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IAEA

Fusion Codes & Standards: Current Challenges and Future Directions

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Vision

Achieve sustainability through fusion technology.

01 Develop fusion as a global technology for both emerging and mature economies.

02 Harness fusion to offset carbon debt and move closer to net-zero.

03 Drive engineering innovation to redefine high-tech manufacturing limits.

Mission

Deliver engineering solutions to the fusion community to solve complex technical and engineering challenges.

01 Accelerate advancements in fusion engineering.

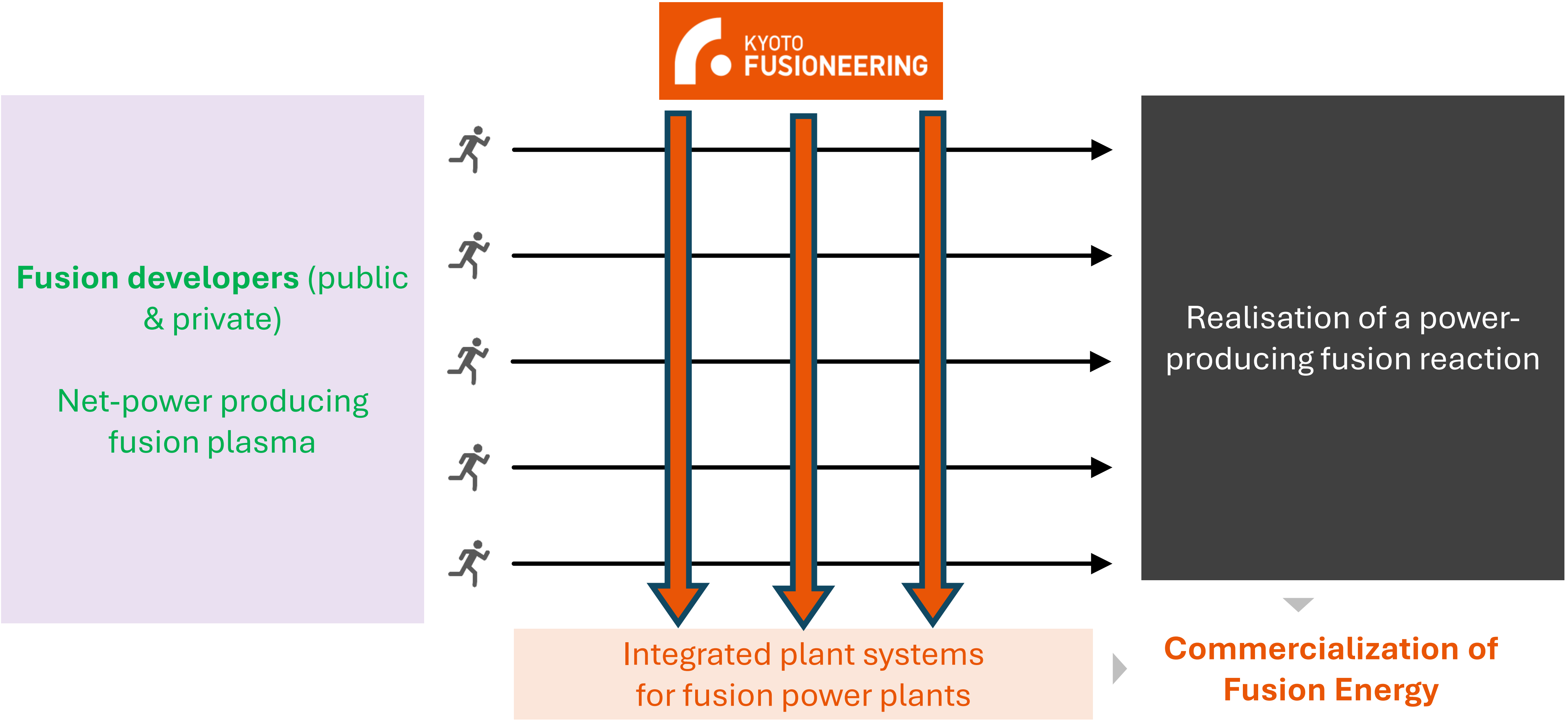
02 Leverage fusion R&D expertise.

03 Help building the fusion sector for tomorrow's energy ecosystem.

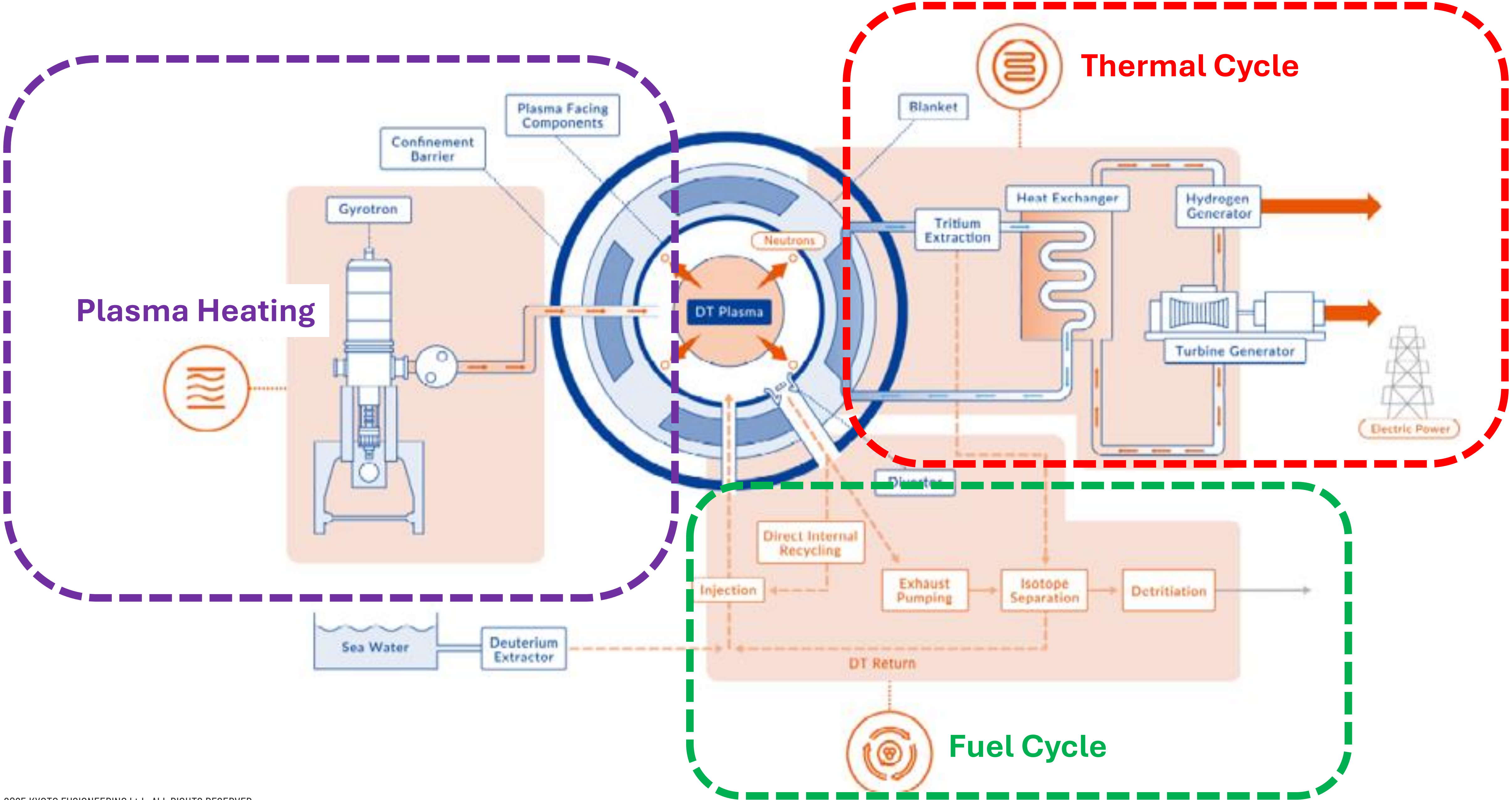
01 Introduction to Kyoto Fusioneering

- **Business model**

Developing the thermal cycle system, to simulate the integration of the fusion power and fuel cycles



01 Introduction to Kyoto Fusioneering



02
KF Experience in Codes and Standards and Engagement with ASME

- **Broad expertise across major frameworks**: extensive experience applying **ASME**, **JSME**, **RCC-MRx**, and **CSA** standards, selecting and tailoring codes according to project requirements.
- **Integration into design and licensing**: proven capability to incorporate C&S into design, manufacturing, and qualification processes for fusion-relevant components and facilities.
- Two case studies discussed:
  - **Hydrogen Isotope Permeation Sensors (TRI-PRISM project with UKAEA)**
  - **UNITY-2 Facility (FFC)**

UK Atomic Energy Authority

FUSION FUEL CYCLES

02 KF Experience in C&S and Engagement with ASME

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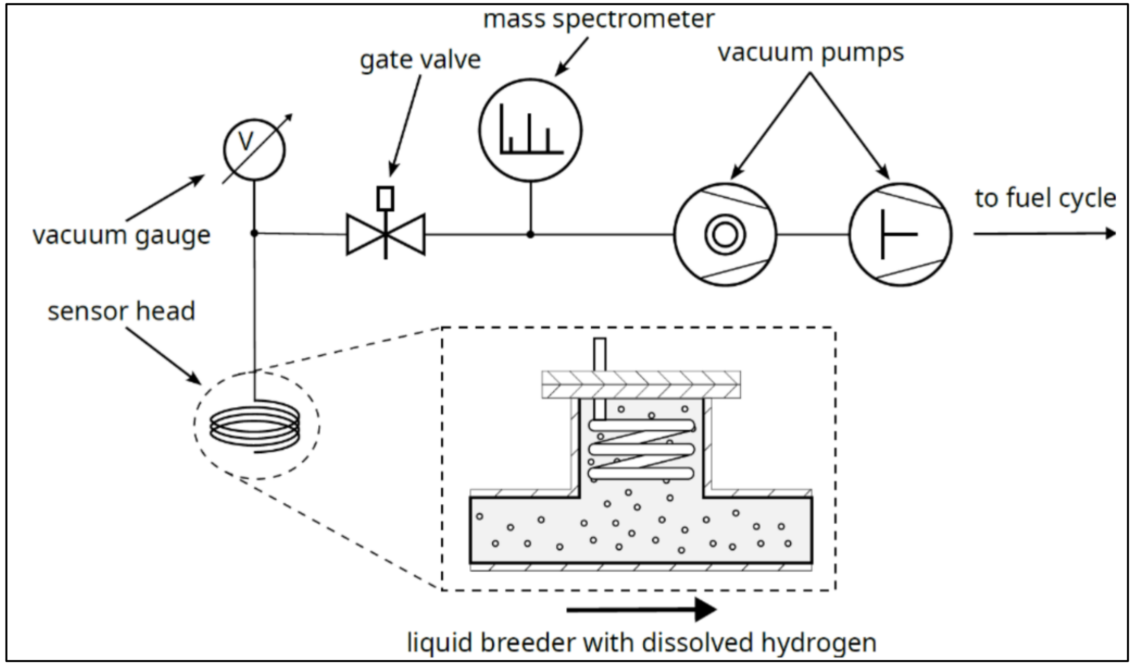
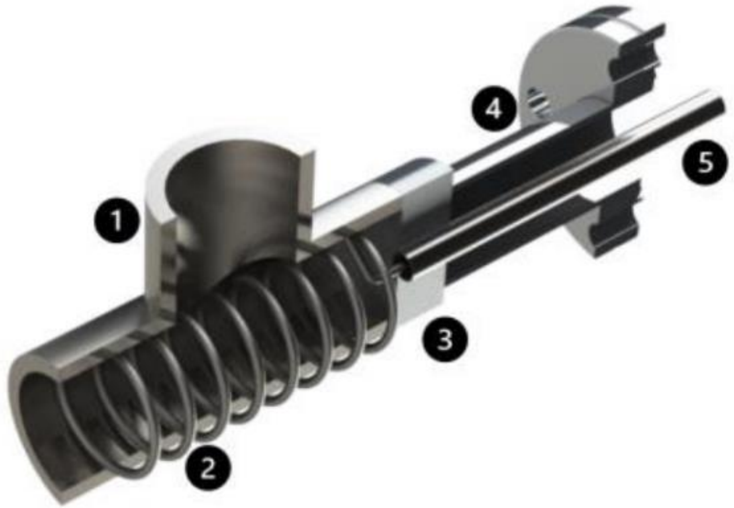
TRI-PRISM: Tritium Permeation Real-time In-line Sensor for Monitoring

- **Hydrogen Isotopes Permeation Sensor (**HPS) monitors hydrogen isotopes to prevent embrittlement, contamination, and hazards.
- Enables **near-instant detection** of tritium migration in LiPb systems.
- Improves tritium measurement over the breeder loop of the LiPb-based fusion reactor, ensuring **closure of tritium mass balance**.





Application of HPS to ITER's WCLL-TBS

[1] L. Candido, et al., Overview of Tritium Management in WCLL Test Blanket System of ITER, Fus. Eng. Des. 200 114163 (2024)

02 KF Experience in C&S and Engagement with ASME

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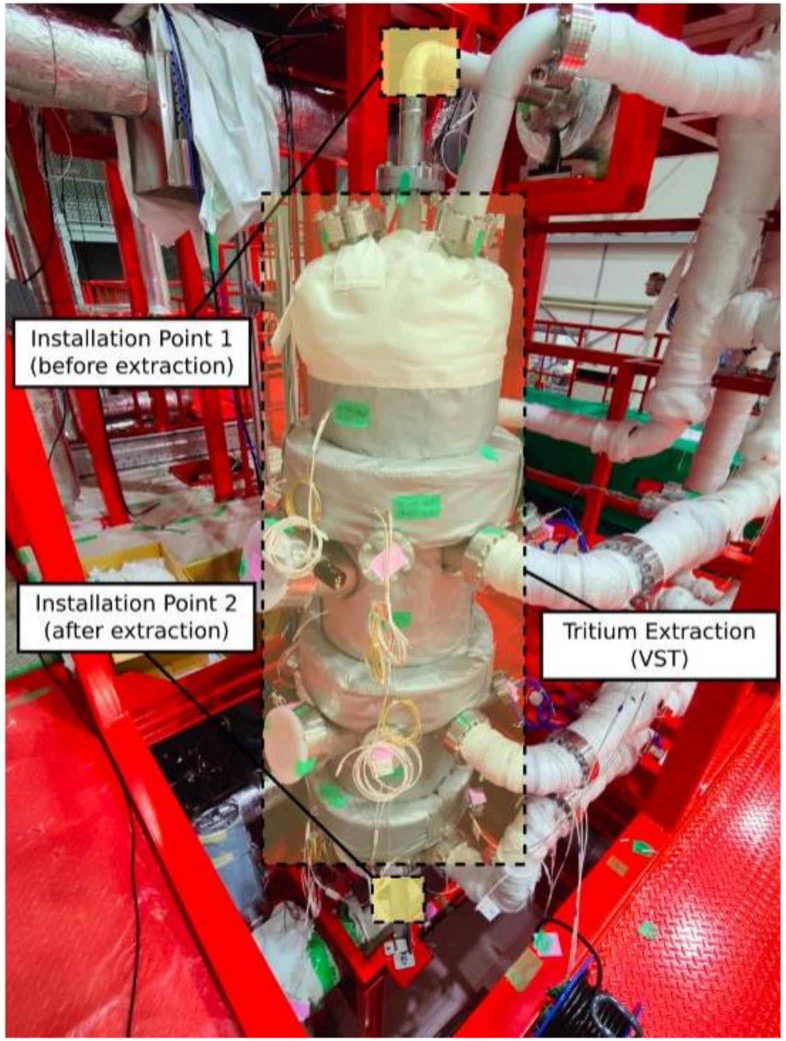
Integration in UNITY-1 carried out according to ASME

- **ASME compliance**: HPS designed to meet ASME BPVC Section III, Div. 1, Subsection NB for Class 1 nuclear components.
- **Stress limits**: NB-3210 requires all stresses to remain below maximum allowable during all operations.
- **Material reference**: ductile cast iron values used as analogue where pure iron limits are not specified.
- **Operating margin**: UNITY-1 conditions are below ASME-calculated limit, satisfying NB-3133.
- **Piping analysis**: NB-3652 ensures combined loads on pipe sections remain within allowable stress.
- **Flanged joints**: NB-3658 sets design limits for moments and pressures on flanged joints.
- **Proven reliability**: sensors previously used in similar campaigns without integrity issues, reinforcing confidence.



02 KF Experience in C&S and Engagement with ASME

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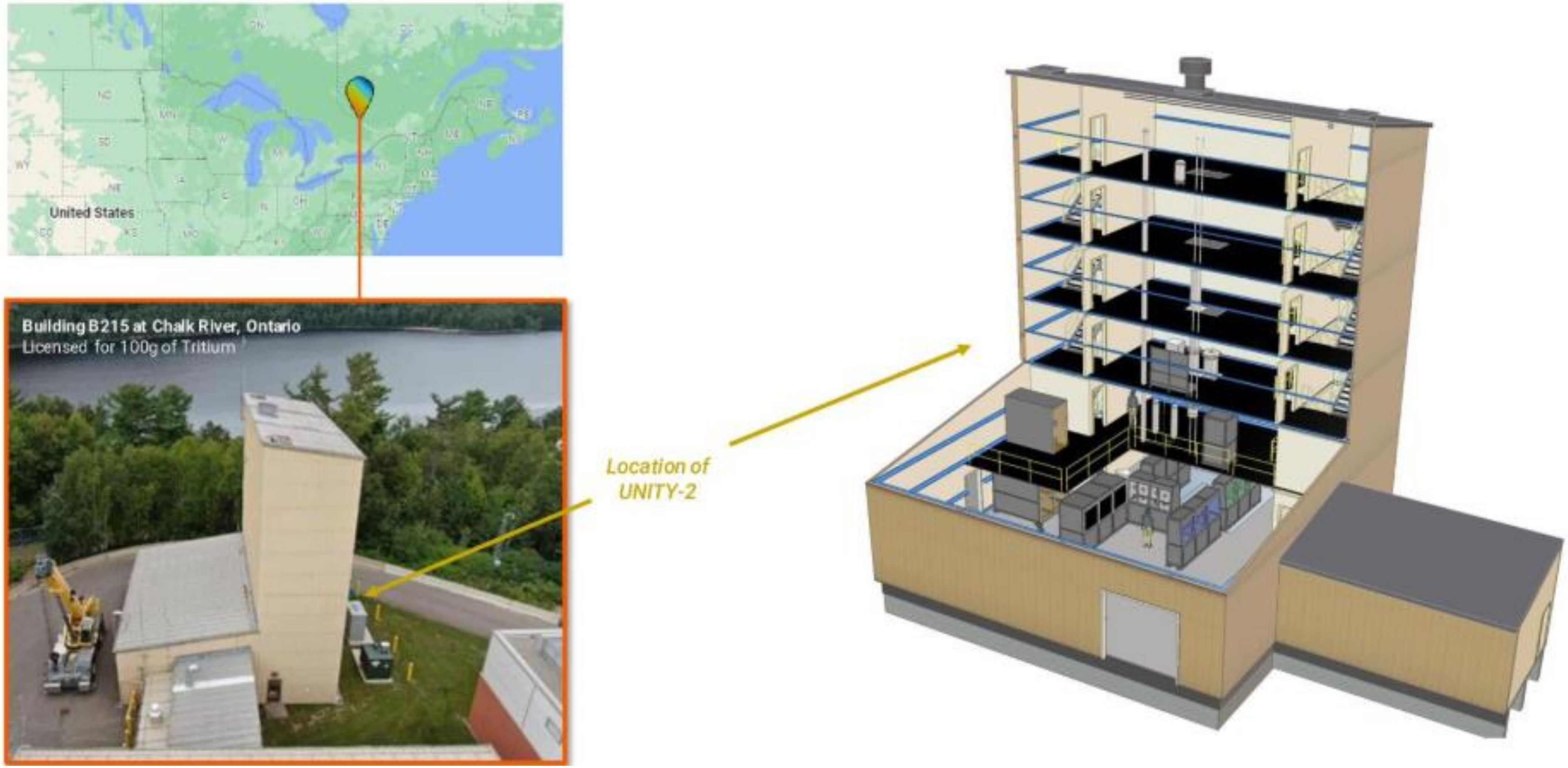
UNITY-2 – Location

- Housed in CNL's existing tritium-licensed facility in Chalk River, Ontario, Canada



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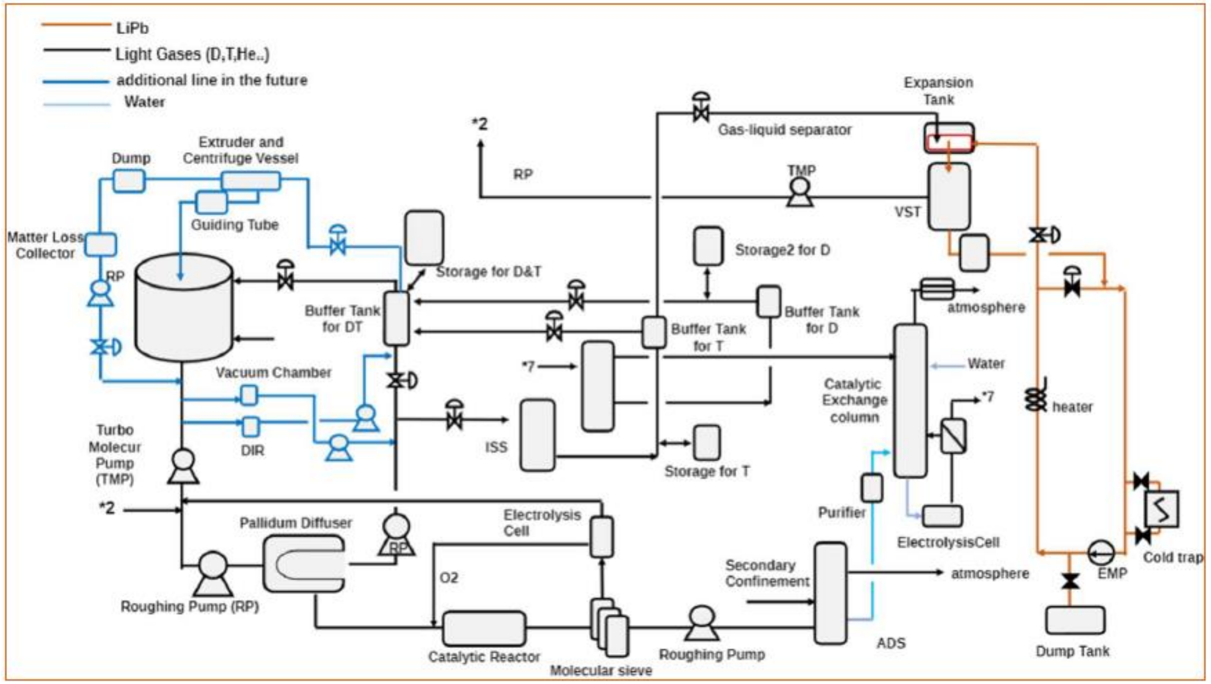
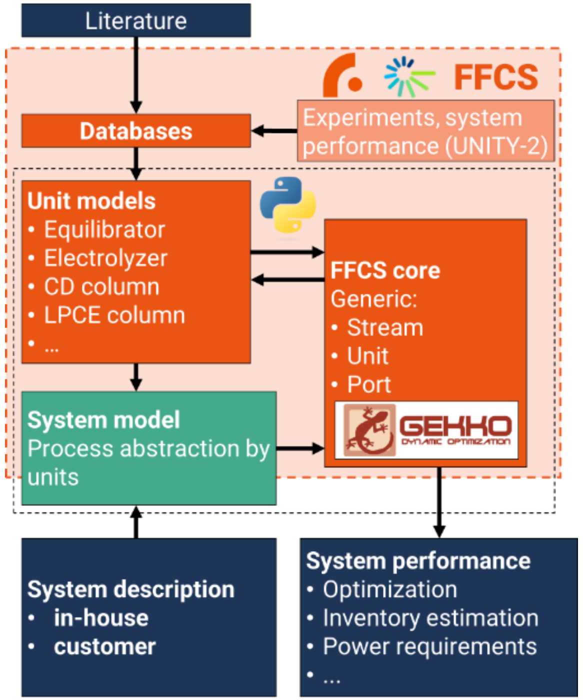
UNITY-2 – Application of Canadian codes and standards





Components:
- Tritium extraction from ~50L LiPb loop (max flow rate 1.63 kg/s)
- Imitating a vacuum environment for the plasma vessel (including PEG gases)
- Multiple tritium storage solutions (dU, ZrCo)
- Outer fuel cycle (WDS, ADS)
- Pellet injection system

Tritium:
- ~30 g inventory
- Steady-state flowrate of 2.3 Pa m^3/s, with factor higher peak values in the inner loop

Modelling:
- Dynamic fuel cycle modelling
- Coolant/breeder inventory
- Pumps, Pd diffuser, getter beds, DT
- delivery mechanisms

02 KF Experience in C&S and Engagement with ASME

UNITY-2 – Application of Canadian codes and standards

- Our approach is to exploit the **existing licensing framework** by working within the CANDU standards environment, specifically those integrated into the **CSA** (Canadian Standards Association) system.
- **CSA is the national standards body**; CANDU standards are incorporated within CSA.
- The challenge lies not merely in selecting CSA standards, but in **applying requirements** such as CSA N285.0 and the associated B51 code to components traditionally designed for the vacuum engineering industry, where these standards have not previously been enforced.
- This approach is driven by our decision to build on the CNL site (B215), which requires **compliance with the established CANDU-related** standards. The complexity arises from the **quality and certification requirements** of these domestic fission-based standards when being applied to a tritium R&D platform for which test components will be manufactured also outside Canada.
- We have developed and applied a graded approach for the classification of **structures, systems, and components** (SSCs), enabling the selection and justification of suitable nuclear and industrial C&S.
- Our team has extensive experience with **CSA B51** (for pressure vessels and piping), **CSA N285** (for CANDU reactor components), and **ASME Sections III, V, and VIII**. We have performed C&S gap analyses and linked CSA and ASME codes for design and licensing purposes.
- **CSA N285** is highly effective for **CANDU reactors** but can be overly restrictive for other applications. Its safety classification is at the system level (unlike ASME's component-level approach), and understanding its principles is key for justifying applications, exemptions, or alternative approaches.

02 KF Experience in C&S and Engagement with ASME

ASME BPVC Section 3 Division 4 Fusion Energy Devices

KF Participation:

- **Subgroup –** Committee member (*R. Holmes*)
- **Special Working Group for Fusion Stakeholders –** Committee chair (*R. Holmes*)

→ Attended every Code Week since Feb 2024

KF Contribution:

- Presentation by *D. Yagi* on **"Challenges and suggestions for fusion codes and standards"** (Aug 2024)
- Responded to **Div. 4 survey on quality assurance processes and standards** (Jan 2025)
- Input to the **Div. 4 database for fusion concepts, components and materials** – SCYLLA Breeder Blanket information (Mar 2025)

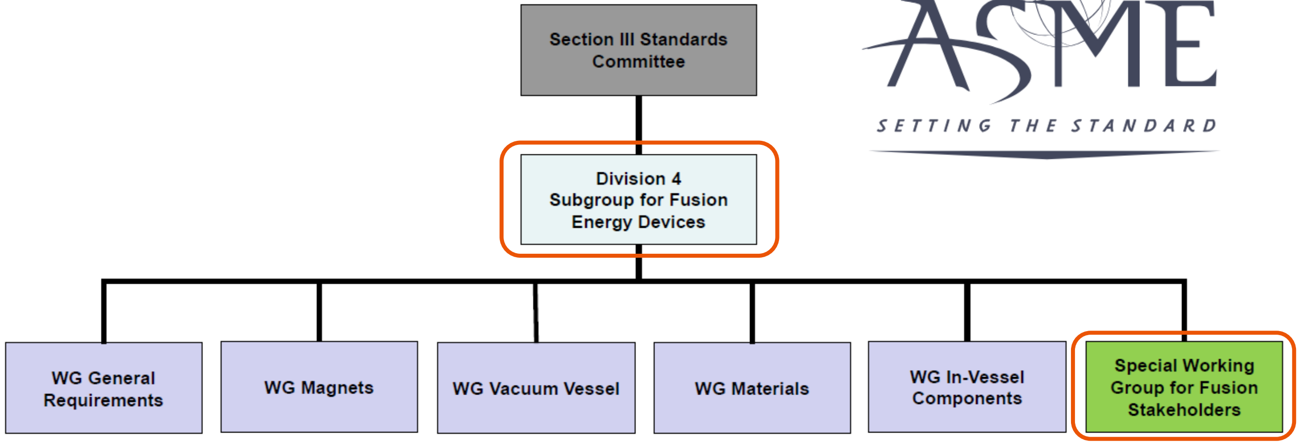


Fig. ASME BPVC Sec. 3 Div. 4 committee and working group structure [2]

Fusion Device Name	
Thermal Power (MWt)	1750
Electrical Power (MWe)	TBD (~500 expected)

Website: https://kyotofusioneering.com/en/

Notes: Data received Mar 2025

Parameter	Fusion Machine Component							
	Breeder Blanket	Divertor	Vacuum Vessel	In-vessel Components	First Wall	Intermediate Heat Transfer System	Tritium Extraction System (focus on TEU)	Other
Coolant/Fluid	LiPb eutectic (15.7 at.% Li)				LiPb eutectic (15.7 at.% Li)		No coolant, VST technology for extraction	
Operating Pressure	5-20 bar (indicative range, TBO)				5-20 bar (indicative range, TBO)		<0.1 Pa	
Min Operating Temperature	500 °C				500 °C		600-650 °C	
Max Operating Temperature	1000 °C (max LiPb)/ 860 °C (outlet)				983 °C		600-650 °C	
Code/Class	N/A				N/A		N/A	
Material	SiCf/SiC				W		Stainless steel 316L (TBC)	
Manufacturing Methods (Fabrication/Joining/Coating)	Dispersion Particle Matrix, Liquid Phase Sintering, Textile Fabric Prepreg (TBO)				TBD		TBD	
Product Form (Casting/Forging/Extruding/Bar/Plate/Sheet/Tube/Additive Manufacturing	TBC				TBD		TBD	
Other Environmental Factors	TBD				TBD		TBD	
Component Lifespan	2-3 y (TBC)				TBD		TBD	
Component Function (shielding, heat transfer, T breeding, etc.)	Breeding, shielding, absorb radioactive particles and heat, heat removal, vacuum confinement, etc.				Thermal loads management, plasma particle mitigation, resilience to transient events		Tritium extraction from LiPb	

HB11 Energy | Helical Fusion | Helicity Space | Helion Energy | Horne Technologies | JA DEMO | K-DEMO | Kyoto Fusioneering SCYLLA BB | LaserfusionX | Longview Fusion | LPP Fusion | Marathon Fusion | Mar

Fig. Kyoto Fusioneering SCYLLA BB data input to the Div. 4 database [3]

[2] Davis, T. P., (2023) "The Need for Codes and Standards in Nuclear Fusion Energy", *Journal of Fusion Energy*, 42 (13), https://doi.org/10.1007/s10894-023-00350-2
[3] ASME BPVC Sec. 3 Div. 4, "Fusion Concepts, Components and Materials Database", Version 2, Aug 2025

03 Examples of Present Gaps and Shortcomings

Material qualification challenges and inspection needs

- **Qualification gap**: several key fusion materials (composites, advanced alloys) lack full coverage in current ASME and RCC-MRx frameworks.
- **Ongoing efforts**: international projects and ASME Section 3 Division 5 initiatives are exploring qualification pathways for high-temperature and reduced-activation materials.
- **Dynamic landscape**: material specifications remain under optimisation, requiring close monitoring of evolving standards and collaborative R&D programmes.
- **Two items discussed**:
  - Construction codes and standards for **advanced materials**, including SiC_f/SiC, V-alloys
  - Inspection standards for **tritium permeation barrier** coatings

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Construction Codes and Standards for Advanced Materials

KF Materials of Interest (high-temperature operations):

- **SiC_f/SiC –** Breeder blanket structural material
  - Currently not covered by ASME Sec. 3 Div. 4 or RCC-MRx
  - No clear framework for qualifying composite materials
  - Material specification is not available because optimisation is still ongoing
  - Observing ongoing efforts in ASME Sec. 3 Div. 5 (High-T fission) to qualify SiC_f/SiC
- **Vanadium alloys –** Breeder blanket structural material
  - Currently not covered by ASME Sec. 3 Div. 4 or RCC-MRx
  - Material specification is not available because optimisation is still ongoing
  - "IMPACT" project to qualify reduced-activation V-alloy, supported by DOE [4]
- **RAFM Steels –** Breeder blanket structural materials
  - Currently not covered by ASME Div. 4
  - Material specification for Eurofer-97 in RCC-MRx
  - Eurofer-97 is partially qualified in RCC-MRx, and F82H qualification is ongoing
  - "IMPACT" project to qualify advanced-RAFM steel (CNAs), supported by DOE [5]
- **Molybdenum alloys –** Heat exchangers
  - Currently not covered by ASME Div. 4 or RCC-MRx

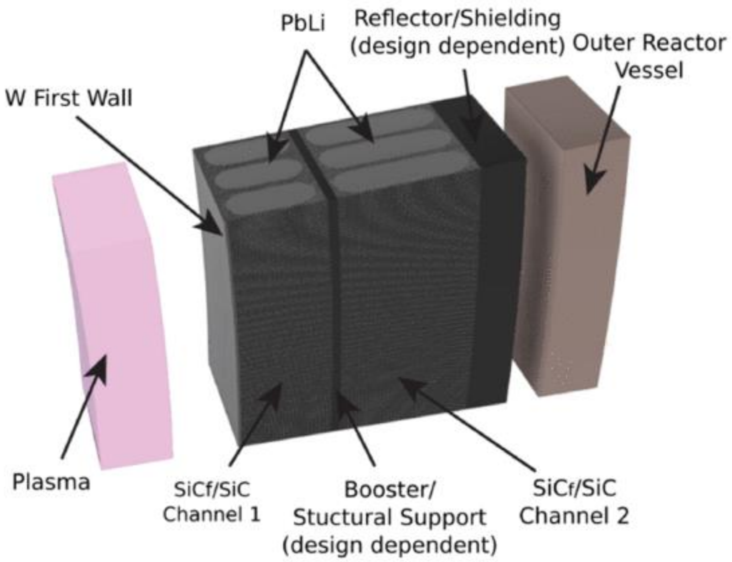

Fig. Kyoto Fusioneering SCYLLA BB concept [4]

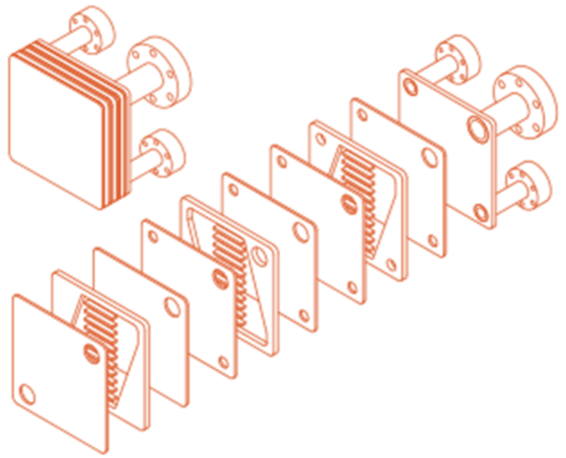

Fig. Kyoto Fusioneering plate-type heat exchanger

[4] Pearson, R. et al., (2022) "Overview of Kyoto Fusioneering's SCYLLA© ("Self-Cooled Yuryo Lithium-Lead Advanced") Blanket for Commercial Fusion Reactors", *IEEE Transactions on Plasma Science*, 50 (11), 4406-4412, https://doi.org/10.1109/TPS.2022.3211410
[5] https://news.utk.edu/2025/01/16/ut-secures-20-million-doe-grant-to-develop-critical-nuclear-fusion-materials/

03 Present Gaps and Shortcomings

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Multi-functional barriers, tritium permeation barriers

- **What exists** – applicable, but not fusion-specific
  - **Permeation performance**
    ISO 17081 (electrochemical method) to quantify hydrogen/tritium permeation through coated metals, works for RAFM and stainless steels.
  - **Coating thickness**
    ISO 2178 (magnetic method on steel) and related eddy-current methods (ISO 2360/21968, referenced within 2178) for non-destructive thickness verification.
  - **Adhesion/Integrity**
    ISO 14916 (tensile adhesion for thermal-spray), ASTM C633 (adhesion/cohesion of thermal-spray), and ASTM C1624 (scratch test for thin hard ceramic coatings) to qualify bond strength and failure modes.
  - **Microstructure/porosity (thermal-spray)**
    ISO 14923 for general characterization and test methods.
- **Gaps**
  - **No coating-specific acceptance criteria** in **ASME BPVC Sec III Div 4** or **RCC-MRx** for **tritium permeation barrier coatings** on **RAFM or stainless steels.**
  - No codified tests for LiPb/tritium exposure ageing, in-situ inspection, or service-life surveillance.
  - Our review found **no explicit rules**; acceptance must currently be project-specified.)
- **Possible application**
  - Coated internal surfaces of blanket pipes (e.g. WCLL) to reduce corrosion and minimise permeation
  - **Connecting pipes** in **solid breeder loops** or **loops carrying tritiated gas** to minimise permeation and enhance safety in fusion reactors.

04
Conclusion

- KF has demonstrated practical use of ASME and CSA standards in real fusion projects (e.g., TRI-PRISM, UNITY-2).
- Active participation in international standards bodies (ASME) to help define the rules for fusion.
- Clear gaps remain:
  - Qualification pathways for advanced materials (SiC_f/SiC, V-alloys, RAFM, Mo-alloys) are still missing.
  - Fusion-specific acceptance criteria for tritium permeation barrier coatings are not yet codified.
- We advocate for enabling, harmonised standard, i.e. requirements that support innovation, not restrict it.

05 Conclusion

We hope ASME will lead the global harmonisation of codes and standards. We want to contribute across countries, not only our own, because international standardisation makes engineers' lives easier by removing differences between codes.

We also recognise that today the priority is defining the route to harmonisation: requirements must be enabling, not overly strict or premature. This is an ongoing process that should be underpinned by dedicated experimental activities and safety analyses.

Thank you for your attention!
ご清聴ありがとうございました!

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Back-up Slides

BS Presentation abstract

The development of fusion energy requires robust, harmonised Codes and Standards (C&S) to ensure safety, reliability, and regulatory acceptance. Kyoto Fusioneering (KF) has extensive experience applying ASME, JSME, RCC-MRx, and CSA frameworks to real projects, including hydrogen isotope permeation sensors (TRI-PRISM) and the UNITY-2 tritium facility. KF actively contributes to shaping future standards through participation in ASME BPVC Section III Division 4, providing technical input and data from advanced blanket and fuel cycle systems.

Despite progress, significant gaps remain: qualification pathways for high-temperature and reduced-activation materials (e.g., SiCf/SiC, vanadium alloys, RAFM steels) and the absence of fusion-specific acceptance criteria for tritium permeation barrier coatings. Addressing these challenges requires international collaboration, experimental validation, and pragmatic approaches that avoid overly restrictive requirements at this early stage. KF advocates for ASME to lead global harmonisation efforts, supported by evidence-based processes, to enable safe, efficient, and timely deployment of fusion technologies worldwide.

BS Introduction to Kyoto Fusioneering

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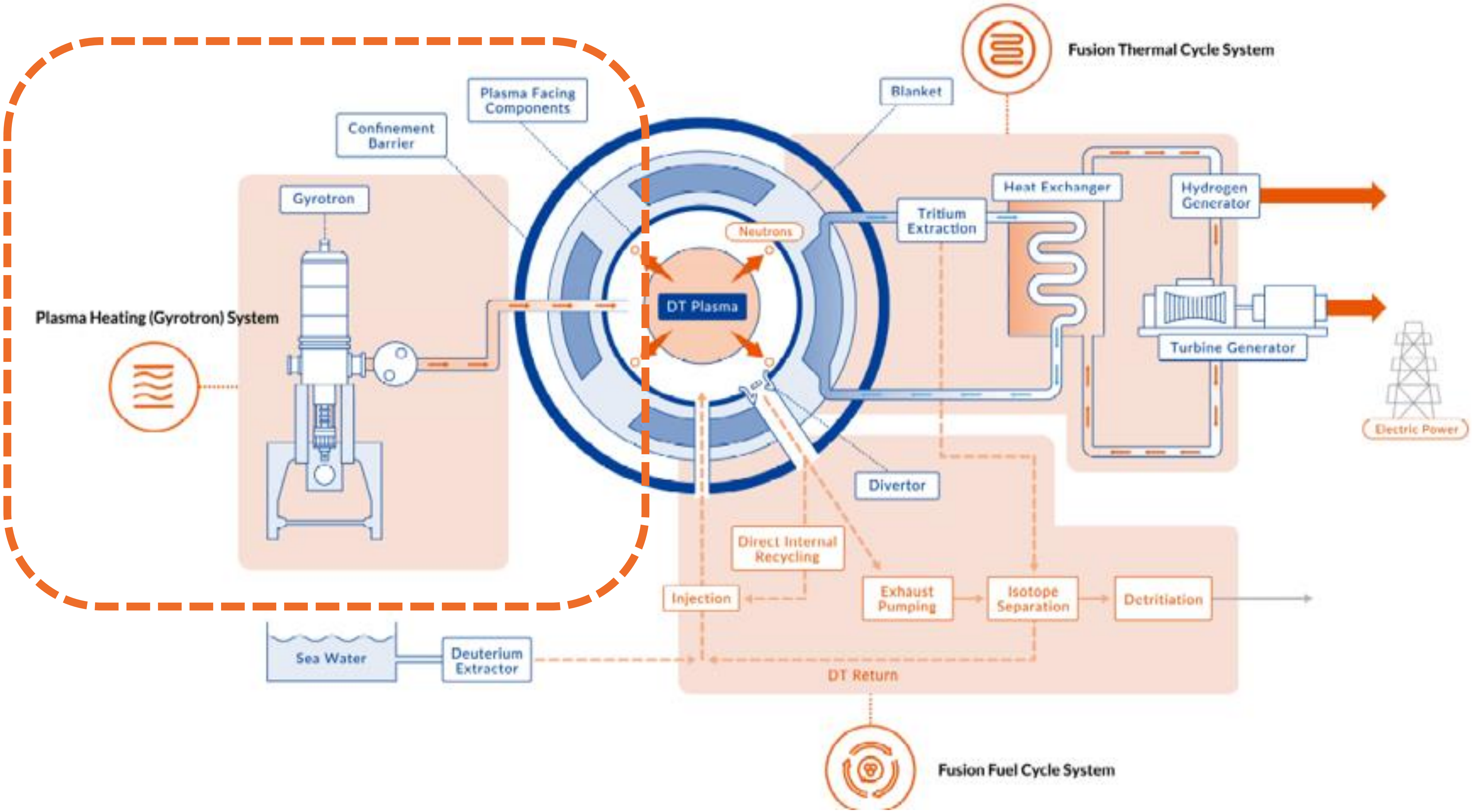

BS Introduction to Kyoto Fusioneering

Gyrotron

Gyrotrons provide the **heating necessary to ignite and sustain a stable fusion plasma** in magnetic confinement-type fusion power plants.

Gyrotrons have long been the subject of research and development involving **national research institutes** and many engineers.

Building on this technology, **we are conducting R&D to improve performance** and promote the global adoption of gyrotrons.

Our R&D efforts include the development of **higher power, higher frequency** and **higher efficiency** gyrotrons, ensuring their transition to industrial applications.

KF prioritises excellence in **product management** and **quality assurance**, for the successful implementation of gyrotrons.

- Gyrotrons capable of **the frequency range of 28 – 236 GHz** *236GHz is currently under development
- **Received orders** from UKAEA and overseas start-up companies.
- Engaging in extensive cooperation with major Japanese technology and manufacturing companies for **collaborative product development**.
- Developing a combination of technologies that are expected to be applied not only to the fusion industry but also to **other industries**.

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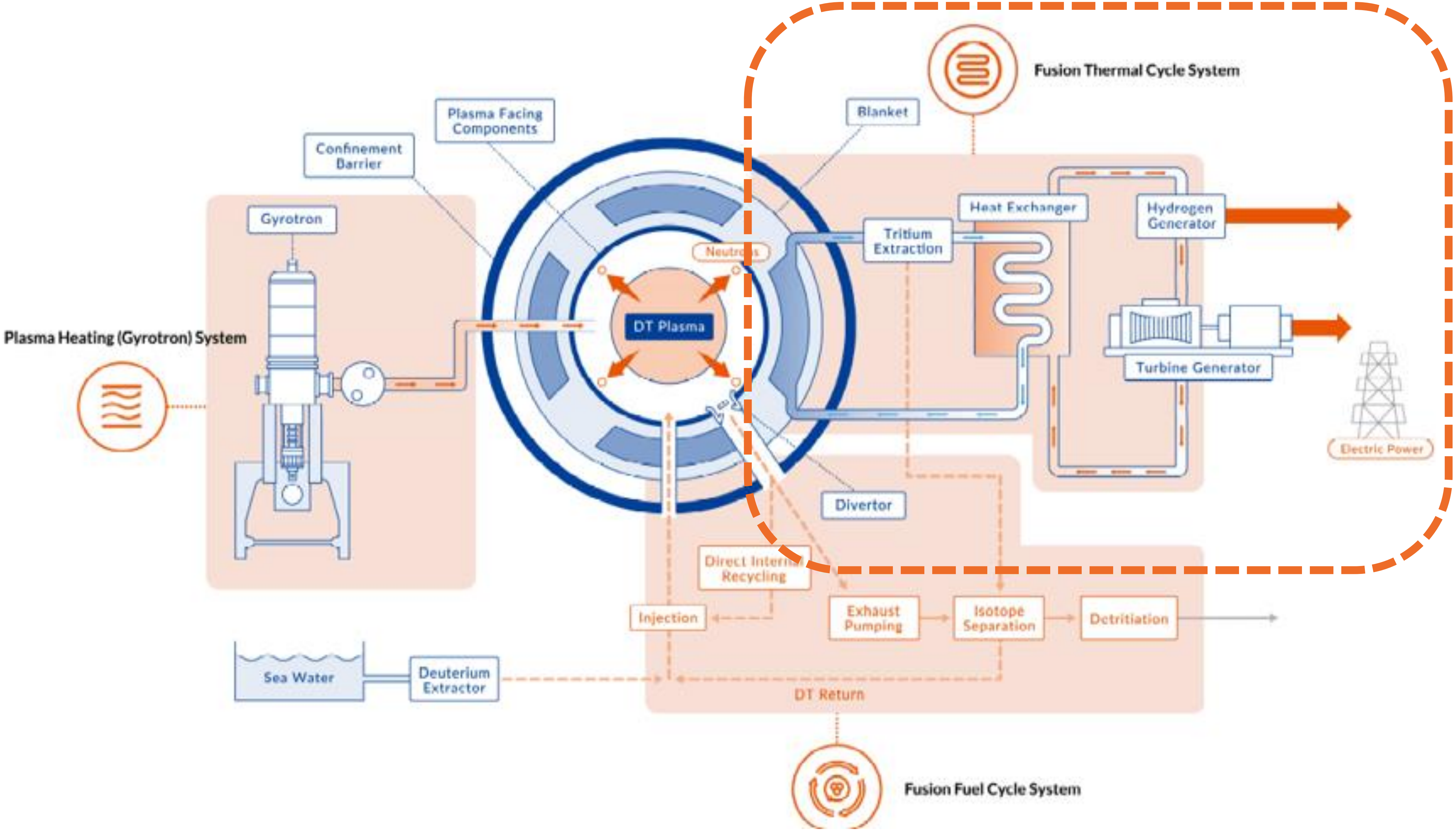

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Thermal Cycle System

KF is actively involved in the development of components designed to **harness heat from the fusion core**, all while withstanding the unique environment of fusion energy.

This includes considerations for high energy and flux **neutron irradiation**, elevated **magnetic field**, and **extreme temperatures**.

Our equipment is specifically engineered to **endure** these demanding conditions without compromising **thermal efficiency**.

We are currently commissioning the world's first* fusion power generation test plant, "**UNITY-1**".
(*As of the announcement in July 2022)

- Development of **advanced materials** (e.g. SiC composites) with high heat resistance (up to 1000 °C) and low activation.
- Design and development of **advanced blankets** with heat recovery and tritium breeding capabilities at high temperatures, as well as the design of liquid metal and molten salt loops (LiPb, Li, FLiBe).
- Design and development of **advanced heat exchangers** and innovative **power generation cycles** using helium and other media.
- Exploration of **hydrogen production** using zero-carbon, high-temperature heat sources derived from fusion energy, and **carbon fixation** technology through the pyrolysis of biomass.

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UNITY-1

Location: Japan (under commissioning)

Thermal Cycle and Blanket System:

- Blanket test section (1000°C LiPb, Li, FLiBe)
- 300 L LiPb inventory
- 4T NbTi magnet
- IH heating and surface heating for blanket module 30 x 30 x 70 cm
- Two heat exchangers and power conversion (first electricity generation from a blanket module)

Fuel Cycle:

- Deuterium injection as proxy for tritium
- Tritium extraction via VST, electrochemical
- Exhaust pumping from vacuum vessel (pump train)
- DIR testing with proton conductor pump

Materials:

- Compatibility in flow conditions (up to 50 L/min via 3 EMPs)
- FLiBe and Li piping material tests
- MHD testing with SiC_f/SiC insulators

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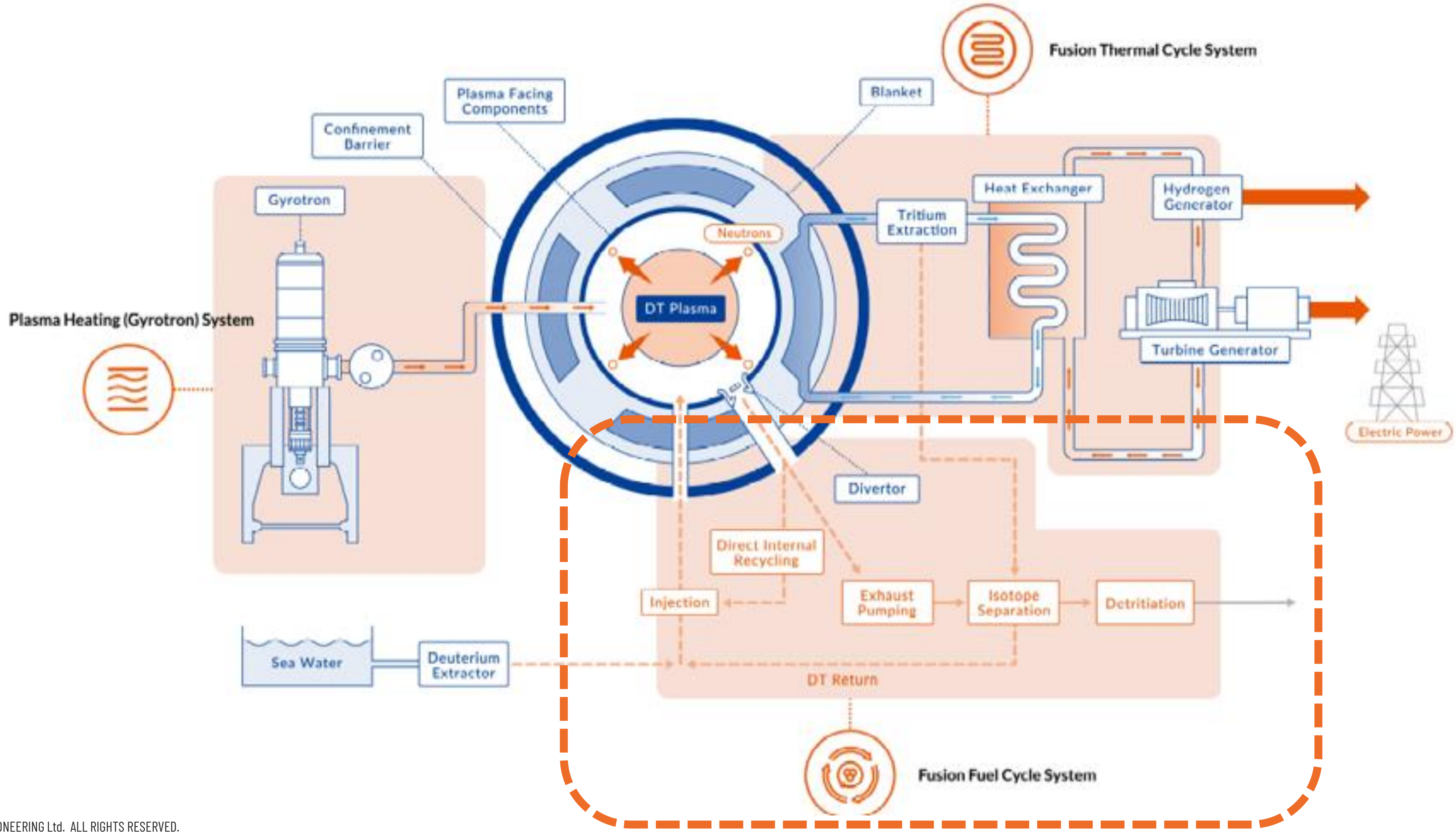

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Fuel Cycle System

One of the most significant challenges for the fusion industry is to **secure a continuous fuel supply**.

KF is actively engaged in the R&D of **fuel cycle technologies**.

These technologies are designed to **exhaust, separate, and circulate hydrogen isotope gases**, such as deuterium and tritium, which serve as fuels for the fusion core.

This work **builds on many years of research** at Kyoto University and other esteemed institutions.

We are collaborating with the **Canadian Nuclear Laboratory (CNL)**, a leading institution with extensive experience and specialised technologies for handling and managing hydrogen isotopes, to develop the **"UNITY-2"** test plant via the **Fusion Fuel Cycles Inc.** JV.

- Development of technologies and equipment to enable efficient **tritium extraction from liquid breeder** systems.
- Design and development of **plasma exhaust systems** (divertors, pumps, direct internal recycling system) and **separation technologies** (impurity gas removal, isotope separation system) to maintain continuous burning of fusion plasma through efficient tritium recovery.
- **Optimisation** of fuel cycle systems and investigation of **cost-competitive designs**.