Microwave Power Injection Schemes Study At IMP With Superconducting ECR Ion Source SECRAL

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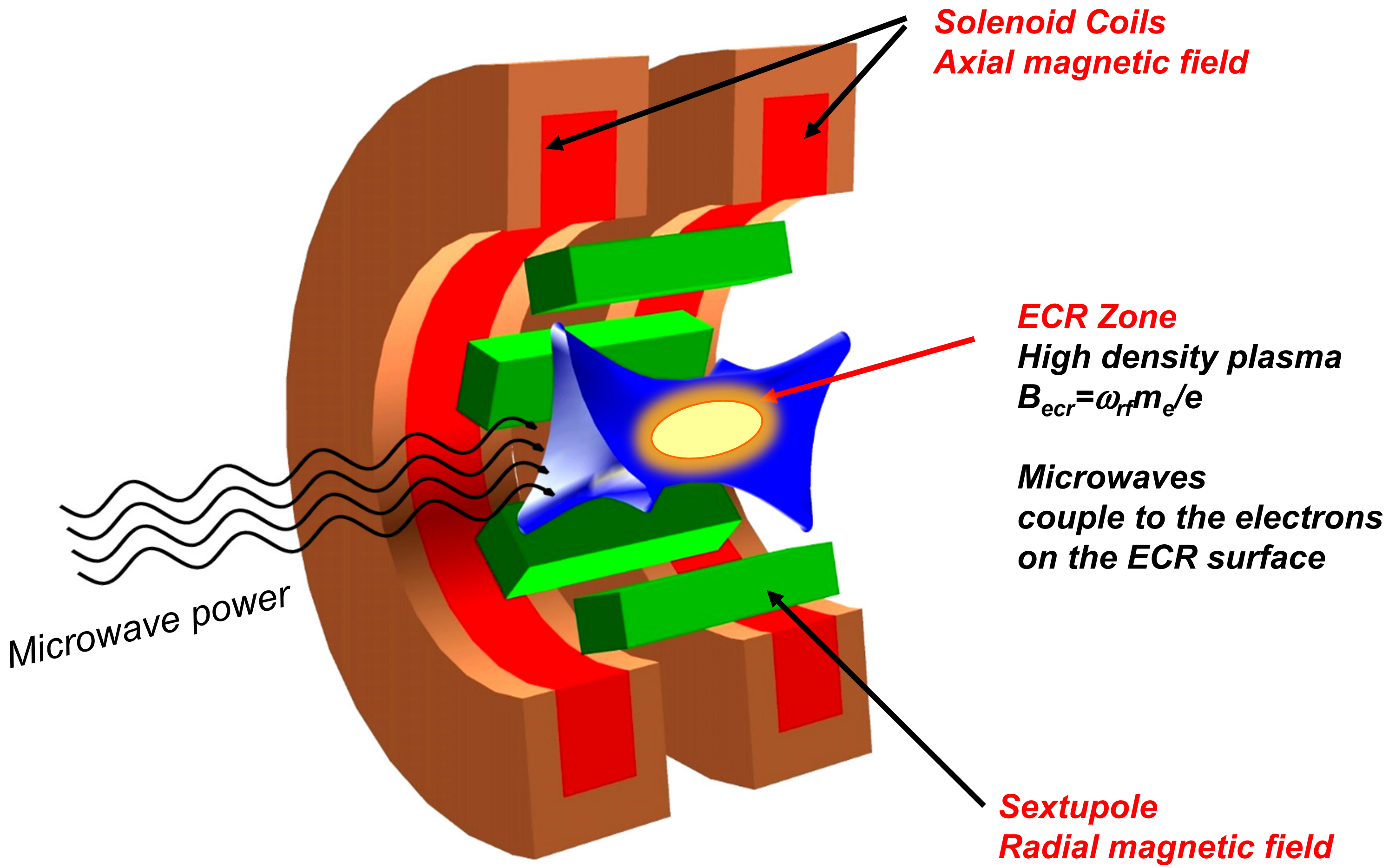
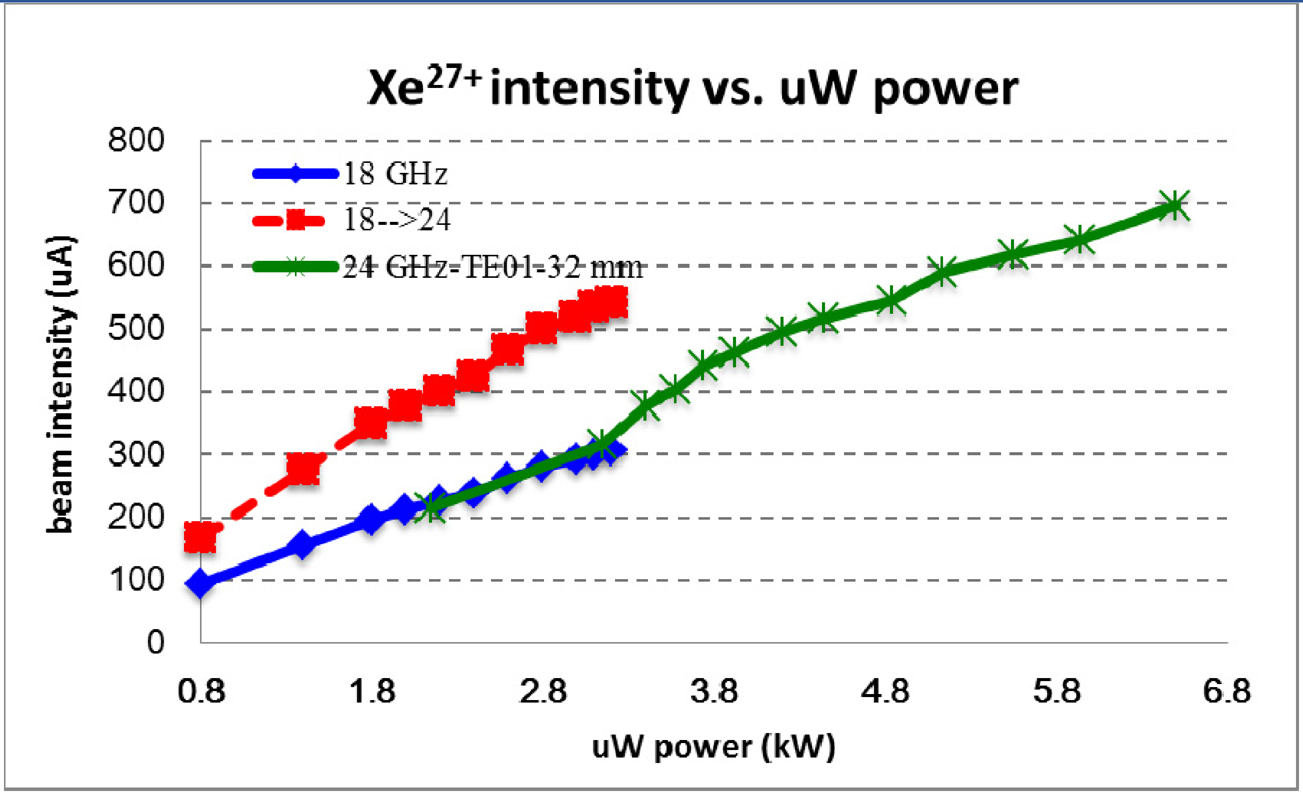
Outline

- Background
- Design of mode convertors
- Test results of various injection schemes
- Summary & outlook

Microwave coupling to ECR Ion Source



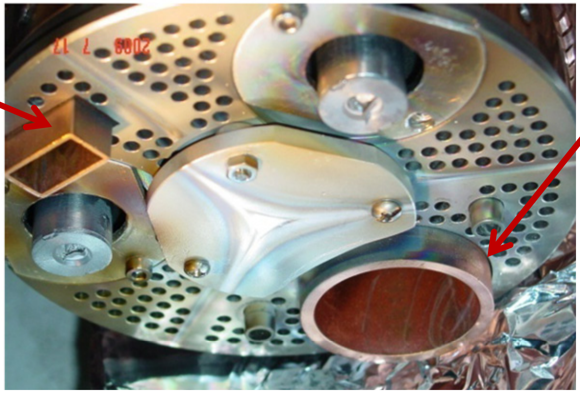
Xe^{27+} production with TE_{01} @ 32 mm



- **A quasi-linear extrapolation of the results at 18 GHz**
- **ω^2 effect is not evident**

The characteristics of the 2nd and 3rd G ECRIS RF system

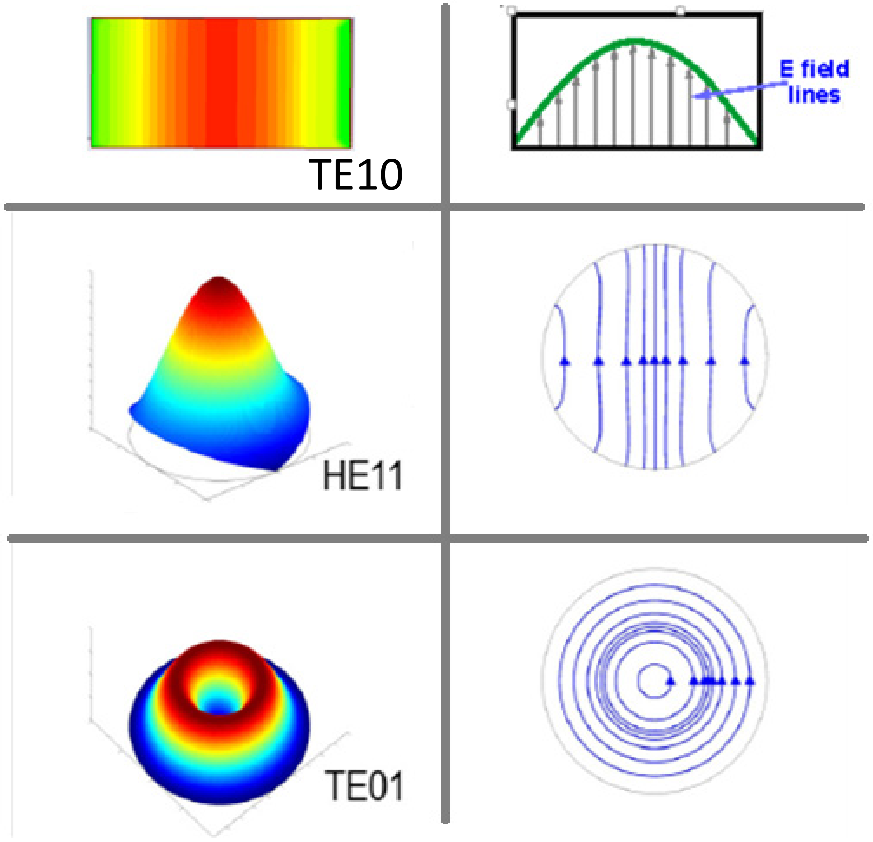
10-18 GHz TE_{10} rectangular waveguide



24-28 GHz TE_{01} oversized circular waveguide

	2nd G ECRIS RF system	3rd G ECRIS RF system
Generator	Klystron/TWT	Gyrotron
Transmission mode	Single-mode	Multimode
Injection mode	TE_{10} (rectangular waveguide)	TE_{01} (circular waveguide)
Waveguide model	Standard: WR62 (18GHz)	Oversized (WC128-Φ33mm)
Frequency adjustment	√	X (fixed)
Bandwidth	750 MHz (TWT)	50 MHz
Maximum power	0.5-2 kW	5-10 kW

Microwave mode: TE_{10} TE_{01} and HE_{11}



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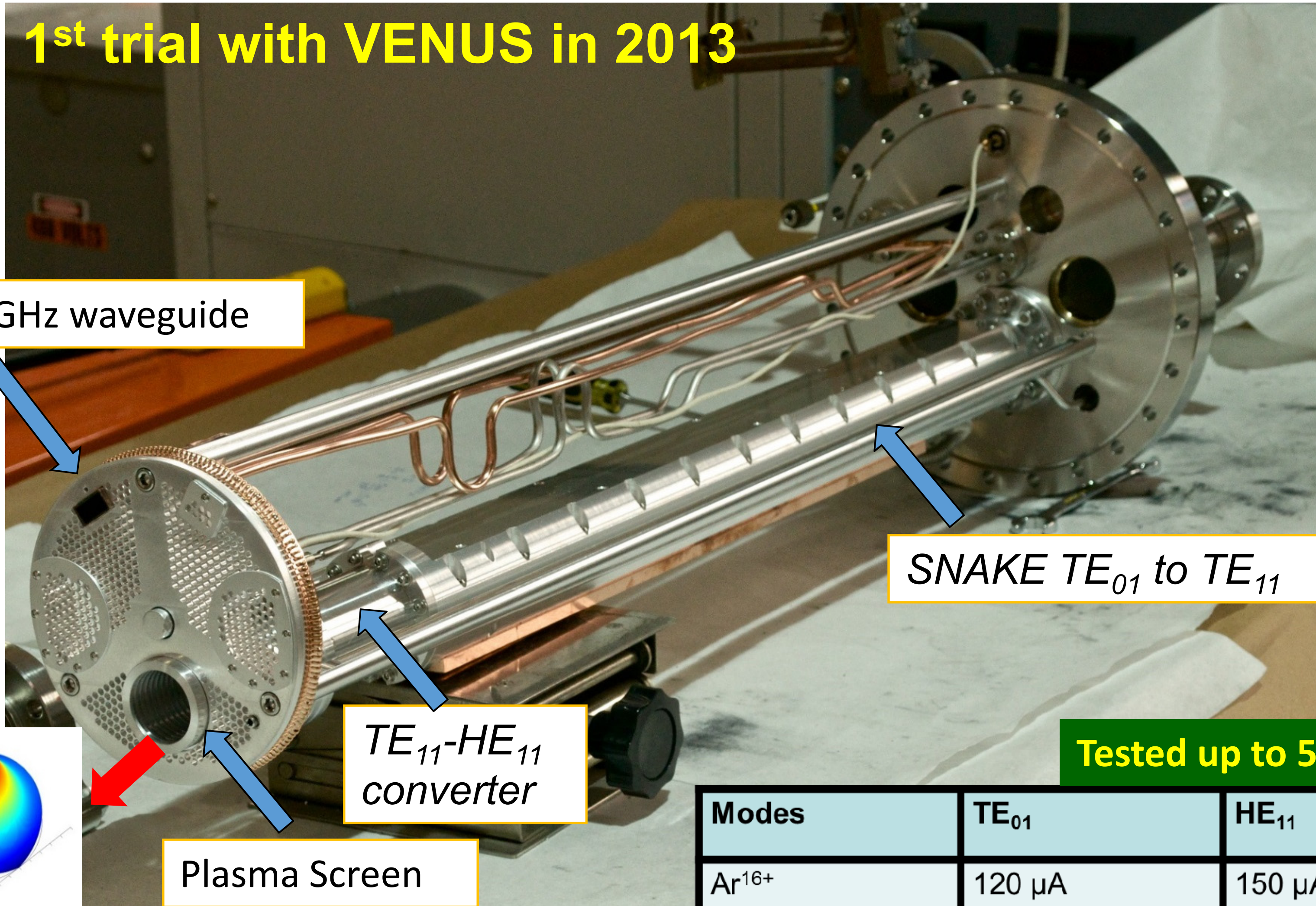
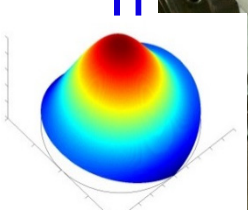
RF coupling with HE_{11} mode



HE_{11}



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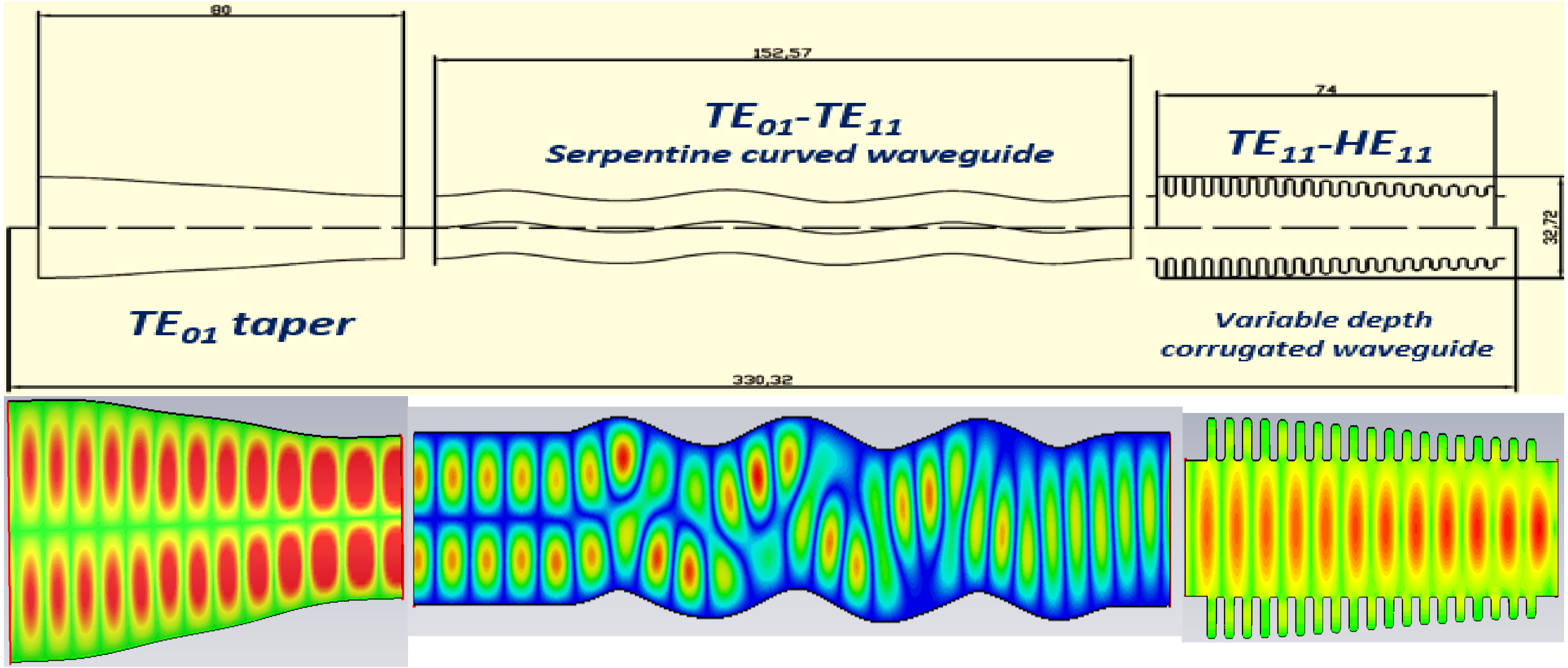
Tested up to 5.0 kW

Modes	TE_{01}	HE_{11}
Ar^{16+}	120 μA	150 μA
Xe^{27+}	330μA	370 μA

Compact design of mode convertors

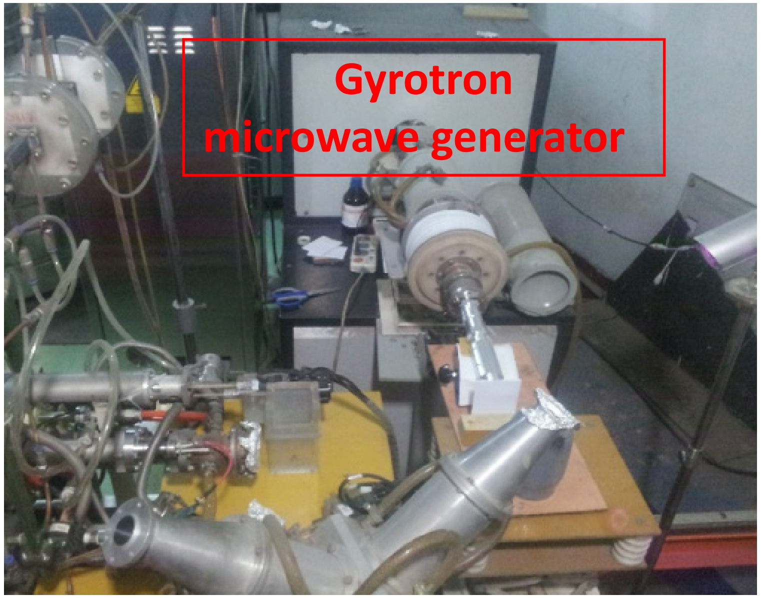
- **Waveguide ID: Ø32.6 mm→Ø20 mm**
- **Convertor length: 745 mm→330 mm**
- **maximum diameter: 48 mm→32.7 mm**

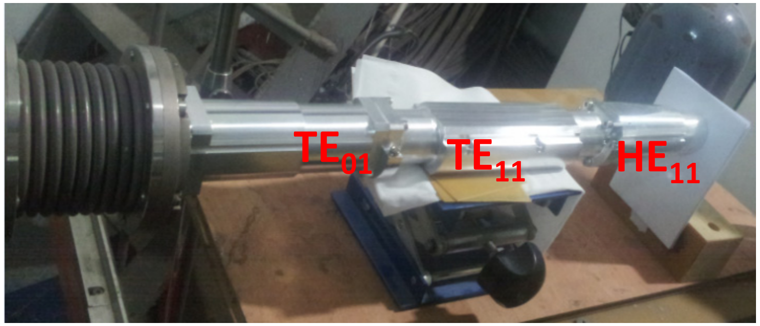


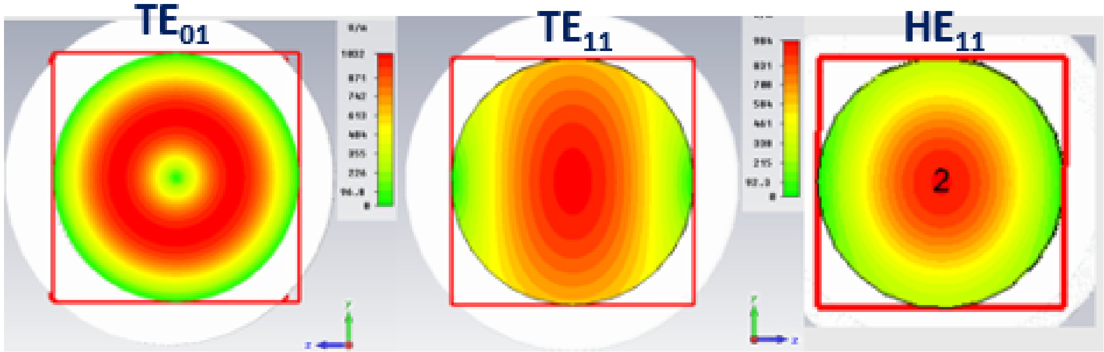
Power distribution on the longitudinal cut plane of the TE_{01}-TE_{11}-HE_{11} converter

- **Calculated by a relevant code-written based on the coupled wave theory**
- **Verified by the Commercial Microwave Studio CST Software**

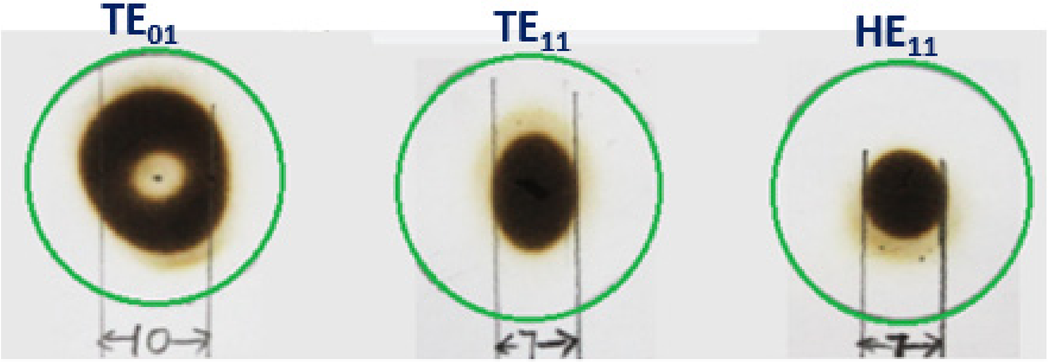
Off-line test of the mode converters





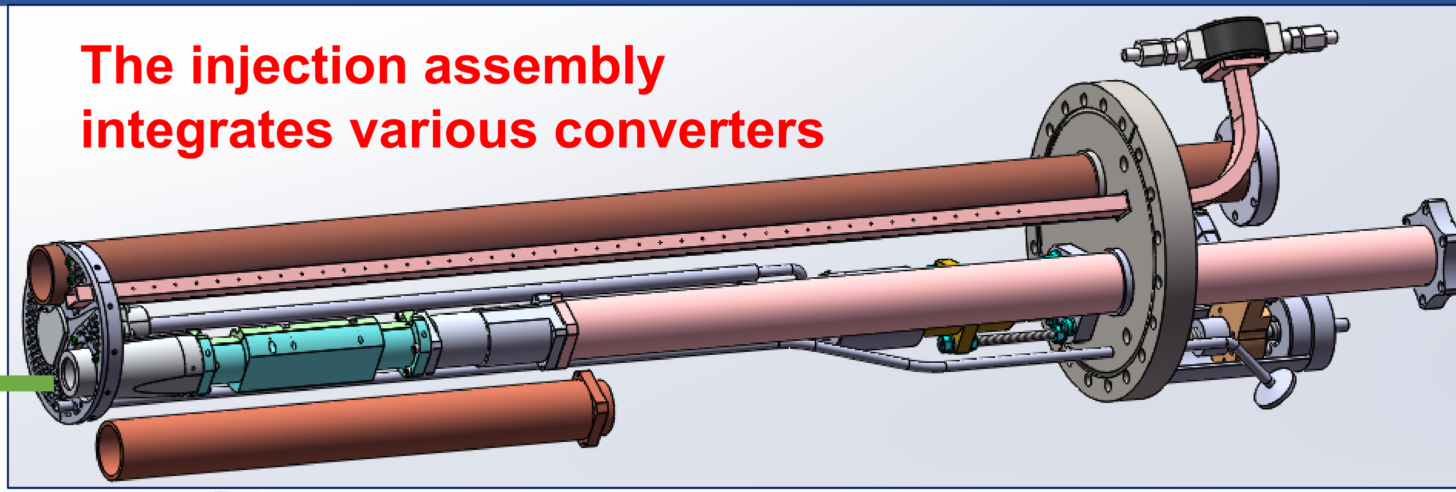


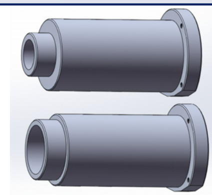
Calculated power distributions for the TE_{01}-TE_{11}-HE_{11} mode converters



Burnt spots for the TE_{01}-TE_{11}-HE_{11} mode converters

Various microwave power injection schemes





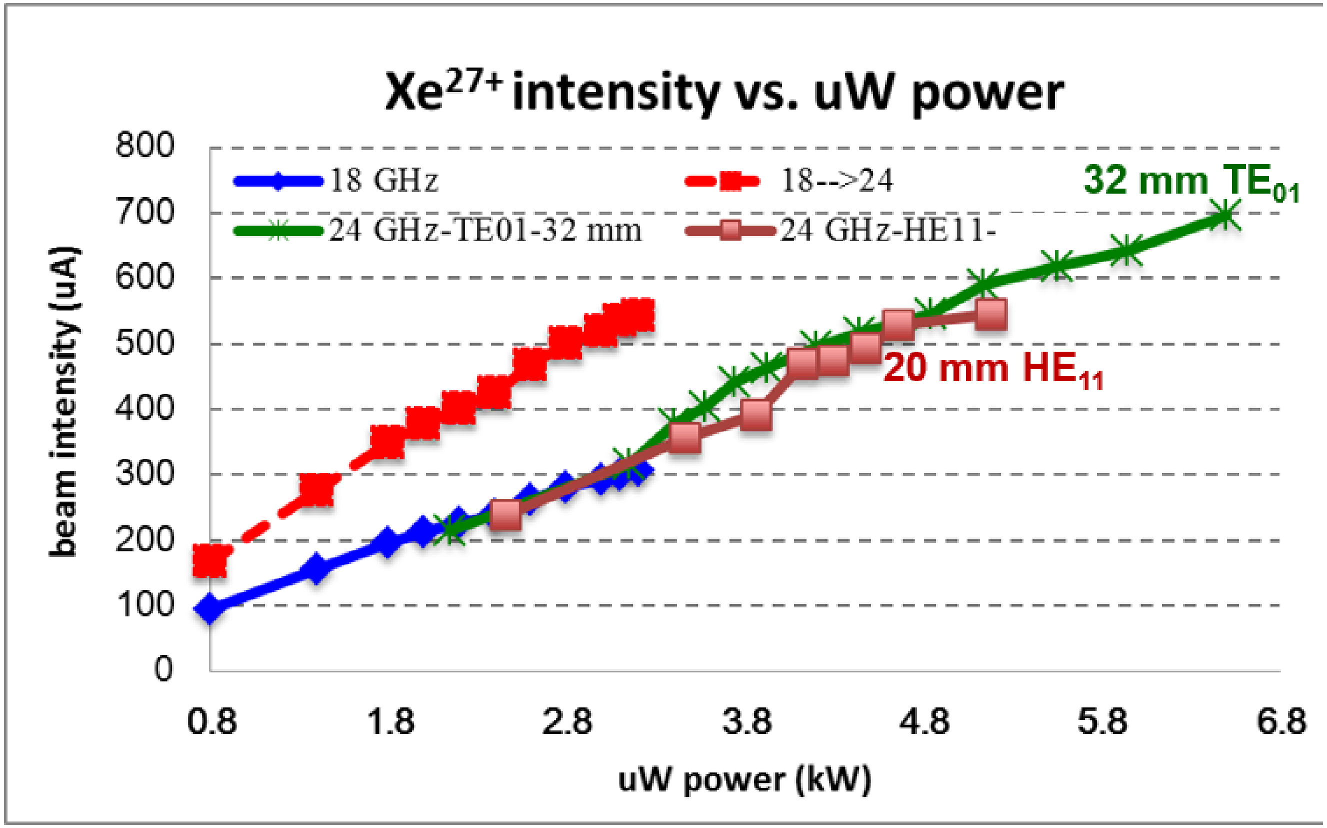
f=24.1 GHz

$$d_{\min TE_{11}} = \frac{1.841}{\pi f \sqrt{\mu\varepsilon}} = 7.3mm$$

$$d_{\min TE_{01}} = \frac{3.832}{\pi a \sqrt{\mu\varepsilon}} = 15.2mm$$

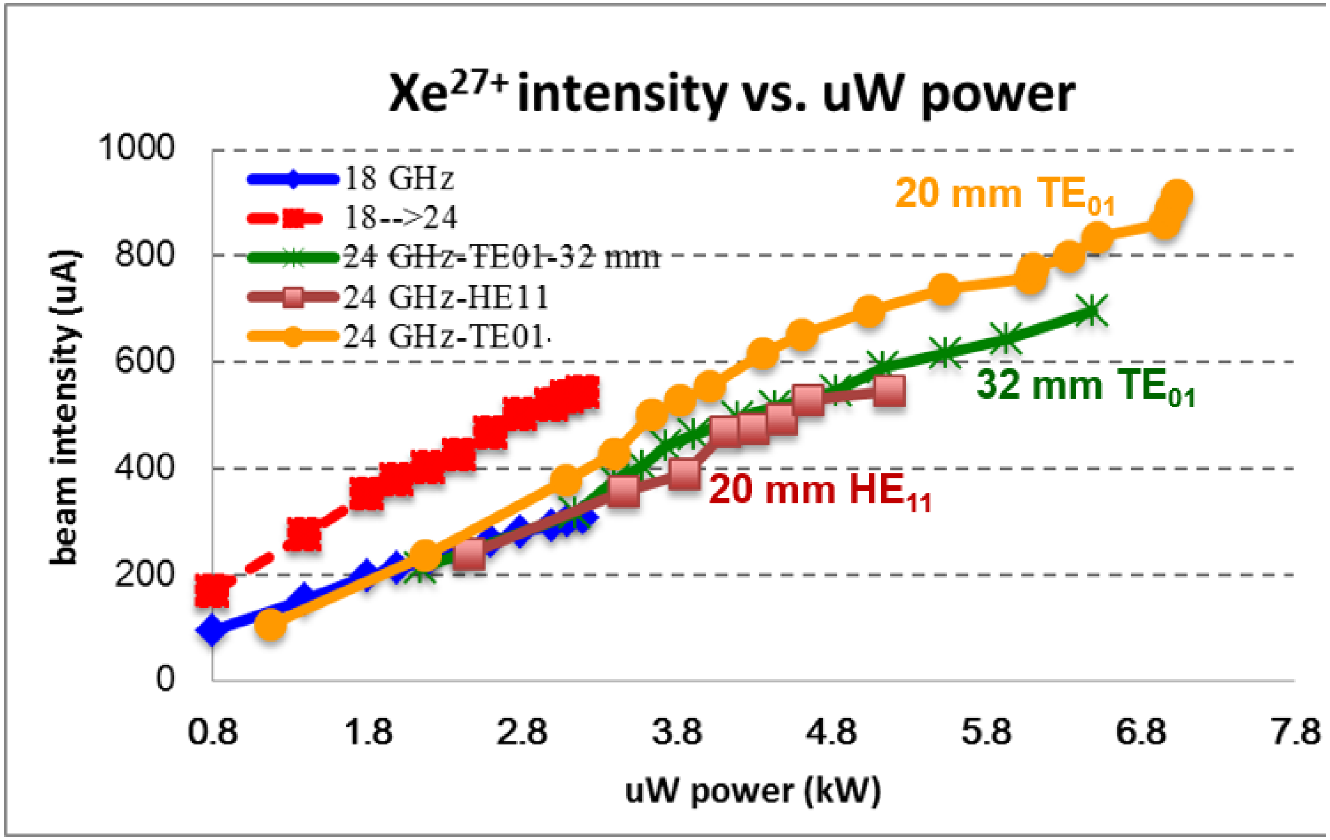
Microwave mode	Waveguide diameter (mm)
HE_{11}	20.24
TE_{11}	8
TE_{01}	16
	20.24
	26
	32.54

Xe^{27+} production with HE_{11} @ 20 mm



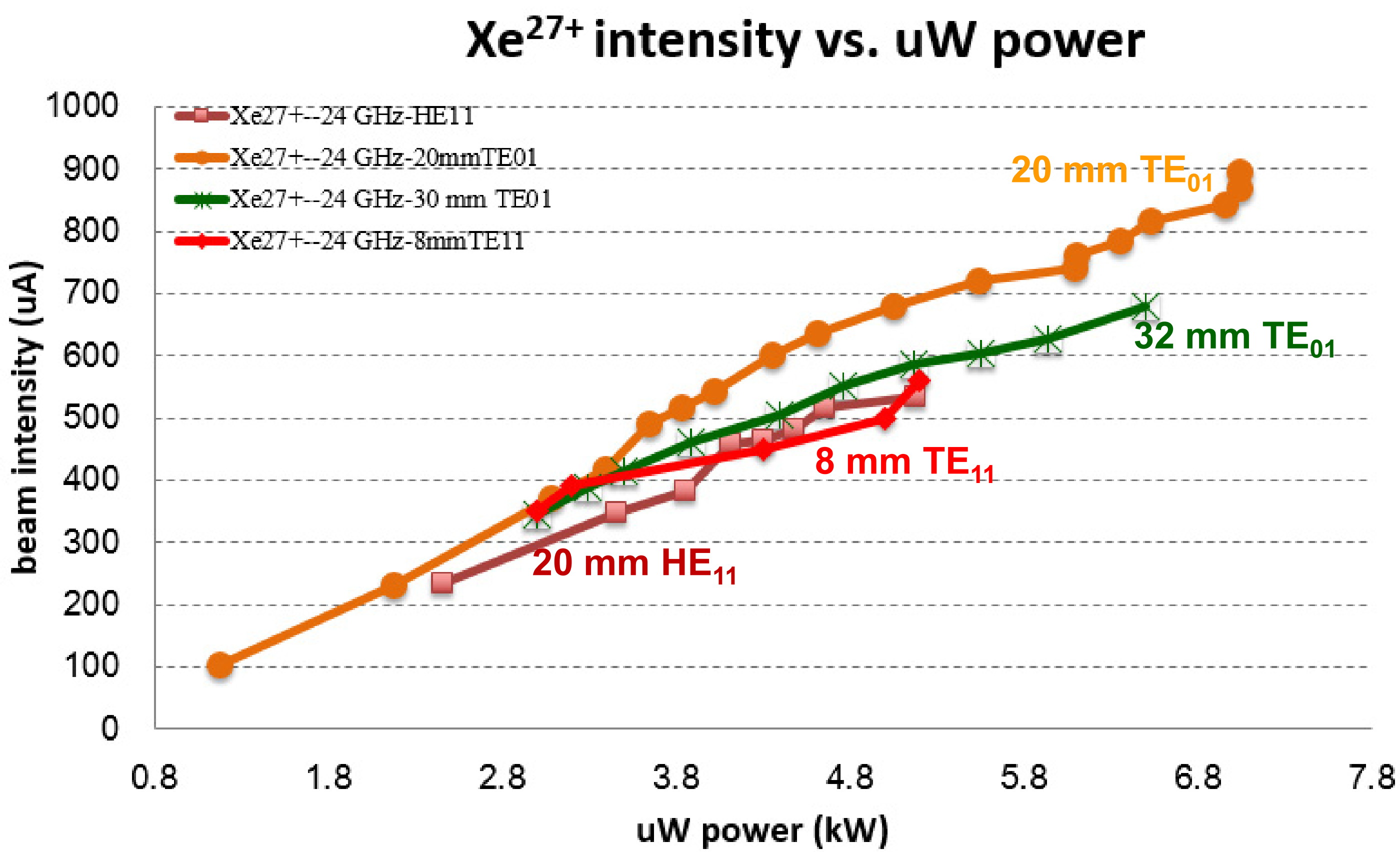
- **HE_{11} mode did not show any sign of advantage over TE_{01} in terms of HCI production**
- **Plasma is less stable at high power level with HE_{11}**

Xe^{27+} production with TE_{01} @ 20 mm



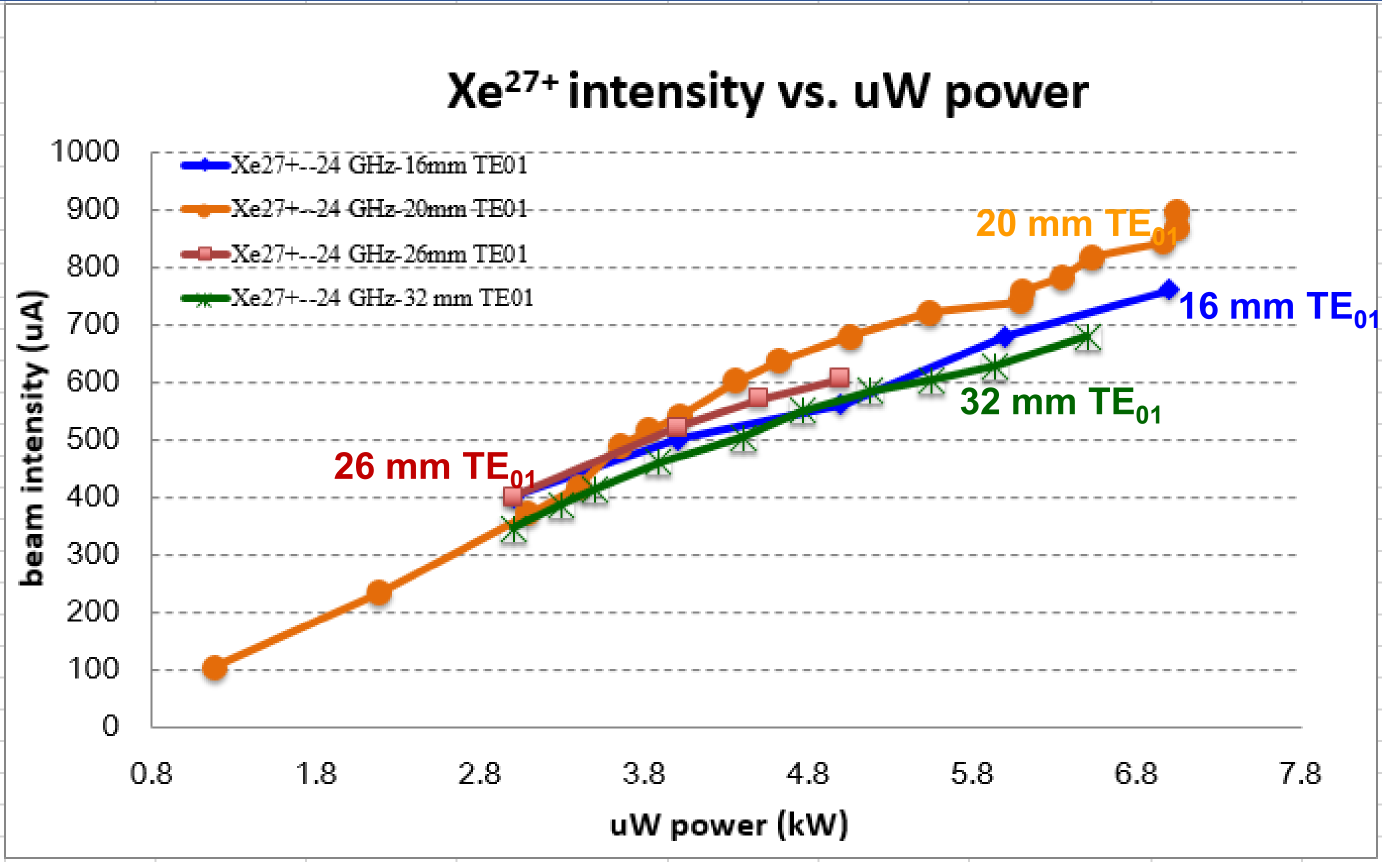
- **Ø20 mmTE_{01} shows obvious advantage in HCI production at high power level**
- **No sign of saturation even at high power level**

Xe^{27+} production with TE_{11} @ 8 mm



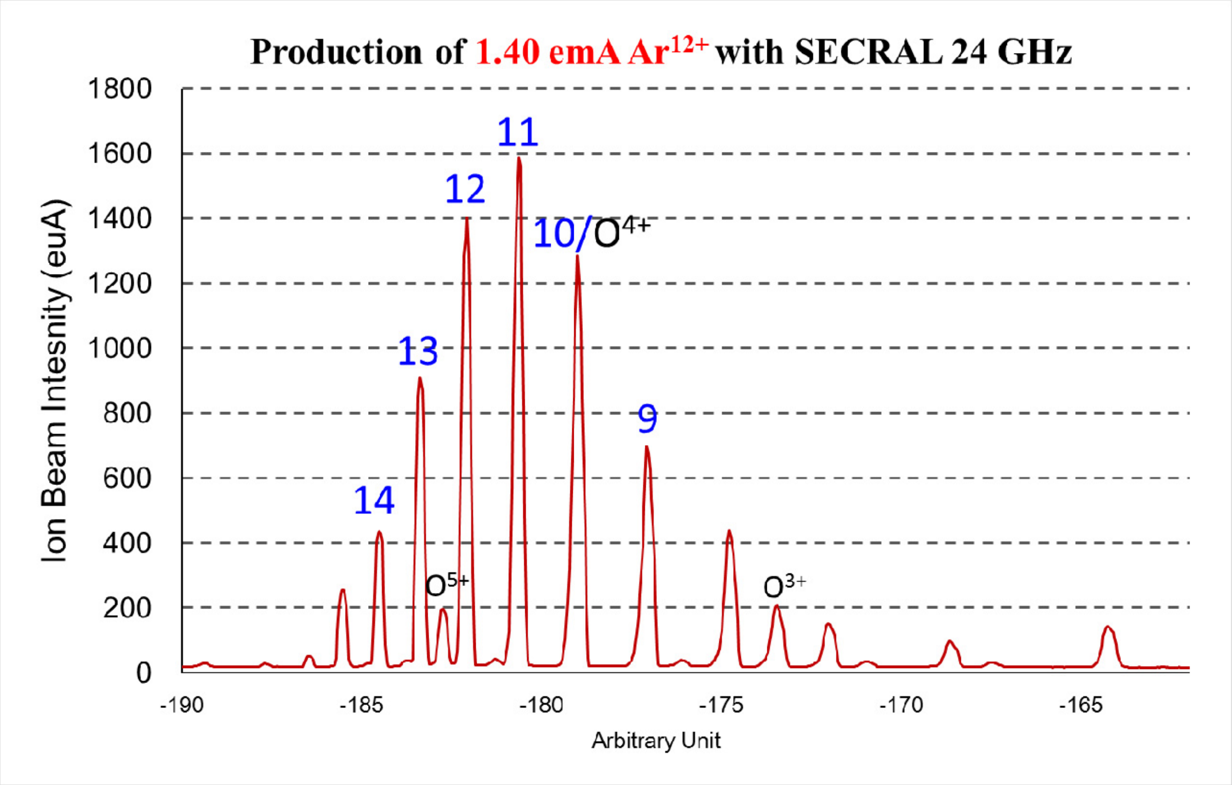
- **The size of the waveguide is only 8 mm**
- **Plasma is less stable at the power level over 5 kW**

Xe^{27+} production with TE_{01} @ 16/26 mm



- TE_{01} @ 16 mm: it is possible to couple high level of µW power, but not too much gain
- TE_{01} @ 26 mm: output tends to saturation at the power level over 5 kW

Typical results with TE_{01} @ 20 mm



Ion	Intensity (euA)
Ar^{11+}	1620
Ar^{12+}	1420
Ar^{13+}	930
Ar^{14+}	846
Ar^{16+}	350
Ar^{17+}	50
Xe^{26+}	1100
Xe^{27+}	920
Xe^{30+}	322
Xe^{34+}	90

Summary & outlook

- A series of mode convertors have been designed and manufactured successfully
- Ø32 mmTE_{01} is not the only choice
- Ø20 mmTE_{01} show obvious advantage in HCI production at high power level
- significant potential in improving performance of ECRIS by studying microwave coupling

- Further experiments and test power coupling of Gyrotron frequency microwave are planned on SECRAL and SECRALII
- The approach of microwave launching and coupling to ECR plasma needs better understanding and more investigation

Thanks for your attention!

Design of mode convertors -Theoretical analysis

- A waveguide with perturbations will cause energy coupling between different propagation modes and thus creates mode conversions

$$\frac{dA^{+}_{mn}}{dz} = -j\gamma_{mn} A^{+}_{mn} - j\sum_{mn}\left[C^{+}_{(mn)(mn)}A^{+}_{mn} + C^{-}_{(mn)(mn)}A^{-}_{mn}\right]$$

$$\frac{dA^{-}_{mn}}{dz} = j\gamma_{mn} A^{-}_{mn} + j\sum_{mn}\left[C^{+}_{(mn)(mn)}A^{-}_{mn} + C^{-}_{(mn)(mn)}A^{+}_{mn}\right]$$

$$A^{+}_{mn}\big|_{z=0} = [(1,0),(0,0),\cdots(0,0)]^{T}$$

$$A^{-}_{mn}\big|_{z=L} = [(0,0),(0,0),\cdots(0,0)]^{T}$$

Equations constitute of boundary value problem of the coupling wave differential equations.

TE_{01}–TE_{11} mode conversion can be realized by a circular waveguide where the diameter is constant but the center is displaced in the y direction as a function of path in one plane

$$y(z) = \varepsilon_1 \cos\frac{2\pi z}{\lambda_{1[mp,m'q]}} - \varepsilon_2 \sin\frac{2\pi z}{\lambda_{2[mp,m_1n_1]}} - \varepsilon_3 \sin\frac{2\pi z}{\lambda_{3[mp,m_2n_2]}}$$

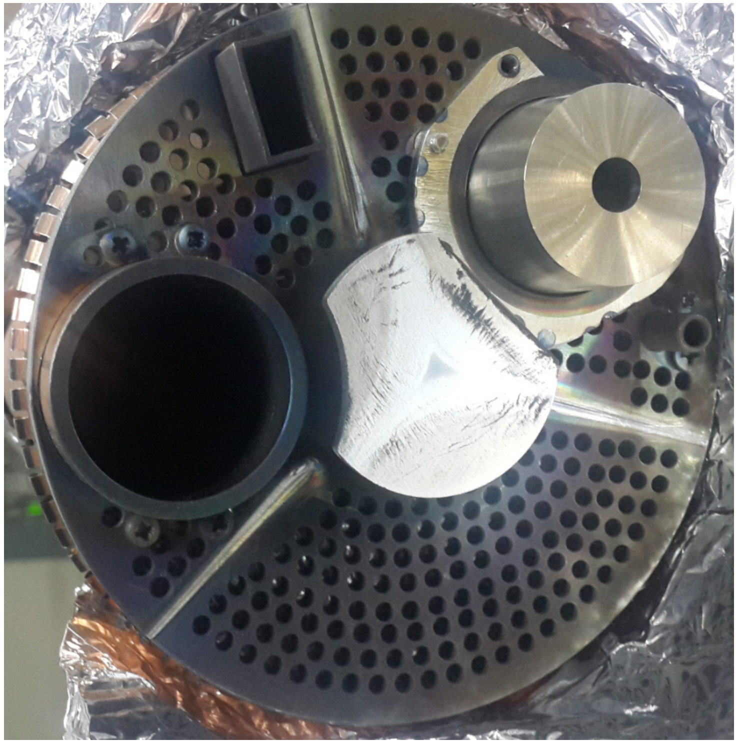
serpentine curved

where the main perturbation period

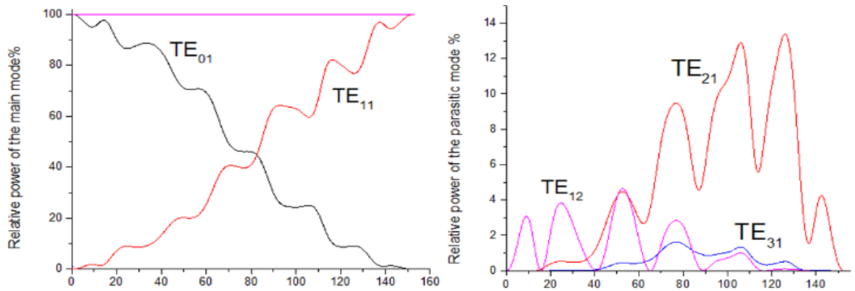
$$\lambda = (1+\delta)\lambda_{B[mp,mq]}$$

λ_B is the beat-wave length between two modes, λ , δ , ε is the axis perturbation period, perturbation factor and amplitude respectively

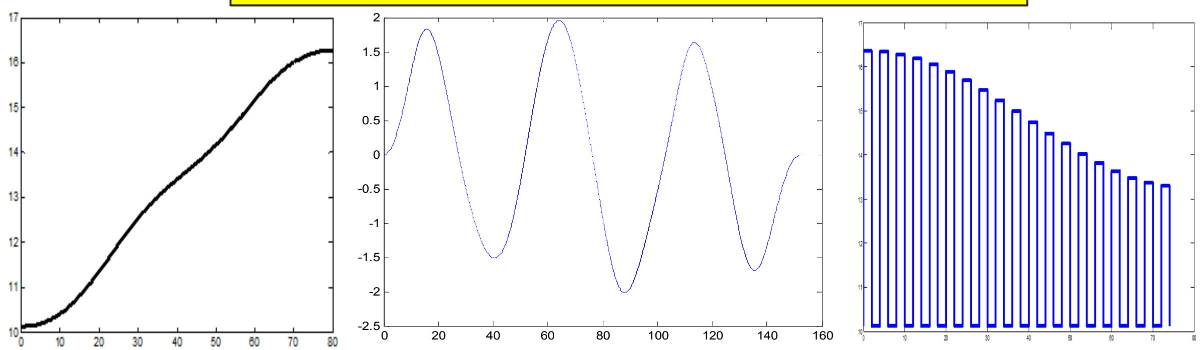
H.F. Li, M. Thumm, Mode conversion due to curvature in corrugated waveguides. Int. J. Electron. 71(2), 333–347 (1991)



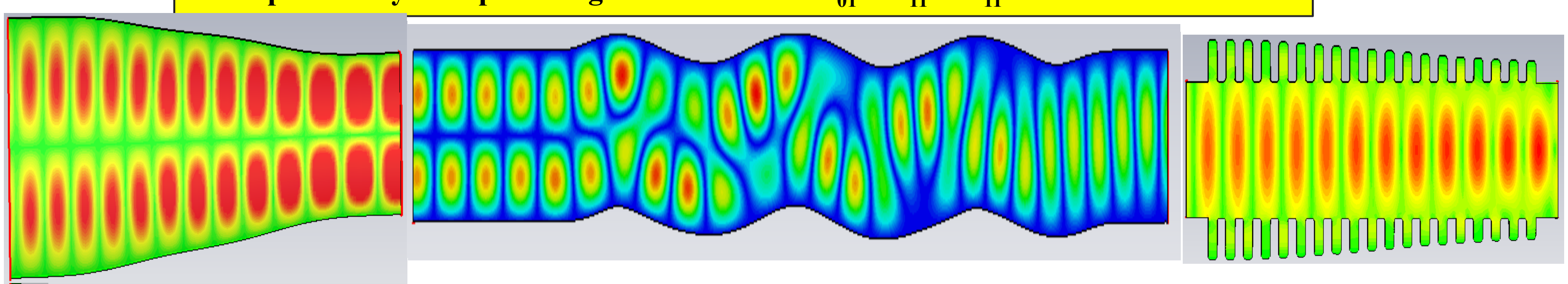
Design of mode convertors



Calculated mode conversion along the path length z



The profiles by the optimizing calculation of TE_{01}-TE_{11}-HE_{11} mode converter

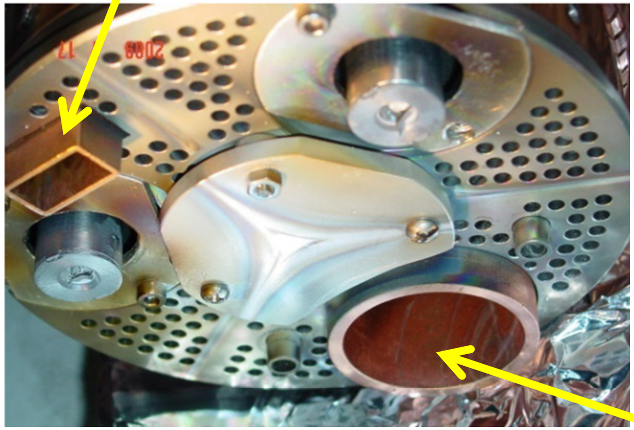


Power distribution on the longitudinal cut plane of the TE_{01}-TE_{11}-HE_{11} converter

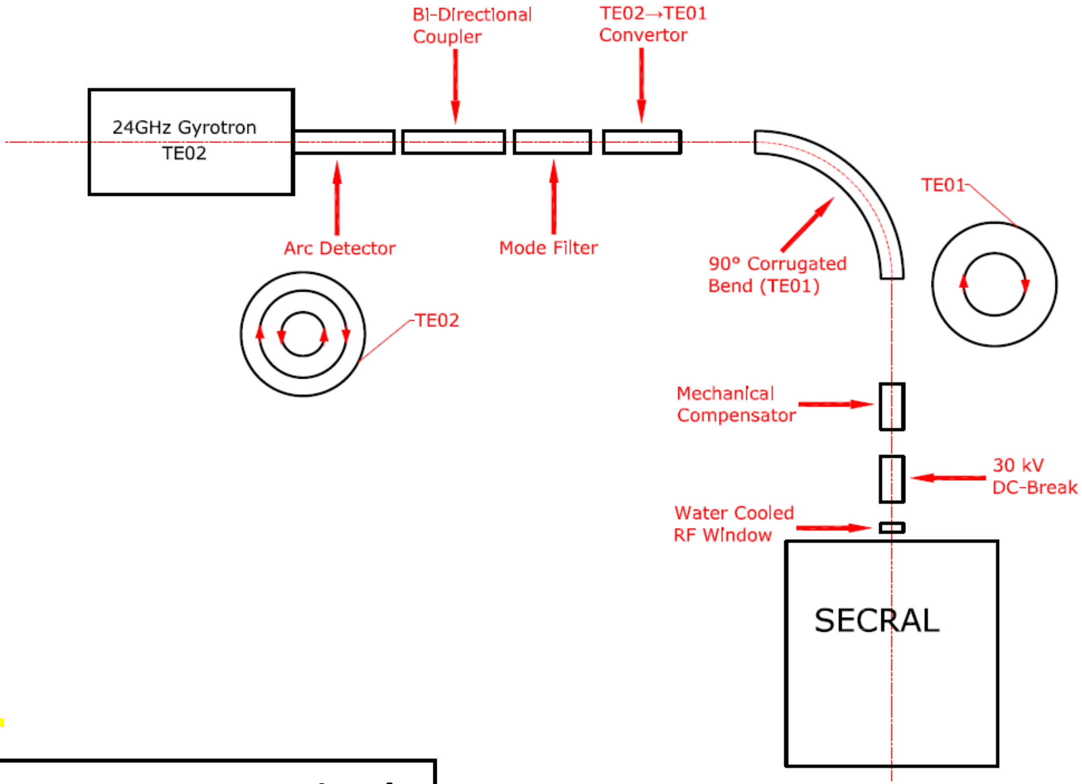
Conventional RF coupling scheme of ECRIS

- 24 GHz RF coupling to SECRAL similar to that of SERSE and VENUS at 28 GHz
- Over-sized circular waveguide with a diameter about Ø33.0 mm excited in the TE_{01} mode

10-18 GHz TE_{10} rectangular waveguide

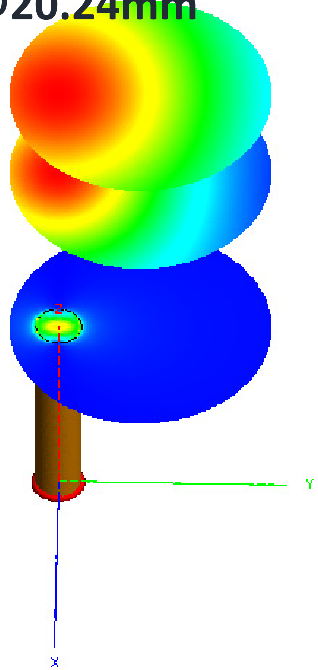


24-28 GHz TE_{01} oversized Circular waveguide

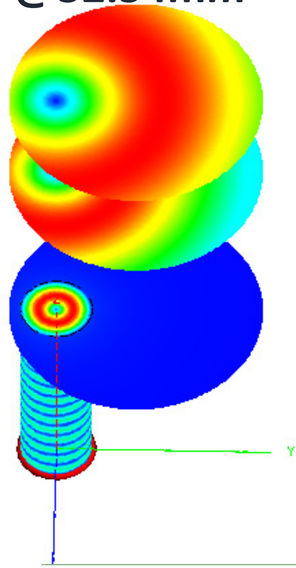


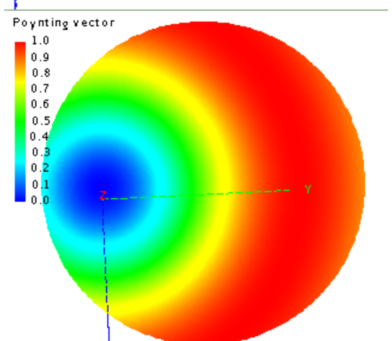
Free space radiation

24.13 GHz-HE11
@20.24mm



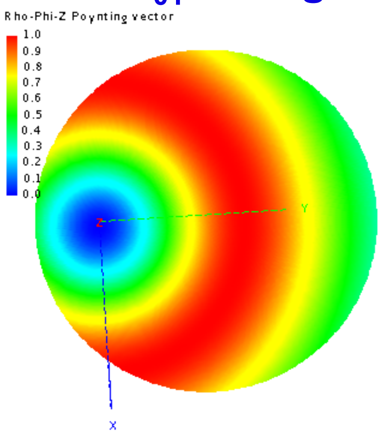
24.13 GHz-TE01
@32.54mm





Power distribution with
Ø20 mm TE_{01} waveguide

Power distribution with
Ø32 mm TE_{01} waveguide



Power distribution with
Ø20 mm HE_{11} waveguide