Modeling Plasma Discharge Cleaning of SRF Cavities

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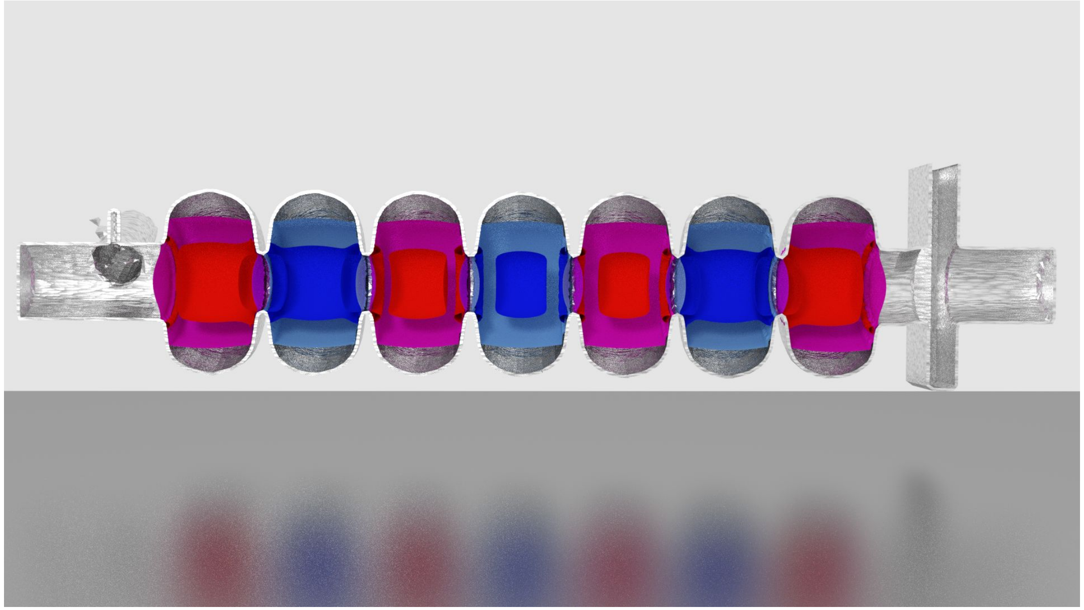
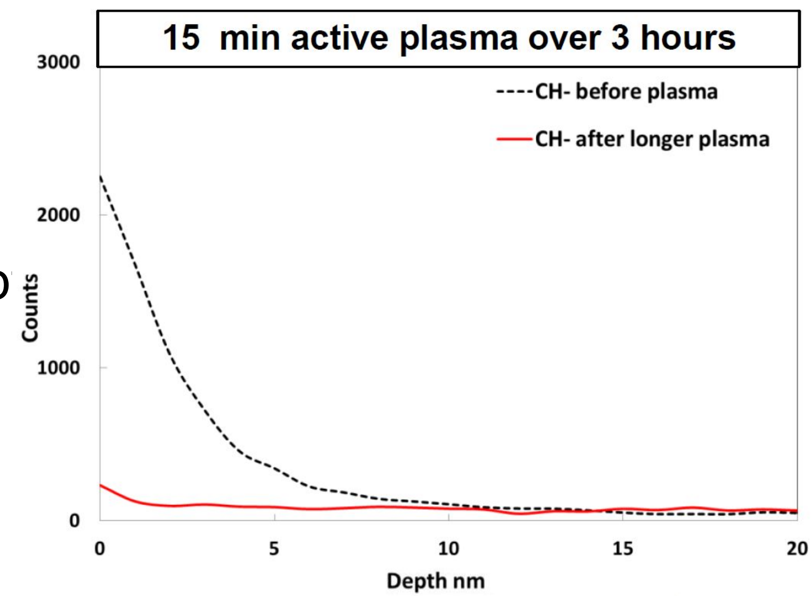
Overview

- Introduction to SRF cavities
- Electromagnetic simulation
  - EM modes
- Kinetic plasma simulation
  - Ionization cascade
  - Ionization threshold
- Hybrid model
  - Description
  - Benchmarking
- Other accomplishments



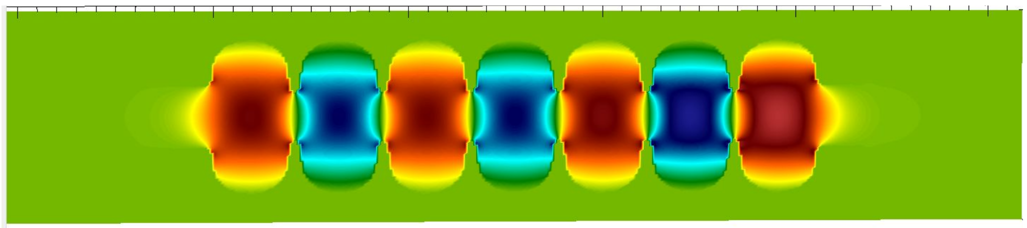
Introduction

- 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



Electromagnetic simulation: Introduction

- Confirm that VSim can get the same result as CST for resonant electromagnetic modes in the C100 cavity
- Pi-mode is the accelerating mode where each cell of the cavity has an alternating sign of axial magnetic field



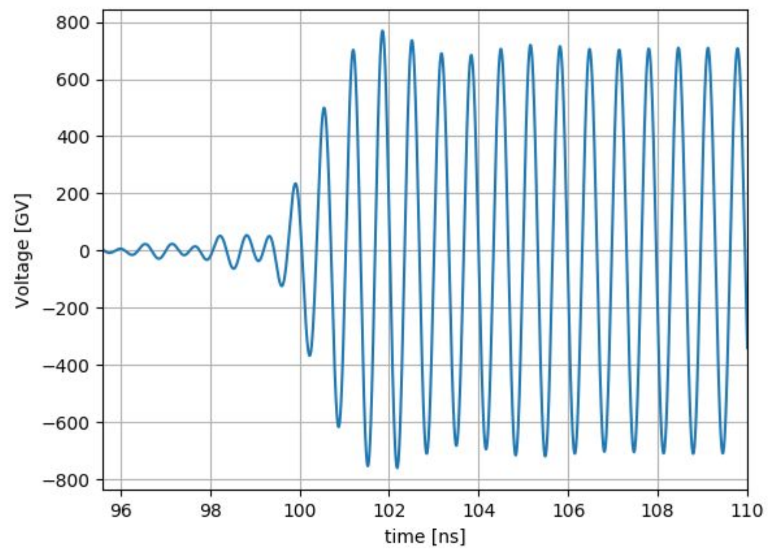
- We are looking for the pi-mode frequency – C100 cavity designed for this to be 1.497GHz
- How do we set up the problem in VSim?

Electromagnetic simulation: Running

- Run long enough for the cavity to ring up and back down (ie. in this case more than 150ns)

- After current density source is gone, cavity will still continue to ring at the frequency of the resonant modes

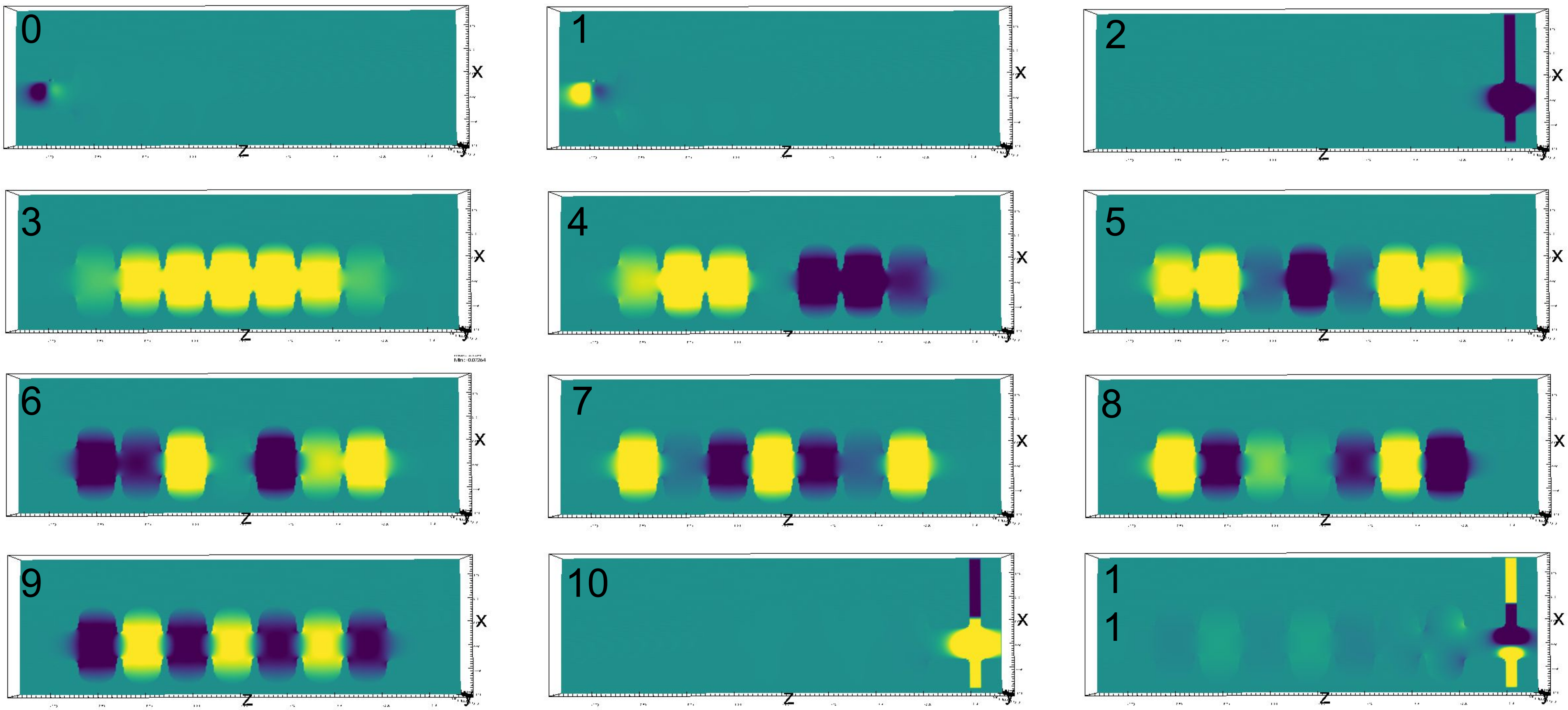
- Simple analysis – Fourier transform resulting signal and look at peak frequency to find dominant mode



- But we can do better!

Electromagnetic simulation: Extract Modes

- Structures for all the found modes:



Electromagnetic simulation: Pi-Mode

- Mode 9 is the pi-mode:

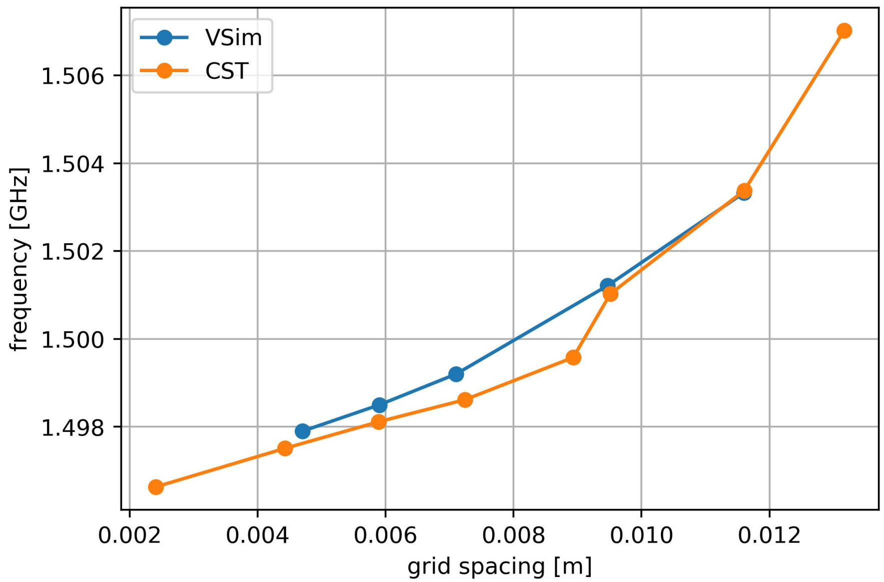
Mode	f_r (Hz)	f_i (Hz)	lam_vac (m)	cont	rel-err	abs-err
9	1.495699e+09	-0.000000e+00	2.004363e-01	4.03e-02	3.56e-09	1.43e-10

- 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



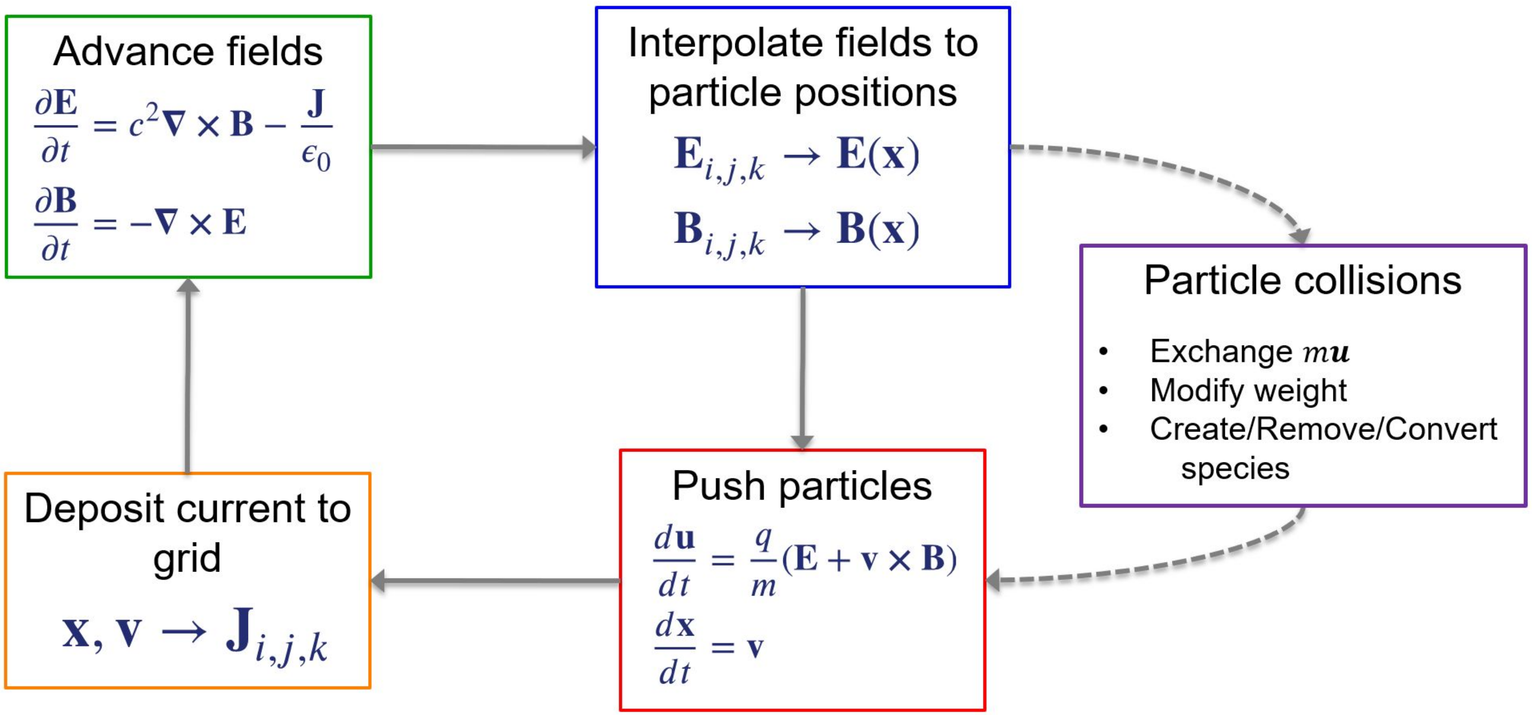
Plasma simulation: Introduction

- 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

Particle-in-cell: Introduction

VSim is an electromagnetic PIC code

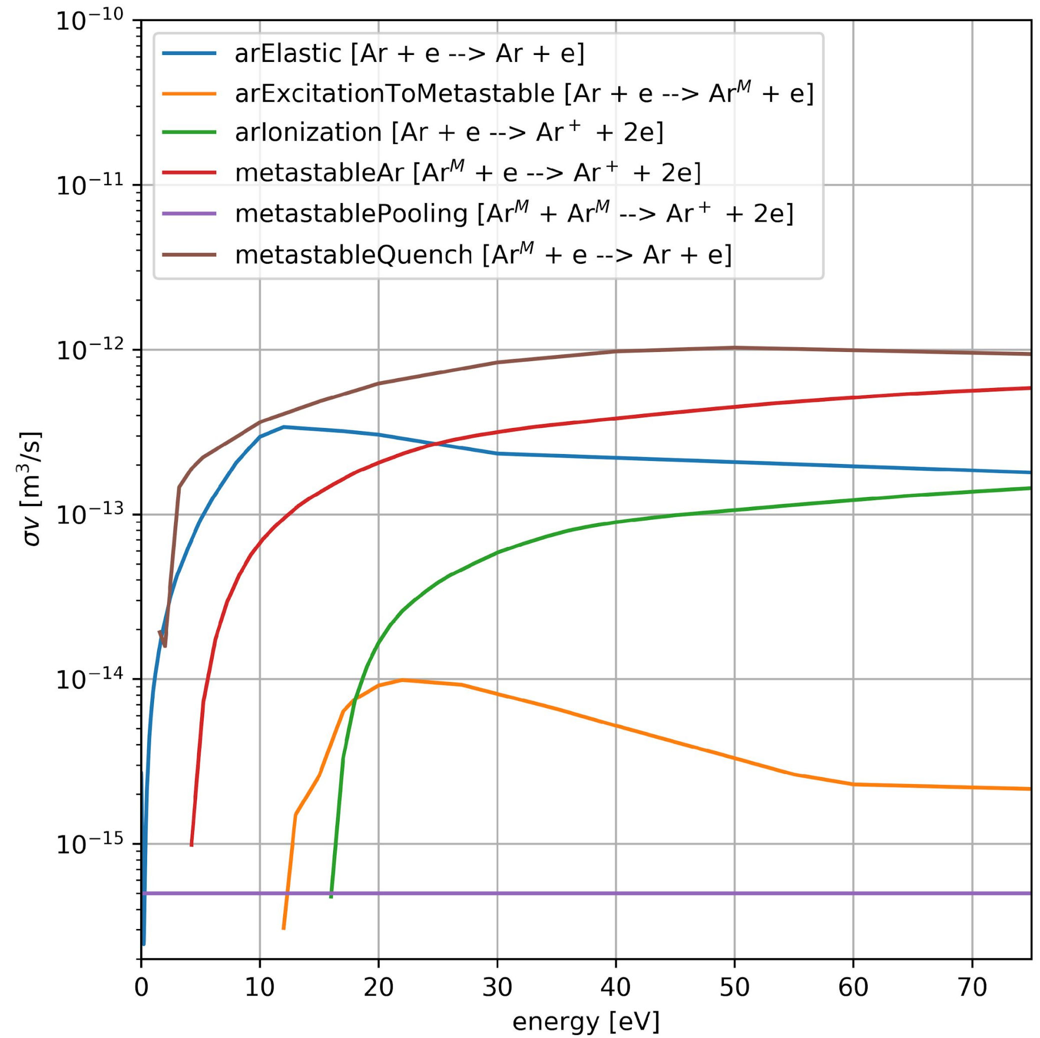


Plasma ignition simulation: Assumptions

- 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

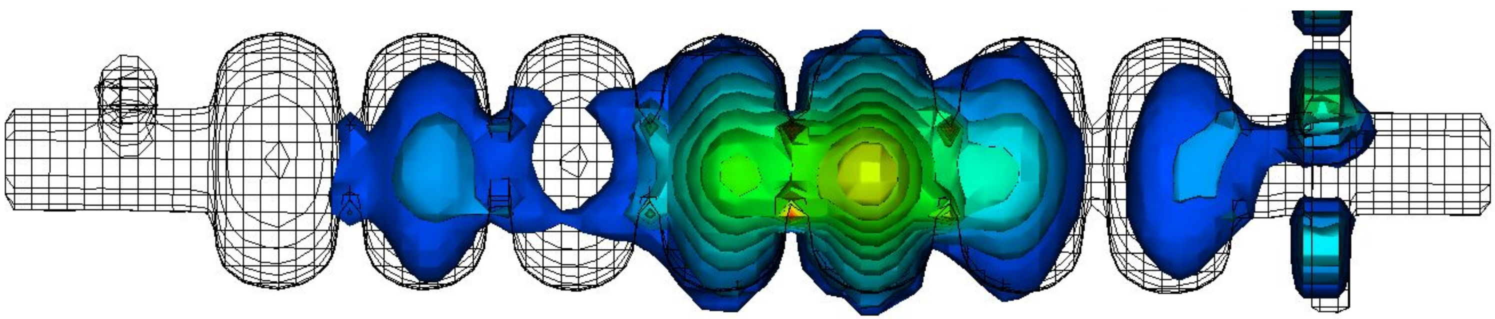
Plasma ignition simulation: collision cross-sections

- Cross-sections found in literature for all reactions thought to be important for ionization cascade/plasma formation
- It turns out that the metastable reactions are not significant in the regimes of interest



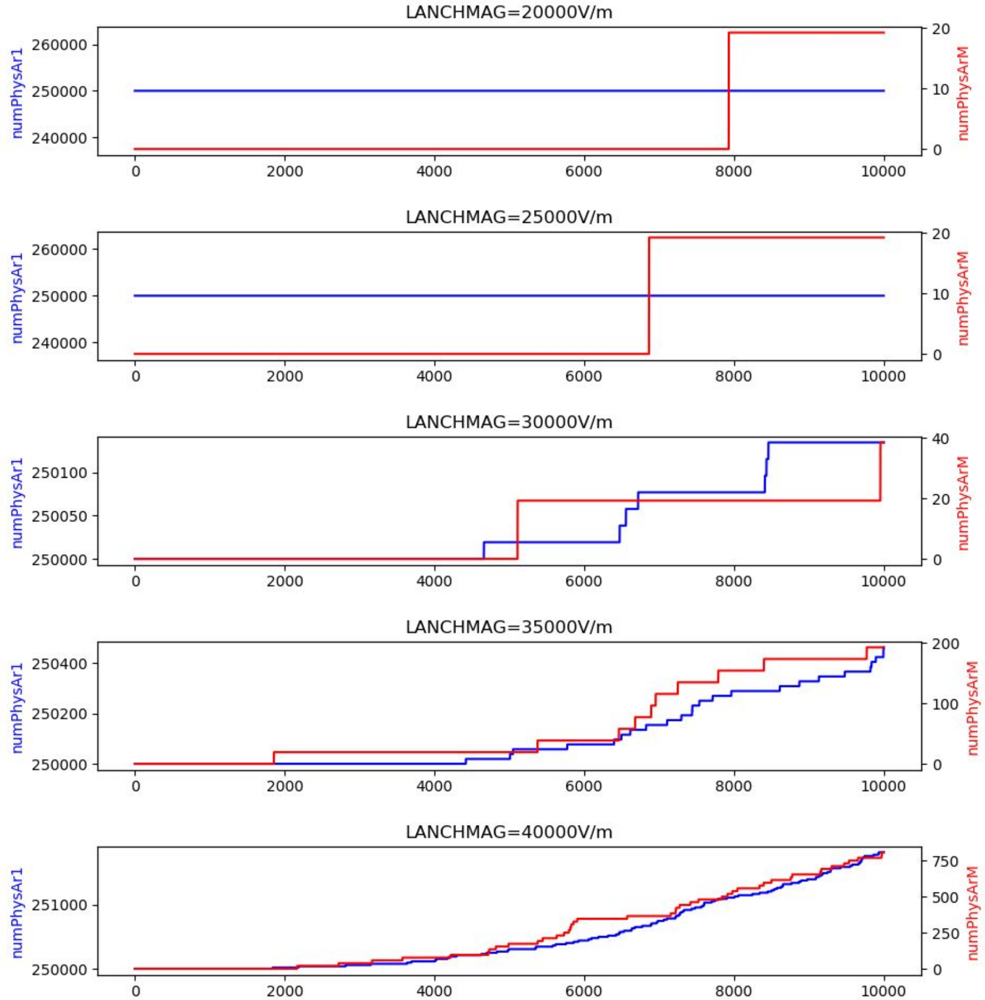
Plasma ignition simulation: Converting from E to P

- 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 ($17.2\times$)



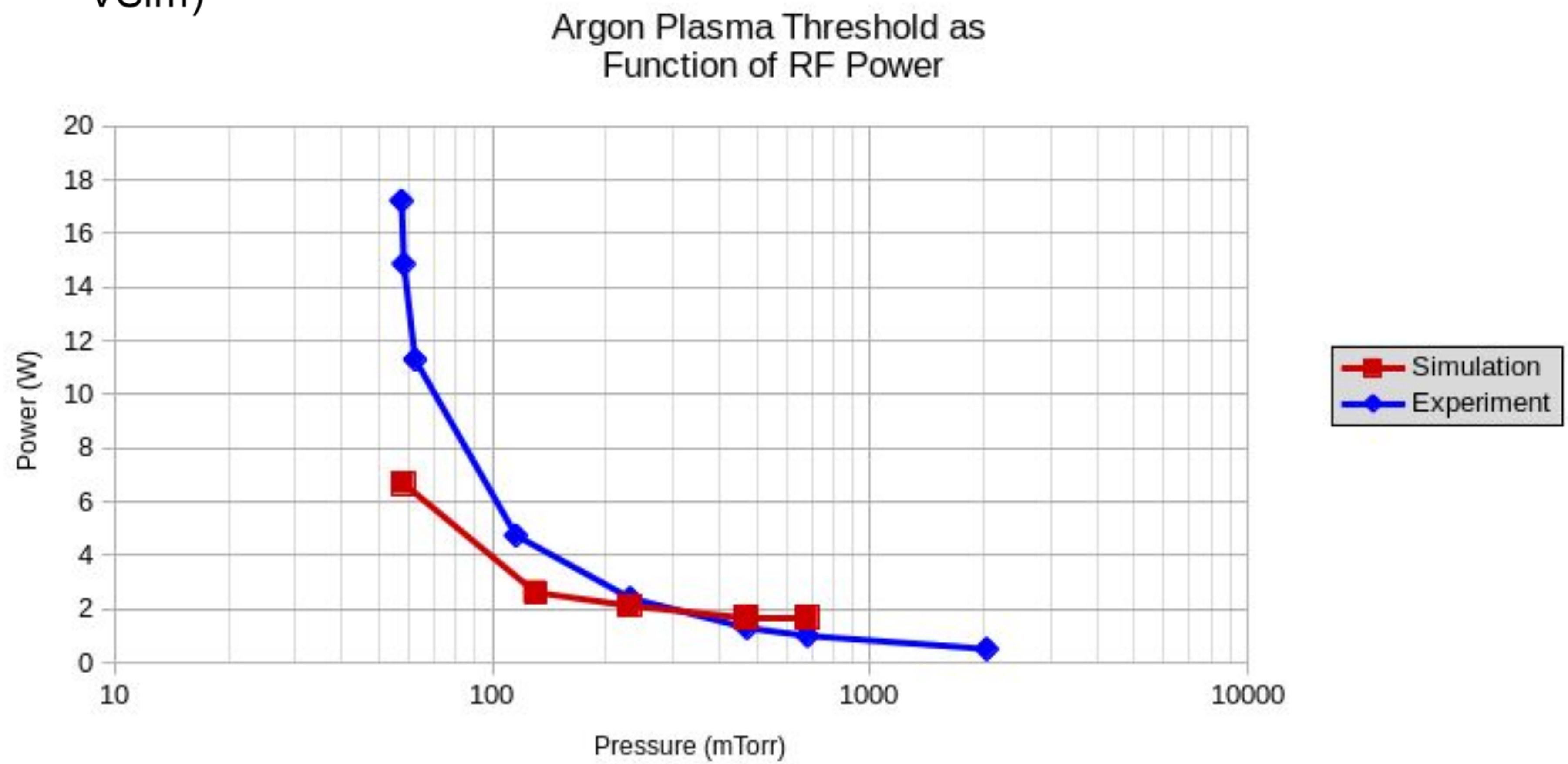
Plasma ignition simulation: Power Threshold Determination

- 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)



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 Ohms Law

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

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

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

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

Hybrid Plasma Simulation Benchmarks

- We are currently developing the hybrid model implementation, and have been simultaneously working on benchmarks for when it is finished

- These benchmarks will be able to assess the accuracy and speed of the algorithm

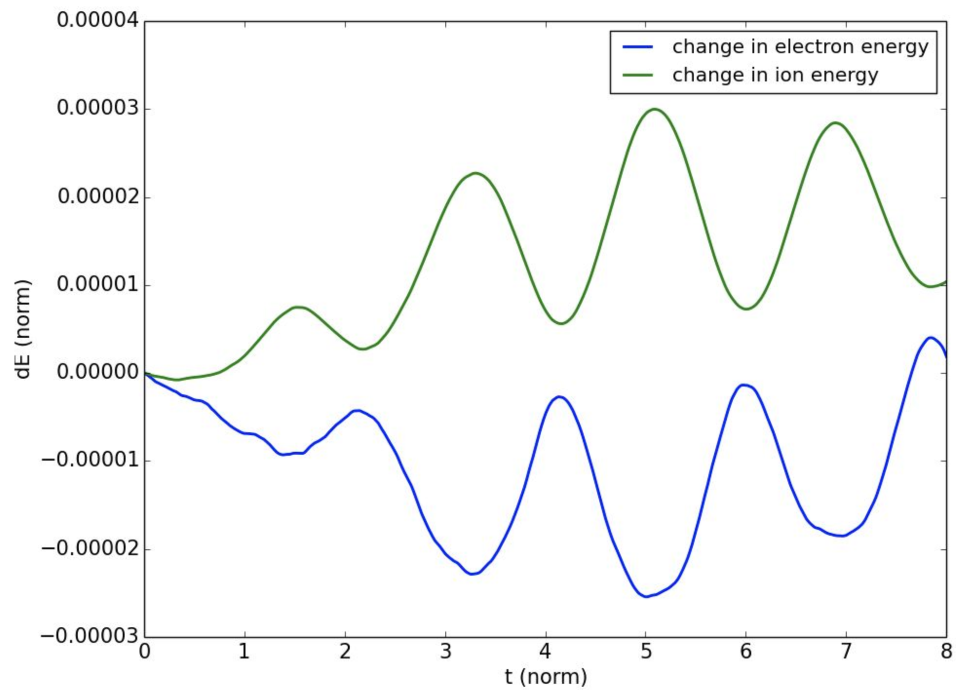
- We have chose 2 physics problems, each of which will be simulated with full fluids (eg. MHD), full kinetic (PIC), and hybrid
  - Landau damping of ion acoustic wave: fluids should give wrong answer, hybrid and kinetic should give correct answer
  - GEM problem (reconnection): fluids can give close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

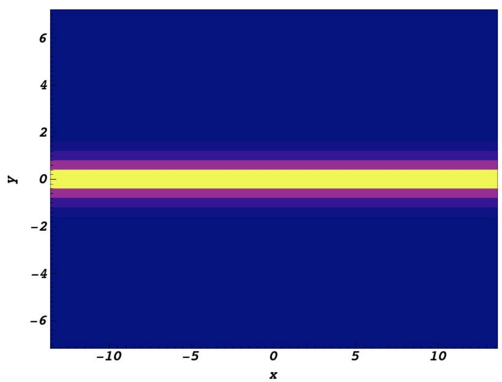
Our full kinetic model



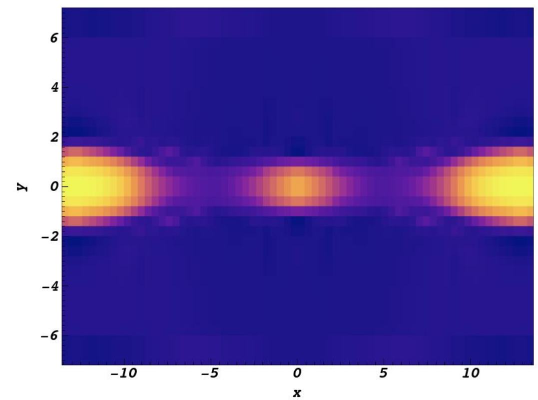
- We developed such a full kinetic model as a benchmark for our hybrid model; this will allow timing benchmarks of hybrid speedup

Test #2: extended MHD models of magnetic reconnection

Initial density



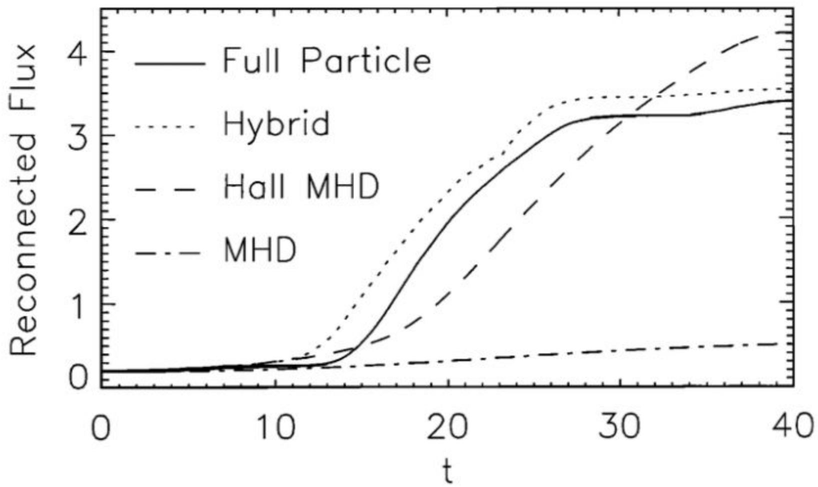
Density after reconnection



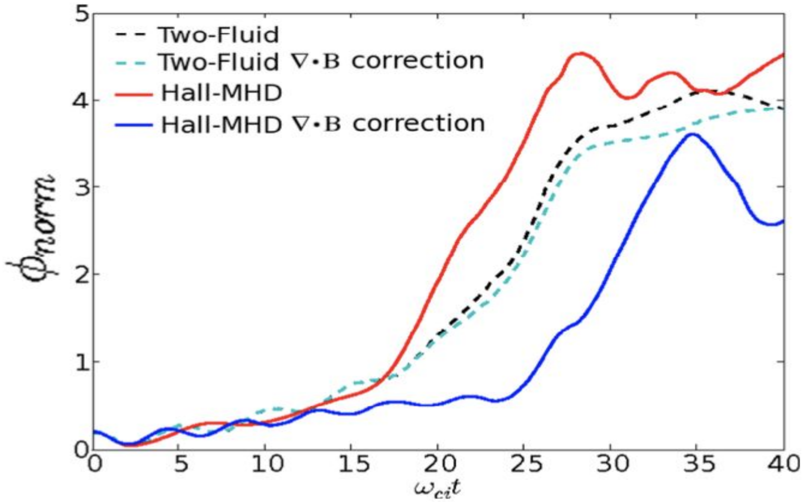
- Another standard test of hybrid models is magnetic reconnection
- In this test, the initial condition is a current sheet directed out of the plane
- Ideal fluid models will hold this initial condition indefinitely
- However, realistic (non-ideal) effects such as resistivity and charge separation will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

Test #2: extended MHD models of magnetic reconnection

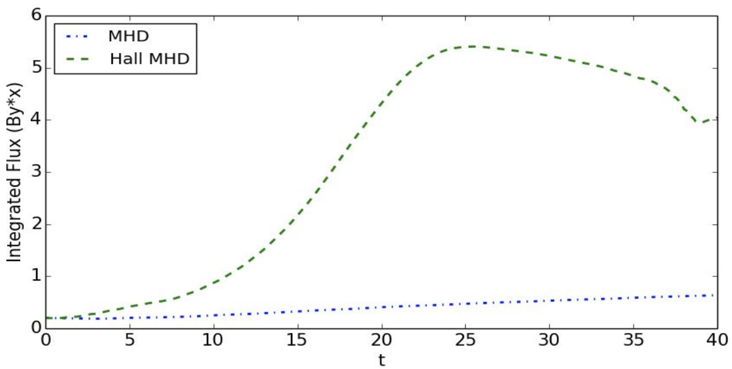
Birn '01



Srinivasan '11



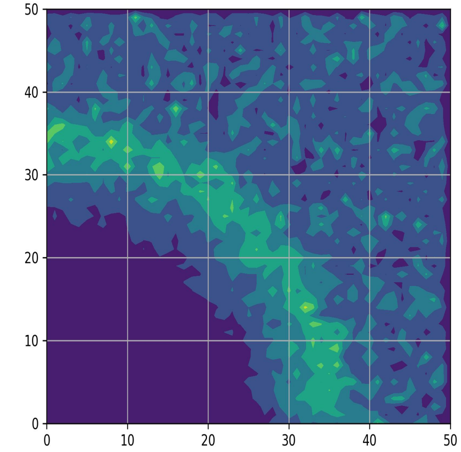
Our work



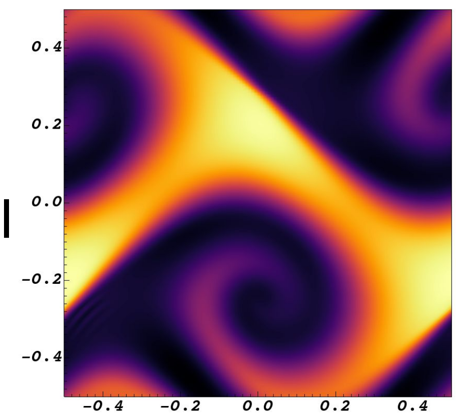
- We have reproduced several advanced fluid models of magnetic reconnection
- Next steps are to benchmark our hybrid models on this same set of initial conditions

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 (neutral fluid)



  - Market research and analysis of potential customers

Thank you!

Questions?

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