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°, 90°, 60°, 45°, 30°) 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
- B₀ = 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
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

- **Inner divertors**: high vacuum pumping
- **Neutral beams**: up to 21 MW, 30 ms
- **Formation sections**: ~15 mWb trapped flux
- **Outer divertors**: high vacuum pumping
- **Plasma guns and biasing electrodes**: high voltage & long pulse capability
- **Confinement vessel**: skin time <3 ms
- **Magnet system**: field ramp & active control

Parameter | Value
--- | ---
$B_{\text{ext}}$ | $0.1 - 0.3$ T
$r_s$ | $40$
$L_s$ | $2 - 3$ m
$n_e$ | $(1 - 3) \times 10^{19}$ m$^{-3}$
$T_{\text{tot}} = T_i + T_e$ | 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

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 = $2 \times 10^{19}$ m$^{-3}$
- Anisotropic cold plasma in the torus with artificial collisions
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Conclusions

• 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

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
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