



マイクロ波イメージング*

長山好夫¹,
土屋隼人¹, 山口聡一郎², 杉戸正治³, 桑原大介⁴

¹ 核融合科学研究所; nagayama.yoshio@nifs.ac.jp

² 関西大学・システム理工学部

³ 分子科学研究所

⁴ 東京農工大

*Supported by NINS Imaging Science project (KNSI001), NIFS Int. Nat. Network (KEIN111) and LHD project (008).

1. なぜプラズマをマイクロ波でみるのか？
2. 2Dマイクロ波検出器の開発
3. LHDでのマイクロ波イメージング反射計 (MIR)
4. 実験データ
5. 乳癌検出のマイクロ波CTを目指す

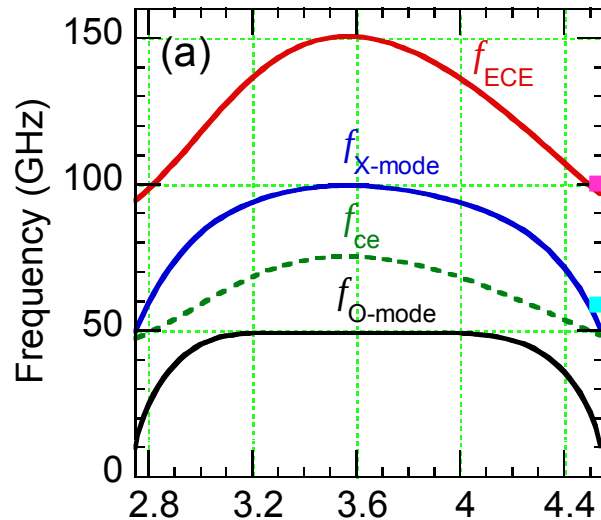
Plasma can be seen by microwave. Plasma fluctuations has 3D structure.



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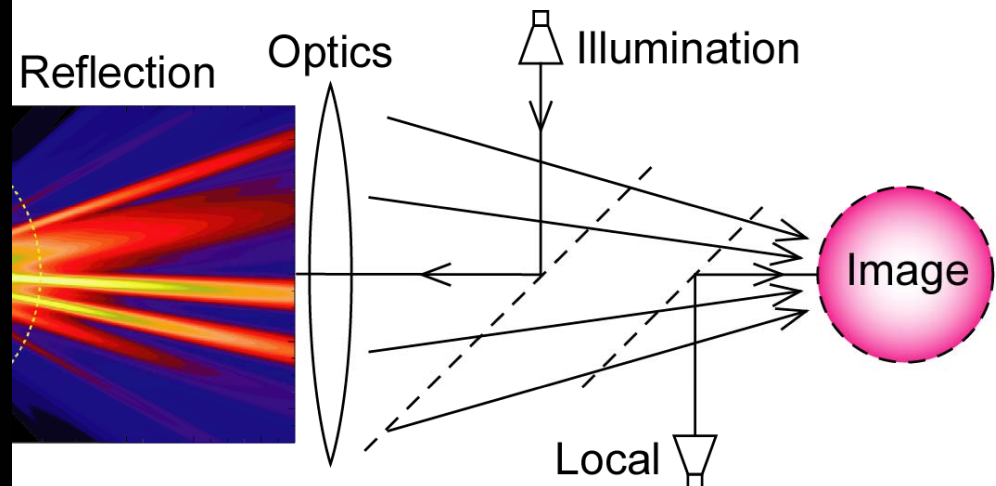
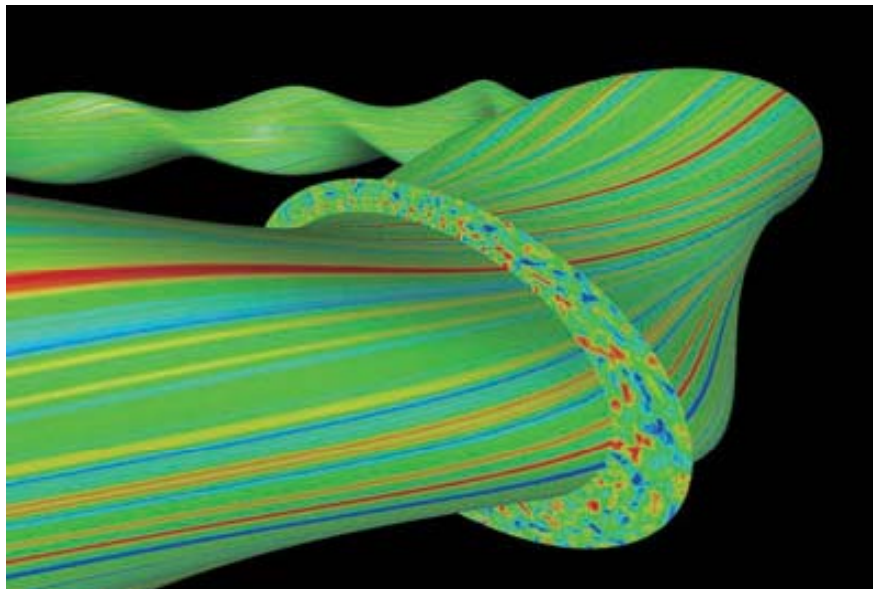
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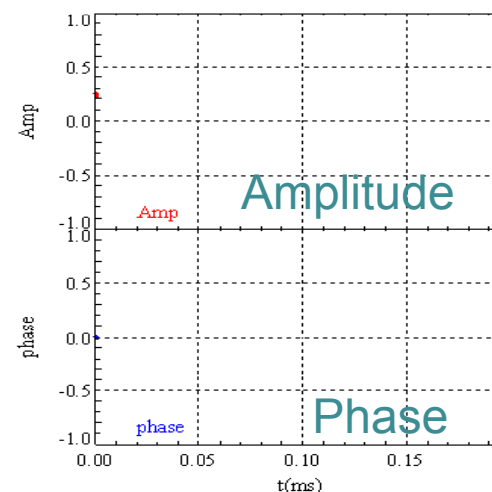
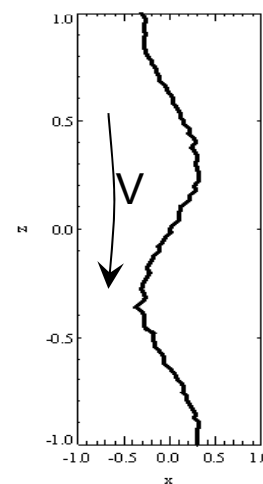
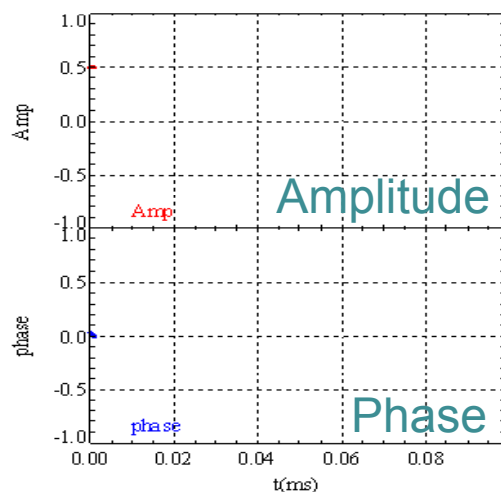
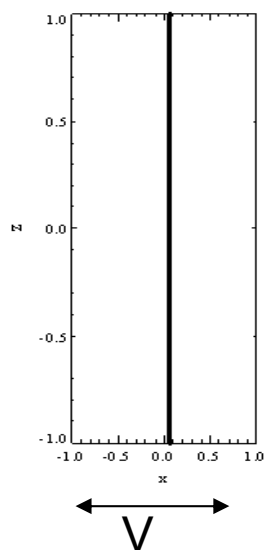
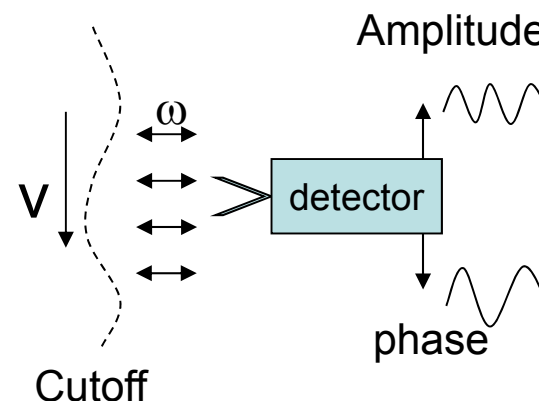
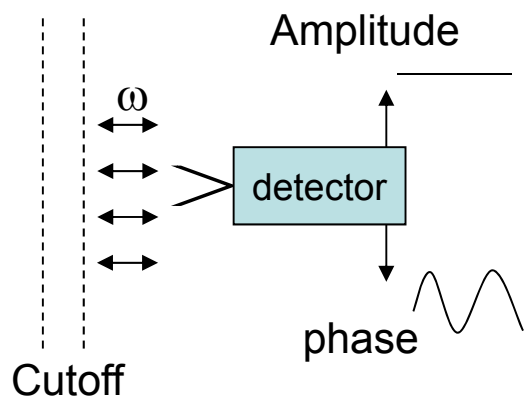
ECEI
(97-105GHz)

MIR
(60-65GHz)

- Plasma fluctuation is extended along field line and is broken in poloidal and radial directions.
- 3D fluctuation structure can be observed with 3D microwave imaging.

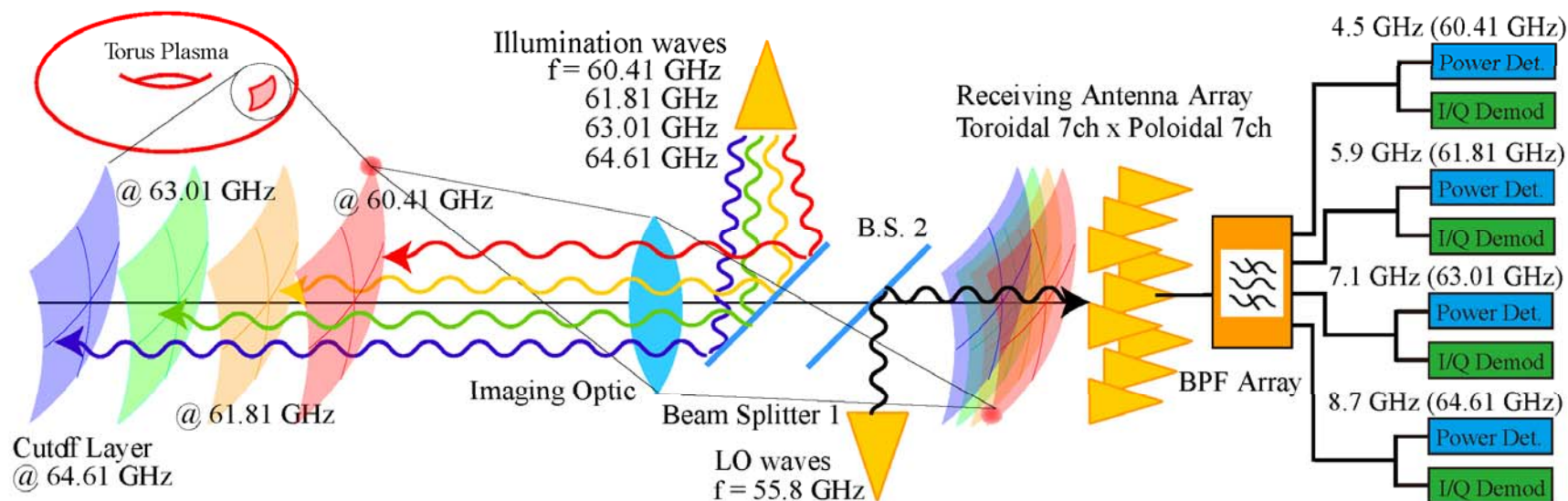
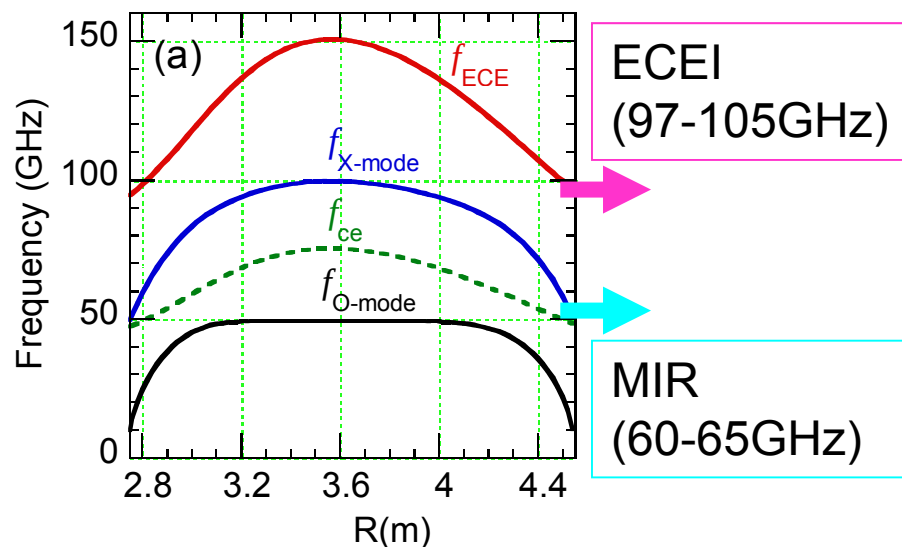


Amplitude and phase changes as the cutoff surface moves due to n_e fluctuation.



Vibration of plane reflector does not change amplitude but phase only.

Wave fluctuates both in amplitude and phase.



Two types of antenna array on board

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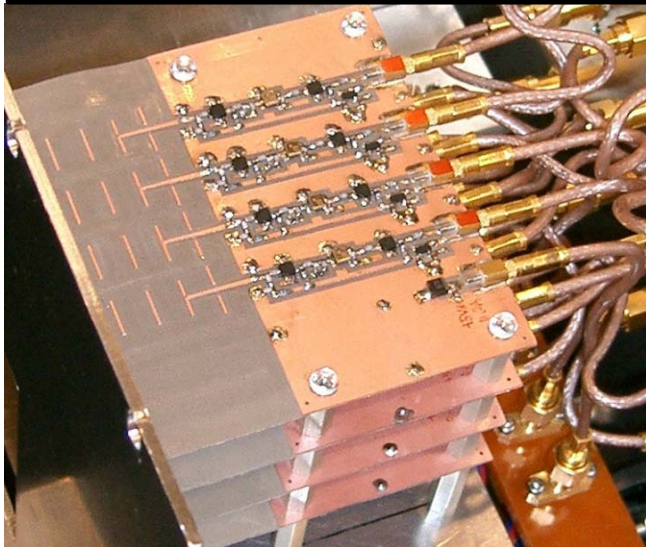
TOKYO TECH
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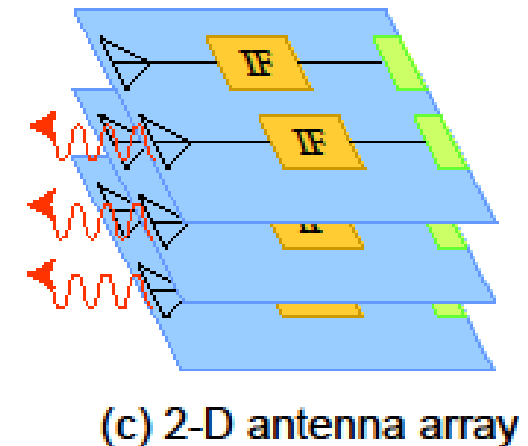
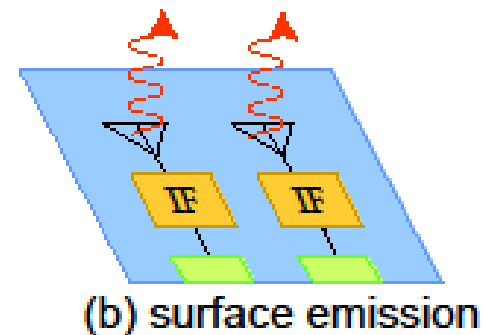
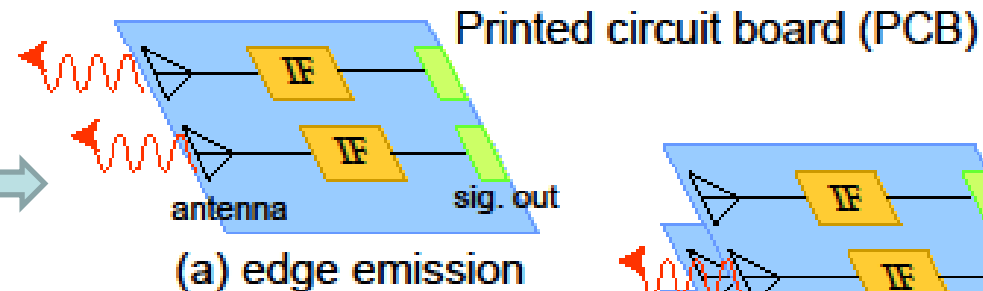
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20GHz Planar Yagi-Uda
antenna array for TPE-RX

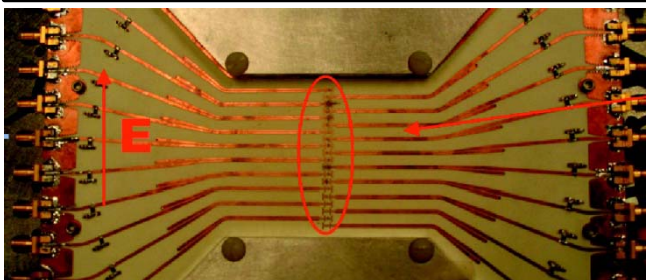


- Two types of antenna arrays
 - (a) Edge emission (NIFS)
 - (b) Surface emission (UC Davis)
- 2-D array can be made by stacking the edge emission type antenna arrays.



UCDAVIS

Dual dipole antenna
array for ECE imaging



1. Y. Nagayama, S. Yamaguchi, Z. B. Shi, et al, PFR 3, 053 (2008).
2. Z. B. Shi, Y. Nagayama, S. Yamaguchi, et al, Phys. Plasmas 18, 102315 (2011)

Yagi-Uda antenna array has an interference problem.

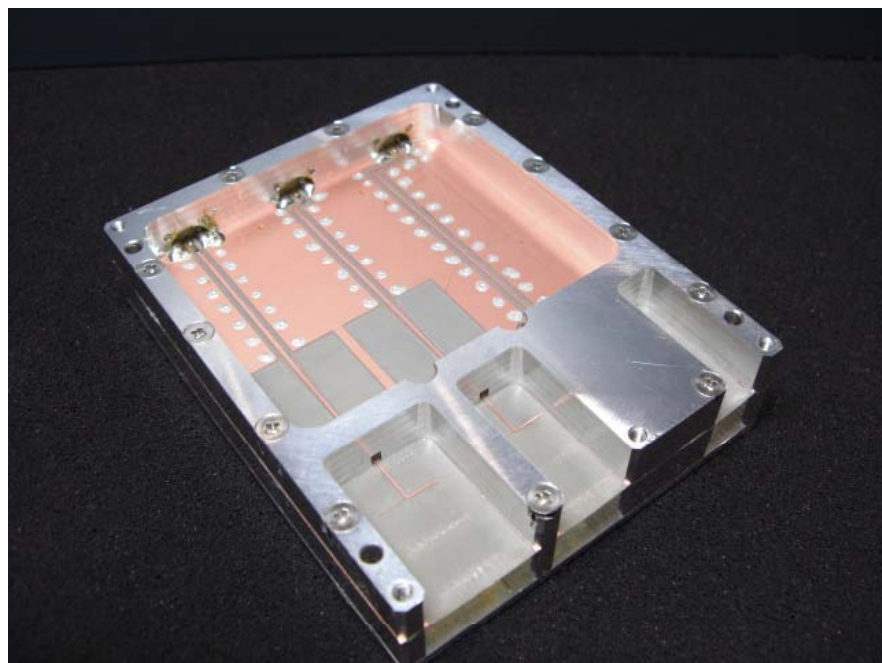
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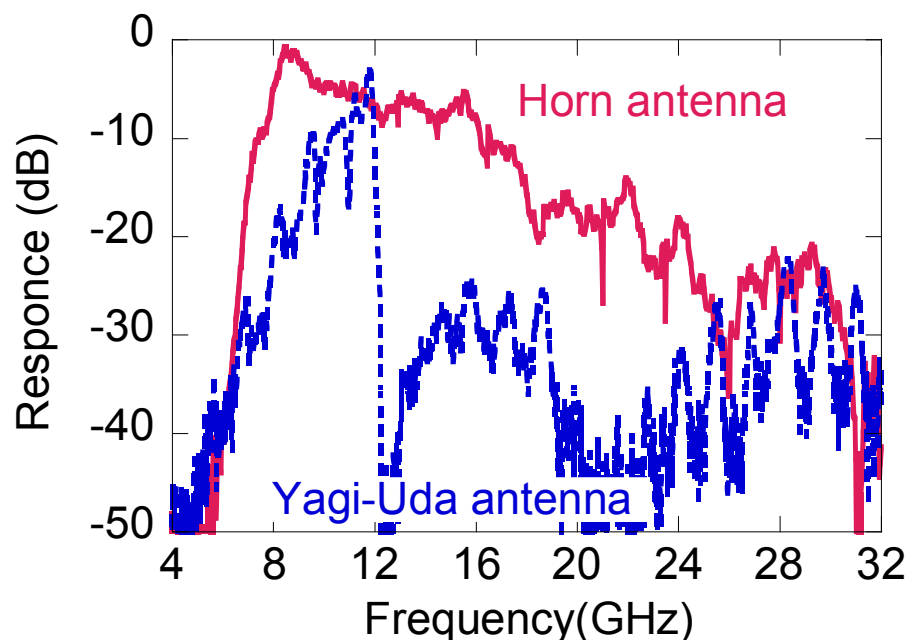


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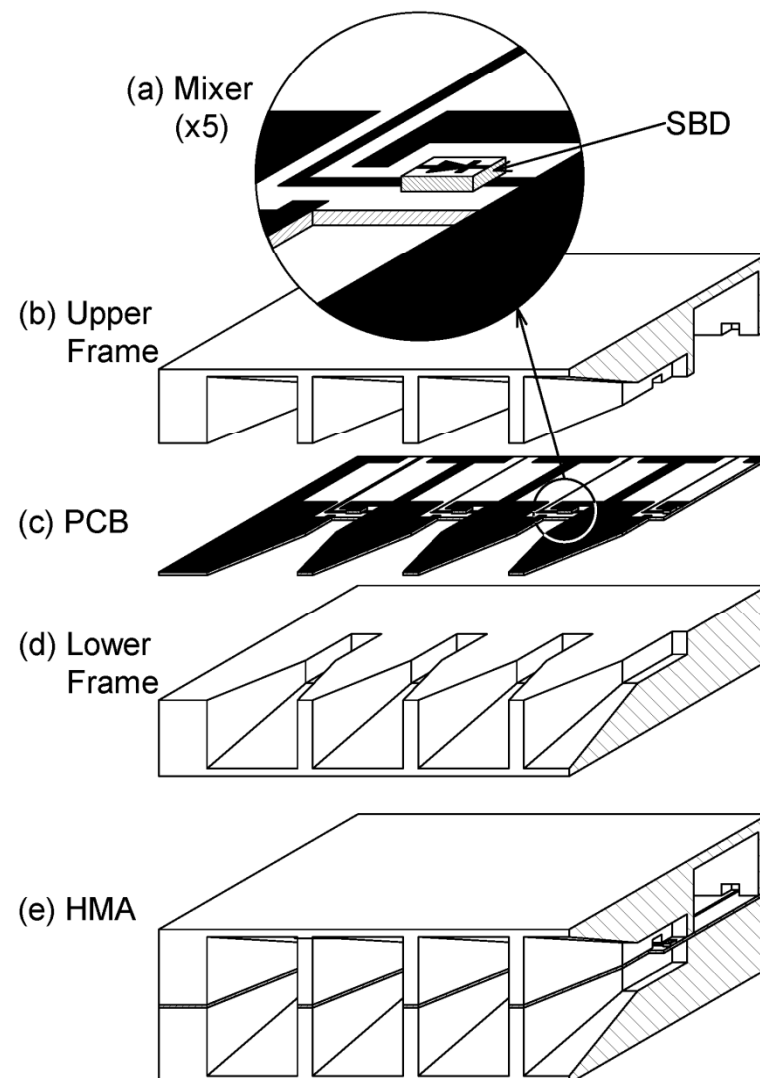
- The Yagi-Uda antenna array has a dip in the frequency response due to the interference among antennas. (Single Yagi-Uda antenna has broad response)
- Partition is required to avoid interference.
- Horn antenna has a wide frequency response.



Test piece of partition



- アルミ板にホーンの型を切削し、
ホーンアンテナアレイを成型
- 受信回路を成形したプリント基板
(PCB)を半割ホーンアンテナア
レイで挟む
 - ミキサダイオードを導波管内に
設置
 - IF信号はPCB上で増幅
- スタックすると三次元ホーンアン
テナアレイ



Frequency response and directivity of HMA

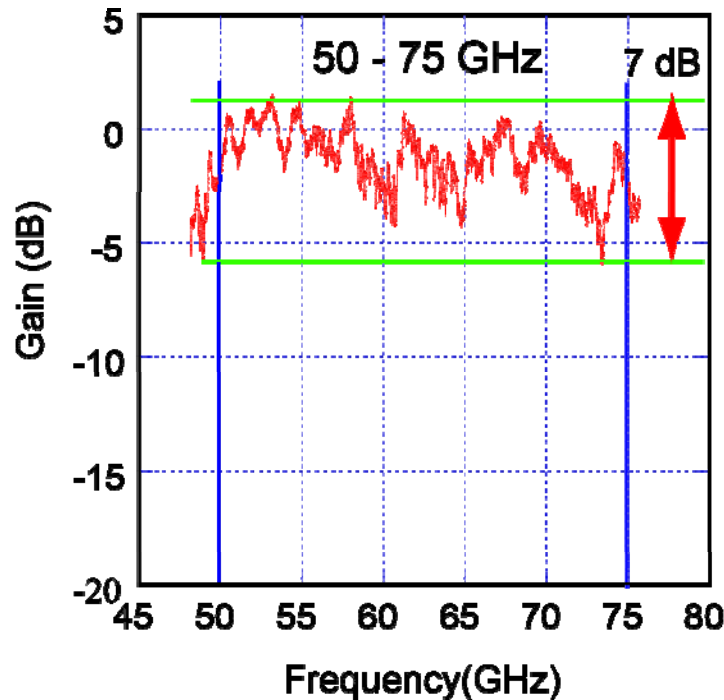


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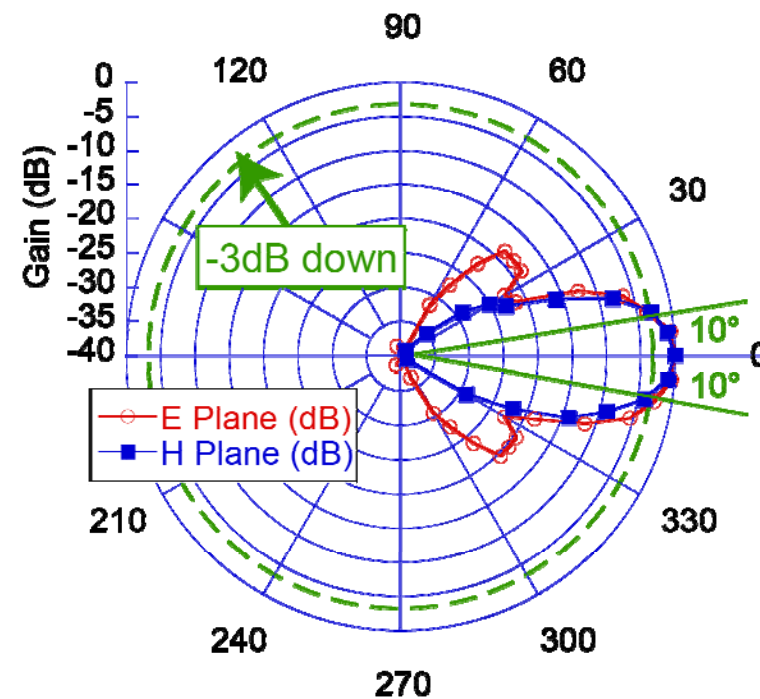
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Frequency response



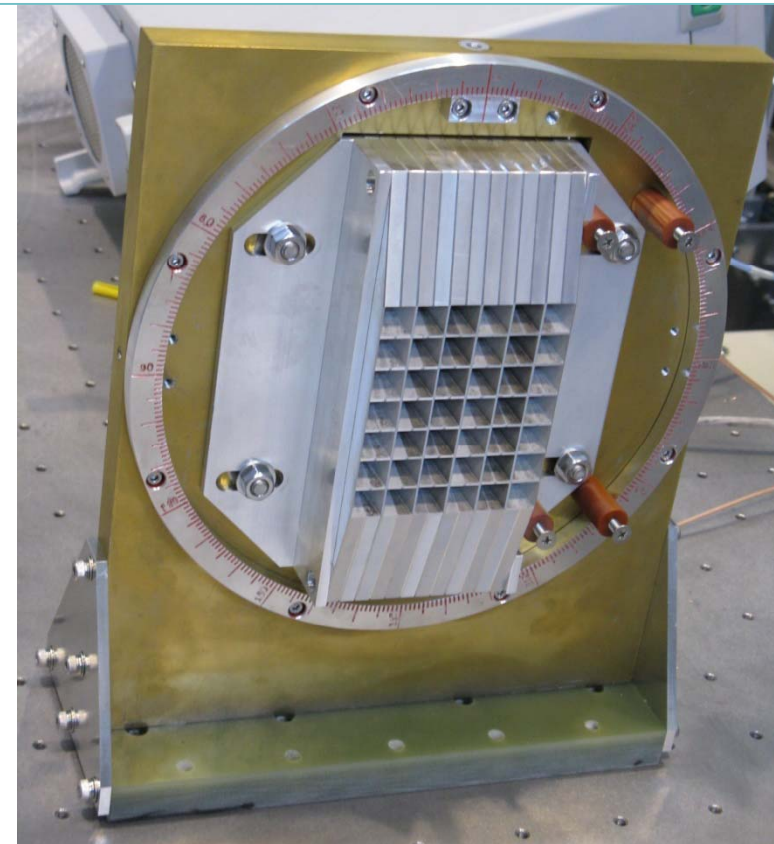
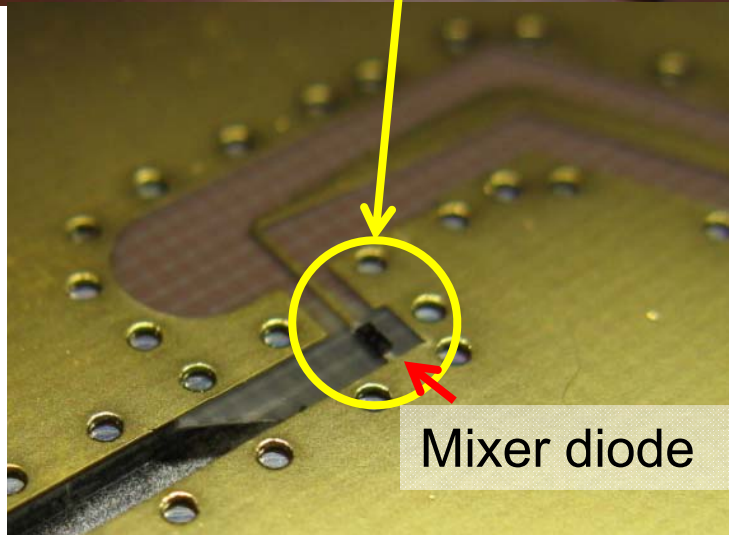
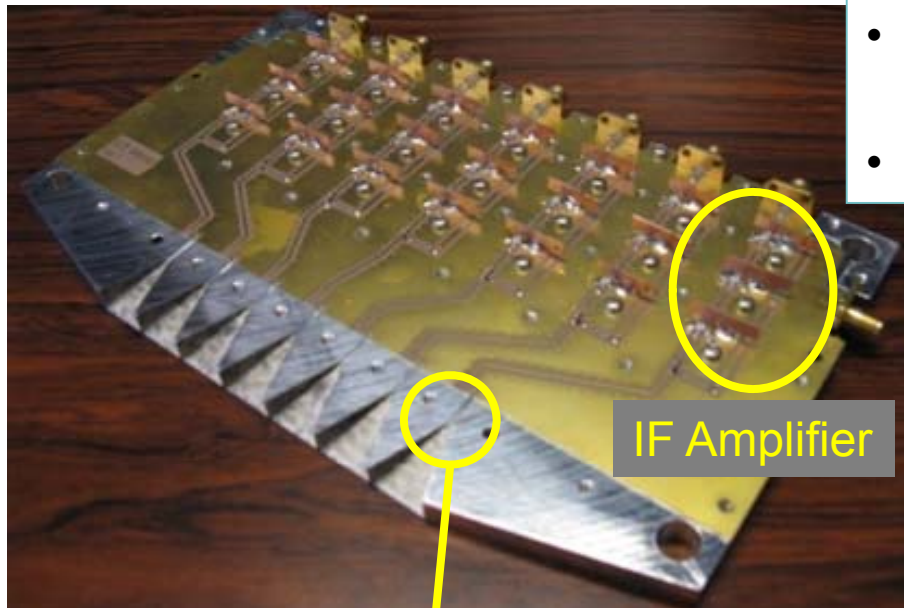
Directivity



- V-band (50-75GHz) HMA has broad frequency response between 50 and 108 GHz.
- Directivity is 17 degrees (aperture: 13x13mm), while commercially available pyramid horn antenna is 10 degrees (45x30mm).

HMA (Horn-antenna Mixer Array)

- HMA is a sandwich of a PCB with mixers and aluminum frames with half cut horns.
- Mixer and RF amplifiers are installed on PCB.



3. D. Kuwahara, et al., J. Plasma Fusion Res. SERIES, 9, 125 (2010).
4. D. Kuwahara, et al., J. Plasma Fusion Res. SERIES, 8, 649 (2009).

Microwave Source and Optics of Microwave Imaging in LHD

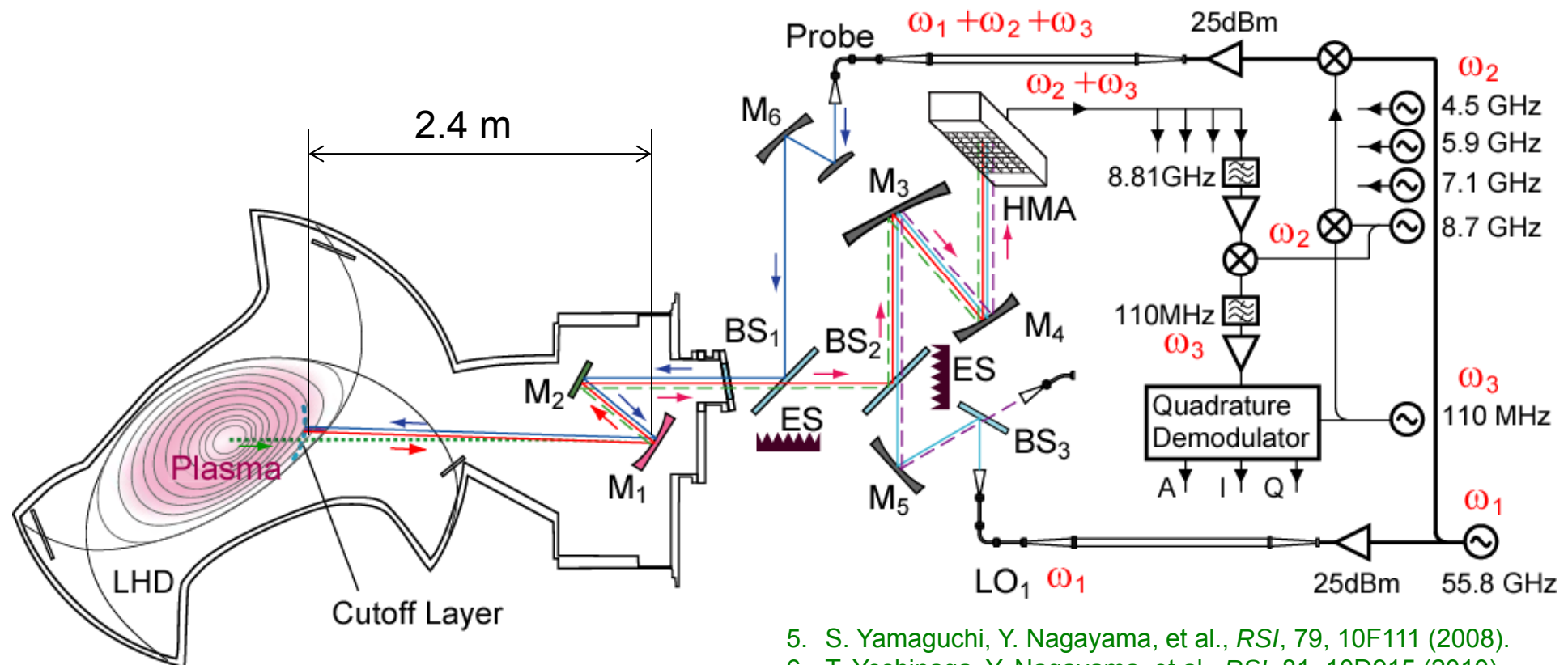


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- Microwave is mixture of 3 sources:
 - Base band (ω_1), 1st IF (ω_2), 2nd IF (ω_3)
- Probe beam illuminates plasma and reflected wave is focused onto HMA.



5. S. Yamaguchi, Y. Nagayama, et al., *RSI*, 79, 10F111 (2008).

6. T. Yoshinaga, Y. Nagayama, et al., *RSI*, 81, 10D915 (2010).

LHDでのマイクロ波イメージング光学系



NIFS

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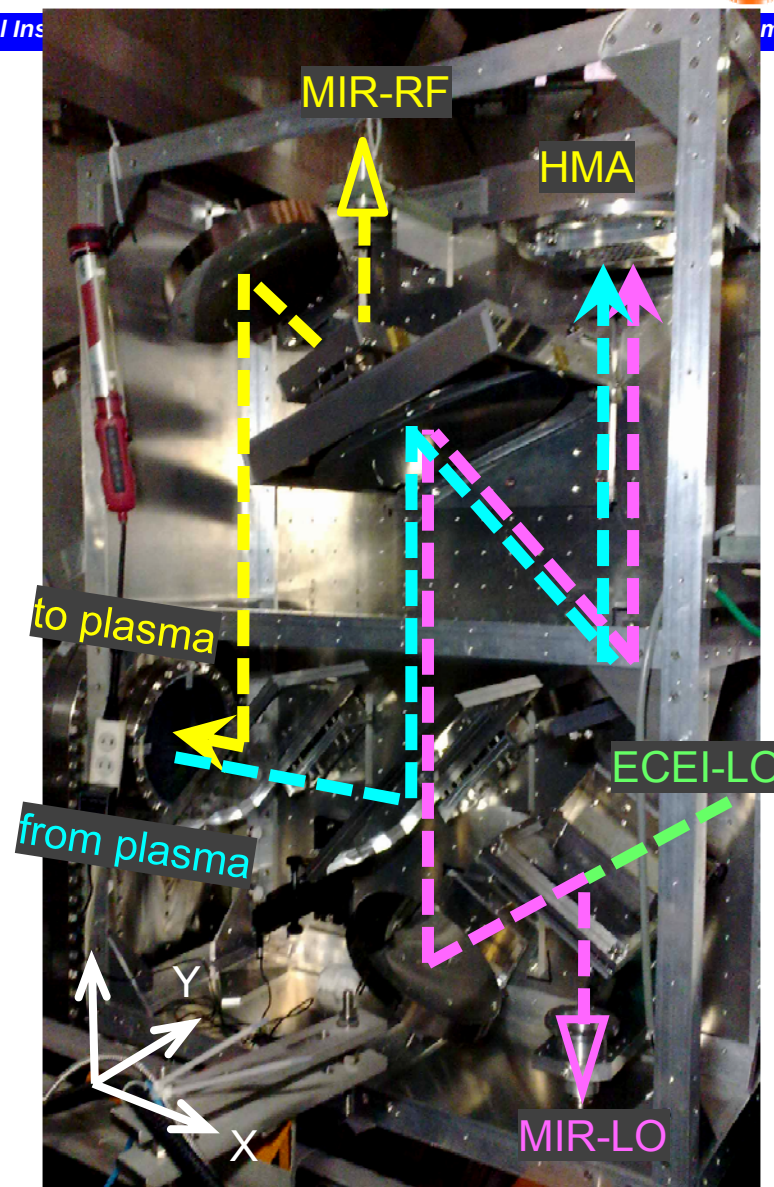
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Horn-antenna Mixer Array



Object mirror in vacuum vessel



Observation of edge plasma fluctuation



Cutoff density of X-mode microwave:

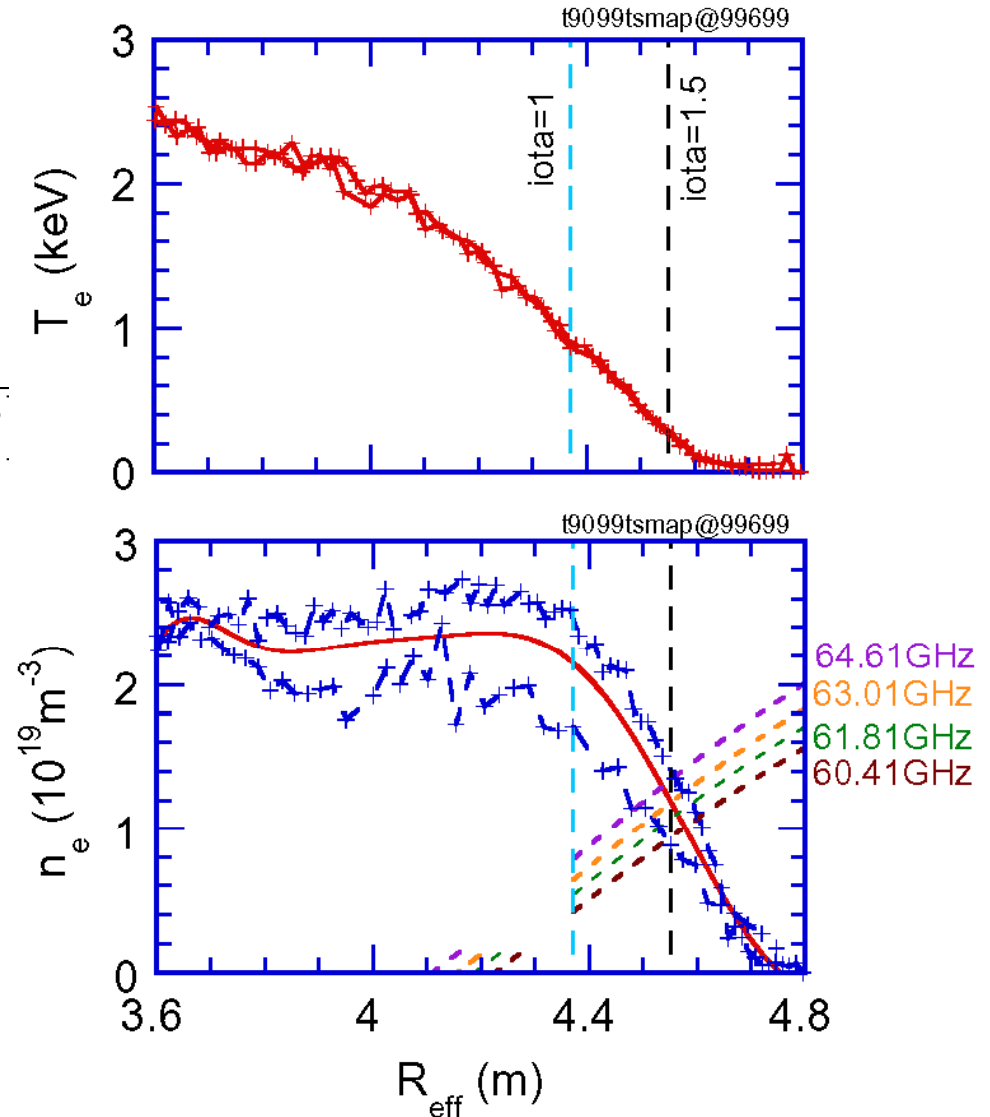
$$n_{cutoff} = \frac{f_R^2 - f_R f_{ce}}{806.4}$$

$$f_R = \frac{1}{2} \left\{ f_{ce} + \sqrt{f_{ce}^2 + 4f_{pe}^2} \right\}$$

$$f_{ce} [\text{GHz}] = 28B [\text{T}], f_{pe} [\text{GHz}] = 28.4 \sqrt{n_e [10^{19} \text{m}^{-3}]}$$

We measure the equilibrium plasma edge in the case of high field operation. Plasma pressure is still high at the edge.

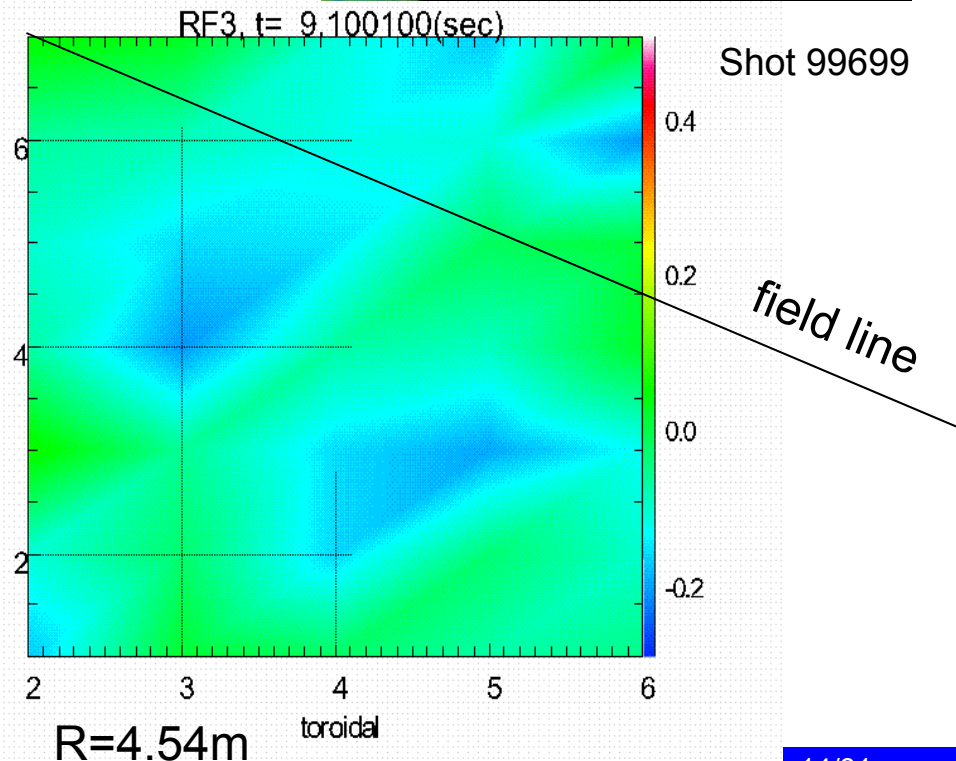
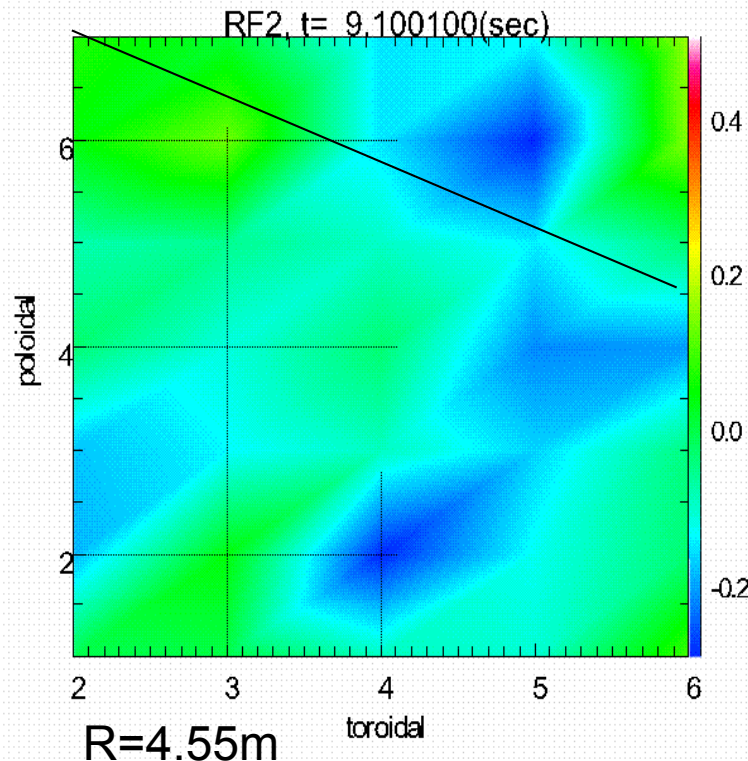
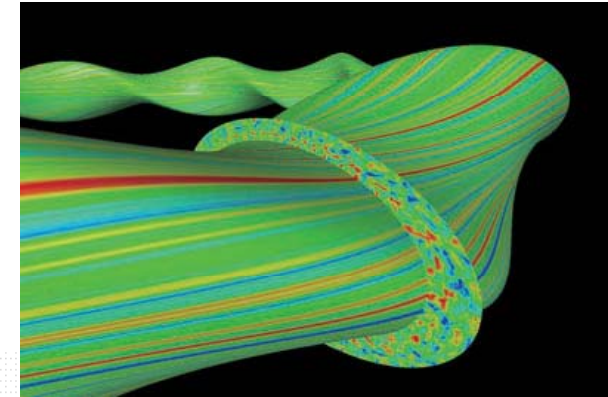
- Equilibrium Plasma edge: $R=4.55\text{m}$
- $\text{iota}(=1/q)$: 1.5
- $T_e=0.3\text{keV}$
- $n_e=1 \times 10^{19} \text{m}^{-3}$



MIR image of edge plasma fluctuation



- Two types (at least) are observed
 - Strong and long along field line
 - Weak and short length
- Some fluctuations are not along the field lines.
 - Further work is required to compare with theoretical predictions.



Shot 99699

4D MIR image of fundamental frequency shows how EHO proceeds

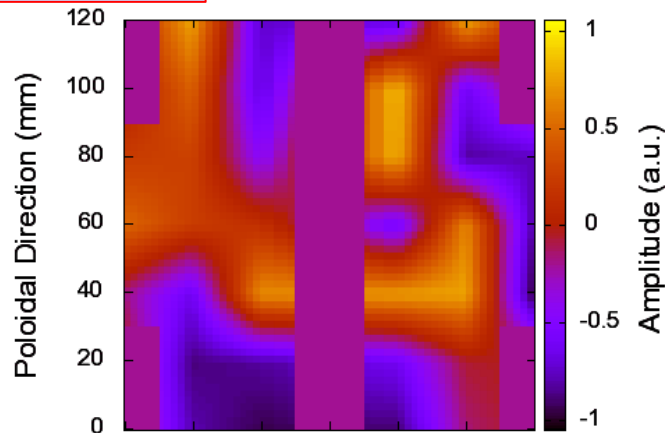


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Freq1 (60.41 GHz)

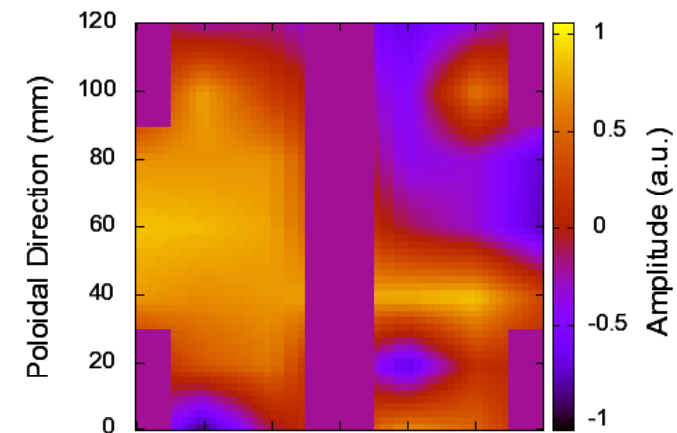
Time = 0 usec



Freq3 (63.01 GHz)

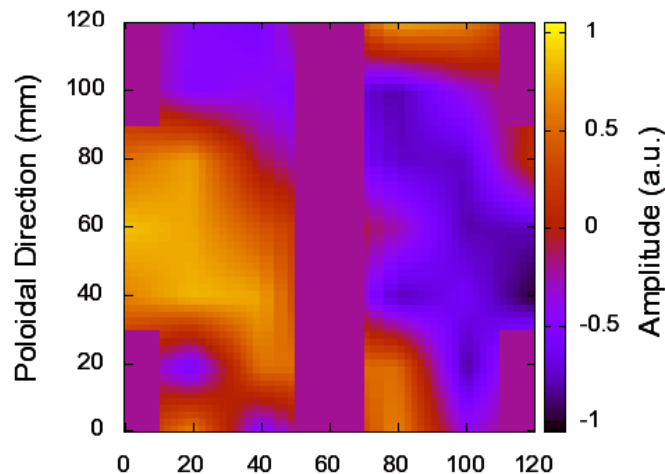
Time = 0 usec

Shot 106139



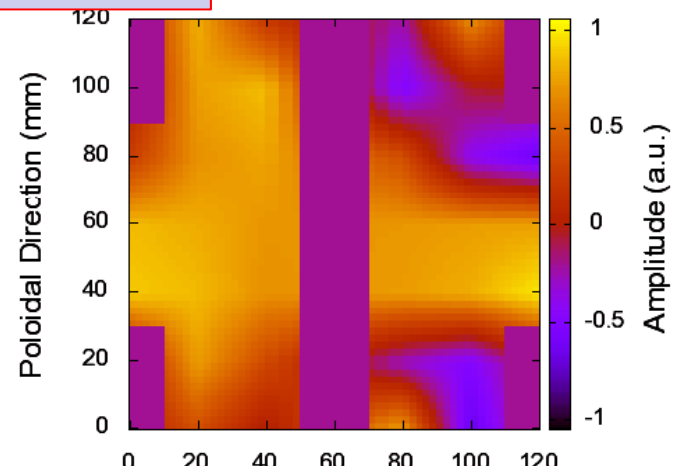
Freq2 (61.81 GHz)

Time = 0 usec



Freq4 (64.61 GHz)

Time = 0 usec



Toroidal Direction (mm)

Toroidal Direction (mm)

Preliminary analysis of coherence (t-p) plane high Ti mode and EHO



NIFS

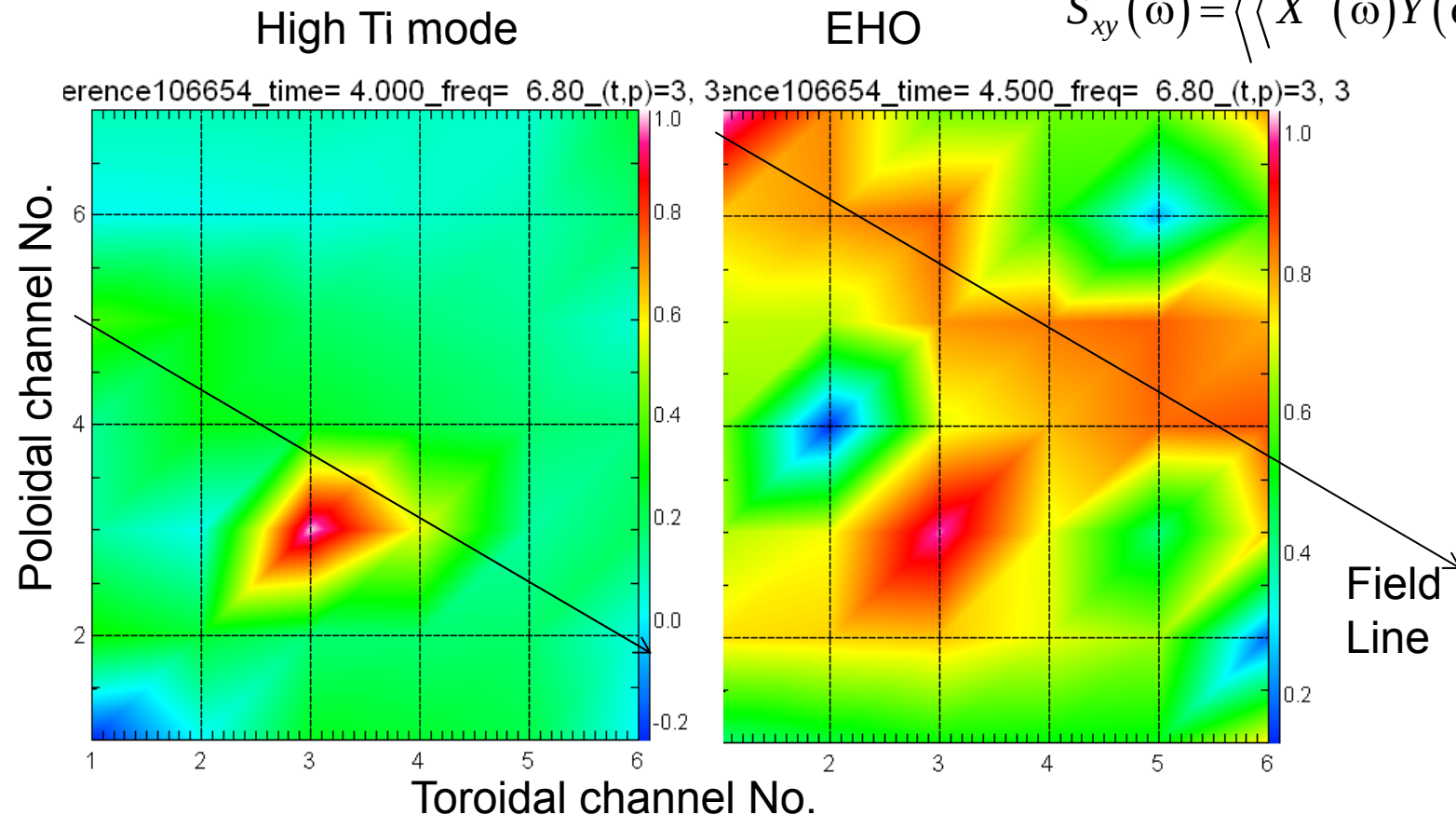
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- High coherence is observed in the case of EHO.
- Coherence looks extends along the field line.

$$C_{xy}(\omega)^2 = \frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)}$$

$$S_{xy}(\omega) = \left\langle \left\langle X^*(\omega)Y(\omega) \right\rangle_{t-\Delta t}^{t+\Delta t} \right\rangle_{\omega-\Delta\omega}^{\omega+\Delta\omega}$$

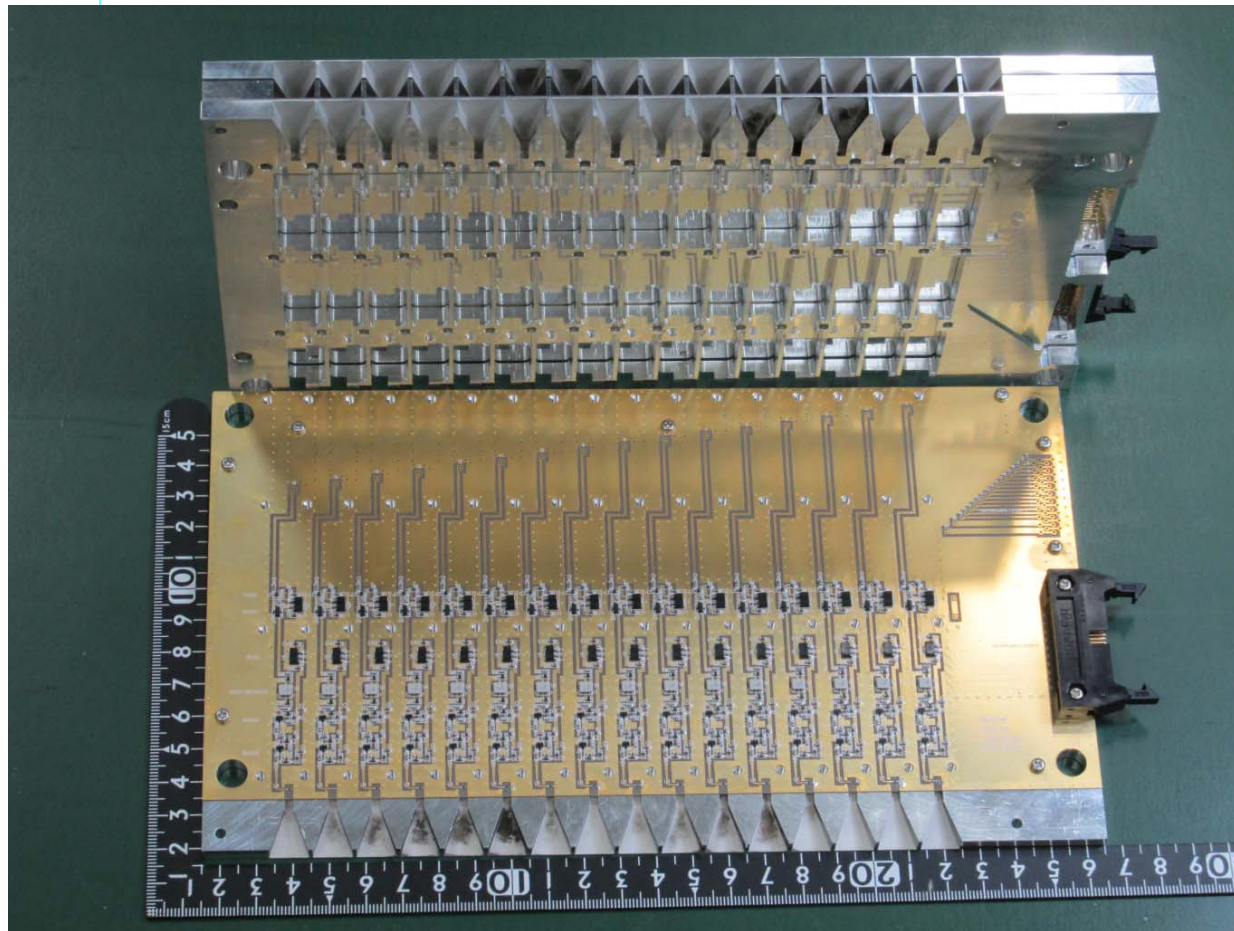


- MHD不安定性のような大きな揺動は、磁力線方向に変動する
- 小さな揺動は、磁力線方向に相関がない
 - これまでの常識（揺動は磁力線方向に反する
 - 説得力のある実験データが必要
- 実験の欠陥
 - Xモード反射（カットオフ周波数が密度だけでなく磁場にも依存する）
- 現在、Oモード計測へ改造中

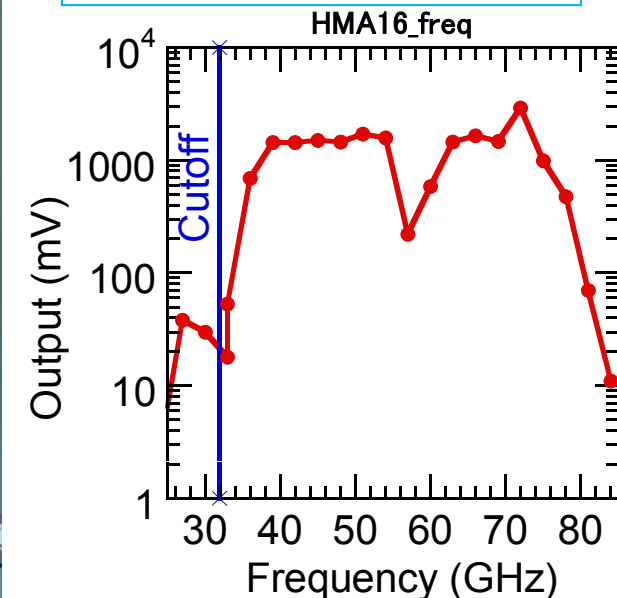
16ch撮像デバイスの試作機



- 多チャンネル化への課題
 - 薄型多チャンネルコネクタ、狭い回路幅
- 平成24年度、ホーン部分の機械加工に成功
 - 放電加工: 20万円/1アレイ、多チャンネル試作機が予算的に可能になった



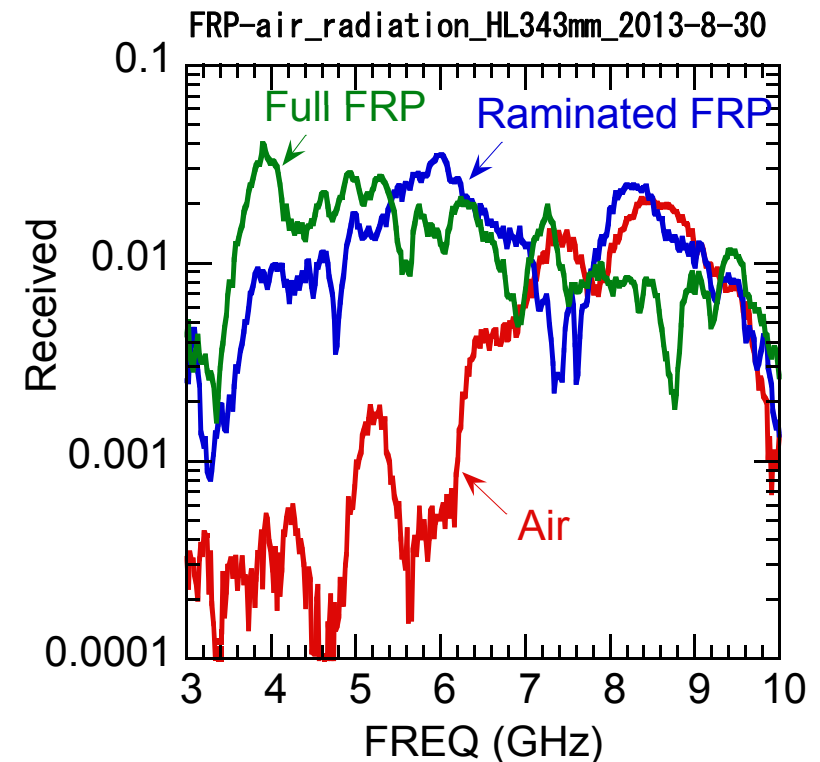
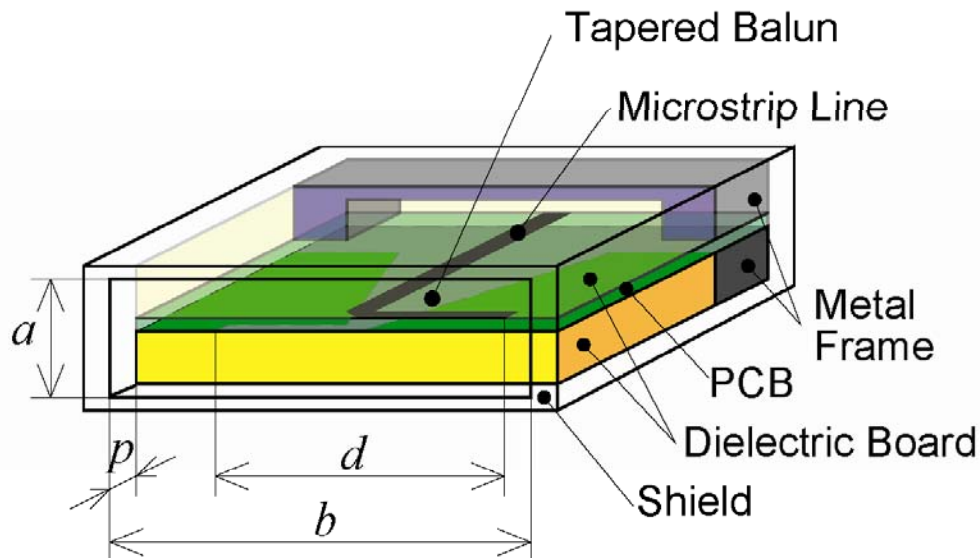
ホーンアンテナアレイ
16チャンネル
ピッチ: 12 mm
受信波長: 2~5 mm
中間周波数: 10.7 MHz



誘電体積層Dipoleアンテナ

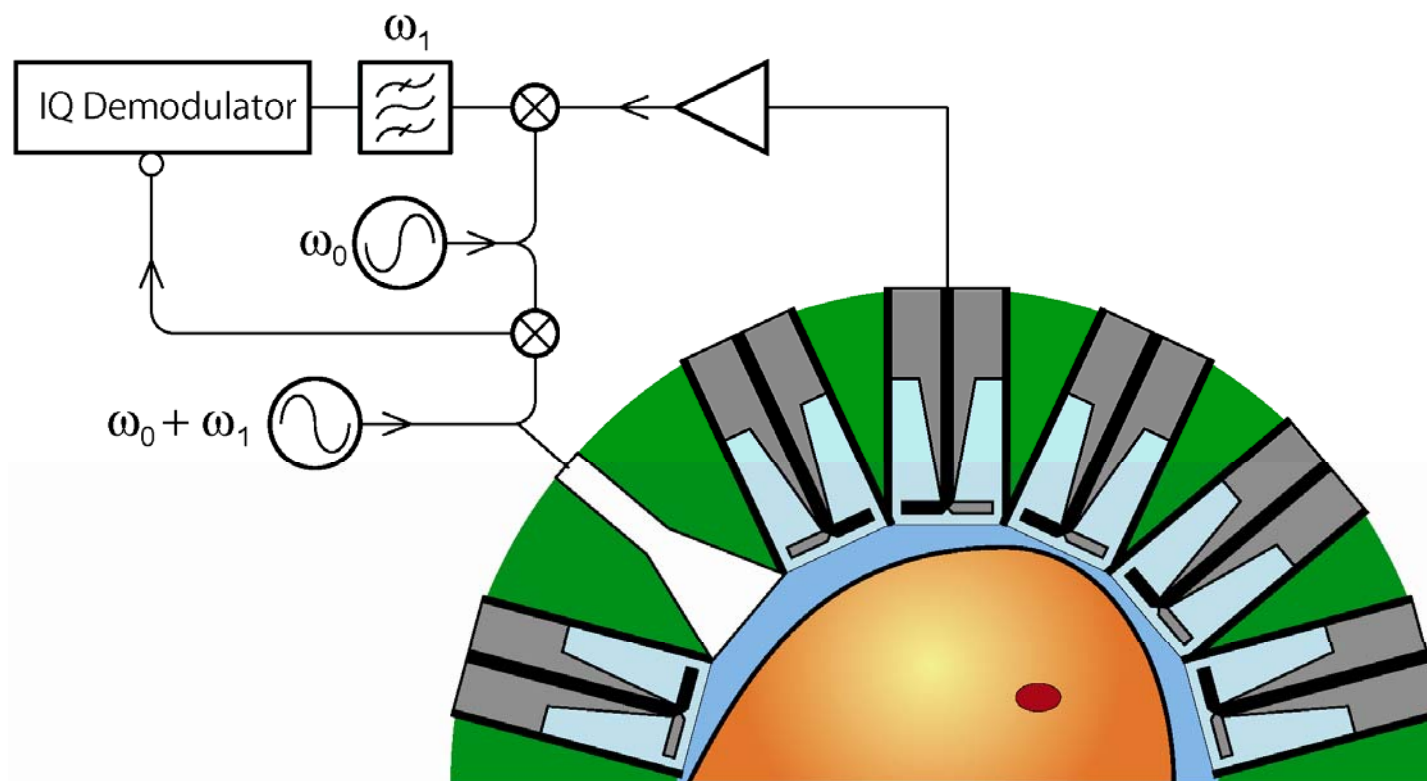


- マイクロ波CTには波長よりはるかに薄いアンテナが必要
- 誘電体と一体化することで波長短縮効果により, 低周波特性が向上
- 薄いアンテナをスタック状に並べると, クロストークが発生
- 金属板でシールドする
→導波管効果



乳癌検出の3Dマイクロ波CT

- 誘電体積層Dipoleアンテナは3Dマイクロ波CT用検出器として使える
 - 形が単純 → FDTD法
 - 薄い → 多チャンネル化
 - 無指向性
 - 固い → 装置を組み立てられる



まとめ



- プラズマ計測のためのマイクロ波イメージング
 - マイクロ波放射強度から電子温度イメージング→ECEI
 - マイクロ波反射から電子密度揺動イメージング→MIR
- 受像素子の発展
 - 20GHz, 平面Yagi-Udaアンテナアレイ→TPE-RX実験
 - 50 – 100GHz, ホーンアンテナアレイ(HMA) →LHD実験
 - 4 – 9 GHz 誘電体積層ダイポールアンテナ→乳癌検診
- LHD実験
 - MHD不安定性は磁力線方向に伸びる
 - 微小不安定性は磁力線を気にしない→ミステリー→OモードMIRの開発
- 産業・医療応用を目指したマイクロ波イメージング開発
 - マイクロ波CT: 乳癌, コンクリート非破壊検査
 - 誘電体積層ダイポールアンテナ
 - 実機製作を目指す