Modeling in Support of Lower Hybrid Current Drive Experiments on the EAST Tokamak

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9th US-PRC Magnetic Fusion Collaboration Workshop
June 5-7, 2018
Modeling and simulation is aimed at understanding the role of full-wave effects and parasitic losses in the SOL in LHCD experiments in EAST

• Use coupled full-wave / Fokker Planck simulations to understand the regimes where ray tracing approach is valid.

• Develop reduced model for LHCD actuator that is usable in control level Plasma Control System algorithms and fast transport solvers.

• Evaluate the effect of increasing LH source frequency on nonlinear parametric decay instability in the SOL.
LHCD in the EAST Tokamak

- LHCD experiments in EAST are in the weak damping regime where full-wave effects and interference effects can potentially be important [1, 2]:
Ray tracing / Fokker Planck simulations using GENRAY / CQL3D [3,4] over-estimate driven LH current with completely hollow profiles

Launcher spectrum ($N_\parallel = 2.05, -6$)

Total current: 545kA

Completely hollow
Set-up for TorLH full-wave simulations

• Use experimental profiles and EFIT equilibrium reconstruction for discharge 048888.05500:
  – $B_0 = 2.31$ T, $I_p = 373$ kA, $a = 0.42$ m, $R_0 = 1.85$ m, $T_e(0) = 3.2$ keV, $n_e(0) = 3.6 \times 10^{19}$ m$^{-3}$.

• RF parameters:
  – $P_{LH} = 2$ MW, $f_0 = 4.6$ GHz, $n_{//} = -1.80$

• Status of TorLH [1], GENRAY [3], and CQL3D [4] executables:
  – NERSC: Edison
  – MIT-PSFC Engaging Cluster
  – IPP Shenma Cluster
Numerical implementation and mode resolution requirements for TorLH

• Semi-spectral ansatz is assumed for the electric field:

\[ \tilde{E}(\vec{x}) = \sum_{m,n} \tilde{E}_{m,n}(\psi) e^{im\theta + in\phi} \]

  – Spectral decomposition in the poloidal \((m)\) and toroidal \((n)\) directions.
  – \(E_{m,n}(\psi)\) are represented by finite elements in the radial direction (cubic Hermite interpolating polynomials).

• Using the ansatz above, the wave equation can be put in a weak variational form (Galerkin method):

  – Each toroidal mode \((n)\) is solved separately assuming \(N_m\) poloidal modes and \(N_r\) radial elements.
  – This results in a block tri-diagonal matrix to invert [5].
Poloidal mode resolution requirements for TorLH to simulate LH wave propagation in EAST

- Must resolve the shortest perpendicular wavelength in the system, which is given by the LH dispersion relation:

\[ k_\perp \approx k_\parallel \frac{\omega_{pe}}{\omega} \approx \frac{m}{r} \]

- For an EAST discharge at \( r/a \sim 0.5 \) with \( B_0 = 2.3 \) T, \( T_e(0) \sim 1 \) keV, \( n_e(0) \sim 2.0 \times 10^{19} \) m\(^{-3}\), \( f_0 = 4.6 \) GHz, we have:

\[ k_\perp = 17 \text{ cm}^{-1} \quad (\text{for } n_\parallel \sim n_\parallel_0 = 2) \quad \Rightarrow \quad m \approx rk_\perp \approx 372 \]

and \( N_m = 2m + 1 = 745 \)

\[ k_\perp = 46 \text{ cm}^{-1} \quad (\text{for } n_\parallel \sim n_\parallel_{ELD} \sim 5.5) \quad \Rightarrow \quad m \approx rk_\perp \approx 1019 \]

and \( N_m = 2m + 1 = 2038 \)

- May need \( N_m \sim 4000 \) to resolve LH wave at edge \( \sim 45 \) cm.
Convergence is only achieved on innermost flux surface \((r/a \approx 0.1)\) at \(N_m = 255\)
Convergence continues to improve on flux surfaces out to $r/a \approx 0.5$ as $N_m$ is increased to 2047.

![Graph showing the spectrum of Re($E_\xi$) vs. flux with $N_m = 2047$.](image)
Find that convergence is achieved on all flux surfaces as $N_m$ is increased to 4095.

- Simulation required 0.57 hours of wall clock time on Edison platform at NERSC using 32,256 cores.
LH power deposition profile is peaked on-axis at $N_m = 255$, but starts to broaden as $N_m$ is increased.

- Broadening of the LH power deposition profile is consistent with adding higher $k_{/\parallel}$ components to the spectral solution in TorLH that correspond to higher $m$. 
At $N_m = 4095$ the full-wave absorption profile is clearly off-axis (for Maxwellian electron damping) $\rightarrow$ consistent with ray tracing prediction

$N_m = 4095$
Workflow for TorLH-CQL3D simulation has been automated using the Integrated Plasma Simulator (IPS)

a) Execute TorLH in “toric” mode using Maxwellian electron Landau damping (ELD):
   i. Perform a resolution scan to determine how many poloidal modes are needed to resolve the LH wave in EAST.

b) Re-run TorLH in “qldce” mode to compute the RF diffusion coefficients ($D_{ql}$) from the electric field solutions computed in Step (a):
   i. Remap $D_{ql}$ from the TorLH (radial, velocity) space mesh to the CQL3D (radial / velocity) space mesh.

c) Run CQL3D to obtain first iterate for the quasilinear electron distribution $f_e(v_\perp, v_\parallel, r)$:
   i. Create look-up table for $\text{Im}\{\chi_{zz}\}$ due to ELD.

d) Repeat steps (a) – (c) until $f_e(v_\perp, v_\parallel, r)$ and $D_{ql}$ ($f_e$) are self-consistent.
TorLH - CQL3D has been iterated to convergence using the IPS with 1023 poloidal modes.

Agreement in profiles of LHRF power deposition from TorLH and CQL3D indicate convergence.
TorLH - CQL3D has been iterated using the IPS with 4095 poloidal modes for 5 iterations.

Simulation starting to exhibit features of convergence but must be extended to 15-20 iterations.
Developing a control level model for LHCD using GENRAY / CQL3D

- Must reduce the hyper-sensitivity of LHCD prediction.
- Broadening of LH wave spectrum is introduced:
  - Phenomenological model of wave scattering due to density fluctuation (Note this model is experimental)
- Initial result is promising, reducing the variation of predicted profiles.

Previous data show off-axis peaks at large rho
The LH magnetic loop probes are installed next to the 4.6 GHz antenna to detect the wave-field on the first pass to the plasma.

The intermediate frequency stage down-converts the wave frequency from 4.6 GHz to 20 MHz, allowing to perform FFT analyses.
Initial measurement of the frequency spectrum at 4.6 GHz shows the absence of the PDI sideband at $\bar{n}_e = 3 \times 10^{19} \text{ m}^{-3}$ (see poster by M. Li)

Upon the completion of the diagnostic, the wave $k_{//}$ spectrum will be examined under various plasma conditions in the upcoming campaign.
Parametric dispersion relation analysis indicates reduced growth rates for decay waves at 4.6 GHz relative to 2.45 GHz.

- **D plasma**, $n_e = 5 \times 10^{18} \text{ m}^{-3}$, $T_e = T_i = 30 \text{ eV}$, $B_t = 1.83 \text{ T}$, $n_{0//} = 2$, and the ion mode $n_{//} = 7$

- The electric field is found from the WKB approach.
Converged full-wave / Fokker simulations have been obtained thus far using partially converged full-wave LH fields ($N_m = 1023$):

- Iterated simulations with $N_m = 4095$ are ongoing.
- Preliminary results agree qualitatively with ray tracing / Fokker Planck predictions.

Development of a control level model for LHRF power deposition and CD has benefited from the use of a phenomenological model of wave scattering due to density fluctuations in order to reduce model sensitivity.

- Higher LH source frequency in EAST (4.6 GHz) is effective for mitigating the effects of PDI.

Work supported by the US DOE under Contract Nos. DE-SC0010492 and DE-SC0018090.
References and Acknowledgements

Disruption prediction development on EAST, and proposed runaway electron research on EAST and J-TEXT

R.S. Granetz, C. Rea, R.A. Tinguely, K. Montes
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Z.Y. Chen
Huazhong University of Science and Technology, Wuhan, China

9th US-China collaboration workshop
Xi’an, China
2018/06/05-07
Our disruption research on EAST is focused on two principal goals:

- Development of real time disruption prediction
  - Construction of a large database of disruption-relevant plasma parameters for training prediction algorithms (nearly finished)
  - Testing of several different machine learning methods offline to develop a credible disruption prediction algorithm
  - Incorporate algorithm into the EAST plasma control system to enable real time prediction

- Comparison of disruption prediction on EAST with similar efforts on Alcator C-Mod and DIII-D (and soon KSTAR)
  - Is a universal disruption predictor possible?
  - IAEA presentation on this in October
The EAST disruption warning database is one of several that we have developed

<table>
<thead>
<tr>
<th>Machine</th>
<th>Shots</th>
<th>Time slices (records)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-MOD</td>
<td>5507</td>
<td>498925</td>
</tr>
<tr>
<td>EAST</td>
<td>14713</td>
<td>1209217</td>
</tr>
<tr>
<td>DIII-D</td>
<td>10258</td>
<td>2356519</td>
</tr>
<tr>
<td>KSTAR</td>
<td>4219</td>
<td>773083</td>
</tr>
</tbody>
</table>

~50 plasma parameters are recorded at each time slice

- shot (primary key)
- time (primary key)
- time_until_disrupt
- shot (primary key)
- time_until_disrupt
- ip
- lp_error
- dip_dt
- dlpprog_dt
- v_loop
- p_rad
- p_oh
- p_icrf
- p_lh
- p_nbi
- rad_input_frac
- rad_loss_frac
- n_equal_1_mode
- pressure_peaking
- zcur
- z_error
- v_z
- z_times_v_z
- V_0
- v_mid
- v_edge
- beta_n
- beta_p
- dbetap_dt
- kappa
- li
- dli_dt
- dWmhd_dt
- H98
- n_e
- dn_dt
- r_dd
- q95
- q0
- qstar
- lower_gap
- upper_gap
- power_supply_railed
- Greenwald_fraction
- Te_width
- Intentional_disruption
For every EAST plasma discharge, disruptive and non-disruptive, we take time slice data every 100 ms
For each disruptive shot, we take additional time slices every 10 ms during the 250 ms period before the disruption.
We train our prediction algorithms on a subset of the signals in the databases

By examining the many signals in our databases we have identified a subset of 10 signals that show a clear change in behavior on some disruptions on some machines:

<table>
<thead>
<tr>
<th>Signal description</th>
<th>Variable name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent error between measured and programmed plasma current, ((I_p - I_{prog})/I_p)</td>
<td>ip_error_frac</td>
</tr>
<tr>
<td>Poloidal beta, (\beta_p)</td>
<td>betap</td>
</tr>
<tr>
<td>Greenwald density fraction, (n/n_G)</td>
<td>n/nG</td>
</tr>
<tr>
<td>Safety factor at 95% of minor radius, (q_{95})</td>
<td>q95</td>
</tr>
<tr>
<td>Normalized internal inductance, (\ell_i)</td>
<td>li</td>
</tr>
<tr>
<td>Radiated power fraction, (P_{rad}/P_{input})</td>
<td>prad_frac</td>
</tr>
<tr>
<td>Loop voltage, (V_{loop}) [V]</td>
<td>Vloop</td>
</tr>
<tr>
<td>Stored plasma energy, (W_{th}) [J]</td>
<td>Wmhd</td>
</tr>
<tr>
<td>(n = 1) mode amplitude, normalized to (B_{tor})</td>
<td>n_equal_1_normalized</td>
</tr>
<tr>
<td>Electron temperature profile width, normalized to plasma minor radius</td>
<td>Te_width_normalized</td>
</tr>
<tr>
<td>- not available for C-Mod -</td>
<td></td>
</tr>
</tbody>
</table>

We use this subset to train and test our machine learning algorithms
Disruption precursor behavior is very different on C-Mod, DIII-D, and EAST

**DIII-D**: \( l_i \) starts to increase ~400 ms before a disruption occurs on a significant fraction of disruptions.

**EAST**: \( l_i \) shows almost no change in behavior before a disruption occurs.

**C-Mod**: \( l_i \) starts to decrease, but only ~4 ms before a disruption occurs.
Some basic concepts of our application of AI machine learning to disruption prediction

- We are formulating our application as a **supervised classification** problem, specifically a **binary classification** problem
  - Every time slice in the database is known a priori to belong to one of only two possible ‘classes’
  - We choose our two classes to be ‘close to disrupt’ and ‘not close to disrupt or belongs to a non-disruptive discharge’

- Our large dataset is randomly split into a ‘training’ dataset and a ‘test’ dataset
  - An algorithm is trained (i.e. optimized) using only the data in the training set
  - The test data is then fed to the trained algorithm, and its predicted classes are compared to the a priori known classes for the test data
Most of our effort has focused on an AI Machine Learning method known as Random Forests

Random Forests consist of many independent, uncorrelated decision trees

• Each decision tree tries to divide up the space of plasma physics time slice data into the specified classes, based on objective splitting rules.

There are a number of reasons why Random Forests is an attractive Machine Learning method:

— The architecture of a Random Forest involves only one design parameter, which is easily optimized
— Different features (plasma parameters), with vastly different numerical ranges, present no issues
— For Random Forests, the degree to which each feature contributes to the classification decision can be characterized (“white box”)
The Random Forests method is easy to understand, but I don’t have the 15 minutes that it takes to explain them.
Comparison of Random Forest performance on DIII-D, EAST, and C-Mod

Results are for flattop period only, for all shots in 2015 campaigns

"recall" = TP/(TP+FN) = fraction of "close to disrupt" that are correctly predicted

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>EAST</th>
<th>C-MOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>True label</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>far from disruption or non-disruptive</td>
<td>TN 34672</td>
<td>TN 36592</td>
<td>TN 3768</td>
</tr>
<tr>
<td>close to disruption</td>
<td>FP 765</td>
<td>FP 1511</td>
<td>FP 16</td>
</tr>
<tr>
<td>FN 1498</td>
<td>TP 4222</td>
<td>FN 4280</td>
<td>FN 273</td>
</tr>
<tr>
<td>TP 4222</td>
<td></td>
<td>TP 6972</td>
<td>TP 147</td>
</tr>
</tbody>
</table>

Miss rate = 1 - recall = “close to disrupt” that are not caught

Miss rate = 1 - TP/(TP+FN) = 1 - recall

False alarm fraction = FP/(TP+FP)

“F1 score” = weighted combination of miss rate and false alarm rate
But Random Forests lack one significant feature which may be important for disruption prediction.

RF classification is done on each time slice independently:

- Information from previous classification decisions is not used in determining the classification of the current time slice.
- The classification of the current time slice is not available for classification decisions of future time slices.
Neural Networks are another AI method for classification problems.
Neural Networks are another AI method for classification problems

Many design parameters that can be difficult to determine:

- How many hidden layers?
- How many nodes in each hidden layer?
- 1000’s or millions of weights to determine/optimize
  - Deep Learning; back-propagation;
- Difficult to determine the degree to which each feature contributes to the classification decision (“black box”)

But their complexity can incorporate features such as temporal history
Recurrent Neural Networks (RNN’s) have the capability to include past classification information in current and future decisions.

**LSTM Layer Architecture**

This diagram illustrates the flow of a time series $X$ with $D$ features of length $S$ through an LSTM layer. In this diagram, $h$ denotes the output (also known as the *hidden state*) and $c$ denotes the *cell state*.
Recurrent Neural Networks (RNN’s) have the capability to include past classification information in current and future decisions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input gate (i)</td>
<td>Control level of cell state update</td>
</tr>
<tr>
<td>Forget gate (f)</td>
<td>Control level of cell state level (forbid)</td>
</tr>
<tr>
<td>Layer input (g)</td>
<td>Add information to cell state</td>
</tr>
<tr>
<td>Output gate (o)</td>
<td>Control level of cell state added to output</td>
</tr>
</tbody>
</table>

This diagram illustrates the flow of data at time step $t$. The diagram highlights how the gates forget, update, and output the cell and output states.

The learnable weights of an LSTM layer are the input weight $W_i$ (input weight), the recurrent weight $W_r$ (recurrent weight), and the bias $b_i$ (bias). The matrices $W_i$, $W_r$, and $b$ are concatenations of the input weight, the recurrent weight, and the bias of each component, respectively. These matrices are concatenated as follows:

$$W = \begin{bmatrix} W_i & W_r \end{bmatrix}, \quad b = \begin{bmatrix} b_i \\ b_r \end{bmatrix},$$

where $i$, $f$, $g$, and $o$ denote the input gate, forget gate, input input, and output gate, respectively.

The cell state at time step $t$ is given by

$$c_t = f_t c_{t-1} + i_t \tilde{c}_t,$$

where $\otimes$ denotes the Hadamard product (elementwise multiplication of vectors).

The output (hidden) state at time step $t$ is given by

$$h_t = o_t \tanh(c_t),$$

This table shows the formula for each component at time step $t$.

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input gate</td>
<td>$i_t = \sigma(W_i x_t + b_i)$</td>
</tr>
<tr>
<td>Forget gate</td>
<td>$f_t = \sigma(W_f x_t + b_f)$</td>
</tr>
<tr>
<td>Layer input</td>
<td>$g_t = \tanh(W_g x_t + b_g)$</td>
</tr>
<tr>
<td>Output gate</td>
<td>$o_t = \sigma(W_o x_t + b_o)$</td>
</tr>
</tbody>
</table>

Here, $\sigma$ denotes the sigmoid function given by $\sigma(x) = (1 + e^{-x})^{-1}$. 
We have very recently started to train a simple, one-hidden-layer RNN on EAST disruption data

fraction of disruptive time slices in training dataset = 9.54%
fraction of disruptive time slices in test dataset = 9.33%

layers =
5x1 Layer array with layers:
1  ''  Sequence Input  Sequence input with 9 dimensions
2  ''  LSTM  LSTM with 50 hidden units
3  ''  Fully Connected  2 fully connected layer
4  ''  Softmax  softmax
5  ''  Classification Output  crossentropyex

Training on single CPU.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Iteration</th>
<th>Time Elapsed (seconds)</th>
<th>Mini-batch Loss</th>
<th>Mini-batch Accuracy</th>
<th>Base Learning Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.05</td>
<td>0.3987</td>
<td>68.87%</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>3.76</td>
<td>0.1472</td>
<td>94.56%</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>6.85</td>
<td>0.0870</td>
<td>97.22%</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
<td>10.53</td>
<td>0.1010</td>
<td>96.50%</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>14.38</td>
<td>0.1002</td>
<td>96.64%</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>250</td>
<td>18.74</td>
<td>0.1439</td>
<td>95.08%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>22.99</td>
<td>0.1460</td>
<td>93.68%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>26.66</td>
<td>0.0641</td>
<td>97.69%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>31.03</td>
<td>0.0865</td>
<td>96.86%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>35.41</td>
<td>0.1296</td>
<td>97.51%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>40.00</td>
<td>0.1130</td>
<td>97.56%</td>
<td>0.0100</td>
</tr>
<tr>
<td>2</td>
<td>504</td>
<td>40.46</td>
<td>0.0540</td>
<td>98.14%</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

disrupt_class_threshold_time = 1.000 s

TP = 3644  FP = 1354  TN = 85546  FN = 5294

accuracy  precision  recall  F1
0.933  0.723  0.480  0.577
We have very recently started to train a simple, one-hidden-layer RNN on EAST disruption data.
Future plans for disruption prediction work

- Continue work on database
  - Add 2018 data; normalizations; add real time signals, etc.
- Optimize recurrent neural network
  - # of hidden layers, # of nodes per layer, …
- Install in plasma control system
  - Algorithm must be trained on actual signals coming into the PCS, including EFIT RT
  - Algorithm must be packaged in a way that can be incorporated into PCS, and receive/pass data with to/from PCS
  - Our recent experience installing a disruption predictor into the DIII-D PCS should help a lot with EAST
Examples of our real time disruption predictor operating in the DIII-D PCS

output begins climbing ~350 ms before the disruption occurs

no warning alarm is triggered in healthy plasma
Continue with disruption mitigation on EAST

We also propose to collaborate with studies of runaway electrons on EAST and J-TEXT

- RE research on EAST: Zeng Long
  - IR imaging; studies of primary and avalanche growth processes
  - Zeng will visit MIT in October to discuss collaboration

- RE research on J-TEXT: Chen ZhongYong
  - IR imaging; MGI and SPI mitigation of runaways

- RE research on C-Mod
  - Synchrotron spectral analysis
    - We can bring the spectrometers to EAST and/or J-TEXT
  - Visible synchrotron imaging analysis
C-Mod RE research

Synchrotron spectra can inform energy distribution of runaway electrons (REs) [Tinguely NF 2018]

- Absolutely-calibrated visible spectrometers
- $B_0 = 2.7, 5.4, 7.8$ T
- Test particle model for energy [Martín-Solís PoP 1998] and density [Connor NF 1975, Rosenbluth NF 1997]
- Synthetic diagnostic SOFT [Hoppe NF 2018] generated synthetic spectra
- For fixed $E/E_C$, increasing $B_0$ is consistent with decreasing RE energy
Synchrotron images can inform spatial distribution of REs

• Distortion-corrected, wide-view visible camera
• Full momentum space distributions from CODE [Landreman CPC 2014] needed to capture spatial effects
• MHD activity seems to increase RE transport, shrinking size of RE beam
• Distinct periods of RE growth are seen, including secondary avalanching
• To present at Runaway Electron Meeting and EPS
Development of fullwave RF simulation code based on the open source FEM library

S. Shiraiwa and J. C. Wright

With contributions from
P. T. Bonoli, N. Bertelli\textsuperscript{1}, J. Myra\textsuperscript{2}, T. Kolev\textsuperscript{3}, M. Stowell\textsuperscript{3},
Y. Lin, C. Lau\textsuperscript{4}, G. Wallace, S. Wukitch, L. Zhou, W. Beck, the Alcator C-Mod team and RF-SciDAC
PSFC-MIT, PPPL\textsuperscript{1}, Lodestar\textsuperscript{2}, LLNL\textsuperscript{3}, and ORNL\textsuperscript{4}
Leading-class computing facilities allow for accurate RF wave physics simulations in core and edge regions with great detail.

These models compute RF wave propagation and absorption including linear and non-linear effects:
- Full wave spectral code simulations of core LH and IC waves
- FDTD (finite difference time domain) simulation of ICRF antenna on C-Mod

These models are now being able to couple RF non-linear effects such as modification of velocity distribution function and RF sheath rectified potential.

However, core and edge regions are modeled separately…
Requirements for self-consistent (hot core + realistic 3D antenna) RF simulations have been widely recognized

Many physics issues require to couple a hot core plasma with an edge (antenna and SOL) model having high geometrical fidelity

- Edge parasitic losses observed on many experiments (Alcator C-Mod ICRF\(^{[1]}\)/LH\(^{[2]}\), NSTX HHFW\(^{[3]}\))
- Antenna coupling in 3D geometries (C-Mod field aligned ICRF, stellarators)
- Multiple-pass absorption regimes
- Impact of edge turbulence (See next talk).

- “monolithic ” approach?
  - Half torus ICRF simulation on Alcator C-Mod using a FDTD code (cold core plasma)
  - FEM (finite element method) simulation of LH waves (iterative inclusion of electron Landau damping)

1) S. J. Wukitch et al, Phys. Plasmas 20, 056117 (2013)
4) T. G. Jenkins and D. N. Smithe, 26th IAEA FEC (2016) TH/P4-34
Outline

• HIS (Hybrid integration SOL) approach
  • Formulation/implementation
  • Verification using a stand alone TORIC simulation

• 2D Simulation and comparison with Alcator C-Mod experiment

• 3D Simulation
  • w/o 3D antenna structure
  • with 3D antenna structure

• Future plans and conclusion
HIS (Hybrid integration of SOL) - TORIC

**Core**
- **Axisymmetric** flux surface regular grid
- Hot plasma conductivity
- Dense Matrix Solver

**Edge**
- **Unstructured mesh** with complicated geometry (either 2D or 3D)
- Cold plasma with collision.

[Diagram of HIS (Hybrid integration of SOL) - TORIC]
Core and edge connecting rule = cascading of RF components

RF network characterized by the Scattering matrix, $S$

$$\vec{V}_{out} = S \vec{V}_{in}$$

When connecting two networks…

$$\vec{V}_{out} = U(T_2, S) \cdot T_1 \vec{V}_{in}$$

$T_1$: response to the power from the external input

$T_2$: response to the power from $S$
Final solution constitutes from three components

Fourier decomposed modes (poloidal/toroidal), not discrete RF port voltages.

This method is exact – no approximations.

Equivalent for requiring the continuity of tangential E and B on the connecting boundary.

Changing antenna excitation does not require re-computing (b)

The reconstructed solution is very similar to a standalone TORIC simulation.

- In the core region, the superimposed solution (left) agrees well with the core solution of TORIC standalone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.
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- In the core region, the superimposed solution (left) agrees well with the core solution of TORIC standalone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.
- Mode amplitude of superimposed solution (blue) spread wider than the antenna excitation amplitude (red).
Detailed verification: $E_\psi$ continuity is retained at domain boundary

- Continuity of radial component is not given by construction and provides a way to verify the approach.
- Smoothly connected at TORIC/FEM boundary, but it is not at vacuum/plasma boundary.
- Consistent with a continuous dielectric at the former boundary, while it is not at the latter.
In D-(H) MH, the power is absorbed dominantly in the core

- D-(H) loading 16.1 Ω, power partition: 15% edge, 85% core. (note: \( T_{e_{SOL}} = 15 \text{ev} \), which is low for C–Mod experiments)
- D-(3He) loading 14.5 Ω, power partition, 50% edge, 50% core.
- Loading is different than efficiency: power does not necessarily go into the core.
- In D-(3He), significant power lost in far SOL – possible source of far field RF sheath rectification
In D-(3He) MC, absorption in SOL increases due to weaker absorption

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Our HIS formulation extends to 3D naturally

However, significantly larger resources are required

Geometry made by revolving previous poloidal cross section.
  - 60 deg vessel section
  - two strap antenna

Even a FE mesh, which is fine enough to resolve only the relatively long wavelength fast waves, yields a linear problem with \(~5\) M DoF.

Expecting 30 M ➔ 100 M DoF for resolving slow waves.
SOL RF wave simulation built on Petra-M; an FEM modeling tool using the scalable MFEM library

- Scalable MFEM library
  - http://mfem.org/features

- Petra-M physics based FEM modeling interface

- Workflow management using πScope
  - http://piscope.psfc.mit.edu

Image uses cold plasma in the entire domain and solved by MFEM
3D simulations using simply revolved 3D geometry indicates we need more realistic antenna structure

D-(H) case on Alcator C-Mod

Accurate toroidal spectrum can be essential for finding RF amplitudes ‘far’ from antenna[1].

1) N. Tsujii, PhD thesis (2010)
J-port antenna RF geometry model built from engineering CAD drawing

3D antenna structure and SOL plasma (diverted geometry is made from EFIT) is added
3D geometry introduces coupling among toroidal modes.

Different toroidal modes communicate each other via surface RF current on the antenna structure.
Core-edge integrated solution for C-Mod field-aligned ICRF antenna

Wave propagates smoothly from antenna to the core
Surface currents indicates phasing is not exactly 0-\pi-0-\pi
HIS realized high degree of geometrical fidelity with hot core.

Validation is on-going using Alcator C-Mod experimental data

- RF voltage/current probes
- PCI diagnostics
- LAPD, high density data points
Investigation of slow wave has begun

Slow wave excitation in the low density region near the antenna structure…

- has very short wave length
- produces nonlinear RF rectified potential
- responsible for impurity regeneration

Work with J. Myra (Lodestar)

Fig.2 from Berro and Morales IEEE Trans. (1990).

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Possible application to EAST

EAST B-antenna

Unstructured geometry mesh was generated (3M DoFs for EM)

What we need…

• Equilibrium
• 1D Core temperature and density profiles (for TORIC)
• 2D SOL density (ideally temperature too) profiles
Conclusions

A new RF modeling capability permits exploration of core – edge interactions in many areas

- Technique applies to any full wave RF simulation in any frequency regime.
- Builds upon existing code infrastructure, algorithms and methods.
- Newly developed SOL FEM simulation built on the scalable MFEM library
- Integrates for the first time, antenna coupling, SOL propagation with realistic geometry, and hot core plasma.

A step towards whole device scale RF modeling

RF sheath models
Core Fokker-Planck models
SOL fluid and turbulence models
Impurity generation and transport models

HIS approach adopted by “Center for Integrated Simulation of Fusion Relevant RF Actuators”
How to stitch to two regions…

Let’s follow the power flow….

• Antenna current inject the RF power to SOL
How to stitch to two regions…

Let's follow power flow…

- Antenna current inject the RF power to SOL
- The RF power goes through the SOL and across the connecting boundary to enter the core
How to stitch to two regions…

Let’s follow power flow…

• Antenna current inject the RF power to SOL

• The RF power goes through the SOL and across the connecting boundary to enter the core

• The power not being absorbed comes out to SOL
How to stitch to two regions...

Let's follow power flow….

• Antenna current inject the RF power to SOL

• The RF power goes through the SOL and across the connecting boundary to enter the core

• The power not being absorbed comes out to SOL

• The power is sent back to core or to the transmitter