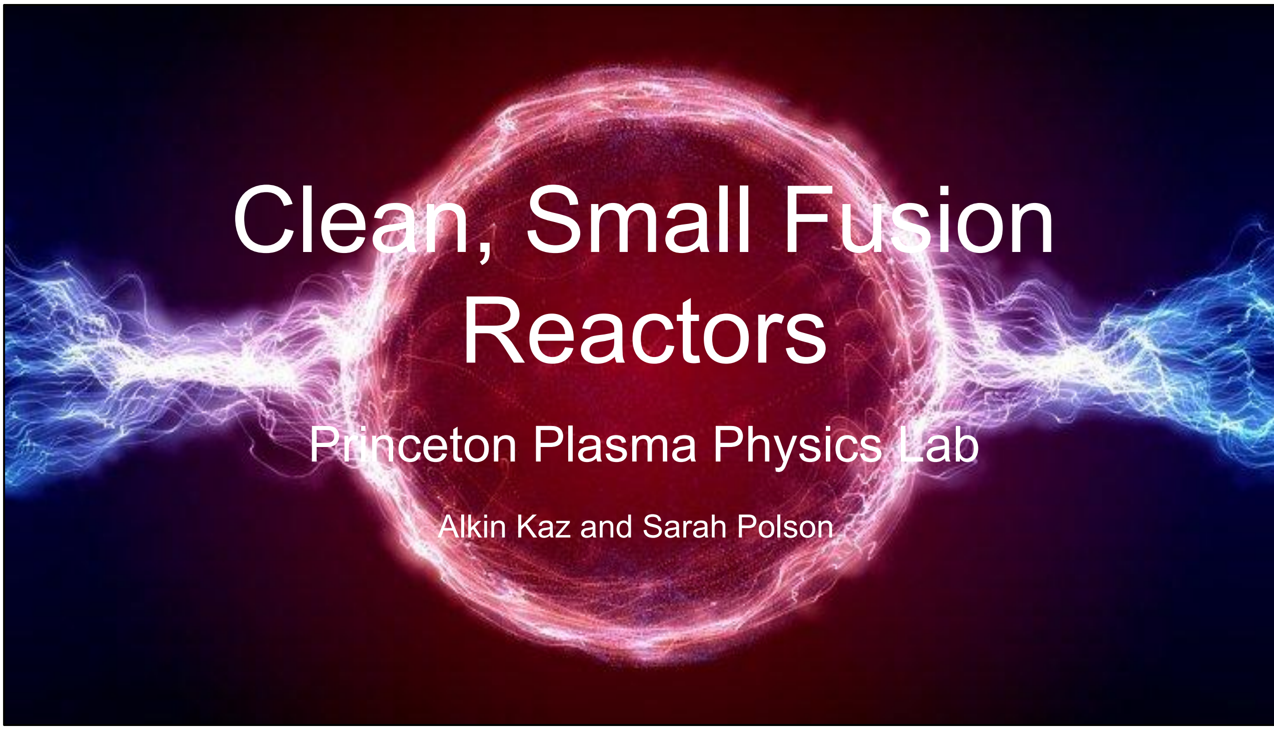
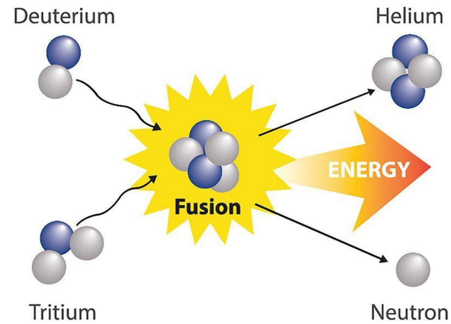
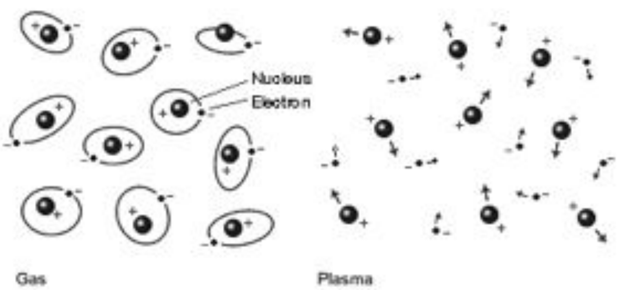


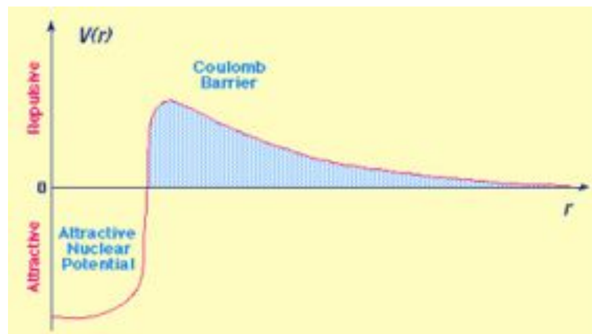
*Princeton Plasma Physics lab under prof. Samuel cohen
Working remotely -- alkin from turkey and me from chicago
Our presentation will start off with some nuclear fusion background and move into specifics on our individual projects

Plasma Fusion General

Premise: replicate on Earth the production of energy that occurs within the Sun







Main questions to answer within this slide:
To give some background, firstly I will discuss where the energy from fusion comes from. The term fusion refers to a reaction in which two nuclei are fused together to form new products. The difference in mass between the reactants and products is manifested as a release of energy. The diagram on the top right describes this reaction with two of the common fuels (deuterium and tritium) used in nuclear fusion reactors today. This is the production of energy that occurs within the Sun, and it is this phenomena that labs and private companies all over the world seek to replicate on Earth.

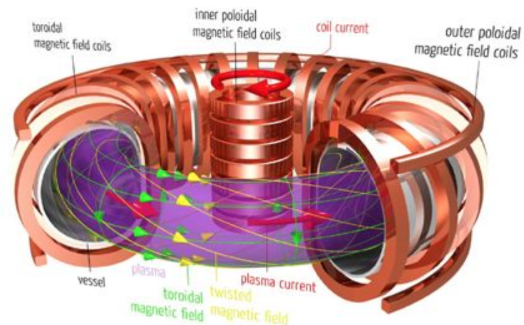
For this to happen on Earth, we need to be able to heat up a plasma and sustain it at very high temperature to density ratio so that collisions can occur--plasma being an ionized gas, as seen on the bottom left photo. In order to overcome the strong repulsive force (represented on the bottom right diagram as the coulomb barrier) and for fusion to occur, the plasma must be heated up to temperatures on the order of ~200,000,000º C! The next question then becomes how to confine and sustain the plasma. Since we are dealing with ions, the natural solution is through magnetic confinement…

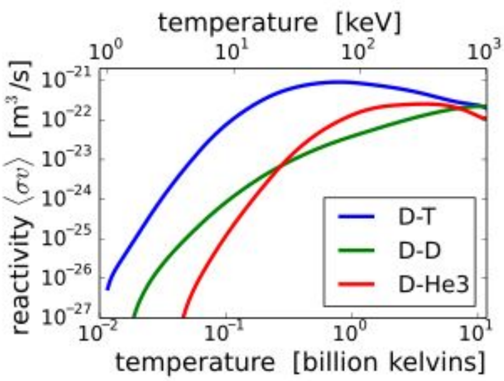
(This difference in mass arises due to the difference in atomic "binding energy" between the atomic nuclei before and after the reaction.)
(at these temperatures Deuterium D and Tritium T are ionized – a plasma (need to heat up these fuels to be very hot but also keep them confined→ since we are dealing with ions, the natural solution is through magnetic confinement)
--big question that is hoping to be answered is whether we can sustain fusion

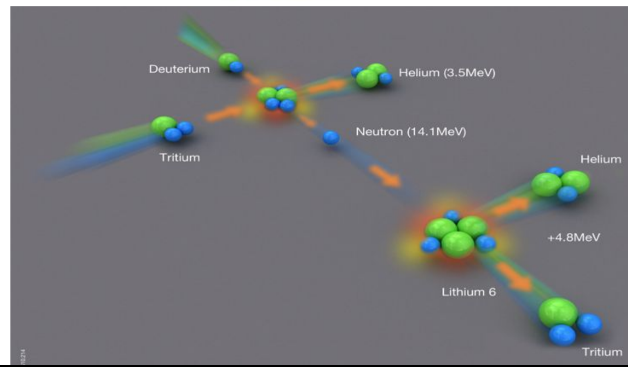
grade plasmas:

Plasma Fusion General

- Many possible fuels for fusion (and designs for reactors)
- “Neutron problem”







There are Many different models for fusion reactors and proposed answers to this question. The reactor design with the highest level of investment is called the tokamak (pictured in the upper right hand corner). Right below this picture, there is a diagram of the fuels (the same deuterium and tritium as seen on last slide) as well as their products. Here, we see two reactions. Ideally, the neutron product of the initial fusion reaction would be collided with lithium 6 in order to breed more tritium which was one of the initial fuels. While this closed system seems ideal, issues arise because the emitted neutron is not affected by the confinement of magnetic fields, and so it can damage the internal structure of the walls of the machine. Using a different fuel which does not produce neutrons as a byproduct has the potential to solve this problem. However most fusion devices must use D-T because it is the easiest fuel to use temperature-wise which the lower left graph shows. Most reactors do not have a high enough beta (the ratio of the plasma pressure to the magnetic pressure) to sustain other fuels. The design of the reactor that we studied does, and it uses deuterium and helium 3 to avoid neutron products.

and the metallic coils have electric current driven through them to produce both a current within the plasma
Fuels we are concerned with are the easiest “most reactive” fuels → generally where the coulomb barrier is low (minimize number of protons...)
Deuterium and tritium are both hydrogen isotopes and the choice of fuel for many reactors --shown in reactivity graph we see why DT is common choice for fuel since it is easier to fuse and tokamaks (leading design for fusion reactors) do not have a high enough beta to use a different fuel. PFRC model does! Enables use of different fuels

and gets around “neutron problem”

→ connect to PFRC by talking about PFRC being a solution to the “waste management” or ability to have a different fuel

PFRC

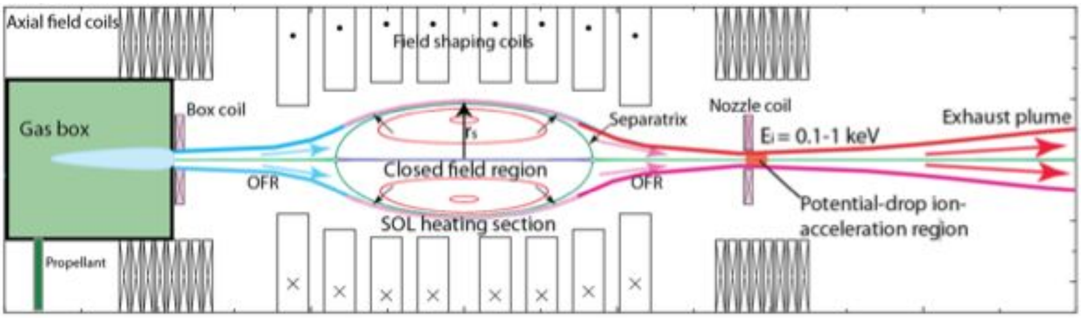


Figure 1: The outline of the PFRC-2 design and the magnetic field lines

"[Modular Aneutronic Fusion Engine,]" Y. Razin, G. Pajer, M. Breton, E. Ham, J. Mueller, M. Paluszek, A.H. Glasser, and S. Cohen, presented at the *63rd International Astronautical Congress* (1-5 October 2012, Naples Italy).

- Without any external current through the middle axis, compact tokamak-like field lines are formed.
- Gas is propelled into the box follows the field lines to arrive at fusion region (closed field region). The waste of the reactions exit from the exhaust.
- ~1 MW ~= 700 people (neighborhood-based small plant system is a possibility)
    - Focus on smaller and de-centralized fusion reactors, says Ryan Umstattd (Director at Fusion Industry Association)
- PFRC1-2-3-4 … now 2 years left until PFRC-3, 5 years each

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PFRC

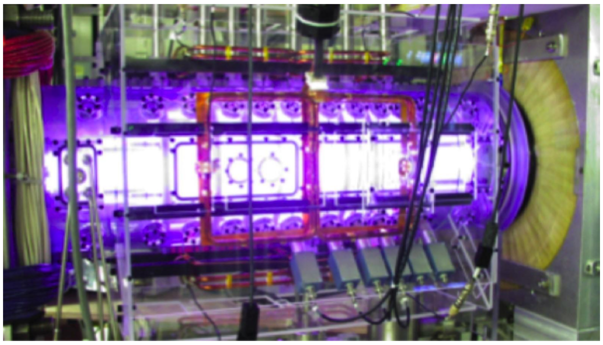

Figure 2: PFRC-2 in operation, note RF antennas (orange)

Image Source: "Direct Fusion Drive Rocket for Asteroid Deflection," J.B. Mueller, Y.S. Razin, M.A. Paluszek, A.J. Knutson, G. Pajer, S.A. Cohen, and A.H. Glasser, presented at the 33rd International Electric Propulsion Conference, The George Washington University, USA (6-10 October 2013).

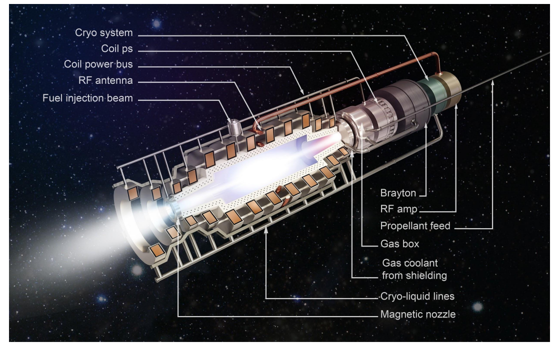

Figure 3: Direct Fusion Drive (DFD) design

Image Source: "Fusion-enabled Pluto Orbiter and Lander," S.J. Thomas and M.A. Paluszek (Princeton Satellite Systems, Plainsboro, NJ, 08536) and S. Cohen (Princeton Plasma Physics Laboratory, Princeton, NJ, 08543), in preparation (2018).

- RF antennas create what we call Rotating Mag Field, “the magnetic field is closely aligned with plasma configuration.

~1 MW ~= 700 people (neighborhood-based small plant system is a possibility)

- Focus on smaller and de-centralized fusion reactors, says Ryan Umstattd (Director at Fusion Industry Association)

The exhausted charged particles can also be used to gain thrust in space, hence Direct Fusion Drive

- Include Princeton Satellite Systems

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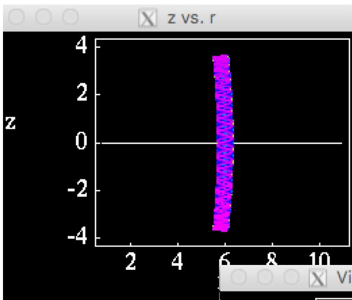
Sarah

- RMF (Rotating Magnetic Field) code
  - Developed by Dr. Alan Glasser
  - Numerically integrate nonlinear differential equations (Hamiltonian)
  - Output: single particle trajectories
- Modeling
  - Electron/ion orbits
  - Ion heating
  - Energy distributions
  - Particle escape

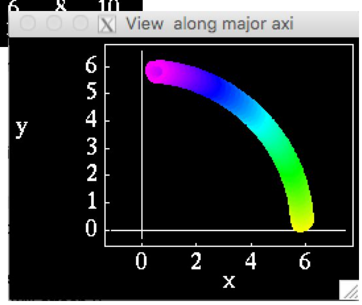
```
variable names
0       tau            !orbit time normalized to cyclotron period
1       r              !radial position of orbital point
2       z              !axial position of orbital point
3       phi            !azimuthal position of orbital point
4       pr             !raidal momentum of orbital point
5       pz             !axial momentum of orbital point
6       pphi           !angular momentum of orbital point
7       en_r           !radial contribution to total energy
8       en_z           !axial contribution to total energy
9       en_phi         !aximuthal contribution to total energy
10      en_prp         !kinetic energy of motion perpendicular to B
11      en_par         !kinetic energy of motion parallel to B
12      energy eV      !particle energy
13      error          !relative error in conservation of conserved energy
14      bmod           !|B|, magnitude of magnetic field at orbital point
15      mu             !magnetic moment of particle
16      x              !cartesian component of particle position
17      y              !cartesian component of particle position
18      omfac          !ratio of rmf to cyclotron orbit frequency
19      ppar           !parallel component of particle momentum
20      pprp           !perpendicular component of
21      ptot           !total particle momentum
22      log10 rlfac    !ratio of Larmor radius to fieldline curvature
23      energy_r       !radial component of kinetic energy
24      energy_phi     !aximuthal component of kinetic energy
25      energy_z       !aximuthal component of kinetic energy
26      psi            !magnetic flux at particle position
27      defac          !relative change from intial particl energy
28      psi_normal     !defac normalized to particle motion
29      xx1            !cartesian component of particle position in rotating frame
30      yy1            !cartesian component of particle position in rotating frame
31      jr             !parameter of Poincare surface of section
32      beta           !relativistic ratio v/c
33      gamma          !relativistic factor 1/sqrt(1-beta^2)
34      kinetic        !relativistic kinetic energy
35      omega          !relativistic cyclotron frequency
36      log10 cradius  !magnetic fieldline radius of curvature
37      varphi         !electrostatic potential of fermi antennas
38      varphi_z       !axial derivative of varphi
```

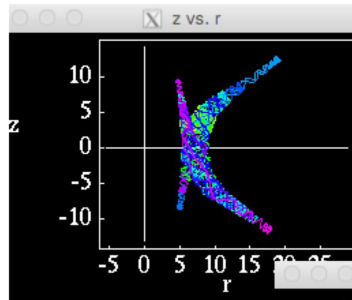
My individual project was centered around the RMF code developed by Dr. alan glasser which simulates single particle trajectories within the PFRC (or any configuration that the user inputs). The code works by integrating the Hamiltonian equations which describe the system. On the left I included a list of all of the code's outputs to emphasize the versatility of the code. The obvious benefit from having such a model is that it is easy to change parameters and see the effect → much easier than building a whole new PFRC machine and running tests to confirm theory.

Sarah

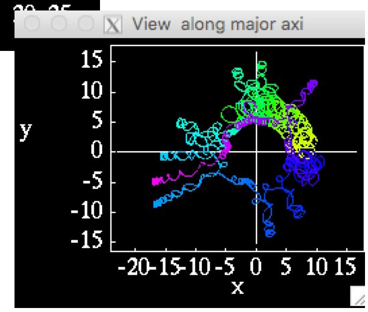


Mirror only





FRC + Mirror



Here i wanted to showcase some of the code's capabilities. For simplicity I have neglected to include many of graphs that the code is capable of making--these are any combination of the earlier slide's variables as well as spatial graphs of the magnetic flux and field lines. The left side screen grabs show an electron trajectory under the influence of just a magnetic mirror. From the top r versus z graph you can see the particle bounces nicely between the two mirror points, and through the x y graph, we can see a nice drifting circular trajectory. However, turning on the FRC on the right, we can see the trajectories get vastly more complex, even among two well confined particles.

While this mirror only simulation (the left hand side) looks simple, my project was centered around trajectories in mirror simulations that were not this clear. For my project, I studied various plasma parameters in mu non-conservational occurences within this environment.

My project was initially to compare parameters of trajectories within a Hills vortex field distribution (which the code currently functions with) with that of a grad-shafranov distribution.

--note that there are also graphs of magnetic field lines & flux which I chose not to include since this is very busy

**note these two screenshots differ not only in whether the frc is turned on but also different initial parameters among those coil strength, position and radius.

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Alkin

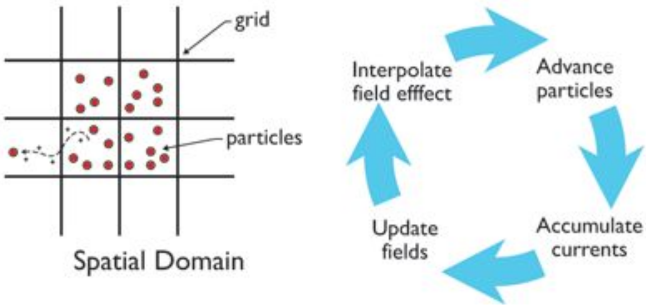

Figure 4: Particles are merged together inside cells to create “macroparticles” (hence particle-in-cell), which then are used to calculate the electromagnetic fields and advance the particles to their new positions

Image Source: Running VPIC on Roadrunner, LANL

Vector Particle-In-Cell (VPIC) is,

- a general particle-in-cell simulation code for modeling plasmas
- an open-source project
- developed and maintained by Los Alamos National Lab scientists
- providing massive parallelization options for supercomputers by supporting Message Passing Interface (MPI).

Small primer on kinetic and pic method - how it is useful to investigate the core and SOL region

Compare with Sarah’s code:

- Single particle and much less time consuming
- Billions of particles and days of supercomputer power required
- Sarah’s meant to be a guide, VPIC is meant to be more detailed / exactly capturing the plasma processes / time consuming.

Alkin

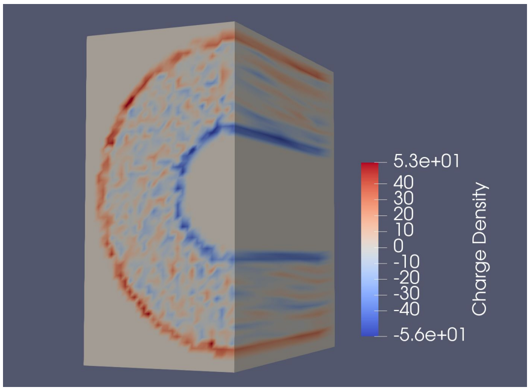

Figure 5: Accumulation of charges on conducting surfaces in a concentric cylindrical plasma capacitor

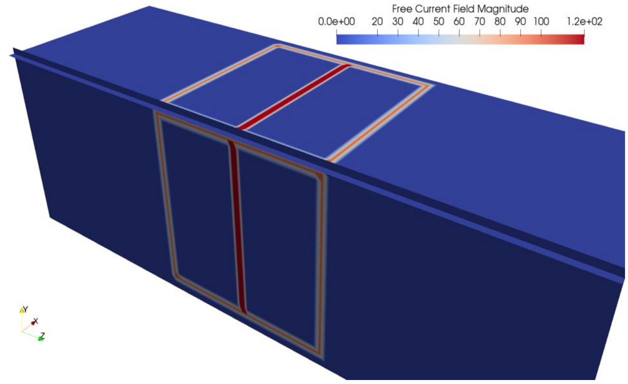

Figure 6: Modeling of the RMF antennas with external free current field input to VPIC (courtesy of Dr. Demir)

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Conclusions

- Both projects are continuing and we are proud that we expedited their progress.
- We learned about the current research fronts of the field as well as the fundamental basics.

Science Undergraduate Laboratory Internship (SULI) Introduction to Fusion Energy and Plasma Physics Course

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Acknowledgements

- PEI
- PFRC Research Group (specifically Prof. Samuel Cohen)
- Many thanks to individual mentors
  - Alkin: Dr. Mehmet Demir
  - Sarah: Dr. Stephanie Thomas