Overview of the Vacuum Pumping Systems for the SPARC Tokamak

Oliver (Ollie) Mulvany[1], Christian Day[2], Matt Fillion[1], James Fountas[1], Adam Kuang[1], Fabio Ravelli[1]
[1]Commonwealth Fusion Systems, [2]Karlsruhe Institute of Technology

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Commonwealth Fusion Systems

Outline

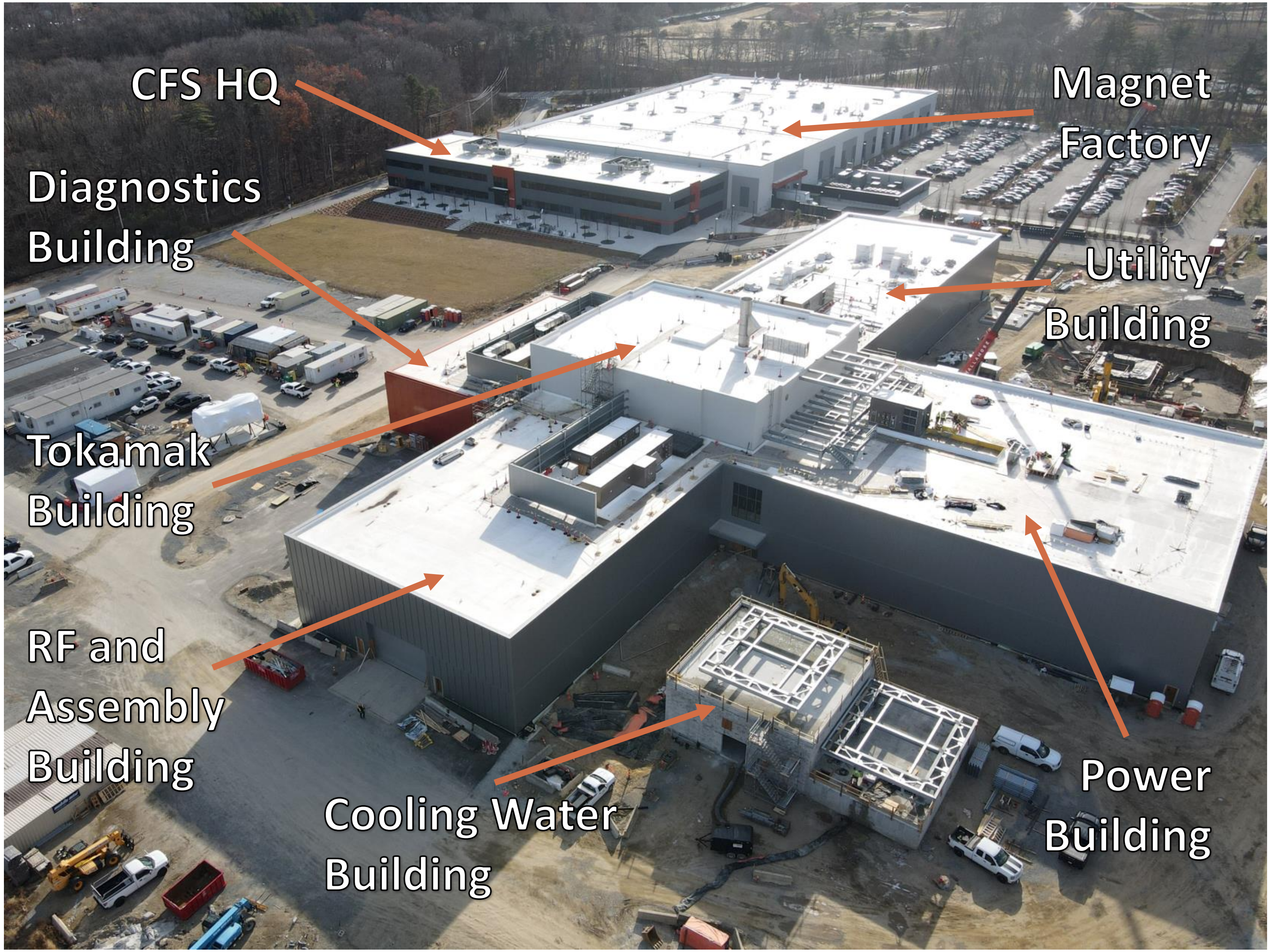
- Brief Introduction to CFS and SPARC
- SPARC Vacuum Pumping Systems
  - Cryostat Pumping System
  - Leak Detection System
  - Torus Pumping System

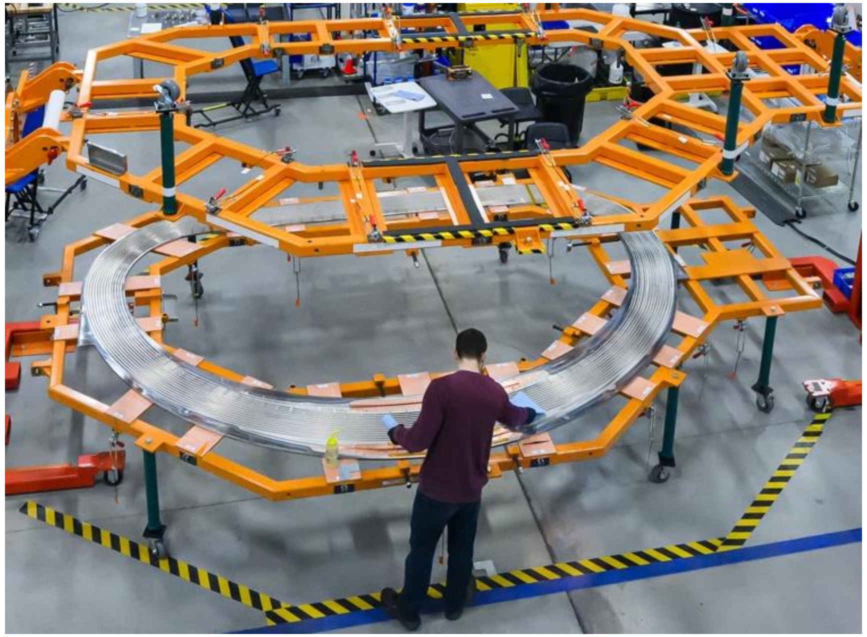
Brief Introduction to CFS and SPARC

CFS Mission is to Deliver Commercial Fusion Energy

- Commonwealth Fusion Systems was founded in 2018
- Spun out of MIT with the goal of commercializing fusion energy to combat climate change
- Raised more than $2 billion
- Diverse team, with people from startups, industry, national labs, academia, and many external partners worldwide
- More than 650 employees
- Core Technology: high-temperature superconducting (HTS) magnets allow for a compact tokamak

Construction of SPARC and Magnet Factory in Devens, MA





CFS Vision

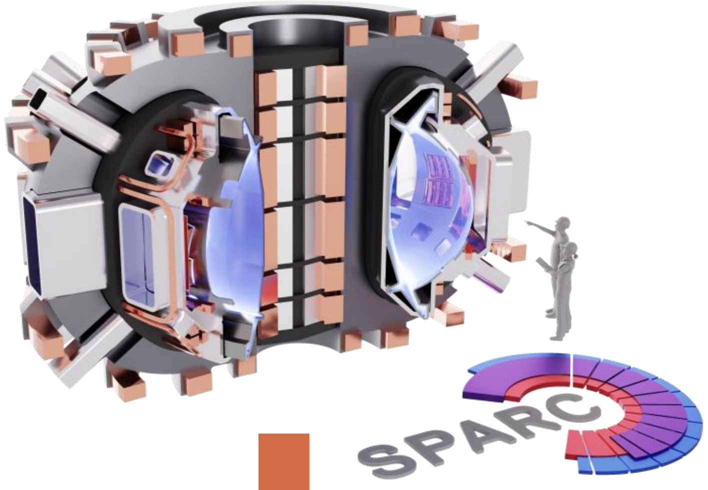
Building on tokamak physics demonstrated in machines around the world

COMPLETED:
Demonstrate groundbreaking HTS magnets

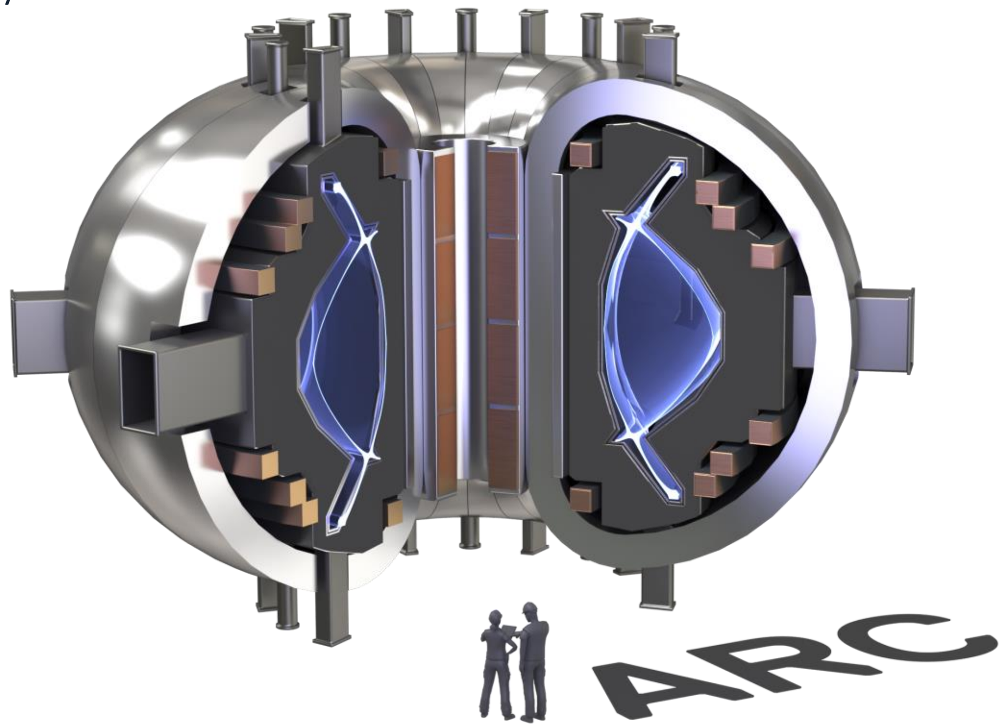
SPARC CONSTRUCTION UNDERWAY:
SPARC Q>1
Achieve net fusion energy

EARLY 2030s:
ARC deployed
~400 MWe

SPARC-relevant scale, achieved ~20 T peak field on conductor [1]



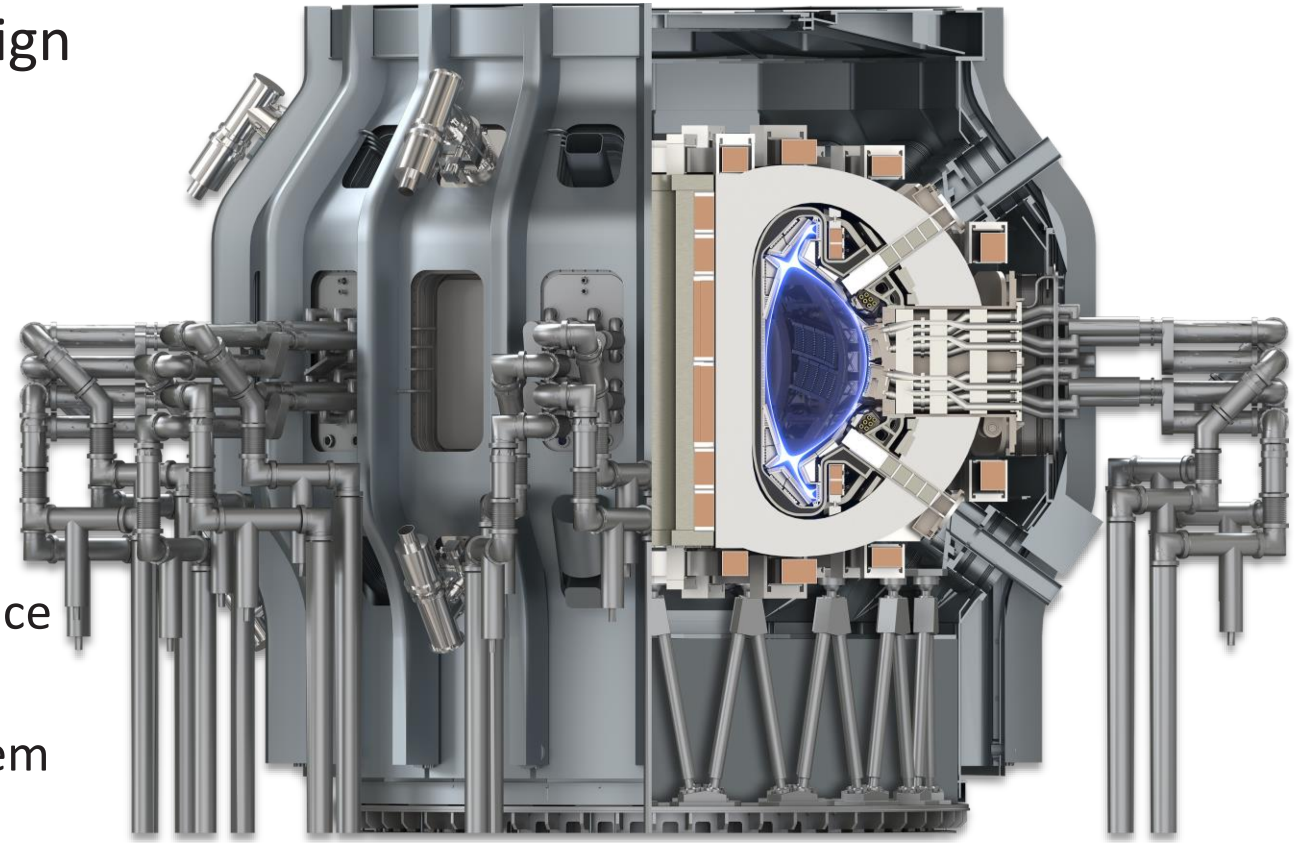
Commercially relevant net fusion energy [2]



Carbon-free commercial power on the grid

SPARC Overview

- Heavily peer-reviewed and validated by simulations
- Will close gaps in physics, technology, and manufacturing supply chains for ARC
- Expected to achieve Q>1 during first campaign
- Comprises many sub-systems
  - Vacuum Vessel Systems – e.g., vacuum vessel, plasma-facing components, vessel conditioning
  - Cryogenic Systems – e.g., cryostat, cryoplant
  - Magnet Systems – e.g., toroidal and poloidal field coils
  - **Vacuum Pumping Systems**
  - Diagnostics – suite to monitor SPARC performance
  - Fueling and Tritium Management Systems
  - RF Heating Systems – e.g., ion cyclotron RF system
  - Central Control Systems, and more…



SPARC Vacuum Pumping Systems

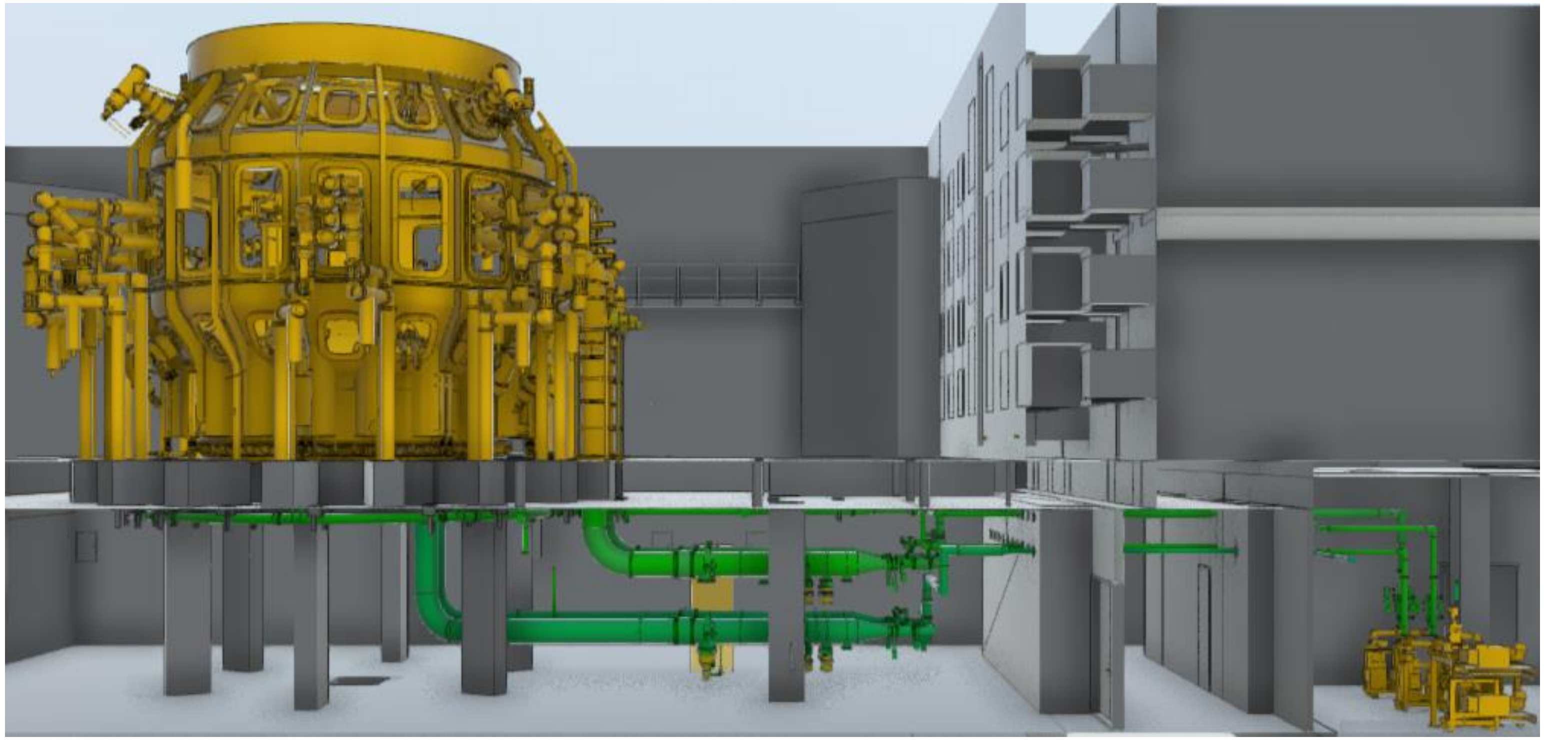
SPARC Vacuum Pumping Systems

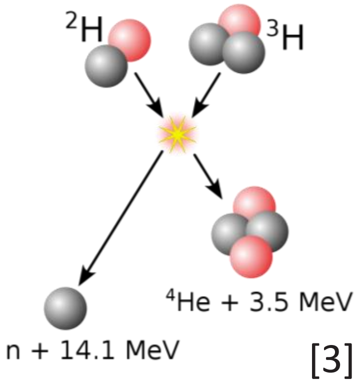
- Cryostat Pumping System (CPMP): Vacuum insulation for superconducting magnets and other structures
- Leak Detection System (LKDT):

1. Vacuum guard for SPARC vacuum interspaces and double seals
2. Secondary tritium containment

- Service Pumping System (SPMP): Mobile pumping carts for SPARC auxiliary systems requiring rough or high vacuum
- Torus Pumping System (TPMP):

1. Maintain torus base pressure and pressure between plasma pulses
2. Neutral particle (He “ash”) control through divertor region pumping
3. Primary tritium containment

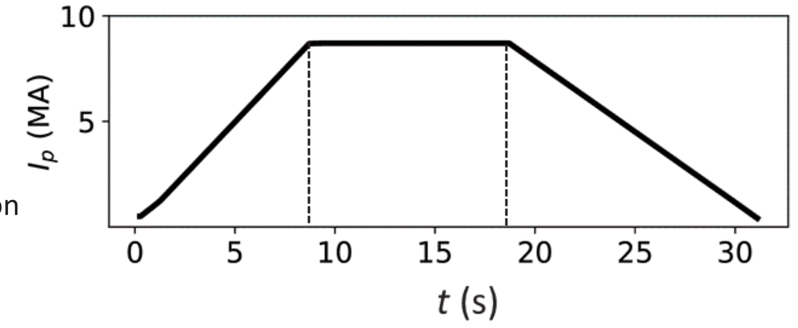


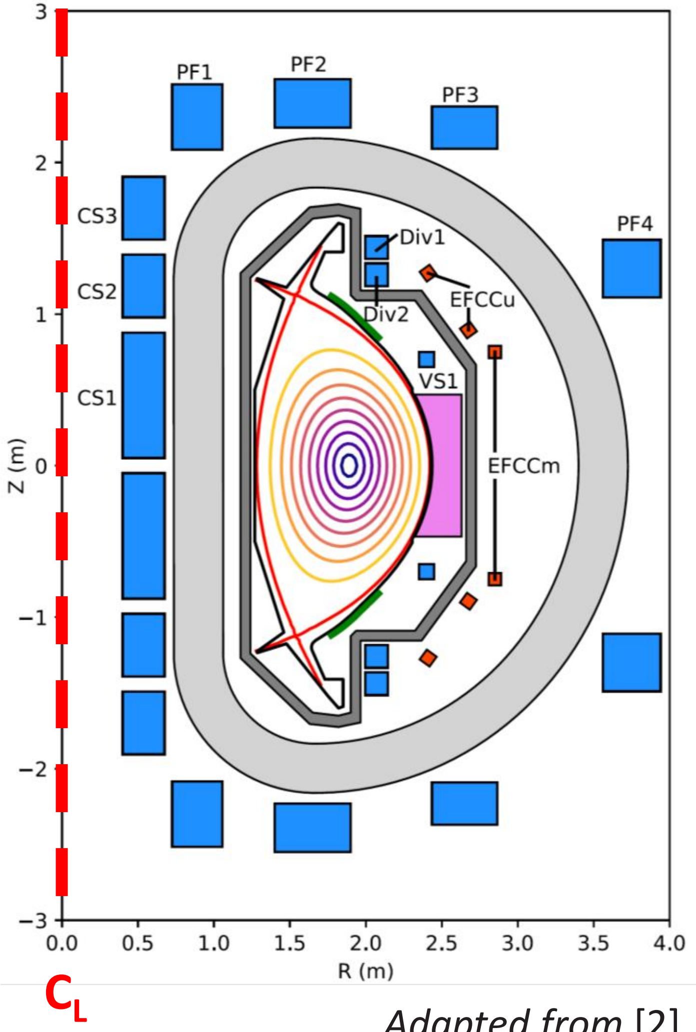


[3]

Some Challenges

- Plasma operations
  - One “pulse” every 20 minutes
  - Ramp up in ~9 s to maximum current
  - Flattop for 10 s, achieving maximum P_{fusion}
  - Ramp down in ~10 s
- Transient & high strength magnetic field
  - Magnetic field is ~0.5 T where VACP components begin
  - Influences material and equipment choices
  - Magnetic shielding = large electromagnetic forces and plasma perturbations
  - Must avoid electrical loops
- Radiation
  - High neutron fluence over the lifetime of SPARC
    - Component damage, e.g., seals and electronics
    - Undesirable heating of components, e.g., cryopump stages
  - Primary and secondary tritium boundaries
- Design & fabrication for vacuum – *many* systems and components in vacuum



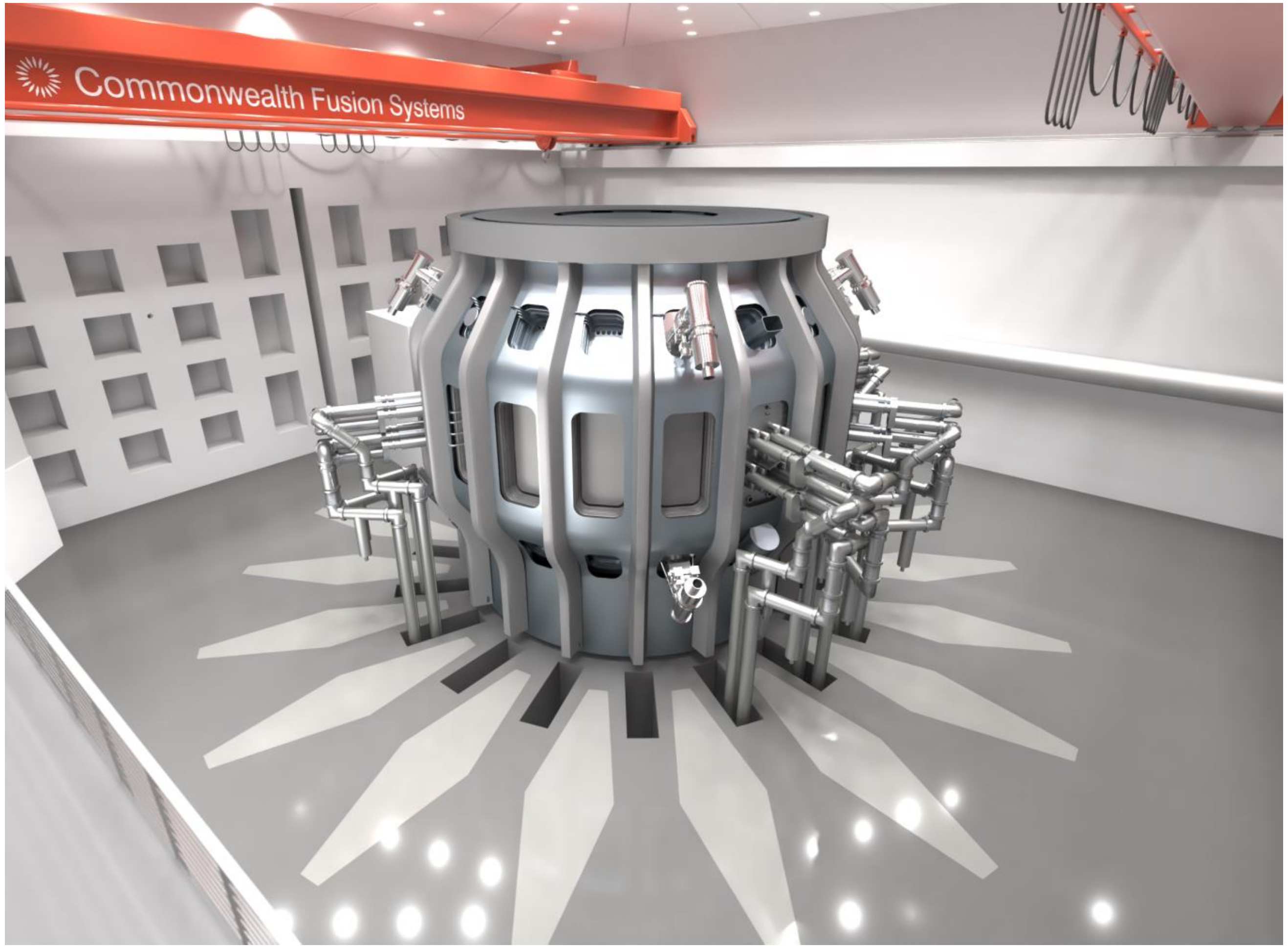


Adapted from [2]

Cryostat Pumping System (CPMP)

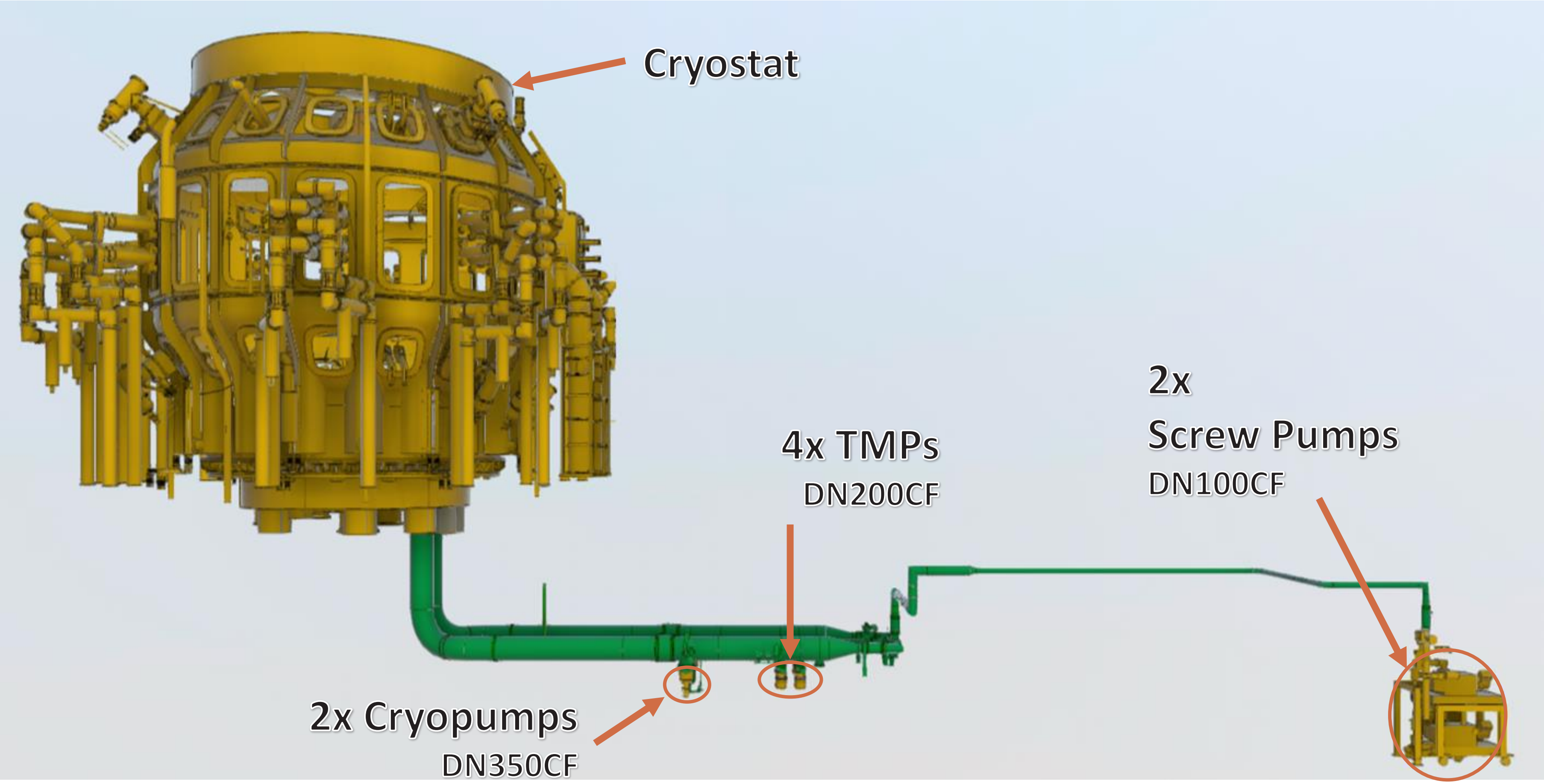
What's in Cryostat Vacuum?

- Cryostat
  - Large vessel, $d_o \approx 9.2$ m, $h \approx 9$ m
  - 316/316L stainless steel fabrication
- Thermal shields
  - GHe-cooled
  - 316/316L stainless steel fabrication
  - Silver plated to minimize emissivity
  - MLI to enhance thermal radiation protection
- HTS and copper magnets
  - Most LHe-cooled, some others conduction-cooled
  - In-vessel magnet supports
- Power feed lines for magnets
  - Use of non-metallics, e.g., in-situ cable joints
- Vacuum vessel (VV) – *details in coming slides*
- Boron carbide (B_4C) neutron shielding
- Lots of additional hardware, e.g., bolts, brackets, thermal/electrical insulation



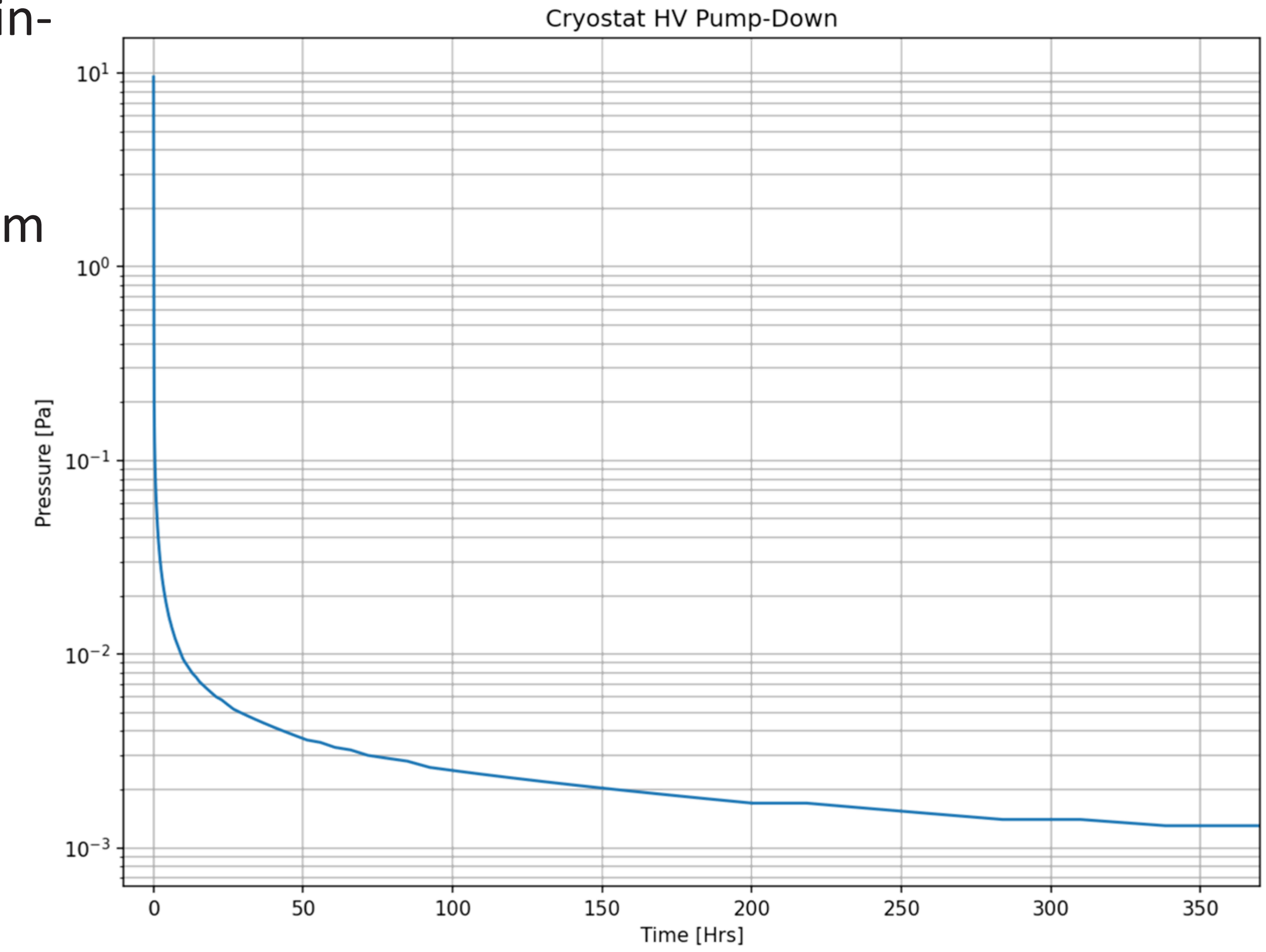
CPMP Layout

- Two parallel pumping trains: DN540 → DN200 → DN100 (roughing line & TMP backing line)
- Discharges to stack, but can be directed to trace tritium recovery (TTR) system
- Radiation-compatible vacuum gauges and RGA



CPMP Pump-Down

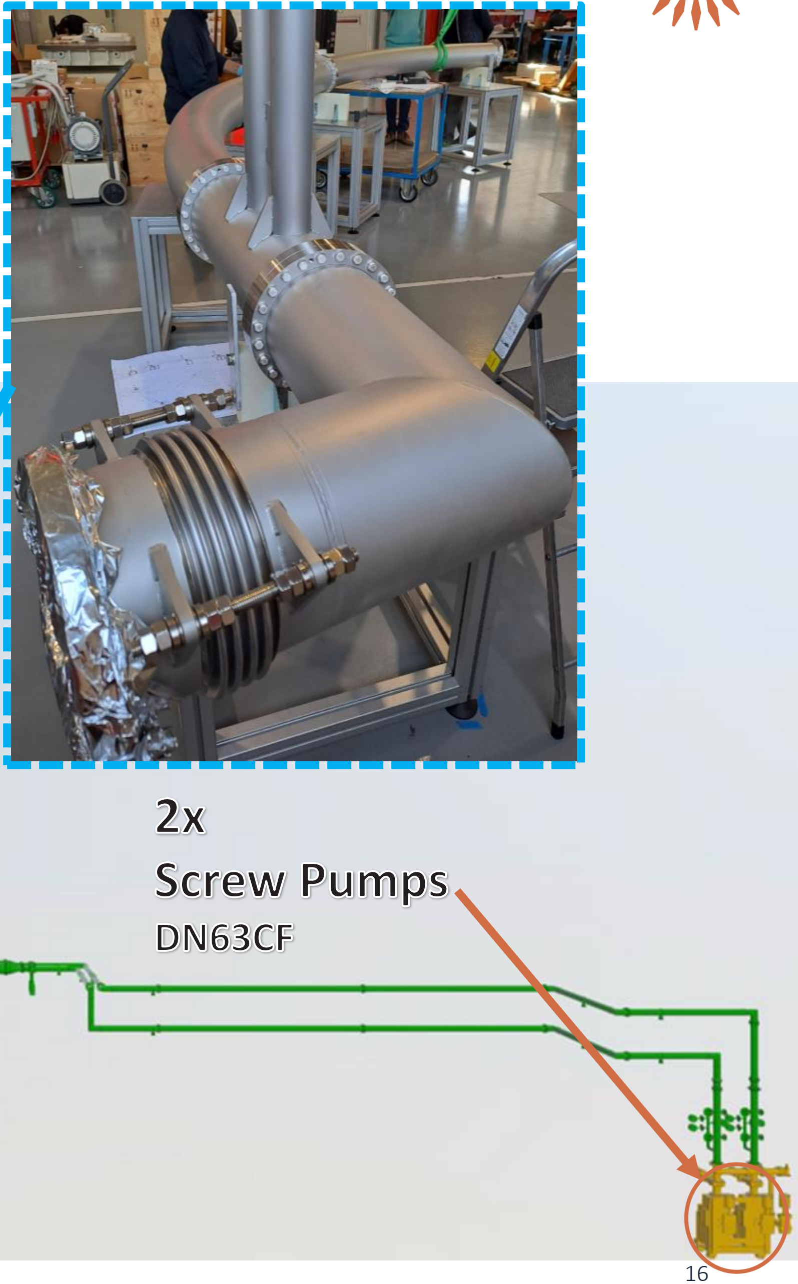
- No in-situ bake-out of CPMP or other in-vacuum components
- All-metal sealed – CF flanges with copper gaskets, including rough vacuum section
- Vacuum volume, V ≈ 312 m^3
- Internal component surface area ≈ 3500 m^2
- Calculated with VacTran
  - Base pressure of **1.3E-3 Pa** reached after **370 hrs (16 days)**
  - Permits cool-down of magnets and structures

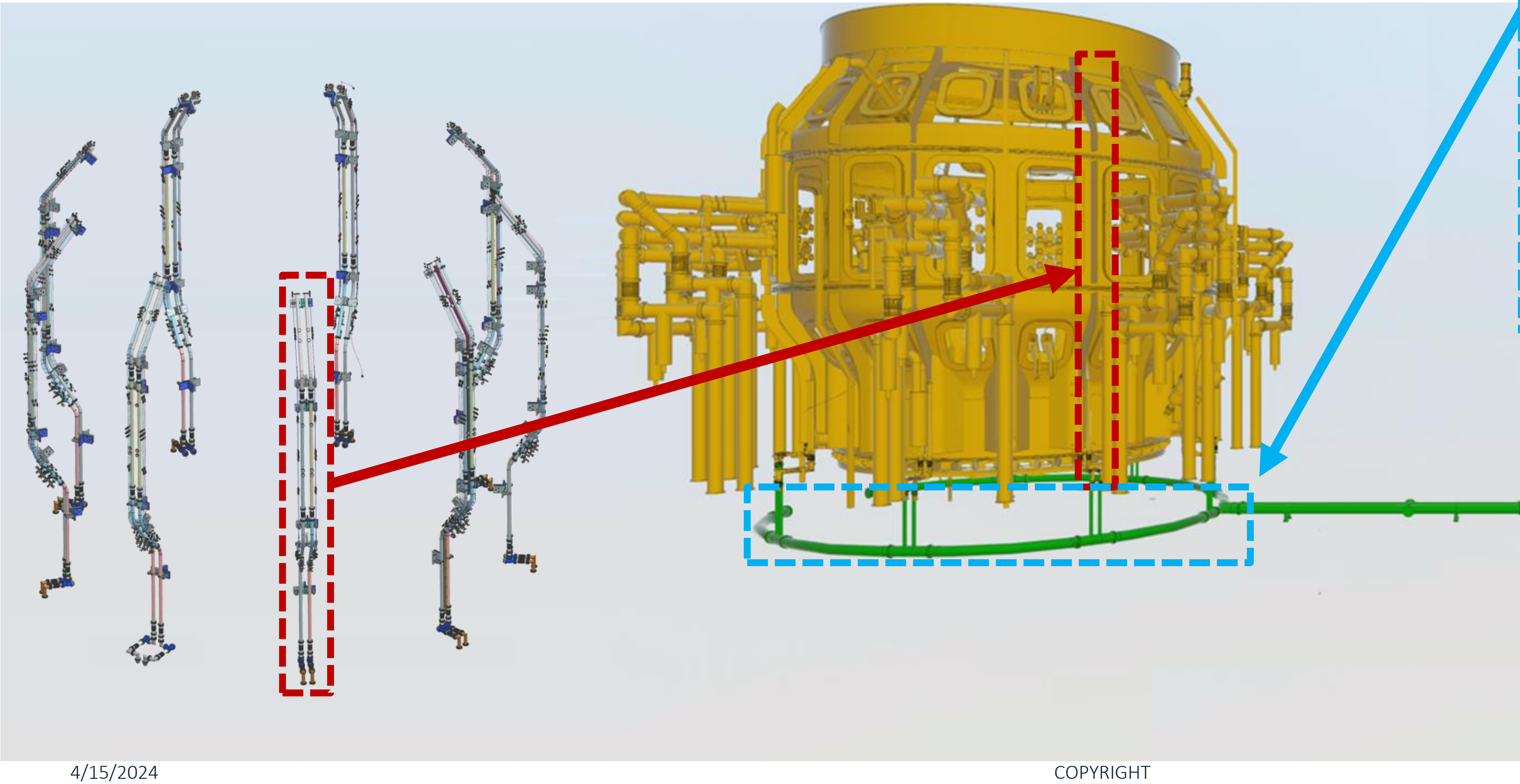


Leak Detection System (LKDT)

Briefly on LKDT

- Rough vacuum pump-down (~100 Pa) and monitoring of vacuum “clients”
- Two parallel pumping lines: DN63 → DN200 → DN100
- Discharges to TTR system or stack
- Radiation-compatible vacuum gauges and RGA





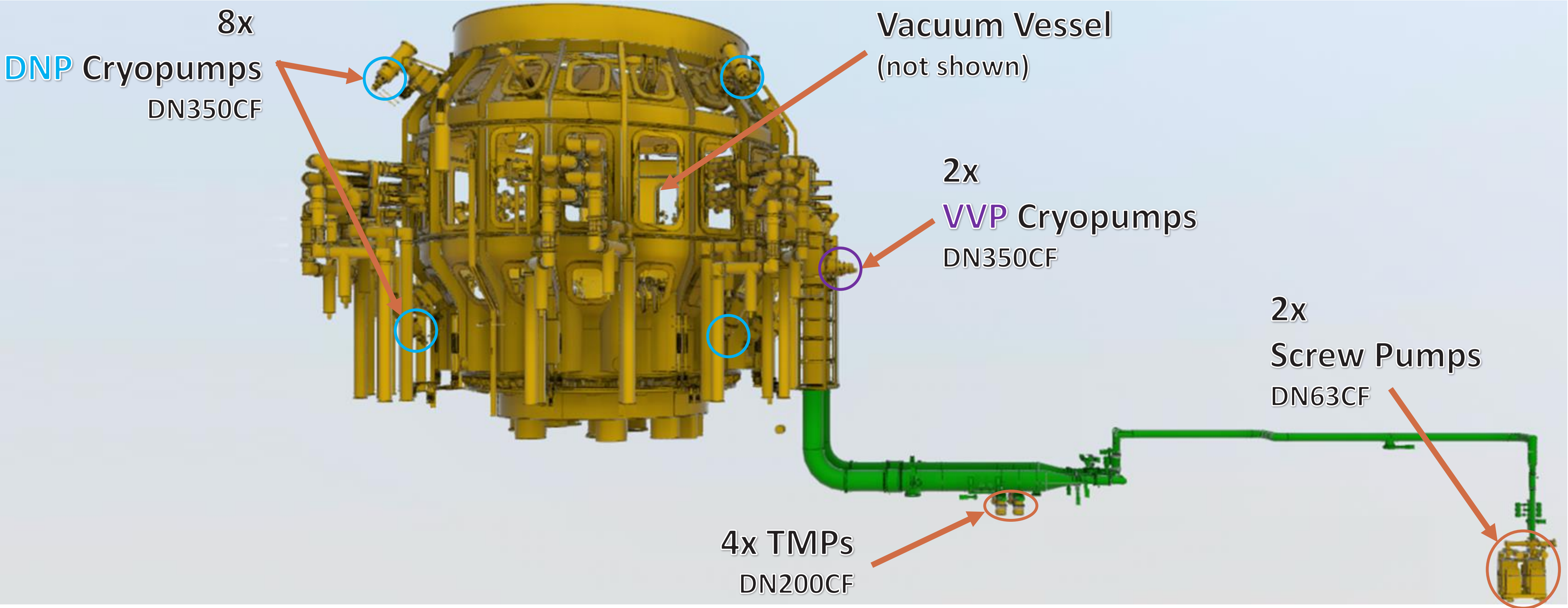
Torus Pumping System (TPMP)

What's in Torus Vacuum?

- Vacuum vessel: $d_i \approx 2.3$ m, $d_o \approx 5.7$ m, $h \approx 3.5$ m
  - Double-walled to permit gaseous heating and cooling
  - Primarily XM-19 (Nitronic 50) fabrication
- Ports and port plugs
  - Essentially large vacuum feedthroughs to the vacuum vessel for RF plasma heating, fueling, diagnostics, etc.
- Plasma facing components (PFCs)
  - Composed of many tungsten alloy tiles
  - Heat fluxes up to 200 MW/m^2 in divertor
  - Plasma disruptions = flash heating possible
  - "Boronization" as oxygen getter and impurity trap [5]
- Fuel injection (helium, hydrogen, deuterium, **tritium**, etc.)
- Boron carbide (B_4C) neutron shielding – also reduces vacuum conductance in ports
- Lots of additional hardware

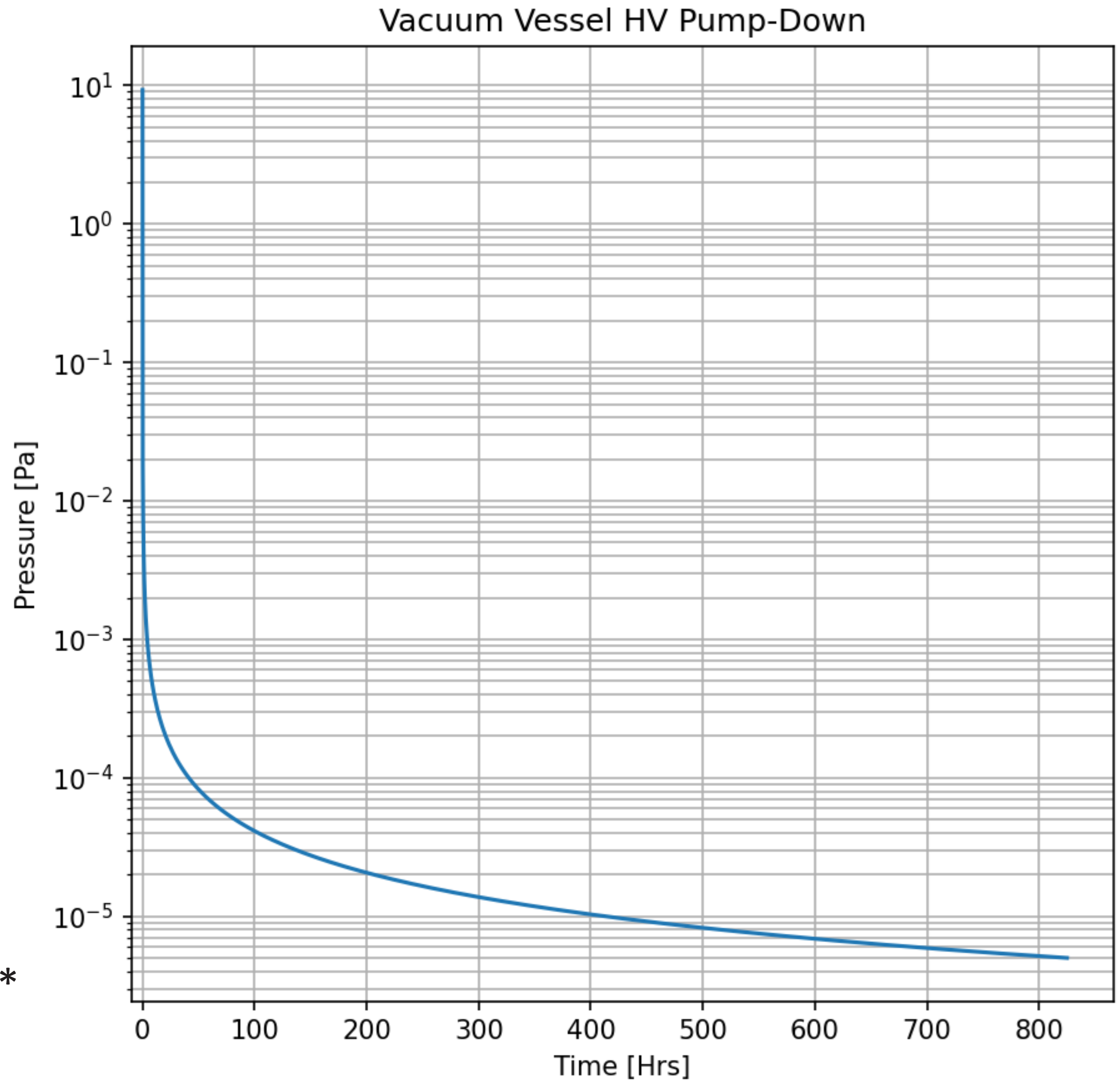
TPMP Layout

- Two parallel pumping trains: DN540 → DN200 → DN100 (roughing line & TMP backing line)
- At low tritium concentrations, VV pumping (VVP) discharges to TTR system
- Divertor neutral pumping system (DNP) regenerates into the VV, and gas is directed to torus exhaust purification (TEP) system via VVP – higher content of tritium anticipated
- Radiation-compatible vacuum gauges and RGA



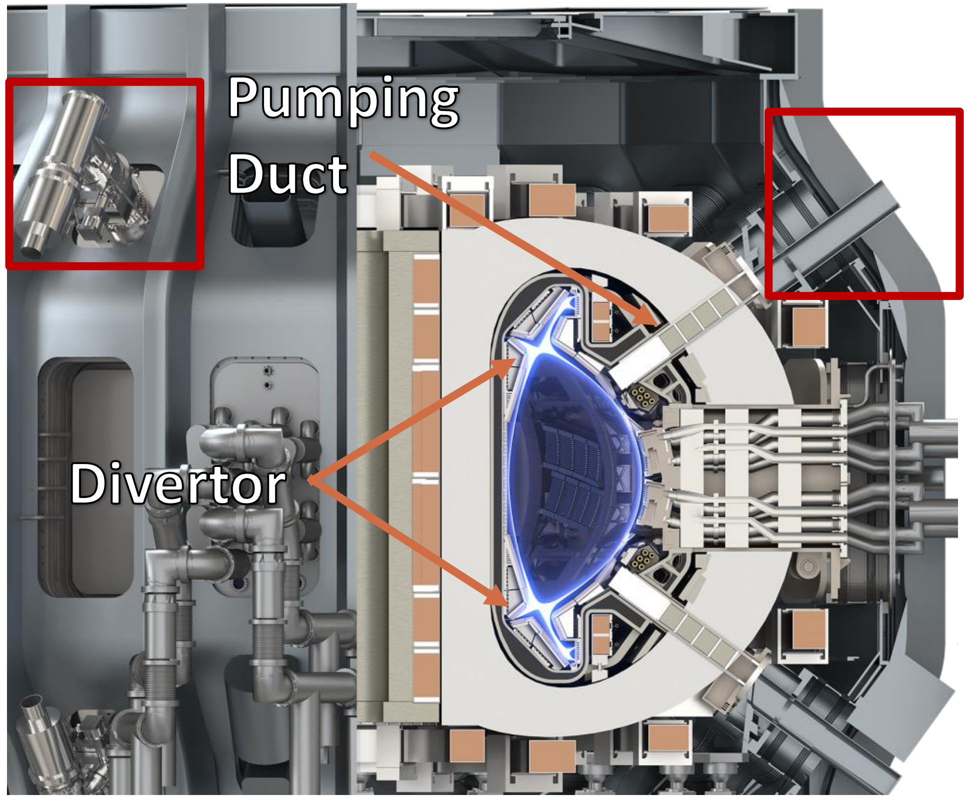
TPMP Pump-Down

- TPMP is not baked, but the vacuum vessel is conditioned:
  - To recover adsorbed fuel and remove impurities at the beginning and end of campaigns:
    - "High temperature" bake to 350°C
    - Glow discharge cleaning
  - More frequent vessel condition during campaigns:
    - "Low temperature" bake to 150°C
    - Ion cyclotron discharge cleaning via intentionally poorly confined plasma
- All-metal sealed, double-walled components (electrical breaks, bellows), tritium-compatible
- Vacuum volume, V ≈ 70 m^3
- Internal component surface area ≈ 1500 m^2
- Calculated with VacTran
  - Base pressure of **5E-6 Pa** reached after **825 hrs (~35 days)**
    - *Not including cryopumps or vacuum vessel bake-out*
  - Inter-pulse pressure of **1E-4 Pa** reached after **12 minutes**



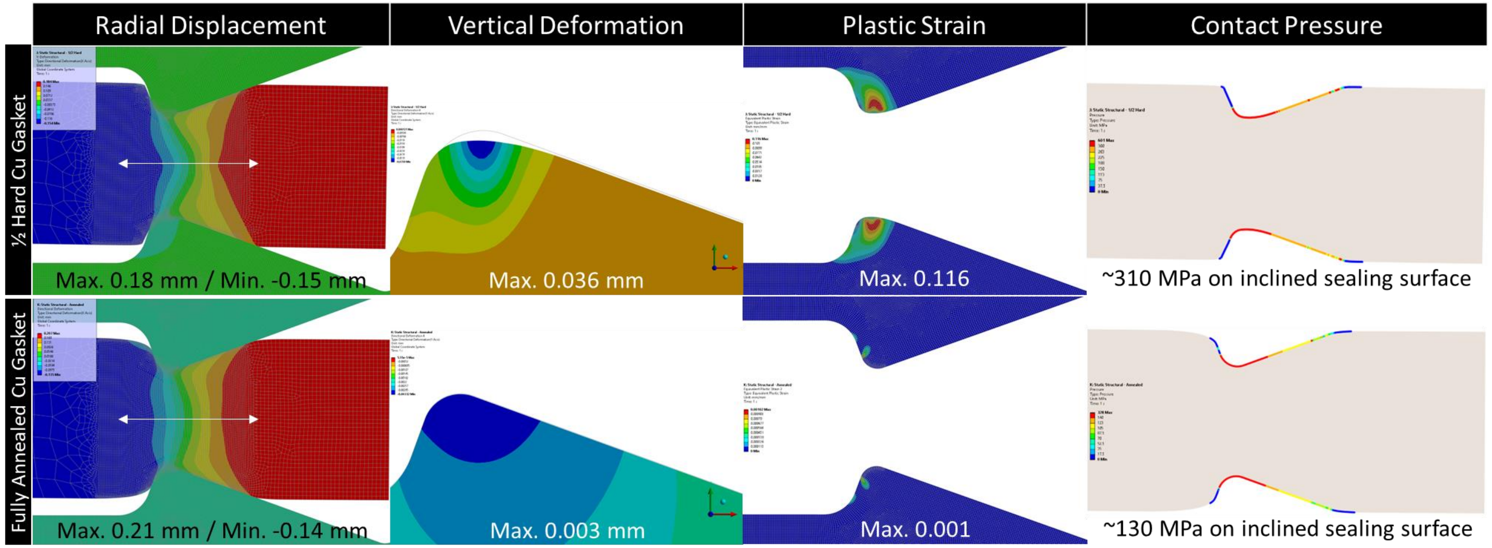
Divertor Neutral Pumping

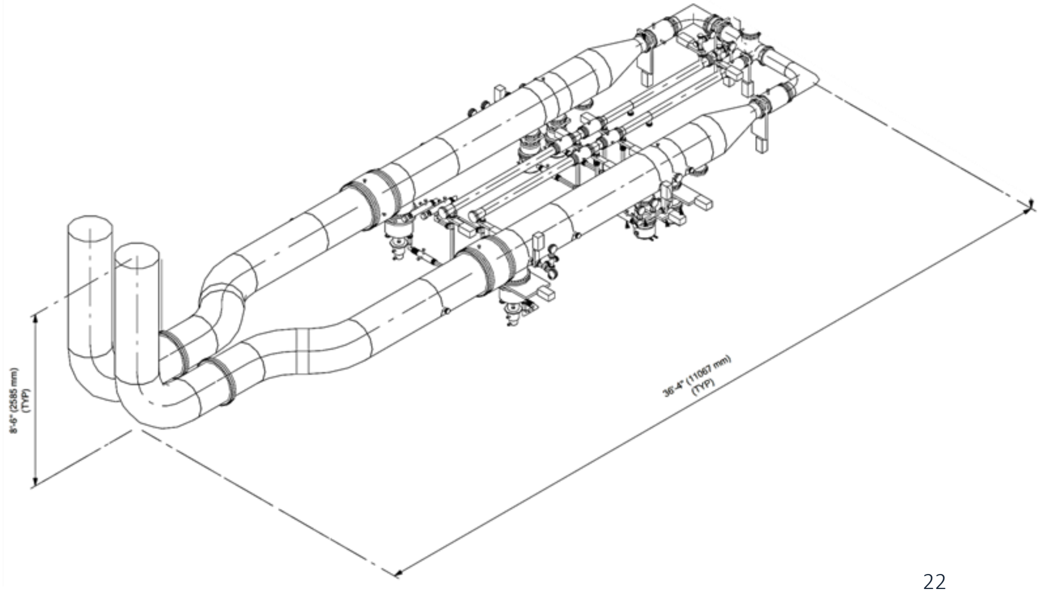
- What is a divertor?
  1. Primary exhaust for heat and ash produced by the fusion reaction
  2. Protects surrounding walls from thermal loads
  3. Minimizes plasma contamination [6]
- QTY 8 “toroidally symmetric” pumps in divertor region
- Pumped via custom cryopumps
  - Closed-loop, refrigerator-cooled
  - Tritium compatible
  - Halogen-free and radiation-resistant charcoal binder
  - Added thermal mass on second stage for increased throughput
  - Transient operation due to nature of plasma pulses
- Effective pumping speed analyzed using transitional flow capabilities of COMSOL, with B_4C shielding geometry accounted for
- Variable conductance vacuum valve allows:
  1. Neutral gas pressure control within the divertor
  2. Fast-actuated closure during disruption mitigation events (~100 ms)



Large Bore Piping to Maximize Vacuum Conductance

- CPMP & TPMP require ~50 m total of large bore piping, D ≈ 540 mm
- Flange seals must be suitable for UHV and radiation environment
  - Double spring-energized metal seals with interspace pumping or a CF gasket
- Calculations completed and prototyping efforts underway for a large rotatable and non-rotatable CF-style knife-edge flange
  - Documented use of similar sizes at CERN and GSI FAIR
- Custom large bore, two-ply electrical breaks and bellows also required for TPMP





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Thank you!

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