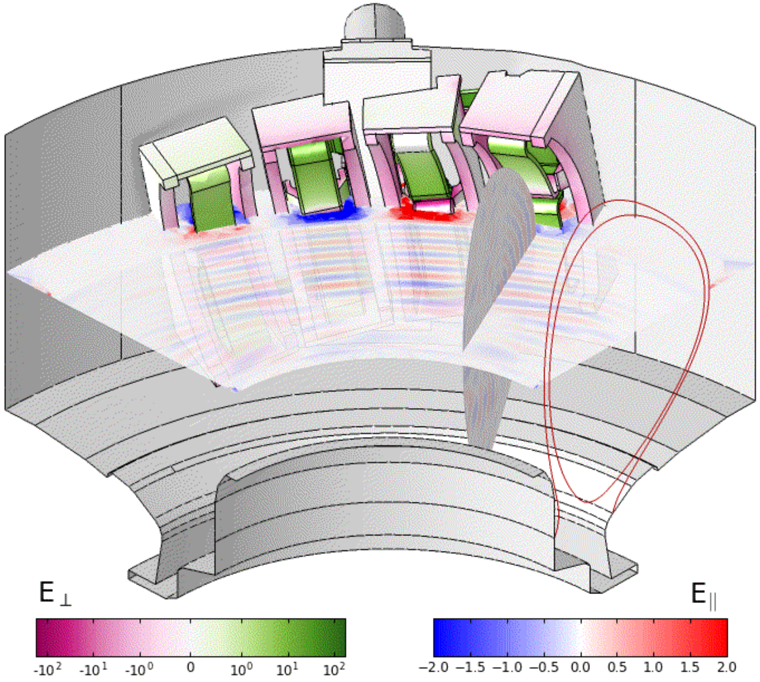
Antenna to Core: A New Approach to RF Modelling



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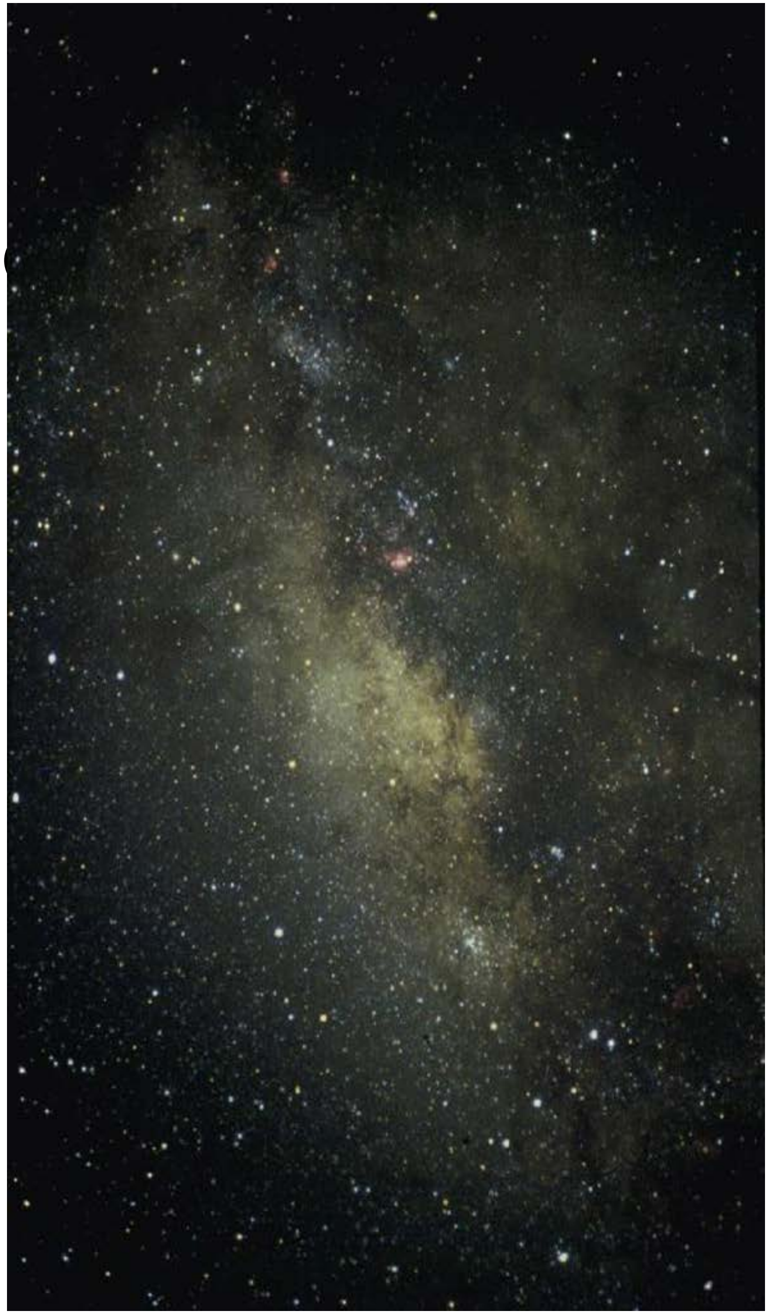
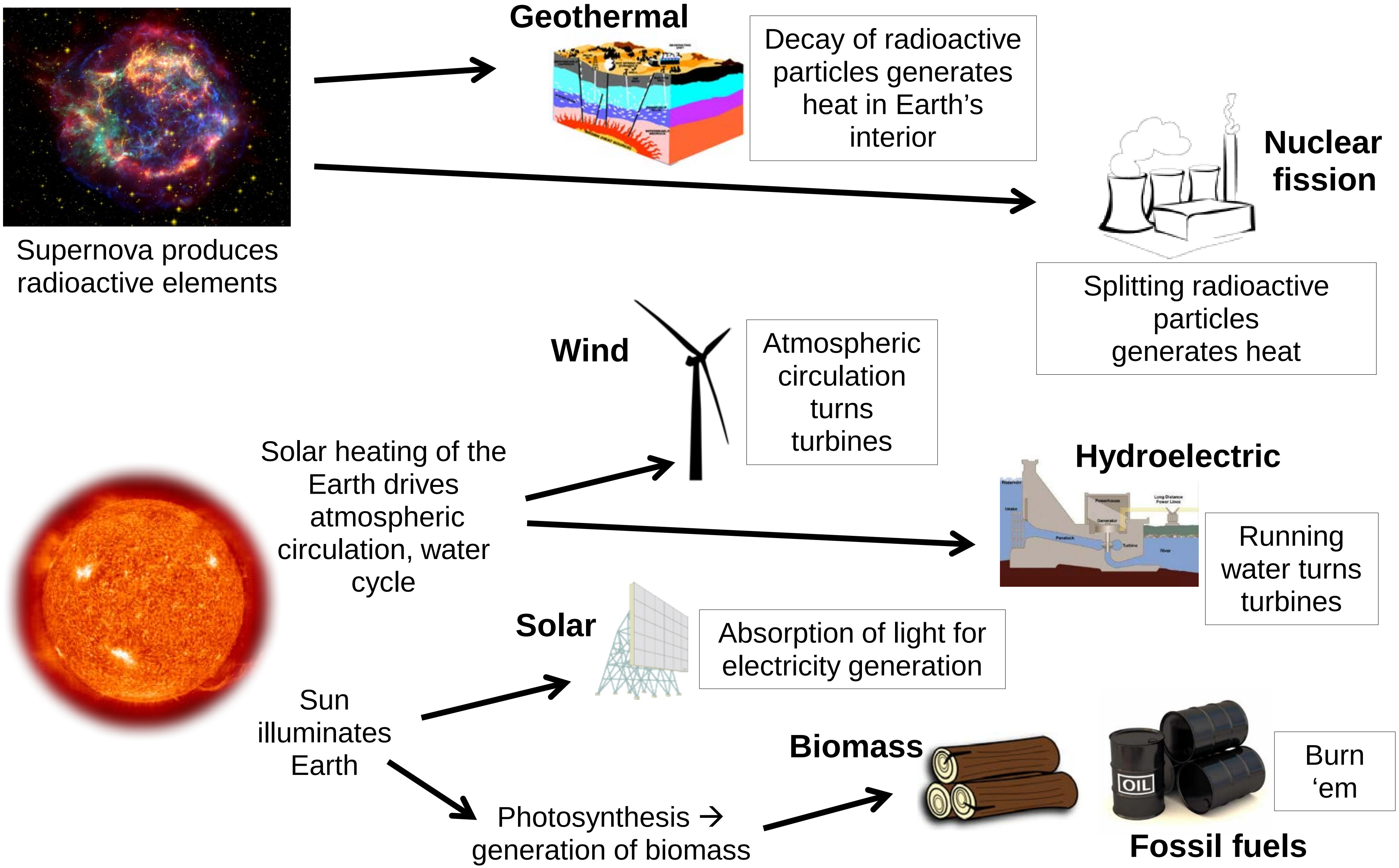
Thanks to: S. Shiraiwa, P. Bonoli, J. Lee, T. Kolev, M. Stowell, and the RF SciDAC team.

Fusion is a form of *nuclear energy*

- A huge amount of energy is released when isotopes lighter than iron combine to form heavier nuclei, *with less final mass*
- It is an ubiquitous energy source in the universe
- It is not (yet) a practical energy source on earth



Terrestrial energy sources have their origin in the nuclear fusion reactions of stars



Supernova produces radioactive elements

Geothermal

Decay of radioactive particles generates heat in Earth's interior

Nuclear fission

Splitting radioactive particles generates heat

Solar heating of the Earth drives atmospheric circulation, water cycle

Wind

Atmospheric circulation turns turbines

Hydroelectric

Running water turns turbines

Sun illuminates Earth

Solar

Absorption of light for electricity generation

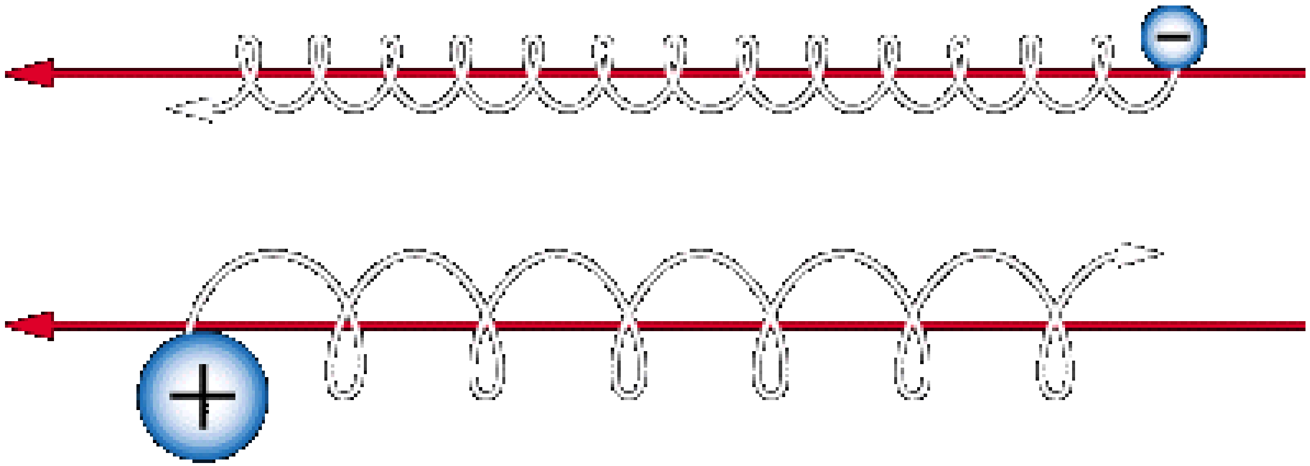
Photosynthesis → generation of biomass

Biomass

Fossil fuels

Burn 'em

Gyro-motion Of Charged Particles Enables Magnetic Confinement, *perpendicular to B-field*



Ionized particles are deflected by the Lorentz force and bent into circular orbits.

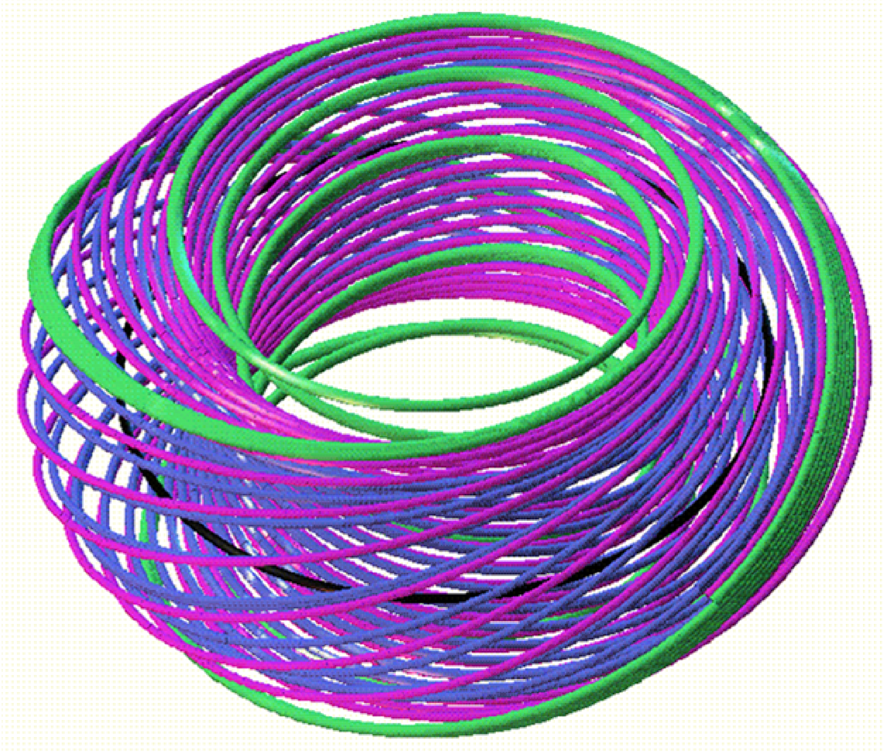
Gyro-radius $\rho = \frac{mV_\perp c}{qB} \propto \frac{\sqrt{mT}}{B}$

Gyro-frequency $\omega_c = \frac{eB}{mc}$

At B = 5T, T = 10keV

- ρ_e = 0.067 mm
- ρ_i = 2.9 mm
- R/ ρ_i > 1,000
- $\omega_e = 8.8 \times 10^{11}$ rad/sec (μwaves)
- $\omega_i = 4.8 \times 10^{8}$ rad/sec (FM radio)

Close the ends, and . . .

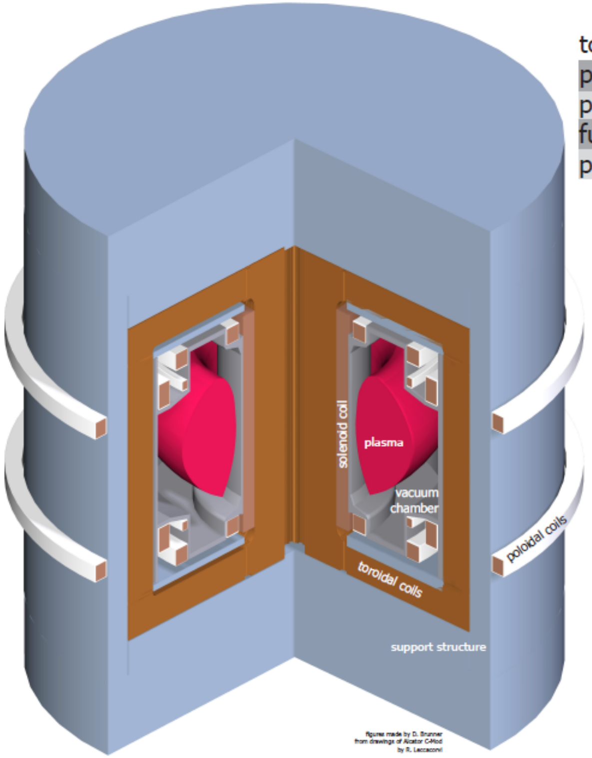


. . . toroidal confinement is born
(the tokamak)

“Donuts. Is there anything they can’t do?”
--H. Simpson

What is a tokamak?

тороидальная **ка**мера с **ма**гнитными **к**атушками (toroidal'naya kamera s magnitnymi katushkami)
“A toroidal chamber with magnetic coils”



figures made by D. Brunner
from drawings of Alcator C-Mod
by R. Leccacorvi

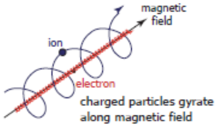
tokamak have lead the way in magnetic confinement fusion:

plasma temperature	520,000,000°C	JT-60, Japan
plasma pressure	1.8atm	Alcator C-Mod, USA
fusion power	16MW	JET, EU
pulse length	5+hours	TRIAM-1M, Japan

toroidal vacuum chamber
protects and isolates plasma

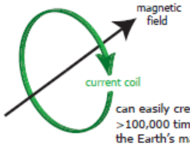
efficient fusion power production
and good plasma confinement
require ultra high vacuum environment

magnetic coils confine plasma
and insulate from chamber wall



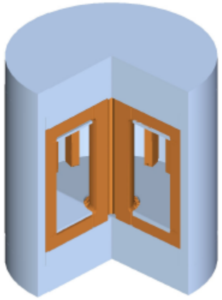
charged particles gyrate
along magnetic field

magnetic field created with
coils of current

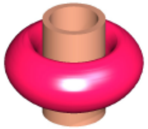


can easily create magnetic fields
>100,000 times stronger than
the Earth’s magnetic field

strong structure supports
forces from magnetic coils

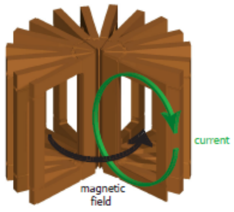


solenoid coil drives current in plasma,
necessary for stability

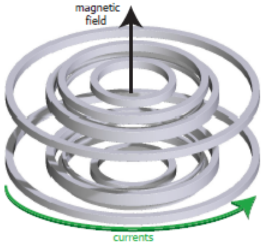


couples current to plasma with
no direct contact in the same way
a transformer couples power
between circuits

toroidal coils create main
confining field

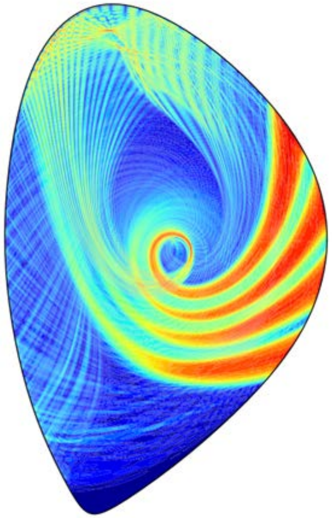


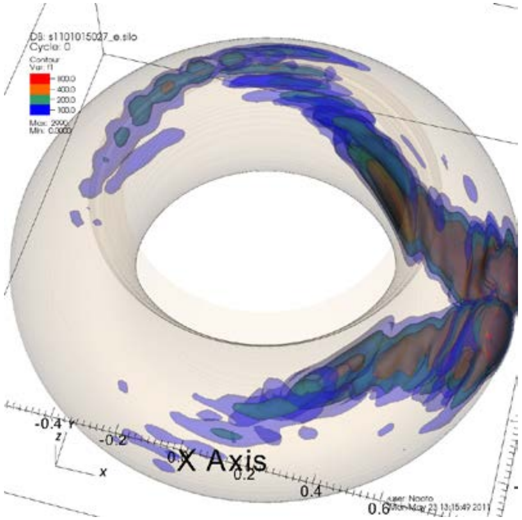
poloidal coils keep force balance
and shape plasma to improve confinemnt



Leading-class computers allow for modeling of RF wave heating physics in core and edge regions with great detail – but separately

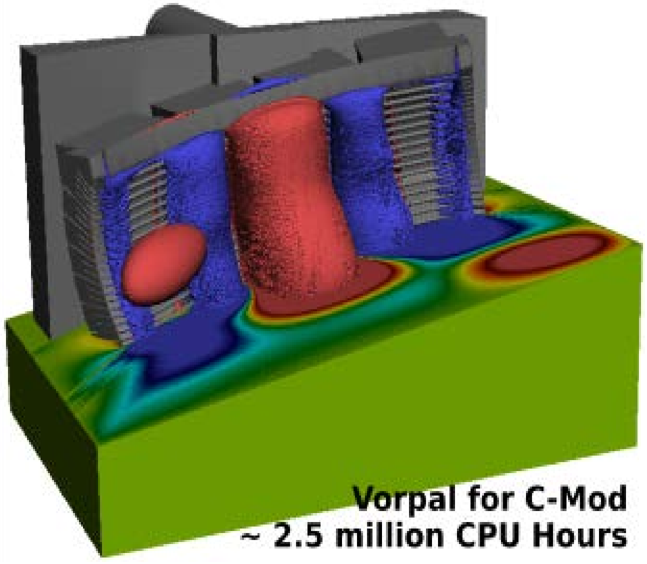
Short wavelength
Lower hybrid
waves
In TORLH – 5 x 10^3 cpu-hours





Long wavelength
Ion cyclotron fast
waves in 3D
with AORSA –10^6 cpu-hours

- RF field in
  - Core
  - SOL/antenna
- RF boundary sheath
- However, core and edge regions are modeled separately…



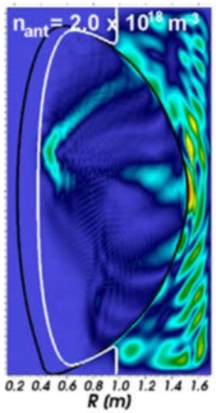
Vorpal for C-Mod
~ 2.5 million CPU Hours

RF Simulations have been progressing towards more realistic geometries.

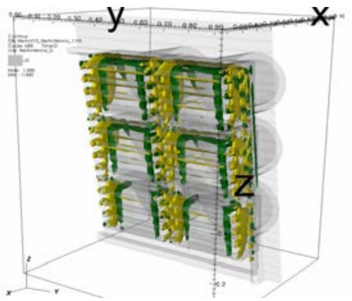
- Need of models with realistic 3D antenna and edge geometries that also account for the plasma response.
- Several physics issues require inclusion of edge plasma and antenna with confined core plasma simulations to be understood:
  - anomalous edge losses observed in several tokamaks,
  - efficiency of antenna coupling accounting for the full 3D geometry and in small device plasmas where wavelength is comparable to the device size,
  - and experiments where the waves are weakly absorbed and reflect from the device walls.
- Individually, good simulations for each region are available. However, extending them to the entire domain is difficult.
- The approach described here is applicable to all these cases.

Solution: Hybrid (core spectral / edge FEM) simulation.

AORSA



Vorpal (FDTD)



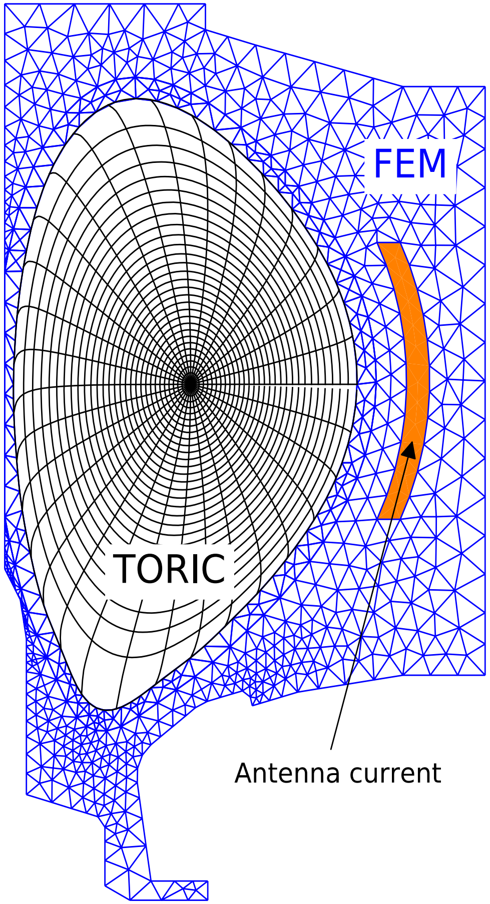
Spectral:

- Hot plasma formulation is algebraic
- Availability of mature scientific codes
- 2D or 3D by single toroidal mode analysis
- Dense matrices
- Handling of sharp geometrical features more difficult

FEM/FV:

- Accurate geometry description (antenna, wall, SOL, ...)
- Cold plasma wave with collisions are straight-forward to implement
- Sparse matrices
- Not easy to deal with hot plasma dispersion ($k_{||}$)

TORIC-FEM coupling retains the best of both methods



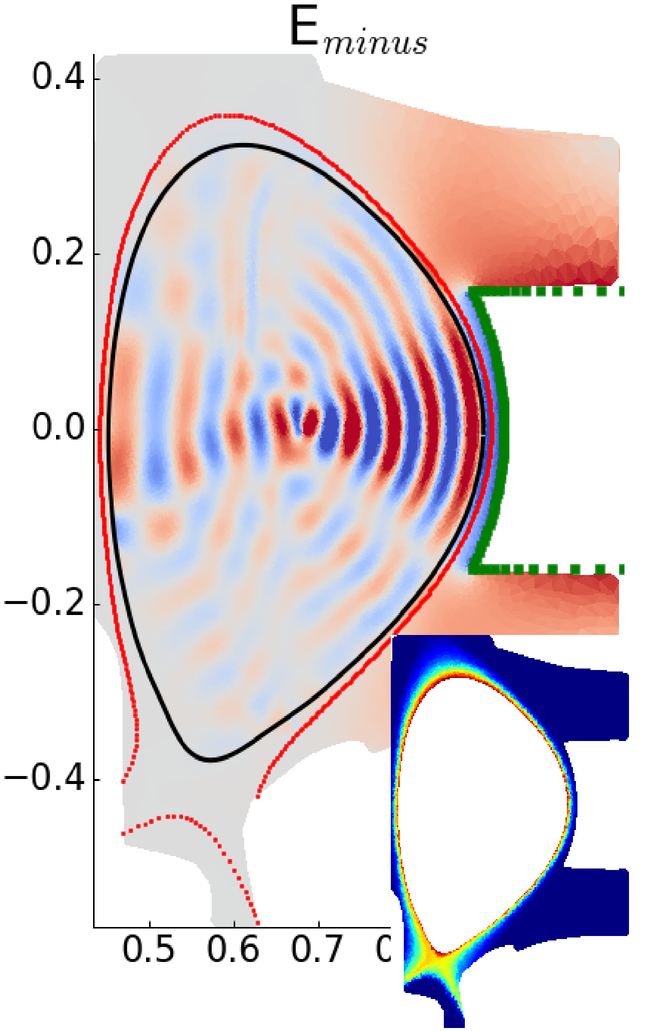
Core

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

Edge

- **Unstructured mesh** with complex geometry (either 2D or 3D)
- Cold plasma with collisions.

Boundary **matching technique** to build integrated solution

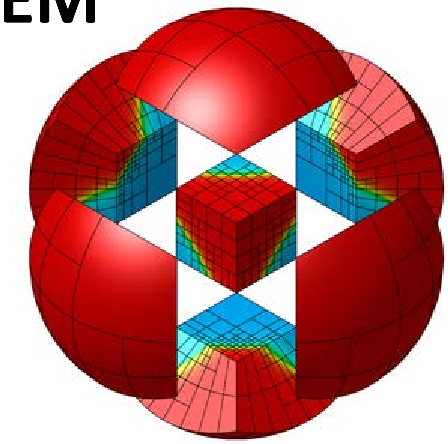


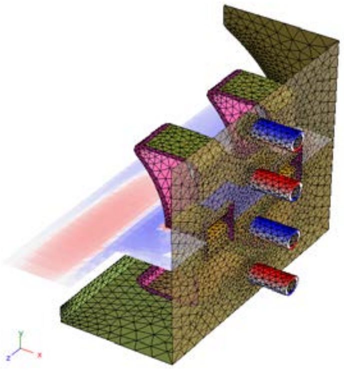
Density in SOL

- Mode matching technique is mathematically equivalent to impedance/admittance load methods used some antenna loading calculations.

FEM solution and workflows are done with open source tools

MFEM

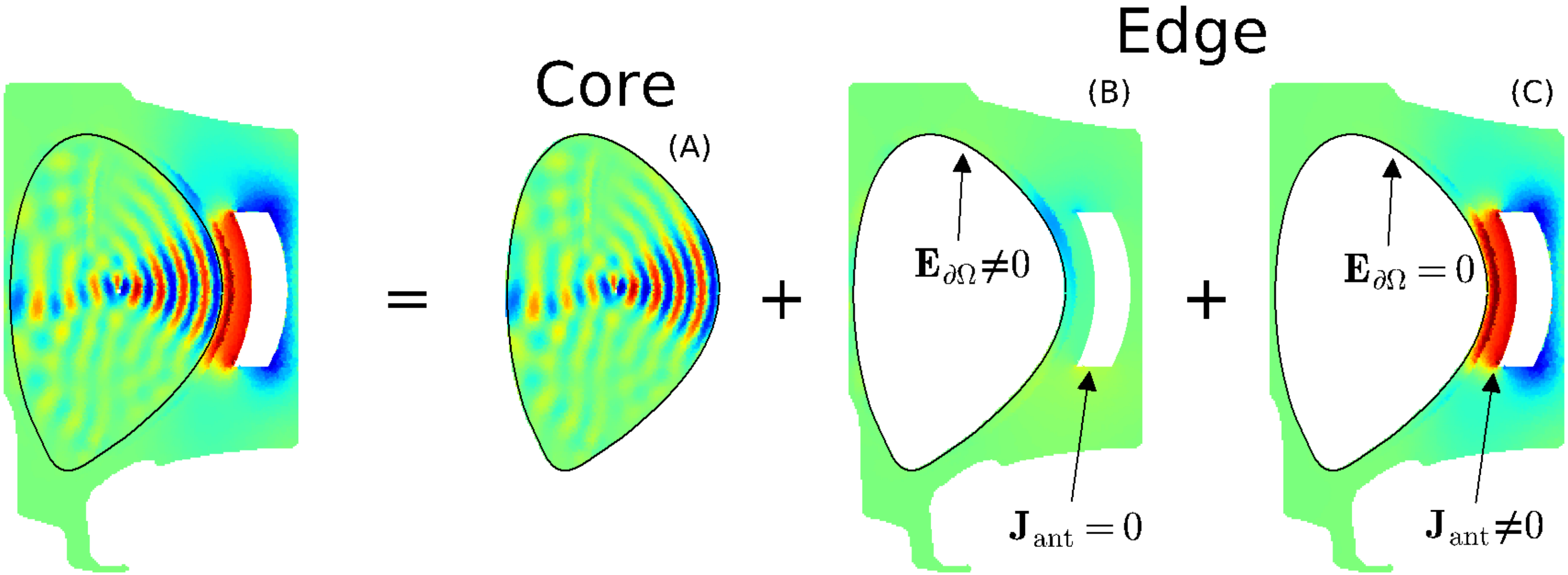




πScope

- MFEM is a free, lightweight, scalable library for finite element methods (see http://mfem.org/features for details.)
- PyMFEM – custom python class for constructing MFEM simulations.
- πScope - workflow manager with GUI to execute physics cases, see http://piscope.psfc.mit.edu

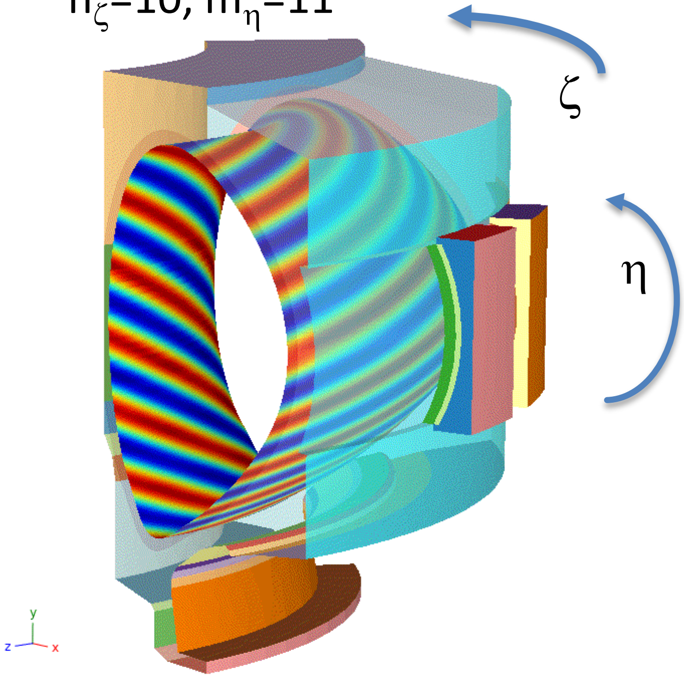
Domain decomposition at LCF to separate regions

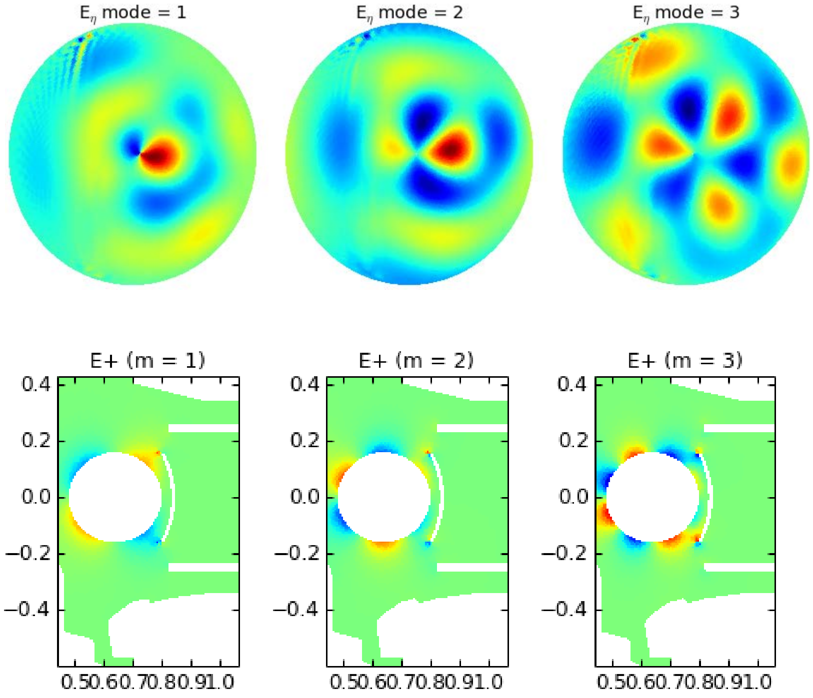


- Calculate the separate Green’s function solutions for the core (in) and edge (out) regions for different modal excitations (full solutions in each domain are shown above).
- Superimpose the solutions so that boundary conditions are satisfied – superposition principle in linear Maxwell’s equations.
- This method is exact – no approximations.
- Analogous to constructing particular solution from homogenous ones.

Green’s function responses found for singular Fourier surface excitations

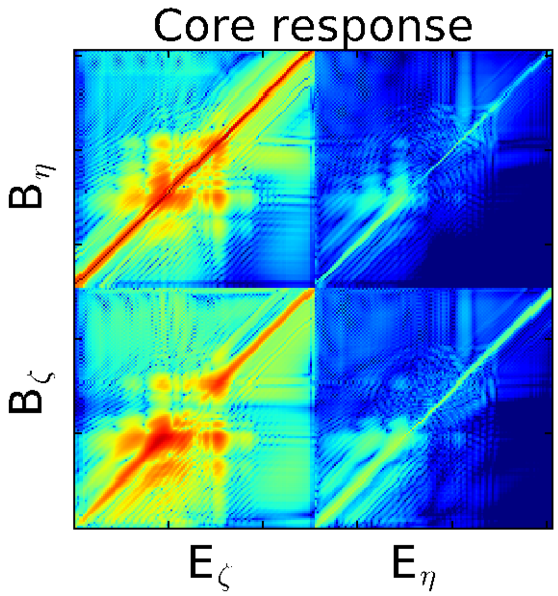
Poloidal E field excitation,
n_ζ=10, m_η=11

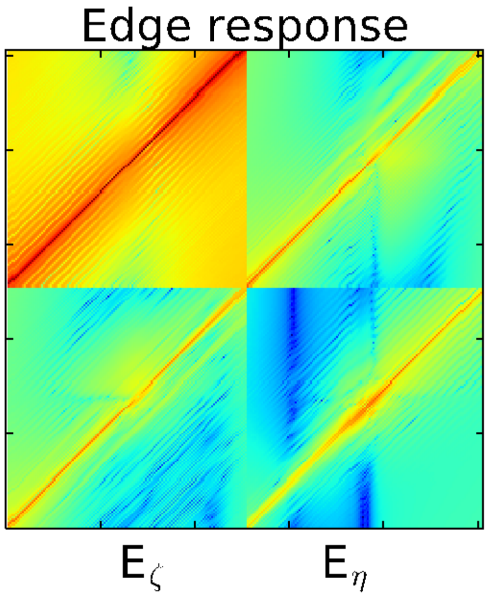




- The domains are connected through an admittance response. (η and ζ are perpendicular and parallel to equilibrium magnetic field)(admittance == B/E)
- The admittance is constructed for a Fourier poloidal and toroidal basis.

Admittances are matched at the domain boundary to determine the solution





255x255 modes

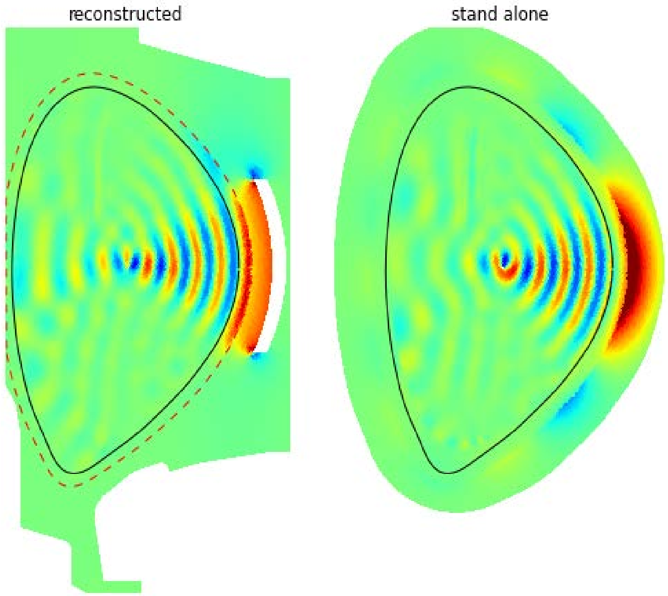
- Inner and outer electric field modes match for each mode at interface by construction.

$$\sum_m a_m E_{core\ m} = \sum_m a'_m E_{edge\ m}$$

- Matching magnetic fields in presence of antenna currents given the matching amplitudes => a small matrix system:

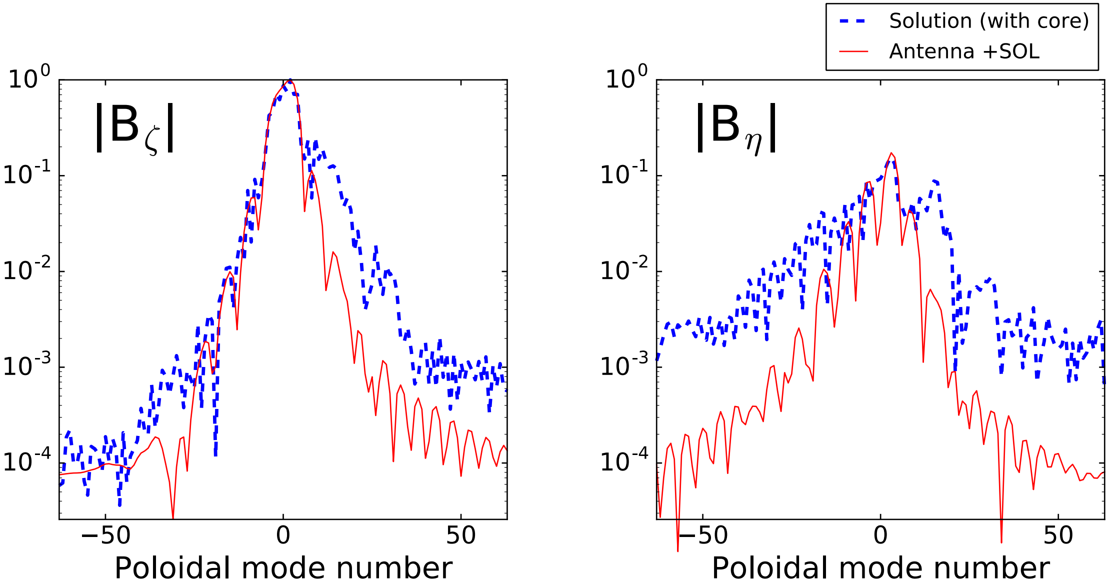
$$\sum_m a_m B_{core\ m} = \left(\sum_m a_m B_{edge\ m} + B_{ant\ m}\right)$$

Verification: the reconstructed solution is very similar to a standalone TORIC simulation.

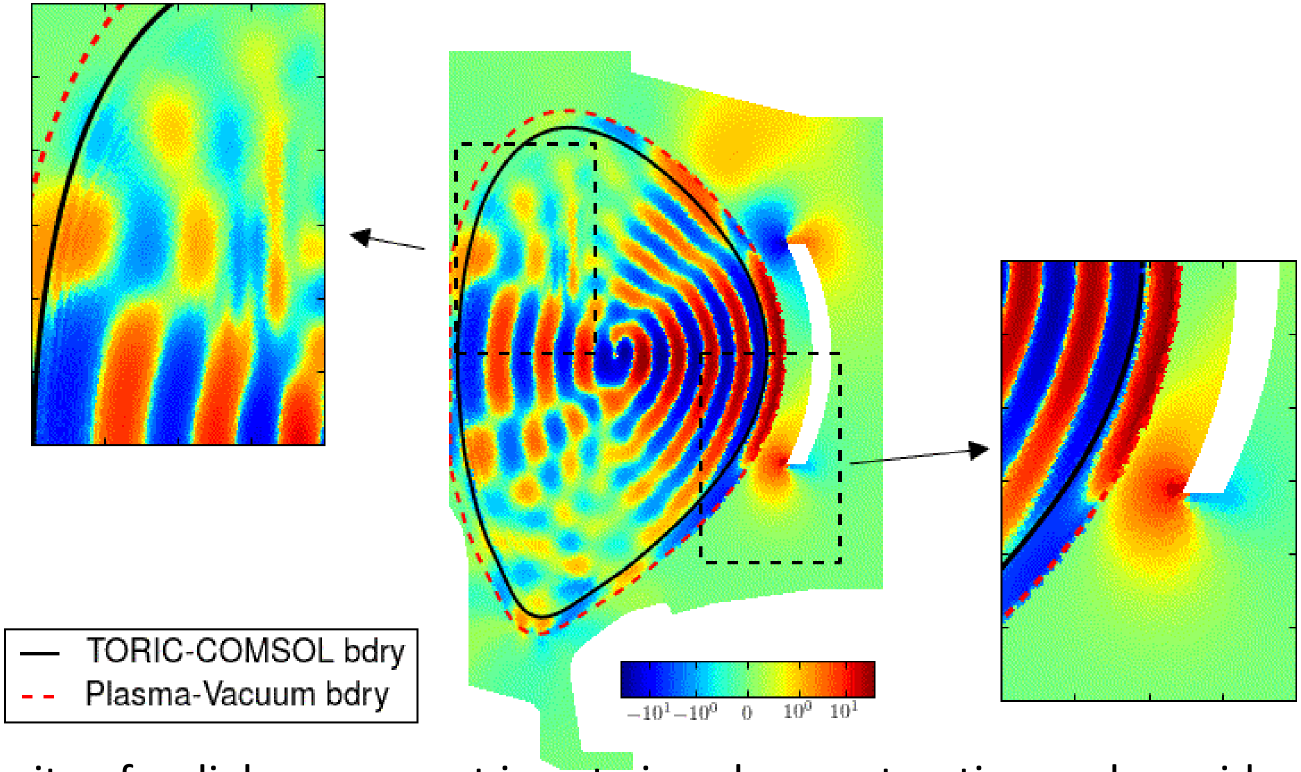


- In the core region, the superimposed solution (left) agrees well with the core solution of TORIC stand alone simulation (right) providing verification of the method.
- There is only vacuum outside LCF.
- Mode amplitude of superimposed solution (blue) spread wider than the antenna excitation amplitude (red).

[Wright RF 2015]



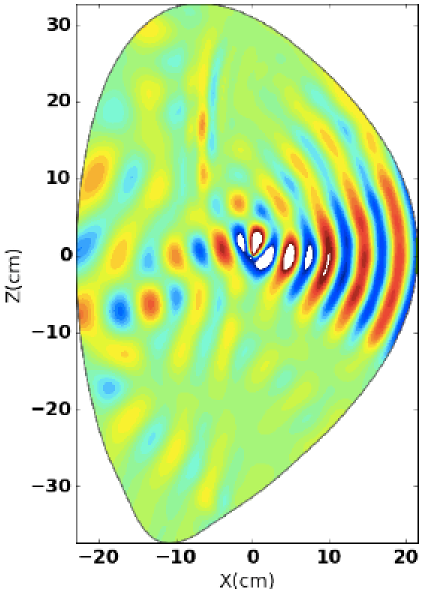
More verification: Radial E_ψ continuity is retained at domain boundary

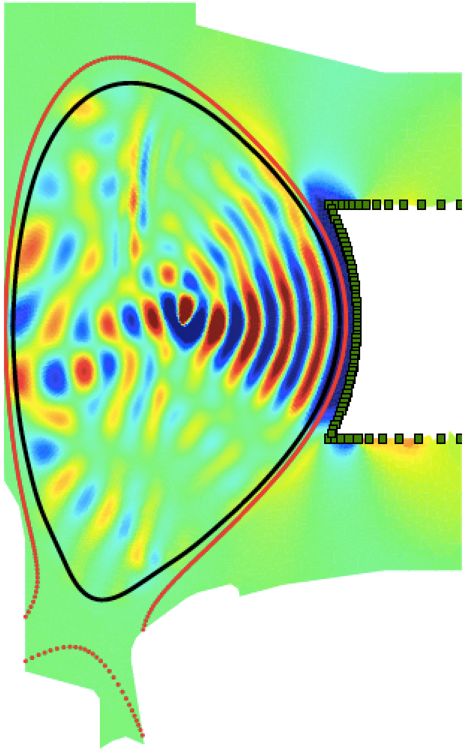


- Continuity of radial component is not given by construction and provides a way to verify the approach.
- Smoothly connected at TORIC/FEM boundary, but it is not at vacuum/plasma boundary.
- Consistent with a continuous dielectric at the former boundary, while it is not at the latter.

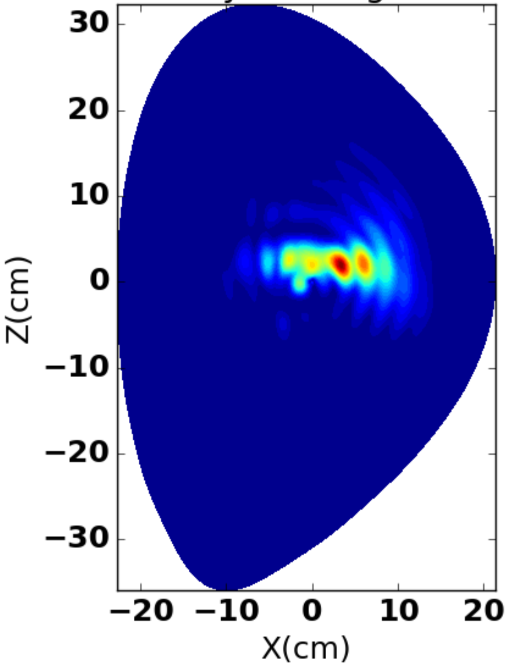
Warm plasma power absorption is obtained from an additional run of core code with mode matched amplitudes

Real Poloidal E-field





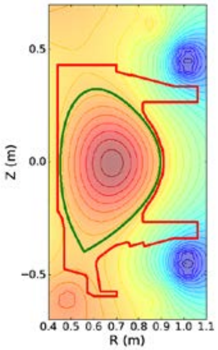
H Minority Heating contours

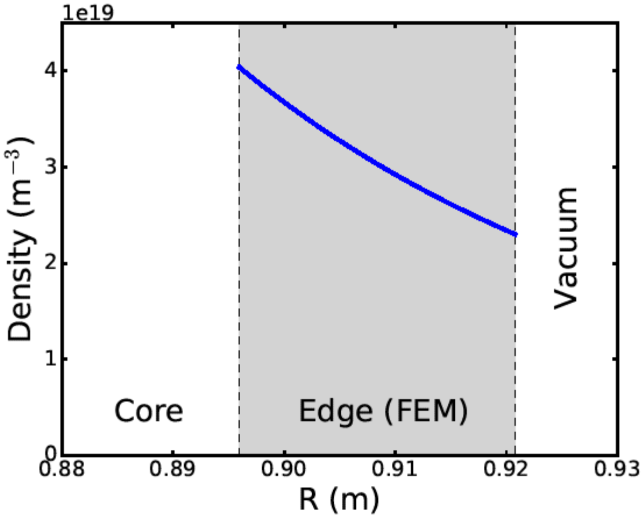


- The composite field contours from the two codes are shown in the center plot.
- Left shows core field reconstruction, Right shows minority ion heating from running core solver with amplitude from matching calculation – needed for kinetic effects.

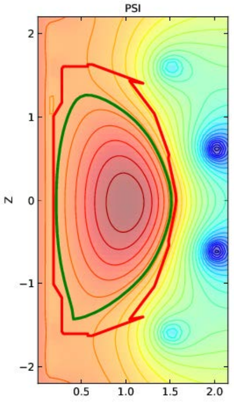
Power absorption in the edge plasma from collisional resistivity

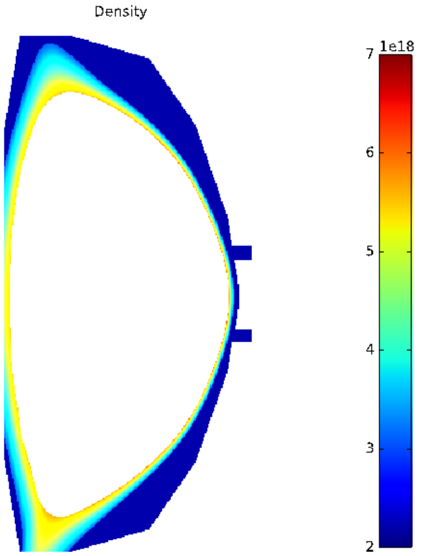
C-Mod





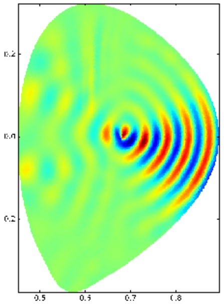
NSTX

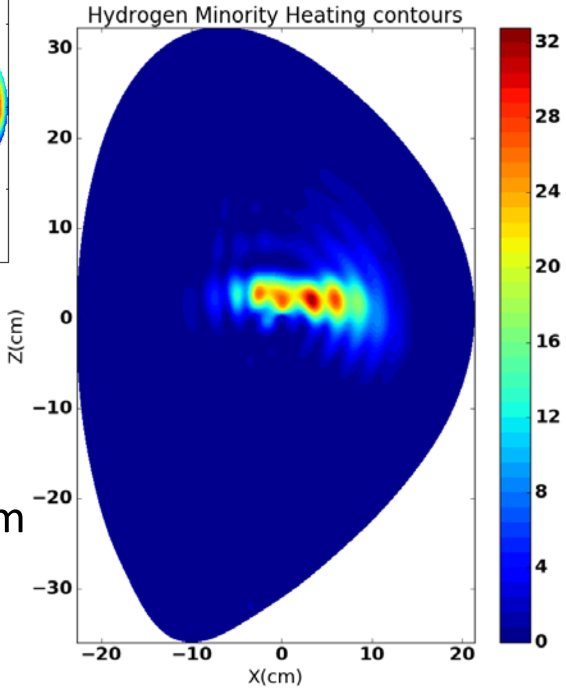




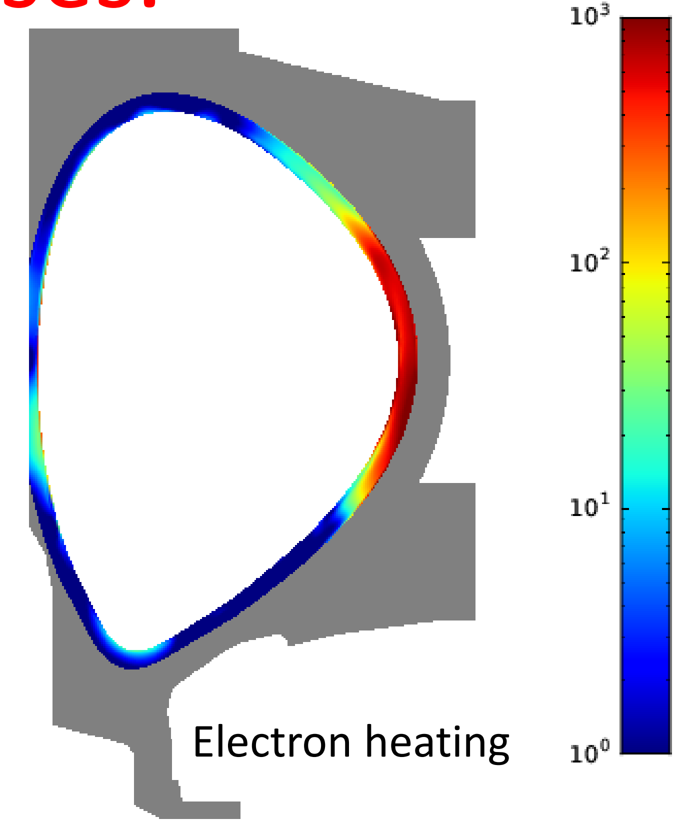
- Density SOL profiles as a function of poloidal flux with gradient scale length. Resistive power losses to electrons from collisions are calculated.
- Significant power coupled from the antenna can be lost in the SOL, even to resistive only losses – loading vs efficiency.

Absorption in SOL increases in weaker absorption cases.





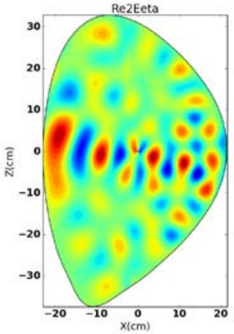
Bulk Deuterium plasma

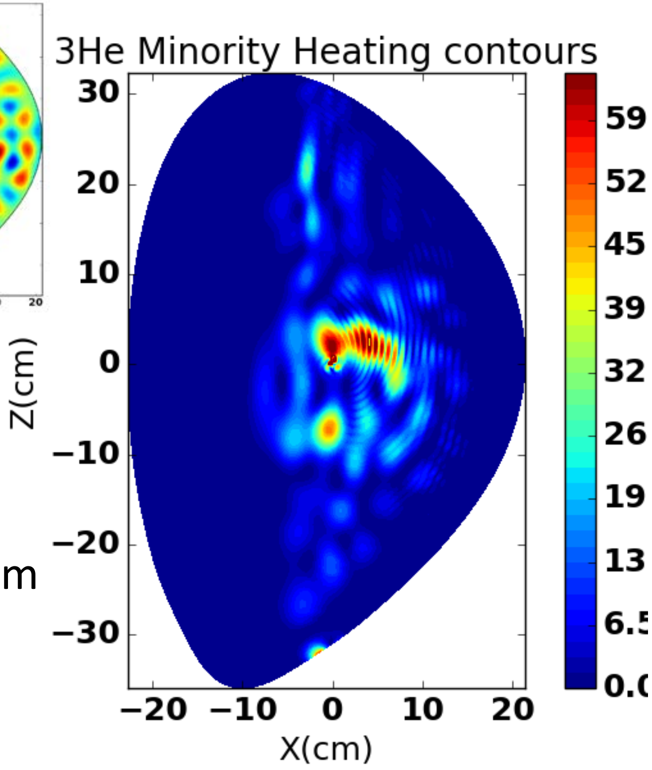


Electron heating

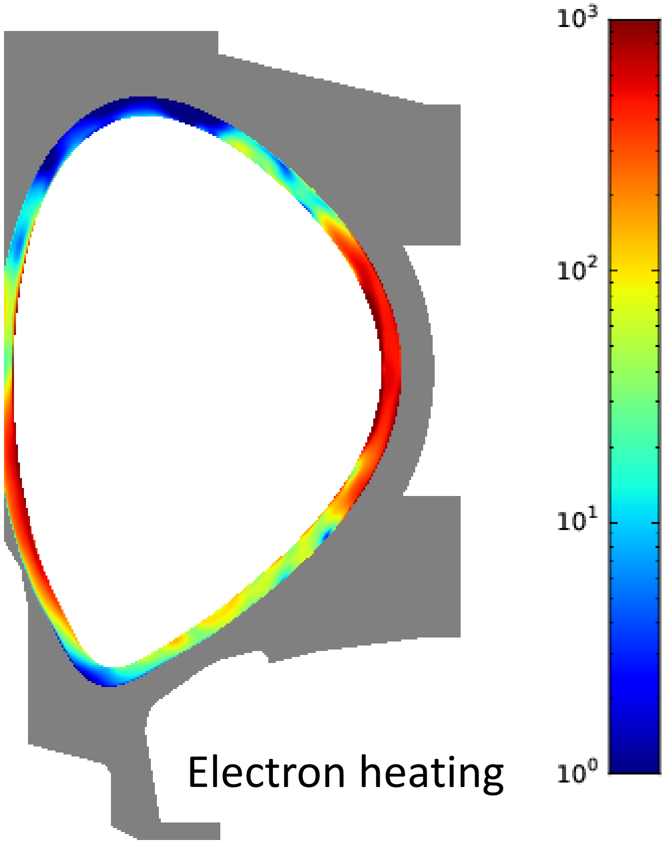
- Power partition: 15% edge, 85% core for Hydrogen heating.
- Loading is about 15 Ω in both cases, different than efficiency: power does not necessarily go into the core.

Absorption in SOL increases in weaker absorption cases.





Bulk Deuterium plasma



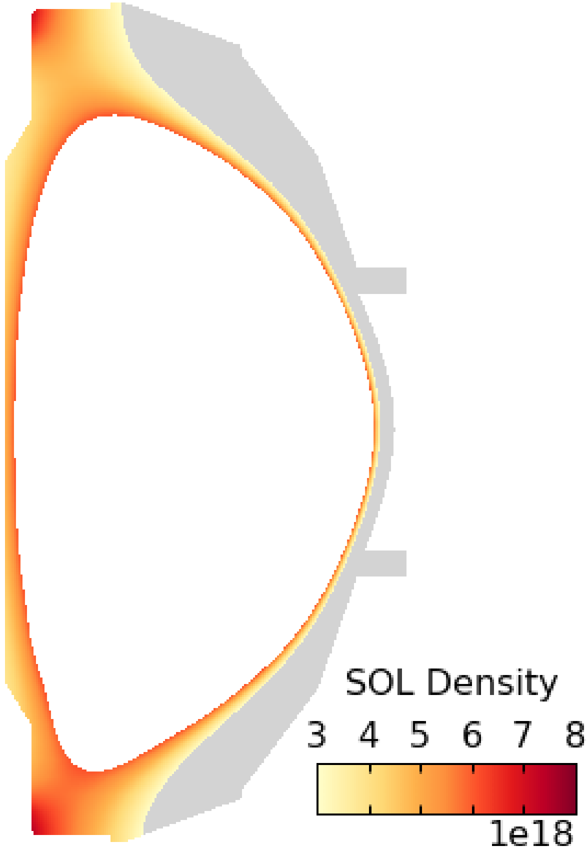
Electron heating

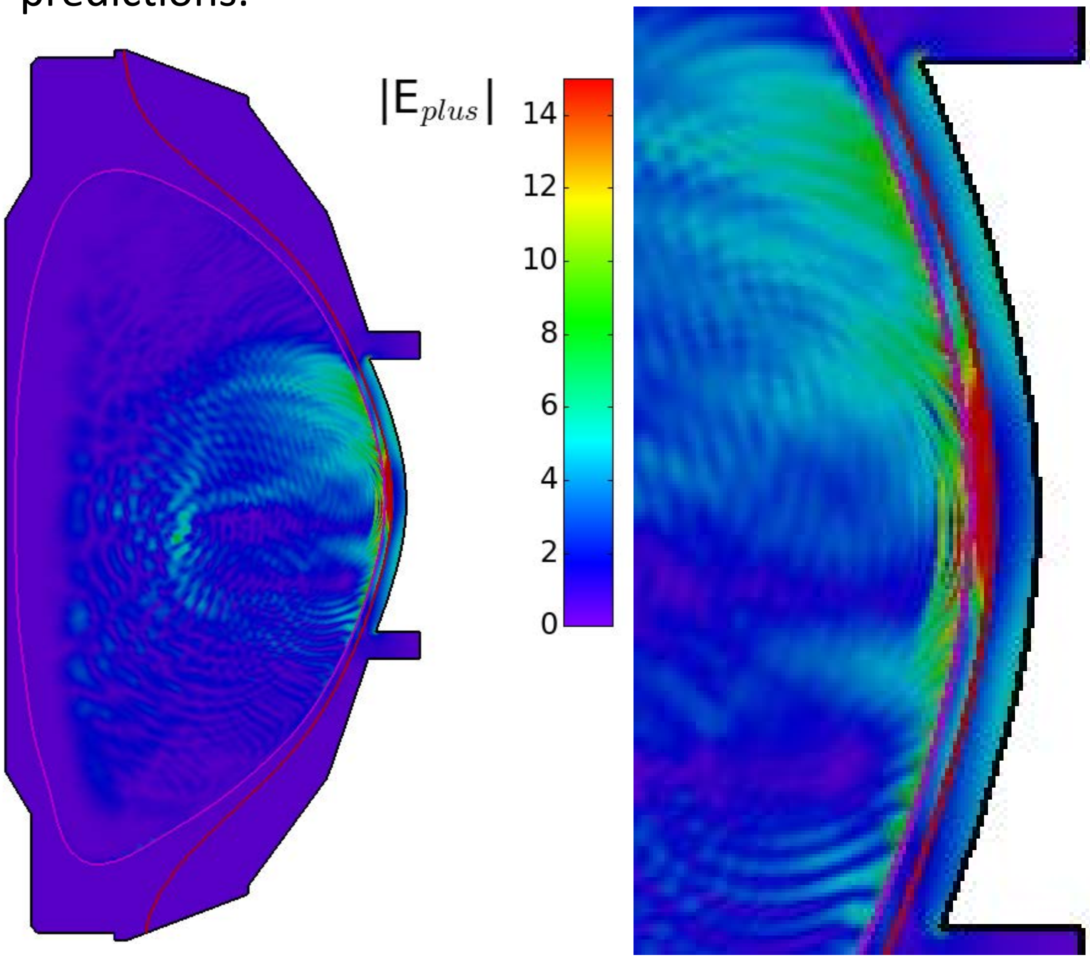
- Power partition: 50% edge, 50% core for Helium heating – these results are for the fairly small Alcator C-Mod device, larger devices should not suffer the same degree of edge losses.
- Note power lost in edge plasma on opposite side of plasma.

Effects of edge plasma propagation

- Loading 4 Ω
  20% power lost in SOL.

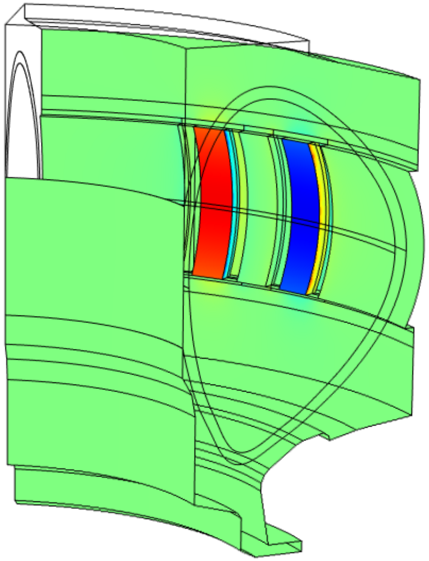
- At high densities (> 2×10^{18} m^{-3}) in SOL, fast waves can propagate.
- Accurate geometry is essential for quantitative predictions.

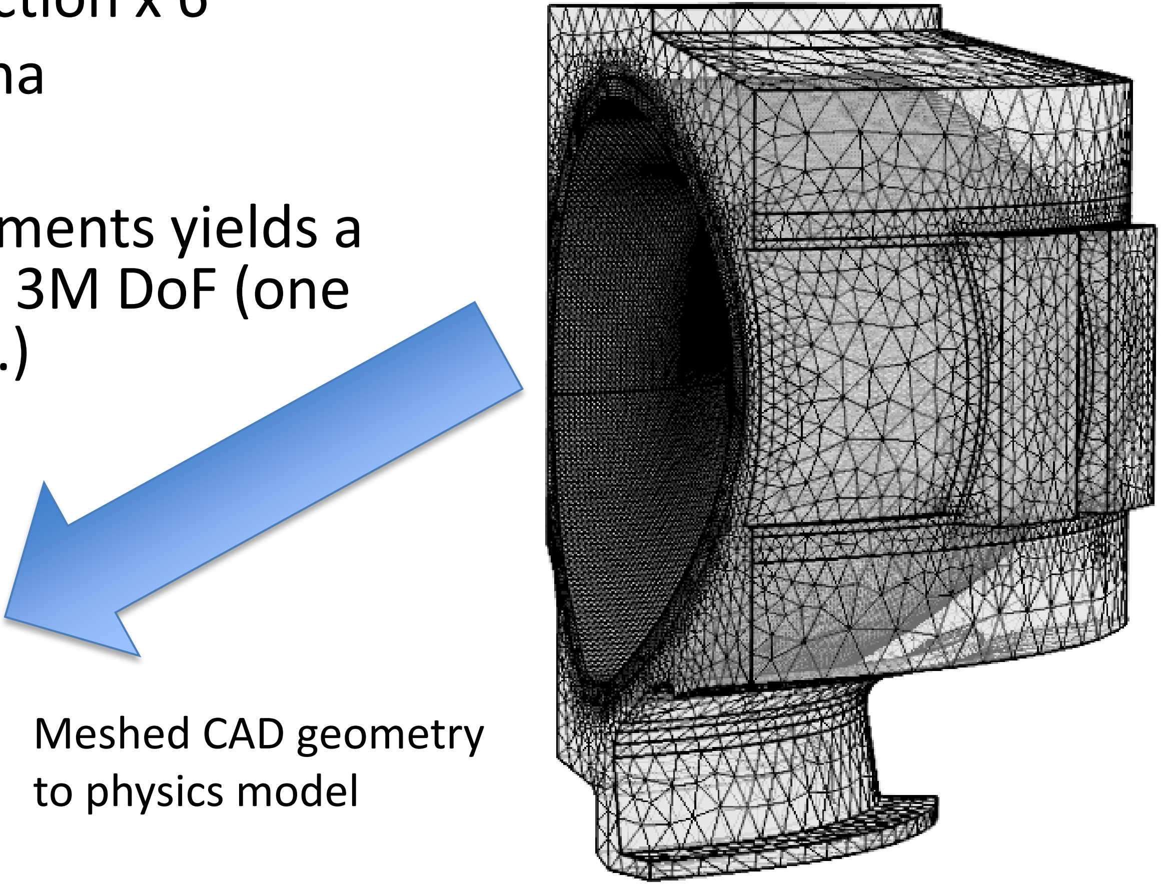




Extending to 3D

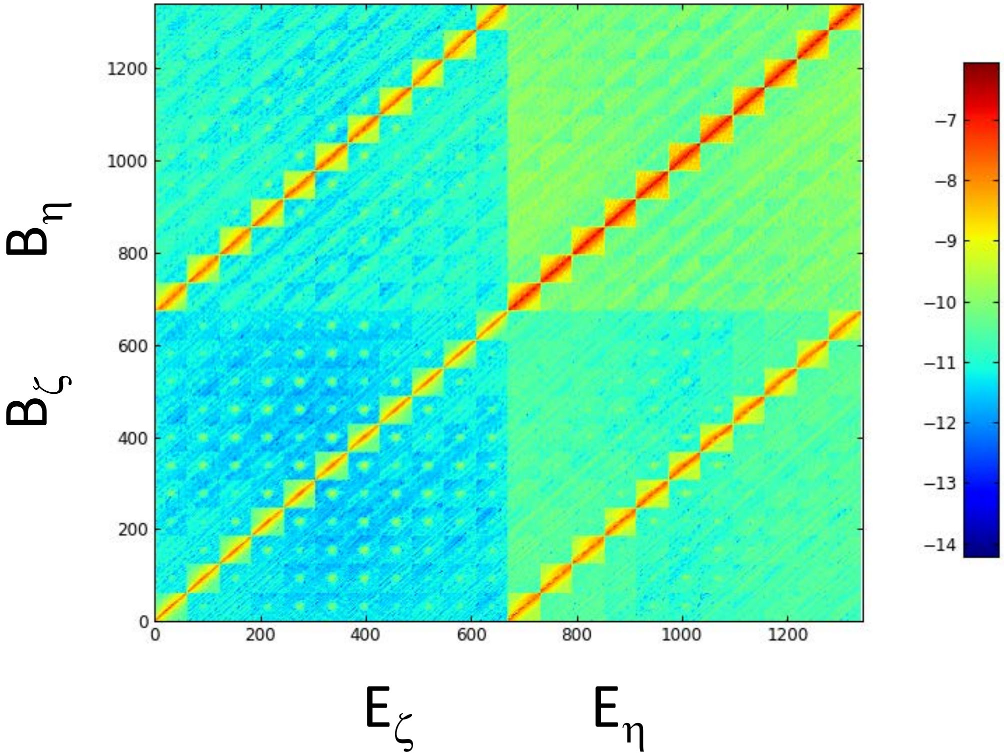
- Realistic Geometry
  - 60 deg vessel section x 6
  - two strap antenna
  - LCFS from EFIT
- Quadratic EDGE elements yields a linear problem with 3M DoF (one model takes 30 min.)





Meshed CAD geometry to physics model

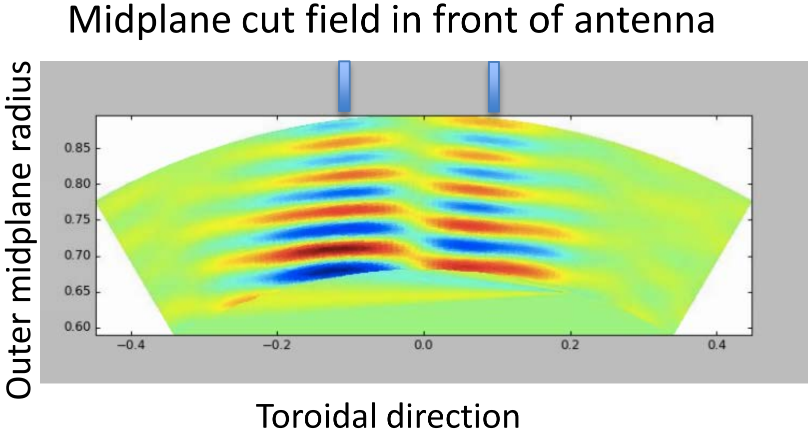
3D simulations are a natural extension of the method

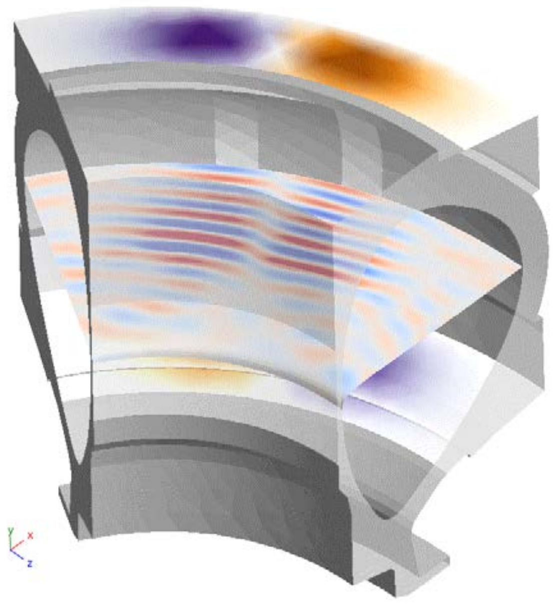


- Model permits structures in SOL that couple toroidal modes in the core.
- In this case, antenna straps are flush and determine the toroidal spectrum but produce minimal toroidal coupling – this can be seen by small but finite off-axis amplitudes.
- 1342 x 2 solutions for core and edge to produce this result.

3D simulations needed for toroidal structure of fields

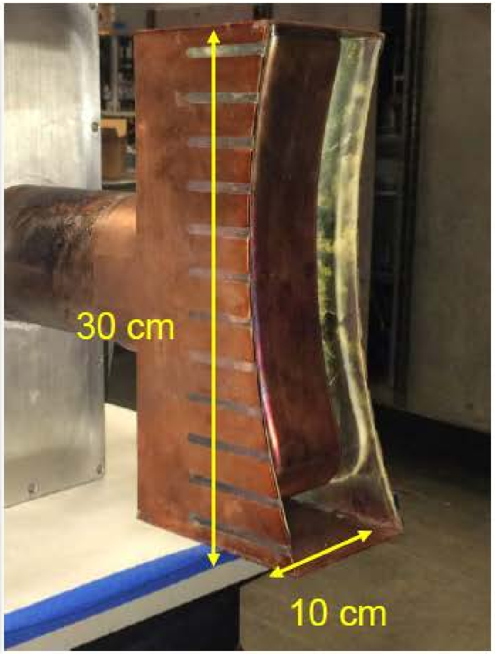
- D-(H) case on Alcator C-Mod
- Voltages on antenna structures are calculated. May be used for studying losses on surfaces.
- Accurate toroidal spectrum coupled to the core can be essential for finding RF amplitudes ‘far’ from antenna [N. Tsujii, PhD MIT 2010].

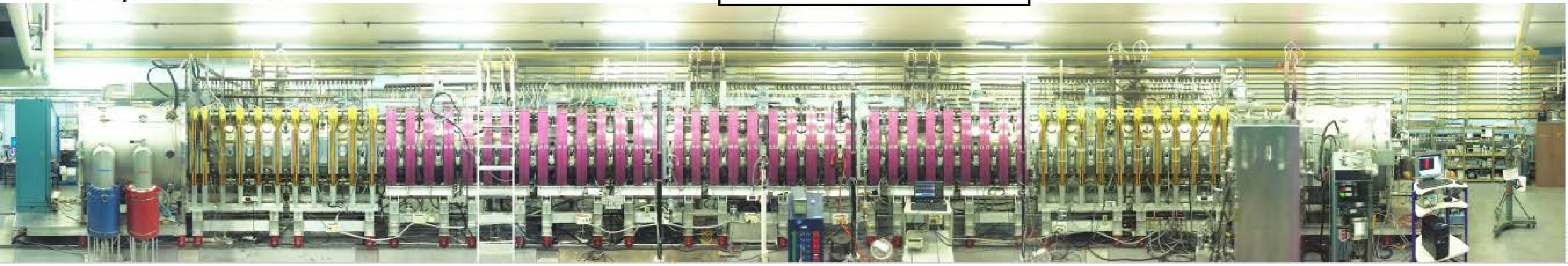

Midplane cut field in front of antenna

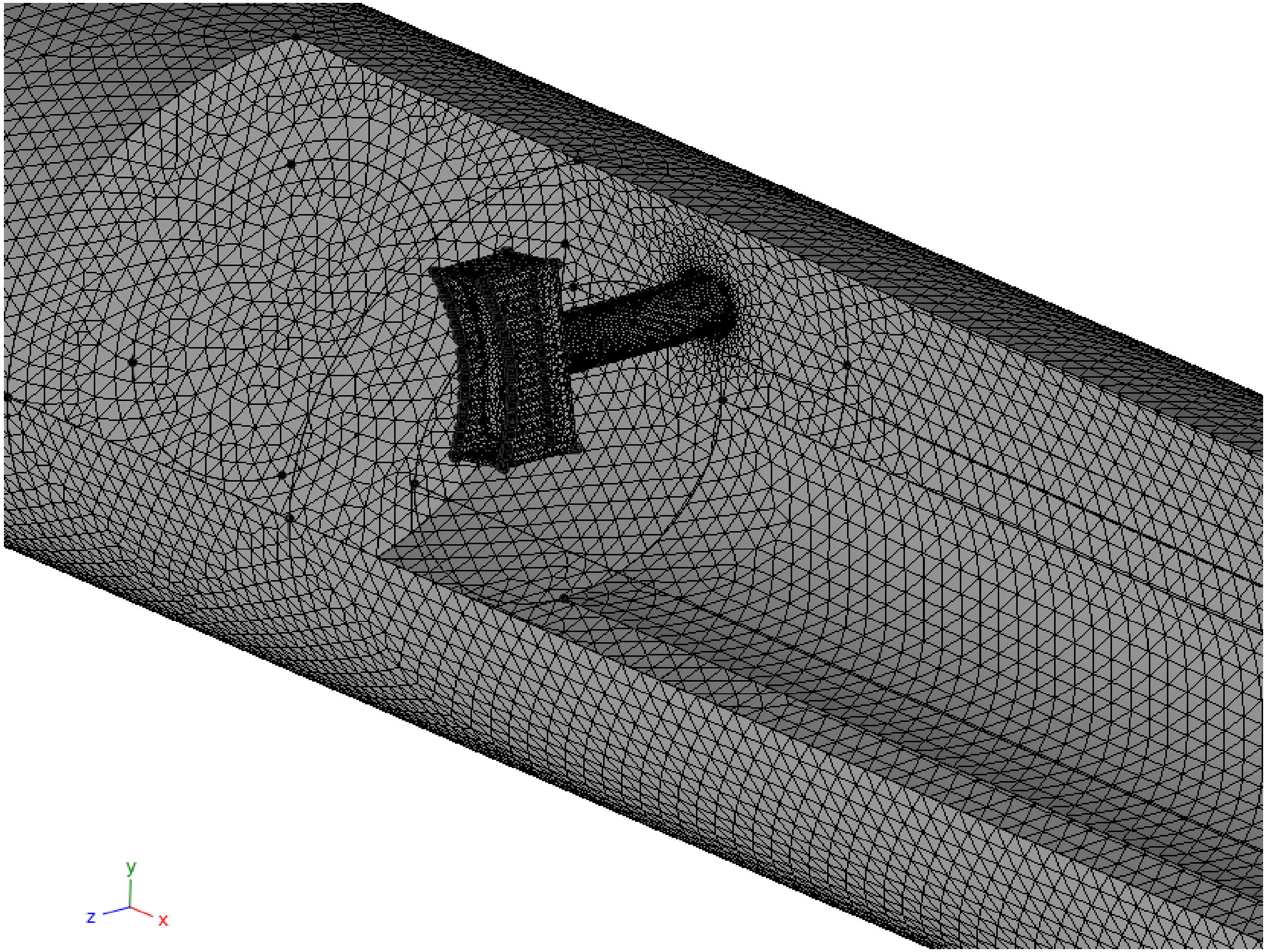


Brief introduction to LAPD

- LAPD is ~18 m long plasma column
- .5-.6 m plasma diameter
- Hydrogen-helium plasma with n_e up to 1×10^{19} m^{-3}, T_e up to 10eV, B~1000-1500G,
- Plasma pulse ~ 15 ms at 1 Hz
- 2-D (radial and axial) probe drives
  - Multiple axial locations allow for possible 3-D datasets
- ~100 kW, 2.38 MHz, 1ms pulse 1-strap antenna







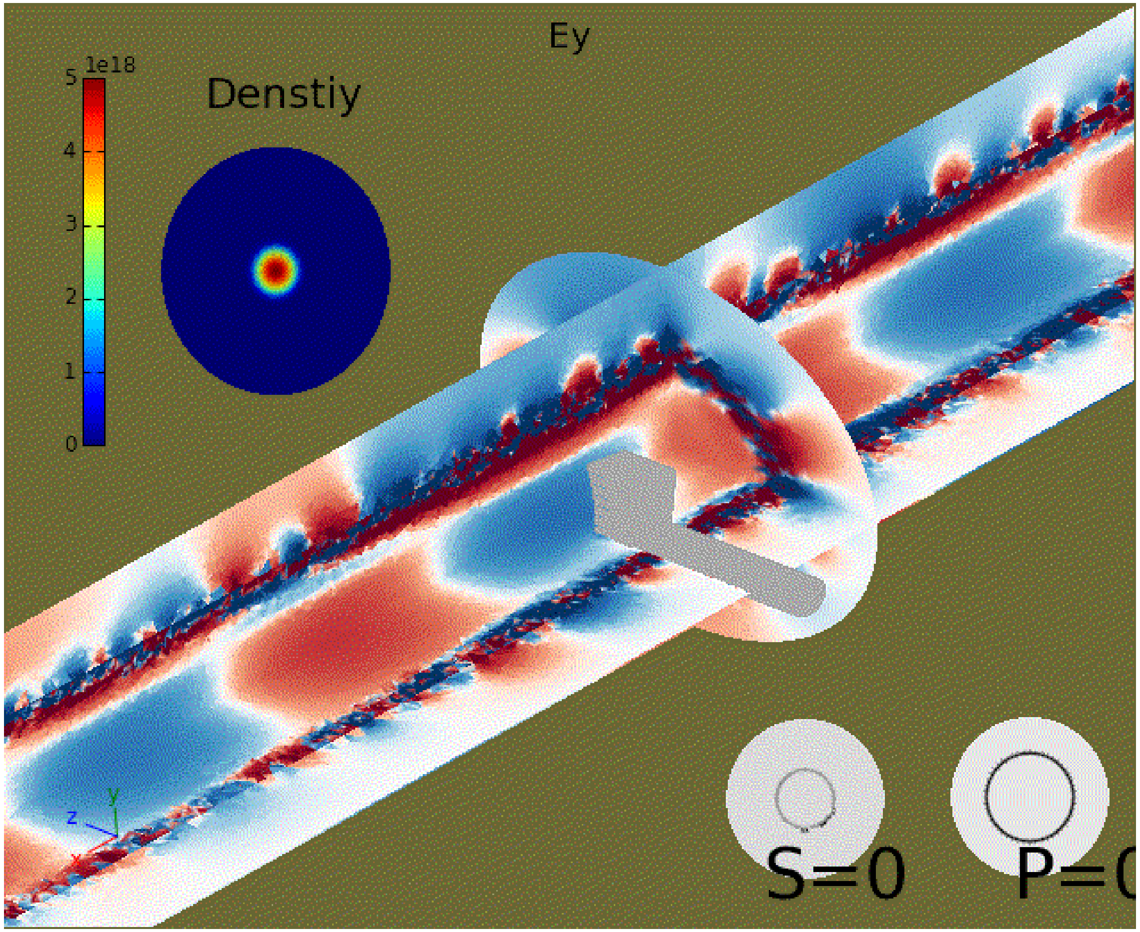
3D Tetrahedral Mesh of LAPD

- Includes antenna structure, two limiters, full 18 meters
- Imported from original COMSOL mesh into PetraM framework

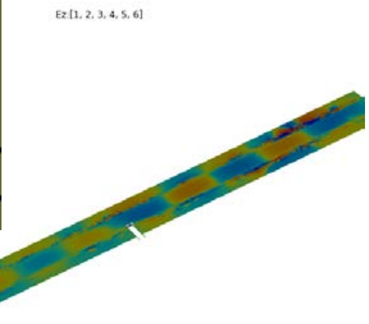
Simulation of Fast and Slow waves in LAPD

Helium
plasma 10^{13}
B = 1000
Gauss
f=2.4 MHz

S=0 and P=0
resonant
layers in
plasma

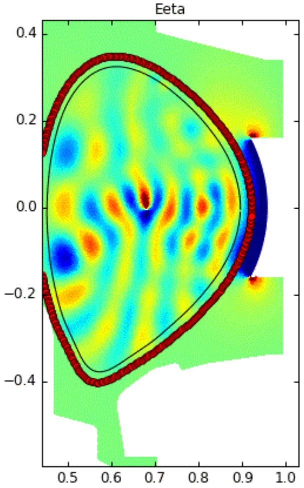


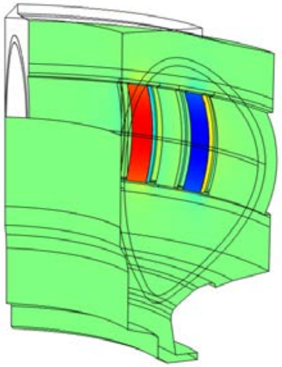
About 5 standing
wavelengths
axially.

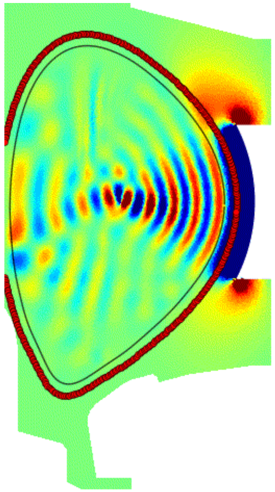


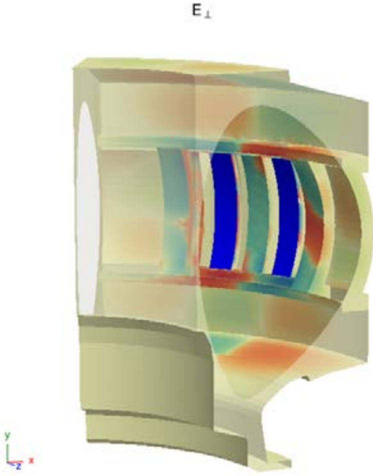
Conclusions: A new capability in whole device RF modeling permits exploration of core – edge interactions in many areas

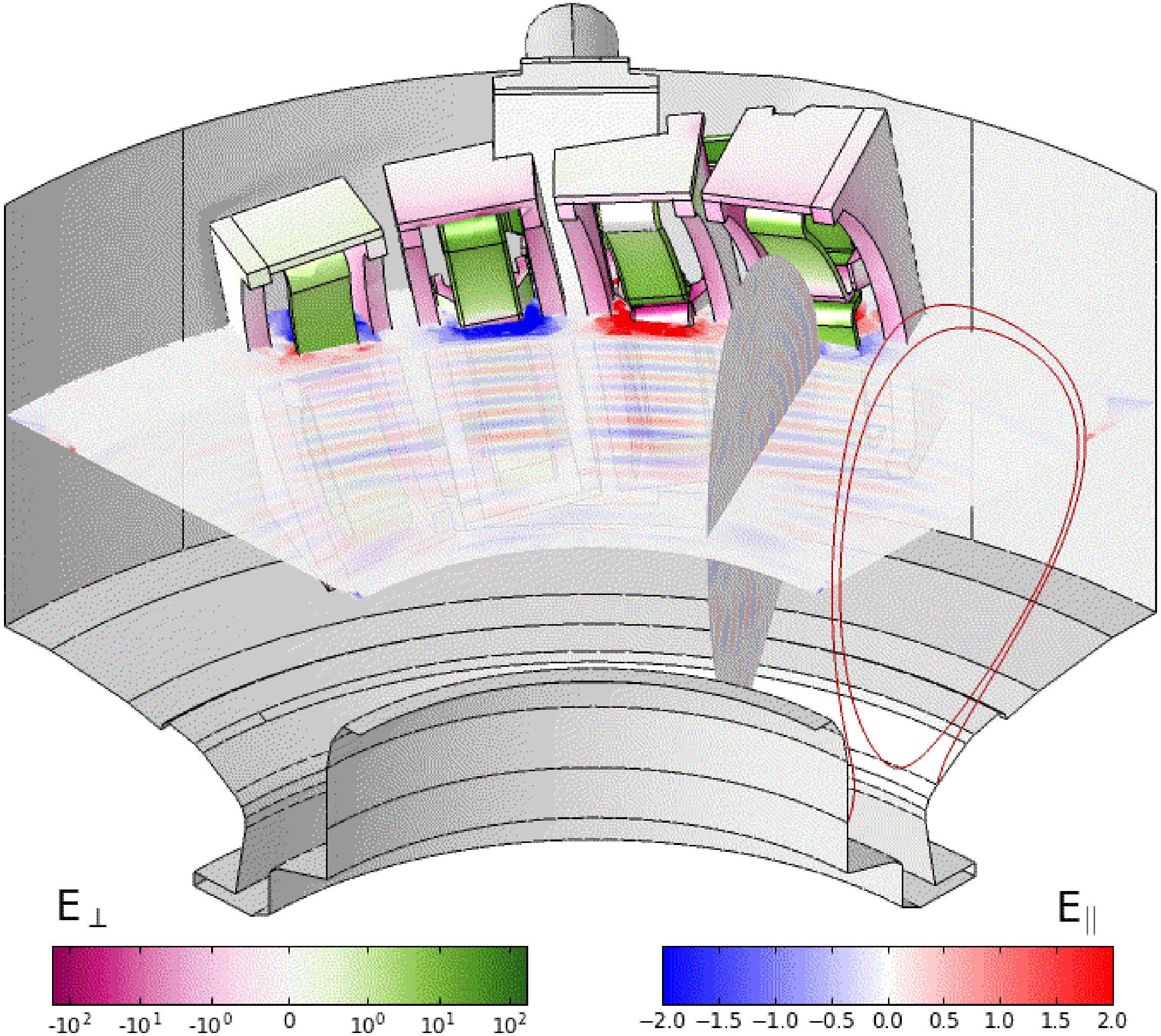
- Technique applies to any full wave RF simulation in any frequency regime.
- Builds upon existing code infrastructure, algorithms and methods.
- Integrates for the first time, antenna coupling, SOL propagation with realistic geometry, and propagation and deposition into core hot plasma.









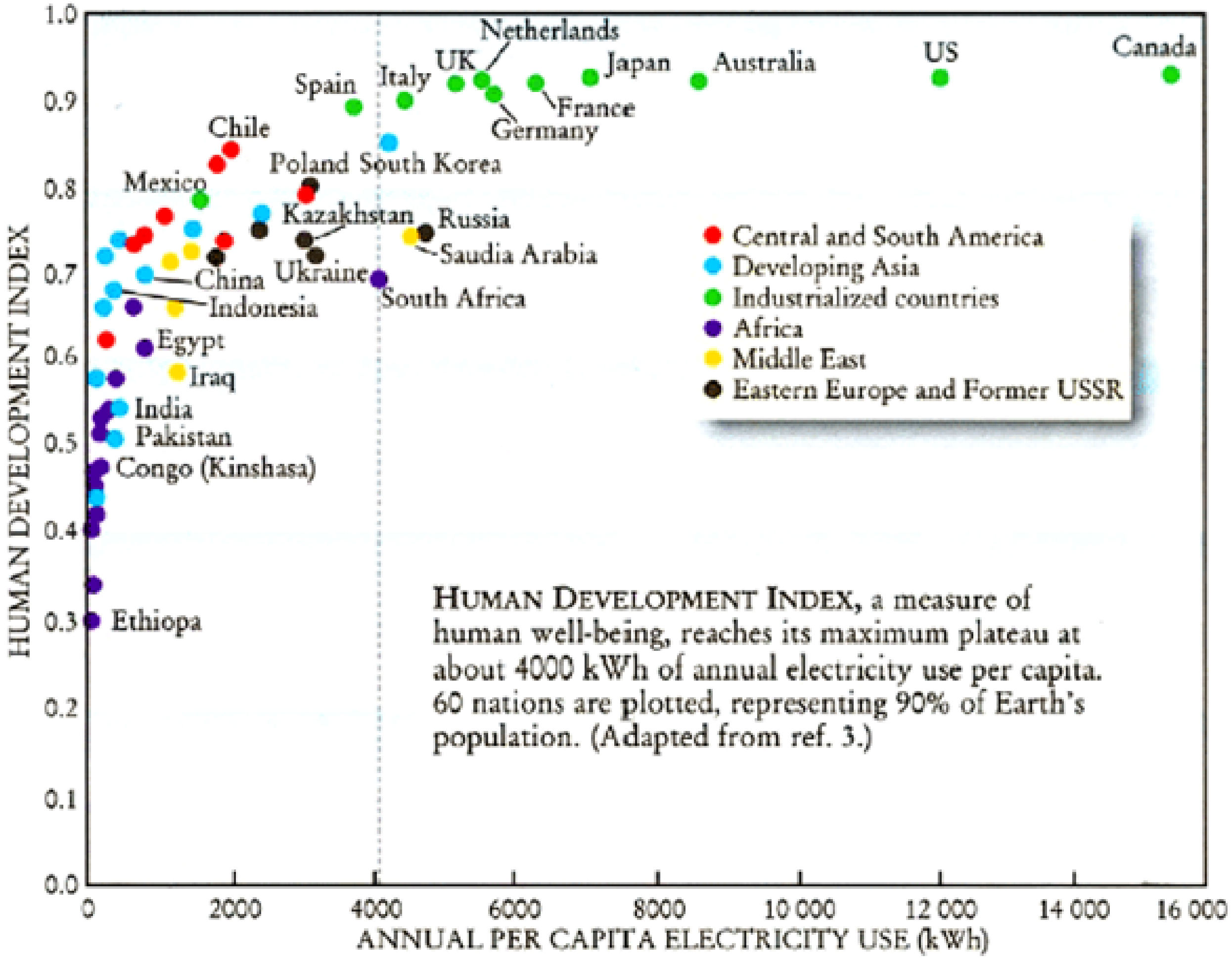


Title image: rotated field aligned four strap antenna on Alcator C-Mod tokamak at MIT. ¼ of full volume is modeled. Electric fields on antenna and in plasma are shown.

Extra info on fusion and energy.

BACKUP SLIDES

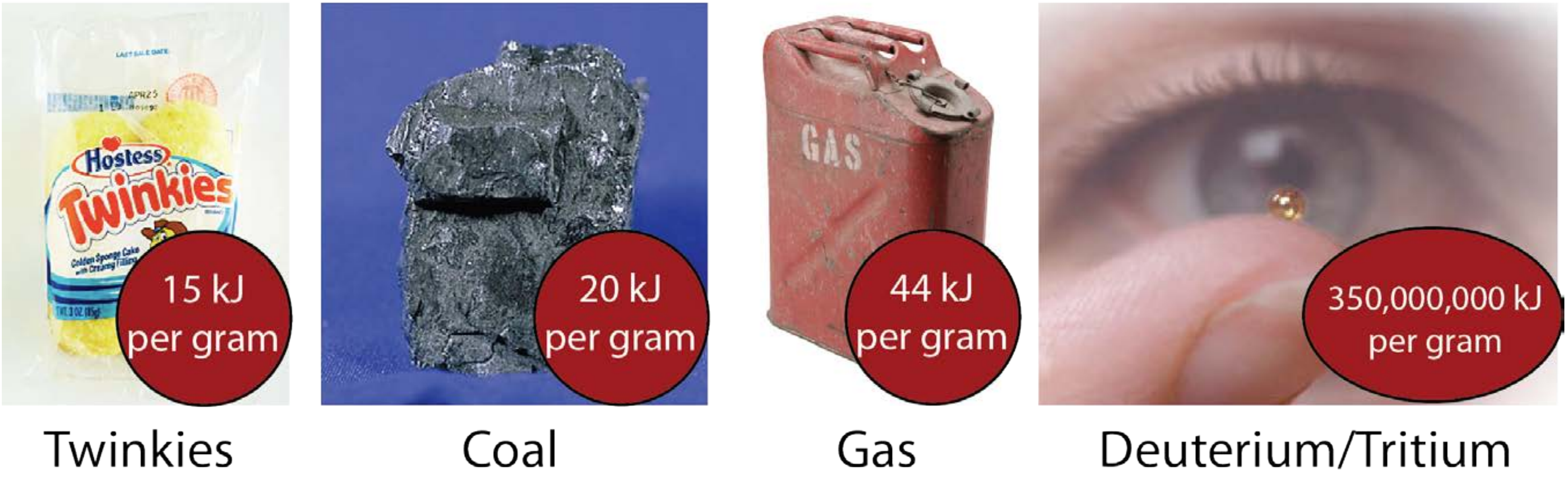
Earth-dwellers want to consume more energy . . .



HUMAN DEVELOPMENT INDEX, a measure of human well-being, reaches its maximum plateau at about 4000 kWh of annual electricity use per capita. 60 nations are plotted, representing 90% of Earth's population. (Adapted from ref. 3.)

Fusion, like all nuclear energy, produces a tremendous amount of energy from a very small mass of reactants.

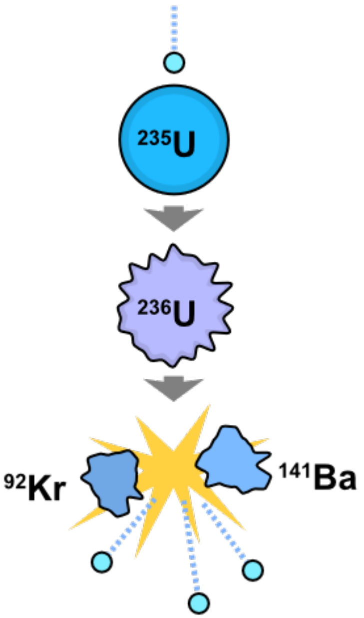
Energy Content in Different Fuels



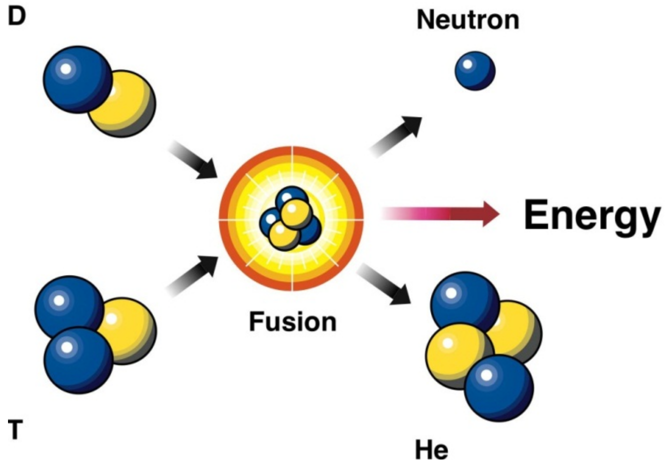
- Typical energy scales for chemical bonds – electron-volts (eV)
- Typical energy scales for nuclear reactions – millions of electron-volts (MeV) ($E=mc^2$)
- This means that a gigawatt-class fusion power plant will use about **a pickup truck full of fuel** (lithium and deuterium) **per year**.
  - Compare to a 1 GWe coal plant – nearly **8,000 tons of coal per day**!

3 days worth of coal supply for a 500 MWe plant

Two types of nuclear reactions:



- Fission – split heavy nuclei
  - (e.g. Uranium)



- Fusion – fuse light nuclei
  - (e.g. hydrogenic isotopes)

D + T → He + n + 17.6 MeV

Fuel Supply - Fusion

- Plenty of D from the ocean
- No natural T – half life = 12 years
- Need to breed T in the reactor, then burn with D.

Li-6 + n → He + T + 4.8 MeV

D + T → He + n + 17.6 MeV

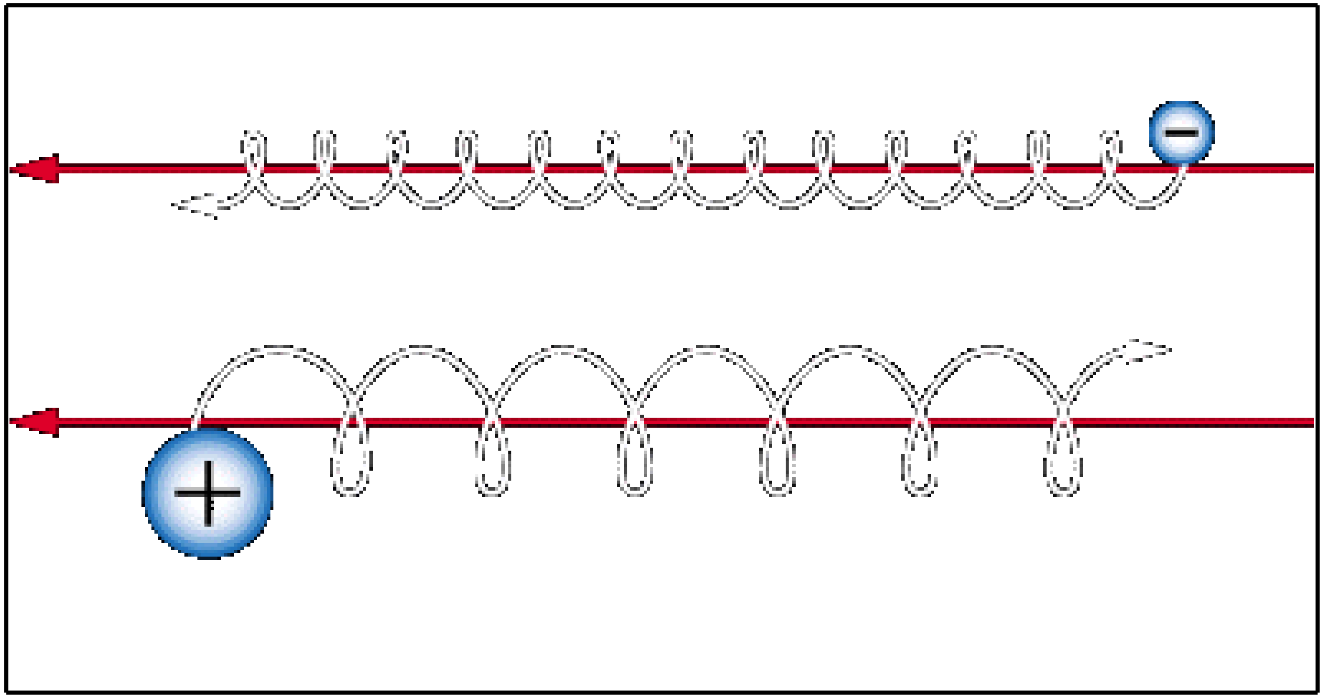
- Li-6 is 7% of natural lithium
- 1000's of years of natural lithium

Fuel for a fusion power plant:

30 t/day seawater
(extract deuterium)

350 kg/yr lithium
(breed to tritium)

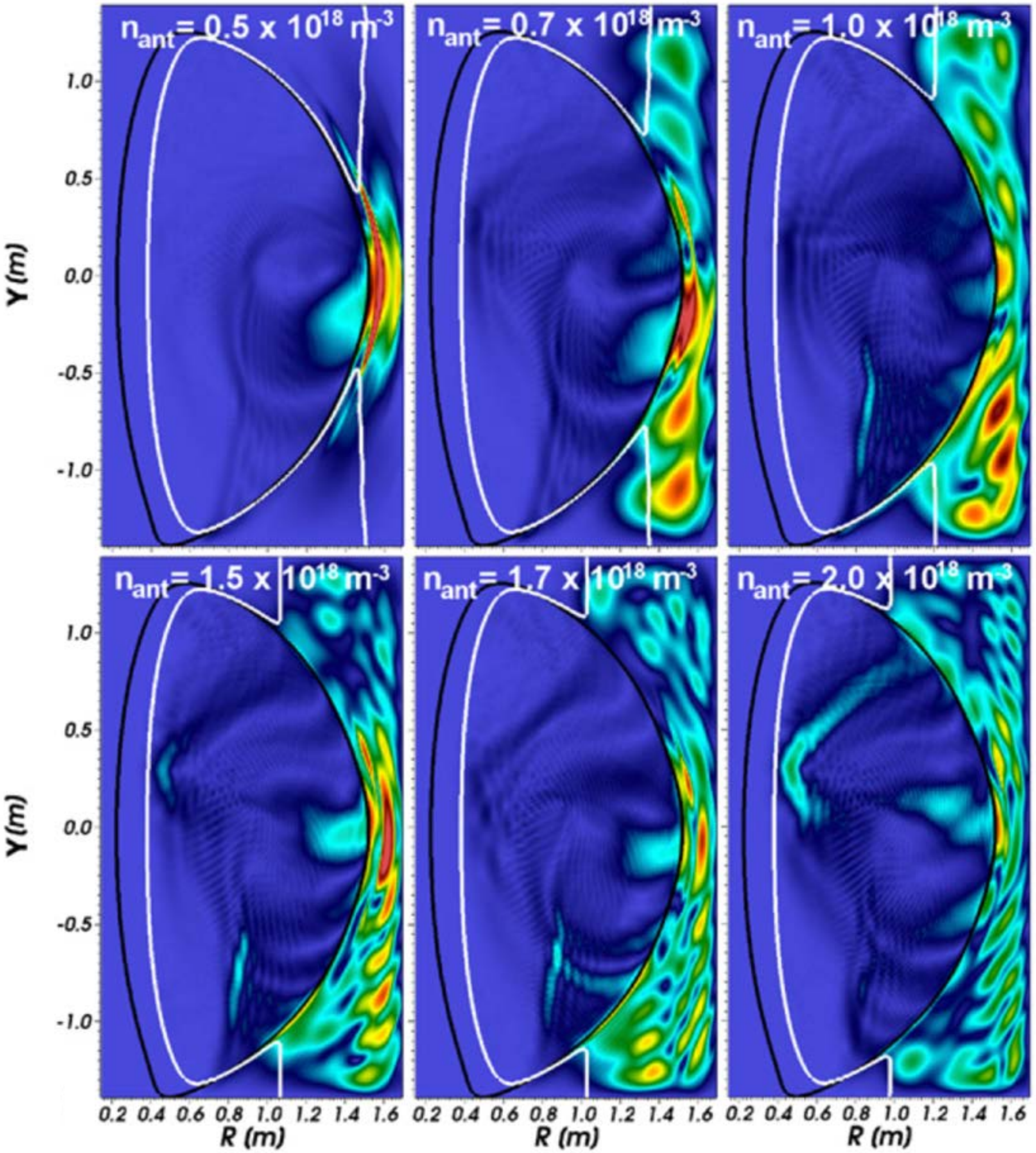
What about the ends?



- At the temperatures involved, ions are moving at over 1,000 km/s
- For a practical device, the end losses must be eliminated

NSTX – HHFW

- AORSA simulations have uniform density outside antenna surface and no limiter surfaces.
- Difference in wave fields from TORIC+MFEM may be due to more restricted density.



Bertelli PoP 2016