Simulations of ICRF Mode Conversion in Alcator C-Mod and ASDEX Upgrade with a Fully Converged Spectral Code

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TORIC is a Finite Larmor Radius Full Wave Code

- Solves Maxwell's equations for a fixed frequency with a linear plasma response in a mixed spectral-finite element basis. Where $\mathbf{J}^A$ and $\mathbf{J}^P$ are the antenna and plasma currents.

$$\nabla \times \nabla \times \mathbf{E} = \frac{\omega^2}{c^2}\left\{E + \frac{4\pi i}{\omega}\left(\mathbf{J}^P + \mathbf{J}^A\right)\right\} \leftarrow \mathbf{E}(x) = \sum_m \mathbf{E}_m(r)\exp\left(im\theta + in\phi\right)$$

- Presently, the TORIC dielectric models IBW, ICW, and FW dispersion; LH dispersion is in development.

- Resolution requirements depend on the specific wave scenario being modeled.
  - MC - presence of IBW implies $k_\perp \rho_i \simeq 1$ and if $k_\perp \sim \frac{m}{r}$, or $M_{\max} \leq \rho^* = 255$, for typical device parameters.
  - In LHRF, $(\Omega_e \gg \omega \gg \Omega_i)$, dispersion yields: $\frac{\omega_{pe}}{\omega} k_\parallel \sim k_\perp \sim \frac{m}{r} \rightsquigarrow M_{\max} \sim 1000$

The Computational Problem in TORIC is one of Matrix Inversion

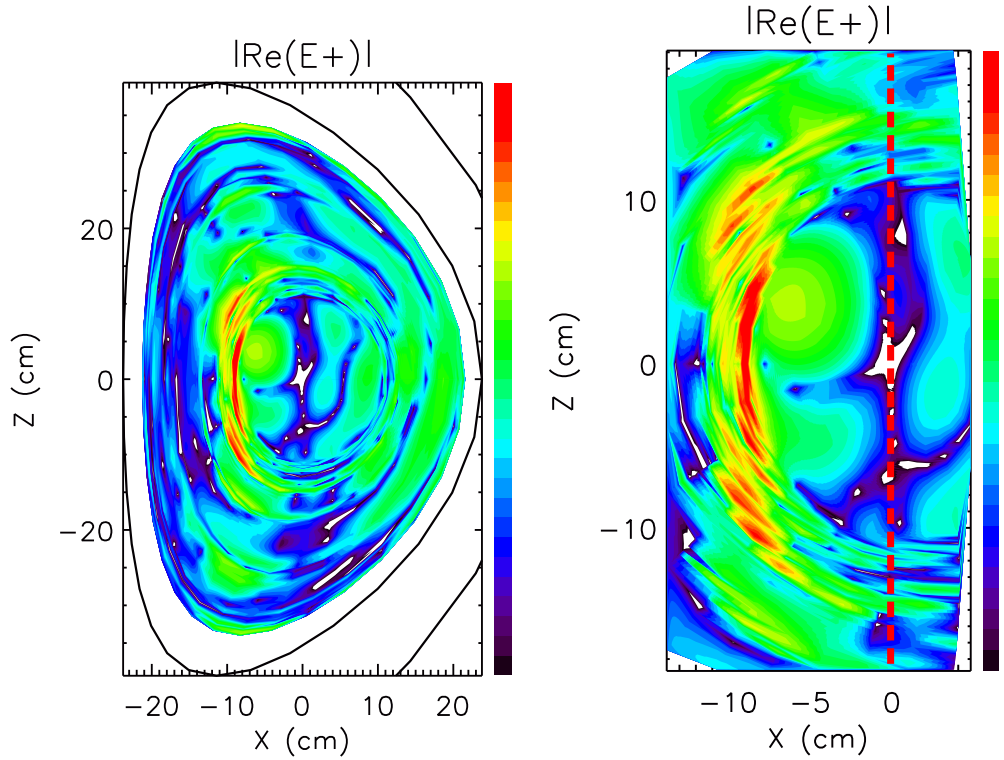
$$\underset{\rightrightarrows}{\mathbf{A}} \cdot \mathbf{E} = \mathbf{J}_A \text{where } \underset{\rightrightarrows}{\mathbf{A}} = \begin{pmatrix} \mathbf{D} & \mathbf{U} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{L} & \mathbf{D} & \mathbf{U} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{L} & \mathbf{D} & \mathbf{U} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{L} & \mathbf{D} & \mathbf{U} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{L} & \mathbf{D} \end{pmatrix}$$

- Discretizing the BVP produces a matrix equation, in which the blocks, **L**, **D**, and **U** are each dense matrices of size $O(6N_m)^2$.
- The individual $3N_r$ blocks are inverted using `(SCA)LaPack` to do an **LU** decomposition. When run in parallel mode, `TORIC` distributes the memory of each block (which can be as large as 0.6 GB, for the larger runs) across the processors as well.
- An out-of-core technique in which inverses of blocks are temporarily stored on disk greatly extends the size of problem that can be done with both serial and parallel versions of the code.

New Code capabilities lead to new physics regimes

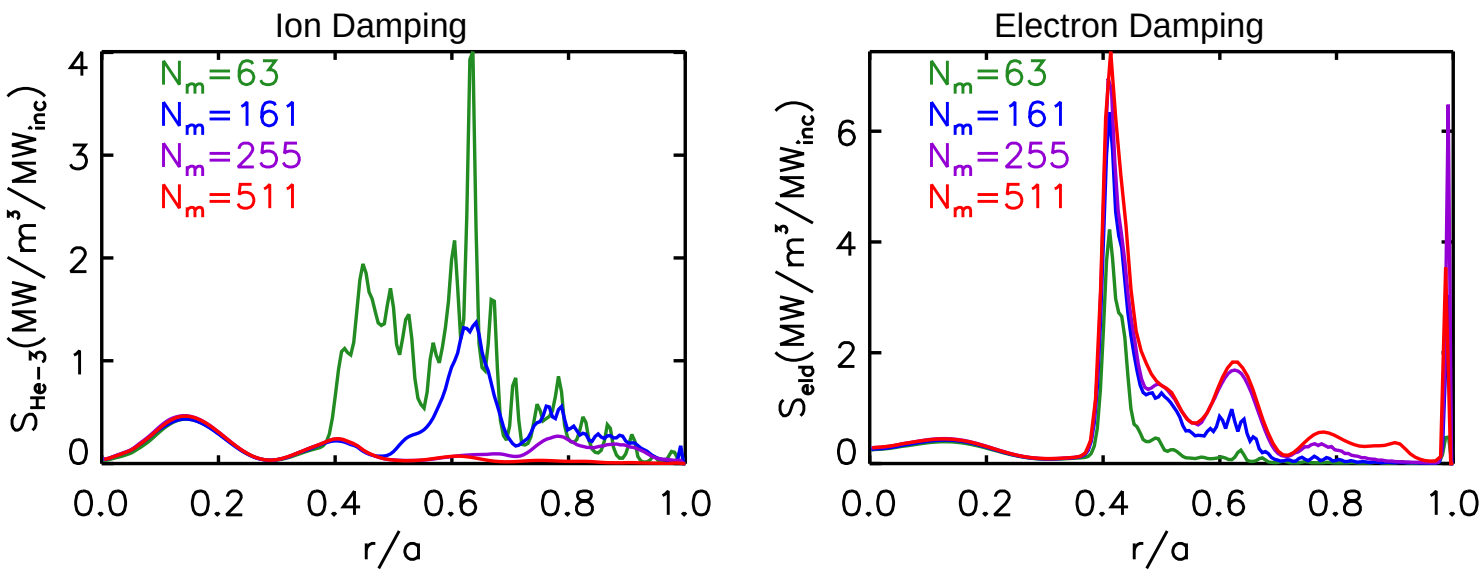
- Serial Improvements: out of core solver, algorithmic improvements in power calculations, and in-lining of some temporary arrays.
- Parallelization of `TORIC`: Distribution of matrices across processors, use of `ScaLapack` for parallel matrix operations.
- High Harmonic Damping
- EFIT Equilibria
- Integrated Electron Fokker-Planck Routines for Current Drive using QL diffusion from all toroidal harmonics

15 Poloidal Modes are insufficient to resolve MC layer



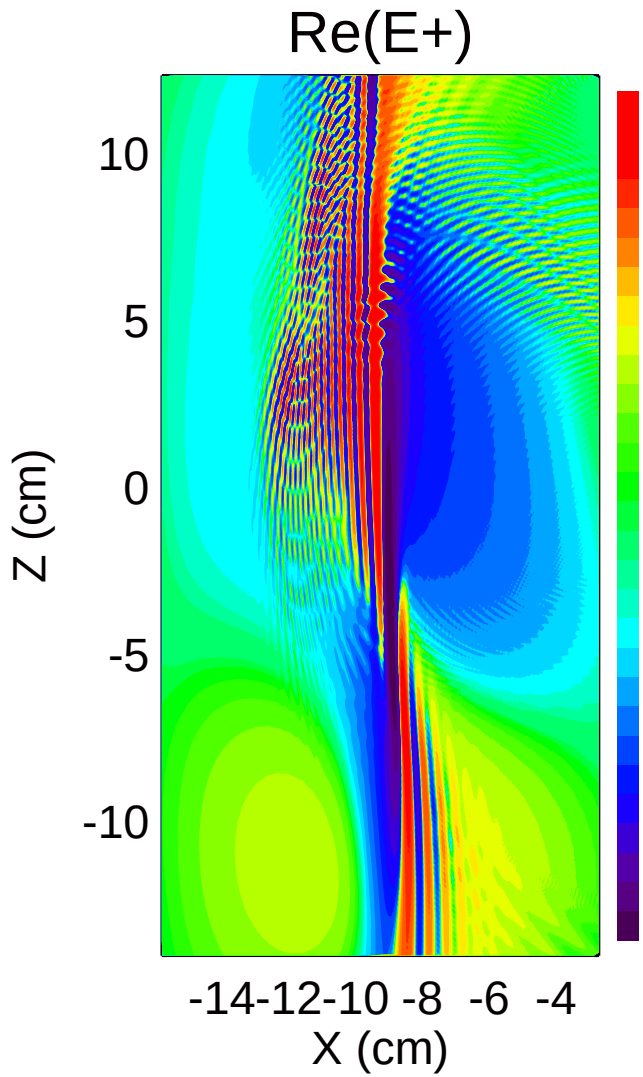
- $N_m = 15$ for $\mathrm{D}(47\%) - \mathrm{He}^3(24\%) - \mathrm{H}(5\%)$ mode conversion case.
- Proper radial localization in a vertical layer IS NOT captured. Magnification of the layer shows a tendency to follow flux surfaces.
- Spurious minority damping$\rightarrow$ power balance of 85% ions and 15% electrons.

CMOD mode conversion is fully resolved at $N_m = 511$



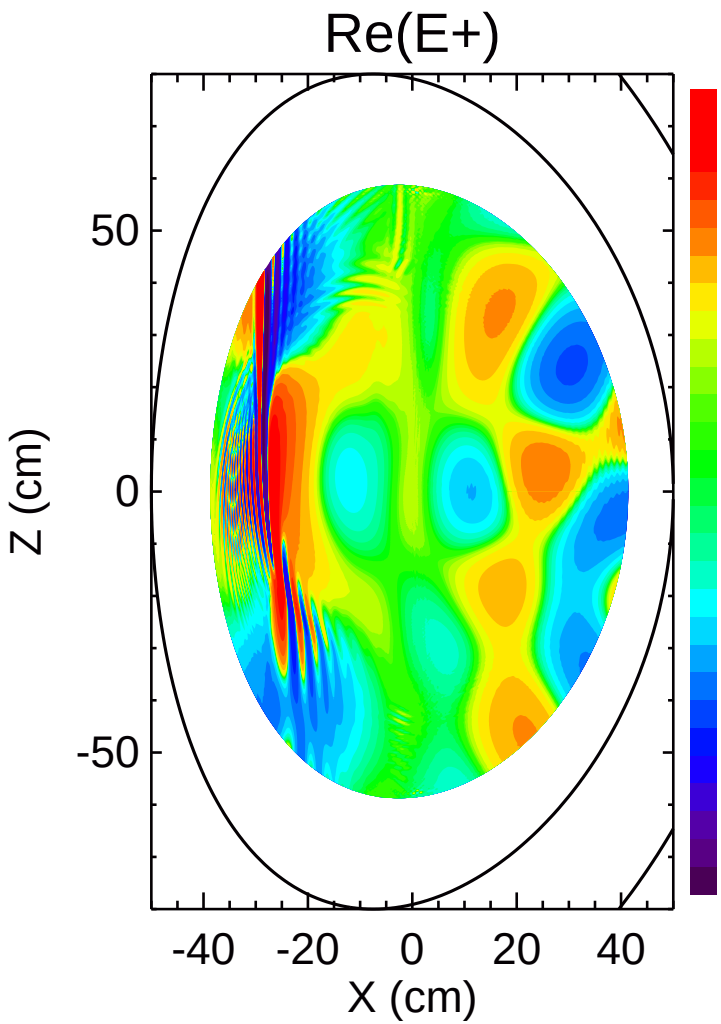
- With sufficient resolution, we see most off-axis damping on He^3 was an artifact.
- The IBW damping increases and broadens. Final power balance of 7% ions and 93% electrons.
- The 511 run required one node of an IBM-SP with 32 processors and 32 GBytes of RAM and completed in 3 hours. (The run was not possible with earlier serial versions of the code)

High resolution needed by LH is possible



- A resolution of $N_m = 1023$ and $N_r = 480$ is more than enough to resolve the mode conversion layer.
- A simulation of this size uses 128 pc on an IBM-SP and takes 13 hours to run.
- This is enough resolution to resolve full-wave LH physics.

Asdex MC layer is at a larger minor radius



- In this typical Asdex MC shot, the layer is far from the center of the device and requires much more poloidal resolution than the CMOD case.
- While the CMOD simulation converged acceptably at $N_m = 255$, Asdex requires at least $N_m = 511$.
- This is the first converged full-wave simulation of this Asdex scenario.

Summary

- With the new parallel version, the code runs with sufficient resolution to resolve the mode conversion layer. While previously, only 160–170 poloidal modes was feasible, `TORIC` now runs quickly enough that studies with $N_m = 511$ are routine, and 1023 is done within a day.
- Recent numerical and physics enhancements to `TORIC` will now permit the exploration of the full-wave LH regime in toroidal geometry.
- ρ^* scaling of MC resolution requirements has important implications for modeling the next generation of fusion devices.