Coupling of Microwave Power into ECR Ion Source Plasmas at Frequencies above 20 GHz

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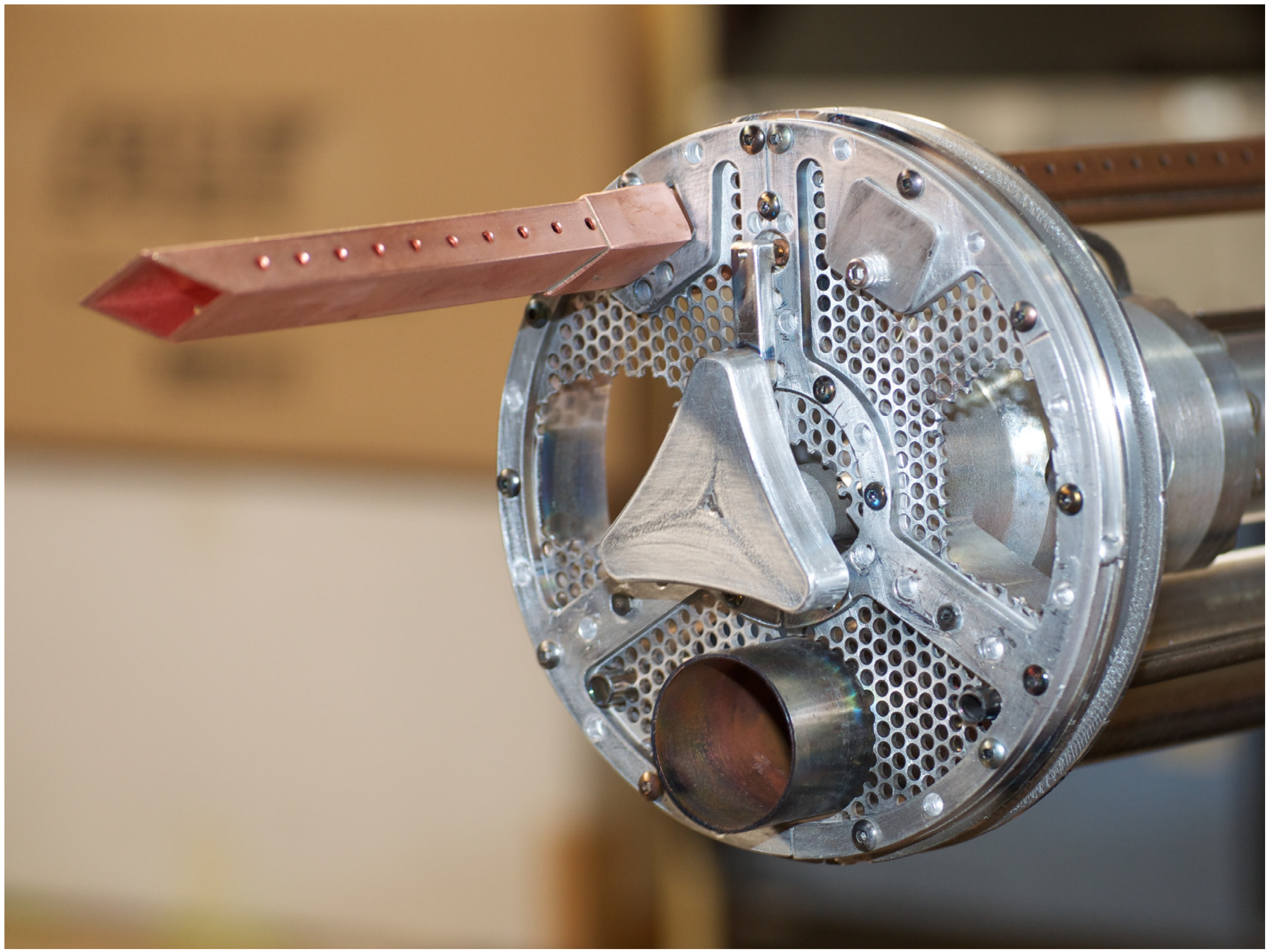
LBNL

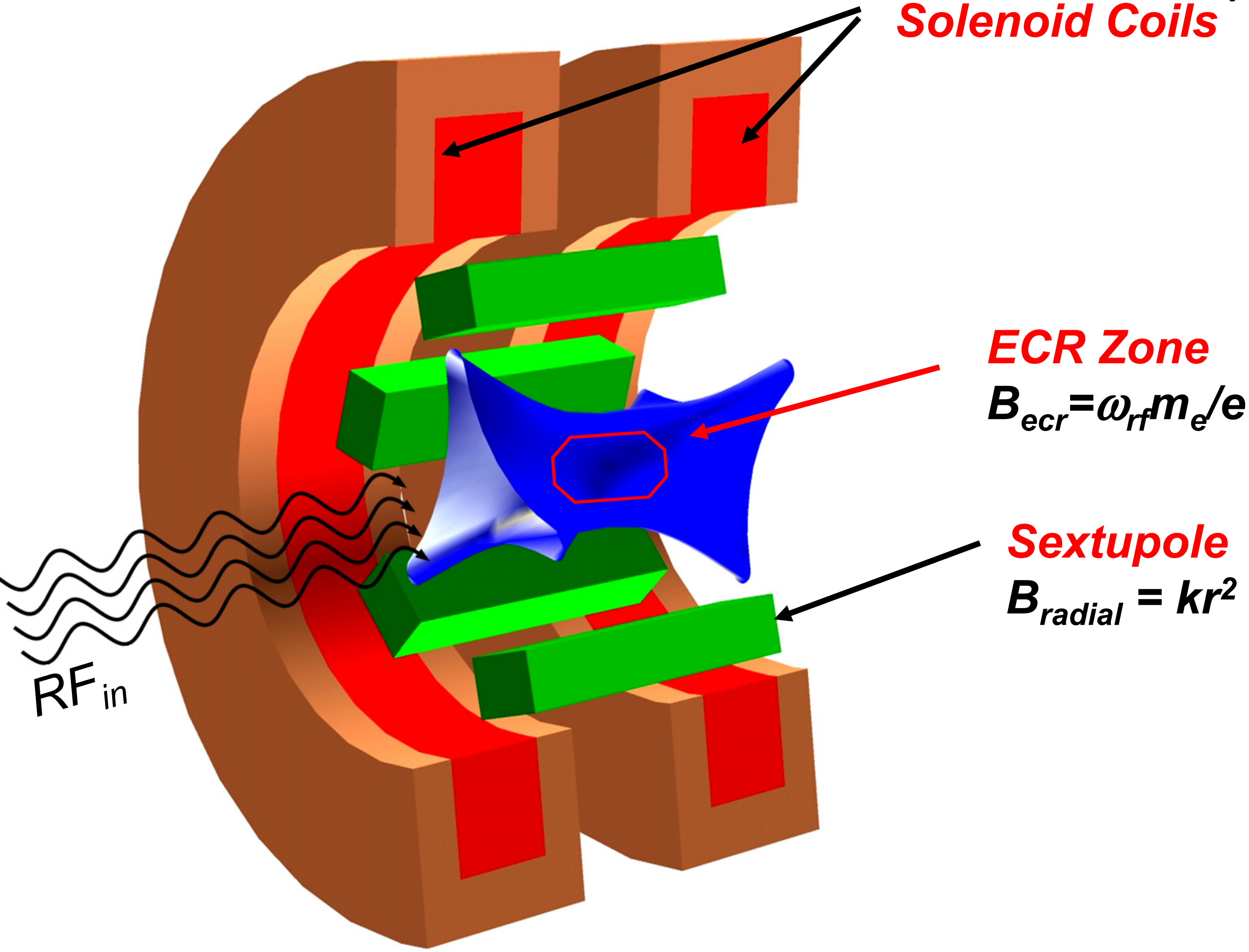


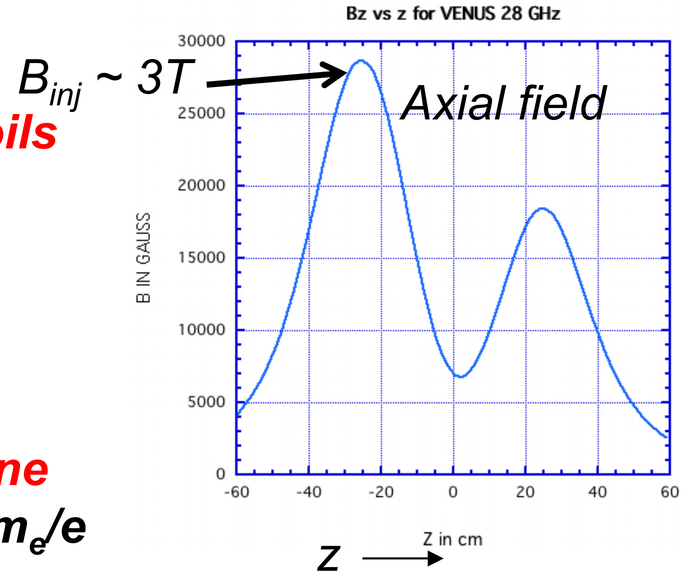
How do we view an ECR chamber with plasma loading?

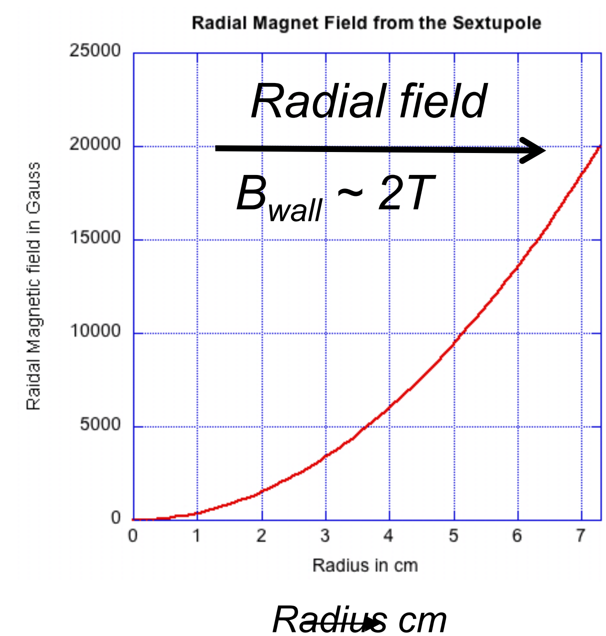
TM_{010} mode superconducting cavity
Resonant Frequency 2.865 GHz Q_0 ~ 10^9

Microwave Oven Multimode Cavity
Operating Frequency 2.45 GHz

Minimum-B field Confinement for 28 GHz ECRH



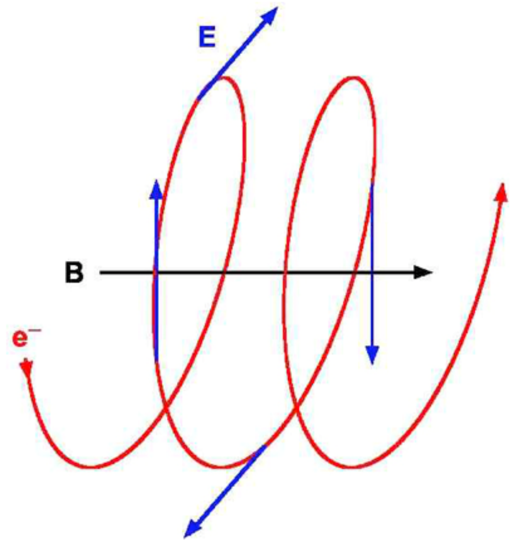




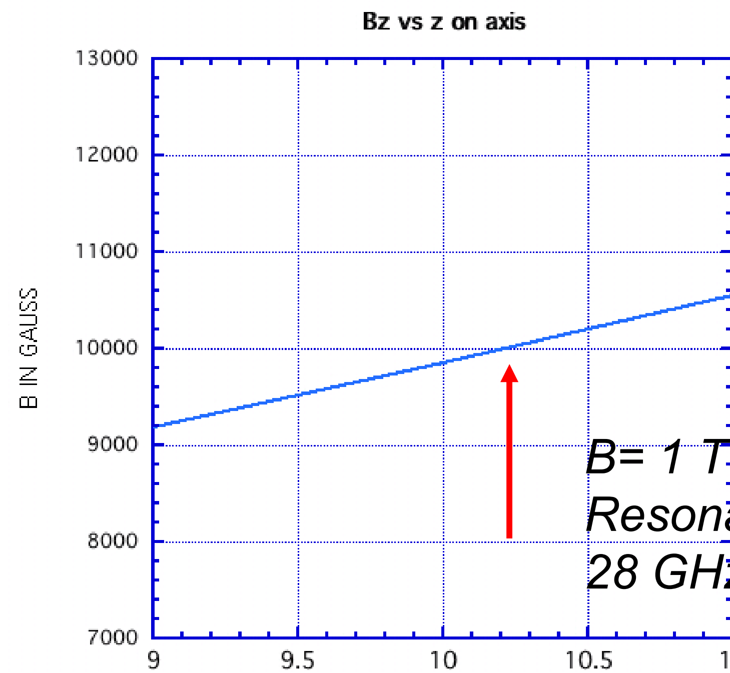
Solenoids produce mirror field to plug the ends and the sextupole gives radial confinement

First Harmonic Electron Cyclotron Resonance Heating

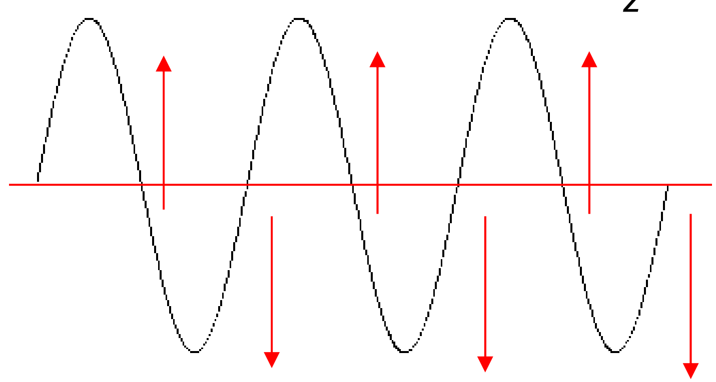
Right Hand Wave Coupling



$\omega = eB/m_e$



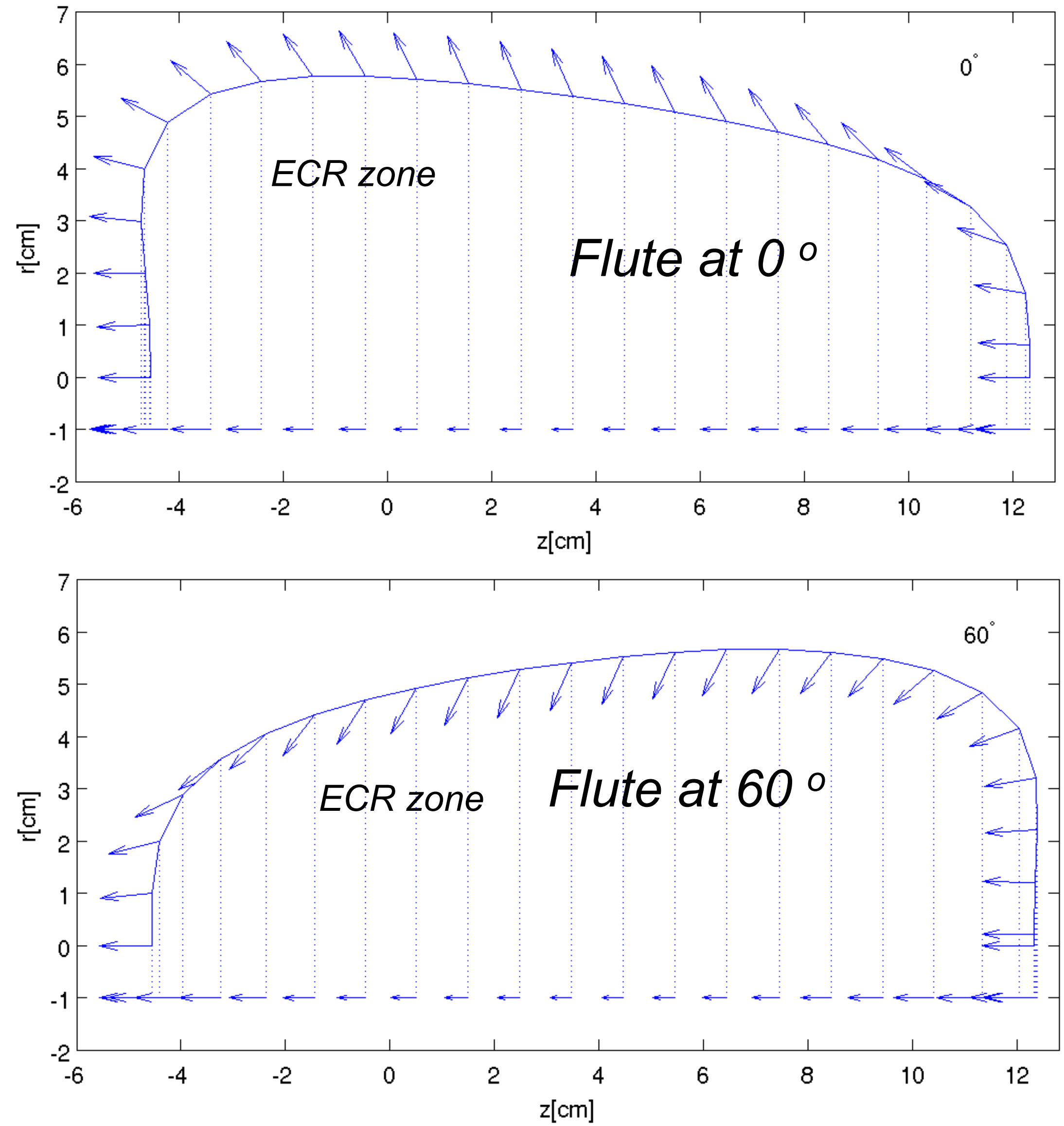
B_z vs z^z



Transverse polarized RF E field vs time can be viewed as a sum of a right hand and left hand wave

ECR heating occurs when the electron cyclotron frequency equals the RF frequency

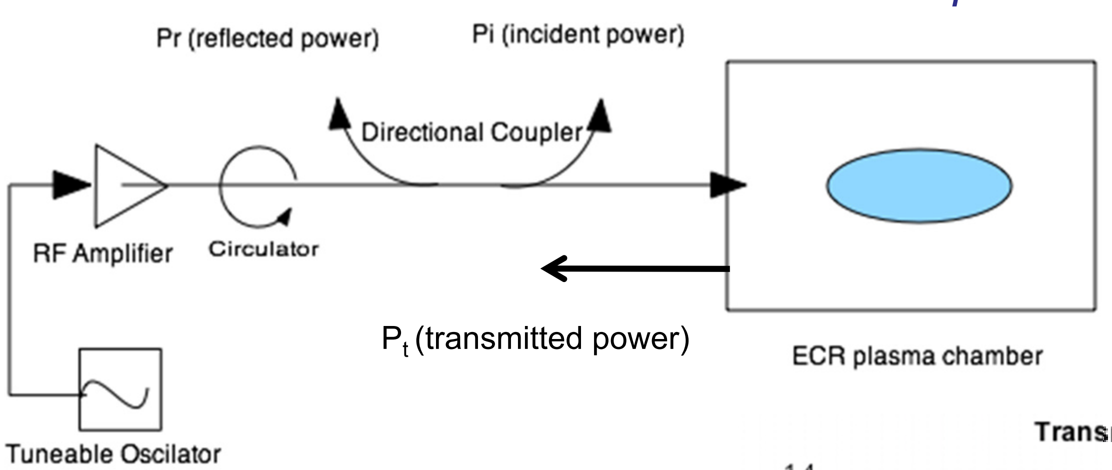
Polarized microwaves should have strong right hand wave coupling in this region



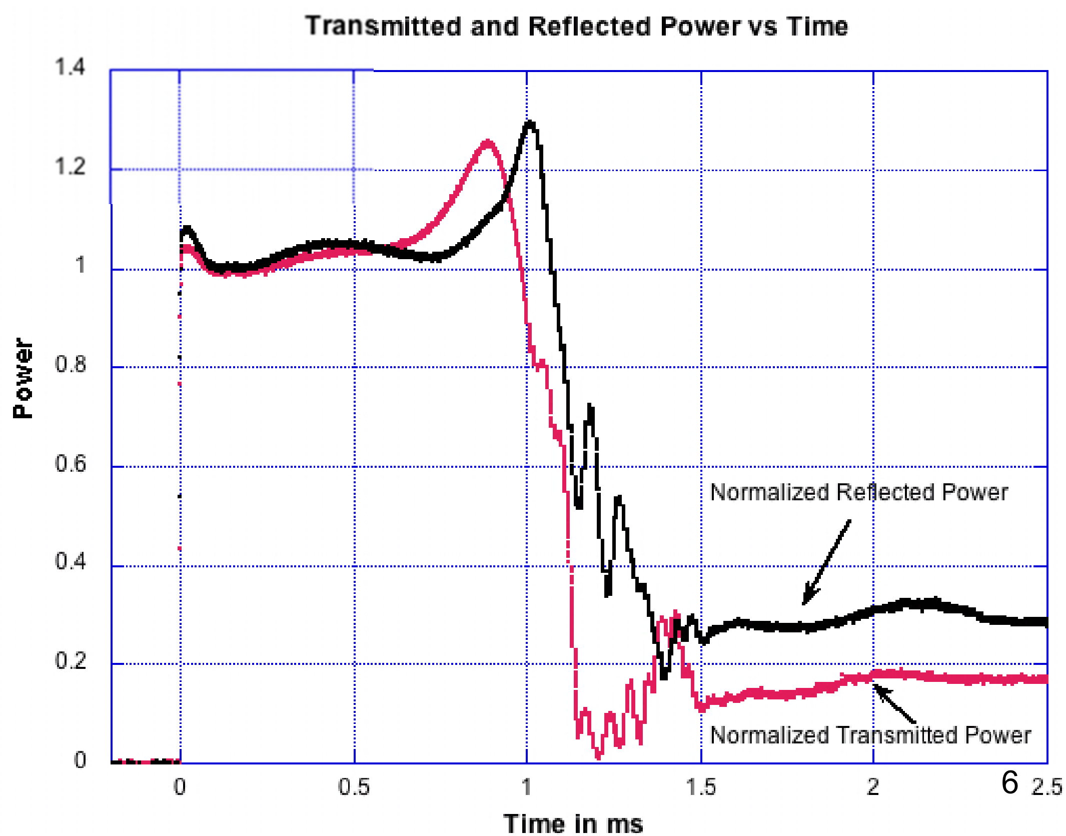
Magnetic field vectors at the ECR Surface

Transient Response of Venus at 18 GHz, 1640 W

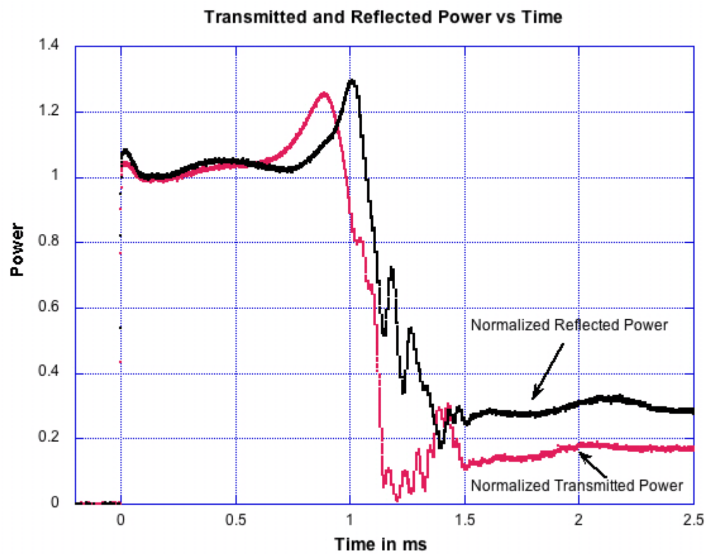
Measured quantities Pi ,Pr, Pt

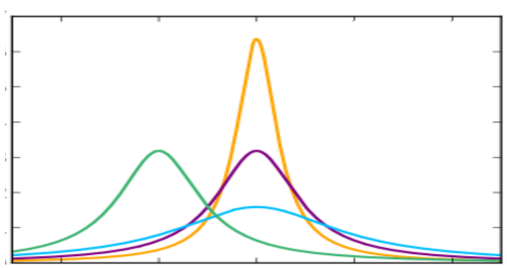


Note: the transmitted power is proportional to the stored Microwave energy



- T=0 RF On
- Chamber RF power fills in 1 μs
- ~ 1 ms plasma breakdown
- Transmitted power decreases to almost zero
- Reflected power also drops
- After a few oscillations between plasma and microwave energy an approximate equilibrium is established.



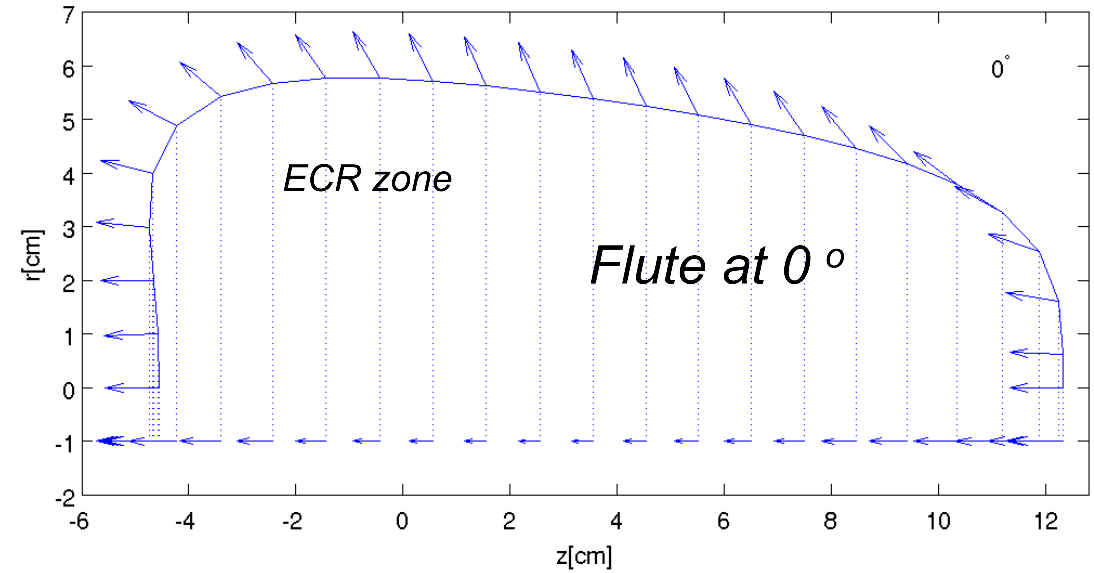


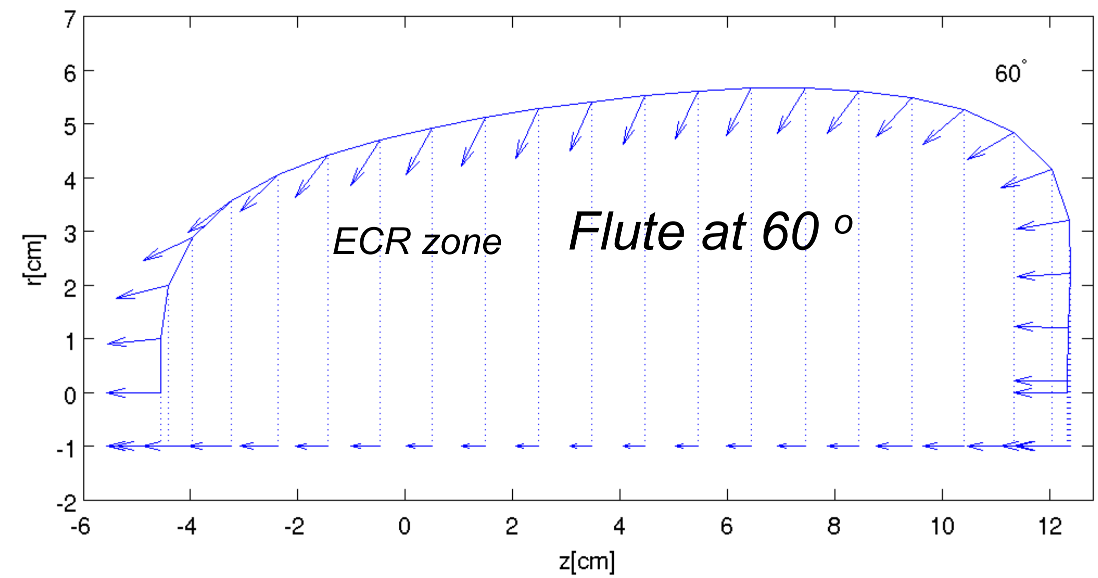
- For small volume, weak coupled, lower frequency ECR such as the GSI Caprice-14, cavity mode-like behavior can exist.
- The transmission measurements on VENUS demonstrate that the plasma is not a small perturbation but completely changes the stored microwave energy, decreasing it by a factor of 10 damping out any mode structure
- In VENUS the wavelength is 11 mm the diameter 144 mm and the average mode spacing is 160 kHz, much narrower than an single mode bandwidth with plasma, so mode-like behavior is washed out.

- Venus is more like an oven than a microwave cavity, while the walls reflect the microwaves there is no way to select the distribution of microwave energy distribution with the wall geometry.

Can we launch the microwave power in a way to maximize the first pass coupling and improve the heating of electrons?

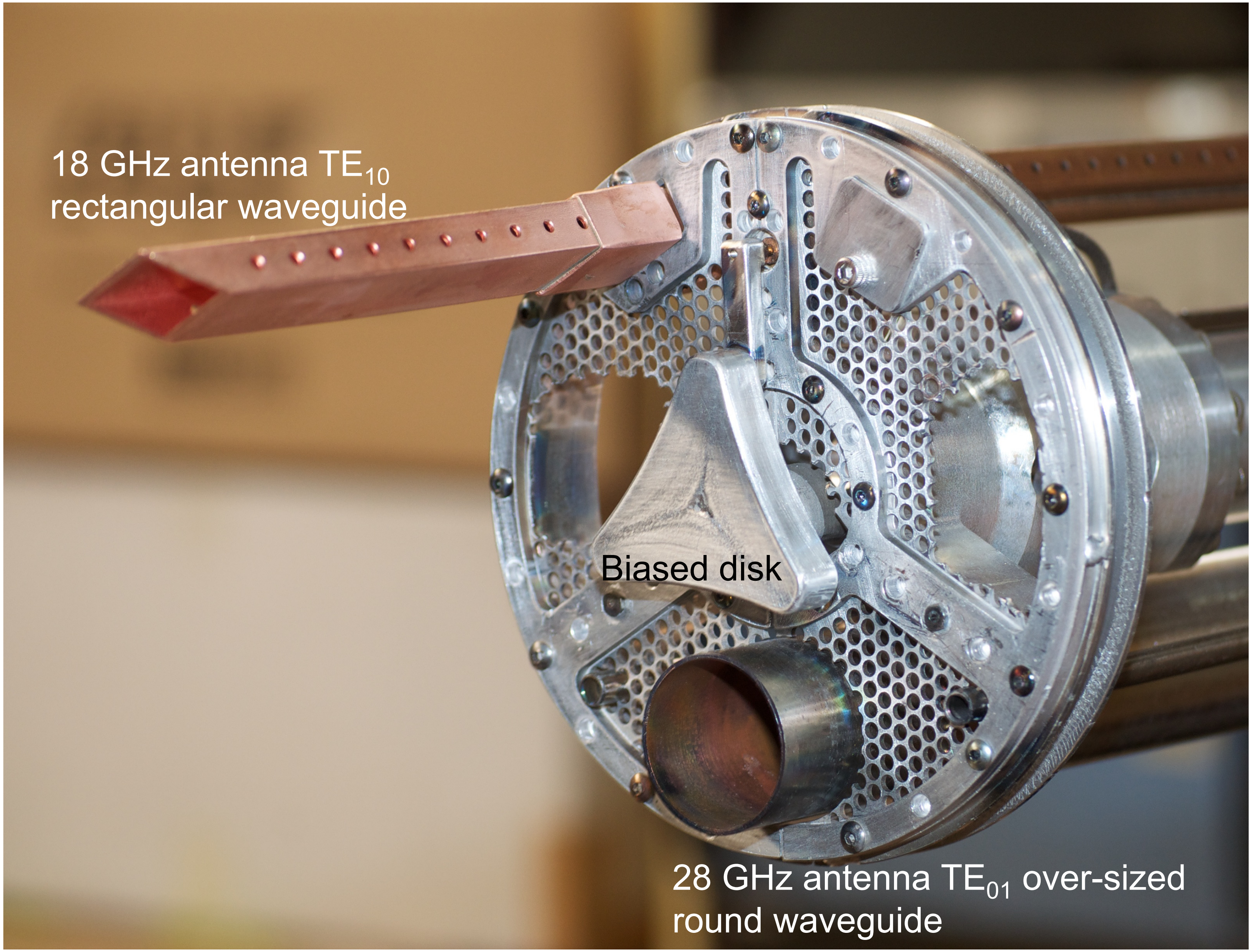
Polarized microwaves should have strong right hand wave coupling in this region



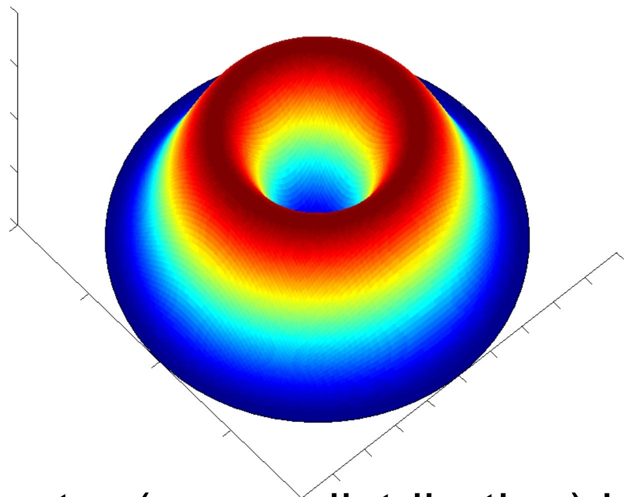


Magnetic field vectors at the ECR Surface

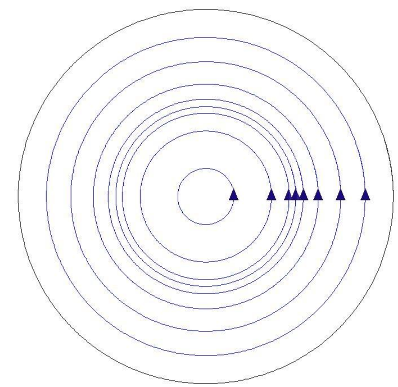
Microwave injection geometry for VENUS



TE_{01} Waveguide mode
Electric Field Lines



S vector (power distribution) in the waveguide

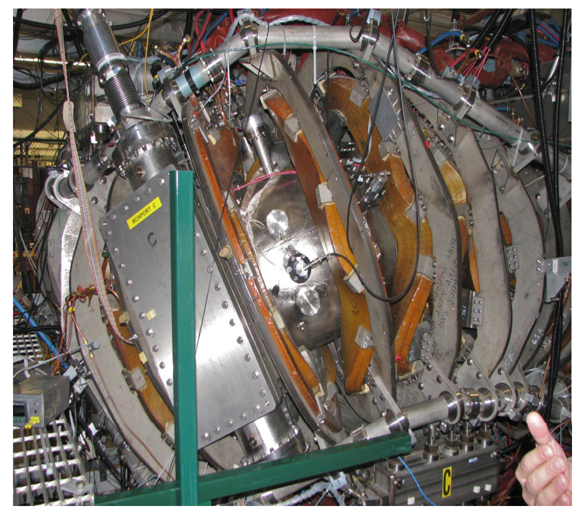


Electric field lines are circular.

- The present 28 GHz microwave antenna is a over-sized round waveguide, which is excited in the TE_{01} mode
- This mode has low attenuation for transport the microwave ~ 4 meters from the gyrotron to the source
- However, it has a hollow energy distribution and is not linearly polarized

ECRH in Plasma Fusion

- High power microwave technology at frequency above 20 GHz is mainly driven by the requirements for plasma fusion.
- In the 60's there were mirror machine experiments, but now most of the work is focused on toroidal machines, tokamak's and stellerators. The typically use power ≥ 100 kW with frequencies from 28 to 170 GHz.
- Initially they launched the microwaves using waveguide modes such as TE_{01} or TE_{02} to now they have developed quasi-gaussian, polarized modes such as the HE_{11} or TM_{000} to improve the coupling between the microwaves and the plasma.
- A few examples,
  - HSX stellarator, Wisconsin, 28 GHz
  - W7-AS Stellarator, Garching,140 GHz
  - DIII-D Stellarator, San Diego, 60 GHz
  - ITER, 170 GHz, under construction

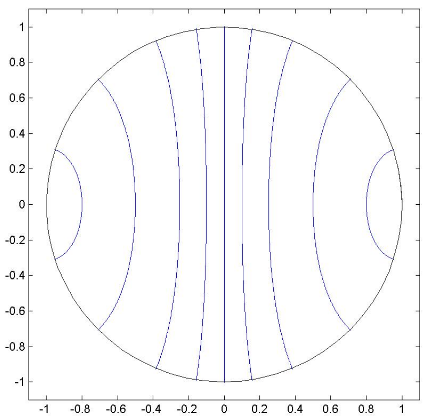


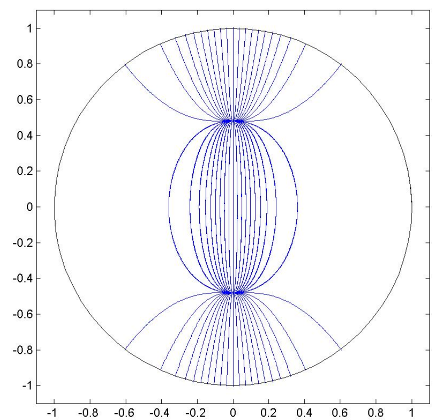
HSX stellarator

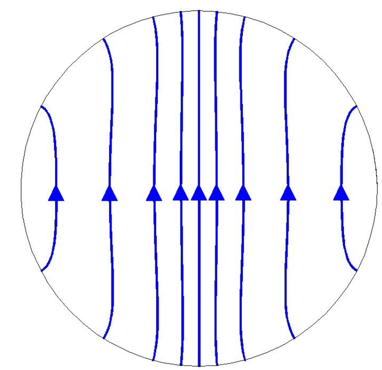
HE_{11} quasi-gaussian waveguide mode

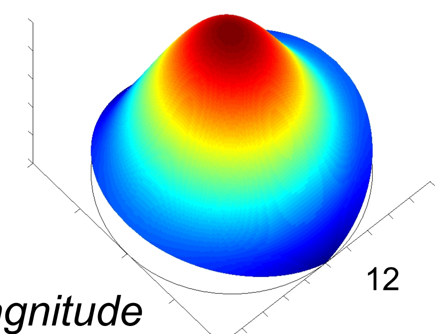
J. L. Doane : "The HE_{11} mode in a corrugated waveguide is in many respects ideal for use near plasma devices. Its radiation pattern from an open-ended wave guide has a narrow central beam containing 98% of the radiated power. The radiation is linearly polarized with virtually no cross-polarization. Since the field distribution of the HE_{11} mode inside a corrugated waveguide is a close approximation to a gaussian mode, the HE_{11} will couple efficiently to a free space gaussian mode."[13]

TE_{11} + $c\,TM_{11}$ = HE_{11}









HE_{11} Poynting Vector magnitude

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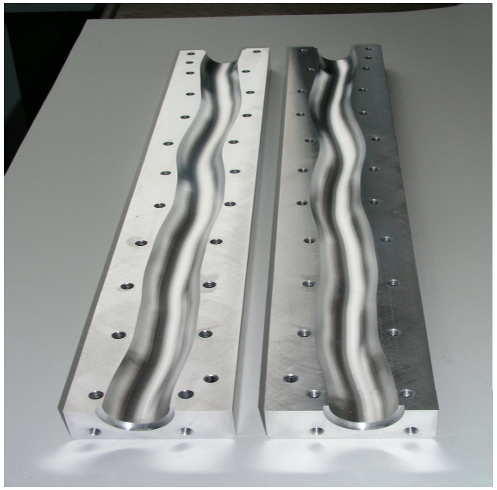
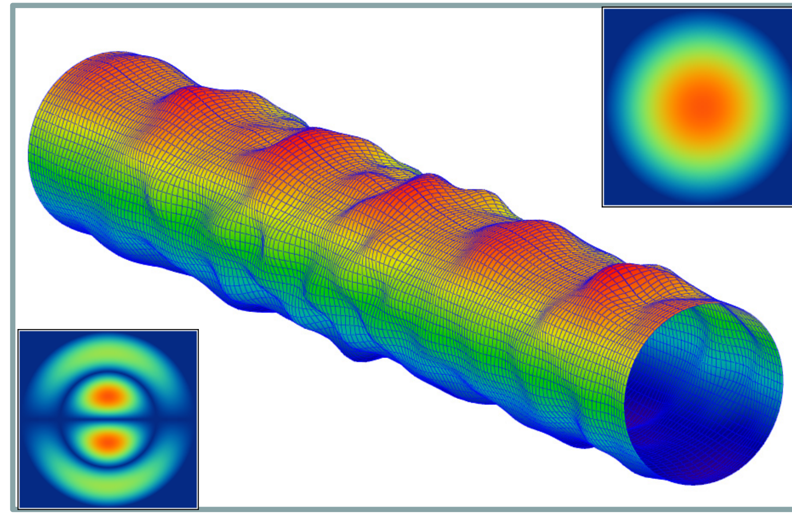
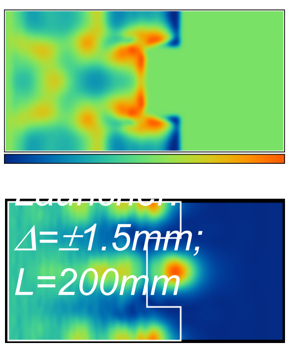
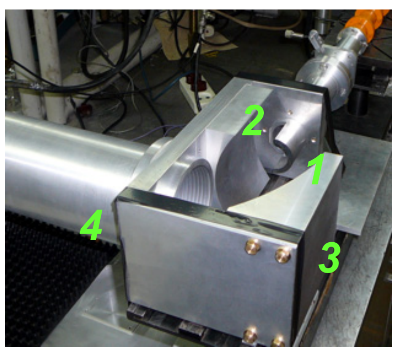


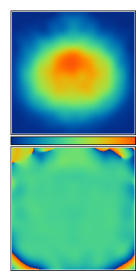
Waveguide Snake



Waveguide converter of the mode TE_{02} to the Gaussian beam. Frequency 28 GHz, length 20 cm







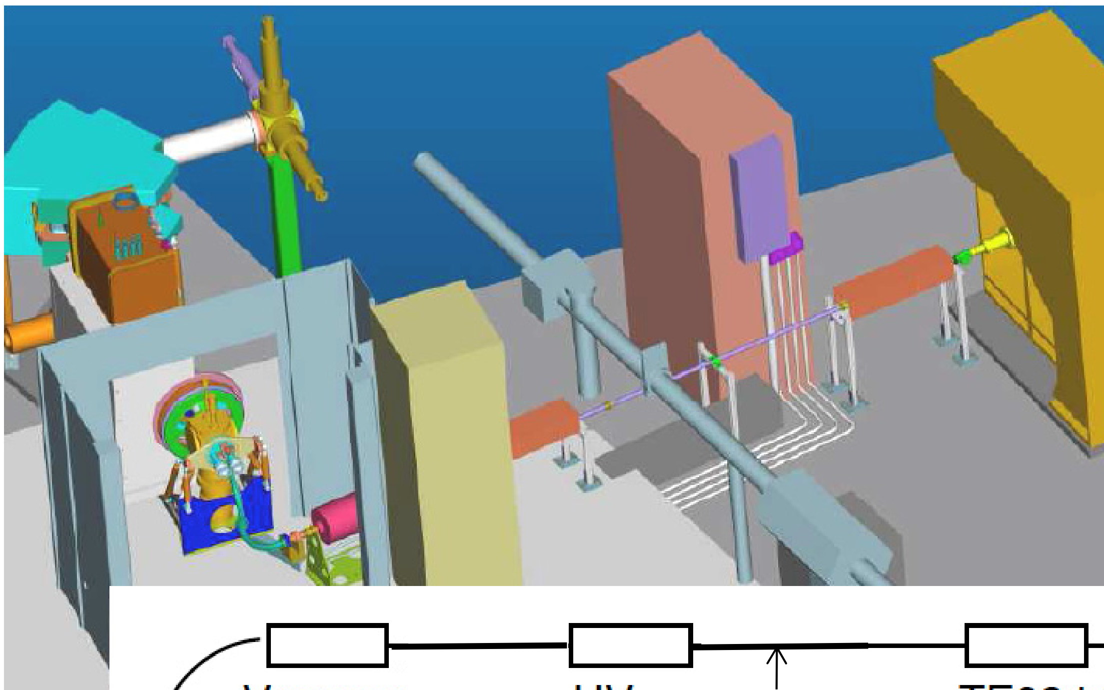
$\eta_a/\eta_{a,\varphi}$ %:

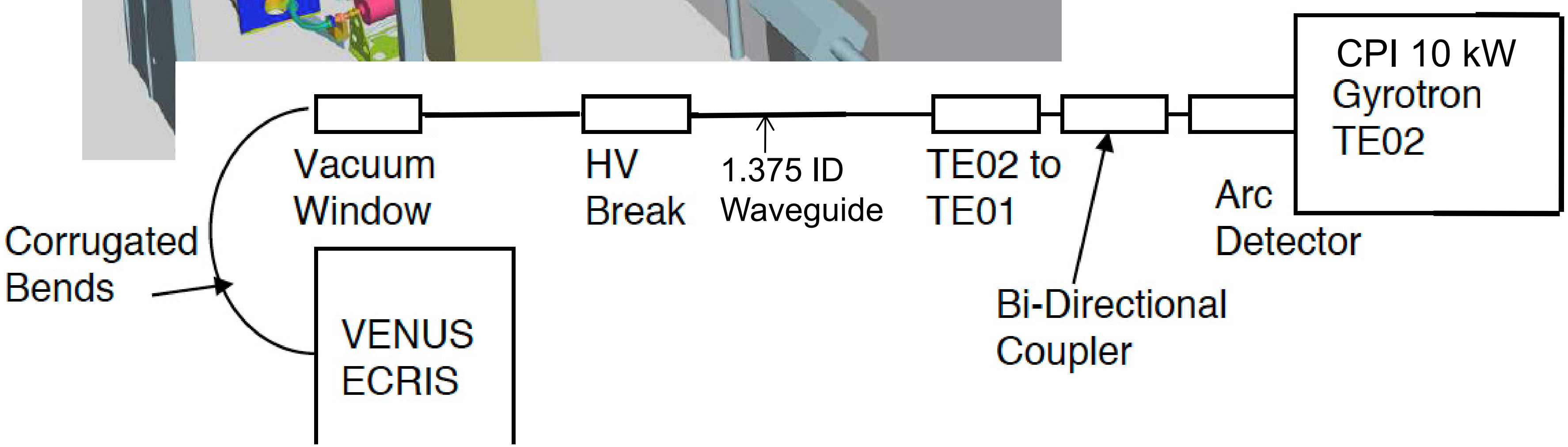
HE_{11} - 98.0 / TEM_{00}

1. Waveguide ∅33mm with the cut 40mm×180°
2. Parabolic mirror
3. Synthesized mirror 120×129×10mm^3
4. Corrugated waveguide ∅88.9mm

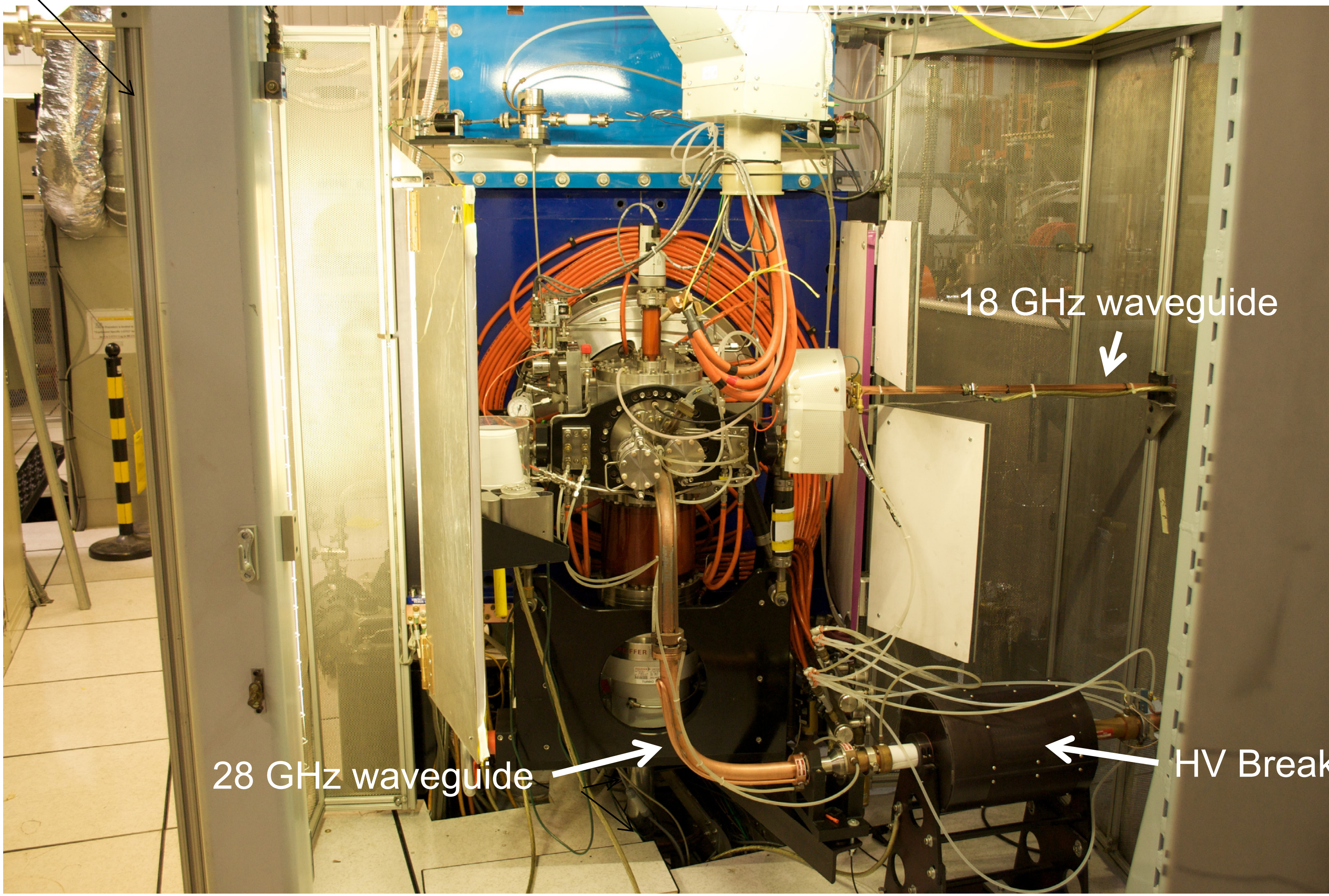
TE_{02}-HE_{11} converter, 28 GHz

28 GHz Microwave System

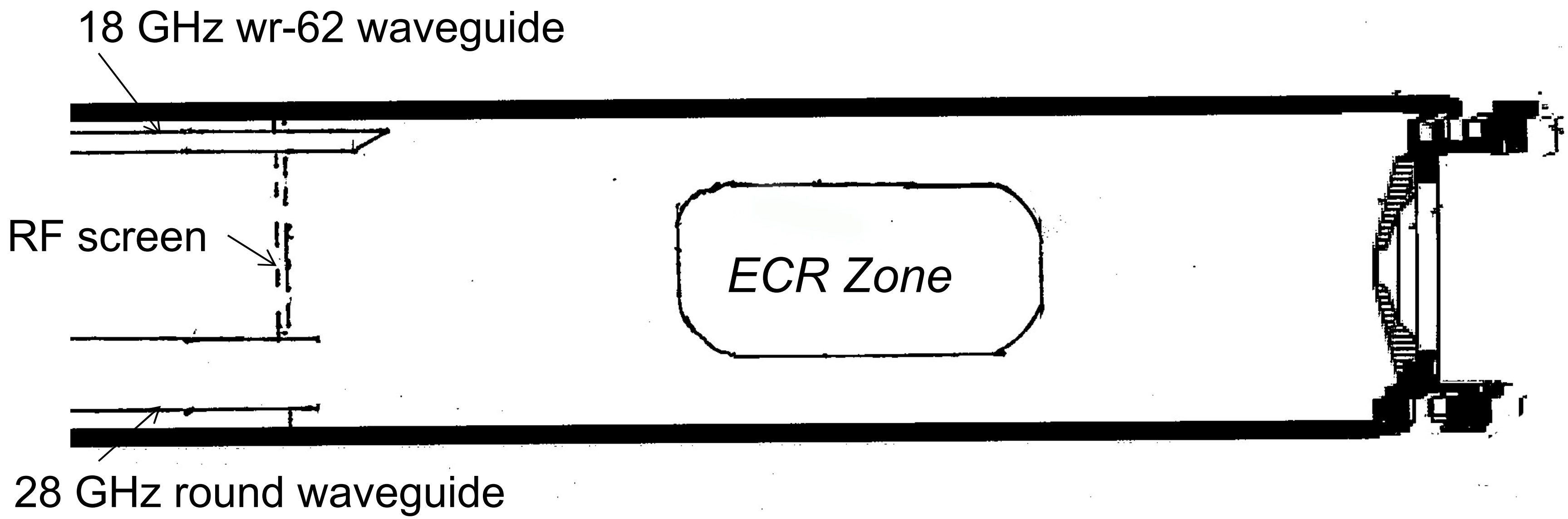




VENUS Injection

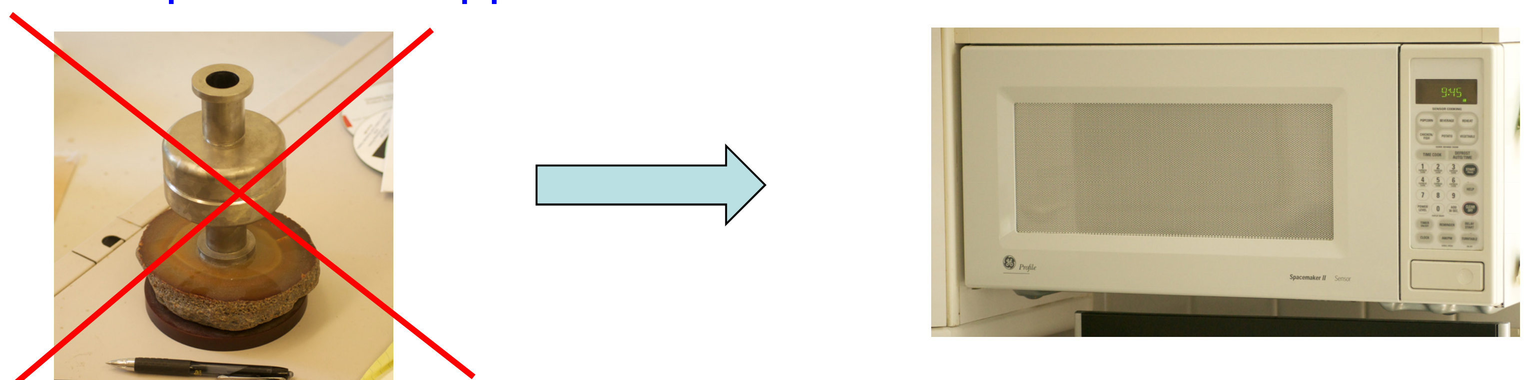


VENUS Plasma Chamber



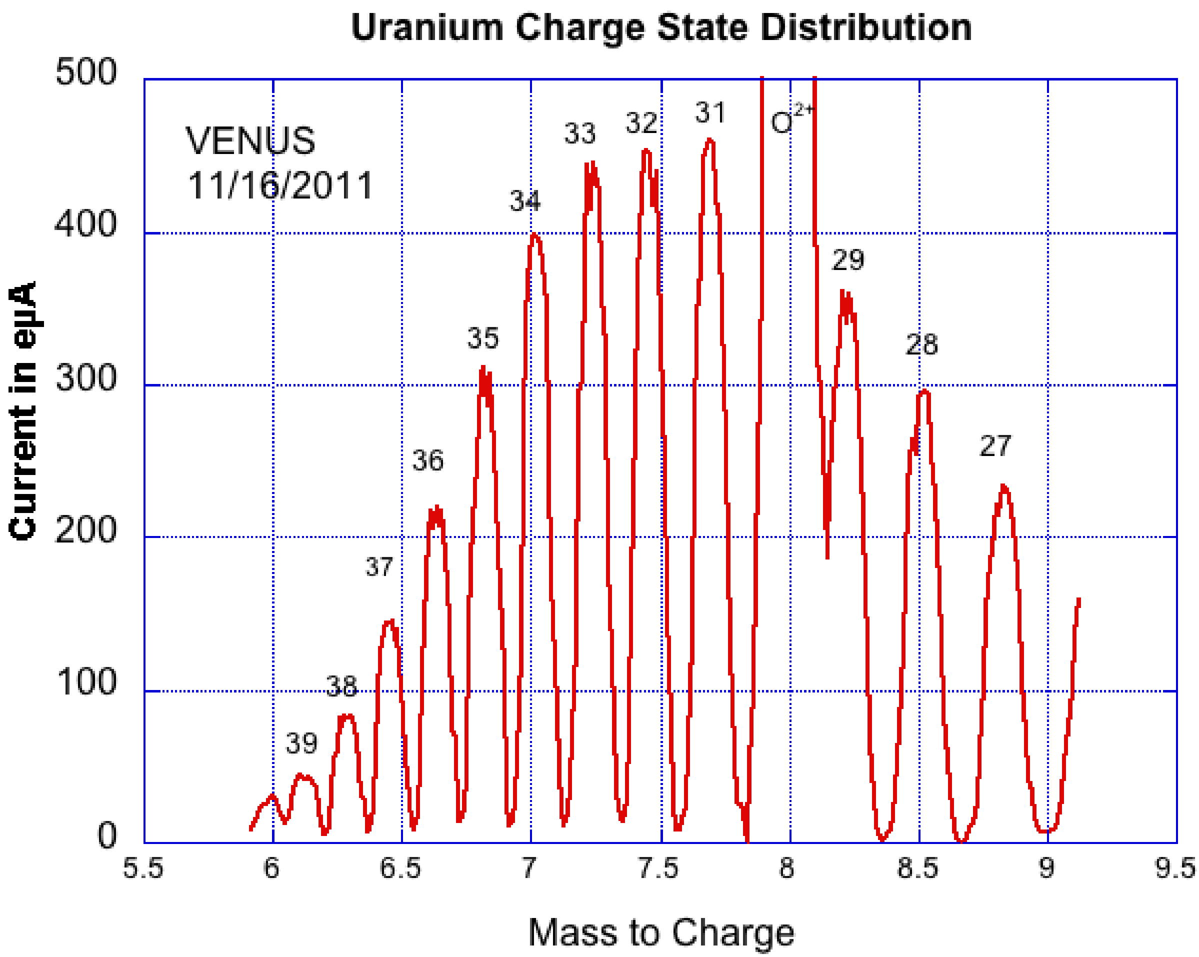
- To modify VENUS for a quasi-gaussian 28 GHz antenna
- Modify injection to move 28 GHz wg close to the axis and directed toward the ECR zone
- Convert from TE01 to HE11 in the injection line and use corrugated waveguide

- For large high frequency sources like VENUS
  - The best chance to improve microwave coupling is to use the waveguide/antenna system to control the first pass microwave fields
  - The chamber walls play only a secondary role and cavity mode analysis is not a useful approach
  - The basic technology for microwave mode conversion is already well developed by the plasma fusion community
  - Theory of microwave coupling to plasmas is not advanced enough to predict the outcome, so the next step is the experimental approach



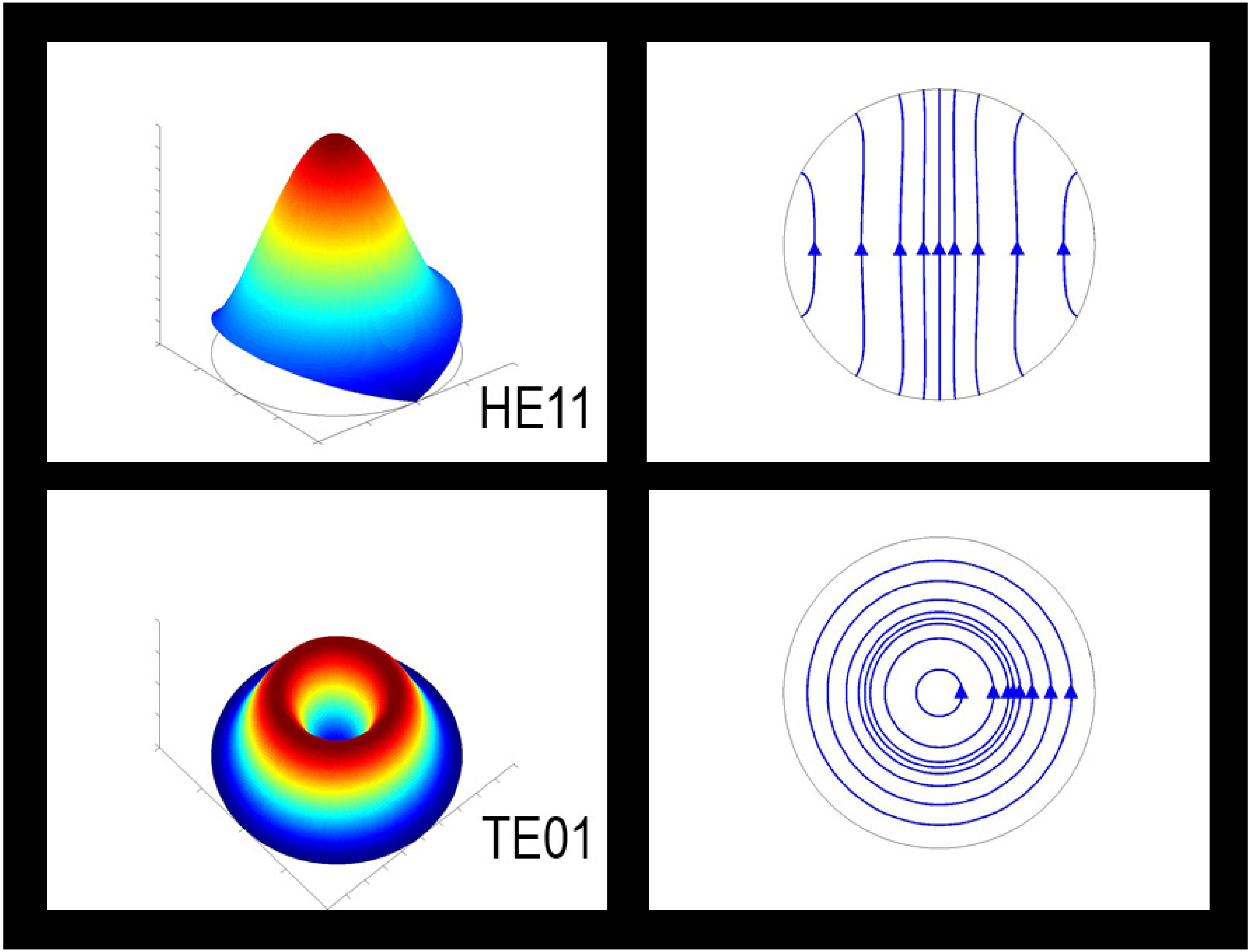
VENUS Recent Results

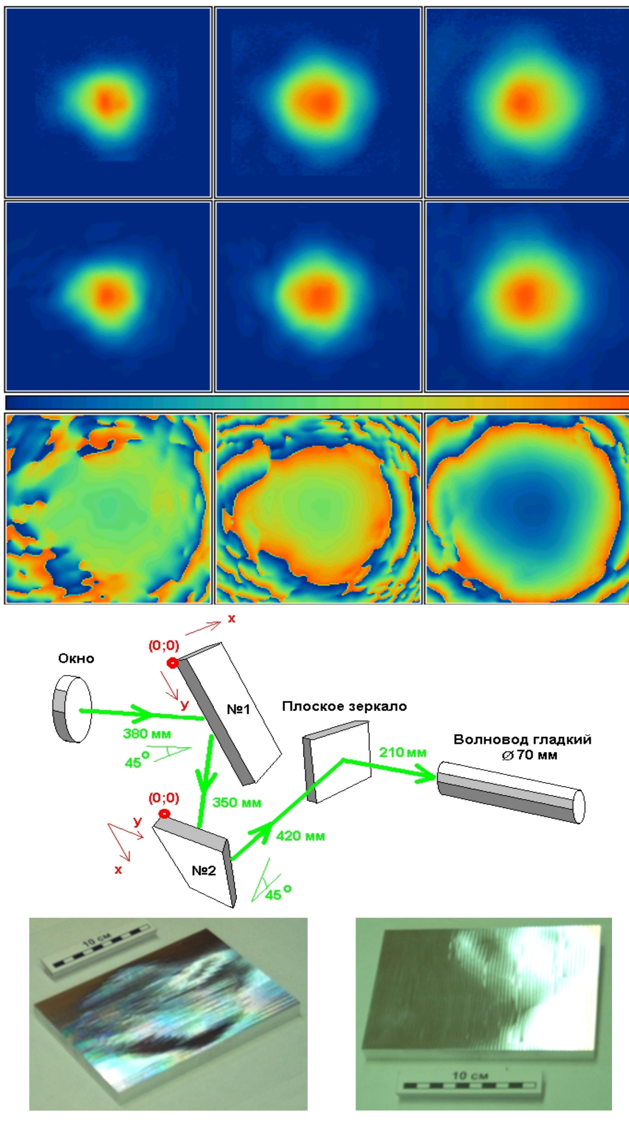
(Details Thursday Janilee Benitez' Talk)



Ion	Intensity eμA
He^{2+}	11,000
O^{6+}	3,000
Ar^{11+}	860
Ca^{11+}	400
Bi^{31+}	300
Bi^{50+}	5
U^{33+}	440
U^{50+}	13

HE_{11} and TE_{01} modes





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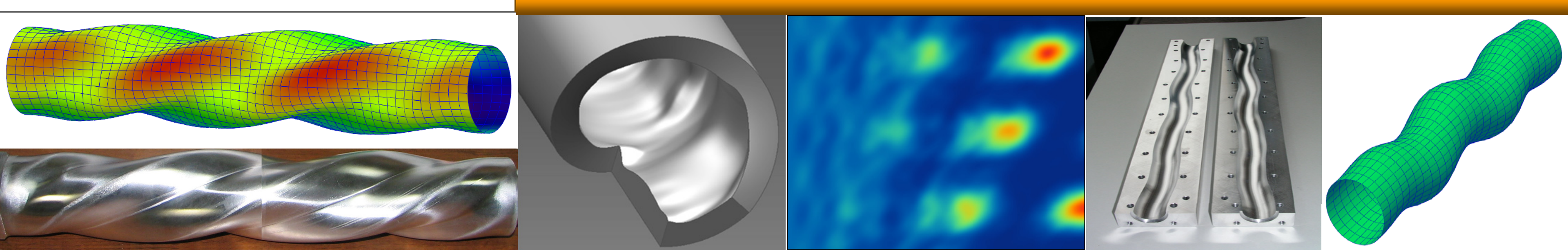
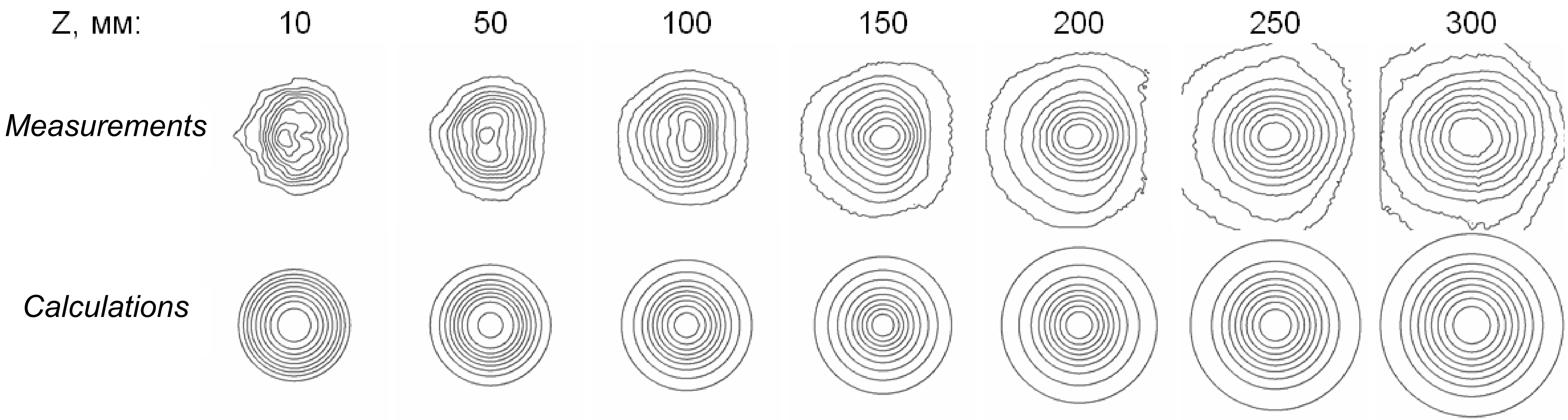
Waveguide Components





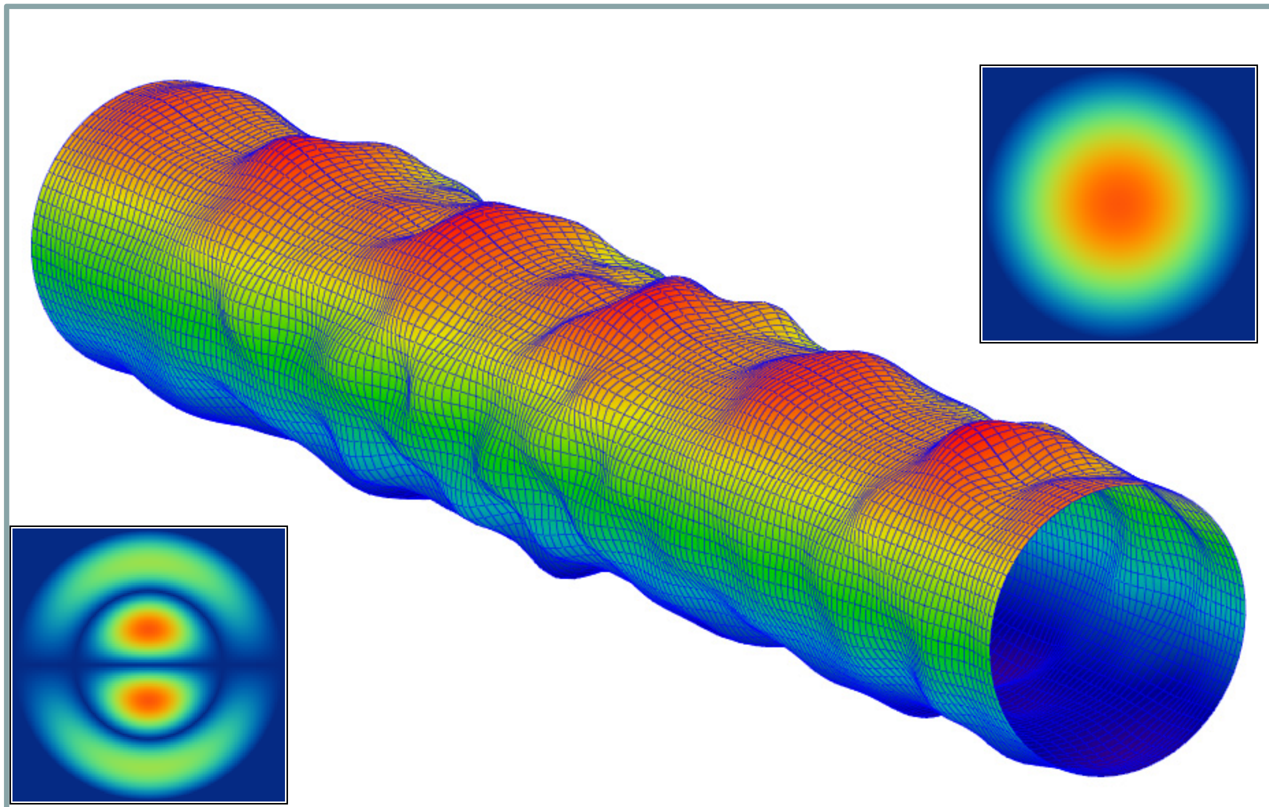
η_a, %:	97.9	98.5	97.8	97.8	97.9	98.3	98.4

Mutual power between amplitude patterns, measured at the converter output and calculated for radiated HE_{11} mode at the distance Z from the waveguide ∅88.9 mm end

η'_a, %:	100	99.4	98.8	98.6	98.6	99.1	99.1

Mutual power between amplitude patterns at the converter end, measured and reconstructed after phase retrieval procedure

Waveguide converter of the mode TE_{02} to the Gaussian beam. Frequency 28 GHz, length 20 cm, average waveguide radius 1.63 cm, calculated efficiency over 99.9%.



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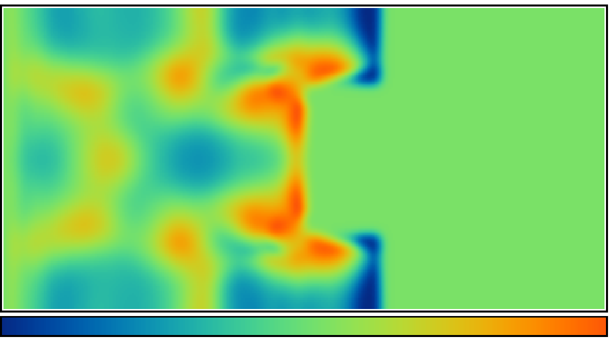
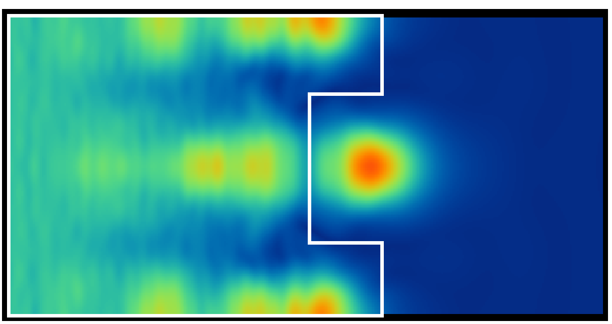
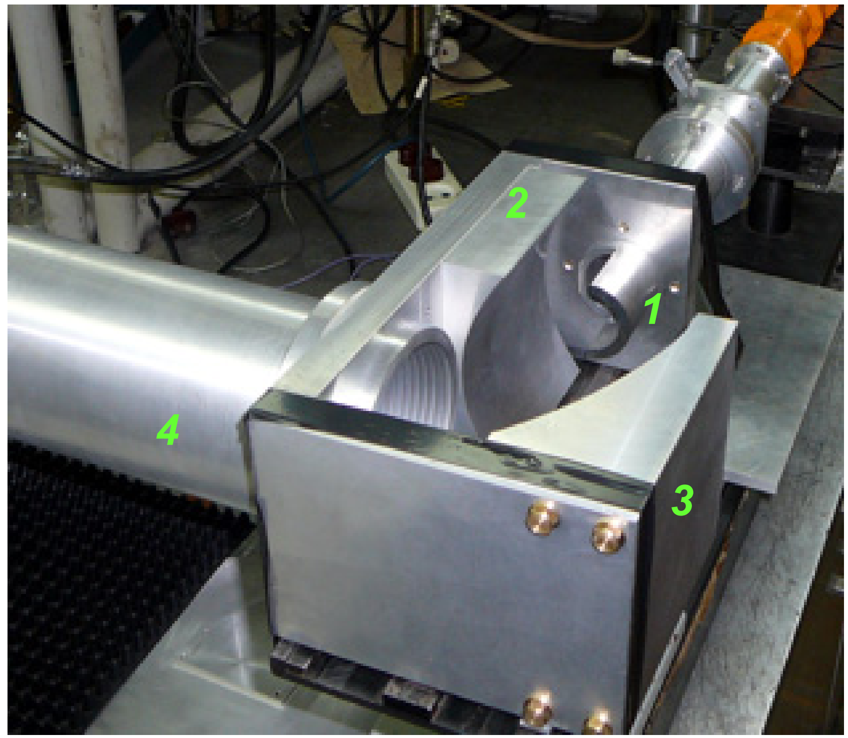
Simultaneous synthesis of the launcher and matching mirror

TE_{02}-HE_{11} converter, 28 GHz







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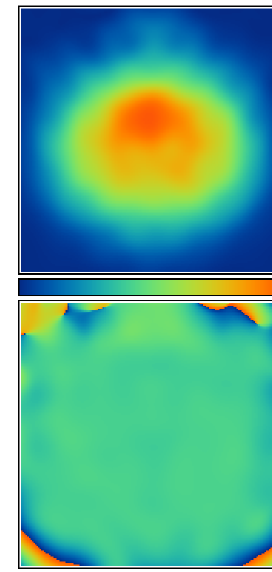

$\eta_a/\eta_{a,\varphi}$ %:

TEM_{00}- 98.4 / 97.7
HE_{11} - 98.0 / TEM_{00}- 98.4 / 97.7

HE_{11} - 98.0 / 97.3

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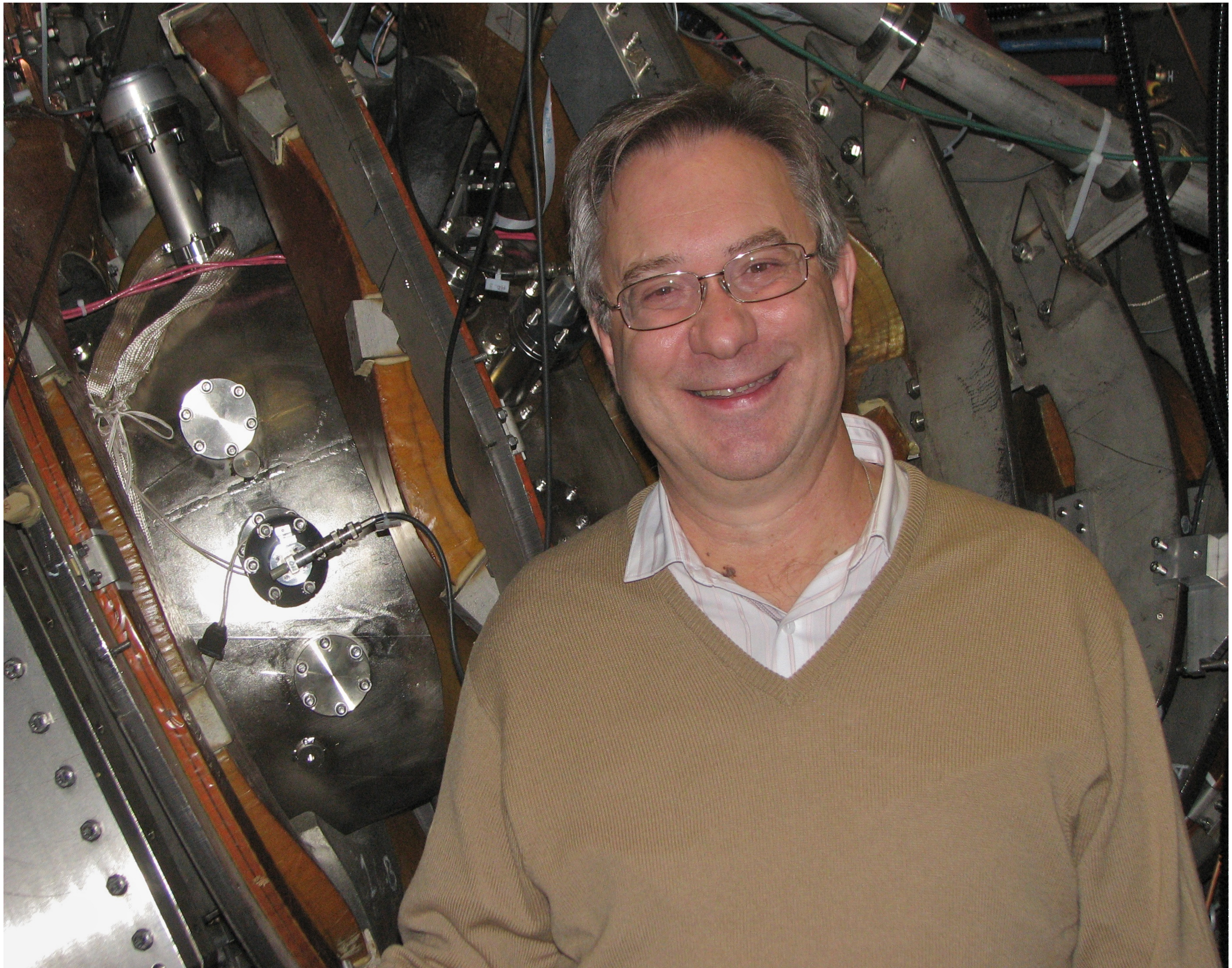
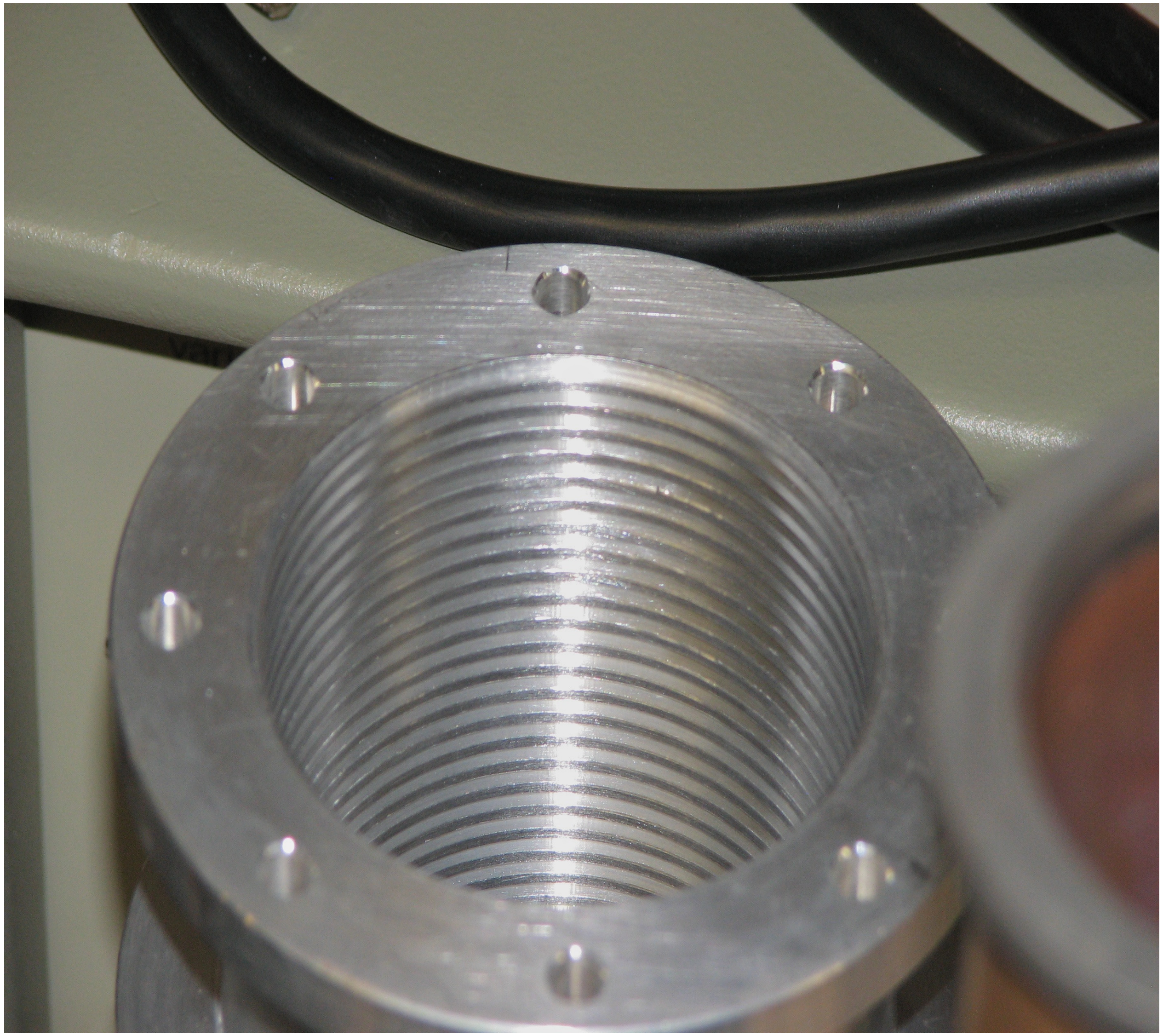
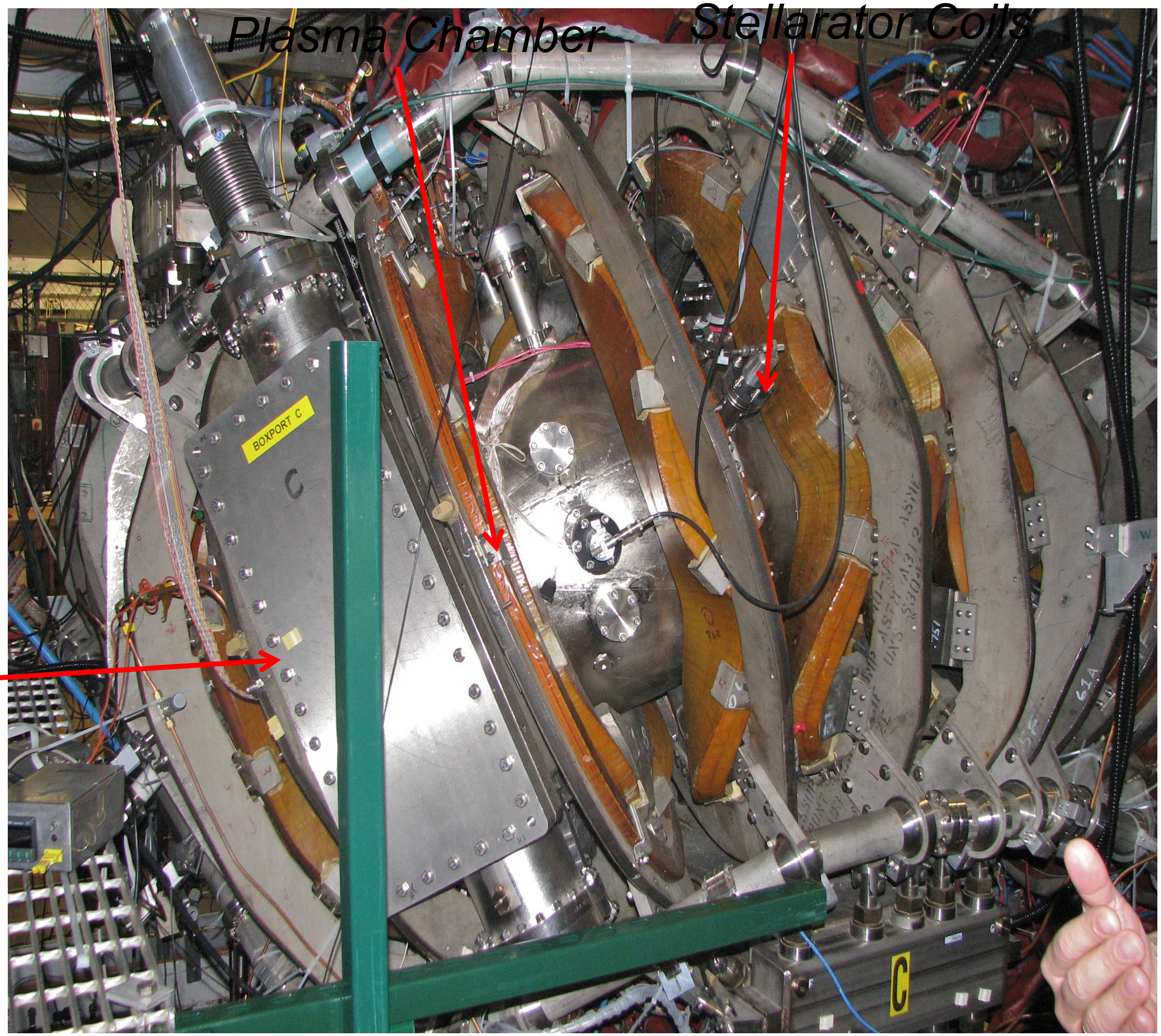
Konstantin Likin and HSX plasma chamber



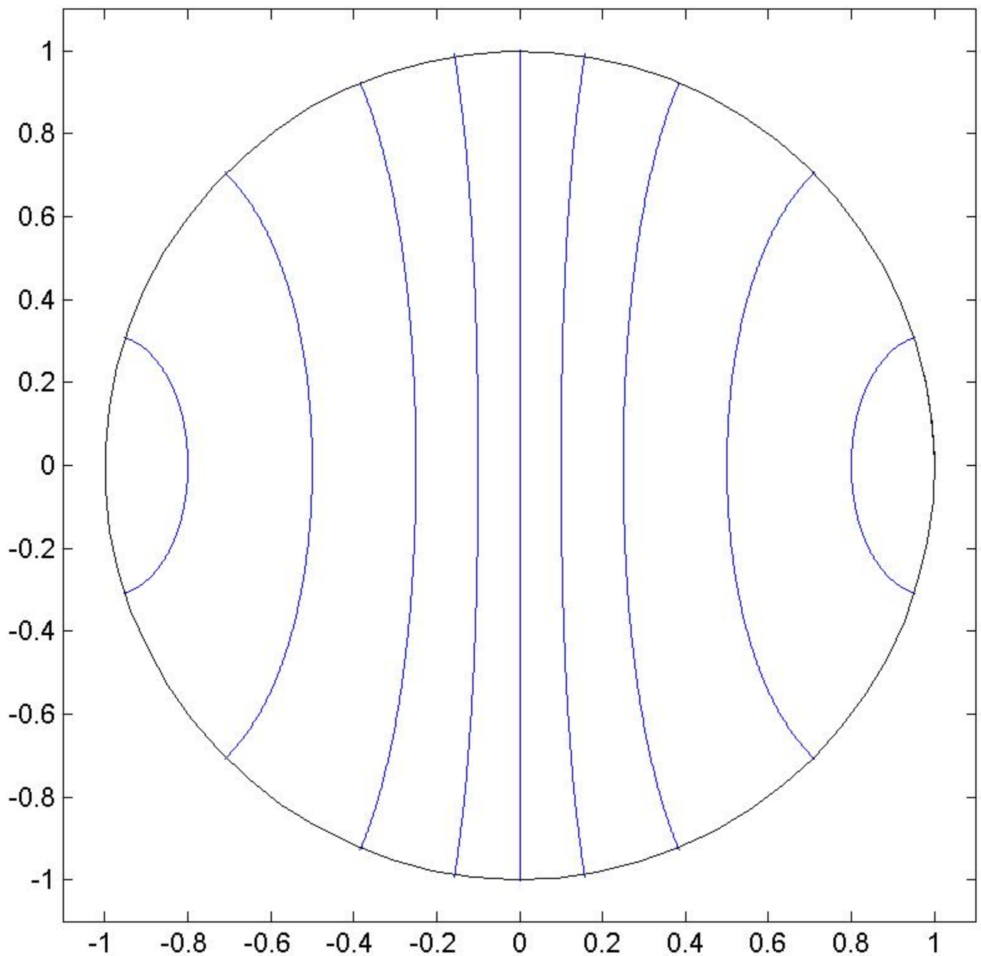
TE11 to HE11 converter old waveguide system



HSX stellarator plasma chamber and magnet coils



TE01 Electric field lines



TM11 Electric Field Lines