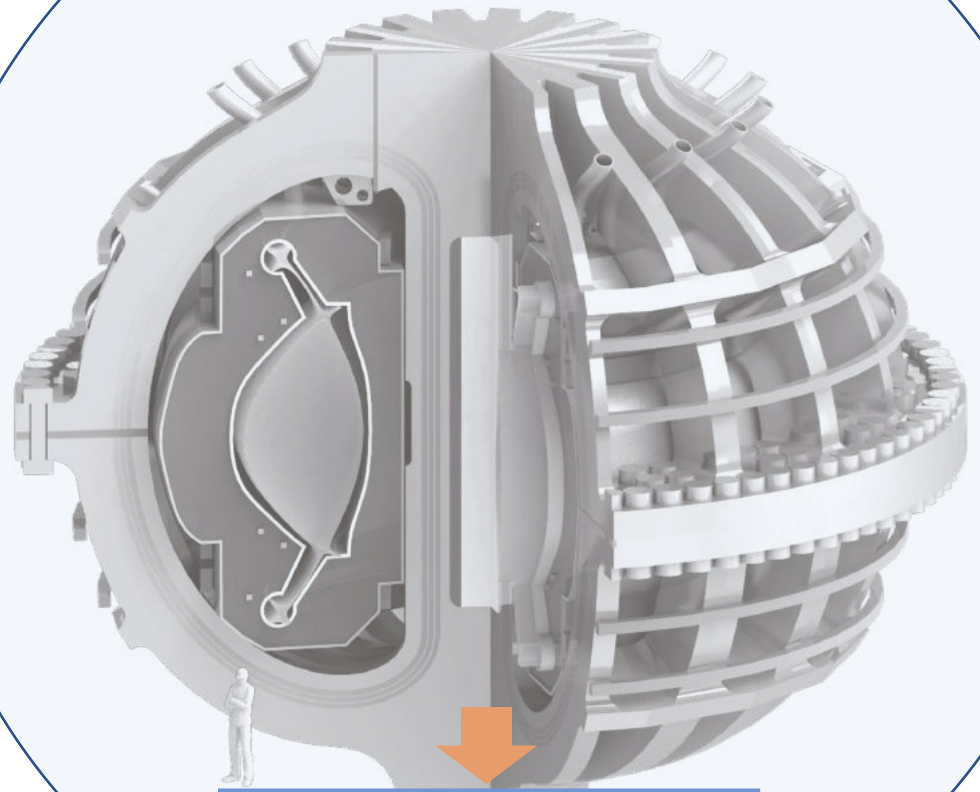
COMPLETED
TFMC demonstrated
September 5, 2021

FUNDED at 1.8 B$
December 1, 2021

CONSTRUCTION PLANNING UNDERWAY for 2025 LAUNCH
SPARC achieves net energy

Net energy

Early 2030s
ARC fusion power on the grid



Carbon-free scalable commercial power

Thank you

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Professor, Nuclear Science and Engineering
MIT

MIT PSFC