TOPICA : a virtual prototyping suite for plasma facing antennas

TOPICA:
A Virtual Prototyping Suite for Plasma Facing Antennas

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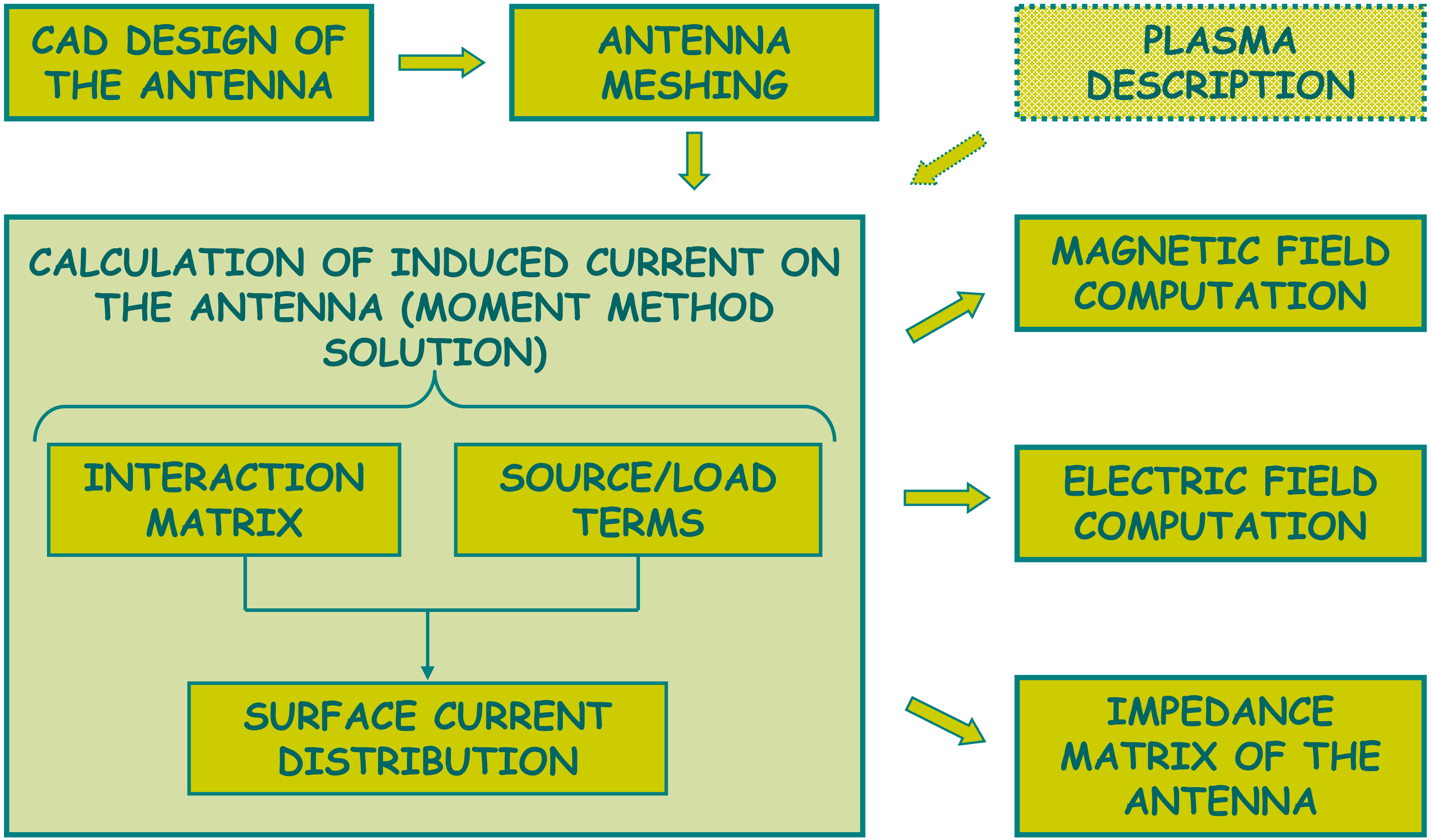
Presentation Outline

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

Objectives of the Work

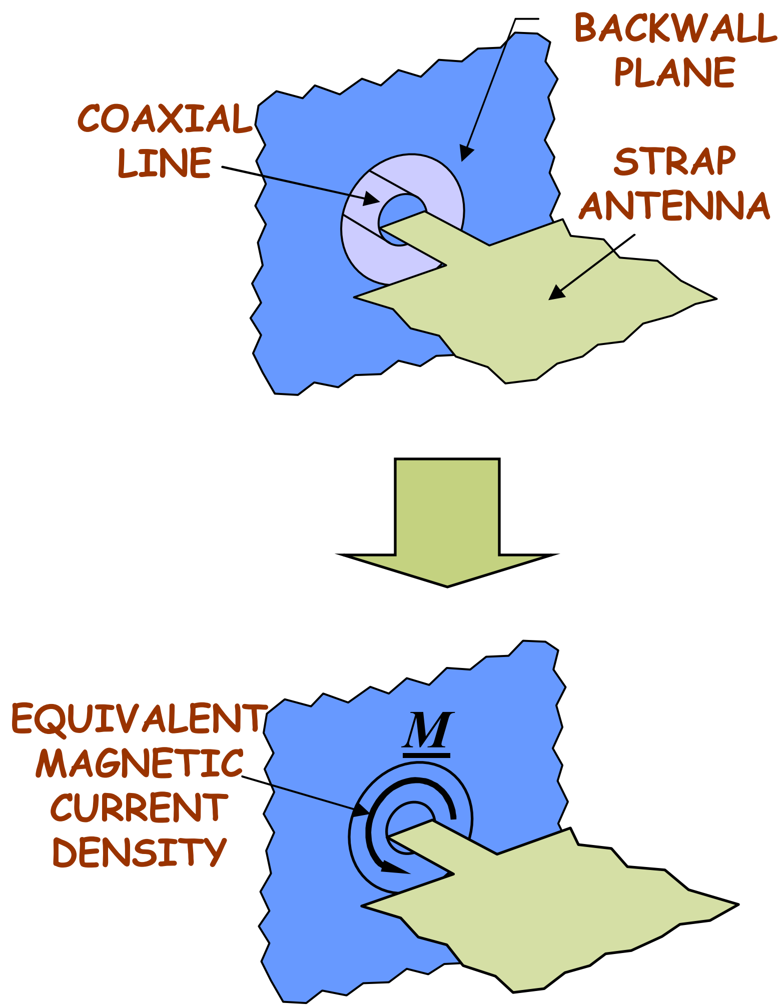
- To study a **realistic antenna** geometry with a reasonable CPU time
- To include an accurate and **realistic plasma** description into the model (FELICE plasma module)
- To get reliable information about:
  - **antenna input parameters** which allow an accurate design of *tuning & matching* control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

"Virtual Prototyping Laboratory"



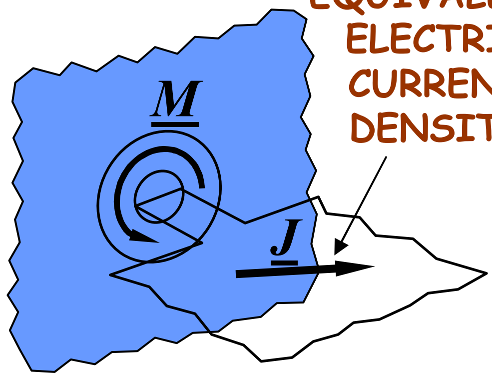
Statement of the Problem (1)

- 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**



$$\underline{E}_{\mathrm{p}}(\underline{\rho},x)=\iint_{\Sigma_c} d^2\rho'\,\underline{\underline{g}}_{\mathrm{m}}(\underline{\rho}-\underline{\rho}',x)\cdot\underline{M}(\underline{\rho}')$$

$$\underline{E}_{\mathrm{s}}(\underline{\rho},x)=\iint_{\Sigma} d^3r'\,\underline{\underline{g}}(\underline{\rho}-\underline{\rho}',x,x')\cdot\underline{J}_{\mathrm{s}}(\underline{\rho}',x')$$

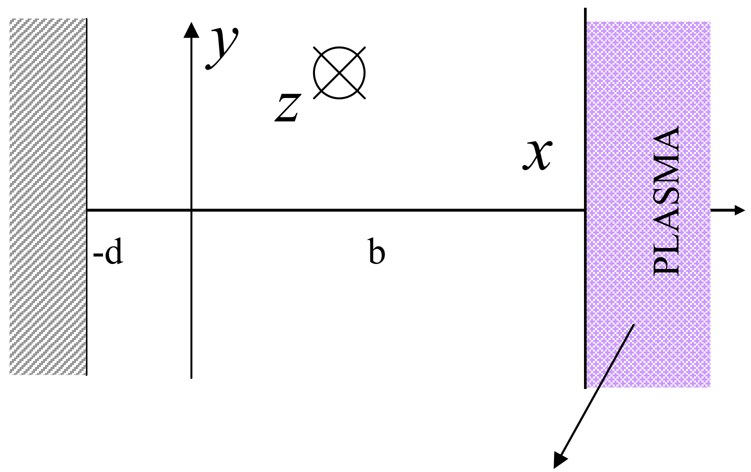
- Enforcing **boundary conditions** on antenna surface yields the relevant **EFIE**

$$\hat{n}\times\left(\underline{E}_{\mathrm{p}}+\underline{E}_{\mathrm{s}}\right)\Big|_{\Sigma_{\mathrm{a}}}=\underline{0}$$

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

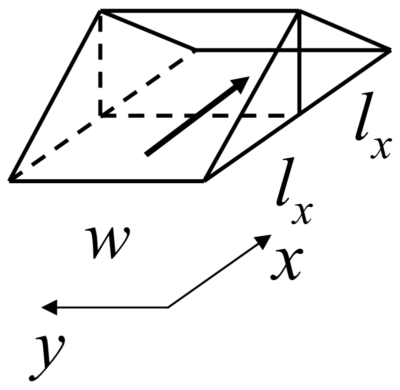
- The unknown current is expressed as linear superposition of suitable **basis** functions : $\underline{J}_s = \sum_{n=1}^{N} I_n \underline{f}_n$
- The EFIE is projected onto the **test** functions and a linear algebraic system is obtained:

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

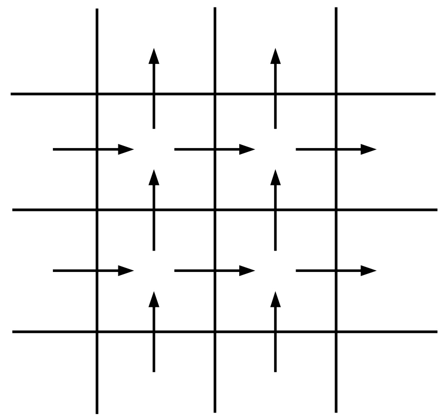
- Matrix entries contain Green's function: Parseval identity is used to transform them into **spectral** domain

Basis and Test Functions

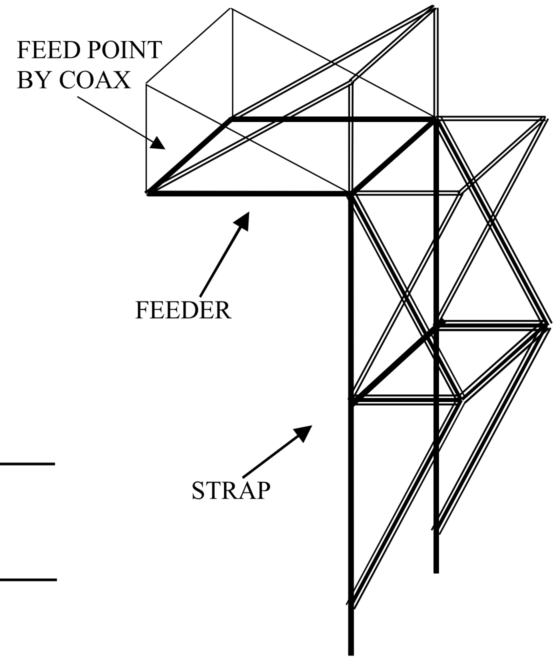
- **Choice** criteria:
  - Must be *Div-conforming* to avoid spurious solutions
  - Antenna geometry (plane surfaces)
  - simplicity
- **Rooftop** function features:
  - Rectangular support
  - Linear interpolating
  - Piece-wise constant div



SKETCH OF
A ROOFTOP



GRID COVERING



A SAMPLE
MESHING

Interaction Matrix Entries (1)

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

- Analytical integration over *x* and *x′* to save time
- Numerical integration over k_t is critical since:
  - Green’s function $\underline{\underline{\tilde{G}}}(\underline{k}_t)$ diverges asymptotically
  - Basis function spectra $\underline{\tilde{f}}_m$ 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)

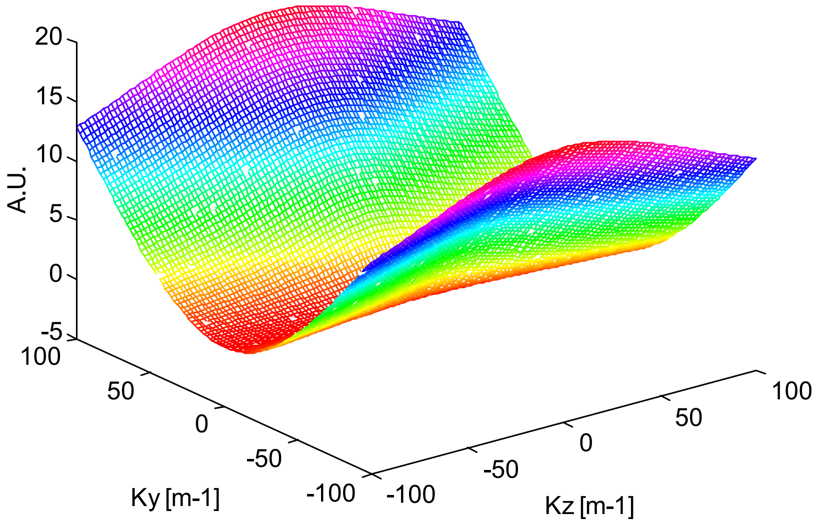
$$\underline{\underline{\tilde{G}}}(\underline{k}_{t}) = \underline{\underline{\tilde{G}}}_{vac} + \underline{\underline{\tilde{G}}}_{reg}$$

$$\underline{\underline{\tilde{G}}}_{vac} \rightarrow \underline{\underline{g}}(|\underline{r} - \underline{r}'|) = \left(\underline{\underline{I}} + \frac{\nabla\nabla}{k_{0}^{2}} \right) \Phi(|\underline{r} - \underline{r}'|)$$

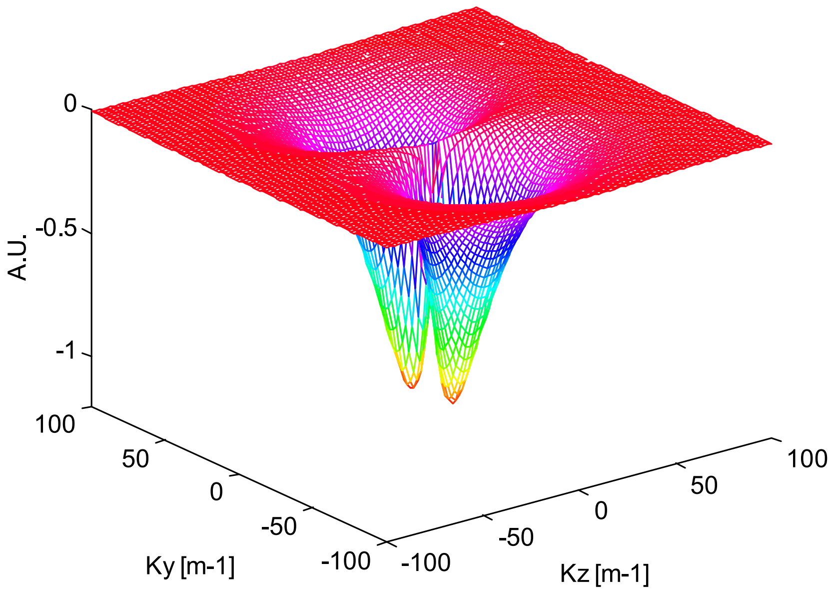
- **Vacuum** contribution to matrix entries is evaluated **separately** in the spatial domain, also providing a useful (fast) **free-space** characterization of the antenna

Vacuum Extraction Procedure (2)

Before



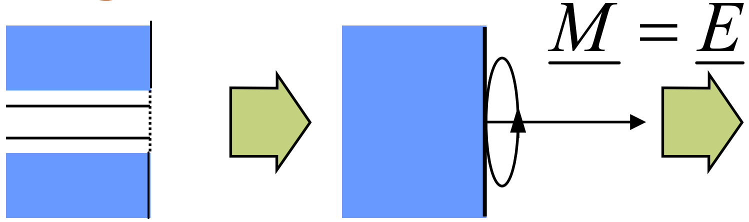
After



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

Source Term [*V*]

Magnetic current

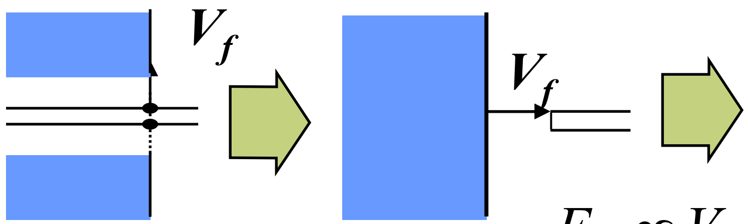


$$\underline{M} = \underline{E}_{TEM} \times \hat{n}$$

$$\underline{E}_{TEM} = V_f \, \underline{e}_{TEM}$$

$$V_m = \left\langle \underline{f}_m, \underline{E}_{\mathrm{p}}(\underline{M}) \right\rangle$$

Voltage gap

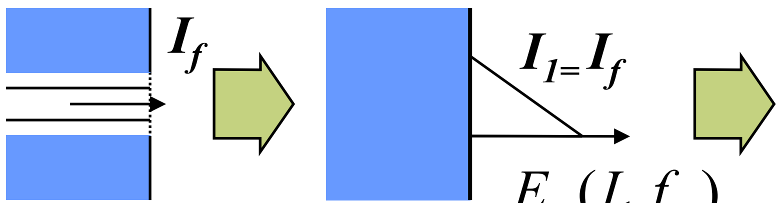


$$\underline{E}_{\mathrm{p}} \propto V_f \,|_{x=backwall}$$

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

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

Complex power (current source)



$$\underline{E}_{\mathrm{p}}(I_1 \underline{f}_1)$$

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

Antenna Input Impedance

- Once J_s has been computed:
  - Magnetic current (coax)

$$I_{\mathrm{TEM}} = -\frac{\left\langle \underline{M}, \underline{H}_{\mathrm{s}}\left(\underline{J}_{\mathrm{s}}\right)\right\rangle}{2V_f} \qquad Y_{\mathrm{in}} = -\frac{\left\langle \underline{M}, \underline{H}_{\mathrm{s}}\left(\underline{J}_{\mathrm{s}}\right)\right\rangle}{2V_f^2}$$

  - Voltage gap

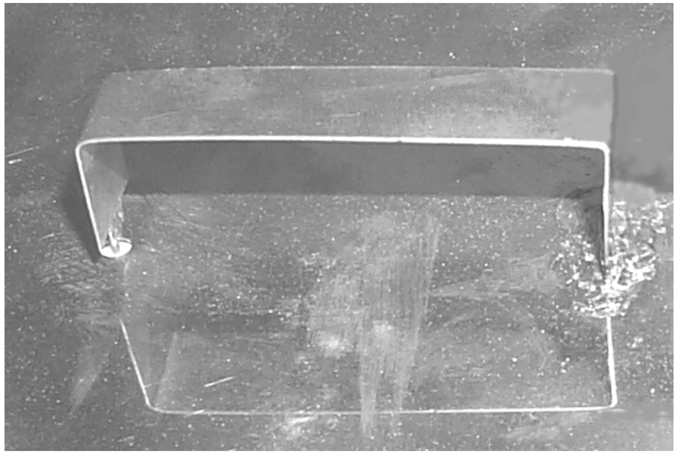
$$Z_{\mathrm{in}} = \frac{V_f}{I_n}$$

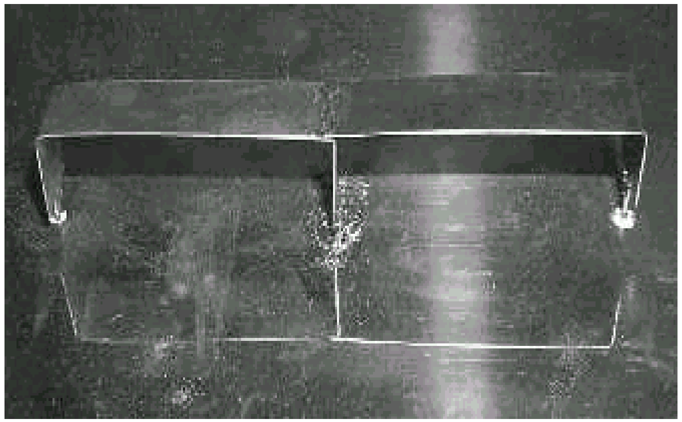
  - Complex power (current source)

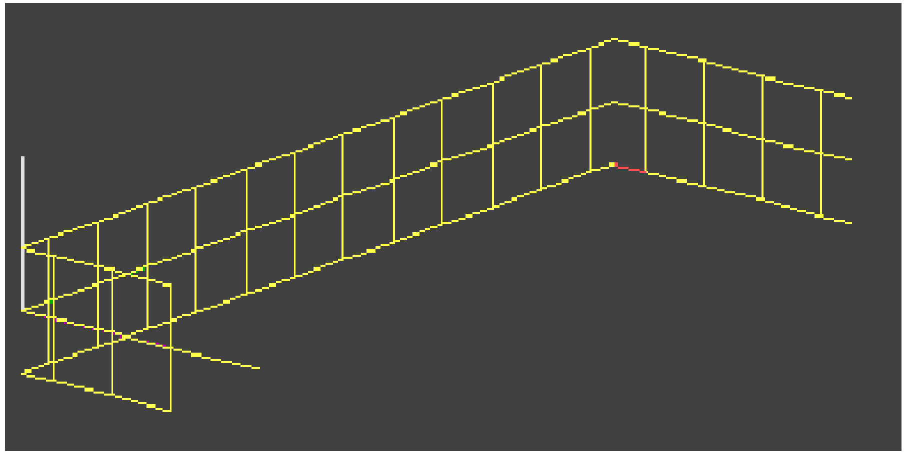
$$Z_{\mathrm{in}} = -\frac{\int_{\Sigma} d\Sigma \underline{E}_s \cdot \underline{J}_{\mathrm{s}}^*}{\left|I_f\right|^2} = -\frac{[I]^{T*}[Z][I]}{\left|I_f\right|^2}$$

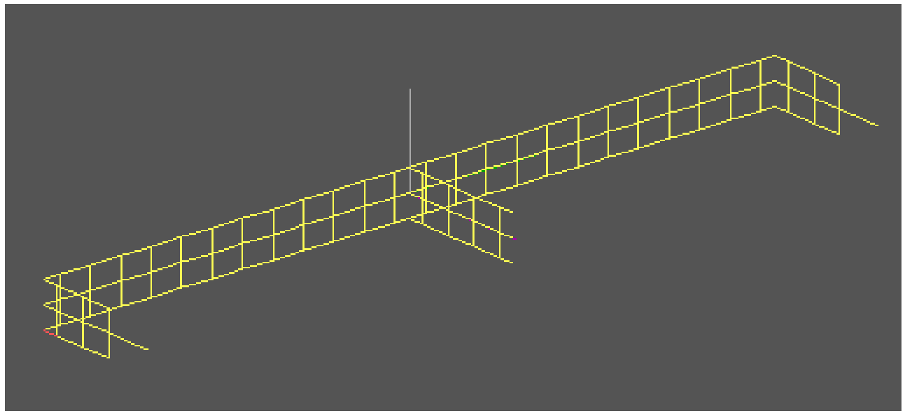
Validation in Vacuo

- Single and double loop antenna

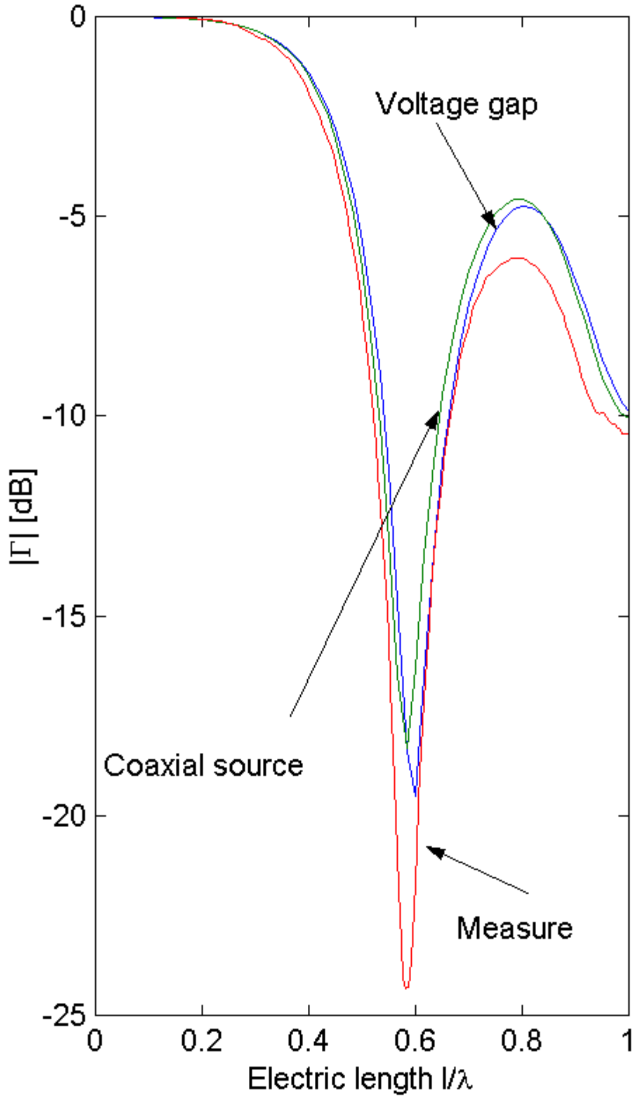


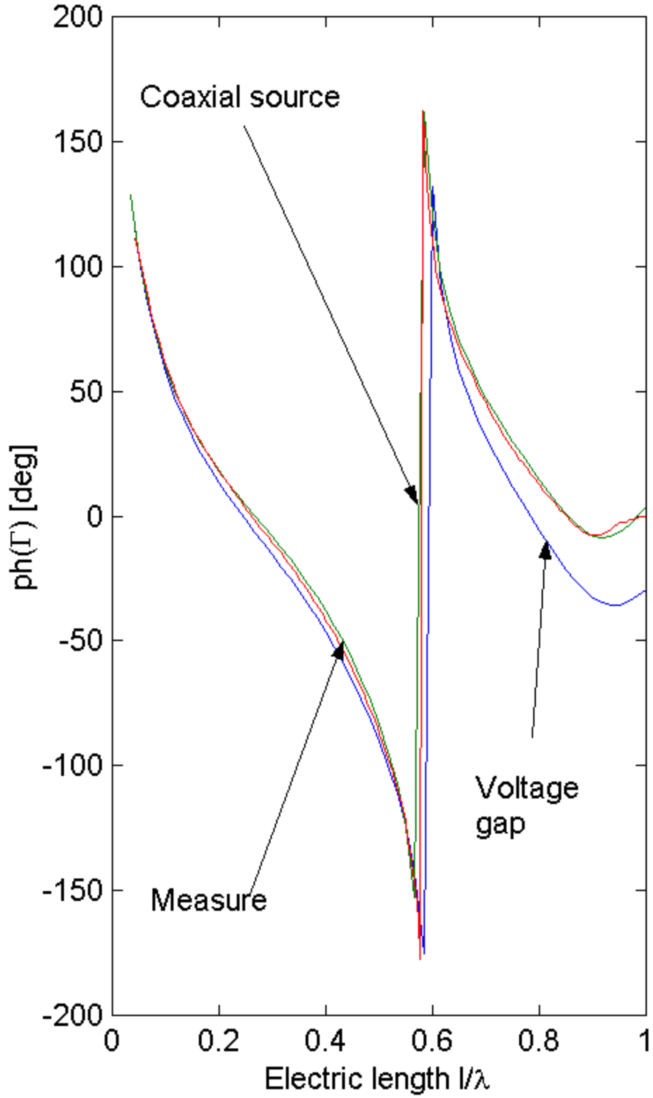




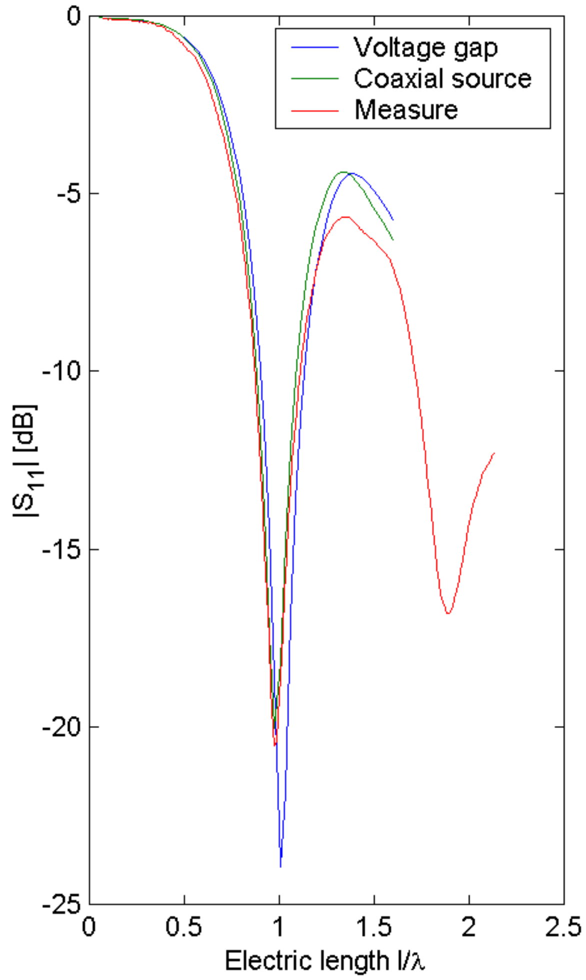


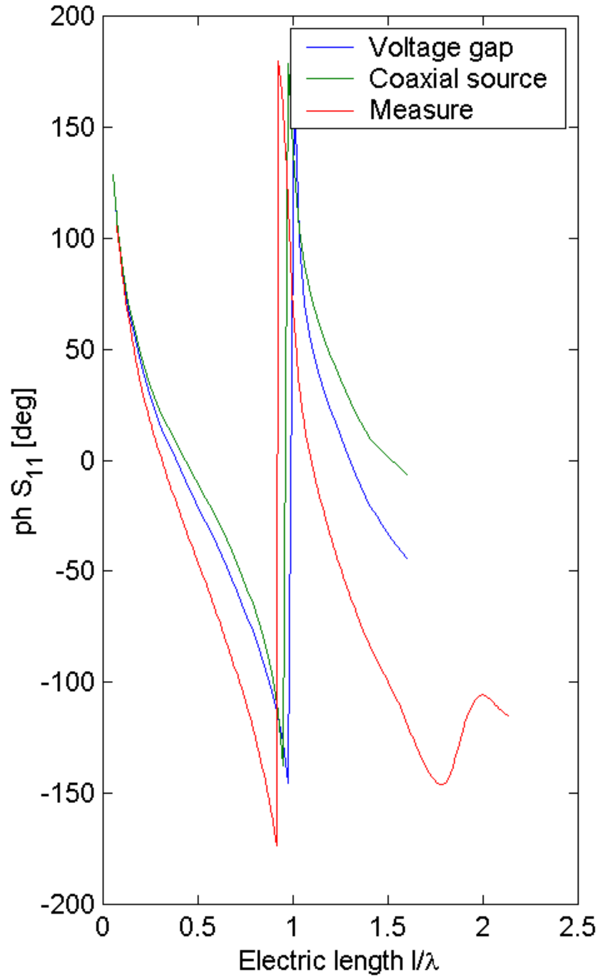
Validation in Vacuo: Single Loop



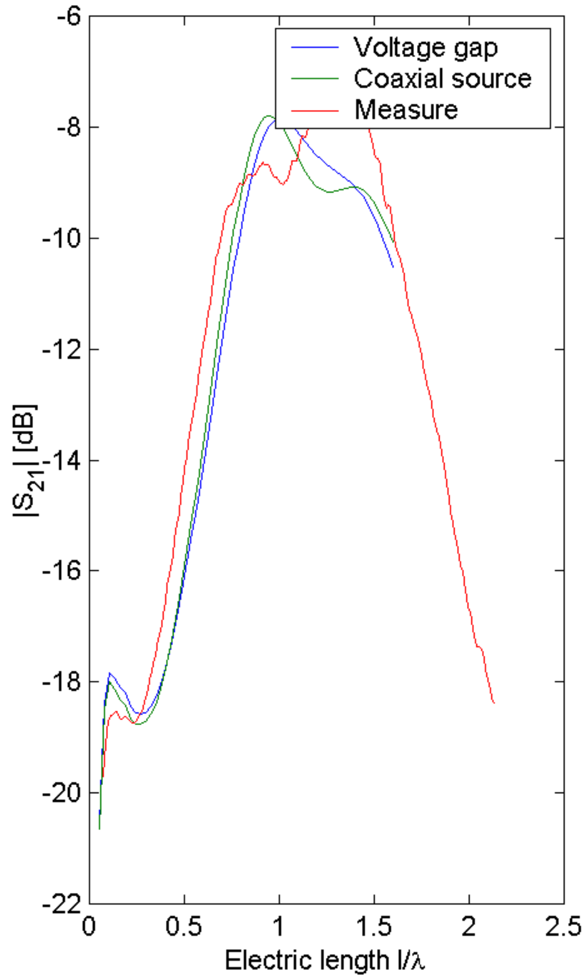


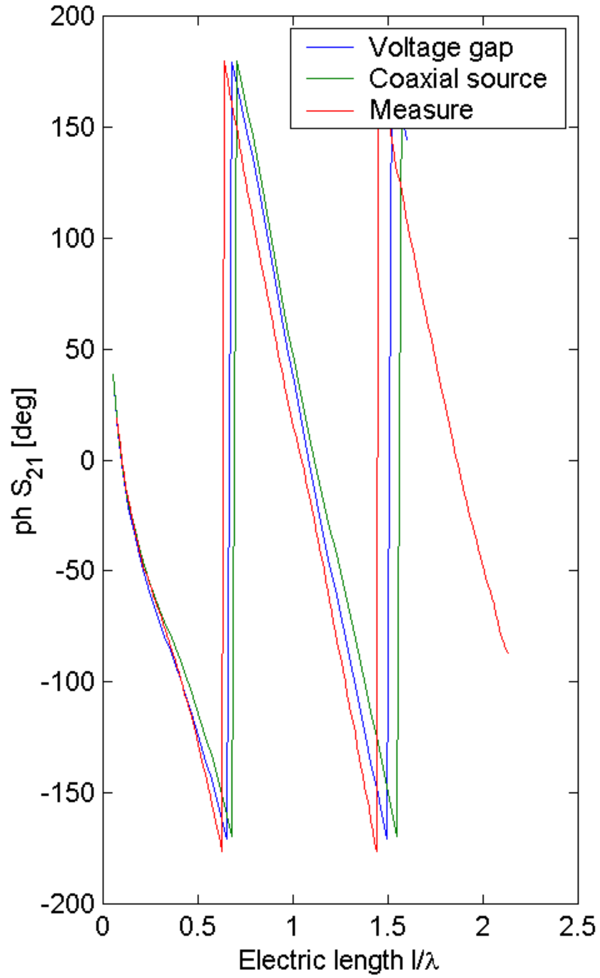
Validation in Vacuo: Double Loop (1)





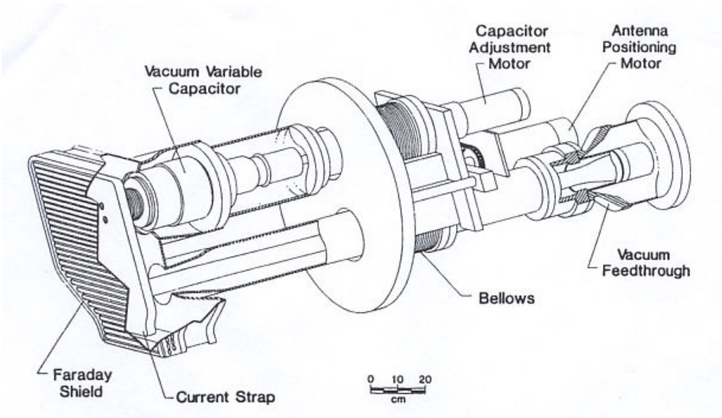
Validation in Vacuo: Double Loop (2)

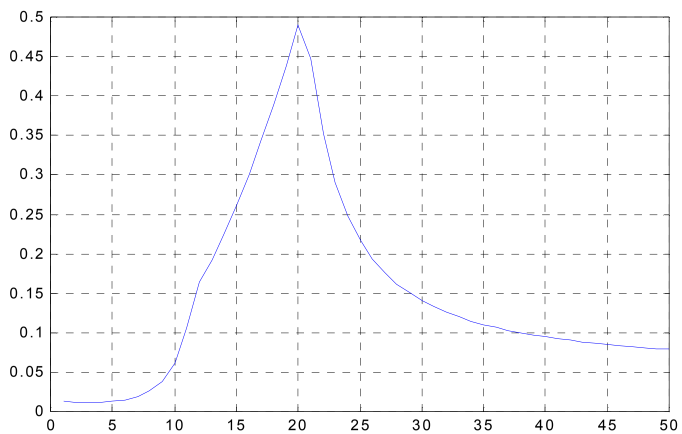


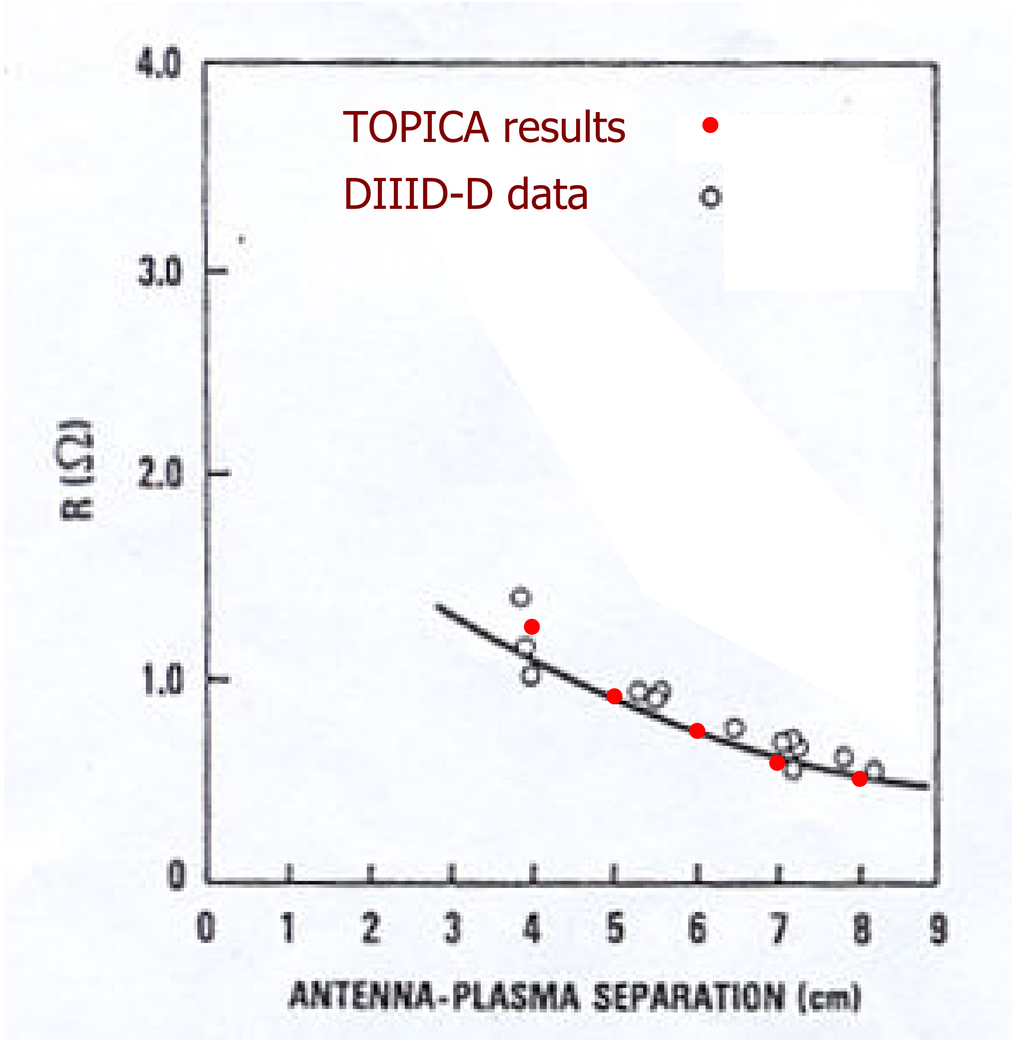


Validation with Plasma: DIII-D

Nuclear Fusion, Vol. 30, No. 4



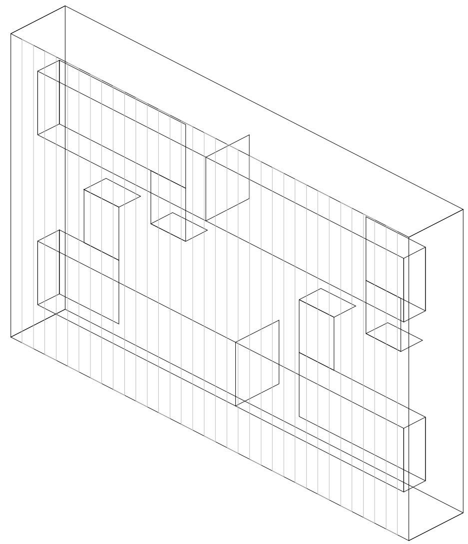


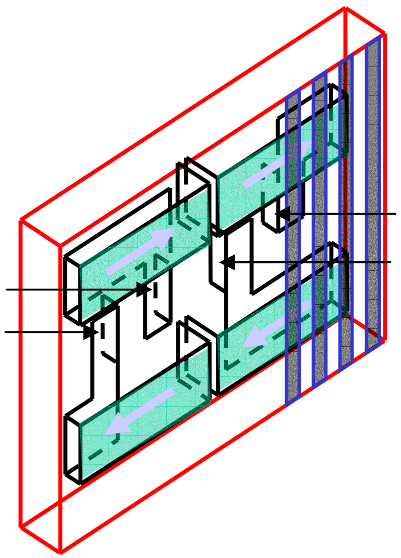


IGNITOR Antenna

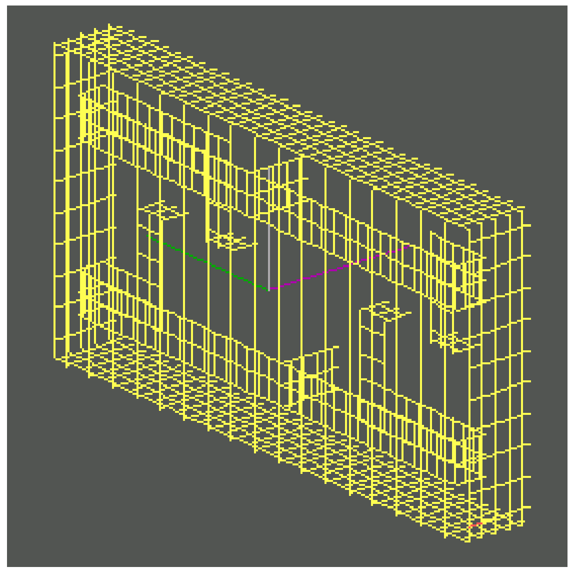
1) 100 MHz (9.8 T, He3 minority)
2) 110 MHz (10.8 T, He3 minority)
3) 120 MHz (11.8 T, He3 minority)
4) 130 MHz (12.8 T, He3 minority)
5) 130 MHz (8.8 T, H minority)
6) 140 MHz (9.5 T, H minority)

CAD drawing

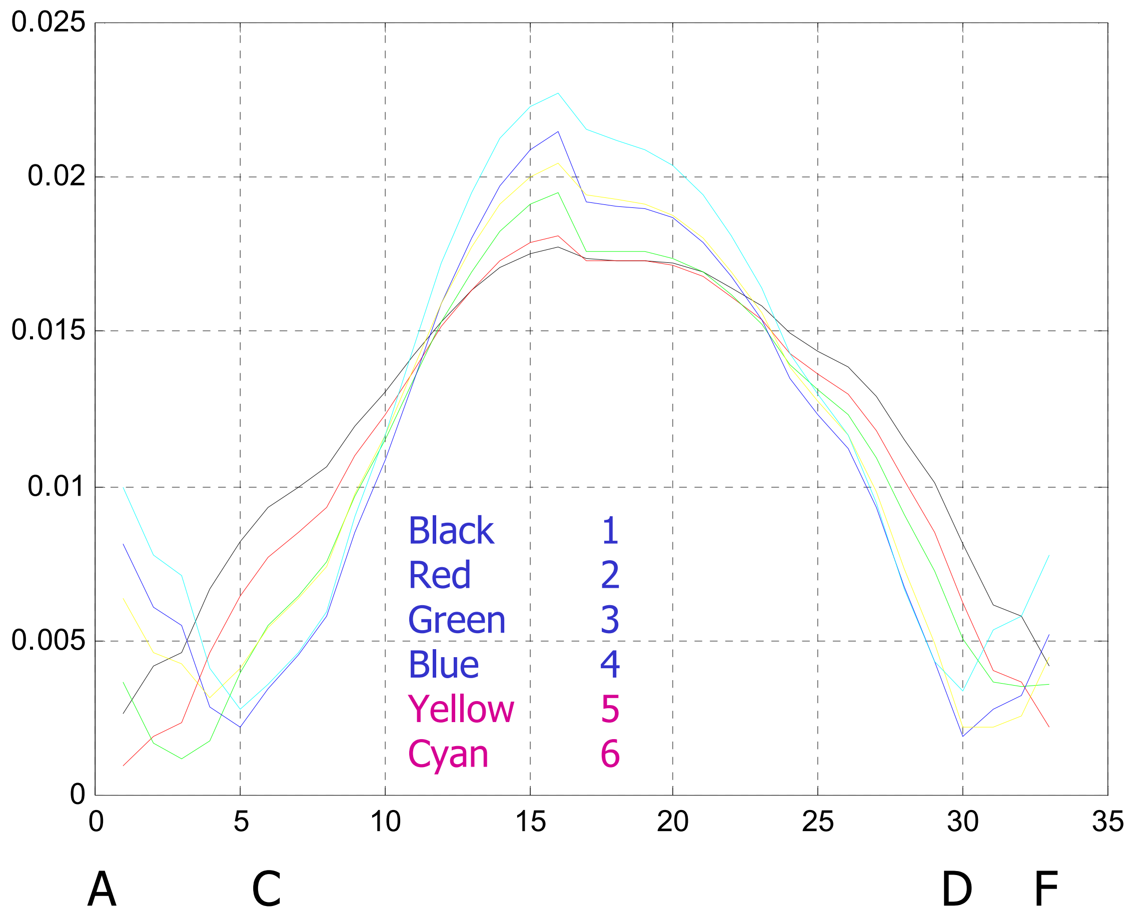


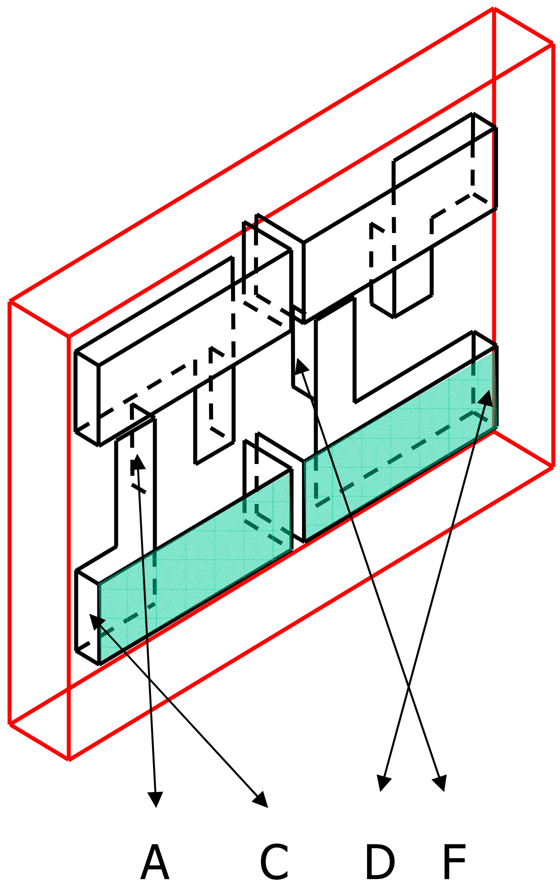


EM model

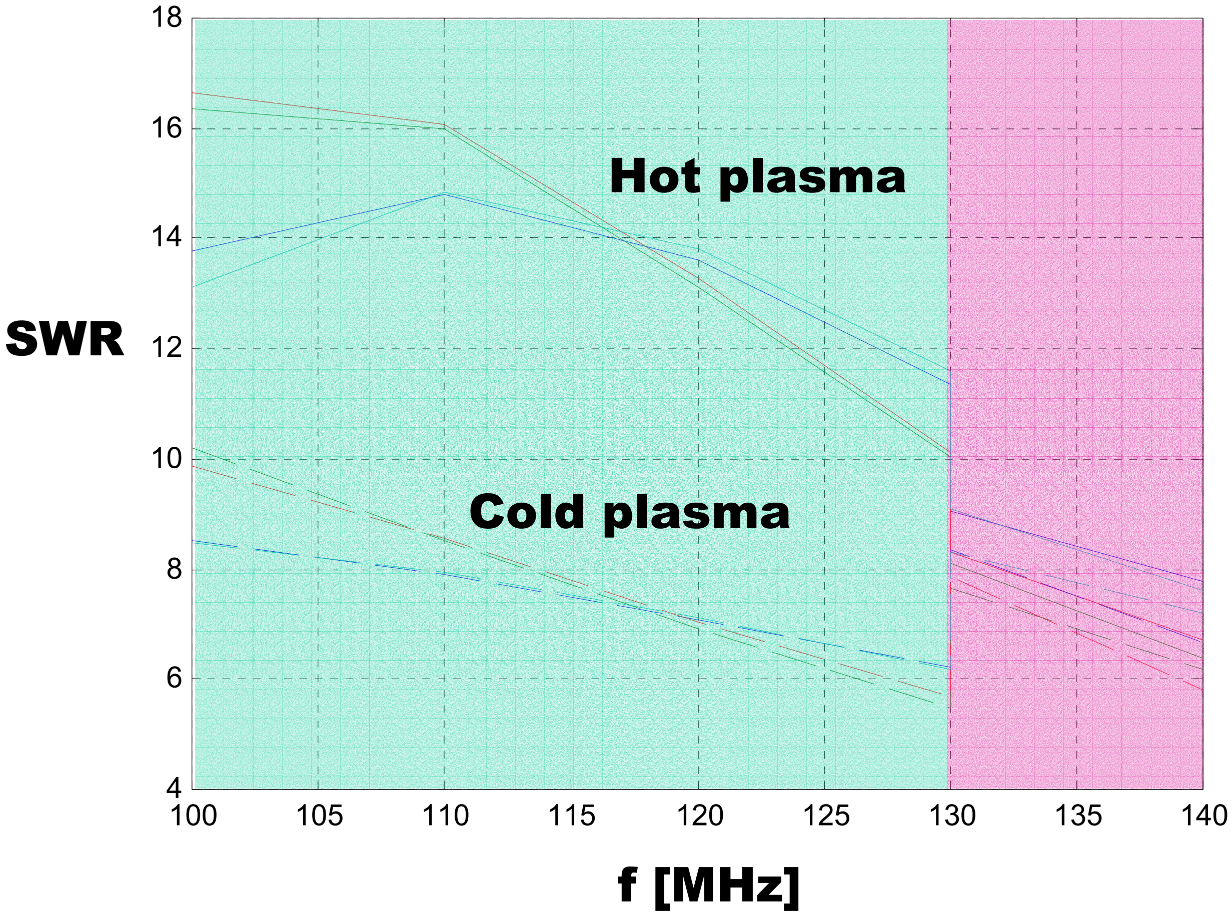


Current Distribution

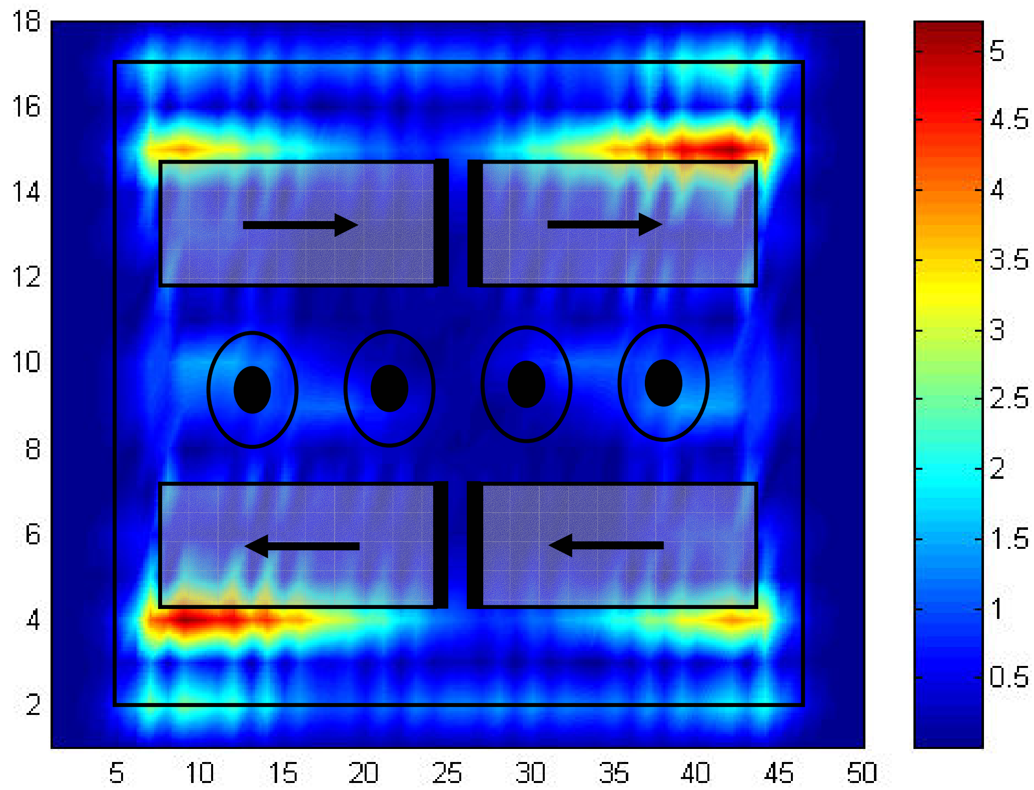




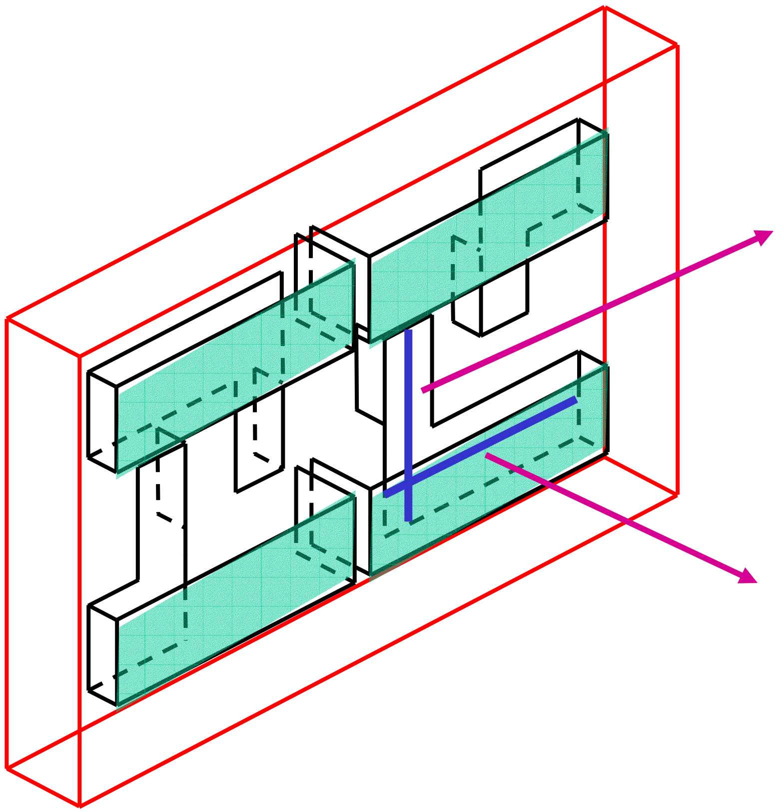
Cold-Hot Plasma Comparison



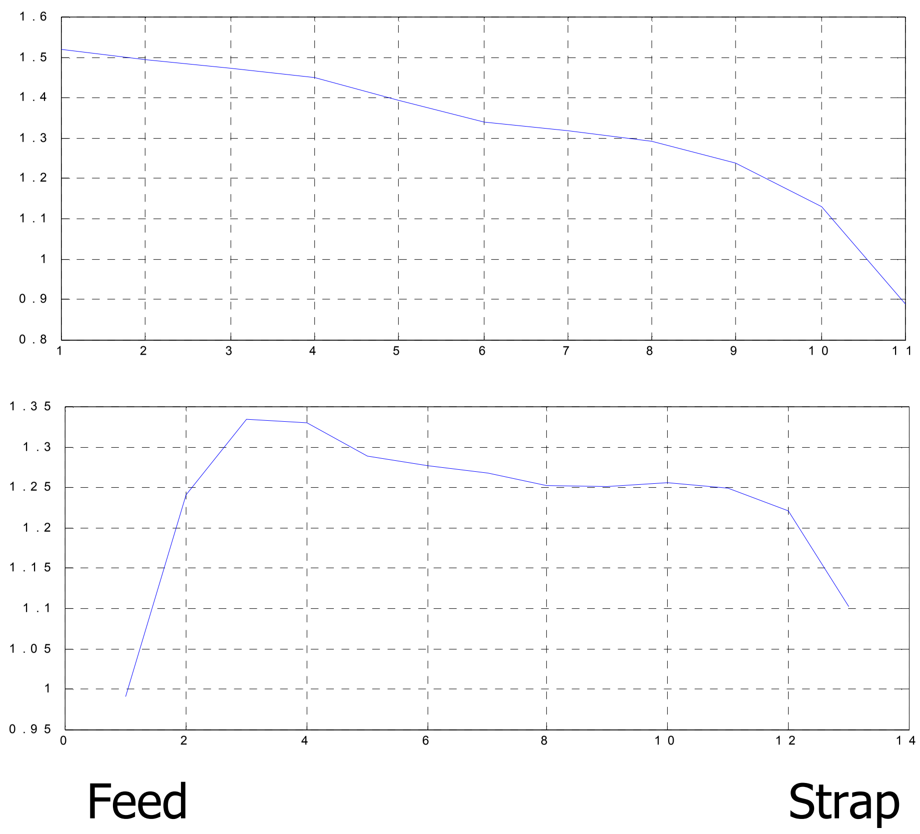
Ez-field Distribution



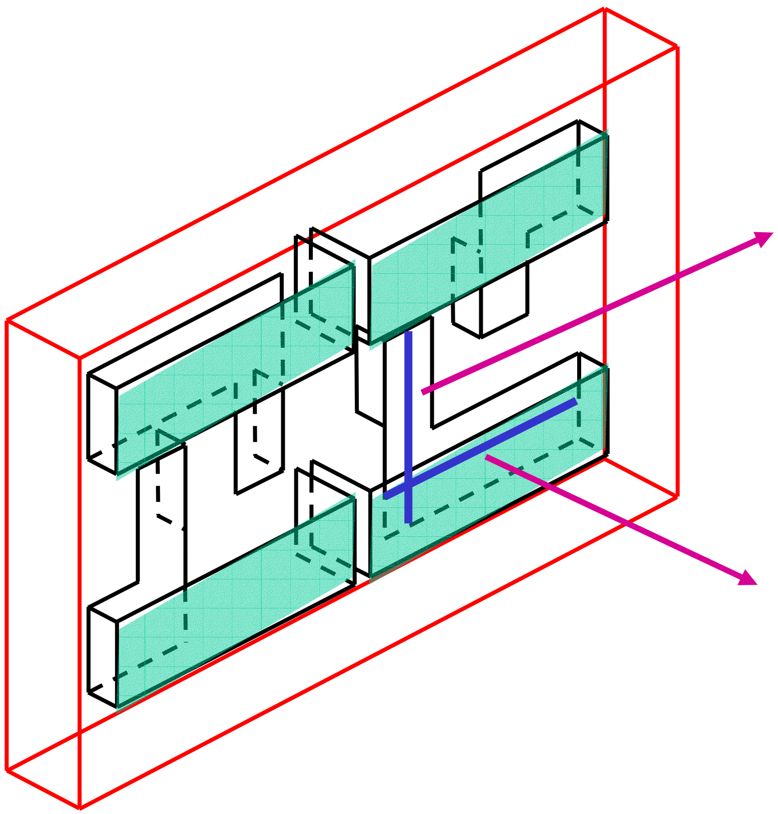
Voltage Standoff (1)



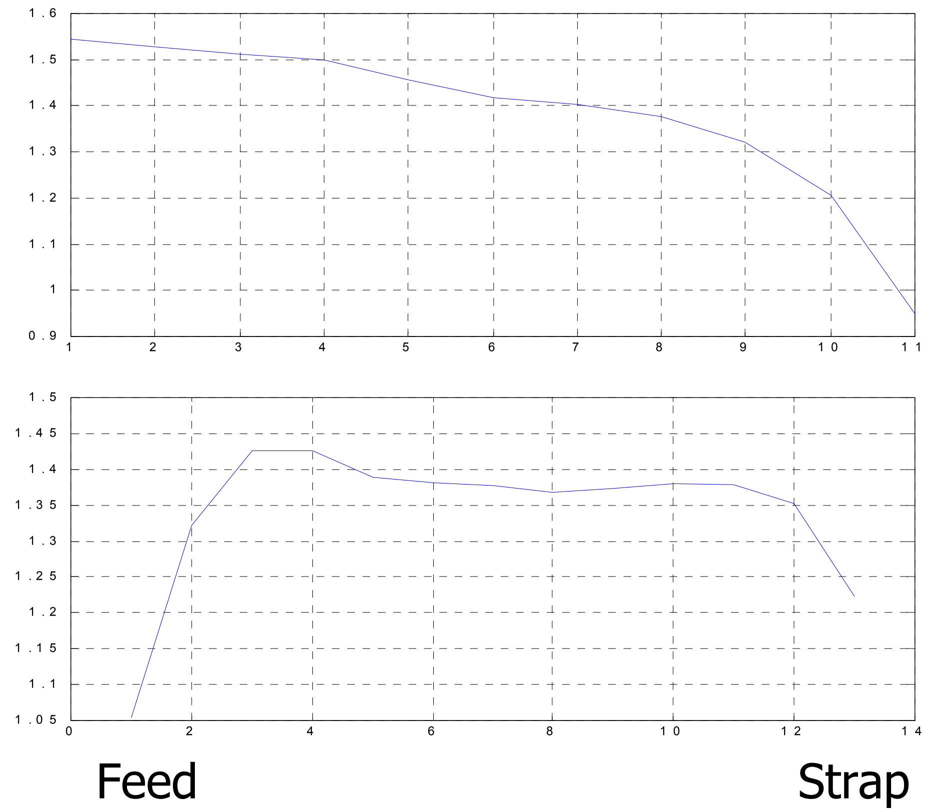
Vx/Vfeed (abs), 100 MHz (He3)



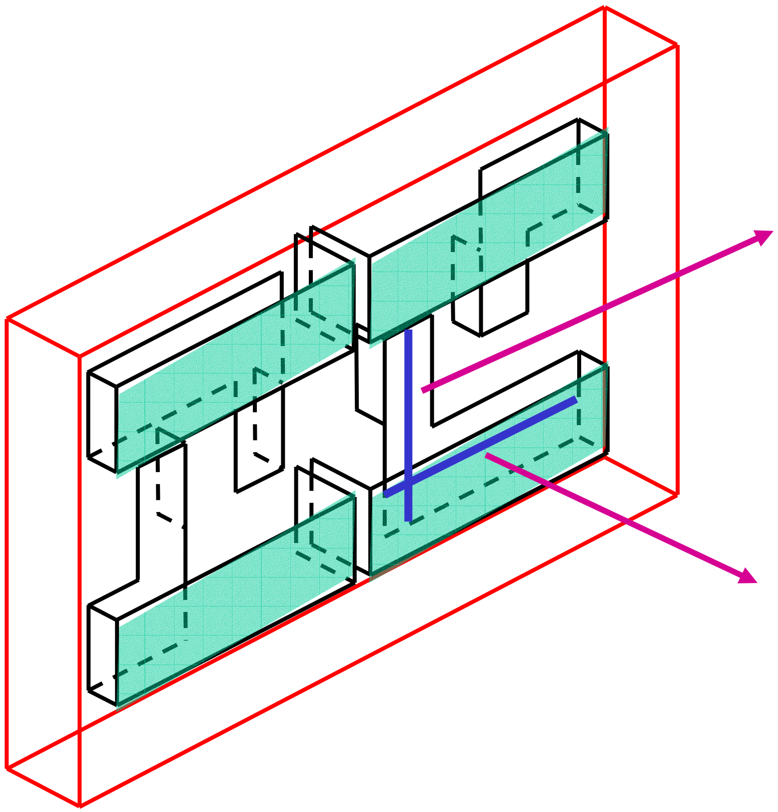
Voltage Standoff (2)



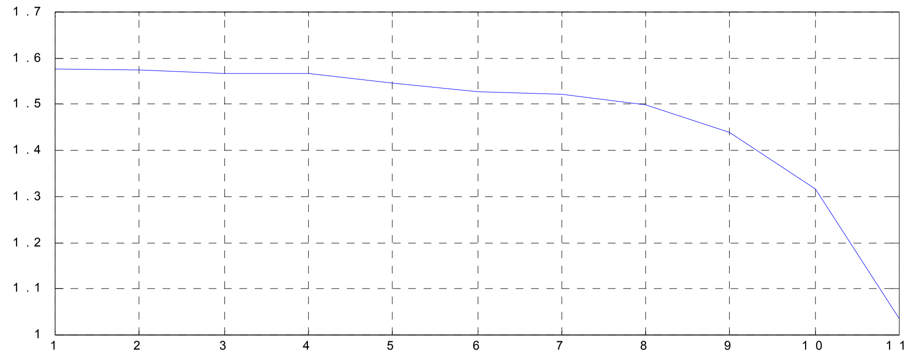
Vx/Vfeed (abs), 110 MHz (He3)

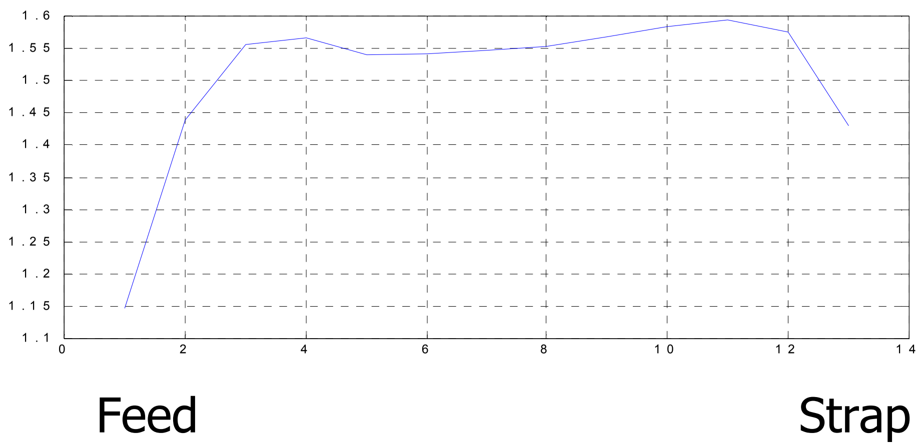


Voltage Standoff (3)

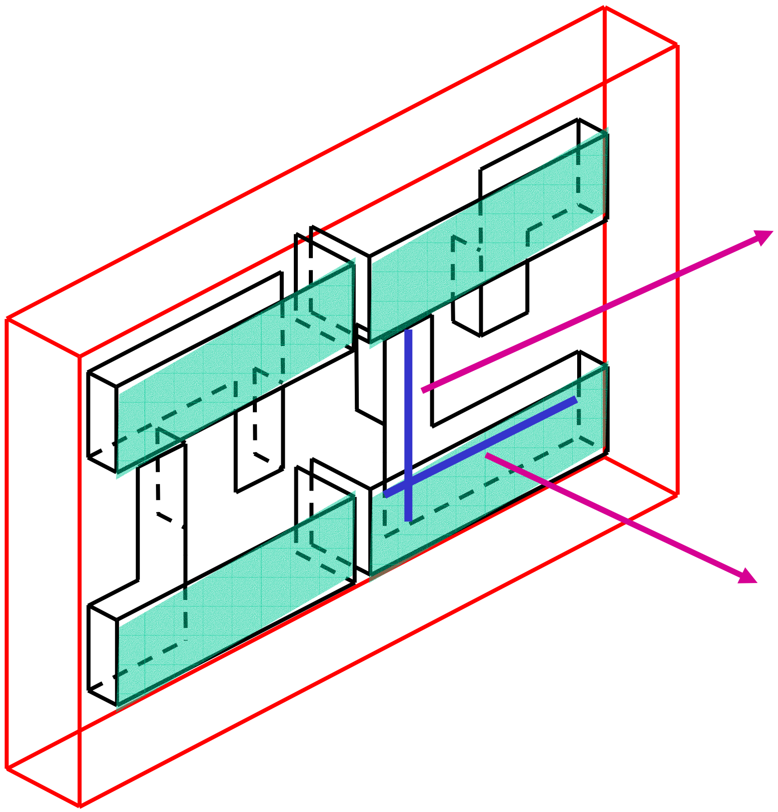


Vx/Vfeed (abs), 120 MHz (He3)

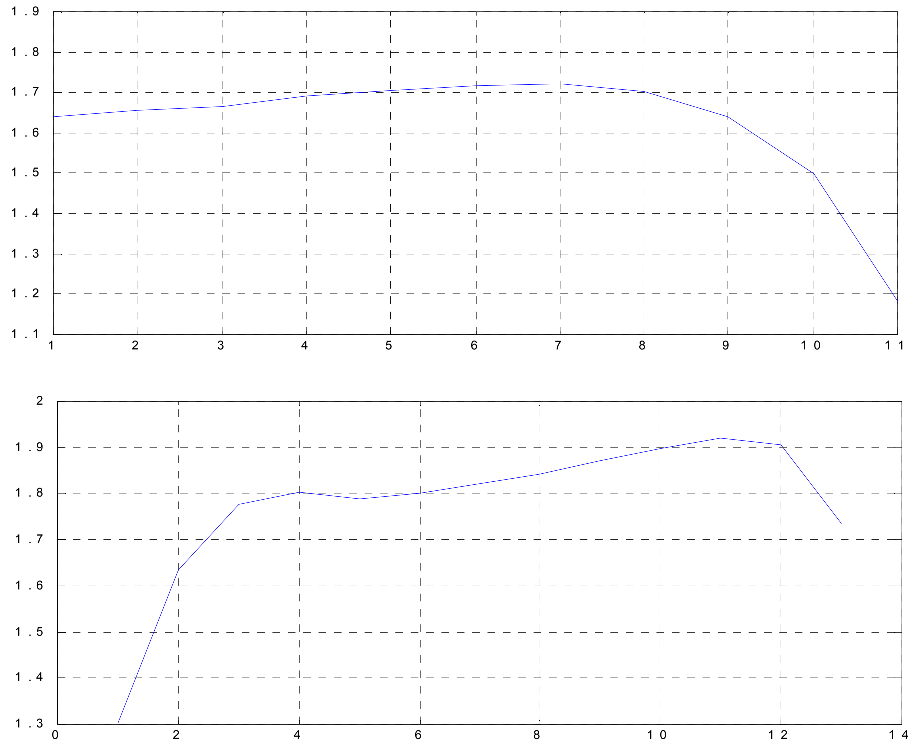




Voltage Standoff (4)

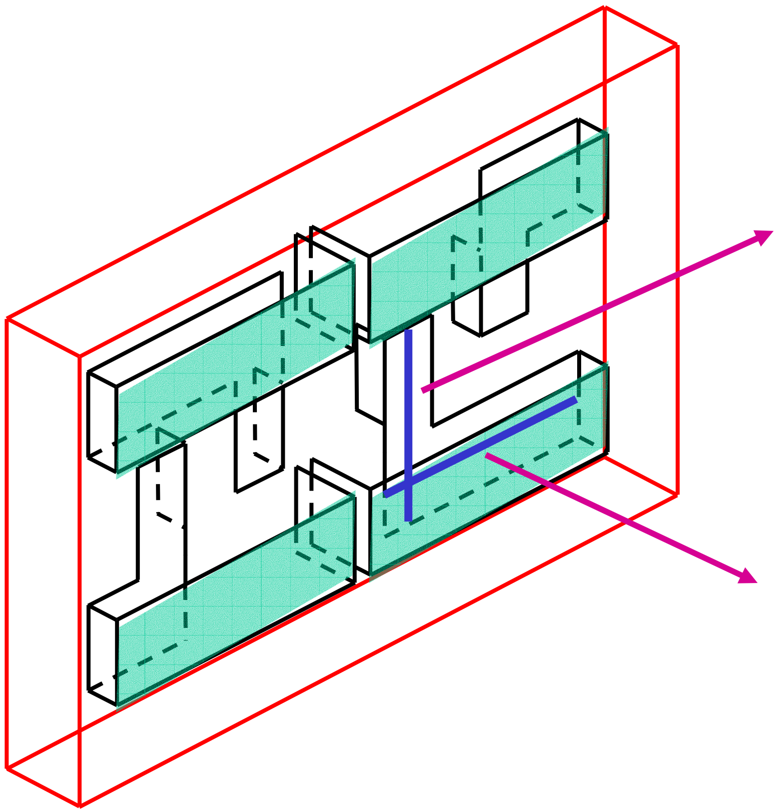


Vx/Vfeed (abs), 130 MHz (He3)

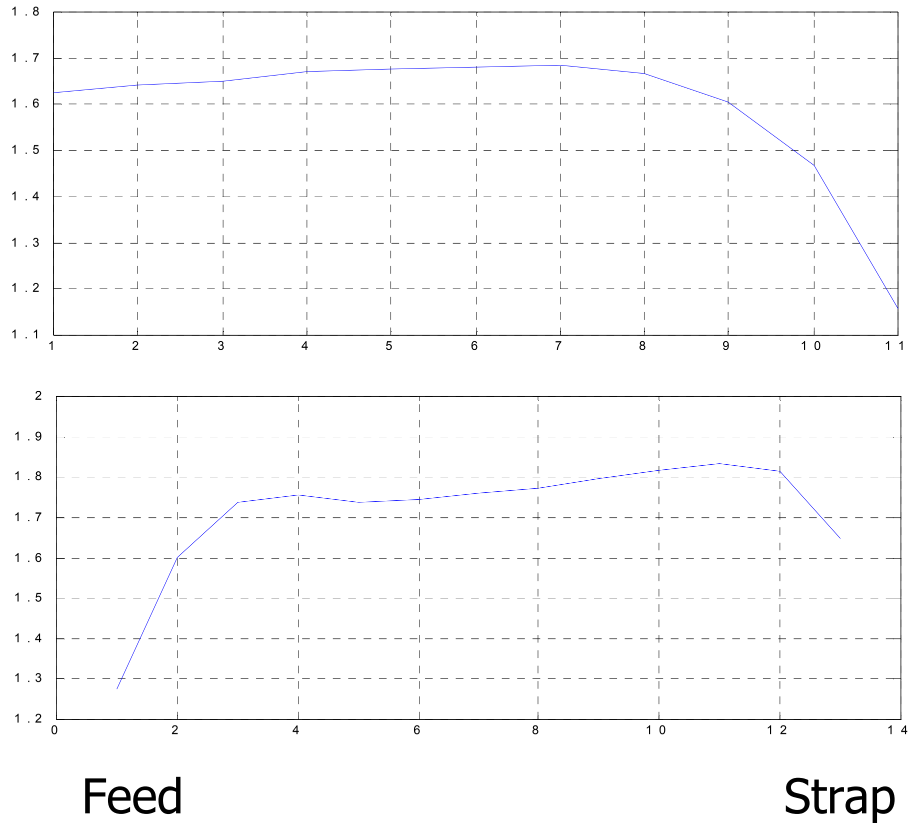


Feed Strap

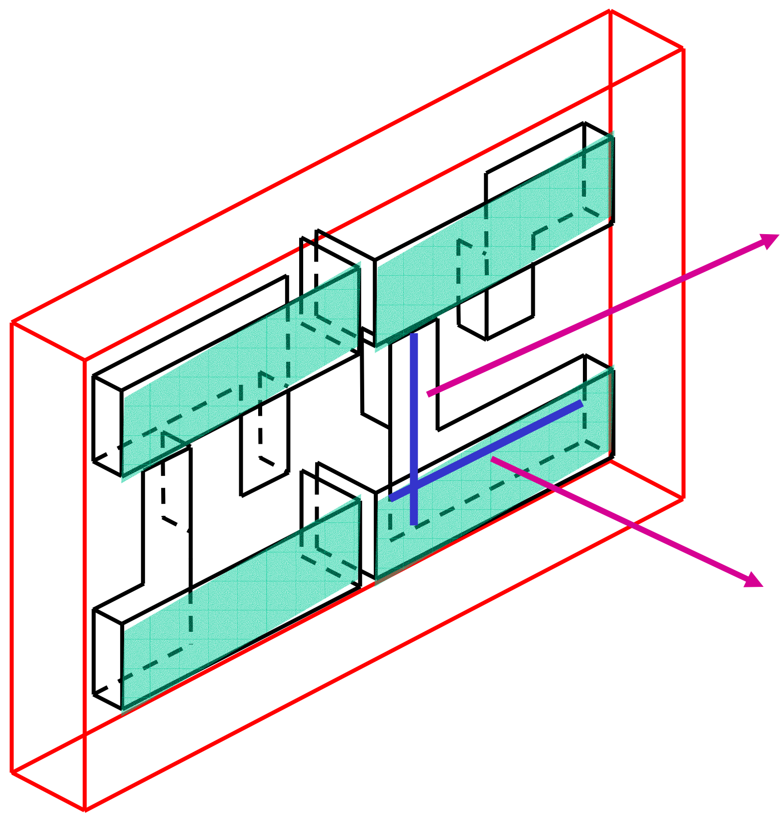
Voltage Standoff (5)



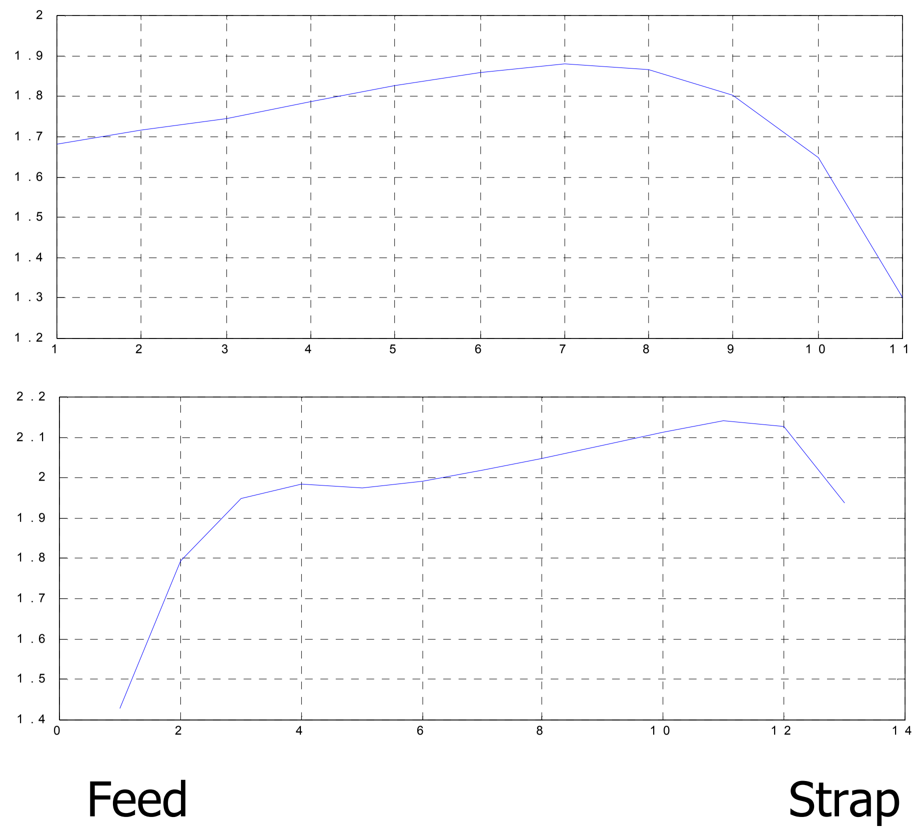
Vx/Vfeed (abs), 130 MHz (H)



Voltage Standoff (6)



Vx/Vfeed (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)