Conceptual design study for heat exhaust management in the ARC fusion pilot plant

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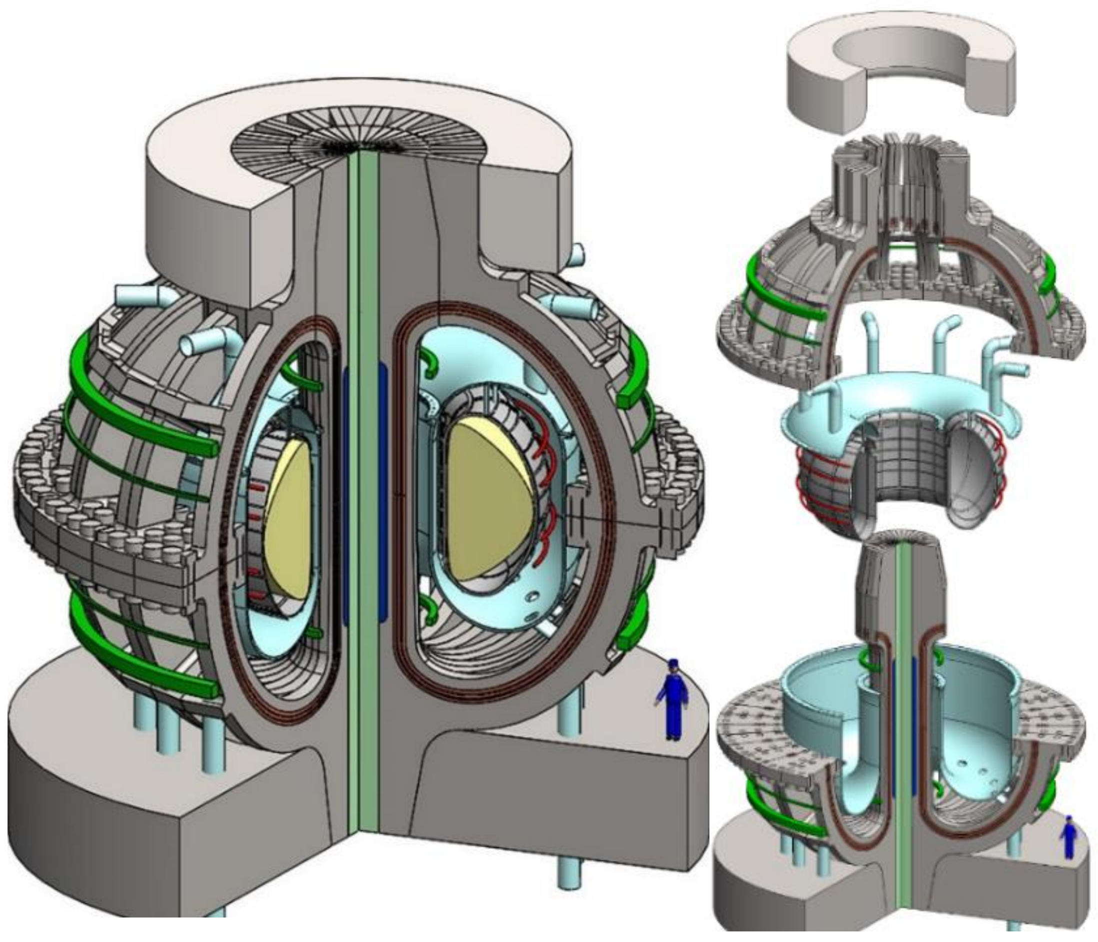
ARC - Affordable, Robust, Compact[1]

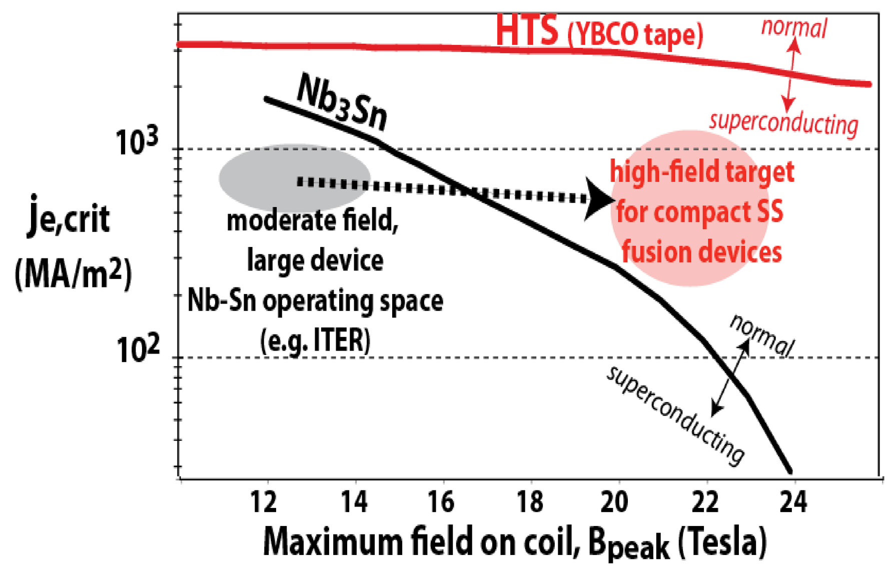
- ITER power levels (P_{fusion} = 525 MW).
- JET sized (R_0 = 3.3 m) tokamak.
- On-axis fields of 9.2 Tesla made possible by the use of high temperature superconductors (HTS).
- Demountable toroidal field coils (TF).
- Vacuum vessel immersed in a molten FLiBe blanket that acts as both the neutron shield and the coolant.
- Vacuum vessel replacement every 1-2 years.



Design Parameters	Value
Fusion Power	525 MW
Total Thermal Power	630 MW
Conversion Efficiency	0.40 – 0.50
Net Electric Power	~200 MW
Power Multiplication Factor	~3
Plasma Gain, Q	>10
LHCD + ICRF Coupled Power	38.6 MW
Major Radius, R	3.3 m
Toroidal Field, B_T	9.2 T
Plasma Current, I_p	8 MA
Bootstrap Fraction	0.63
Avg. Plasma Temperature	14 keV
Avg. Plasma Density	1.75 x 10^{20} m^{-3}
Tritium Breeding Ratio	~1.1
Plant Lifetime	~10 FPY

HTS magnets are key enabling technology

- HTS remain superconductors at very high magnetic fields with high critical current densities.
- Higher current density allows more magnet volume to be used for structure, so magnetic field is limited by the stress that the structure can withstand.



Goals for the conceptual design study of a heat exhaust management system for ARC

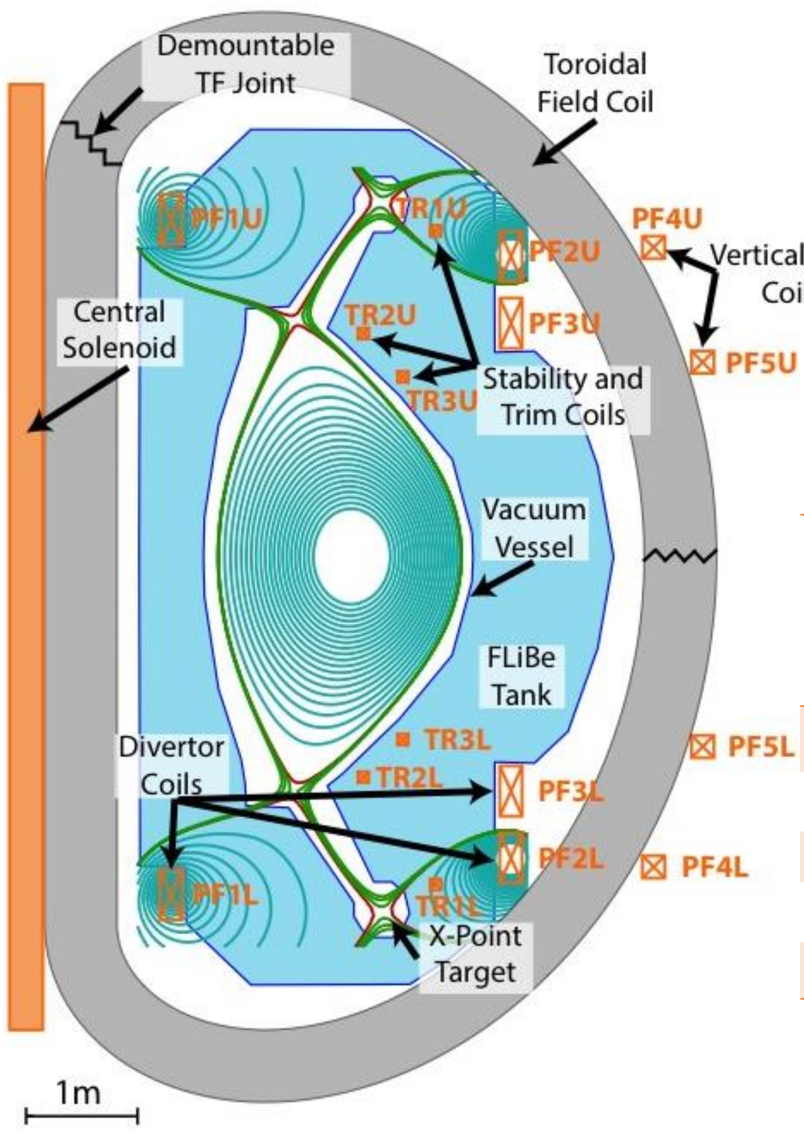
ARC design parameters must not be impacted:

- ☑ Core plasma volume
- ☑ TF coil geometry
- ☑ Plant lifetime of 9 FPY
- ☑ Tritium breeding ratio >1

Use unique features associated with the ARC design:

- ☑ Demountable TF enables internal PF coils.
- ☑ Molten FLiBe immersion blanket is both a coolant and a neutron shield.
- ☑ FLiBe is optically transparent and has low conductivity.

Successfully implemented long-leg divertor with no impact on core plasma and TF coil geometry

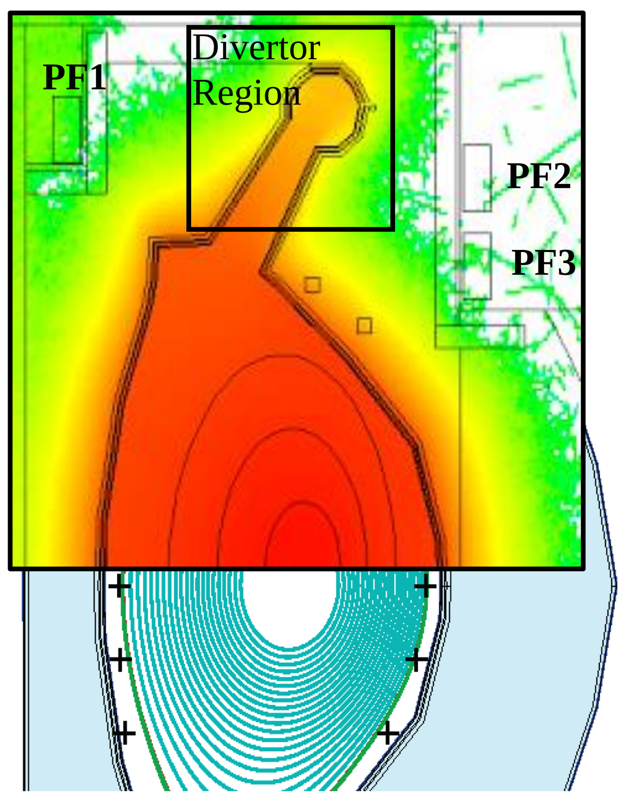


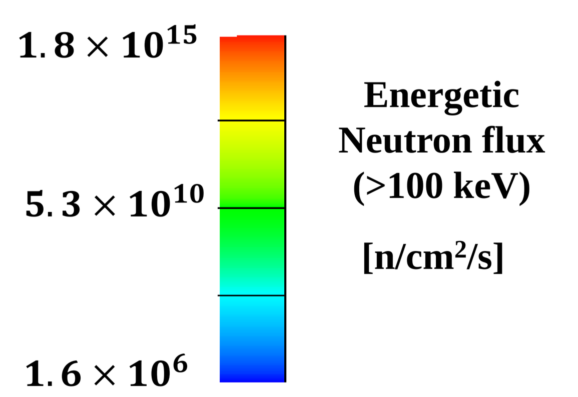
Coil	Current-Turns [MA-turns]
PF1	3.9
PF2	5.2
PF3	4.4
PF4	1.4
PF5	3.5

- Coils to scale based on critical current density in tape of 350 A/mm² at 17 T and 20 K (achievable using YBCO superconductors available in 2015).
- Coils are 20% tape and 80% structure.
- Coil stresses are well within manageable limits.
- Coil placement allows vertical removal of the vacuum vessel (VV) for maintenance.
- Minimally conducting FLiBe means magnetic sensors can be adequately shielded from neutron damage without impacting sensor delay time (<50 ms).
- Coupled with copper trim coils located close to the plasma, provide plasma position control.

High fidelity neutronic simulations show FLiBe immersion blanket and long leg geometry allows tritium breeding ratio greater than one and sufficient shielding of coils

- Monte Carlo N-Particle (MCNP) code[2] used to model ARC with a full 3D layered vacuum vessel.
- Approximately 2.2×10^{20} 14.1 MeV neutrons per second are produced during full-power operation.
- Tritium breeding ratio of 1.08 is greater than unity.
- Magnetic coils sufficiently shielded to last the 9 full power years of operation.



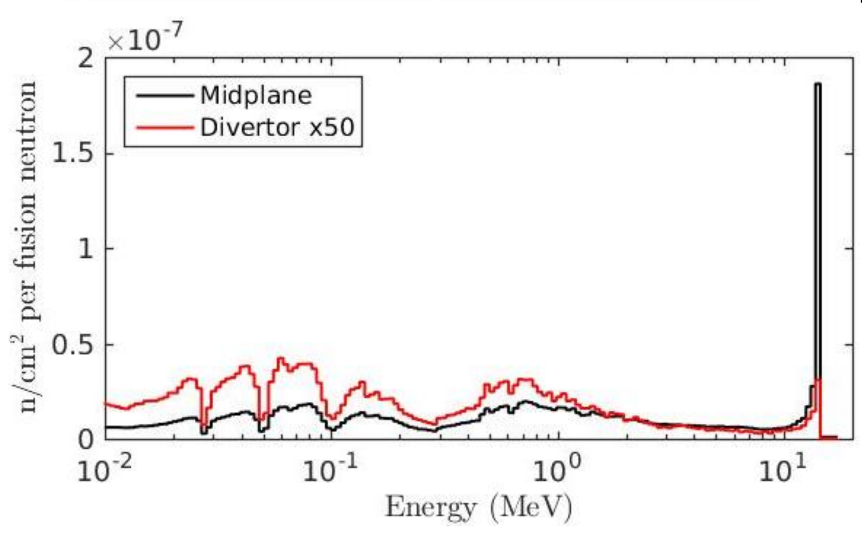


Coil	Lifetime [FPY]
PF1	11.3
PF2	76.2
PF3	12.5

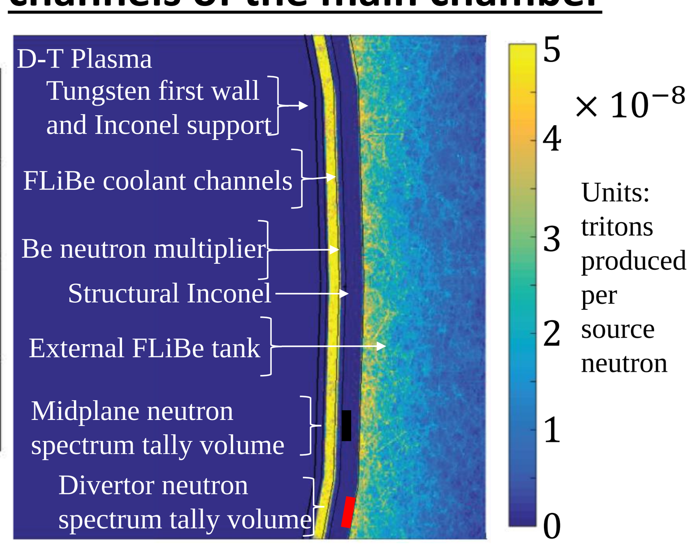
- Long-leg geometry protects the divertor from neutrons.
- The ~1 m of FLiBe on the line-of-sight between core plasma and divertor provides shielding and significantly softens the neutron spectrum.
- This results in reduced neutron damage and He production.
- Most tritium made in VV cooling channels (fast neutron population is highest).

Layer	Average volumetric heating [MW/m³]	DPA/yr	He/DPA [appm]
W inner wall	24.1	5.4	0.45
Inner VV Inconel	11.3	27.7	7.52
Be multiplier	6.3	9.2	287.7
Outer VV Inconel	7.4	16.4	6.37
Divertor Region			
Divertor W inner wall	9.6	1.9	0.38
Divertor inner VV Inconel	3.8	9.0	6.65
Divertor outer VV Inconel	2.1	4.5	5.46

Reduction and softening of neutron spectrum from midplane to divertor

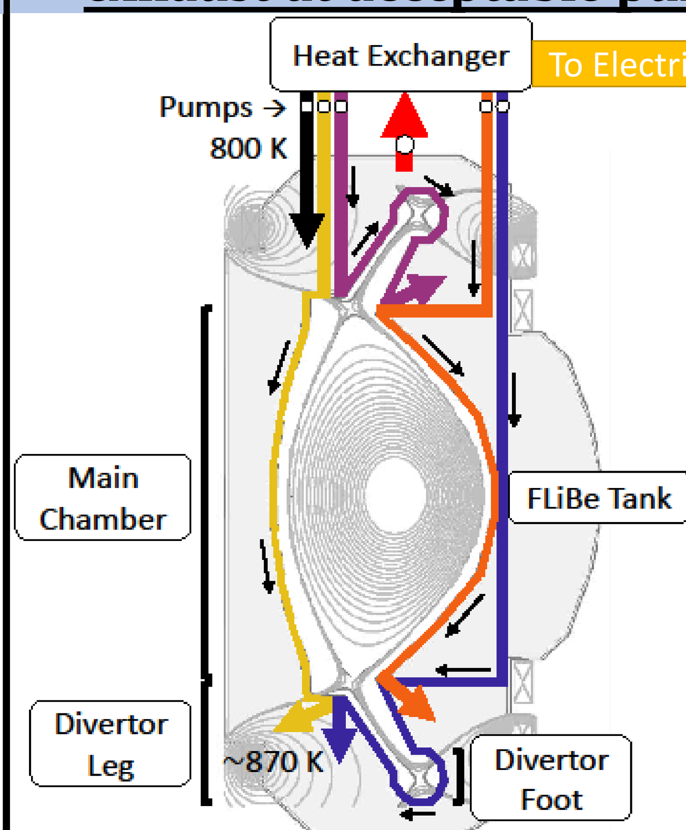


Tritium production highest in cooling channels of the main chamber



Neutron spectrum is at midplane of main chamber and midplane of divertor foot. Location within vacuum vessel layers is shown by black and red boxes respectively.

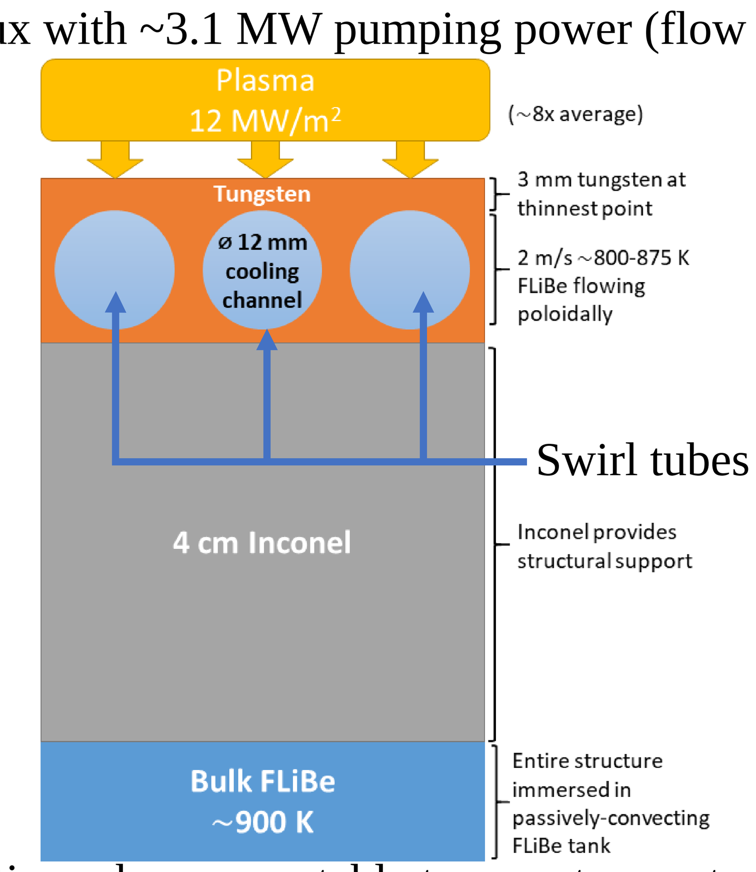
Thermohydraulics show use of FLiBe in an integrated cooling system allows power exhaust at acceptable pumping power



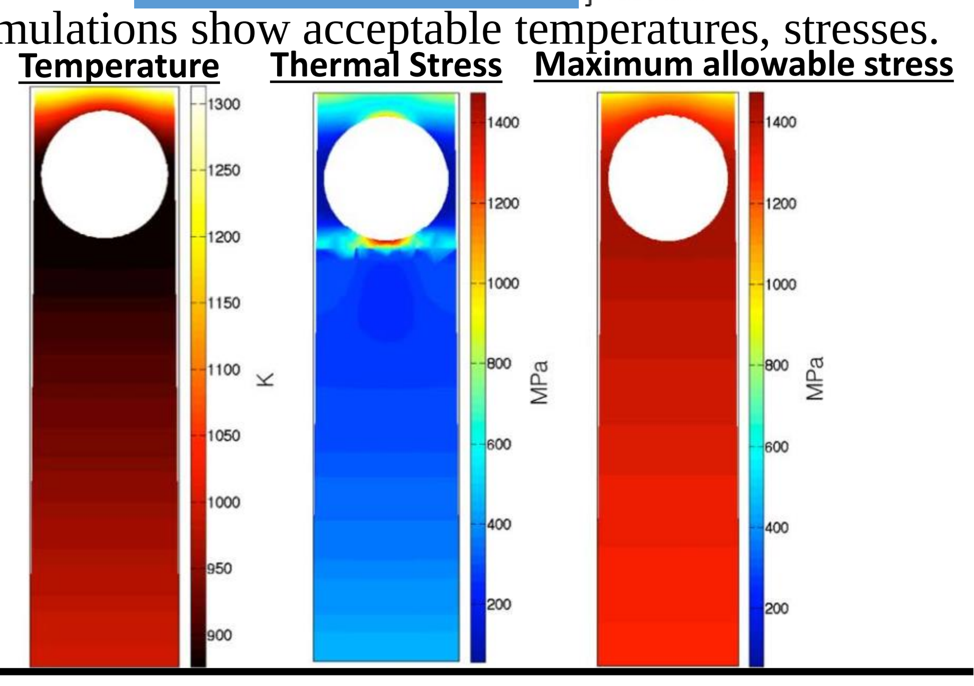
Divertor Heating Key Figures

Surface Area [m²]	66
Total Rad. Power [MW]	93
Total Vol. Heating [MW]	36
Avg. Rad. Heat Flux [MW/m²]	1.4
Avg. Vol. Heating [MW/m³]	3.0

- Detached double null radiative X-point target design significantly reduces peak divertor heat fluxes.
- Long-leg shielded divertor decouples neutron heating problem from peak surface heating problem.
- Coolant cycle extracts heat for electricity generation while maintaining manageable VV temperatures.
- COMSOL study of convective heat transfer and pressure drop shows good cooling of 12 MW/m² heat flux with ~3.1 MW pumping power (flow rates 2 m/s).

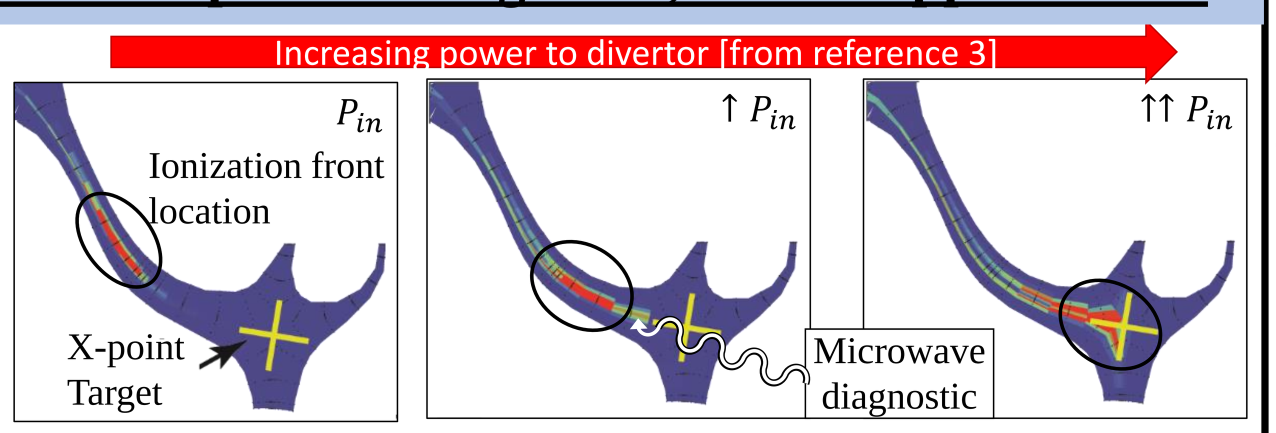


- Simulations show acceptable temperatures, stresses.



Optically transparent FLiBe blanket and long-leg divertor open new diagnostic, control opportunities

- Most plasma diagnostics cannot be used in reactors due to neutron environment and prevention of access by solid neutron blankets.
- ARC's unique features allow use of reactor-relevant diagnostics.
- Transparent FLiBe allows **thermal imaging of the VV**. Optics can be located behind shielding.
- FLiBe acts as a scintillator for fusion neutrons. Fast neutrons moving in FLiBe generate fast free electrons. Those moving faster than the local speed of light produce **Cherenkov radiation**.
- **Microwave reflectometry/interferometry** can detect ionization front location in long-legged divertor. The front location moves[3] with changes in divertor heat flux, allowing feedback control of divertor heat flux.



Accompanying publication:

This poster is based on the publication Kuang, A.Q. et al. (2018) *Fusion Engr. and Design.* Vol. 137, available at link corresponding to QR code.

References:

[1] Sorbom, B.N., et al. (2015). *Fusion Engr. and Design.* Vol. 100
[2] M.C. Team (2003) Los Alamos Nat. Lab. Report: LA-UR-03-1987.
[3] Umansky, M., et al. (2017), *Physics of Plasmas.* Vol. 24

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