

## TOPICA : a virtual prototyping suite for plasma facing antennas

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**TOPICA:**  
**A Virtual Prototyping Suite for  
Plasma Facing Antennas**

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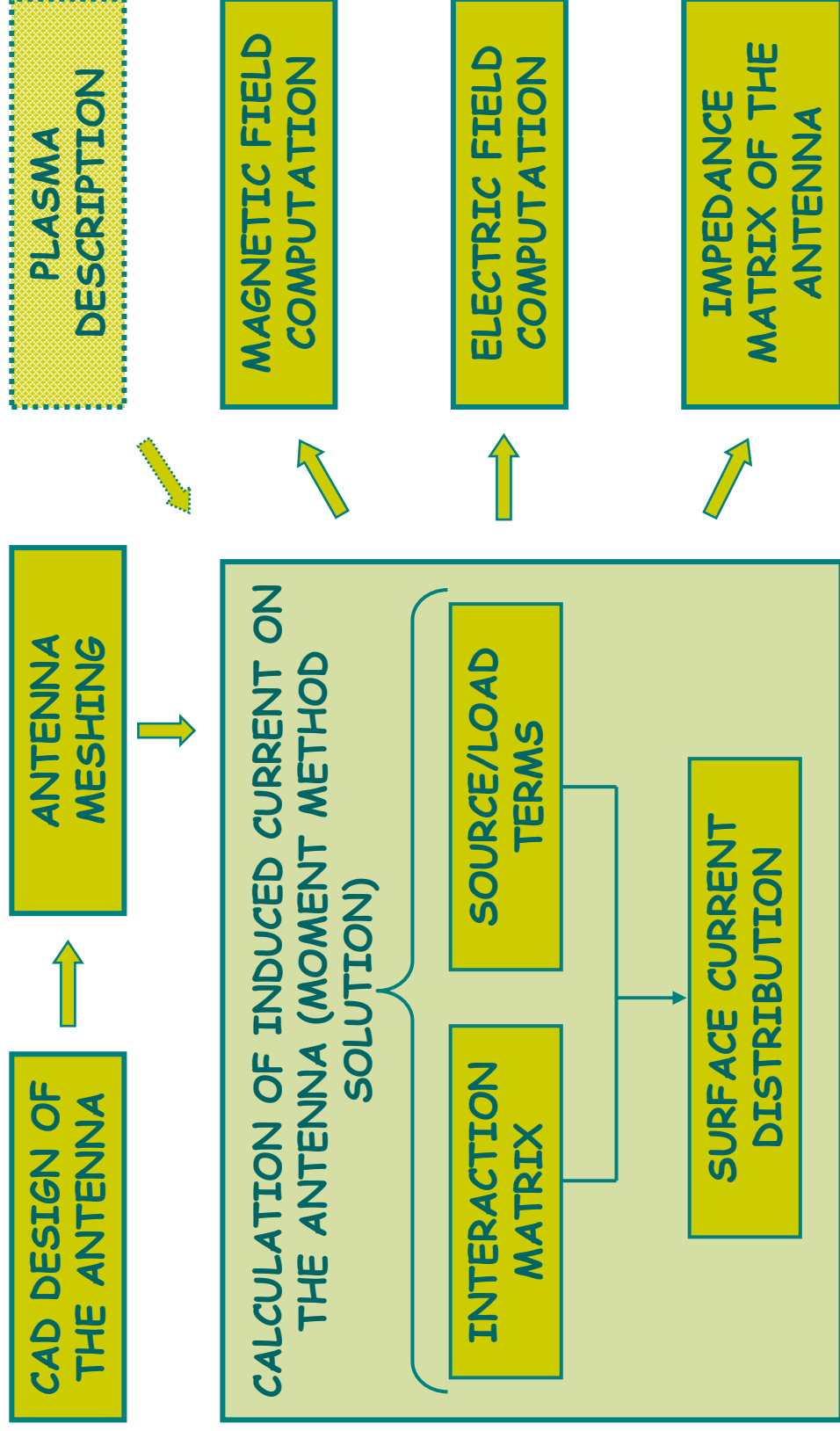
# Presentation Outline

- Objectives of this work
- “Virtual Prototyping Laboratory”
- Statement of the problem
- Numerical strategy
- Validation of TOPICA suite
- Examples and results

# Objectives of the Work

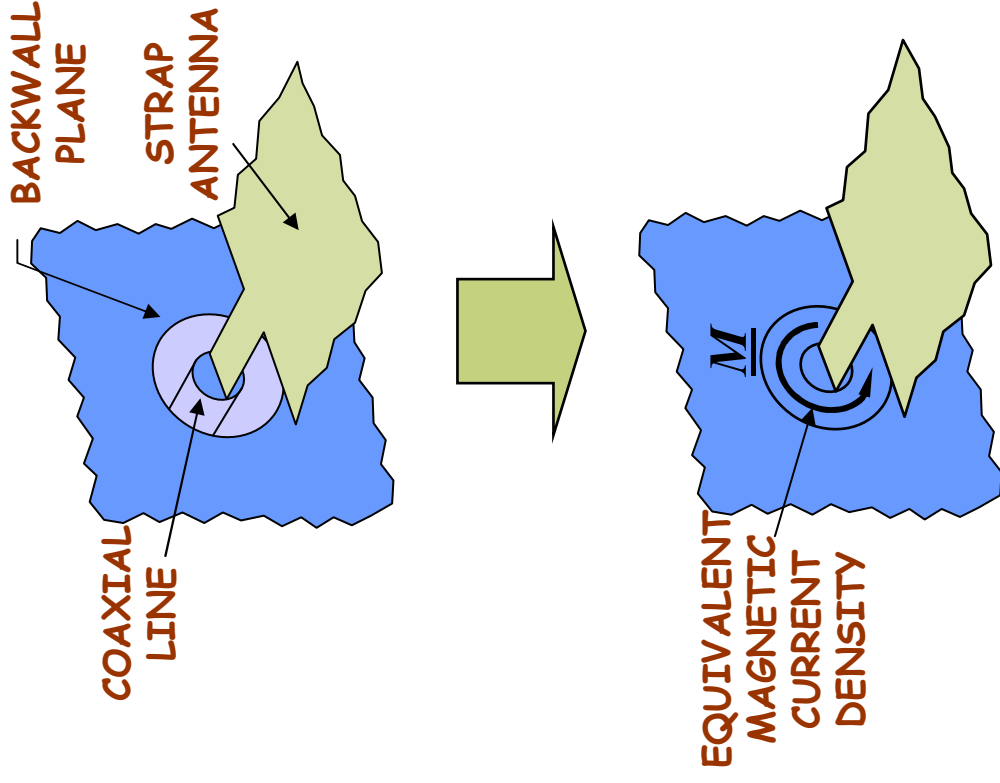
- To study a **realistic antenna** geometry with a reasonable CPU time
- To include an accurate and **realistic plasma** description into the model (FELICE plasma module)
- To get reliable information about:
  - **antenna input parameters** which allow an accurate design of *tuning & matching* control system
  - **electric field** distribution (hot spots)

# “Virtual Prototyping Laboratory”



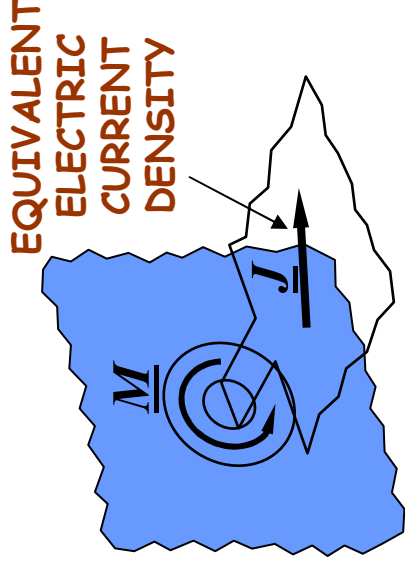
# Statement of the Problem (1)

- The antenna is fed by a coaxial line truncated at the back wall section
- Equivalence theorem is invoked first to replace the coax with a surface magnetic current



# Statement of the Problem (2)

- **Equivalence theorem** is applied **again** to replace the antenna with a surface **electric current**



$$\underline{E}_p(\underline{\rho}, x) = \iint_{\Sigma_c} d^2 \underline{\rho}' g_{\underline{=im}}(\underline{\rho} - \underline{\rho}', x) \cdot \underline{M}(\underline{\rho}')$$

$$\underline{E}_s(\underline{\rho}, x) = \iint_{\Sigma} d^3 r' g_{\underline{=}}(\underline{\rho} - \underline{\rho}', x, x') \cdot \underline{J}_s(\underline{\rho}', x')$$

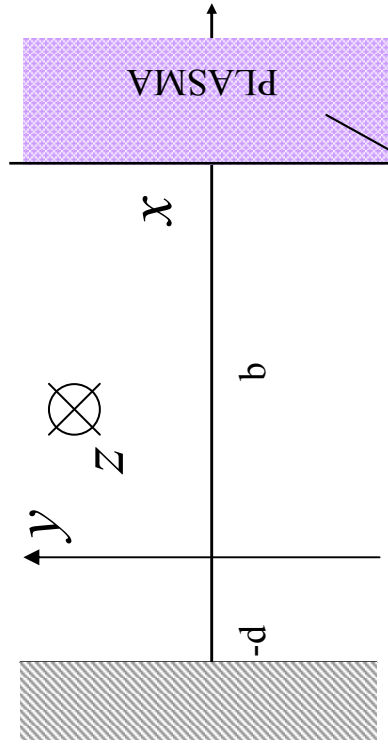
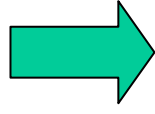
- Enforcing **boundary conditions** on antenna surface yields the relevant **EFIE**

$$\hat{n} \times (\underline{E}_p + \underline{E}_s) \Big|_{\Sigma_a} = \underline{0}$$

# Green's Function and Plasma

Planar (slab) plasma: 3D(antenna)/1D(plasma)

The relevant Green's functions involve the vacuum-plasma boundary condition



Non-homogeneous,  
full-wave, hot

Plasma impedance matrix expressed in the 2D **spectral** (wavenumber) domain



# Moment Method Procedure

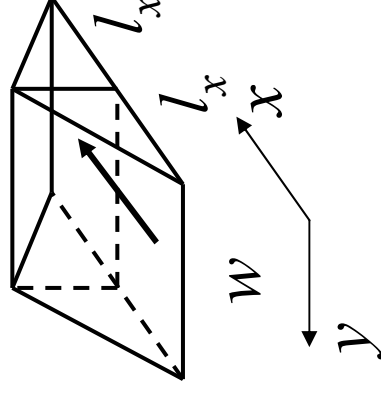
- The unknown current is expressed as linear superposition of suitable **basis** functions : 
$$\underline{J}_s = \sum_{n=1}^N I_n \underline{f}_{-n}$$
- The EFIE is projected onto the **test** functions and a linear algebraic system is obtained:

$$[Z][I] = [V]$$

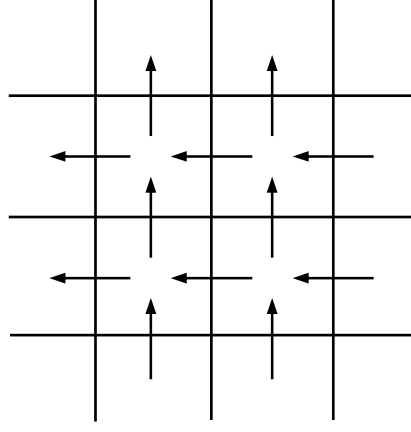
- Matrix entries contain Green's function:  
Parseval identity is used to transform them into **spectral** domain

# Basis and Test Functions

- **Choice criteria:**
  - Must be *Div-conforming* to avoid spurious solutions
  - Antenna geometry (plane surfaces)
  - simplicity

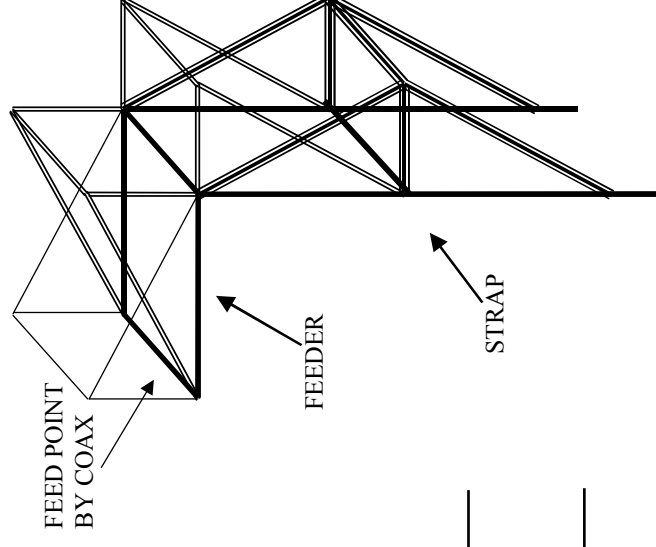


SKETCH OF A ROOFTOP



GRID COVERING

- **Rooftop function features:**
  - Rectangular support
  - Linear interpolating
  - Piece-wise constant div



A SAMPLE MESHING

# Interaction Matrix Entries (1)

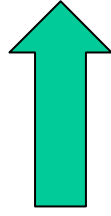
$$Z_{m,n} = \iint d^2 k_t \int dx \int dx' \tilde{f}_{-m}(-\underline{k}_t, x) \cdot \tilde{\underline{\underline{G}}}(k_t, x, x') \cdot \tilde{f}_{-n}(\underline{k}_t, x')$$

- Analytical integration over  $x$  and  $x'$  to save time
- Numerical integration over  $k_t$  is critical since:
  - Green's function  $\tilde{\underline{\underline{G}}}(k_t)$  diverges asymptotically
  - Basis function spectra  $\tilde{f}_{-m}$  oscillate and decay slowly

# Interaction Matrix Entries (2)

Observation:

- asymptotic behavior of actual Green's function is the same as of vacuum Green's function
- Reaction integrals (matrix entries) associated to vacuum may be evaluated in **spatial** domain in a standard manner (though singular)



Hybrid spectral-spatial  
formulation with extraction  
of vacuum contribution to  
matrix entries

# Vacuum Extraction Procedure (1)

- Extract vacuum Green's function: remainder is regular (asymptotically decreasing spectrum)

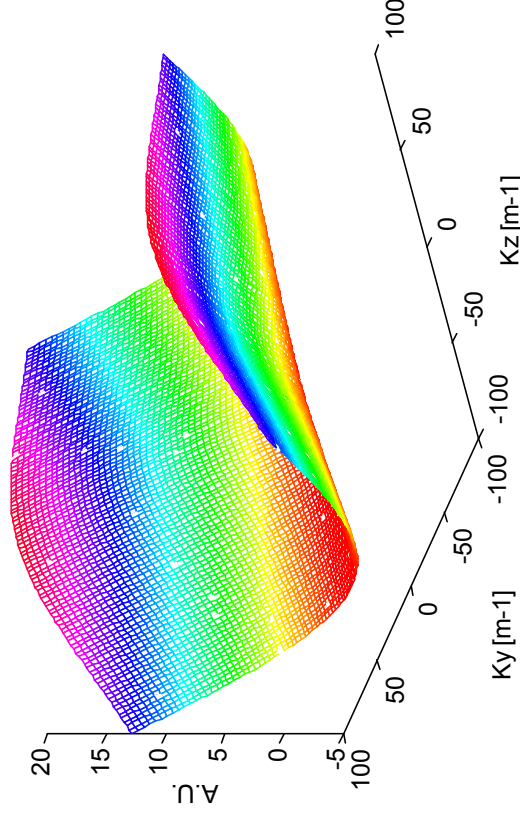
$$\underline{\underline{\tilde{G}}}(k_t) = \underline{\underline{\tilde{G}}}_{\text{vac}} + \underline{\underline{\tilde{G}}}_{\text{reg}}$$

$$\underline{\underline{\tilde{G}}}_{\text{vac}} \rightarrow \underline{\underline{g}}(|r - r'|) = \left( I + \frac{\nabla \nabla}{k_0^2} \right) \Phi(|r - r'|)$$

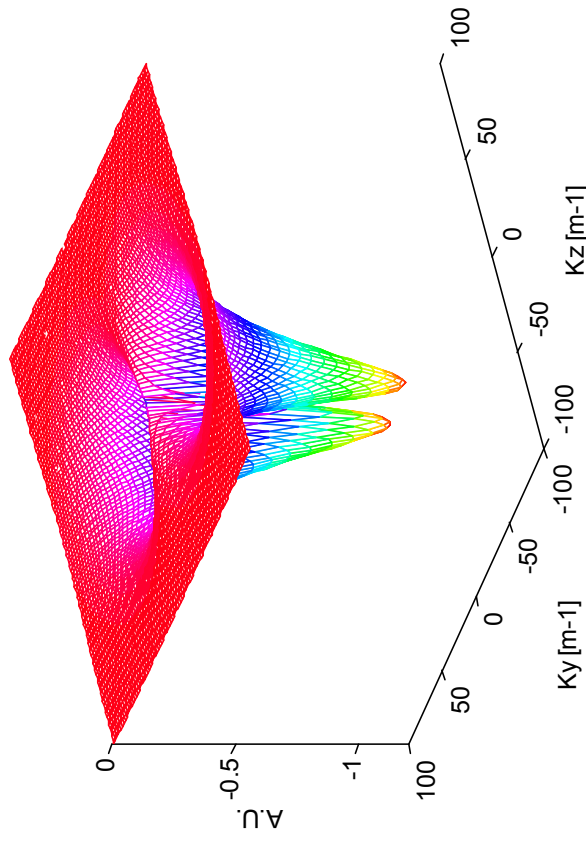
- **Vacuum** contribution to matrix entries is evaluated **separately** in the spatial domain, also providing a useful (fast) **free-space** characterization of the antenna

# Vacuum Extraction Procedure (2)

Before



After

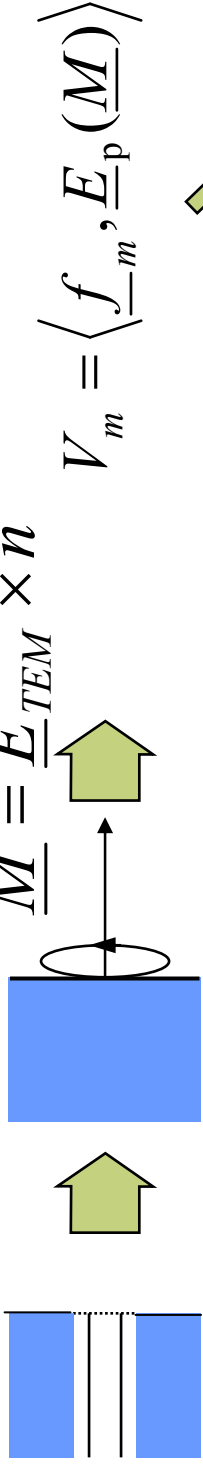


$$\text{Im} \left\{ \tilde{\underline{\underline{G}}}_{yy} \right\} = \text{Im} \left\{ \tilde{\underline{\underline{G}}}_{yy}^{\text{reg}} + \tilde{\underline{\underline{G}}}_{yy}^{\text{vac}} \right\}$$

$$\text{Im} \left\{ \tilde{\underline{\underline{G}}}_{yy}^{\text{reg}} \right\} = \text{Im} \left\{ \tilde{\underline{\underline{G}}}_{yy} - \tilde{\underline{\underline{G}}}_{yy}^{\text{vac}} \right\}$$

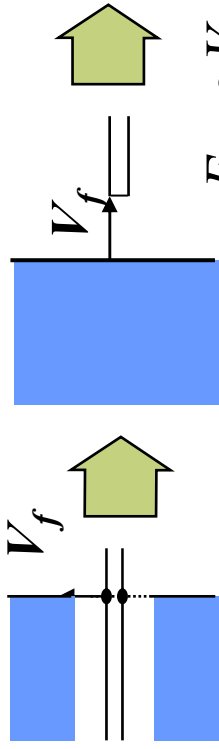
# Source Term [V]

## Magnetic current



$$V_m = \langle \underline{f}_{-m}, \underline{E}_{-p}(\underline{M}) \rangle$$

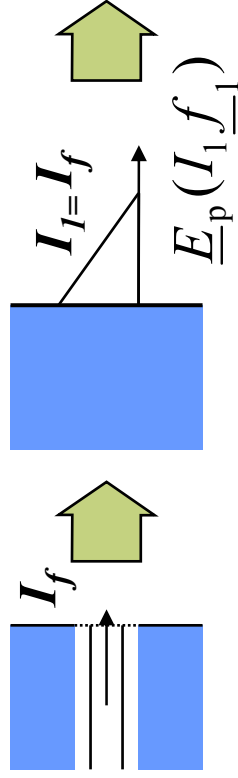
## Voltage gap



$$[V] = \begin{bmatrix} 0 \\ \vdots \\ V_f \\ \vdots \\ 0 \end{bmatrix}$$

$$[I] = -[Z]^{-1}[V]$$

## Complex power (current source)



$$[V] = [Z_{m1}]^T I_f$$

# Antenna Input Impedance

- Once  $J_s$  has been computed:

- Magnetic current (coax)

$$I_{\text{TEM}} = -\frac{\langle \underline{M}, \underline{H}_s(\underline{J}_s) \rangle}{2V_f} \quad Y_{\text{in}} = -\frac{\langle \underline{M}, \underline{H}_s(\underline{J}_s) \rangle}{2V_f^2}$$

- Voltage gap

$$Z_{\text{in}} = \frac{V_f}{I_n}$$

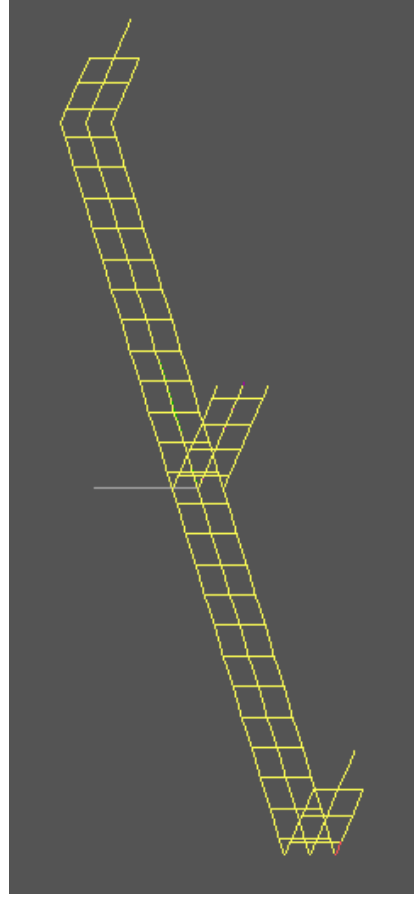
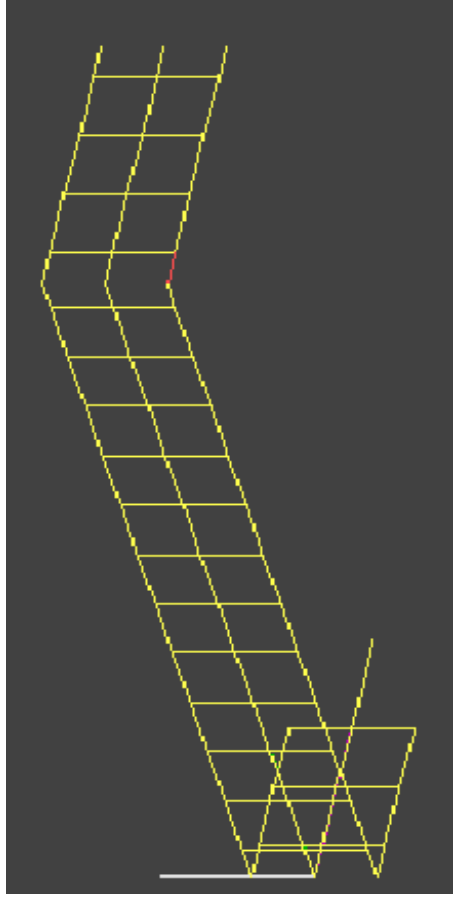
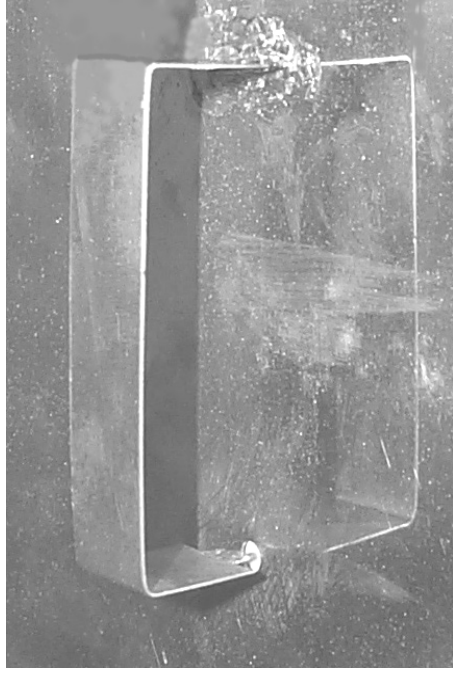
- Complex power (current source)

$$Z_{\text{in}} = -\frac{\int_{\Sigma} d\Sigma \underline{E}_s \cdot \underline{J}_s^*}{|I_f|^2} = -\frac{[I]^{T*} [Z] [I]}{|I_f|^2}$$

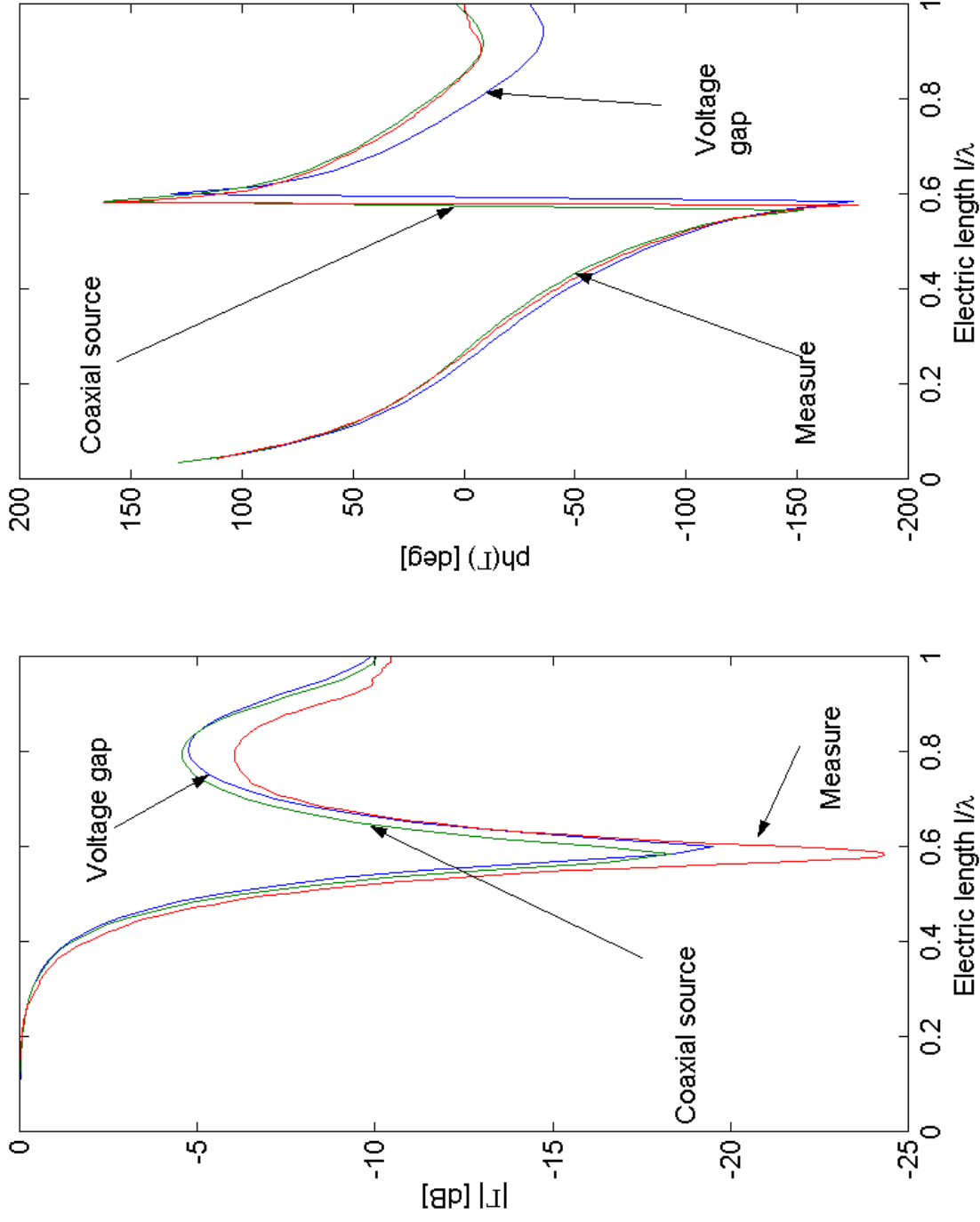


# Validation in Vacuo

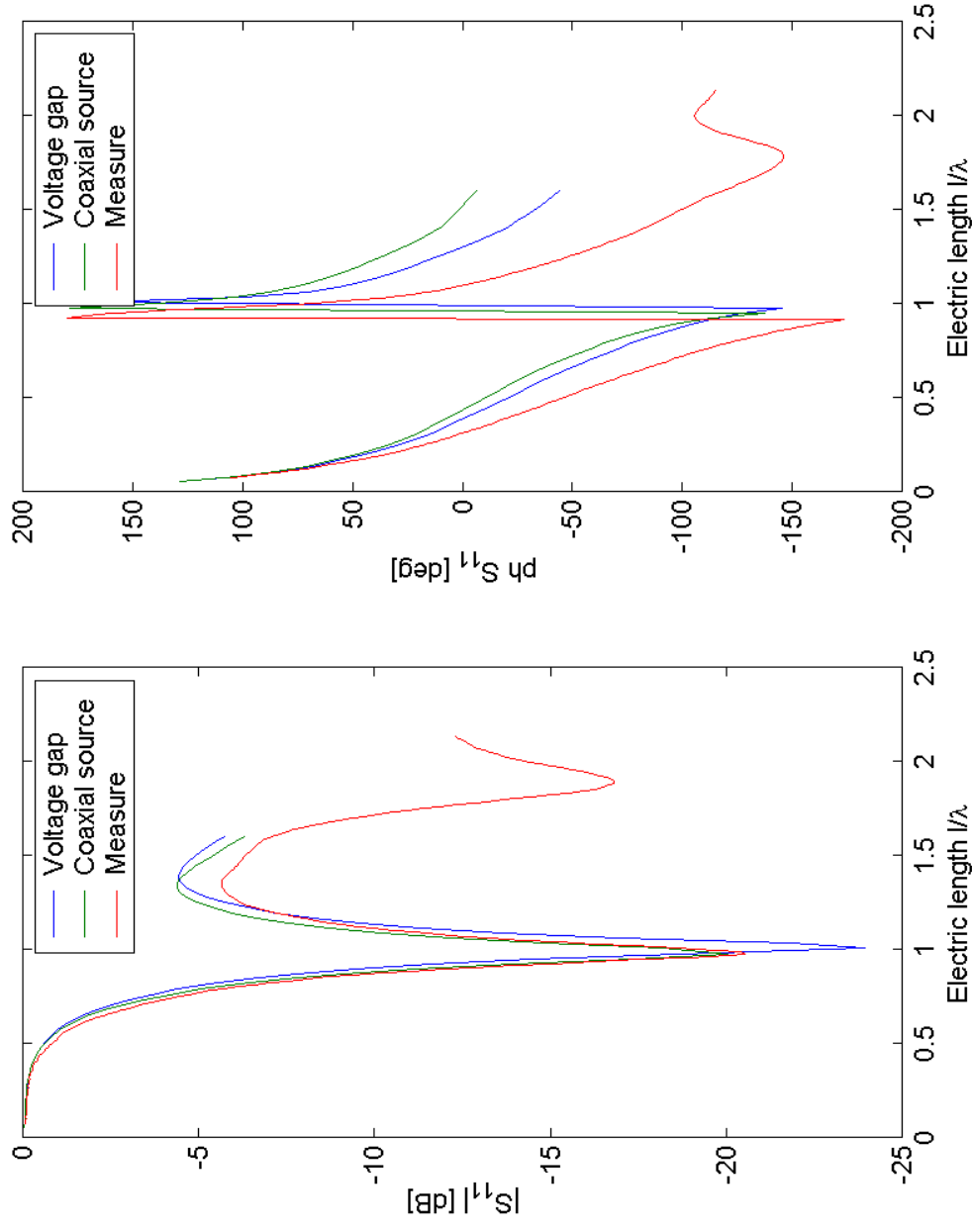
- Single and double loop antenna



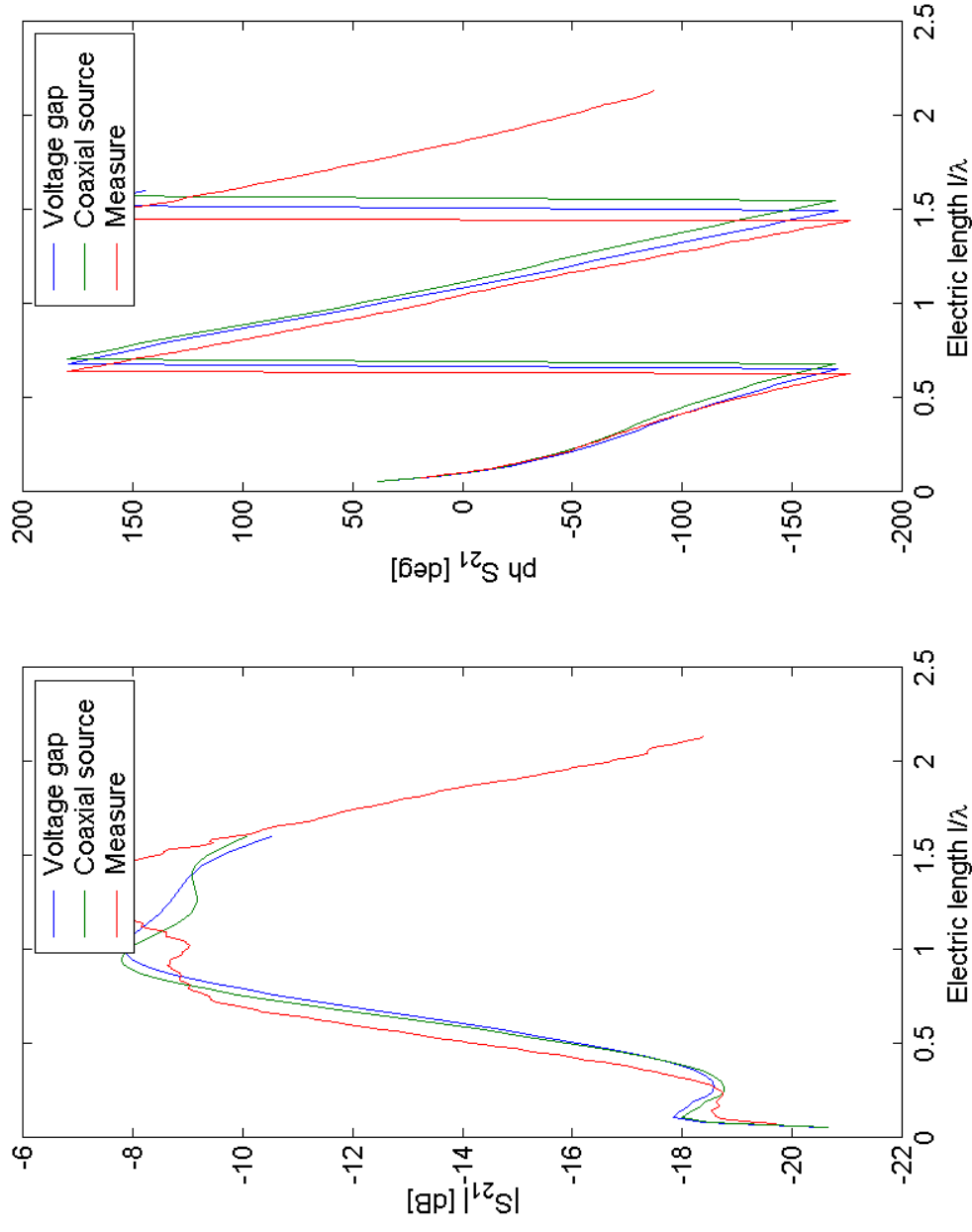
# Validation in Vacuo: Single Loop



# Validation in Vacuo: Double Loop (1)

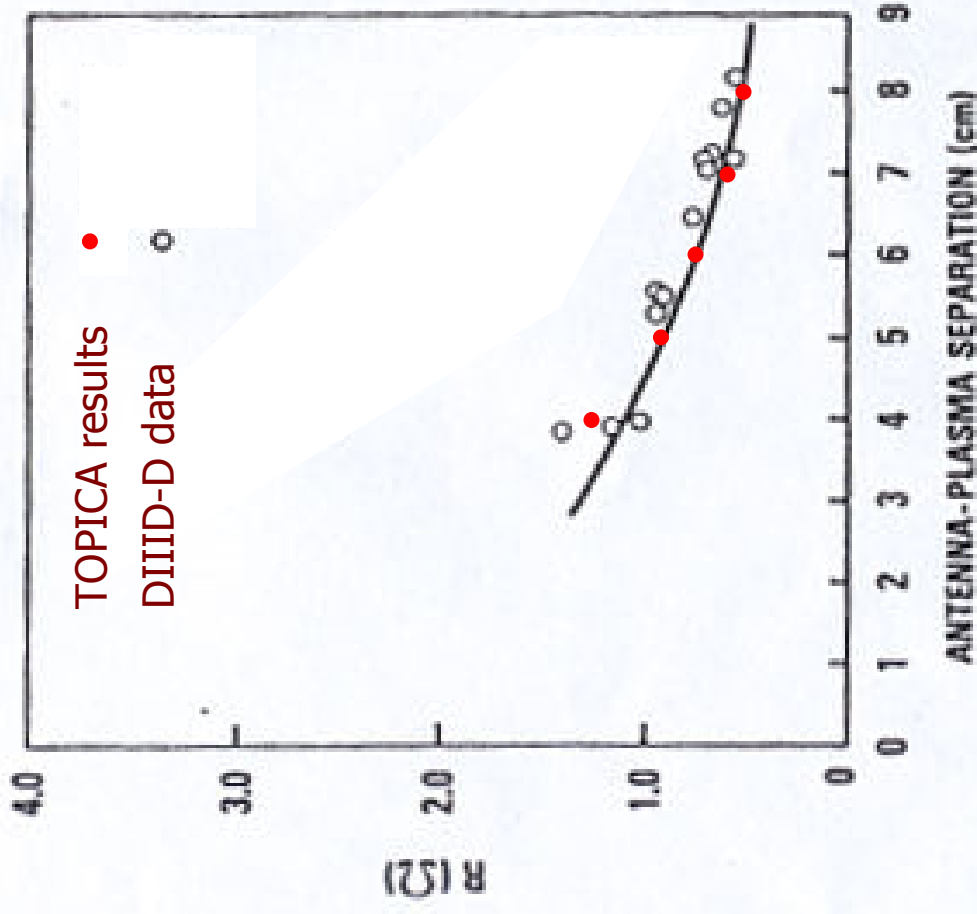
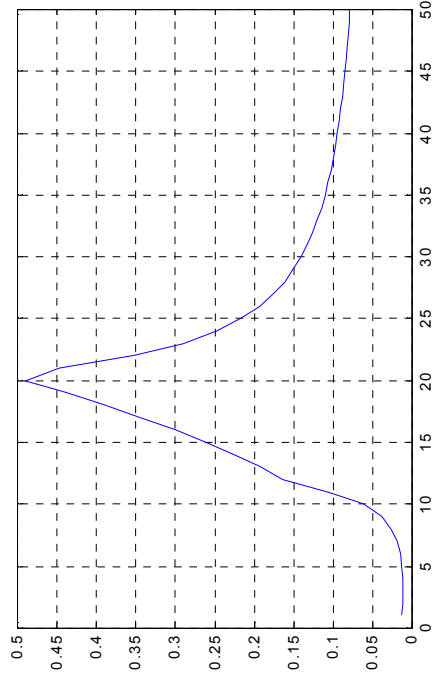
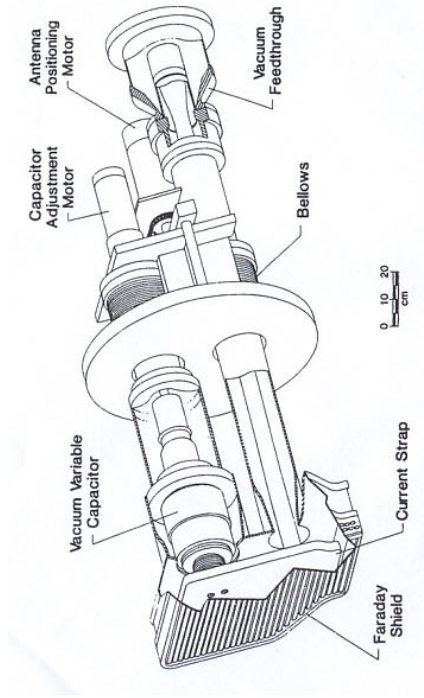


# Validation in Vacuo: Double Loop (2)



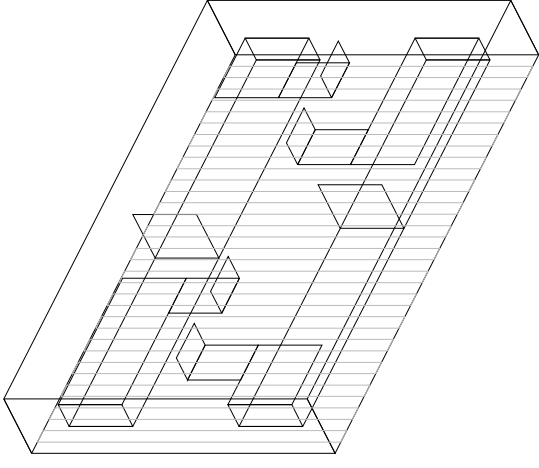
# Validation with Plasma: DIII-D

Nuclear Fusion, Vol. 30, No. 4

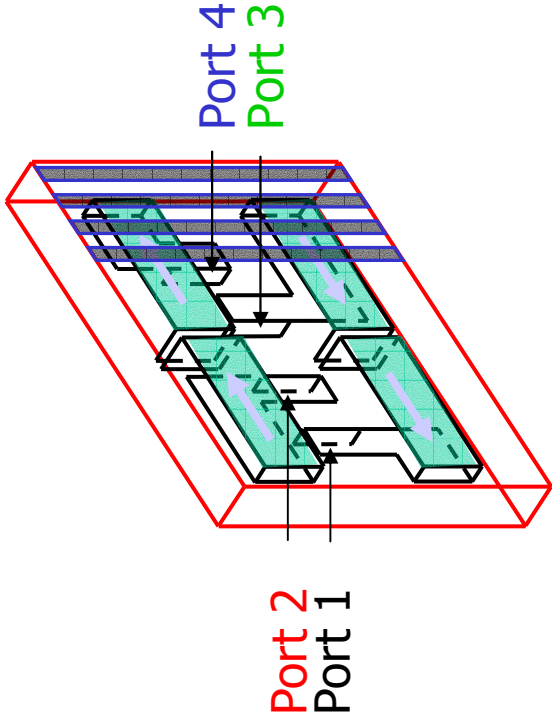


# IGNITOR Antenna

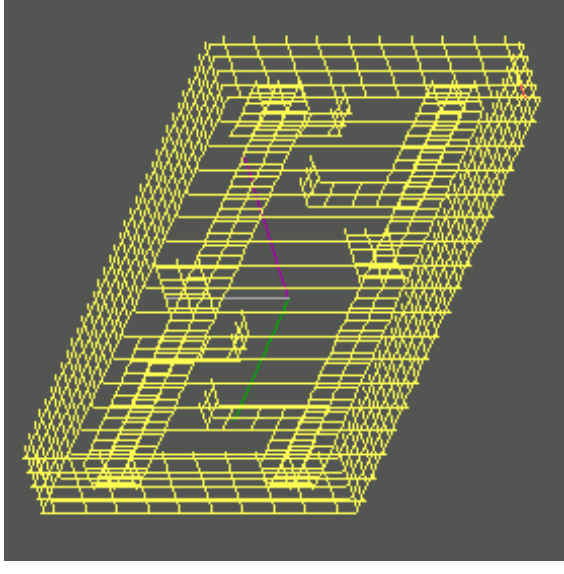
- 1) 100 MHz (9.8 T, He3 minority)
- 2) 110 MHz (10.8 T, He3 minority)
- 3) 120 MHz (11.8 T, He3 minority)
- 4) 130 MHz (12.8 T, He3 minority)
- 5) 130 MHz (8.8 T, H minority)
- 6) 140 MHz (9.5 T, H minority)



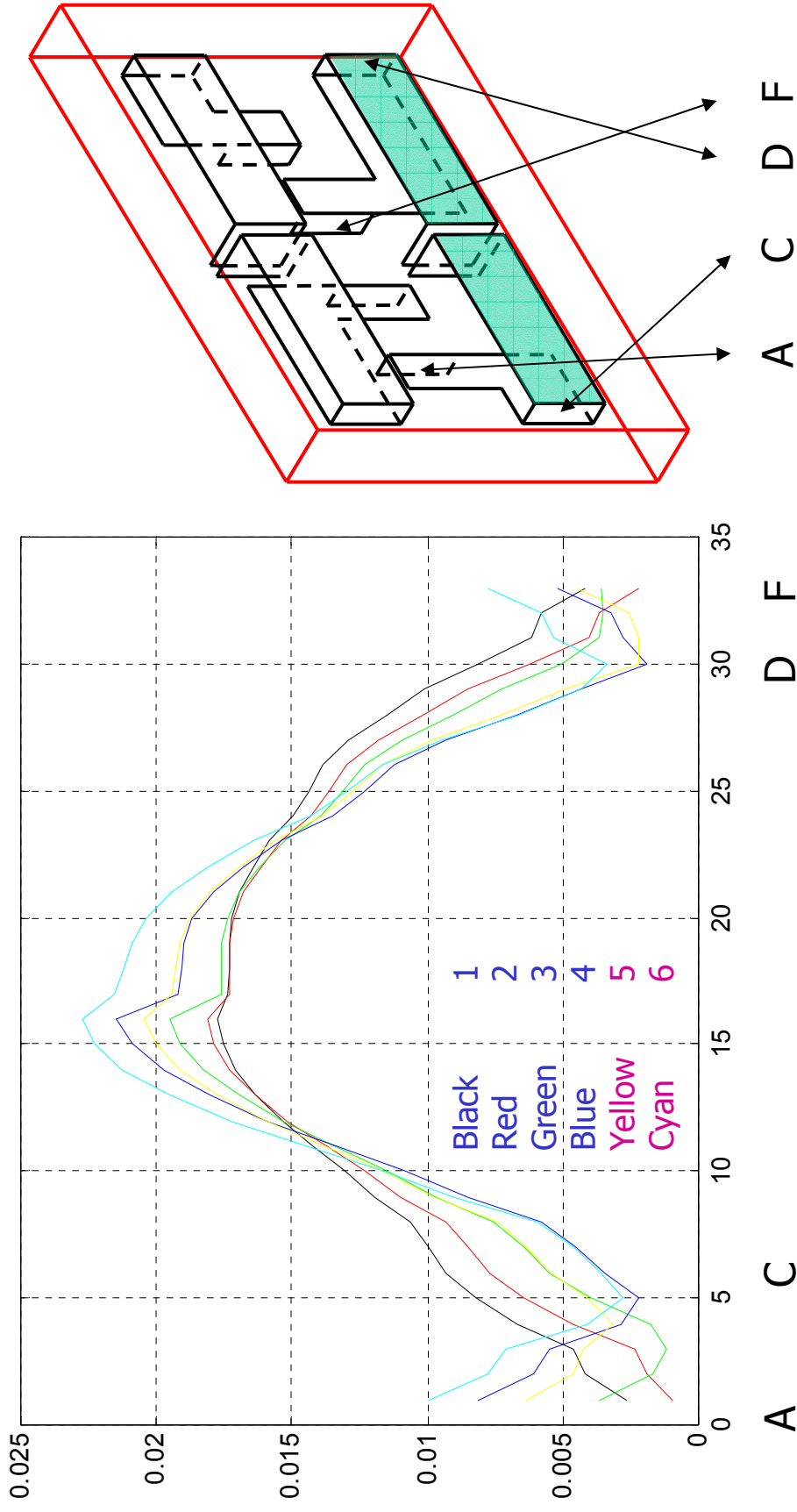
CAD drawing



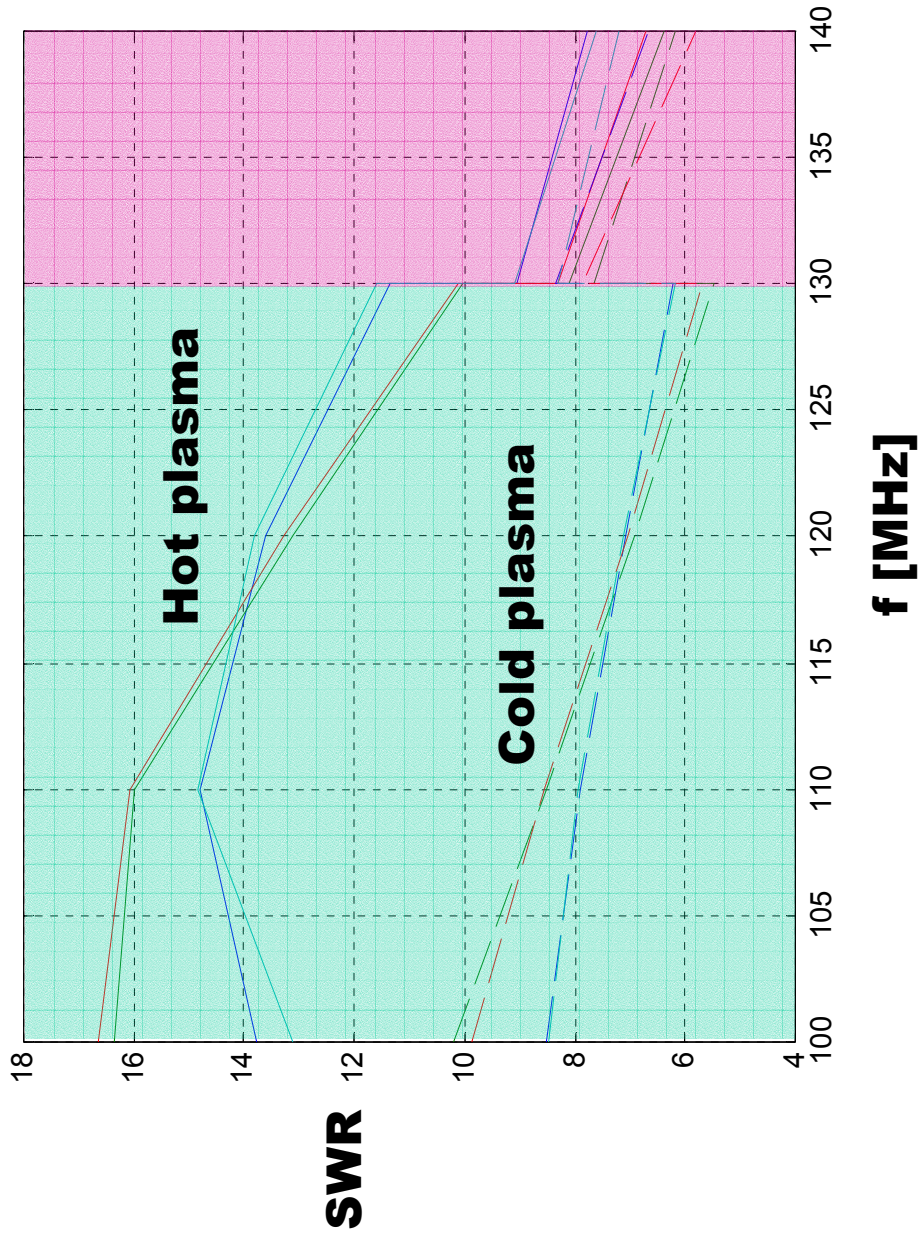
EM model



# Current Distribution

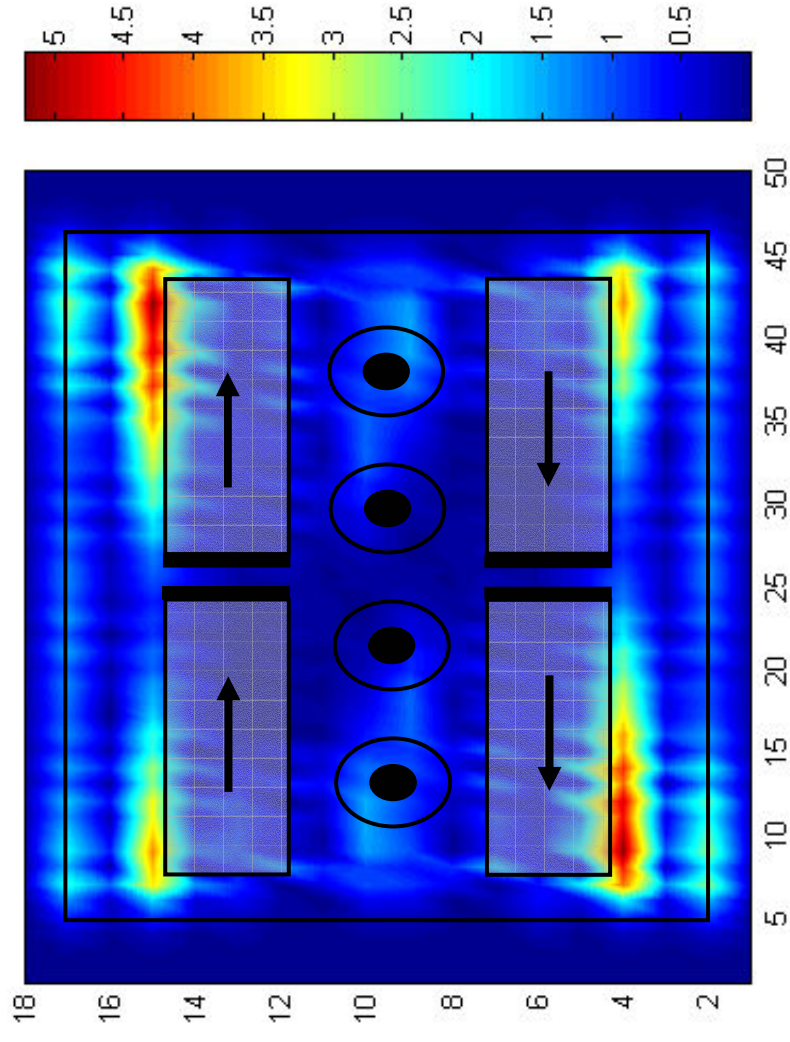


# Cold-Hot Plasma Comparison

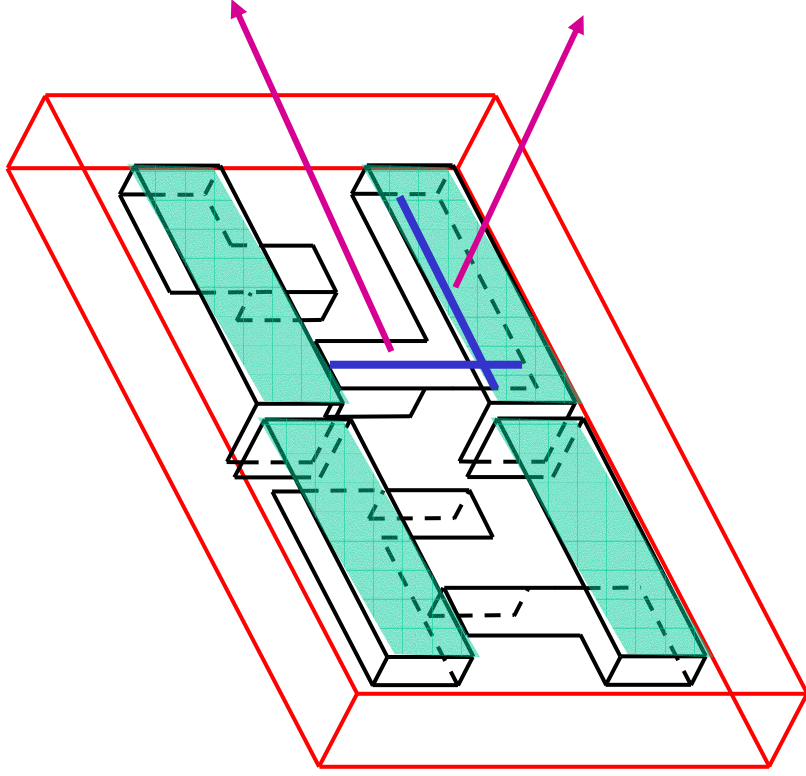




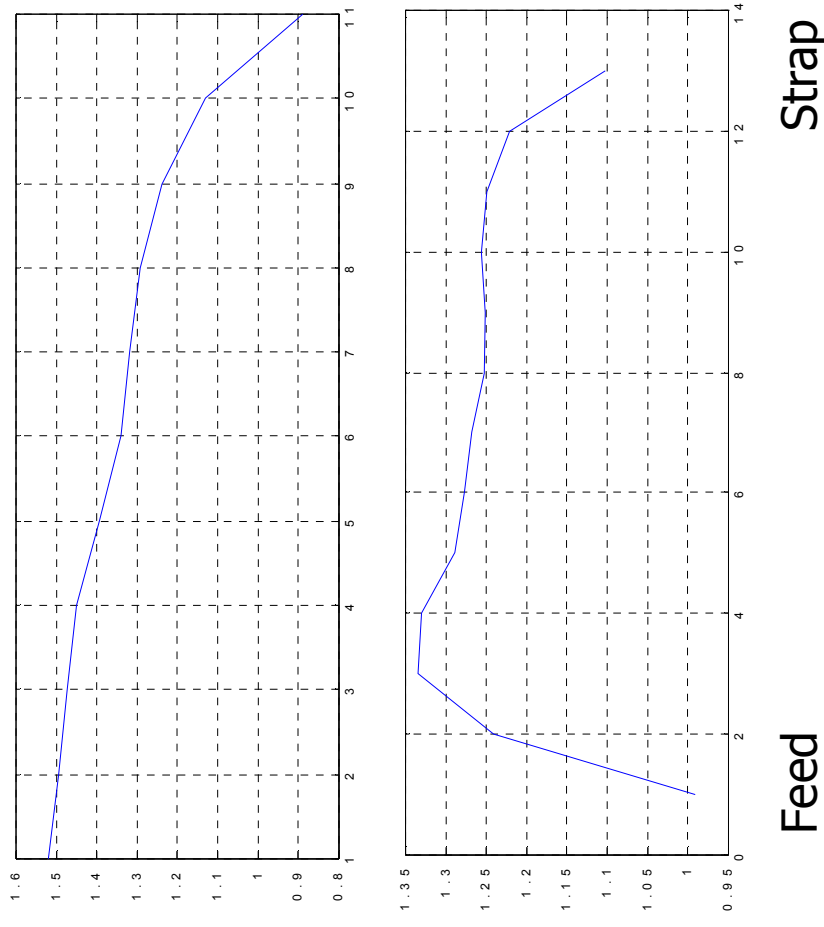
# Ez-field Distribution



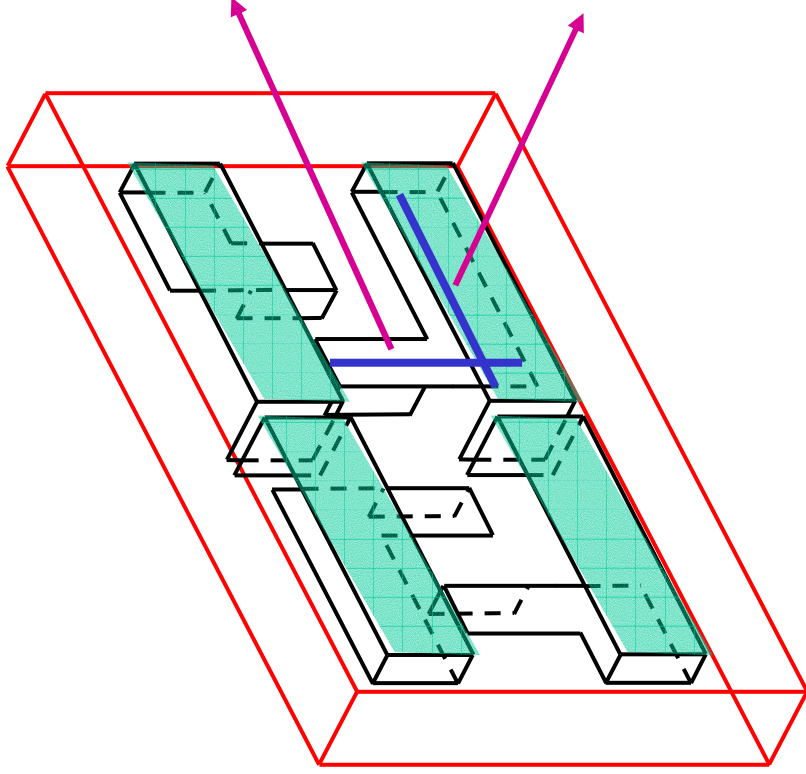
# Voltage Standoff (1)



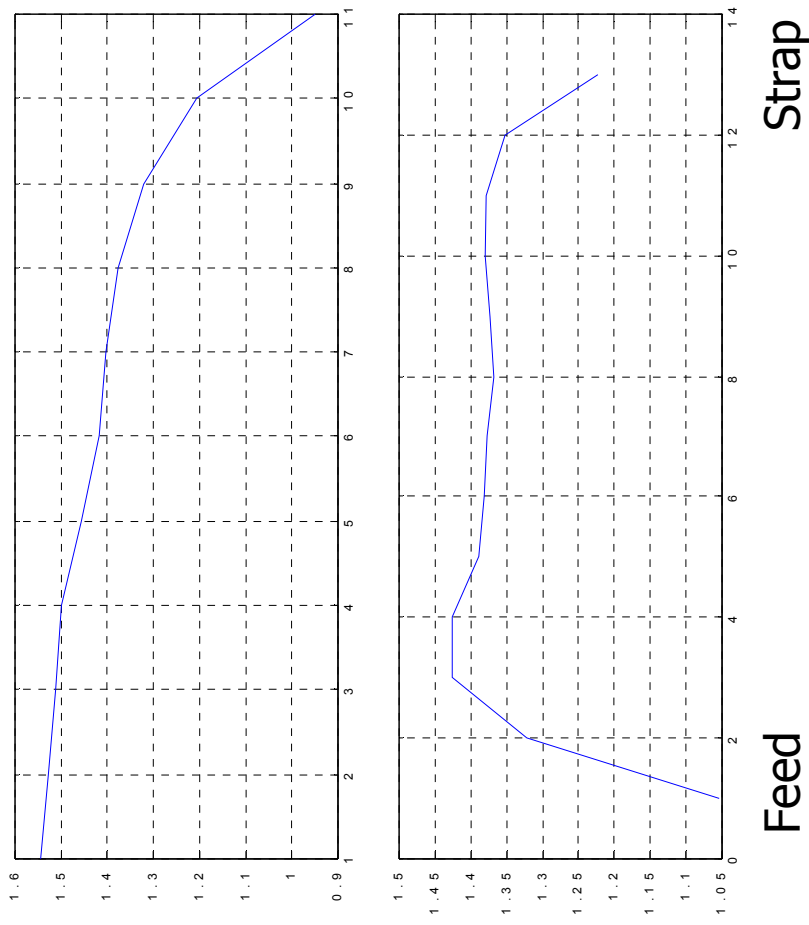
$V_x/V_{\text{feed}}$  (abs), 100 MHz (He3)



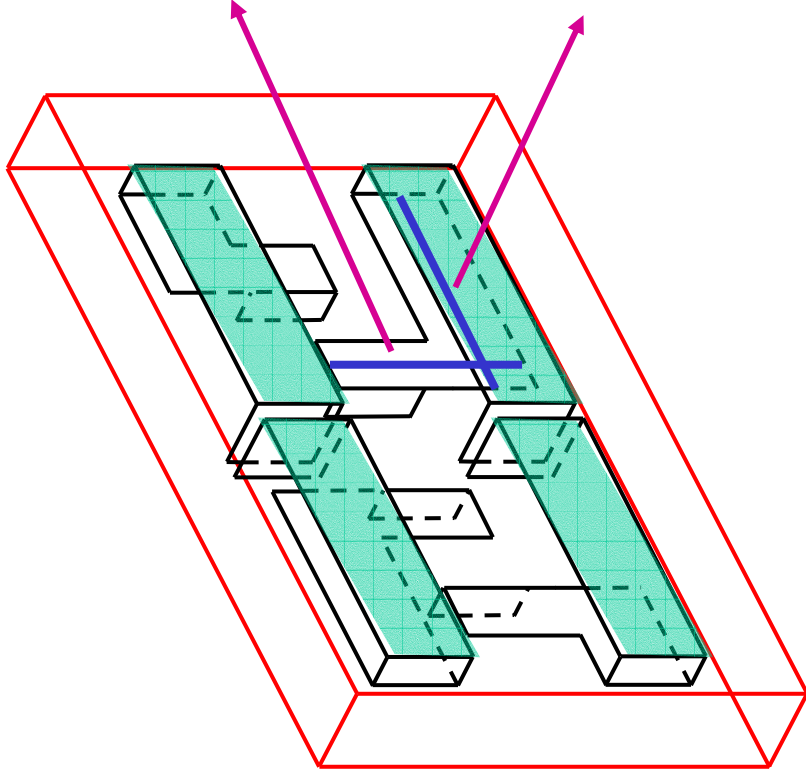
# Voltage Standoff (2)



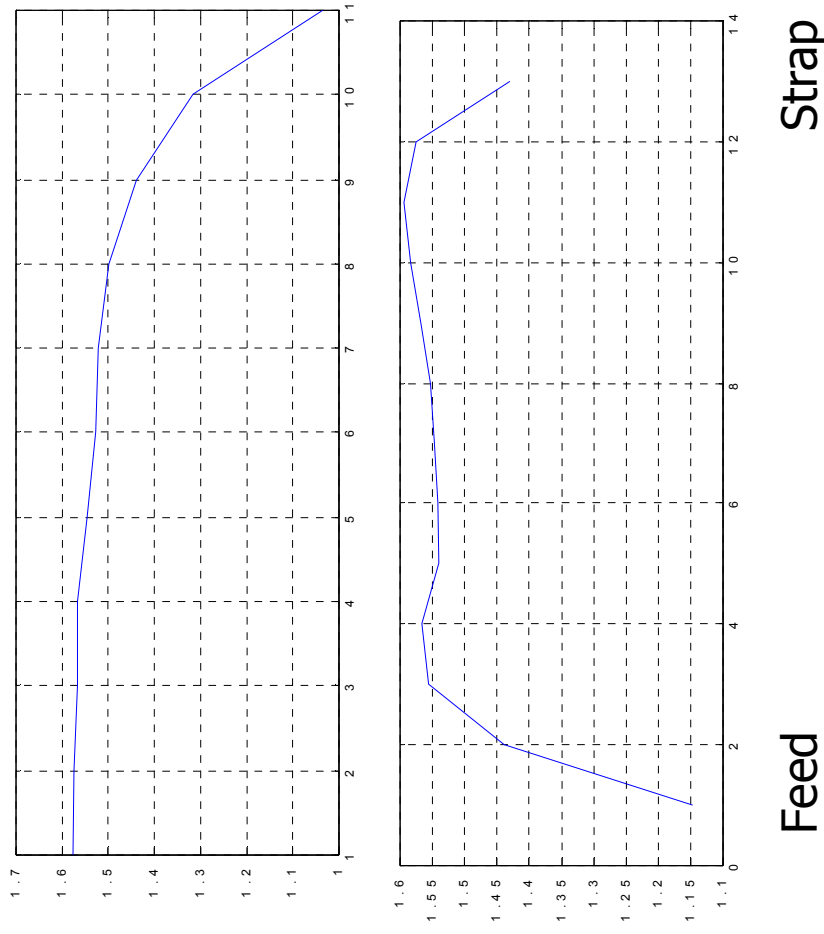
$V_x/V_{\text{feed}}$  (abs), 110 MHz (He3)



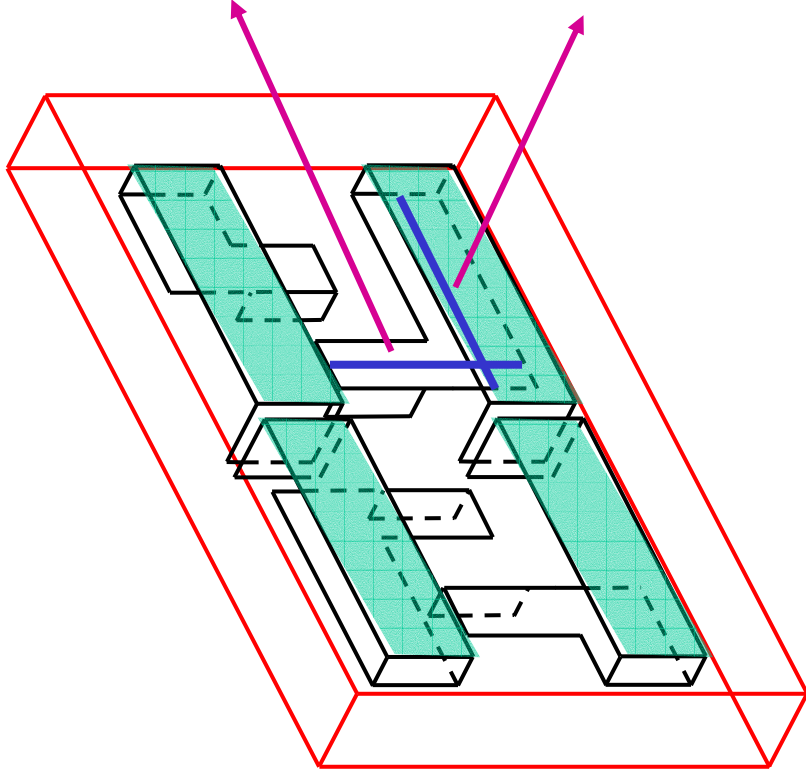
# Voltage Standoff (3)



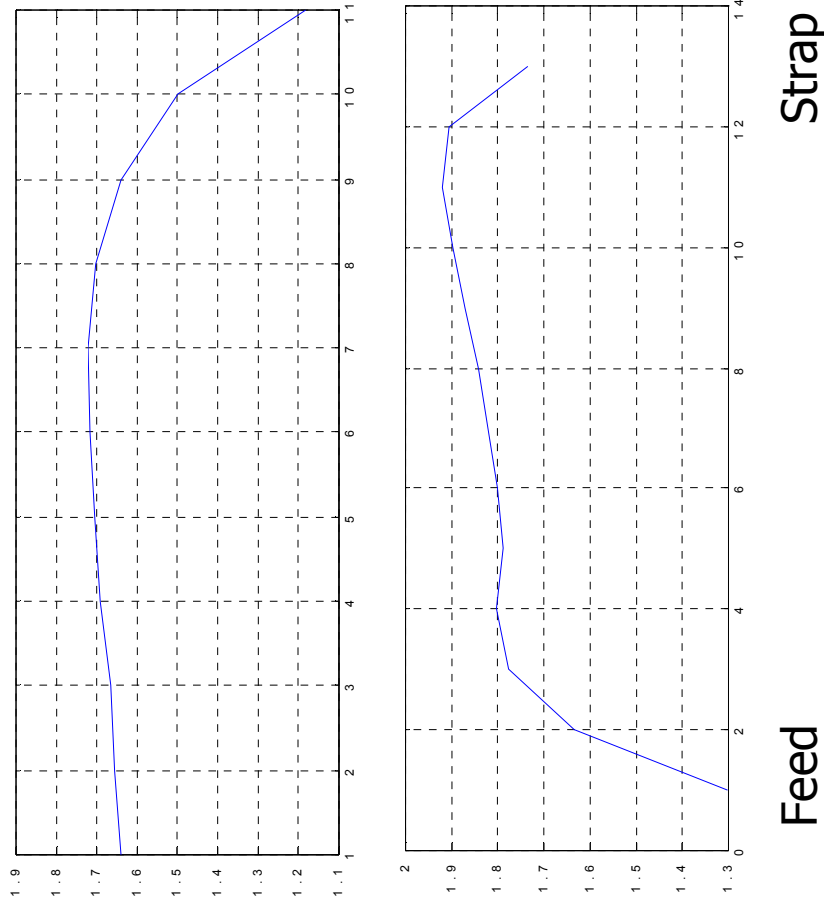
$V_x/V_{\text{feed}}$  (abs), 120 MHz (He3)



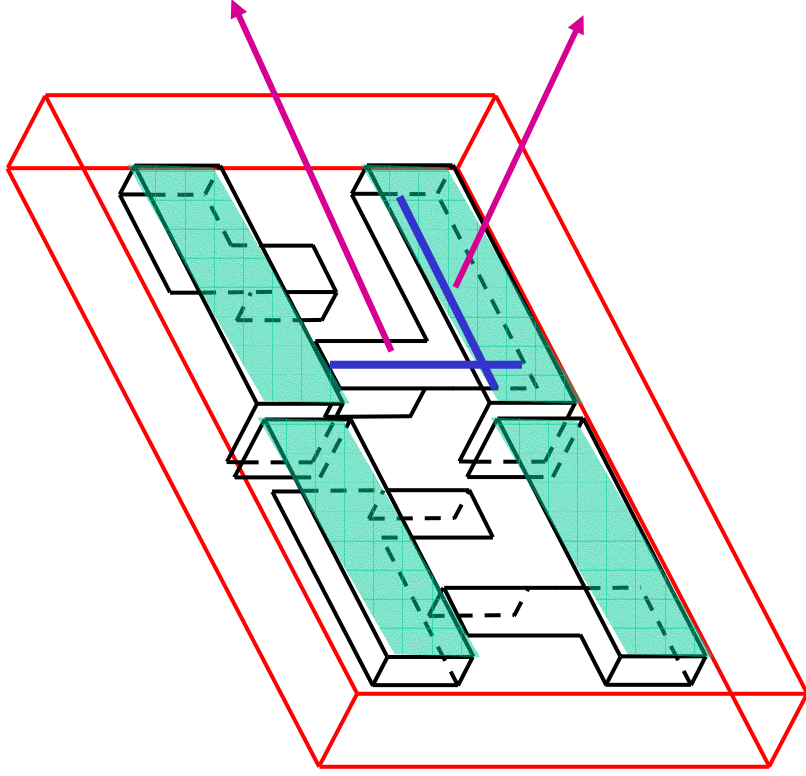
# Voltage Standoff (4)



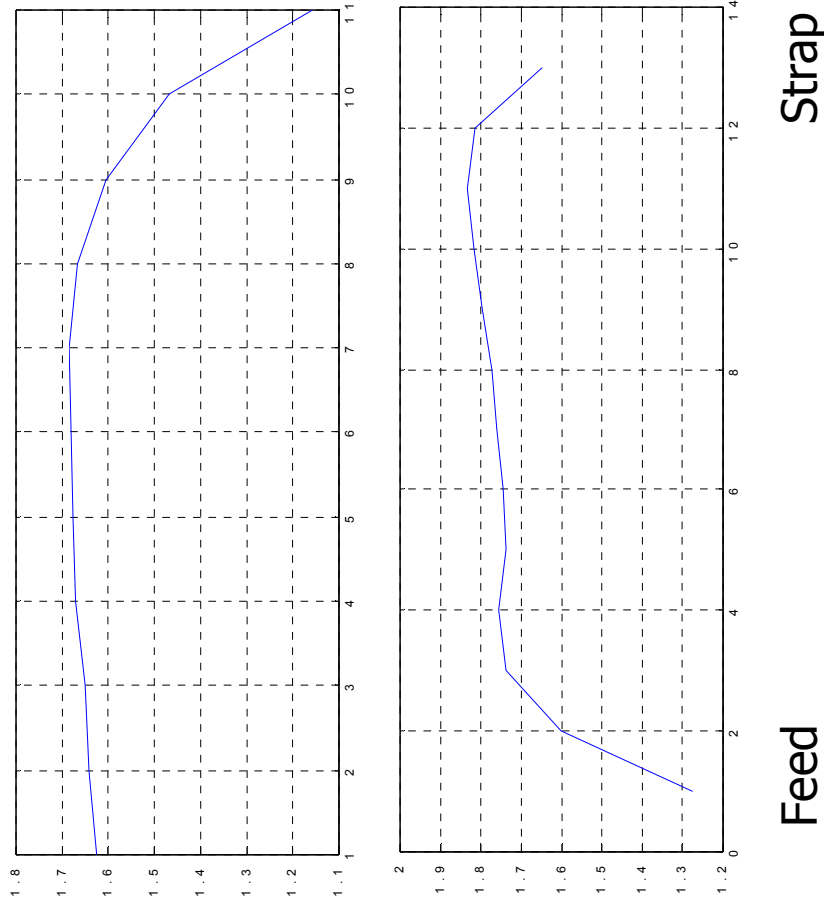
$V_x/V_{\text{feed}}$  (abs), 130 MHz (He3)



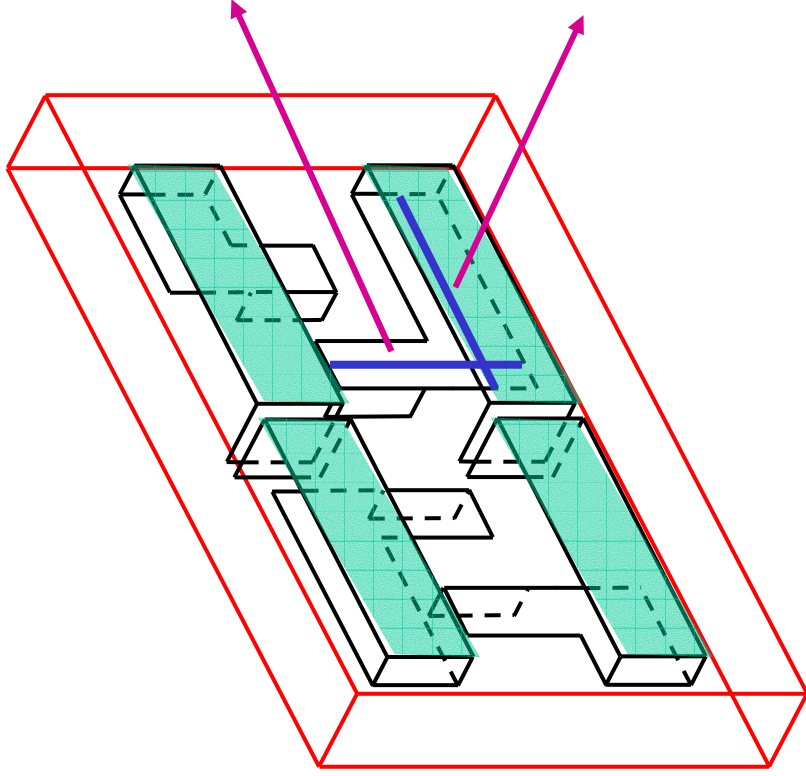
# Voltage Standoff (5)



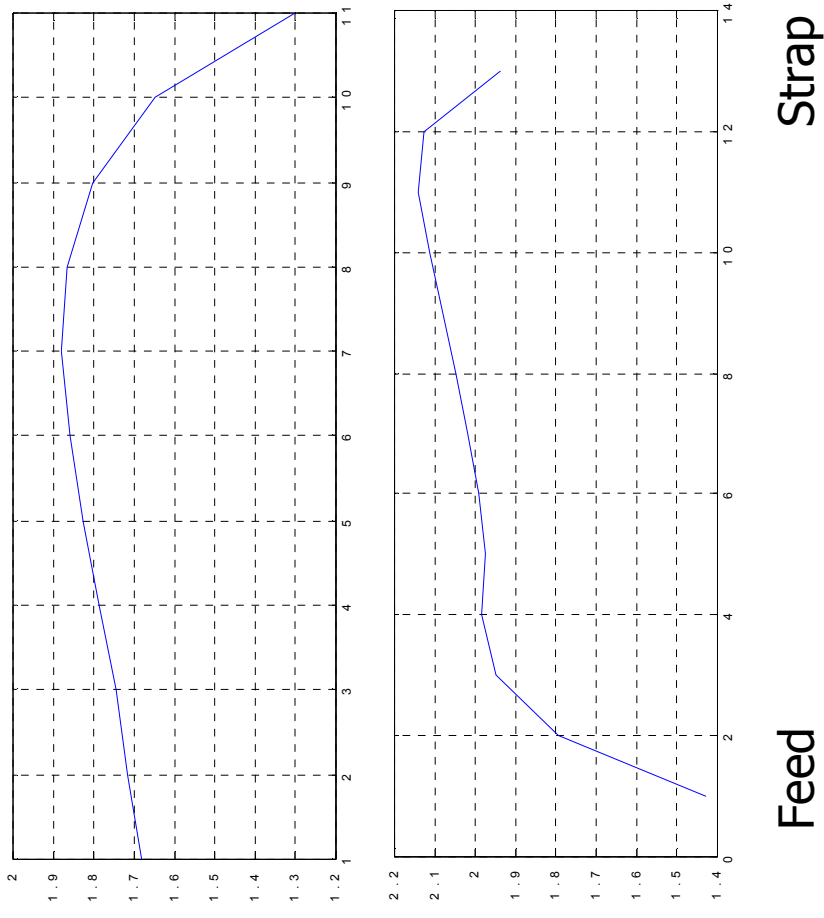
$V_x/V_{\text{feed}}$  (abs), 130 MHz (H)



# Voltage Standoff (6)



$V_x/V_{\text{feed}}$  (abs), 140 MHz (H)



# Conclusions and Future Work

## **TOPICA**© simulation suite:

- 3D antenna structure model (including FS, box, ...)
- 1D plasma, non-homogeneous, FLR, absorption (FELICE code)
- Structure geometry drawn in CAD (e.g. Autocad®) and imported into TOPICA core
- Multi-port (typ.: 4 ports) circuit parameters (Z, Y, S matrices) calculation
- Coax, Voltage and current excitation of strap ports
- Accurate model of coaxial-to-strap feed
- Computes current, fields, and voltage everywhere around antenna and housing
- Boundary-element method, high efficiency, controllable convergence, affordable CPU times

## **Future work:**

- More validation against measured data
- 2D/3D hybrid spatial-spectral code
- Triangular meshing (vacuum case: done)

