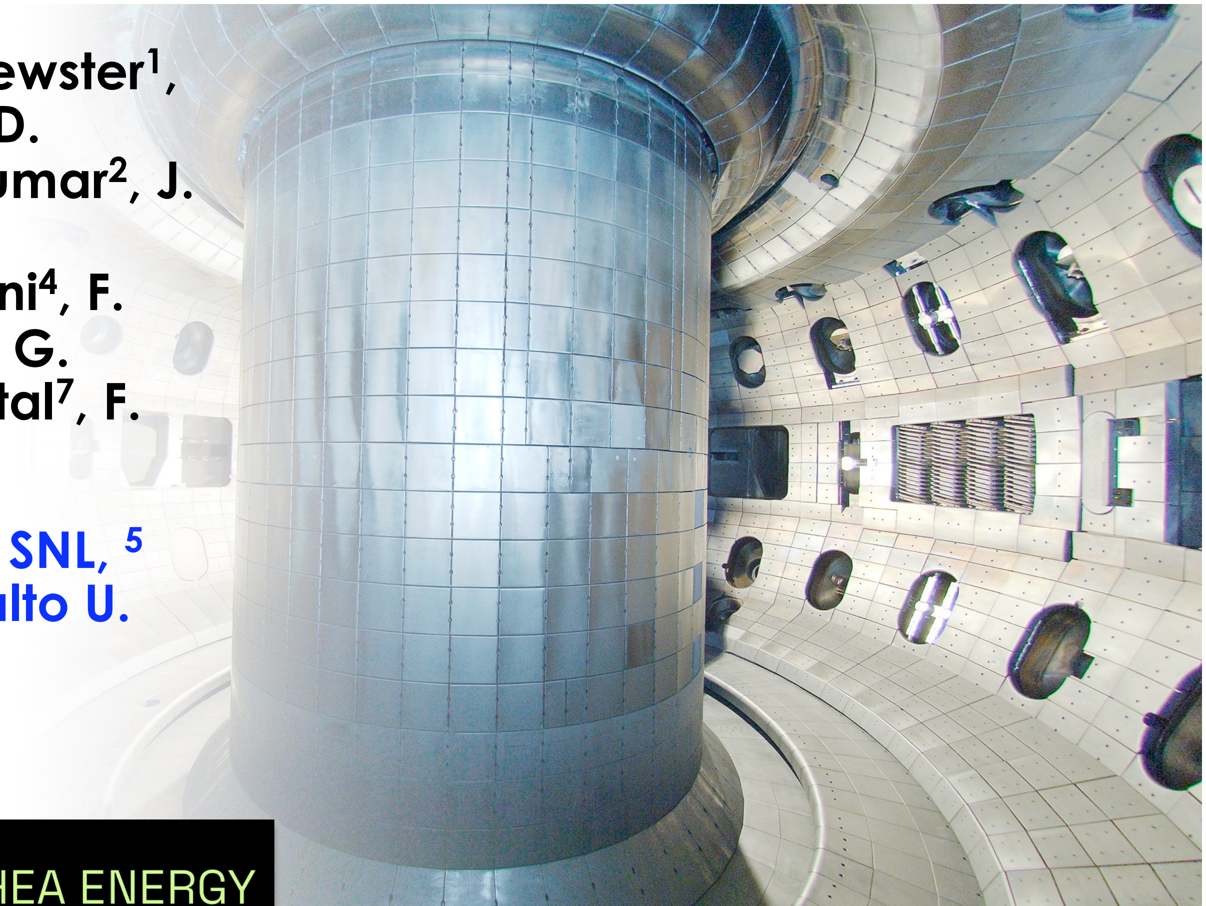
Development of Renewable Plasma-Facing Surfaces in Magnetic Fusion Devices at DIII-D (collaboration between UCSD and Thea Energy)



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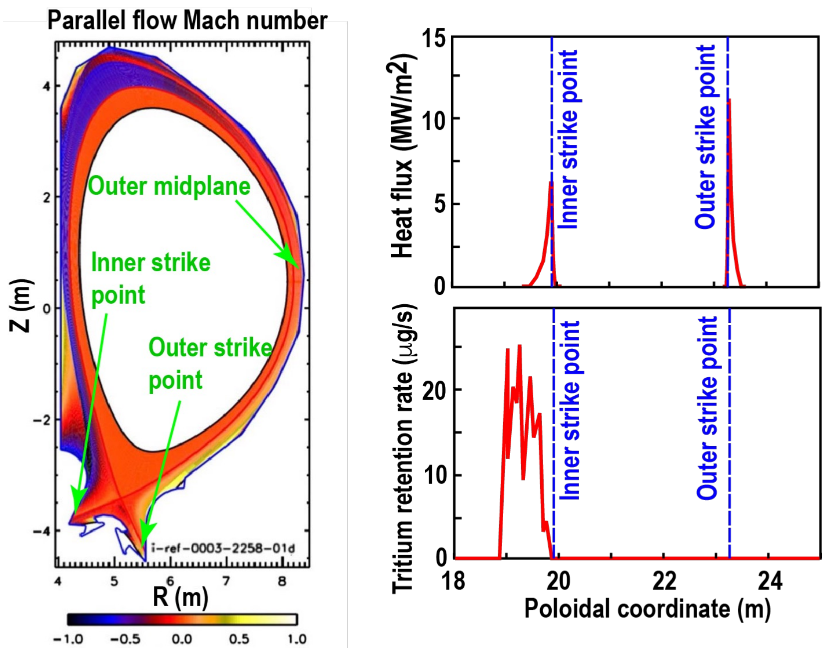
DIII-D Industry Day 2025

Motivation – magnetic fusion reactors will probably require renewable wall material in some localized areas

ITER simulations

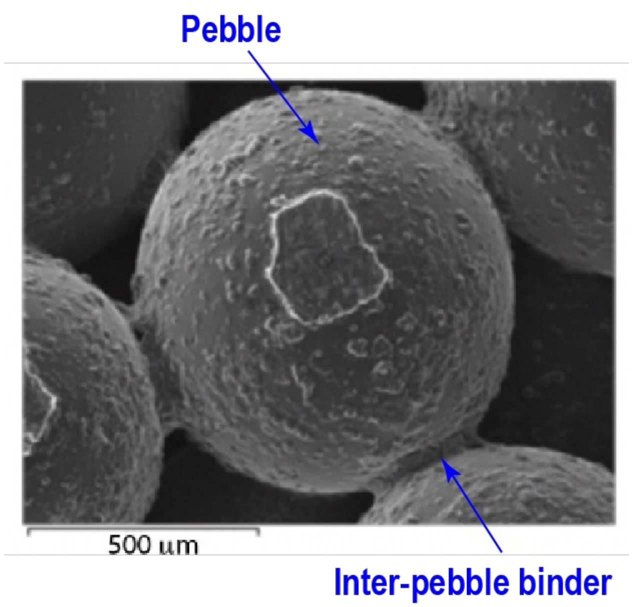


(WallDYN simulations from Khan, NME, 2019)

- **All MFE FPP configurations will have localized first wall problem areas.**
- **In tokamak geometry, likely FPP problem areas are:**
  - **1) Outer strike point: huge steady heat loads (40 MW/m^2) [Bachmann, FED, 2018].**
  - **2) Inside inner strike point: huge deposition (metric tons/year). [Stangeby, PPCF, 2022]**
  - **3) Outer midplane: huge transient heat loads (>10 GW/m^2) [Igitkhanov, NME, 2016].**
- **Present state-of-art fixed wall solution (W monoblock [You, NME, 2018]) cannot address these problem areas – need to develop renewable wall solutions.**

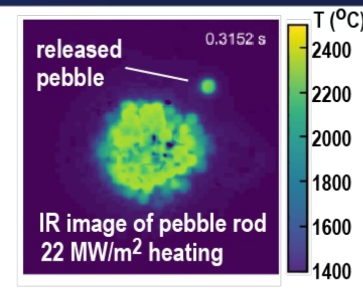
Pebble aggregate being investigated as possible renewable wall material

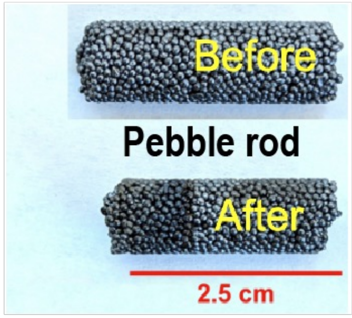
- **Consists of pebbles loosely bound by inter-pebble binder.**
- **Pebbles break off under plasma exposure and can be recovered by gravity.**
- **Aggregate can be extruded out through channels to form renewable wall.**
- **Can be formed (baked) quickly from slurry in closed-loop relevant timescales (several minutes).**



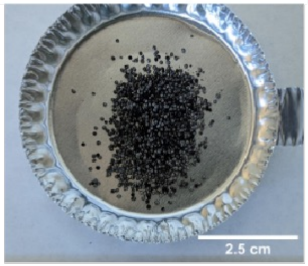
Most successful pebble aggregate design made of glassy carbon pebbles + carbon-based binder

- Can (have) been made of almost any material (B, C, B_4C, BN, W, etc) [Martinez-Loran, NME, 2025].
- Most successful design to-date used glassy carbon pebbles + carbon-based binder.
  - Successful handling of up to 50 MW/m^2 (perp, steady-state) without melting or significant dust release [Martinez-Loran, JAP, 2023].
  - Tunable recession/heat handling rate by varying binder strength [Martinez-Loran, FST, 2024].
  - Successful FEA simulation of observed recession rate [Martinez-Loran, FST, 2024].
  - Reliable intact pebble recovery.





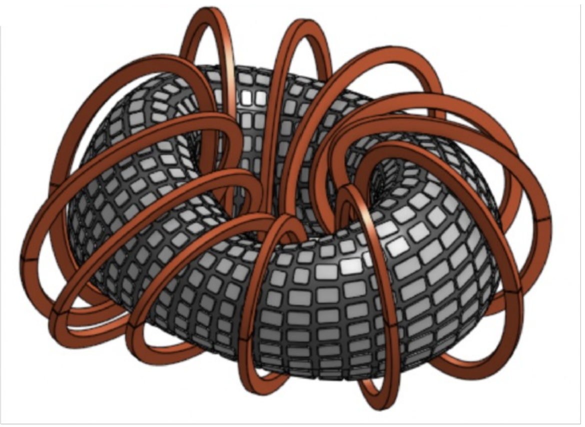
Recovered pebbles



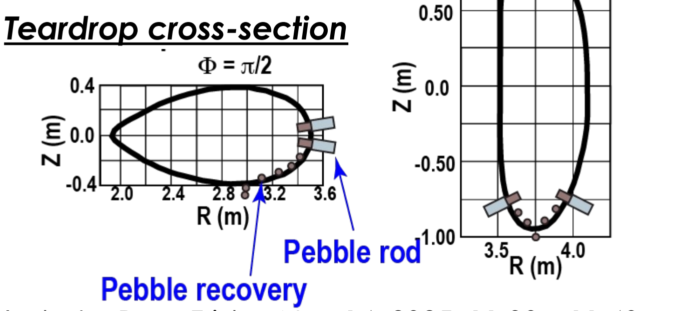
Motivation for Thea/UCSD collaboration (1/2)– measure pebble aggregate material release and core uptake in confinement device

- **Material release can be quite different in toroidal geometry vs bench tests.**
  - **Grazing incidence heat flux.**
  - **Gyro-radius of order pebble size.**
- **Uptake of pebble material into core important for understanding effect on core performance.**
- **Migration of pebble material to other wall regions important for tritium retention.**

Thea Energy's planar coil stellarator

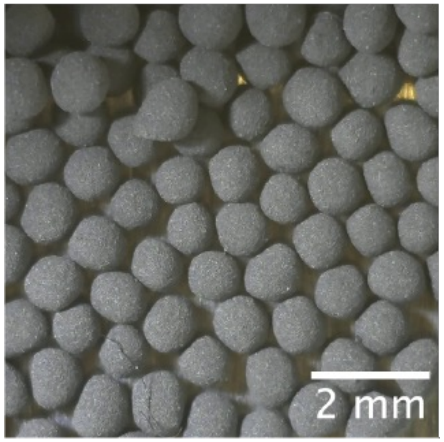


Pebble rod placements in a stellarator geometry



Motivation for Thea/UCSD collaboration (2/2)– develop and test boron-based pebble aggregate

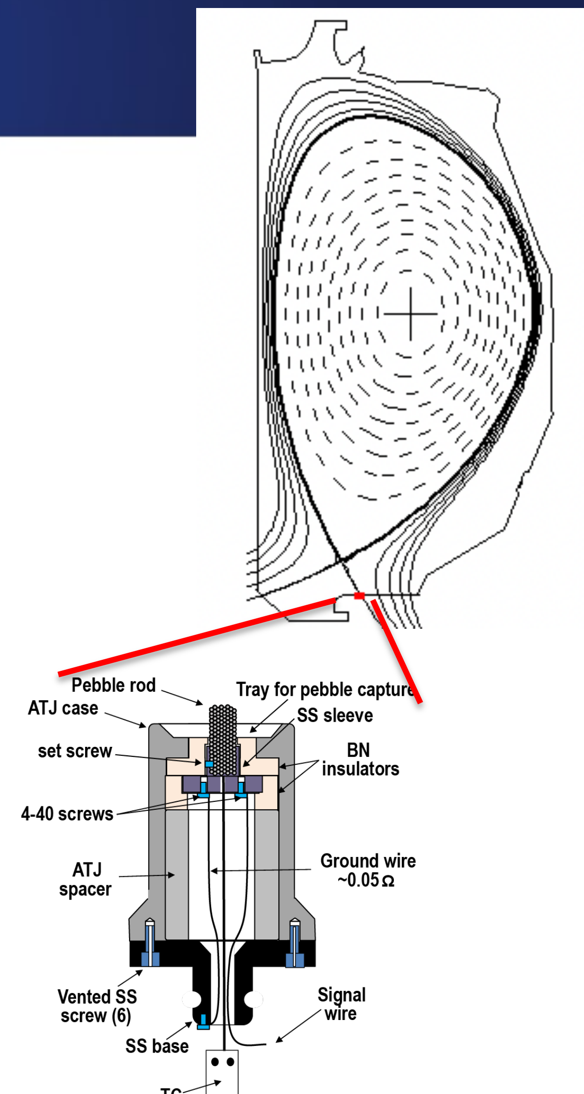
- **Thea Energy is planning on using renewable boron divertors.**
  - **- Boron for excellent core performance (better than C, far better than W).**
  - **- Boron has 10x lower T retention than C.**
  - **- Can hopefully reduce main chamber T co-deposits to acceptable level with hot main chamber walls.**
- **UCSD presently making amorphous sintered boron pebbles by cutting stock into cubes and tumbling.**
- **Glassy (hard) boron cannot by processed in this manner.**
- **Two binders have been developed:**
  - **- carbon based binder.**
  - **- BN based binder.**



Amorphous boron spheres

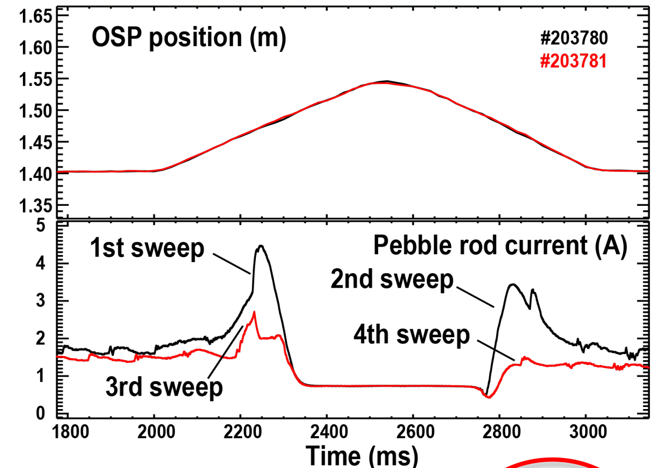
DIII-D experiment overview

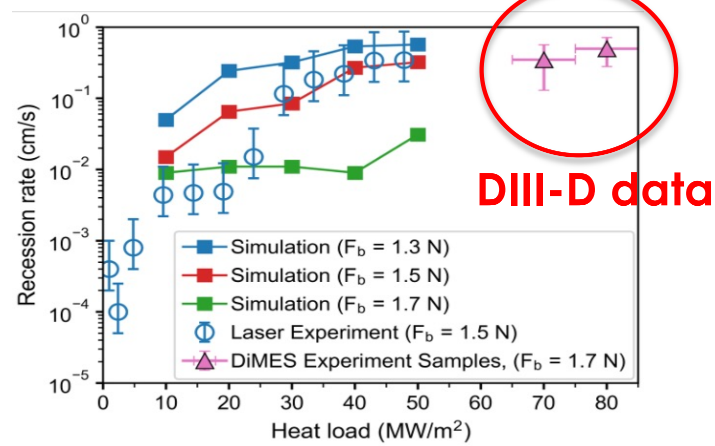
- 1/3 day experiment exposing 3 pebble rod samples.
  - Two initially 2 mm proud one initially 5 mm proud samples.
  - All used ~1-2 mm boron pebble aggregate with carbon binder.
- Just use single fixed pebble rod (not extruded array like in reactor).
- Use high-power L mode plasmas with OSP sweep over DiMES for good signal levels and avoiding complexity of ELMs.
- For this first experiment, used very strong C binder on each sample to make sure there was no breaking during installation.
  - Prioritize getting good core uptake data over tuning pebble aggregate erosion rate.



Total erosion rate of pebble rods well measured in DIII-D experiments

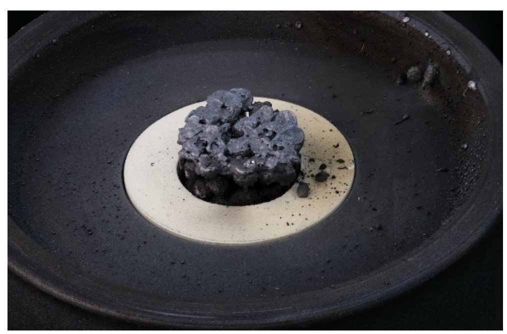
- **Can infer pebble rod projected area from measured current into sample.**
- **Heat flux on proud pebble rod is huge ($q_{//}$~80 MW/m² peak) during OSP sweep.**
  - **- New regime not tested in bench tests.**
- **Melting and dust release observed – binder/pebbles not optimized yet for these conditions.**





Initial sample

Final sample



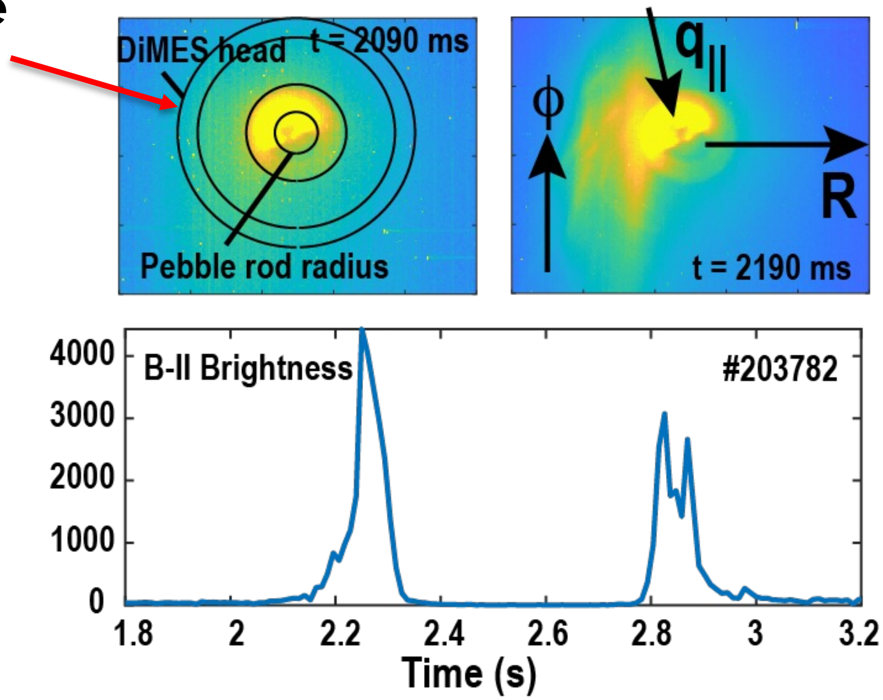
Good data obtained on structure of boron emission from pebble aggregate

- Measure local atom emission from sample with B-II imaging using DiMES TV.

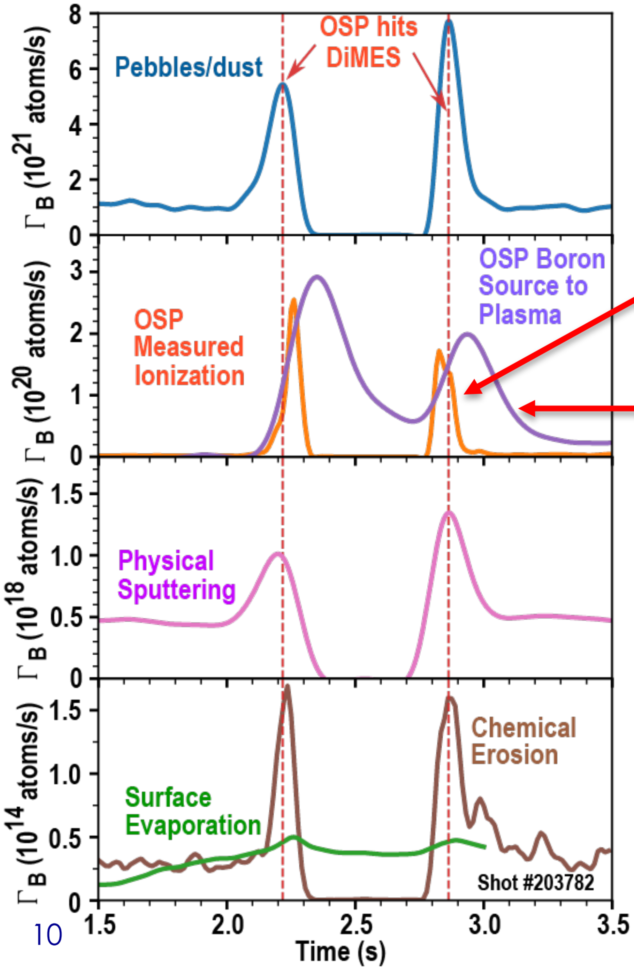
- Can use this with S/XB factor to measure B atom release from B sample (includes vapor, sublimation, and sputtering).

- Also obtain good data on structure of BD emission (chemical erosion).

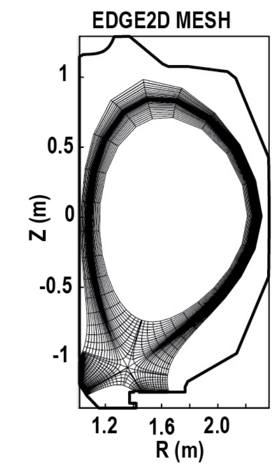
- Emission patterns being studied with ERO modeling.

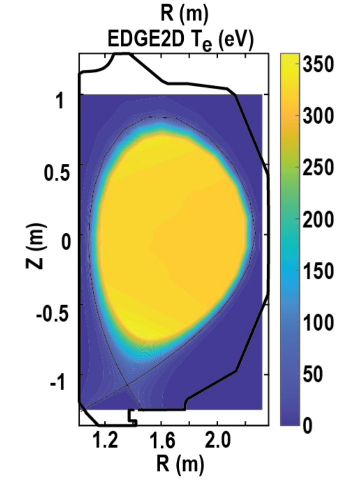


Confirm that most of boron emitted not ionized in OSP



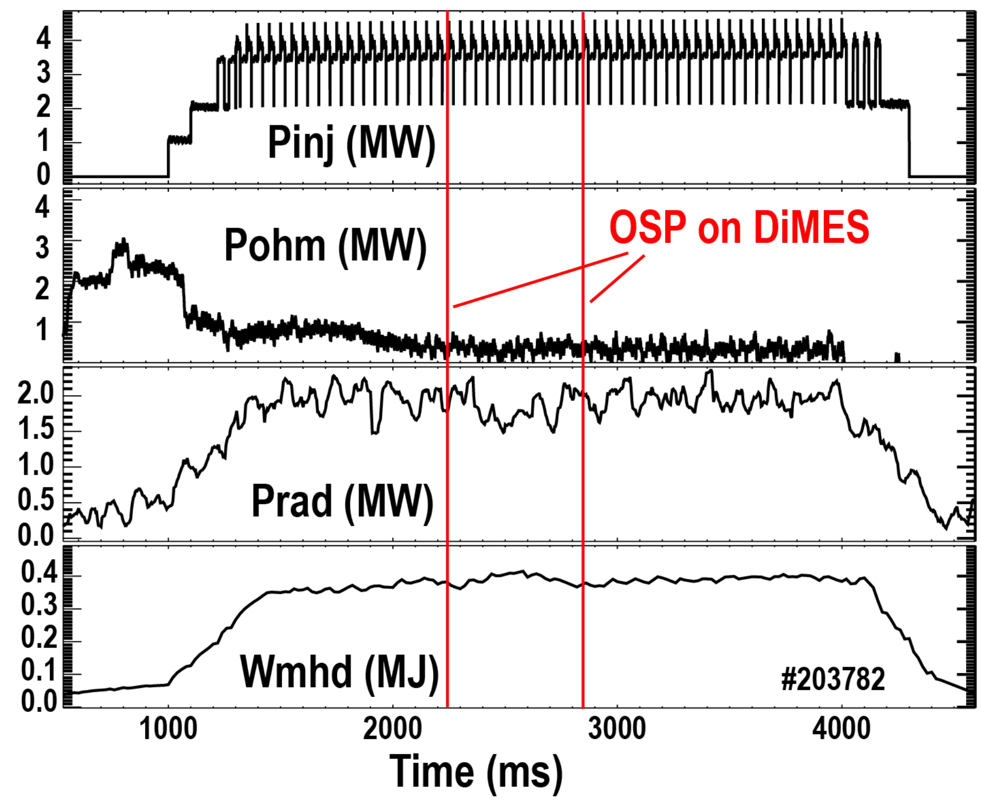
- Want to recover most of boron lost from aggregate.
- Do confirm that ionization source at OSP 20x smaller than B emitted as pebbles.
- OSP ionization source also consistent with B uptake into core from EDGE2D modeling.
- Physical and chemical sputtering small.
  - Dominant B ionization source probably from atoms vaporized off dust?





As expected, large boron source from OSP does not adversely effect core performance

- **These experiments had non-optimized pebble aggregate which gave large boron source term.**
  - **Atom source 20x lower than pebble release.**
  - **Want to reduce melting/dust production to reduce atom source more.**
- **Even with large boron source, little effect on radiated power.**
  - **boron well-known to be compatible with good core performance even at several % level.**



Summary: Thea/UCSD collaboration working toward developing renewable boron-based first wall material

- **Experiments on confinement device (DIII-D)**

  - Pebble release under large grazing-incidence heat loads looks consistent with bench tests.

  - Chemical and physical sputtering patterns from pebble aggregate being studied with ERO simulations.

  - Core uptake of boron release from OSP consistent with EDGE2D simulations.

- **Material development**

  - Have successfully developed first boron-based pebble aggregate using amorphous boron spheres and carbon binder.

  - Not optimized for DIII-D OSP yet – need faster release binder to avoid melting and glassy spheres to avoid dust release.

  - Work in progress to develop pebble aggregate based on glassy boron spheres and boron-based inter-pebble binder.