Perspectives on High-Power Microwave Coupling in Gyrotron Frequency ECR Ion Sources

J. W. Guo, L. Sun, X . Z. Zhang, W. Lu, W. H. Zhang, H. W. Zhao

Institute of Modern Physics (IMP), Chinese Academy of Sciences

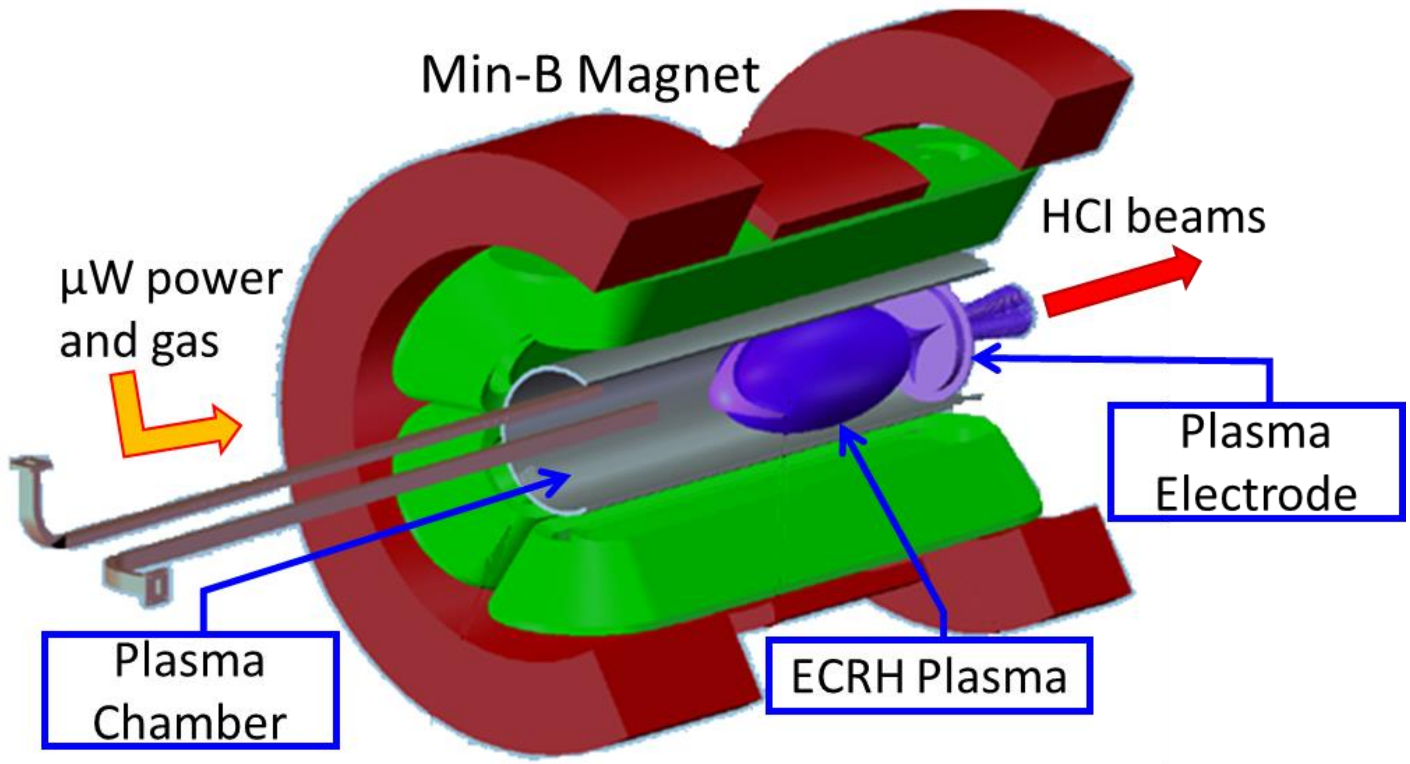
X. J. Niu

University of Electronic Science and Technology of China

Outline

- **Background**
- **Previous results review**
- **Analysis of microwave coupling**
- **45 GHz coupling solutions**
- **Summary**

Microwave coupling to ECR Ion Source

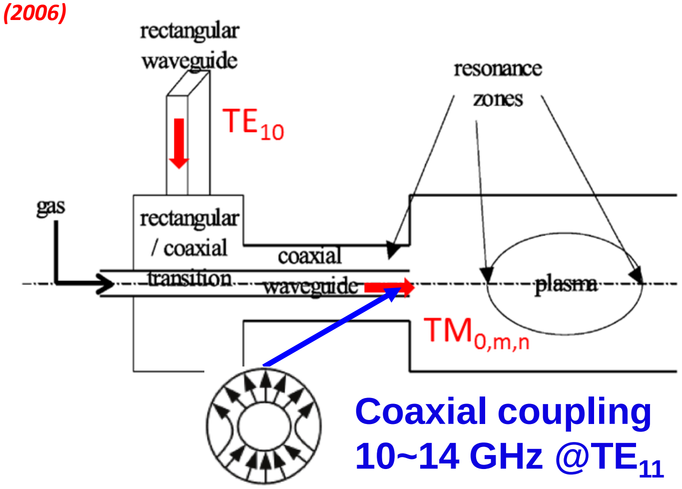


ECR Zone
High density plasma
$B_{ecr} = \omega_{rf} m_e / e$

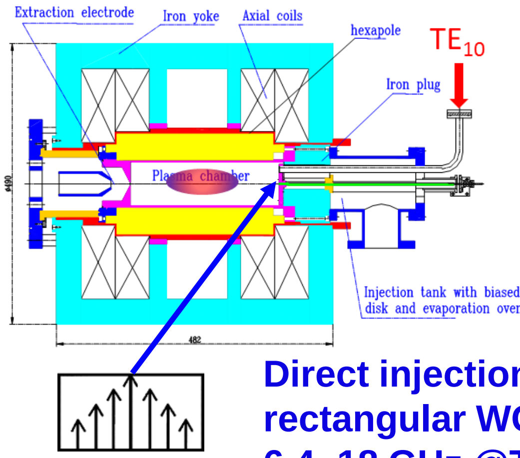
Microwaves power couple to the electrons on the ECR surface

Microwave coupling to ECR Ion Source

Denis HITZ, Advances in Imaging and Electron Physics, Vol. 144 (2006)



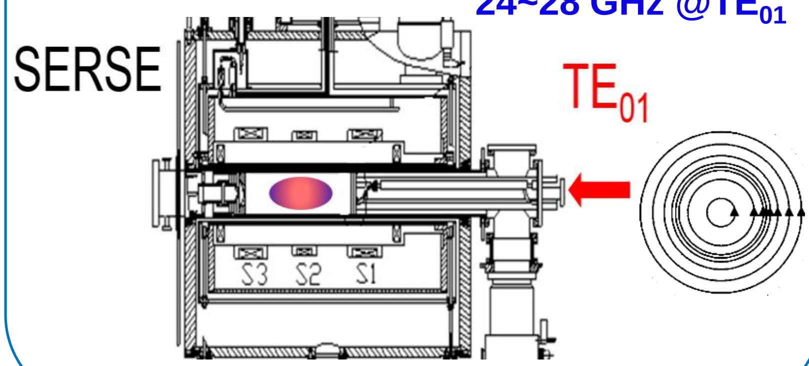
Coaxial coupling
10~14 GHz @TE_{11}

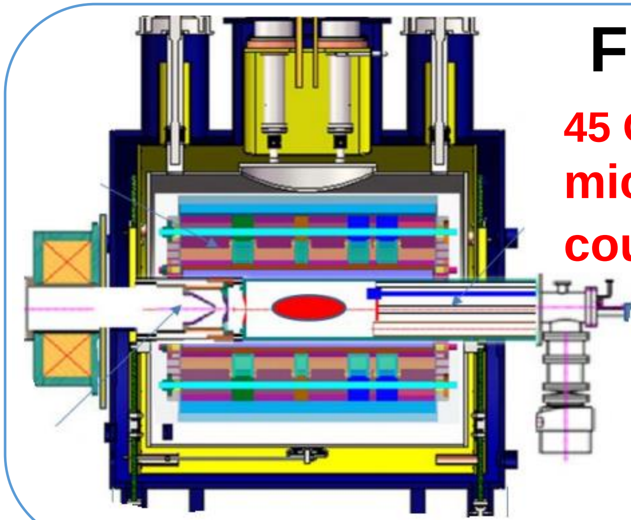


Direct injection with rectangular WG
6.4~18 GHz @TE_{10}

S. Gammino, et al, Rev. Sci. Instrum. 72, 4090 (2001)

Direct injection with circular WG
24~28 GHz @TE_{01}

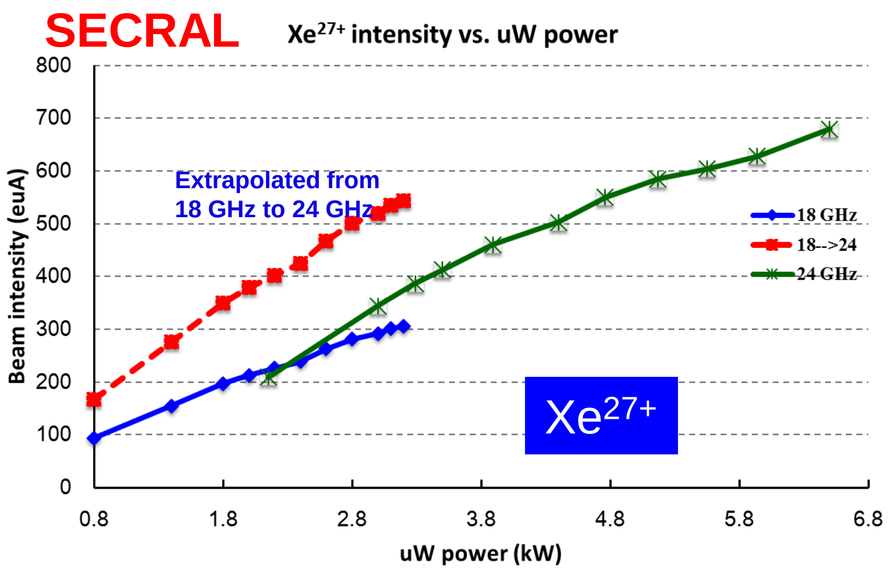


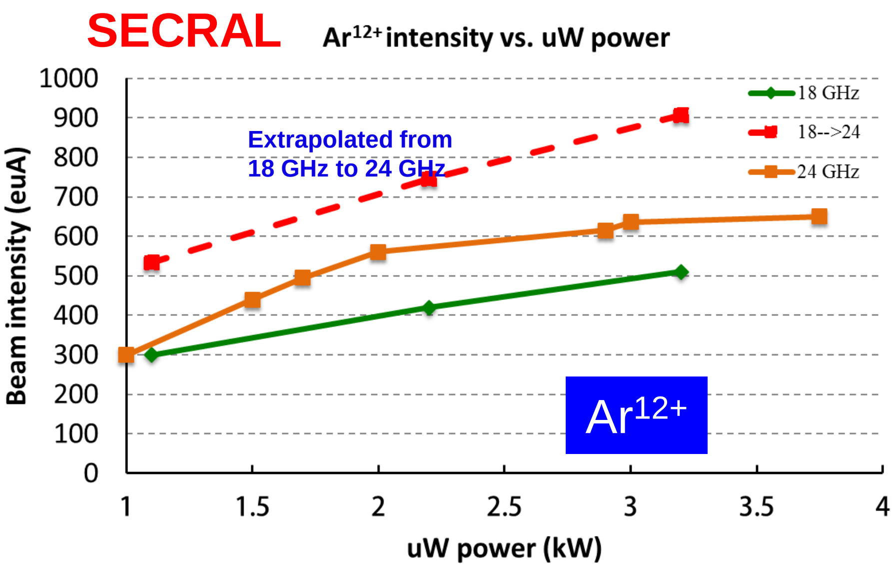


FECR

45 GHz/20 kW microwave coupling ?

3rd Gen ECRIS microwave coupling efficiency



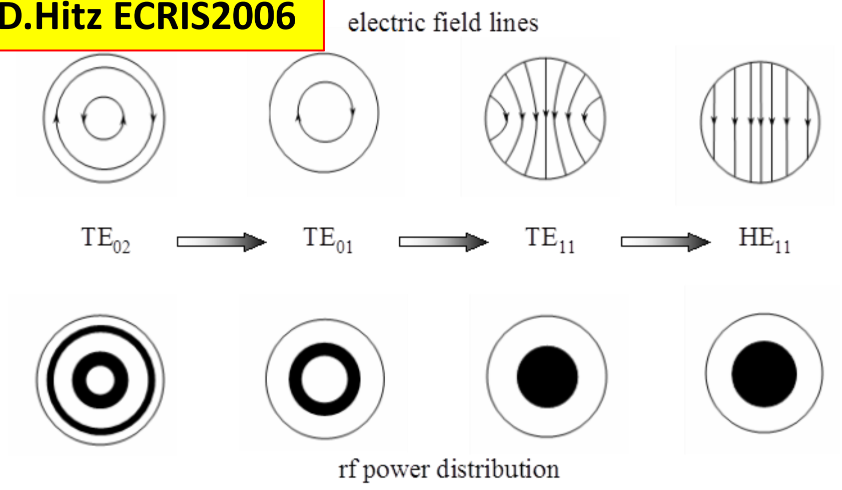


- ☐ **Gyrotron frequency boosts beam intensities (with suitable magnetic fields)**
- ☐ **Beam intensity increase more like μW power scaling**
- ☐ **Frequency effect not obvious**

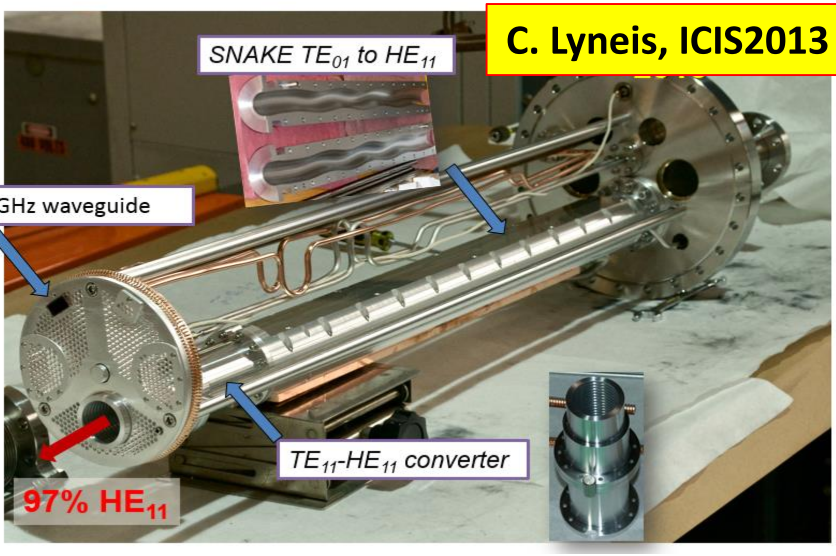
Similar results have also been observed with VENUS and SUSI

Previous exploration

D.Hitz ECRIS2006

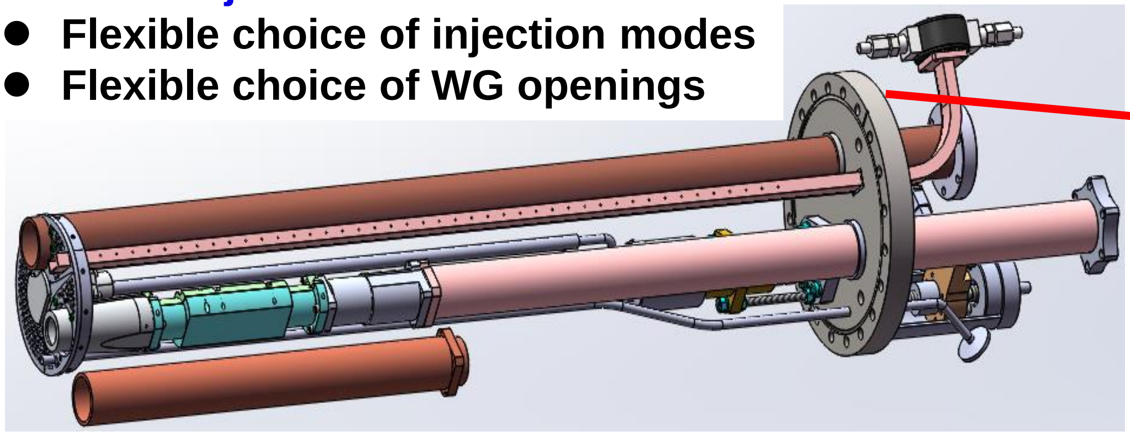


C. Lyneis, ICIS2013

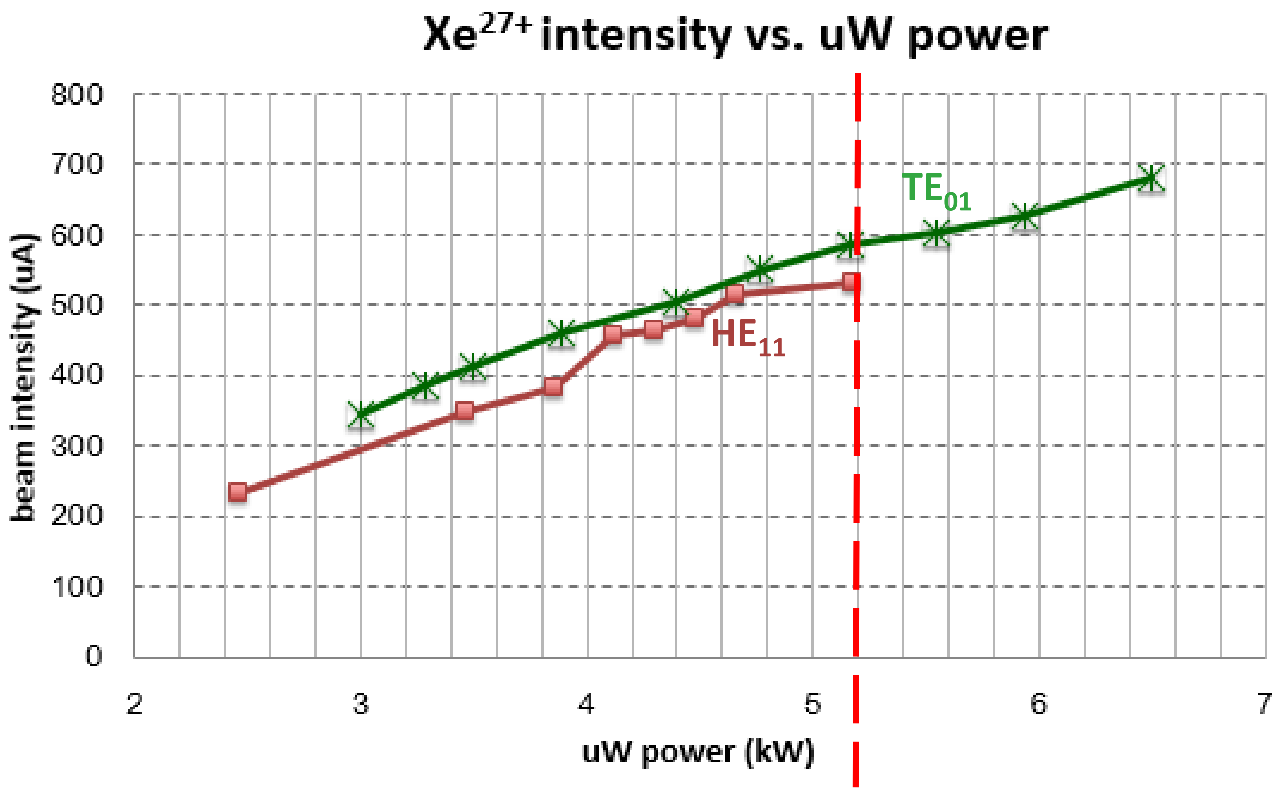


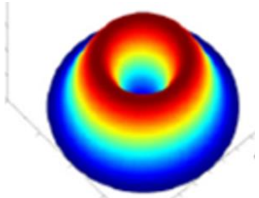
SECRAL Injection Parts

- **Flexible choice of injection modes**
- **Flexible choice of WG openings**

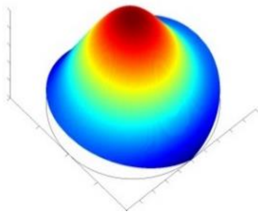


Previous results with microwave modes





TE_{01}

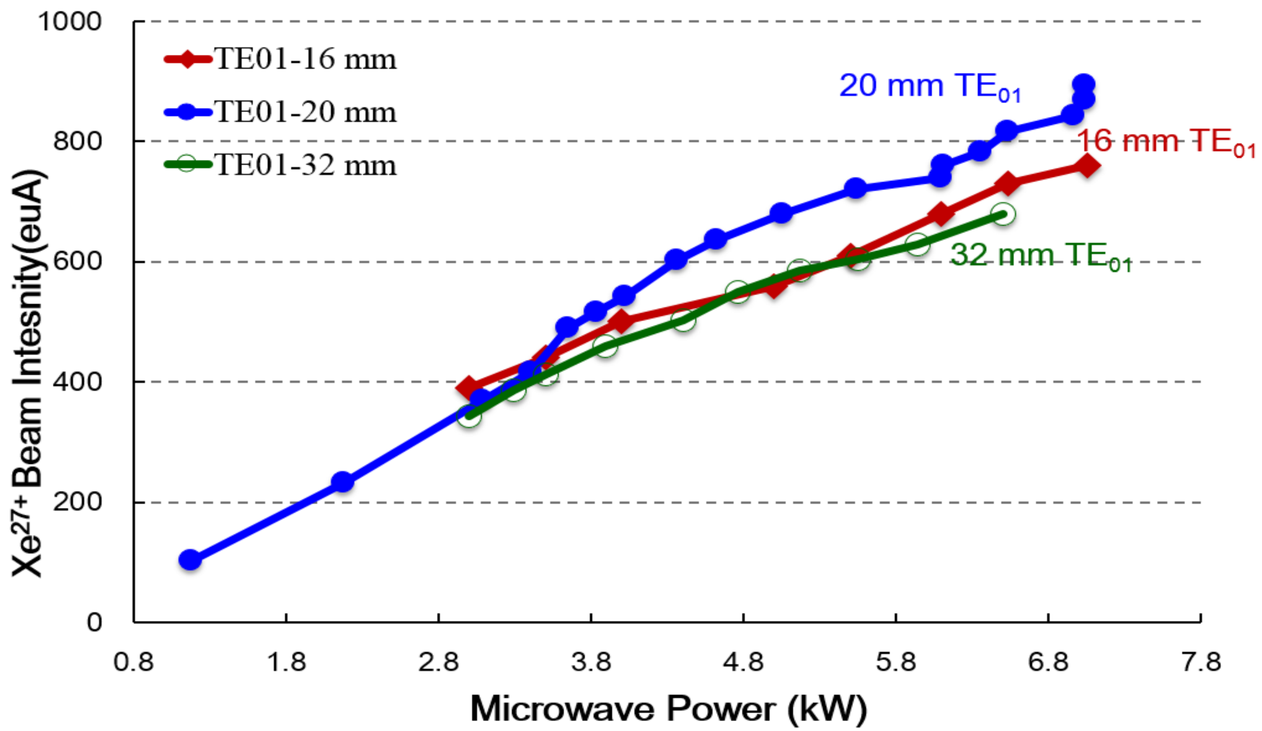


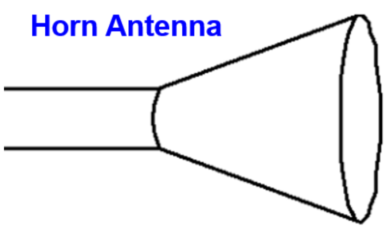
HE_{11}

- Above 5 kW of microwave power, the plasma shows instability and it is difficult to keep it stable.

- **HE_{11} did not show any sign of advantage over TE_{01}**

Previous results with waveguide diameters

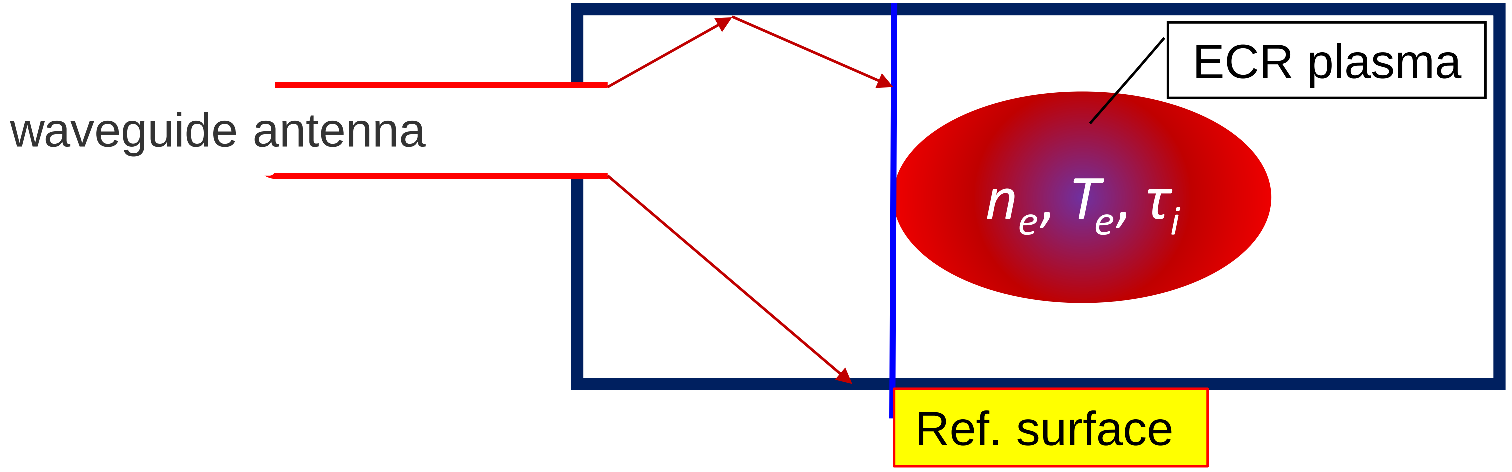




- TE_{01} @ Ø16 mm: it is possible to couple high μW power, but not too much gain
- **TE_{01} @ Ø20 mm shows obvious advantage in HCI production at high power level. No sign of saturation even at high power level.**

why ?

Analysis of microwave coupling



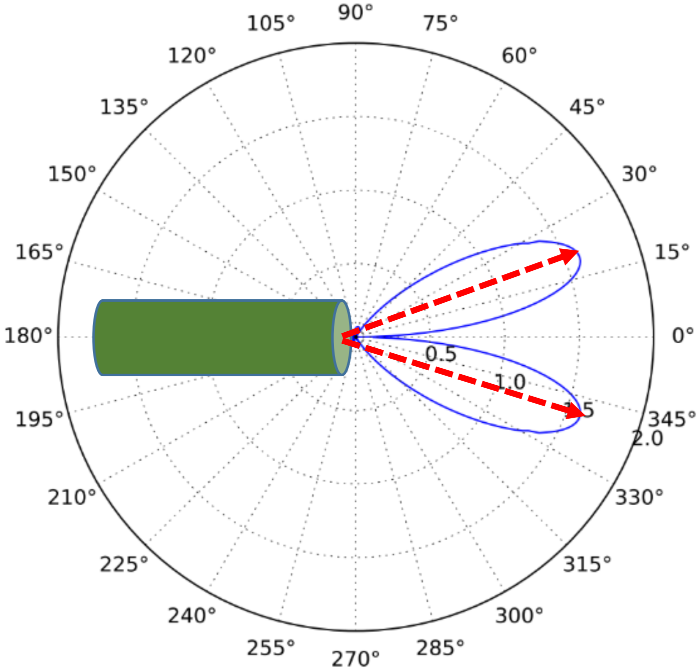
Two models for RF into ECR plasma chamber

- **Excitation of rf modes based on cavity[1]** **(Travelling wave dominated system)**
  Frequency tuning experiments indicate that the rf wave structure in the ECRIS plasma chamber is important since the extracted ion currents are sensitive to small changes (less than 1%) in the rf frequency.

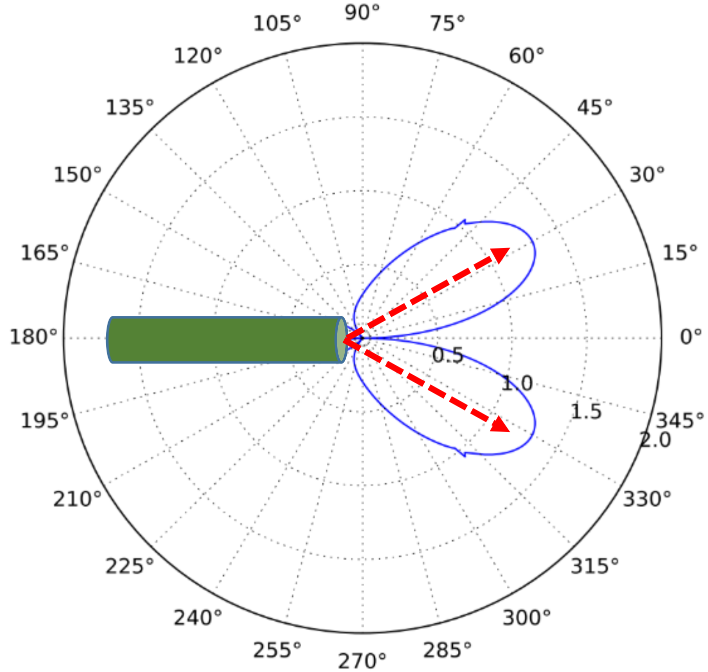
- **1st pass absorption is important[2,3]** **(Standing wave dominated system)**
  Most of the electromagnetic power is absorbed by the 1st ECR surface of plasma.

[1] L. Celona, et al., Rev. Sci. Instrum. 79, 023305 (2008)
[2] C. Lyneis et al, ECRIS2012
[3] B. Cluggish and J. S. Kim, NIM A664(2012)84

Free space radiation angle of TE_{01}



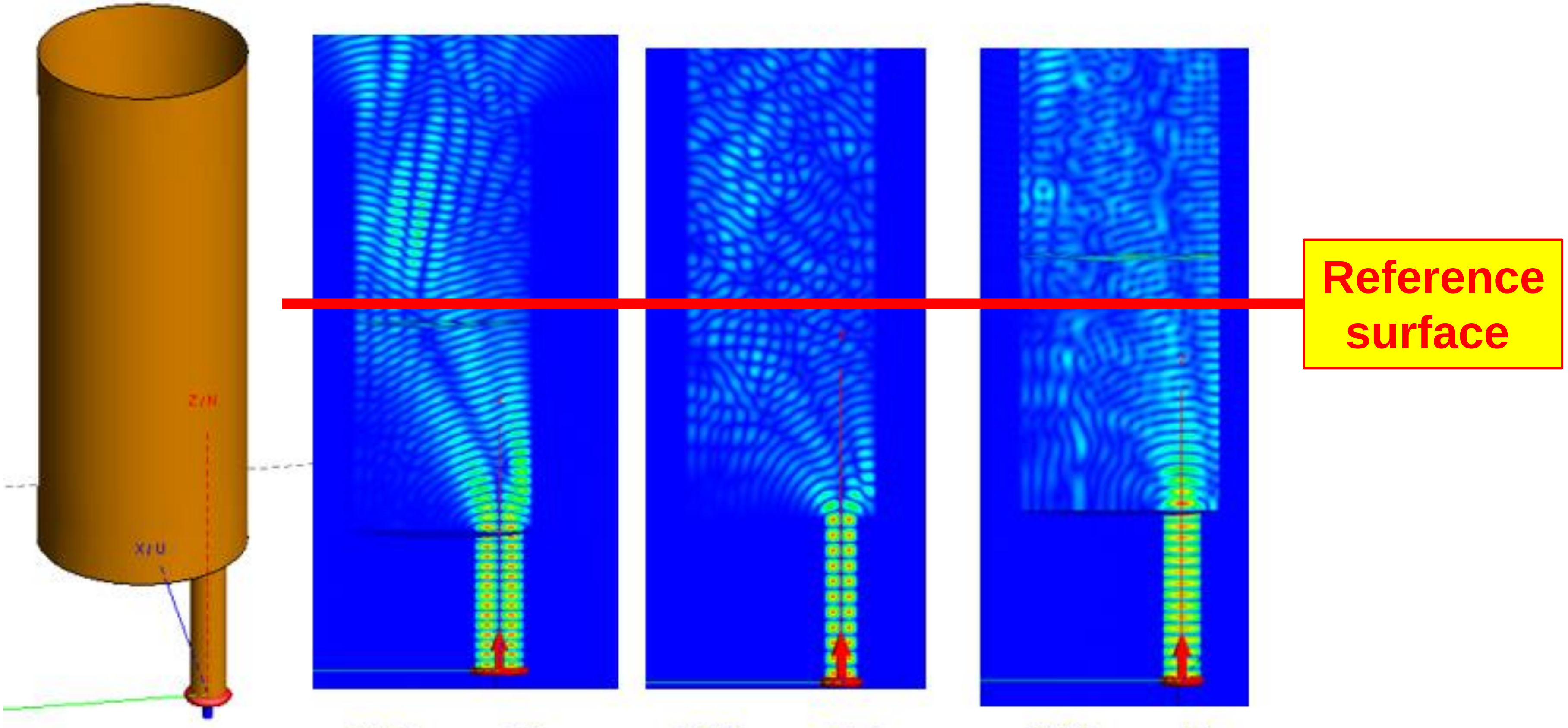
Ø32 mm radiation angle is 19 °



Ø20 mm radiation angle is 30 °

$$F_E(\theta) = F_H(\theta) = \left| \frac{1}{(\frac{K \sin\theta}{K_{01}})^2 - 1} (\cos\theta + \frac{\beta_{01}}{K}) J_1(\frac{2\pi}{\lambda} R \sin\theta) \right|$$

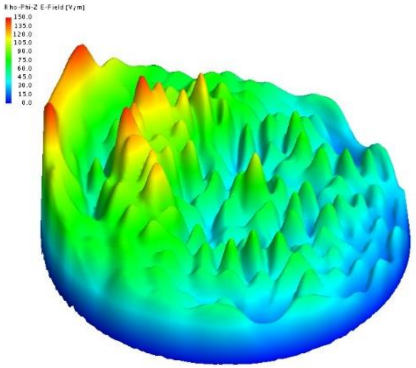
Power distribution simulation with chamber

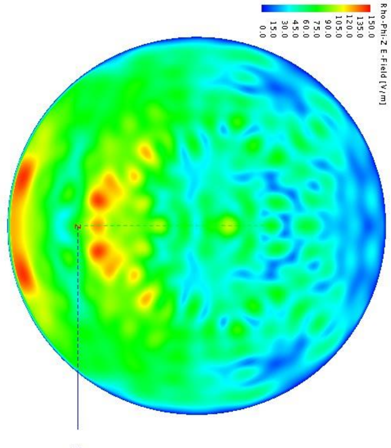


Ø32 mm TE_{01} Ø20 mm TE_{01} Ø20 mm HE_{11}

Power distribution on the Ref. surface

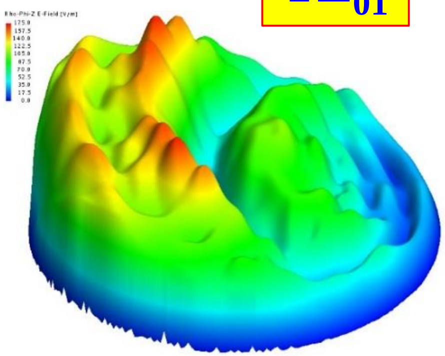
HE_{11}



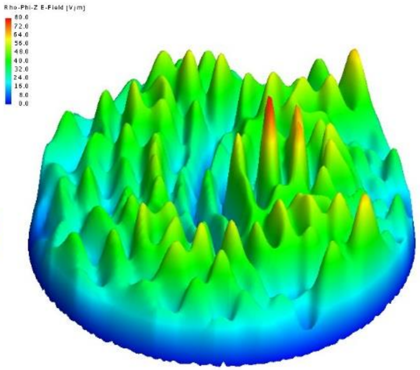


E_{max} =150 a.u.

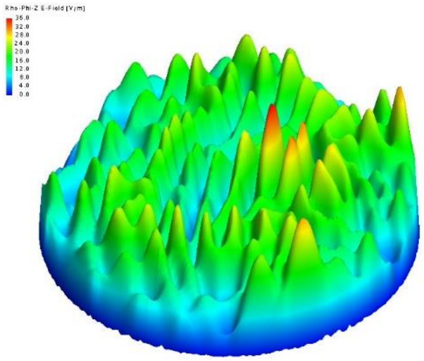
TE_{01}



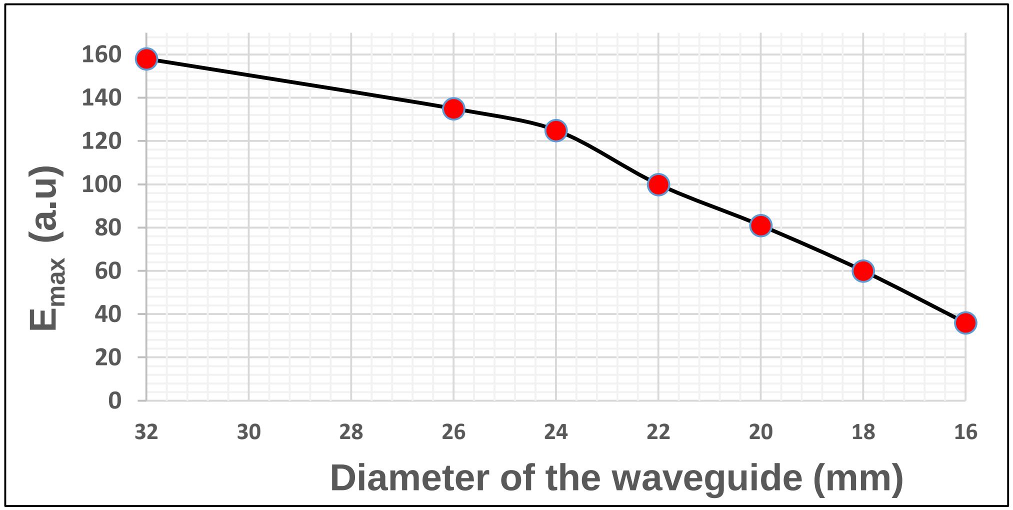
Ø32 E_{max} =175 a.u.



Ø20 E_{max} =80 a.u.



Ø16 E_{max} =36 a.u.



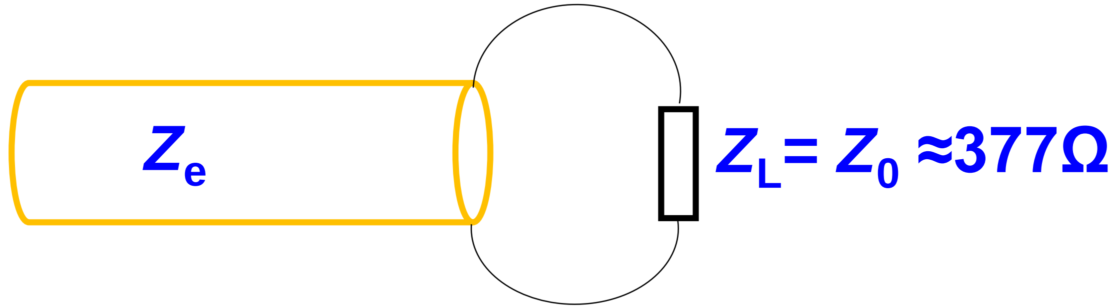
Impedance matching

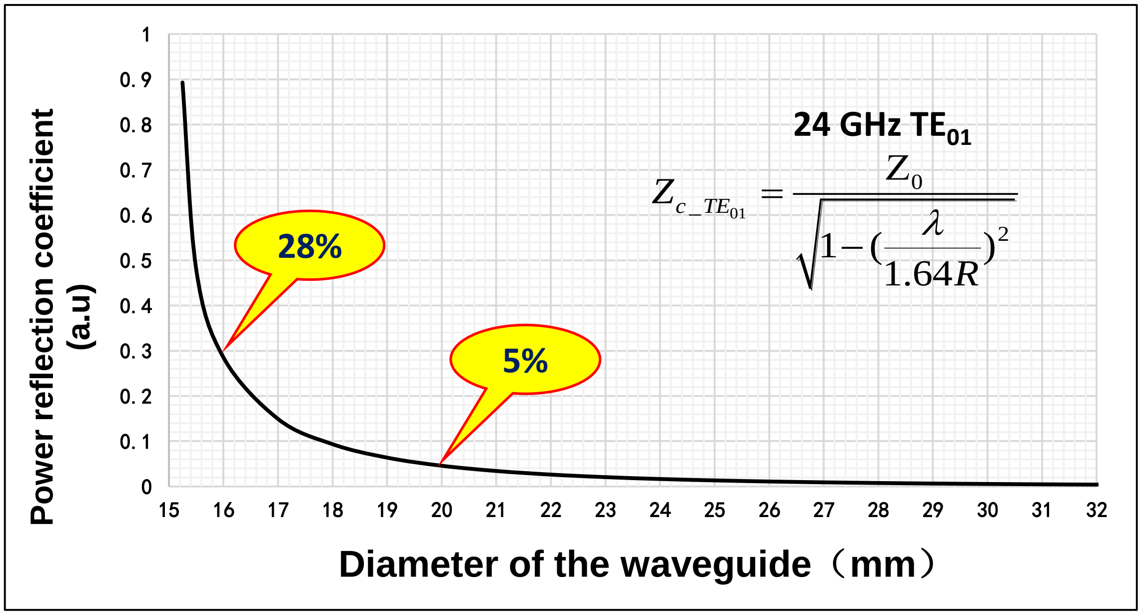
- **The significance of impedance matching**

To maximize the power transportation from the open-ended waveguide to load

$$\Gamma = \frac{\lambda_g - \lambda}{\lambda_g + \lambda_0} = \frac{Z_c - Z_0}{Z_c + Z_0}$$

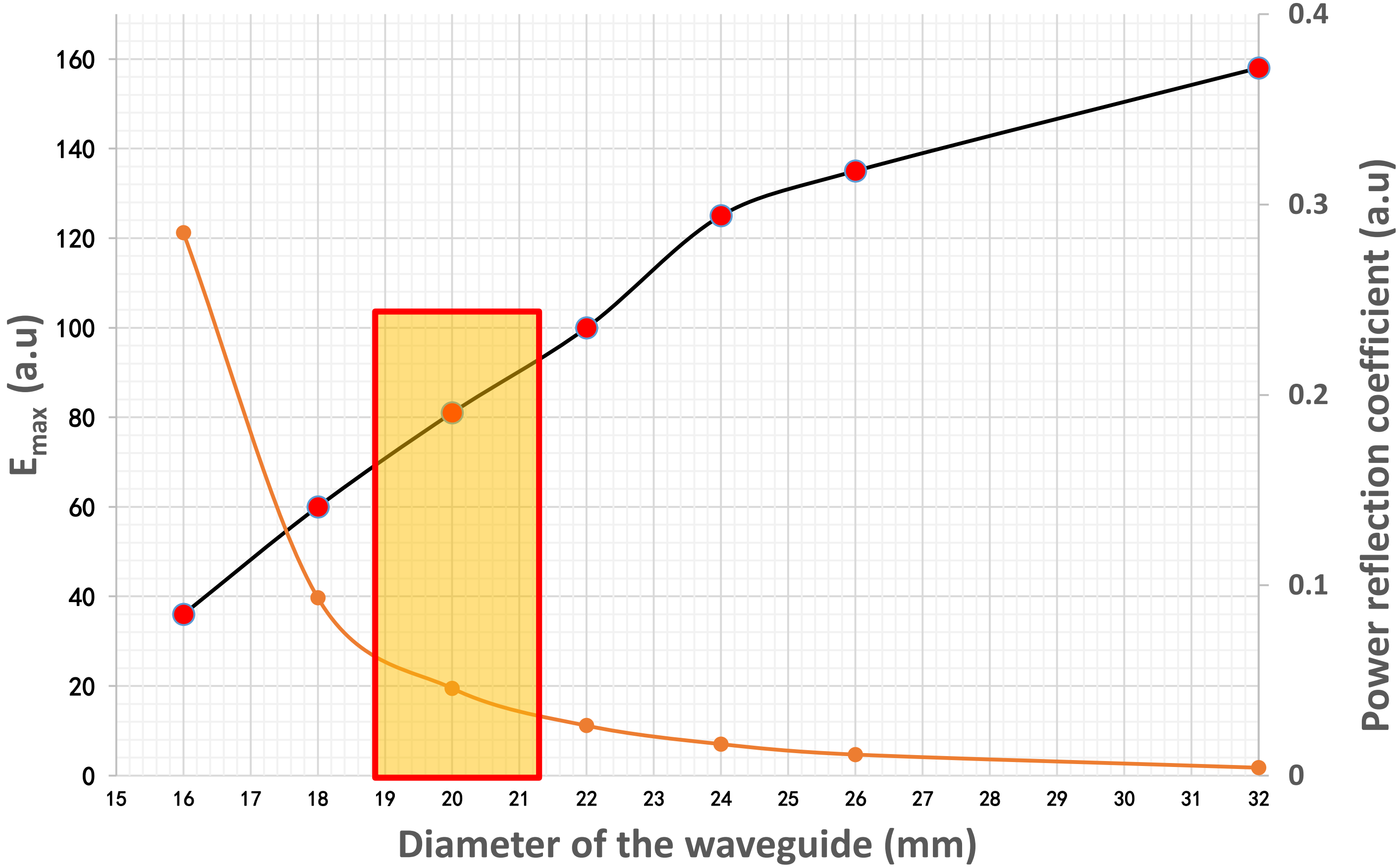
$$\eta = p_r / p_t = |\Gamma|^2 = \left(\frac{VSWR-1}{VSWR+1}\right)^2$$





Power distribution & Impedance matching

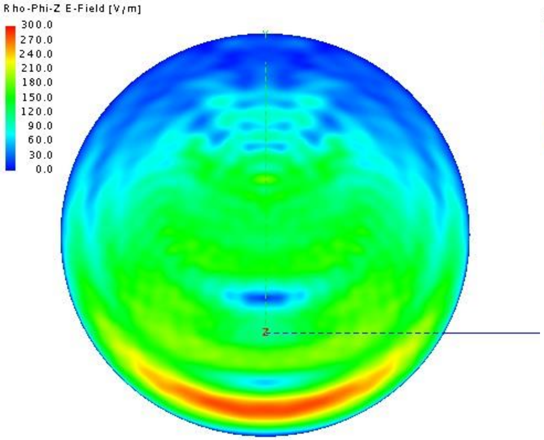
Impedance matching and power distribution need to be considered together



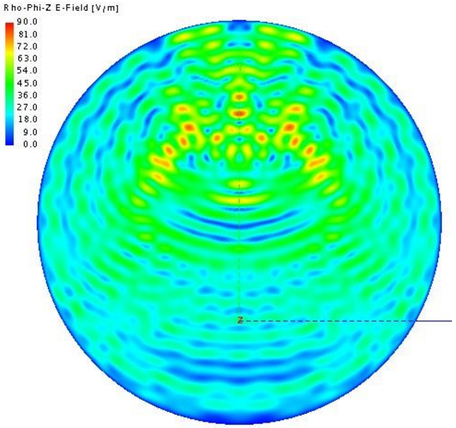
TE_{01}@ 20 mm is an optimized rf coupling scheme for the 24-28 GHz ECRISs

45 GHz/20 kW coupling solutions

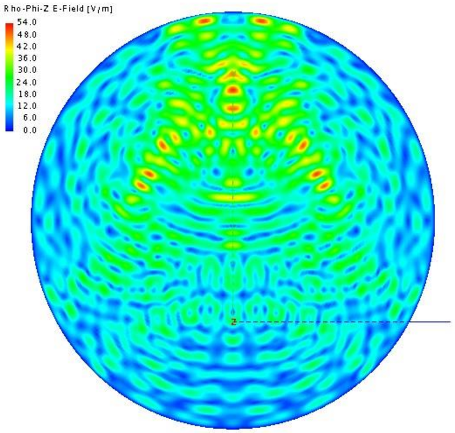
TE_{01}



Ø32 E_{max} =300 a.u.

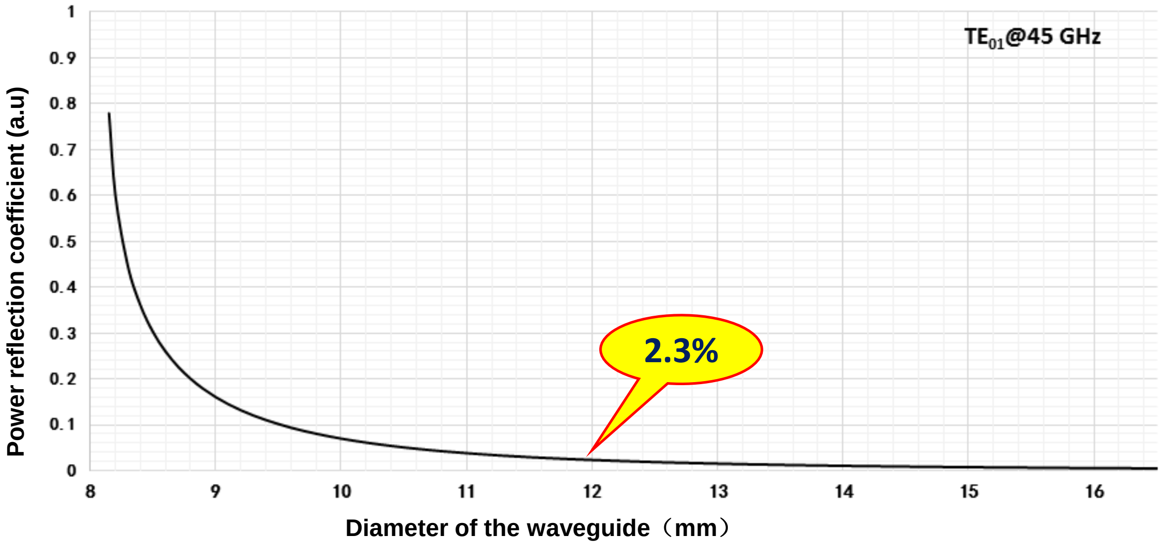


Ø16 E_{max} =90 a.u.

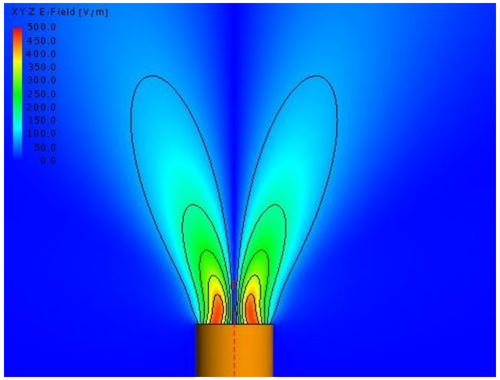


Ø12 E_{max} =54 a.u.

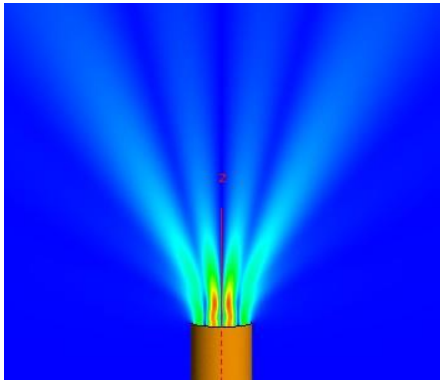
TE_{01}@ Ø12 mm



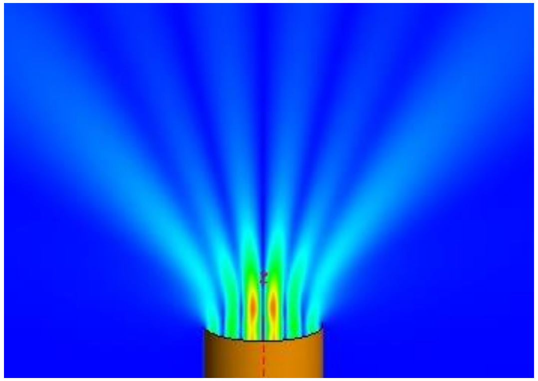
45 GHz/20 kW coupling solutions



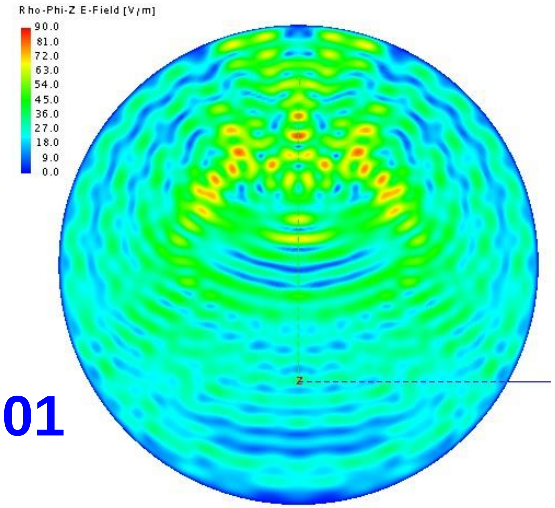
TE_{01}



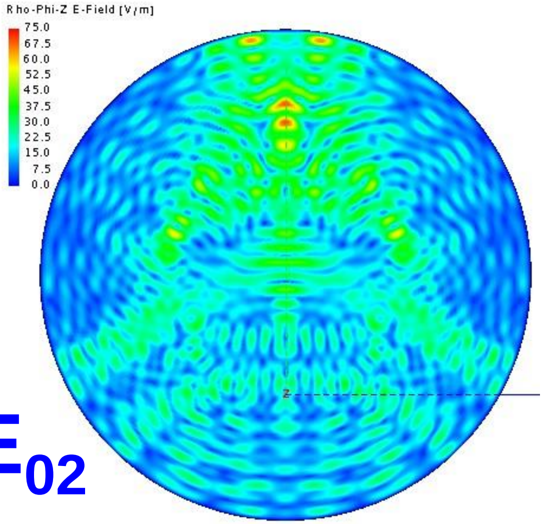
TE_{02}



TE_{03}



TE_{01}



TE_{02}

Ø16 E_{max} =90 a.u.

Ø20 E_{max} =75 a.u.

Summary

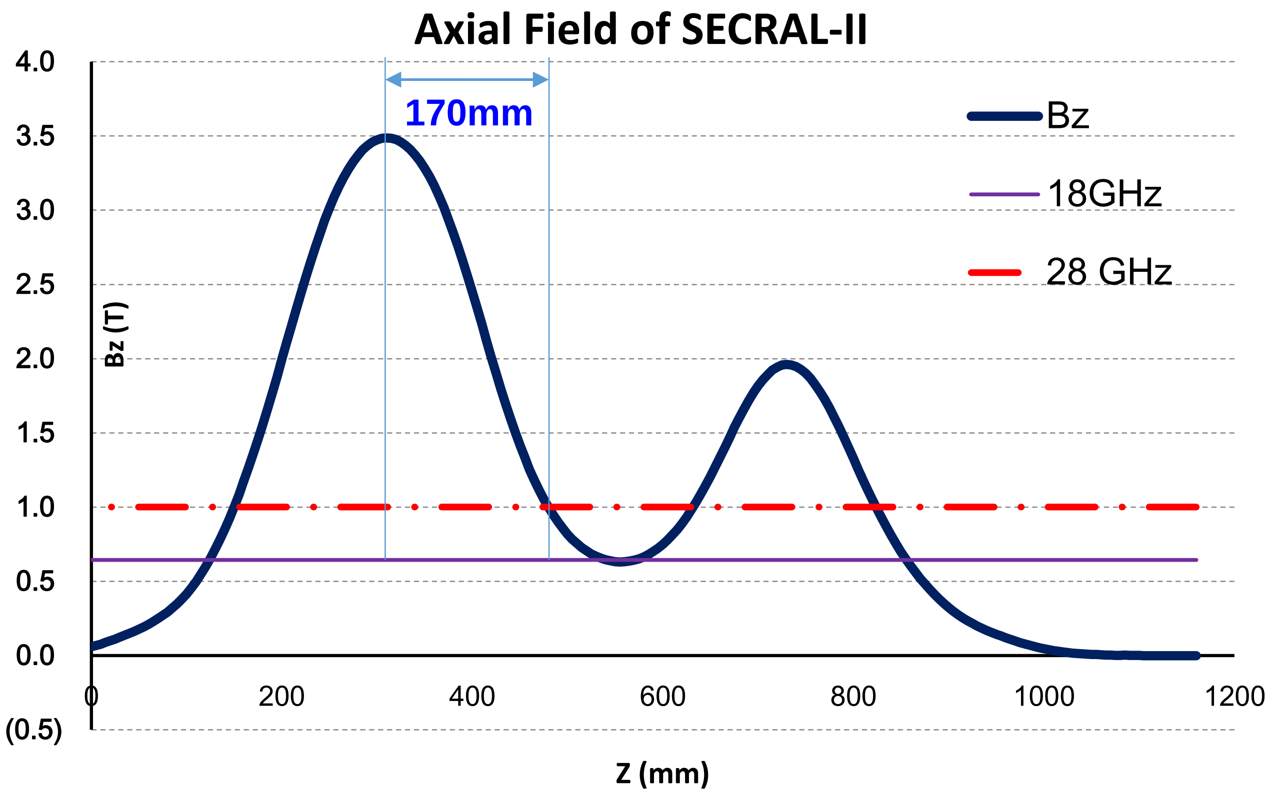
- TE_{01}@20 mm is an optimized rf coupling scheme for the existing 24-28 GHz ECR ion source
- Power distribution is more important than microwave mode itself
- Impedance matching and power distribution need to be considered together
- As for 45 GHz/20 kW , TE_{02} or TE_{03} coupling scheme seems better

- ☐ To optimize the microwave power coupling scheme for Gyrotron frequency ECR Ion Sources, one needs better understanding and more investigation

Acknowledgement

Claude Lyneis, Daniel Xie, Denis Hitz

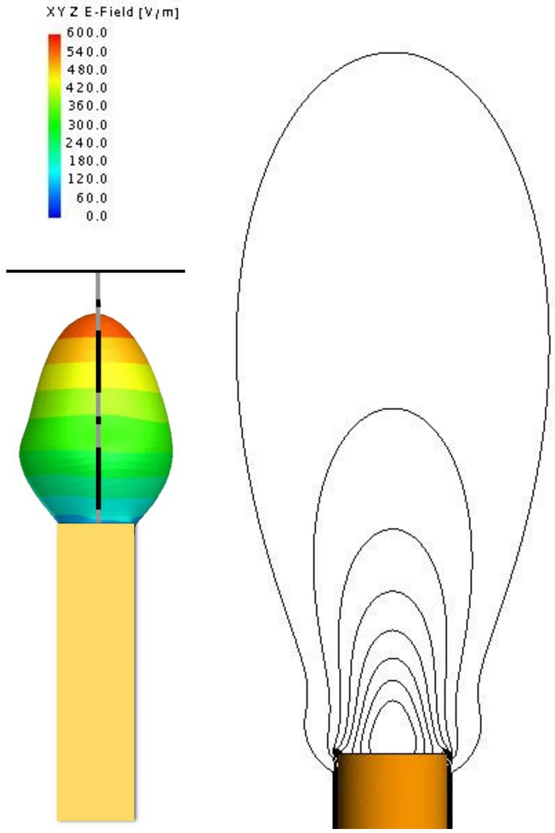
Thanks for your attention!


Axial Field of SECRAL-II
170mm
Bz
18GHz
28 GHz
Bz (T)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
(0.5)
0
200
400
600
800
1000
1200
Z (mm)

➢ RF diffusion

$$D_{rf} = \frac{\pi}{2}\left(\frac{eE}{2m}\right)^2 \frac{d}{L\omega}$$

Perret C., Girard A., Khodja H. et al. Limitations to the Plasma Energy and Density in Electron Cyclotron Resonance Ion Sources. Phys. Plasmas, 1999, Vol. 6(8), 3408-3415


XYZ E-Field [V/m]
600.0
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0

HE_{11}