In-Flight Hydrogen Microwave Plasma Processing of Iron Ore Fines

Binit Singh, Thomas Cameron, Siebe Dijcks

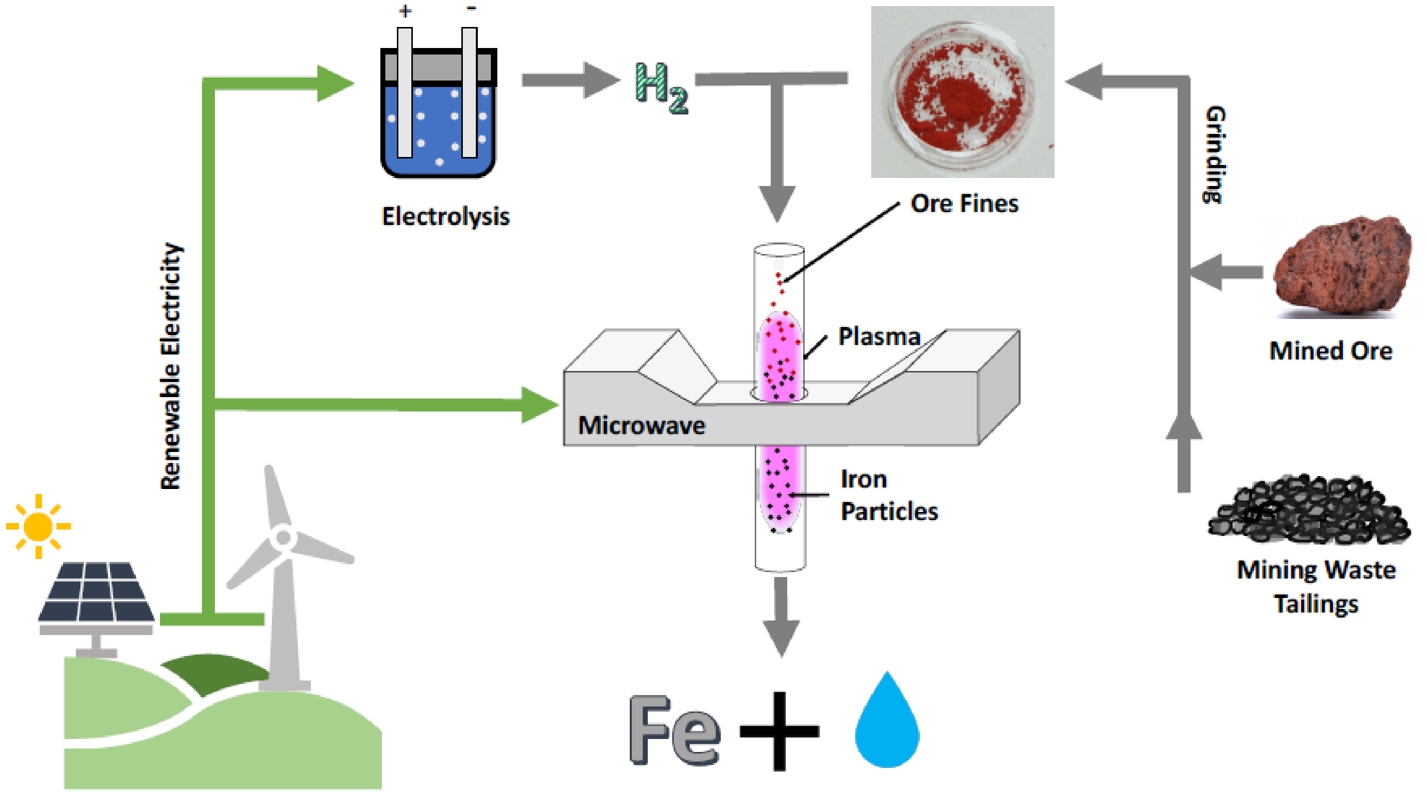
Uwe Kortshagen, and Peter Bruggeman

High Temperature and Plasma Laboratory (HTPL)

University of Minnesota – Twin Cities

This work was supported by the Department of Energy, Advanced Research Projects Agency–Energy, through project DE-AR0001901.

H_2 MW Plasma Process

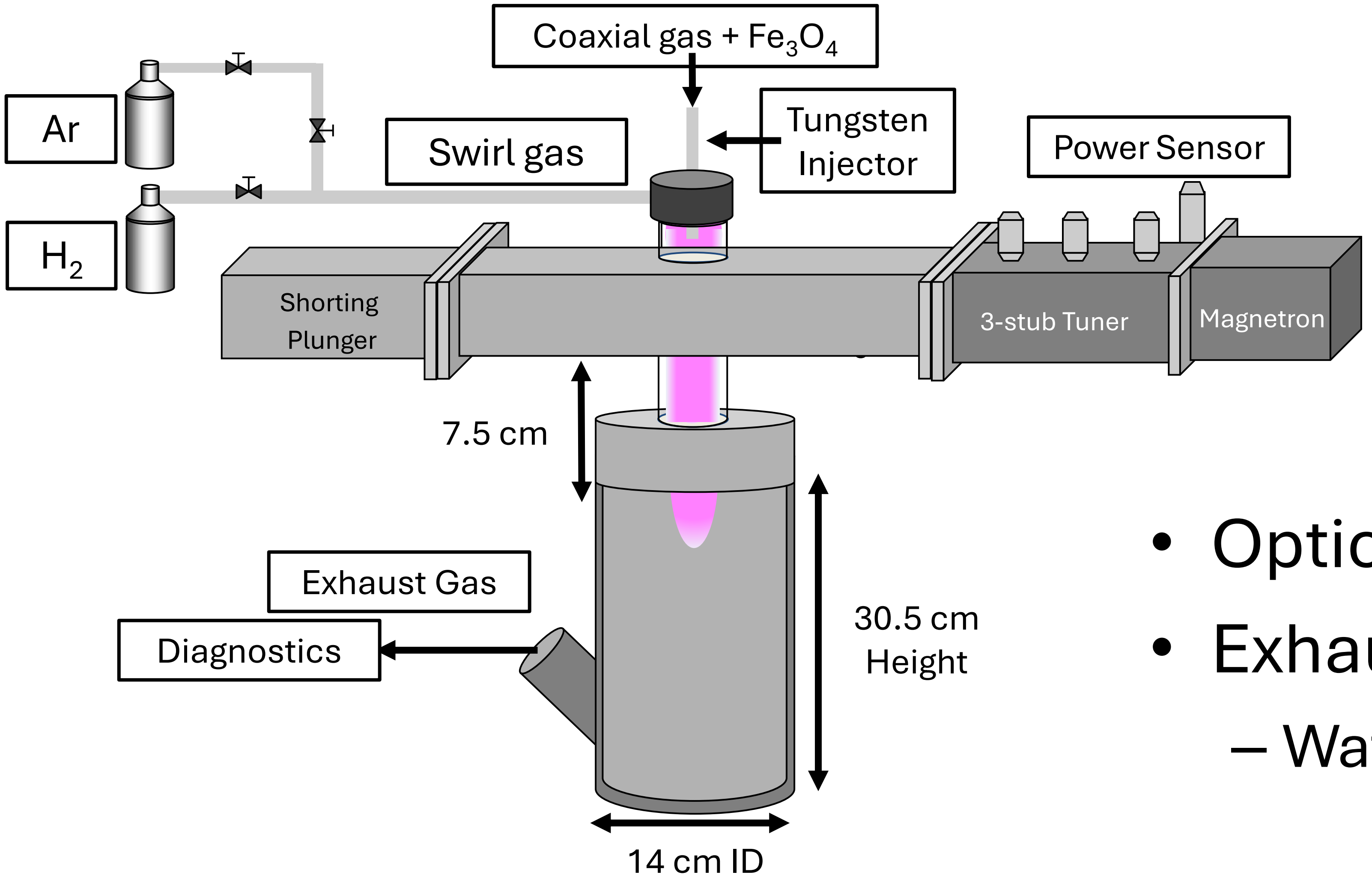


- Carbon free
  - Faster than thermal
- No pelletizing
- Fully electrified
  - Rapid on/off

$$\begin{cases} Fe_2O_3 + 3H_2 \rightleftharpoons 2Fe + 3H_2O \\ Fe_3O_4 + 4H_2 \rightleftharpoons 3Fe + 4H_2O \end{cases}$$

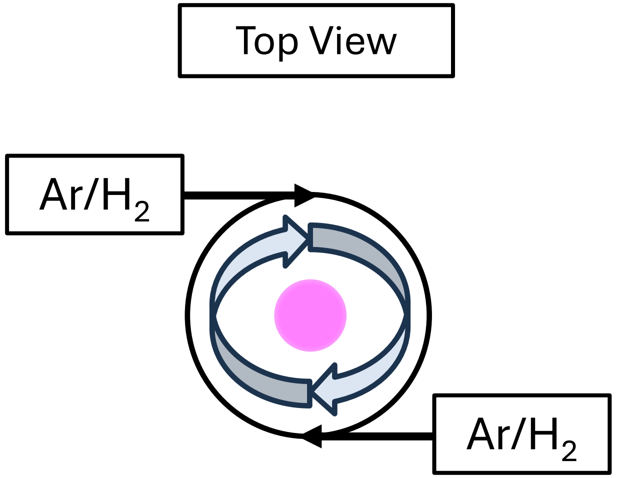
"Solid compound rapid reduction systems and methods."
U.S. Patent Application No. 18/195,188. (2023)

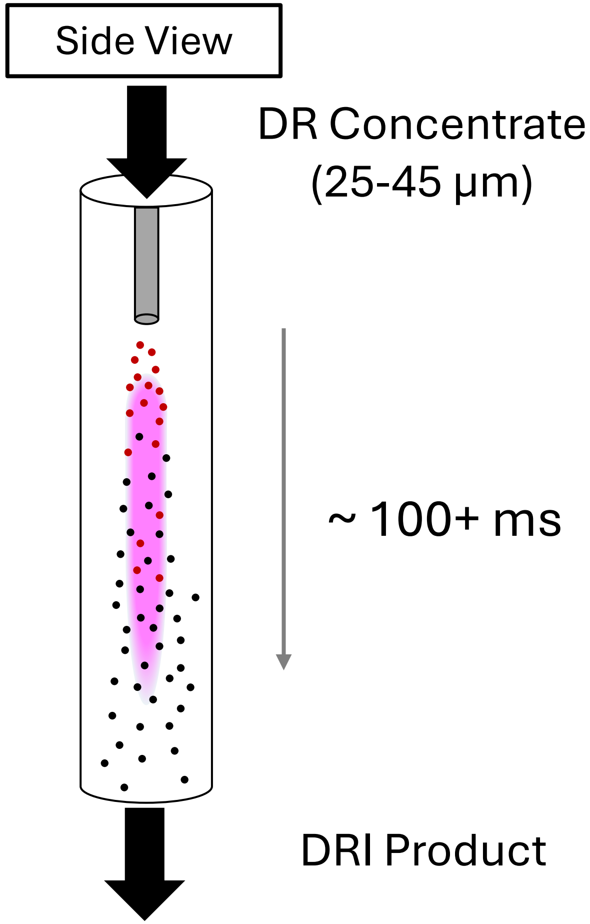
In-Flight Reduction Reactor



- Optical emission
- Exhaust gas analysis
  - Water, Hydrogen

In-Flight Reduction Process

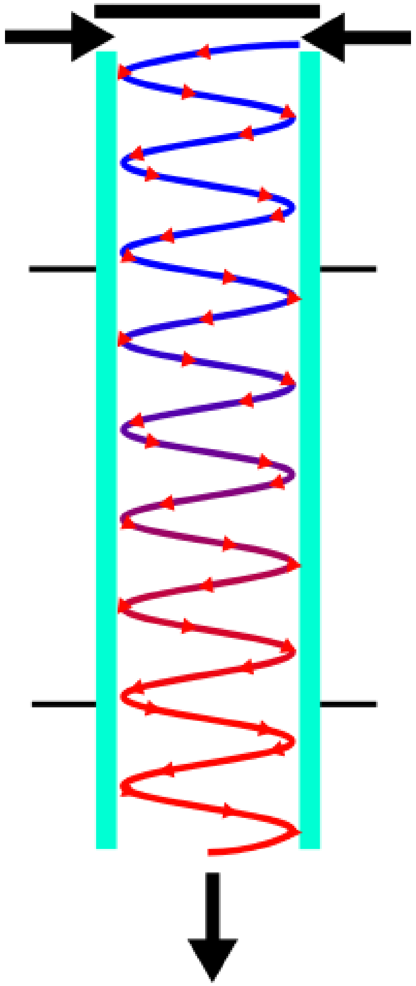




- Argon (Ar) & Hydrogen gas mixture swirl

- Plasma ignition
  - Instant on/off
- Coaxial feeding
- Residence time

In-Flight Reduction Process – Key Advantages



Powder product

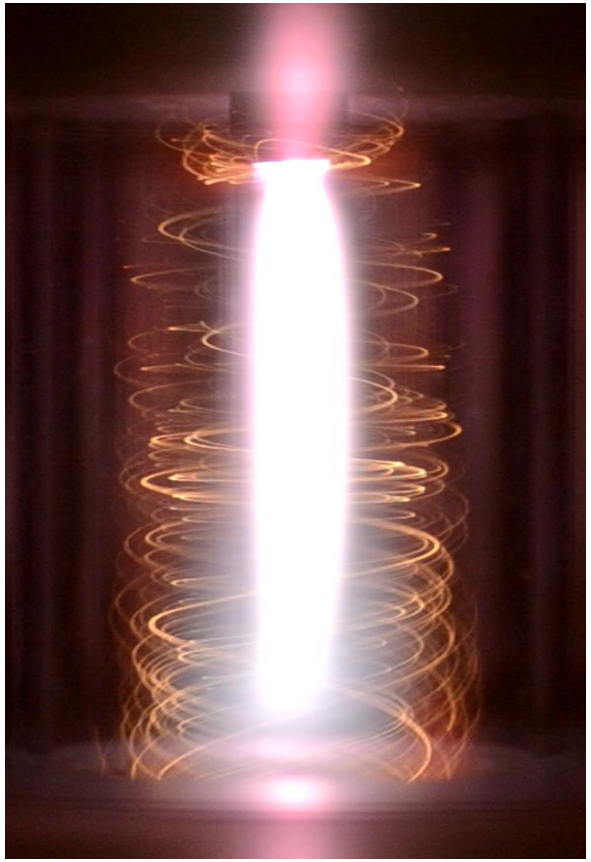
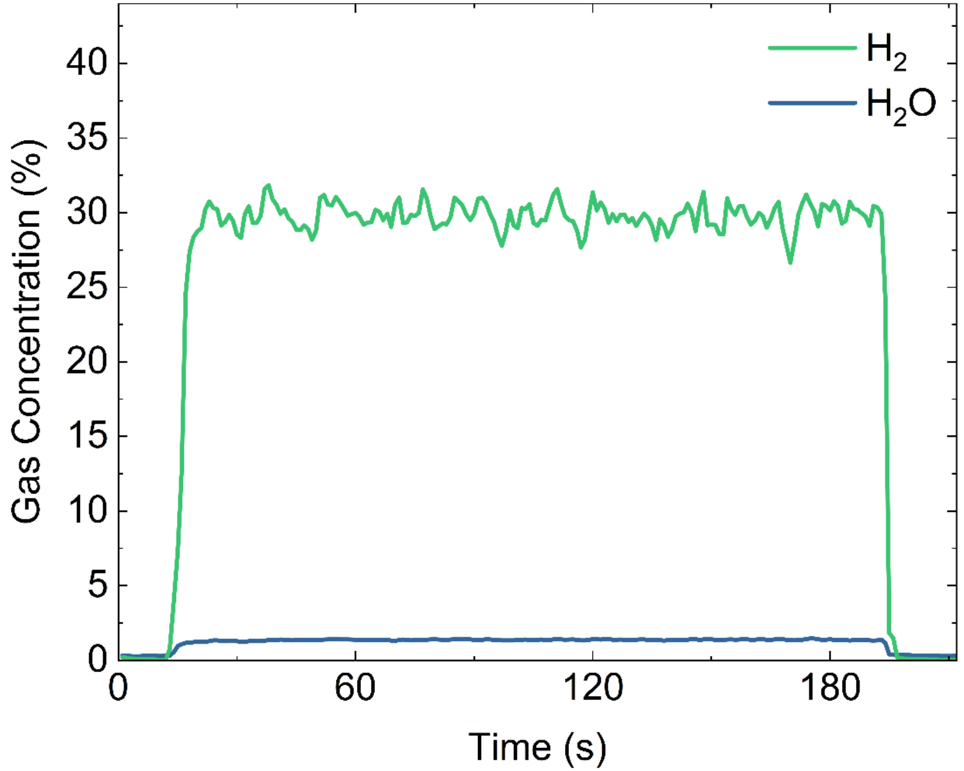
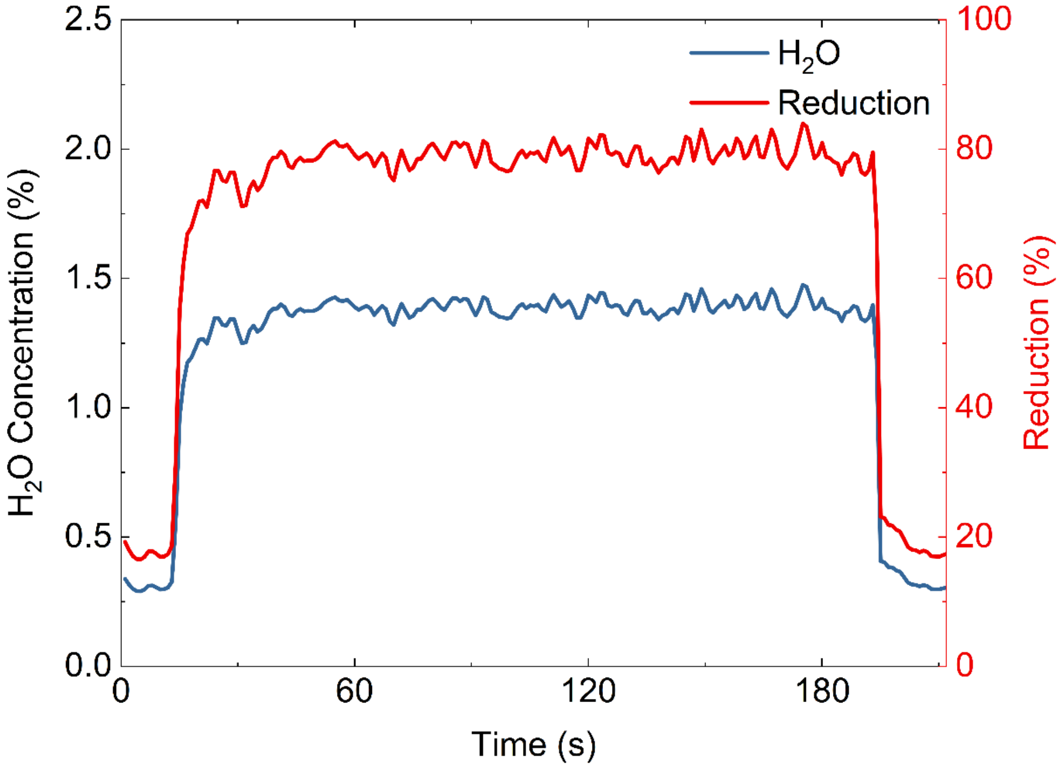


Photo of plasma with particles

- Fines reduce ultrafast
  - Short-lived H-radicals
  - Faster than thermal alone
- Efficient gas heating
  - Fully electric
- Output morphology

In-operando Diagnostic (RLGA)



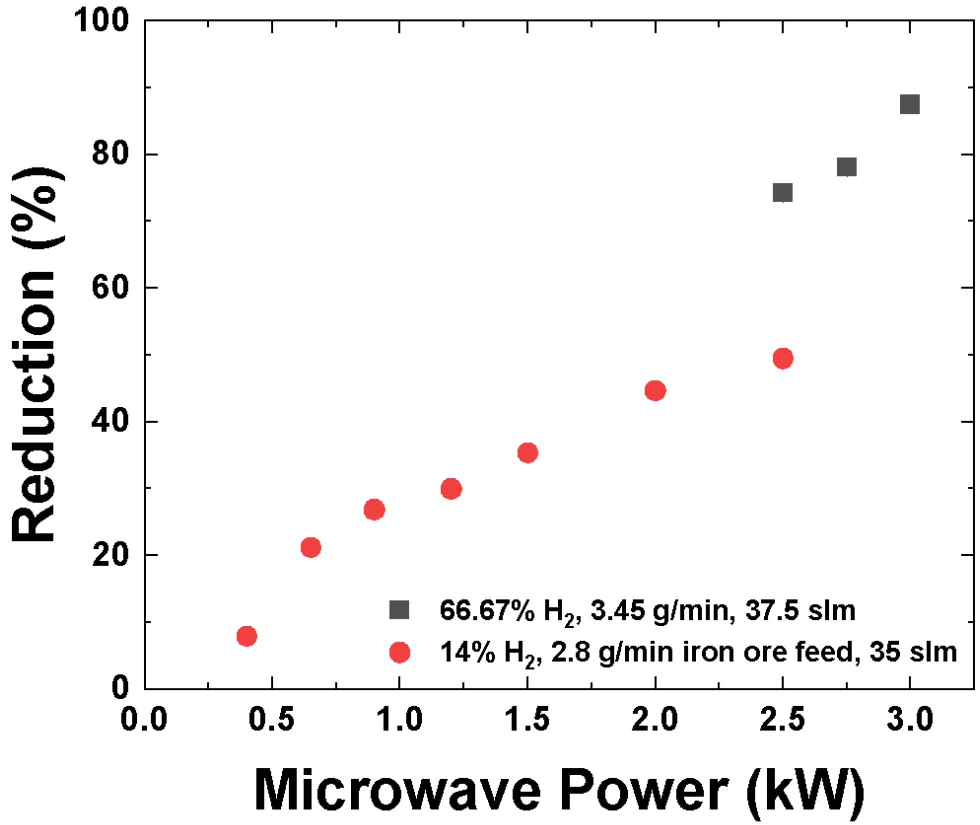


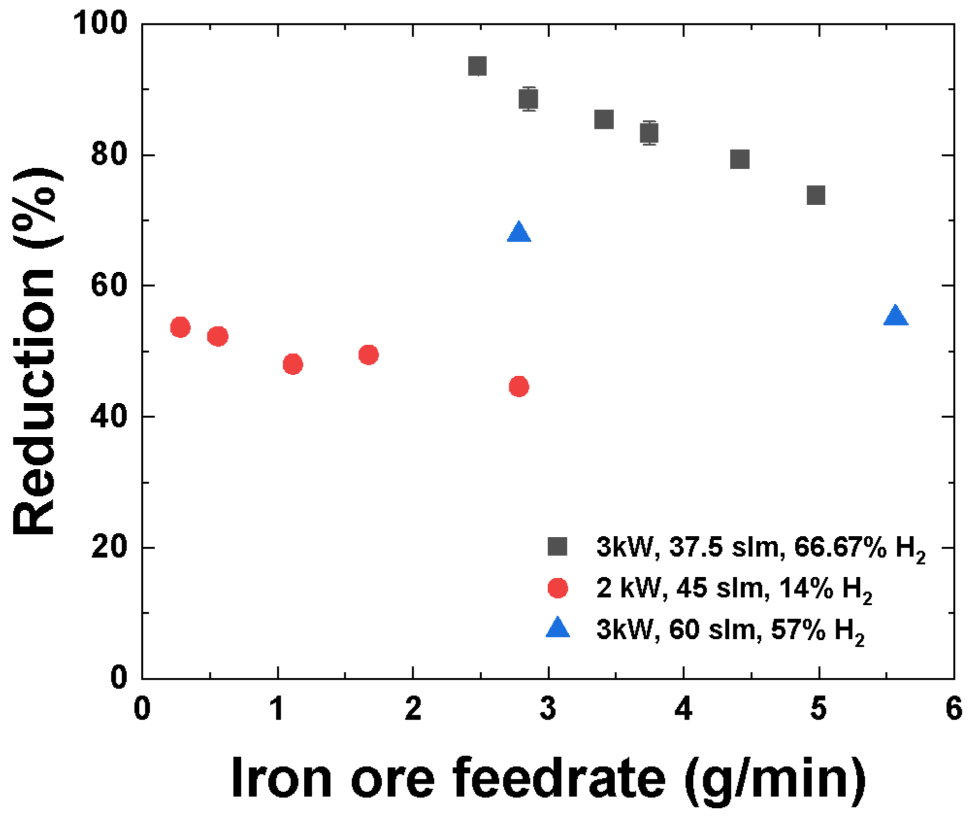
- Raman Laser Gas Analyzer (RLGA)
  - Exhaust H_2O & H_2 signals
  - Instantaneous Reduction %

$$\%\ \text{Reduction} = \frac{\text{mass of oxygen exhausted}}{\text{mass of oxygen in feed}}$$

Power (kW)	Feed Rate (g/min)	H_2 (%)	Total Flow (SLM)
3	3.6	66	87.5

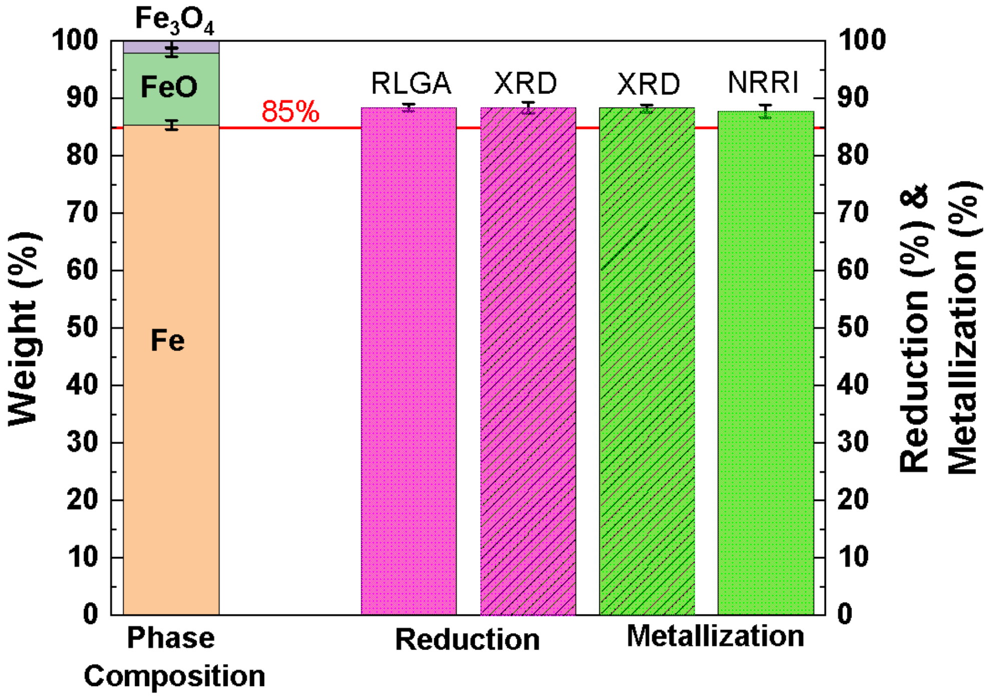
Parametric Effects

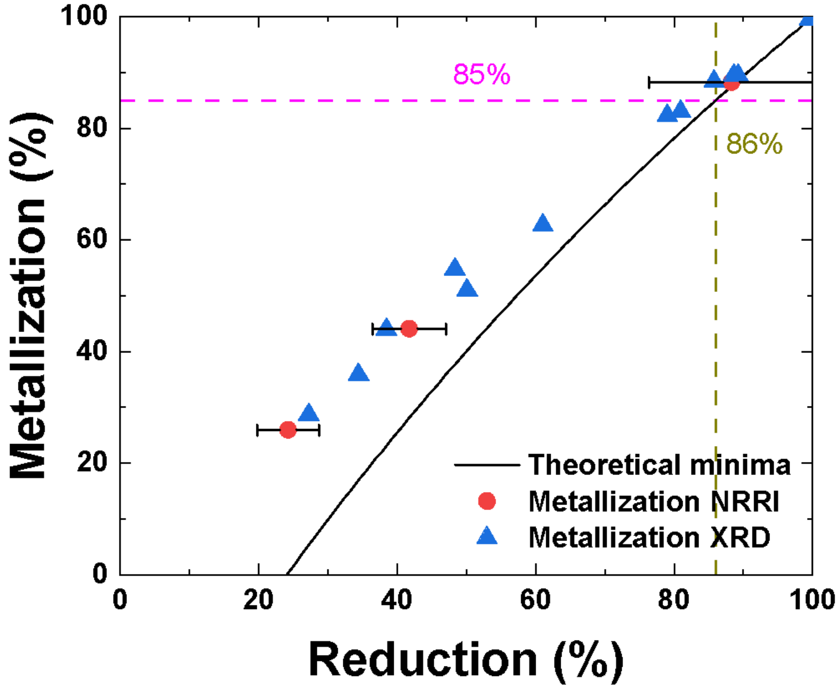




- Energy input & material feed

RLGA Validation



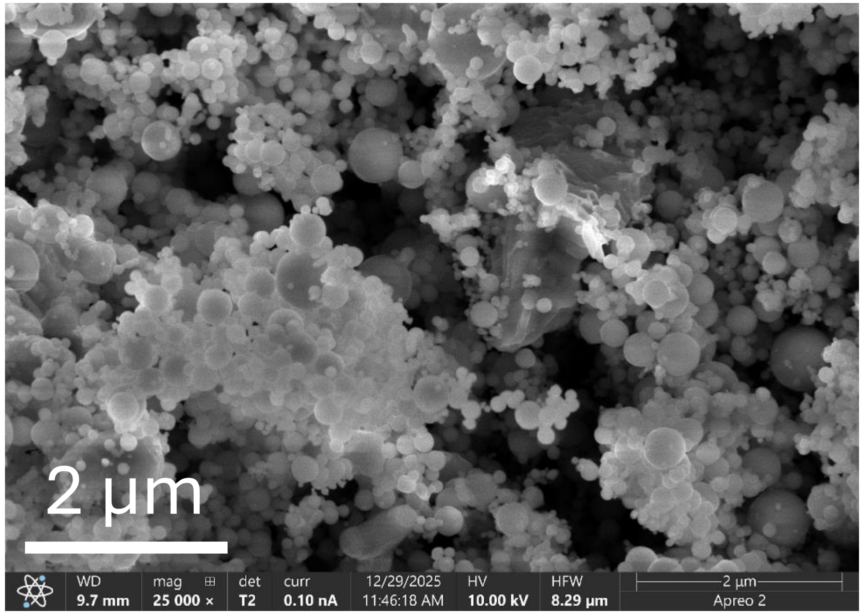


- Powder x-ray diffraction analysis (XRD) fitting
- Natural Resources Research Institute (NRRI) Collaboration

Power (kW)	Feed Rate (g/min)	H_2 (%)	Total Flow (SLM)
3	4.3	66	87.5

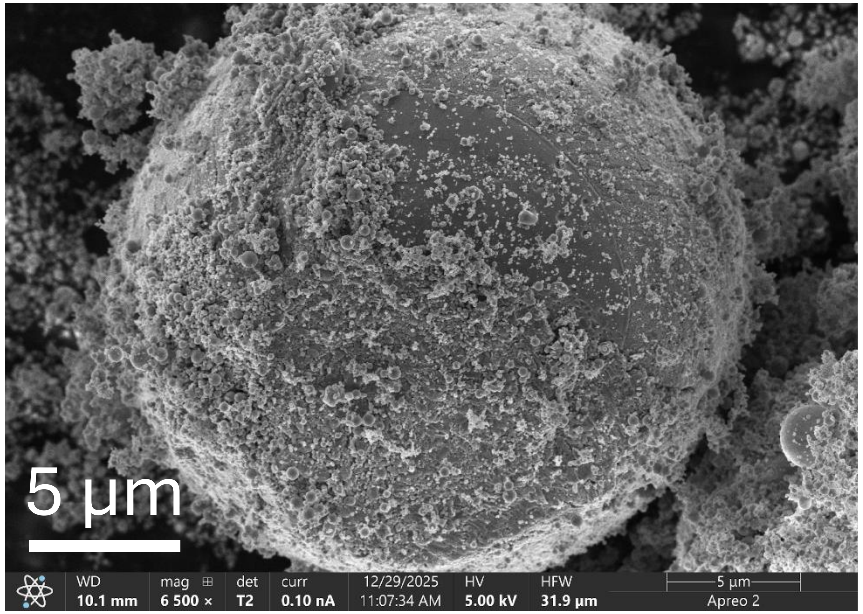
Material Output

Nanomaterial



< 100 nm avg. diameter

Microparticles



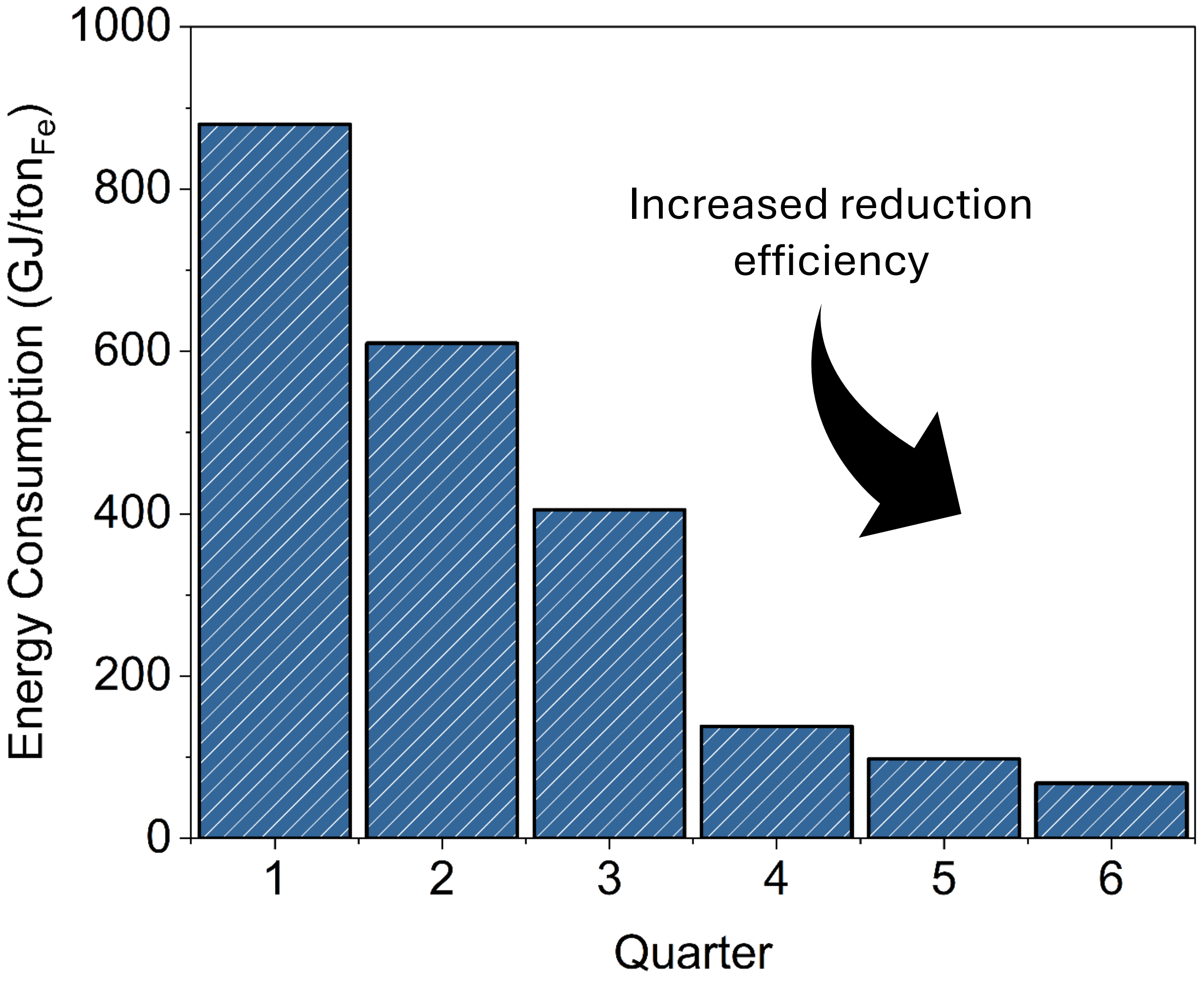
> 5 µm avg. diameter

Bulk Material

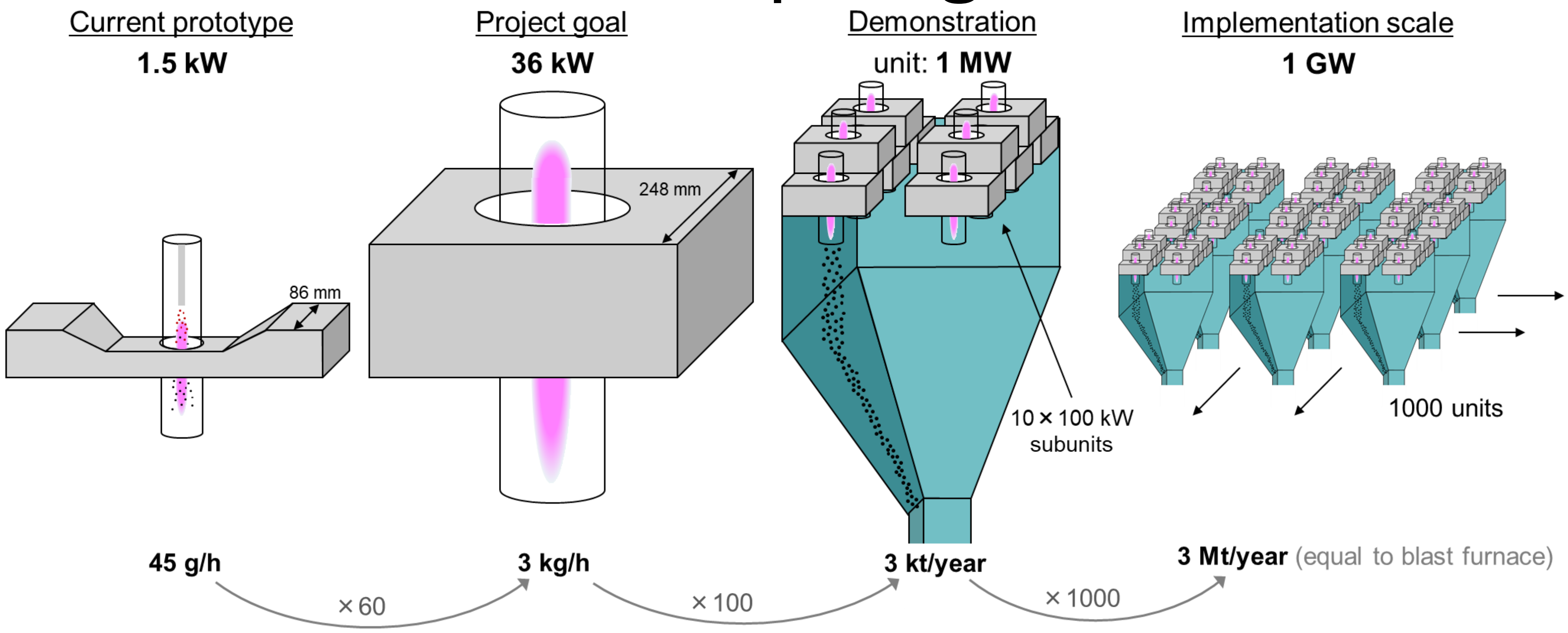
Scale Up & Energy Efficiency

Within the project duration:

- Production Scale
  - From 16 to 280 g/hr
- Energy Consumption
  - From 880 to <70 GJ/ton_{Fe}
  - > 80% Fe metallization

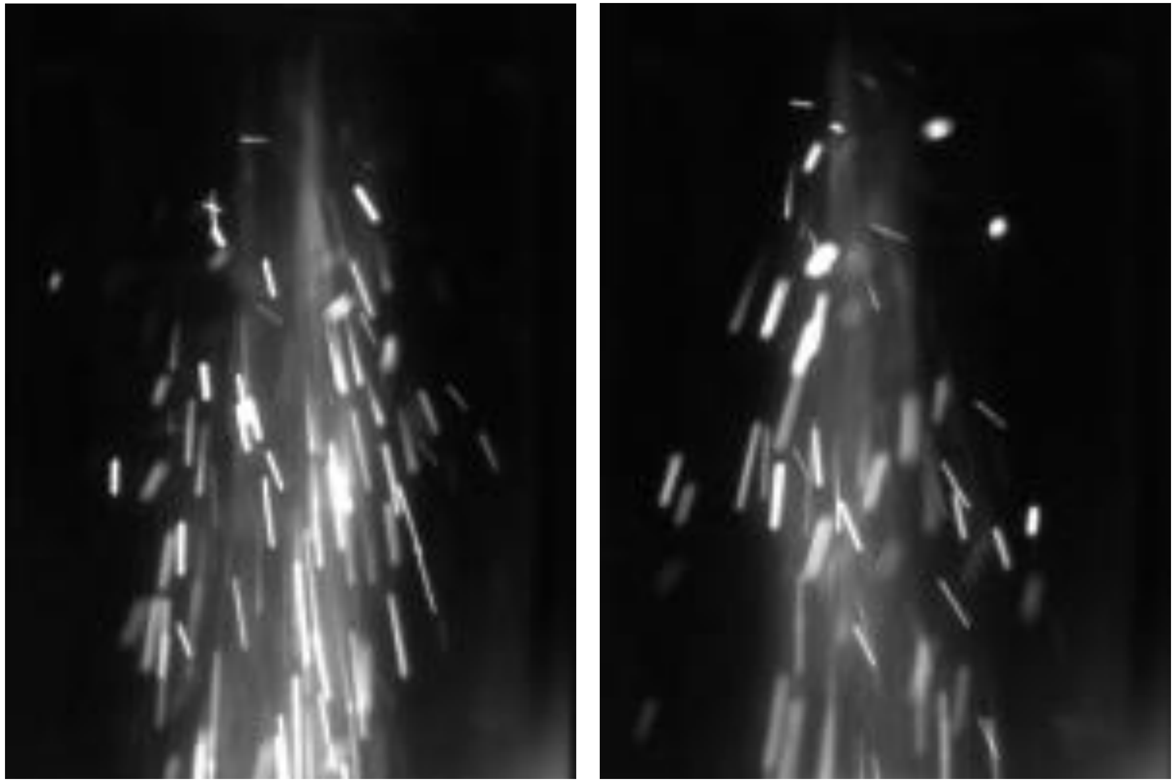


Scale Up Targets



- Target project goal
  - 36 kW reactor & 3 kg/hr

Ongoing Development & Outlook



Plasma with iron ore fines (25-45 μm)

Plasma plume during operation

- Energy efficiency improvements
- Powder collection
- Feedstock flexibility

R&D Focus

Energy efficient scaling

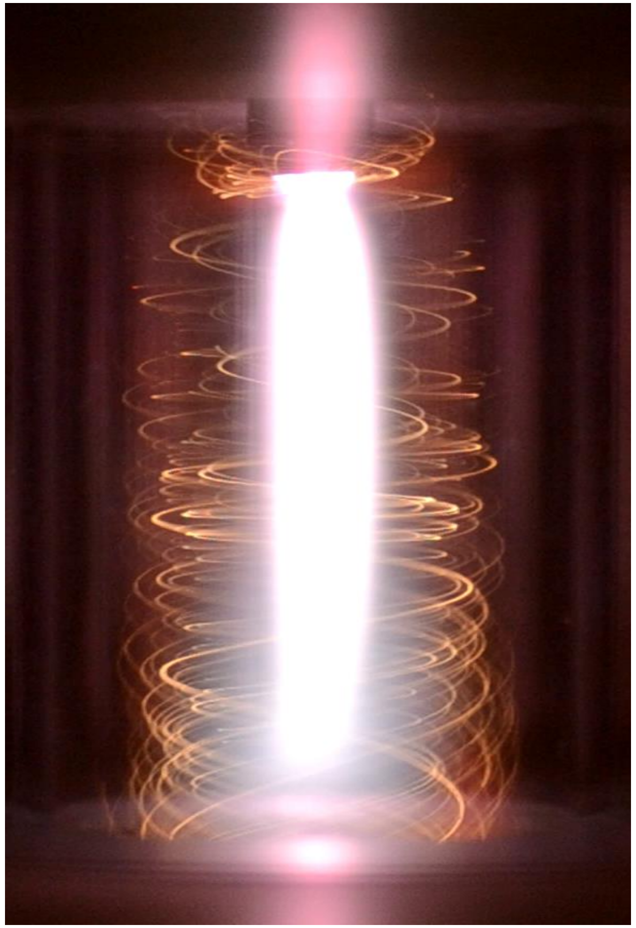
- Heat utilization
- Gas handling

Production scale

- Powder delivery
- Continuous operation

Conclusions

- Ultrafast H_2 enabled reduction
  - Carbon free
  - Electrified
- *In-operando* diagnostics support research and operation
- Energy efficient at-scale operation is achievable



Acknowledgements

- David Haugen and Brett Spigarelli
  - Natural Resources Research Institute (NRRI) University of Minnesota – Duluth
- Akin Akinshilo
- Dr. Sachin Kumar

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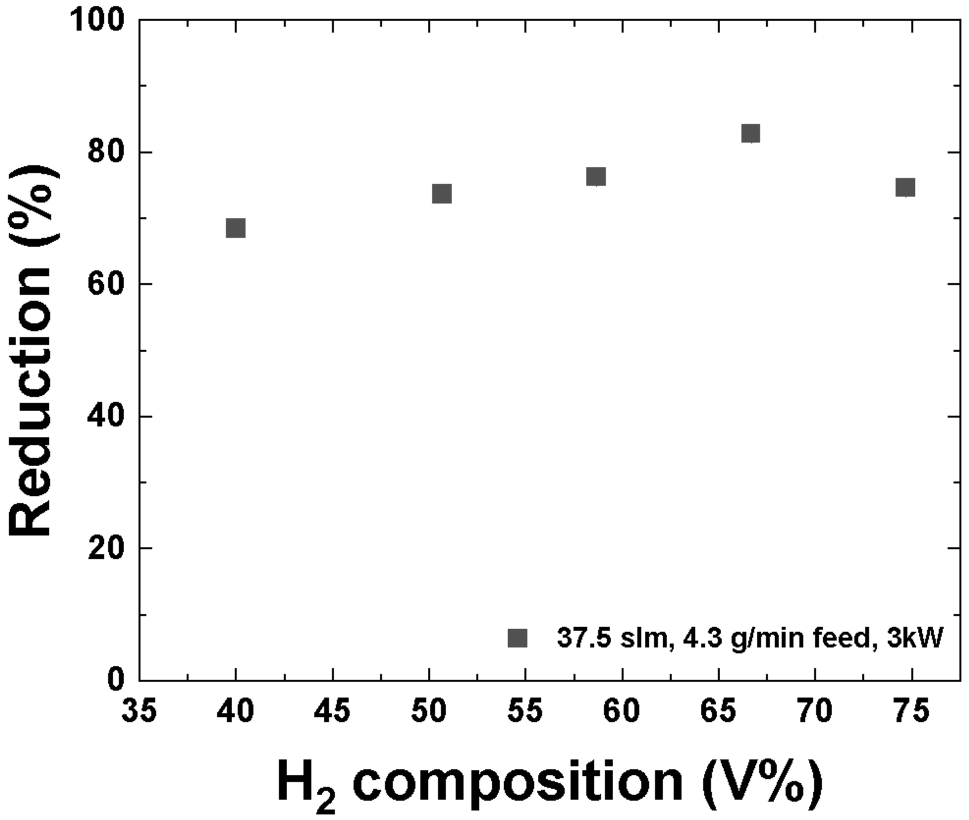
Questions?

Supplementary Slides

What about gas composition?



- H_2 is excess – slight improvement in red.% up to 66% H_2

What methods are used to verify iron purity?

- Collaboration with Natural Resources Research Institute (NRRI):
  – Their testing validates finding from our diagnostics.

Analysis	Procedure Used	References
Iron Metallic	In-House Colorimetric	ASTM 246 Part B – Total Fe Reduction ISO 5416 Bromine/Methanol Metallic refluxed portion ASTM D3872 Ferrous portion
Iron Total	In-House Potentiometric	ISO 11257 Part 4

Energy consumption calculation?

$$\text{Energy Cost} = \frac{\text{Power Input} * \text{Operational Time}}{\text{Mass of Iron Produced}}$$

Conditions	7.5% H_2	15% H_2	37.5% H_2
Power (kW)	1.5	1.5	2.5
Feed rate (g/min)	0.4	0.4	2.78
Collection efficiency (%)	81.6	81	80
Reduction (%)	53.5	71	69.6

- Blast furnace is more energy efficient (6-11 GJ/ton_{Fe})
  - Our technology can fill niche production demands