# Synthetic Diagnostic Approach to Analysis of Imaging Bolometer Data from LHD

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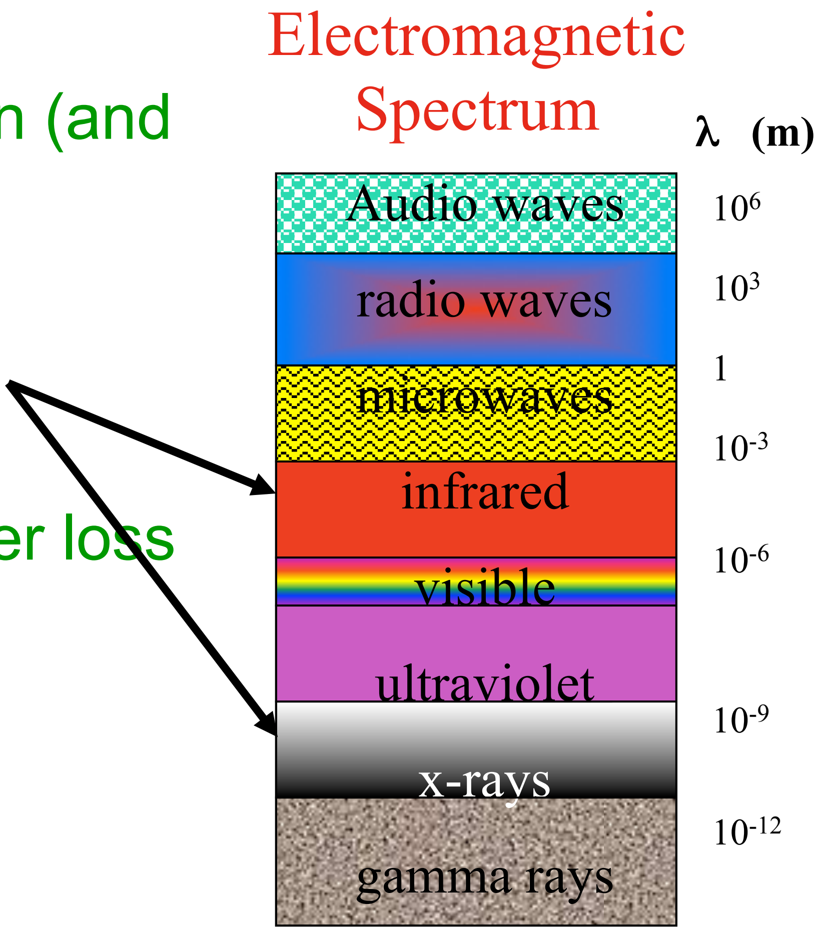
***National Institute for Fusion Science***

## Outline

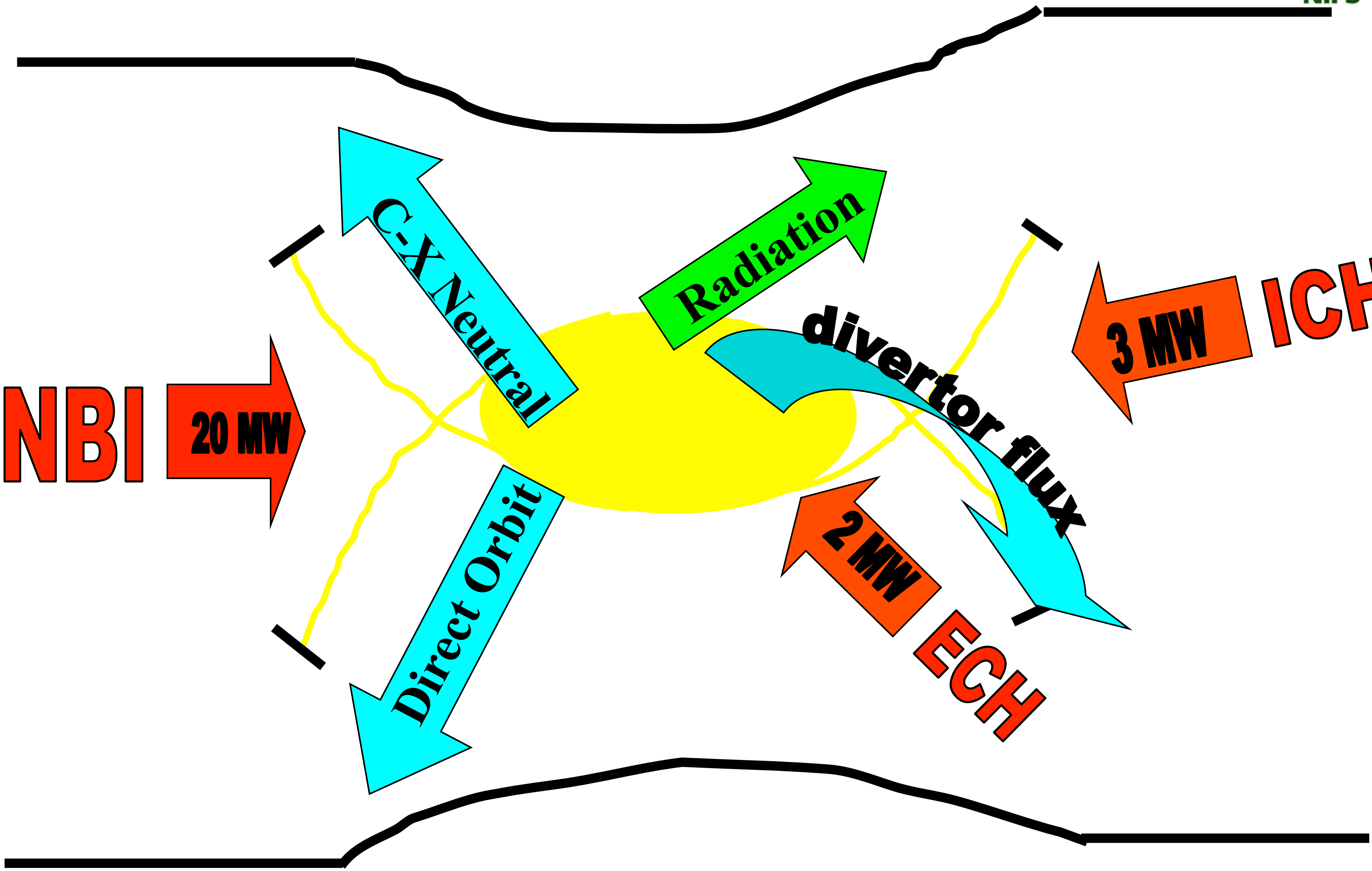
- IRVB concept
- IRVBs on LHD
- Calculation of geometry matrices
- Synthetic instruments vs tomography
- Detachment using magnetic island
- Conclusions

# Bolometry

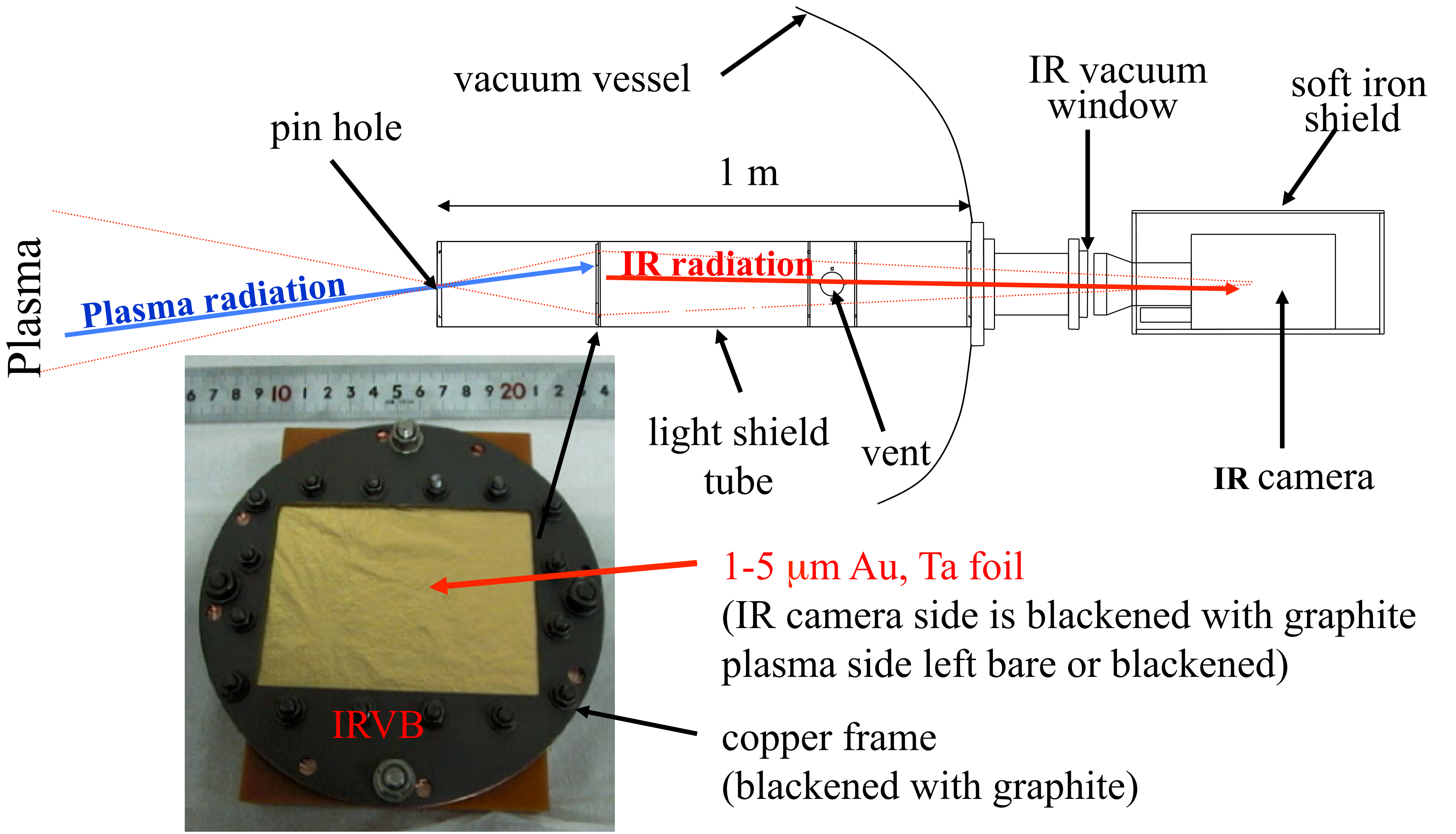
- Measures total radiation (and neutrals) from plasma
- From IR to soft x-rays
- Estimate radiative power loss for power balance
- Study role of impurities



# Power Balance (LHD)



# IR imaging Video Bolometer (IRVB)






[1] B.J. Peterson, *Rev. Sci. Instrum.* **70** (2000) 3696. [2] B.J. Peterson *et al.*, *Rev. Sci. Instrum.* **72** (2001) 923.

# IRVB - Concept

Solve foil 2D heat diffusion equation for $P_{rad}$

$$-\Omega_{rad} + \Omega_{bb} + \frac{1}{\kappa}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}$$

foil thermal diffusivity

2-D Laplacian

$$\Omega_{bb} = \frac{\varepsilon\sigma_{S-B}(T^4 - T_0^4)}{kt_f} \qquad \varepsilon \cong 1$$

black body cooling term

$$\Omega_{rad} = \frac{P_{rad}}{kt_f l^2}$$

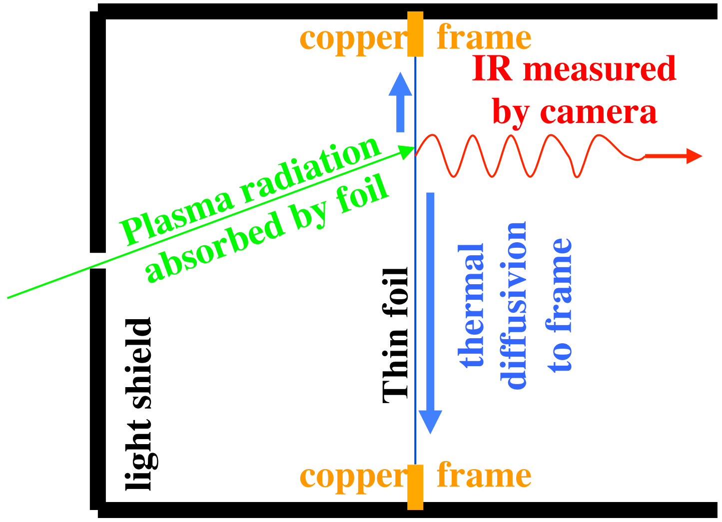
foil thermal conductivity

foil thickness

bolometer pixel area

plasma radiated power is determined by numerically solving heat diffusion equation using a Crank-Nicholson scheme

IRVB pinhole camera




B.J. Peterson *et al., Rev. Sci. Instrum.* **74** (2003) 2040.

# IR Imaging video Bolometer (calibration technique)

The two-dimensional heat diffusion equation

temperature on the foil

Detected radiation Power density from solving heat diffusion equation

$$S_{rad} = S_{bb} + C_s \frac{\partial T}{\partial t} - k t_f \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right]$$

Black body radiation from the foil

foil surface thermal capacity

Foil thermal conductivity

Foil thickness

Parameters to be determined locally on the foil through calibration experiments

Blackbody thermal emissivity

$$S_{bb} = \varepsilon \sigma_{S-B} (T^4 - T_0^4)$$

$$S_{rad} = \frac{P_{rad}}{l^2}$$

the incident radiation power to the foil

Bolometer pixel area

**LHD:** B.J.Peterson, et.al., Rev. Sci. Instrum. **74** (2003)2040

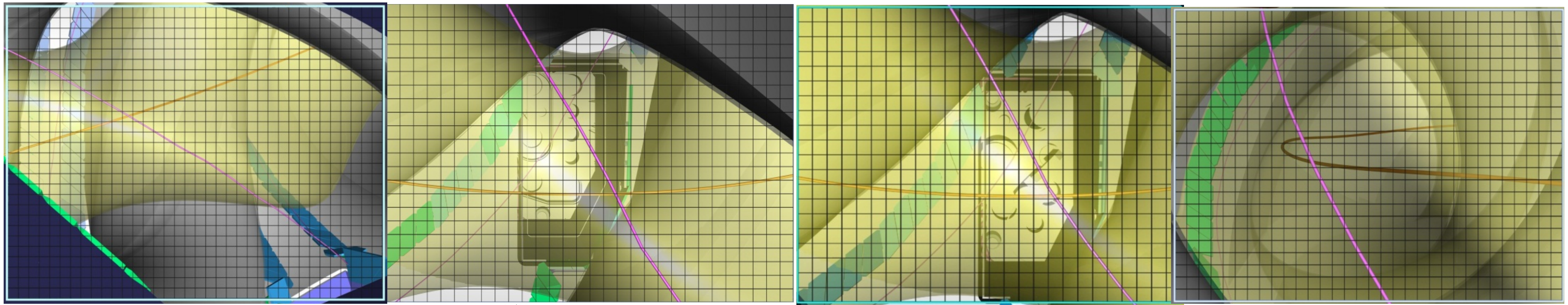
**JT-60U:** H.Parchamy, B.J.Peterson, et.al., Rev. Sci. Instrum. **77** (2006)515

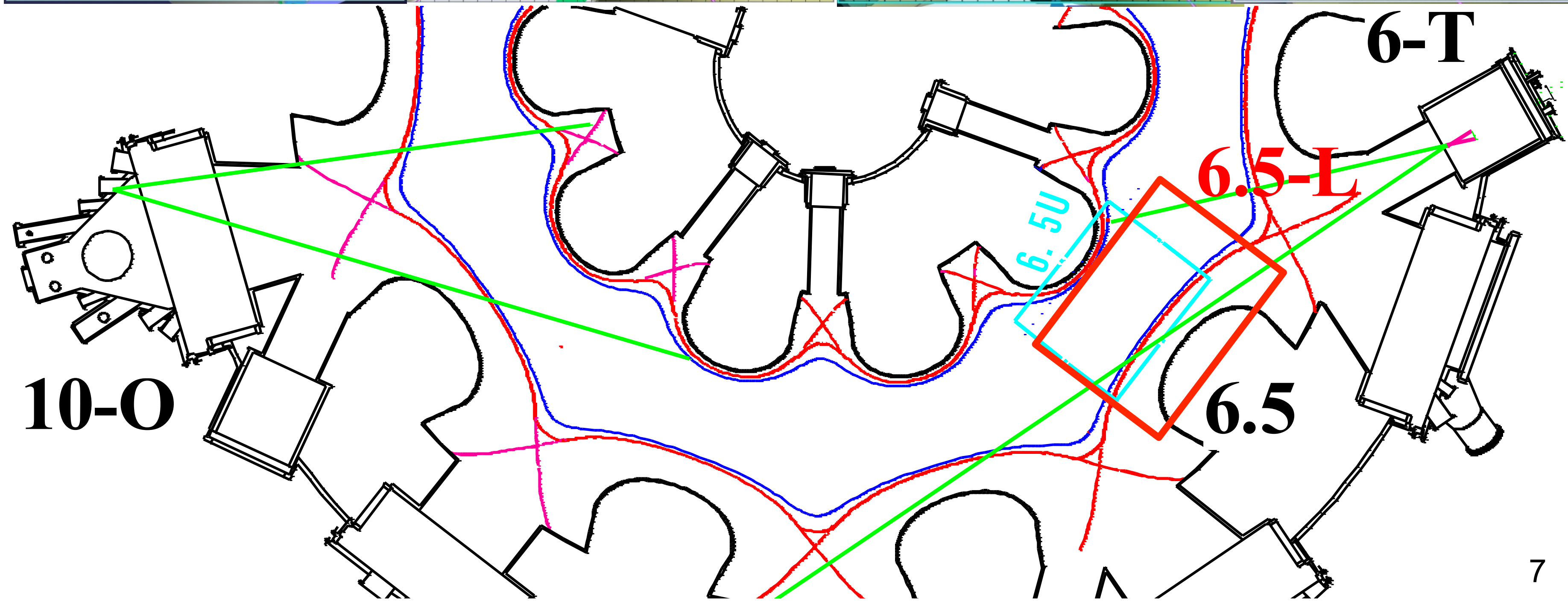
**LHD:** E. A. Drapiko, et.al., Rev. Sci. Instrum. **81** (2010) 10E128.

# 4 IRVBs operating on LHD

Total 2528 channels

| Port 10-O 24x32 ch (SC500 -> SC7600) | Port 6.5-L 20x28 ch (Omega -> SC655) | Port 6.5-U 18x24 ch (SC655) | Port 6-T 24x32 ch (SC4000) |
|---|---|---|---|





# Geometry matrix calculation for synthetic diagnostic for LHD IRVB

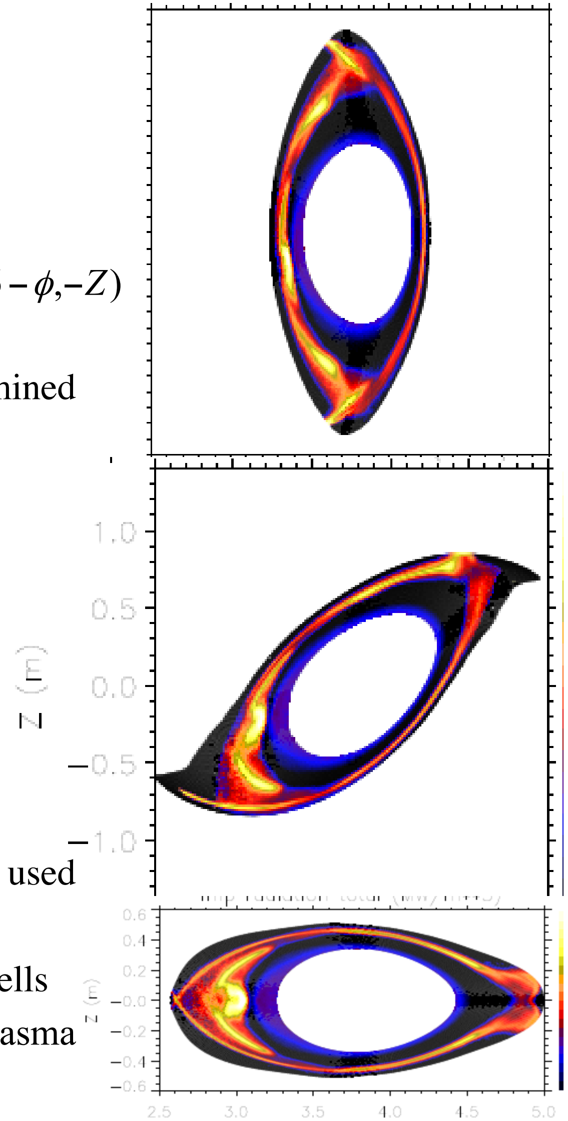
- Plasma is divided into volumes using R, z, $\phi$
- $\Delta R$ = 5 cm, $\Delta z$ = 5 cm, $\Delta\phi$ = 1 degree
- 2.5 m < R < 5.0 m (50 divisions)
- -1.3 m < z < 1.3 m (52 divisions)
- $\phi$ = 0 - 18 degrees (18 divisions) assume helical symmetry $S(R,\phi,Z) = S(R, 36-\phi, -Z)$
- total 46,800 cells
- Intersection of plasma volumes and bolometer chord volumes, $V_{ij}$, is determined using subvoxels < 1 cm
- Solid angle, $\Omega_{ij}$ for the center of each subvoxel is calculated

$$\Omega_{i,j} = A_{\mathrm{det}} / d^2$$

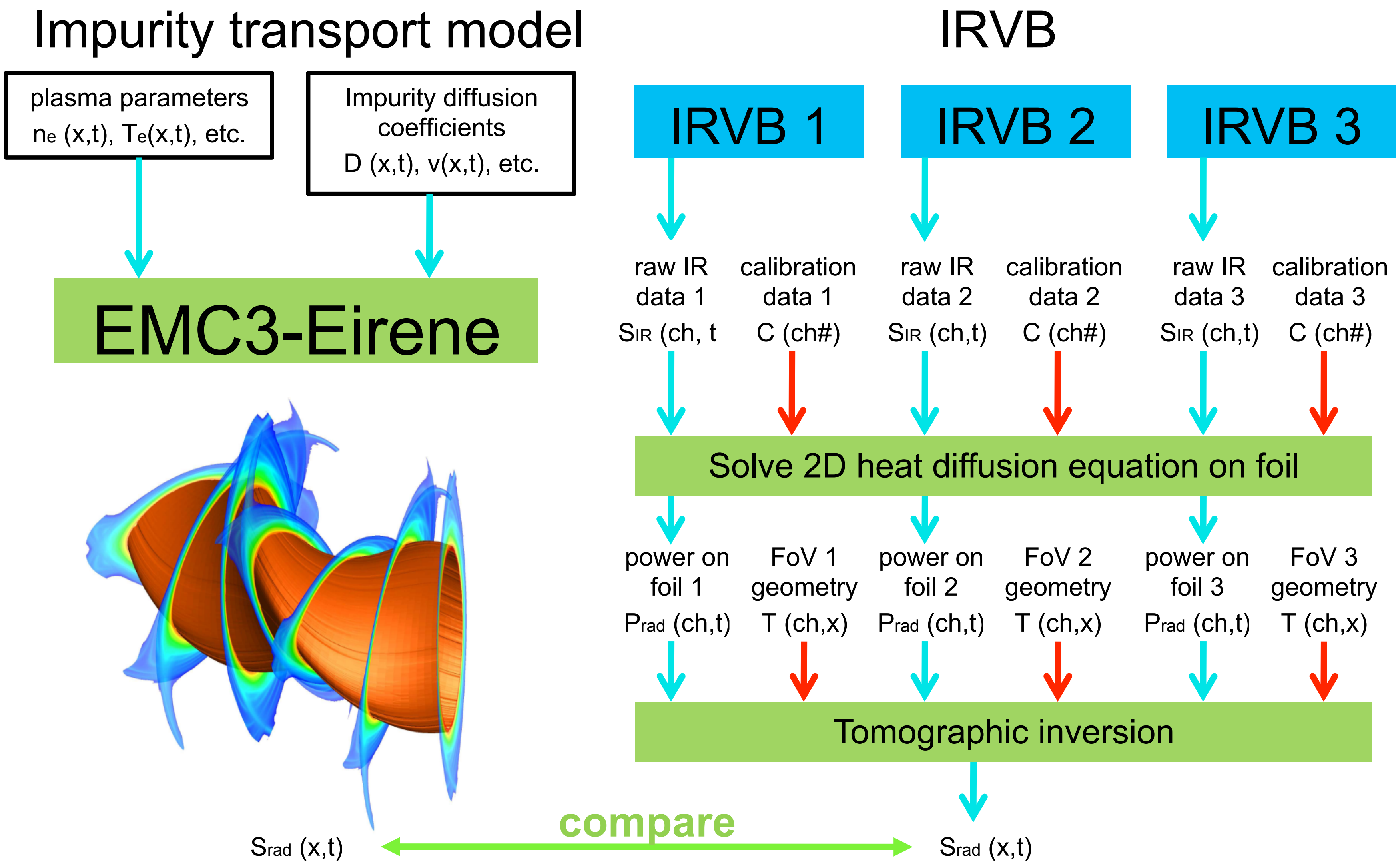
- Write system of equations for detector power, $P_i$, and volume emissivity, $S_j$

$$P_i = \sum_j \frac{\Omega_{ij}}{4\pi} V_{ij} S_j = \sum_j T_{ij} S_j$$

- Then geometry matrix, $T_{ij}$, is determined
- 3-D C radiation data from EMC3-EIRENE is resampled to 5 cm x 5 cm x 1°is used as $S_j$ to calculate $P_i$ at detector
- Use code data to remove non-radiating voxels from edge (by factor 4) to13,161cells
- At each step location of subvoxels is checked to make sure it is within plasma subvolume region and does not intersect wall.
- avg 44 sightlines per voxel, maximum is 113
- All plasma voxels can be seen by at least one IRVB channel



# Tomography – applied to imaging bolometers



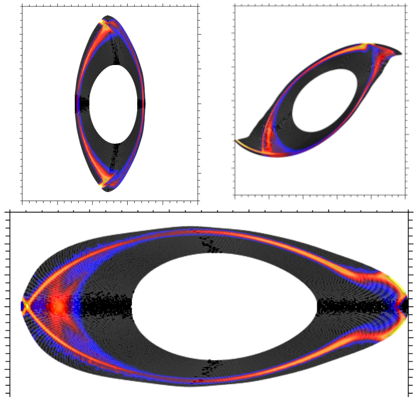

See next presentation by R. Sano

# Synthetic diagnostic – applied to imaging bolometer

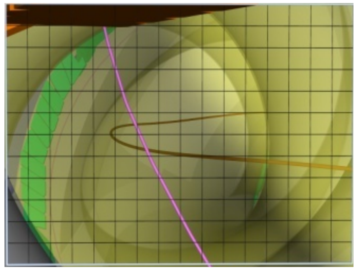
plasma parameters
$n_e\,(x,t)$, $T_e(x,t)$, etc.

Impurity diffusion coefficients
$D\,(x,t)$, $v(x,t)$, etc.

**EMC3-Eirene**



$S_{rad}\,(x,t)$

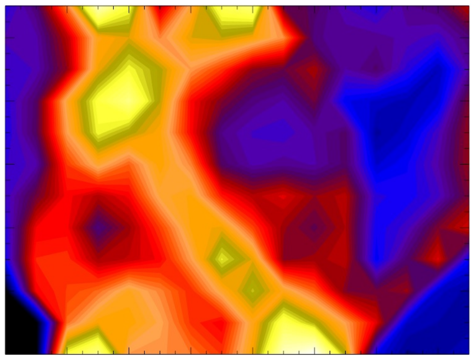


FoV geometry
$T\,(ch,x)$

**geometrical transform (synthetic diagnostic)**

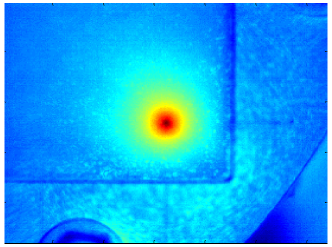
power at foil
$P_{rad}\,(ch,t)$

$$P_i = \sum_j T_{ij} S_j$$



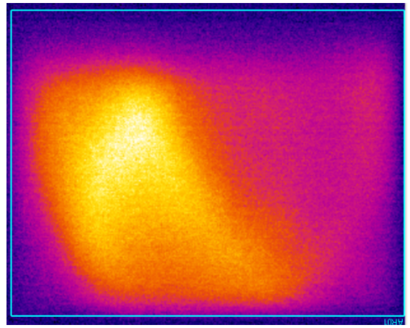
**compare**

**IRVB**

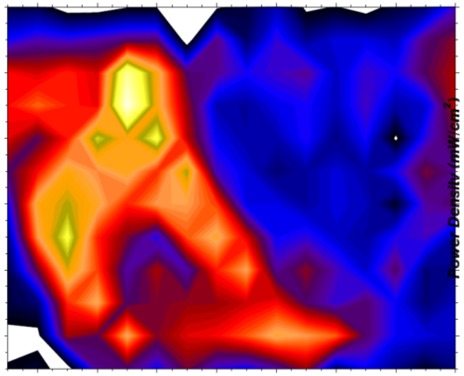


calibration data
$C\,(ch\#)$

raw IR data
$S_{IR}\,(ch,t)$



**Solve 2D heat diffusion equation on foil**



power on foil
$P_{rad}\,(ch,t)$

# Calculation of matrices and synthetic image from EMC3-EIRENE model

Step :1

*Emissivity Matrix*

*Regularize and resample EMC3-EIRENE data to 5 cm X 5 cm X 1º grid for every field period*

*Stack the re-sampled data from all the field periods to give $S_j$ matrix*

Step :2

*Geometry Matrix*

*Plasma is divided into volumes using R, z, $\phi$*
*$\Delta R$ = 5 cm, $\Delta z$ = 5 cm, $\Delta\phi$ = 1 º*
*where*
*2.5 m < R < 5.0 m (50 divisions)*
*-1.3 m < z < 1.3 m (52 divisions) & $\phi$ = 0 – 180 º*
*(total 468,000 cells)*

*Intersection of plasma volumes and bolometer chord volumes, $V_{ij}$, is determined using subvoxels < 1 cm*

*Solid angle, $\Omega_{ij}$ for the center of each sub-voxel is calculated* $\Omega_{i,j} = A_{det}/d^2$

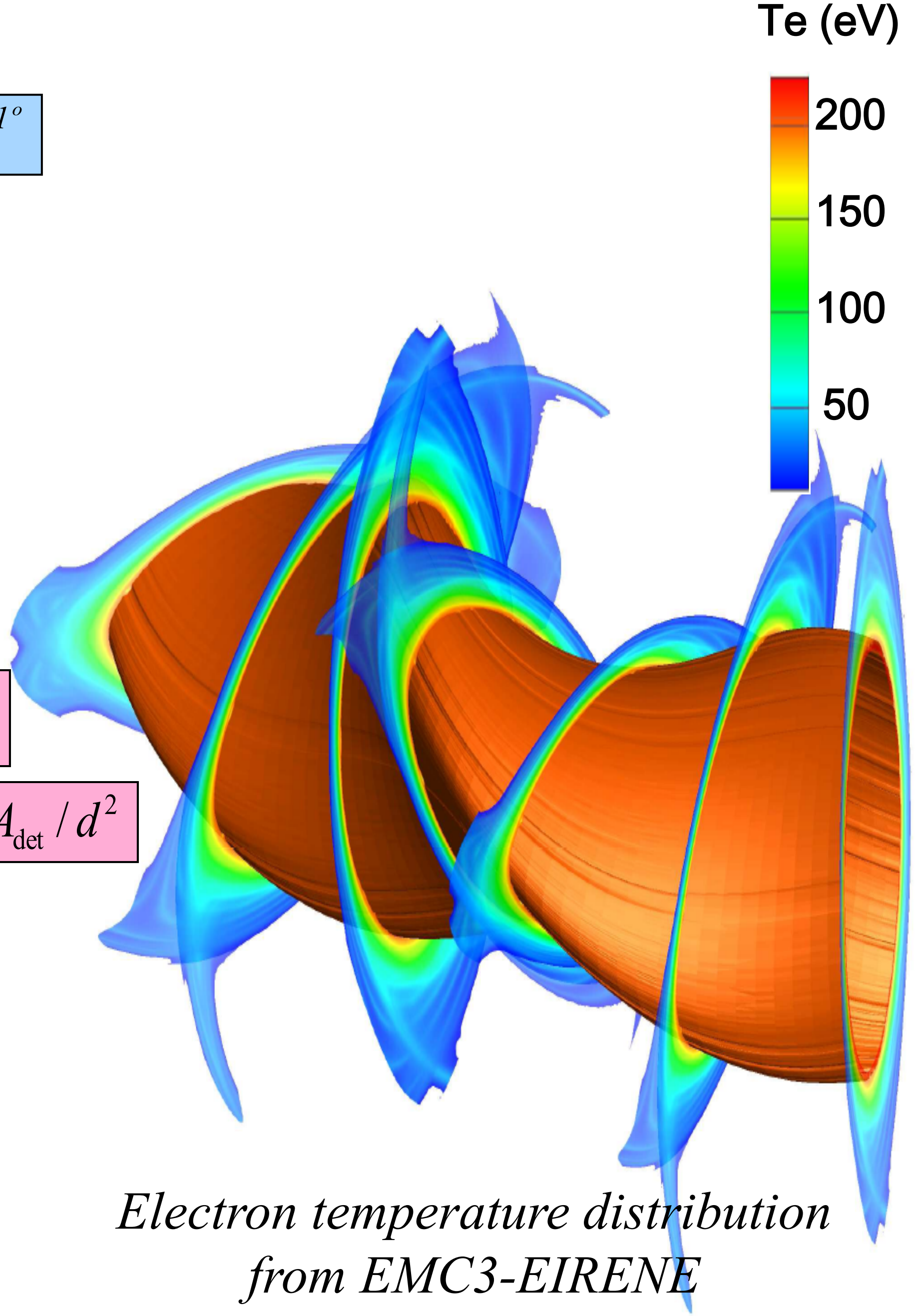
*Geometry matrix, $T_{ij}$, is determined as* $T_{ij} = \frac{\Omega_{ij}}{4\pi} V_{ij}$

Step :3

*Detector Power*

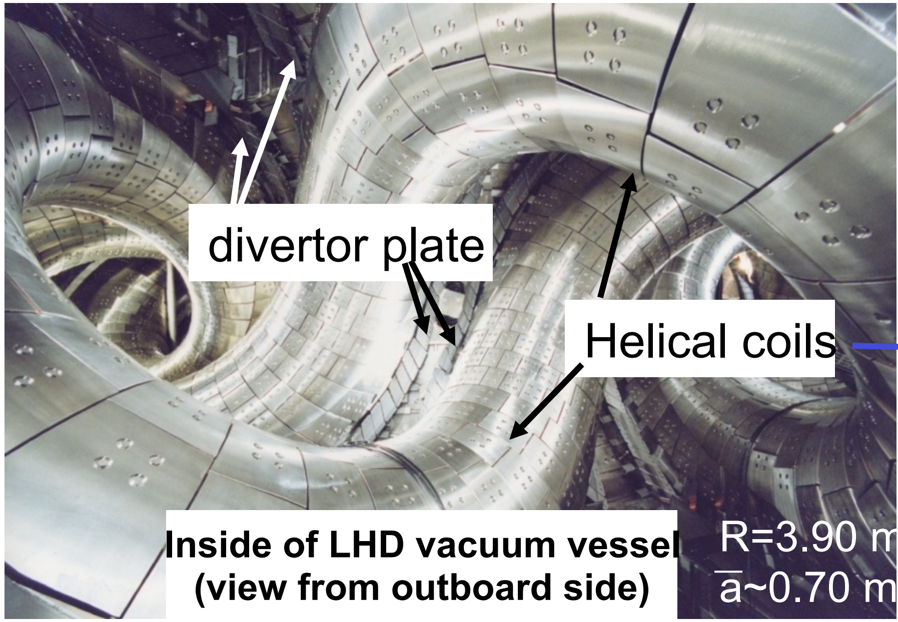
*Detector power, $P_i$ can be determined by multiplying geometry matrix and emissivity matrix*

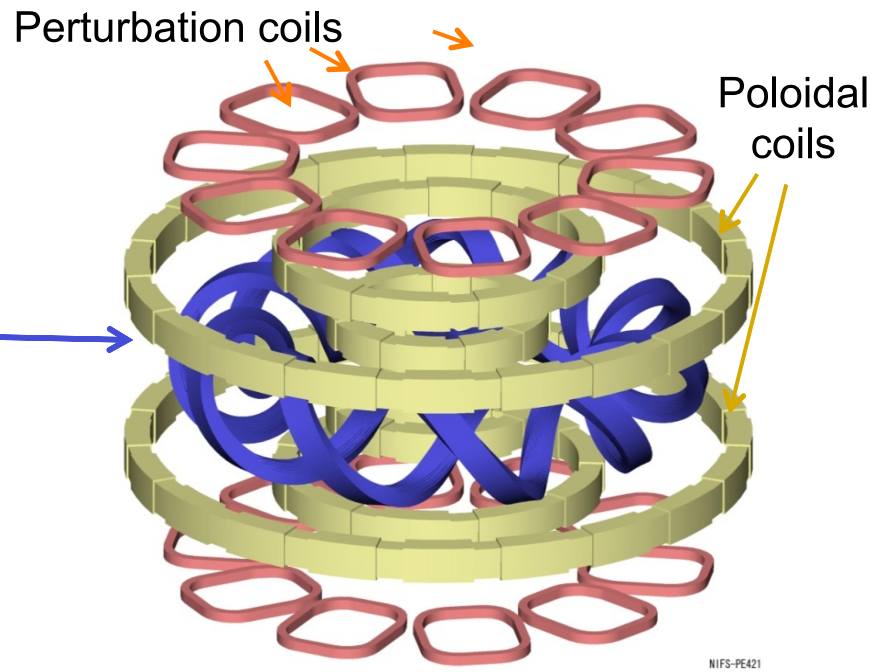
$$P_i = \sum_j \frac{\Omega_{ij}}{4\pi} V_{ij} S_j = \sum_j T_{ij} S_j$$

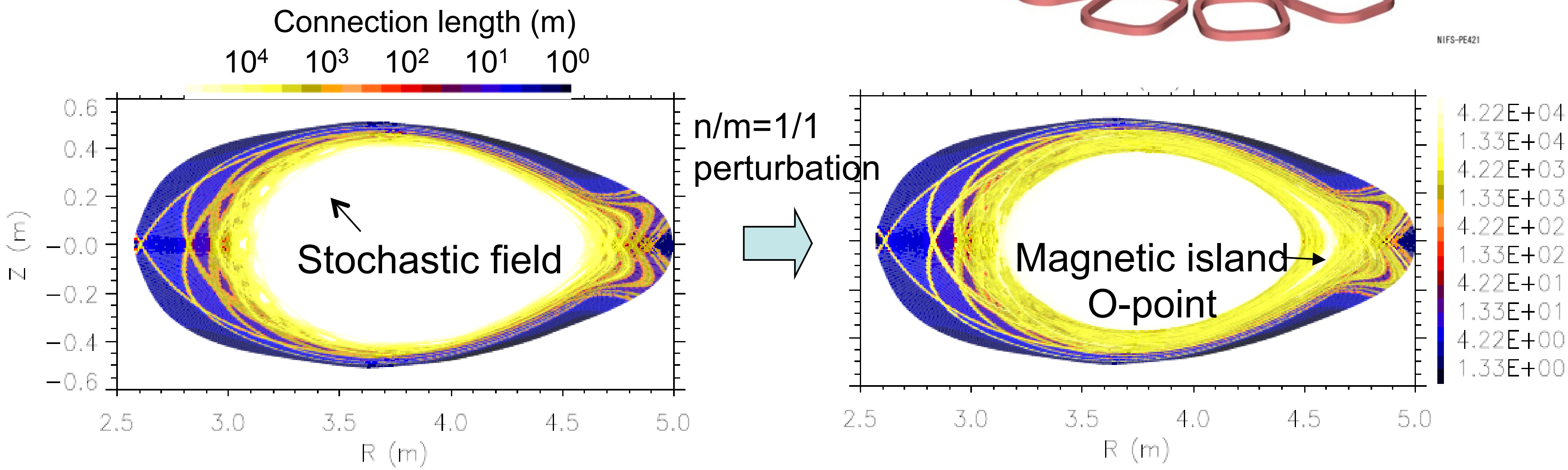



*Electron temperature distribution from EMC3-EIRENE*

## Edge stochastic magnetic field and modification by n/m=1/1 resonant perturbation



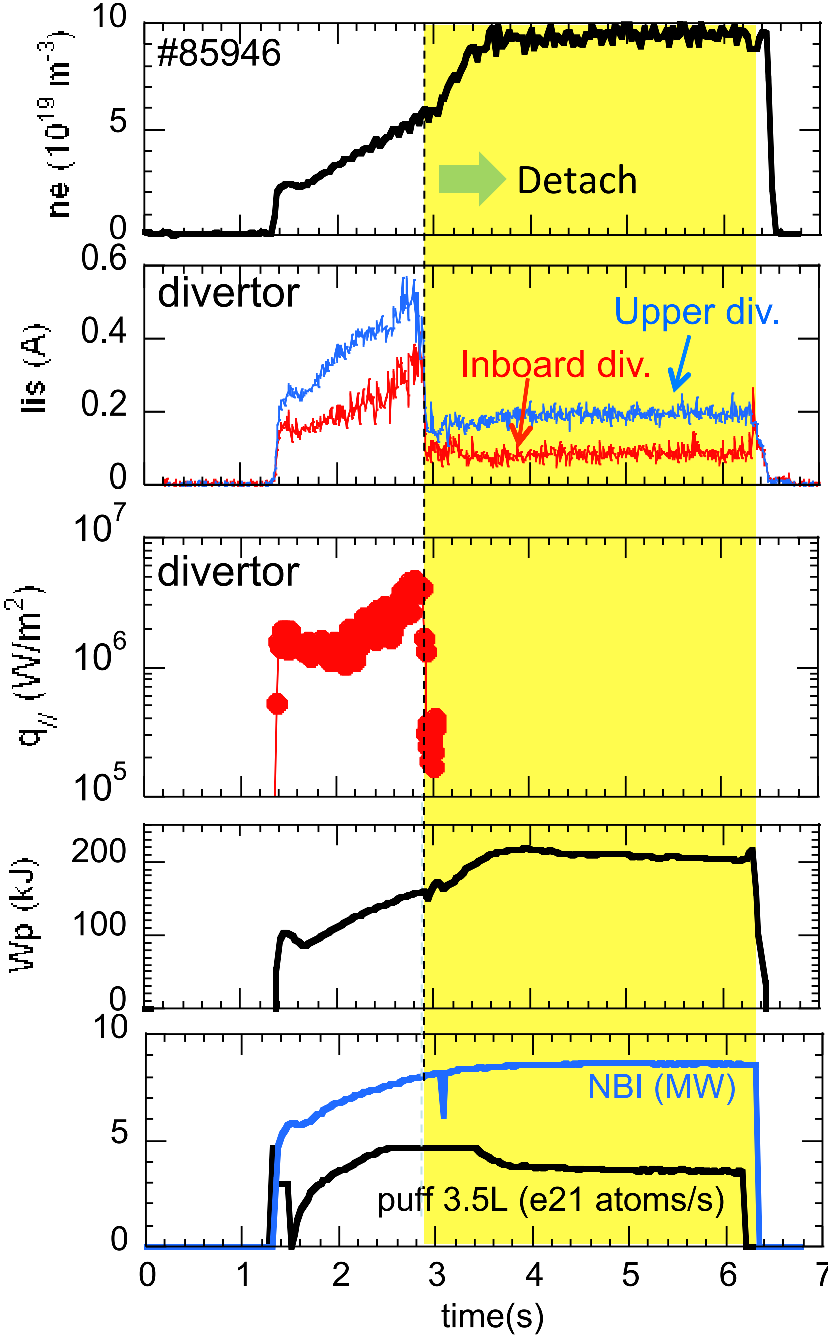



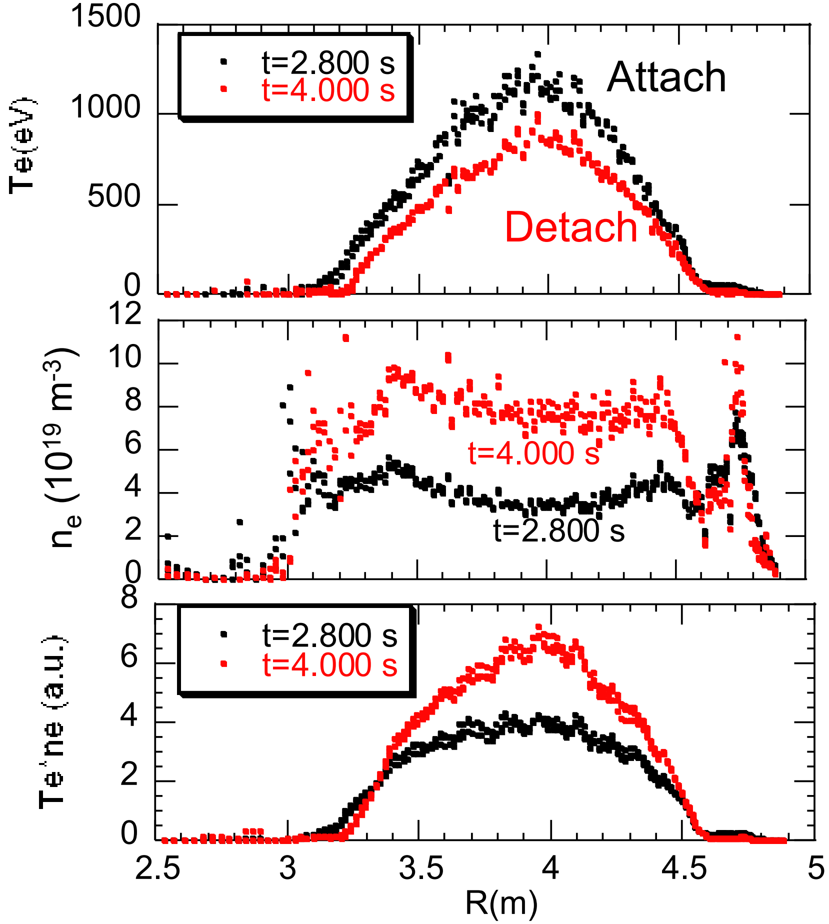

Large flexibility in changing field structure of LHD edge region:
1/1 Island size, radial/toroidal location, stochastic boundary thickness

M. Kobayashi, PoP 17 056111 (2010)

# Sustained detachment with application of n/m=1/1 island




1/3 reduction of divertor particle flux
1/10 reduction of divertor energy flux
The discharge was terminated by stop of NBI heating.
No confinement degradation, even slight improve.

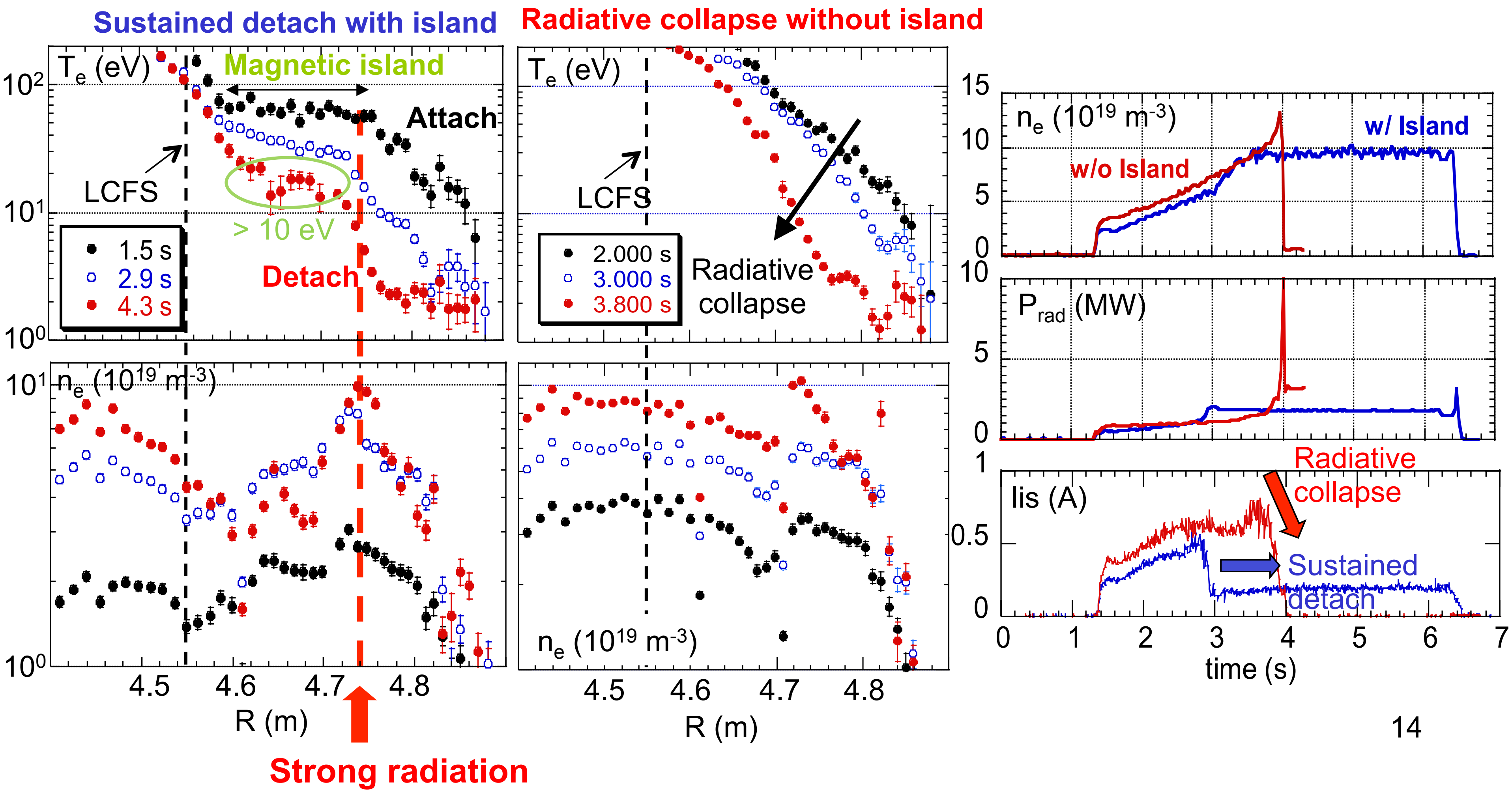


## The island structure seems to stop radiation region penetrate inward

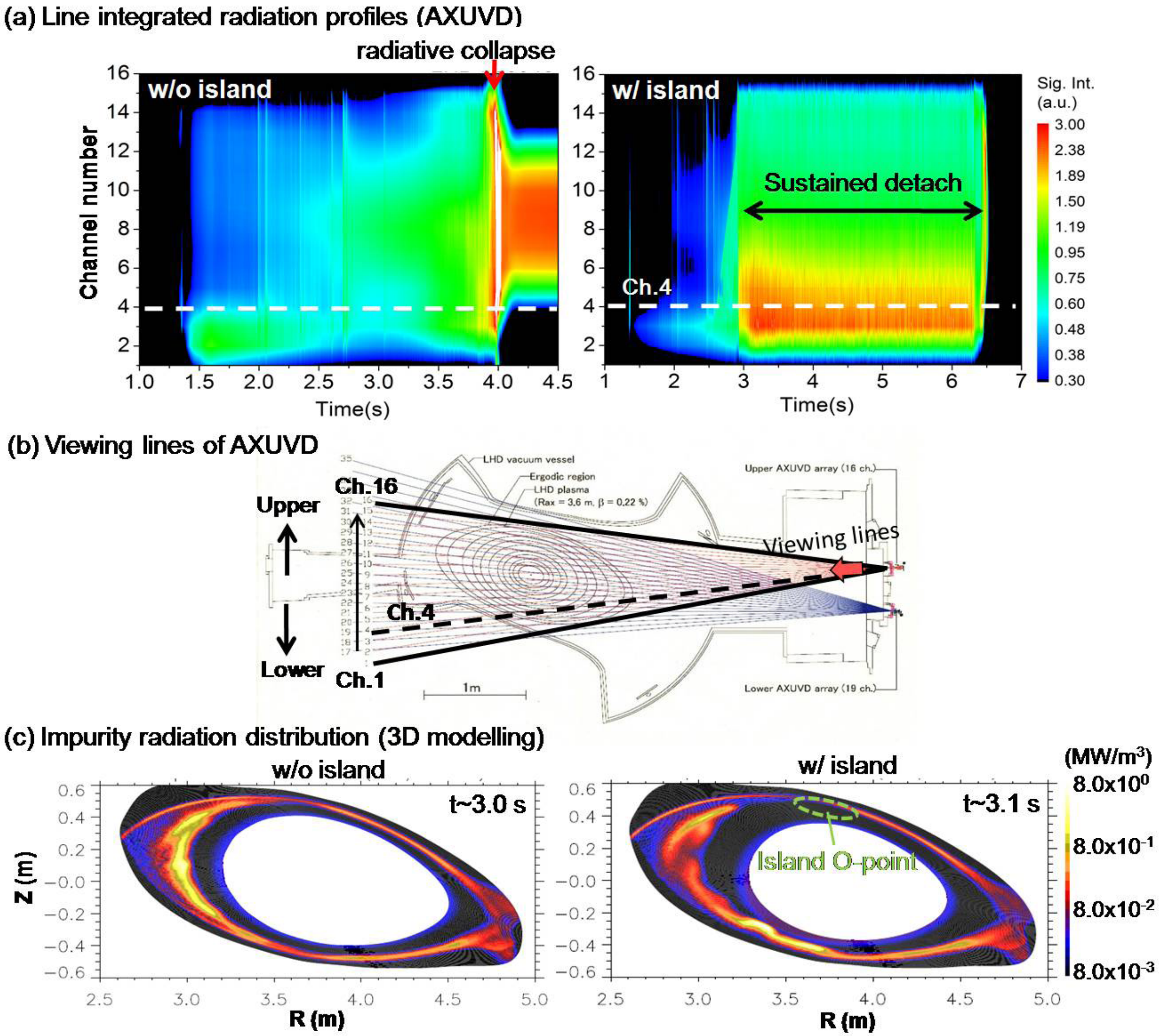
**Inside island parallel transport dominant**

- **→ kept more than 10 eV > carbon radiation peak Te**
- **→ Stop radiation region penetrate inward**
- **→ few eV & $10^{20}$ $m^{-3}$ plasma (strong radiation) outside LCFS**
- **→ Indicates strong radiation around separatrix**

**Density ramp up leads to radiative collapse without n/m=1/1 island.**



# Detached plasma with magnetic island in LHD

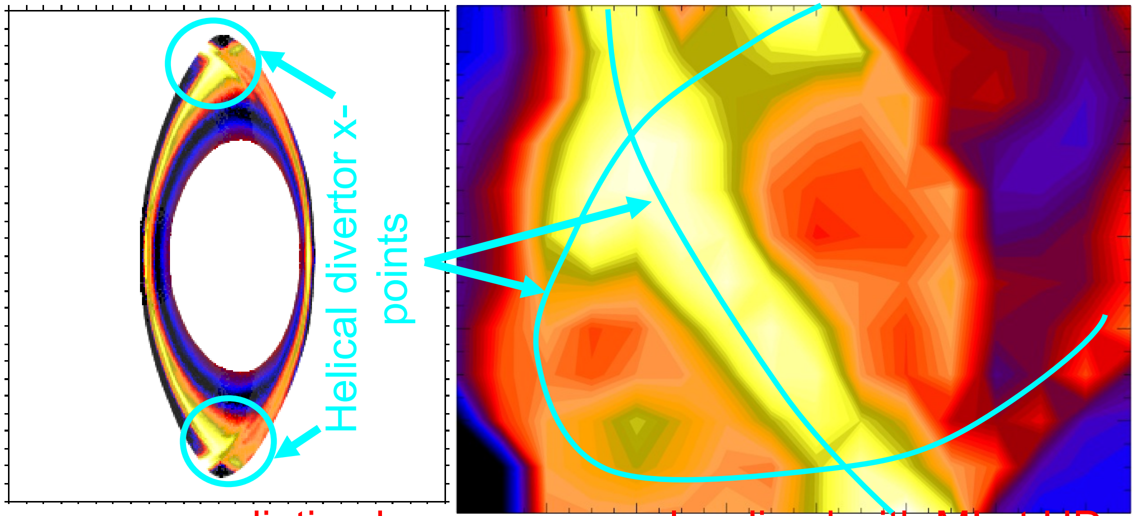



M. Kobayashi, et al., PoP

# Radiation Localization at HD X-points with Magnetic Island

C radiation data from EMC3-EIRENE

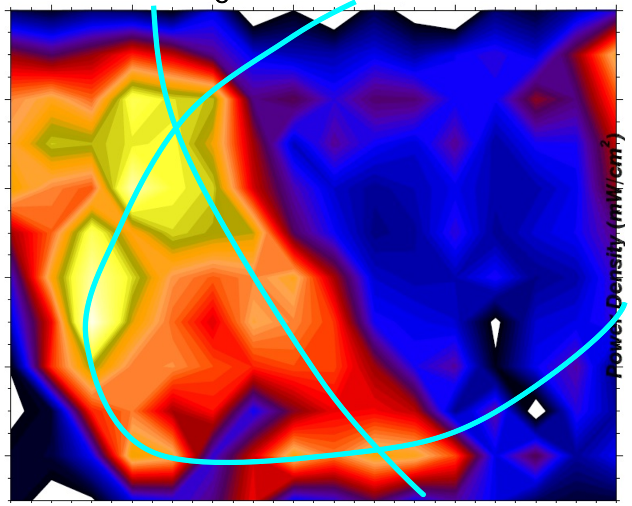
no island, $n_{LCFS}$ = 4x10$^{19}$, attached




Imaging bolometer data

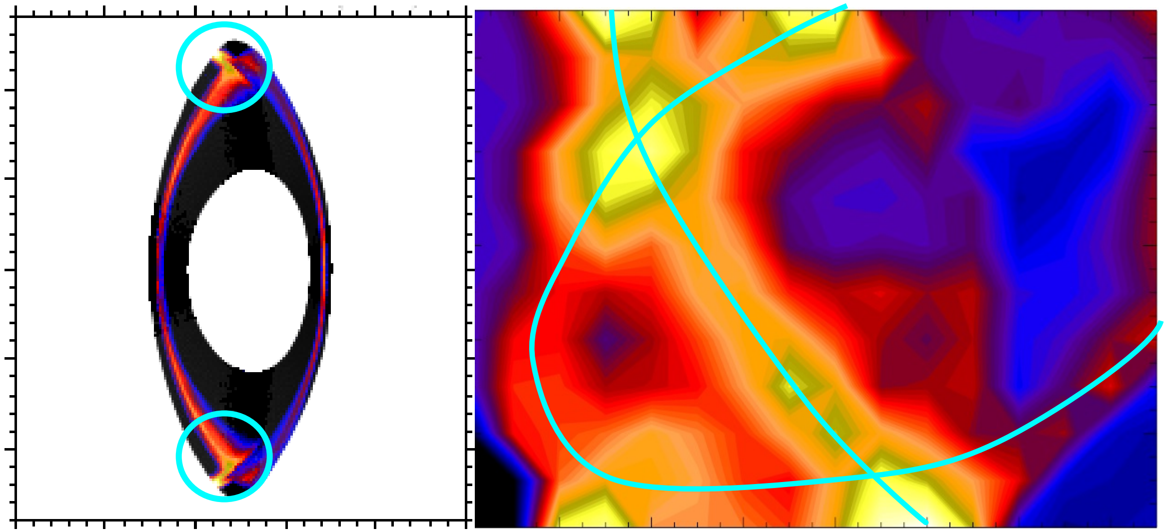
**Shot 97365, t=4.5 s**

no island, $n_e$ = 5x10$^{19}$, attached



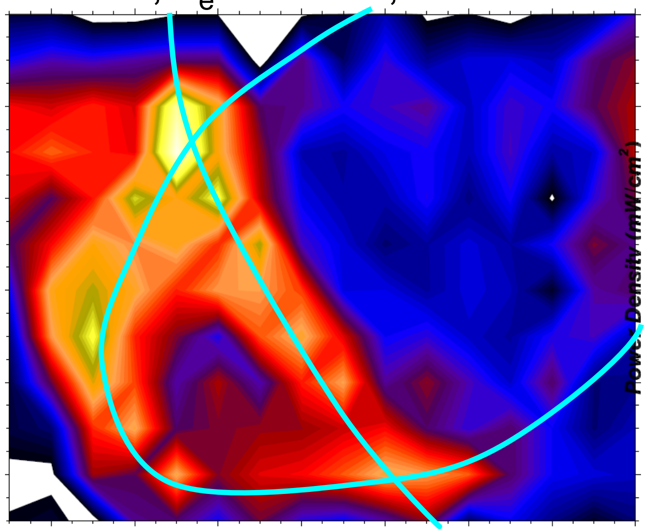
radiation becomes more localized with MI at HD x-point as predicted by code

with island, $n_{LCFS}$ = 4x10$^{19}$, attached



**Shot 97327, t=4.5 s**

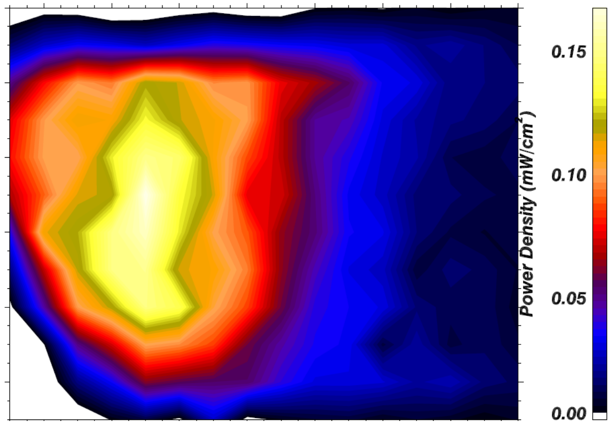
with island, $n_e$ = 5x10$^{19}$, attached



# Radiation becomes more well defined in helical divertor with increasing density and the addition of magnetic island

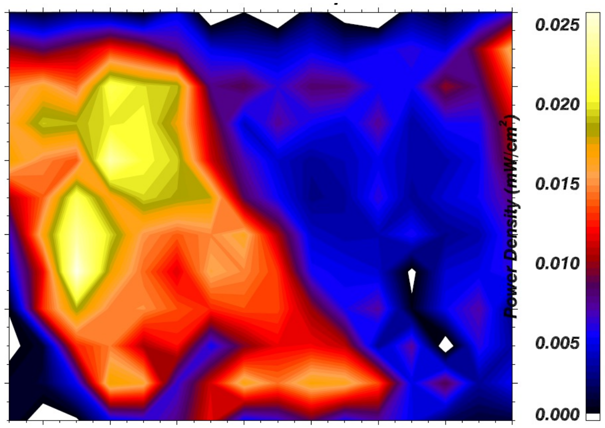
Shot 97353, t=5.3 s

no island, $n_e$ = 1.5x$10^{19}$ attached



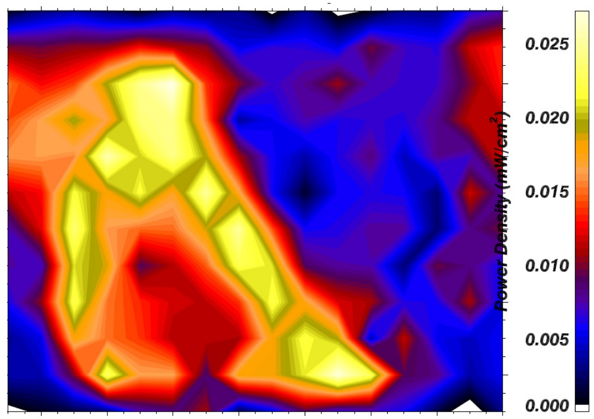

Shot 97365, t=4.5 s

no island, $n_e$ = 5x$10^{19}$ attached



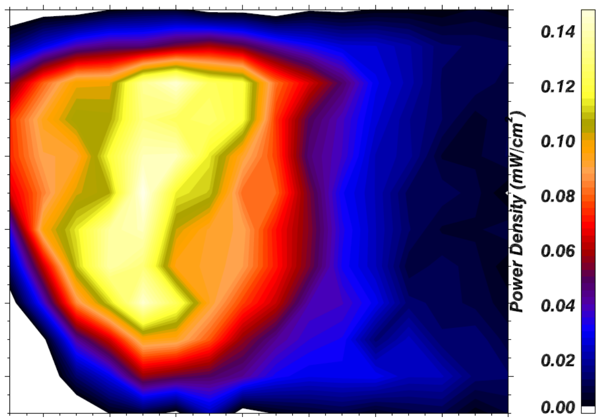

Shot 97365, t=6.0 s

no island, $n_e$ = 7x$10^{19}$ attached



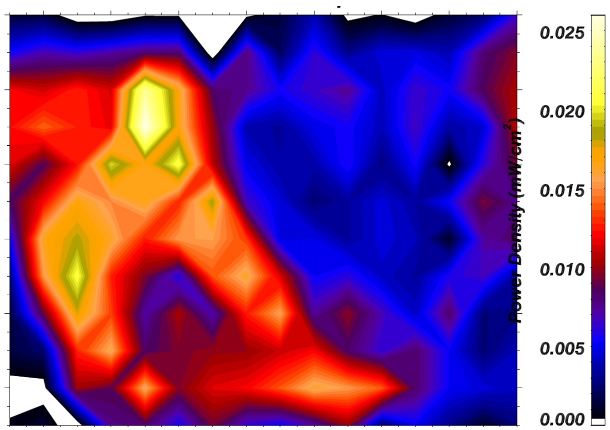

Shot 97354, t=5.3 s

with island, $n_e$ = 1.5x$10^{19}$ attached



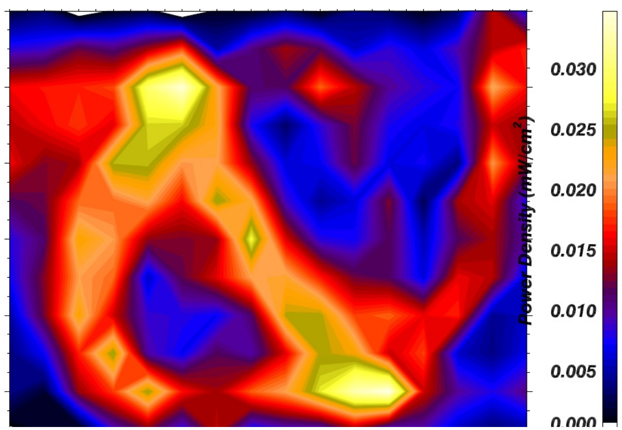

Shot 97327, t=4.5 s

with island, $n_e$ = 5x$10^{19}$ attached




Shot 97327, t=6.0 s

with island, $n_e$ = 6x$10^{19}$ detached



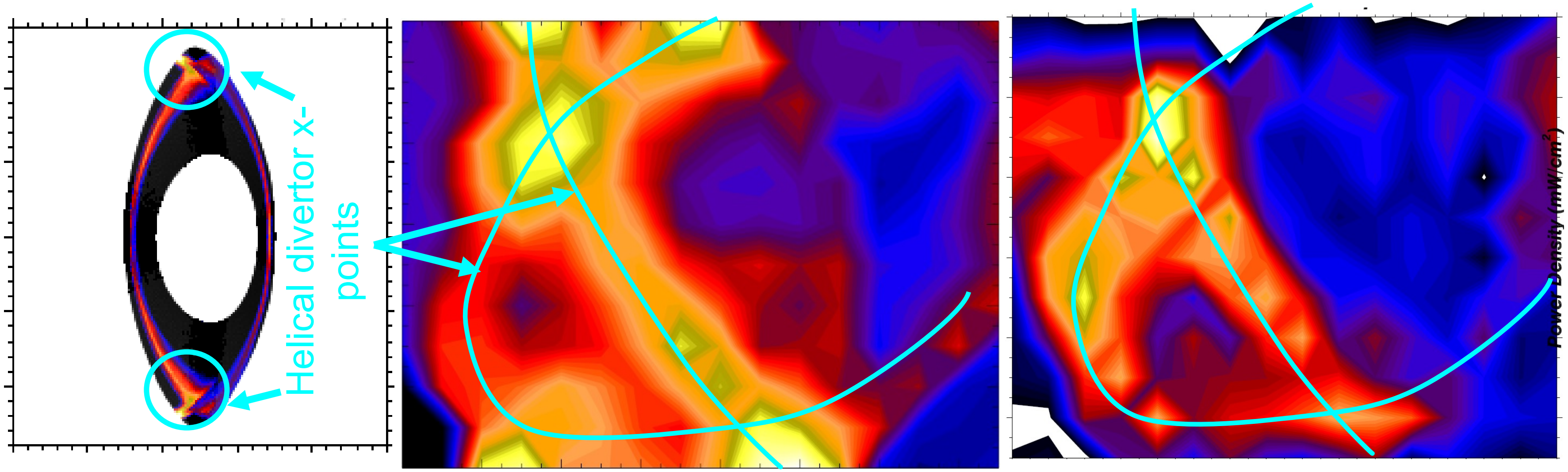
# Increase in MI X-point Radiation with Detachment

C radiation data from EMC3-EIRENE

Imaging bolometer data

with island, $n_{LCFS} = 4 \times 10^{19}$, attached

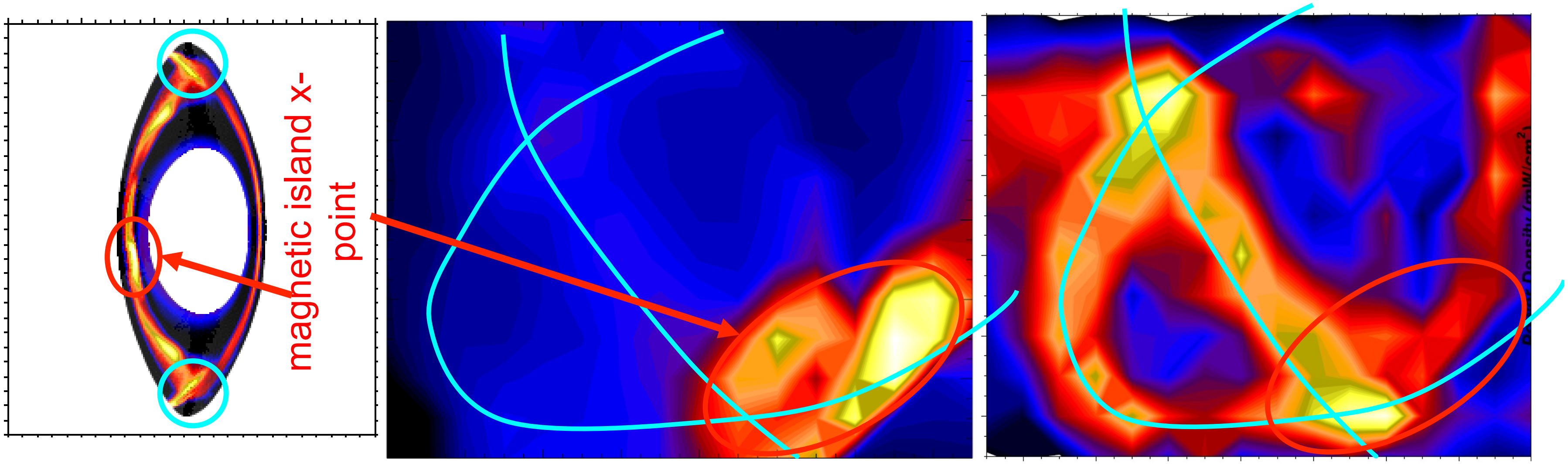
with island, $n_e = 5 \times 10^{19}$, attached




MI x-point radiation increases with detachment as predicted but overestimated by code

with island, $n_{LCFS} = 5.5 \times 10^{19}$, detached

with island, $n_e = 6 \times 10^{19}$, detached



# Detached plasma with magnetic island in LHD viewed from 6-T

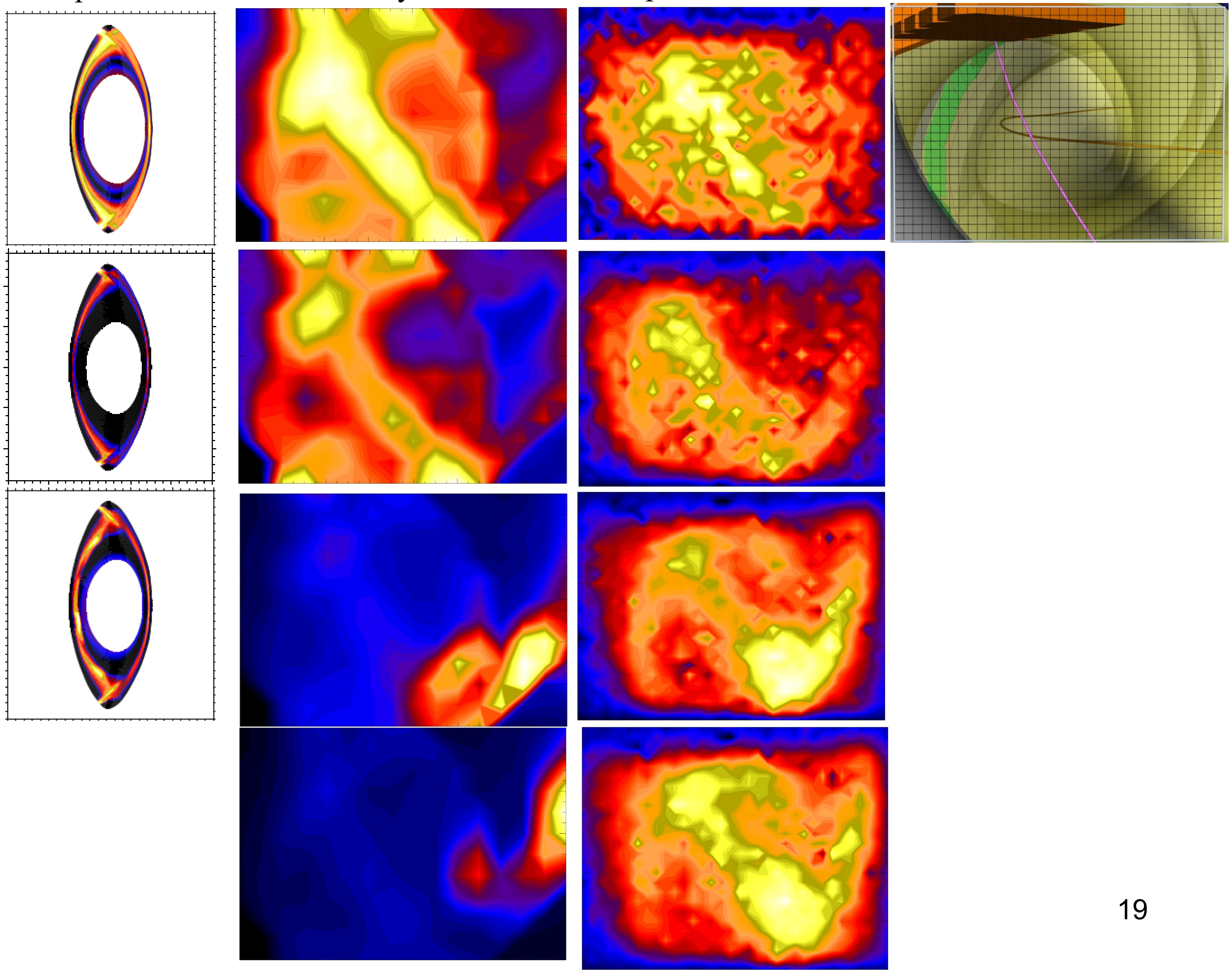
Model – pol. xsection | Model – synth. instrum. | Experiment - IRVB

without MI attached

with MI at 6-O attached

with MI at 6-O detached

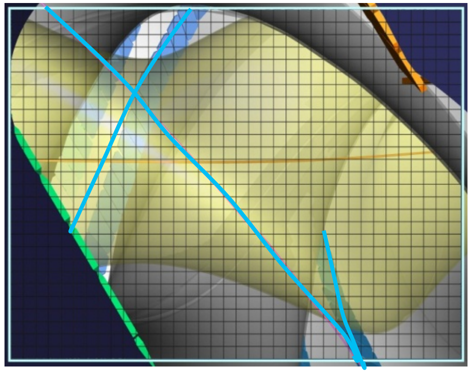
with MI at 7-O detached

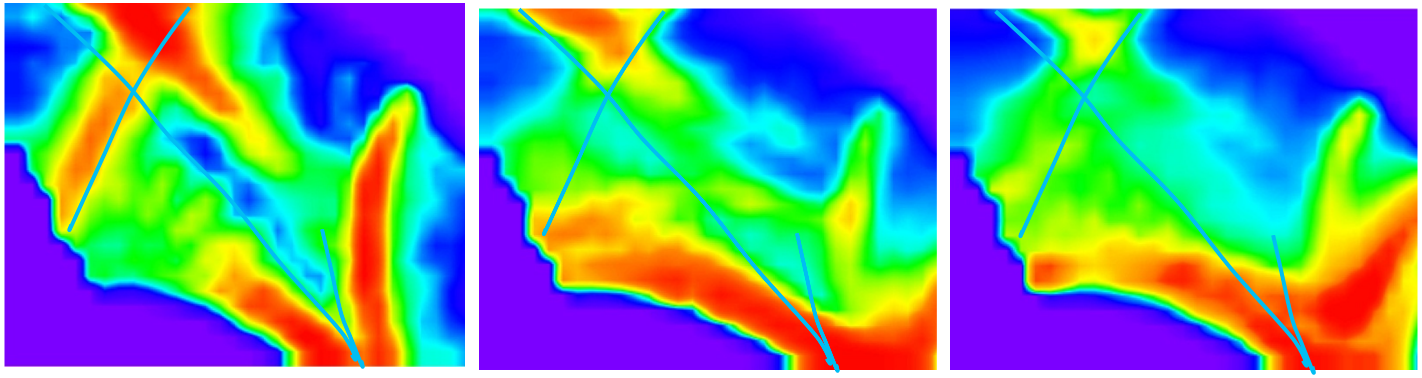


# Detached plasma with magnetic island from LHD port 10-O

**CAD view from Port 10-O**

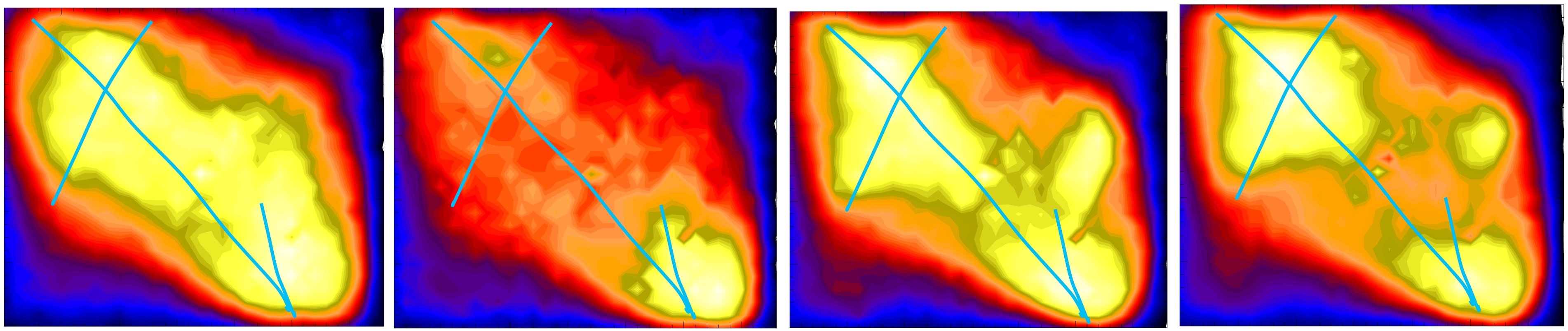
**Synthetic Images from EMC3-EIRENE data**



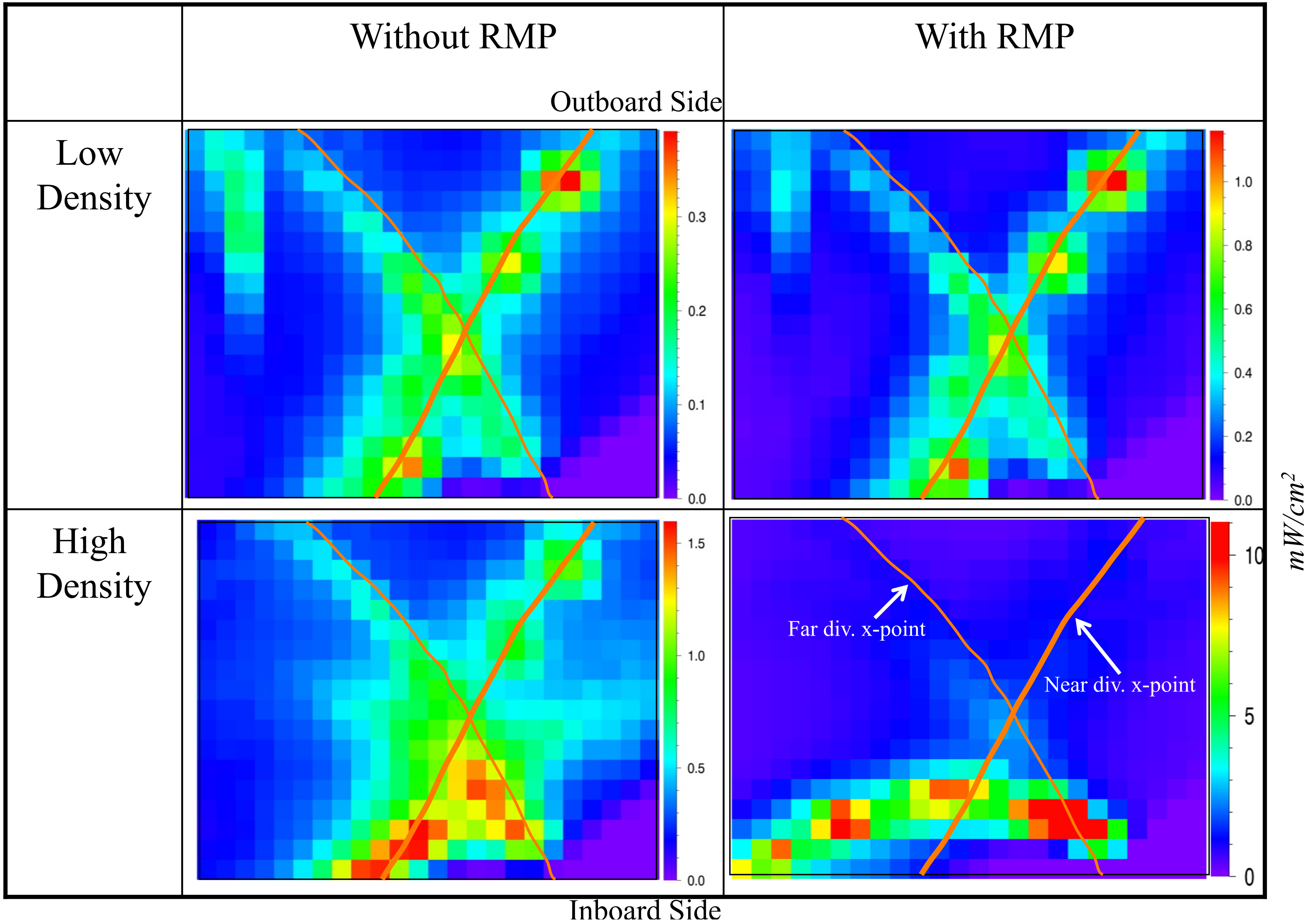


**IRVB data**

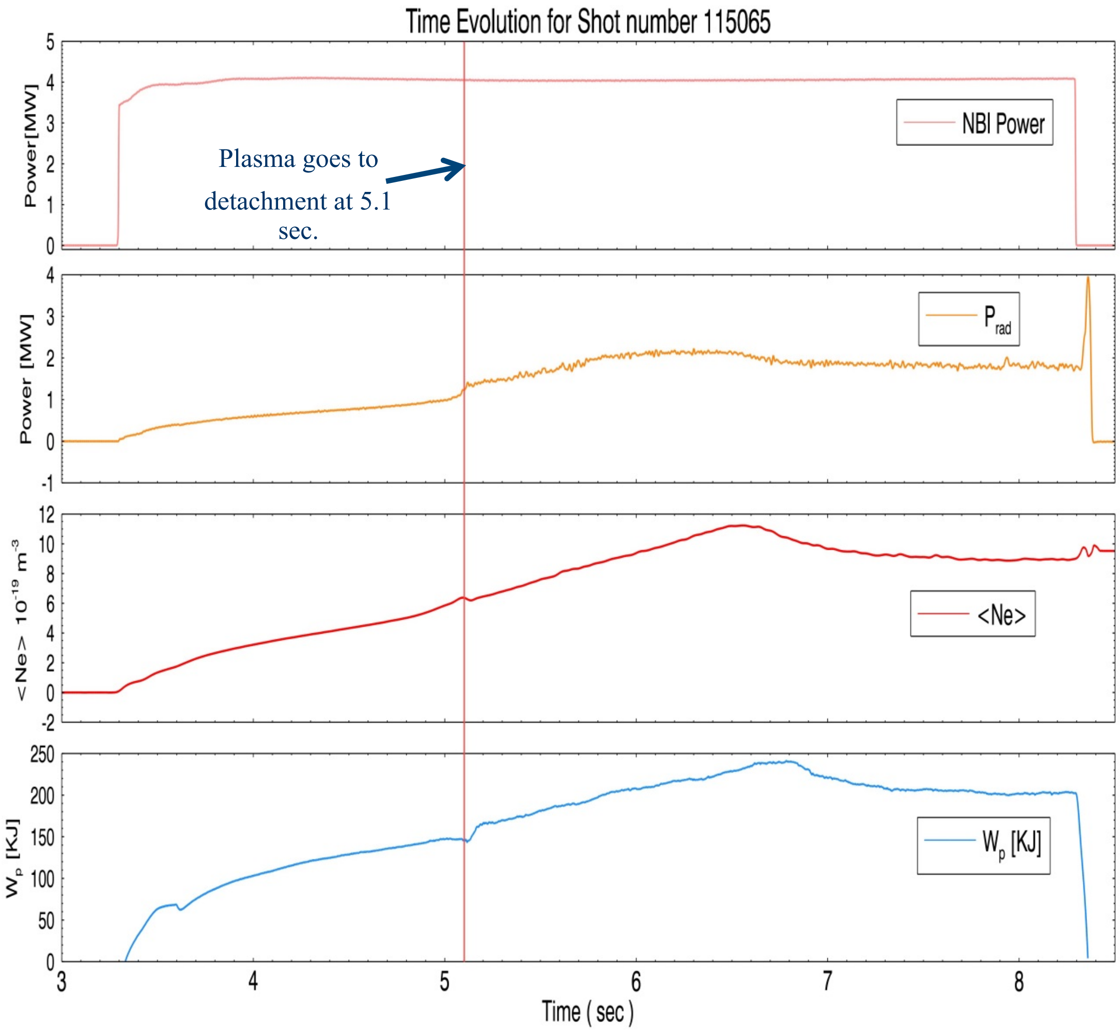
No MI attached | with MI at 6-O attached | with MI at 6-O detached | with MI at 7-O detached

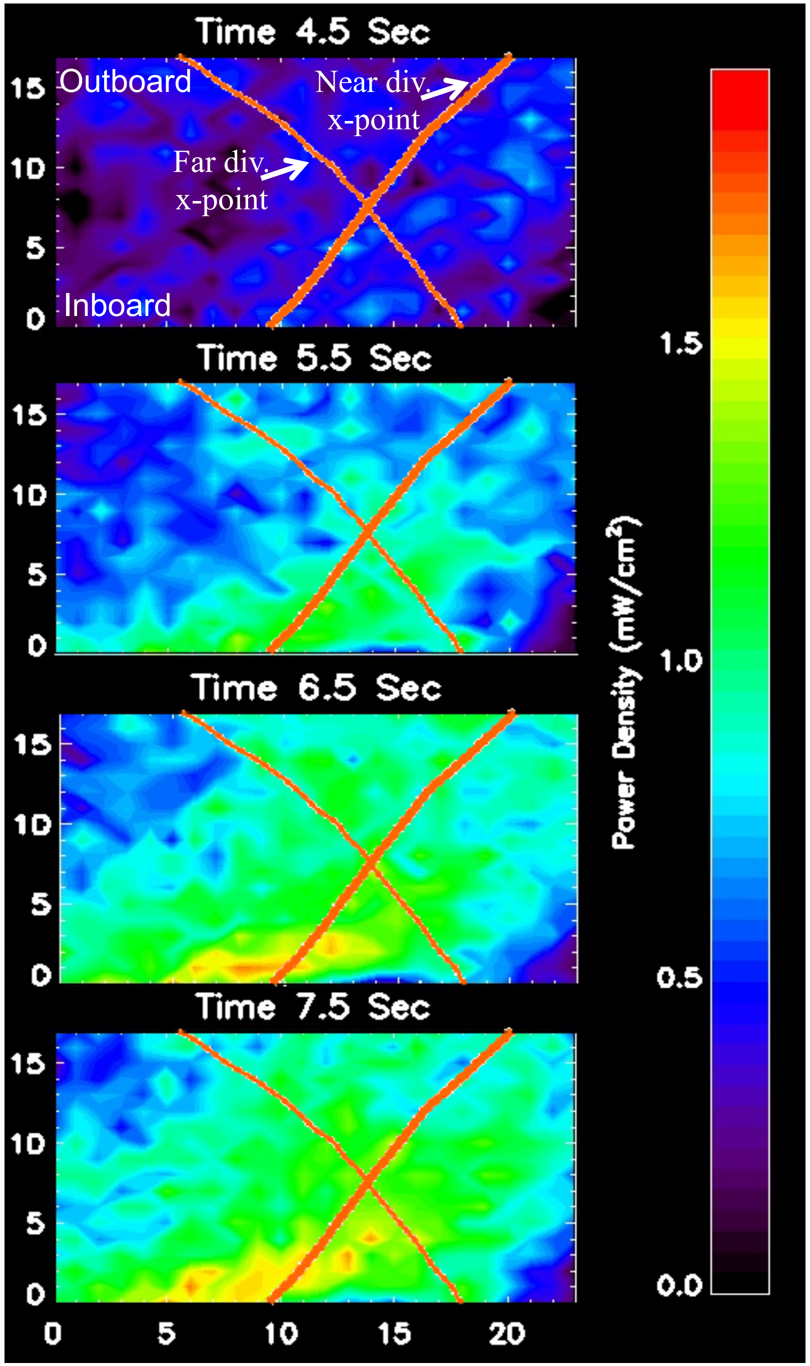


# Model predicts radiation localization in island X-point during detachment



# Experiment shows radiation localization near island X-points as detachment occurs

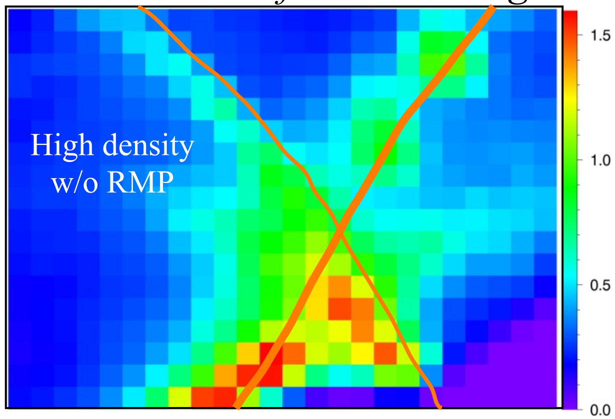


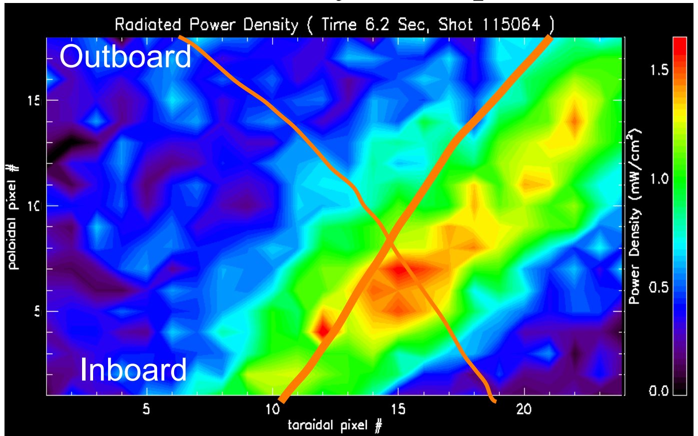



# Experiment and Modeling – a comparison

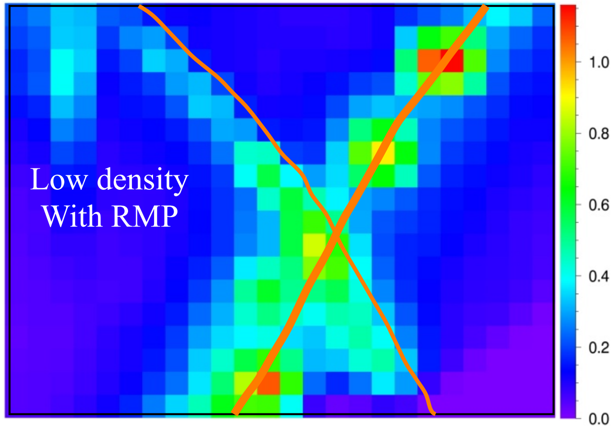
*General observations* | *Carbon radiation from modeling* | *Plasma radiation from Experiment*

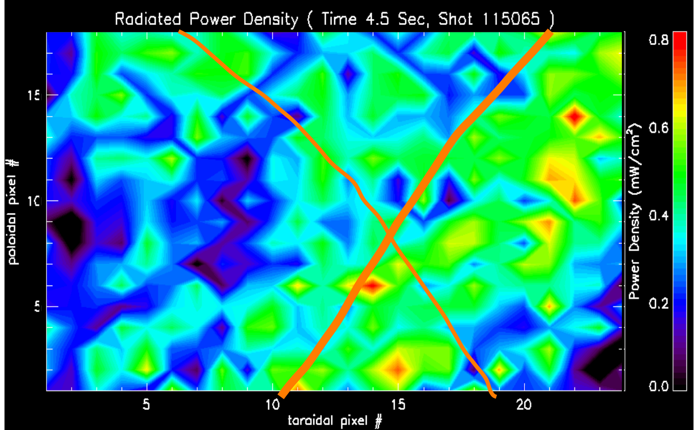
- *Modeling – radiation along far and near divertor X-point trace*
- *Experiment – stronger radiation from near divertor X-point*
- *Power densities nearly match*



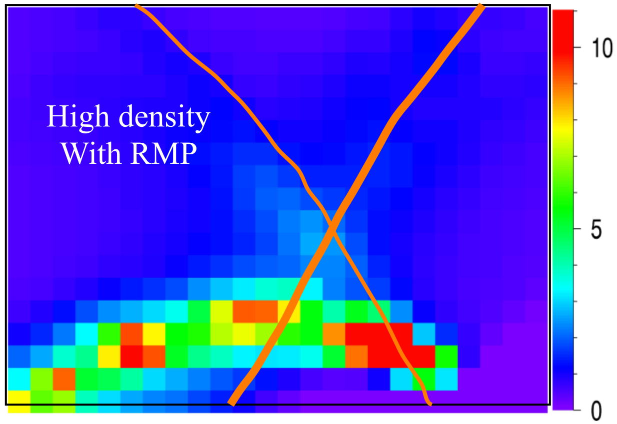



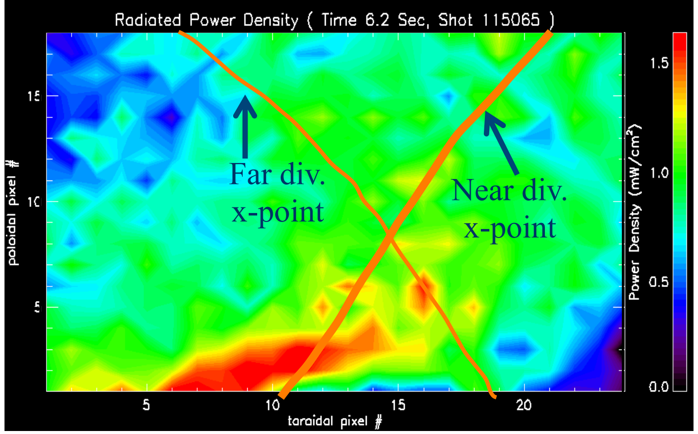

- *Modeling – radiation along far and near divertor X-point trace*
- *Experiment –radiation from both near and far divertor X-points*
- *Power densities nearly match*




- *Modeling and experiments shows radiation localization near the island X-point towards inboard side*
- *Modeling - power densities 7 times higher than experiments*
- *The change in radiation pattern is similar both in modeling and experiments*



# Conclusions and Future Research

- Last year’s results
  - Three Imaging bolometers are installed on LHD
    - Ports 10-O, 6-T , 6.5-L and 6.5-U
    - 6-T and 10-O (24 x 32 channels each)
    - 6.5-U 18 x 24 ch
    - 6.5-L 20 x 28 (total 2528 ch)
    - laser calibration data is being analyzed (Itomi)
    - Study of detached plasma with and without island (Pandya, Drapiko, Peterson)
    - geometry matrices have been calculated for all IRVBs (Peterson, Sano)
- This year’s plan
  - Operate IRVBs at 6-T (SC4000), 10-O (SC500), 6.5-L (Omega) to study:
    - Evolution of Magnetic island assisted detached plasmas (Pandya)
    - 3-D properties of asymmetric radiative collapse (Sano)
  - install periscope at 6.5-U (Pandya)
  - Optimize FOVs at 6-T and 10-O using geometry matrix program (Peterson, Sano)
  - Sample data (from code and measurements) and geometry matrices to Iwama, Teranishi et al. for development of 3D tomography software (Sano)
  - Finish analyzing calibration data and incorporate into analysis for absolute measurements (Itomi, Pandya, Sano)

# Upgrade IRVBs on LHD

- **Currently 4 IRVBs on LHD (2528 ch)**
  - **tangential (6-T) (24 x 32 ch) (SC4000)**
  - **semi-tangential (10-O) (24 x 32 ch) (SC500 -> SC7600)**
  - **top (6.5-U) (18 x 24 ch) (SC655, add periscope)**
  - **bottom (6.5-L) (20 x 28 ch) (omega -> SC655)**

- **increase number of channels in 2014**
  - **add radial (8-O) (24 x 32 ch) (SC655) (direct view of closed divertor)**
  - **Increase lower (6.5-L) and upper (6.5-U) (24 x 32 -> 36 x 48 ch) (by adding periscope)**
  - **total 5000 channels from 5 IRVBs optimized for 3D tomography**