National Aeronautics and Space Administration
Ames Research Center • Entry Systems and Technology Division

Expanding the measurement capabilities of the mARC II arc-jet to map the operating envelope for high-enthalpy air flows

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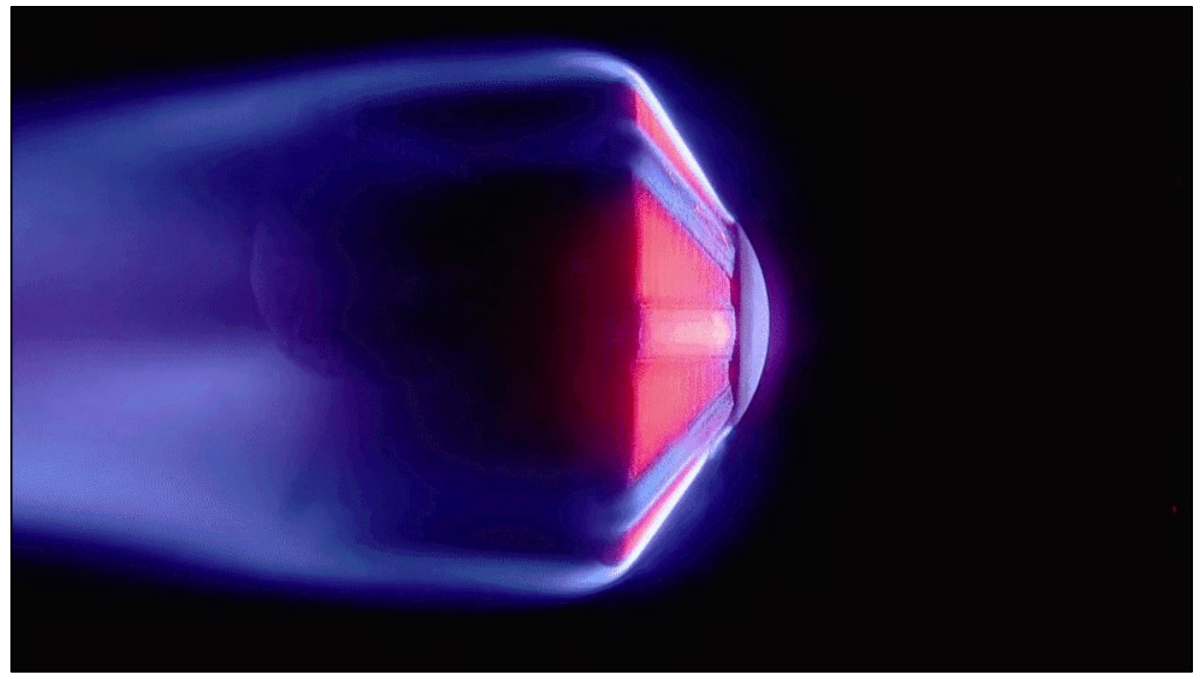
GT-19: MEASUREMENTS IN CHALLENGING ENVIRONMENTS II.

Motivation

Supporting the development and testing of low-maturity level technologies

NASA Ames has a strong legacy in ground-testing:

- Operates six high-power arc-heaters (10–60 MW) to deliver high-enthalpy flows (convective and/or radiative) for extended periods of time and for various gas mixtures
- Relied upon for every NASA mission with entry phase



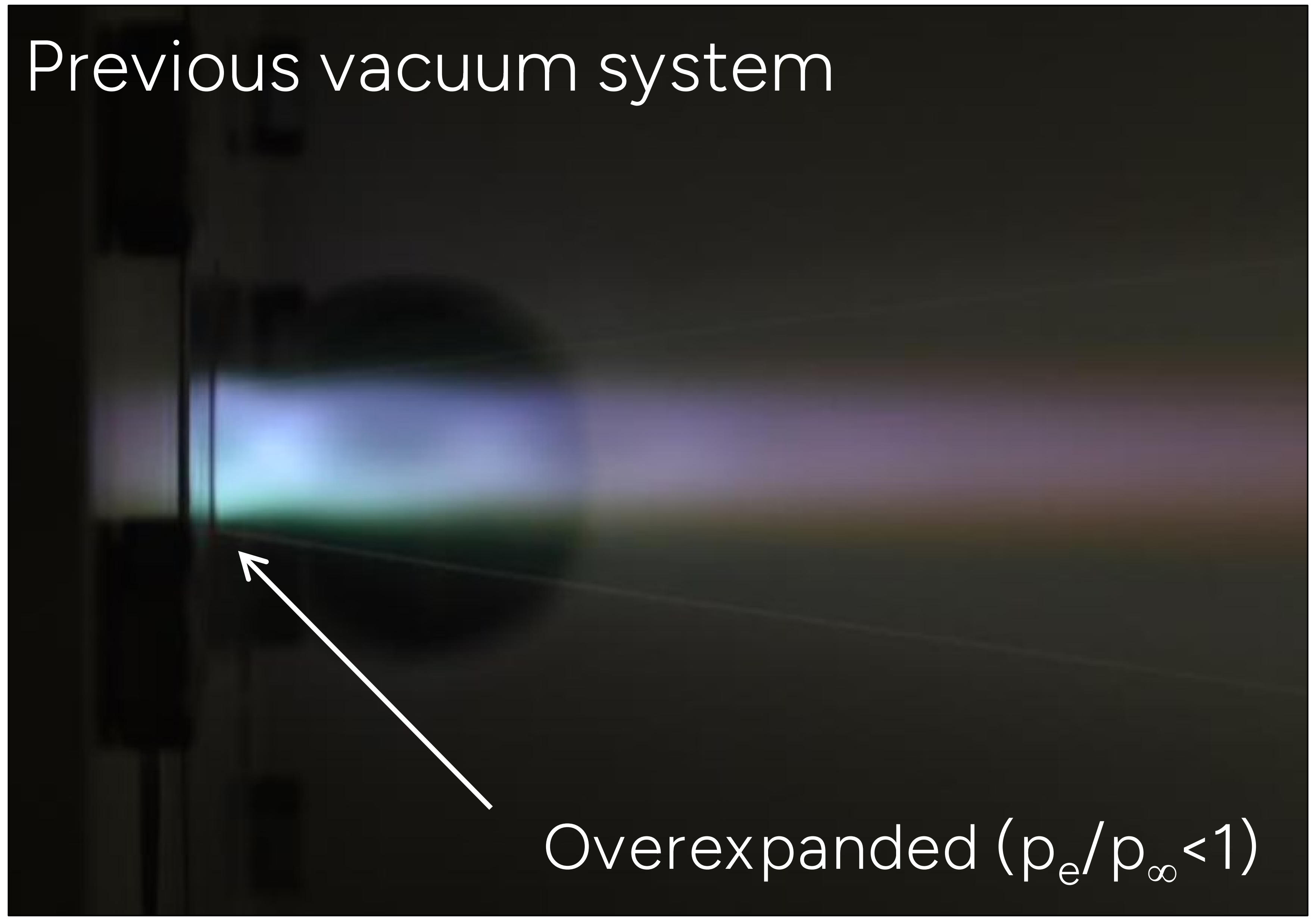
ADEPT arc-jet test – 60 MW IHF
Credit: NASA/TSF

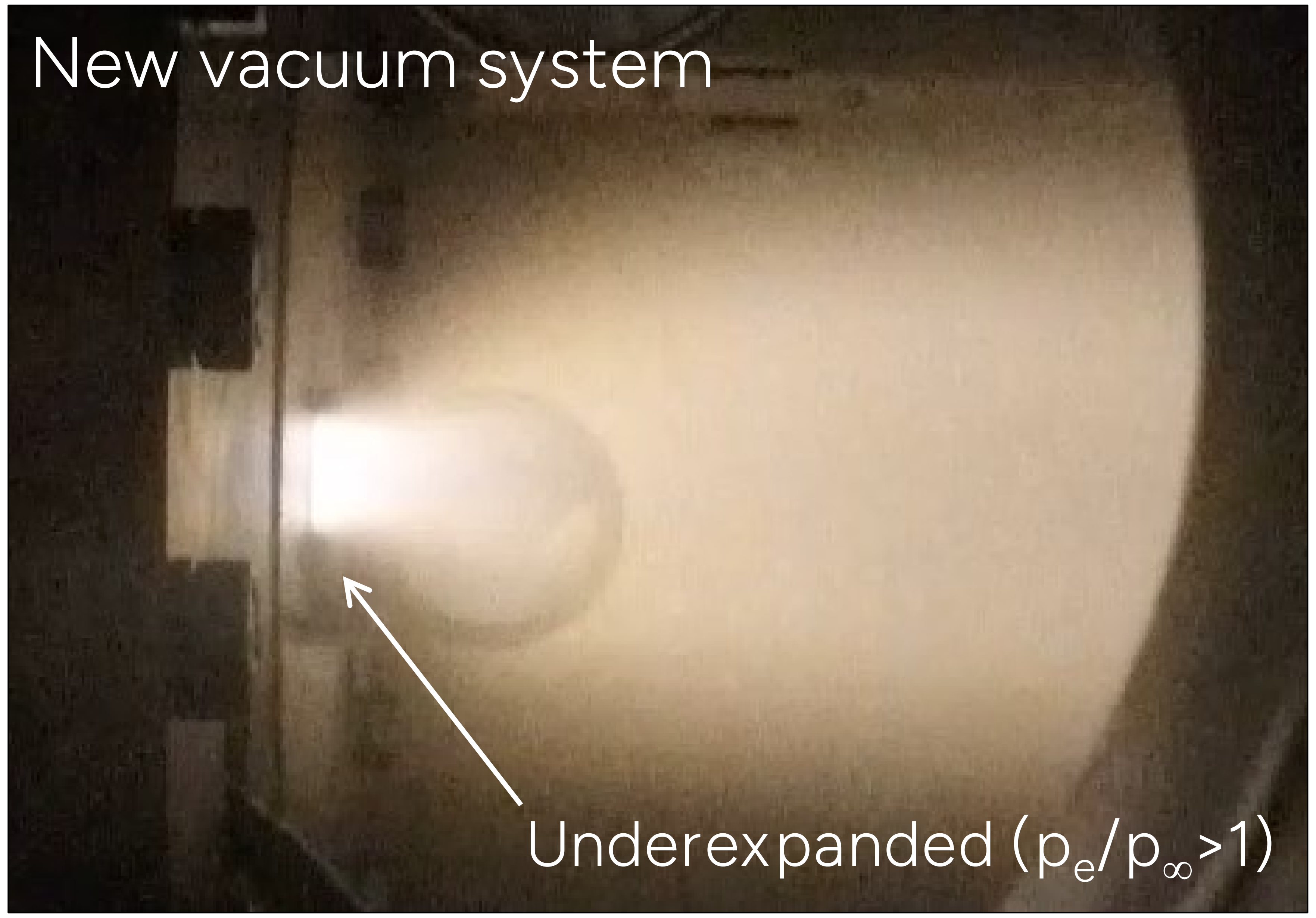
Demand for a smaller-scale facility to support the rapid, low-cost development of low-maturity technologies prior to them being implemented/tested in the larger facilities:

- Materials (e.g., screening of novel TPS)
- Instrumentation (e.g., intrusive flow measurements)
- Diagnostics (e.g., non-intrusive flow measurements)

New vacuum system sustains underexpanded flow during tests

100 A
0.25 g/s





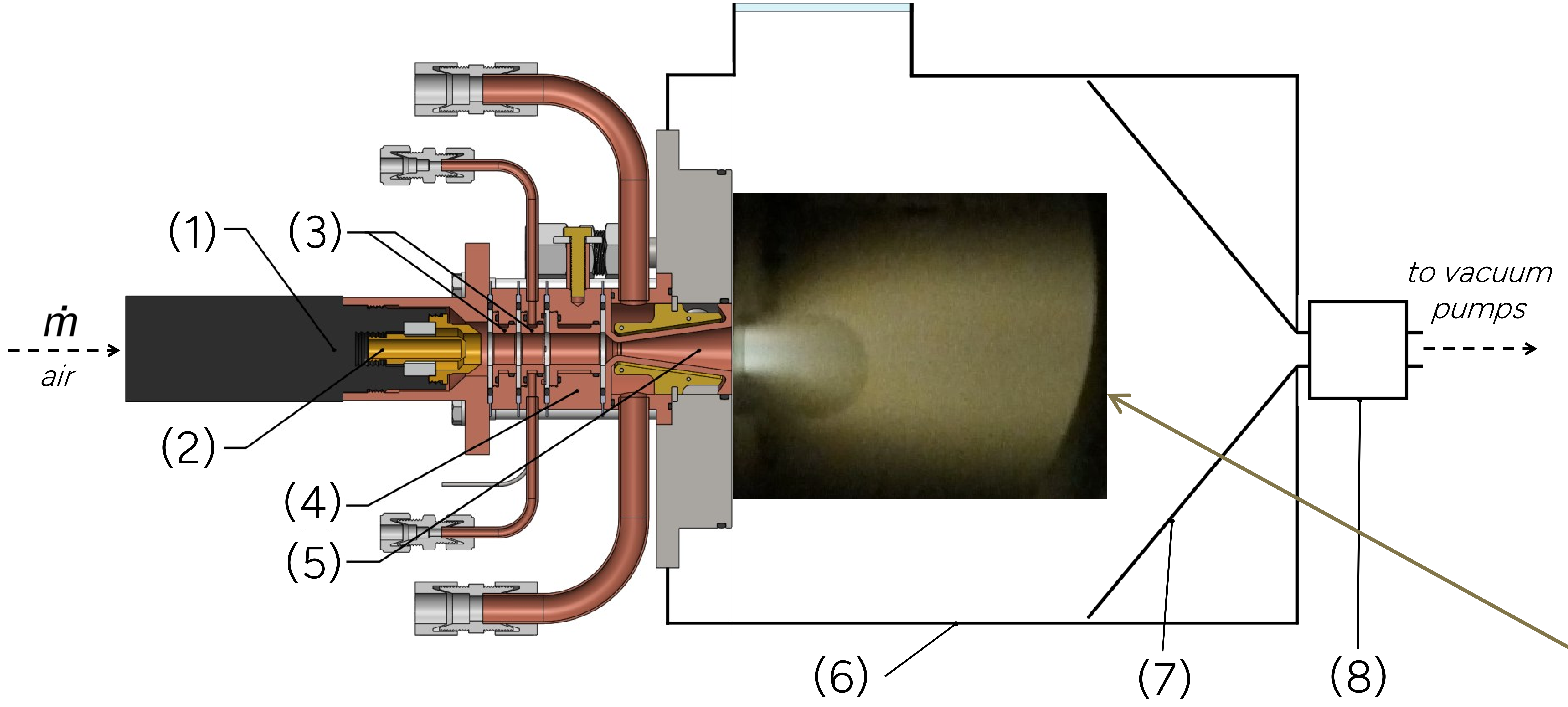
- Underexpanded flow ($p_e/p_\infty>1$) is desirable.
- High test box pressures after arc-on were the root cause of overexpanded flow.
- To reliably sustain $p_e/p_\infty>1$, a new vacuum system was implemented.

mARC II

miniature Arc-jet Research Chamber (second-generation)

Facility — arc heater & test box

30 kW segmented constricted arc-heater



<u>Components</u>:

1. MAX 200 torch body
2. Cathode
3. Constrictor disks (x2)
4. Anode
5. Nozzle
6. Test box
7. Diffuser (*new*)
8. Heat exchanger (*new*)

Cooling circuit 1 (items 1–2)

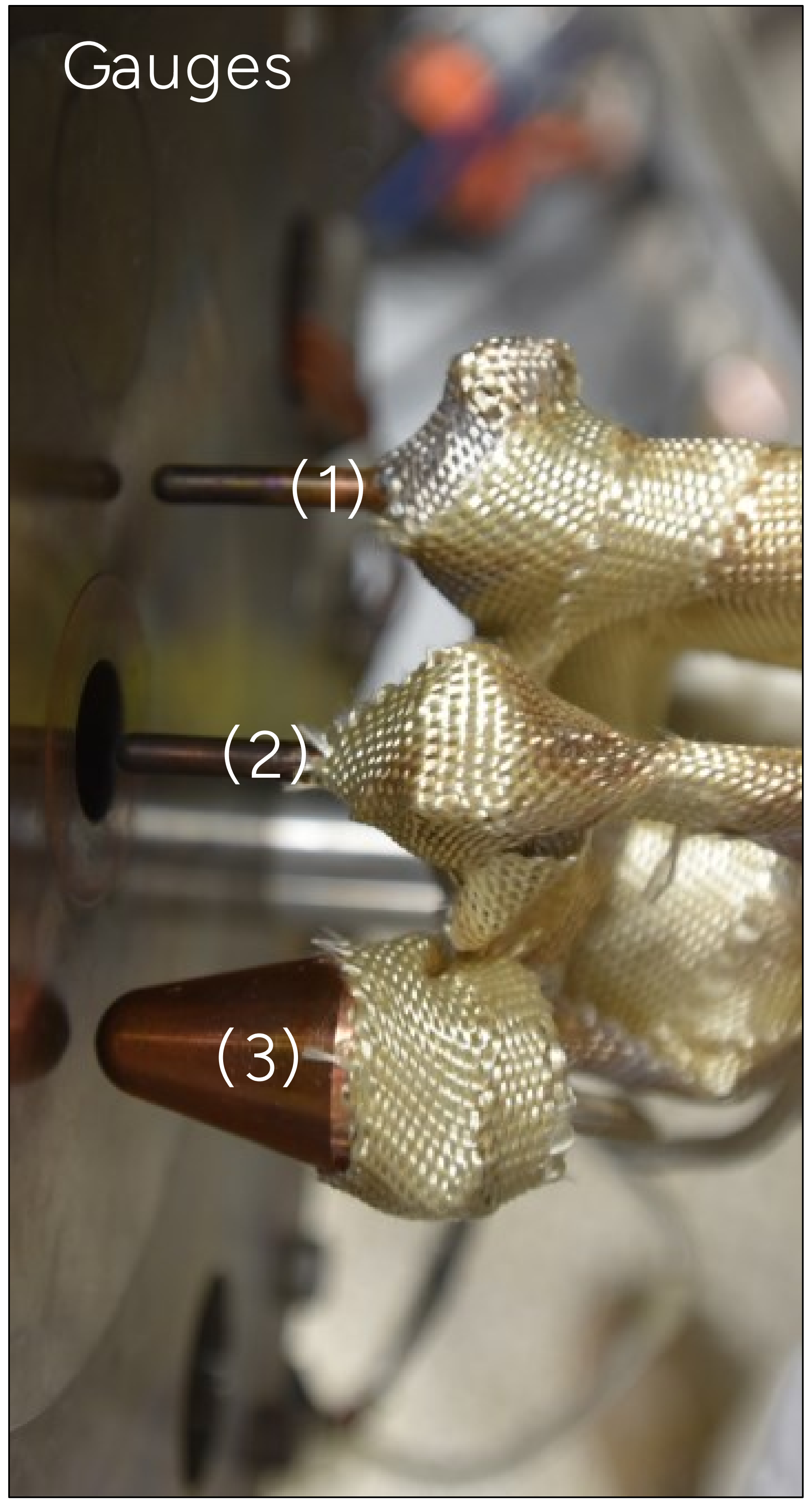
Cooling circuit 2 (items 3–8)

+ three-mount sweep arm for intrusive flow characterization

Facility — intrusive flow characterization

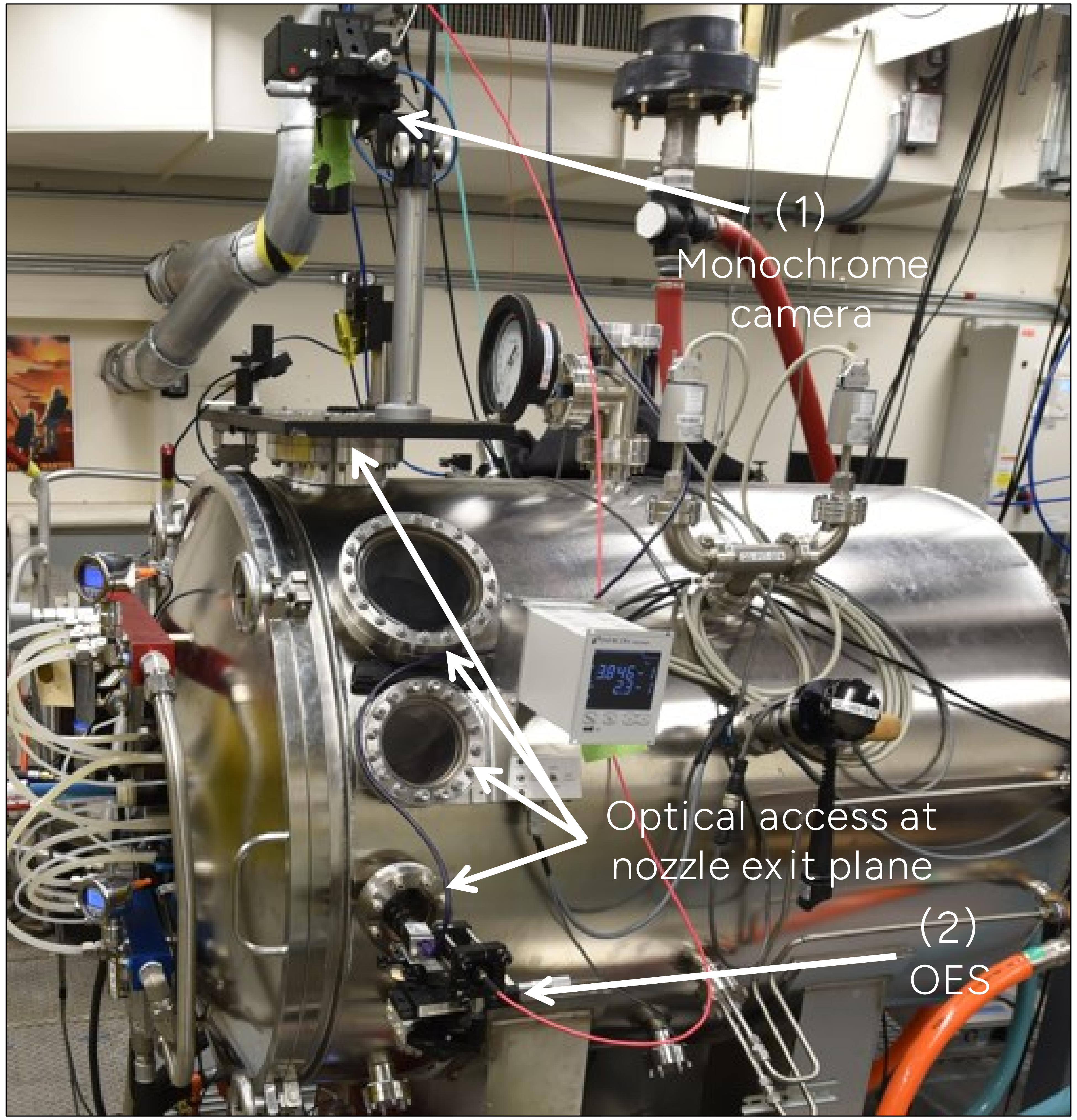
Sweep arm with trident (three-mount) holder

(1)	Water-cooled Pitot probe (3/16″ hemispherical)	1 s dwell	Stagnation pressure p_0
(2)	Water-cooled Gardon gauge (3/16″ hemispherical)	1–2 s dwell	Stagnation heat flux $\dot{q}_0$
(3)	Coaxial thermocouple sensor (1/2″ sphere-cone)	0.7 m/s linear sweep speed	Radial heat flux profile $\dot{q}(r)$



Facility — non-intrusive flow characterization

(1)	Spectrally-filtered imaging	30 fps 780±5 nm	Freestream flow and sensor imaging
(2)	Optical emission spectroscopy	*In progress*	Freestream flow characterization



Arc-jet performance

Bulk flow and centerline enthalpy

Bulk flow enthalpy — ASTM E341–08 standard

A bulk enthalpy estimate can be calculated according to the ASTM E341–08 standard via an energy balance, with experimental measurements from the arc power P_{arc} and the power lost in the arc heater cooling circuit ΔP_{cool}:

$$\bar{h} = \frac{P_{\text{arc}} - \Delta P_{\text{cool}}}{\dot{m}_{\text{air}}} = \frac{(IV) - (\dot{m} c_p \Delta T)_{\text{anode/disks/nozzle}} - (\dot{m} c_p \Delta T)_{\text{cathode}}}{\dot{m}_{\text{air}}}$$

- Commonly used in the high-power arc-jet facilities at NASA Ames.

Centerline enthalpy — ASTM E637–22 standard

The stagnation enthalpy h_0 can be calculated according to the ASTM E637–22 standard, with experimental measurements for stagnation point heat flux $\dot{q}_0$ and stagnation pressure p_0:

$$h_0 = \sqrt{\frac{r_{\mathrm{N,hemi}}}{K^2}} \frac{\dot{q}_0}{\sqrt{p_0}}$$

where:

- K = 3.905 x 10^{-4} kg N^{-5} m^{-5} s^{-1} is the heat transfer gas constant for air.
- $r_{\mathrm{N,hemi}}$ = 2.36 mm is the nose radius of the hemispherical heat flux gauge (i.e., Gardon).

Test matrix for heater with 2 disks

Six runs are presented.

Run	Sensor location z [mm]	Arc current I_{arc} [A]	Air flow rate $\dot{m}$ [g/s]
1	69	42	0.13
2	69	42	0.14
3	69	41	0.21
4	69	40	0.25
5	2	186	0.20
6	2	188	0.25

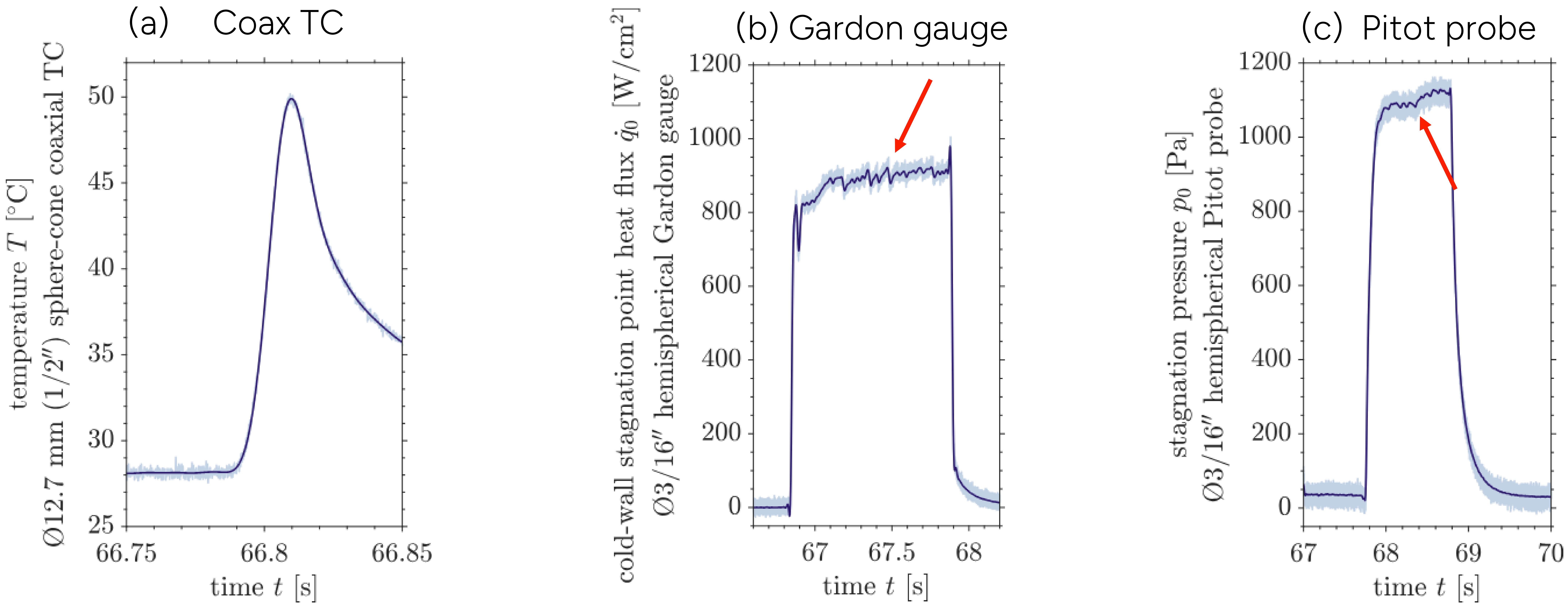
Lower bound (runs 1–4)

Upper bound (runs 5–6)

Results & Discussion

Time-resolved insertion data

I = 188 A, z = 2 mm



- Swept through flow (~20 ms)
- Tridiagonal matrix algorithm is solved to compute heat flux

- Dwelled in flow (1 s)
- Average heat flux taken across steady-state pulse

- Dwelled in flow (1 s)
- Average total pressure taken across steady-state pulse

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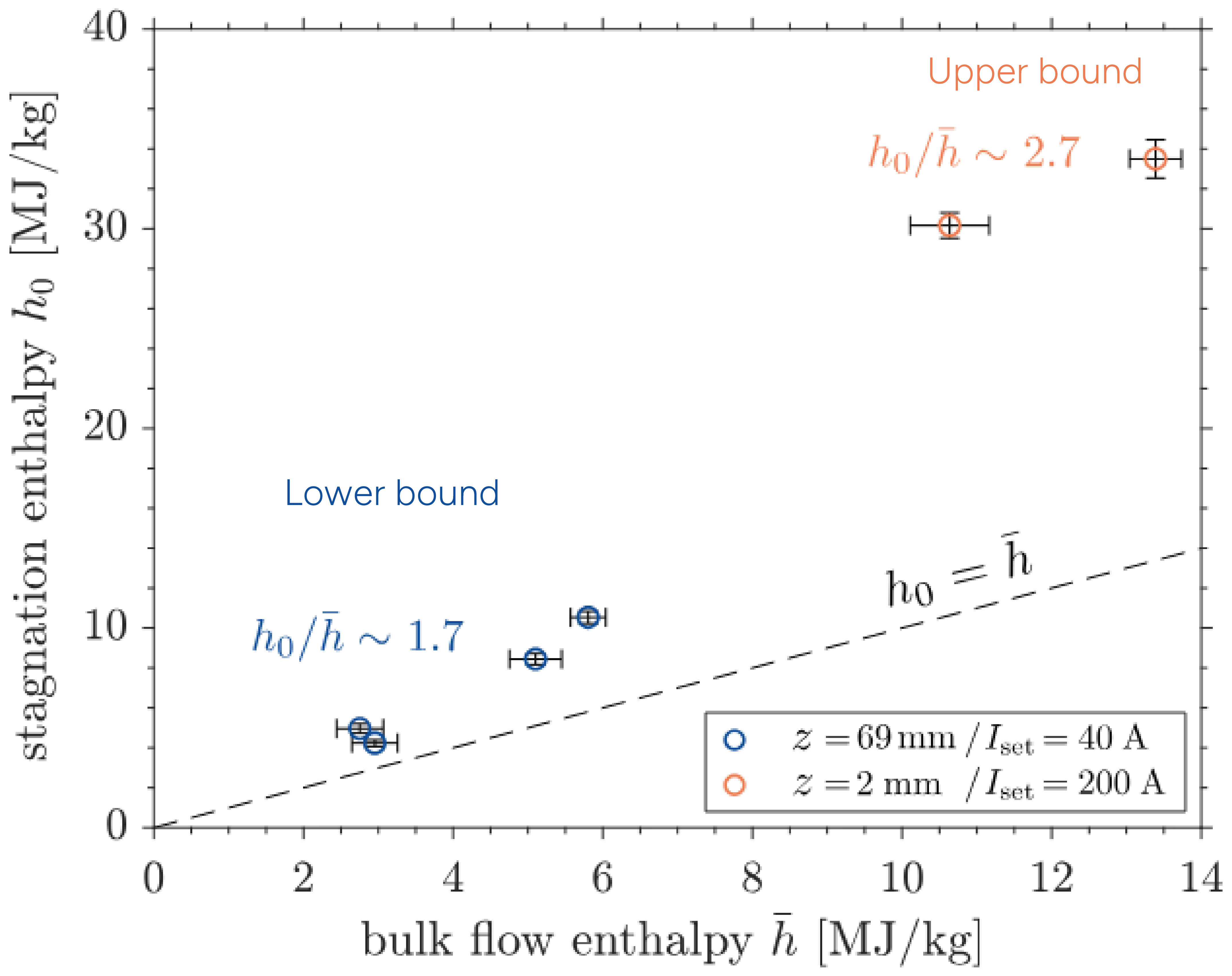
Flow enthalpy
Bulk and centerline

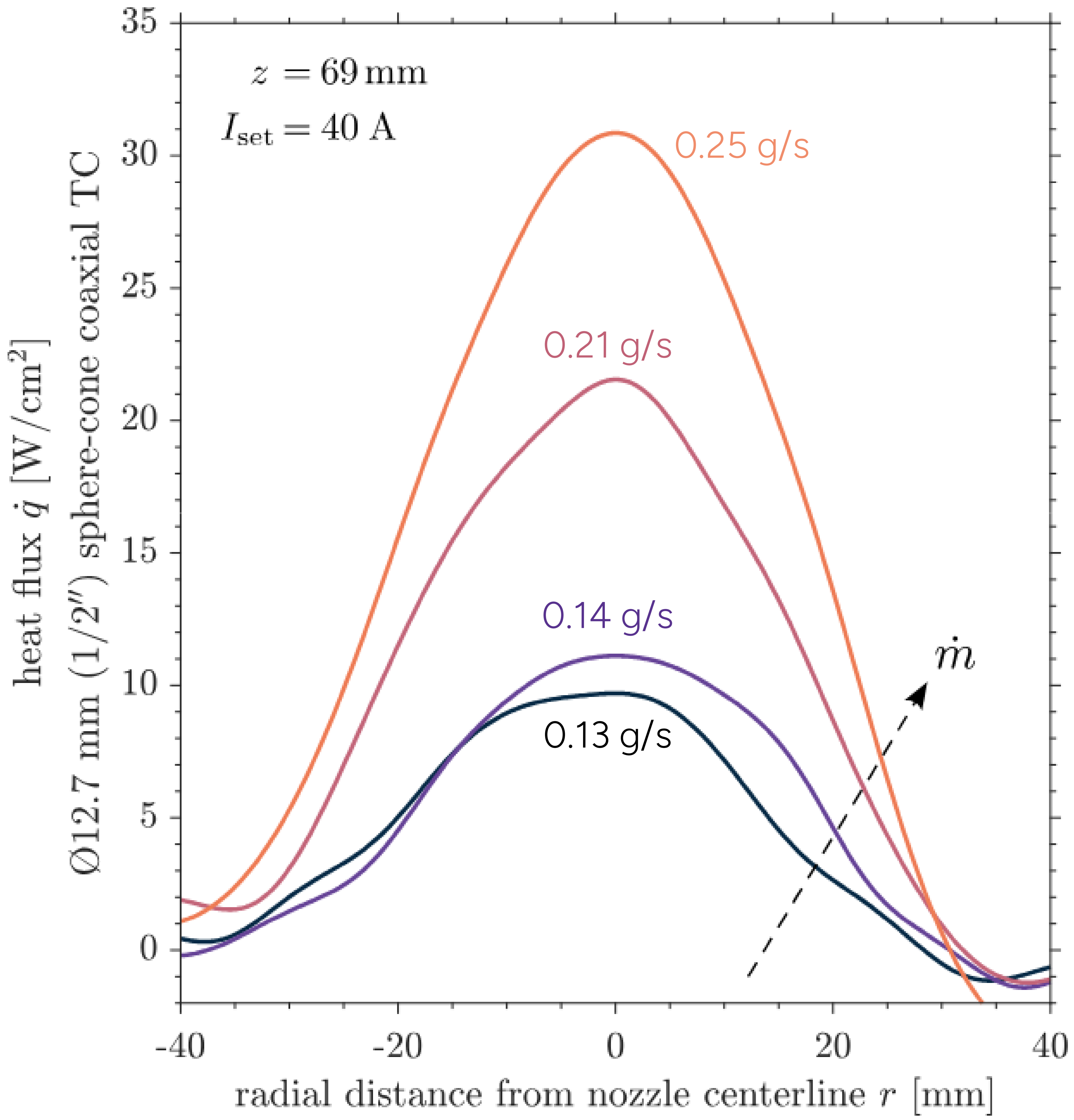
- Stagnation enthalpy exceeds bulk enthalpy in all cases.
- The average enthalpy ratio for the lower-bound runs is ~1.7 and for the upper-bound runs is ~2.7.
- Stagnation enthalpy values >30 MJ/kg and bulk enthalpy values >12 MJ/kg are generally considered high.



Radial heat flux profile

Lower bound (I_{set} = 40 A, z = 69 mm)

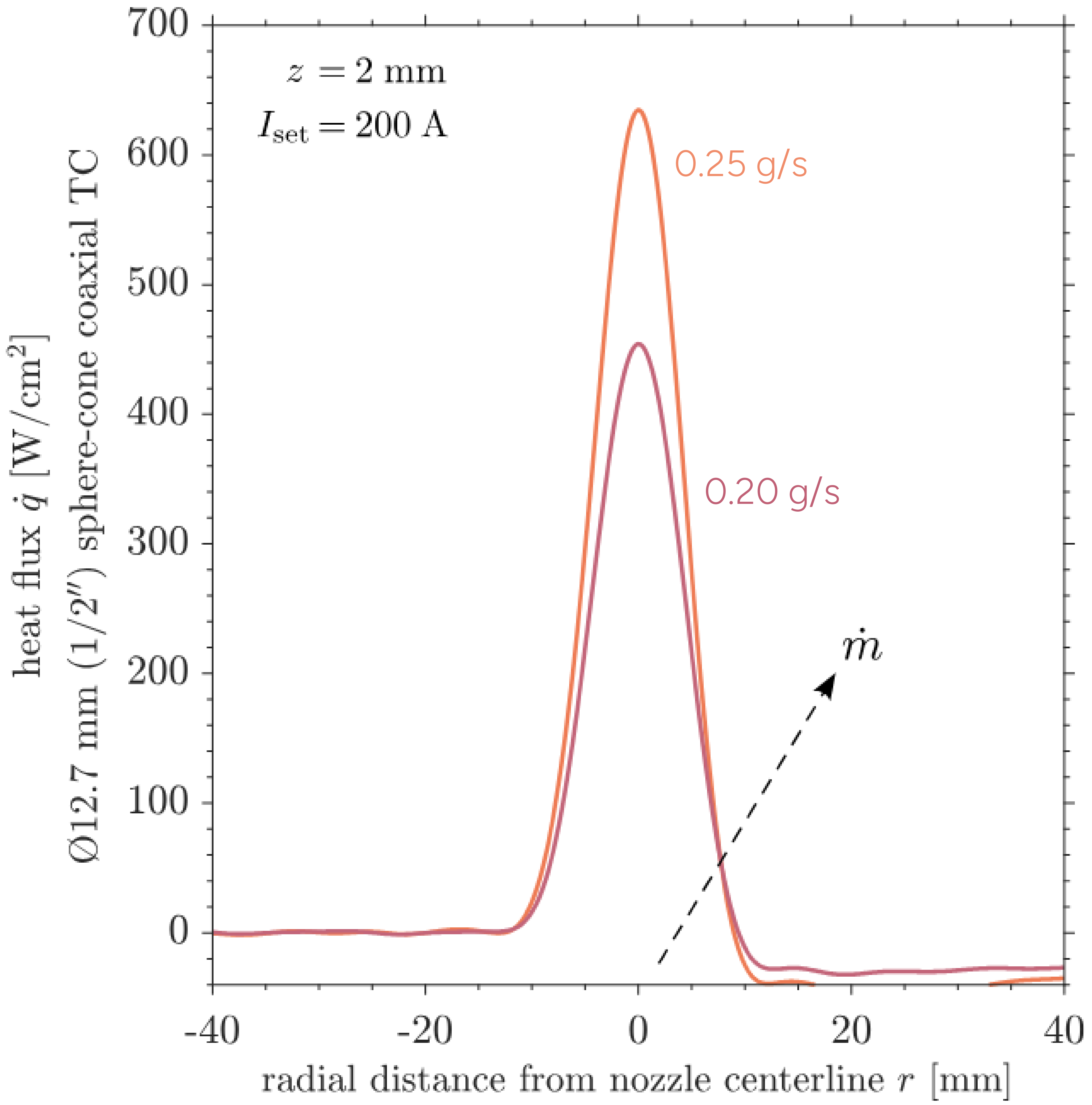
- Time-series is converted to radial coordinates using motor speed and sweep arm length.
- Peak heat fluxes of 10 W/cm^2 and 31 W/cm^2 for the lowest and highest mass flow rates of air tested (0.13 g/s and 0.25 g/s, respectively).
- As mass flow rate of air is increased, the heat flux profiles have more pronounced peaks and sharper radial distributions.



Radial heat flux profile

Upper bound (I_{set} = 200 A, z = 2 mm)

- Peak heat fluxes of 455 W/cm² and 635 W/cm² for the lowest and highest mass flow rates of air tested (0.20 g/s and 0.25 g/s, respectively).
- Measurements seem to exhibit parabolic profiles, typical of laminar flows.
- Sharper peaks can be attributed to higher pressure gradients and centerline velocities.

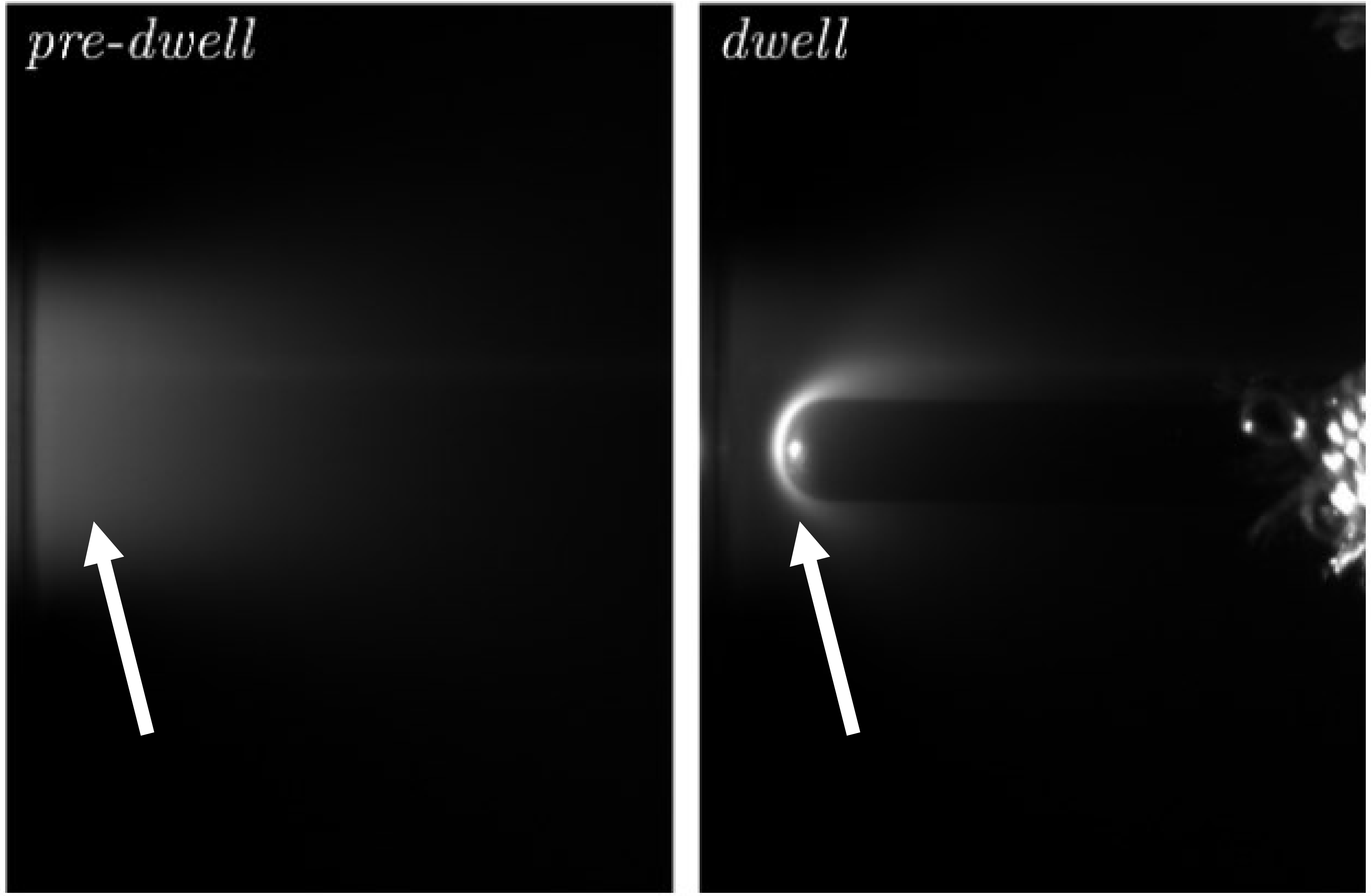


Flow imaging using 780±5 nm filter

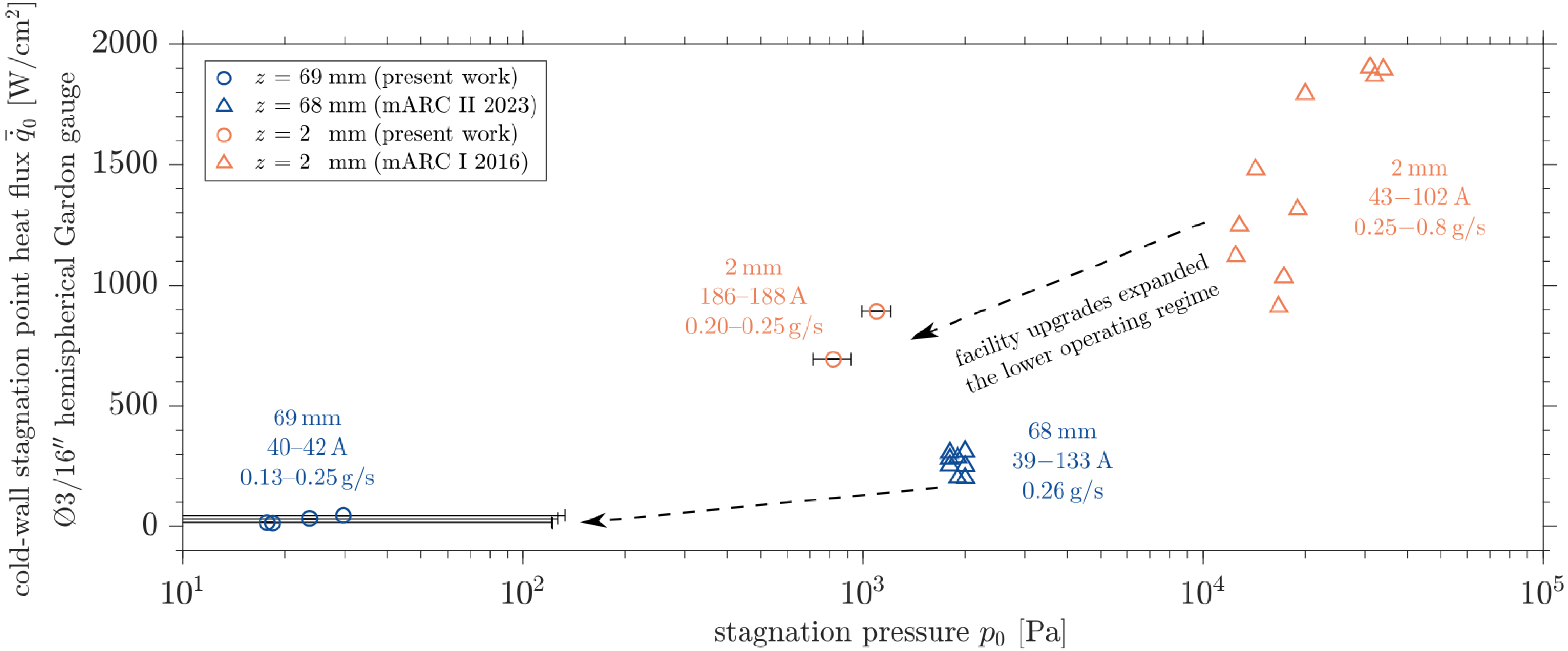
Upper bound (I_{set} = 200 A, z = 2 mm)

- Brightness corresponds to flow regions emitting radiation from 777 nm atomic oxygen and/or where materials thermally radiate due to .
- Pre-dwell: atomic oxygen seems concentrated in the core flow.
- Dwell: bow shock upstream of Gardon gauge is captured.

$\dot{m} = 0.25$ g/s $\quad I_{set} = 200$ A $\quad z = 2$ mm



Operating envelope



- Reduced test box pressure during test not only <u>enables testing at lower heat fluxes</u> (15–46 W/cm²) but also <u>enables testing at lower stagnation pressures</u> (18–30 Pa).
- Improves test flexibility by introducing the <u>test box pressure</u> p_∞ as additional control variable.
- <u>kW/cm² heat fluxes</u> and <u>kPa stagnation pressures</u> are anticipated for ↑ currents, ↑ flow rates, ↑ test box pressures, and ↓ distance from nozzle.

Concluding Remarks & Future Work

Concluding Remarks

1. The vacuum system upgrade had a significant impact on mARC II performance:

   Significantly expanded the mARC II facility’s lower operating regime, enabling consistent and reliable operation at lower test box pressures.

2. Radial heat flux profiles quantified:

   Heat flux profiles were characterized using 2D correction terms for spherical effects.

3. Spectrally-filtered diagnostic was successfully implemented:

   Enabled the imaging of freestream flow and bow shock upstream of sensor during dwell.

Future Work

1. Full characterization of mARC II's operational envelope using air flows will be completed using 2 and 3 constrictor disks in the arc-heater, including uncertainty quantification.

2. Numerical simulations will be used to compare with full characterization dataset.

3. Optical diagnostics have been implemented to study the properties of the freestream flow — further refinements and expansions planned.

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Thank you!

for the benefit of all

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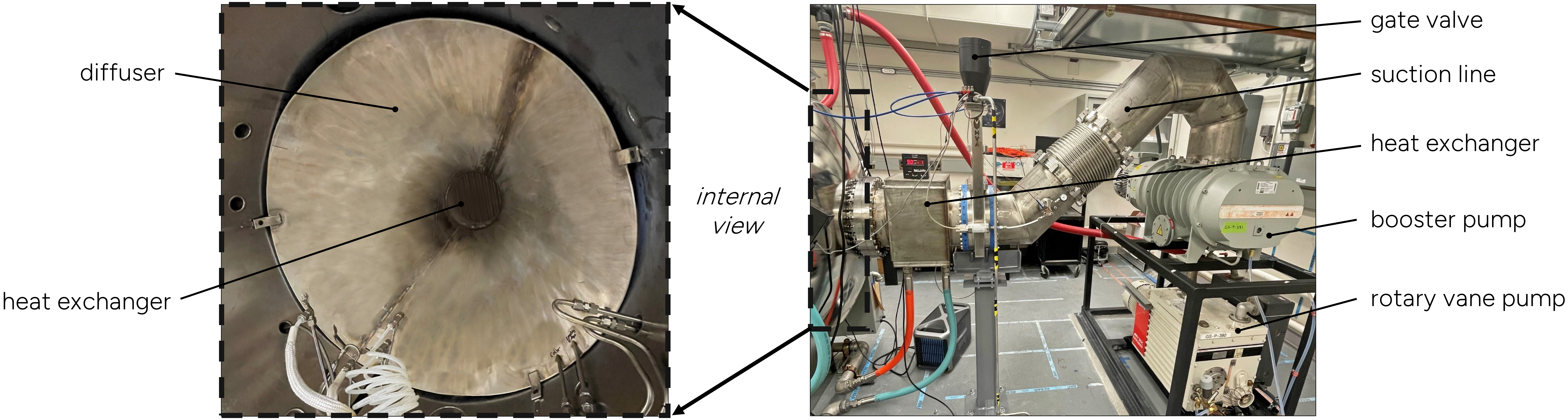
Additional slide(s)

Facility — upgraded vacuum system



- Refurbished mechanical booster pump was procured and coupled to the existing two-stage direct drive rotary vane pump (both water-cooled).
- Water-cooled diffuser and a heat exchanger were designed in-house and installed.