Fermilab
Proton Improvement Plan-II

PIP-II

US-DOE
India-DAE
Italy-INFN
UK-STFC-UKRI
France-CEA, CNRS/IN2P3
Poland-WUT, TUL

FERMI NATIONAL ACCELERATOR LABORATORY

October 23rd 2026

First Cobotic-Assisted String Assembly of PIP-II SSR2 Cavities at Fermilab

Tommaso Aiazzi - Mattia Parise

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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FERMILAB-SLIDES-26-0170-TD

About Me



Tommaso Aiazzi

Mechanical Engineer · Fermilab

- Grew up in **Italy**
- **Mechanical Engineering**, University of Pisa, where I started on accelerators
- **Fermilab**, Illinois: SRF accelerator components

My work combines **mechanical design** with **testing and manufacturing**, in close coordination with different teams and external partners

What I work on

1 SRF cavities

Fabrication and qualification of SSR1 and SSR2 jacketed cavities

LINAC'24 · SRF'25

2 Cavity processing

High-pressure rinse simulations and plasma processing of spoke cavities

LINAC'24 · SRF'25

3 Power couplers

Coupler fabrication and the yield of the ceramic windows

TTC

4 Robotics & automation

For accelerator assembly: first cobotic coupler installation (2023) and string (2025)

LINAC'24 · this talk

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About the Team

Scientists

- **G. Wu**

Cleanroom Team

- **D. Bice**, **R. Kirschbaum**, **T. Fermanich**, **M. Battistoni**, **M. Chlebek**, **T. Ring, D. Santucci**

University Partners

- **A. Ciaramella**, **A. Vivai** [UniPi]
- **N. Giffen, J. Imburgia, B. Whitlock, C. Denton, I. Salehinia, J. Ryu [NIU]**

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Mattia Parise



Donato Passarelli



Tommaso Aiazzi



Colin Narug



Jacopo Bernardini



Outline

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01

PIP-II, the Cleanroom and Cobots

PIP-II at Fermilab

An **800 MeV** superconducting H^- linac to power **DUNE**

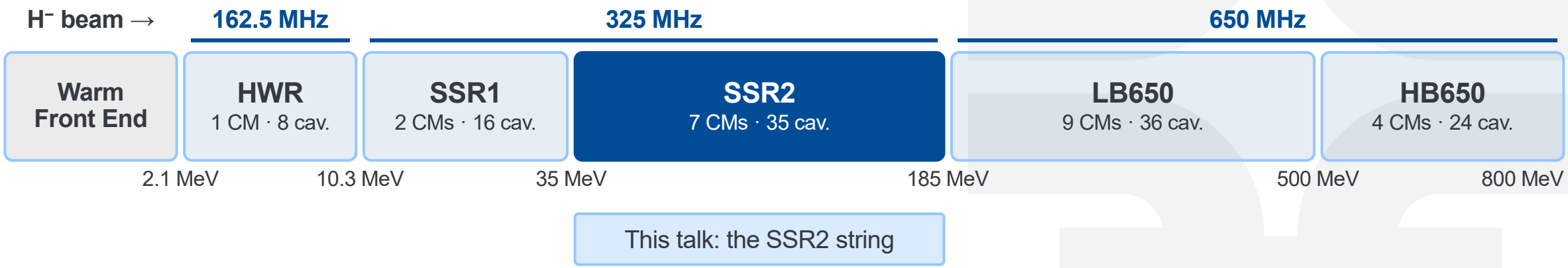
- Will power the world's most intense high-energy **neutrino beam**, sent **1,300 km** to **DUNE**
- Beam power upgradeable to **multi-MW**
- **5 cavity types** at **3 RF frequencies**: 162.5, 325 and 650 MHz
- First U.S. accelerator project built with **major international contributions**

800 MeV
H^- beam energy

1.2 MW
beam power on the LBNF target

23
superconducting cryomodules

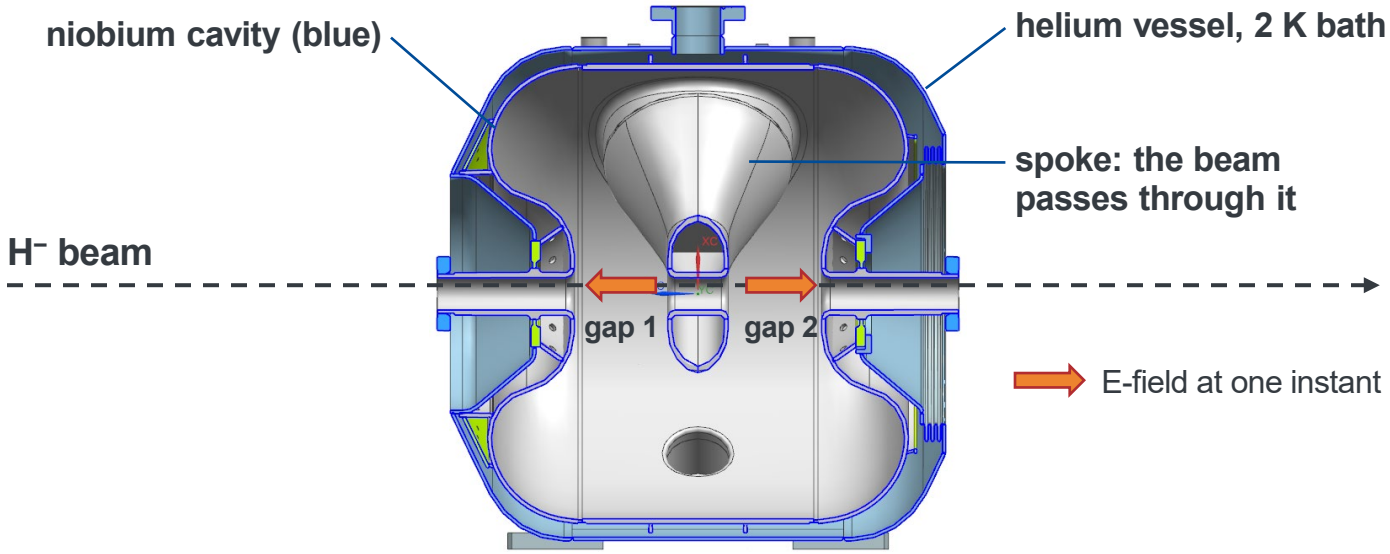
119
SRF cavities at 2 K



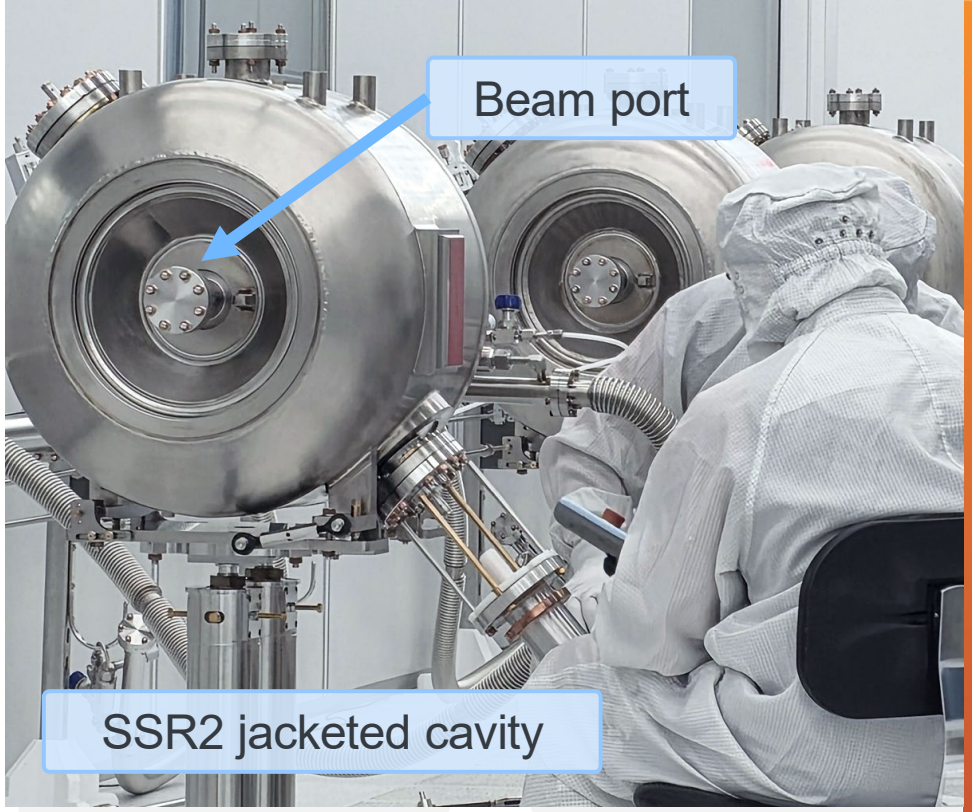
This talk: the SSR2 string

PIP-II SSR2 cavity

The cavity is where the beam gains energy



- RF power fills a hollow **niobium** shell with an oscillating **electromagnetic field**
- The bunch crosses **two gaps**; the field flips every half RF period, so it is **accelerated in both**
- **Superconducting at 2 K**: RF losses ~10^5–10^6× lower than in copper



325 MHz
RF frequency

0.47
optimal β = v/c

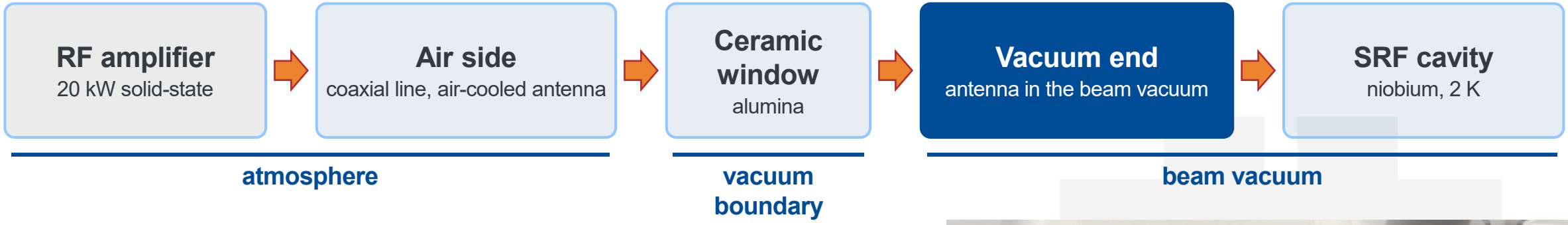
11.5
MV/m nominal gradient

40 mm
beam aperture

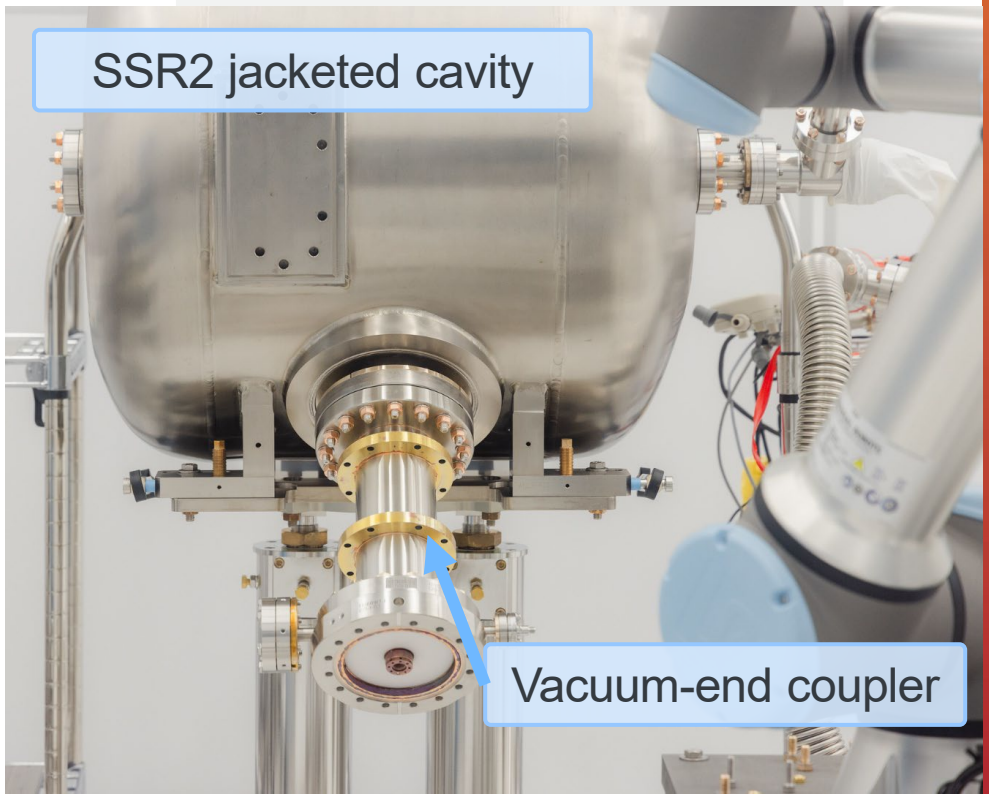
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HighPower Coupler

The coupler feeds RF power into the cavity, across the vacuum boundary

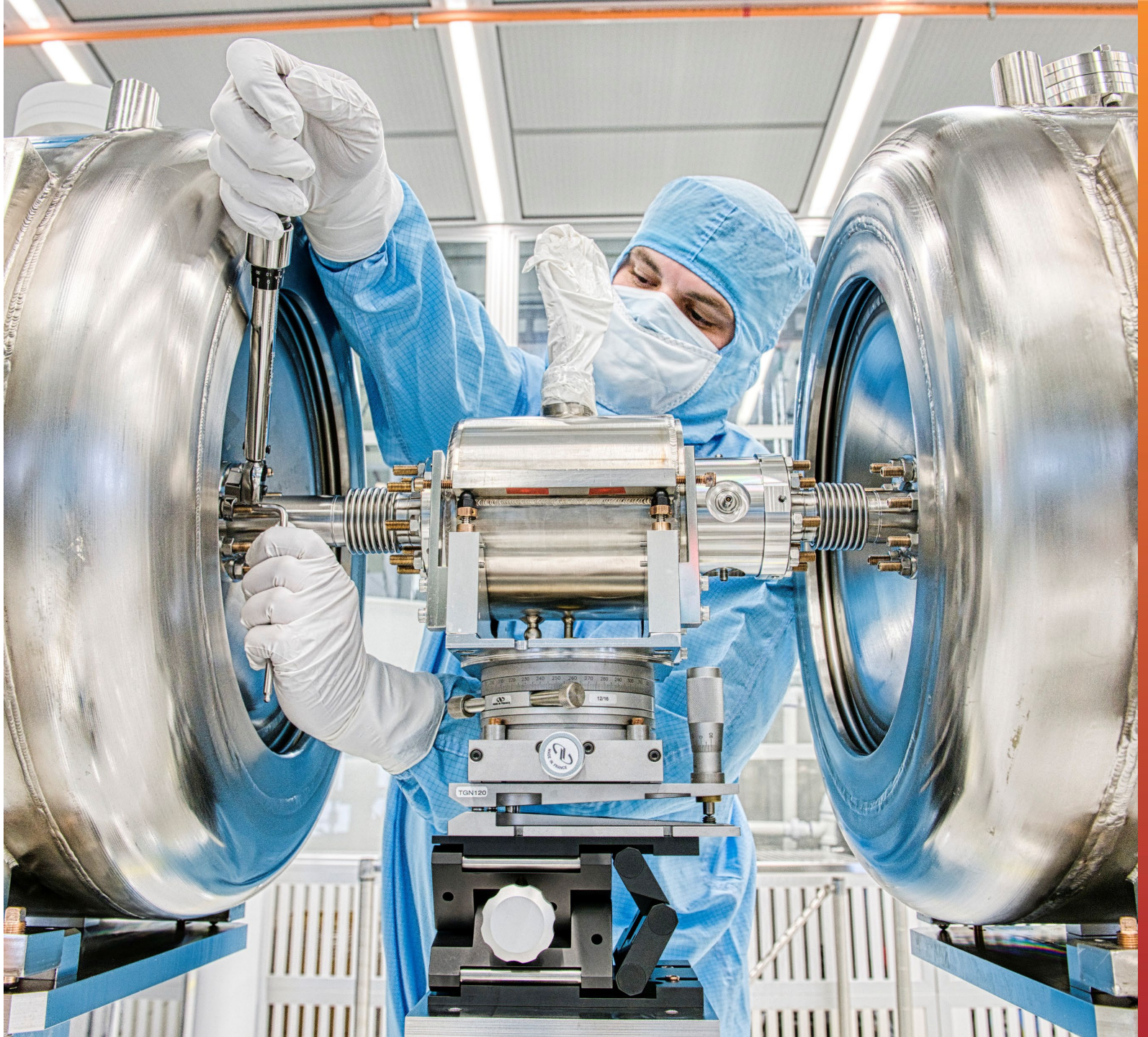


- A **coaxial antenna** couples the amplifier's RF power into the cavity field
- A single **alumina ceramic window** keeps the beam vacuum sealed from the air
- The **vacuum end** is bolted onto the cavity port **in the cleanroom, with the cavity open**: the step the cobot performs



Introduction

- Particulate contamination triggers field emission, local quenching, and degrades quality factor (Q_0) and accelerating gradients
- Cleanrooms maintain cleanliness by continuously flushing highly filtered air from the ceiling to the floor or sides
- Operator experience and tooling design are essential for successful SRF cavity string assembly



Introduction

Manual tooling for cleanroom assemblies is a double-edged sword:

- Flexible component positioning
- Eliminates operator weight-bearing
- Multi-part complexity (threaded/sliding connections)
- Steep 6-DOF learning curve requiring specialized training
- Rapid obsolescence when designs or projects change



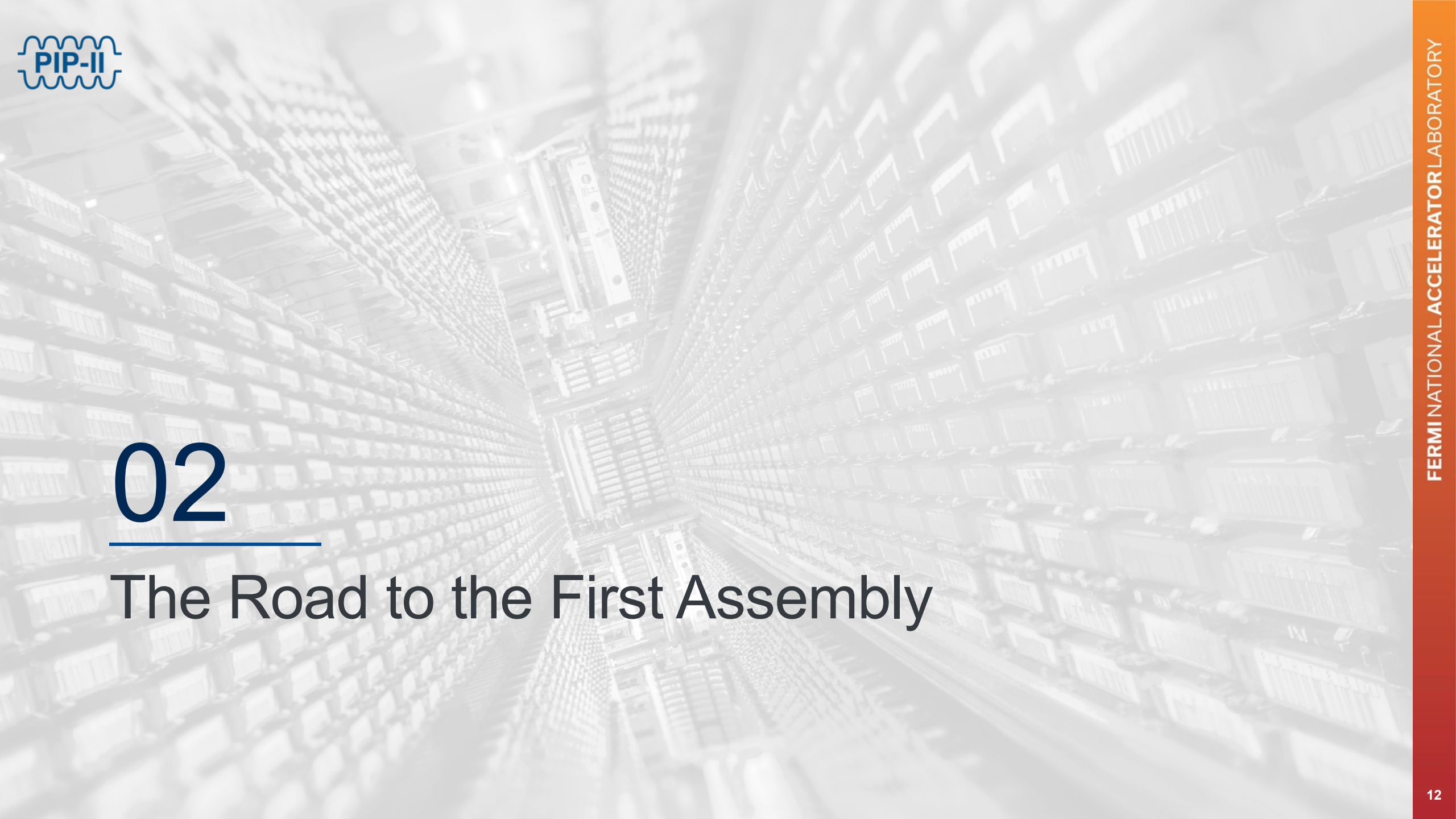
Robotic Arm

A **Universal Robots UR16e** cobot was chosen to begin development

- First **Cobot** (UR16e) procured in late 2023
- **December 2023**: the first Cobotic installation of a vacuum-end high power coupler on an SSR2 cavity for PIP-II
  - C. Narug, Robotic-Assisted Technology for Assembling PIP-II SRF Couplers onto Cavities in Cleanroom, TTC 2023, Fermilab
- We procured two additional cobots: one **UR16e** and one **UR5e**
- Students from **University of Pisa** and **NIU** worked on development for cleanroom SRF applications
  - C. Narug, Clean Room Protocols and Robotic Techniques for PIP-II, TTC 2025, Daejeon, South Korea
  - C. Narug, SRF Robotic Assembly Development at Fermilab, TTC 2026, Saclay, France



Feature / Specification	Details
Axes	6
Payload Capacity	16 kg (35.3 lbs)
Reach	900 mm
Integrated Sensors	End effector load cell
Force Accuracy	±5.5 N
Torque Accuracy	±0.5 Nm
Cleanroom Rating (ISO 14644-1)	Class 5 (at ≤ 40% speed)
Control System	PolyScope 5 pendant



02

The Road to the First Assembly

Road to the First Assembly

Design principles were established

- Use **open-source** options whenever possible
- Encourage **Collaboration** with **Universities**
- The initial goal was to **align**, **approach** and **install** a **vacuum-end coupler**

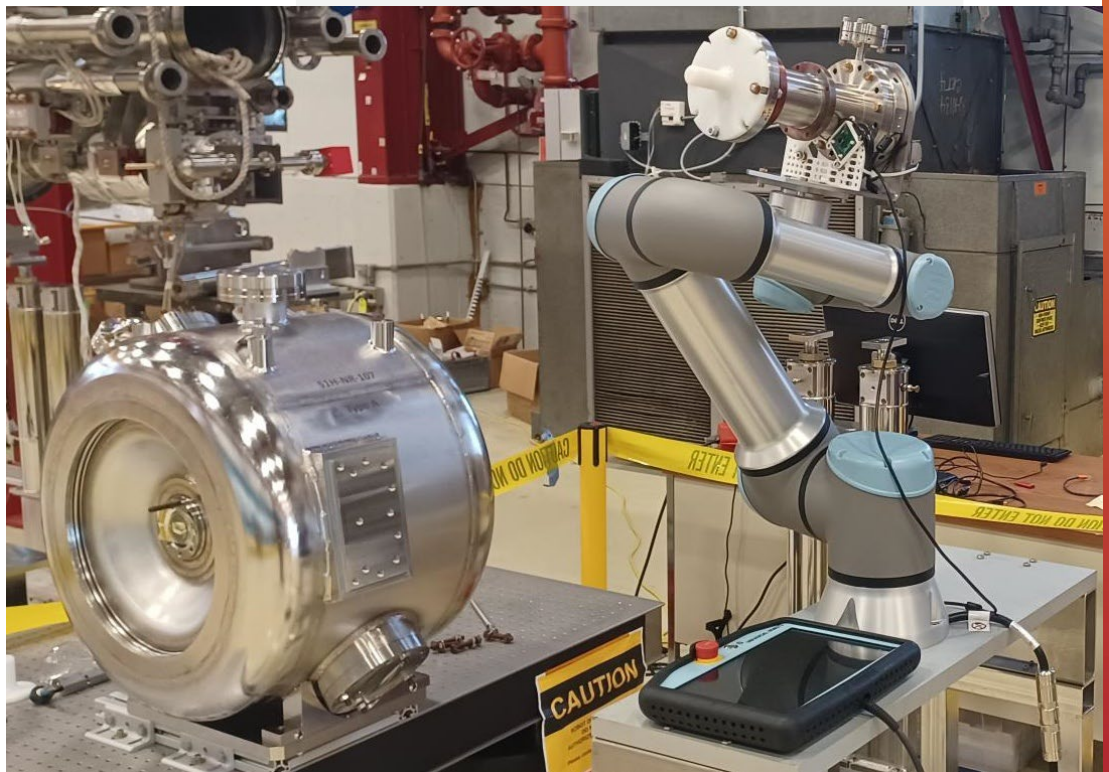
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Development of robotic activities coincided with opportunities to assemble SSR2 Cavities

- To show that robotics were a viable path forward, initial test setup + successful coupler-cavity installation were needed



Road to the First Assembly

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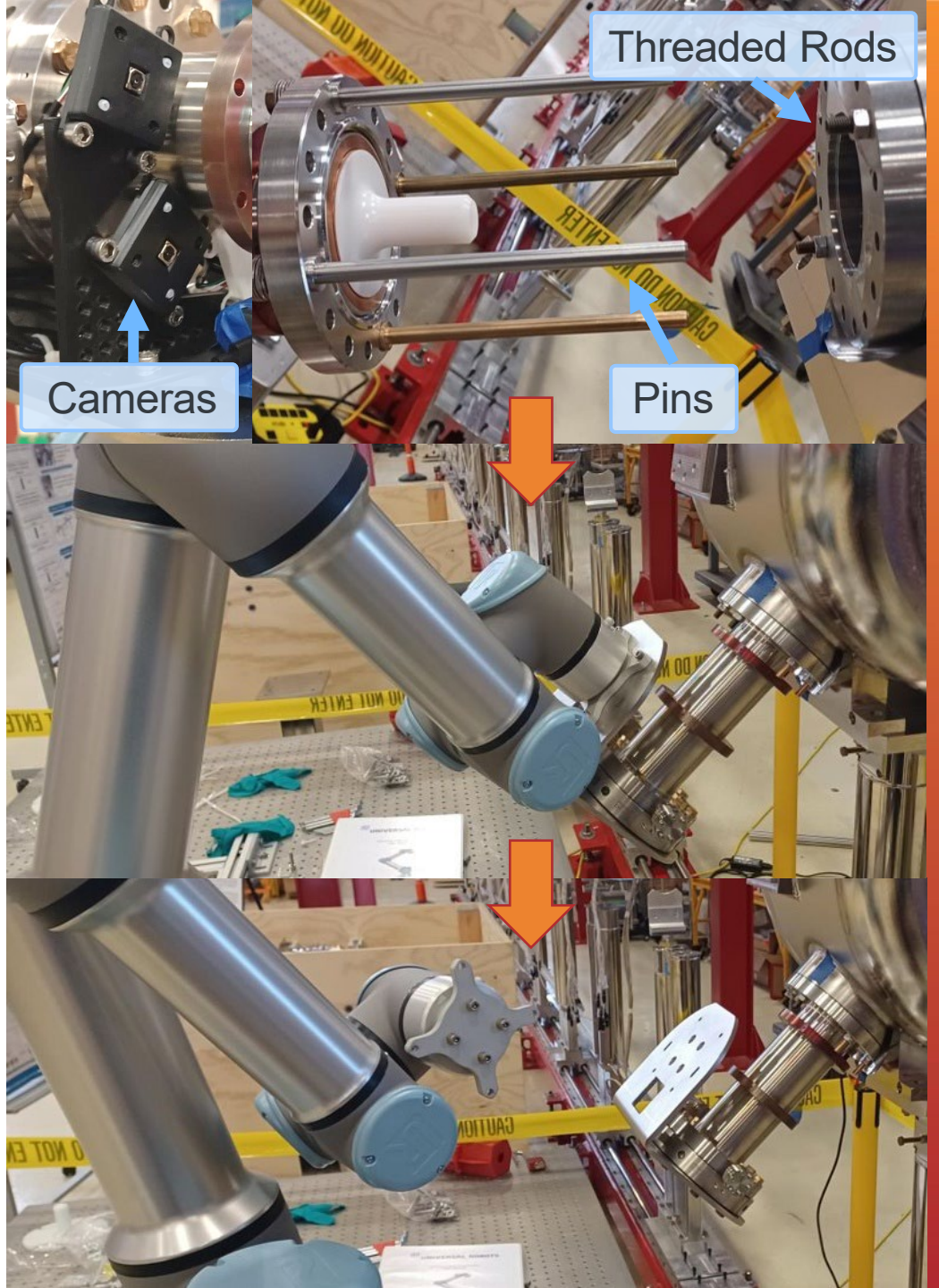
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Four alignment processes were prepared

- Visual
- Camera system
- Alignment pins on coupler side
- Threaded rods on cavity side



First Cleanroom Assembly

Cleanroom Setup



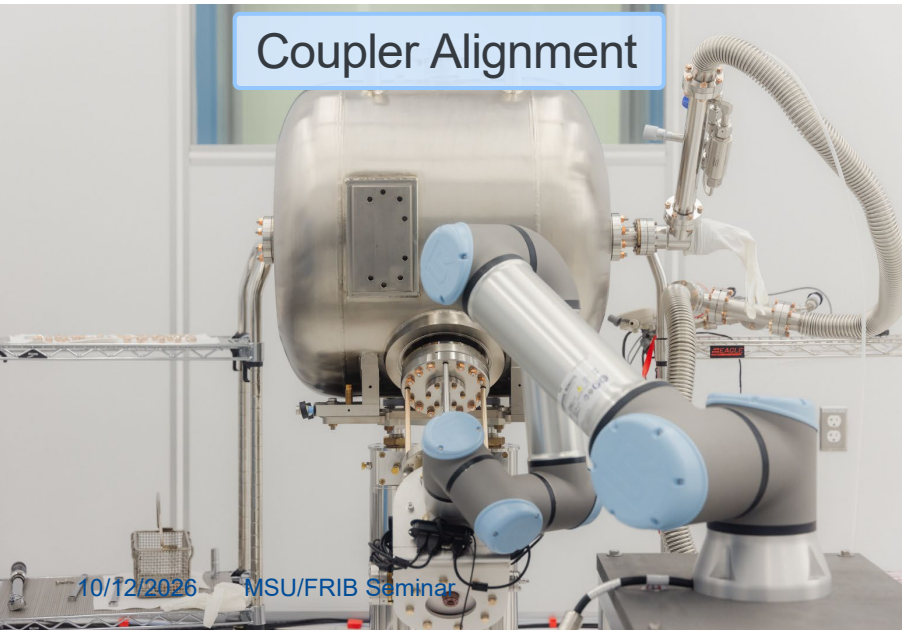
Positioning



Pre-assembly Setup



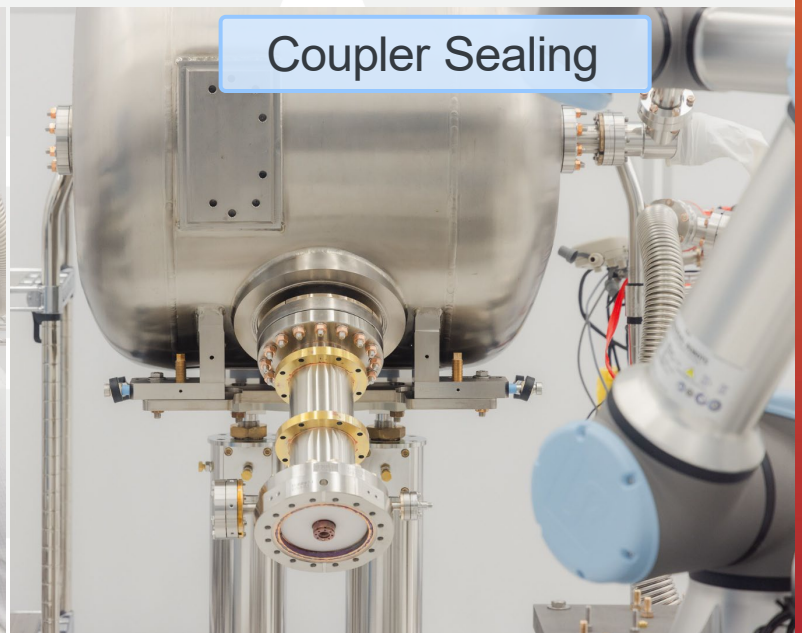
Coupler Alignment



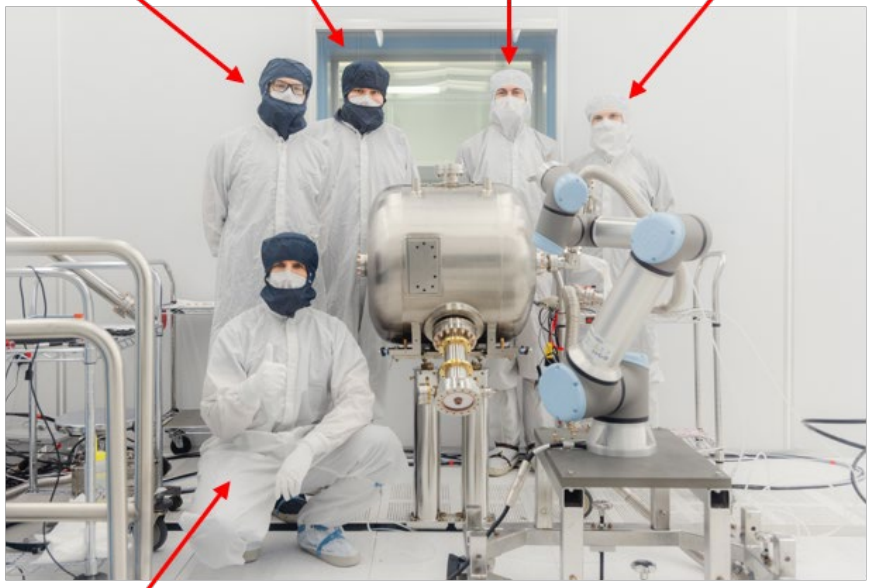
Coupler Sealing



Coupler Sealing



First Cleanroom Assembly



Outside the Cleanroom:

Tommaso Aiazzi, Damon Bice, Tim Ring, Jacopo Bernardini, Genfa Wu

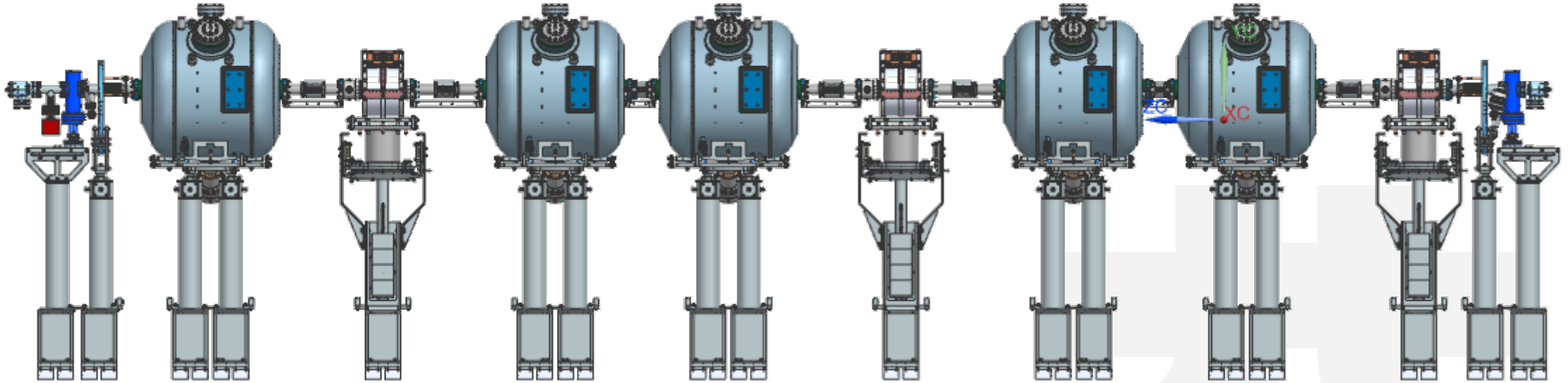




03

The String Assembly

The SSR2 String Assembly for PIP-II



To prepare for the string assembly, additional single cavity assemblies were performed

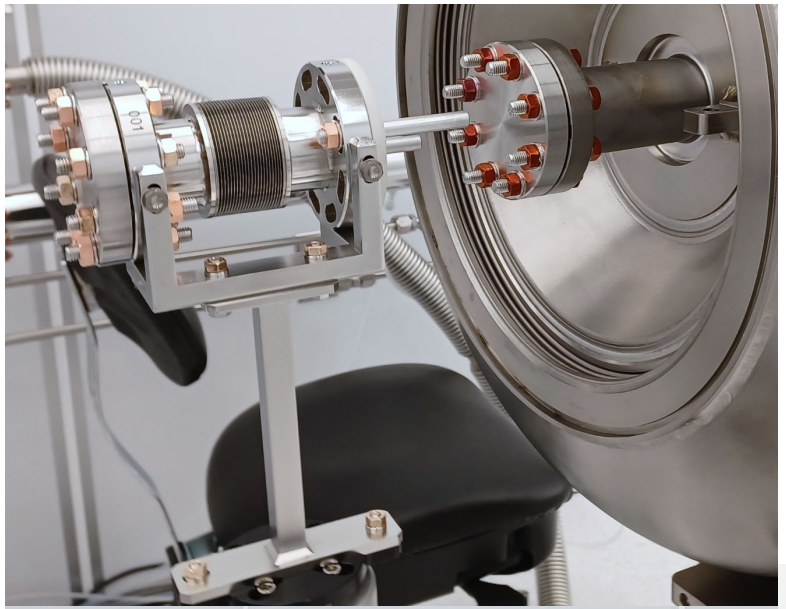
- Assembly missteps identified and excess equipment removed
  - Alignment pins used for final assembly process
- Bellows assembly and tooling processes developed
  - Using the development test station outside the cleanroom

Component	Quantities
Cavities	5
Magnets	3
Interconnecting Bellows	9
Gate Valves	2

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The SSR2 String Assembly

Sept.–Oct. 2025: the first cobotic-assisted string assembly





The SSR2 String Assembly

Sept.–Oct. 2025: the first cobotic-assisted string assembly

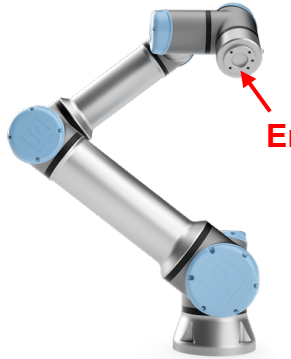




04

The Next Phase: Full Automation

The Hardware



UR16e



Basler a2A4508



Intel RealSense D435i

UR16e collaborative arm

- Carries the RF coupler on the tool flange; 16 kg payload covers coupler + camera bracket.

Intel RealSense D435i

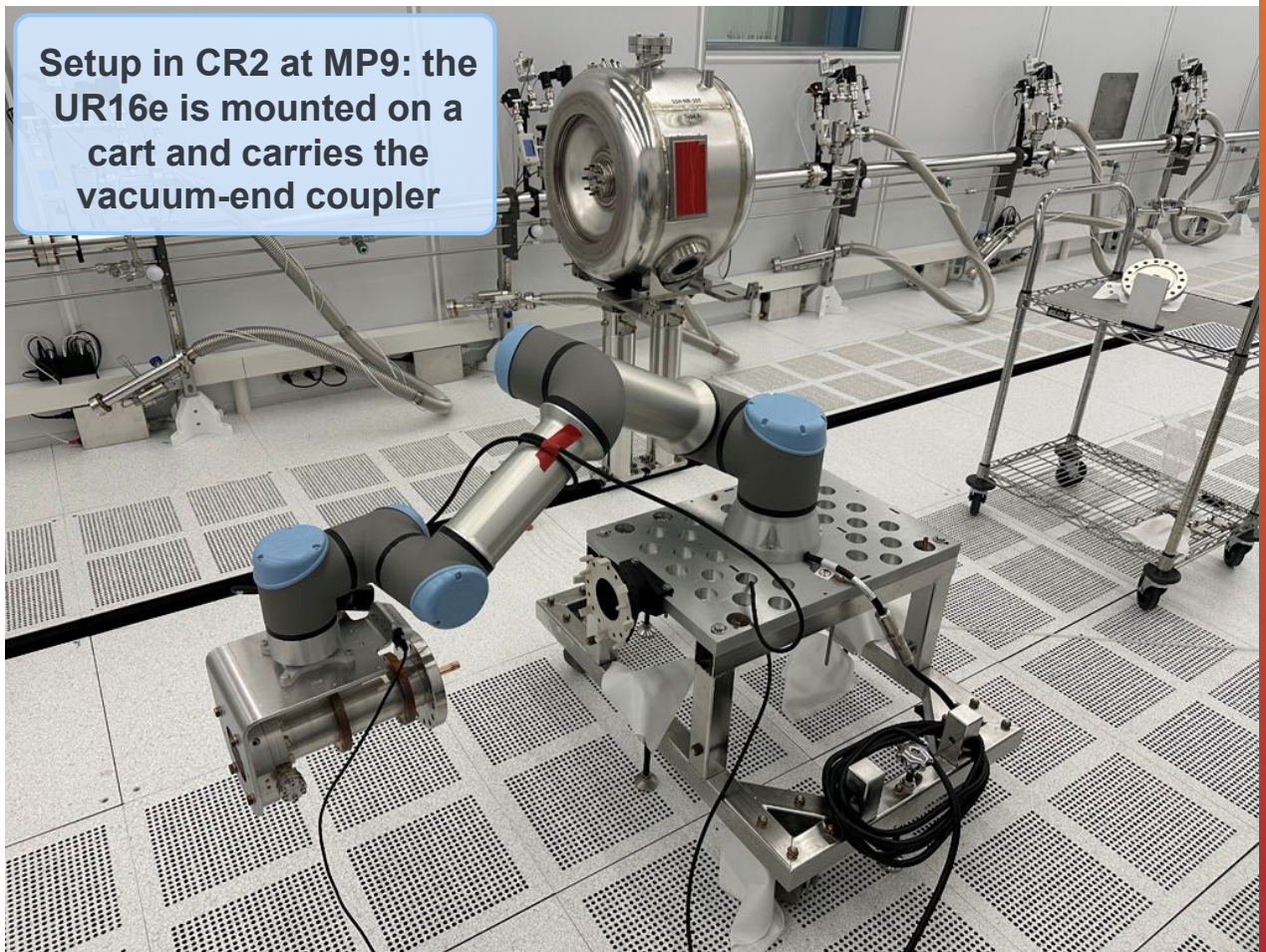
- 1920×1080, calibrated intrinsics.

Basler a2A4508 (18 MP) + Fujinon 16 mm

- Mounted next to the D435i on the wrist; dual-camera mode. Fixed-focus, low FPS, high resolution B&W camera.

Force sensing via the UR16e Cobot

- The cobot measures the force applied at the End-Effector



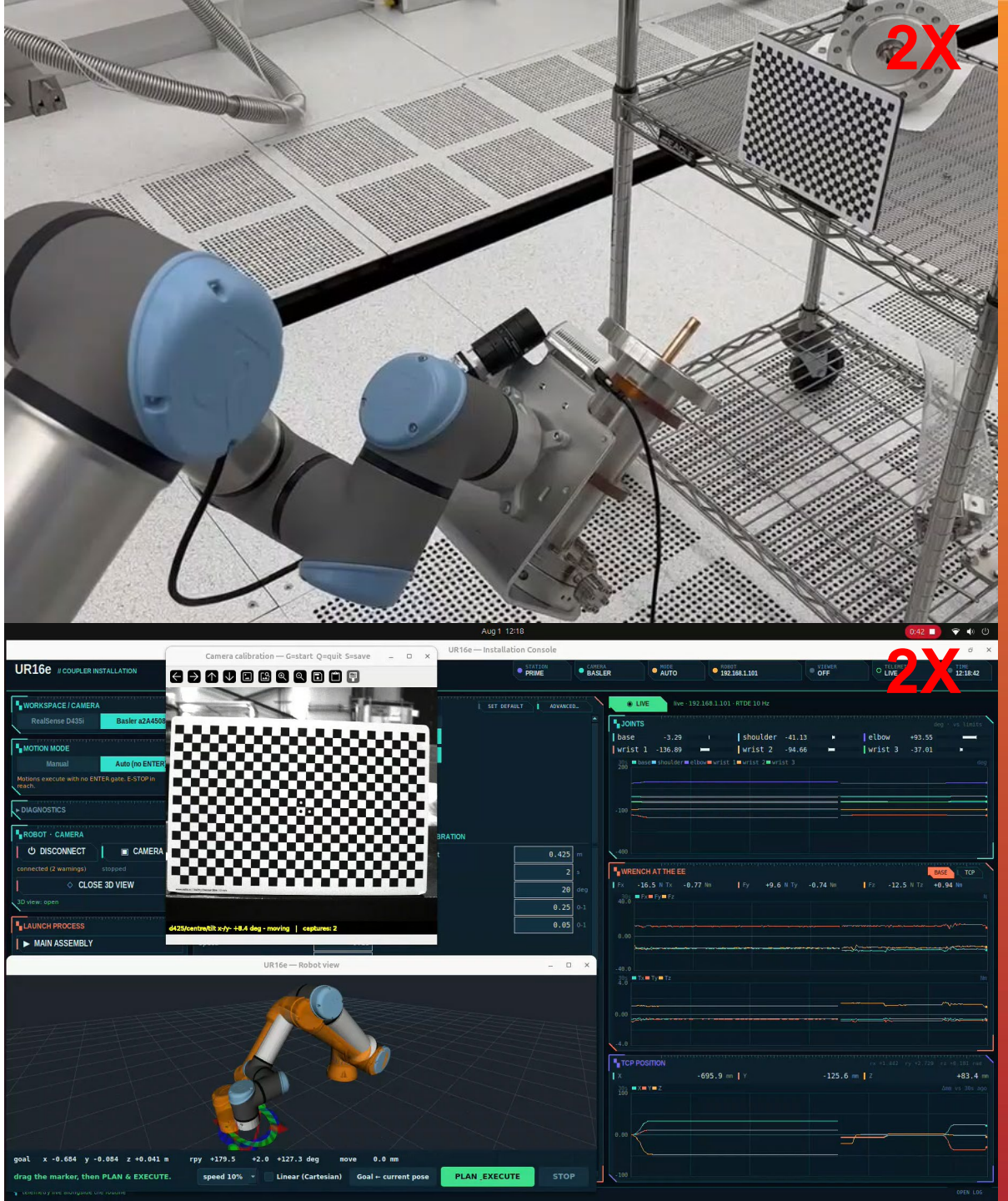
Setup in CR2 at MP9: the UR16e is mounted on a cart and carries the vacuum-end coupler

The Pipeline

1 Camera calibration

Intrinsics + hand–eye: fully automatic

- A fixed checkerboard is used to calibrate both the Intrinsics (Camera Distortion) and the Hand-Eye transformation (where the camera is with respect to the End-Effector)
- 54 photos of the checkerboard are automatically taken at different end-effector poses
- Required only once. Duration ~5 minutes.



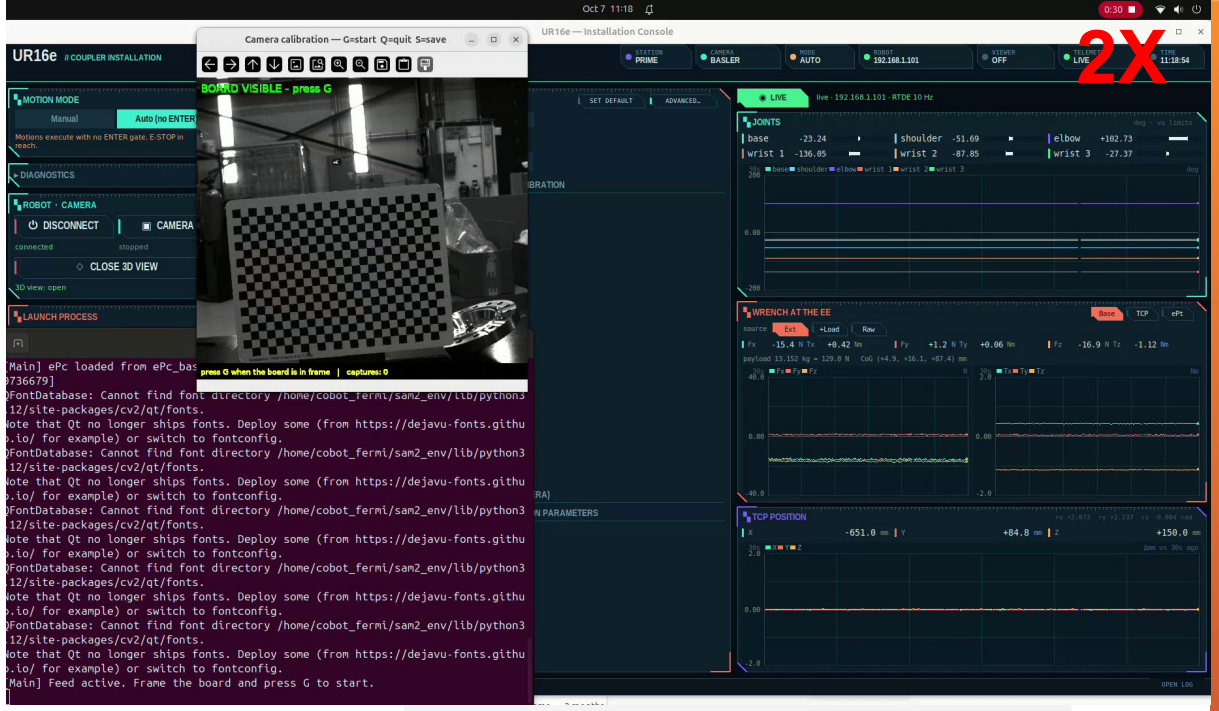
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Leveraging RViz to ensure all 54 poses are reachable without collisions

```
================================================================================
ANSWER 1 — HOW MUCH TILT AND ROLL CAN YOU ASK FOR?
================================================================================

  Scanned by re-planning the whole session at each value and scoring it
  from this same start pose. These two angles are what conditions the
  hand-eye solve (see pose_plan.py), so a headroom of zero is worth knowing
  and headroom you are not using is worth more.

  tilt  set to 30 deg -> 54/54 poses
        30 deg is the most that keeps every pose — it is already at the limit.
        the next rung, 35 deg, drops to 46/54.
        15:54/54  20:54/54  25:54/54  30:54/54  35:46/54  40:39/54  45:37/54

  roll  set to 60 deg -> 54/54 poses
        YOU CAN ASK FOR MORE: every pose still succeeds up to 75 deg.
        the next rung, 90 deg, drops to 50/54.
        15:54/54  30:54/54  45:54/54  60:54/54  75:54/54  90:50/54

  (each rung reads value:reached/planned. The pose COUNT changes with the
   angle because duplicate poses are dropped — that is the plan, not a bug.)

================================================================================
ANSWER 2 — WHERE SHOULD THE BOARD GO?
================================================================================

  THE BOARD IS FINE WHERE IT IS — every pose succeeds from this placement. Do not move it.

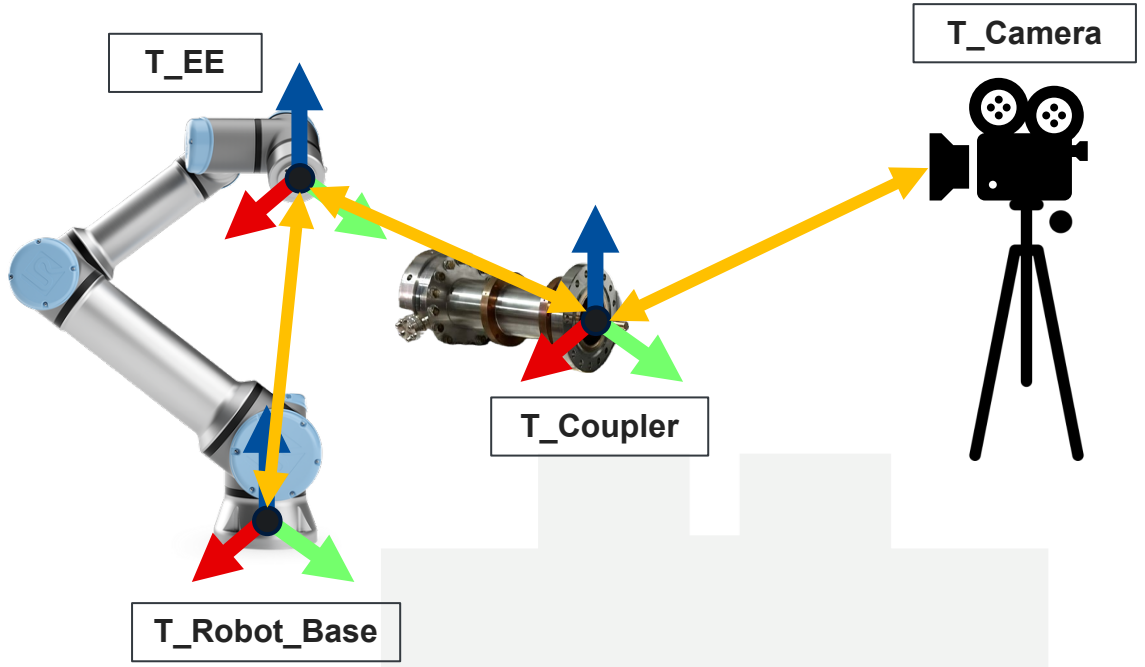
  (117 s)
================================================================================
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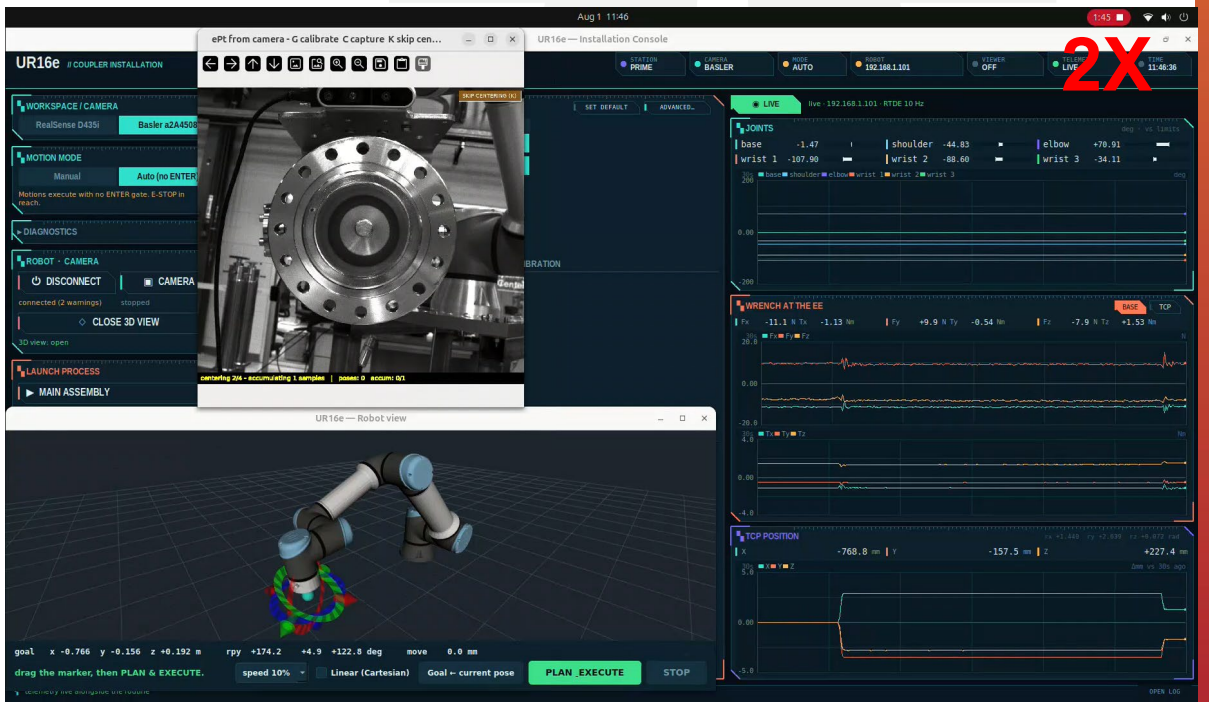
The Pipeline

2 Coupler calibration

Where is the coupler relative to the end-effector?

- Using a fixed camera, we detect the position and orientation of the coupler flange
- The cobot moves the coupler, and we collect several photos at different poses
- By solving AX = YB we can reconstruct the position of the coupler with respect to the end-effector
- Required each assembly: ~5 minutes



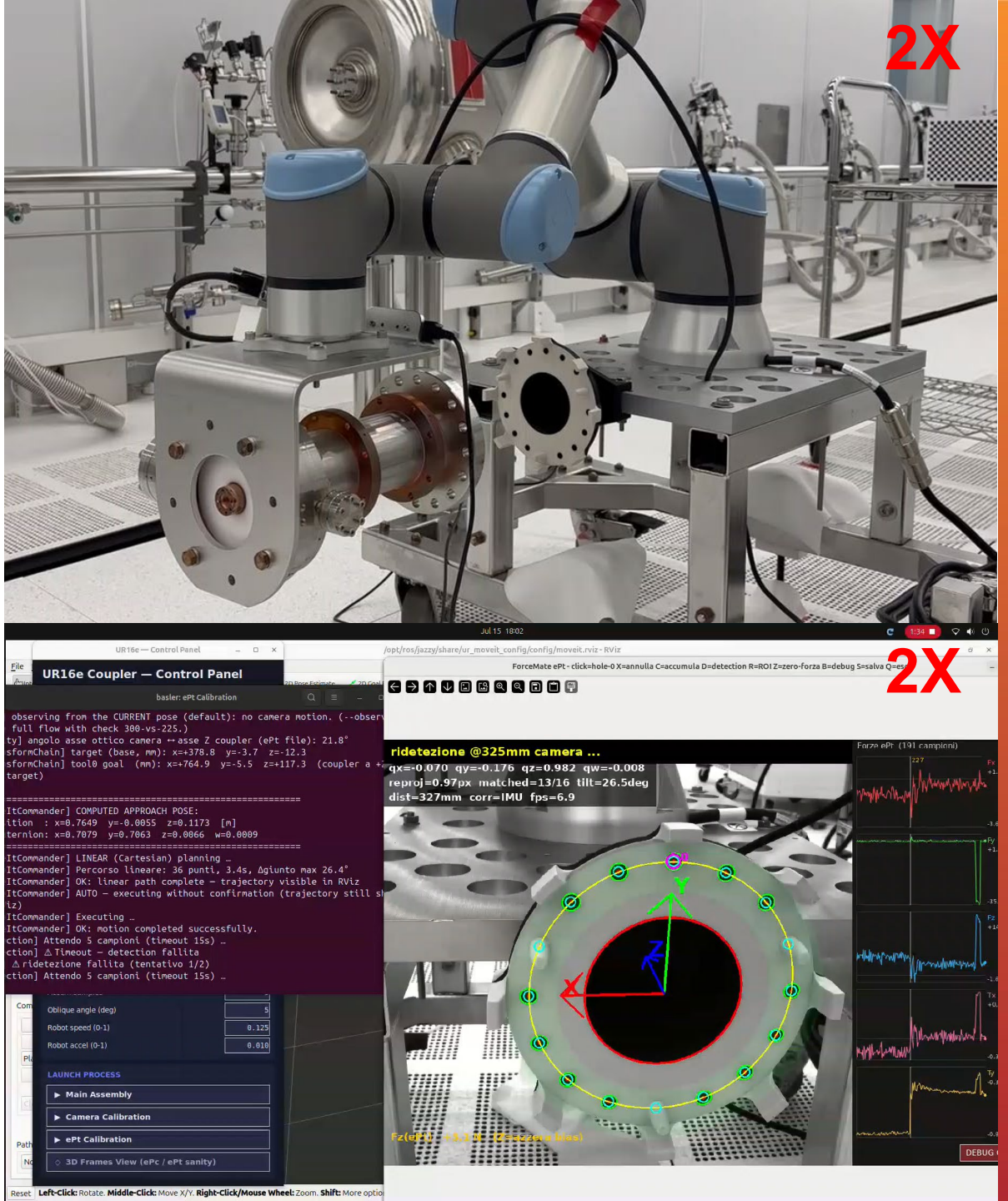


The Pipeline

2 Coupler calibration

Where is the coupler relative to the end-effector?

- Using the camera, we detect the position and orientation of a fixed calibration flange
- The cobot aligns the coupler to the calibration flange
- Fine tuning of the coupler position is performed
- The coupler position and orientation with respect to the end-effector are calculated
- Required each assembly: ~2 minutes



The Pipeline

1 Camera calibration

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2 Coupler calibration

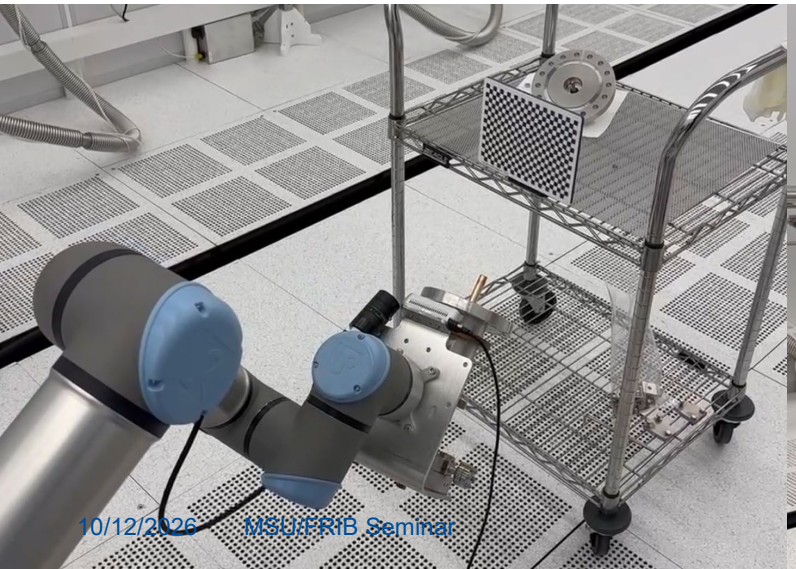
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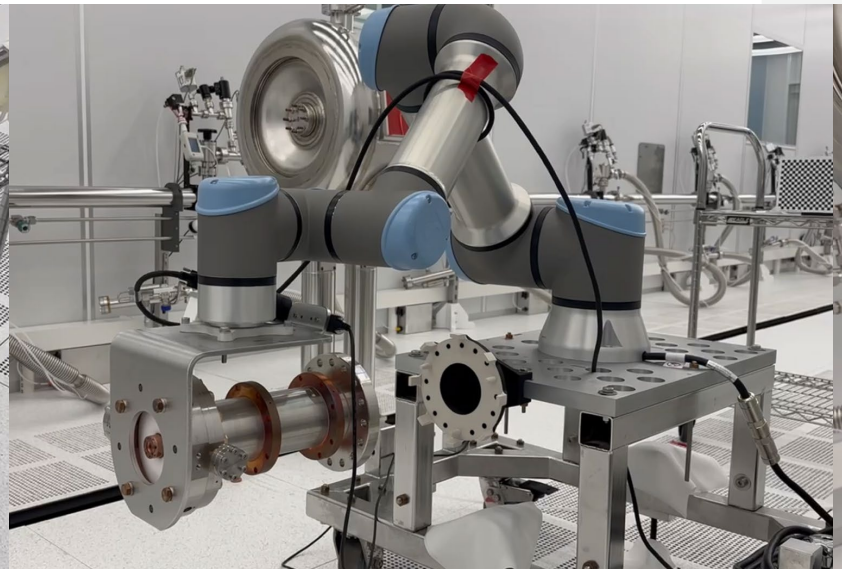
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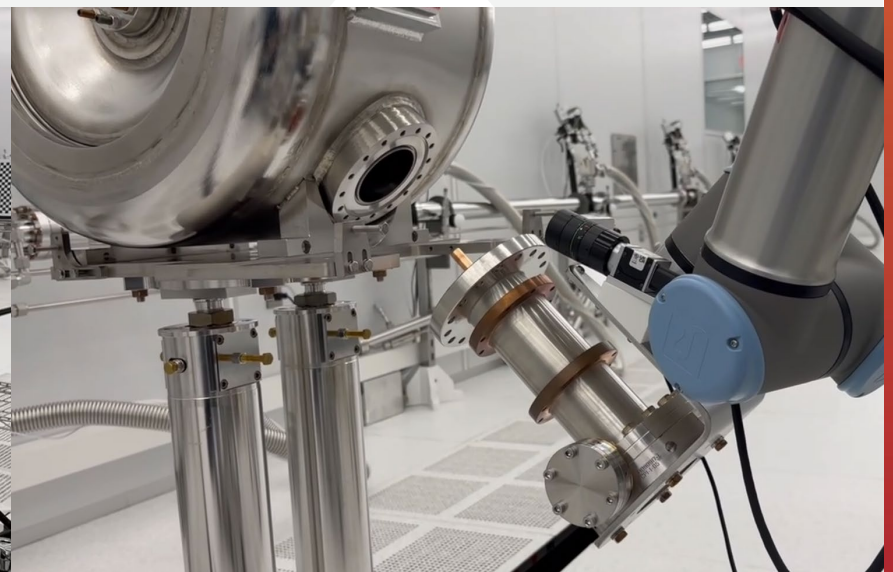
3 Main assembly

Coupler onto the SSR cavity flange

- Coaxial align at a distance, settle, accumulate
- 4 oblique orbits → fuse → frozen target
- Approach close position → 0 mm, one gate per step
- Force-seat: push tiny steps until Force goal is reached







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The Detection

1) OWLv2 (Open-World Localization v2, released by Google DeepMind, 2023)

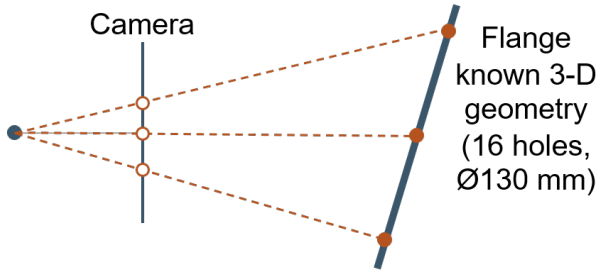
- Zero-shot local AI model: find the flange and crop it. Then it selects the holes inside the crop. Simple gate for size and aspect ratio filters out unwanted features.

2) SAM 2 (Segment Anything Model 2, Meta AI, 2024, open weights)

- SAM 2 is an AI tool that can instantly outline and track any object in both pictures and videos

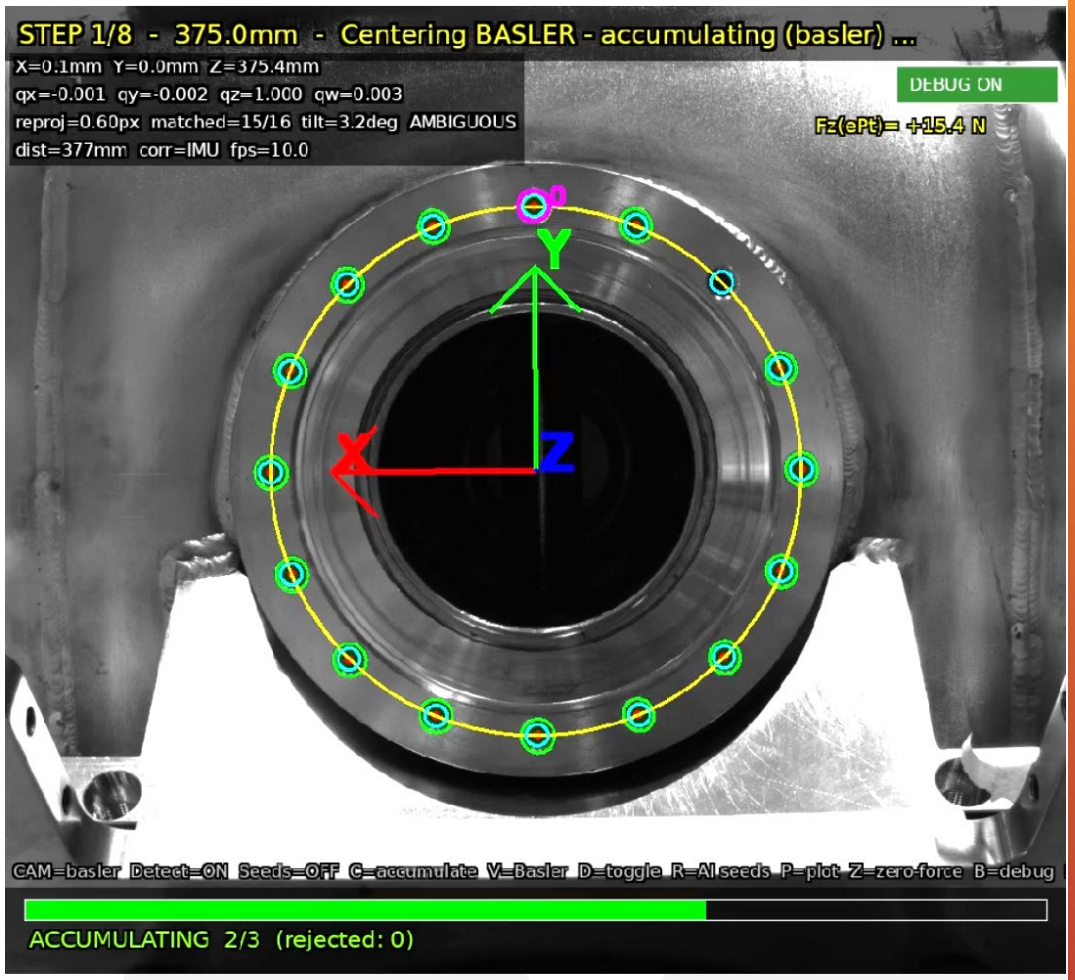


- We create a mask that excludes everything but the bolt holes; ellipses are fitted and their centers computed on the image



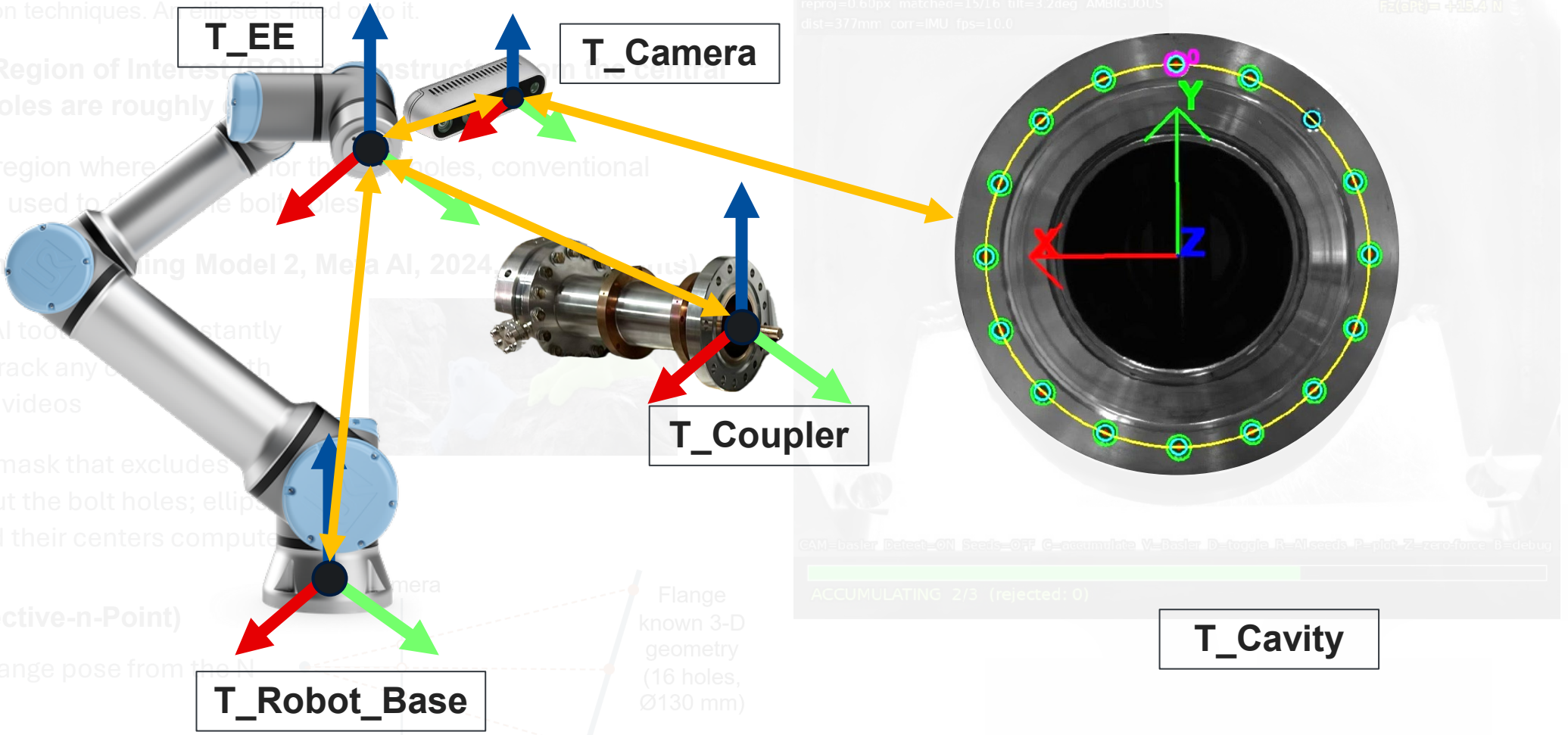
3) PnP (Perspective-n-Point)

- Returns the flange pose from the N hole centers



Machine vision: holes are segmented and fitted with ellipses; centers are used to solve PnP problem resulting in the final pose computation

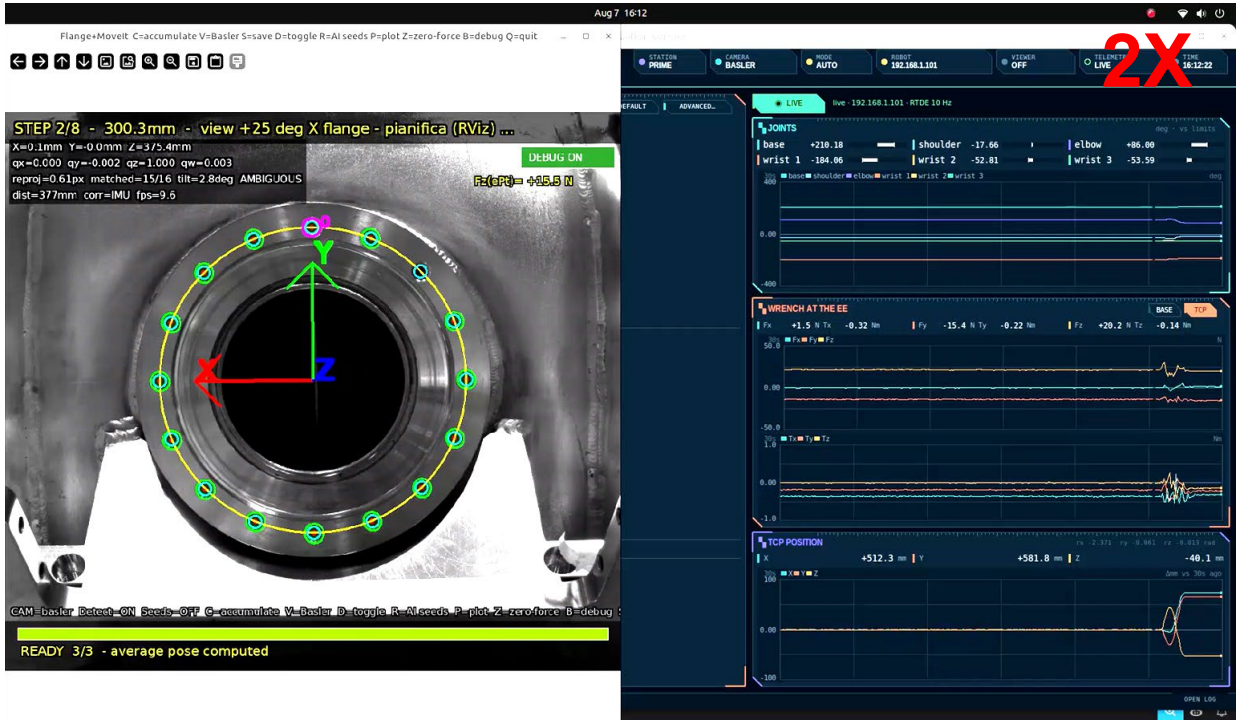
The Detection

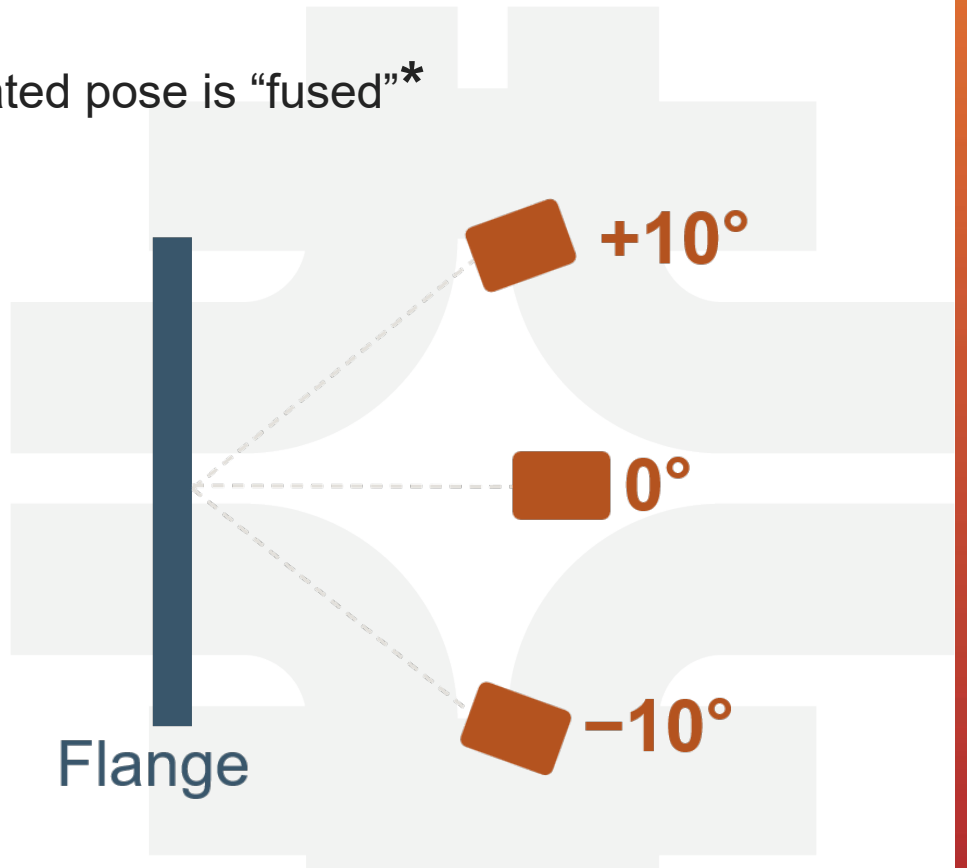


Multi-View Fusion

Single view is weak

- Using 1 image from 1 direction is not sensitive enough to compute the pose (position and orientation) of the cavity flange with sub-mm/sub-degree precision
- Multi-View image fusion was exploited to reduce system complexity as it can be achieved using 1 camera only
- The camera is moved around the detected object and the estimated pose is “fused”*





* F. L. Markley et al., “Averaging Quaternions”, J. Guid. Control Dyn. 30 (2007)

Main Assembly

Duration ~ 1 minute + manual fastener assembly

0 Initial detection and pose accumulation

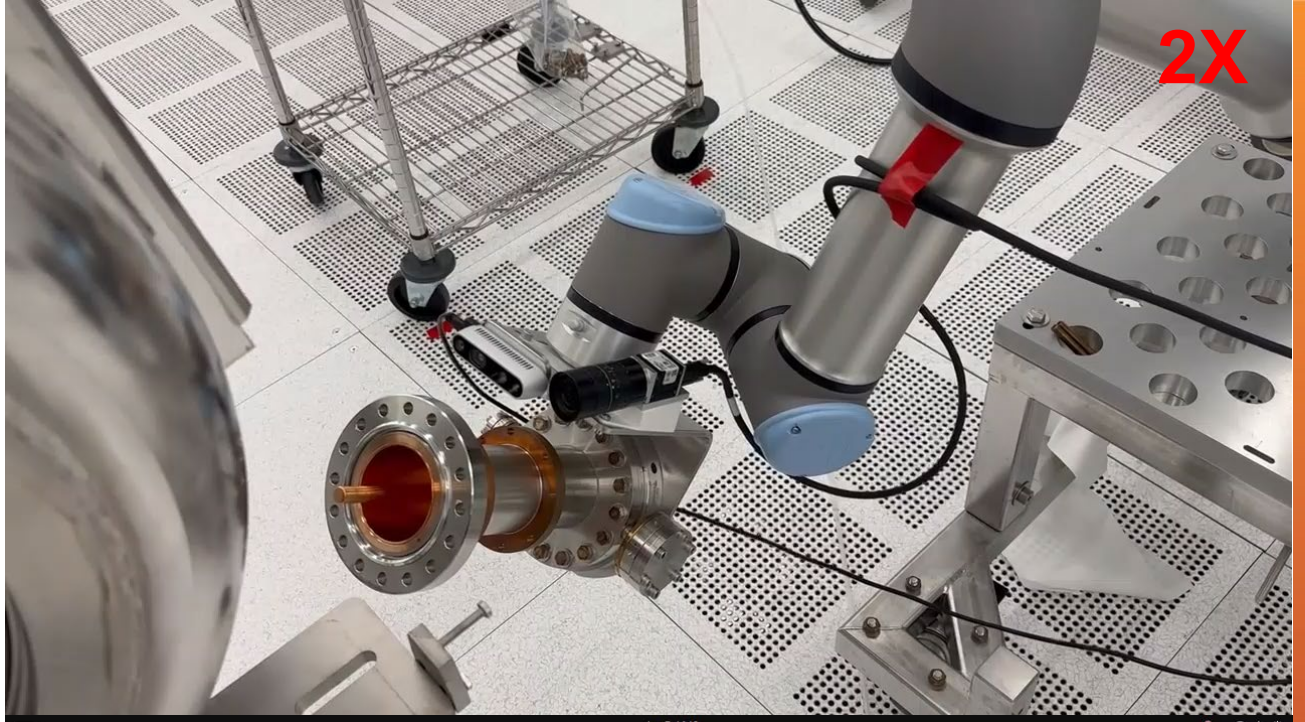
1 Coaxial alignment: coupler centered on the flange axis at a distance, settle 1-3 s

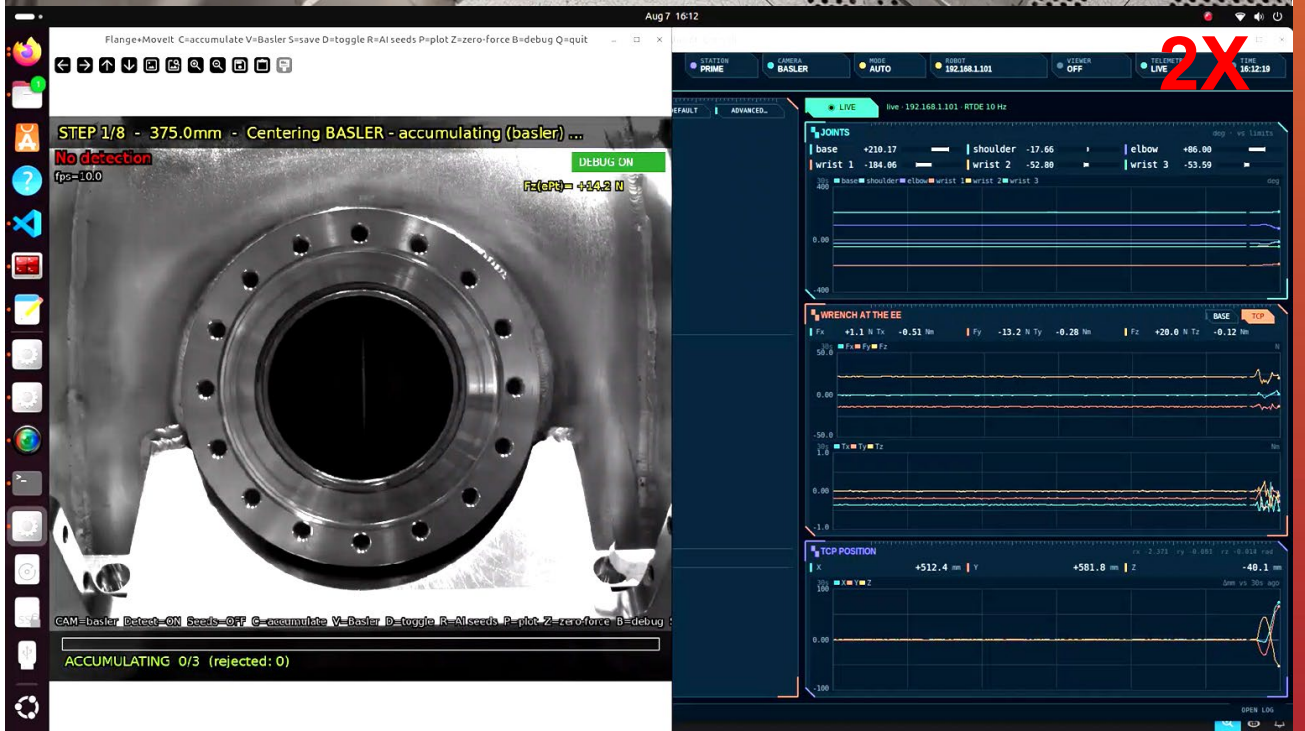
2 Frontal accumulation (5 samples) + 4 oblique orbits ±10-20° about flange X and Y (auto-fallback ±5° if a view sees < 10 holes)

3 Fusion of up to 5 estimates → final target; divergence gates stop the sequence on systematic error

4 Final approach with pose FROZEN: 200-100 mm → 0 mm, one plan-and-confirm gate (RViz) per step, straight-line Cartesian motion

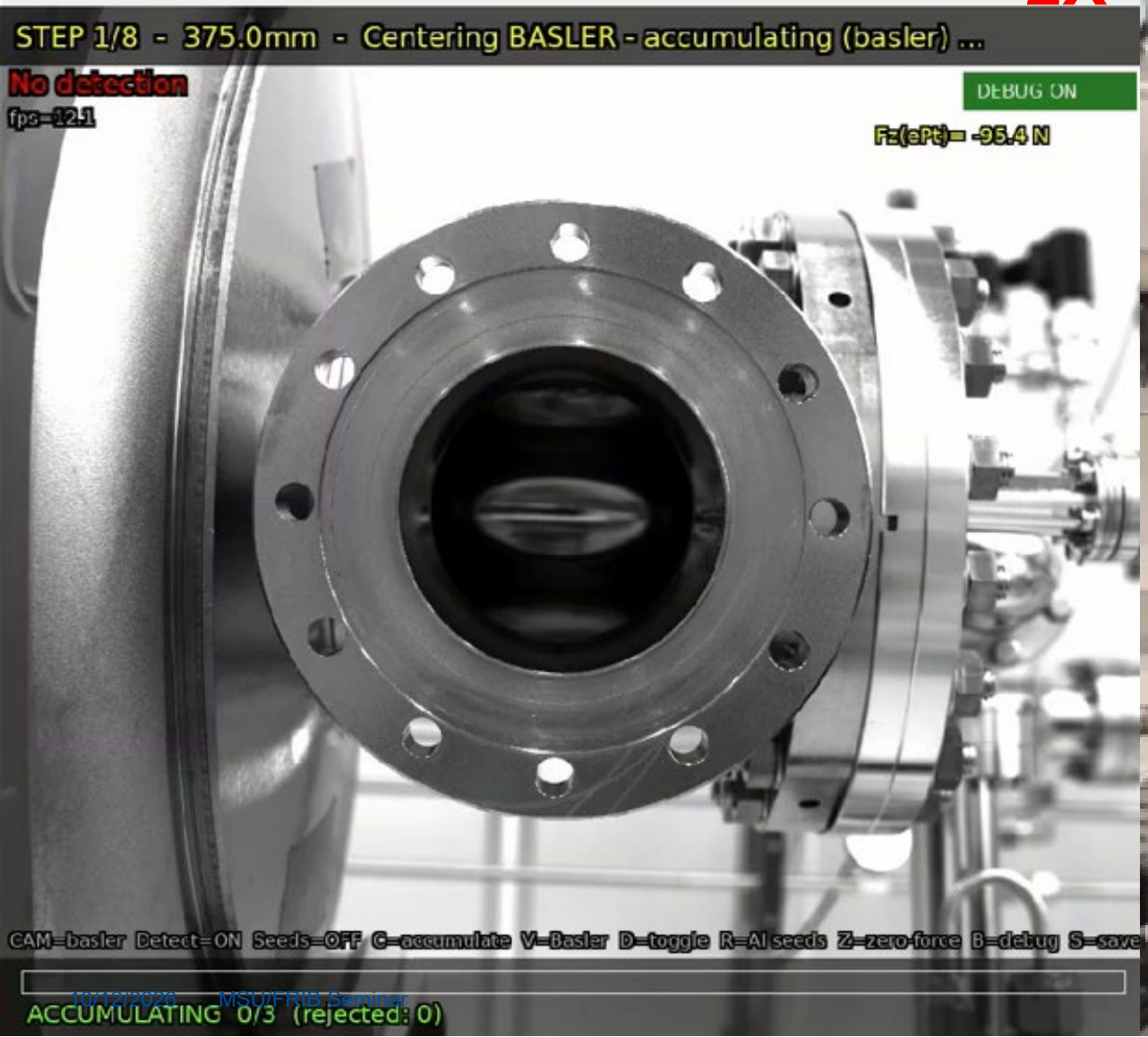
5 Force-seat: while |Fz(ePt)| < 20-100 N advance 0.5 mm along the target axis, up to 10 mm past the estimated plane then STOP with a warning



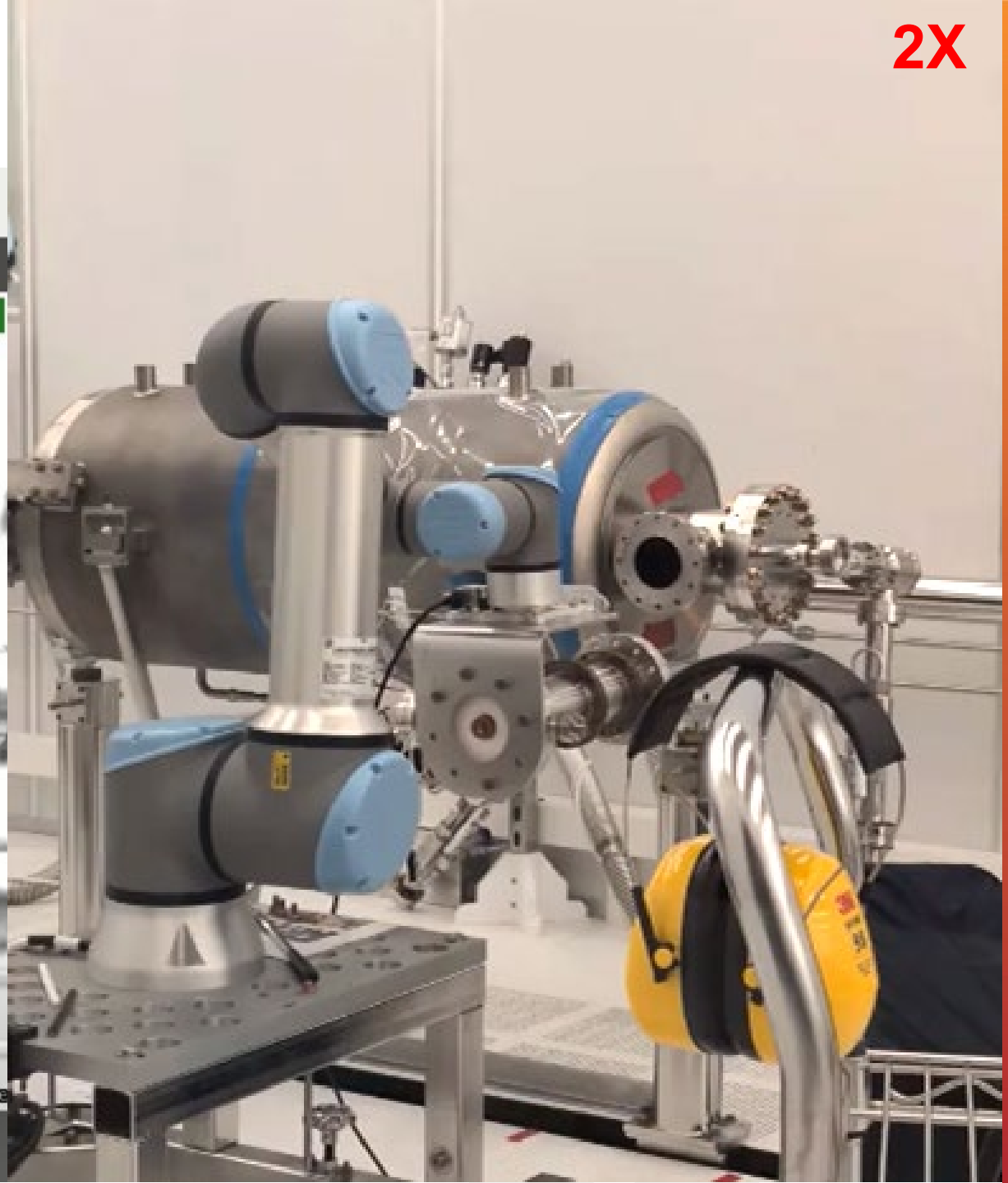


HB650 Assembly

2X



2X

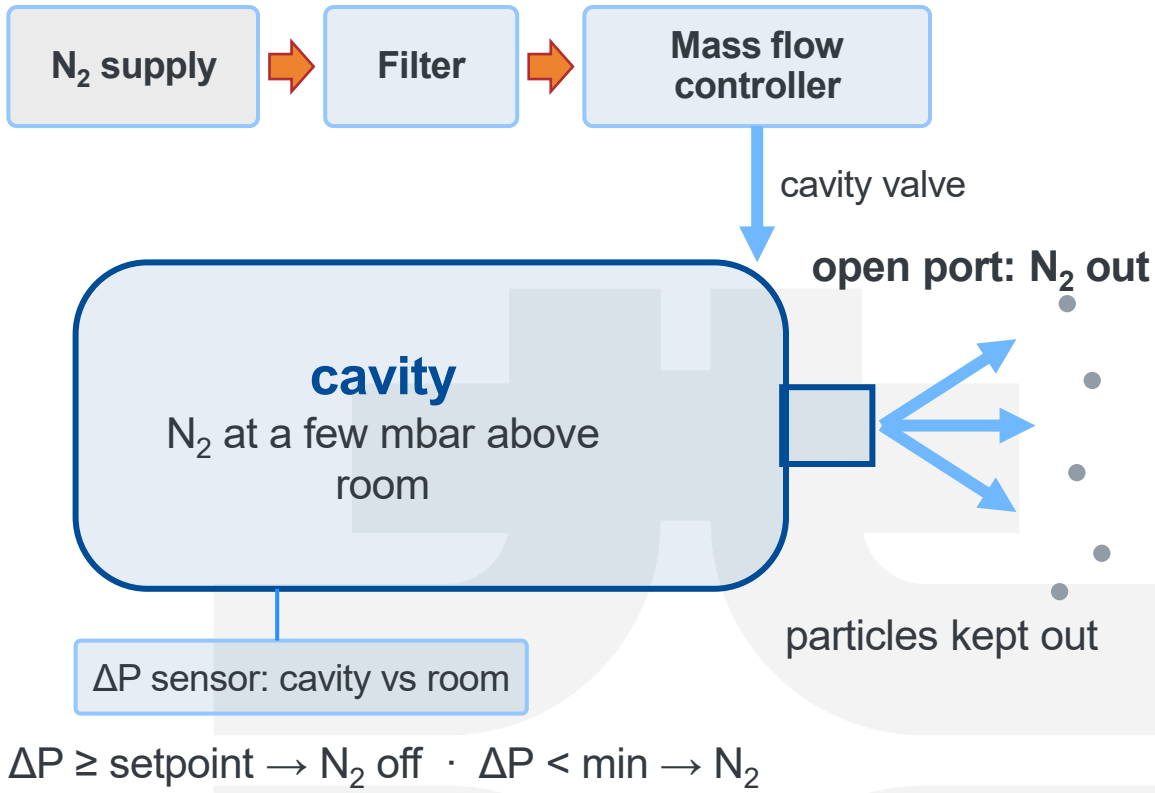


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Purging the Open Cavity

While a flange is open, clean nitrogen flows **out** of the cavity, so particles cannot flow **in**

- **Why:** with the beam vacuum open, an outward flow of filtered N_2 keeps cleanroom particles from drifting into the cavity
- **How:** N_2 enters through the cavity valve; mass flow controllers and a cavity-vs-room pressure sensor hold a small, steady overpressure
- **Low overpressure** (~5 mbar, not 50): no sudden burst when a flange is loosened, which could pull particles back in
- The purge **must run whenever the cavity is open**: losing it during an HB650 coupler installation may have degraded the cavity



~5 mbar
overpressure setpoint (was 50 mbar)

1 mbar
pressure control precision

0.25–15
SLPM mass-flow range

Sealing the Cavity

The squared coupler **seals the cavity**, so the purge can stop before bolting

- A slightly tilted coupler touches the cavity flange on one edge: the contact force creates a **torque** about the coupler origin, **T = r × F**
- The cobot reads the **wrench in the coupler frame** and rotates the coupler to drive **Tx** and **Ty** → **0** (±0.5 N·m), while keeping the axial push
- **Zero torque** ⇒ the contact force passes through the flange center ⇒ faces **parallel, in contact all around**: the cavity is sealed

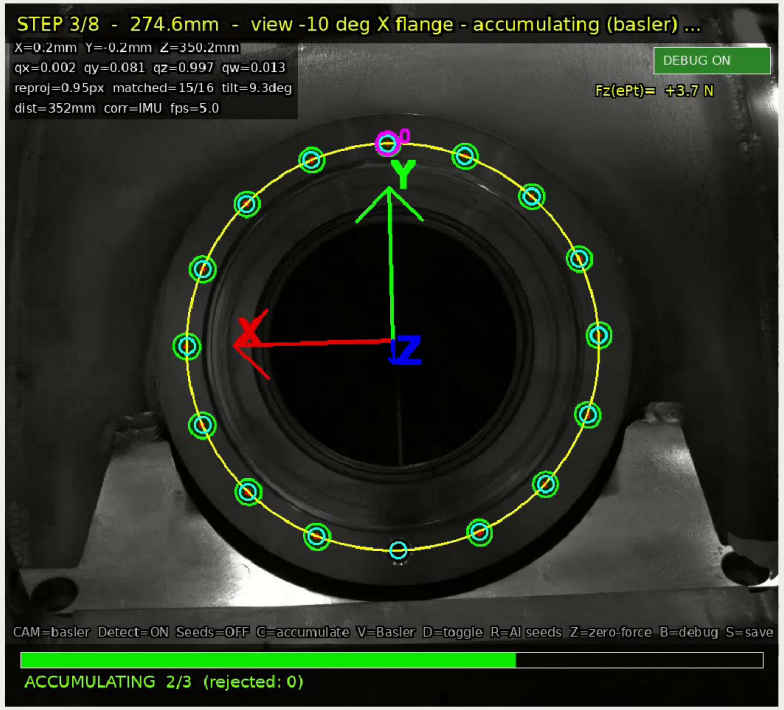
5.5 s

to square (56 samples)

5 → 0.4

torque |T| [N·m]





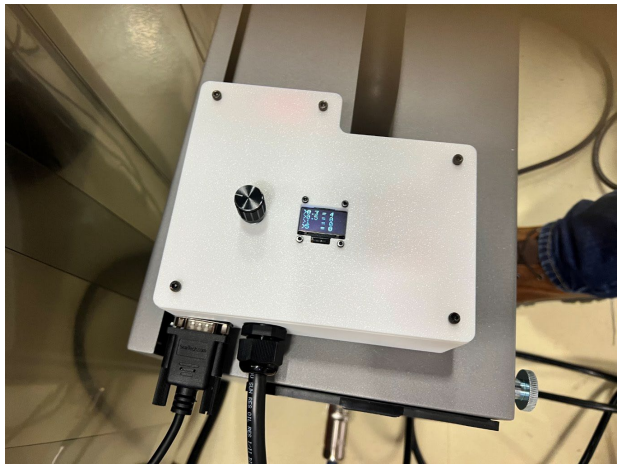
2X

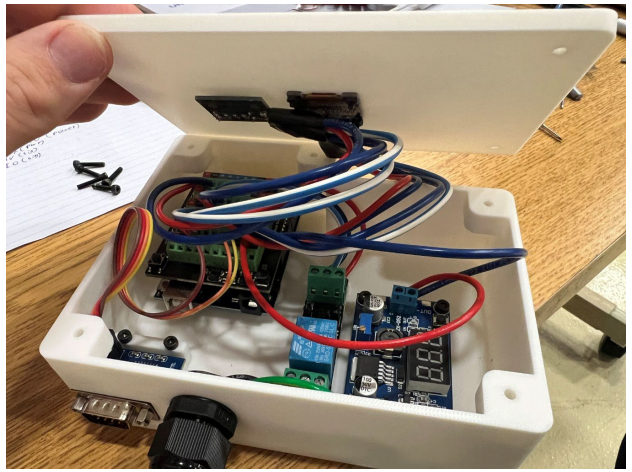
Hardware Cleaning

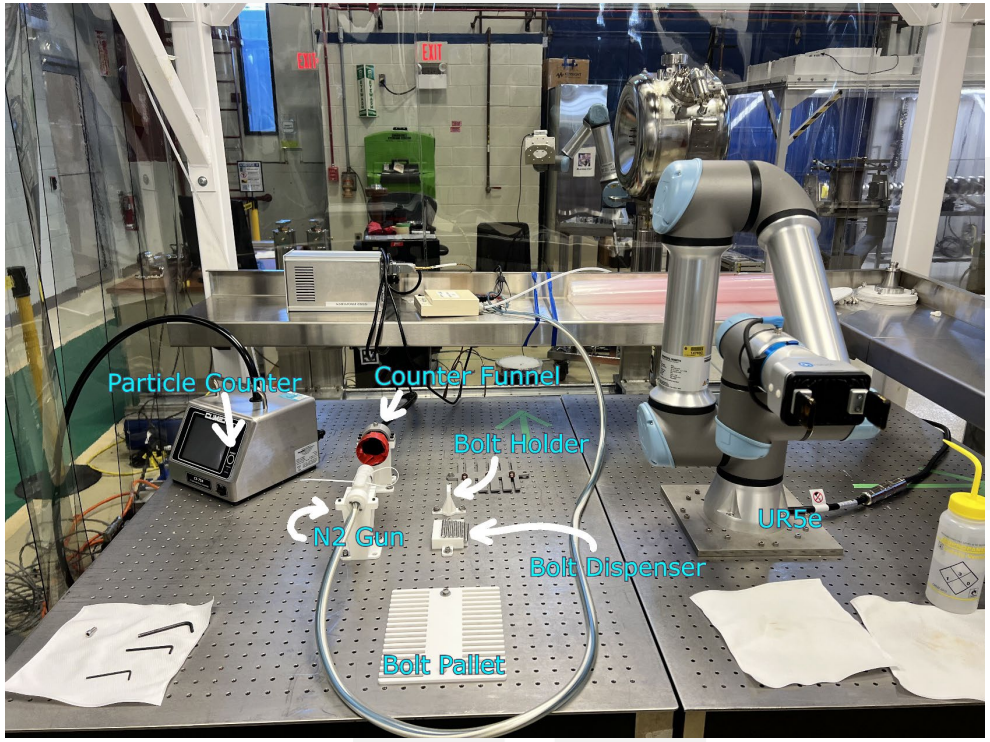
System designed by B. Whitlock of NIU

Before assembling cavities in the cleanroom, hardware must be cleaned.

- Cleaning hardware is time-consuming, but relatively simple
  - Complications in cleaning come from human error
  - Biggest barrier to automation: reading the particle counter
- Custom control box to read the particle counter
- Parts successfully cleaned in the test setup

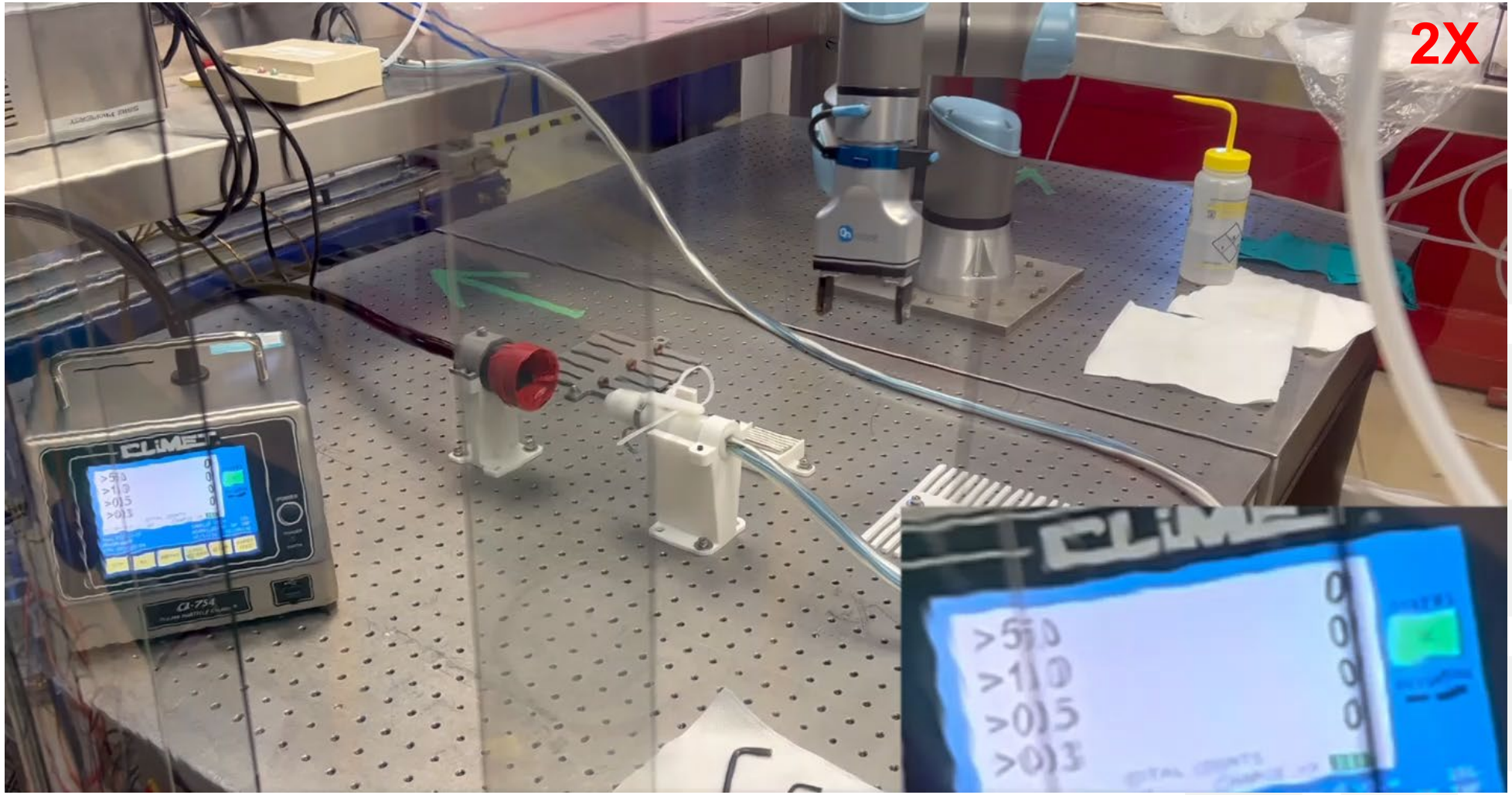






Hardware Cleaning – Prototype Setup

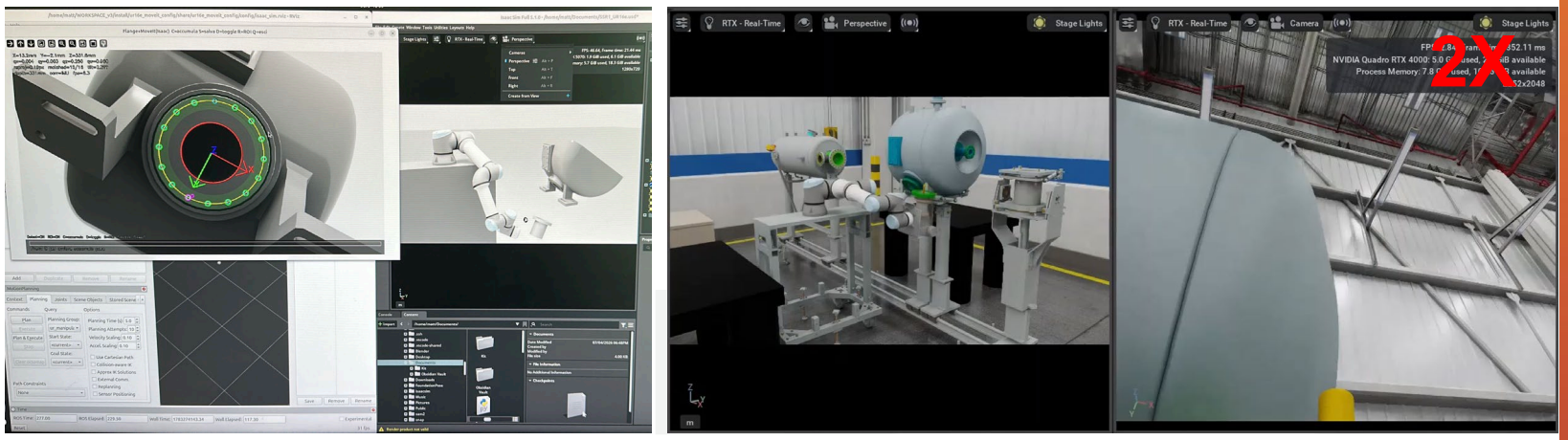
The prototype system successfully cleans hardware



Conclusions

- Leveraging three years of platform development, we completed the **first cobotic-assisted assembly of a complete SRF cavity string** (pre-production SSR2, October 2025) and developed a **markerless** coupler-to-cavity alignment and assembly system that eliminates physical targets on the cavity.

- All the processes and techniques presented today have been replicated in **NVIDIA Isaac Sim**, opening the way to **AI training** models that further optimize and refine the assembly procedures.



- Because the automation architecture is **developed in-house and tailored to the task**, rather than bought as a turn-key industrial product, it can be adapted and redeployed to any high-precision operation requiring cobotically assisted **inspection**, **ultra-clean assembly** or **automated quality control**. Next: extend full automation to the remaining string components, toward **scalable, reproducible SRF cryomodule production**.