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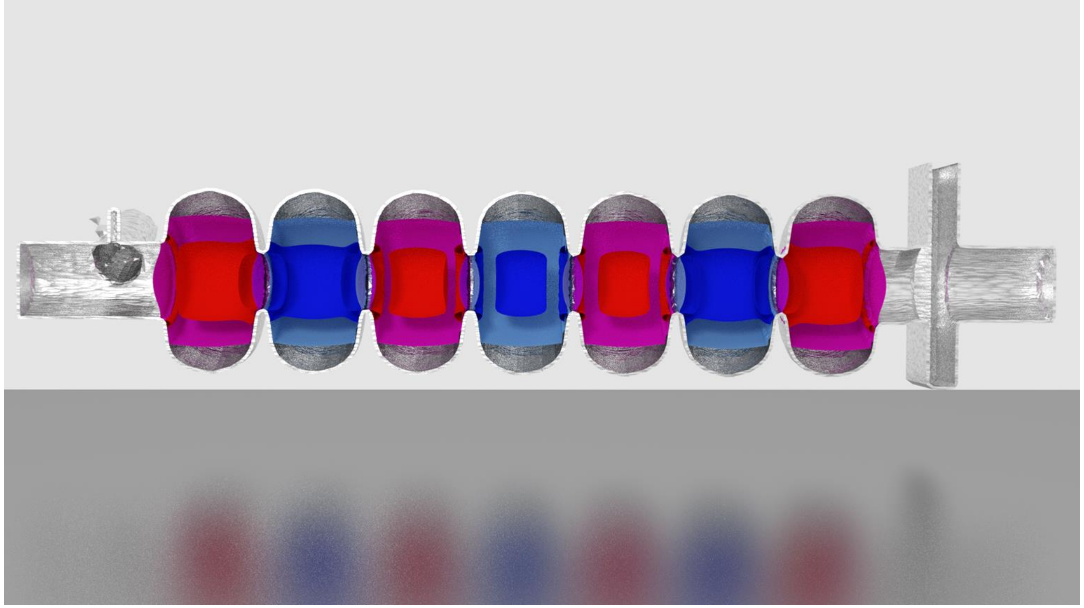
SIMULATIONS EMPOWERING
YOUR INNOVATIONS

MODELING PLASMA DISCHARGE CLEANING OF SRF CAVITIES

Jarrod Leddy
Tech-X Corporation

Overview

- Introduction to SRF cavities
- Overview of previous work
  - EM simulation
  - Ionization simulations
- Progress over the past year
  - Hybrid model
  - Surface reactions
  - Simulations for JLAB
- Other accomplishments



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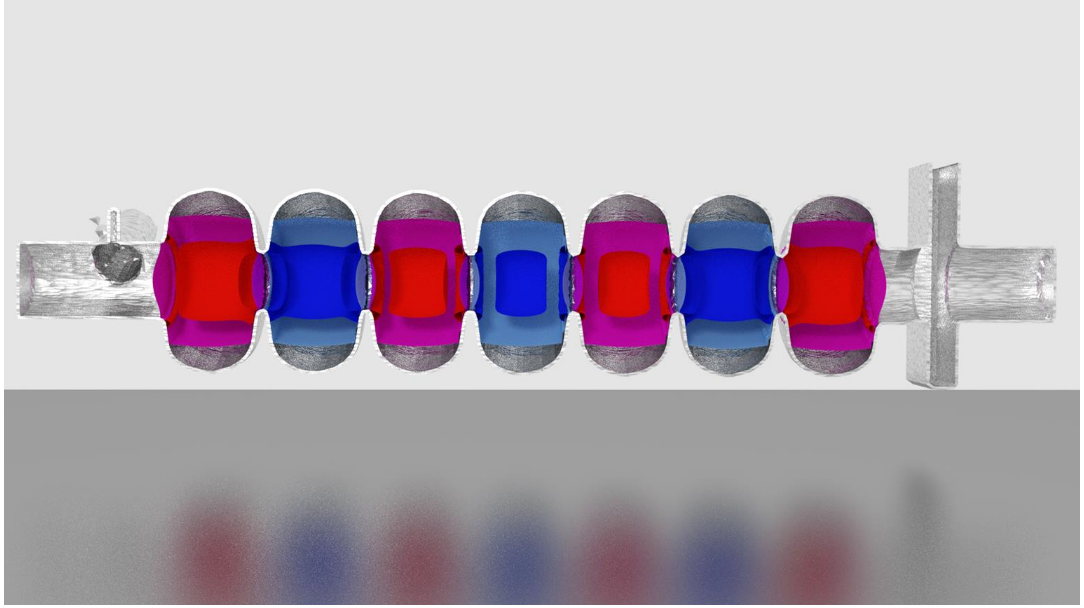
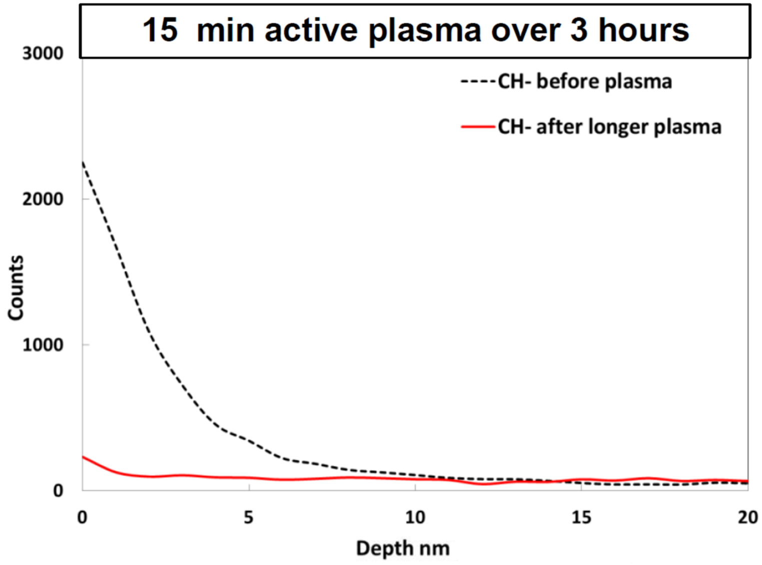


Introduction

- SRF cavities are used for particle acceleration
  - Acceleration gradients limited by surface impurities – cleaning required
- In-situ cleaning via plasmas is desired for limited downtime, cheap cleaning, etc.
- Desired simulation of this plasma because minimal diagnostics possible experimentally
- SBIR Phase I goal was proof-of-concept for plasma simulation allowing for Phase II to include more physics



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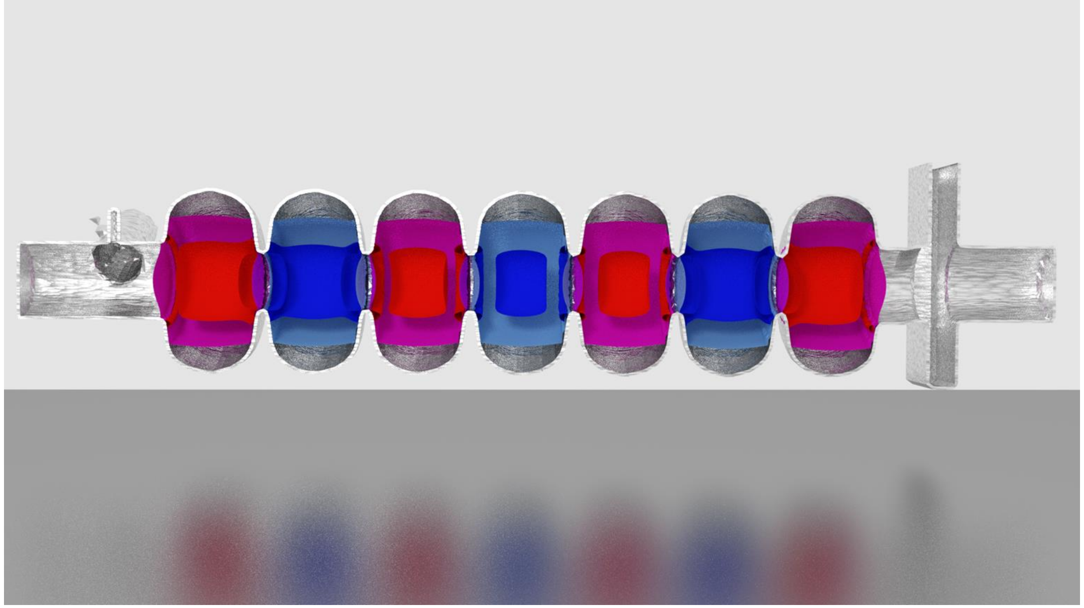
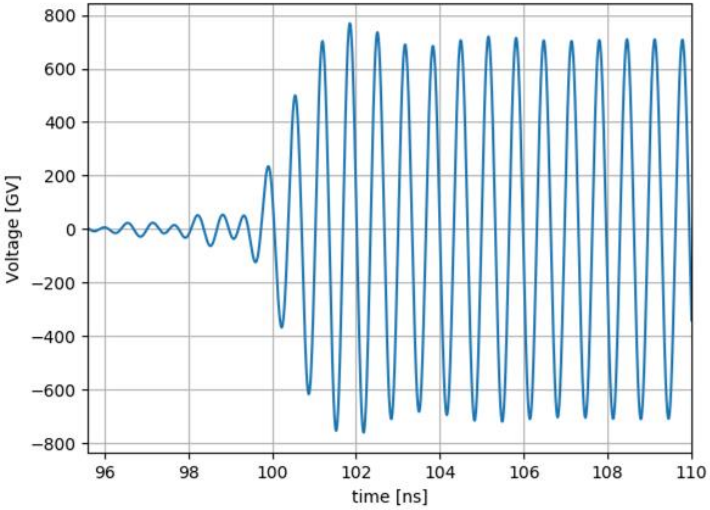


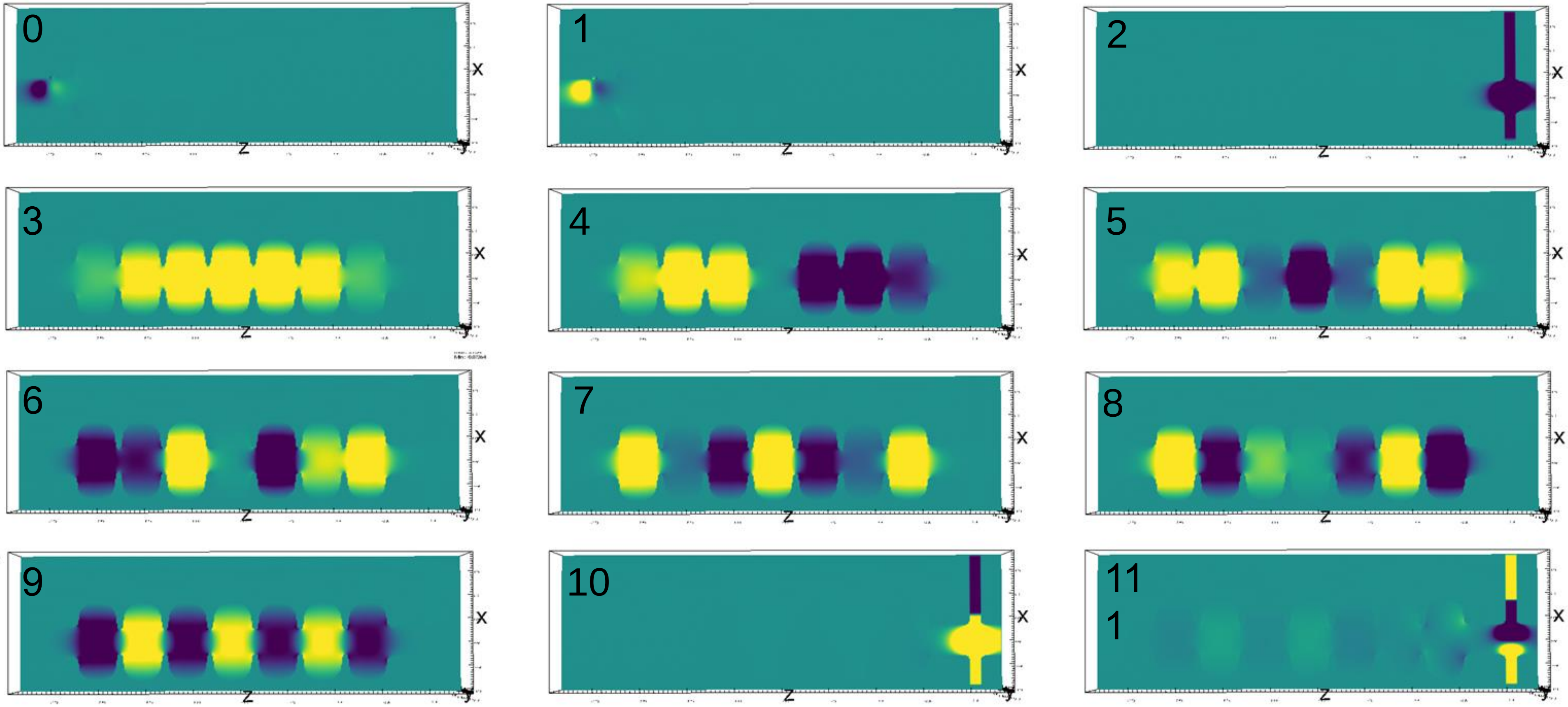
Electromagnetic simulation: Running

- Impose electric field of the modes we are trying to excite, in a band of frequencies
- Run long enough for the cavity to ring up (ie. in this case more than 100ns)
- After E-field source is gone, cavity will still continue to ring at the frequency of the resonant modes
- Simple analysis – Fourier transform resulting signal and look at peak frequency to find dominant mode
- But we can do better!



Electromagnetic simulation: Extract Modes

- Structures for all the found modes:



Extracting degenerate modes, Werner, 2008

Electromagnetic simulation: Pi-Mode

- Mode 9 is the pi-mode:

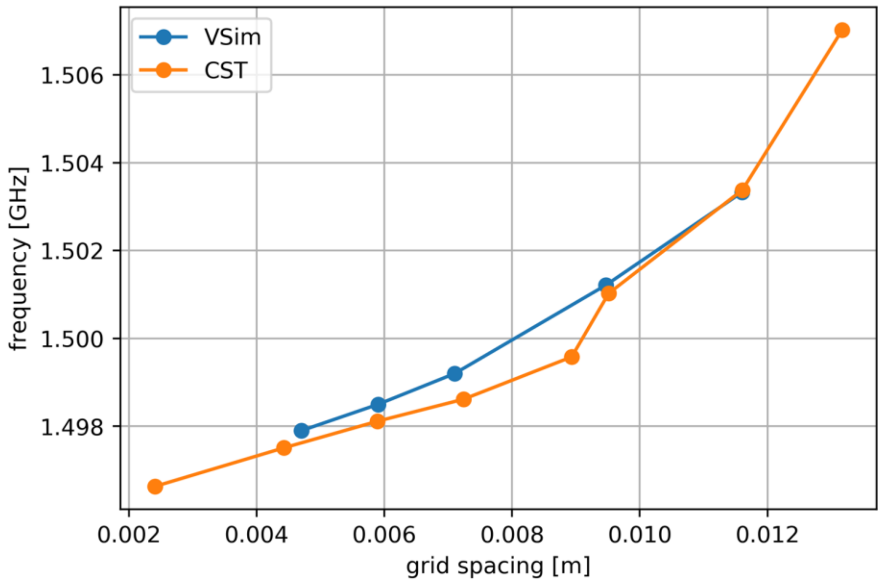
```
Mode    f_r (Hz)        f_i (Hz)       lam_vac (m)     cont       rel-err    abs-err
  9  1.495699e+09 -0.000000e+00  2.004363e-01  4.03e-02  3.56e-09  1.43e-10
```

- This frequency converges to the true frequency as dx→0, so the true frequency can be calculated via Richardson extrapolation

- The pi-mode frequency is:

  1.49549 GHz – VSim

  1.49561 GHz – CST



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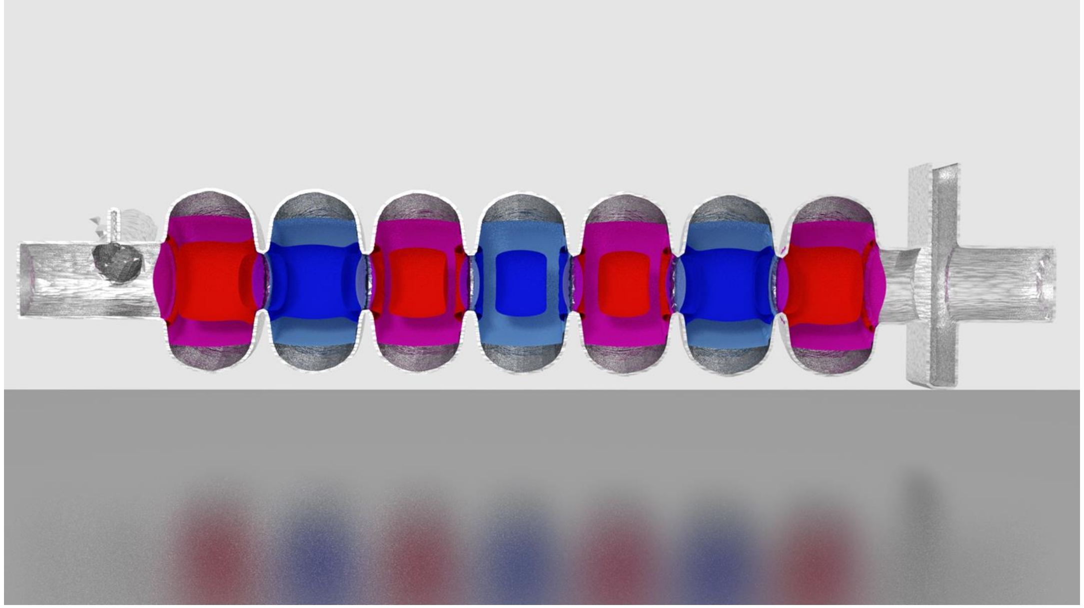


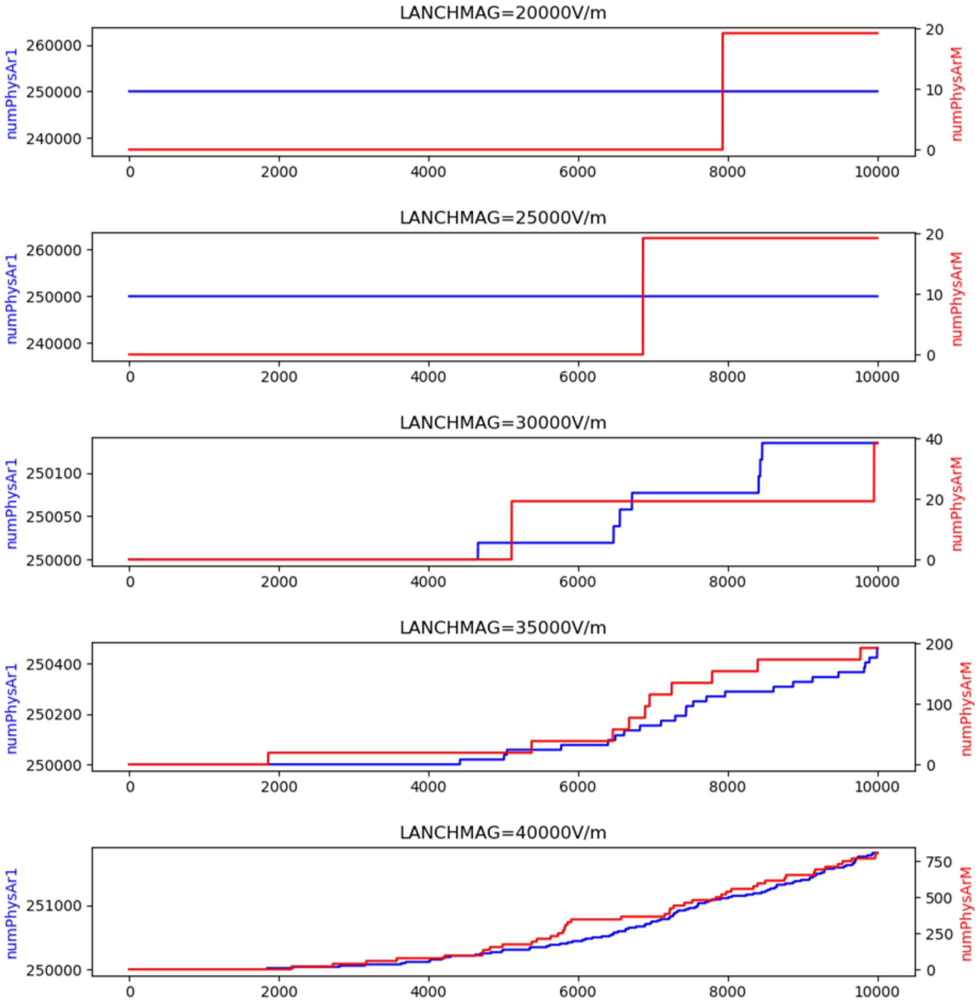
Plasma simulation: Introduction

- Electromagnetics have been validated, next step is plasma simulation

- Basic plasma formation process:
  - Free electrons accelerated by resonant EM modes
  - Impact ionization cascade is initiated, exponentially increasing the plasma density
  - Recombination and walls serve as sinks for plasma
  - Plasma density reaches equilibrium when source and sinks balance

Plasma ignition simulation: Power Threshold Determination

- Multiple simulations each at different power
- Threshold is chosen to be where ionization cascade is seen to occur (ie. exponential growth in electron number)
- Reduce step size as we get closer to threshold (final resolution is 0.25W)



Plasma ignition simulation: Simulation vs. Experiment

- C100 cavity, $2\pi/7$ mode (1.91GHz) power threshold (periodic box simulated in VSim)

Experimental results from Tom Powers (JLab)

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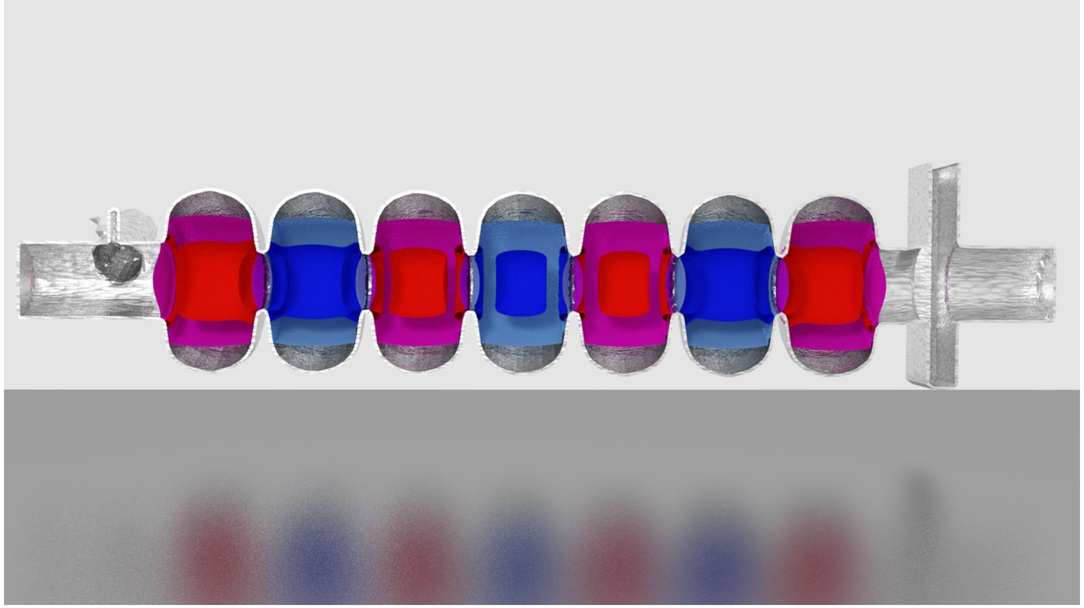


Hybrid Plasma Simulation

For full-device modelling, particle-in-cell simulation is expensive

Instead, implementing hybrid plasma model [Stanier 2018] where:

- electrons are represented as a fluid
- ions are modelled kinetically
- electric field is calculated via Ohm's Law

Allows us to step at electron bulk flow / sound speed time scales (instead of ω_{pe}) and relaxes requirement to resolve Debye length

$$\partial_t f_s + \boldsymbol{\nabla}\cdot(f_s \boldsymbol{v}) + (q_s/m_s)\,(\boldsymbol{E}^* + \boldsymbol{v}\times\boldsymbol{B})\cdot\boldsymbol{\nabla}_v f_s = 0,$$

$$\partial_t \boldsymbol{B} = -\boldsymbol{\nabla}\times\boldsymbol{E},$$

$$\boldsymbol{E} = \boldsymbol{E}^* + \eta\boldsymbol{j} = -\boldsymbol{u}_i\times\boldsymbol{B} + \frac{\boldsymbol{j}\times\boldsymbol{B}}{ne} - \frac{\boldsymbol{\nabla} p_e}{ne} - \frac{\boldsymbol{\nabla}\cdot\overleftrightarrow{\Pi}_e}{ne} + \eta\boldsymbol{j},$$

$$(\gamma-1)^{-1}\left[\partial_t p_e + \boldsymbol{\nabla}\cdot(\boldsymbol{u}_e p_e)\right] + p_e\boldsymbol{\nabla}\cdot\boldsymbol{u}_e = H_e - \boldsymbol{\nabla}\cdot\boldsymbol{q}_e,$$

Hybrid Plasma Simulation Benchmarks

- Developed the hybrid model implementation and conducted benchmarks to validate

- Implemented boundary conditions for conductor so that cavity/shapes can be modelled

- We have chosen 2 physics problems, each of which will be simulated with full **fluids** (eg. MHD), **full kinetic** (PIC), and **hybrid**
    - Landau damping of ion acoustic wave: fluids should give wrong answer, hybrid and kinetic should give correct answer
    - GEM problem (reconnection): fluids can give close answer, depending on assumptions, hybrid and kinetic should both be correct

- In all cases speed should be fluids > hybrid > kinetic

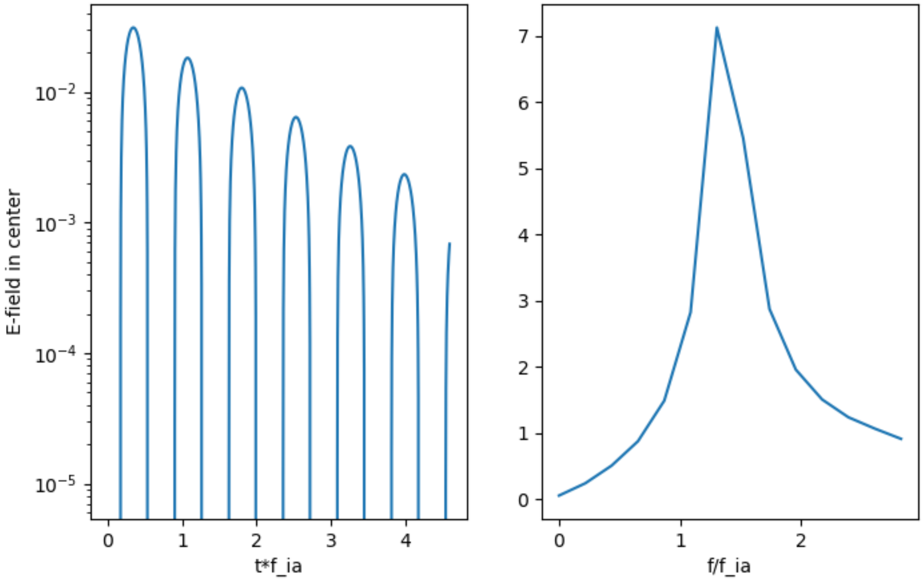
Test #1: full kinetic model of Landau damping

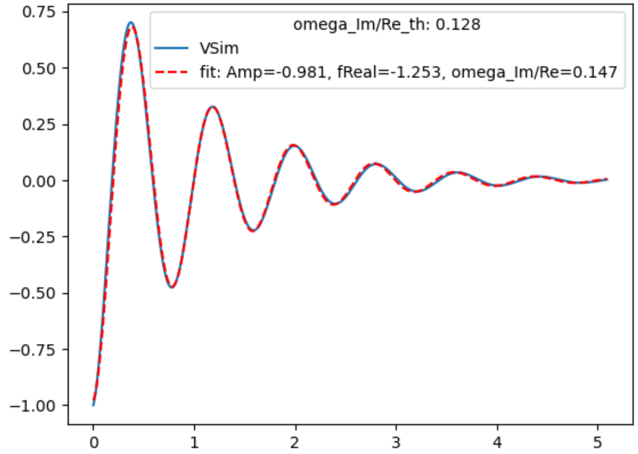
- Landau damping is the exchange of energy between waves in cold ions and resonant hot electrons.

- Fully kinetic models of Landau damping are computationally expensive

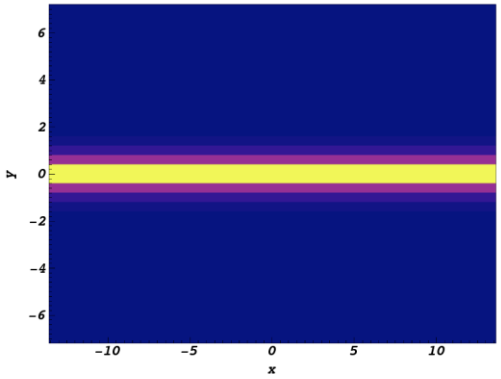
- Hybrid models will capture the relevant physics and be computationally faster

- Damping rate and frequency match theory for ion acoustic Landau damping

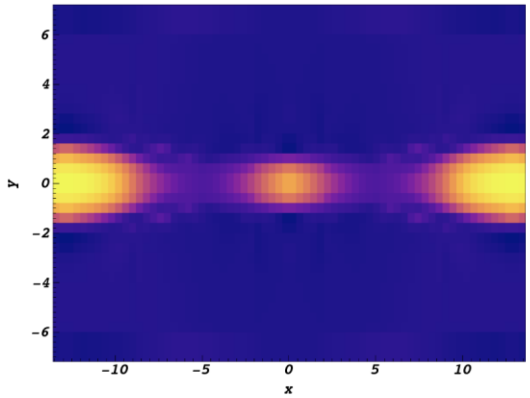




Test #2: extended MHD models of magnetic reconnection



Initial density

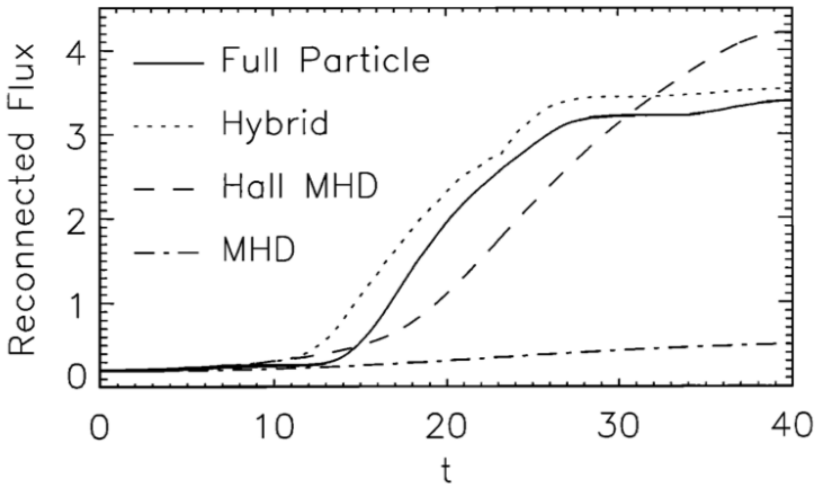


Density after reconnection

- Another standard test of hybrid models is magnetic reconnection
- In this test, the initial condition is a current sheet directed out of the plane
- Ideal fluid models will hold this initial condition indefinitely
- However, realistic (non-ideal) effects such as resistivity and charge separation will break this stability
- Hybrid models are one of the most successful at capturing these effects

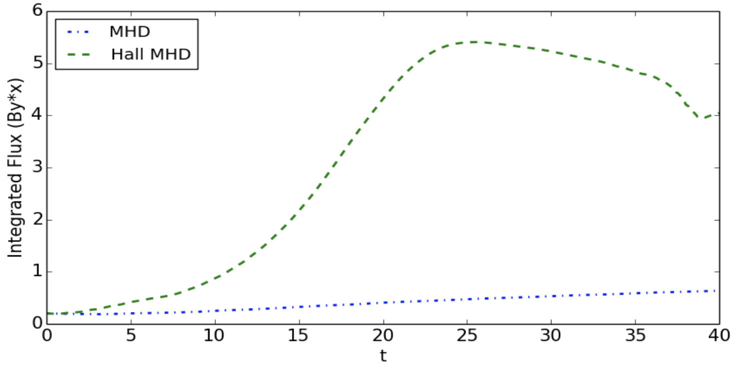
Test #2: extended MHD models of magnetic reconnection

Birn ‘01

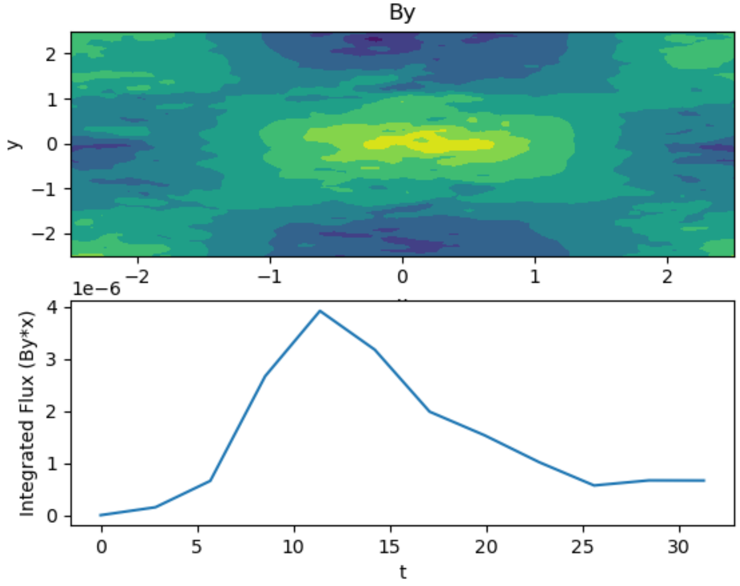


- We have reproduced several advanced fluid models of magnetic reconnection
- Hybrid model flux peaks to roughly correct value but drops back down - still investigating why

Our work



Fluid



Hybrid

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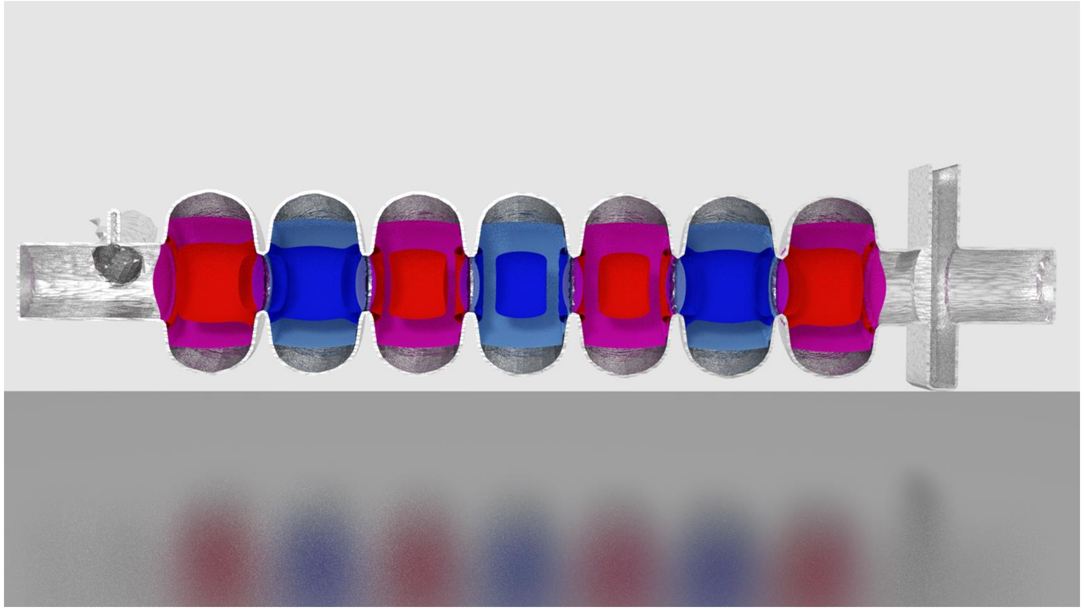
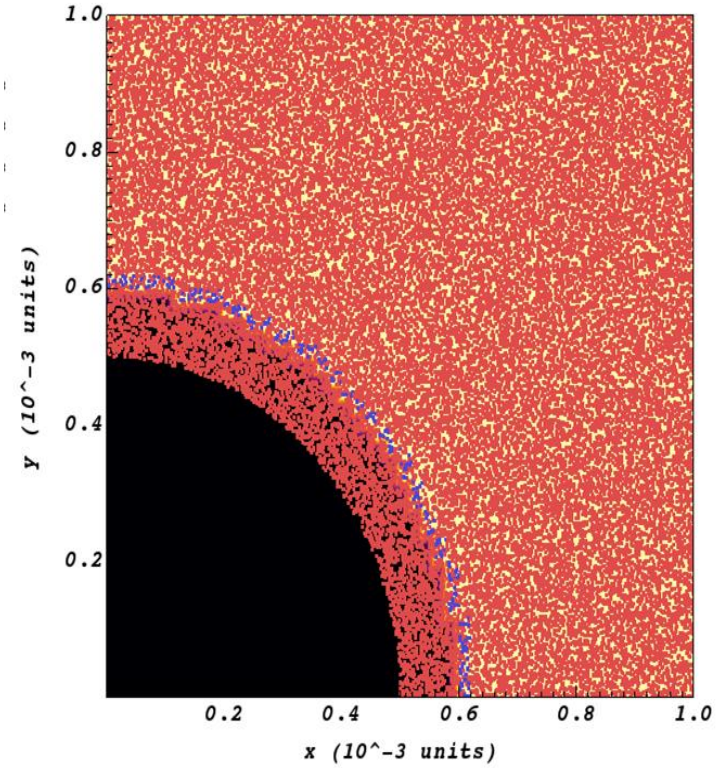


Surface reactions

- Existing framework within the software for bulk reactions - specify cross section and reactants/products

- Implemented ability to use boundary object as a reactant, thus limiting reaction location to boundary edges

- Now have the ability to react impurities on the cavity surface with the fluid and kinetic species within the plasma



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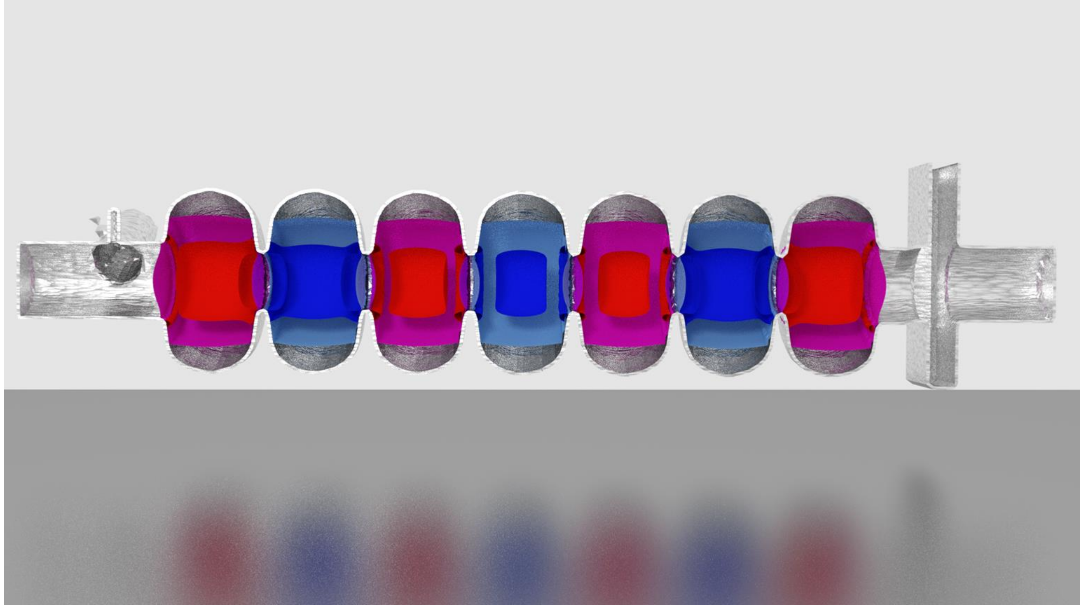
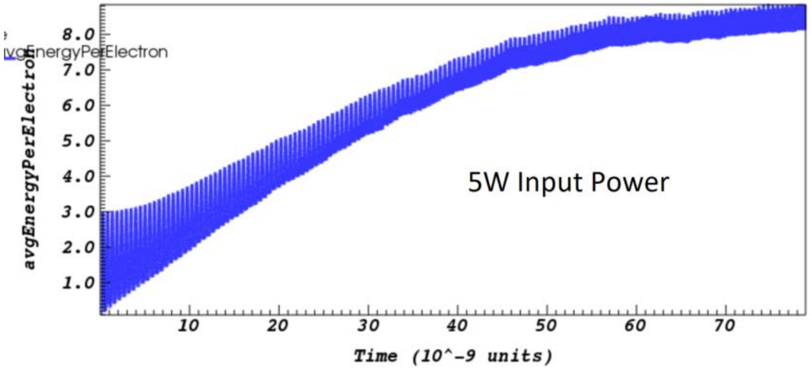


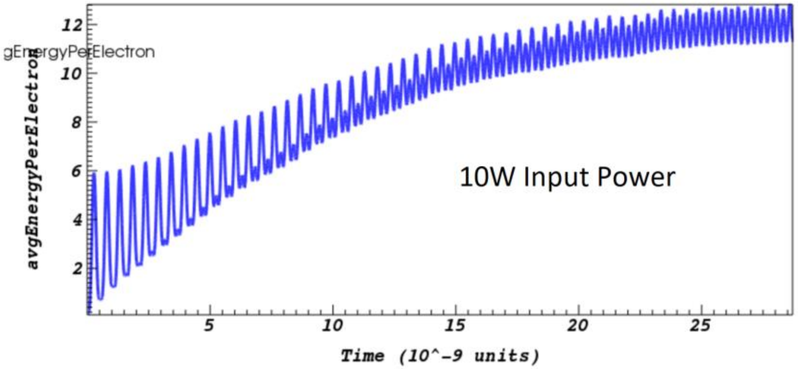
Experimentally Relevant Simulation for JLAB

- JLAB has an experimental campaign ongoing for plasma cleaning of cavities - we aim to be synergistic and supportive

- Of particular interest this past year was a simulation to determine the average energy of electrons ionized by an EM field of a particular power

- We were able to simulate these for a variety of powers and provide the results to JLAB





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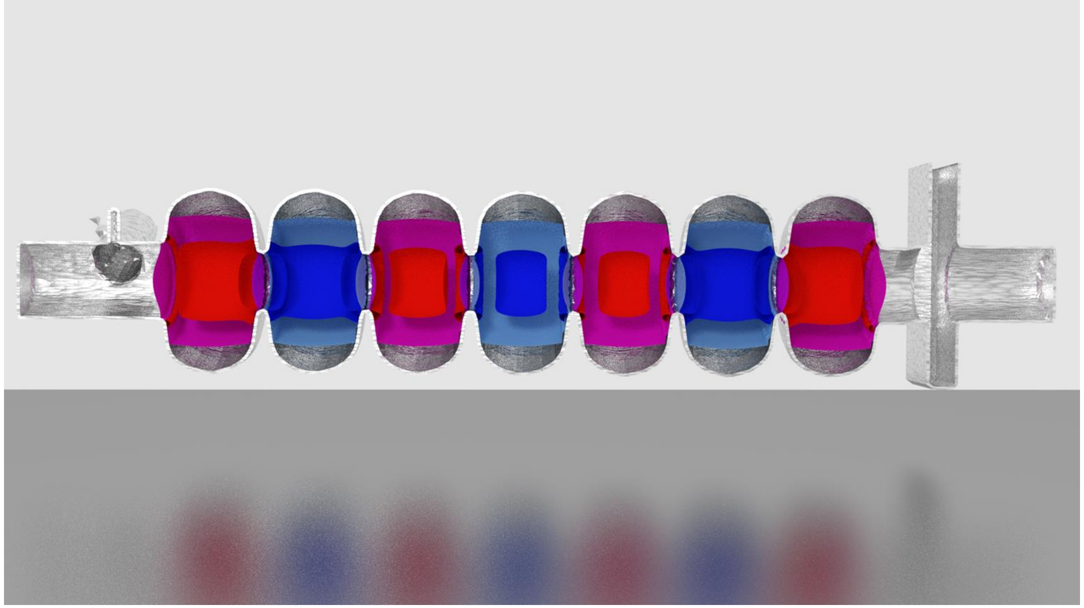
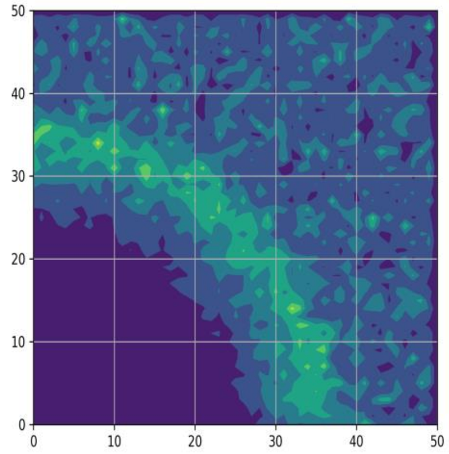
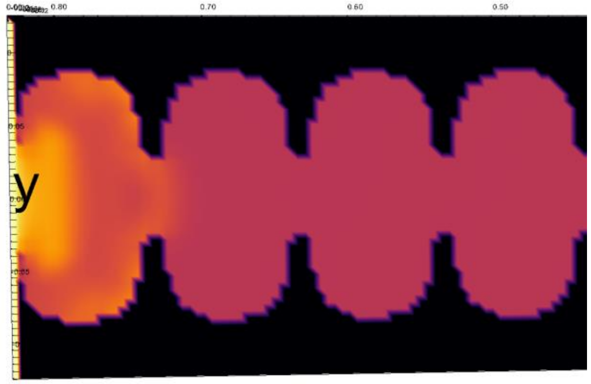


Other accomplishments

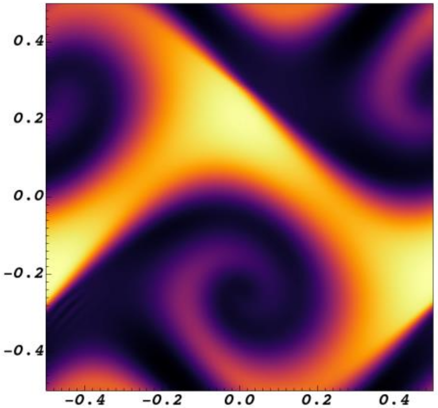
- We have highlighted the most interesting physics work we've been doing, but the project consisted of a variety of other tasks that we've made progress on:
    - Reaction statistics recording (collision frequency as a function of space)
    - GUI improvements allowing alteration of CAD geometries *in situ*
    - Euler fluid implementation on CPU/GPU with conformal boundaries (neutral fluid)
    - Market research and analysis of potential customers

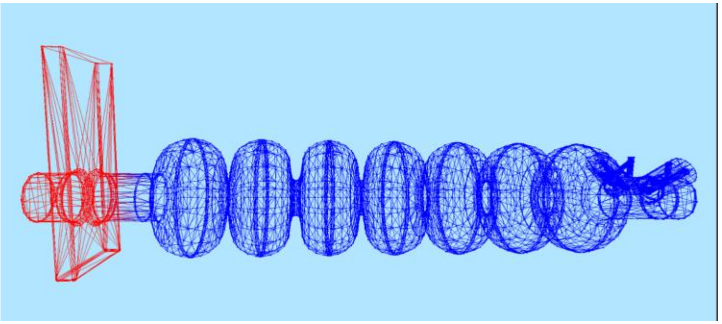




Project Outlook

- Project is in third year with NCE, 9 months remaining
- Development tasks remaining:
  - incorporation of new features into GUI
- Simulation tasks remaining
  - Finish up benchmarking
  - Investigation of HOM coupler arcing (seen in experiment with JLAB)
  - Impurity transport simulation through device
  - In contact with JLAB to see what other simulations we can run that would be useful to them





Thank you!

Questions?

Funding through grant
SBIR DOE-FOA-0001770

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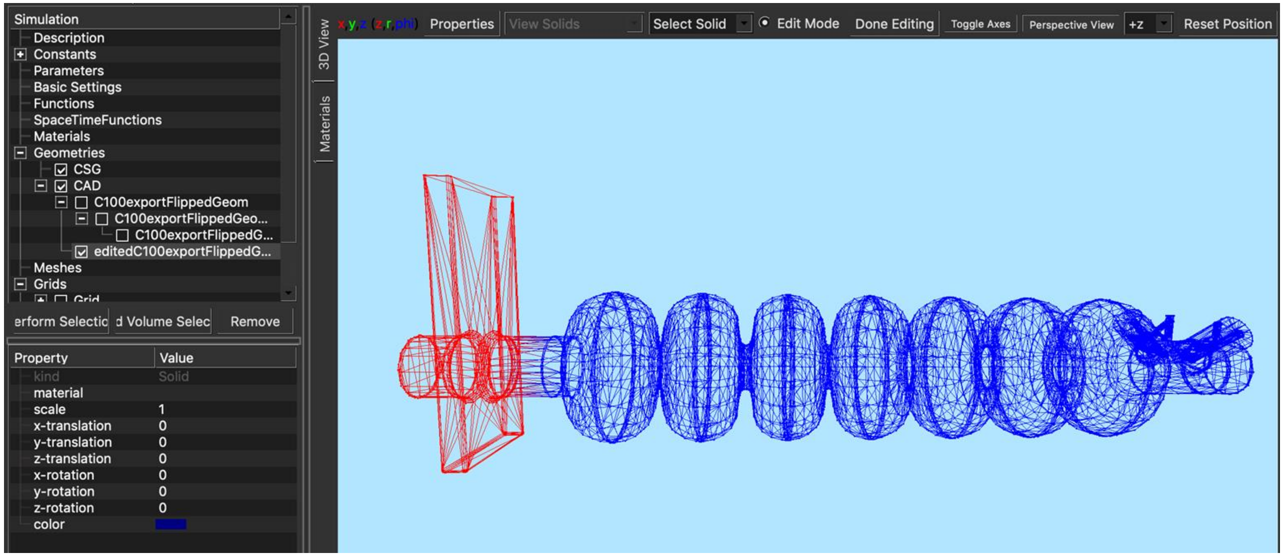
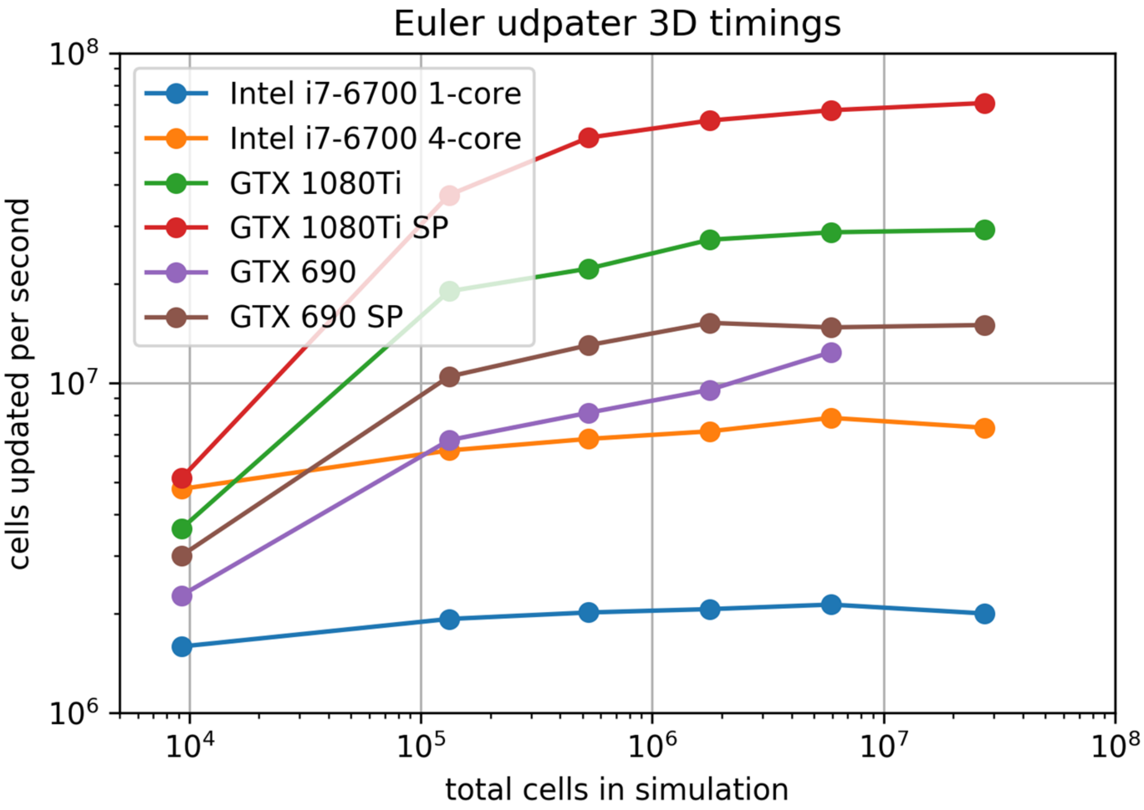


Property	Value
kind	Solid
material	
scale	1
x-translation	0
y-translation	0
z-translation	0
x-rotation	0
y-rotation	0
z-rotation	0
color	🟦

Euler fluid timings

We see considerable speedup using GPUs for our fluid solve



Plasma ignition simulation: Assumptions

- Cavity is large (1m long) with 3D geometry means grid is too big for quick simulation because we must resolve Debye length (~1e-5m) and mean free path
- Let's assume the following:
  - Walls do not play a large role in initial ionization cascade
  - Set of important reactions includes direct ionization, multi-step (metastable) ionization, recombination, inelastic scattering
  - Ionization cascade will result in exponential increase in ions/electrons
- Simulation is periodic box with homogenous E-field oscillating at f=1.91GHz for the 2pi/7 mode (compare with experiment)

Plasma ignition simulation: Converting from E to P

- In simulation we control electric field, *E*, but need to compare to experimental value of input power, *P*
- Steps:
  - Equation: $P = \frac{f_0 U}{Q} = \frac{f_0 \epsilon_0 \langle E \rangle^2 V}{2Q}$
  - Power conversion requires *Q* of cavity. Use data from Tom Powers (*Q* = 931 for $2\pi/7$ mode)
  - Run EM simulation of SRF cavity to get ratio of E_{max} to average field, $\langle E \rangle$, because E_{max} is where ionization will occur ($17.2\,\times$)