3D FEM RF code applications

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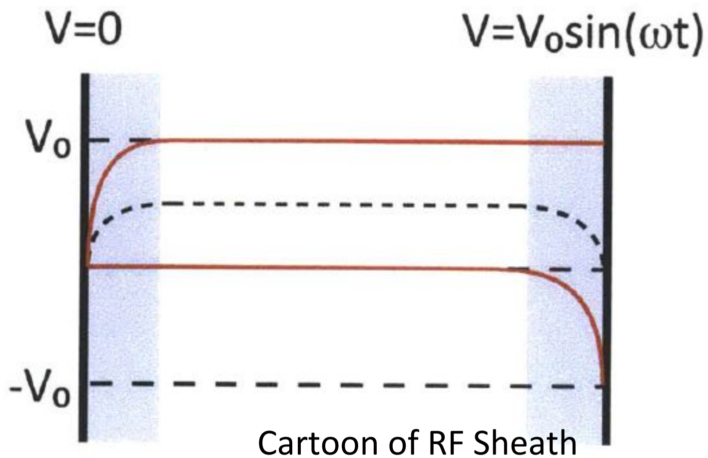
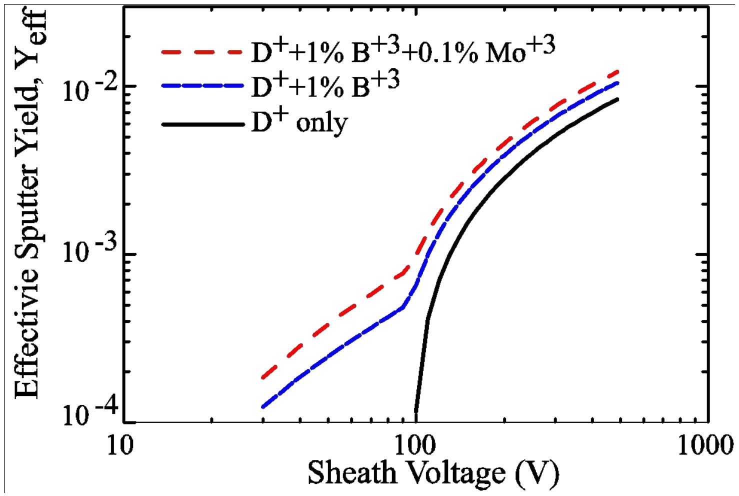
RF-SciDAC : Center for Simulation of Fusion Relevant RF Actuators
http://rfscidac4.org

LAPD RF campaign

- High level physics goals is to study RF wave physics relevant to fusion
  - ○ Validate linear RF physics in 3D antenna simulation
  - ○ Non-linear RF physics (RF sheaths, ponderomotive forces, turbulence etc.)
  - ○ Understanding novel RF antennas (TAE 4-strap, GA helicon antenna)
  - ○ Three ion heating and fast ions
- RF campaign expecting ~ 4 run weeks per year for 2019-2021
  - – Interest from GA, MIT, ORNL, PPPL, RMA, TAE
  - – Two weeks completed in 2019 (one week for non-linear RF physics, one week for linear coupling of TAE 4-strap antenna)
  - – Based on UCLA experiments in 2016-2018



Cartoon of RF Sheath
(M. Garrett 2012 MIT thesis)



Impurity Sputtering (Wukitch PoP2013)

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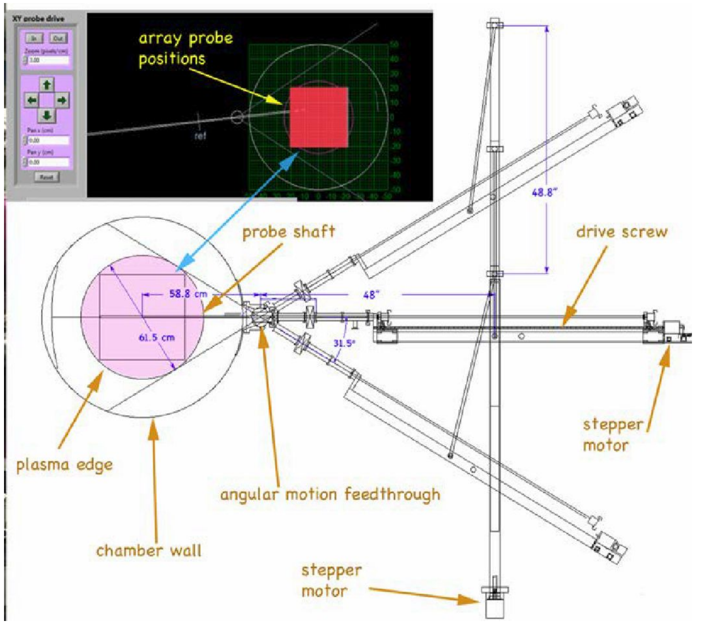
The LArge Plasma Device (LAPD) user facility at UCLA

- Solenoidal magnetic field, cathode discharge plasma (BaO and LaB_6)
- 17 m long, 60 cm diameter plasma
- n_e up to 10^{19} m^{-3}, T_e up to 10 eV
- B_0 up to 0.25 T, 10 separate power supplies
- 20 ms plasma, repetition rate of 1 Hz
- Available 2-D and 3-D probe drives
- 100 kW, 2.38 MHz, 1 ms pulse 1-strap antenna



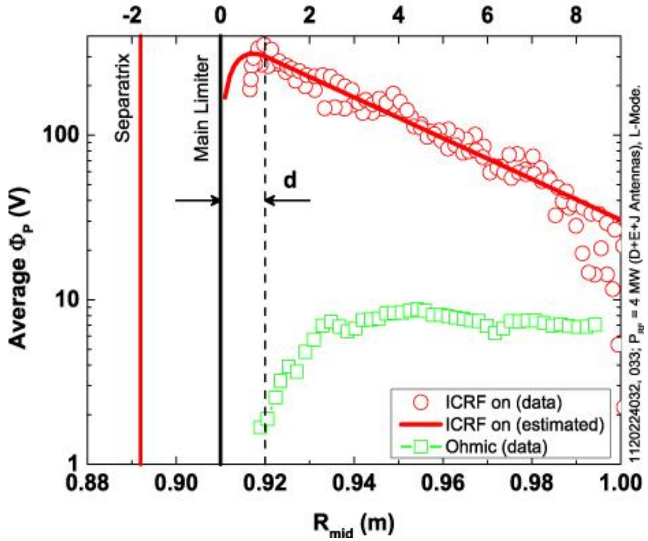
Why study RF physics on LAPD?

- Fusion devices are expensive and have limited runtime and diagnostic access

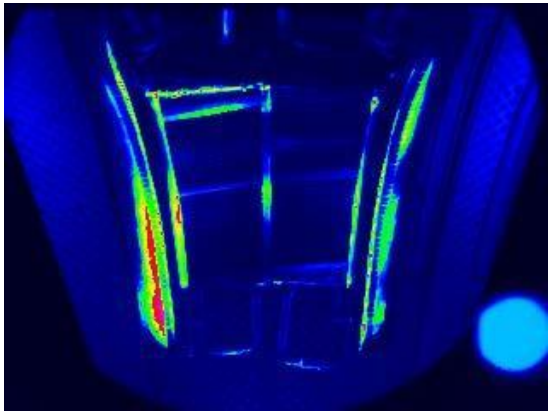
- Smaller devices can elucidate experimental data obtained on large fusion devices by simultaneously measuring local wave fields, density profiles etc… in 2D or even 3D.

- Devices such as LAPD can provide a clearer picture on part or all of these issues and provide a benchmark dataset for simulation codes/ theory development through a close collaboration with the fusion community.

- Recent simulation efforts aim to better incorporate near-field effects, e.g., RF sheath physics in realistic geometry



Emissive probe measurement on Alcator C-Mod (Ochoukov PPCF2013



IR camera image on Tore Supra RF antenna (Litaudon NF 2013)

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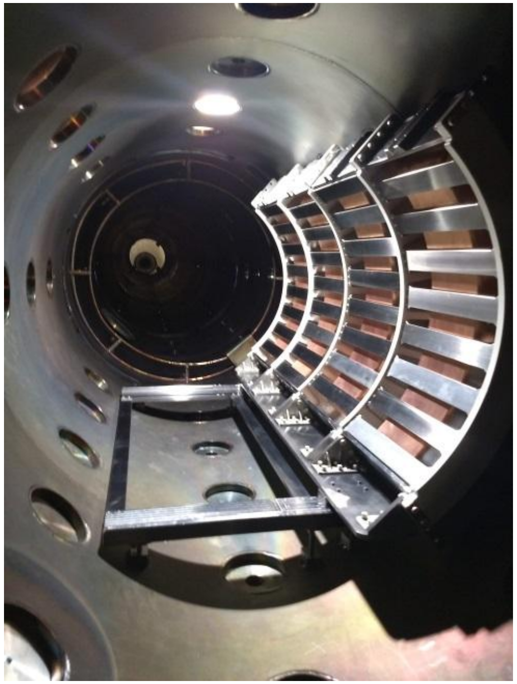
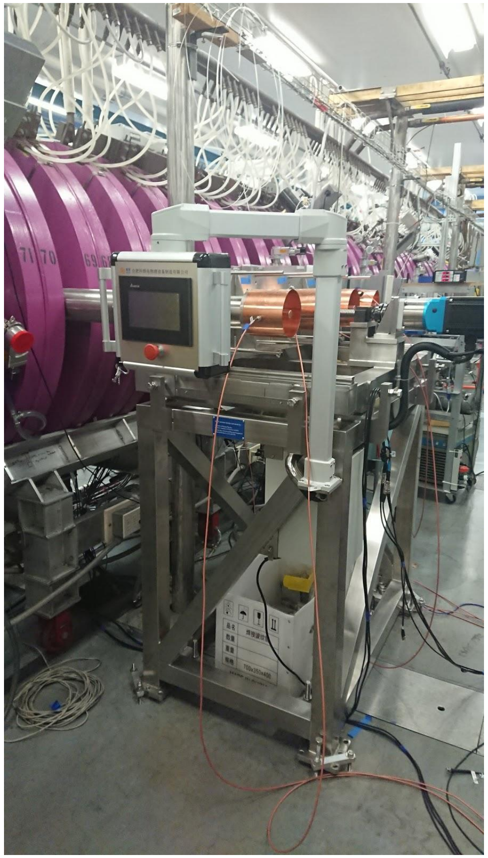
4-Strap HHFW antenna recently installed on LAPD by TAE Technologies





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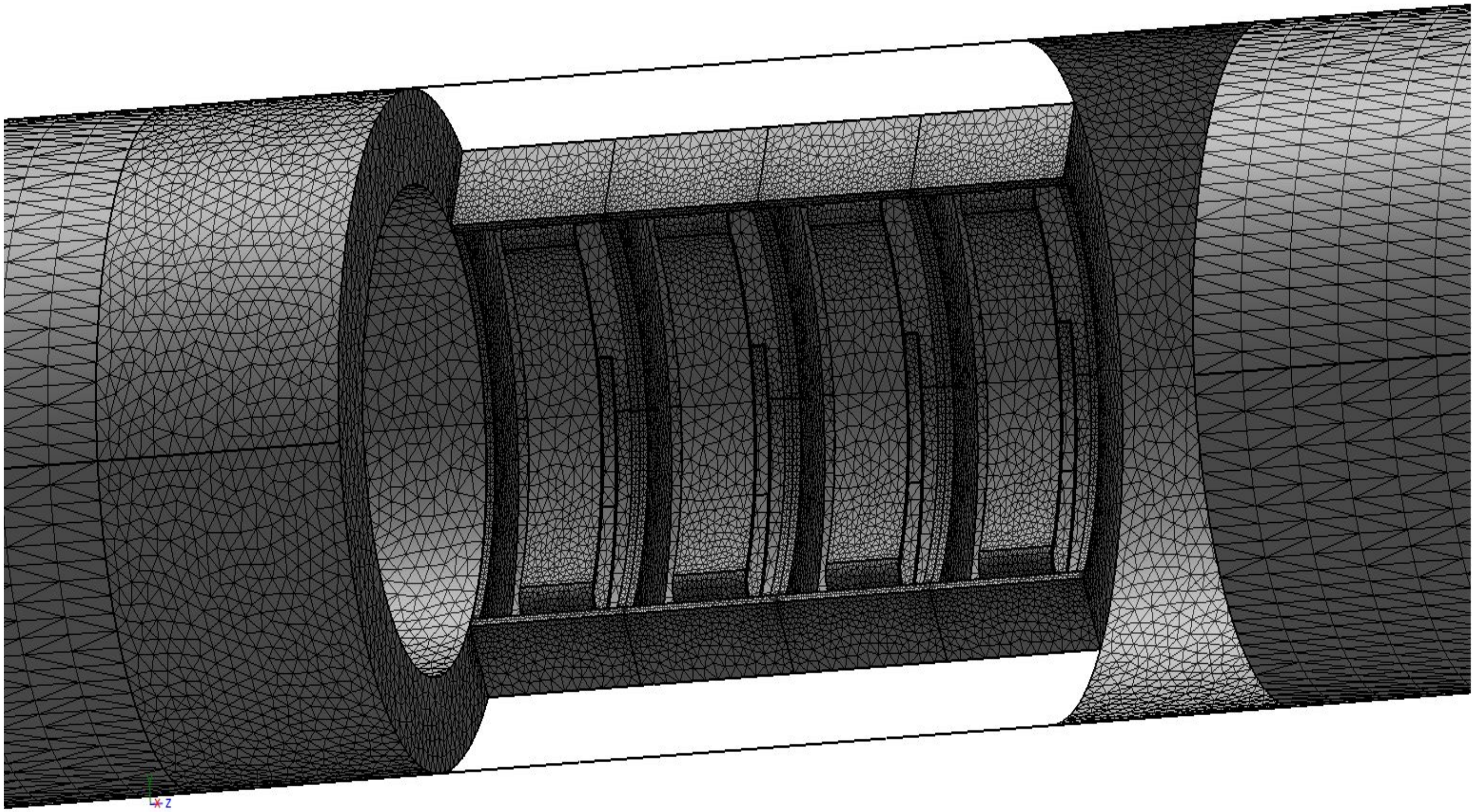
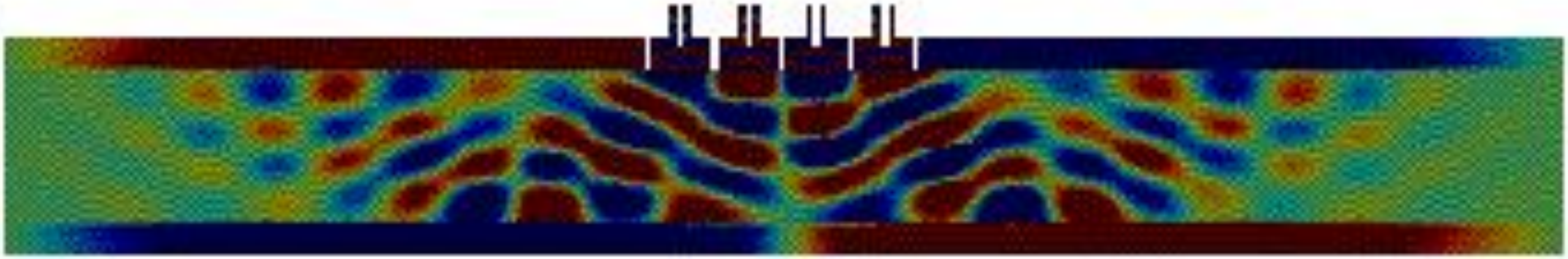
4-3D mesh generated for the 4-Strap HHFW antenna and LAPD



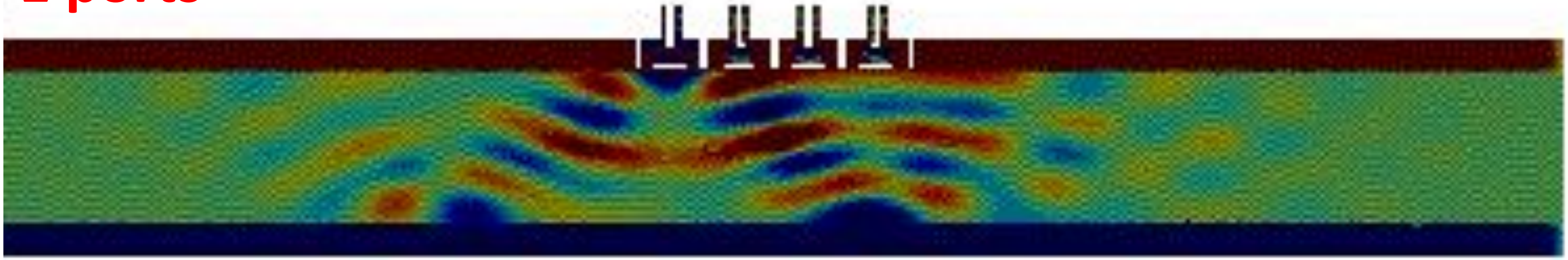
~18 m plasma column

3D simulations of HHFW 4-straps antenna

4 ports



1 ports



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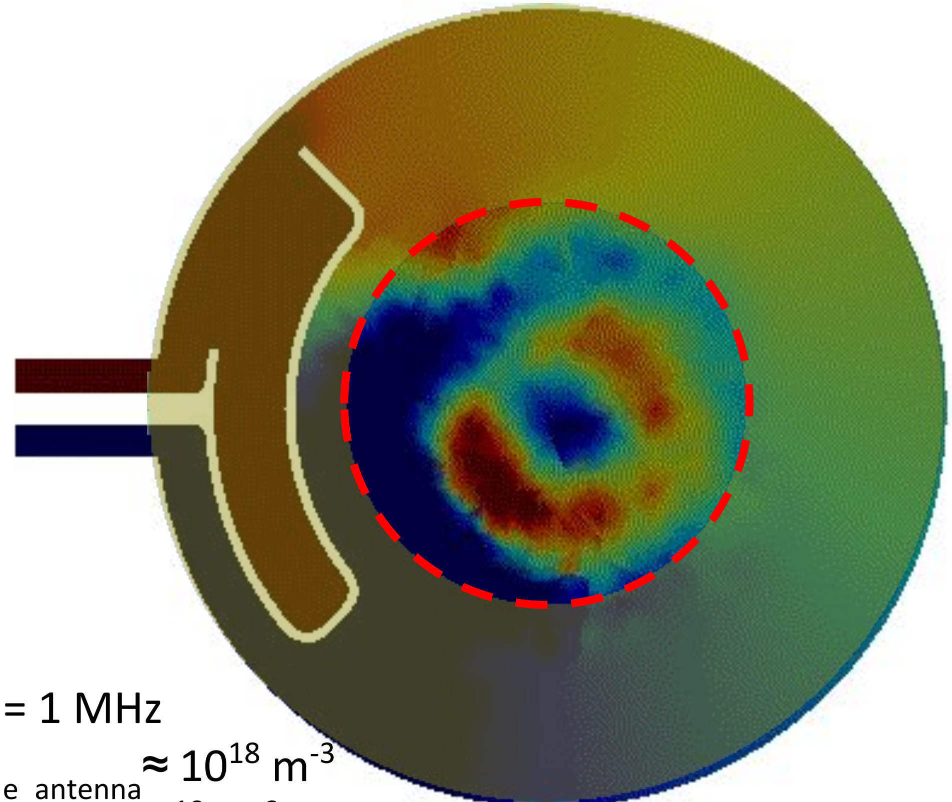
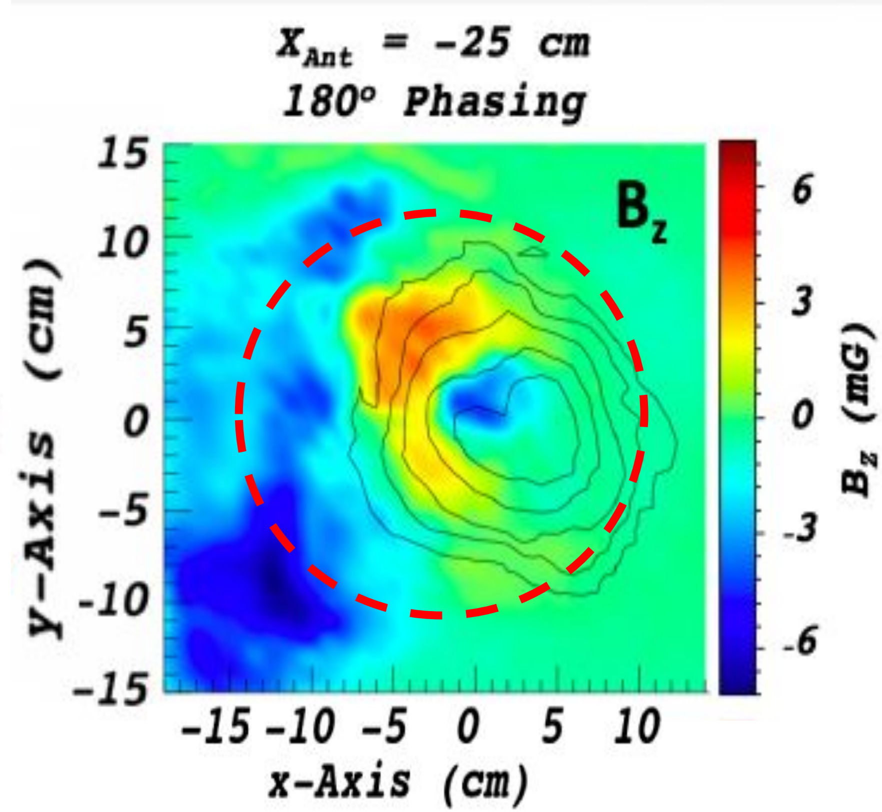
Qualitative agreement between initial simulations and experimental data



f = 1 MHz

$n_{e\_antenna} \approx 10^{18}$ m^{-3}

$n_{e0} \approx 2x10^{19}$ m^{-3}



- The B and E field are measured by scanning probes in the horizontal and vertical plane
- Can be used for direct comparison of field with experiment.
- Unique capability on LAPD(not available on other hot fusion plasmas)

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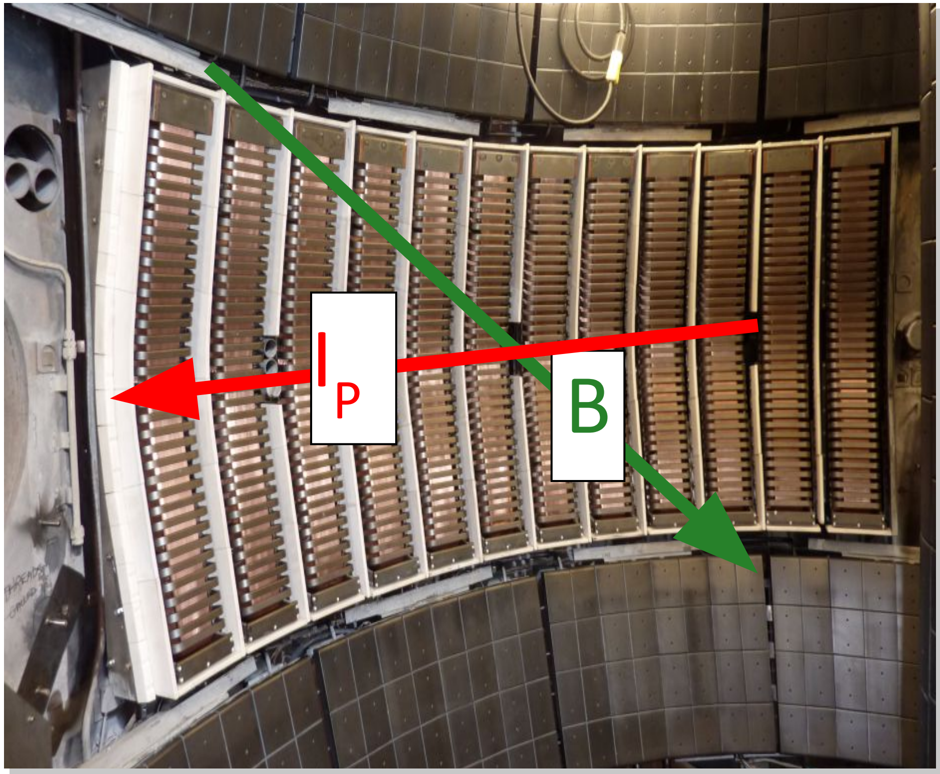
NSTX high harmonic fast wave antenna

- 12-strap antenna located on the outboard midplane and extends 90º toroidally



- Wave frequency = 30 MHz, up to P_{RF} = 6 MW
- Well-defined spectrum
- $|k_\varphi|$ = 3, 8, and 13 m^{-1}
  or
  n_φ = 5, 12, and 21
  when
  $\Delta\varphi$ = 30º, 90º, and 150º

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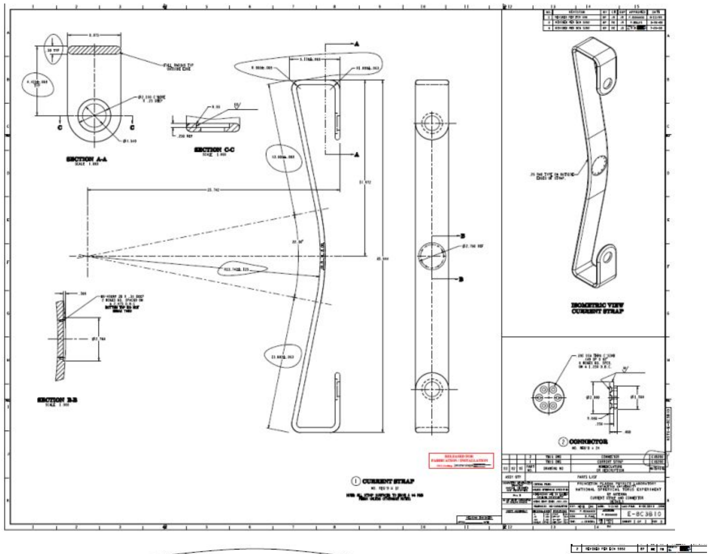
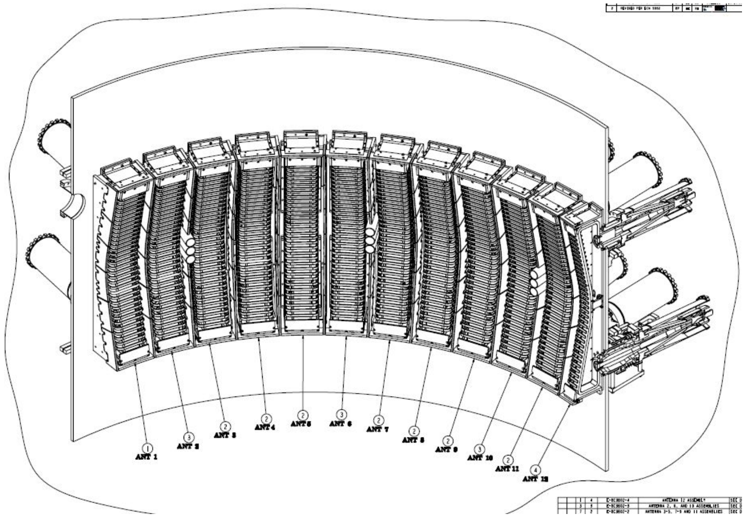
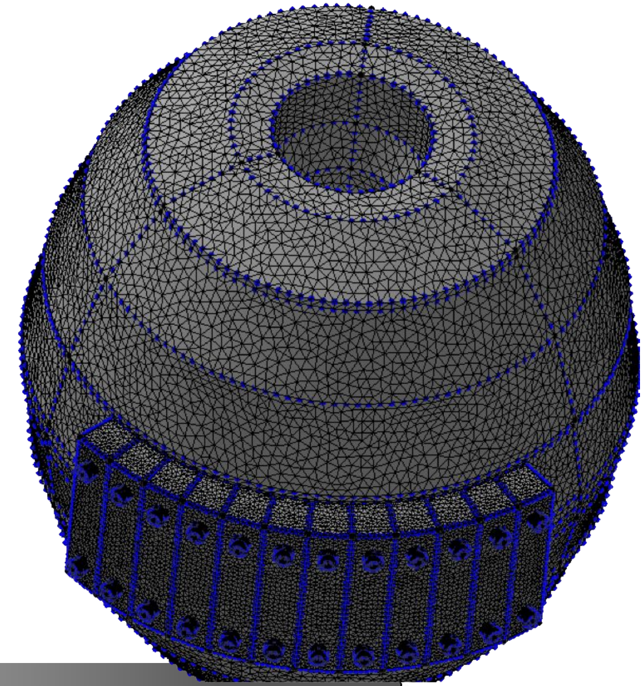
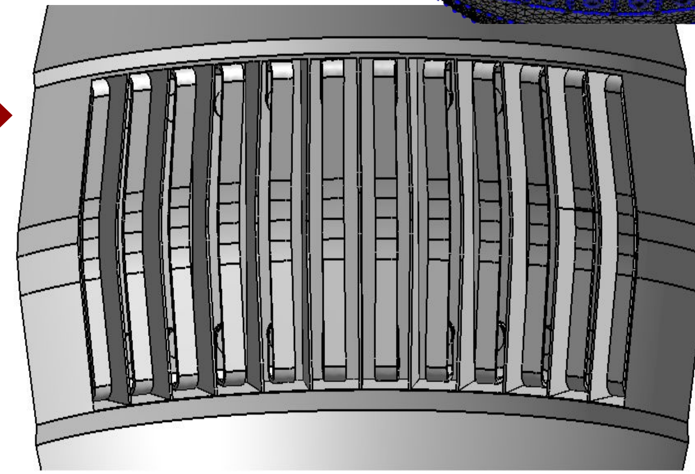
NSTX-U torus vacuum vessel and HHFW antenna meshes was built from drawings





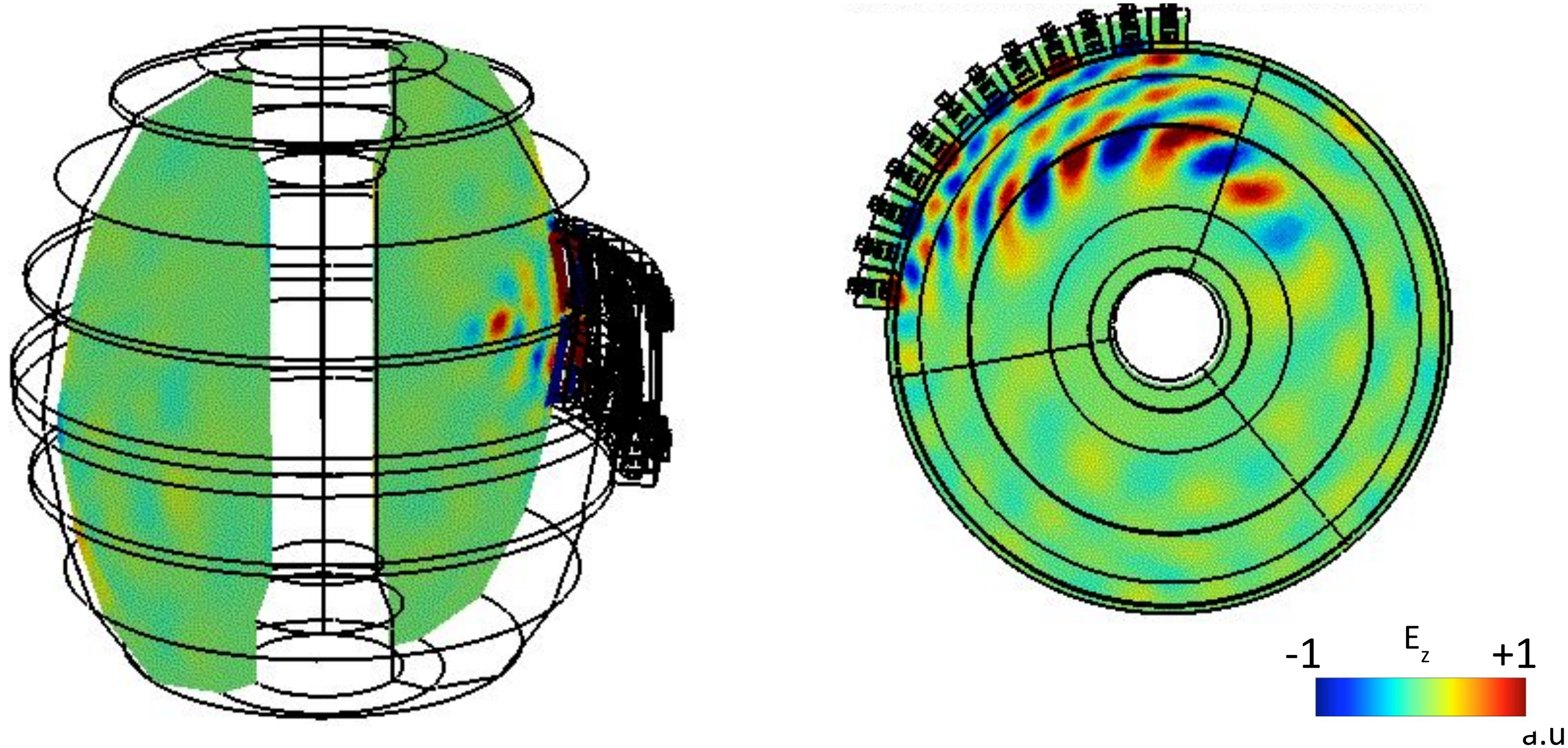




(w/o Faraday screen)

First full 3D torus simulation including realistic antenna geometry

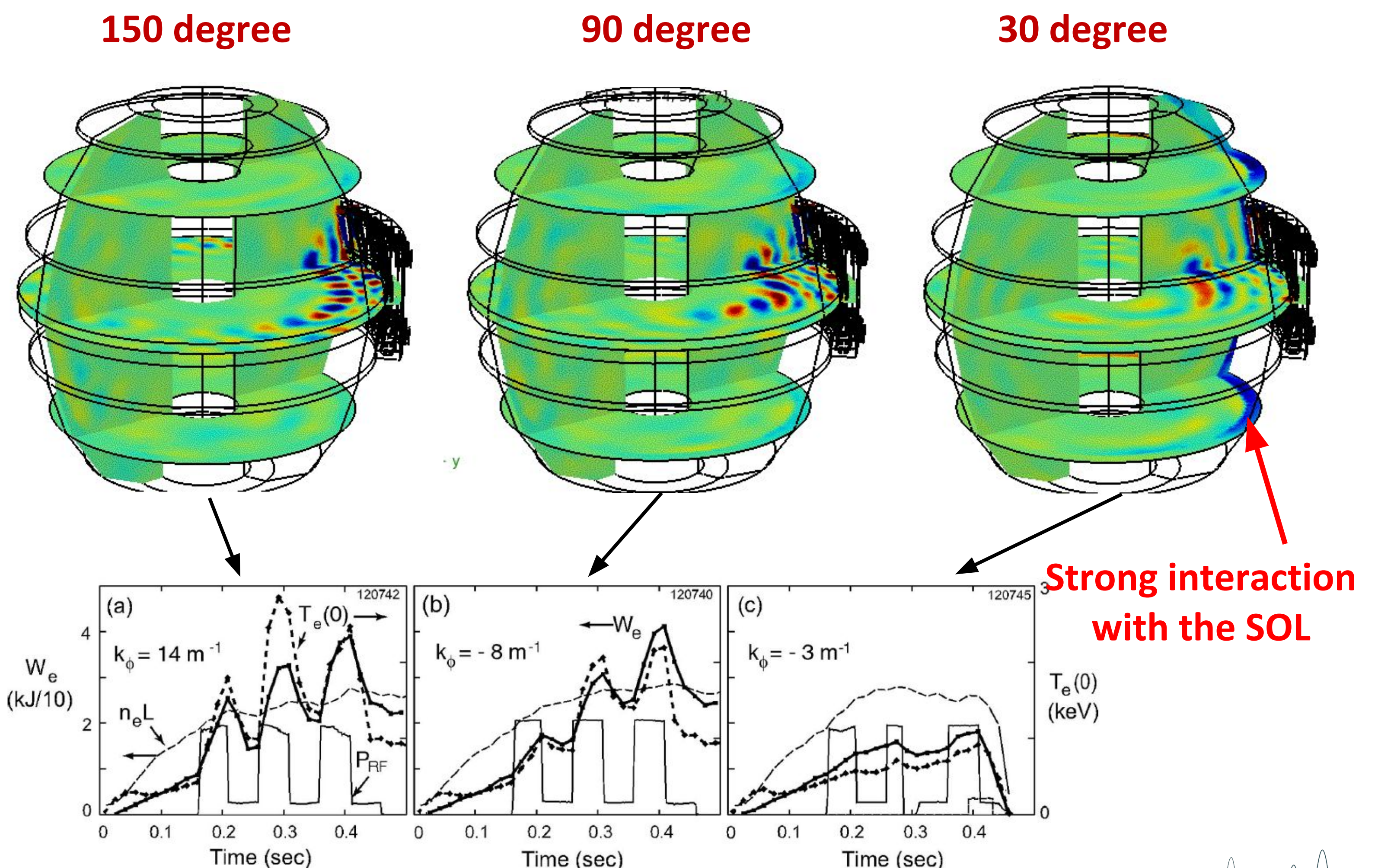
90 degree antenna phasing



- Equilibrium B field from EFIT as well as the diverted geometry
about 50M DoFs
- Analytical density profile with exponential decay in the SOL plasma
- Vacuum in the antenna box and anisotropic cold plasma in the torus with artificial collision

Lower antenna phasing has stronger interaction with SOL plasma

E$_z$ component of the wave field



consistent with observed reductions in We and Te for low k_φ (Hosea PoP 2008)

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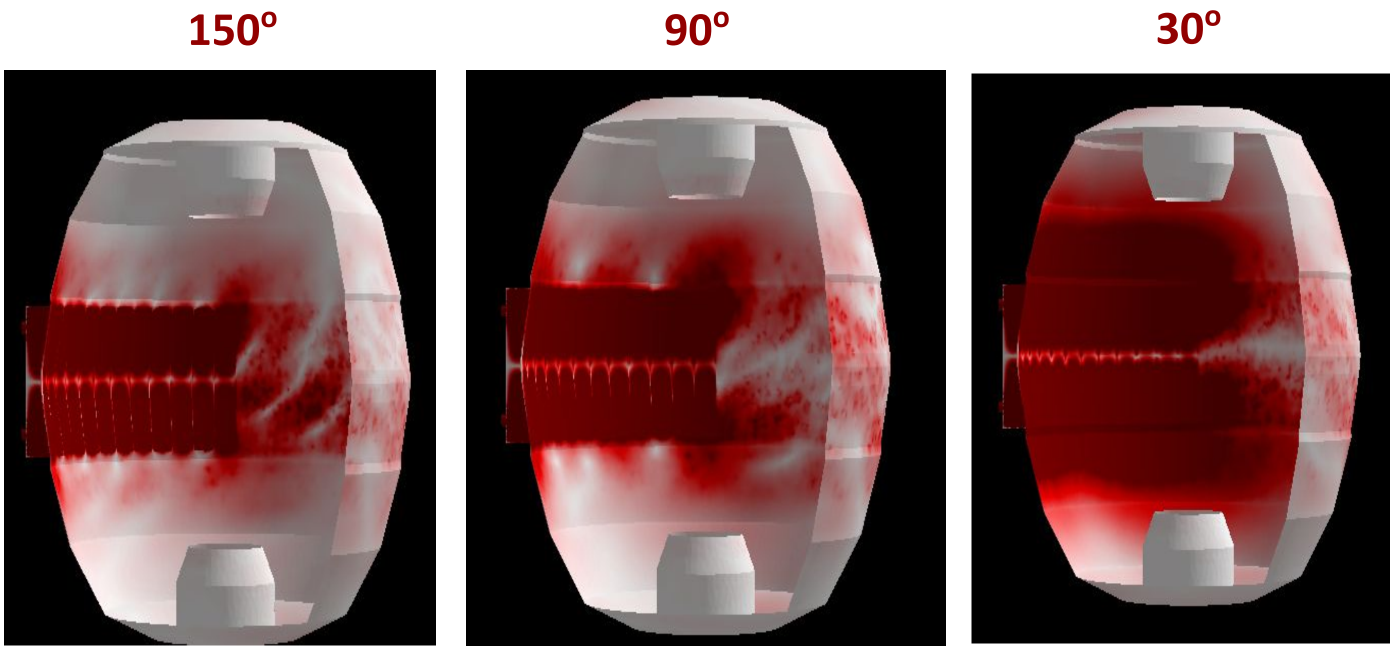
Very strong E field on the wall surface even far away from the antenna

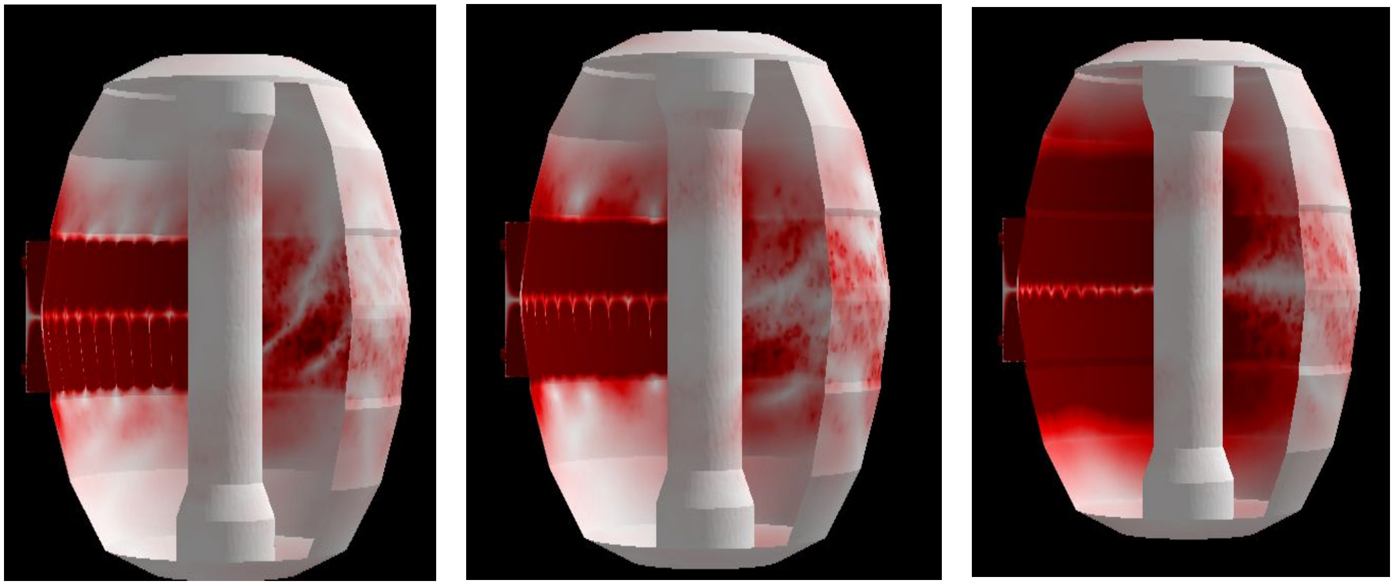


- E field on the surface is stronger for lower antenna phasing
  - corresponds to low cut-off density ($n_{cut\text{-}off} \propto N^2_{//} B \omega$)
  - Low antenna phasing has also generally a poorer RF heating performance (From experiments and AORSA modeling)

RF-SciDAC

Very strong E field on the wall surface even far away from the antenna

150^{o} 90^{o} 30^{o}



- E field also on the center stack surface
- E field on the surface in 3D will be important for studying the antenna impurity generation and RF sheath effects

Further NSTX-U experiment is critical for model validation (2021).

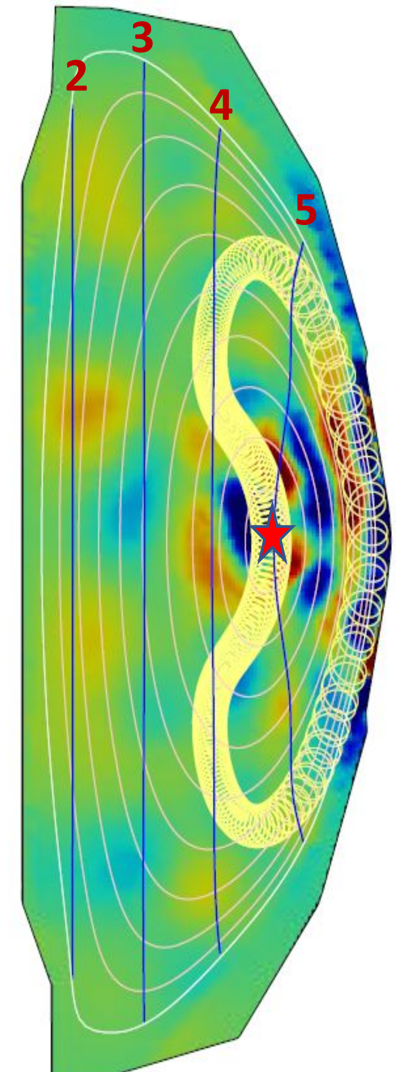
3D RF field combined with following particle code SPIRAL to study the interaction of FW with fast ions

- The SPIRAL code [1] : a test-particle code
  - Used to interpret and plan fast-ion experiments in tokamaks.
- Finite-orbit effects are important for fast ions studies
- Interaction between ICRF heating and fast ions depends on the gyro-motion of the fast ions and is captured in the SPIRAL code.
- Lorentz equation:

$$d\mathbf{v}/dt = q/m\,(\mathbf{v} \times \mathbf{B} + \mathbf{E})$$

- $\mathbf{B} = \mathbf{B}_{eq} + \mathbf{B}_{RF}$
- $\mathbf{E} = \mathbf{E}_{eq} + \mathbf{E}_{RF}$

[1] G. J. Kramer et al, PPCF **55** (2013) 025013



$\mathcal{E}$ = 80 keV
$v_{||0}$=0 m/s
R_0 = 0.95 m
Z_0 = 0.6 m
(n=4 D resonance)

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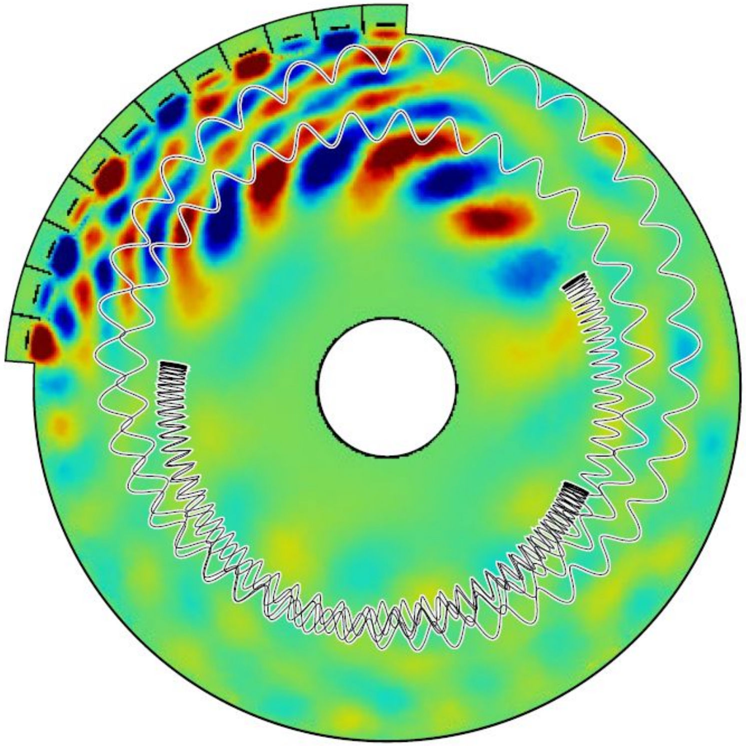
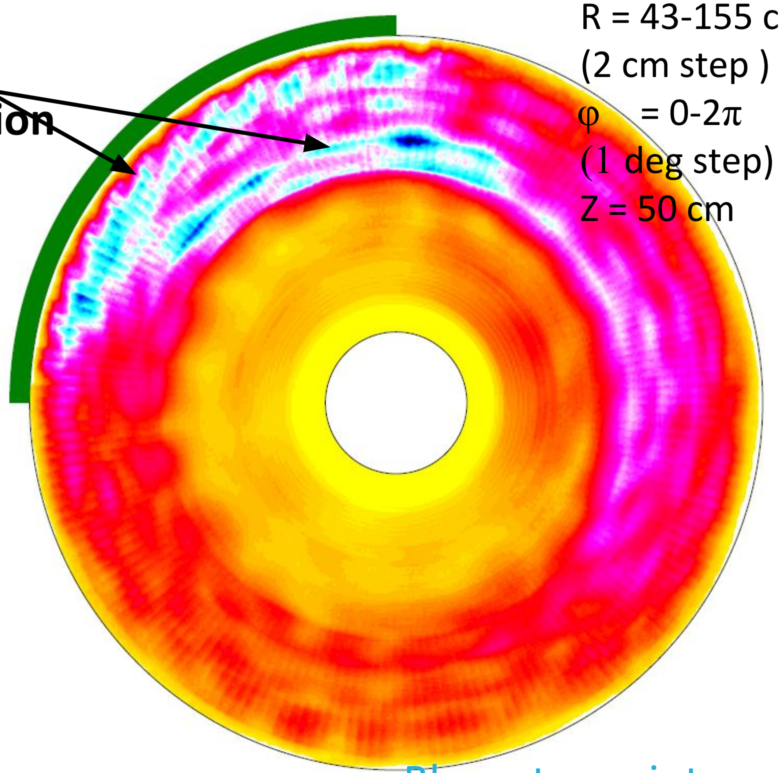
SPIRAL predicts that fast ions are mainly accelerated in front of the antenna region where the RF field is stronger





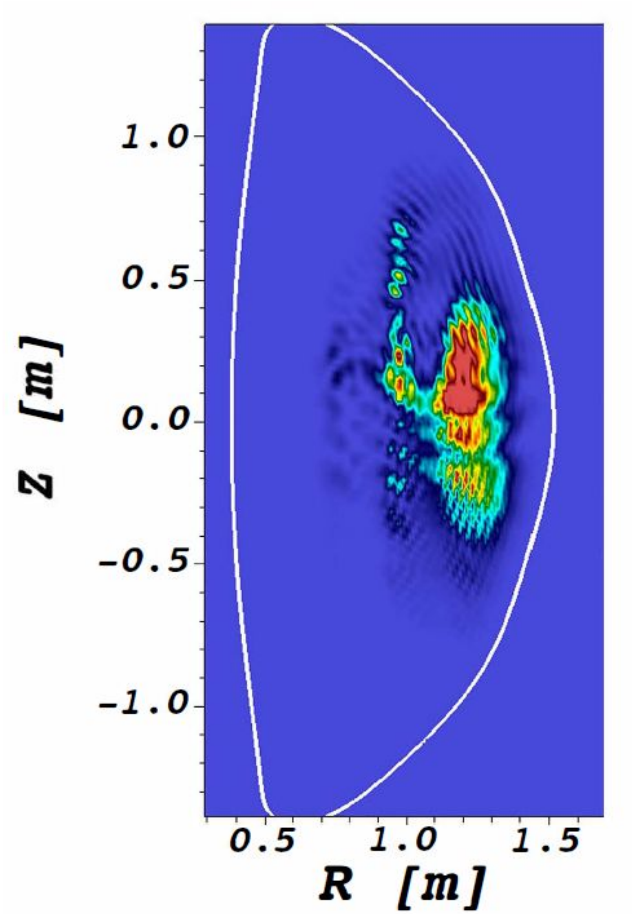
20k particles
E = 80 keV
$v_{\parallel 0}$=0 m/s
R = 43-155 cm
(2 cm step)
φ = 0-2π
(1 deg step)
Z = 50 cm

Blue: strong interaction
Red some interaction
Yellow no interaction

Key questions:

- Does 3D field pattern impacts FW-fast ions interactions?
- How does it compare with the prediction using 2D fields simulation?

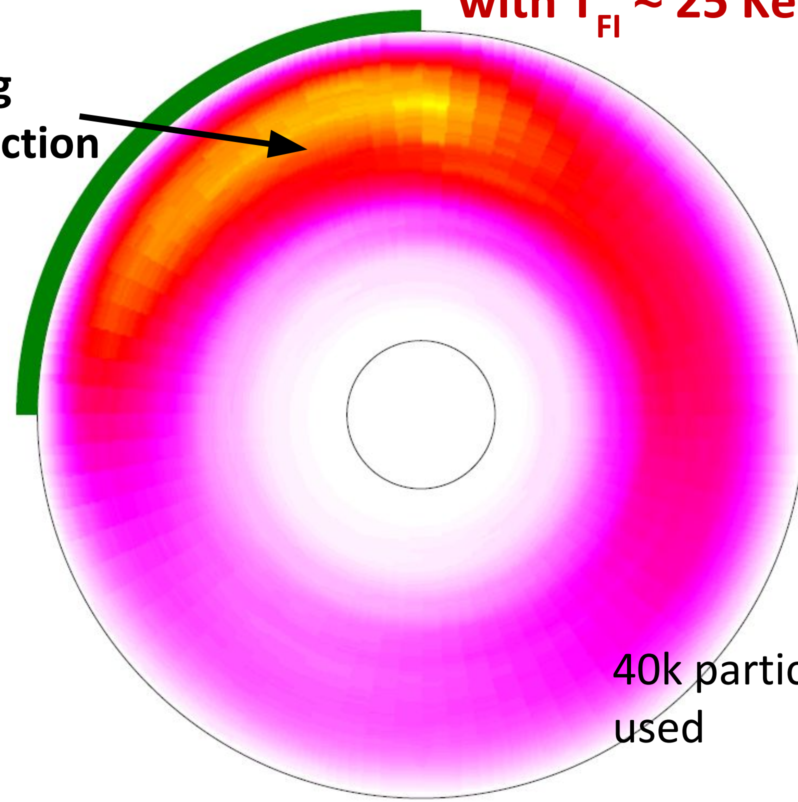
Strong interaction close to 5th D resonance appears similar to AORSA simulation



Fast ions pow. deposition predicted using AORSA 2D simulation, assuming single n_φ and **Maxw. distribution func.**

Assuming a Maxwellian in SPIRAL code with $T_{FI} \approx 25$ KeV

Strong interaction



40k particles used

Yellow strong interaction

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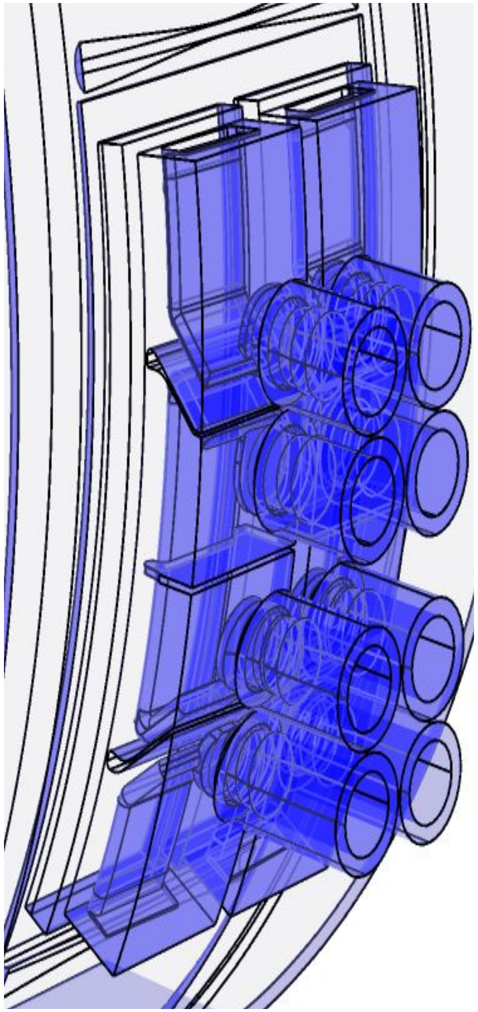
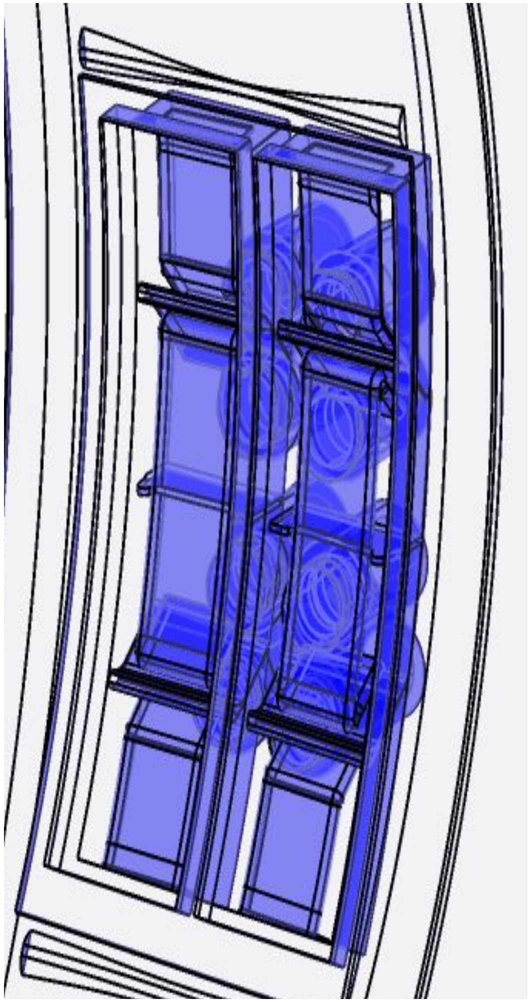
JET ITER-like antenna

- 3D Solid model was generated from the surface geometry data
- We included
  - All straps/separators
  - Antenna limiter,
  - Port structure
- We did not include yet
  - Faraday screen
  - Wiggle on antenna box



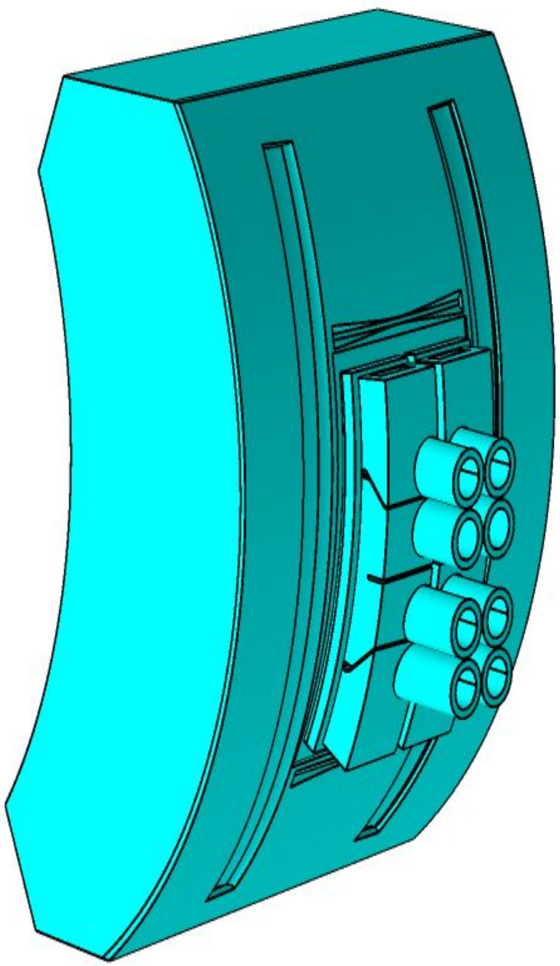


JET

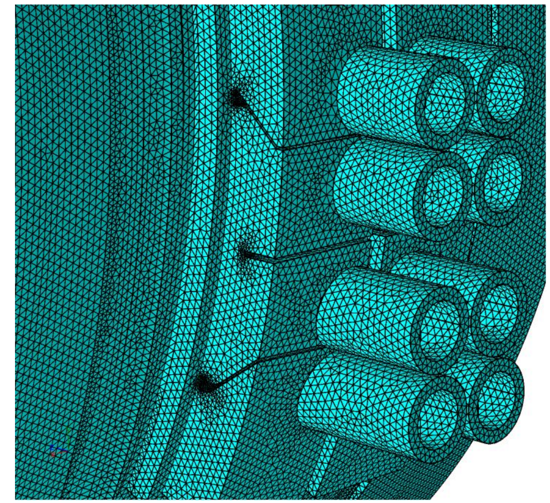
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

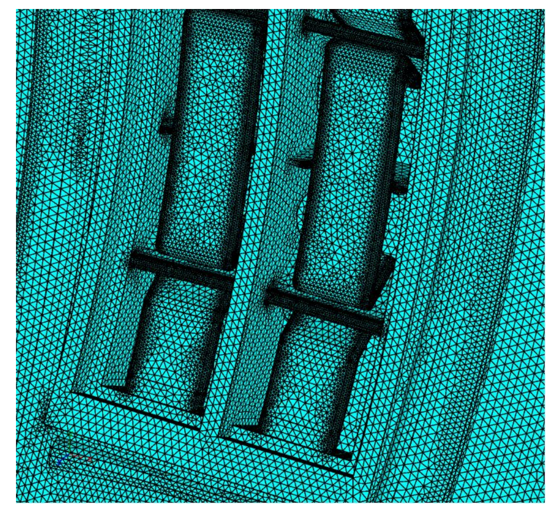
RF-SciDAC

JET ITER-like antenna simulation requires to solve large linear system



- Antenna
  - Meshed with 6mm-2.5cm tetrahedra
- Plasma
  - 1.9 m (width) x 2.8 m (height) x 65 cm (depth)
  - Uniformly mesh with 2.5cm tetrahedra
- Total 6M tetrahedra
- DoF
  - 7.2M for linear
  - ~50M for quadratic





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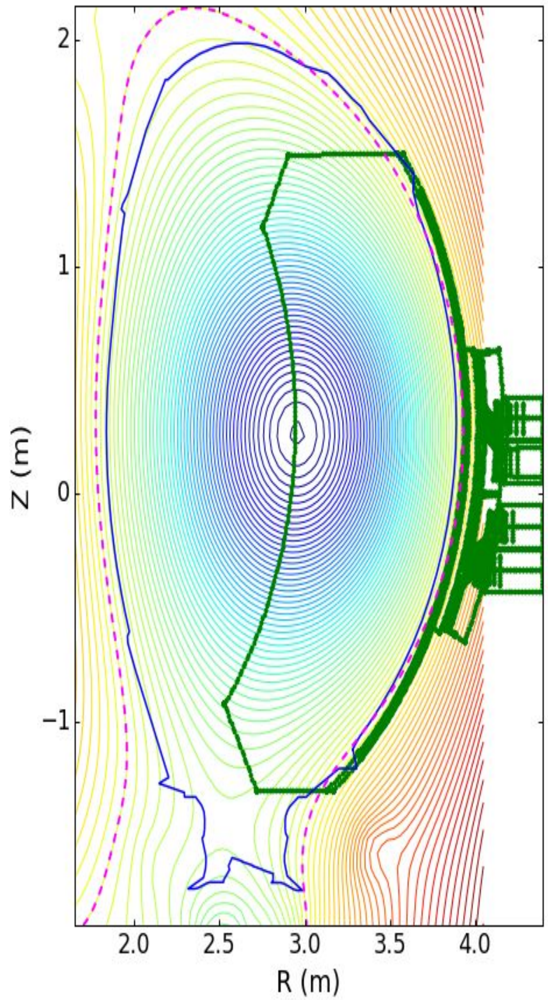
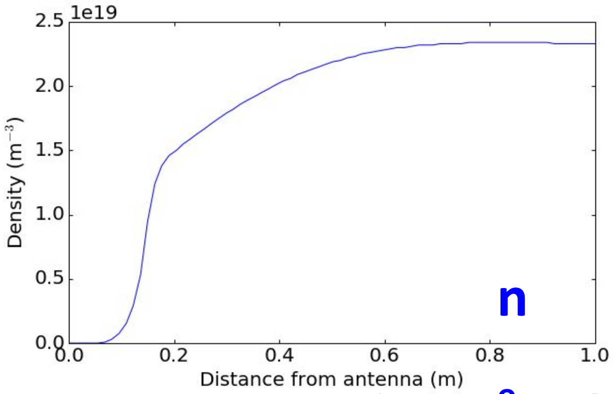
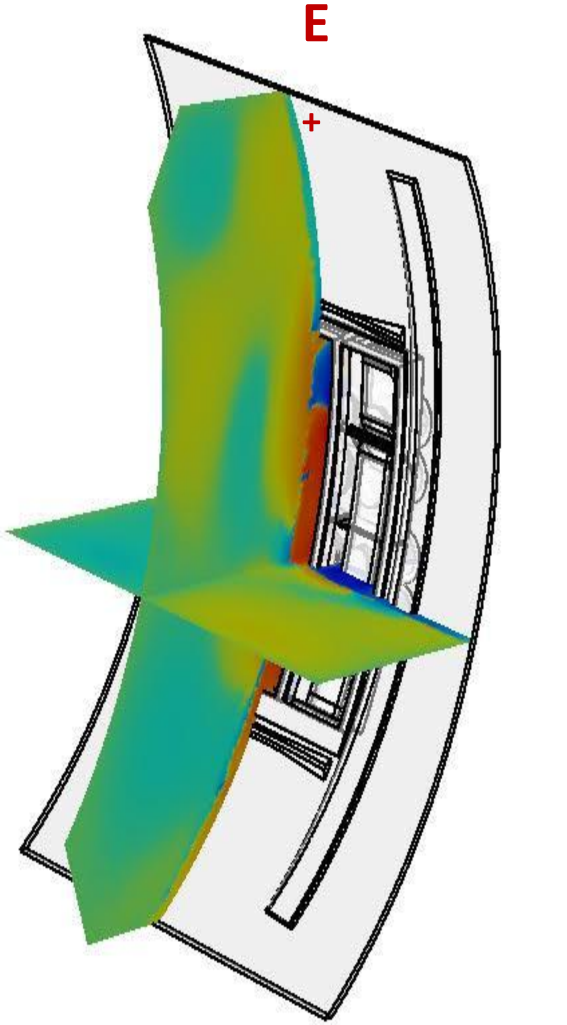
Preliminary JET ILA antenna simulations





kinetic profiles based on [1]



- f = 42 MHz
- B = 2.85 T
- $n_{e\_antenna} \approx 2x10^{18}\ m^{-3}$
- Antenna phasing = 0-pi
- Cold plasma
- Artificial collision

WORK IN PROGRESS

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[1] A. Křivská, et al, Nucl. Mat. and Energy **19** (2019) 324