The University of Texas at Austin
Energy Institute

Enabling the Sustainable Energy Transition: Economic Recovery of Rare Earth Elements

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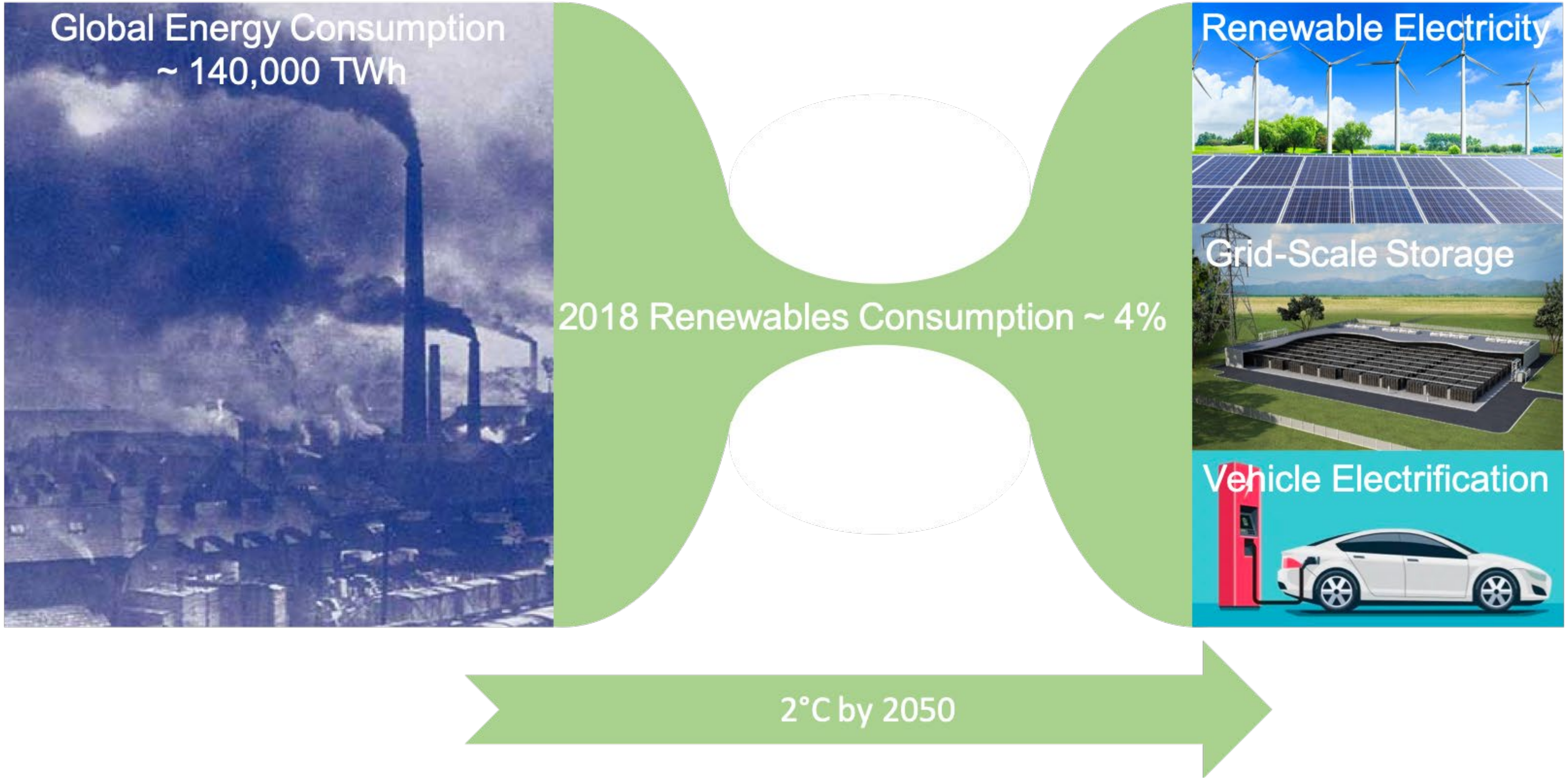
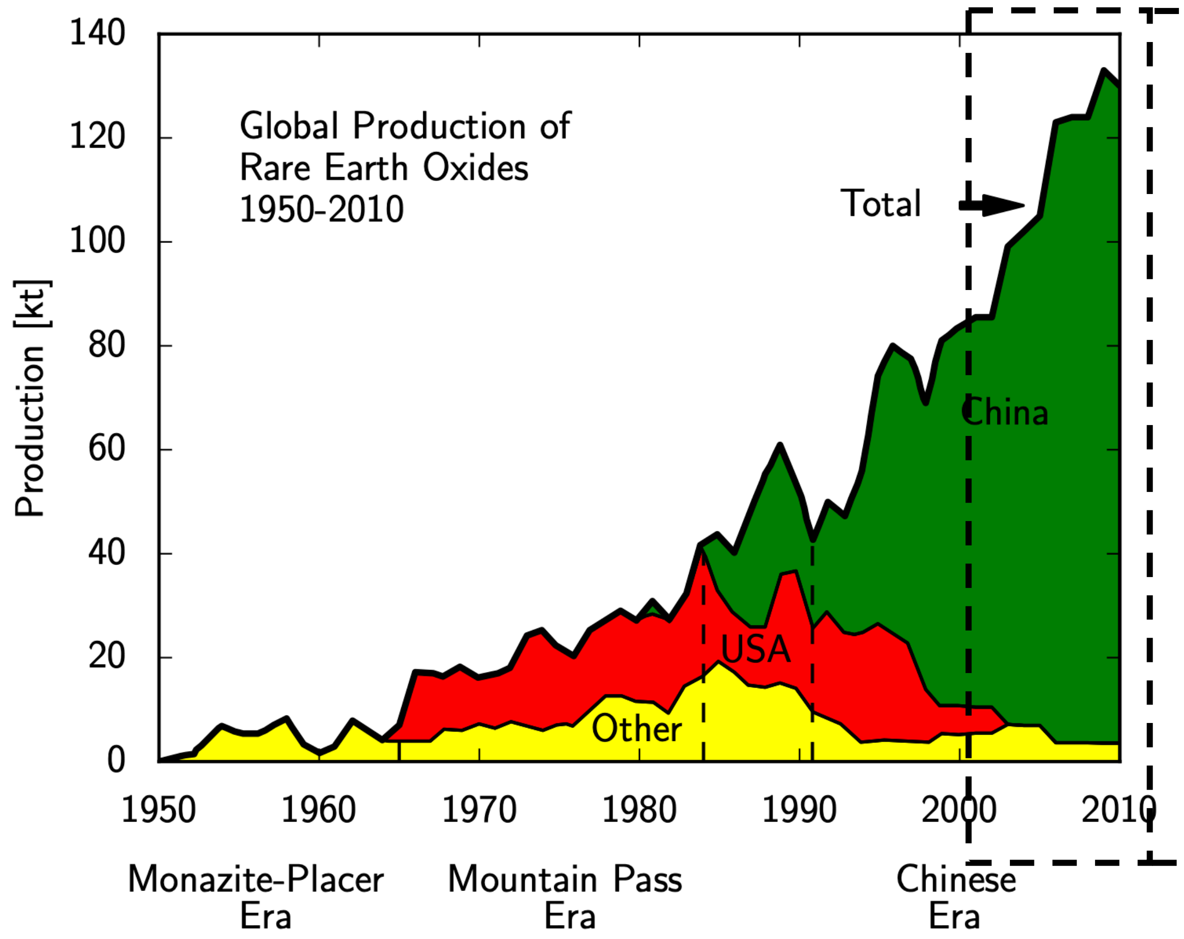
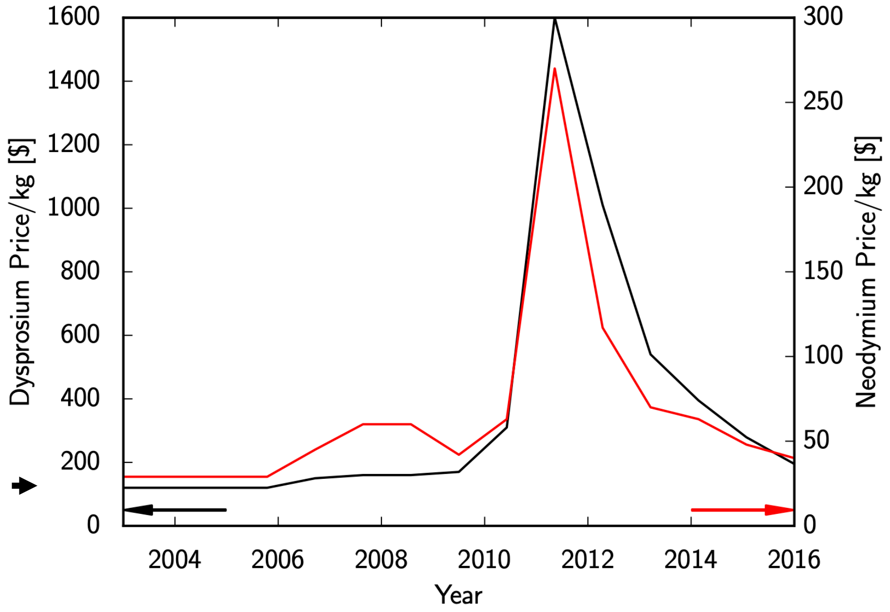
Fueling a sustainable energy transition



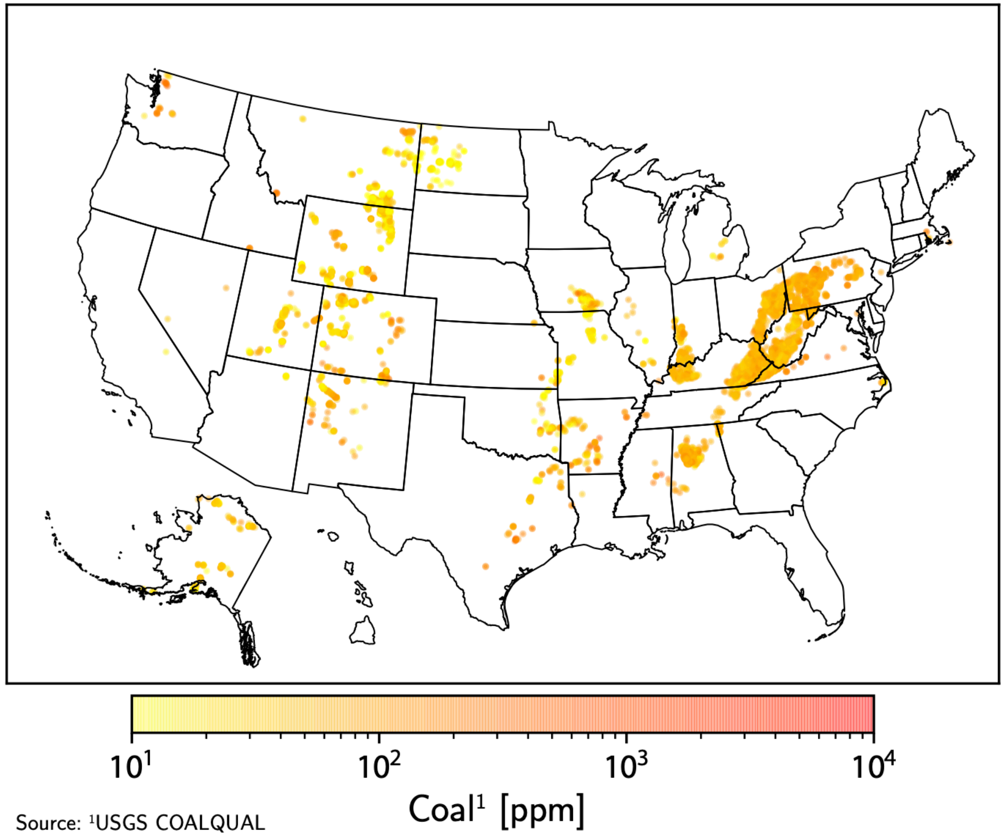
Global production of REEs





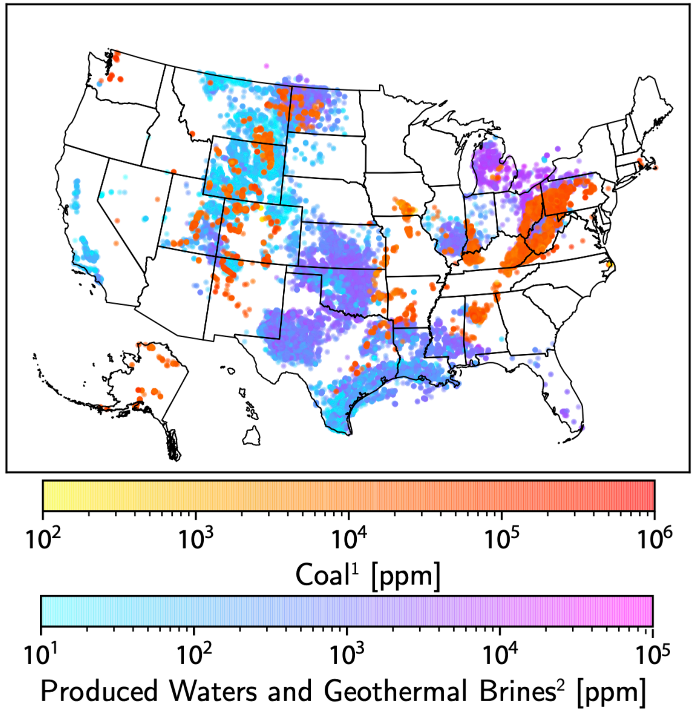
Uncoventional resources for critical minerals

Total Concentration of REEs



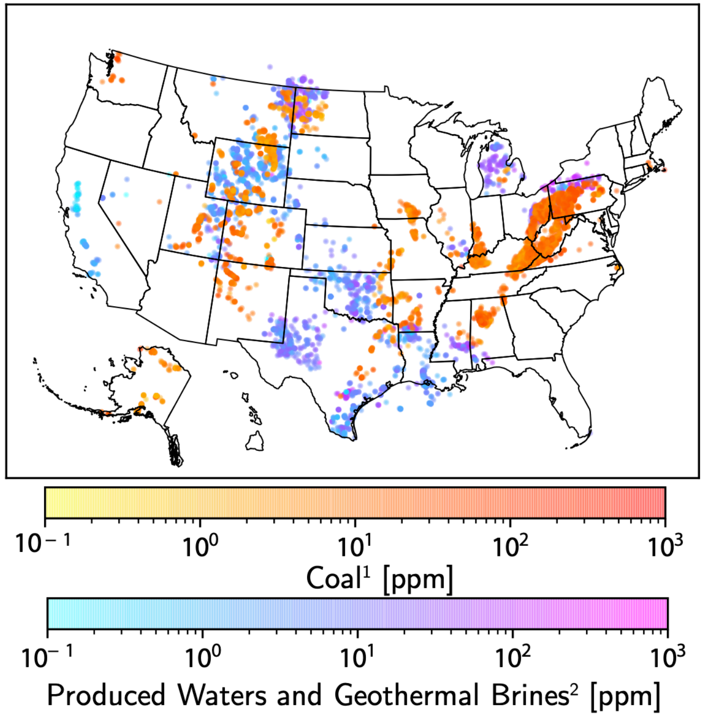
Source: [1]USGS COALQUAL

Total Concentration of CMs



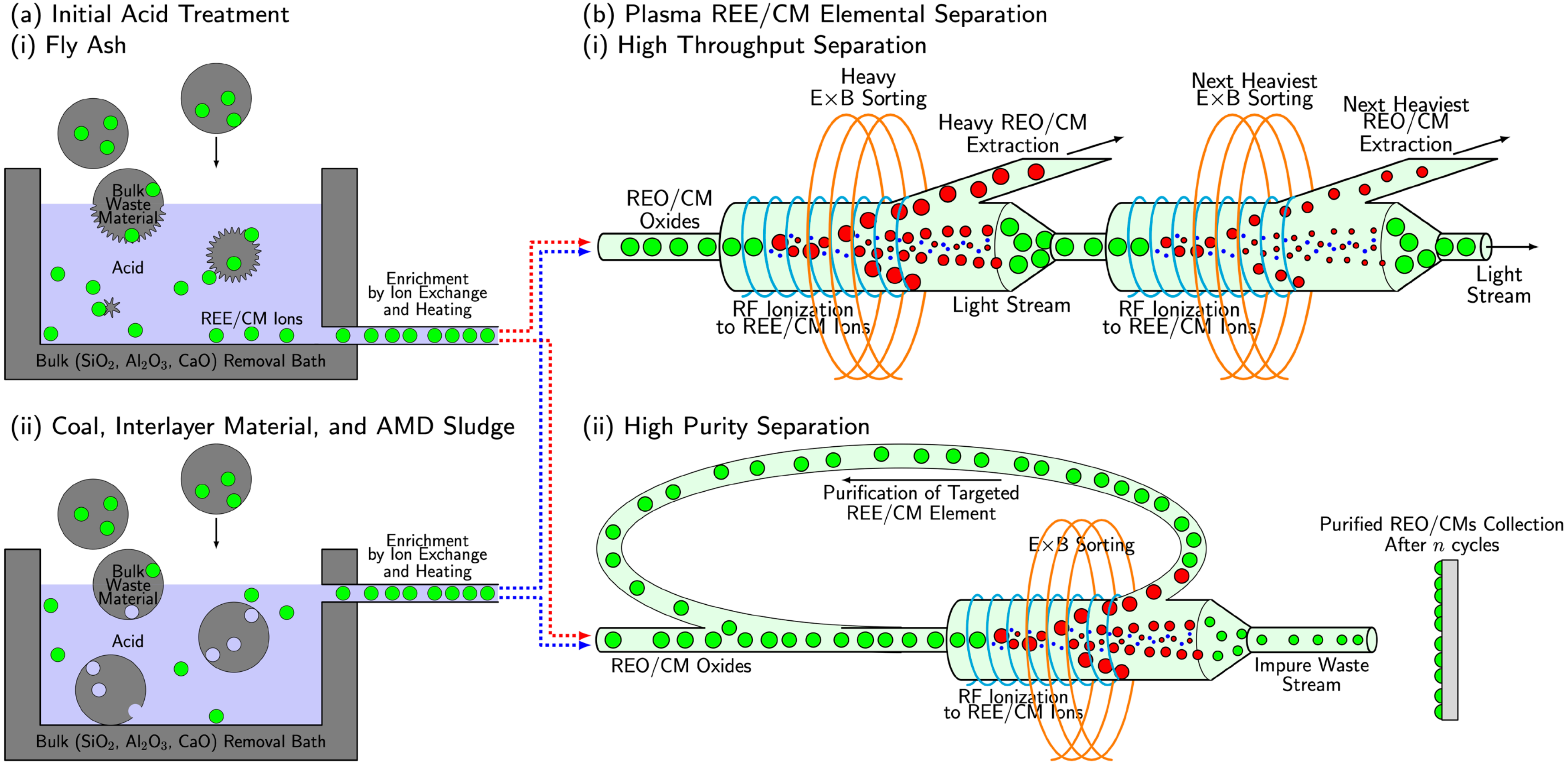
Sources: [1]USGS COALQUAL, [2]USGS Produced Water Databases

Total Concentration of Li



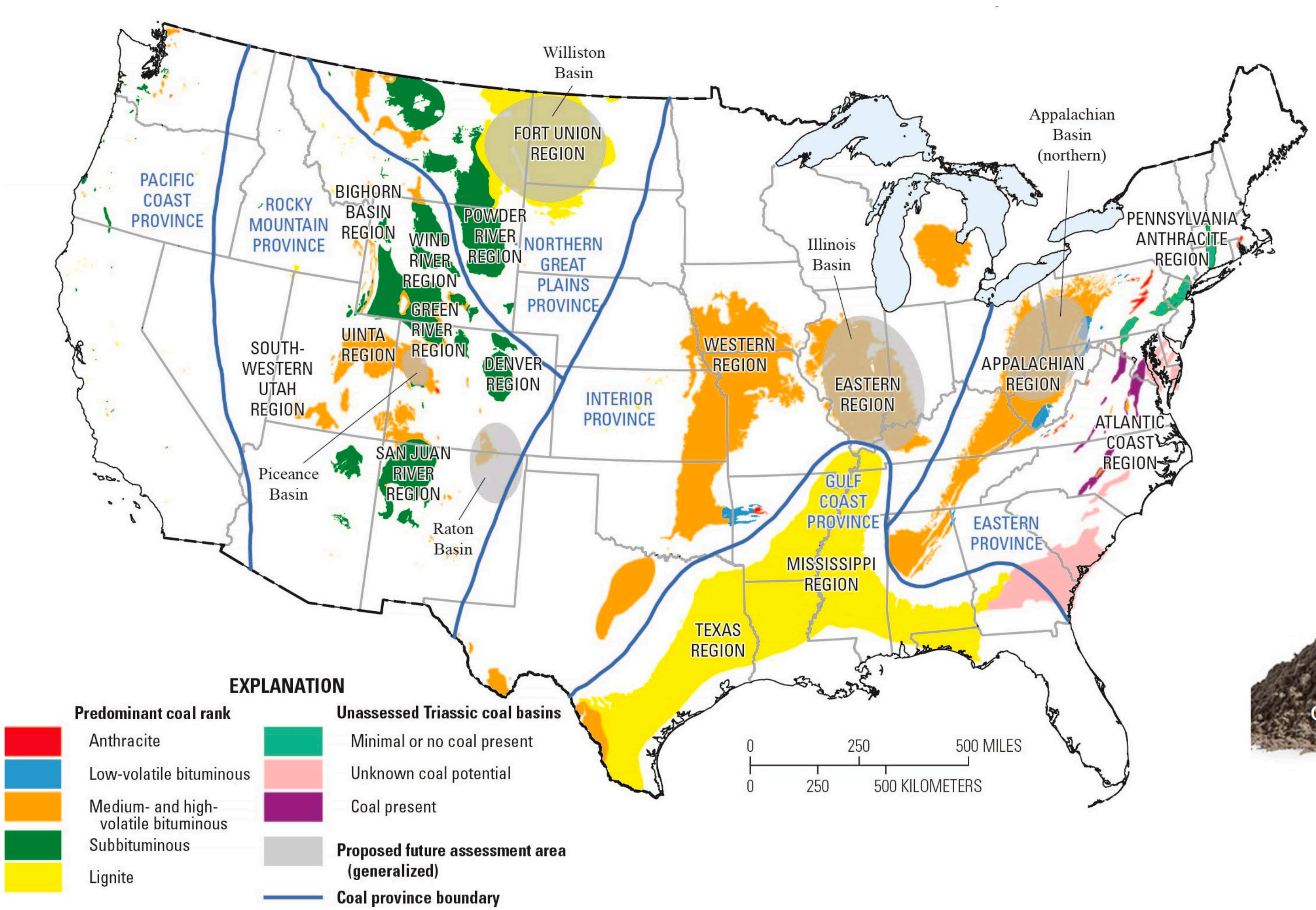
Sources: [1]USGS COALQUAL, [2]USGS Produced Water Databases

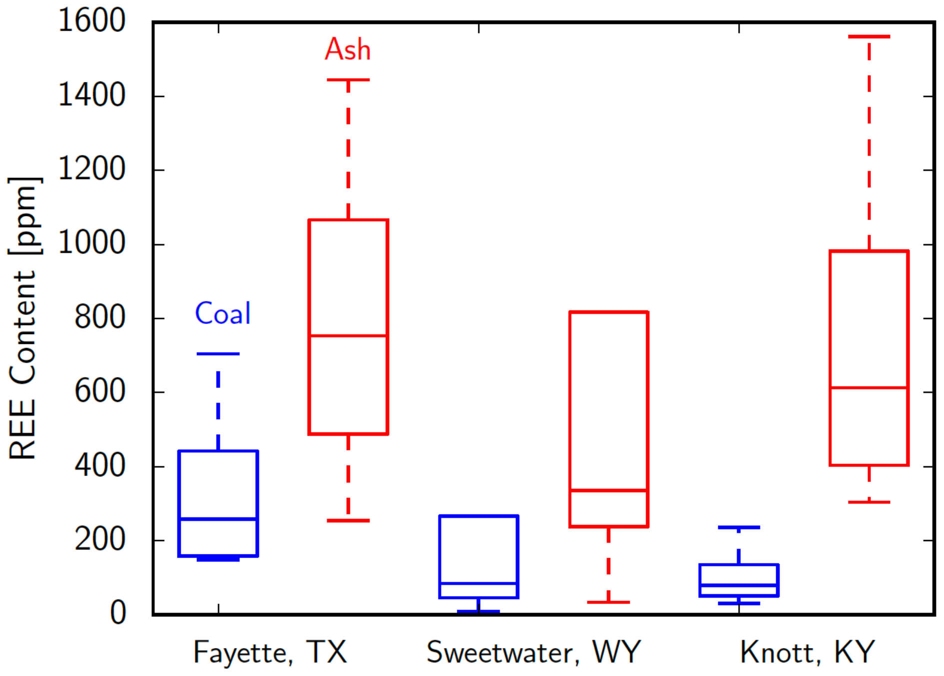
Our Technology: Enriched Plasma Separation



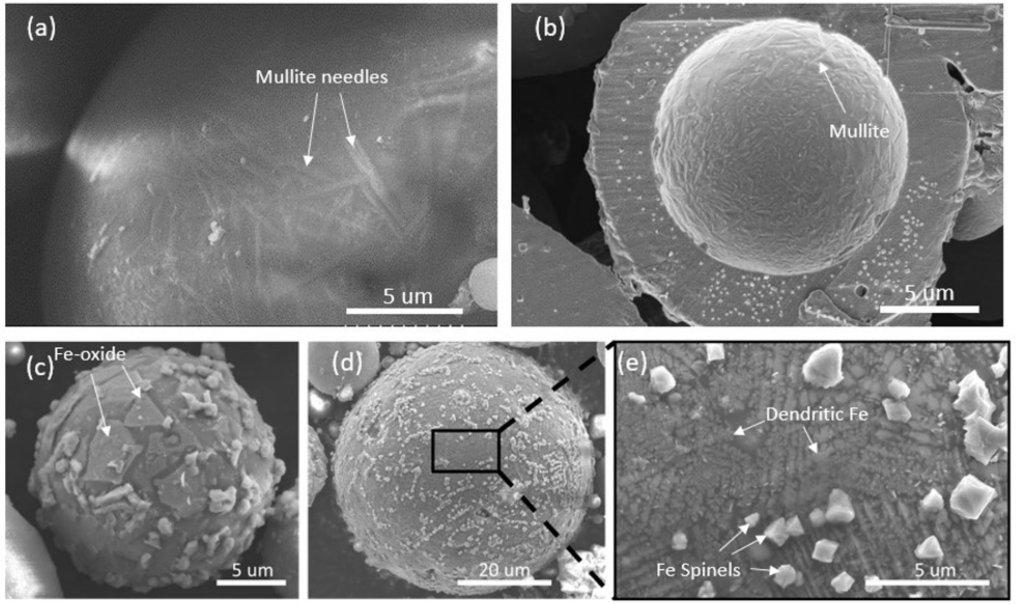
- Recovery up to 99% of available REEs, independent of feedstock composition
- Production of salable > 99% purity REE product
- Low secondary waste production

Resource characterization

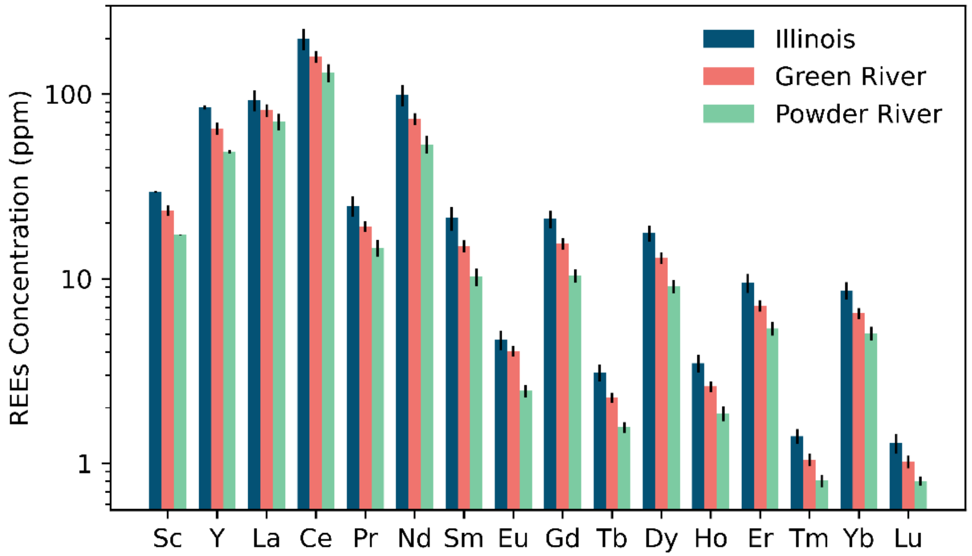


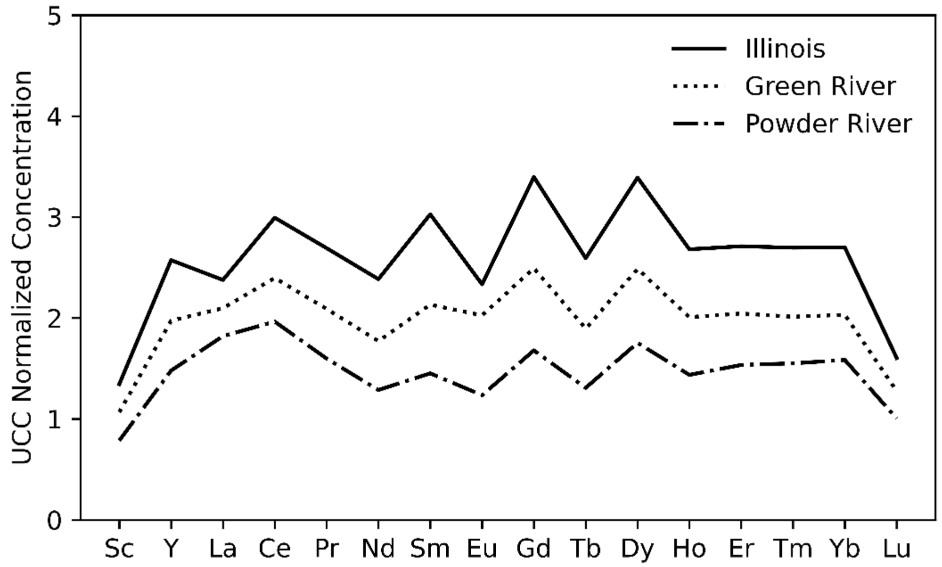


Resource characterization

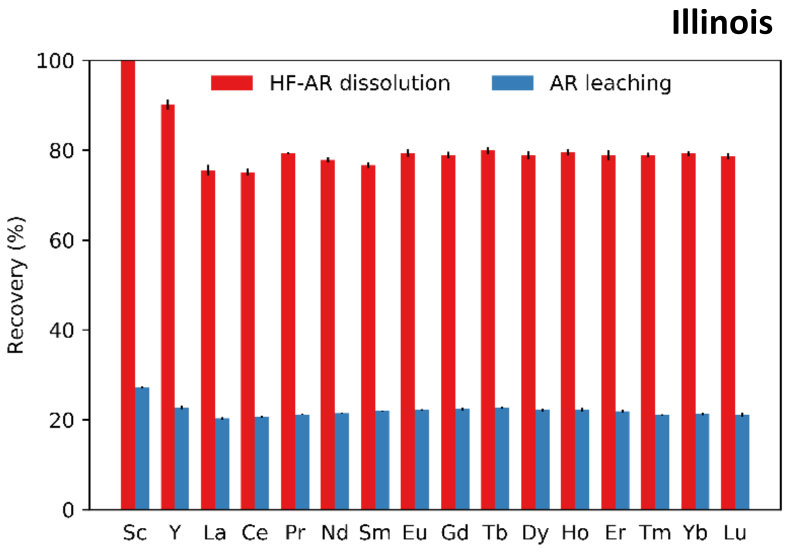


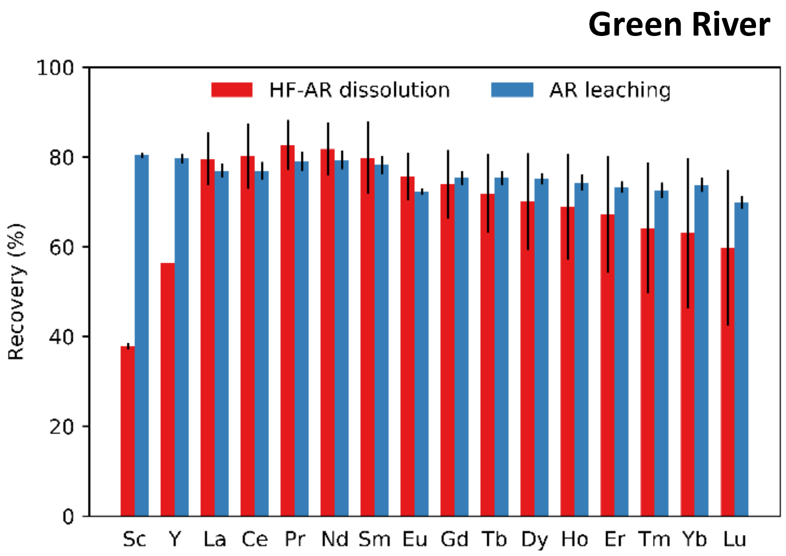
Basin	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	NaO	SiO_2	TiO_2
Illinois	20.6%	2.9%	22.1%	2.5%	1.0%	0.6%	49.4%	0.9%
Green River	17.1%	28.2%	5.8%	0.4%	6.7%	1.8%	38.0%	1.2%
Powder River	17.5%	6.0%	4.3%	1.2%	2.4%	1.6%	65.6%	0.9%

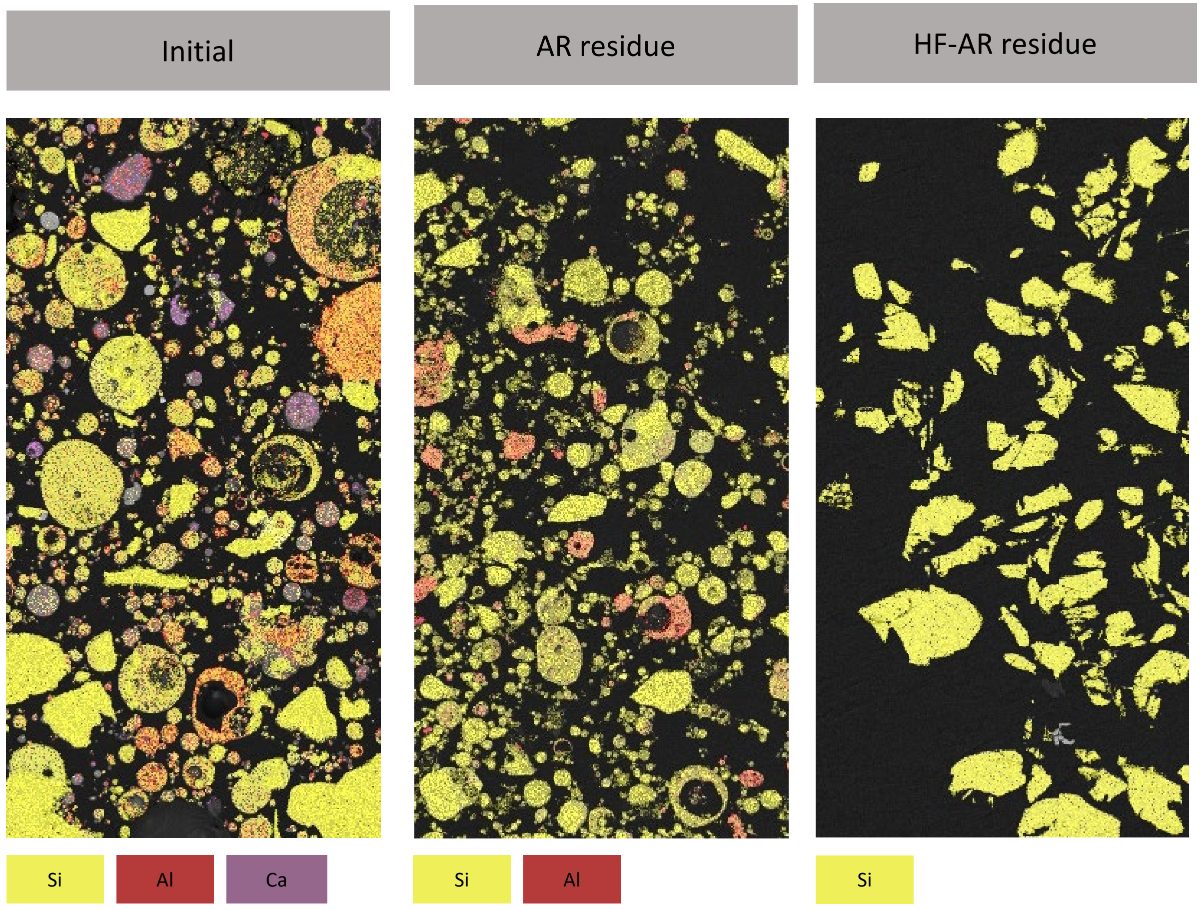




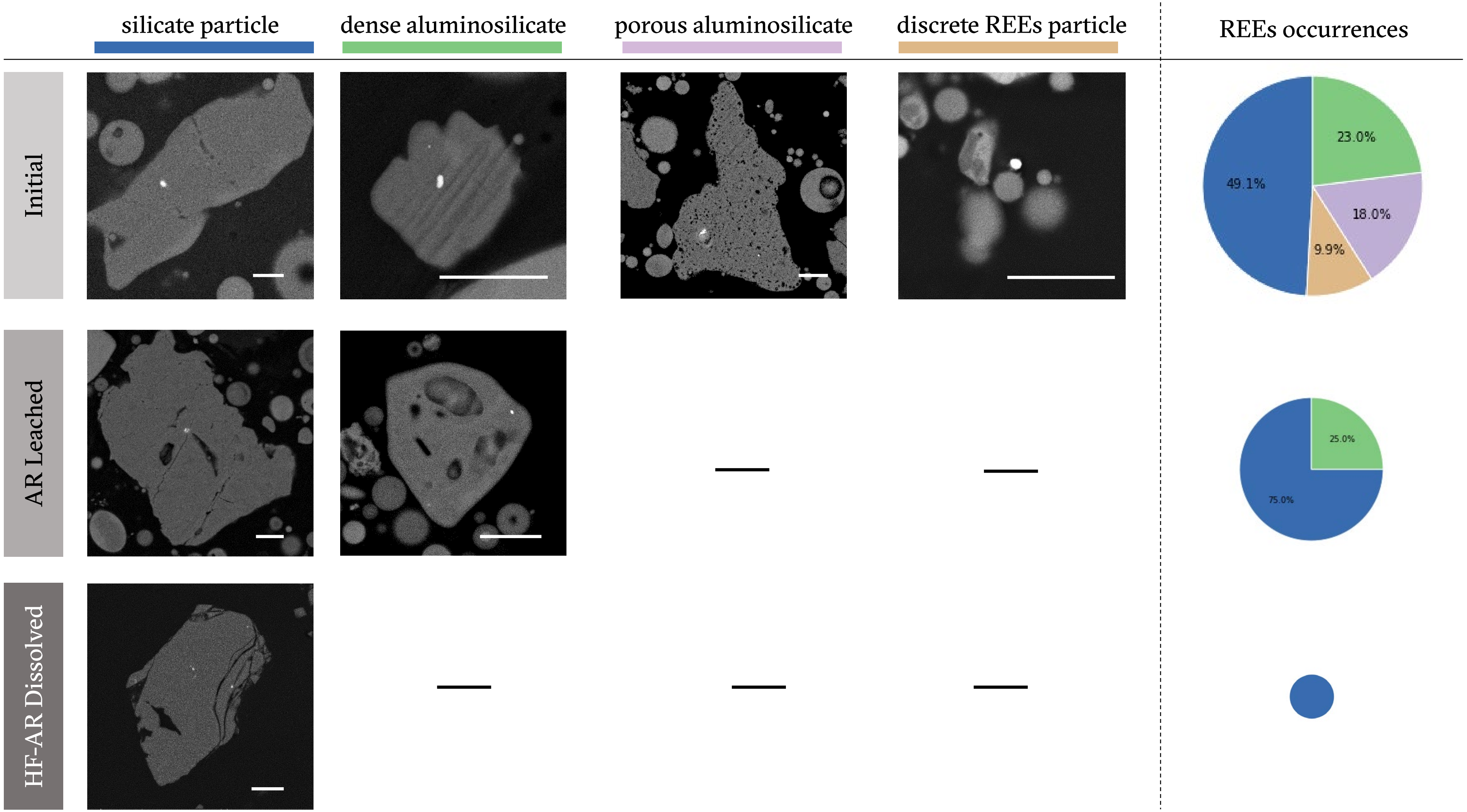
Reagents-based recovery of REEs



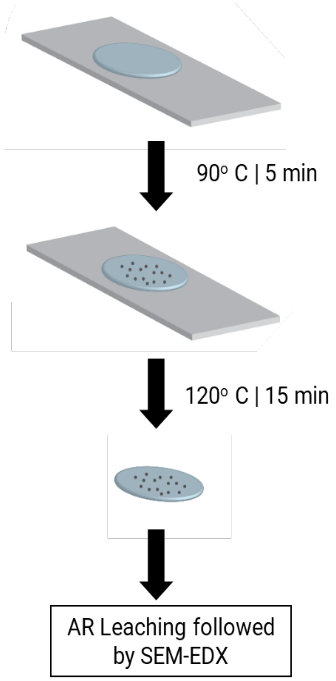


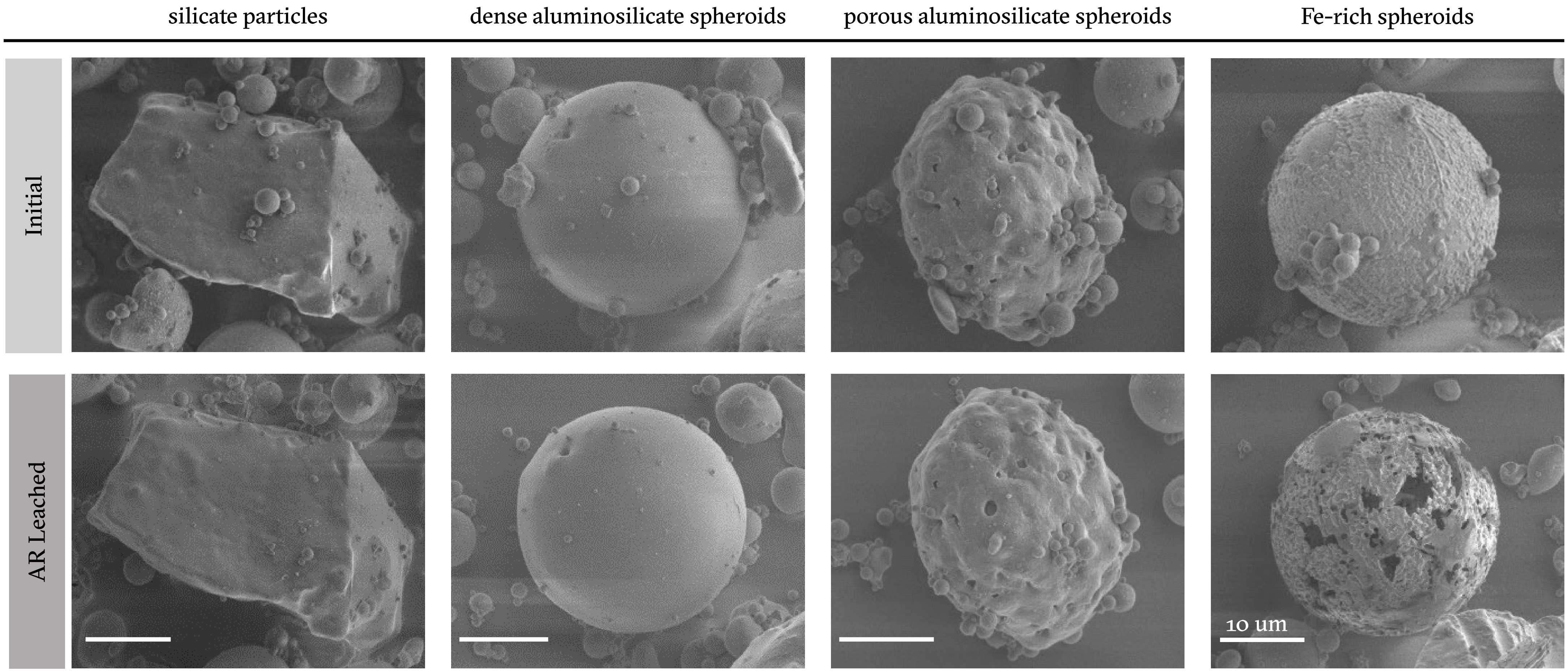


Micro/nano intraparticle porosity

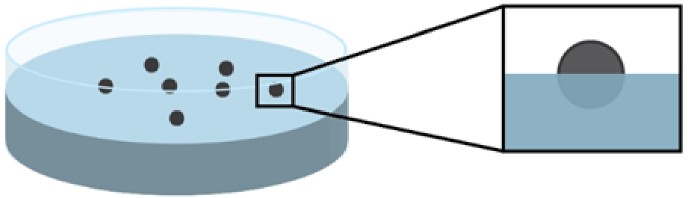


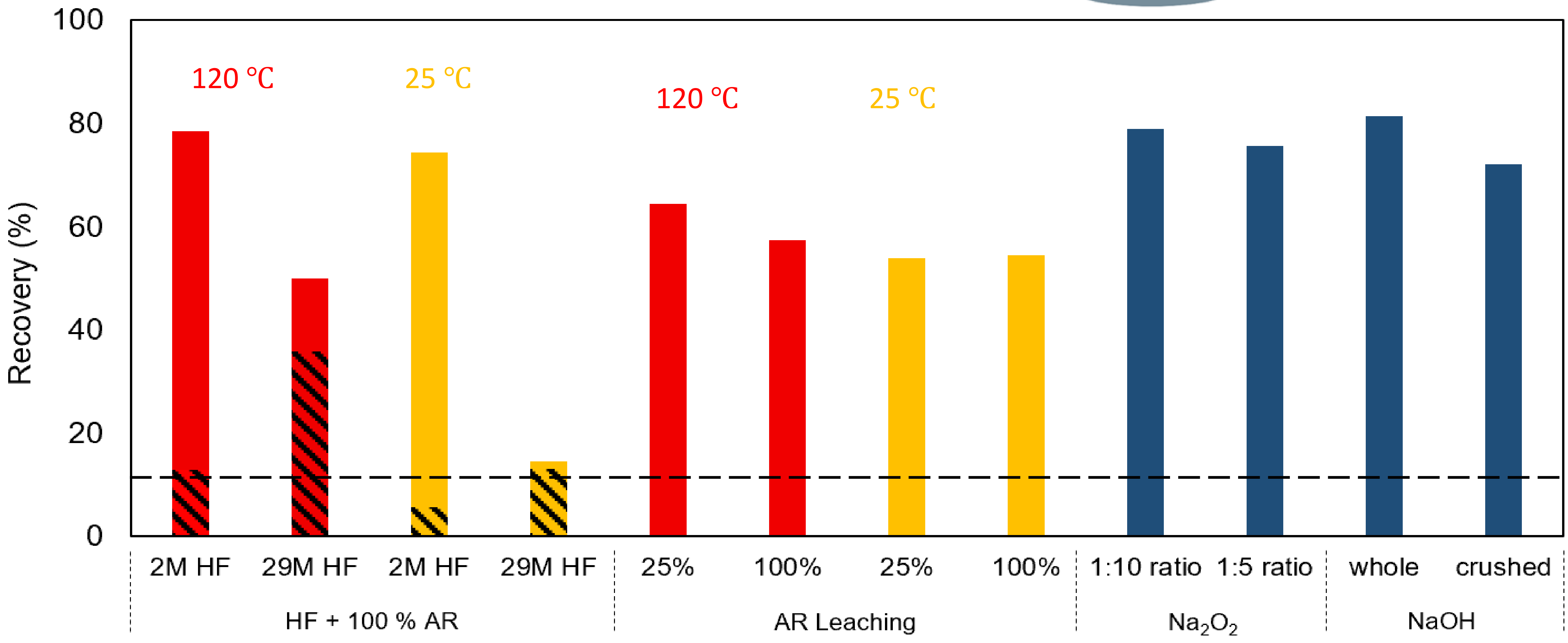
Mineralogic heterogeneity on leaching



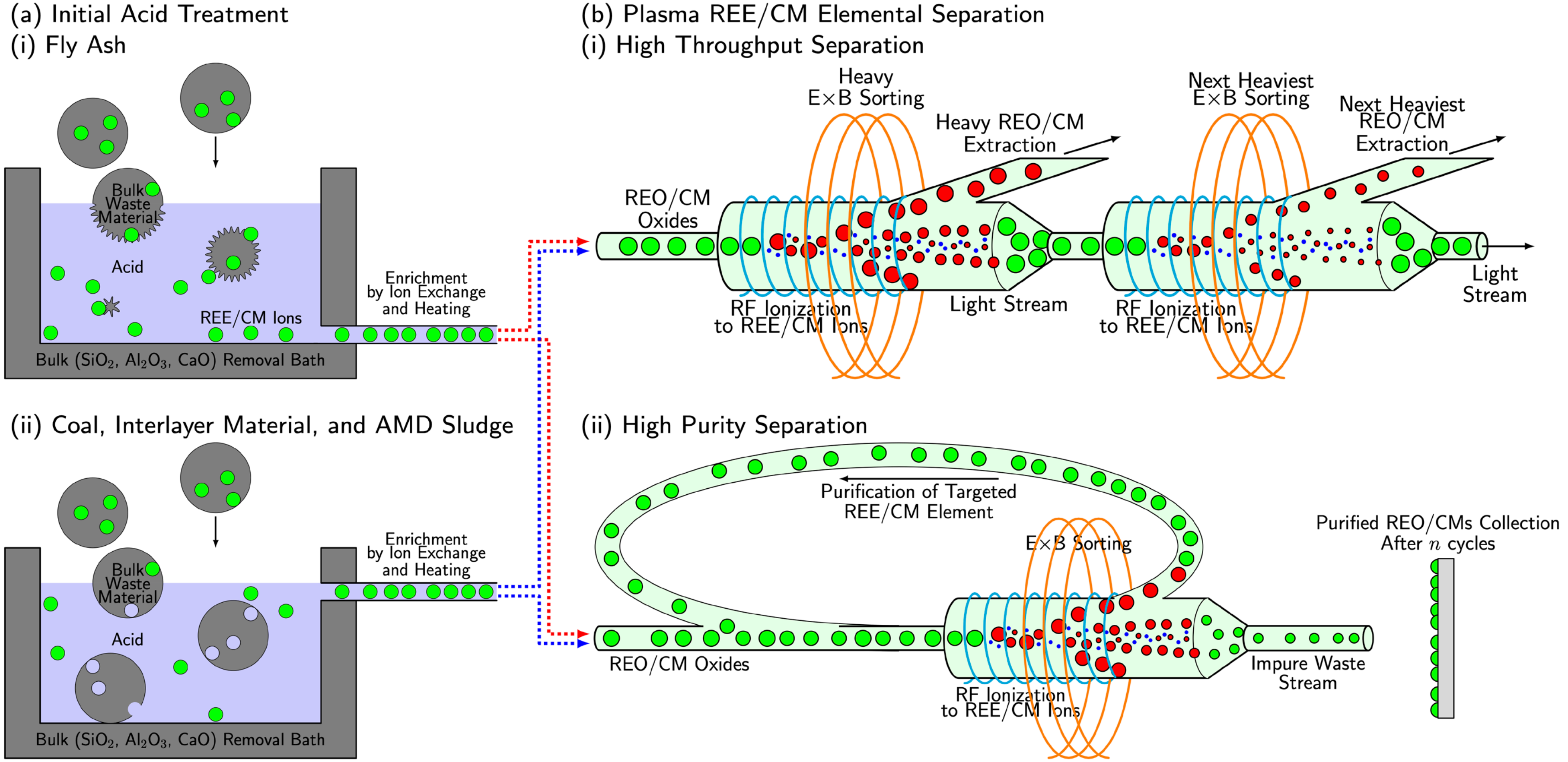


Improved, environmentally-benign REEs recovery





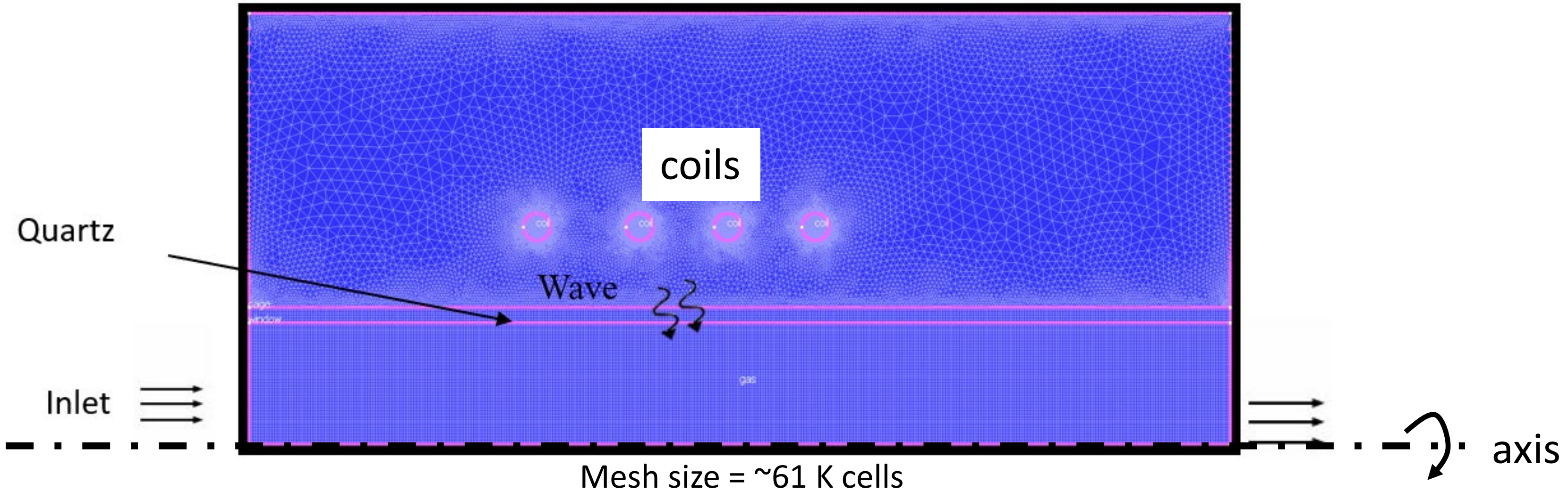
Our Technology: Enriched Plasma Separation



- Recovery up to 99% of available REEs, independent of feedstock composition
- Production of salable > 99% purity REE product
- Low secondary waste production

REE ionization (ICP inductively coupled plasma)

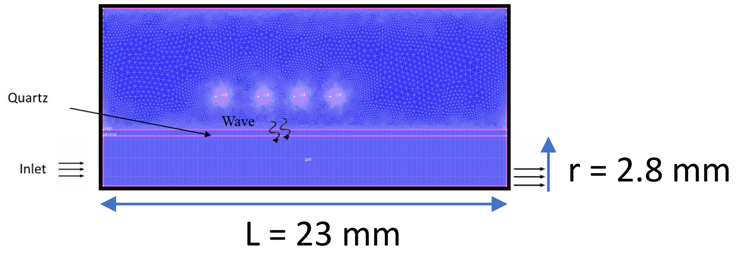
- ICP provide an electrodeless approach to plasma generation and gas ionization (including the RRE species)
- Key questions are:
  1. Optimal geometric requirements and operating conditions for stable ICP generation
  2. Ionization fraction of RRE species (process yield) transported into ICP



Mesh size = ~61 K cells

REE ionization studies based on plasma modeling

- We have performed extensive model-based exploration of the plasma parameter space (pressure, power, flow rates, discharge dimensions, etc.)
- Results indicate REE ionization fraction is strongly dependent on process pressure and power density into plasma
  - Higher pressures support higher ionization fraction
  - Smaller discharge dimensions support higher power density
  - Hence, we have chosen ~mm dia. ICP discharge as baseline geometry for studies



	Parameters		
Feed stream (with mole fraction)	Ar + Ce (10^{-5} mole fraction)		
Inflow Temperature	300 K		
Feed gas mass flow rate	$8.1 \times 10^{-8}\ {}^{kg}/_{s}$ (50 sccm)		
Pressure	0.1 torr	1 torr	100 torr
EM Power	1 W		

Plasma chemistry for argon carrier gas with cerium (Ce) as REE surrogate

#	RXN	RXN Type	RXN Energy (eV)	Ref.
1	$Ar + E \to Ar^{*} + E$	Excitation	11.56	BOLSIG
2	$Ar + E \to Ar^{+} + 2E$	Ionization	15.76	BOLSIG
3	$Ar^{*} + E \to Ar^{+} + 2E$	Step-wise Ionization	4.2	BOLSIG
4	$Ar^{+} + E \to Ar^{*}$	Radiative Recombination	0.0	[1]
5	$2Ar^{*} \to E + Ar + Ar^{+}$		-7.56	[1]
6	$Ar^{*} + E \to Ar + E$	De-excitation	-11.56	BOLSIG
7	$Ar^{*} + Ar \to 2Ar$	De-excitation	-11.56	BOLSIG
8	$Ar^{*} \to Ar$	Radiative Decay	0.0	[1]
9	$2E + Ar^{+} \to E + Ar^{*}$	3-Bdy Recombination	-4.2	[1]
10	$Ar^{*} + 2Ar \to Ar_2^{*} + Ar$		-0.6	[1]
11	$Ar^{+} + 2Ar \to Ar_2^{*} + Ar$		-1.3	[1]
12	$E + Ar_2^{*} \to 2E + Ar_2^{+}$		3.5	[1]
13	$E + Ar_2^{*} \to 2Ar + E$		-10.96	[1]
14	$Ar_2^{*} \to 2Ar$	Radiative Decay	0.0	[1]
15	$2Ar_2^{*} \to Ar_2^{+} + 2Ar + E$		-7.46	[1]
16	$E + Ar_2^{+} \to Ar^{*} + Ar$		0.0	[1]
17	E + CE -> 2E + CE+			[2]

Ionization of Ce (REE surrogate)

Reaction 17: REE surrogate ionization based on theory

$$r(T) = k n_A n_B = Z \rho \exp\left(\frac{-E_a}{RT}\right)$$

$$Z = n_A n_B \sigma_{AB} \sqrt{\frac{8 k_B T}{\pi \mu_{AB}}}$$

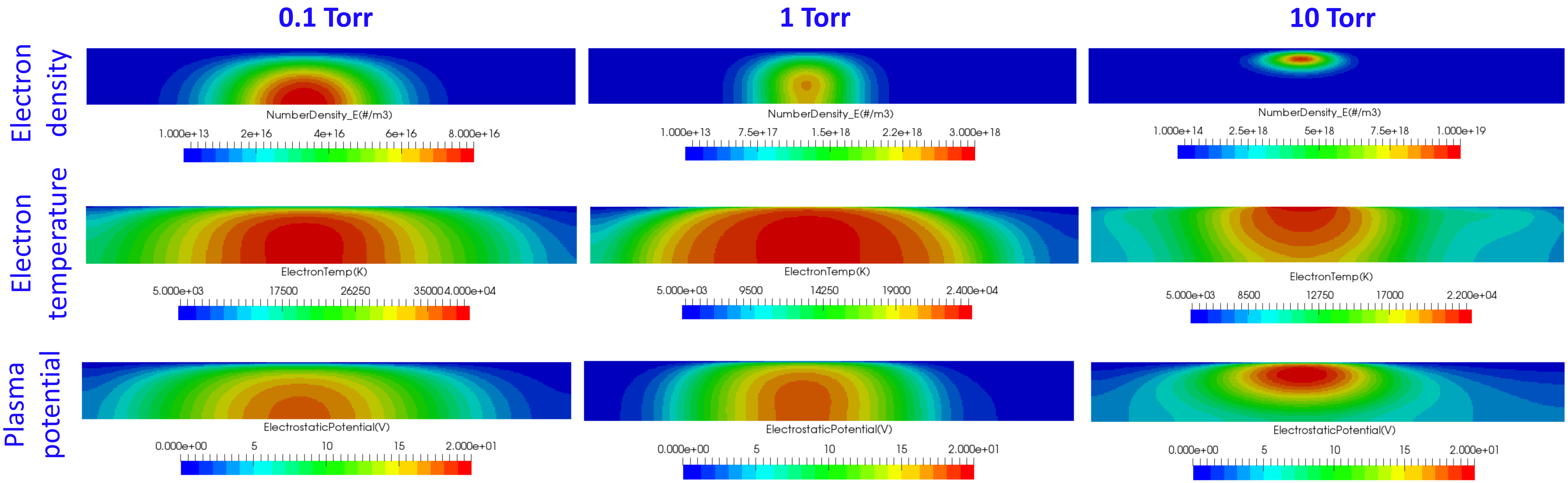
E_a = 5.77 eV

σ_{AB}=1

$T = T_e$

[1] Lay, B., Moss, R. S., Rauf, S. and Kushner, M. J., “Breakdown processes in metal halide lamps”, Plasma Sources Science and Technology, No. 12, 2003, pp. 8-21.
[2] Bringer A., “4f – Ionization of Atomic Cerium”, Solid State Communications, Vol.46, No.8, pp 591-593, 1983.

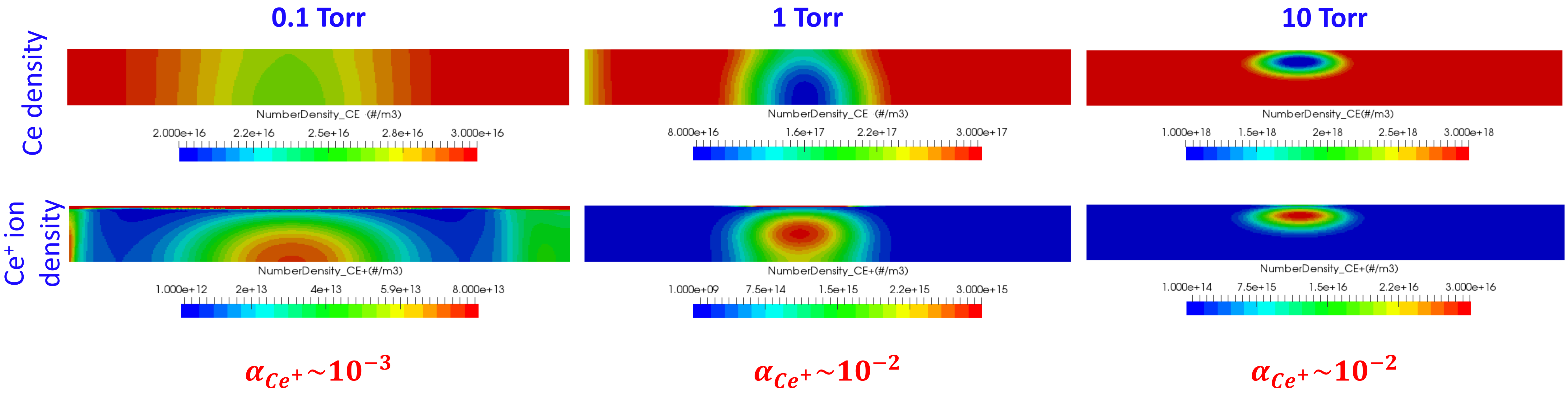
Plasma parameters for varying pressures
(pure argon carrier gas for trace 10^{-5} mole fraction RRE)



- Constant power in all cases
- Increasing plasma density with increasing pressure (anticipate higher throughput for RRE ionization)
- Plasma self constriction for increasing power (anticipate increased slip of unionized RRE)

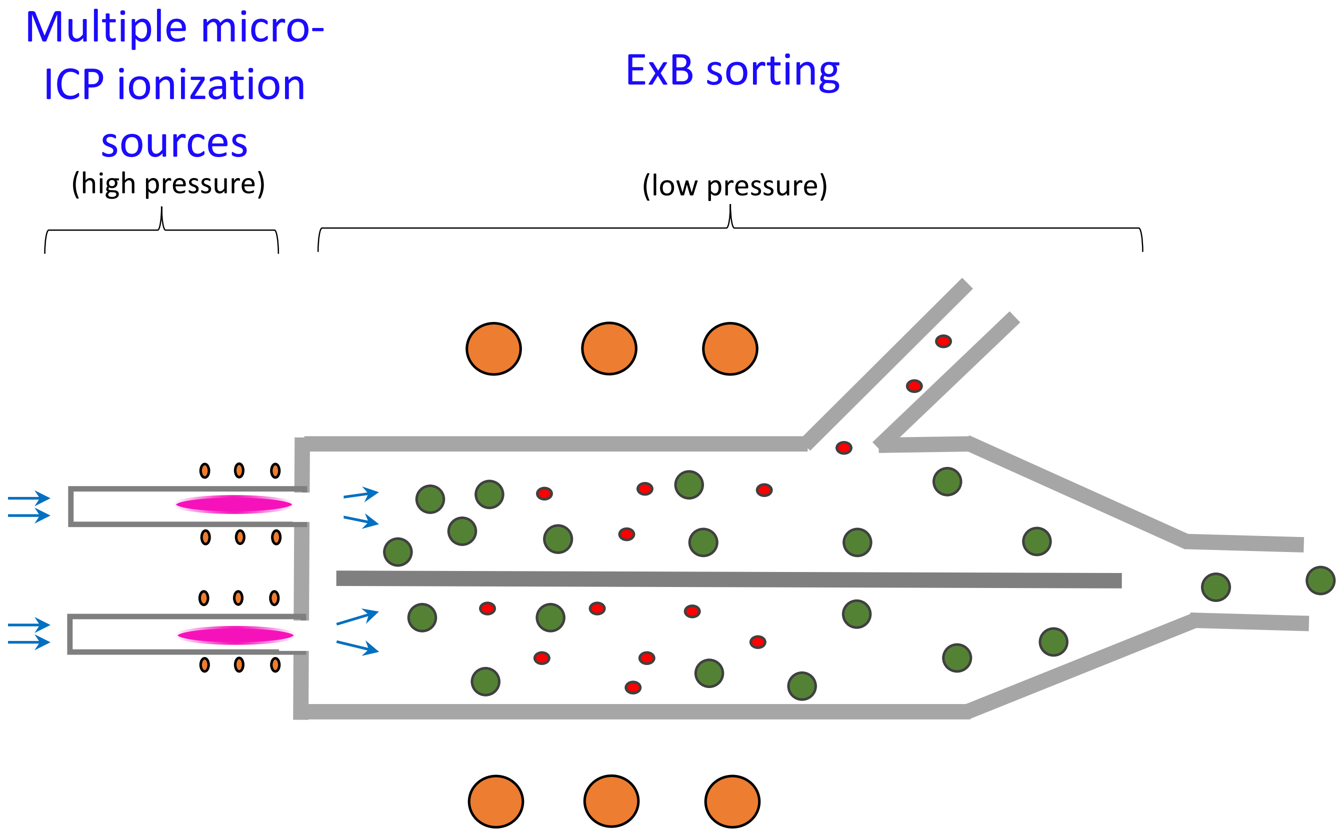
REE ionization for varying pressures

(pure argon carrier gas for trace 10^{-5} mole fraction RRE)

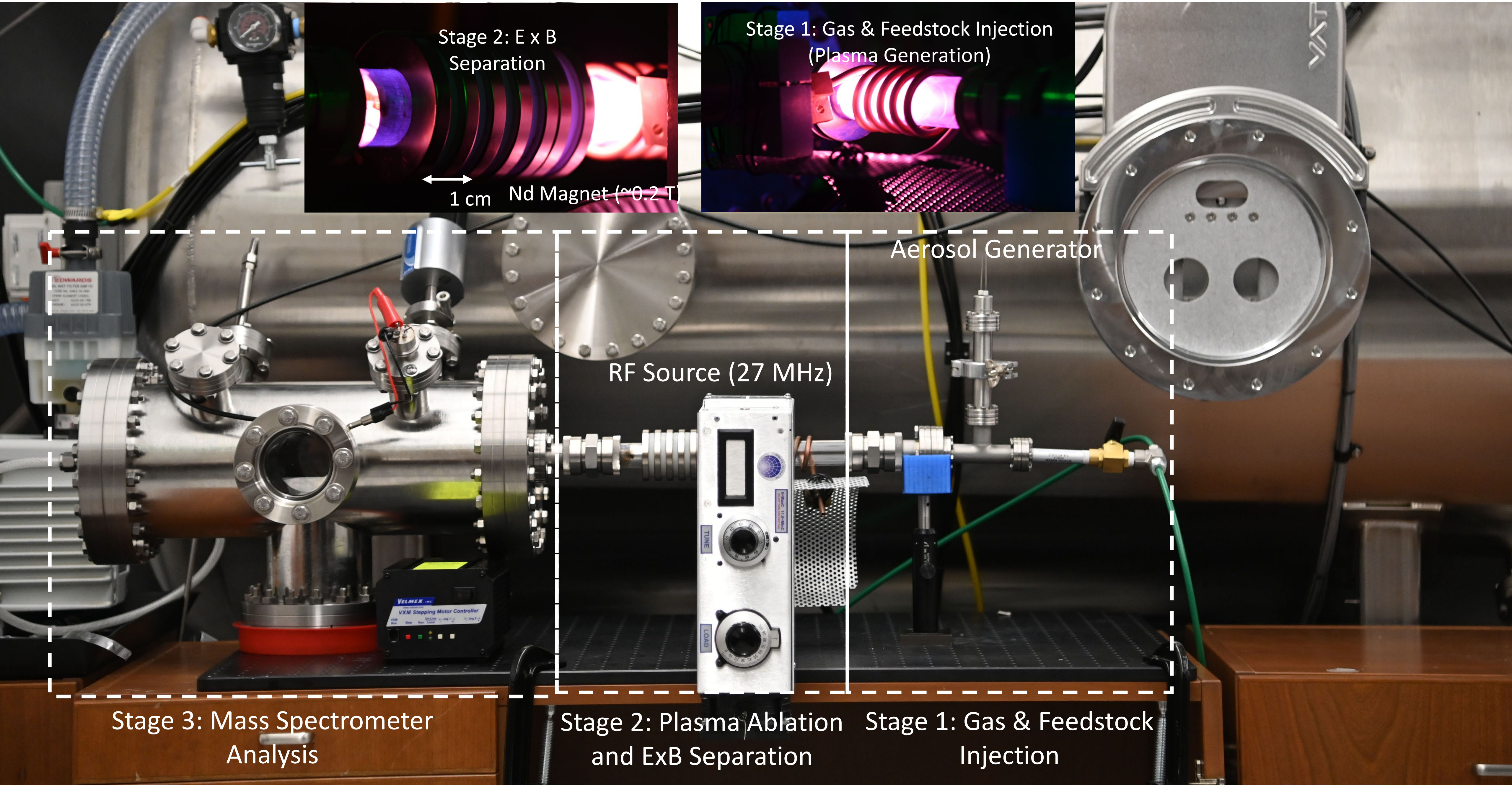


- Peak REE ionization fraction α_{Ce^+} increases for increasing pressures but saturates above 1 Torr
- Ions are quenched rapid at walls downstream of ionization region
- Plasma constriction at the highest pressure of 10 Torr results in significant slip/bypass of unionized Ce
- Hence, optimal pressure is ~ 1 Torr

Rethink of original concept based on modeling insights

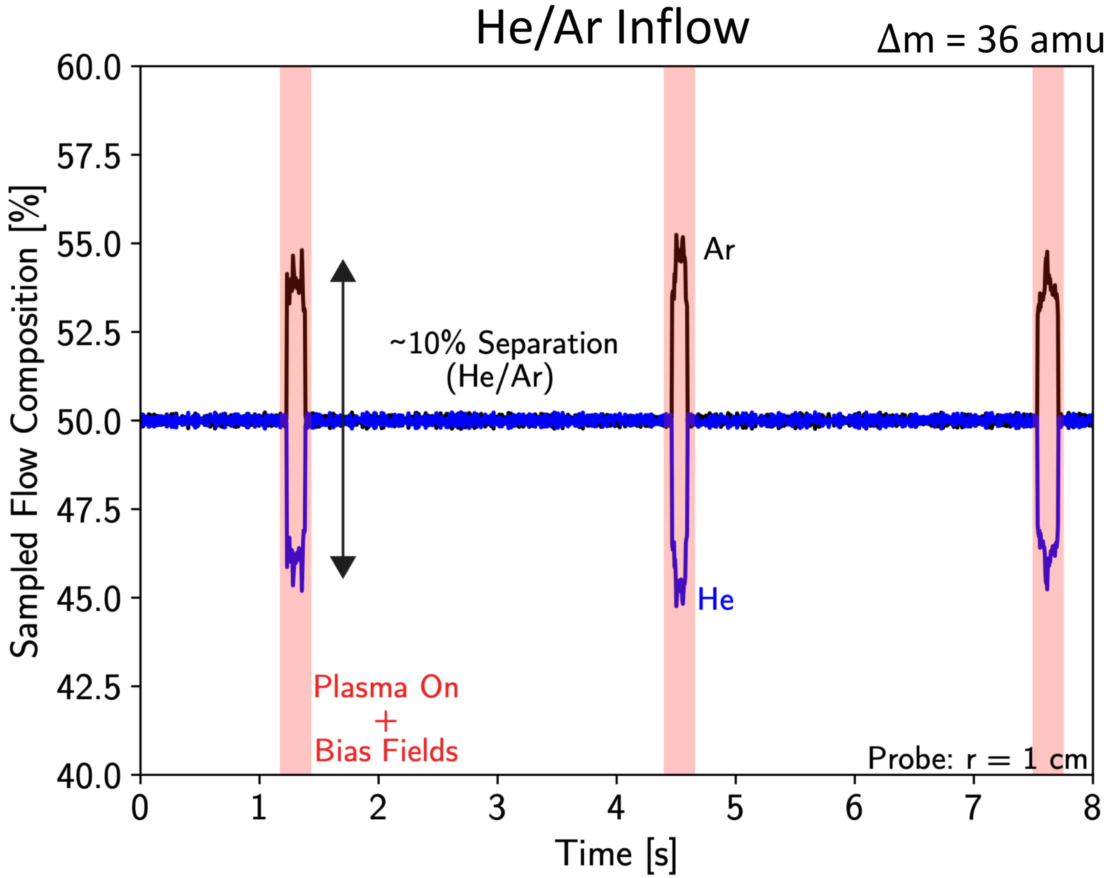


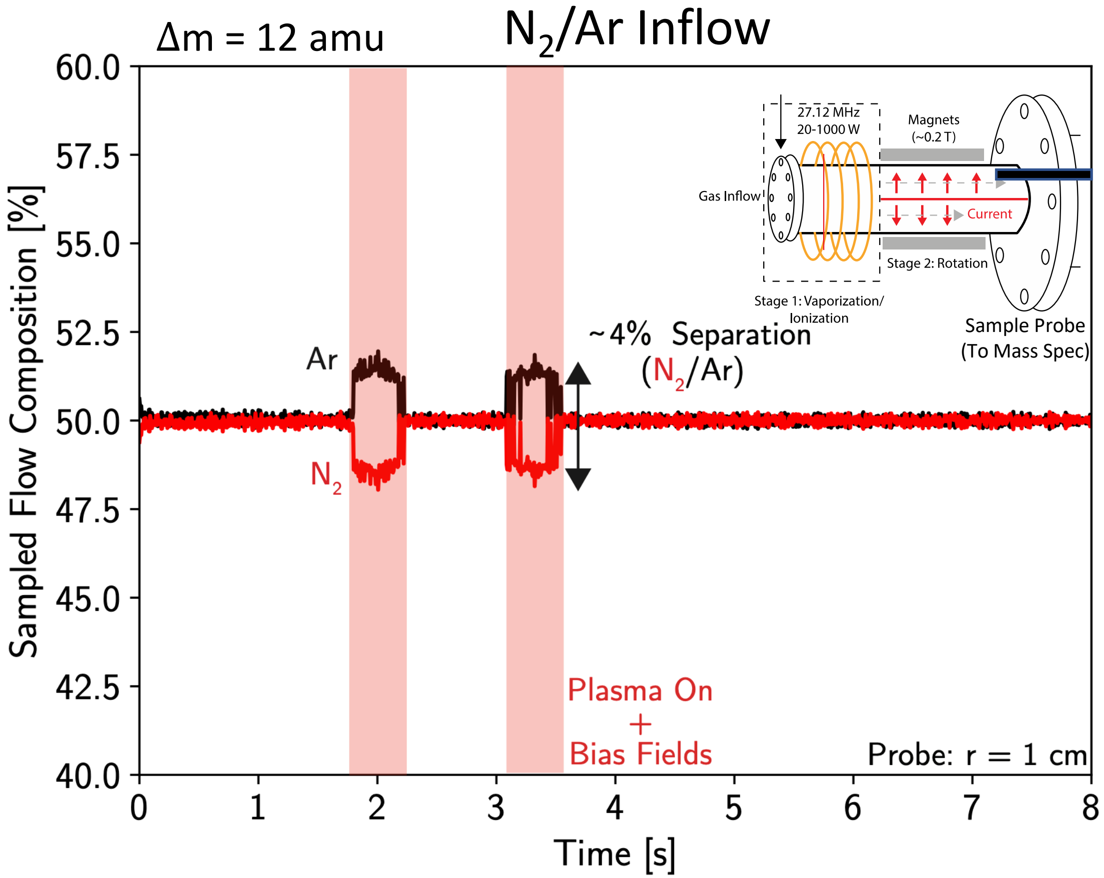
- Operate ICP ionizer at ~ 1 Torr
- Place ICP ionization zone immediately upstream of exit (REE ions are frozen immediately as they evacuate into *ExB* sorting region)



Stage 2: E x B Separation
1 cm
Nd Magnet (~0.2 T)
Stage 1: Gas & Feedstock Injection (Plasma Generation)
Aerosol Generator
RF Source (27 MHz)
Stage 3: Mass Spectrometer Analysis
Stage 2: Plasma Ablation and ExB Separation
Stage 1: Gas & Feedstock Injection

Separation of Gas Streams





Reaction Conditions:

- P_{in} = 100 W
- Residence Time = 0.1 ms
- Pressure = 200 mTorr
- Flow Rate = 50 sccm
- B = 0.2 T, V = 100 V

Advantages:

- Scalable to High Flow Rates
- Scalable to Collisional Pressures
- Fast Separation (~0.1 ms)
- Separation Dependent on Δm

Room for Optimization:

- Residence Time
- Position of Centrifuge
- Process Efficiency (>> 10 eV/Separated Molecule)
- Vaporization

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- Nate Miller

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