

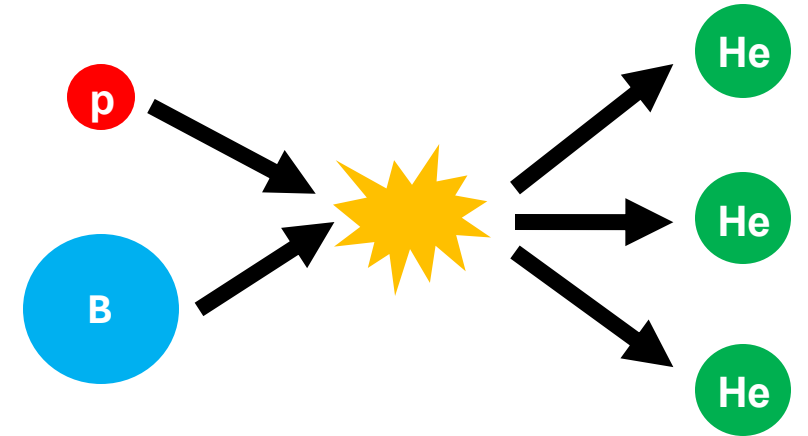
# Economical Proton-Boron<sup>11</sup> Fusion

ARPA-E Open 2021

Nat Fisch

Princeton University

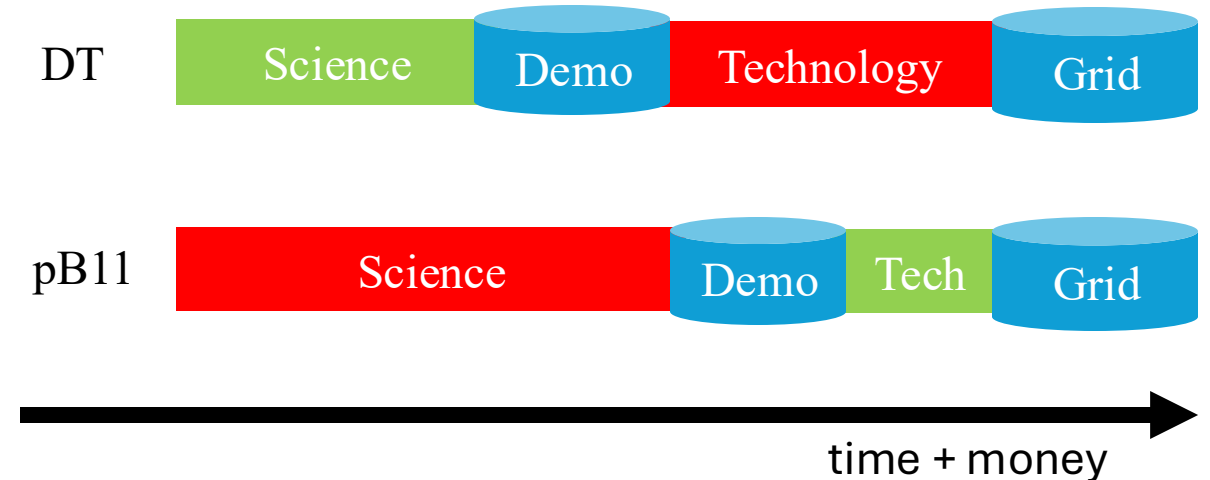
July 9, 2025



Team: Ian Ochs, Elijah Kolmes, Tal Rubin, Alex Glasser, Mikhail Mlodik

## Why pB11?

- No tritium breeding and containment
- No neutron damage and induced radioactivity
- No waste storage issues
- Cheap and non-radioactive reactants
- Easier regulatory environment
- Easier community acceptance



# Typical fusion approach: metric is $nT\tau$

Cook ions in a “soup” -- long confinement times  $\tau$  at high heat  $T$



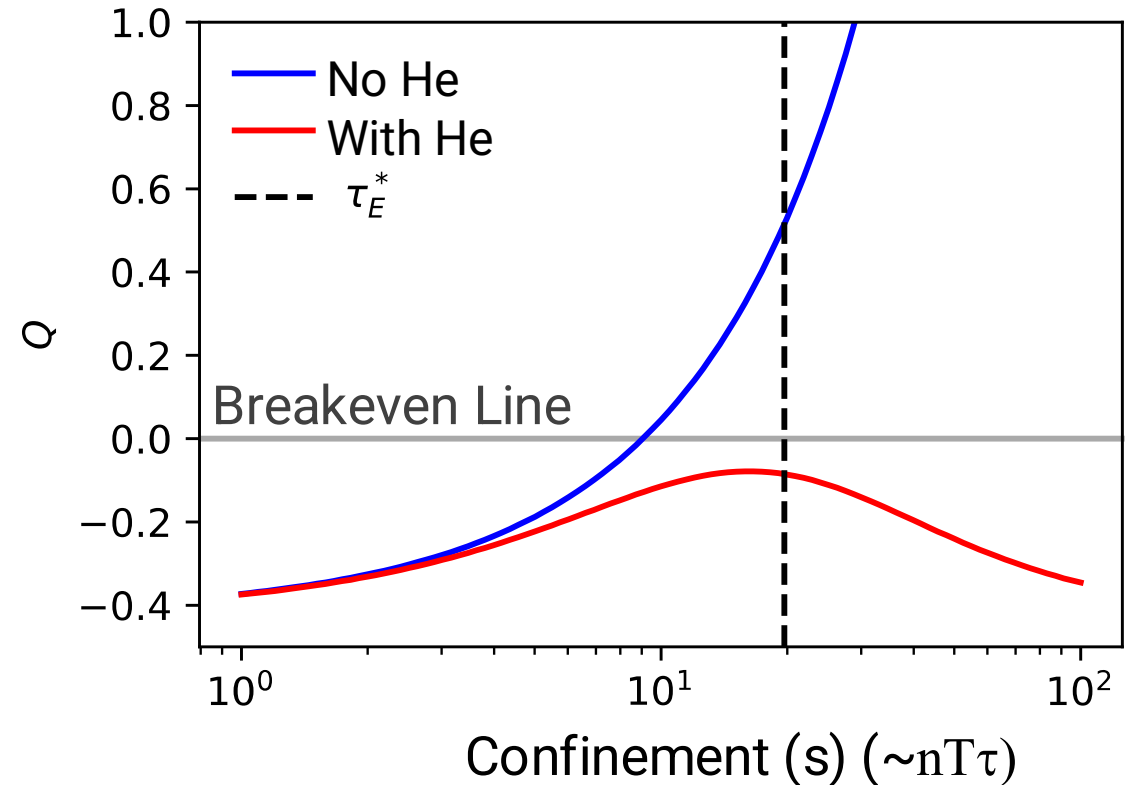
For pB11 fusion: A soup does not work  $\rightarrow$  too much radiation

For pB11 fusion, need

1. *Differential* confinement (p and B, not He)
2. Highly nonthermal approach  
(energetic p, colder e and B)

## In particular: Helium poisoning is an existential issue for pB11

- Reactor performance measured in "Engineering  $Q$ "
  - $Q > 0$  is breakeven
- If helium stays in the soup, the **reactor never reaches breakeven**
  - Even with perfect confinement!
- We need to **strain helium** from the soup!
- We also must **capture the helium energy**
- Essential **starting point** of a pB11 reactor design

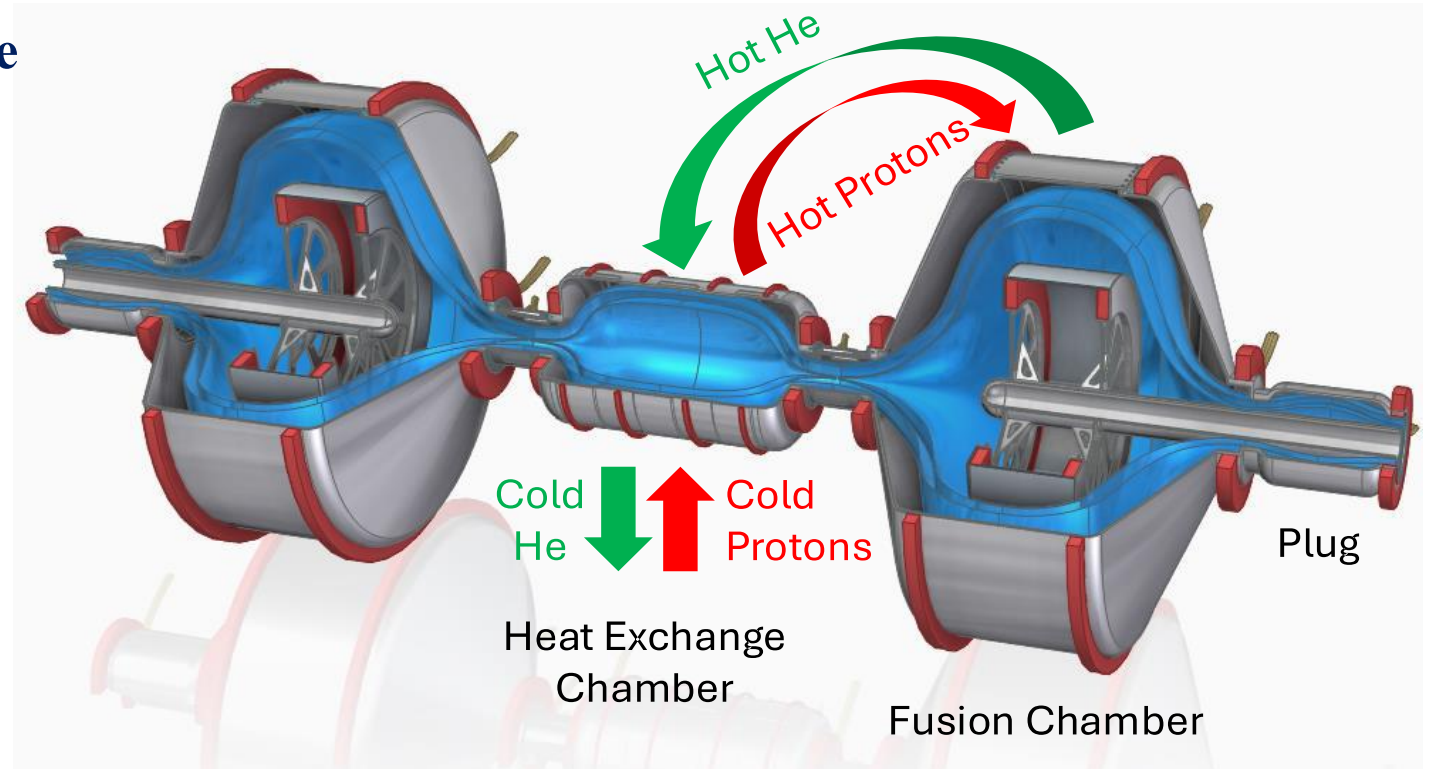


I. E. Ochs, E. J. Kolmes, and N. J. Fisch, *Preventing Ash from Poisoning Proton-Boron 11 Fusion Plasmas*, Physics of Plasmas **32**, 052506 (2025).

# Our solution: multi-chamber centrifugal fusion

- Boron centrifugal-trapped in **fusion chamber**
- Helium and hot protons enter **heat exchange chamber**
- Helium is extracted from heat exchange chamber using **waves**
- Result: helium removed from the fusion region, but energy captured
  1. Start with engineering simplicity
  2. Exploit unique properties of pB11
    - a. Disparate reactant masses and charges
    - b. Disparate byproduct charge/mass ratio
  3. Deal with unique features
    - a. Alpha particles need prompt removal
    - b. Boron need not be hot
    - c. Energy output in radiation not neutrons
    - d. Heat loss by energetic electrons

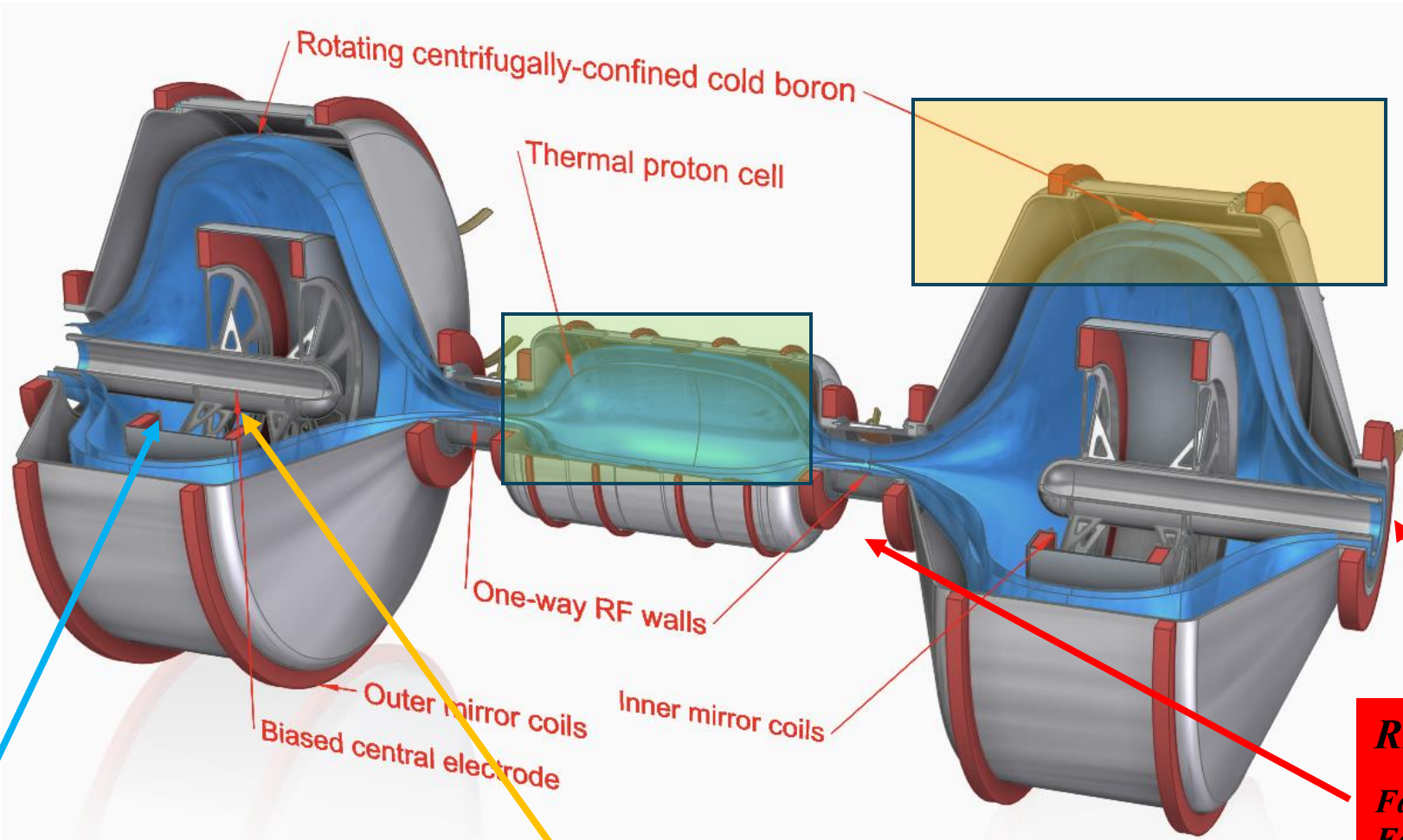
## CHARM: CHambered Aneutronic Rotating Mirror



For Vision 2021, we began with questions

1. Is such a reactor realizable for feasible device parameters?
2. Can centrifugal mirror offer offer sufficient differential confinement?
3. Can rotation be maintained without intolerable voltage drops at walls?
4. Is wave-induced diffusion in the second chamber necessary?
5. Can synchrotron radiation be made tolerable?
6. Can selective ponderomotive barriers regulate ion traffic?
7. Can we make passive ponderomotive barriers?
8. Are one-way walls cost-efficient?
9. Can rotation energy be recovered efficiently?

# *Derisking the Novel Underlying Physics*



## ***Boron Cell***

*Boron centrifugally confined  
Electrons electrostatically confined*

## ***Proton Cell***

*Thermal proton tail boiled off  
Low density → low radiation  
No Boron → low radiation*

## ***How to establish rotation***

*Large voltage drops with minimal dissipation*

## ***RF walls regulate ion traffic***

*Fast protons boiled off to Boron cell  
Fast electrons boiled off to proton cell  
Ponderomotive barriers and diodes  
 $\alpha$ -channeling to establish potential profiles*

***Radiative Transport  
in nonthermal plasma***

## ***Fueling and prompt $\alpha$ Particle Removal***

*Capture  $\alpha$ -particle rotation energy*

# Peer-Reviewed Publications under ARPA-E Support

1. I. E. Ochs, E. J. Kolmes, M. E. Mlodik, T. Rubin, and N. J. Fisch, *Improving the Feasibility of Economical Proton-Boron 11 Fusion via Alpha Channeling with a Hybrid Fast + Thermal Proton Scheme*, Physical Review E **106**, 055215 (2022).
2. E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Wave-Supported Hybrid Beam-Thermal pB11 Fusion*, Physics of Plasmas **29**, 110701 (2022).
3. M. E. Mlodik, V. R. Munirov, T. Rubin, and N. J. Fisch, *Sensitivity of synchrotron radiation to the superthermal electron population in mildly relativistic plasma*, Physics of Plasmas **30**, 043301 (2023).
4. T. Rubin, J. M. Rax, and N. J. Fisch, *Magnetostatic Ponderomotive Potential in Rotating Plasma*, Physics of Plasmas **30**, 052501 (2023).
5. E. J. Kolmes, M. E. Mlodik, and N. J. Fisch, *Extending the Single-Fluid Solvability Conditions for More General Plasma Systems*, Physics Letters A **477**, 128882 (2023).
6. I. E. Ochs, V. R. Munirov, and N. J. Fisch, *Confinement Time and Ambipolar Potential in a Relativistic Mirror-Confined Plasma*, Physics of Plasmas **30**, 052508 (2023).
7. V. R. Munirov and N. J. Fisch, *Suppression of Bremsstrahlung losses from relativistic plasma with energy cutoff*, Physical Review E **107**, 065205 (2023).
8. J. M. Rax, R. Gueroult, and N. J. Fisch, *DC electric fields generation and distribution in magnetized plasmas*, Physics of Plasmas **30**, 072509 (2023).
9. I. E. Ochs and N. J. Fisch, *The Critical Role of Potential Surfaces in Static Ponderomotive End Plugs*, Physical Review E **108**, 065210 (2023).
10. T. Rubin, I. E. Ochs, and N. J. Fisch, *Guiding center motion for particles in a ponderomotive magnetostatic end plug*, Journal of Plasma Physics **89**, 905890615 (2023).
11. J. M. Rax, R. Gueroult, and N. J. Fisch, *Rotating Alfvén waves in rotating plasmas*, Journal of Plasma Physics **89**, 905890613 (2023).
12. I. E. Ochs and N. J. Fisch, *Lowering the reactor breakeven requirements for proton-Boron 11 fusion*, Physics of Plasmas **31**, 012503 (2024).
13. E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Loss-Cone Stabilization in Rotating Mirrors: Thresholds and Thermodynamics*, Journal of Plasma Physics **90**, 905900203 (2024).
14. E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Massive, Long-Lived Electrostatic Potentials in a Rotating Mirror Plasma*, Nature Comm. **15**, 4302 (2024).
15. E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Upper and Lower Bounds on Phase-Space Rearrangements*, Physics of Plasmas **31**, 042109 (2024).
16. I. E. Ochs, *When do waves drive plasma flows?* Physics of Plasmas **31**, 042116 (2024).
17. T. Rubin, I. E. Ochs, and N. J. Fisch, *Flowing plasma rearrangement in the presence of static perturbing fields*, Physics of Plasmas **31**, 082109 (2024).
18. I. E. Ochs, M. E. Mlodik, and N. J. Fisch, *Electron Tail Suppression and Effective Collisionality due to Synchrotron Emission and Absorption in Mildly Relativistic Plasmas*, Physics of Plasmas **31**, 083303 (2024).
19. E. J. Kolmes and N. J. Fisch, *Coriolis Forces Modify Ponderomotive Potentials*, Physics of Plasmas **31**, 112107 (2024).
20. M. E. Mlodik and N. J. Fisch, *Curious Cross-Field Transport Effects in Multi-ion, Magnetized Plasma*, Physics of Plasmas **31**, 112303 (2024).
21. R. Gueroult, S. K. P. Tripathi, F. Gaboriau, T. R. Look, and N. J. Fisch, *Plasma potential shaping using end-electrodes in the Large Plasma Device*, J. Plasma Physics **90**, 905900603 (2024).
22. H. Qin, E. J. Kolmes, M. Updike, N. Bohlsen, and N. J. Fisch, *Gromov ground state in phase space engineering for fusion energy*, Phys. Rev. E **111**, 025205 (2025).
23. J.-M. Rax, E. J. Kolmes, and N. J. Fisch, *Efficiency and Physical Limitations of Adiabatic Direct Energy Conversion in Axisymmetric Fields*, PRX Energy **4**, 013007 (2025).
24. I. E. Ochs, E. J. Kolmes, and N. J. Fisch, *Preventing ash from poisoning proton–boron 11 fusion plasmas*, Physics of Plasmas **32**, 052506 (2025).
25. M. E. Mlodik, E. J. Kolmes, and N. J. Fisch, *Drift-energy replacement effect in multi-ion magnetized plasma*, Physical Review Letters **134**, 205101 (2025).
26. A. Mesa Dame, I. E. Ochs, and N. J. Fisch, *Energy spectrum of lost alpha particles in magnetic mirror confinement*, Physics Letters A **552**, 130631 (2025).
27. T. Rubin and N. J. Fisch, *Ponderomotive barriers in rotating mirror devices using static fields*, Physics of Plasmas **32**, 062104 (2025).
28. I. E. Ochs, *Bounce-Averaged Theory In Arbitrary Multi-Well Plasmas: Solution Domains and the Graph Structure of their Connections*, Journal of Plasma Physics, In Press (2025).
29. E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Ion Mix Can Invert Centrifugal Traps*, arXiv:2504.18634, submitted to Physical Review Letters (2025).

# Pivot to Pale Blue Fusion

T2M encouraged by ARPA-E; supported by Princeton University

Objective: Rapid sprint to pB11 fusion



Cultural pivot: Academic to Start-up

Start where we left off. What did we derisk? What is left to derisk?

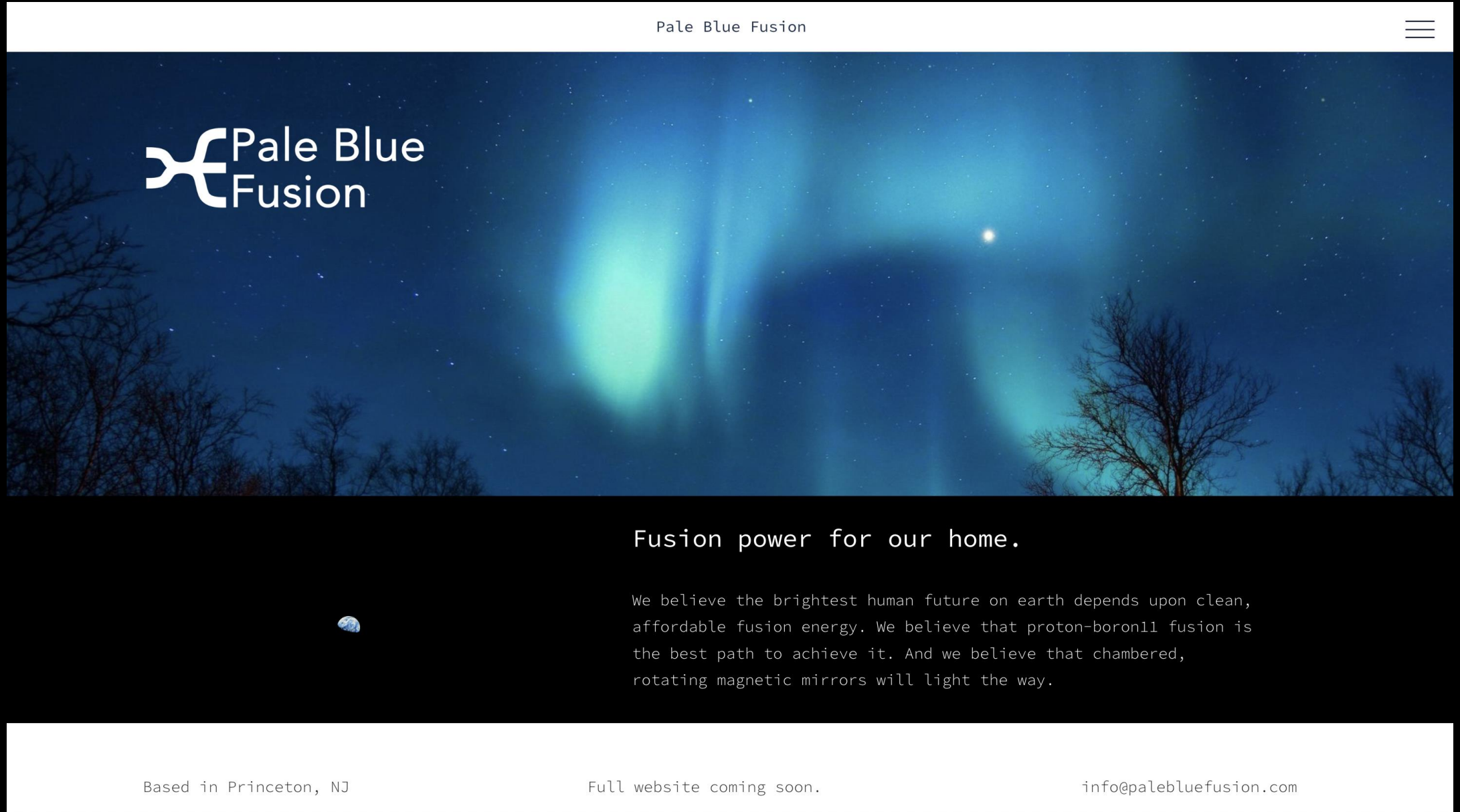
1. Concept captured in 29 publications; also invited talks
2. New theoretical constructs, mechanisms, and inventions
3. Some key risks retired
4. Patent Applications; Large moat protecting concept IP
5. Portfolio of novel computational tools
6. Team with history of working together

Among the new theoretical constructs, mechanisms, and inventions

- Means of regulating particle traffic
- Electrodeless rotation of plasma
- Magnetostatic ponderomotive barrier in rotating plasma
- Rotation energy replacement effect
- Synchrotron radiation mitigation in nonthermal plasma
- Alpha-channeling and ejection of alpha particles

# Approvals and support from Princeton University in place with plan to incorporate as Pale Blue Fusion

Website  
to be  
launched  
soon



Pale Blue Fusion



 Pale Blue  
Fusion

Fusion power for our home.

We believe the brightest human future on earth depends upon clean, affordable fusion energy. We believe that proton-boron11 fusion is the best path to achieve it. And we believe that chambered, rotating magnetic mirrors will light the way.

Based in Princeton, NJ

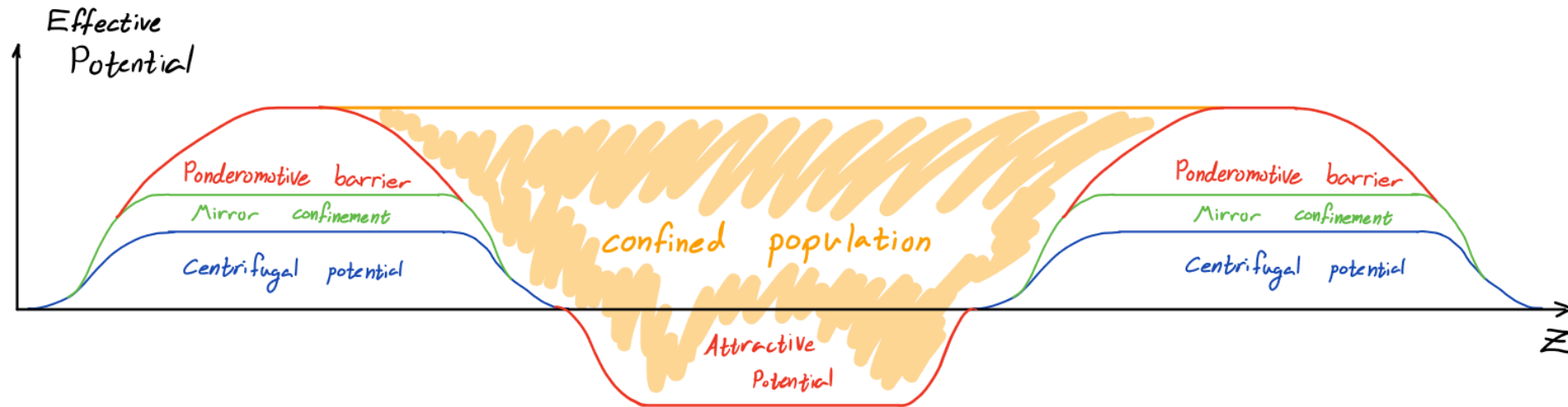
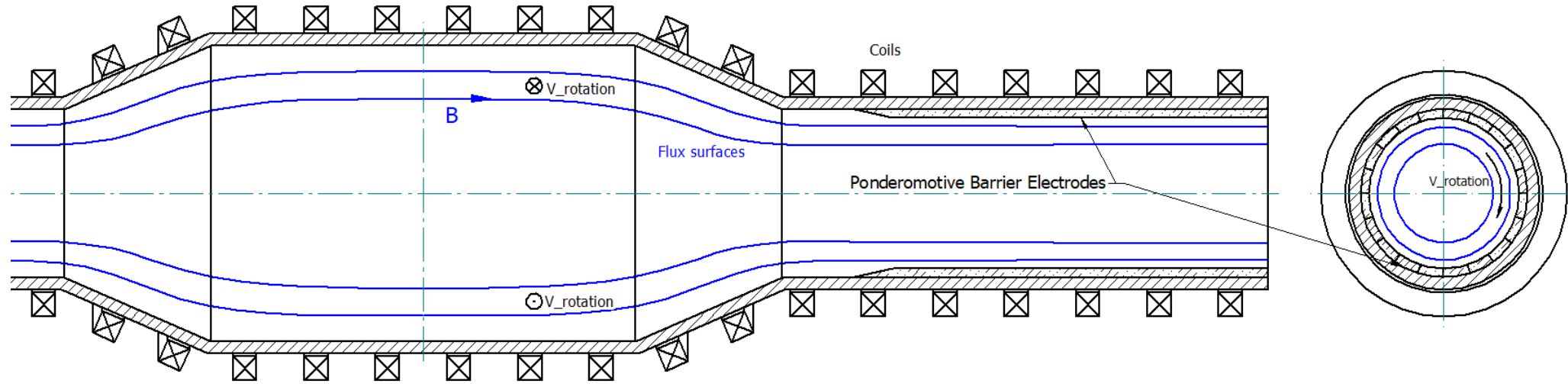
Full website coming soon.

[info@palebluefusion.com](mailto:info@palebluefusion.com)

# Patent Applications

1. **Nonthermal Proton-Boron11 Fusion with Separated Reactant Regions,**  
Nathaniel Fisch, Ian Ochs, Elijah Kolmes, Mikhail Mlodik, and Tal Rubin,  
US Patent Application 19/083,790, filed March 19, 2025.
2. **Enhanced Particle Confinement with Positive and Negative Ponderomotive Potentials,**  
Tal Rubin, Jean-Marcel Rax, Nathaniel Fisch, Ian Ochs, and Elijah Kolmes,  
US Patent Application 19/084,168, filed March 19, 2025.
3. **Systems and Methods for Producing Ultra-high DC Voltages in Open Field Line Traps with Minimal Dissipation and Minimal Damage,**  
Nathaniel Fisch, Elijah Kolmes, Mikhail Mlodik, Ian Ochs, Jean-Marcel Rax, and Tal Rubin,  
US Patent Application 19/175,473; filed April 10, 2025.
4. **Method and Apparatus for Differential Confinement, Mixing, and Demixing of Plasma in a Rotating Trap and Leading to Improved End Plugs,**  
Elijah Kolmes, Ian Ochs, and Nathaniel Fisch,  
US Provisional Patent Application 63/794,470; filed April 25, 2025.

# Example: Ponderomotive Barriers in Rotating Plasma using Passive Elements

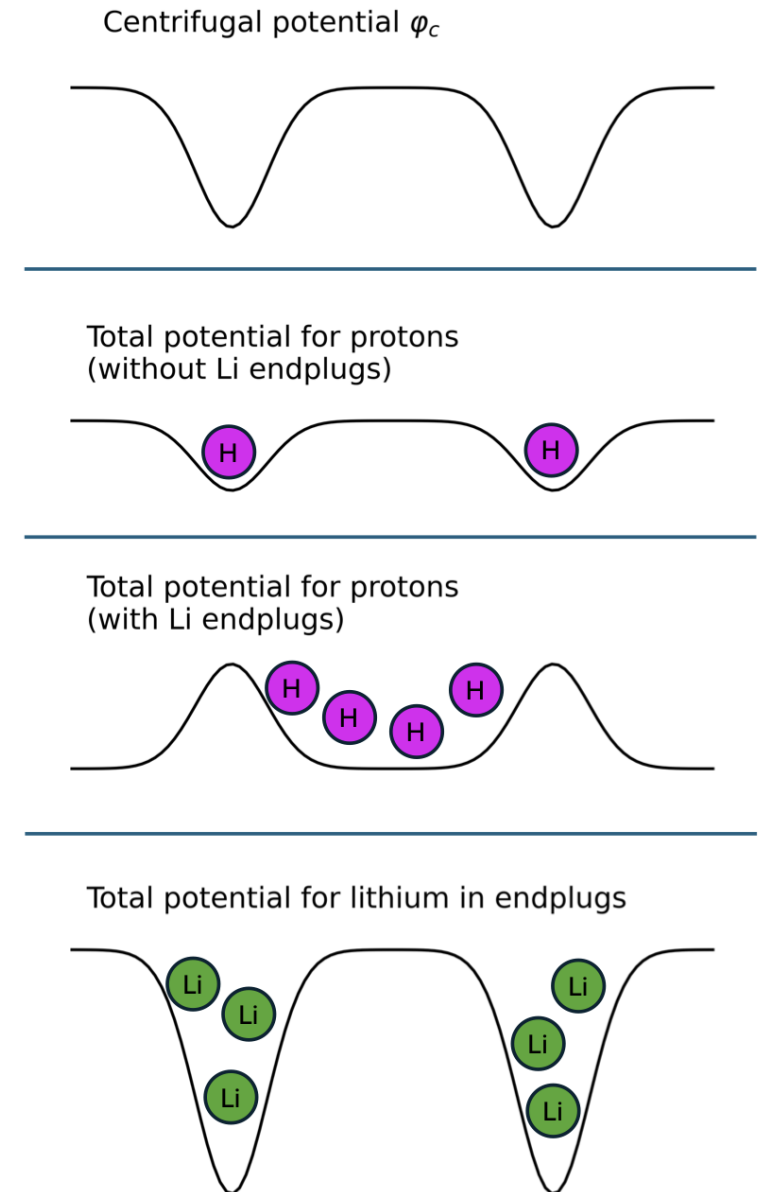


T. Rubin, I. E. Ochs, and N. J. Fisch, *Flowing plasma rearrangement in the presence of static perturbing fields*, Phys. Plasmas (2024). **Editor's Pick**

T. Rubin, JM Rax, N. Fisch, I. Ochs, and E. Kolmes, *Enhanced Particle Confinement with Positive and Negative Ponderomotive Potentials*, US Patent Application 19/084,168, filed March 19, 2025.

# Example: Novel, Mixed-Ion, Centrifugal Endplugs in Rotating Plasma

- Ion mix affects emergent ambipolar electric fields
- This effect can be used to construct centrifugal *barriers*, in which a given ion species can be excluded from a high-rotation region
- Useful for improved (differential) confinement
  - We can **double the centrifugal confinement** without increasing the rotation.



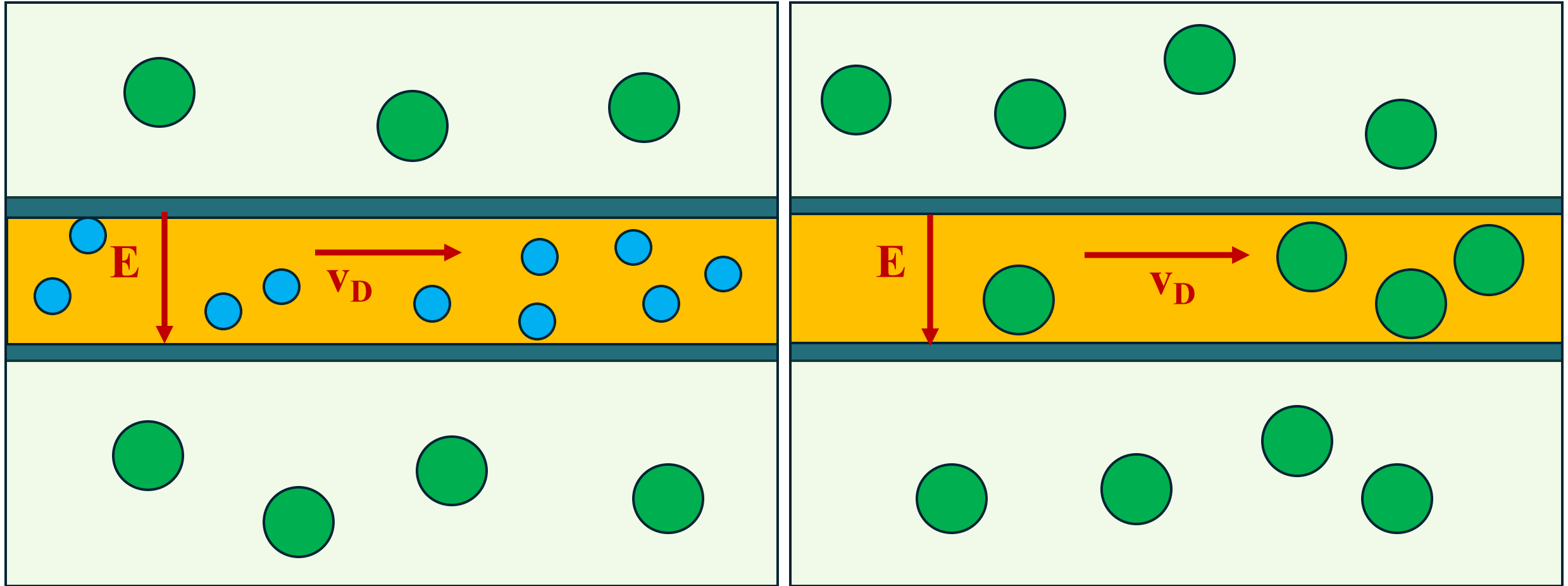
E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Ion Mix Can Invert Centrifugal Traps*, arXiv:2504.18634 under review at Physical Review Letters (2025).

E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Method and Apparatus for Differential Confinement, Mixing, and Demixing of Plasma in a Rotating Trap and Leading to Improved End Plugs*, US Provisional Patent Application 63/794,470.

# Example: *Drift Energy Replacement Effect*

●  $B^{10}$     ●  $He^4$

If no charge moved,  $\mathbf{J} \cdot \mathbf{E} \cong 0$



$\mathbf{B} \otimes$

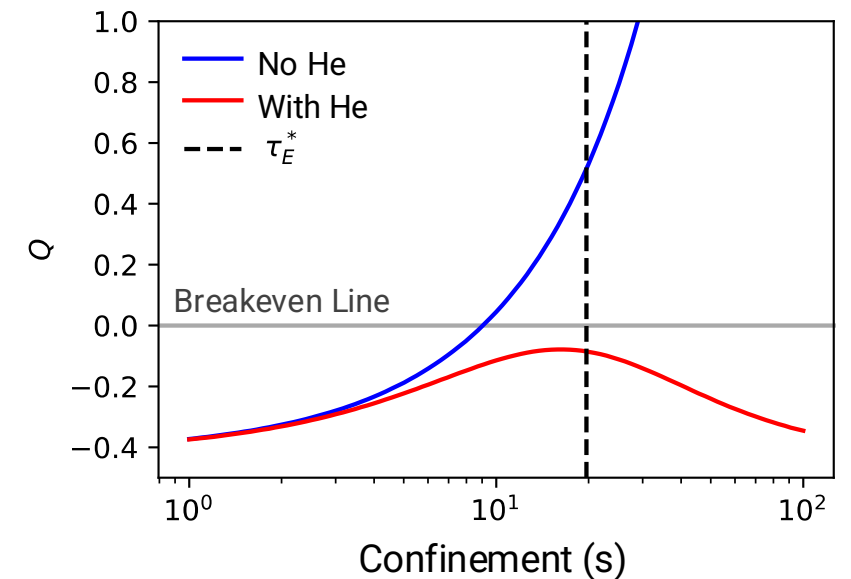
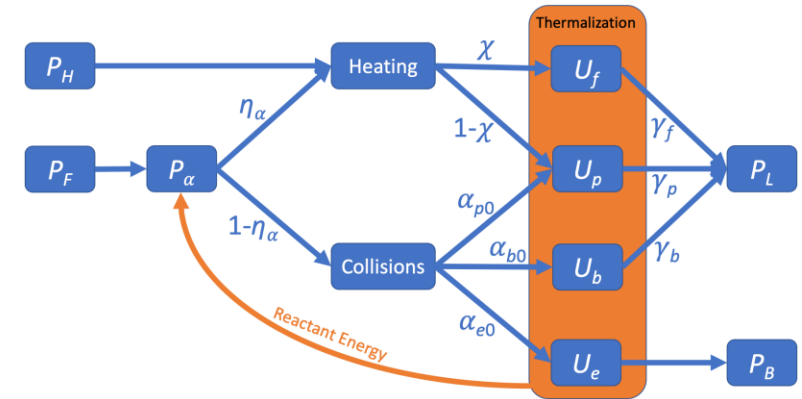
$t=0$

$t= \infty$

# New problems required new computational new tools

## Codes: (PB)<sup>2</sup>: Proton-Boron Power Balance

- 0D power balance code incorporating up-to-date fusion cross sections, reduced kinetic effects, relativistic collisions and bremsstrahlung
- Includes self-consistent helium poisoning
- Good for:
  - Quick approximate profiling of optimal reactor regimes
  - Evaluating the potential upside of various reactor improvements
    - DEC, efficient heating, fat ion tails, etc



I. E. Ochs, E. J. Kolmes, M. E. Mlodik, T. Rubin, and N. J. Fisch, *Improving the Feasibility of Economical Proton-Boron 11 Fusion via Alpha Channeling with a Hybrid Fast + Thermal Proton Scheme*, Physical Review E, **106**, 055215 (2022).

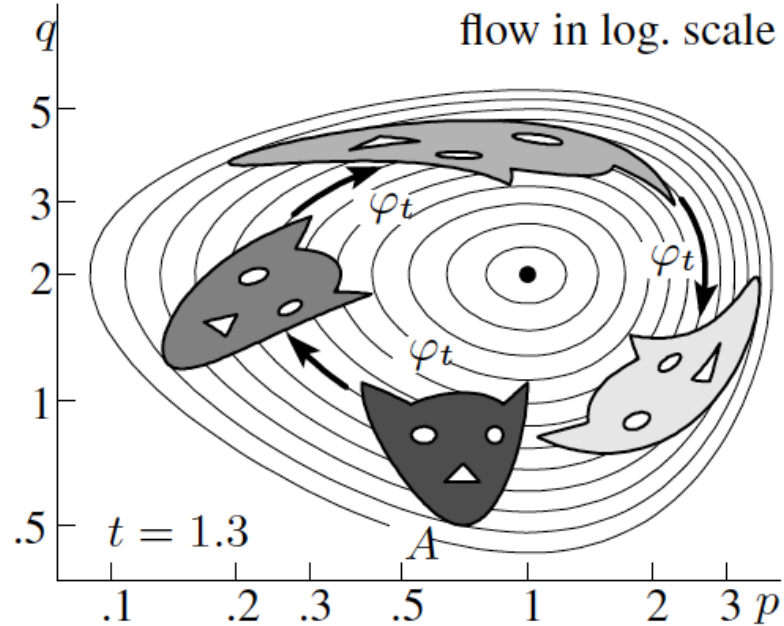
E. J. Kolmes, I. E. Ochs, and N. J. Fisch, *Wave-Supported Hybrid Beam-Thermal pB11 Fusion*, Physics of Plasmas **29**, 110701 (2022).

I. E. Ochs and N. J. Fisch, *Lowering the reactor breakeven requirements for proton-Boron 11 fusion*, Physics of Plasmas **31**, 012503 (2024).

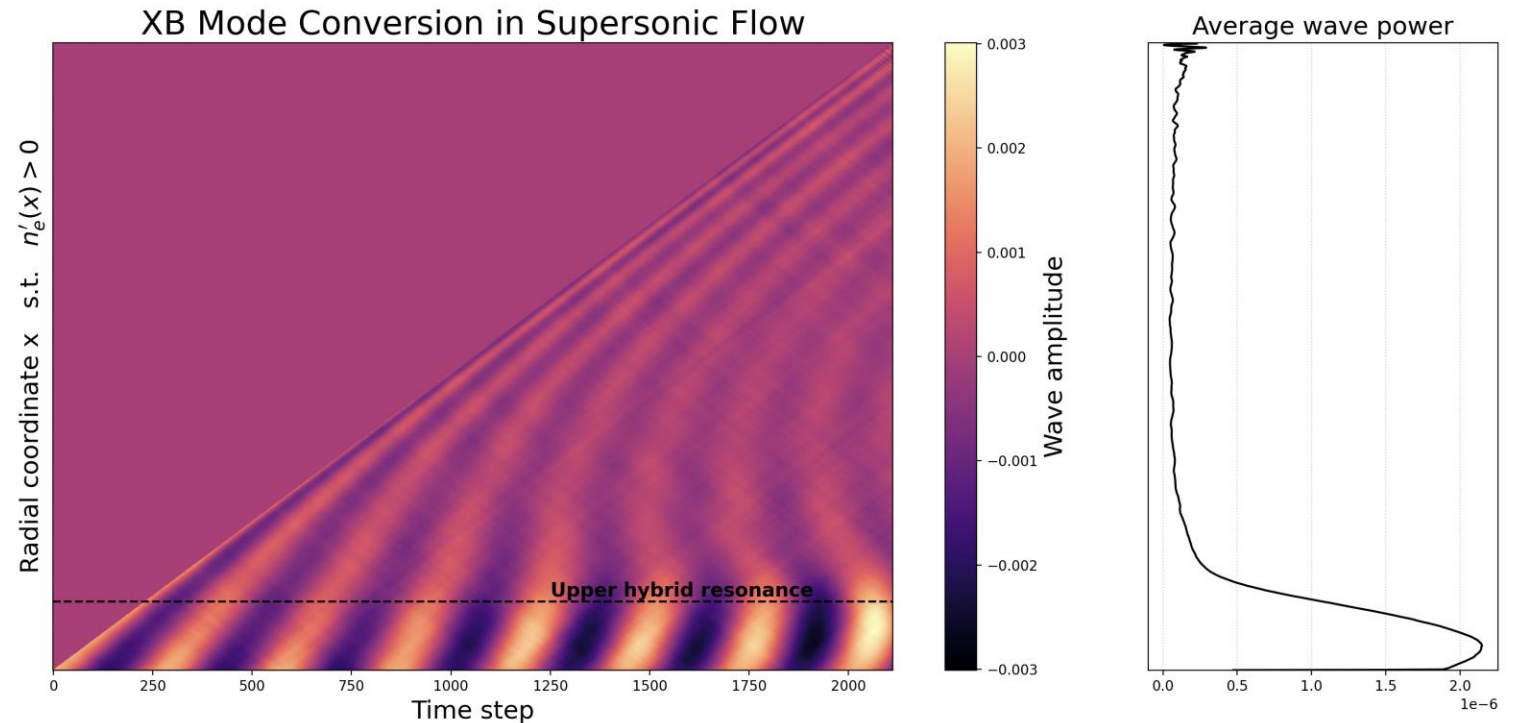
I. E. Ochs, E. J. Kolmes, and N. J. Fisch, *Preventing ash from poisoning proton-boron 11 fusion plasmas*, Physics of Plasmas **32**, 052506 (2025).

# Codes: $S^5$ , a massively-scalable structure-preserving PIC code

- We must accurately model wave-particle interactions in rapidly-rotating collisionless plasmas
- $S^5$  is a new particle-in-cell code, so named because of its powerful properties:
  - **Structure-preserving**: the full hierarchy of Poincaré invariants in phase space is exactly preserved
  - **Symplectic**: charge conservation (via a Gauss's Law momentum map) is also exactly preserved
  - **Scalable**:  $S^5$  reliance on PETSc and the DOLFINx finite element library afford massive scalability
  - **Simplicial**: compatible with cubical and simplicial (tetrahedral) meshes in 1D, 2D and 3D
  - **Spectrally-tunable**: differential operators can be optimized for accuracy at chosen frequencies

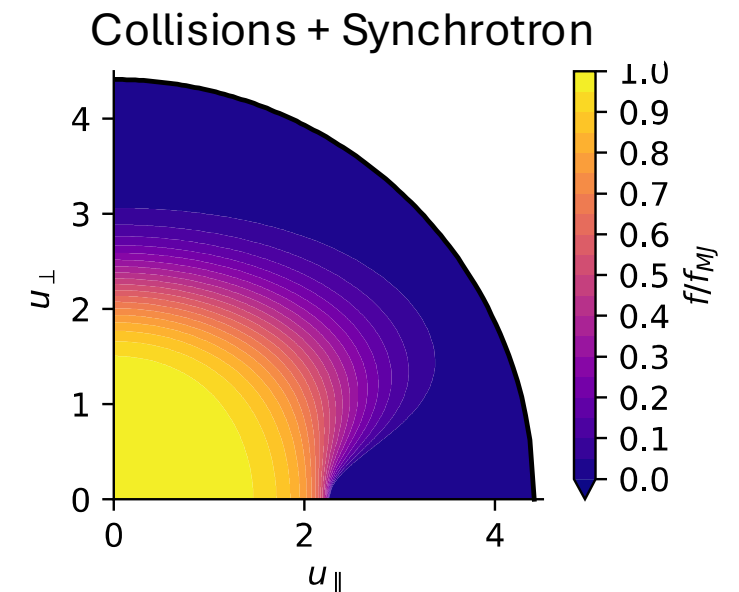
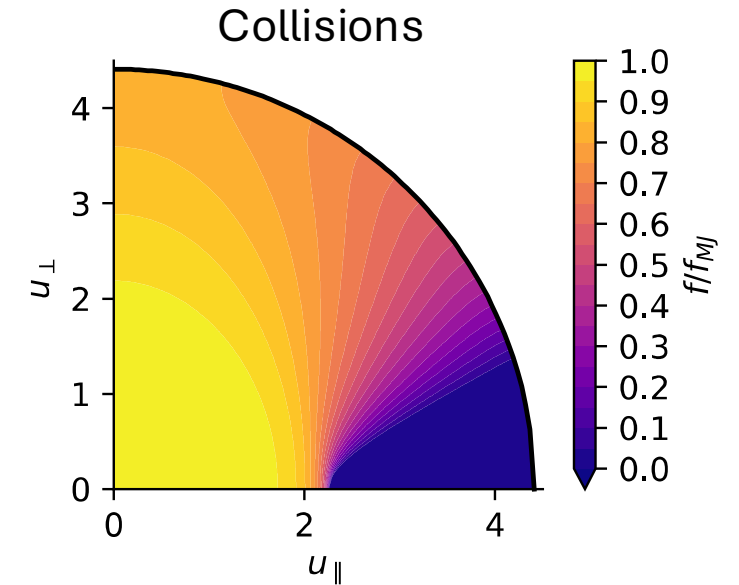


Hairer et al. Geometric Numerical Integration, Springer, Berlin (2006).



# Codes: R<sup>3</sup>FP: Radiative Reabsorption in Relativistic Fokker-Planck

- In a relativistic plasma, synchrotron radiation and collisions equally shape the electron distribution
- Reabsorption processes are critical
- R<sup>3</sup>FP is the first code to handle synchrotron emission and absorption self-consistently alongside collisions and loss cone physics
- R<sup>3</sup>FP captures the kinetic interplay of different processes in ways (PB)<sup>2</sup> cannot
- Extending code to handle multi-chamber functionality to form the basis of an integrated reactor model for CHARM



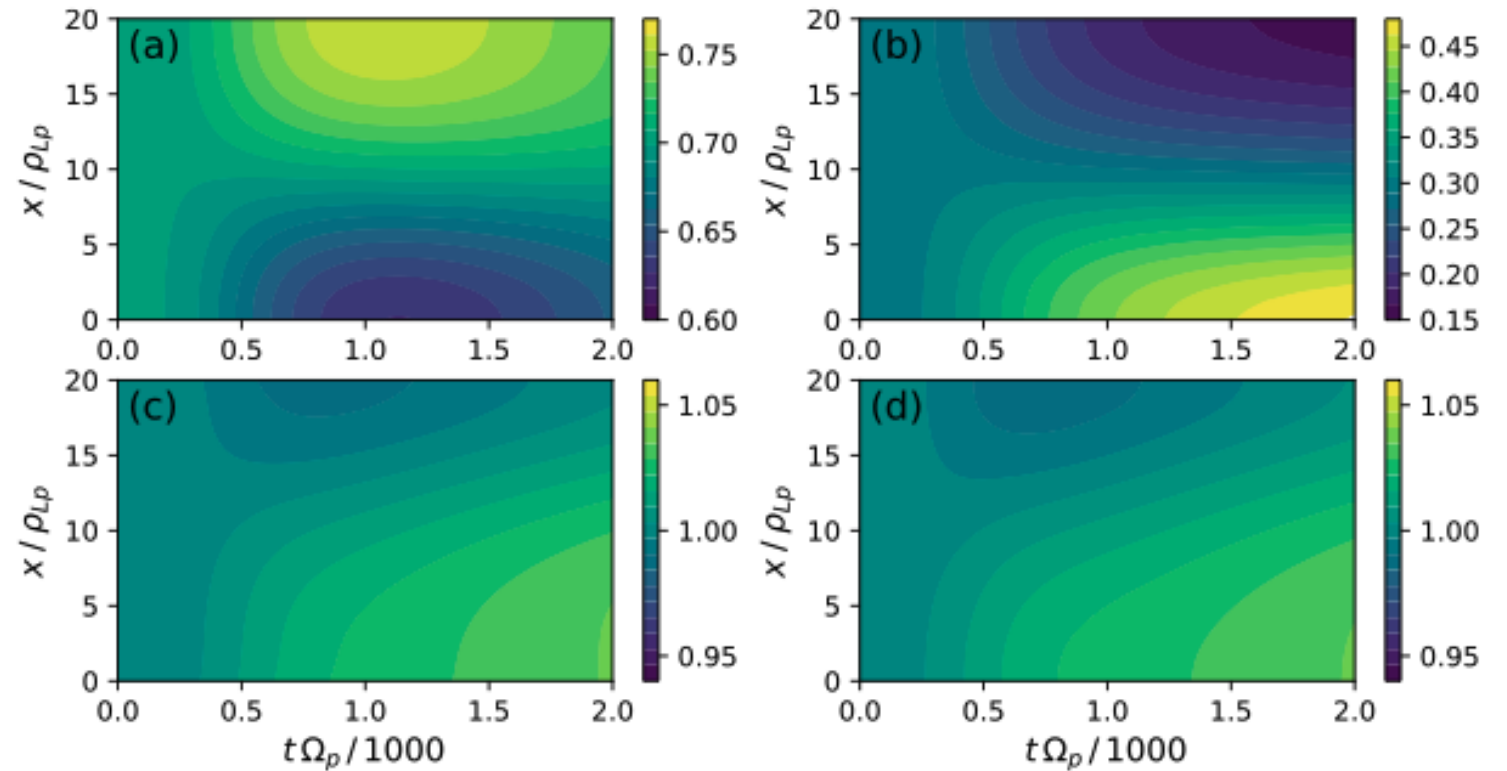
I. E. Ochs, V. R. Munirov, and N. J. Fisch, *Confinement time and ambipolar potential in a relativistic mirror-confined plasma*, *Physics of Plasmas* **30**, 052508 (2023).

I. E. Ochs, M. E. Mlodik, and N. J. Fisch, *Electron tail suppression and effective collisionality due to synchrotron emission and absorption in mildly relativistic plasmas*, *Phys. Plasmas* **31**, 083303 (2024).

I. E. Ochs, *Bounce-Averaged Theory In Arbitrary Multi-Well Plasmas: Solution Domains and the Graph Structure of their Connections*, *Journal of Plasma Physics*, In Press (2025).

## Also: MITNS: Multiple Ion Transport Numerical Solver

- Treats  $N$ -species, magnetized particle, momentum, and heat transport.
- Describes coupled dynamics of the different ion species.
- Particularly useful for uncovering fundamental, new effects governing pB11 plasma.



# The Team



Prof. Nat Fisch  
*Professor of Astrophysical Sciences*

Associate Director for Academic Affairs, Princeton Plasma Physics Laboratory (1993-2024)  
Director of Program in Plasma Physics, Princeton University (1991-2024)  
[2005 American Physical Society Maxwell Prize, 2015 European Physical Society Alfvén Prize](#)



Dr. Ian Ochs \*22  
*Associate Research Scholar*

Thesis: *Controlling and Exploiting Perpendicular Rotation in Magnetized Plasmas*  
Harvard University BS 2015, Jacobus Fellow, DOE Fusion Energy Postdoctoral Fellow at Princeton University  
[2023 APS Division of Plasma Physics Outstanding Thesis Award](#)



Dr. Elijah Kolmes \*22  
*Associate Research Scholar*

Thesis: *Particle, Charge, and Energy Rearrangement in Rotating Magnetized Plasma*  
Princeton University BS 2015, DOE Fusion Energy Postdoctoral Fellow at Princeton University  
[Invited Talk APS 2023: Upper and Lower Bounds on Phase-Space Rearrangements](#)



Dr. Mikhail Mlodik \*23  
*Postdoctoral Research Associate*

Thesis: *Cross-Field Transport in Magnetized, Multi-ion Plasma*  
Nizhny Novgorod State University BS 2016, Postdoctoral Researcher at Princeton University  
[Invited Talk APS 2023: Curious Cross-Field Transport Effects in Multi-ion, Magnetized Plasmas](#)



Tal Rubin  
*Graduate Student*

Graduate student in astrophysical sciences at Princeton University  
Technion-Israel Institute of Technology MS in Mechanical Engineering 2014  
[Invited Talk APS 2024: Ponderomotive barriers in rotating mirror devices using static fields](#)



Dr. Alex Glasser \*22  
*Associate Research Scholar*

Thesis: *Gauge Structure in Algorithms for Plasma Physics* (Advisor: Professor Hong Qin)  
Harvard BA 2006, Procter Honorific Fellow, DOE Fusion Energy Postdoctoral Fellow at PPPL  
[Experience prior to Ph.D.: Led portfolio risk management for a hedge fund startup](#)

## Summary: Where we stand now

- Questions posed and answered:

1. Individual components suggest feasibility of centrifugal, multi-cell pB11 reactor
2. Alpha handling is critical, and accomplishable in heat-exchange chamber
3. Wave-induced diffusion in the second chamber removes alpha particles promptly
4. Synchrotron radiation is manageable through reabsorption
5. Centrifugal drift energy is recoverable
6. Voltage drops can be minimized near walls
7. Selective ponderomotive walls can regulate ion traffic in rotating plasma
8. One-way walls have high energy cost, so use is situational
9. Multi-ion potential methods possibly double the proton confinement

- Now we need to see if these components work together **self-consistently**

- Further research facilitated by portfolio of novel, specialized computational tools

T2M:



### Starting Point for Pale Blue Fusion

Novel Design for pB11

New tricks for *selective* confinement

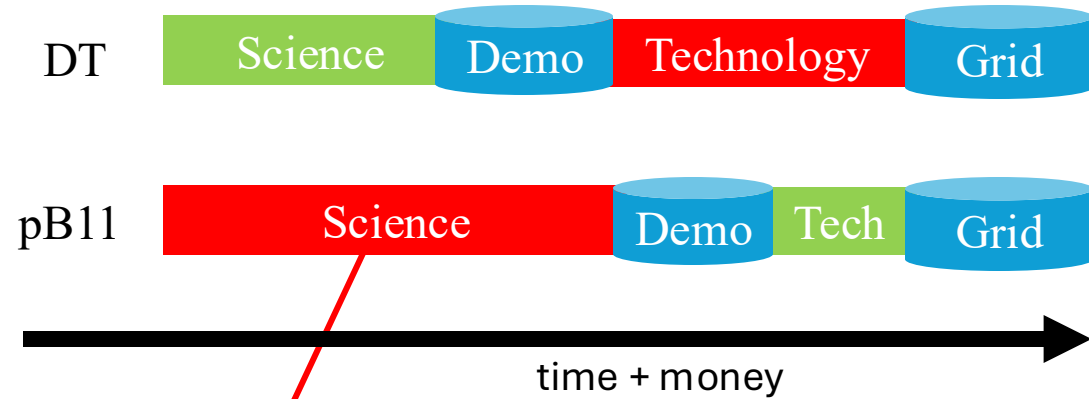
Protected IP: 4 Patent Applications

Publications: 29 Peer-reviewed

Specialized Numerical Codes

Team with history of working well together

### Where we stand on race to economical fusion



To reach goals quickly, we now seek

1. Recruitment
2. Partnerships
3. Collaborations
4. Investment

Derisk the **hardest problems** as **cheaply and quickly** as possible

Develop an **in silico** power-positive reactor

Validate experimentally key innovations