SpaceForgeOS-XAI

A real time power-aware scheduler for orbital semiconductor fabs

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Agenda

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Project Charter / Executive Summary

Problem Statement:

- Rule-based schedulers on orbital fabs break down when power, heat and vacuum dynamics interact non-linearly
- Current Wake Shield Facility data lacks the predictive layer engineers need for 300 mm wafers and longer missions

Objective:

- Use a Spatio-Temporal GNN to forecast 15-min State-of-Charge (SoC) dips and conflict risk, then reorder tasks to keep pressure < 10^{-10} Torr with zero black outs

Core Deliverables:

- C++ physics sim → telemetry logger → graph constructor
- Monte-Carlo shield optimisation to size an 8 m wake for 300 mm wafers
- Train ST-GNN in PyTorch; wrap with Integrated Gradients for XAI
- Tech-memo (31 Jul) → Sim skeleton (15 Aug) → Shield M-C study (31 Aug) → Dataset v0.1 (15 Sep) → ST-GNN prototype (15 Oct) → XAI wrapper (31 Oct) → Closed-loop trials (20 Nov) → IEEE paper (15 Dec)

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Background

Rapidly Increasing Access to Space

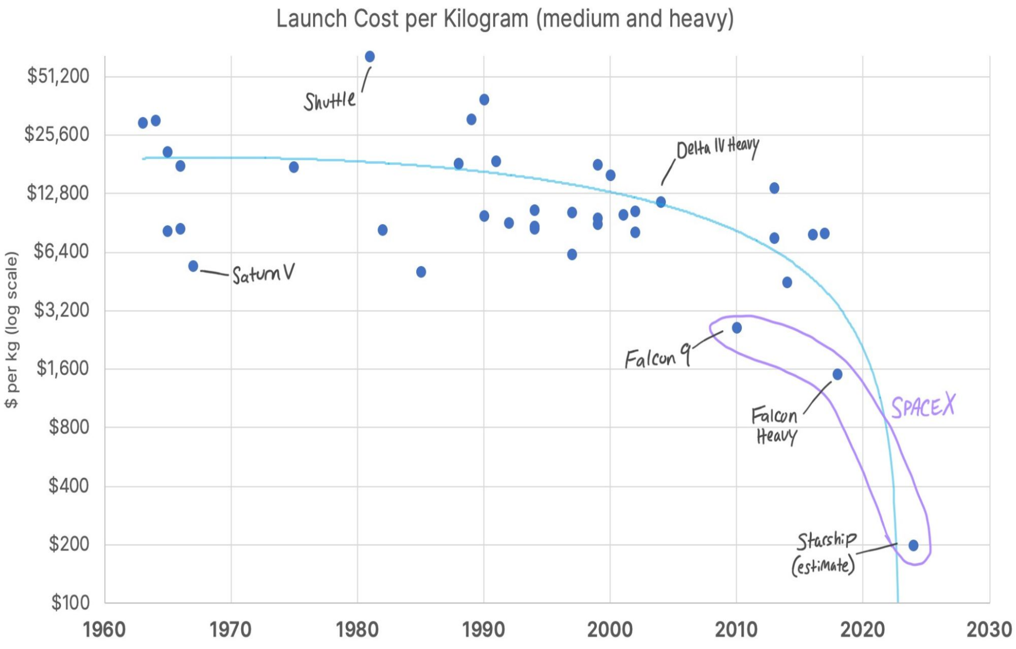

Image Source: Max Olson, FutureBlind.com

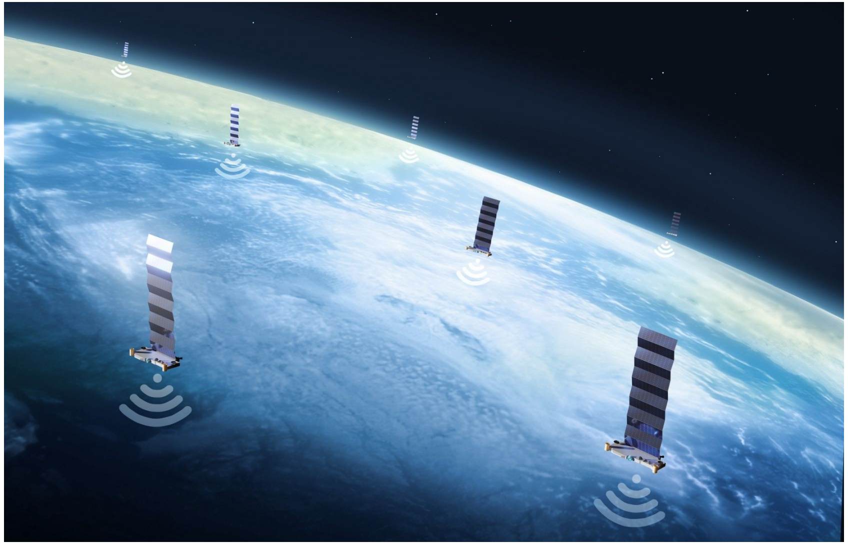

Image Source: SpaceX

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Orbital Manufacturing Prospects

Image Source: TechCrunch.com

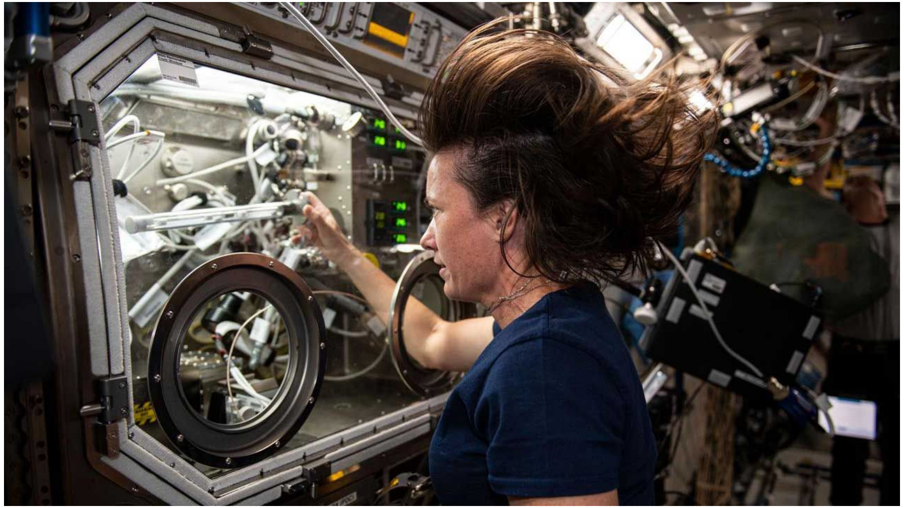

Image Source: ISS National Laboratory

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Wake Shield Facility (WSF)

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Image Source: NASA

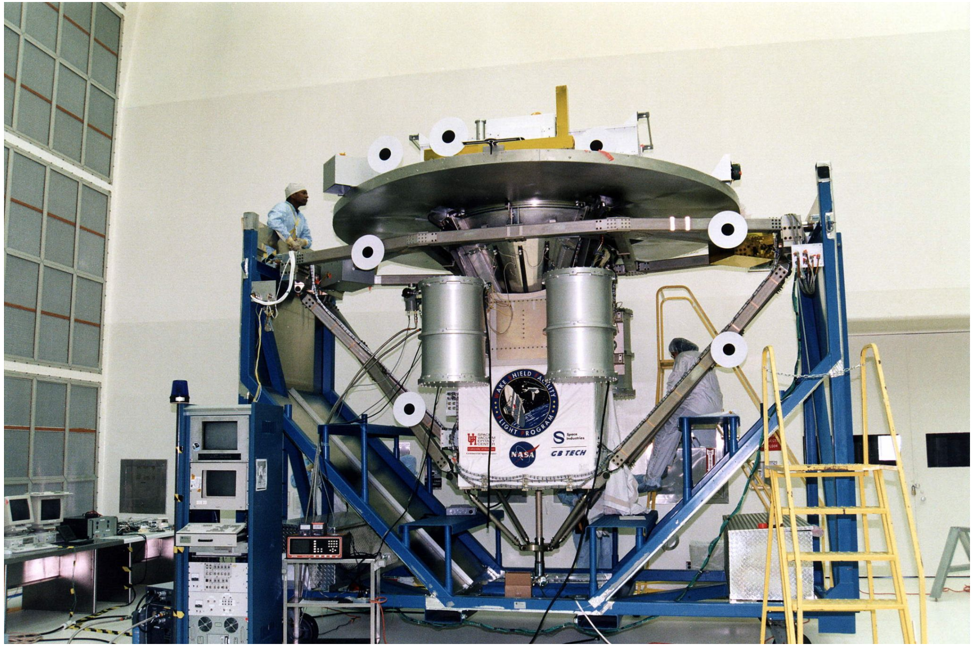
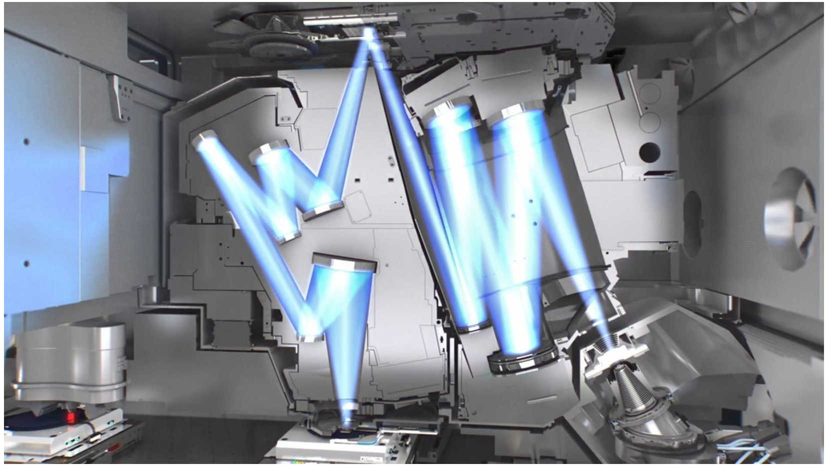


Image Source: Wikimedia

Semiconductor Manufacturing - A simplified overview

General Steps

- **Substrate Preparation:** Melt ultra-pure Si & grow a
  t → Slice into ~0.7mm thick
  clean the wafer surface
- **Oxidation:** Grow a thin layer of silicon dioxide (SiO_2) on wafer surface - used as an insulating/masking layer
- **Ion Implantation:** Bombard wafer with high-energy ions to alter electrical properties create n-type or p-type semiconductors
- **Photolithography:** Apply light-sensitive chemical to wafer → apply patterned photomask → use UV light to transfer the pattern onto the wafer → Chemically reveal pattern in the photoresist



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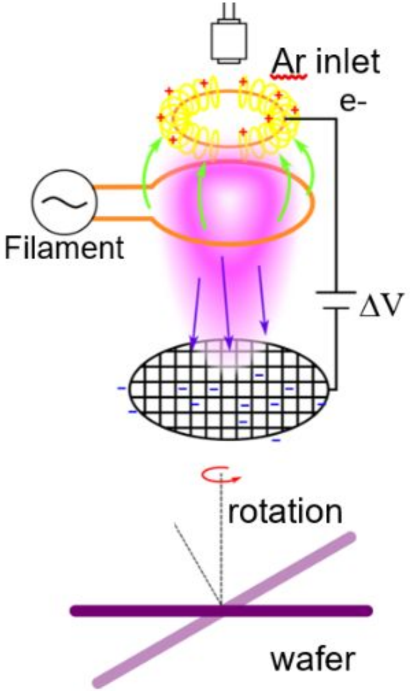
General Steps

- **<u>Etching</u>**<u>:</u> Remove unprotected areas of oxide or other layers using plasma or wet chemicals → creates fine features by carving into the wafer
- **<u>Deposition:</u>** Add new layers of material (metal, dielectric, or semiconductor) using methods like CVD (Chemical Vapor Deposition) or PVD (Physical Vapor Deposition)
- **<u>Chemical Mechanical Planarization (CMP)</u>**<u>:</u> Polish the wafer before adding more layers
- **<u>Repeat:</u>** Photolithography → Etching → Deposition → CMP as needed
- **<u>Metallization:</u>** → Deposit metal layers (e.g., copper or aluminum) to form interconnections between components.
- **<u>Packaging & Testing:</u>** Cut individual chips (die) → test them electrically → package into protective housing → final product ready for integration



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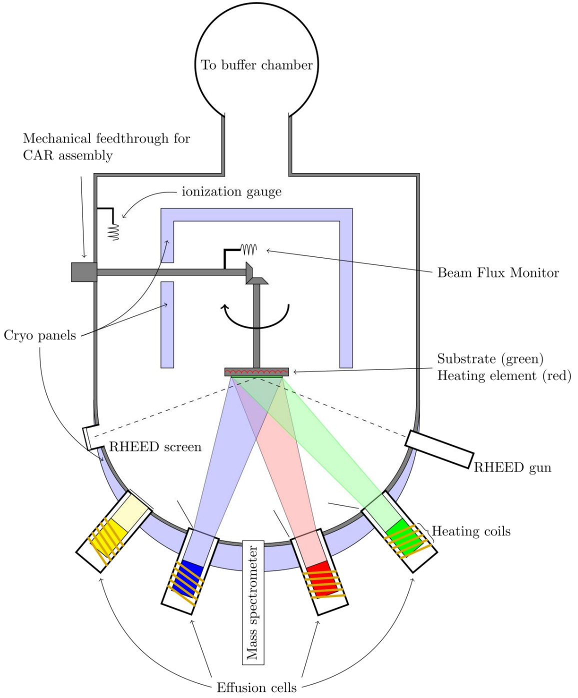
Molecular Beam Epitaxy (MBE)

- **<u>Molecular Beam Epitaxy (MBE):</u>** *Ultra-high-vacuum thin-film growth* technique for thin-film deposition of single crystals
- **Effusion cells heat elemental sources** → directed "molecular beams" hit a *rotating, heated substrate*
- **Growth rates** ≈ 1 monolayer s^{-1} → atomic-level control over layer thickness & composition
- **Requires base pressure < 10^{-9} torr** → WSF's wake provided this naturally



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The Big Picture

SpaceForgeOS-XAI is “timing” The Curve

- Learns from orbital logs to forecast energy shortfalls — before they strike
- GNN predicts SoC dips and highlights which subsystem caused them
- Real-time graph-based foresight replaces brittle rule-based scheduling
- Scalable to any multi-module, power-constrained architecture

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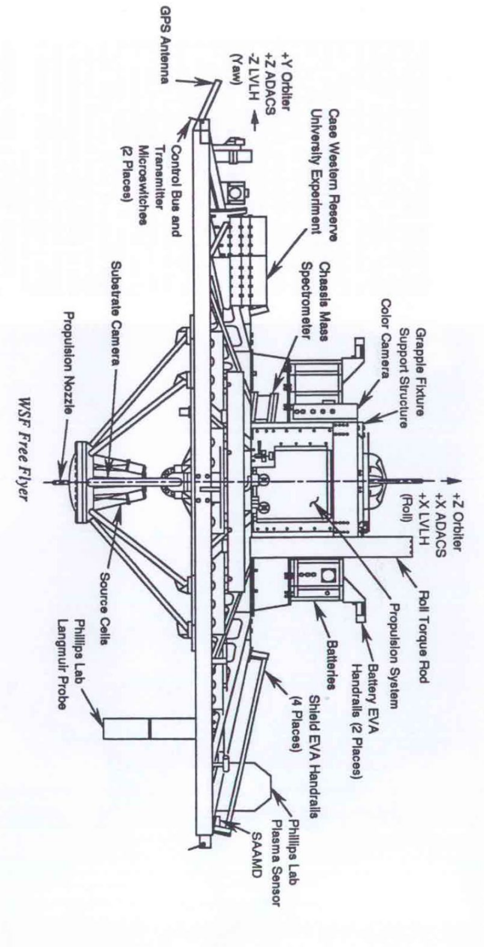
The New Idea

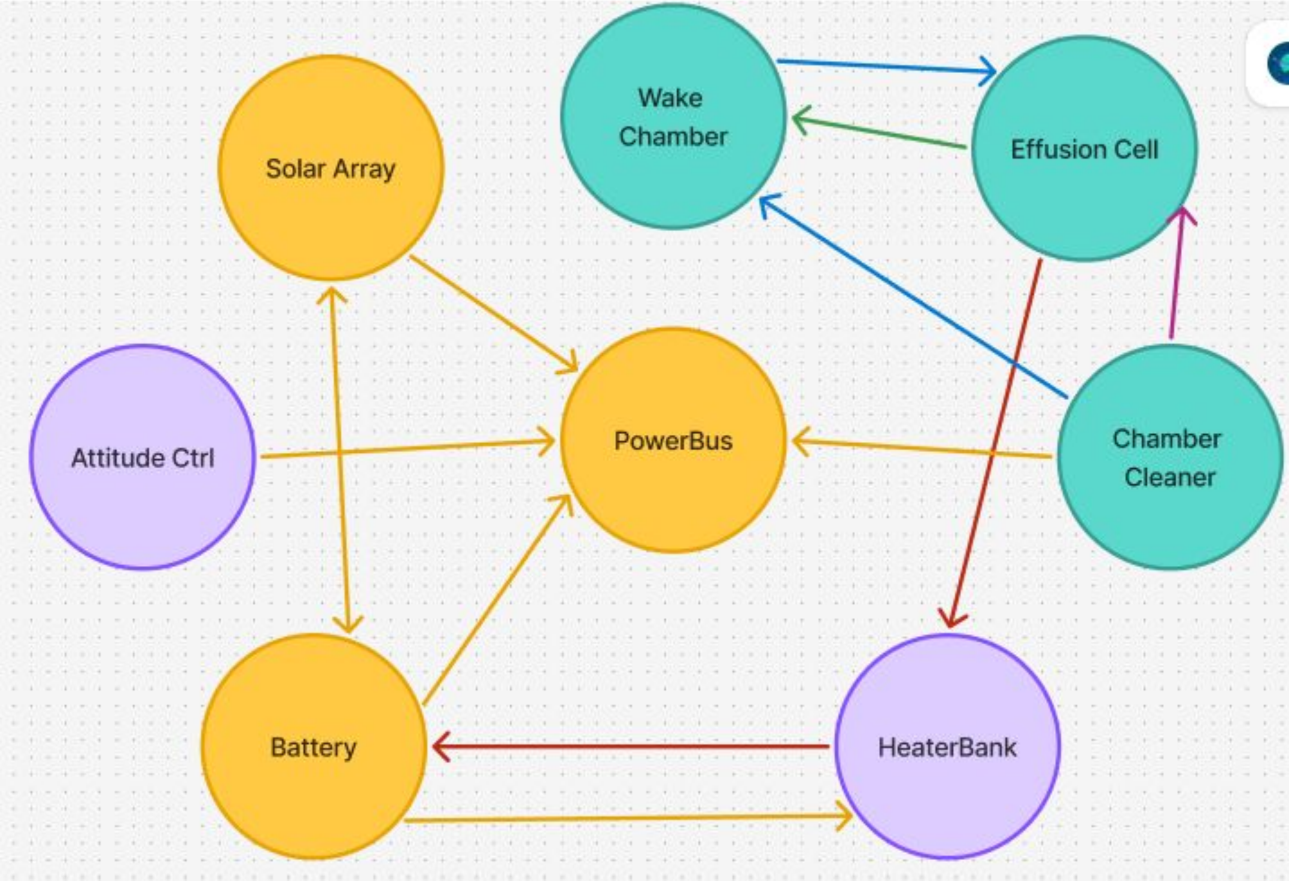
- **Problem:** Rule-based scheduling breaks down when interdependent modules (power, heat, orbit) interact non-linearly over time
- **Solution:** Spatio-Temporal Graph Neural Network (ST-GNN)
  - **Nodes:** PowerBus, SolarArray, Battery, HeaterBank, Effusion Cells (GaAs), wake chamber, etc…
  - **Edges:** Directed power/thermal flows (e.g., SolarArray → PowerBus → HeaterBank)
  - **Input:** past 60 minutes
  - **Output:**
    - Predicts SoC (State of Charge) in 15 Min + conflict risk
    - Wrapped in an XAI operator for explainability (Integrated Gradients)



ST-GNN Design

Edge Classification:

- Yellow: Energy
- Red: Thermal
- Blue: Pressure
- Pink: Maintenance
- Green: Material



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Useful Research Discoveries

$$P_j(T) = kG_{j,total}Q\exp(-E_{des}/kT)/(\exp(-E_{des}/kT_c), \quad (4)$$

- Used in simulation to forecast wake pressure every control-tick from current thermal telemetry

$$Q = Q_0 t^{-n}, \quad (3)$$

- At every simulation tick the equation is used to **update the outgassing rate**. This gets fed into the pressure/vacuum module so the environment automatically gets "cleaner" the longer the shield has been in space.

Wake vacuum measurement and analysis for the wake shield facility free flying platform

J.A Strozier [1], M Sterling, J.A Schultz [2], A Ignatiev

Source: [ScienceDirect.com]

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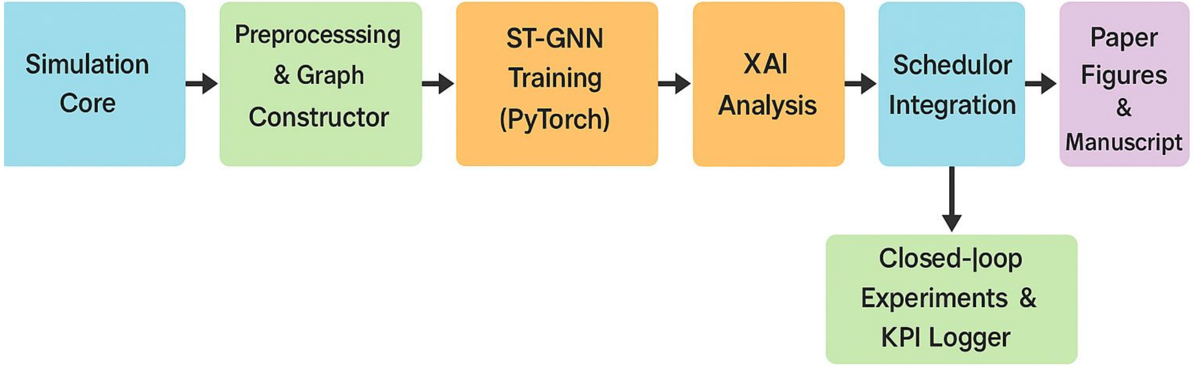
Data Pipeline

- **Simulations generate telemetry** in real time, logging system behavior each tick
- **Preprocessing** scripts convert logs into spatio-temporal graphs that capture recent system states
- Synthetic logs inject diurnal solar-thermal cycles + outgassing noise based on WSF Section 5 findings
- **ST-GNN models** predict short-term system metrics like SoC and conflict risk
- **Explanations and predictions** are integrated into a C++ scheduler for real-time decisions and logged KPIs.



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Data Pipeline - Sample Log Output

Main.cpp	Solar.cpp	Battery.cpp			PowerBus.cpp	HeaterBank.cpp	EffusionCell.cpp	WakeChamber.cpp	ChamberClean.cpp	AttContrl.cpp
A	B	C	D	E	F	G	H	I	J	K
time_utc	SolarArray_power_W	Battery_soc_pct	Battery_current_A	Battery_temp_C	PowerBus_voltage_V	HeaterBank_power_W	EffusionCell_temp_C	WakeChamber_pressure_torr	ChamberCleaner_power_W	AttitudeCtrl_power_W
2025-07-01T00:00:00Z	2500	80	-5	20	28.4	150	850	1.20E-07	0	50
2025-07-01T00:01:00Z	2400	82	-8	21	28.3	100	845	1.15E-07	0	45
2025-07-01T00:02:00Z	500	79	15	22	27.8	0	830	1.30E-07	0	60
2025-07-01T00:03:00Z	0	78	18	23	27.6	0	825	1.35E-07	500	70
2025-07-01T00:04:00Z	2000	79	-2	22	28.1	120	840	1.22E-07	0	55

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Success Metrics

- **Vacuum Pressure Fidelity:** Can the simulation successfully showcase capabilities of creating “wake” <10^-10 Torr over a 24 h run?
- **XAI Faithfulness Score:** Do explanations trace real causality? IG Faithfulness > 0.80
- **Power System Reliability:** Operational robustness of energy scheduling. 0 brownouts per 30-day missions

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Deliverables

1. Annotated bibliography + 3-page tech memo summarising MBE wake-shield physics, pressure regimes, and 300 mm wafer constraints (**Jul 31**)
2. Core C++ simulation skeleton (**Aug 15**)
3. Monte Carlo Simulation: for enhanced shield design to find ideal deflection angle and shield dimensions to fit a 300 mm wafer (**Aug 31**)
4. Data Logger + Dataset v0.1: 30 d synthetic mission run (**Sep 15**)
5. ST-GNN Prototype: Torch model class trained on dataset v0.1 - (**Oct 15**)
6. XAI Wrapper + Feature Attribution Report - (**Oct 31**)
7. Closed-Loop Scheduler Experiments: ST-GNN vs rule-based >= 15 simulated orbits (**Nov 20**)
8. Final IEEE Paper - (**Dec 15**)

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References

- Cho, A. Y., Wuencher, H. F., Melfi, L. T., Hueser, J. E., Naumann, R. J., & Ignatiev, A. (2001, November 8). *Wake vacuum measurement and analysis for The wake shield facility free flying platform*. Vacuum. https://www.sciencedirect.com/science/article/pii/S0042207X01003839?fr=RR-2&ref=pdf_download&rr=954e216efe594f0b
- NASA. (1991, September 6). *The wake shield facility: A space experiment platform - nasa technical reports server (ntrs)*. NASA. https://ntrs.nasa.gov/citations/19920014405

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