Recent Progress of High Harmonic Fast Wave (HHFW) Project in Collaboration with PPPL*

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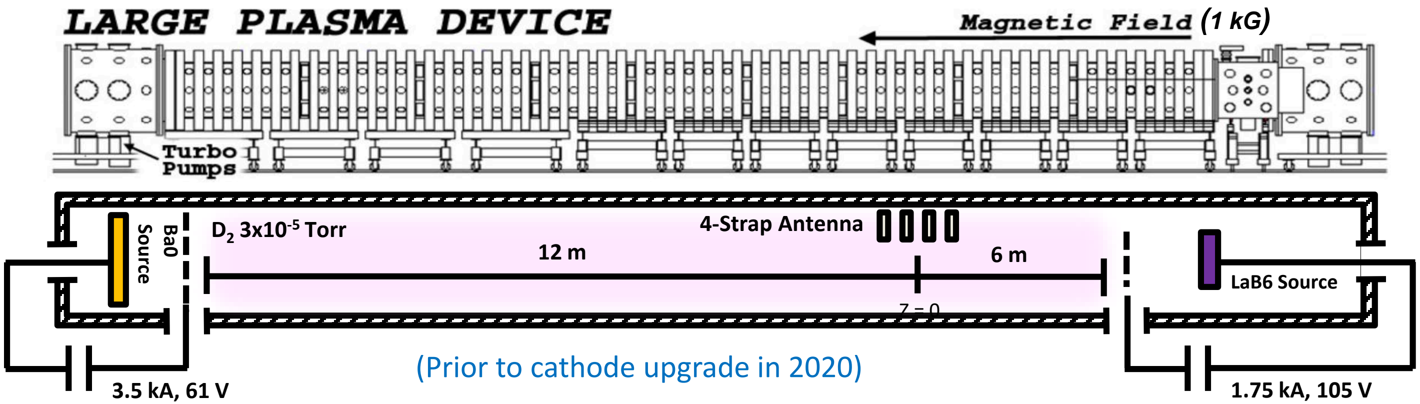
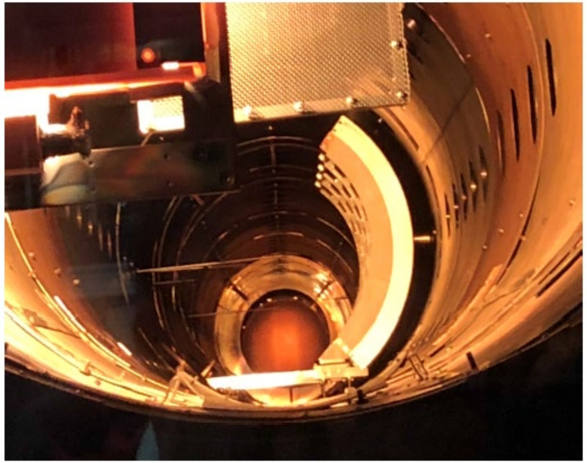
Motivation and Strategic Plans

- Why do we use HHFW electron heating? – Simulation survey demonstrates that HHFW is a promising electron heating scenario for FRC plasma
  - ➢ Has excellent wave penetration into FRC plasma core; doesn't suffer from a cut-off at high density.
  - ➢ Has near 100% single pass power absorption; bulk electrons heating.
  - ➢ Control RF power partition between electrons and ions through antenna relative phasing;
  - ➢ Decouple heating and fueling, help enhance NBI heating and current drive.
- Use LAPD facility at UCLA as the test bed to conduct following crucial studies
  - ❑ HHFWs to plasma coupling and propagation (phased-array 4-strap RF antenna)
  - ❑ Model validation: benchmarking Petra-M full wave code with experiment measurements
- Collaborate with PPPL to develop HHFW as an enabling electron heating actuator
  - ❖ Perform HHFW simulations in FRC plasma by using Petra-M full wave code and phased-array RF antenna
  - ❖ Optimize high power enabling HHFW antenna configuration for beam-driven C-2W FRC device
  - ❖ May utilize the HHFW engineering and simulation tools developed at PPPL to design 4 MW HHFW system

RF System Setup



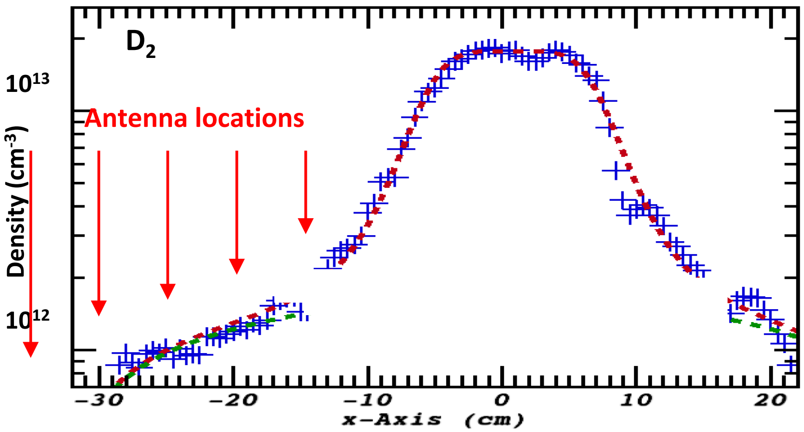


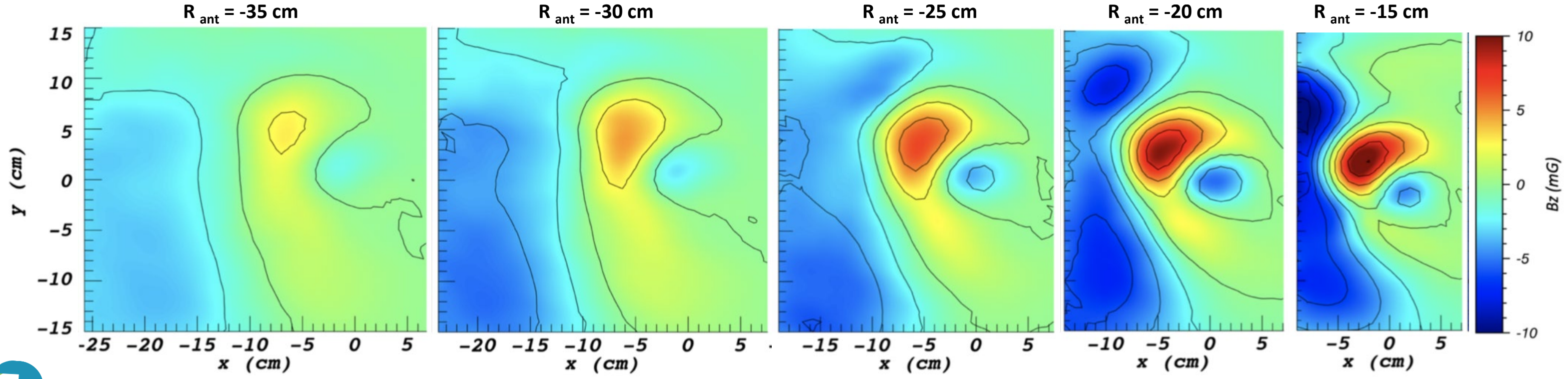
- 4-strap antenna with different relative phase (180^0, 90^0, 60^0, 45^0, 30^0) between straps
- 4 broadband (1 MHz – 35 MHz) RF amplifiers with output power at 400 W each unit
- Antenna (position of antenna front surface is movable from r = 35 cm inward up to r = 15 cm
- B_0 = 1000 G, f = 10 MHz in this RF campaign
- Forward and reflected RF power are measured by directional couplers

Efficient Fast Wave Coupling at All Phases Has Been Achieved

- Fast wave coupling (for all phases) increases as antenna approaches denser plasma
- Fast wave can couple into plasma core even when antenna close to the wall, where $n_e < 1 \times 10^{12}$ cm^{-3}
- Fast wave propagation direction is well controlled by relative phase between antenna straps
- No slow wave has been observed, in good agreement with calculations of fast wave dispersion relation

Prior to cathode upgrade in 2020

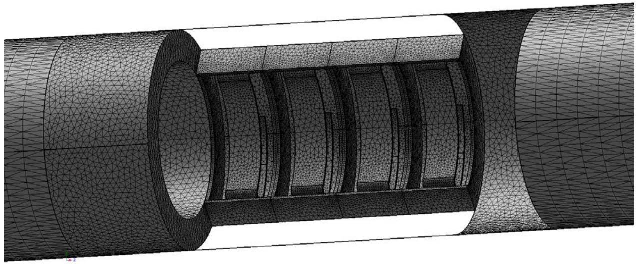


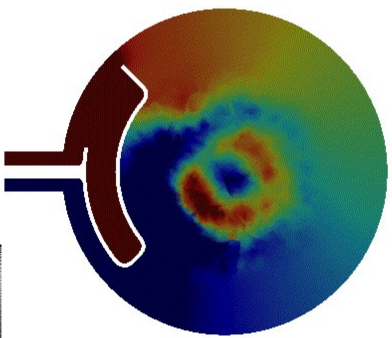


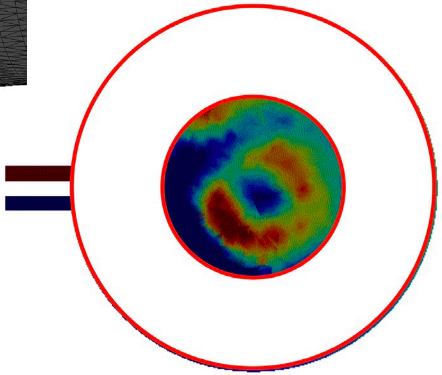
180⁰ phasing

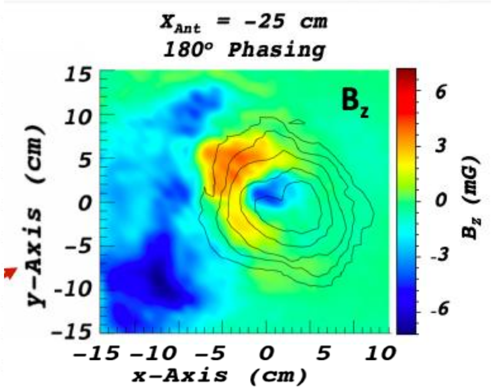
Qualitative Agreement between Initial Simulations and Experimental Data

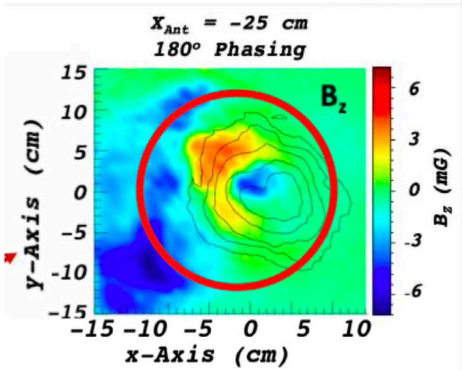
3D mesh generated for the 4-strap HHFW antenna and LAPD



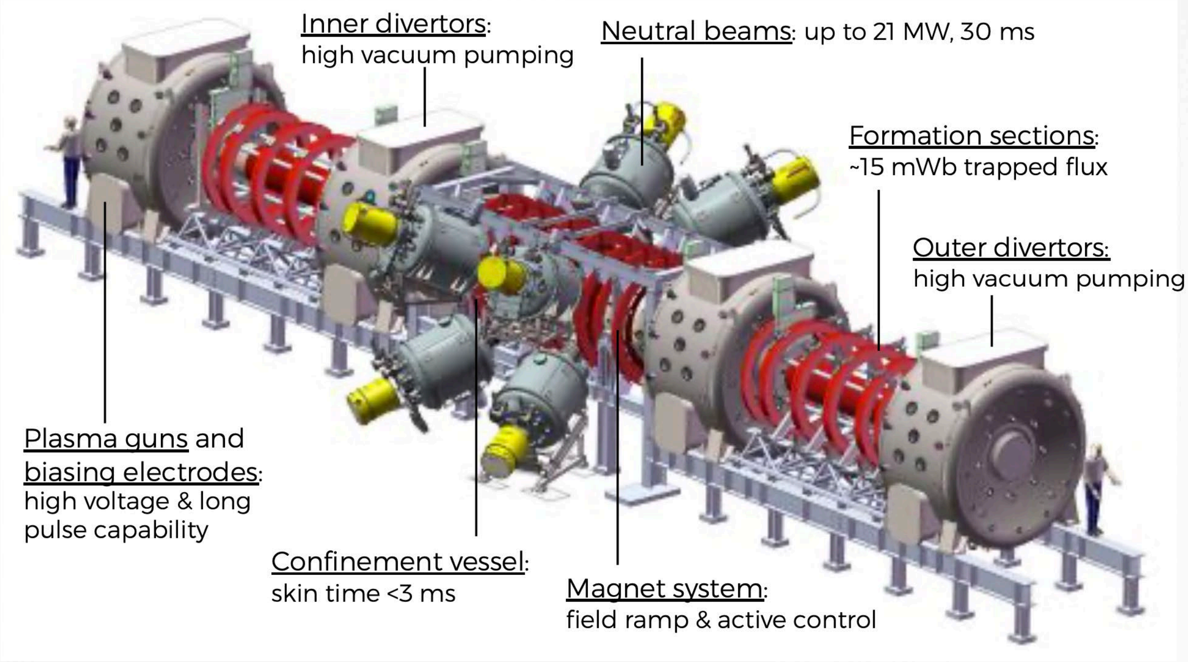








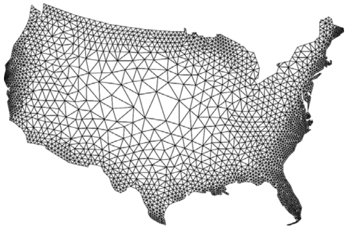
Norman – an Advanced Beam-Driven FRC Plasma Device



Parameter	Value
B_{ext}	~ 0.1 – 0.3 T
r_s	~ 40
L_s	2 – 3 m
n_e	$(1 - 3)\times10^{19}$ m^{-3}
$T_{tot} = T_i + T_e$	up to 3 keV
Pulse length (ms)	up to 30

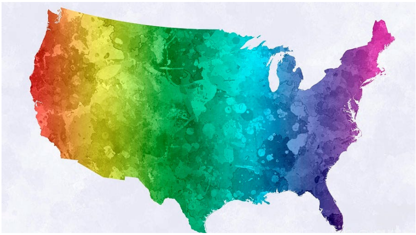
Petra-M: integrated multi-physics FEM platform

- Geometry/mesh generation
  - Utilize GMSH / Open CASCADE
- FEM assembly and solve
  - FEM interfaces from MFEM
  - Tightly integrated with πScope Python workbench
  - RF Physics module (1D/2D/3D)
  - Weakform module
    - Multiphysics coupling
- Solver/Post-processing
  - Steady State and Time dependent solver
  - MUMPS/Strumpack direct solver
  - Hypre iterative solvers
  - Visualization on πScope
- Scales from laptop to cluster



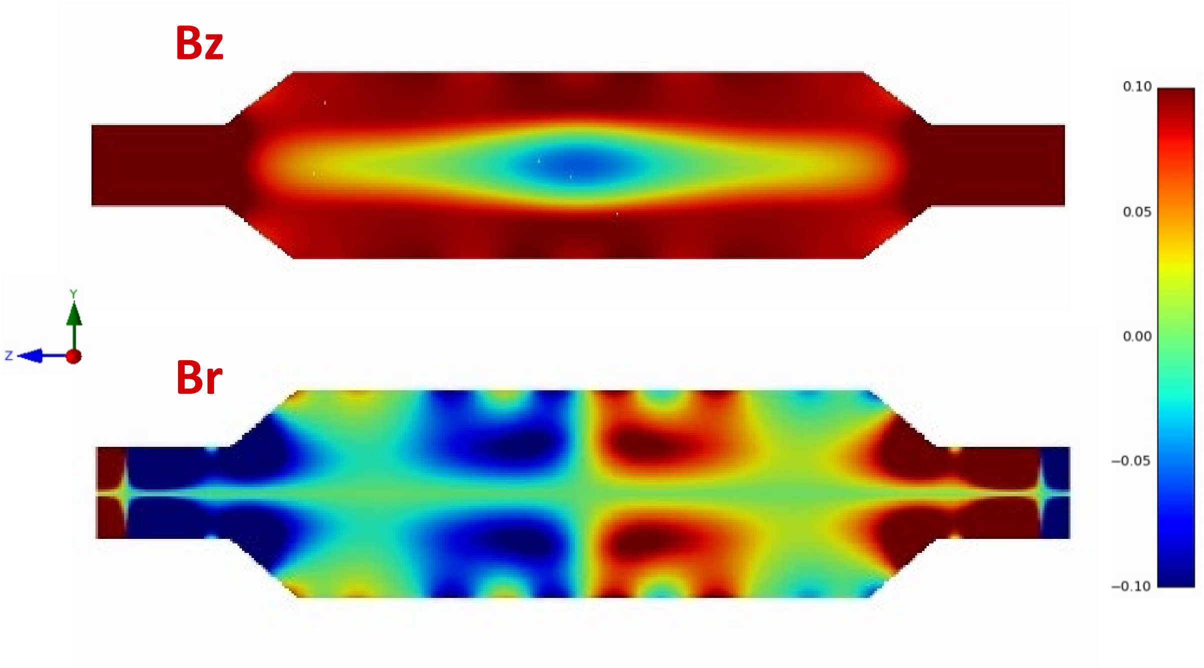
PDEs

(this work: inhomogeneous Maxwell eq. in 3D in frequency domain)



[Shiraiwa et al, EPJ Web of Conf. **157**, 03048 (2017),
N. Bertelli et al,. AIP Conf. Proc. **2254**, 030001 (2020)]

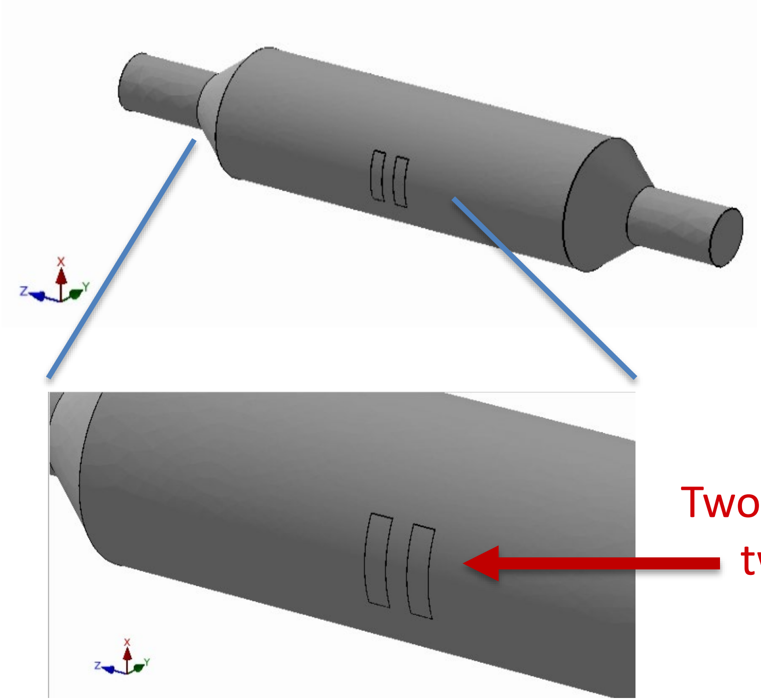
Magnetic field equilibrium obtained by the LR_eqMI code



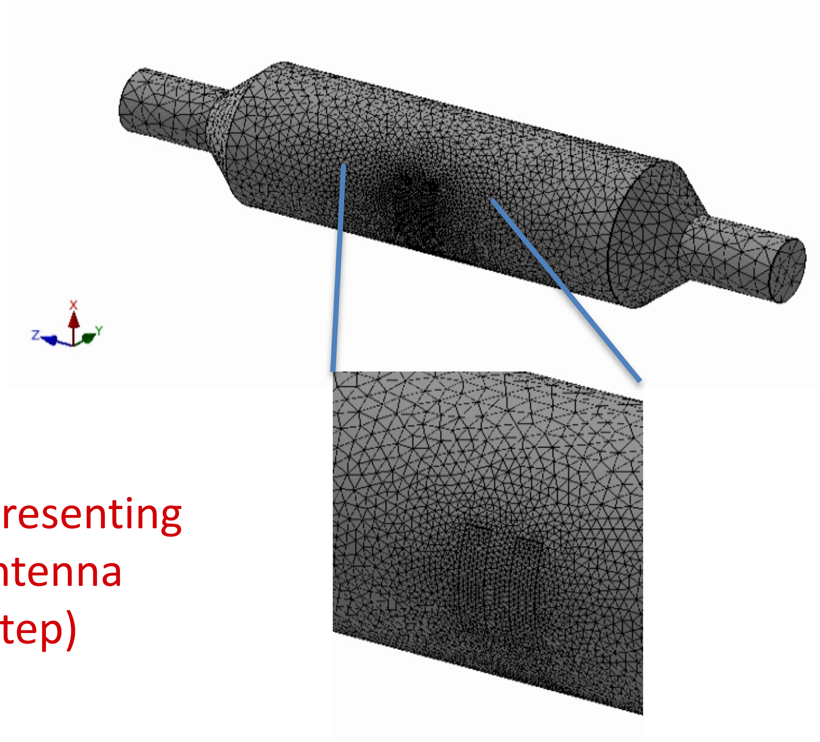
Generated a 3D geometry from this shape (next slide)

[Galeotti et al, Plasmas 18, 082509 (2011)]

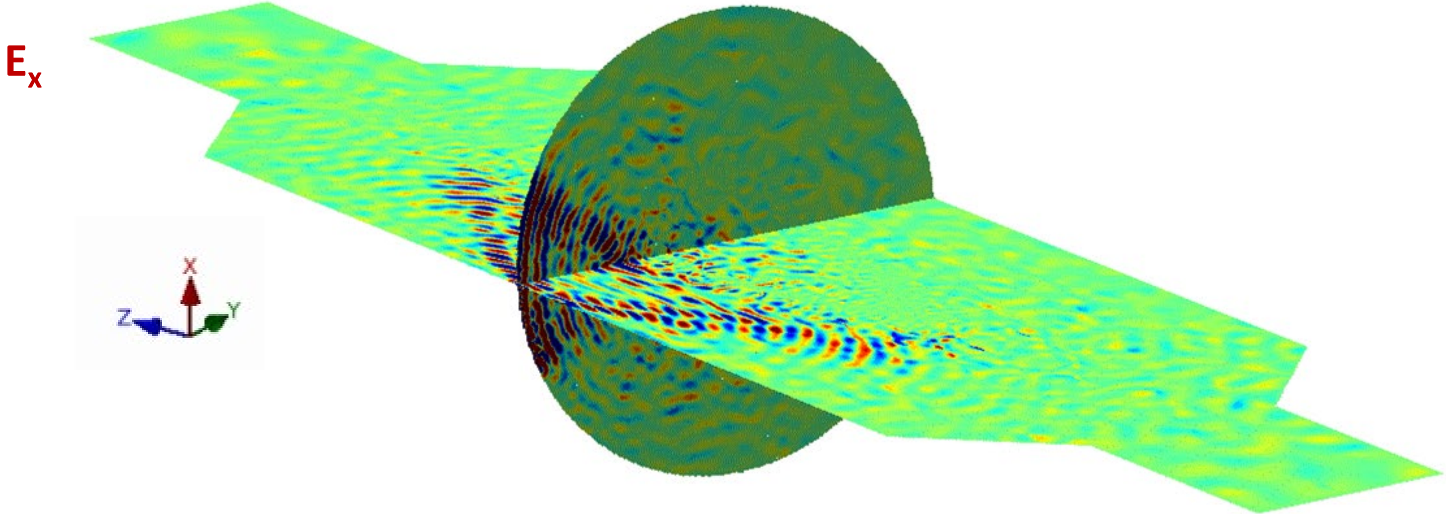
Create a 3D geometry and mesh



Two regions representing two straps antenna (as initial step)

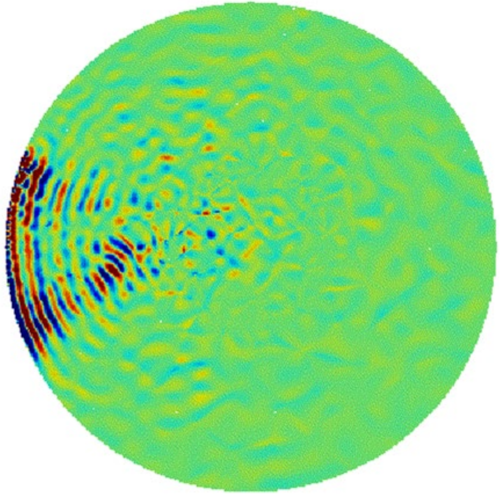


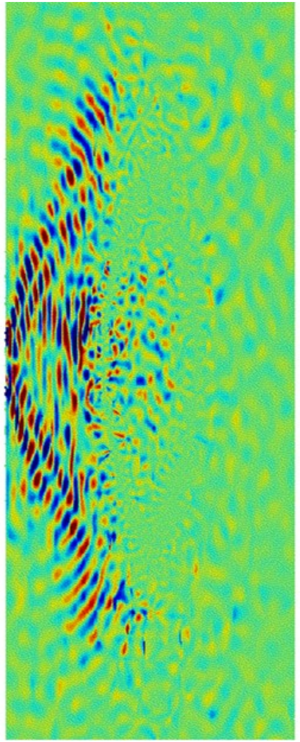
3D full-wave simulations



- Surface J boundary conditions representing the antenna
- frequency = 8 MHz, 180-degree antenna phasing
- Electron density = constant = 2 x 10^{19} m^{-3}
- Anisotropic cold plasma in the torus with artificial collisions

3D full-wave simulations





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Conclusions

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Future steps:

- Investigate the impact of electron density and simplified strap antenna in the RF modeling
- Consider to have a more realistic antenna and device geometry

Acknowledgements

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- The experiments were performed at UCLA's Basic Plasma Science Facility, which is supported by US DoE, and the NSF.

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