Overview of ORNL RF Theory

D. B. Batchelor

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The mission of the ORNL Fusion Theory Program is to develop fundamental plasma theory and the computational base needed to understand plasma behavior in fusion devices, to understand and exploit improved confinement regimes, and to develop new confinement configurations and technologies.

Primary research areas:

– Use of waves for transport barrier control

– Toward wave solutions with infinite resolution

– Monte Carlo treatment of the Fokker-Planck equation

– Antenna modeling

– Future directions

FESAC and Snowmass have identified a set of key program needs which RF potentially can fill, if we commit the resources

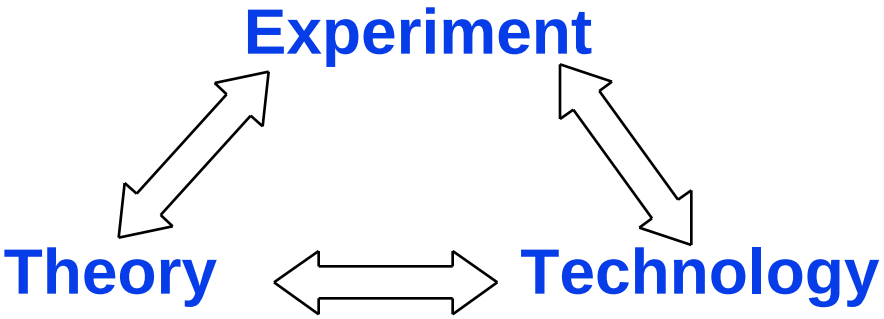
- **Snowmass – Magnetic Fusion concept working Group**
  - **"The second of the major themes is the development and employment of plasma control tools. These plasma control tools are needed to carry out innovative experiments to develop the scientific understanding and they are required for optimizing the performance of the plasmas. Adequate plasma control tools will need innovative technological and scientific solutions, and a true partnership between technology and physics is needed to develop them. "**
  - **"More complete plasma physics and detailed geometric effects must be include into the modeling codes, using advanced computational tools, and taking advantage of new computer hardware capabilities. Plasma control tools needed to modify and control the plasma for detailed physics investigations must be developed and deployed. "**
  - **"Steady-state operation requires the integration of basic science elements; stability, transport, wave-particle, and boundary. Developing a steady-state MFE system involves closely coupled issues of physics and technology, and a close partnership with technology is needed for success."**

- **Snowmass – Transport and Turbulence Working Group**
  - **Goal – "Develop tools and understanding for control of transport and transport barriers"**
  - **"Research opportunities and needs ... include the following:**
    - **1. A vigorous research program aimed at developing the antenna technology for efficient, reliable coupling of IBW waves should be pursued ….**
    - **2. The development of theory of RF wave physics needs to be supported to further the understanding of IBW as a flow shear generation tool. In parallel, such an effort should be directed at the identification of other RF waves that might be suitable for such generation, while being easier to launch. This theory development should occur in concert with the experimental research program."**

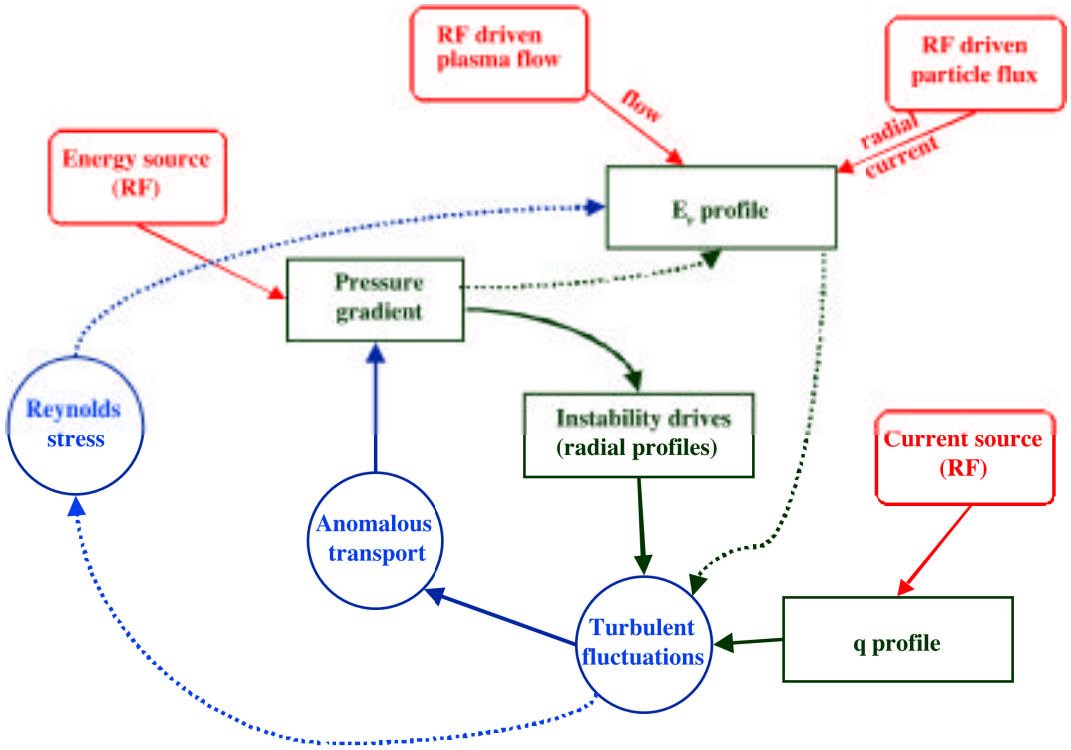
We have two broad classes of task:

- To understand the physics of how the waves work and to learn what kinds of control we can exert with them
- To develop ways to get the waves we need into the plasma and to do so without deleterious effects
  - Antennas – launched spectrum
  - Matching and control circuitry
  - RF/Edge plasma interaction
  - Power handling

We are all in this together



Use of waves to produce and control transport barriers is an important application just being explored

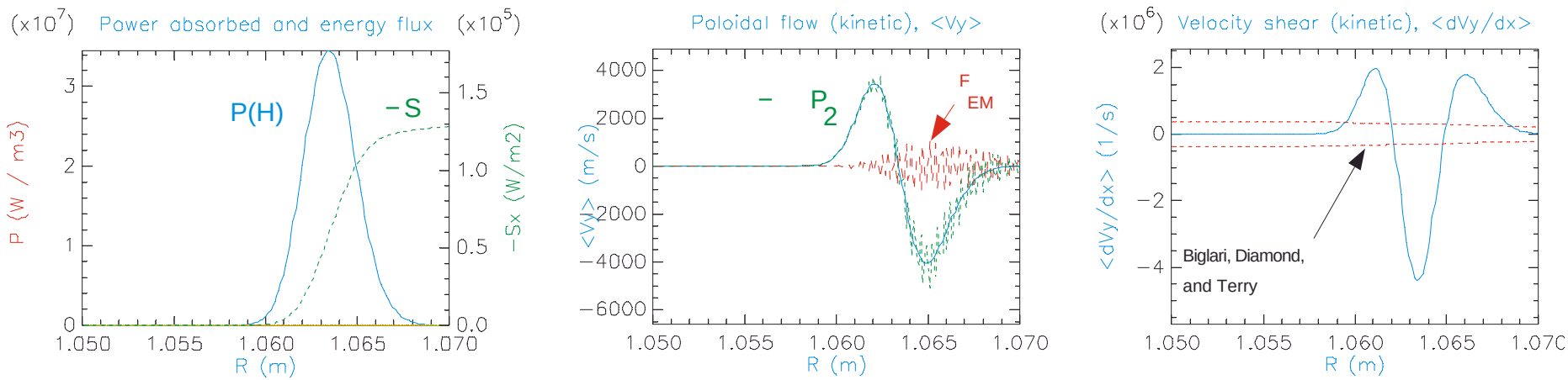


- There are a number of non-linearly coupled processes involved in transport barrier dynamics, several of which can be affected by RF
- RF only H-modes (JET, TEXTOR, DIII-D, ...)
- TdeV lower hybrid H-mode
- Evidence of RF flow drive – PBX-M, TFTR, TFU

We have developed a comprehensive kinetic theory of RF driven plasma force for flow drive in 1D

- **Previous theories made inadequate assumption of Reynolds stress closure of moment equations**
- **These neglected compressibility and kinetic pressure perturbation – not valid at ICRF**
- **The new theory has been applied to IBW experiments on TFTR and FTU, with qualitative agreement**

Calculation of power deposition and driven flow in $4\Omega_D$ IBW experiments on FTU



- **Also predicts a radial, RF driven particle flux, typically comparable to diffusion fluxes ⇒ radial electric field, additional ExB flow**

Directions for future in RF transport barrier control

To get understanding and predictive capability, not just qualitative agreement, we need to:

- **Incorporate into 2D, toroidal RF model – ultimately 3D $\Rightarrow$ much greater computational power**
- **Integrate with neoclassical theory to get more accurate flow damping theory. Include turbulent transport of momentum.**
- **Understand RF driven radial fluxes (same order as transport diffusion), the formation of non-ambipolar radial electric fields and how these fields relax.**
- **Obtain more and better experimental data**

Most promising wave mode is the IBW – we must find ways to successfully launch a spectrum of IBW at high power

Toward wave solutions with infinite resolution – removing the $k_\perp\rho << 1$ restriction

- **Many of the problems we now need to study violate the conventional ordering of our ICRF codes.**

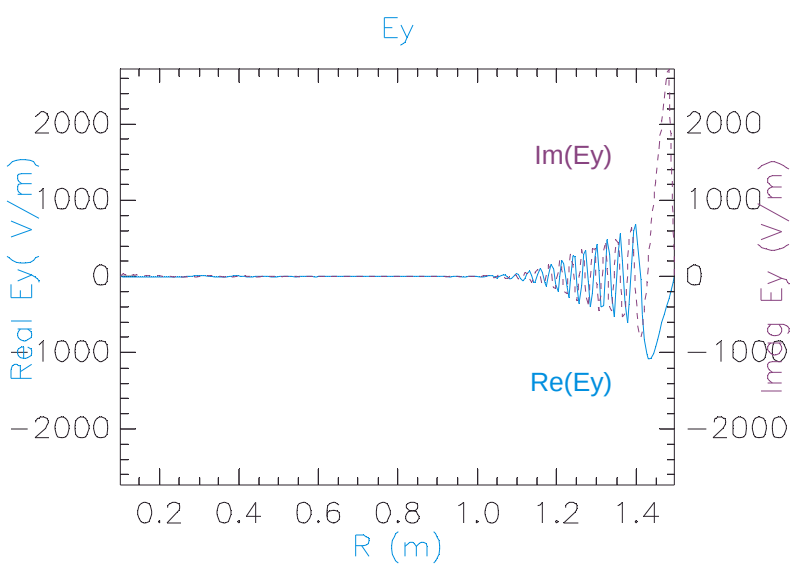
- **The plasma current of a wave is a non-local (in space and time) integral operator on the wave fields**

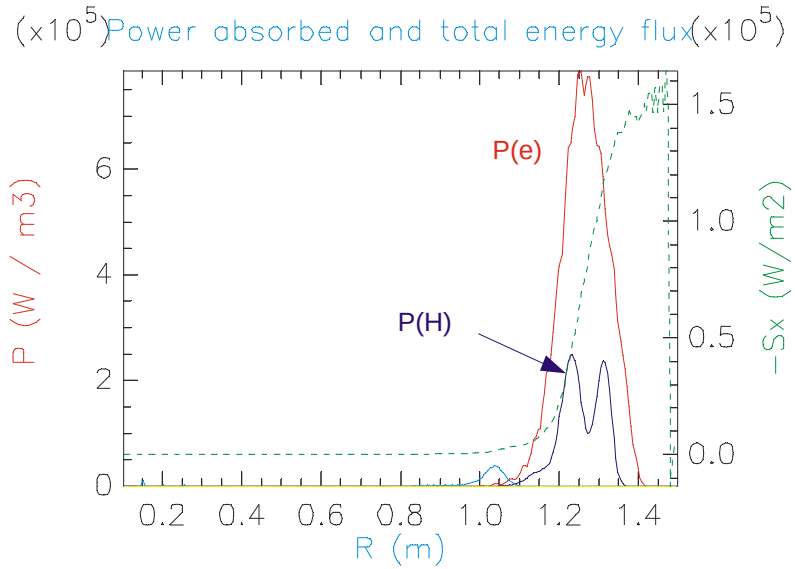
- **To convert this to a low order differential operator must expand in $(k_\perp\rho)^{2.}$ But this imposes severe limits:**
  - **Restricts to $\omega \sim 2\Omega_c$**
  - **Can only treat converted IBW near the conversion layer**
  - **Can't treat direct launch**

- **This eliminates:**
  - **NSTX HHFW – $\omega \sim 4\Omega_D - 20\Omega_D$, $k_\perp\rho>>1$**
  - **TFTR IBW – $\omega \sim 4\Omega_D - 5\Omega_T$, , $k_\perp\rho>1$**
  - **FTU IBW – $\omega \sim 4\Omega_D - 5\Omega_T$, , $k_\perp\rho>1$**
  - **D-IIID fast wave – $\omega \sim 5\Omega_D - 8\Omega_D$,**
  - **Cmod mode conversion – $k_\perp\rho>1$**
  - **NCSX…. – any short wavelength mode on a low field alternate**

All Orders Spectral Algorithm (AORSA) eliminates this expansion

- **AORSA allows arbitrarily high harmonic, arbitrarily short wavelength (limited by computer resources, not model)**
  - **Spectral representation (k_x, k_y, k_z) - k_x modes are coupled (similar to METS)**
  - **Uses local warm plasma conductivity σ, with first order correction in ρ/L (similar to METS, but different from Lausanne integral code)**
  - **HHFW on NSTX**





- **What's needed – massive speedup, generalization to 2D, 3D**

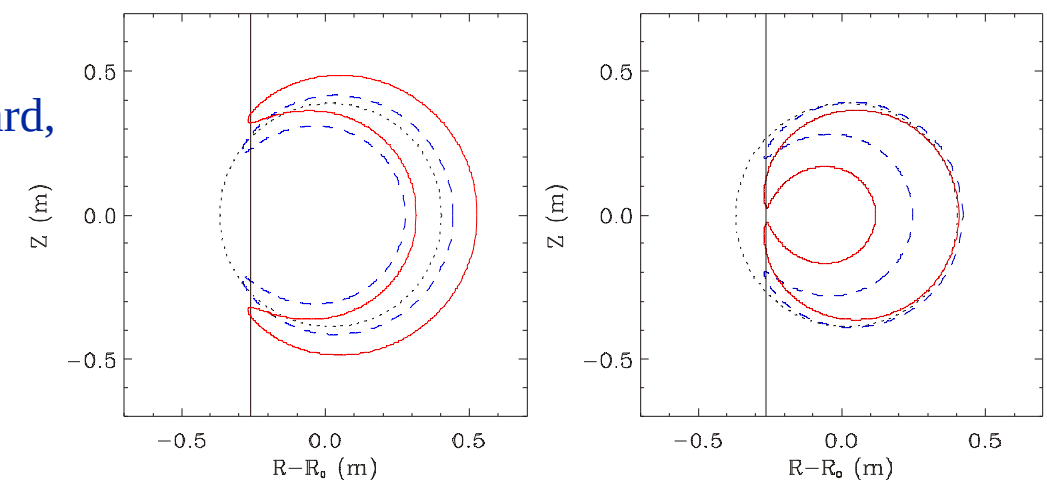
The ultimate piece of information in RF modeling is the plasma distribution function, $f_0(x,v,t)$ – Fokker-Planck equation

We need an accurate picture of the distribution to understand:

- **What energetic tails are we producing? Are we confining them? Are we ultimately heating electrons, ions or what? – sawtooth, TAE stability**
- **What currents are we driving? – q profile control, bootstrap seed current, MHD stabilization**
- **Plasma rotation (toroidal, poloidal) – transport barriers, external kink mode**
- **What f_0 do we put into the RF propagation/absorption codes? – consistency**
- **The standard procedure is to make "local" approximation, neglecting radial deviation from flux surface, solve 2D differential eq. in ($v_{||}$, $v_{\perp}$) on a flux surface**

But for many important applications, orbits deviate significantly from flux surface!

RF can drive particles radially inward or outward, depending on $k_{||}$



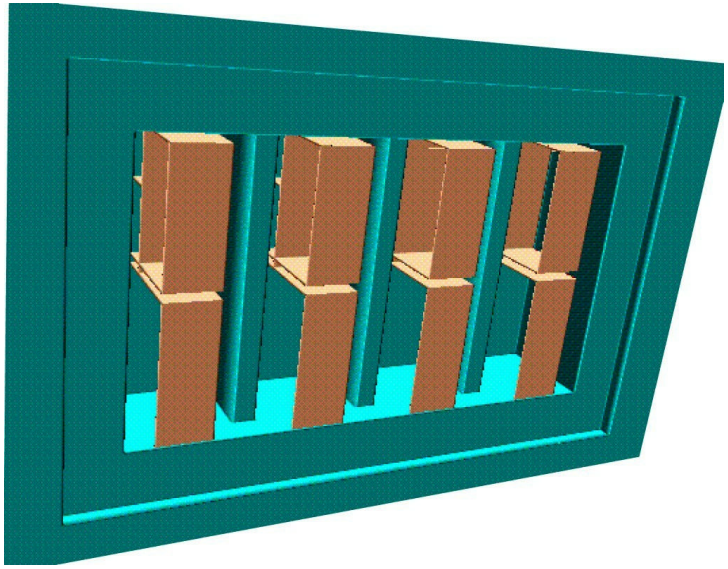
Using Monte Carlo techniques we can include wide orbit effects and wave induced transport

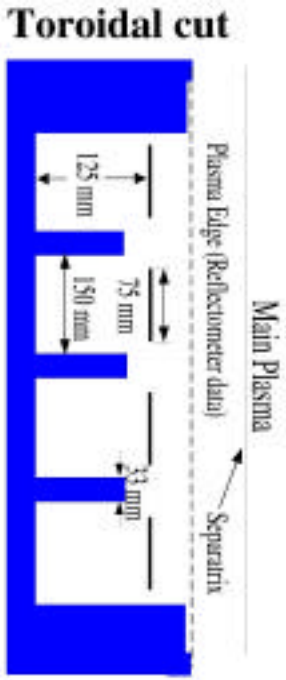
FIDO code

- Toroidal geometry – circular cross section for now
- Solves in constant of motion space – includes all classes of orbits, includes details of finite orbits, radial fluxes
- RF quasilinear operator, orbit averaged collision operator, beam sources
- Applied, or being applied, to:
  - Minority Current drive in JET
  - Effect of tail population on TAE and sawtooth activity in JET
  - Parasitic absorption in Tore Supra
  - TAE destabilization in C-mod
- Loosely coupled to PICES 2D full wave RF code
- New version of code being developed
  - Realistic equilibrium geometry – non-circular, highly shaped
  - Exotic orbit topology – e.g. high β ST
  - Coupling of full distribution function f(r, v) to RF codes (PICES)

Antenna modeling – RANT3D is the world standard for antenna/plasma modeling in the ICRF

DIII-D fast wave antenna front view

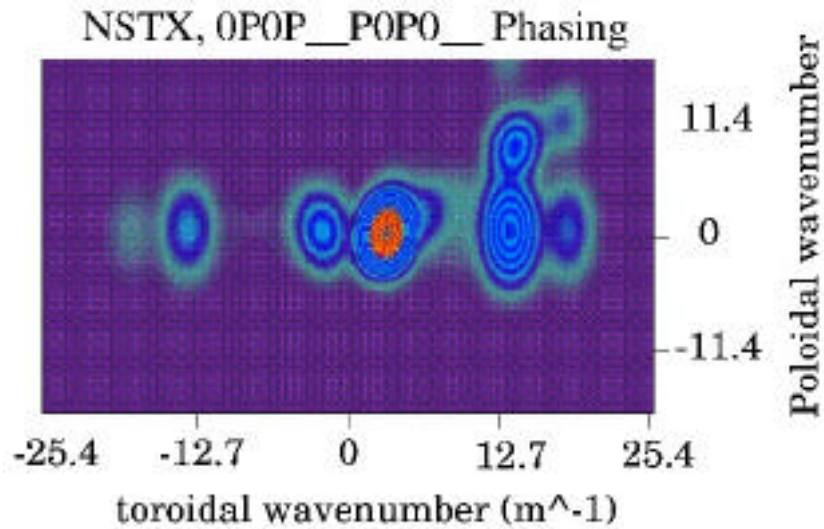




- RANT3D approximates antenna with rectilinear elements, plasma as a 1D slab
- Allows multiple, possibly nested, recesses – permits treatment of multiple height septa, limiters, openings, etc
- Sources include specified arbitrarily oriented straps, feeders, current variation along elements
- Slab plasma model can include warm plasma, arbitrary magnetic field angle, magnetic shear
- Object oriented programming methods permit rapid generation of new antenna geometries
- Coupled to PICES 2D full wave code, which is coupled to FIDO Monte Carlo (soup to nuts RF modeling)

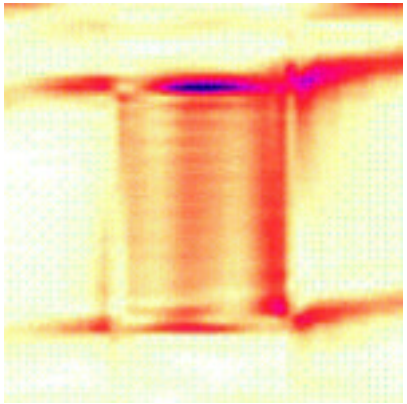
RANT3D is valuable both for understanding launched waves and RF edge field details

- **Calculates quantities related to wave radiation**
  - **Launched k spectrum**
  - **Antenna loading**
  - **Wave fields in the plasma**

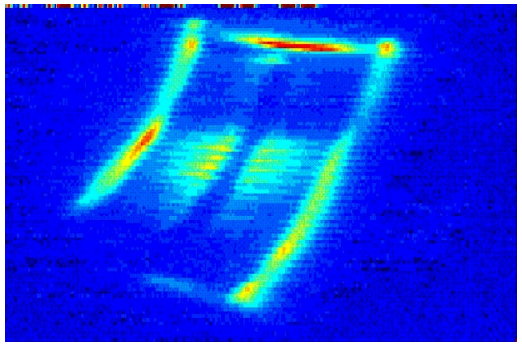


- **Calculates quantities related to antenna performance**
  - **Inter-strap mutual coupling**
  - **Currents in backwalls, septa, limiters**
  - **RF fields in the edge region**

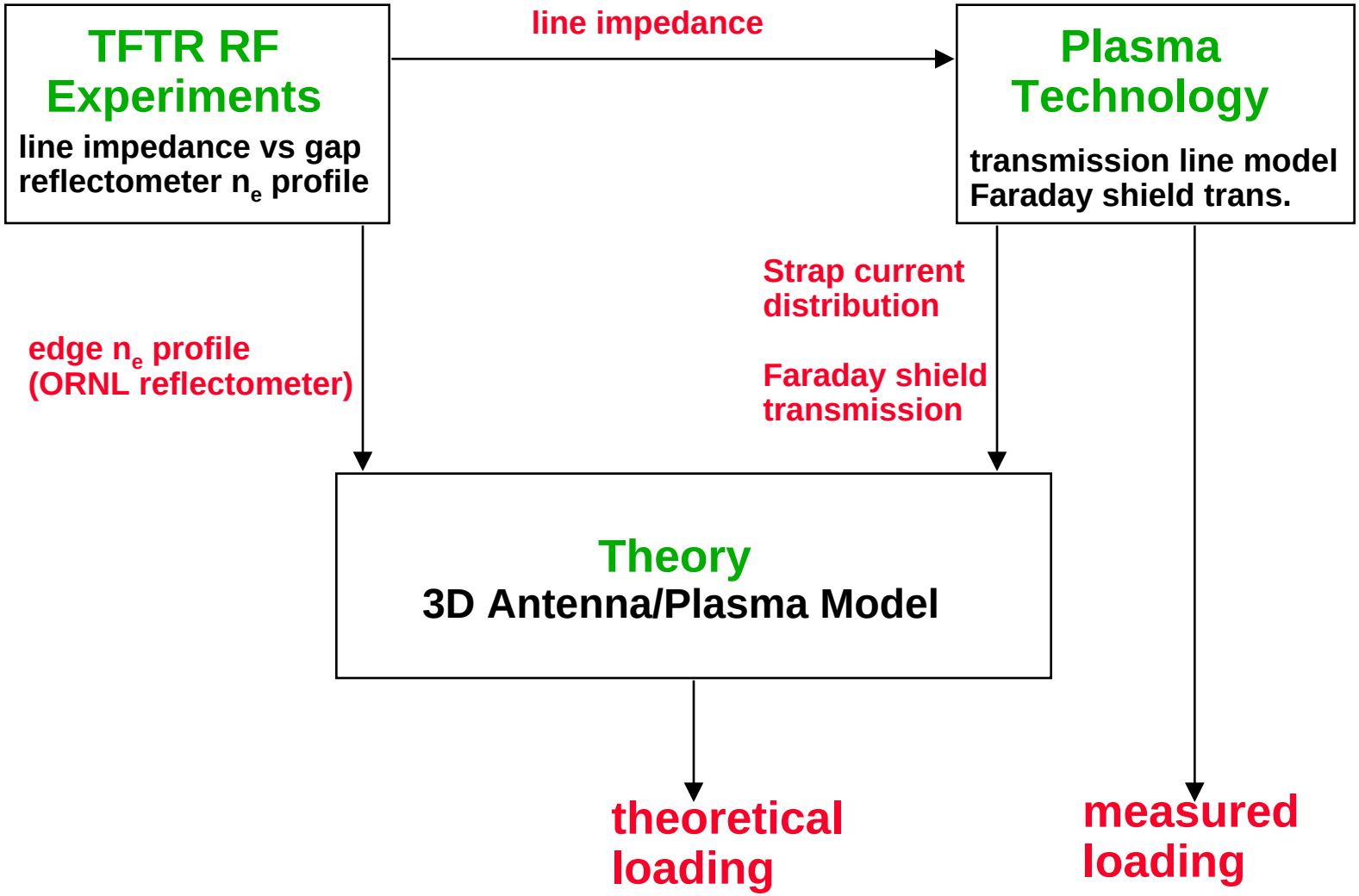
RANT3D calculation of edge E|| in Tore Supra



IR camera image of Tore Supra long pulse ICRF antenna



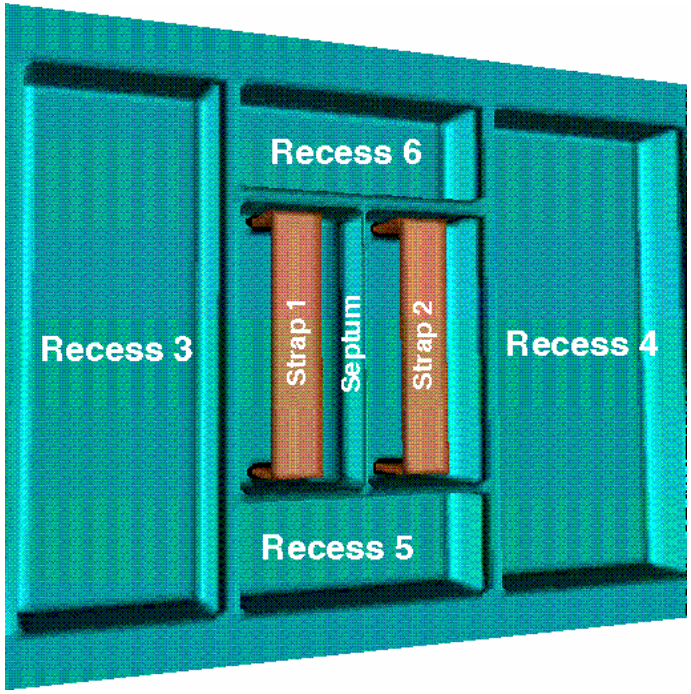
Analyzing ICRF antennas requires integration of theory, experiment and technology

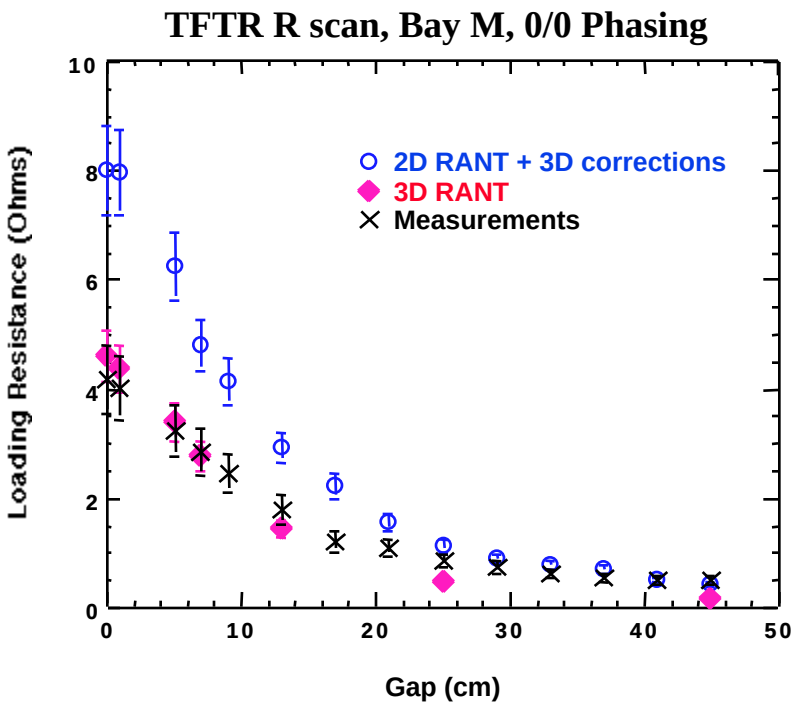


Collaboration led to much improved predictive capability, understanding of antenna geometrical effects on performance

- **Techniques verified in comparisons on: DIII-D, Tore Supra, JT60-U**
- **Design basis for ITER, NSTX**

RANT3D model for TFTR antenna geometry





Greatest challenge so far – NSTX (for details see Ryan/Baity)

Future directions for antenna modeling

- **IBW may play a big role in transport barrier control, we need an effective plasma model for launching IBWs at arbitrary harmonics ⇒**
  - **couple AORSA1D to RANT3D**

- **Transmission line parameters including cross-talk can be important for launch spectrum and control circuits ⇒**
  - **calculate approximate full inductance matrix for coupling between straps in RANT3D**
  - **particular solution to feeder currents in RANT3D to more accurately model capacitive effects near feeders**

- **Plasmas are often not perfectly conformal with the antenna and poloidal mode coupling is possible through toroidal effects ⇒**
  - **Develop a conformal mapping proceedure to map the plasma impedence onto the antenna**
  - **Allow full coupling of poloidal modes in the plasma region calculating the RANT3D impedence match**

US needs to revitalize the research program on RF/edge interaction – critical for IBW

If we are to develop the predictive understanding needed to develop the required plasma control we need a major scale up in computing power

- **Increased resolution – treat IBW, mode conversion, HHFW in 2D**
- **3D – apply RF to stellarators**
- **f_0 consistency – accurate calculation of tails, absorption**
- **Improved conductivity operator (non-local effects) – e.g. δf – correct correct absorption, partitioning between absorption and mode conversion**
- **Integration with transport, stability, plasma dynamics – unravel non-linear couplings between various processes affecting and affected by RF**
- **Detailed comparison with experiment, application to advanced confinement concepts – verify models, plan and design advanced experiments**

Proposing a community wide Plasma Science Advanced Computing Initiative (PSACI) for RF modeling