NUCLEAR DATA NEEDS FOR ADVANCED THERMIONIC ENERGY CONVERSION IN SPACE

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** Actively seeking a postdoctoral appointment*

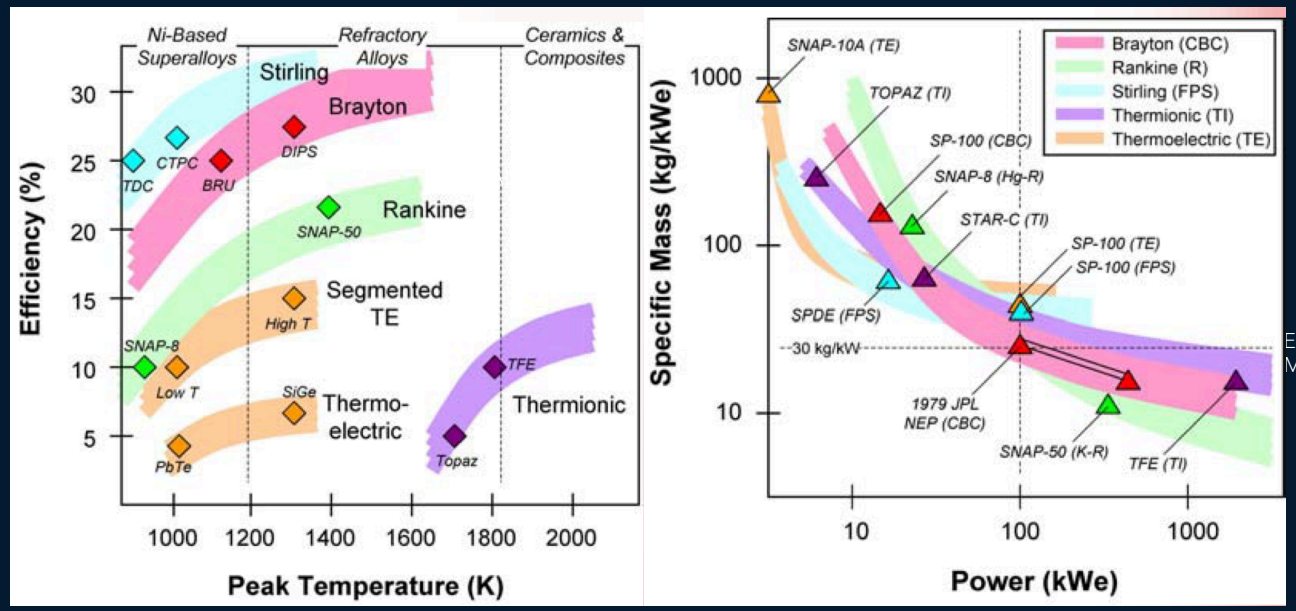
What is Thermionic Energy Conversion (TEC)?

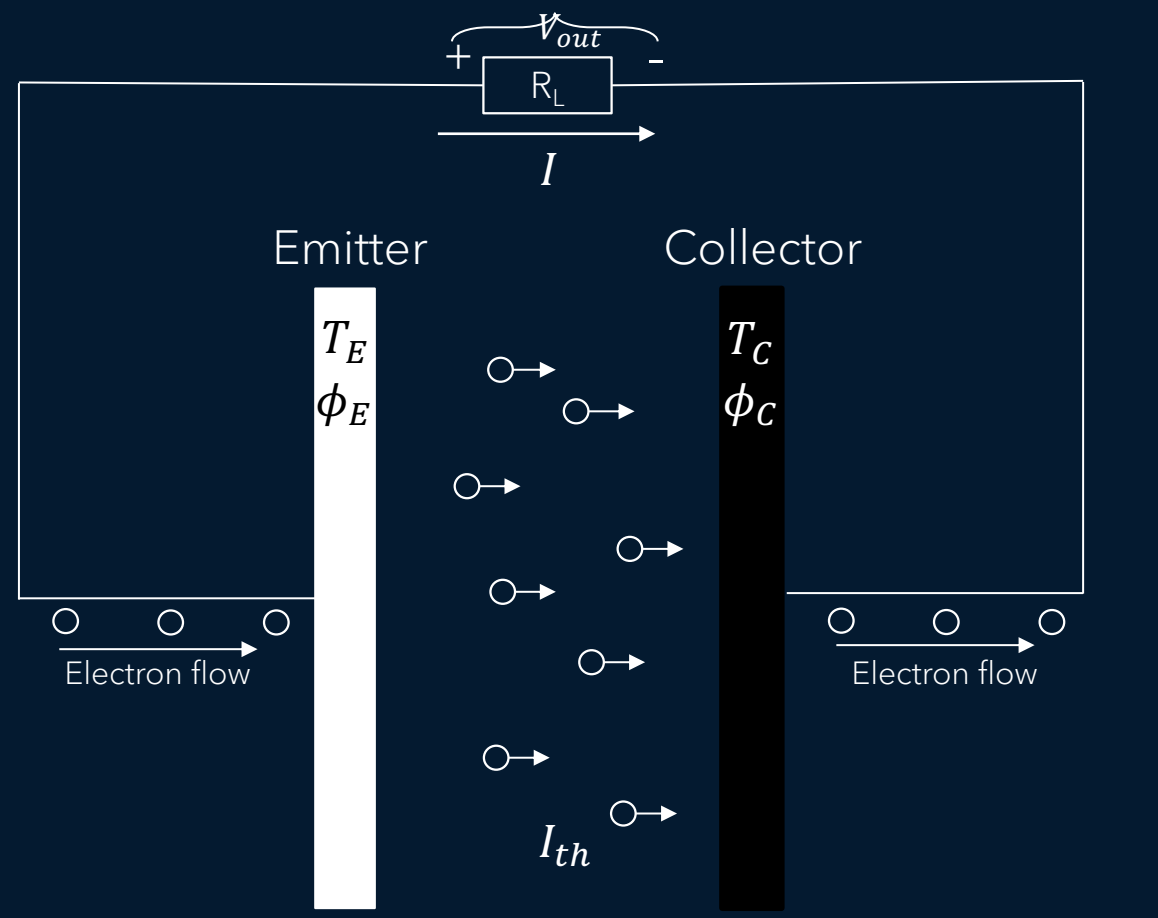
$$I = I_{th} = A_E \frac{4\pi e m_e k^2}{h^3} T_E^2 \exp\left(-\frac{\phi_E}{kT_E}\right)$$

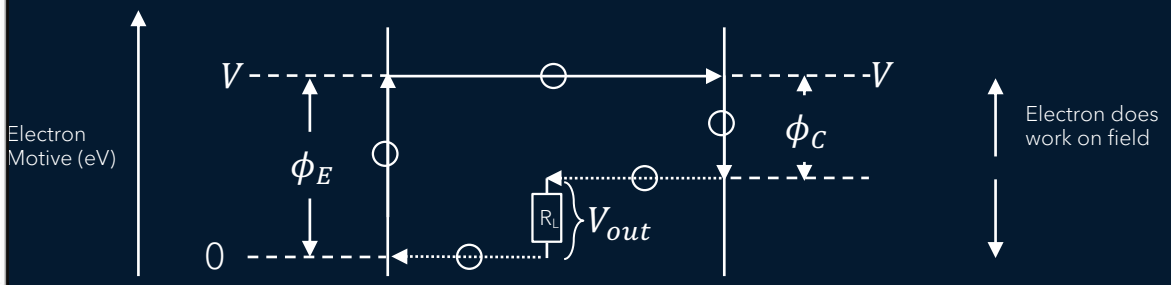
$$V_{out} = (\phi_E - \phi_C)$$

$$P_{out} = I_{th} V_{out}$$

Primary Application: Space Nuclear Power







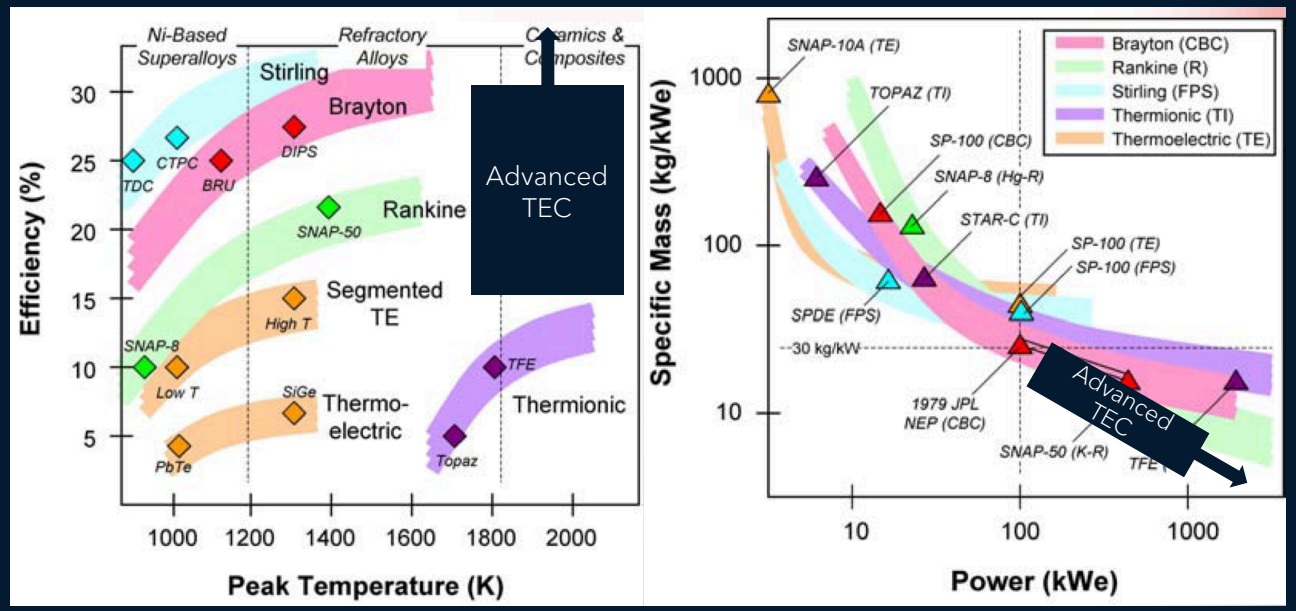
What is Advanced Thermionic Energy Conversion (TEC)?

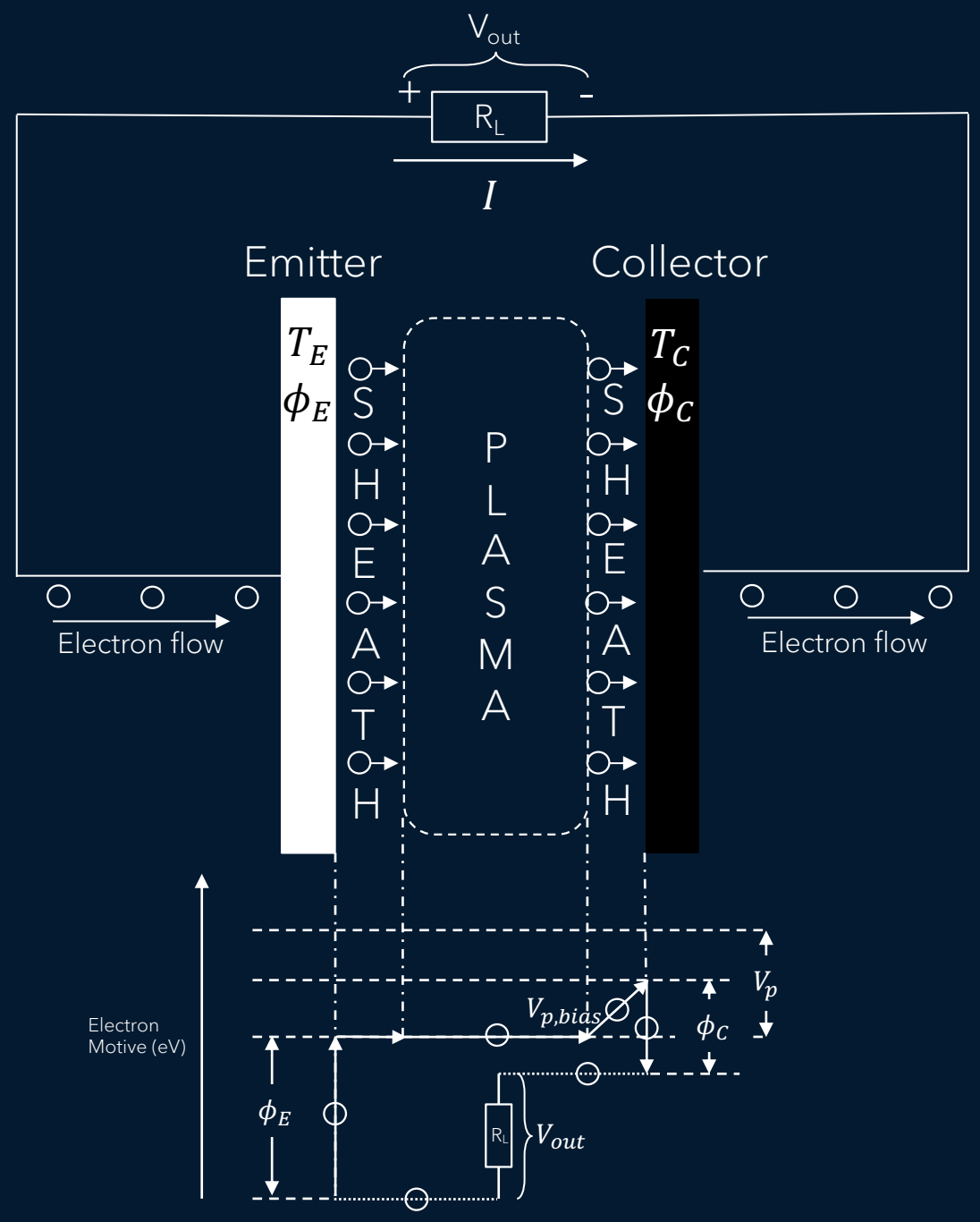
$$I = I_{th} = A_E \frac{4\pi e m_e k^2}{h^3} T_E^2 \exp\left(-\frac{\phi_E}{kT_E}\right)$$

$$V_{out} = (\phi_E - \phi_C) + V_{p,bias}$$

$$P_{out} = IV_{out}$$

Primary Application: Space Nuclear Power

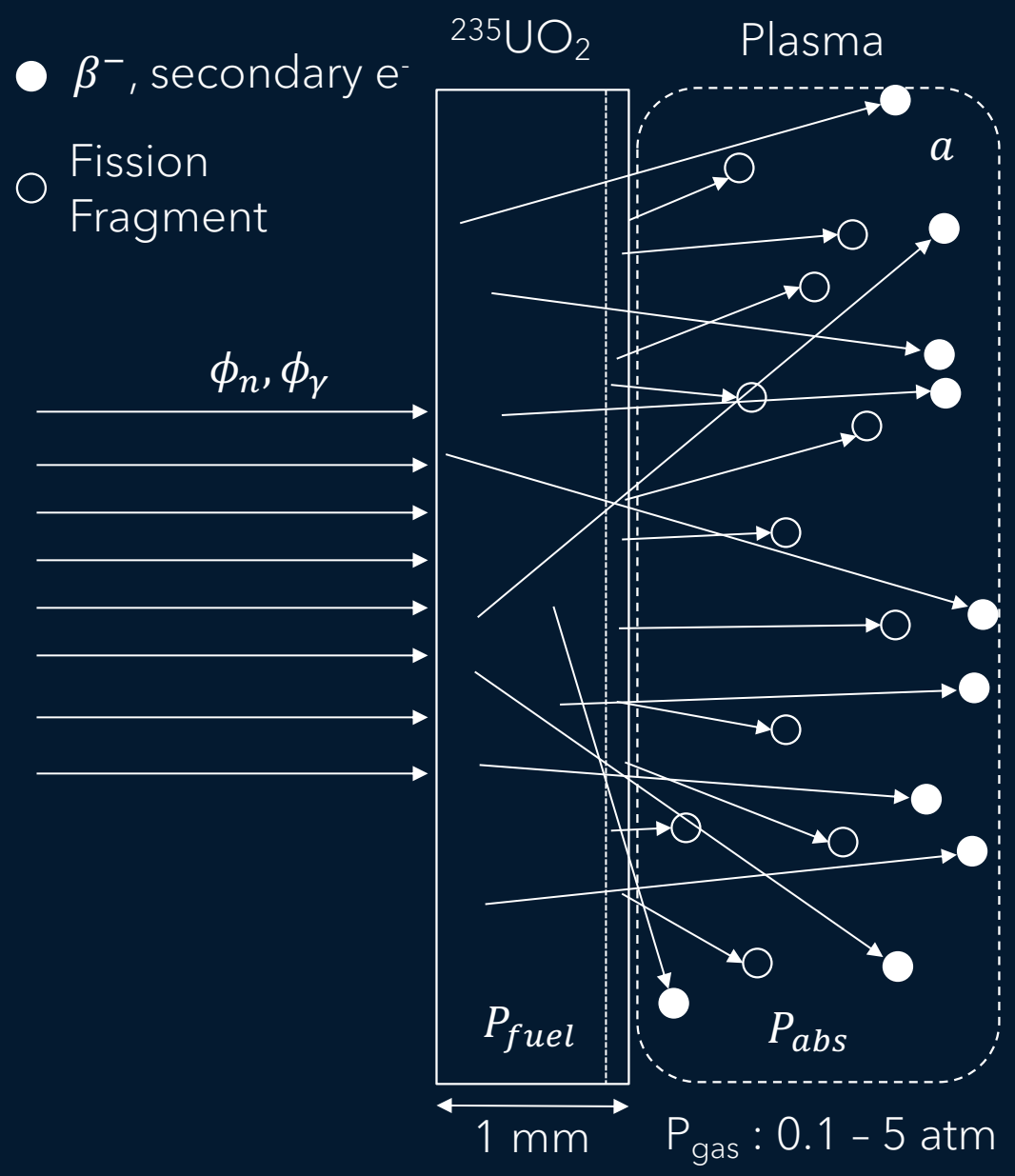




Radiation absorption produces plasmas

$P_{fuel} \approx$(1-5) x 10^3 W cm^{-3}

$P_{abs} \approx 10^{-2}$-10^0 W cm^{-3}



$$P_{abs} = \overbrace{\phi_{th}\sigma_{th}\, n_{fuel}\, E_{fiss}}^{P_{fuel}} \frac{t_{fuel}}{E_{fiss}} f \left\langle \frac{dE}{dx} \right\rangle_{abs}$$

Boltzmann Equation:

Solve for T_e

$$P_{abs} = w_{i,a} \frac{1}{k_{dr}(T_e, T_a)} \left(\frac{n_a \frac{m_e^2}{M} \langle v^3 \sigma_{el,a} \rangle \left(1 - \frac{T_a}{T_e}\right)}{E_{ave,a} - kT_e} \right)^2$$

Energy cost per Ionization (J)

Recombination term (cm^{-3} s)

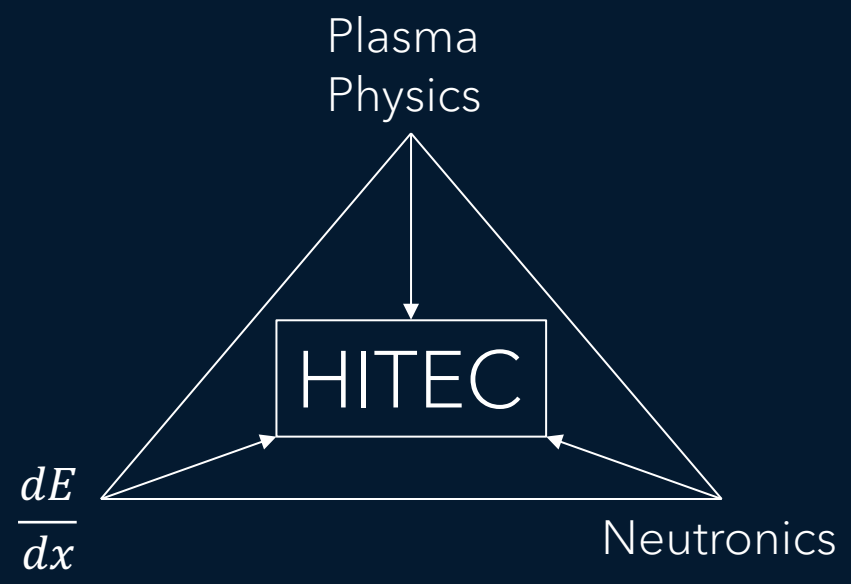
Elastic Collisions (s^{-2})

Charged particle conservation:

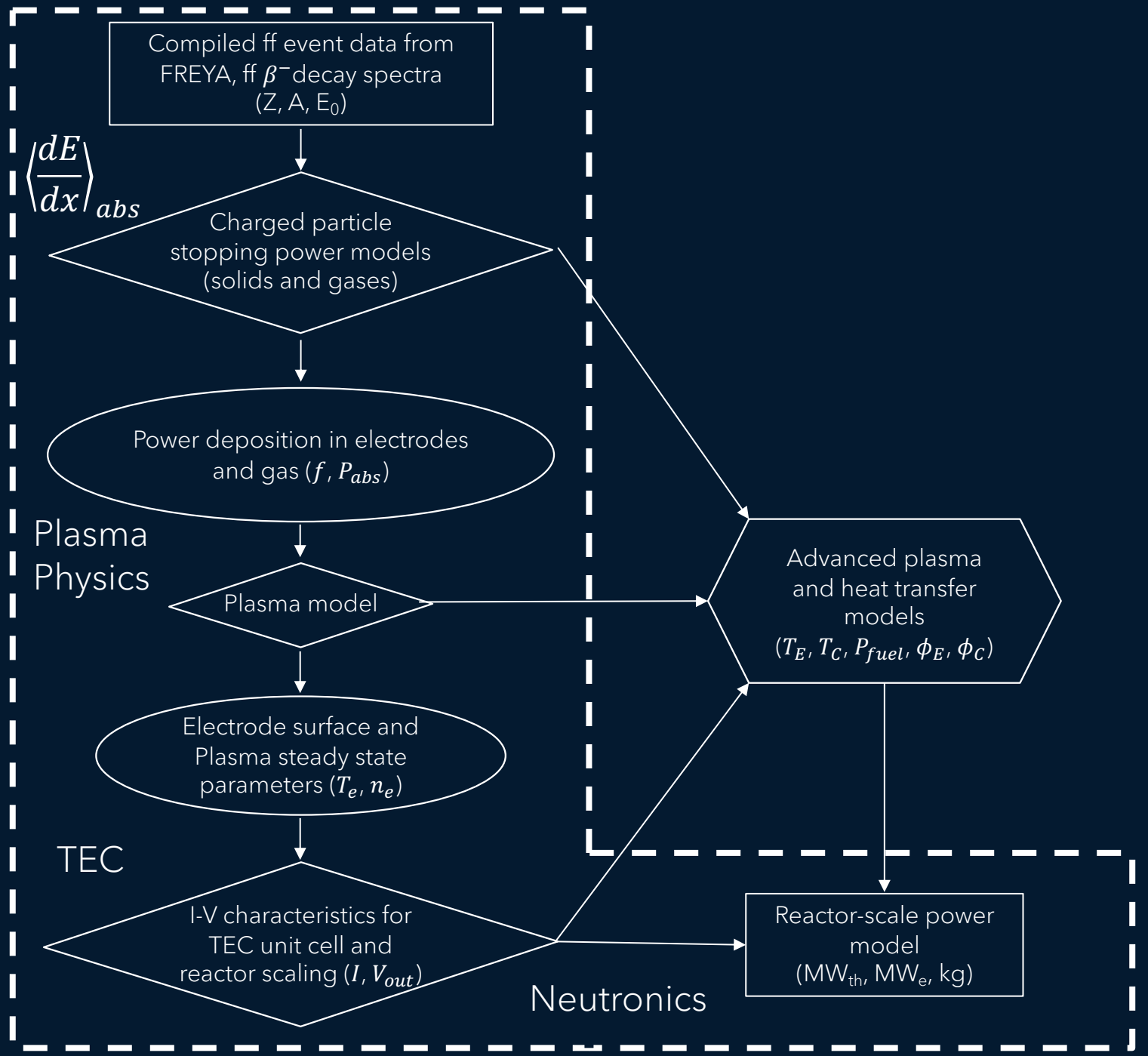
$$n_e^2 = \frac{P_{abs}}{w_{i,a} k_{dr}(T_e, T_a)}$$

Solve for n_e (cm^{-3})

HITEC Model



- A modeling tool for nuclear reactor designers who don't know anything about low temperature plasma physics or thermionic energy conversion…



Thermionic emission is enhanced by radiation of all kinds…

$$I = I_{th} = A_E \frac{4\pi e m_e k^2}{h^3} T_E^2 \exp\left(-\frac{\phi_E}{kT_E}\right)$$

$$I_{th} \uparrow \text{ and } \overleftrightarrow{T_E} \Rightarrow \phi_E \downarrow$$

$$I_{th} \propto P_{out} \Longrightarrow P_{out} \uparrow$$

… Why?

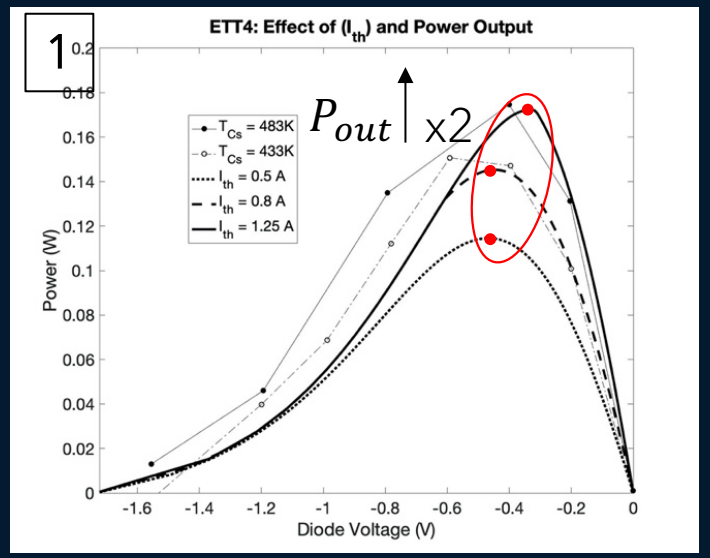
a) Compton Effects

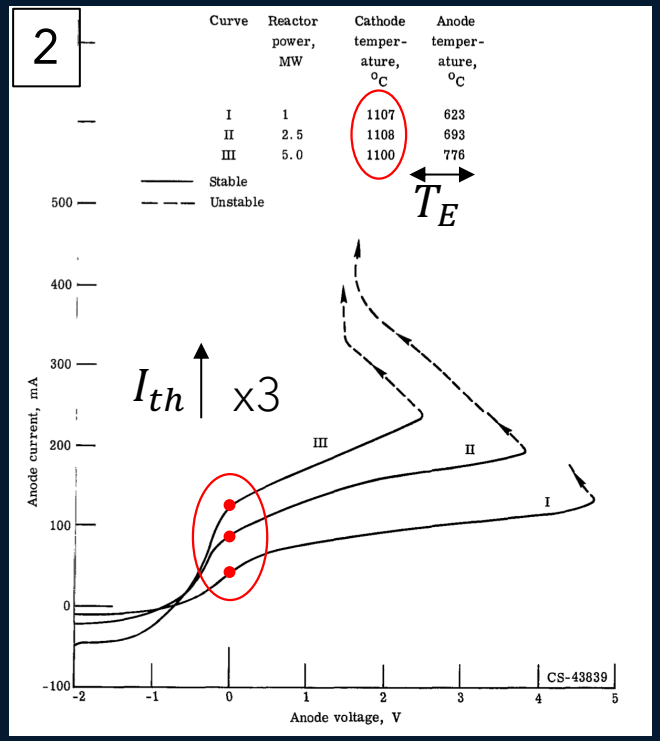
b) Auger Electrons

c) β^- decay

d) Fission Fragments

e) All of the above





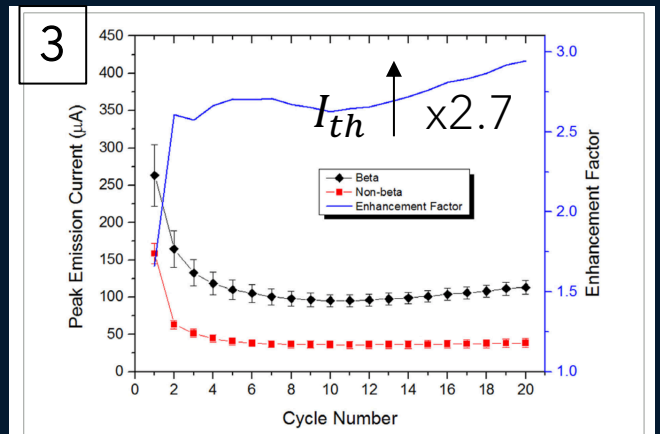


FIGURE 5 | Average temporal peak emission current values for sample set A, showing the beta (^{63}Ni) current to be consistently higher than the non-beta (^{59}Ni) current. The enhancement factor (defined in the main text) is also shown on the right-hand axis. The error bars represent the standard error on the mean of all runs in sample set A.

1. Lo, A. (2020). Fission Plasmas and their Novel Application to Power Producing Nuclear Reactors in Space. PhD Thesis (University of California Berkeley.

2. Forman, R. (1968). Electrical Properties of Xenon-Filled Thermionic Diodes in the Radiation Field of a Nuclear Reactor. *Journal of Applied Physics, 39*(9), 4351-4355. doi:10.1063/1.1656974

3. Croot, A., Wan, G., Rowan, A. et al.(2017). Beta Radiation Enhanced Thermionic Emission from Diamond Thin Films. *Frontiers in Mechanical Engineering, 3*. doi:10.3389/fmech.2017.00017

Nuclear Data Needs

- Measurements under irradiated environments:
  - Work function (ϕ_E and ϕ_C) for Advanced, fueled TEC electrodes
    - CERMETs
    - TRISO
    - Radioisotopes
    - Borides (LaB_6, CeB_6)
    - Carbides (ZrC, HfC)
  - P_{abs} under different irradiation environments (e.g. nuclear reactors, RTGs)
    - *Simultaneous* determination of n_e and T_e in:
      - Noble gases (Ne, Ar, Kr, Xe)
      - Penning mixtures (noble gas:Cs, noble gas:TMA, noble gas:noble gas)
  - P_{aux} coupling effects
    - Inductive Radiofrequency (RF)/Microwave
    - Electron Cyclotron Resonance (ECR

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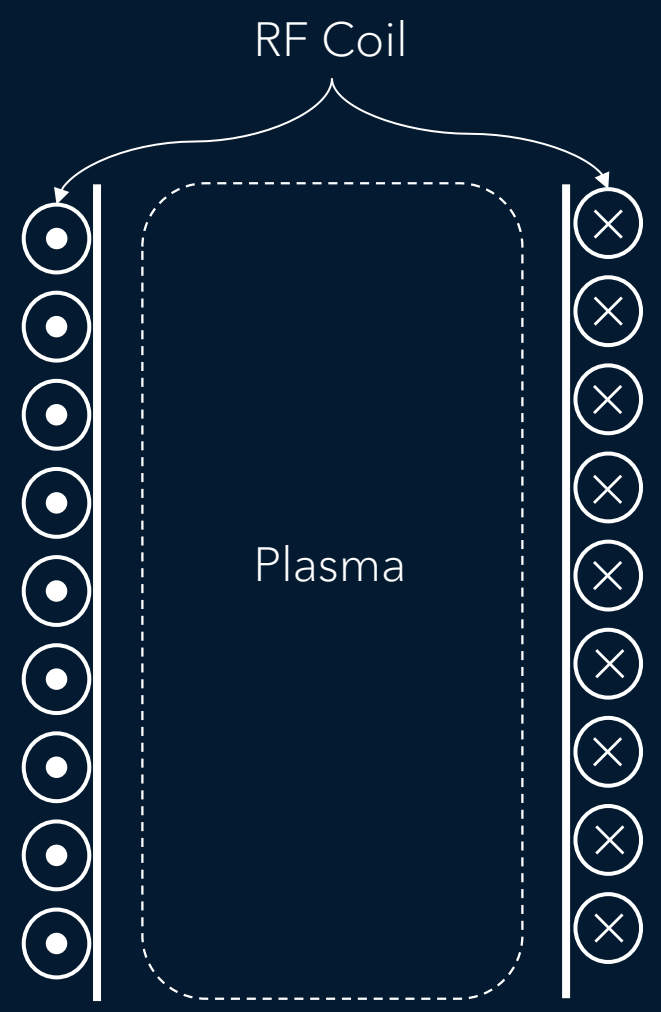
BACKUP SLIDES

Field ionization can improve TEC efficiency



P_{aux} source directly couples to plasma electrons, raising T_e
$\Longrightarrow V_{p,bias} \uparrow$
$\Longrightarrow \eta_T \uparrow$ since P_{aux} does not add to Q_{in}

$$\frac{P_{out}}{Q_{in}} = \eta_T \sim \frac{I(\phi_E - \phi_C + V_{p,bias}) - P_{aux}V_{aux}}{I_{th}(\phi_E + 2kT_E) + Q_{rad}}$$

$P_{aux} > P_{abs} \approx 10^0\text{-}10^2$ W cm^{-3} $\Longrightarrow$ "break-even" for high I and low V_{aux}

<u>Boltzmann Equation:</u>

Elastic collisions | Excitation collisions | Ionization collisions

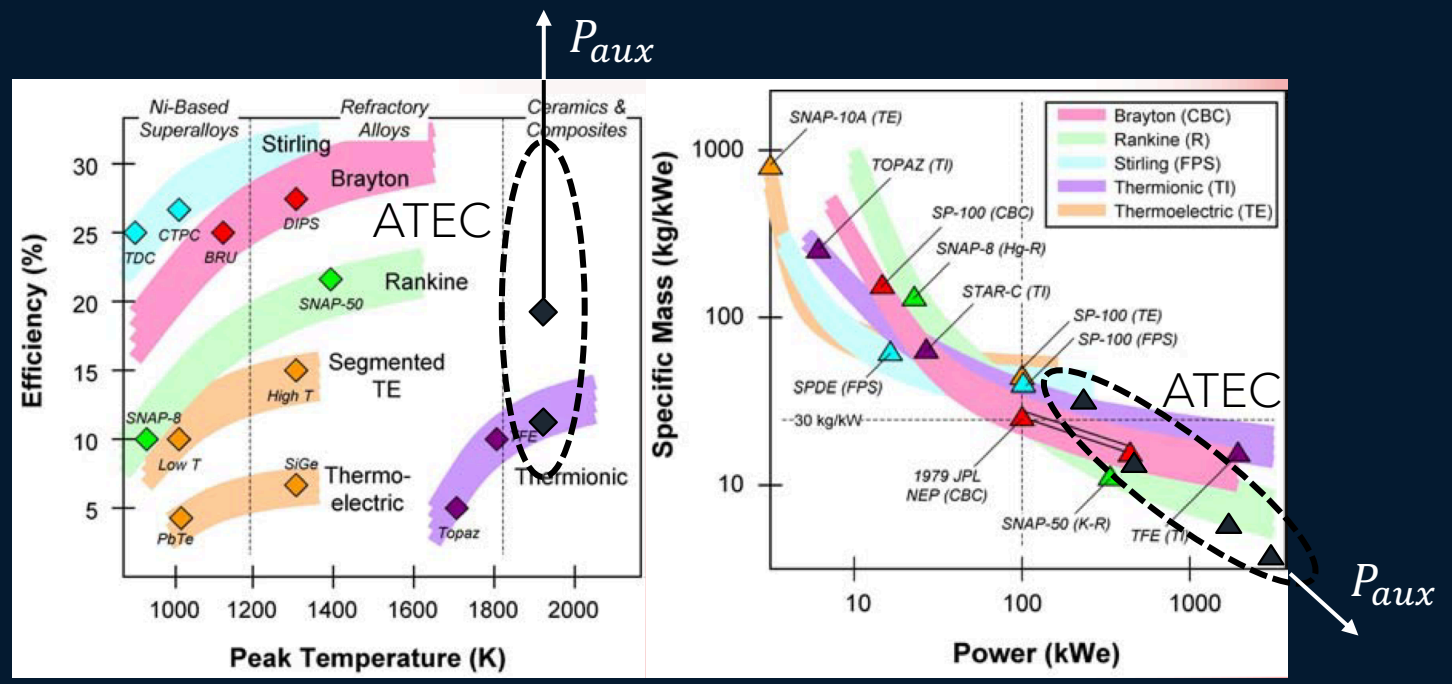
$$P_{aux} = n_a^2 \left(\frac{n_e}{n_a}\right)\left(\frac{m_e^2}{M}\left(1 - \frac{T_a}{T_e}\right) < v^3\sigma_{el}(v) > + K_{ex,i}(T_e)E_{ex,i} + E_{iz,i}K_{iz,i}(T_e)\right)$$

Solve for P_{aux}

Dominant P_{aux} terms

Advanced TEC reactor performance

Exploiting radiation effects:
⇒ Increases efficiency by >x2
⇒ Relaxes dimensional constraint by >x4
⇒ Decreases specific mass
Use of P_{aux}:
⇒ Arbitrarily high thermal efficiency
⇒ Low specific mass



System:		Advanced TEC								TOPAZ-II (Traditional TEC)	
P_{aux} (W cm^{-3})	A	0	2	0	6	75	20	75	60	0	1
Electrical Power (MW$_e$)		0.26		0.43		1.98		3.26		0.004 – 0.006	
Thermal Power (MW$_{th}$)		2.35		2.35		2.35		2.35		0.115 – 0.135	
Thermal Efficiency (%)		.11		0.18		.84		1.39		~0.04 – 0.06	
Specific Mass (with PMAD) (kg/kW$_e$)		36		14		4.5		2.8		200	
Mass factor	System Mass (kg)	3.66				9370				3.66	1061
Cs Reservoir Temperature (K)		600								580	
T_E(max), T_C (K)		1900, 800								1875, 850	