Studium vlastností navázání plazmatu v tokamaku s pasivní-aktivní mnohaspojnou dolnohybridní anténou

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2. HAMAC code
3. Results

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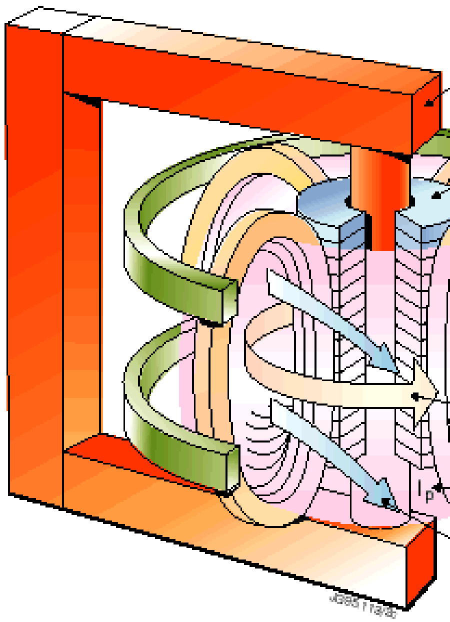
Current Drive (1/2)

In tokamak, plasma current is essential

Plasma stability →
need of poloidal magnetic field →
need of toroidal current.

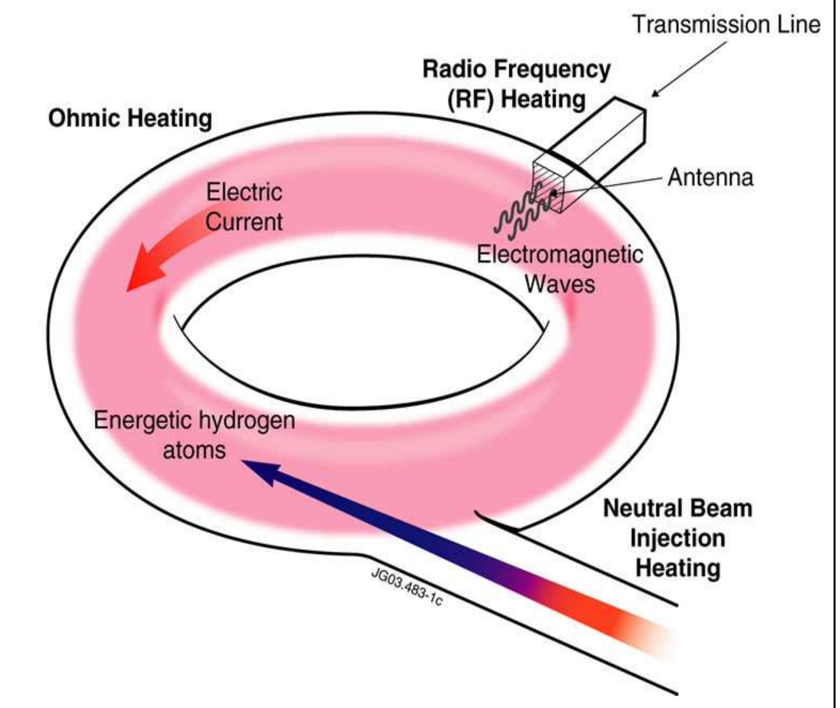
Steady state operation →
non-inductive current drive



Current Drive (2/2)

There are several ways of current driving

- **Transformer effect**
- **Neutral beam injection**
- **EM waves (LHCD)**
- **Bootstrap current**

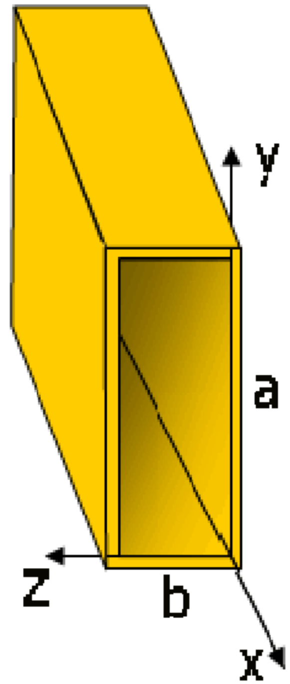


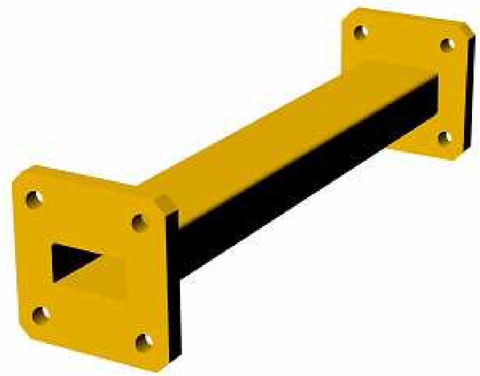
non-inductive heating & CD

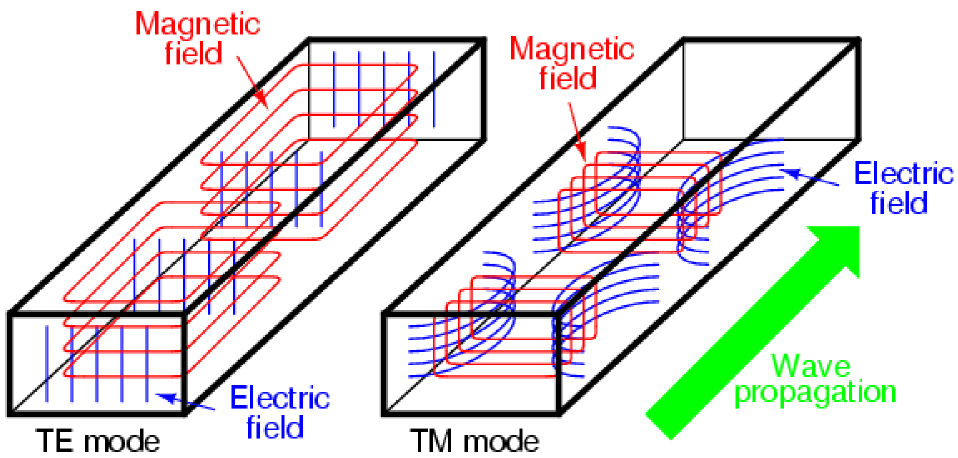
LHCD reveals best CD efficiency of all EM waves possible

Lower hybrid antennas (1/2)

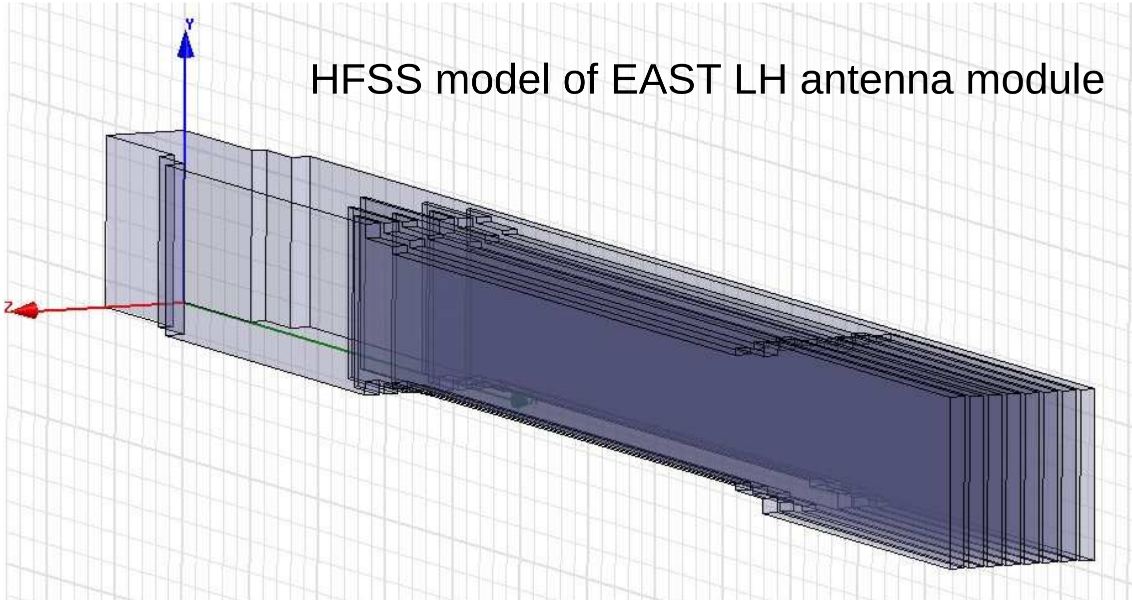
- Frequency range 1 – 10 GHz
- Propagation in waveguides
- EM field described as a superposition of so-called TE and TM modes.
- Mostly, only fundamental TE mode can propagate

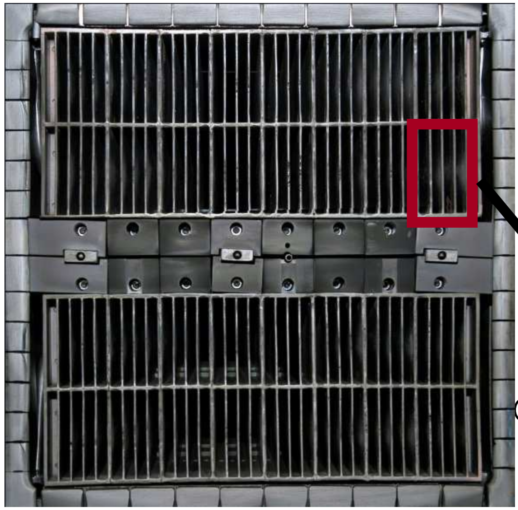






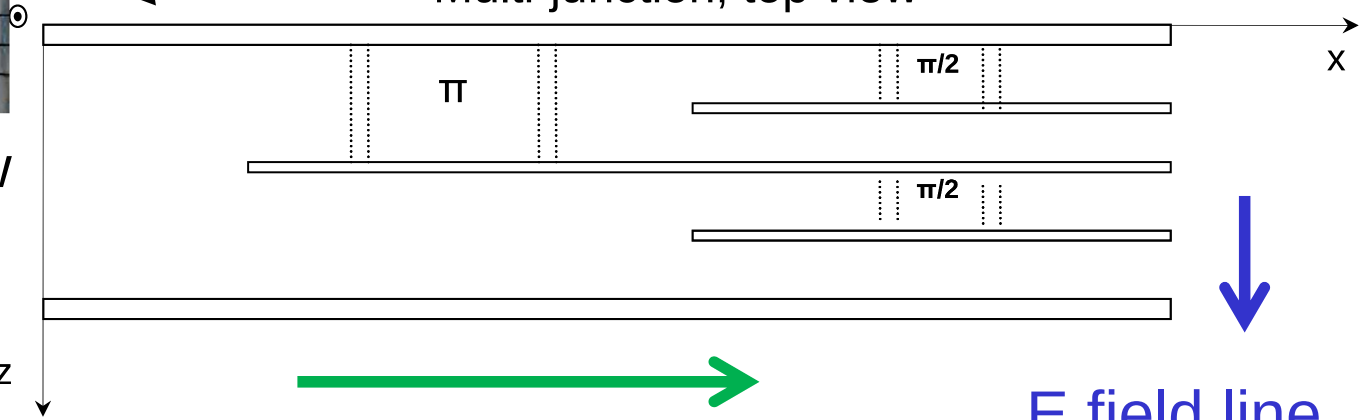
Lower hybrid antennas (2/2)





Antenna frontal view

Multi-junction, top view

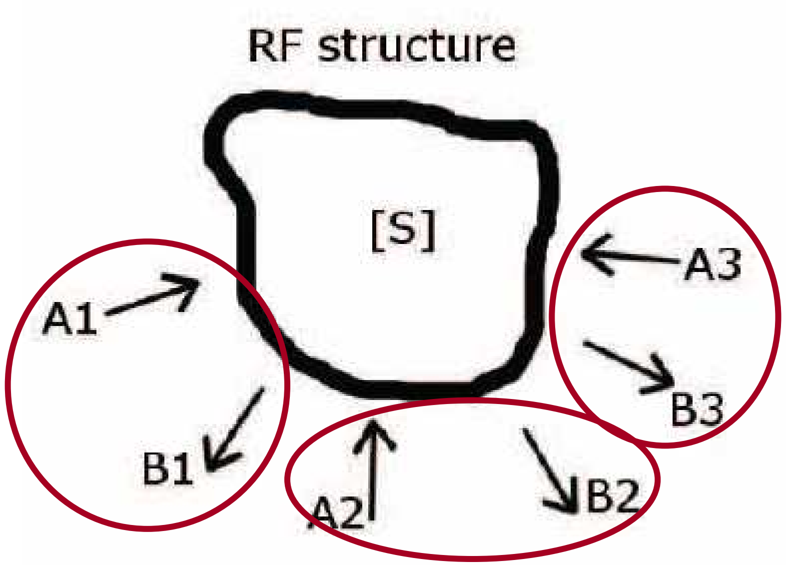


Wave propagation

E field line of TE mode

LH coupling (1/2)

Scattering matrix of antenna module relates the input and output power of any radio frequency structure.

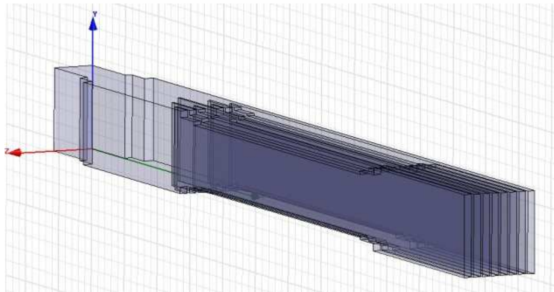


Matrix formulation:

-Power waves in (A)

-Power waves out (B)

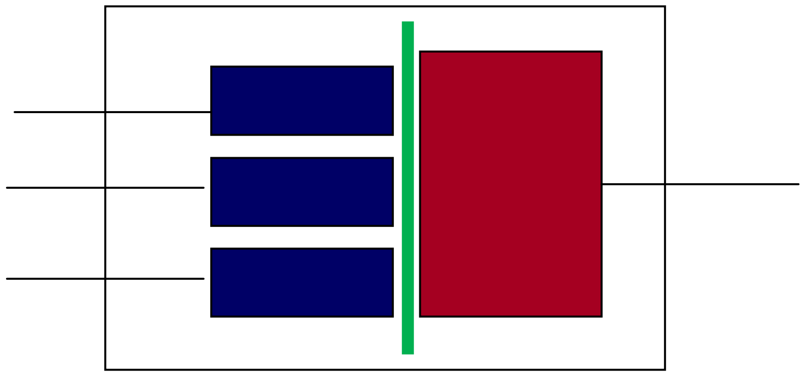
-S parameters



$$\begin{pmatrix} B_1 \\ B_2 \\ B_3 \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix}$$

LH coupling (2/2)

- LH power coupling is the weakest part of LHCD concept
- Coupling is modelised by ALOHA (Advanced LOwer Hybrid Antenna) code developed in CEA.



Global S matrix of antenna + plasma

-Antenna modules description

  -S matrix

-Grill description

  -1D / 2D

-Plasma description

  -Electron density

  -Gradient 1 & 2

HAMAC code gives one of the inputs to the ALOHA code

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Purpose

HAMAC =
Hybrid Antenna Modeling for the ALOHA Code

- Calculates the global **Scattering Matrix** of LH antenna
- Task is to be **a complement** to the Ansys HFSS software
- **TM modes** are taken into account
- Preliminary work done in 2009 by Mélanie PREYNAS

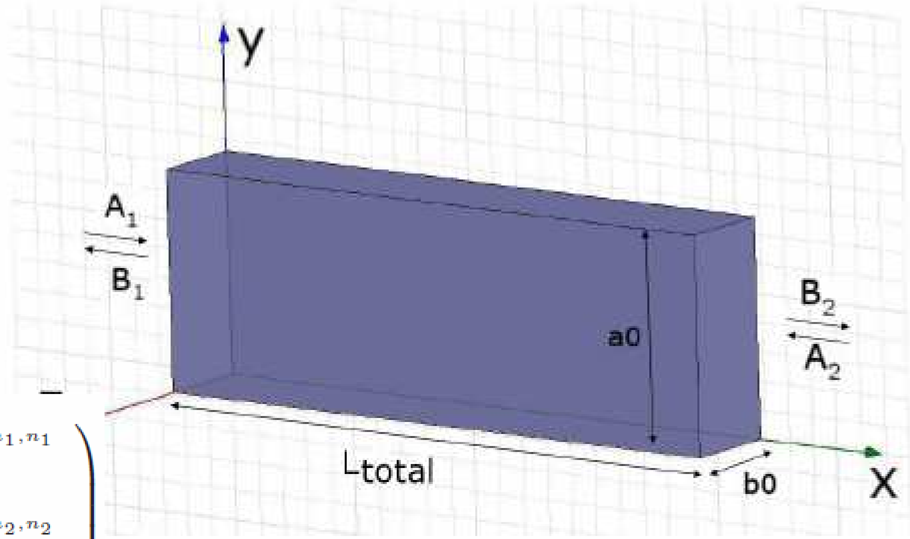
Calculus

- Split the antenna to simple straight waveguides (SW)
- Calculate S – matrix of each SW separately
- Calculate S – matrix of all intersections (discontinuity, bi- , tri- , multi- junction)
- Match all S – matrixes together to get to global one

S – matrix of straight waveguide

Hypothesis of perfect conductor

$$\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{bmatrix} 0 & D \\ D & 0 \end{bmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}$$



$$B_1 = \begin{pmatrix} B_1^{TE} \\ B_1^{TM} \end{pmatrix}$$

$$B_1^{TE} = \begin{pmatrix} B_1^{TE_{m_1,n_1}} \\ B_1^{TE_{m_2,n_2}} \\ \vdots \\ B_1^{TE_{m_q,n_q}} \end{pmatrix}; \quad B_1^{TM} = \begin{pmatrix} B_1^{TM_{m_1,n_1}} \\ B_1^{TM_{m_2,n_2}} \\ \vdots \\ B_1^{TM_{m_p,n_p}} \end{pmatrix}$$

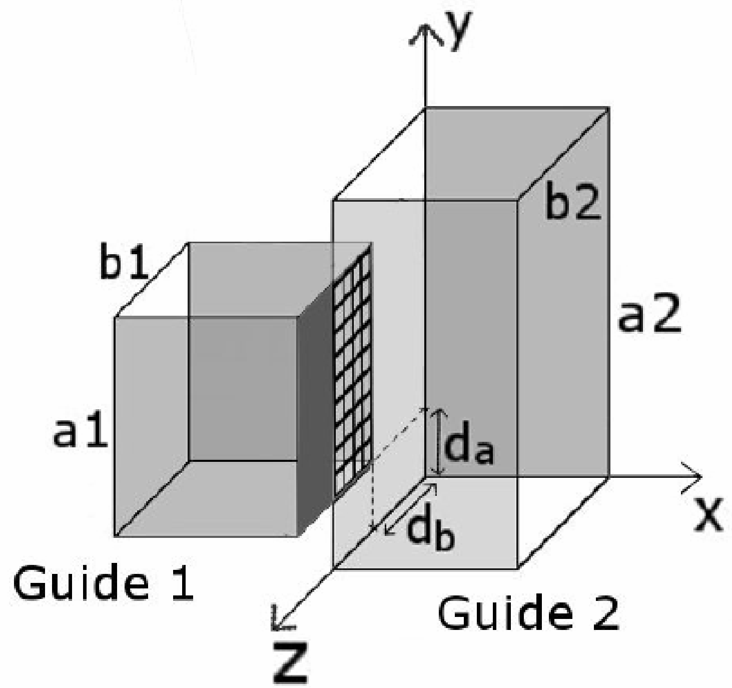
where D is analytically expressed by

$$D = \begin{bmatrix} \mathrm{diag}(\exp(-ik_{g,m,n}^{TE} L_x))_{modes} & 0 \\ 0 & \mathrm{diag}(\exp(-ik_{g,m,n}^{TM} L_x))_{modes} \end{bmatrix}$$

S – matrix of discontinuity

- Discontinuity is only a plane in x=0
- Continuity of transverse EM field at a plane of discontinuity
- Relative positioning

$$\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = [S] \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}$$

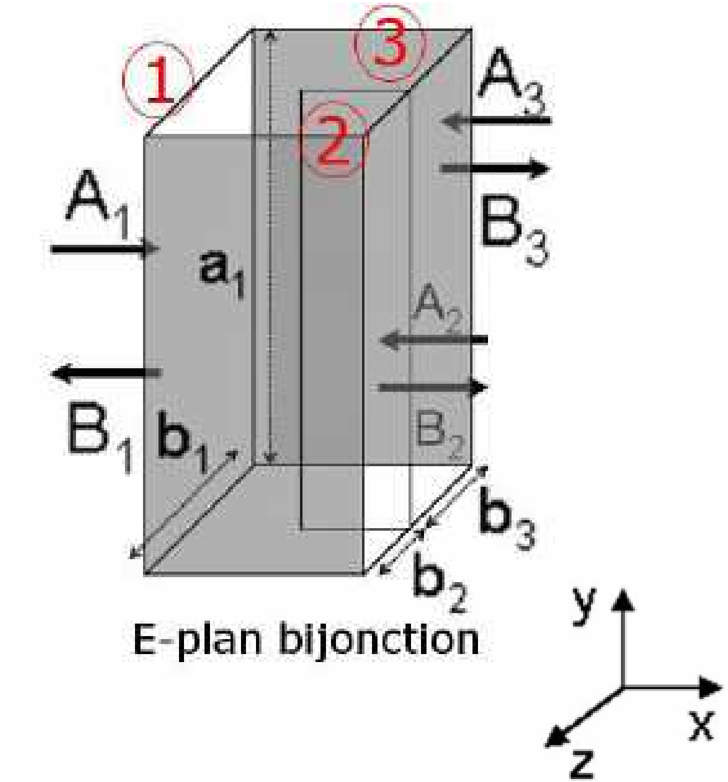


S – matrix of bijunction

- Continuity of transverse EM field in perp. direction to discontinuity plane.
- Bi-junction = 2 discontinuities side by side
- Relative positioning
- Multi – junction possible too

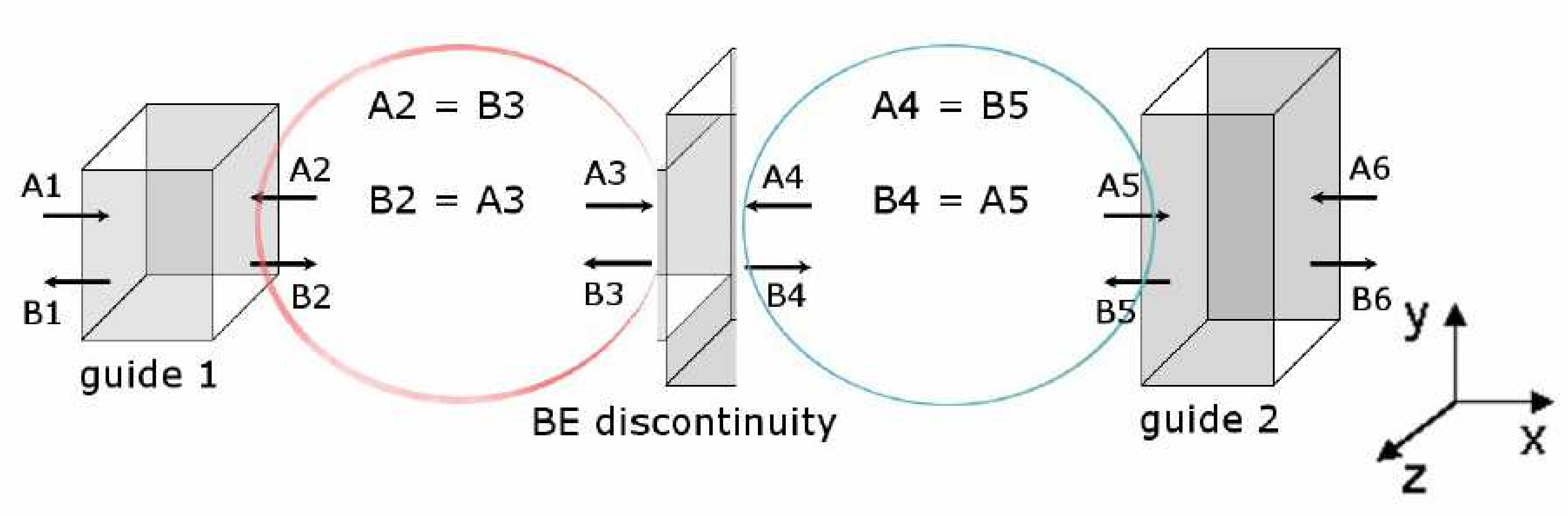
$$\begin{pmatrix} B_1 \\ B_{out} \end{pmatrix} = [S] \begin{pmatrix} A_1 \\ A_{out} \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} A_1 \\ A_{out} \end{pmatrix}$$

$$B_{out} = \begin{pmatrix} B_2 \\ B_3 \end{pmatrix}; \quad A_{out} = \begin{pmatrix} A_2 \\ A_3 \end{pmatrix}$$



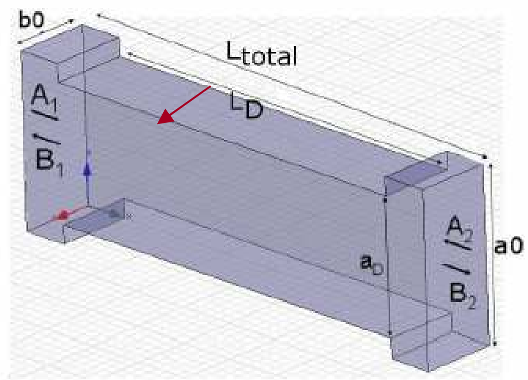
S – matrix cascading

- Need to have the same number and kind of modes on both sides

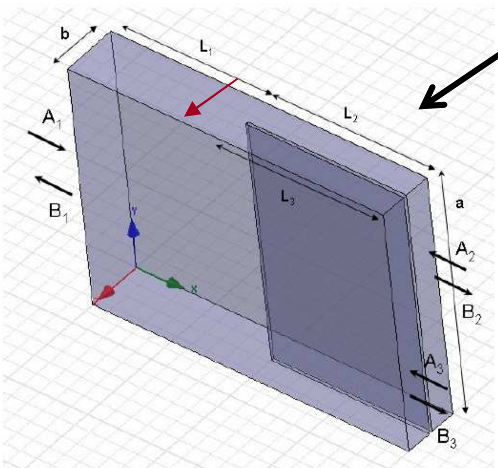


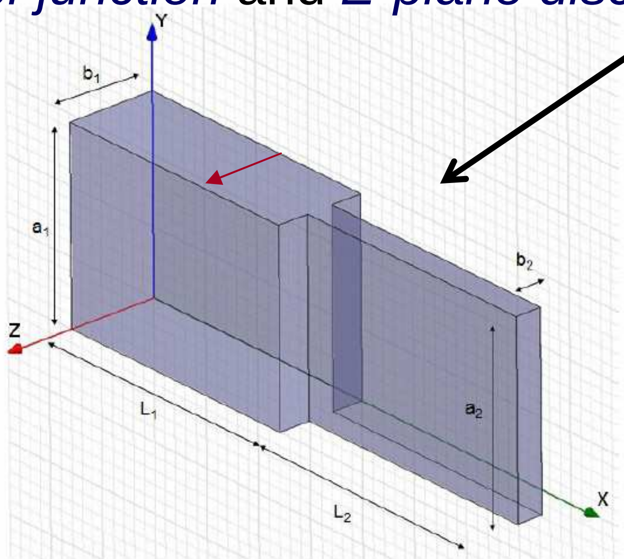
TM modes

- In LH antenna waveguides, TM modes can not propagate
- TM are not necessary when waveguide width keeps constant



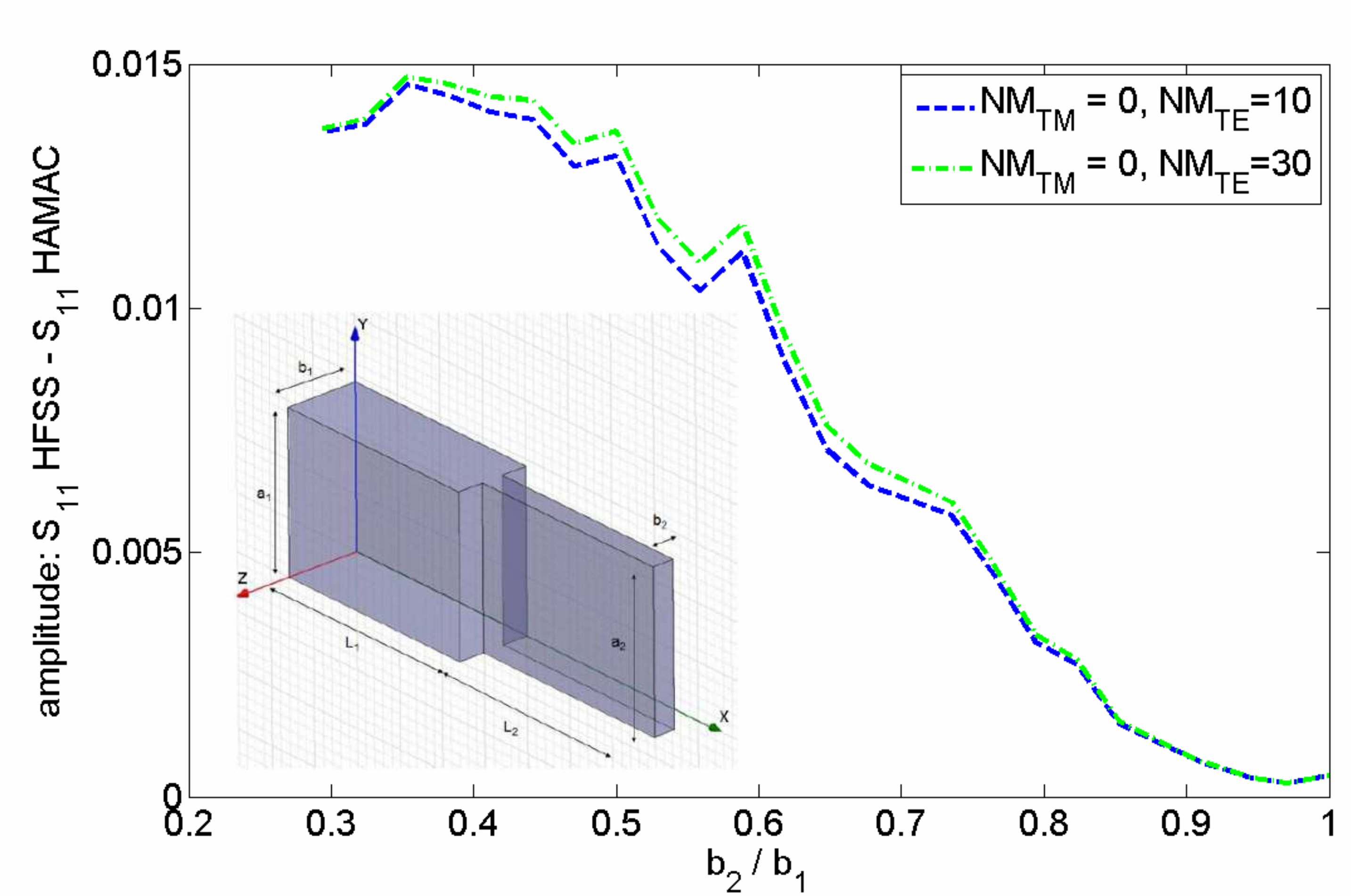
- Doubles time calculation
- Influence S-matrix of *E-plane bi-junction* and *E-plane discontinuity*





TM modes

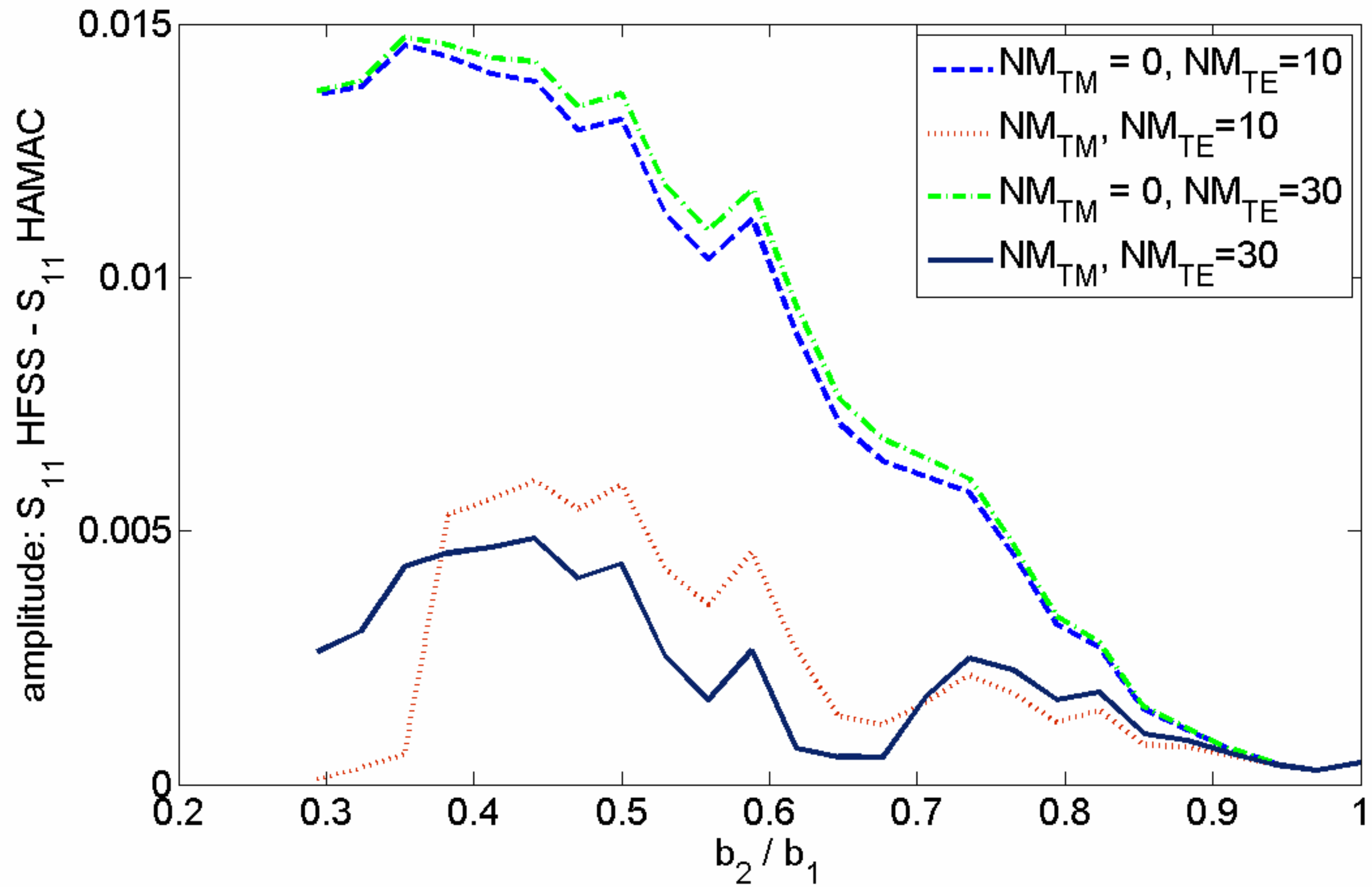
Amplitude difference between HFSS and HAMAC



Only TE modes are forced in the calculation

TM modes

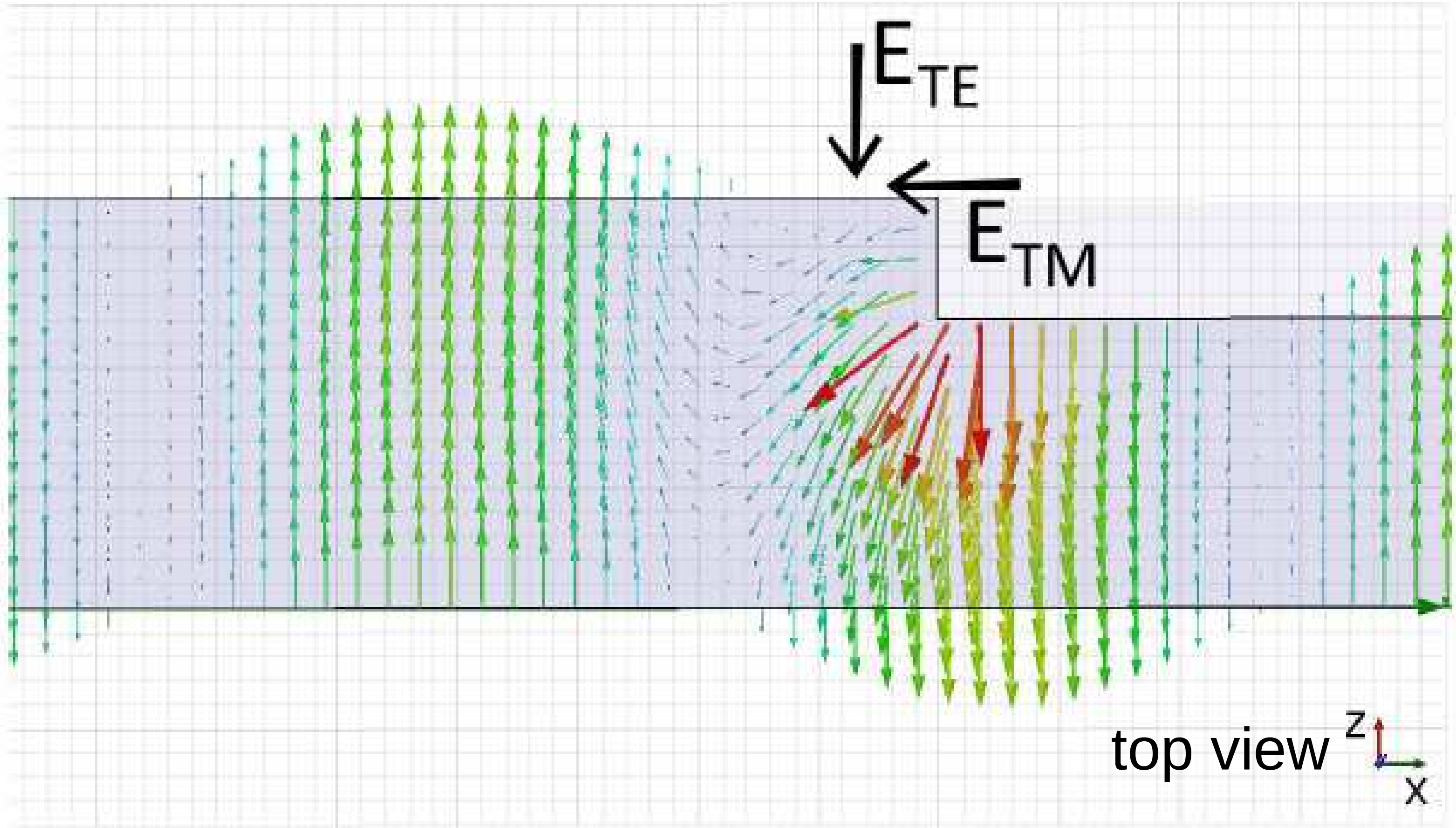
Amplitude difference between HFSS and HAMAC



Difference is smaller when TM modes are taken into account

TM modes

E field in waveguide with E-plane discontinuity



E field has a longitudinal component as TM modes

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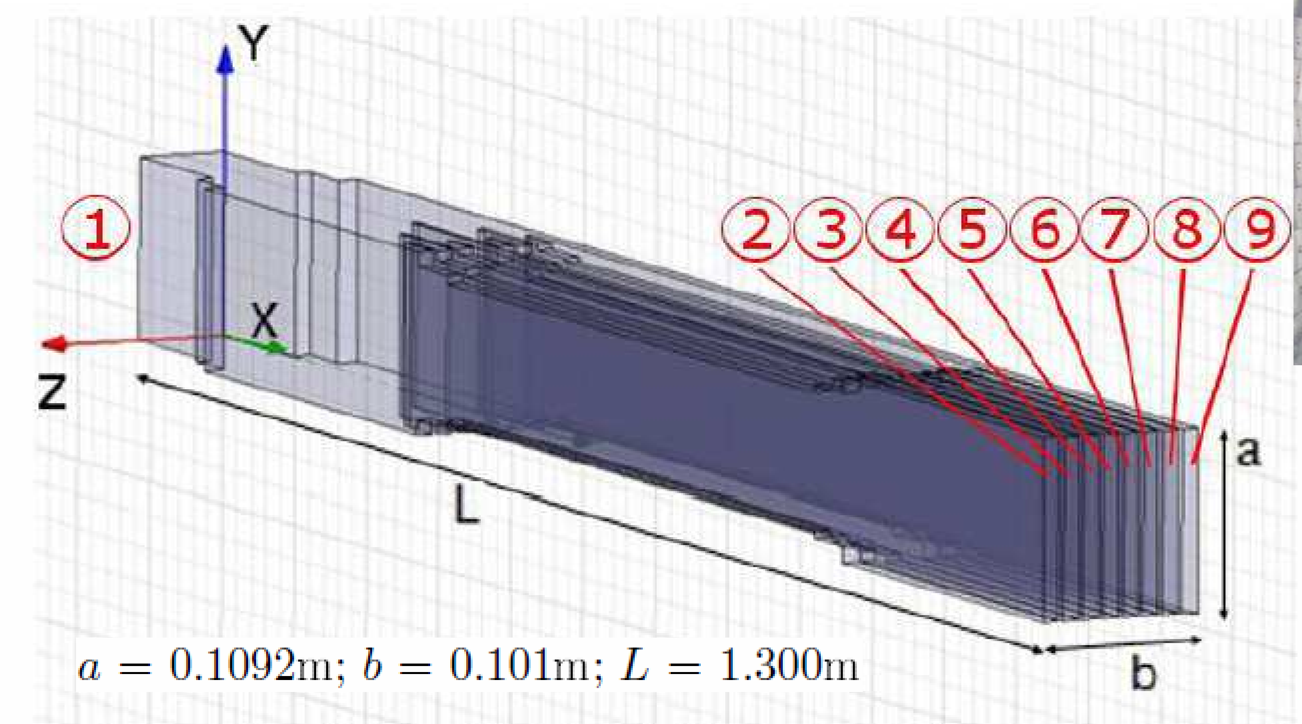
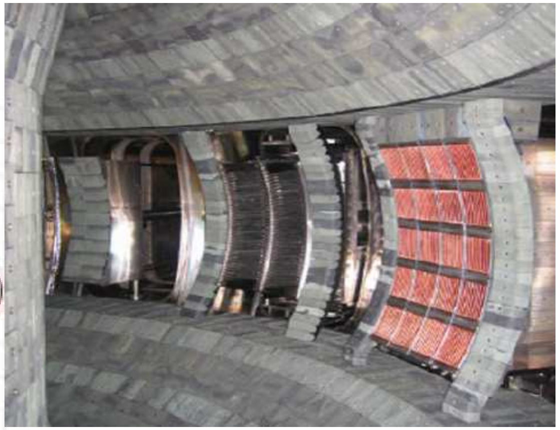
2,45GHz EAST LH antenna

- 20 identical modules, 20 klystrons per 100kW.

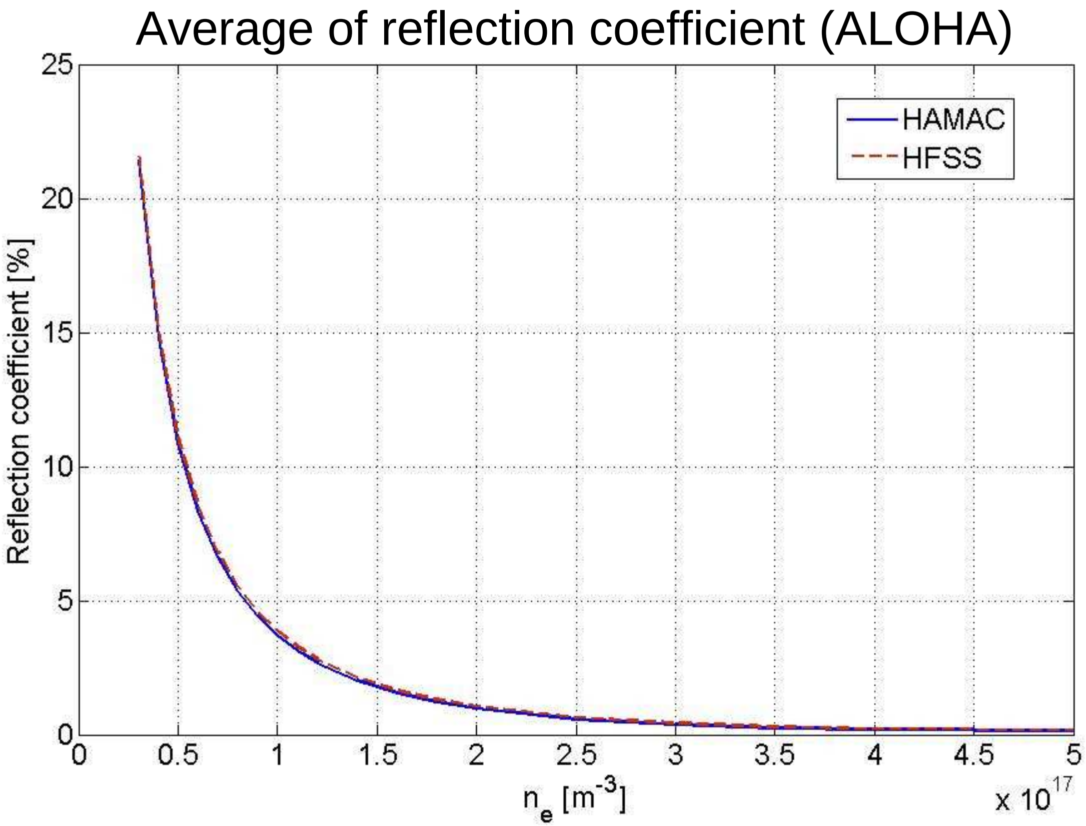




Antenna modeled with 4 modules (1 row) in ALOHA code

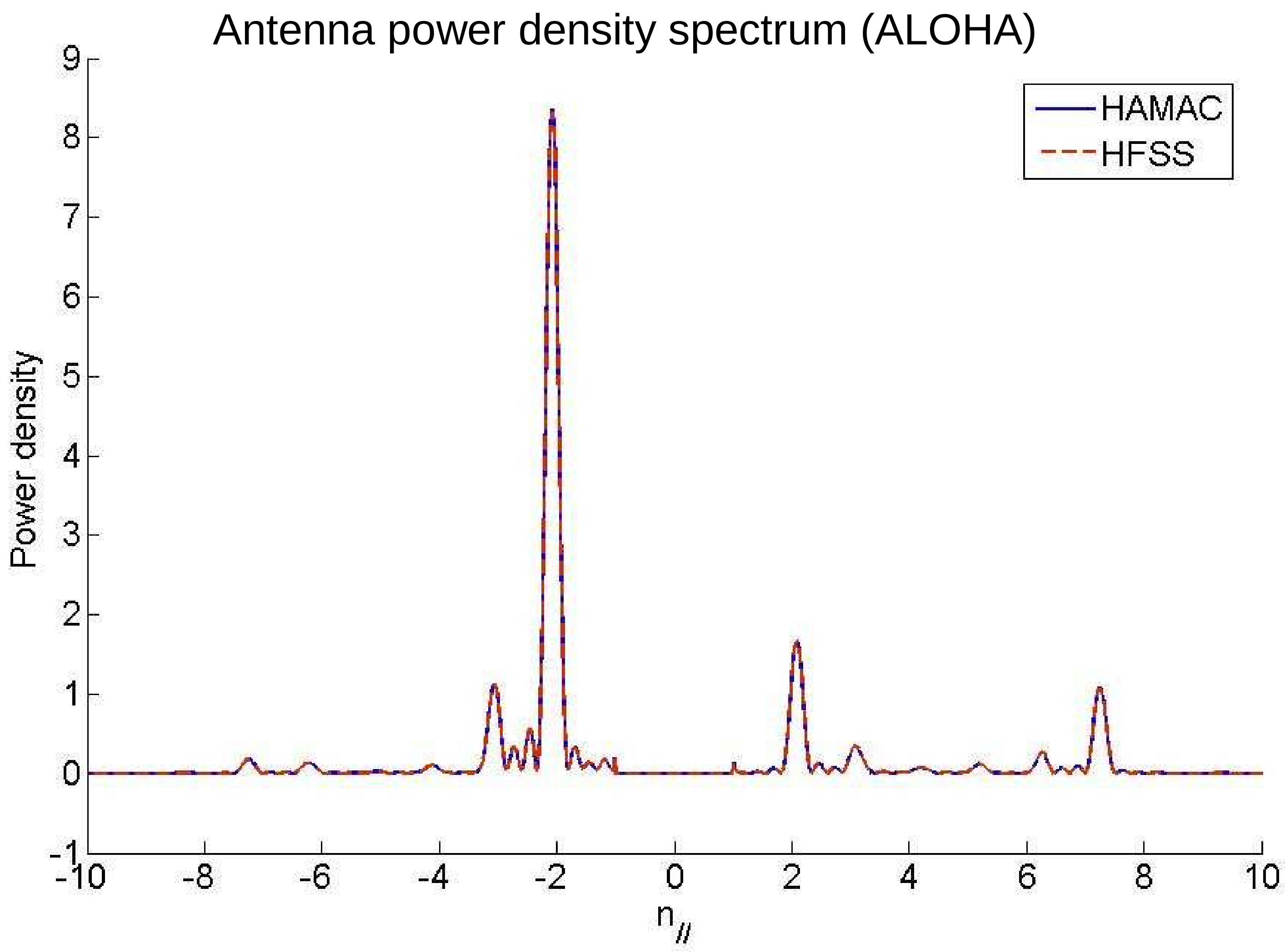
EAST - Results comparison

- HFSS: precision ΔS = 0,001 (FEM code)
- HAMAC: 40TE, 40TM modes



Very good agreement between HFSS and HAMAC

EAST - Results comparison



Very good agreement between HFSS and HAMAC

Conclusion

- New HAMAC version, taking into account TM modes was implemented.

- On 2,45GHz Chinese tokamak EAST LH antenna, HAMAC **validated**, global S-matrix difference from HFSS of order of $\mathbf{1 \cdot 10^{-3}}$ in amplitude and $\mathbf{1^{o}}$ in phase.

- Studies proved needfulness of TM modes

thank you for your attention