Sputtering of beryllium PFCs in JET enhanced by ICRH-induced RF-sheaths

Spectroscopic results from 2011-2012 JET-ILW commissioning plasmas and modeling needs to extract more PMI physics from the existing data

C.C. Klepper, ORNL, 4-Jun-2013

Presentation partly based on paper presented at the 20th PSI (Aachen 2012) with P. Jacquet (CCFE), V. Bobkov (IPP-Garching), L. Colas (CEA, IRFM), T.M. Biewer (ORNL), D. Borodin (FZ-Juelich), A. Czarnecka (IPPLM-Warsaw), C. Giroud (CCFE), E. Lerche (IRM-KMS-Brussels), V. Martin (now at ITER IO), M.-L. Mayoral (now at EFDA, Garching) et al.

Topics

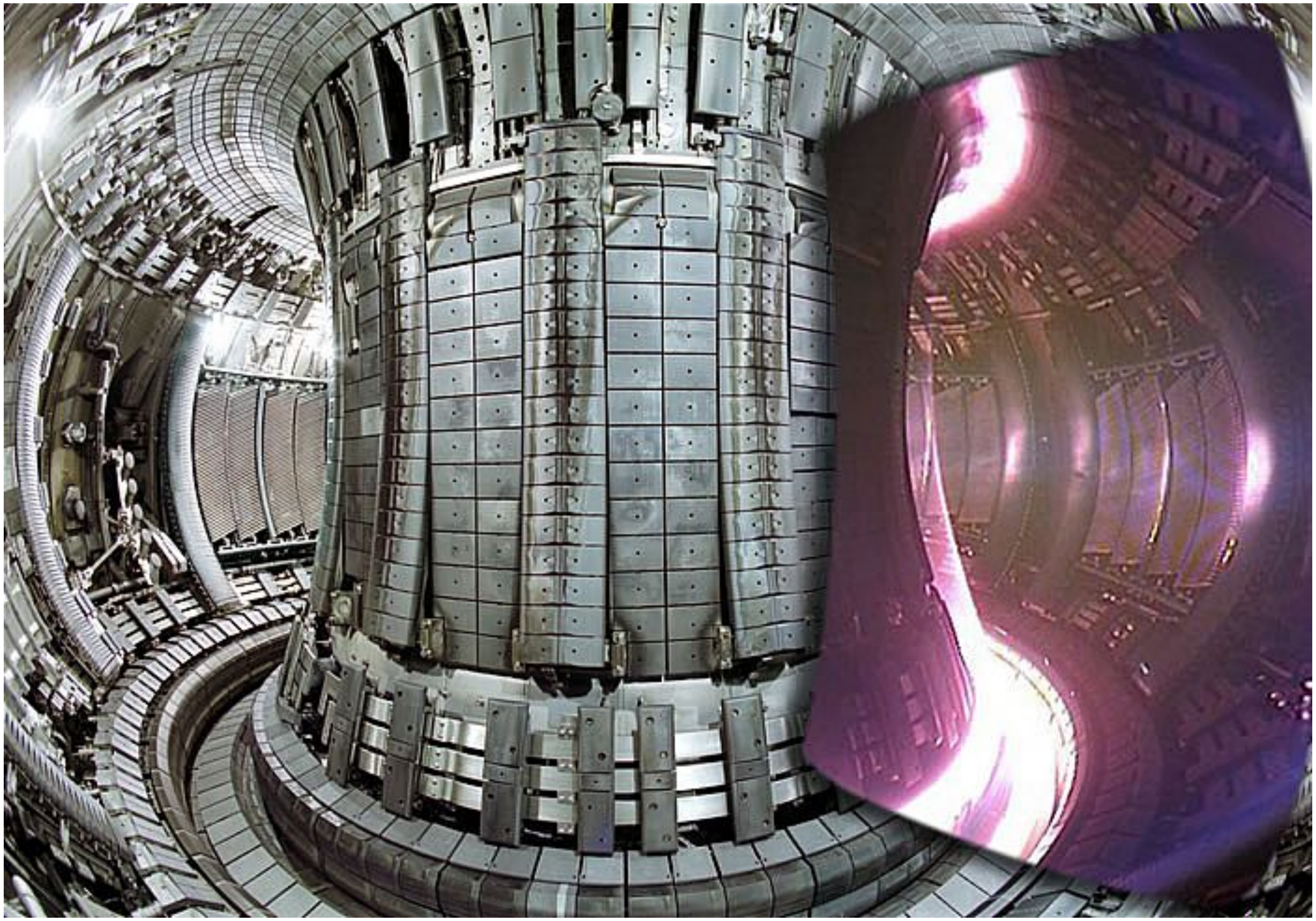
- Quick Review of JET ICRH Physics Findings 2011-2012, including
  - The connection to our collaboration with the IRFM (Tore Supra, now WEST team).
- Plans (hopes) for additional analysis/modeling of existing data, including
  - >ERO code modeling to extract Be erosion and predictions for ITER Be PFCs
- Near and long-term plans for JET-ILW participation, including
  - Improved mapping of Be sources
  - Extension to characterization of W sources

JET ICRH Antennas

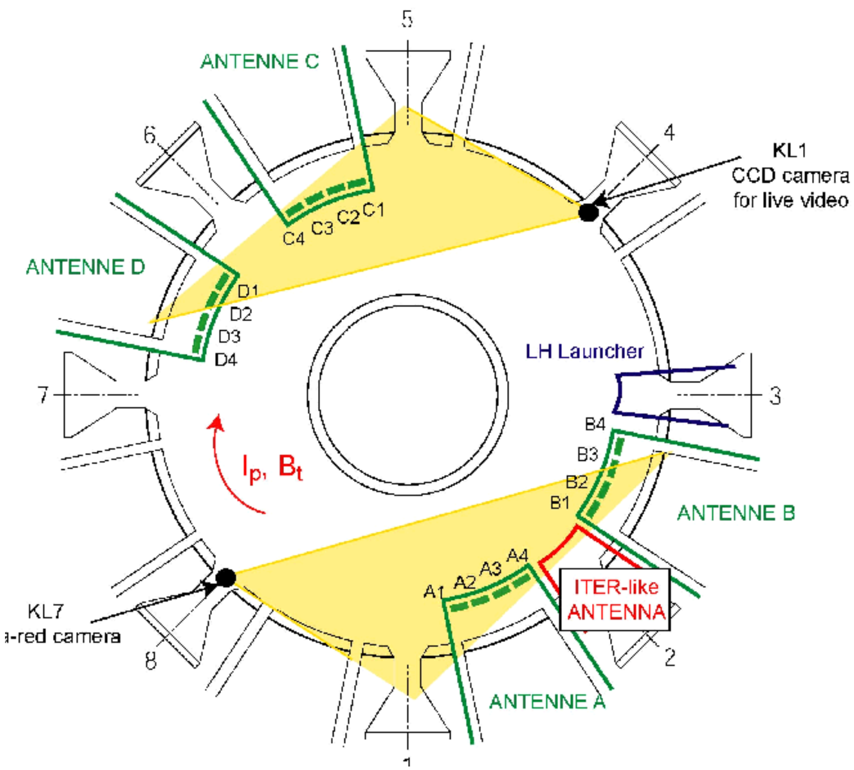
- JET has presently
  - four "traditional" ICRH antennas referred as A, B, C and D and toroidally spaced around the tokamak at $\pi/6$ (between octant 1 and 2), $3\pi/6$ (between octant 2 and 3), $7\pi/6$ (between octant 5 and 6), $8\pi/6$ (between octant 6 and 7) respectively*, and
  - one "ITER-like" ICRH antenna, not presently in operation.
- Each of the traditional antennas features four, independently controlled current straps.
- Each protected by poloidal limiters (PL)
  - Here I'll refer to PL on the left of antenna D, as viewed from the plasma, as D-left; etc.

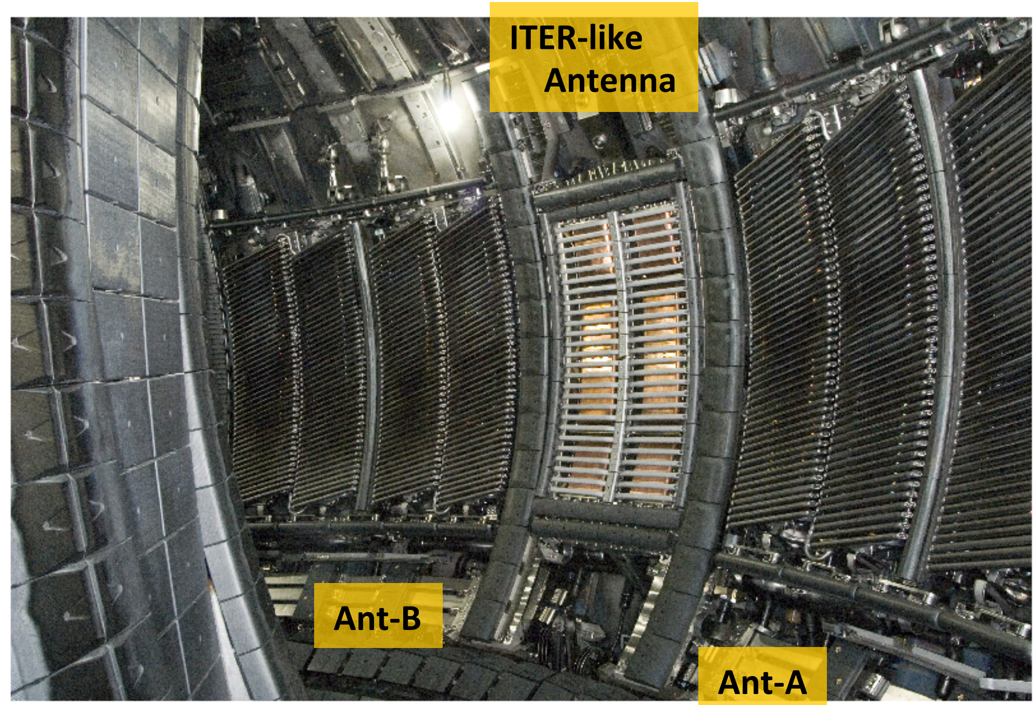
* A. Kaye, T. Brown, V. Bhatnagar, P. Crawley, et al., Fus. Engin. Design 24, 1 (1994)

JET ICRH Antennas



JET ICRH Antennas

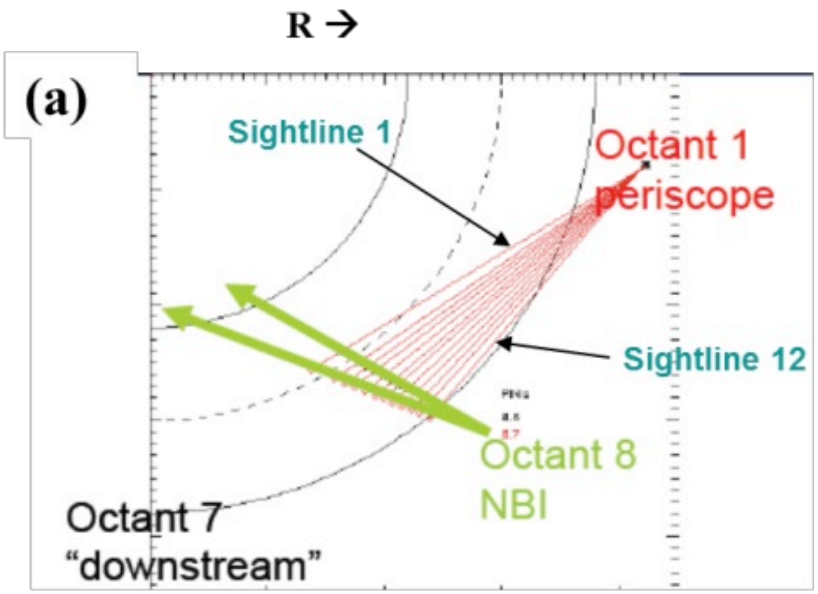




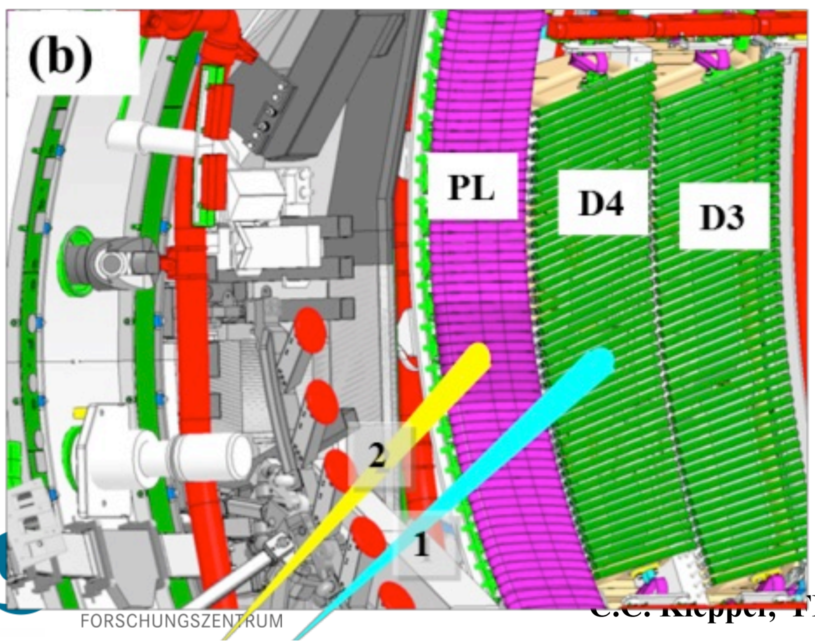
Size of this preview: 800 × 536 pixels

Full resolution (3,872 × 2,592 pixels, file size: 3.85 MB, MIME type: image/jpeg)

Experimental Setup



- Used existing spectroscopic from JET's core plasma CXRS system ("ks5c")
- T.M. Biewer had identified in 2009 views intercepting ICRH and LH antenna

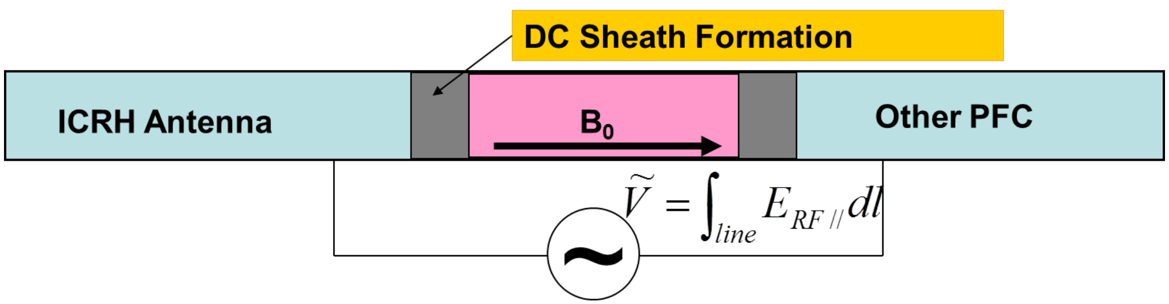


← Illustration of spectroscopic sightlines accessing Antenna D structures.

- ← "D4 Strap"
- ← "PL-D-Left"

MAIN PHYSICS MOTIVATION

- Using existing spectroscopic sightlines on ICRH Antenna structures to look for evidence of dc sheath formation, by looking for correlations between local Be line emission at PFCs and RF power of antenna(s) connected to these location.
    - RF Sheath Rectification Model [1]:



- Parallel to similar study of W I on AUG all W antennas [2]

REFERENCES

[1] O.A. D'Ippolito, J.R. Myra, M. Bures et al., Plasma Physics and Controlled Fusion 33, No.6, 607 (1991)

[2] V. Bobkov et al., Nucl. Fusion 50 (2010) 035004

However, ICRH impact on PFC erosion was also a driving force behind the Be I and Be II Emission Studies

- **Selected spectral lines based on what was used to validate ERO code using PISCES-B (Linear Machine) Be erosion studies (D. Borodin, R. Doerner)**
  - Be I 4572Å (Singlet, 2s3d $^{1}D \rightarrow$ 2s2p ^{1}P)
  - Be I 3322Å (Triplet, **cannot presently access**)
  - **Be II 4673Å (4f $^{2}F \rightarrow$ 3d ^{2}D)**

➢ **Collaboration idea discussed in PMIF-2 Workshop in Juelich.**

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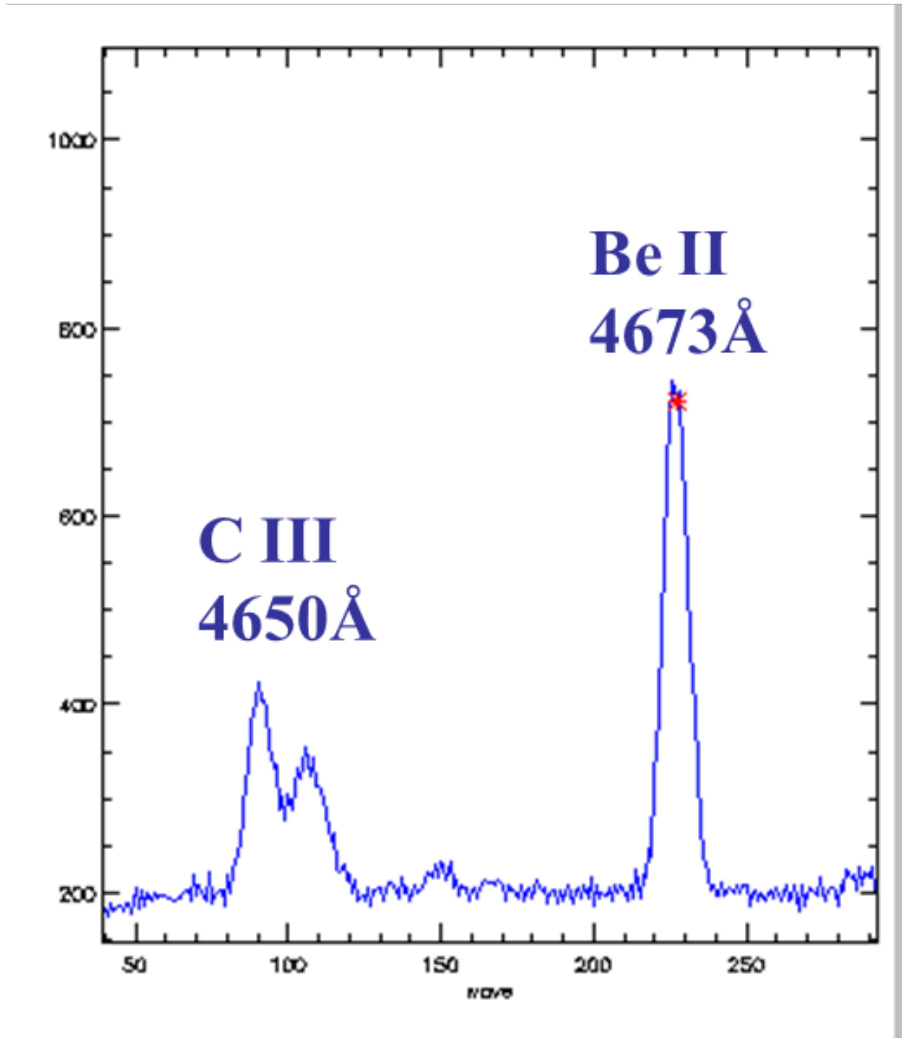
Measured Spectra

- Both Be I 4572Å (Singlet, 2s3d ^{1}D → 2s2p ^{1}P) and Be II 4673Å (4f ^{2}F → 3d ^{2}D) by the CXRS spectrometer but not in the same shot'
- The non-localized C III 4650 Å was simultaneously detected, in both cases.

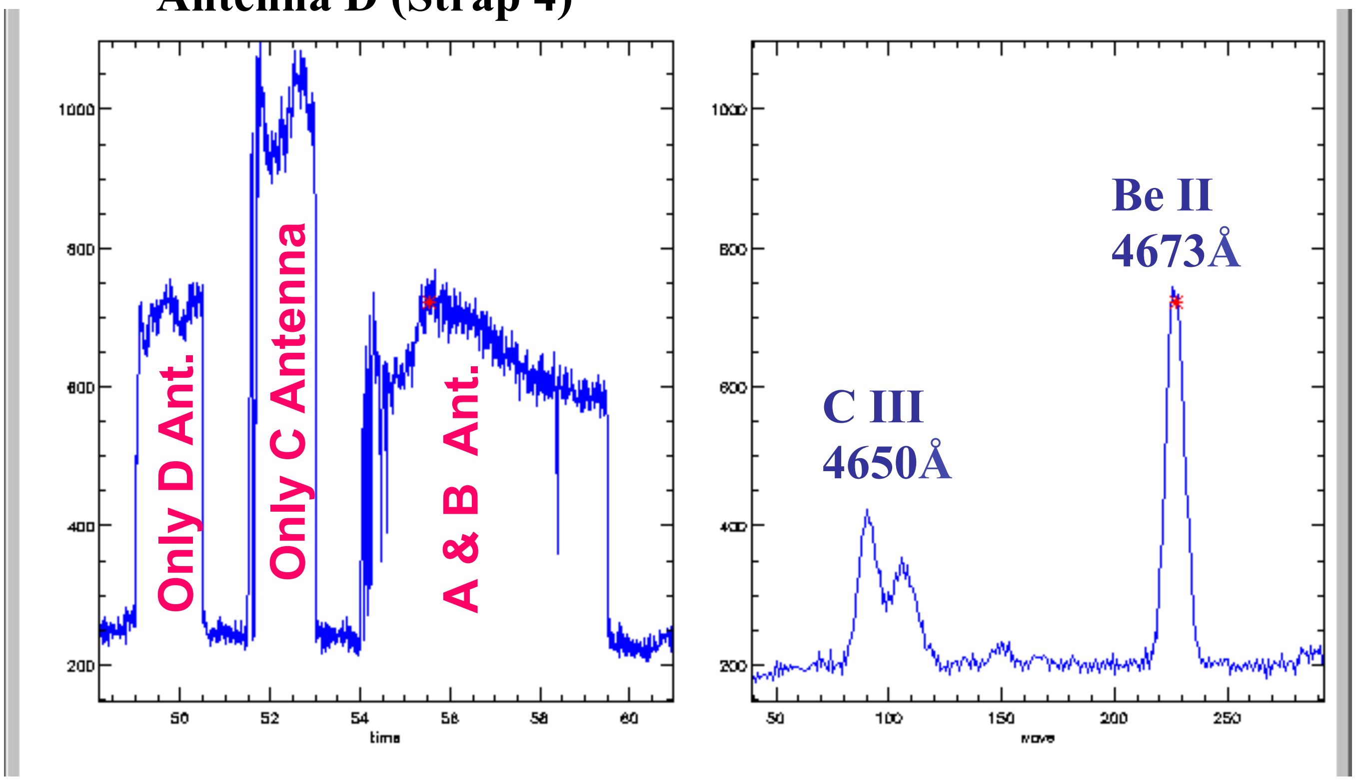
Shot 80806 – Track 8



Main Effect: Enhanced Be Production at Antenna D, by interaction with Antenna C

Be II Time Evolution at Antenna D (Strap 4)

Shot 80806 – Track 8

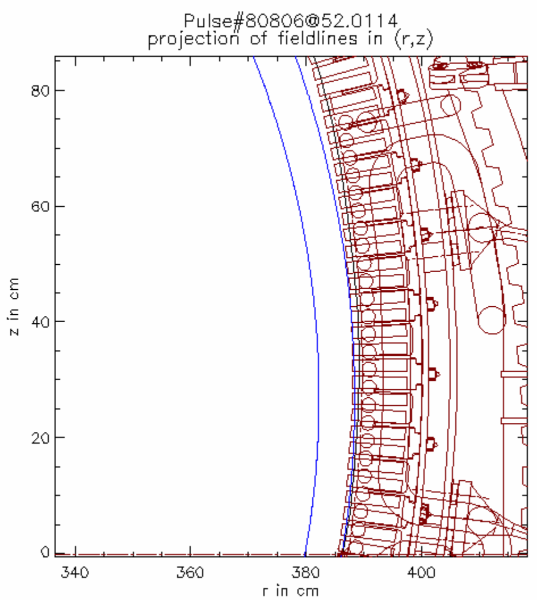


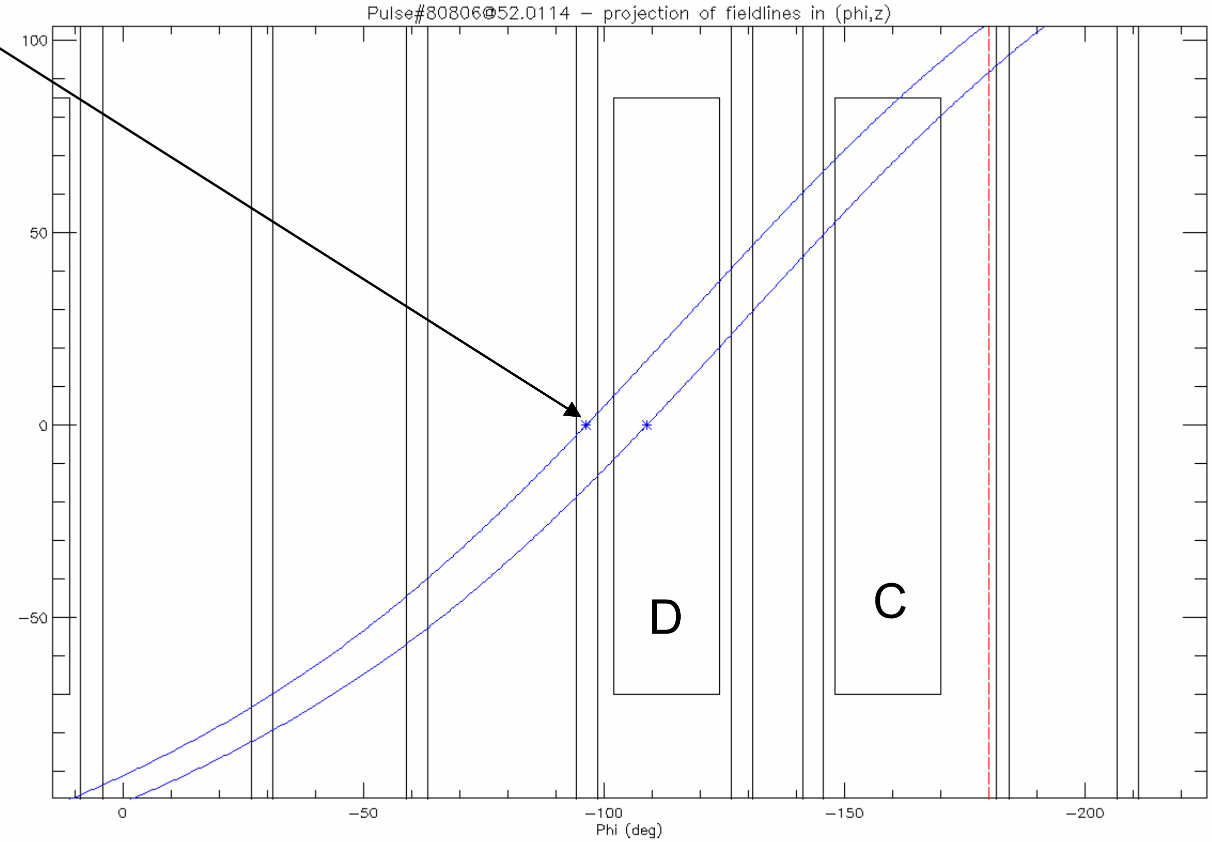
Be I 4572Å can also be accessed, but not at same time as the Be II line.

Plausible Model for Sheath Effect of Antenna C on Faraday Screen of D4

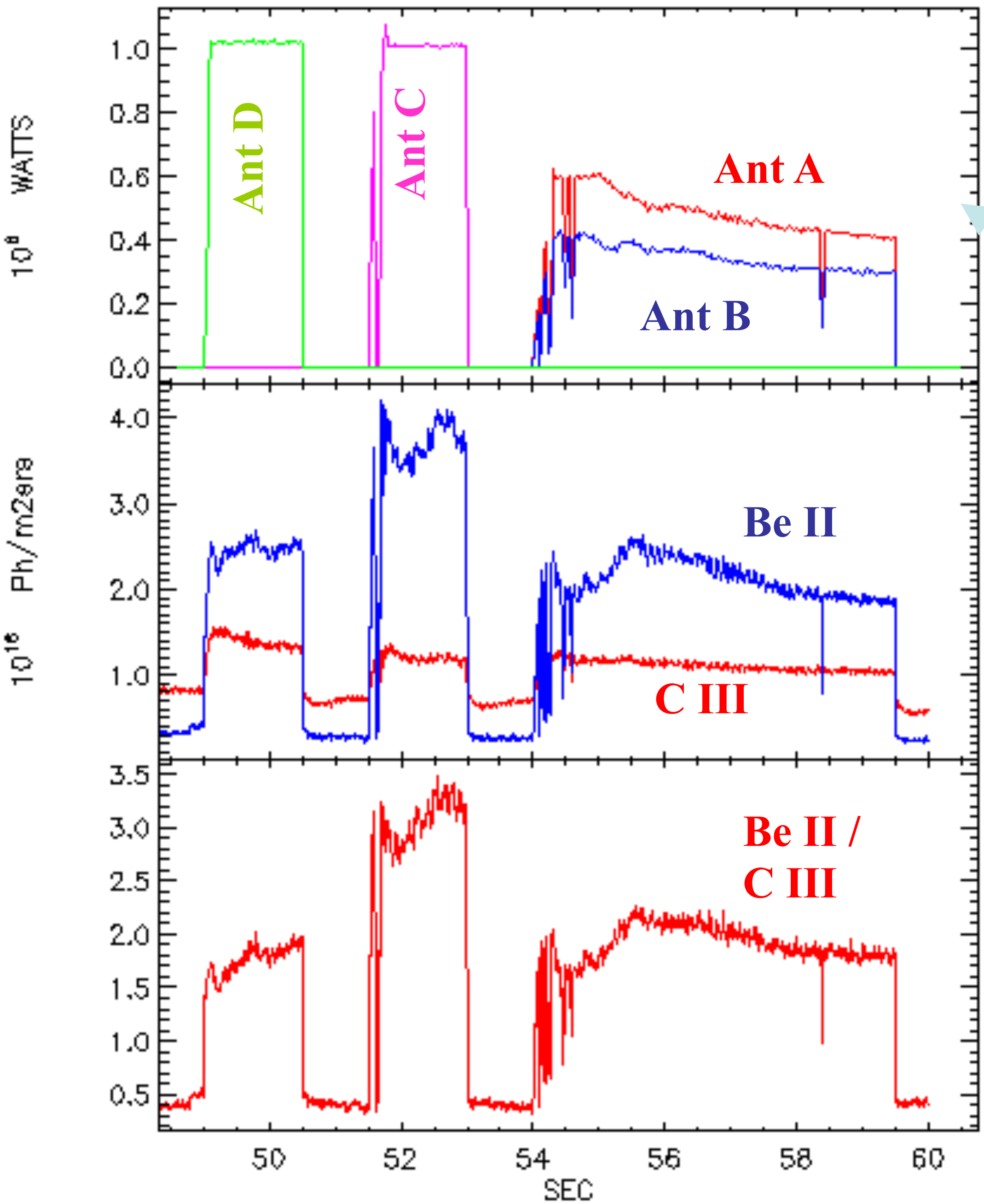
From Ph. Jacquet

Diag may view limiter surface on the side (Ion-drift side) that do not intercept field lines from C





Shot 80806 -- Dipole Phasing of ICRH Antennas

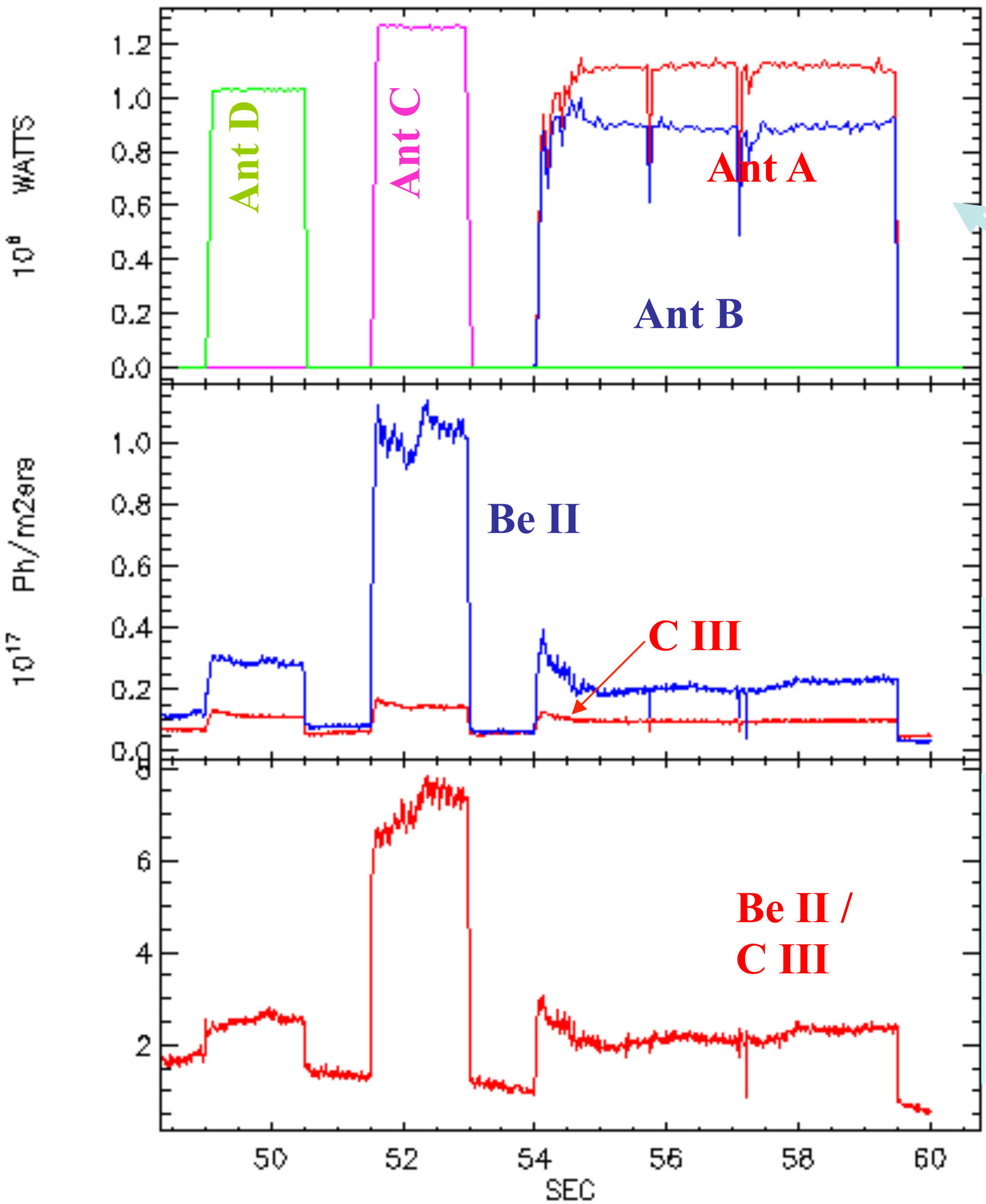


Power coupled in by each of the antennas, with A&B operating together as one system (A+B about same power as C, D).

Intensities of Be II and C III

Be II is now divided by C III as a crude way to take out any local Ne dependence (C III appears to be non-local, which Be II is very localized)

Shot 80860 -- - (π/2) Phasing of ICRH Antennas

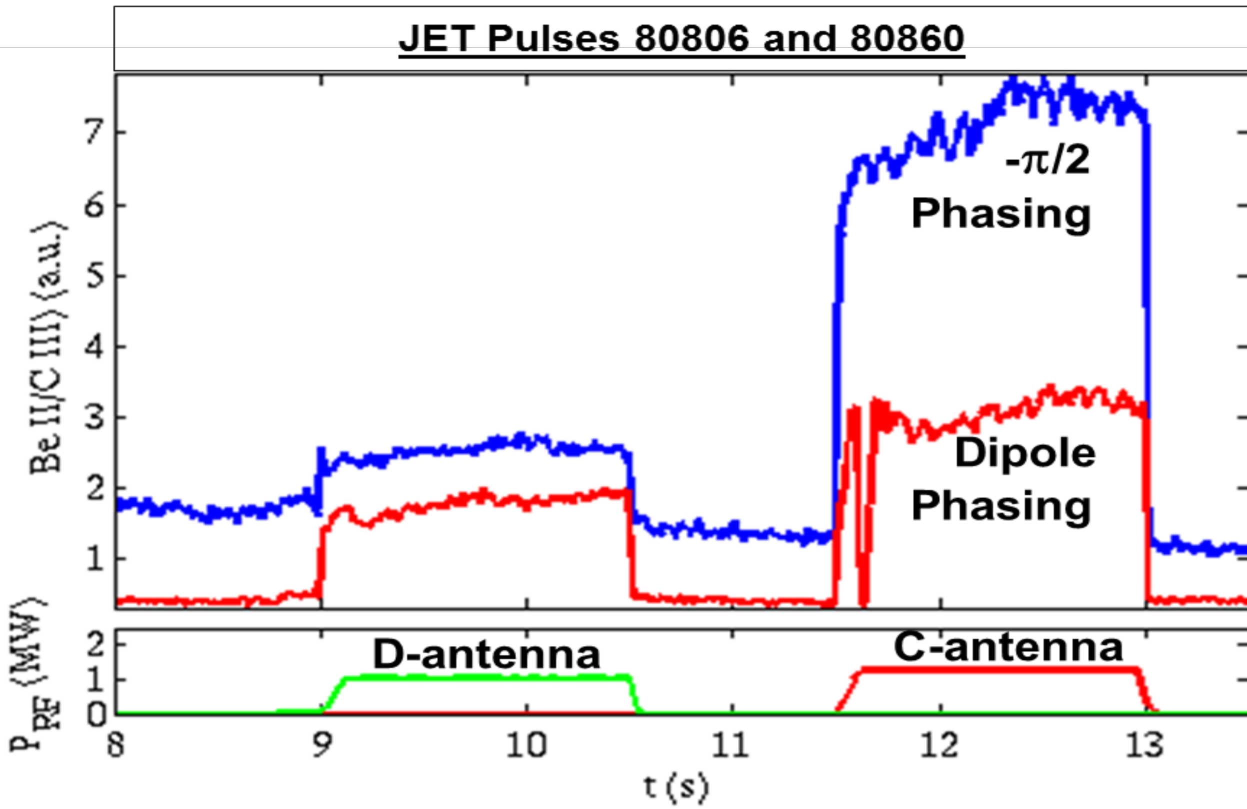


Power coupled in by each of the antennas, with A&B operating together as one system (A+B about same power as C, D).

Intensities of Be II and C III

Be II is now divided by C III as a crude way to take out any local Ne dependence (C III appears to be non-local, which Be II is very localized)

Effect of Antenna Phasing



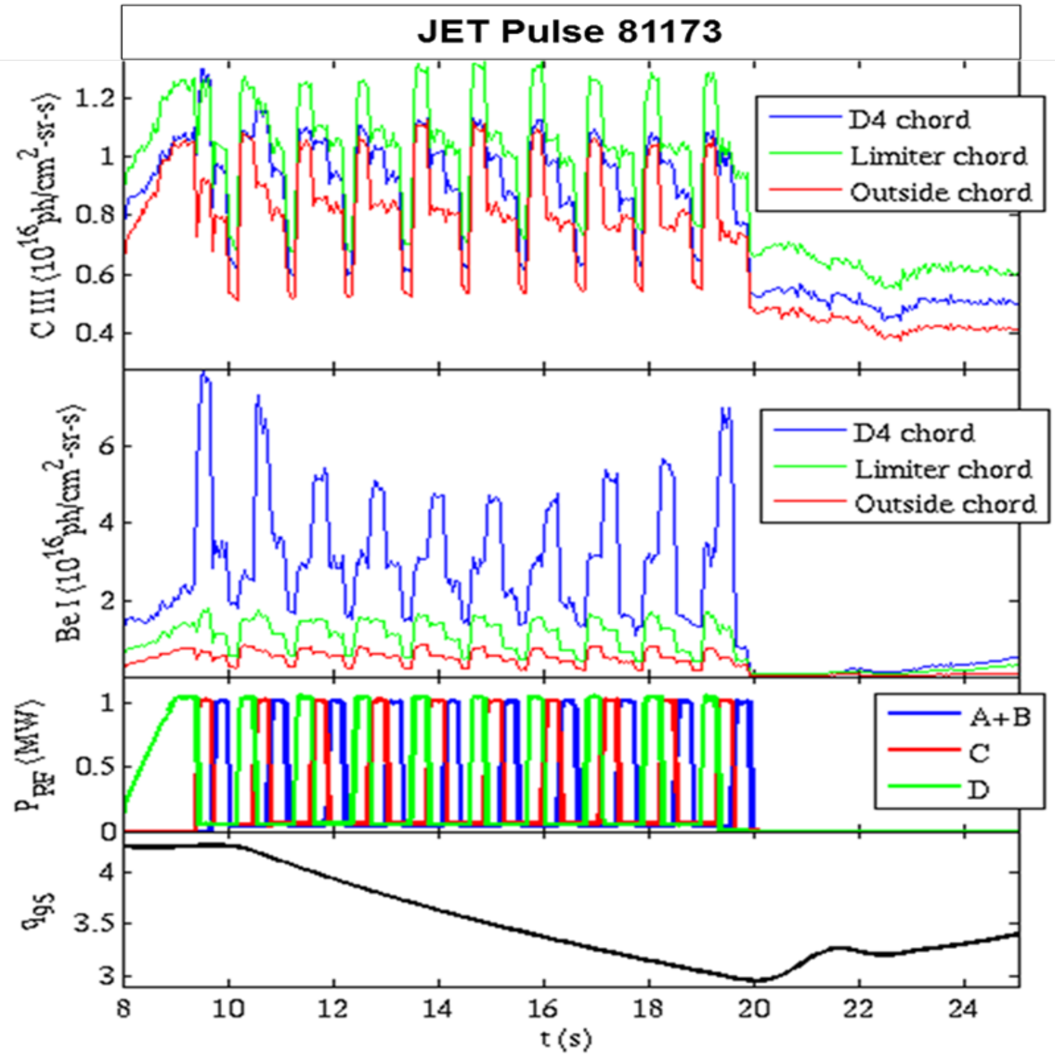
Comparison of the relative change in Be II/C III in two similar shots, primarily differing in the phasing of the antennas.

*** i.e., “-90º phasing” (i.e. current on the straps 90º apart: 135º 45º -45º -135º)**

*** i.e. current on the straps 180º apart: -90º 90º -90º 90º**

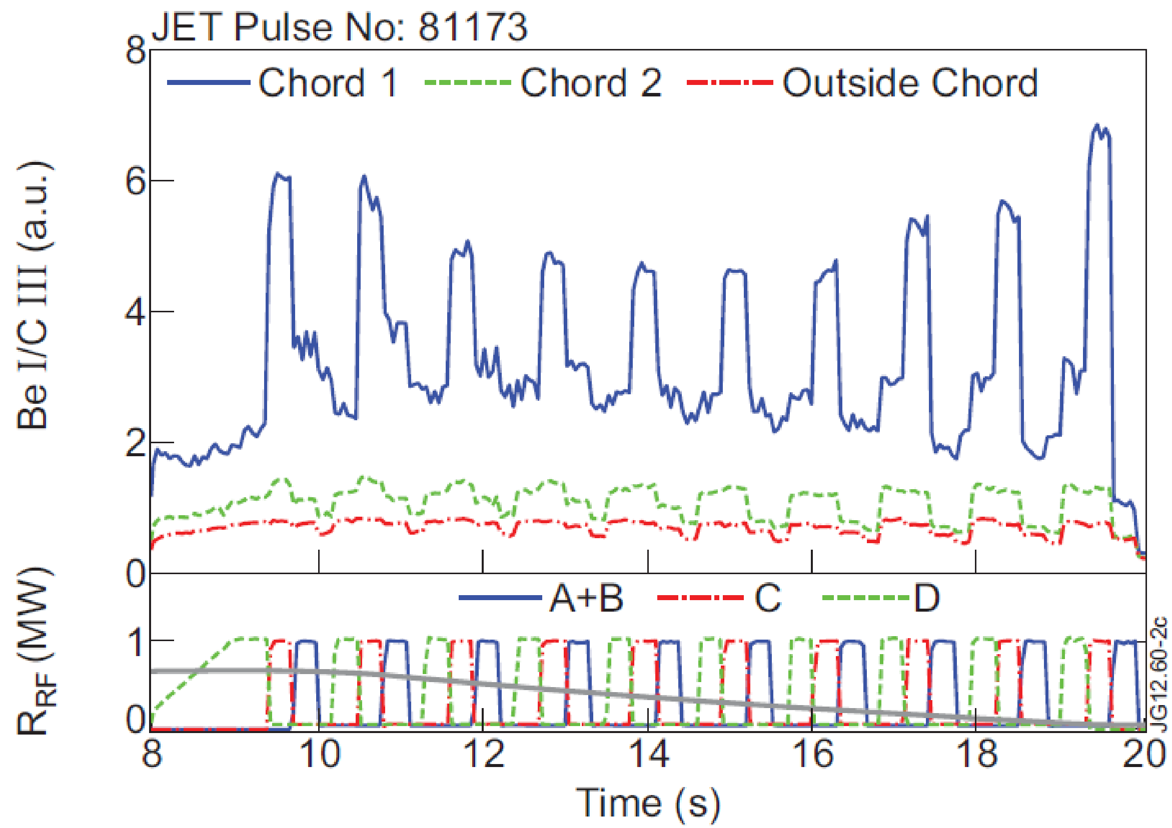
Antenna Modulation with Simultaneous q_{95} scan

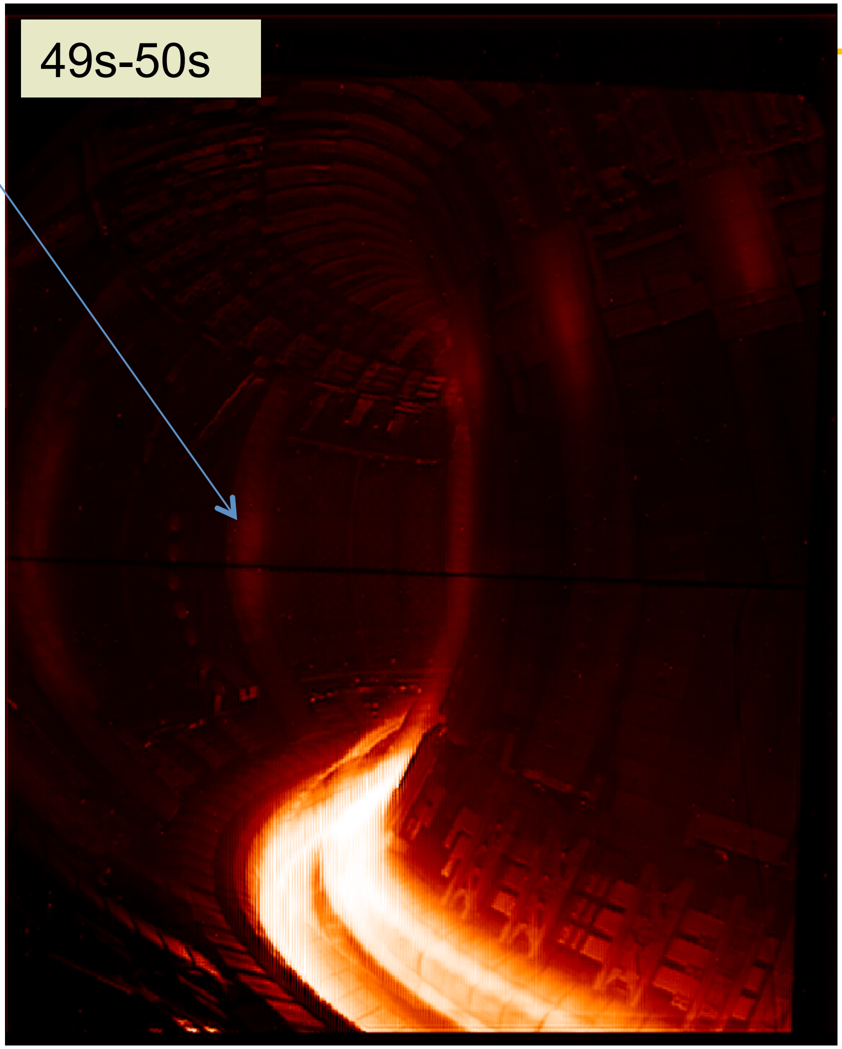
- Antennas C and D were operated independently (all 4 straps functioning), while Antennas A&B were operated as a single antennas (2 straps from each)
- -π/2 phasing
- Edge q_{95} was to change magnetic connections
- Similar response was seen with Be II emission (Pulse 81172, not shown).
- This effect was clearly q_{95} dependent.



Modulation Experiments (continued)

- Sightline 1 (terminating on Strap D4) has, consistently, far higher intensity than Sightline 2 (terminating on PL-D-Left)
- Negligible emission (in the same scale) for sightline missing the antenna and the limiter
- Change in q_{95} seemed to clearly impact which antenna affected the local emission.





KL12 Color Camera Images Processed by Gennady Sergienko (FZ-Juelich)

- KL-1 CCD with Be II Filter did not give clear images in divertor phase
- Here using Color monitoring camera, extracting blue part of the RGB image

KL12 -- Processed by Gennady Sergienko

- Although not clear that one can draw specific conclusion about the Be I, Be II line emission from the color camera images....
- It would appear that the visible emission comes mainly from the limiter and not the Strap (the Faraday screen) region.
- Be line-filtered images (KL-1 diagnostic) planned for this Summer 2013 and subsequent ICRH experiments.

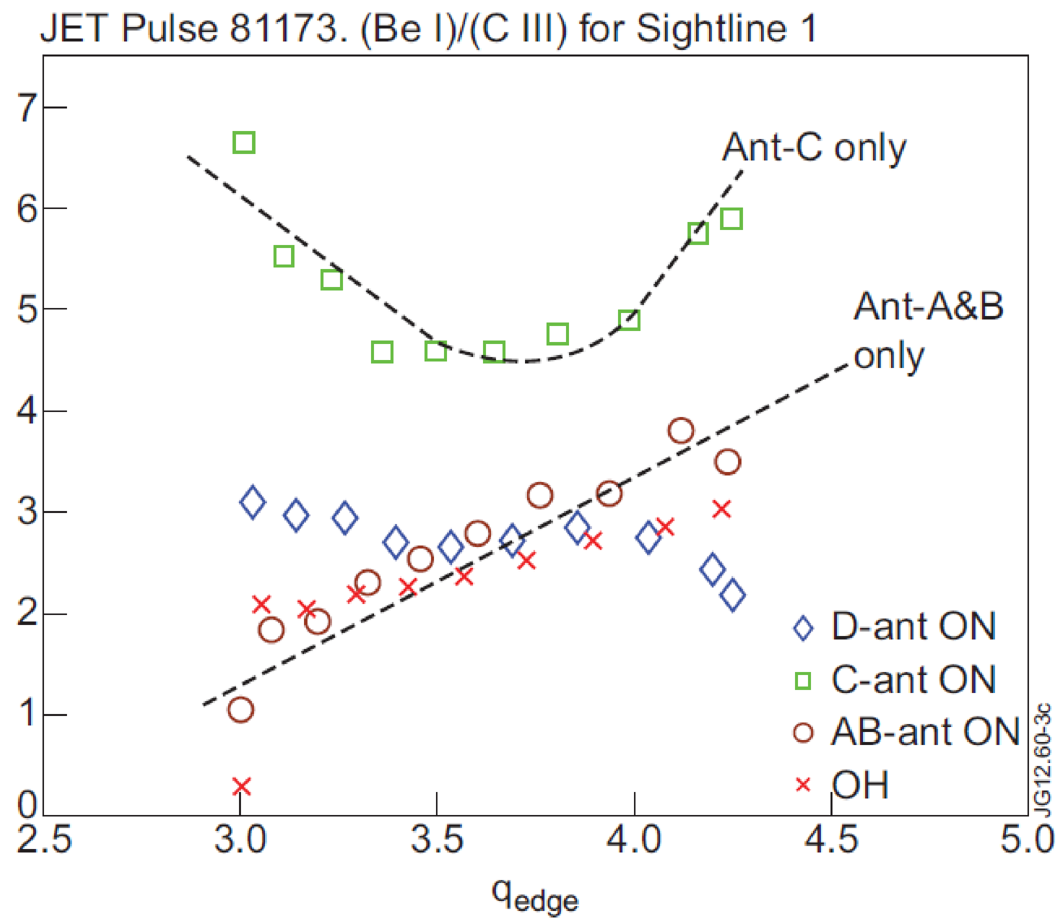
Modulation Experiments (continued)

Processed data by averaging over plateaus of each antenna and in each modulation cycle.

Here mainly focusing on Sightline 1 data.

Main observations:

- Antenna C impact on Be source at PL-D-Left changed from decreasing to increasing dependence on q_{95}
- Ant A&B impact showed monotonic increase.
- Be source at PL-D-Left also increases monotonically with q_{95} in the OH phases of the modulation

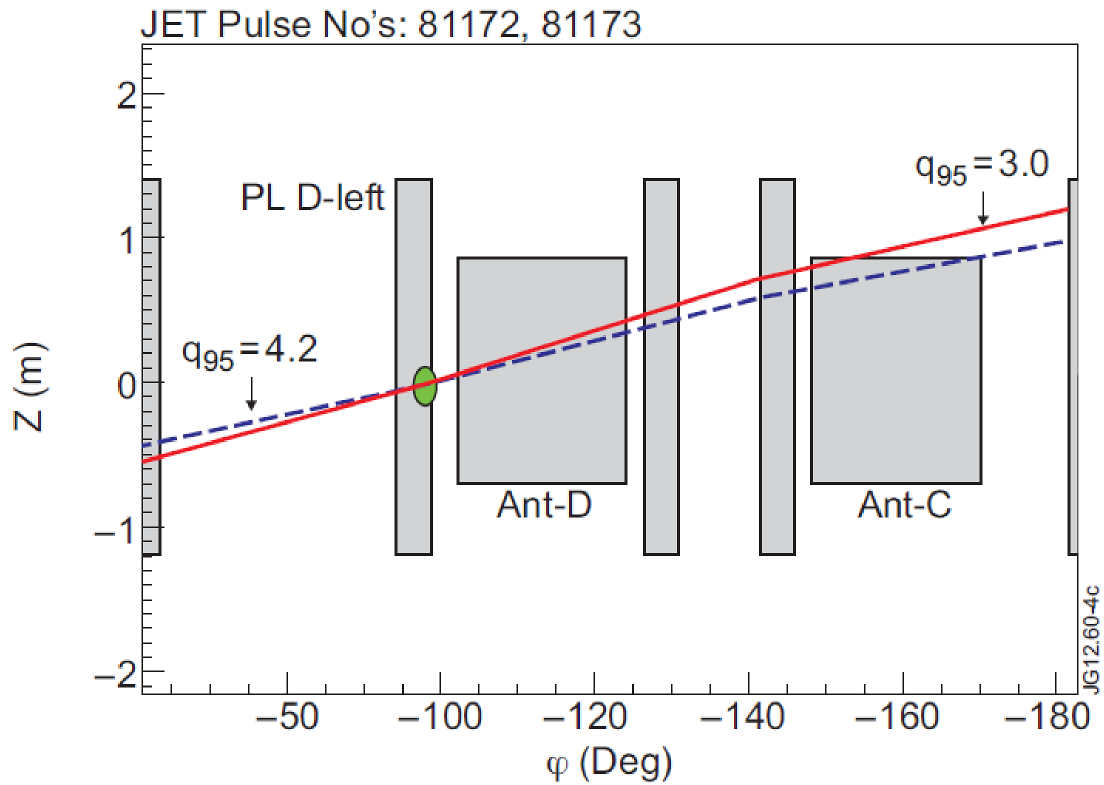


Impact of q_{95}-scan on magnetic connections

More detailed flux tube tracing*

Main Observations:

- Measurement location connects to top part of Ant-C and middle of Ant-D.
- At the 2 "maxima" of the Ant-C impact curve the connection is with a different corner of Ant-C.
- **If the enhanced Be source associated with Ant-C is indeed a result of RF-sheath potentials, the occurrence of maxima at antenna PFC corners is consistent with most modeling results**.

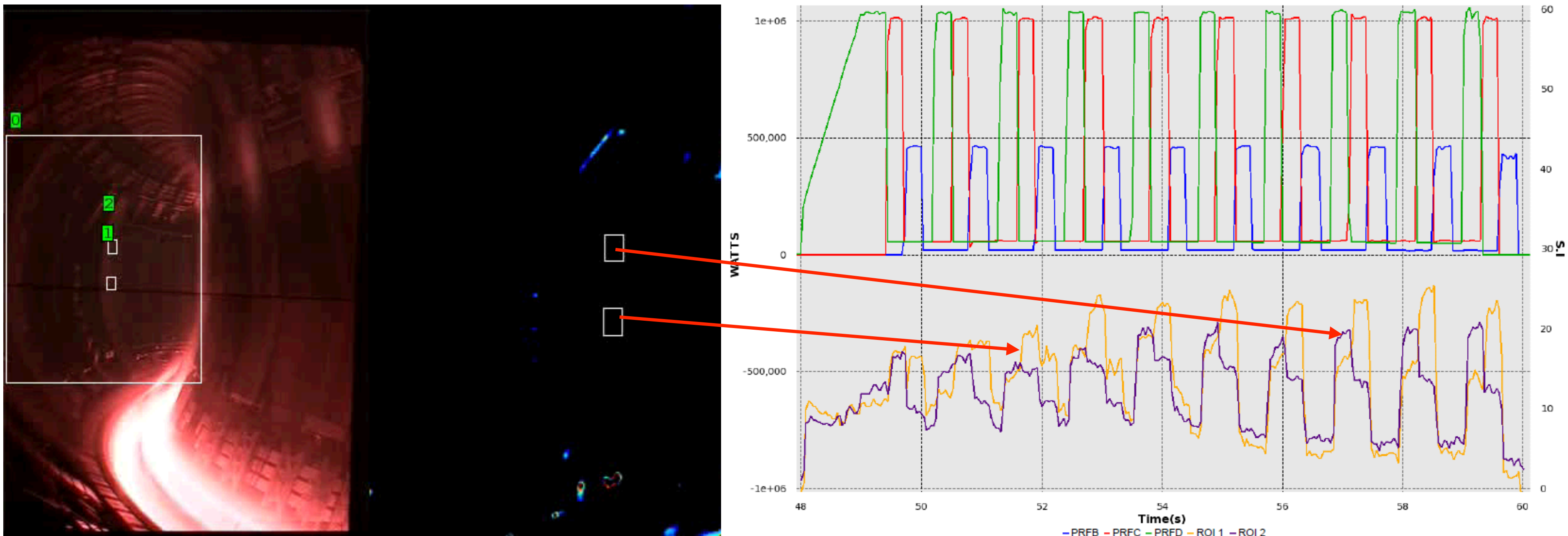


*** VEFI fieldline tracing program, coupled to EFIT**

KL12 – Color Camera – >>Click on image to play the movie…

Processed using PInUP™ Software**

JET Pulse 80875

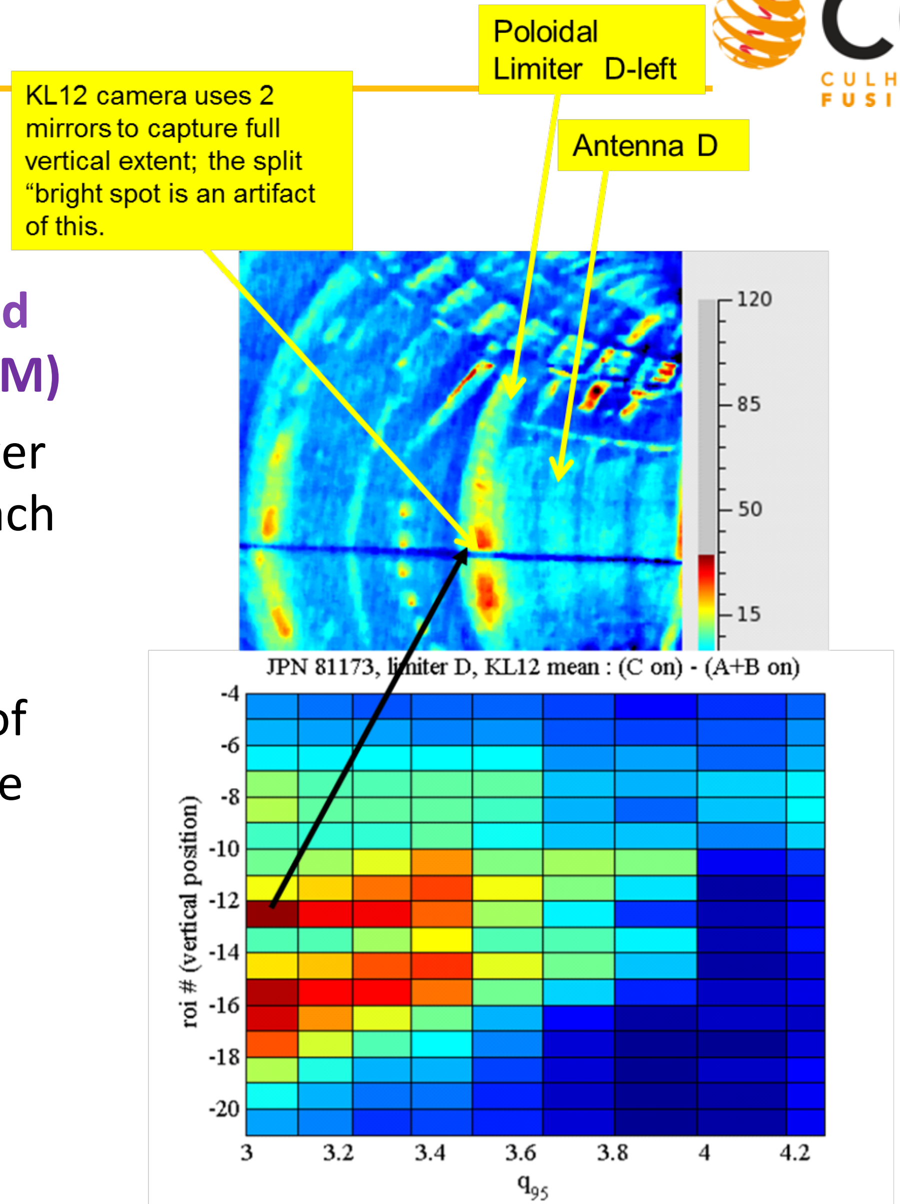


Filtered subtracted image (ref = PTOT=0W)

** Vincent Martin, et al., CEA/IRFM

Additional image processing

- **This work was primarily carried out by Laurent Colas (CEA, IRFM)**
- Applied the same averaging over the modulation plateaus for each antenna and each cycle of the modulation
- Here we show only the effect of Ant-C on PL D-left and using the averages over the "Ant-A&B" phases as the background.
  - **Qualitatively same result is obtained using the averages over the "OH" phases as the background.**



Main conclusions so far*

- Clear correlation between localized, enhanced Be source at poloidal limiters and their magnetic connection to the active ICRH antennas.
  - **Consistent with the predicted effect of an inhomogenous RF-sheath potential on or around these antennas.**
- This constitutes a direct, experimental confirmation of rf rectified sheath potentials on PFCs magnetically connected to energized antennas.
  - **Since present ICRH antenna models predict such effect, this study is also an important step toward experimental verification of ICRH antenna and RF-sheath models.**

*** Klepper et al., PSI-2012 paper, accept for publication in JNM (Available online).**

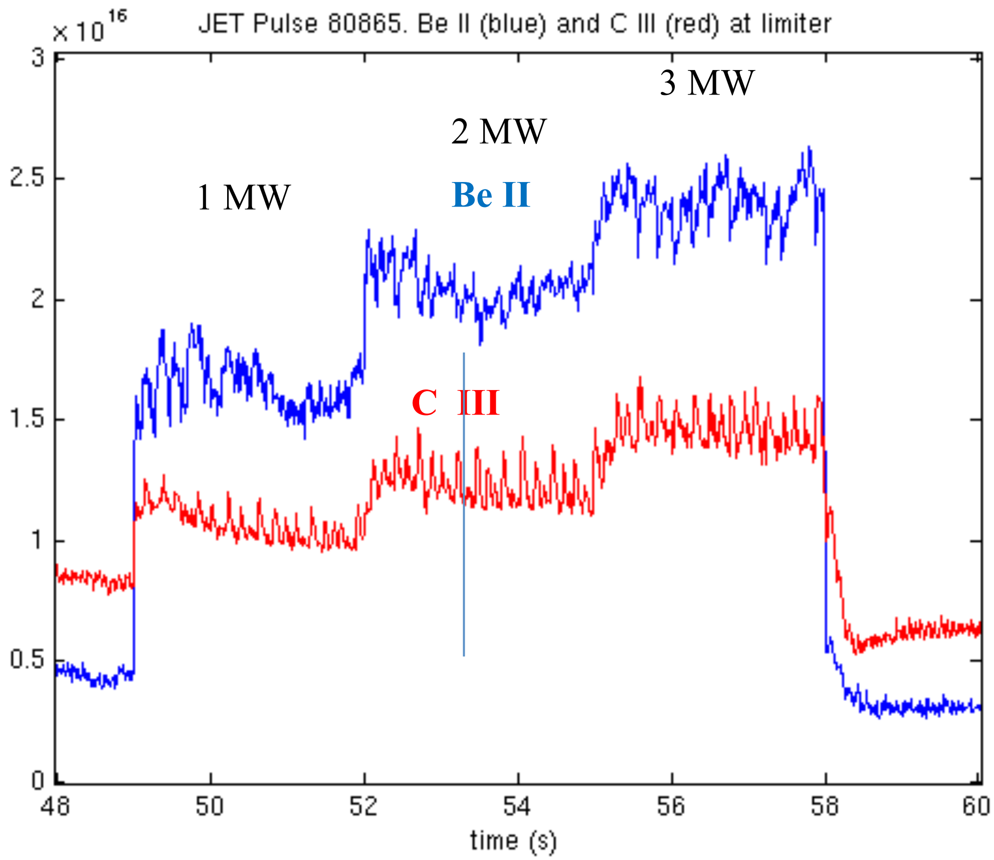
Pending Issues and opportunities to resolve them

- Power dependence of Be sources.
  - **Possibility of new data in Jul-2013 to help better define dependence.**
- Get better mapping of the Be bright-spots
  - **Ideally for all PL's**
  - **Good likelihood for improved, Be-Filtered camera detection for the next set of ICRH experiments.**
- Determine absolute erosion rates.
  - **ITER relevant; help predict life-time of Be PFCs connected to ICRH antennas.**
  - **FZJ collaboration can provide access to ERO code with ~validated Be erosion data but**
  - **Need extra resources* to carry-out the work**

*** Ideally a post-doc at ORNL to work with Dmitry Borodin and Andreas Kirschner – learn the code – apply specific geometry.**

ICRH Be scaling with Power

Plotting separately Be II and C III for Pulse 80865



- **The intensities of Be II scales with power, but so does C III.**
  - **<u>Question</u>: What happens to the ratio? Would it correct of effect on local Ne**

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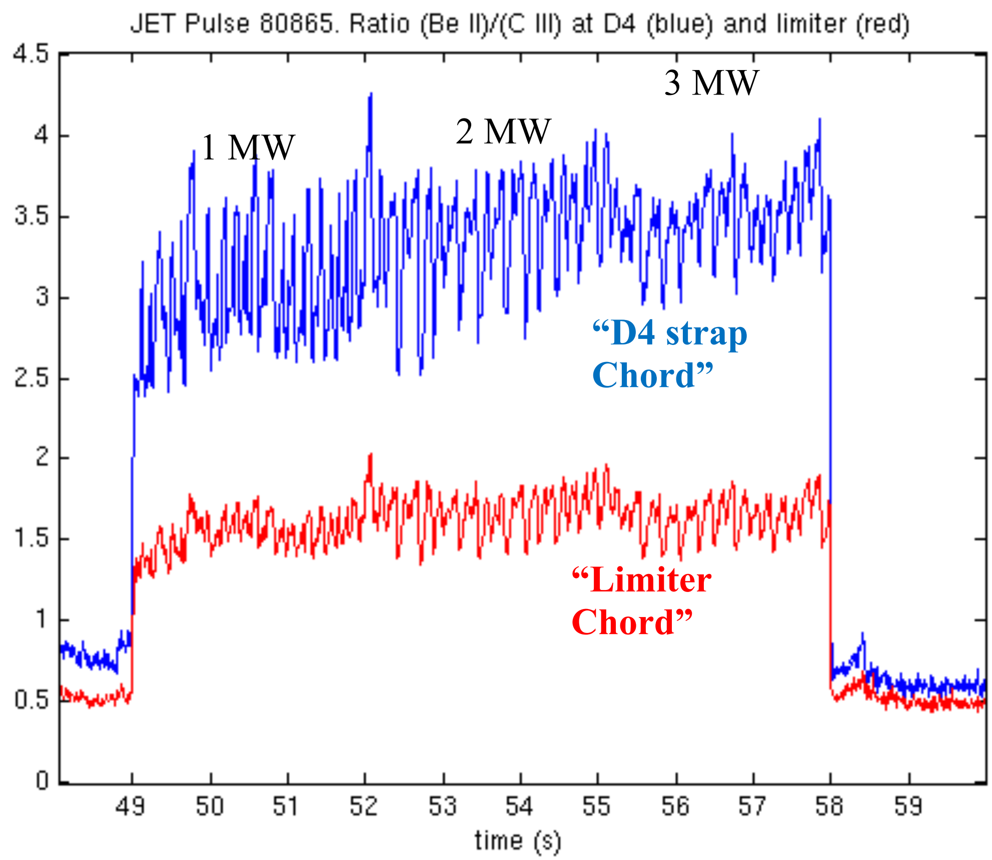
ICRH Be scaling with Power

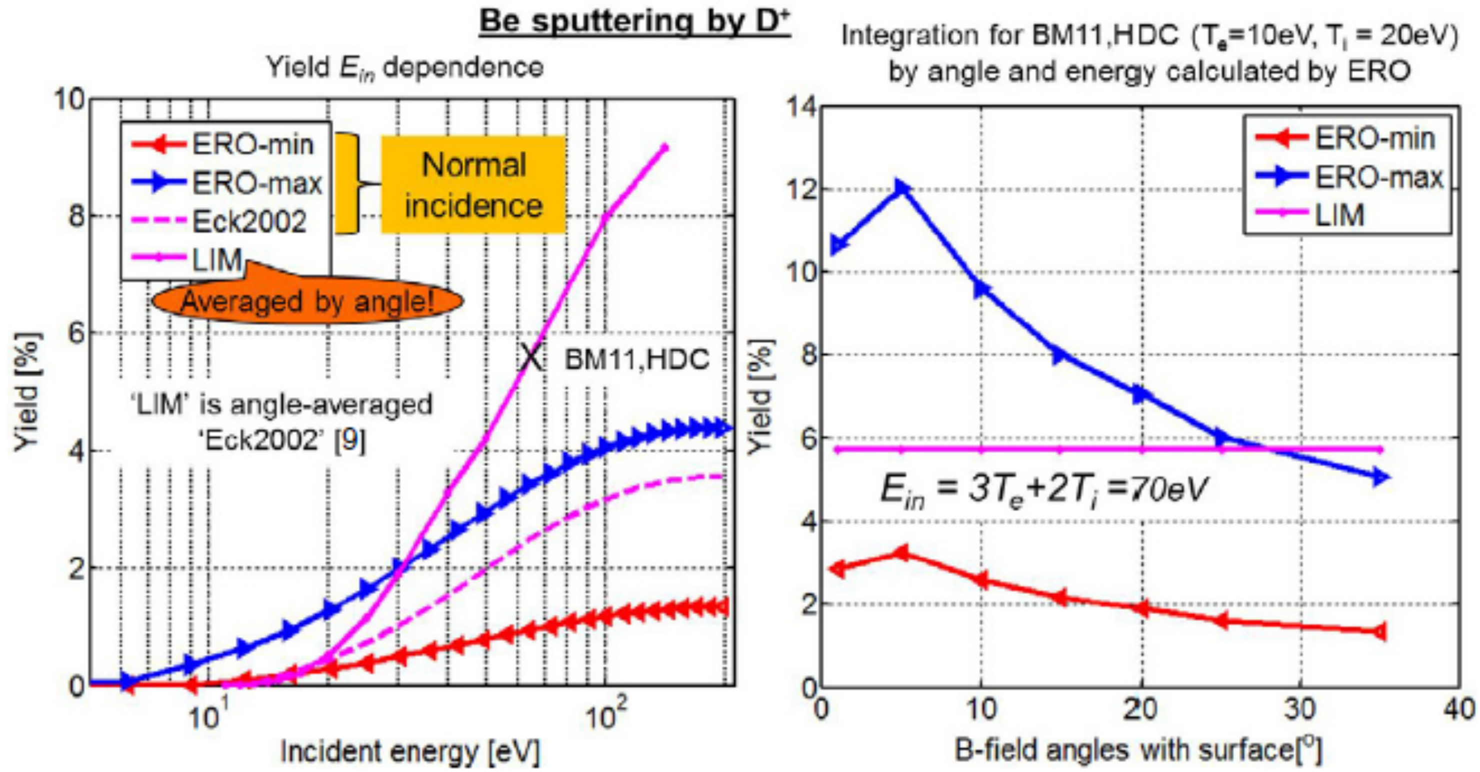
Plotting all (Be II)/(C III) data for Pulse 80865



- The thus normalized Be emission is independent of power at >1MW.
  - This may be reasonable for actual Be sputtering yields

ICRH Be scaling with Power

Be Sputtering Model from Borodin et al 2011



- To first order, Be sputtering yields are flat for E_ion >~100eV.
  - Energy range compatible with RF sheath models
  - JET ICRH Antenna-specific modeling in progress
  - Plans to apply ERO code in near future for erosion model

Status of Collaboration on ERO Code Modeling

- Mainly discussions, so far, since mid-2011, however….
  - D. Borodin, A. Kirschner highly interested in the application
    - They would support effort, particularly if we provide a person to carry out the specific calculations
  - Progress already with D. Borodin to assess how the geometry should be handled (C. Klepper's Julich visit Jan-2013)
  - Ultimately:
- Significant synergy with ERO code work (by same team) on Be sources from outer limiters**
- Excellent way to transition collaboration from TEXTOR to PWI (in addition to our efforts in the linear machines area).

** See Dmitry's Zvenigorod-2013 and PFMC-2013 talks

How to move forward on the ERO Code Collaboration

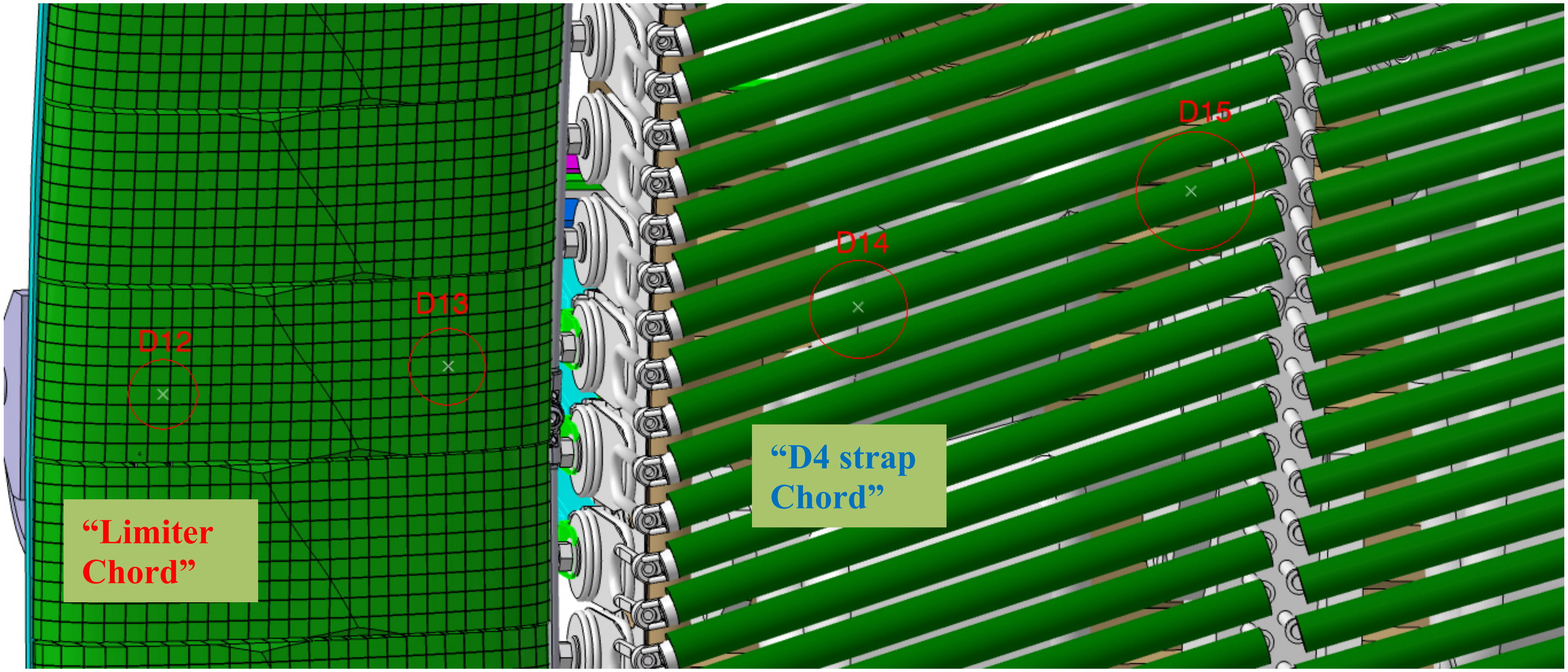
- **Here we should discuss this……**

END OF INFORMAL SEMINAR -- Thanks for your attention!

Spare Slides

Sightline Geometry

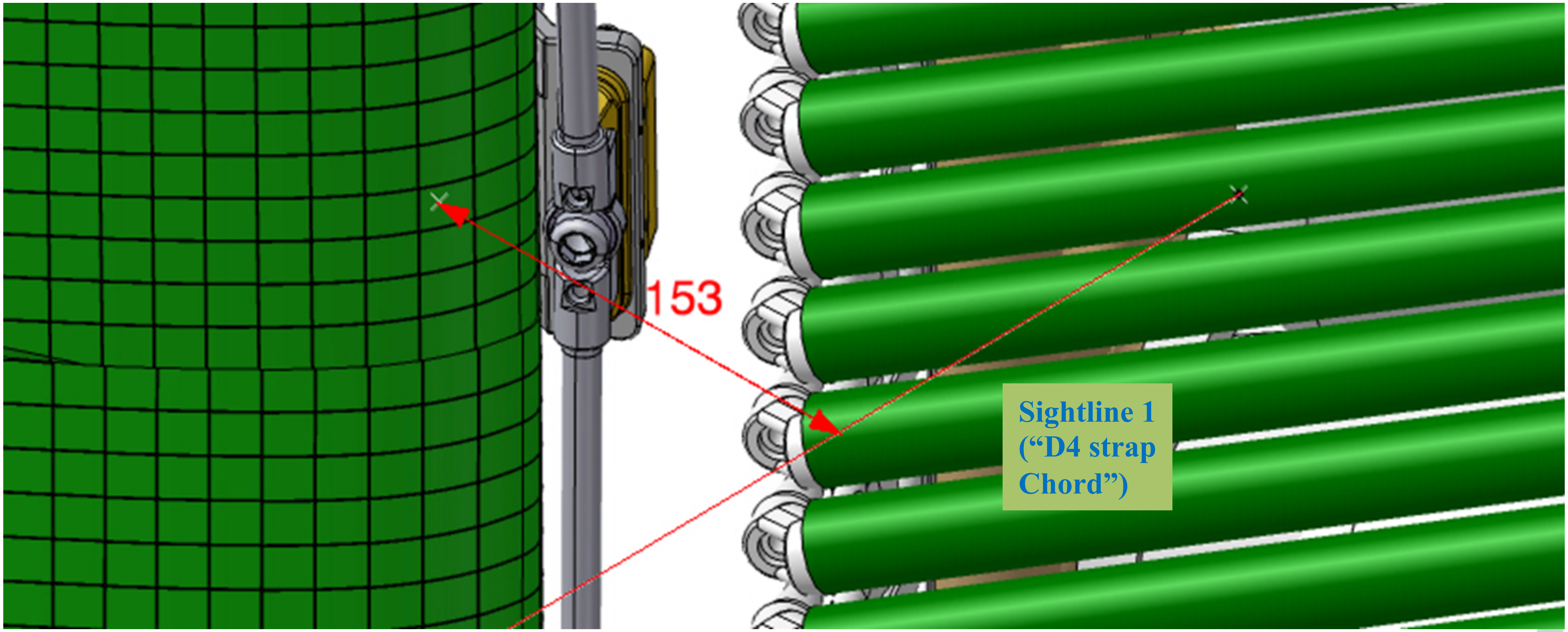
From CAD Drawings (Paul Carman, CCFE)



- **Although “Limiter Chord” falls on side of limiter AWAY from antenna, the limiter seems to be nearly flat at this sightline’s footprint location.**
  - **Both chords terminate on Be surfaces.**

Sightline Geometry**

Here we look at closest pass to limiter (~15 cm)



- For ERO code input, the CAD geometry needs to be exported in a standard file form that can be accepted by the code.
  - Plan to try to obtain this in Jul-2013, when physically at JET.
  - Need to also confirm that the distance of closest pass is consistent with Be I and Be II emission levels from the PL.

**From CAD Drawings (Paul Carman)

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Indirect measurements of rectified RF potentials

-- This one from ASDEX-U Antennas.

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Nucl. Fusion **50** (2010) 035004 VI.V. Bobkov *et al*

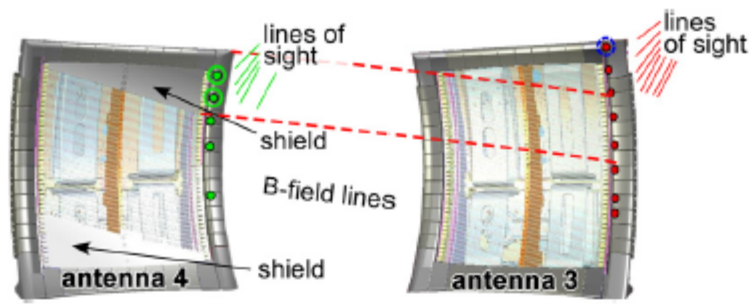

Figure 2. Antenna 4 and 3 configurations and the setup for the spectroscopic observations (green and red circles).

line of sight. Therefore values of Y_W do not contain the error in absolute calibration of the lines of sight. However, there is an uncertainty on the error of the measured D(H) line intensity due to reflections that could affect the analysis of Y_W z-(poloidal) profile. We assume this error to be small.

For a given content of the light impurities (concentrations and charge states), Y_W can be translated into a sheath potential drop. Figure 3 presents the W sputtering yields calculated according to [11], depending on the total accelerating voltage for typical concentrations of light impurities which can be found in AUG and for pure deuterium.

Antenna 4 was modified with triangular shields which cover corners (figure 2) at the locations where long magnetic field lines pass only one strap out of the two (0π)-phased straps of the AUG ICRF antenna.

The light impurity and W content in the plasma is characterized by the spectroscopically measured concentrations. W concentration C_W is measured at an electron temperature of ≈1.5 keV (see [12]). For the discharges presented in this paper, this corresponds to the values of the poloidal radius between 0.4 and 0.9. All of the discharges are divertor plasmas.

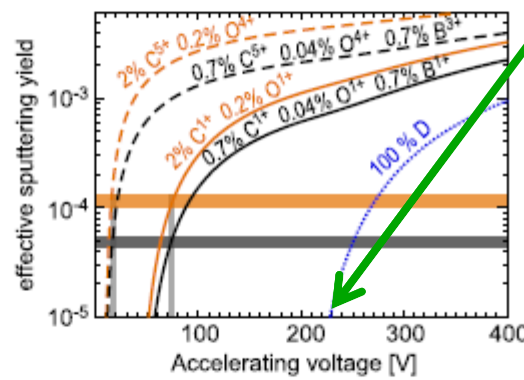

Figure 3. Y_W calculated for typical concentrations and charge sta of light impurities which bombard W surface. Dashed curves represent the maximum achievable charge states during ELMs. Dotted curve corresponds to deuterons as bombarding particles. Light curves reflect the measured O and C concentrations for #23057 before the boronizations (no B detectable) and dark curves reflect the concentrations of O, C and B for #23517 long after boronization. Horizontal lines show Y_W measured at antenna limiter for these two discharges (see [8]).

Bobkov, Dux et al , NF 2012

- **Rectified Potential estimated from W Sputtering Threshold ~100 – 300V**
- **Consistentt with antenna model predictions**
- **Also, assuming ~1mm sheath → 1-3 kV/cm (predicted sheath E-field**

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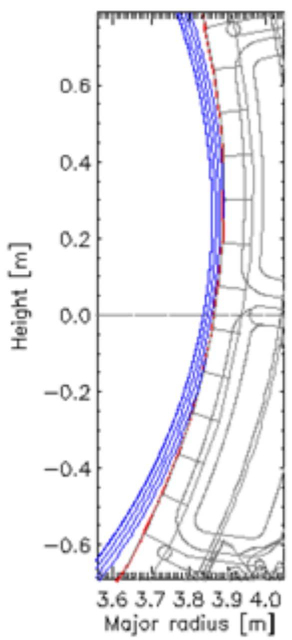
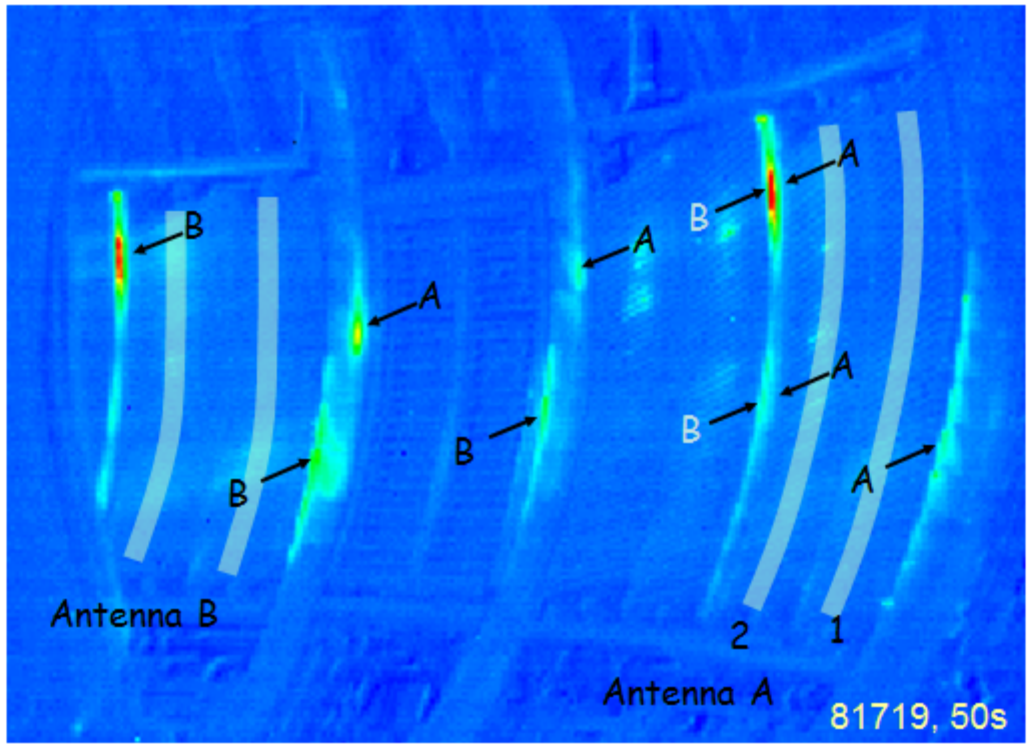
IR measurements – Limited info from PL's

EFDA JET **Qualitative observations, RF hot spots**

$$Q \sim |V_{RF}| \sim \int E_{||}\, dl$$





P. Jacquet, JET Science Meeting, 27/02/2012 4 (13)