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Looking for a Transport Barrier in the TFTR VB Emission Profile *

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When the confinement in TFTR reverse-shear plasmas improves, we are not certain whether the core region has made a transition to greatly reduced transport, or whether some sort of a transport barrier has formed at the edge of this region while the core transport is still either poor or only somewhat improved. The electron temperature, the ion temperature, and the visible bremsstrahlung emission seem to give flattened profiles, while the electron density often becomes more peaked in a transition to enhanced reverse shear shots. Unfortunately, TFTR's electron density profile system has a hole in its array at the center of the large, shifted plasmas characteristic of ERS due to an obstructing PF coil.

We report in this poster the results of a study of these phenomena, concentrating on information from the visible bremsstrahlung emission profile. The radial distribution of visible bremsstrahlung emission in TFTR is measured using a 16 channel array of visible continuum detectors. Since the VB emission depends on the product of the electron density and the ion density, its profile is sensitive to local peaks of either type. We show that impurities (Li and C) appear to collect just outside the region of good confinement, which is marked by sharp decrease in density fluctuation and a steepening of the T_e profile.

Finally, we show some data that hints that there may be a systematic effect in the vb-ne systems, which can be explained by (among other effects) an artifact in the relative peaking of the two profiles at large radius which does not occur at small radius.

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Visible Bremsstrahlung Emission

l Electrons scattering off ions emit a continuous spectrum of radiation. The spectrum and intensity depend on the electron energy and the ionic charge. The dependence on ionic charge makes this radiation a probe of plasma composition. The technique was first applied by Kadota and co-workers on JIPP T-II in 1980†, and soon used world-wide. The best region to measure the radiation is in the visible.

- 4 The spectral region must be free of competing line emission. The region identified by Kadota *et al.* at 523.5±.5 nm is still the most widely used. On TFTR, this range is periodically checked; no major line emission (integrated intensity more than a few percent of the continuum) has even been seen.
- 4 Because the intensity depends on the product of the ion density and the electron density, the density enters as the square. That means that accurate density measurements are critical for the technique.

The emission is given by:

$$\varepsilon = 1.89 \times 10^{-28} \frac{Z_{eff} \langle g_{ff} \rangle n_e^2}{T_e(eV)^{1/2} \lambda^2} e^{-\left[\frac{12,400}{T_e(eV)\,\lambda}\right]} \text{ W-cm}^{-3}\text{-Å}^{-1}$$

where Z_{eff} is

$$Z_{eff} \equiv \sum_{i=1}^{\text{all ions}} Z_i (Z_i n_i / n_e) ,$$

the ionic charge weighted by the electrons the ion contributes to the plasma density.

† Kadota, K., Otsuka, M. and Fujita, J. (1980), “Space- and Time-Resolved Study of Impurities by Visible Spectroscopy in the High-Density Regime of JIPP T-II Tokamak Plasma,” *Nuclear Fusion* **20**, 209-212.

VB Hardware

- TFTR uses the usual hardware[†]:
  - A tangential array of 16 channels; a lazy-susan shutter with closed, open, and 3 quartz windows; and an integral white plate calibration system which operates remotely.
  - Light collection by 600 μ core fibers filled by 50 mm φ lenses, with the fibers running about 30 m to a shielded room.
  - Double interference filters, with a final passband of 1 nm centered at 523.5 nm, and low noise photomultiplier tubes.
  - Preamplifiers rolled off at 18 db/octave at 800 Hz, and digitized 12 bits deep at 2 kHz.
- ... And it has the usual problems:
  - The sightlines end on the outer wall of TFTR where it is armored with carbon tiles, but these tiles have gotten smoothed and are sometimes a bit shiny, and we sometimes see reflections. Lithium injection seems to make things worse.
  - Several sightlines end on metal or glass, and in one case we usually see reflections.
  - There are occasionally outside bright features which radiate in the passband - MARFE's, for example.
  - The outer channels have a very weak signal (the density is very low) and are very susceptible to any kind of pollution.

† Ramsey, A. T. and Turner, S. L. (1987), "HAIFA: A modular, fiber-optic coupled, spectroscopic diagnostic for plasmas," Review of Scientific Instruments **58**, 1211-1220.

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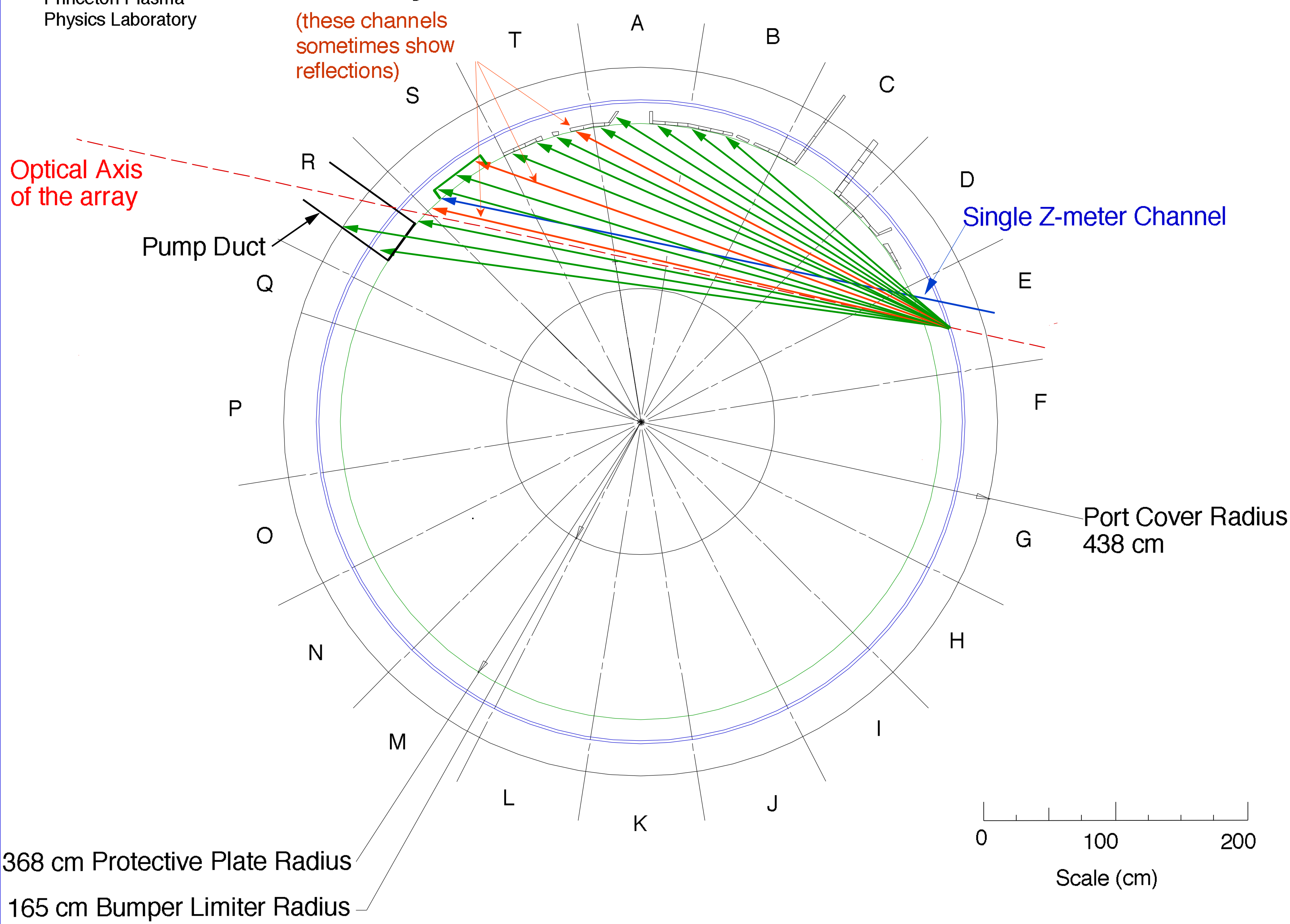
Layout of the 16-Channel VB-array



VB Software

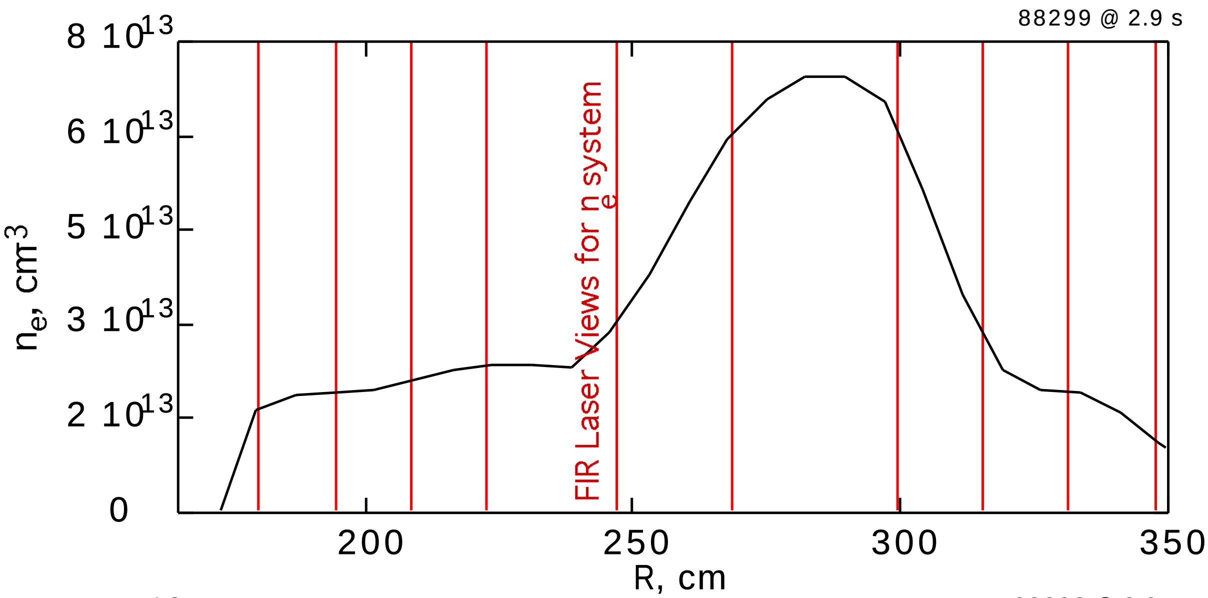
- The raw chordal data is corrected and normalized:
  - Array calibration produces a relative calibration file for all of the 16 chords in the array, which is then normalized to the single VB chord which can be absolutely calibrated. The current version of this file is stored with each shot.
  - The dc off-set of the preamps is removed by using data from before plasma breakdown.
  - The calibration file from the parameter file for the shot is used to turn digitizer counts into relative surface brightness units.
- The chordal data is Abel† inverted:
  - The only assumption made is of toroidal symmetry on the midplane.
  - A least-squares non-linear fit is done in chordal space; that is, a trial inversion is chordally integrated and compared to the sightline data to arrive at the best fit.
  - The fit is only constrained to be continuous in emission space and non-negative.
- The cautions:
  - No matter the details of the inversion process, it is still like peeling an onion; first you remove the outer layer, then the next, and so on *ad terminas*.
  - Such a process is similar to differentiation, and as such tends to introduce noise.
  - Fortunately, noise from one channel damps rather quickly in our geometry.

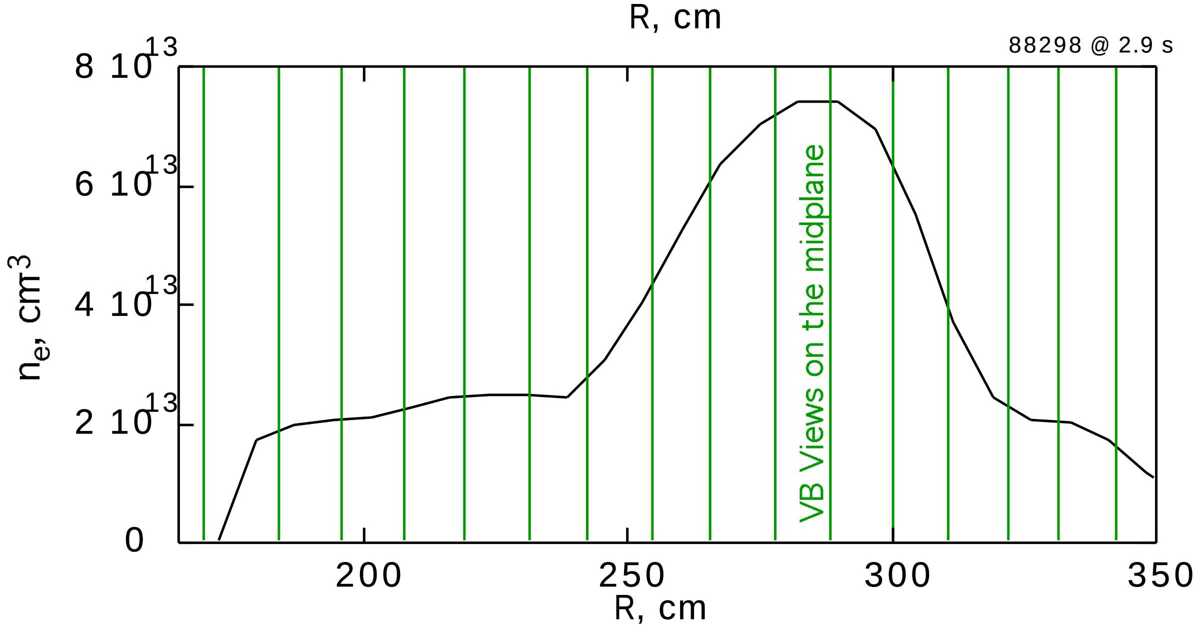
† Niels Henrik Abel, b. Aug. 5, 1802, island of Finnøy, near Stavanger, Nor., d. April 6, 1829, Froland. Norwegian mathematician, a pioneer in the development of several branches of modern mathematics.

Sightlines on Density Profile

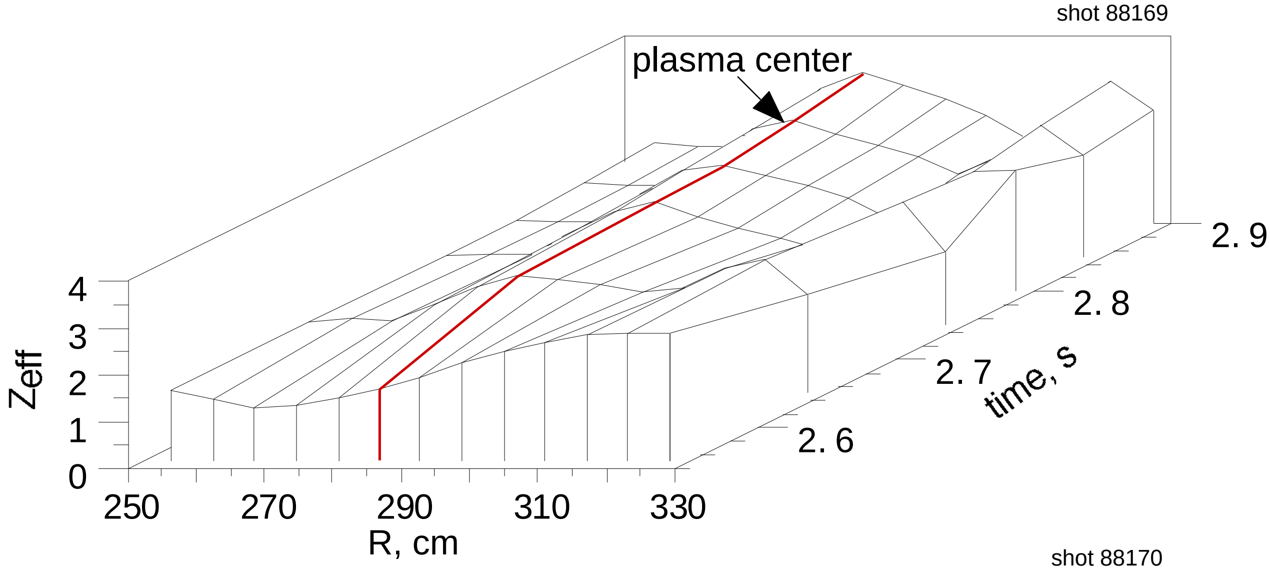
4 Below are drawings of the density and vb sightlines on a enhanced reverse shear (ERS) shot, where the density peak has shifted well out in the vacuum vessel:

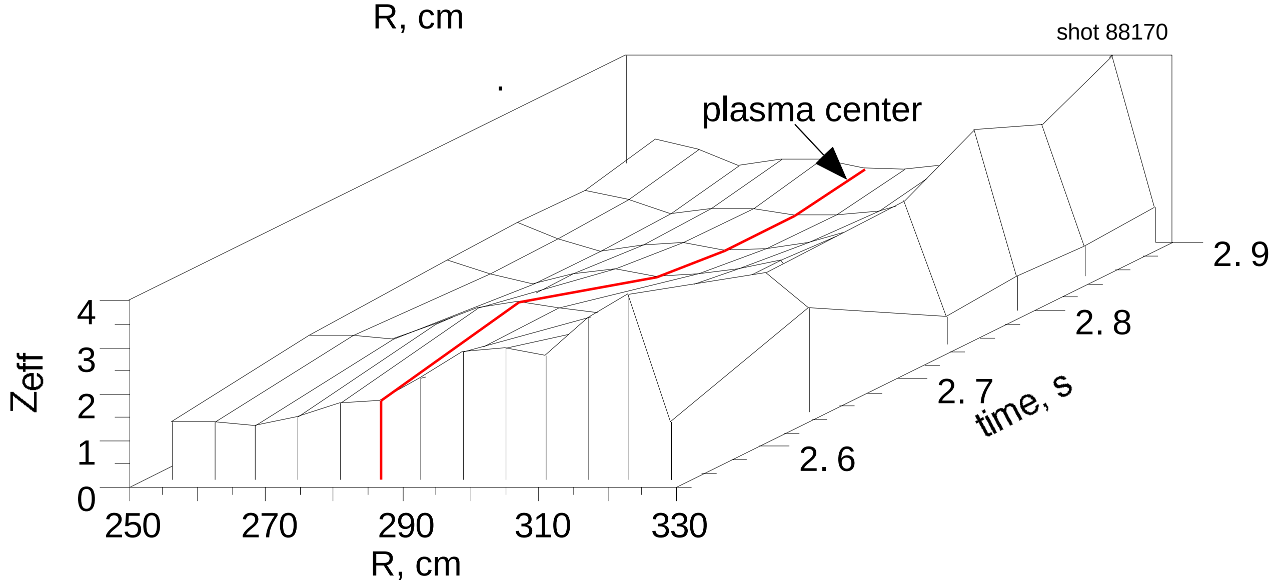
- The hole in density diagnostic access due to a poloidal field coil means there is no density information in the core of the plasma.
- Because the visible bremsstrahlung array is tangentially viewing on the midplane, it has coverage through the pf coil gap





Z_{eff} Profile Evolution of Reversed Shear Shots:
With and Without an ERS Transition

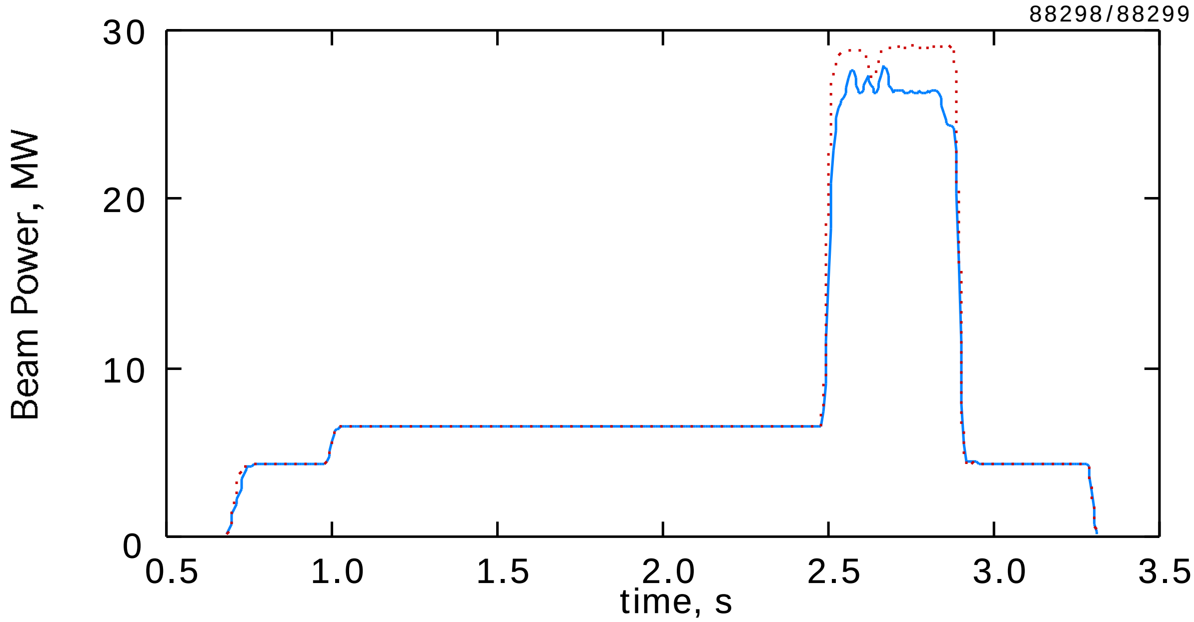


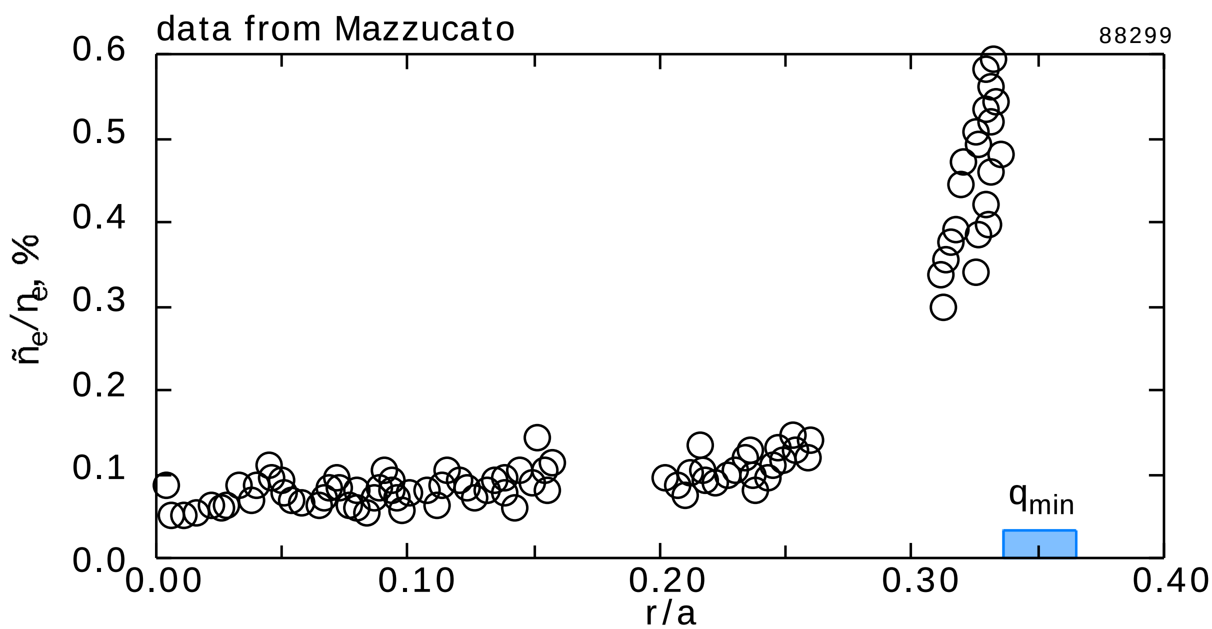


- This is the time evolution of two reverse shear shots taken one after the other. All plasma set-up parameters were the same:
  - The top graph shows the Z_{eff} in the core apparently increasing throughout the shot, as if there were impurity concentration.
  - The lower graph shows that the Z_{eff} profile begins in the same way, but hollows out at the transition to ERS at 2.65 s when the core density climbs sharply.

A look at ERS Profiles:

4 We'll look at a shot pair (RS/ERS) differing only in a 10% higher beam power in the ERS shot, which caused the transition. First we look at the beam power timing, used to create the current profile with a q_{min} at about R=320 cm. We also show the density fluctuation in the ERS shot.





4 The density fluctuation data are low everywhere inside the q_{min} surface, which suggests that the core confinement might be high throughout.

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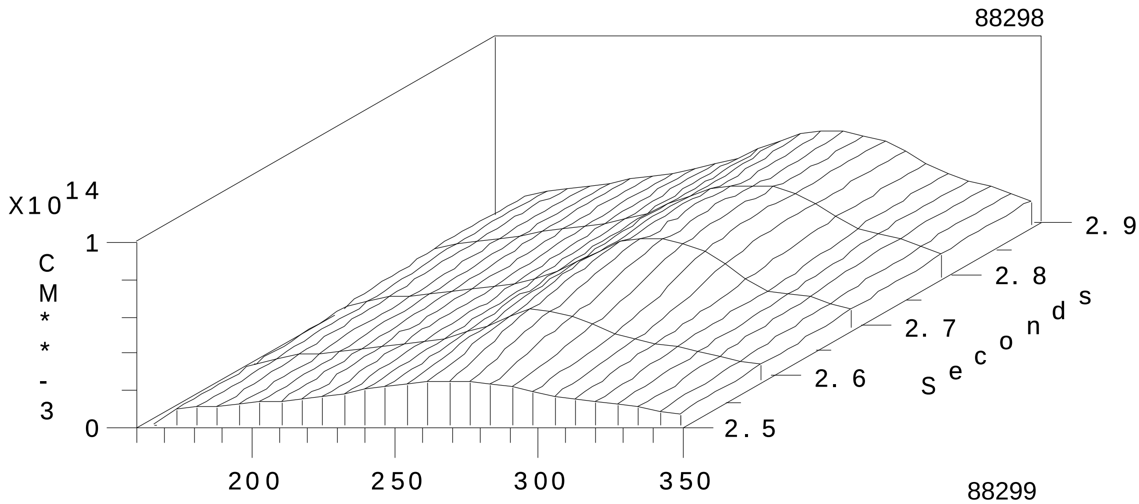
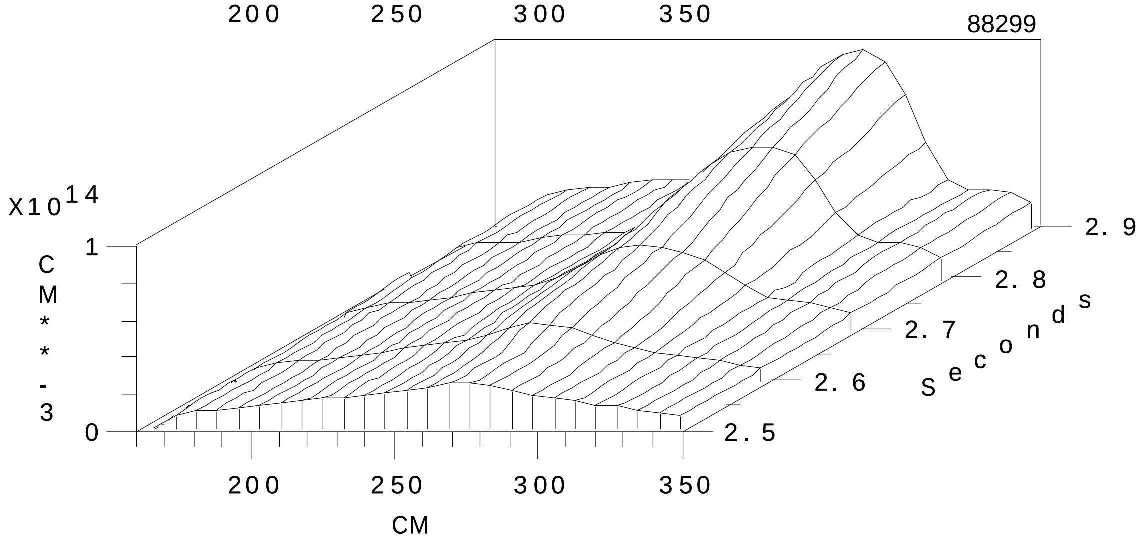
Density Evolution in RS/ERS Shots

4 This shows the density evolution of the same two shots during the high power beam phase.



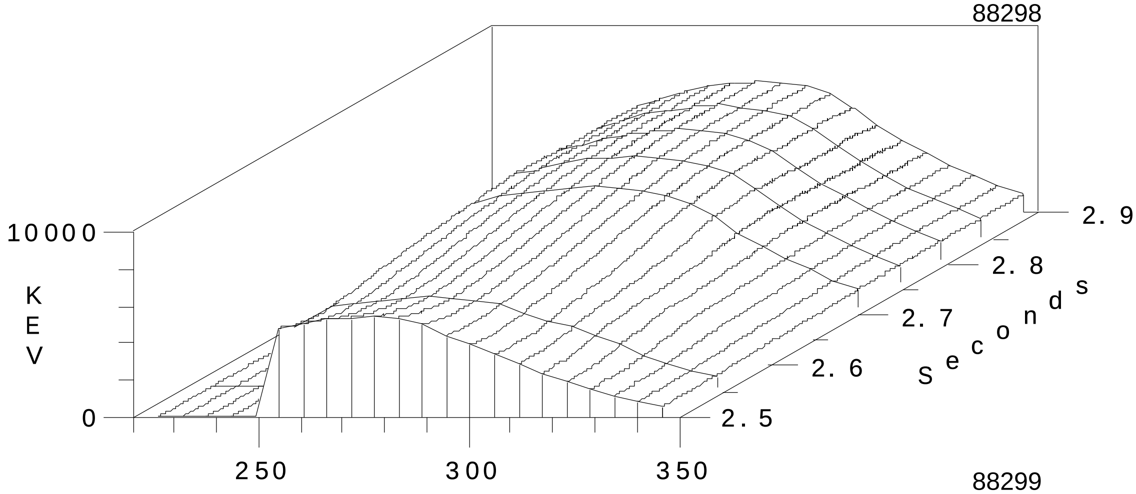


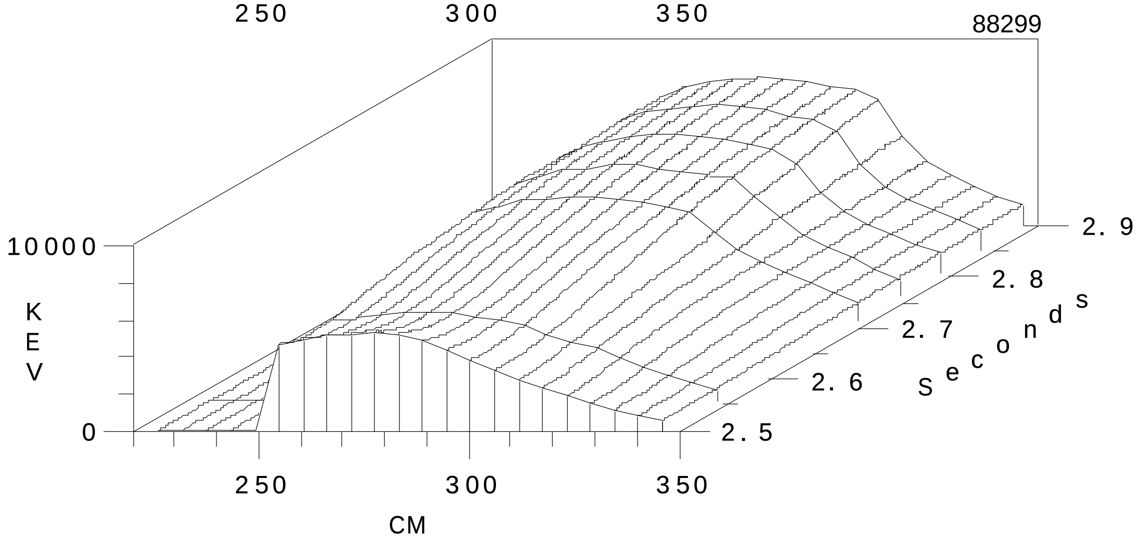
4 There are two differences in the density in the two shots:

- Most obviously, the improved confinement has caused the core density to increase enormously.
- Less obviously, the density profile has narrowed as it has grown - or, at least the reconstruction of the limited data set shows this effect. The ERS shot is the same shot shown above to illustrate coverage of the density diagnostic sightlines.

T_e Evolution in RS/ERS Shots

4 For this particular ERS shot, the T_e didn't increase greatly, as you can see. However, look at the outboard edge of the profile:



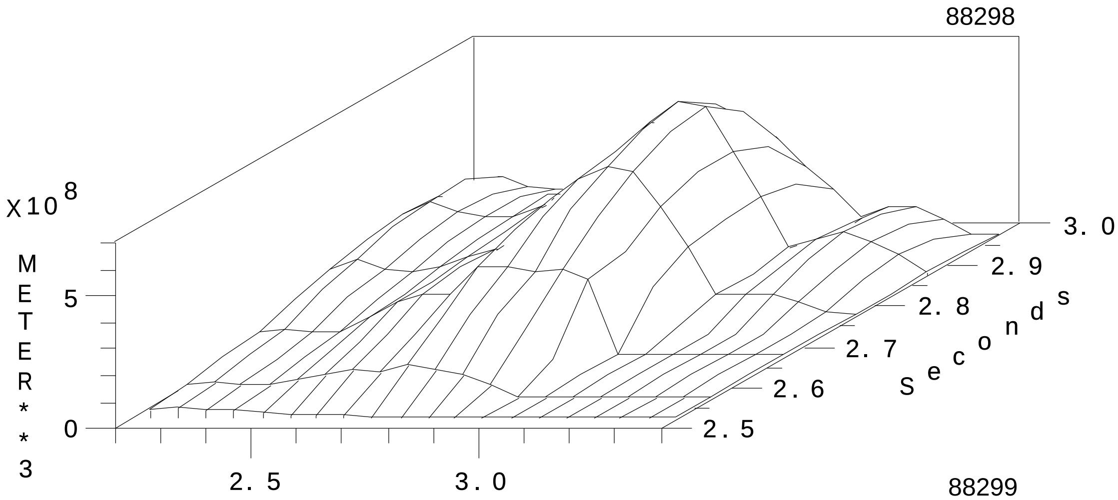


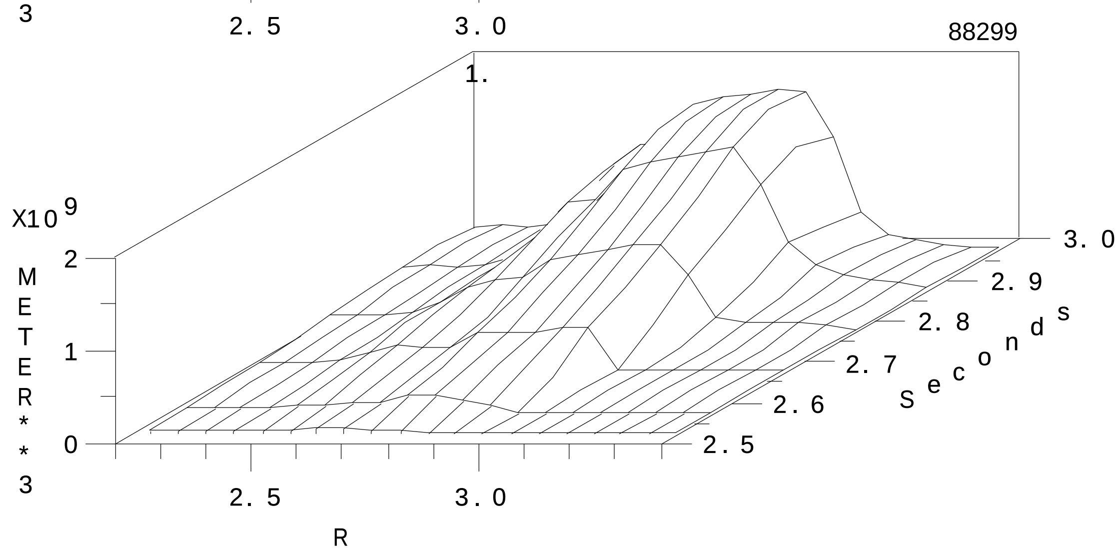
4 Two effects are clearly visible:

- The edge of the profile has steepened.
- The overall shape of the profile is broader.

Visible Bremsstrahlung Evolution in RS/ERS Shots

4 Here's how the VB emission looks for the two shots. NB: the two graphs have different vertical axes.



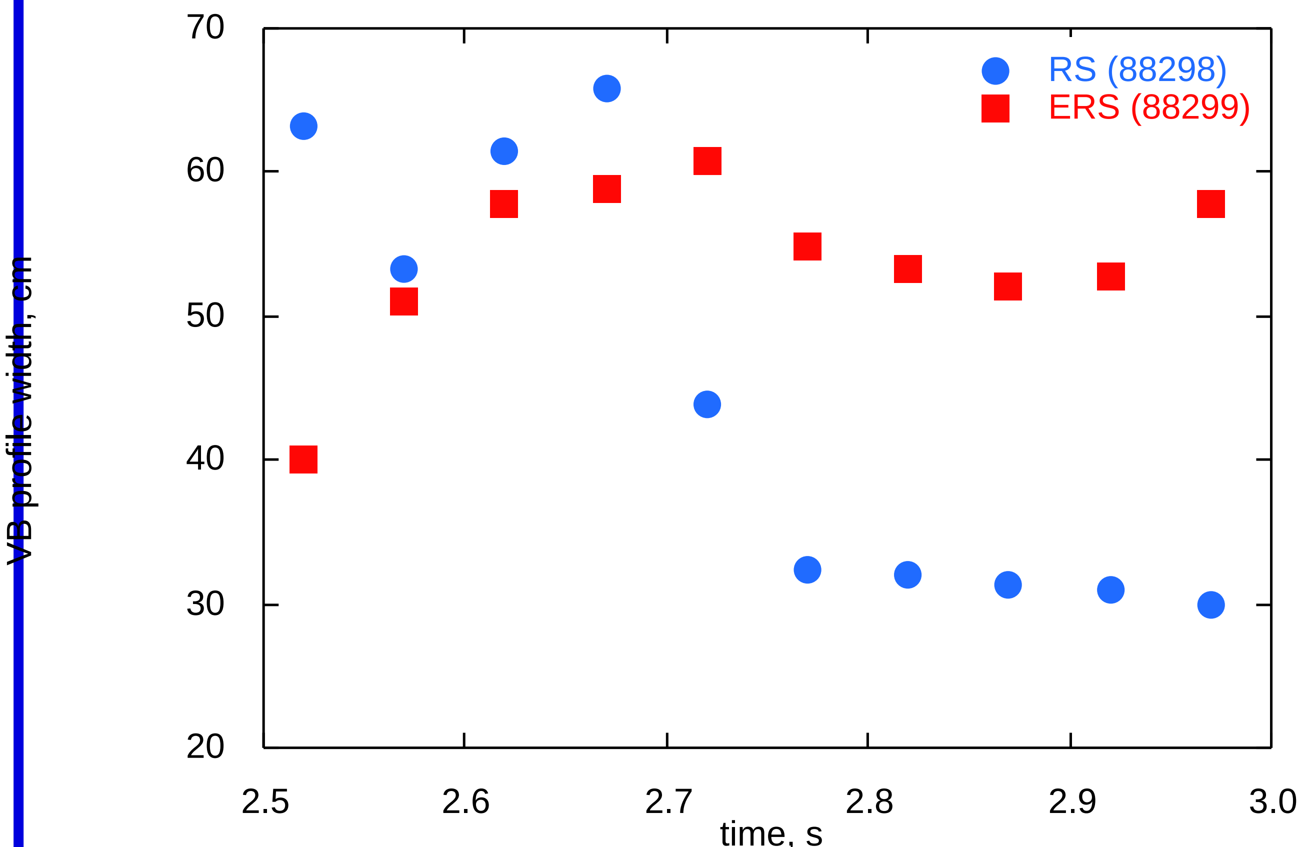


4 Look at two things here:

- The VB profile is noticeable flatter in the ERS shot.
- The flattening is accompanied by an outward shift of the profile and a steepening of the edge. Also, the feature at about 320 cm in the RS shot disappears in the wings of the ERS shot.

Another Look at the Width of the VB Profiles

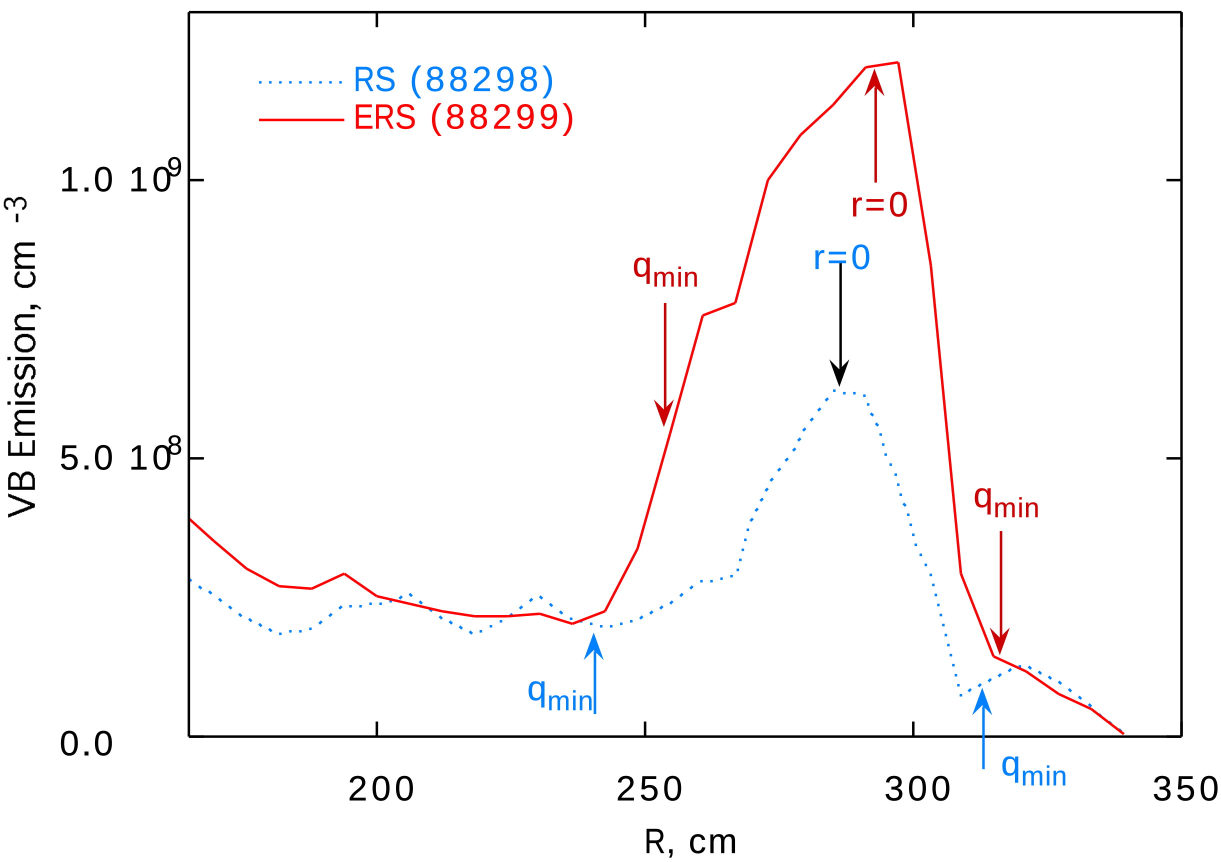
4 Here's another look at the time evolution of the width of the VB profiles shown above. Note above: the high power beam phase is from 2.5 to 2.9 seconds.



4 Until about 2.65 s, the two plasmas have the same VB emission profile. Then, at the time the confinement bifurcates between the two shots, the RS shot width decreases to a much lower value than the ERS shot.

Another Comparison of the VB Profiles....

4 Here's a comparison of the RS/ERS profiles at the peak of stored energy, with the magnetic axis and the q_{min} points marked for comparison.



4 Because of higher stored energy, the plasma has shifted out in the ERS shot, making the bumps in the VB profile at the q_{min} surfaces less noticeable. But see the Z_{eff} profiles, below.

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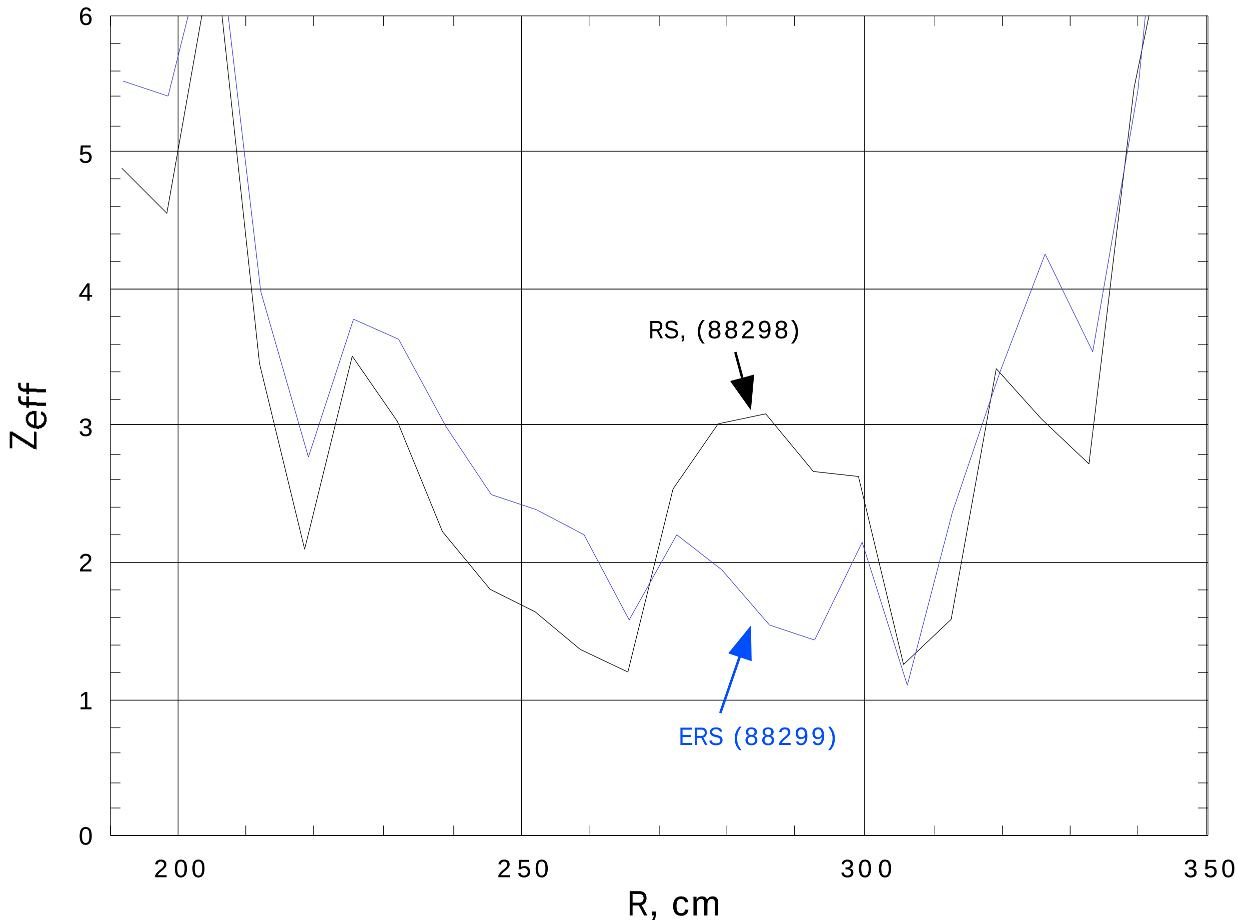
And the Z_{eff} Profiles, RS and ERS

4 Here are the Z_{eff} profiles from the VB profiles shown above, using the density profiles as they stand:

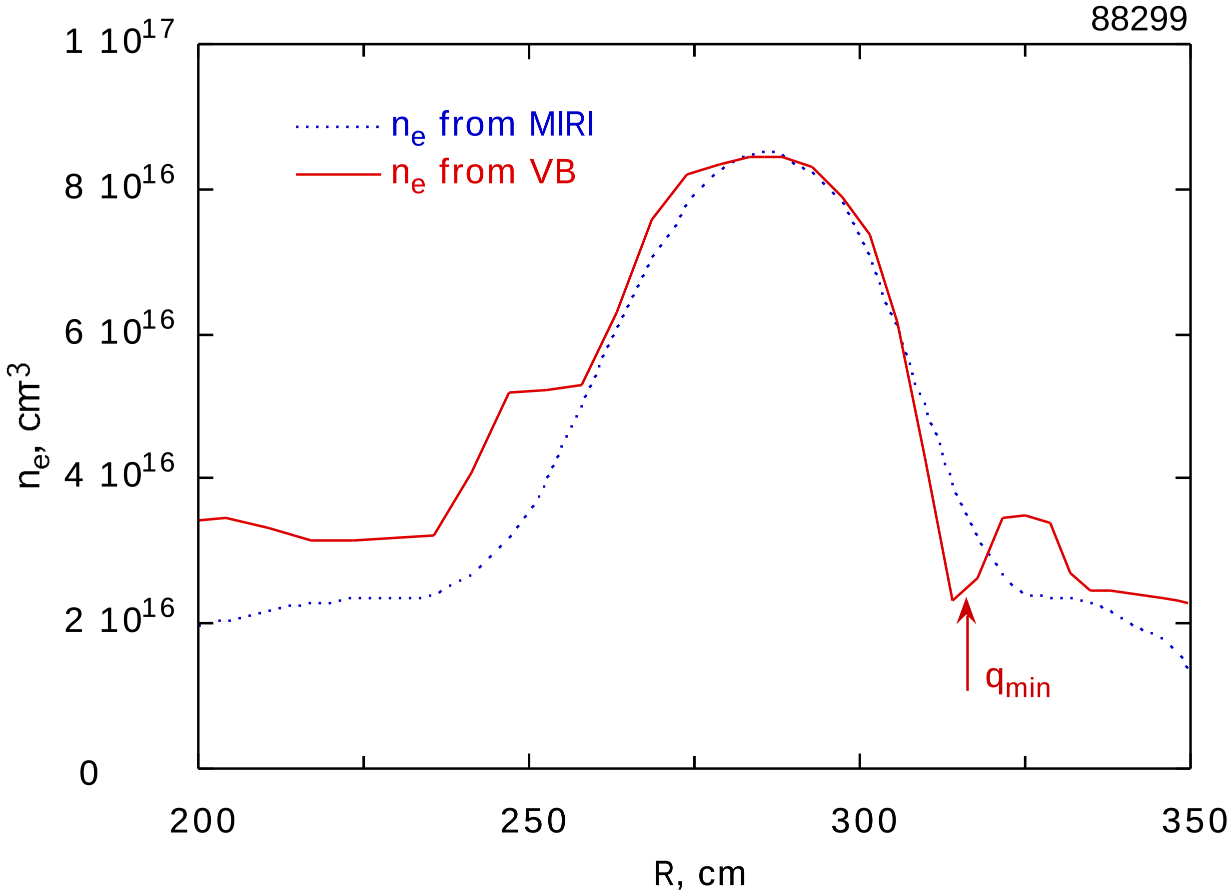


4 The ERS shot clearly shows the hollowing we saw for another RS/ERS shot pair above. There are at least three reasons this could be happening:

- Transport in RS could be causing impurity accumulation which is not present in ERS.
- The deduced VB profile could be flattening more than it really is.
- The deduced density profile could be peaking more than is really is.

VB and n_e: How Different?

4 The hollow Z_{eff} profiles may be real, and perhaps the n_e profile really is peaked even though the other profiles in ERS shots are more flat. Here we make a small change: let the Z_{eff} profile be flat, and back-calculate the density profile:



4 For now, ignore the bumps at the edges of the VB n profile (and see below) and look at the difference in the shape in the core: The VB n_e profile is flatter, as we expected - quite a bit flatter.

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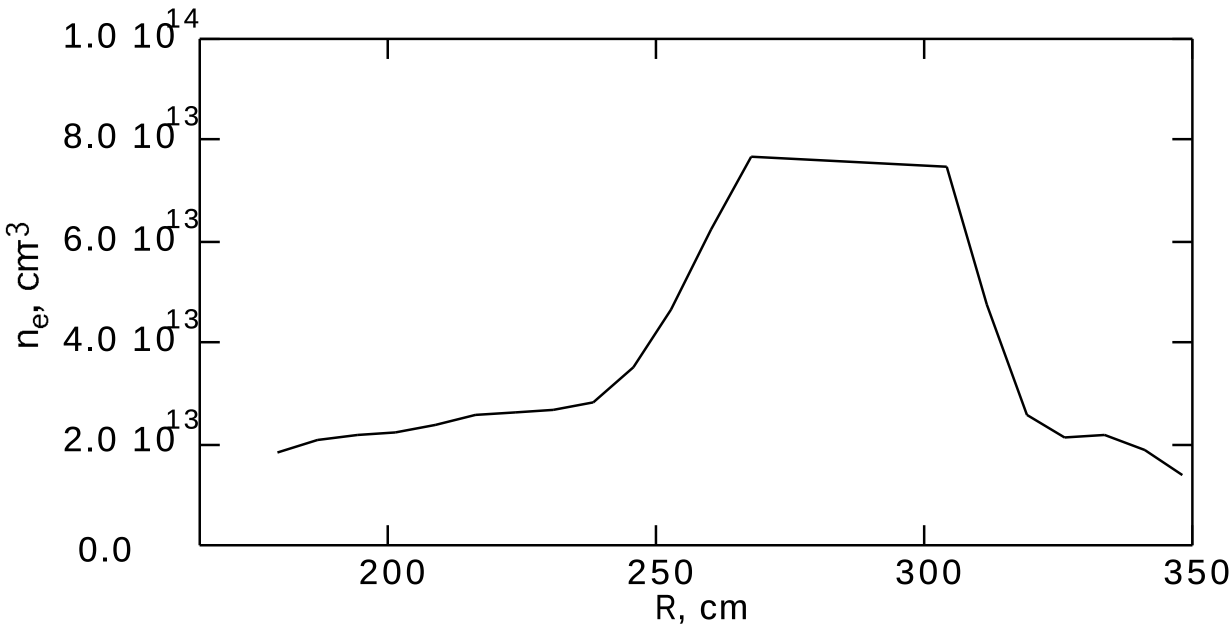
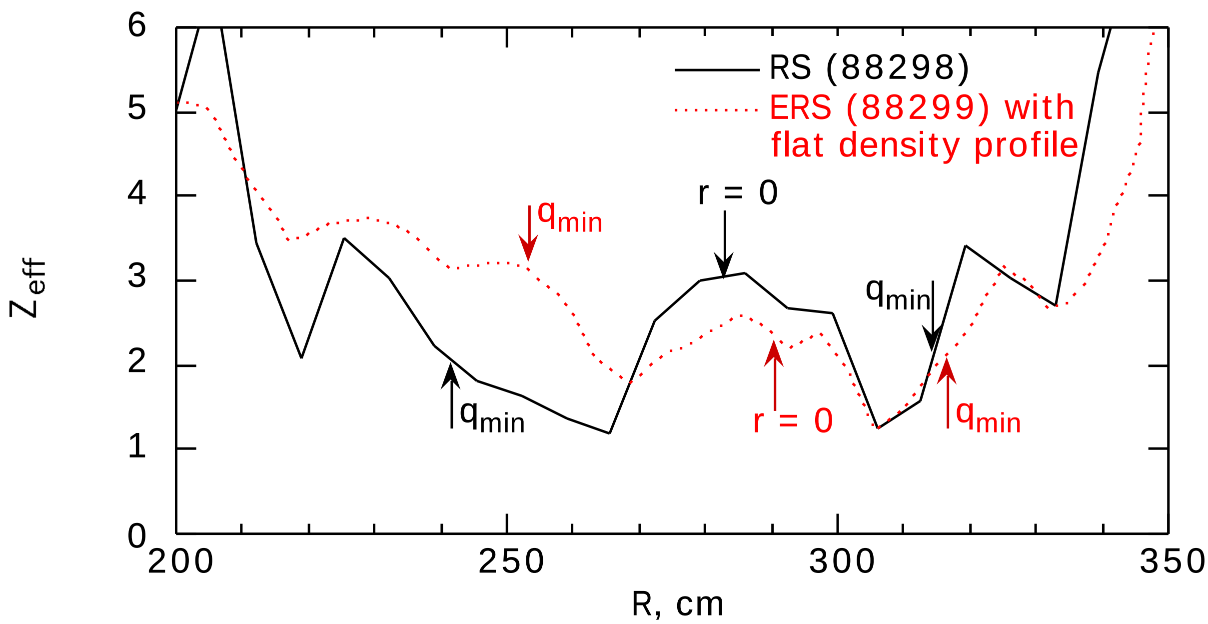
A Very Big Change in n_e?

4 If we suspect that the deduced n_e profile might be too peaked when the magnetic axis falls in the blind zone, let's make the biggest change we are allowed to - since we don't have any data in the region, let's just make the profile flat:

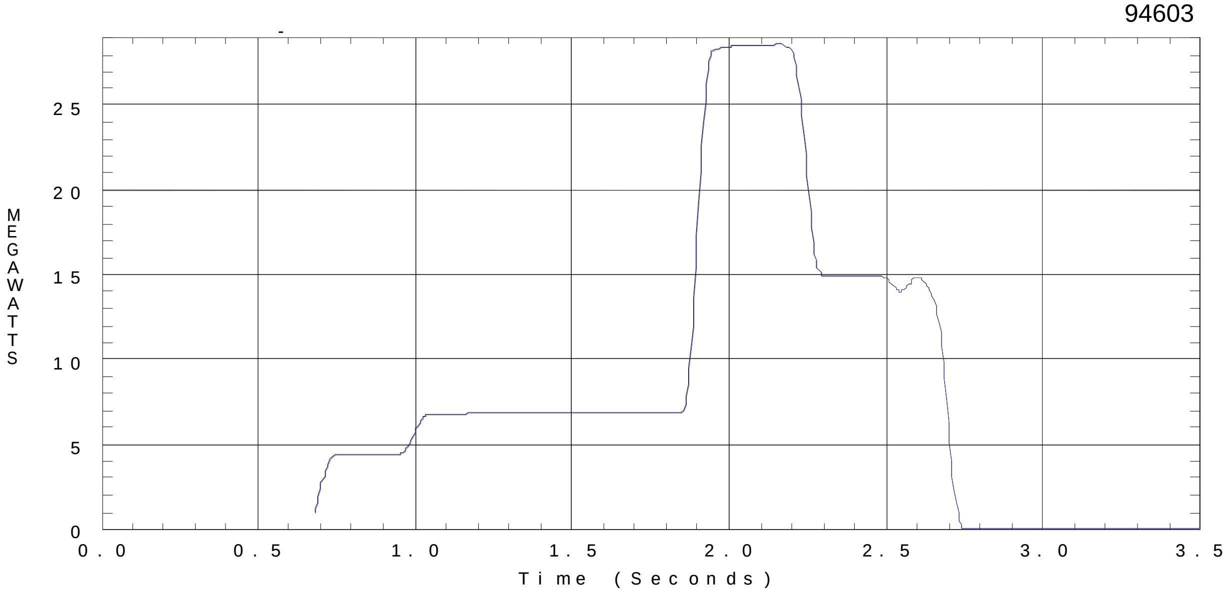


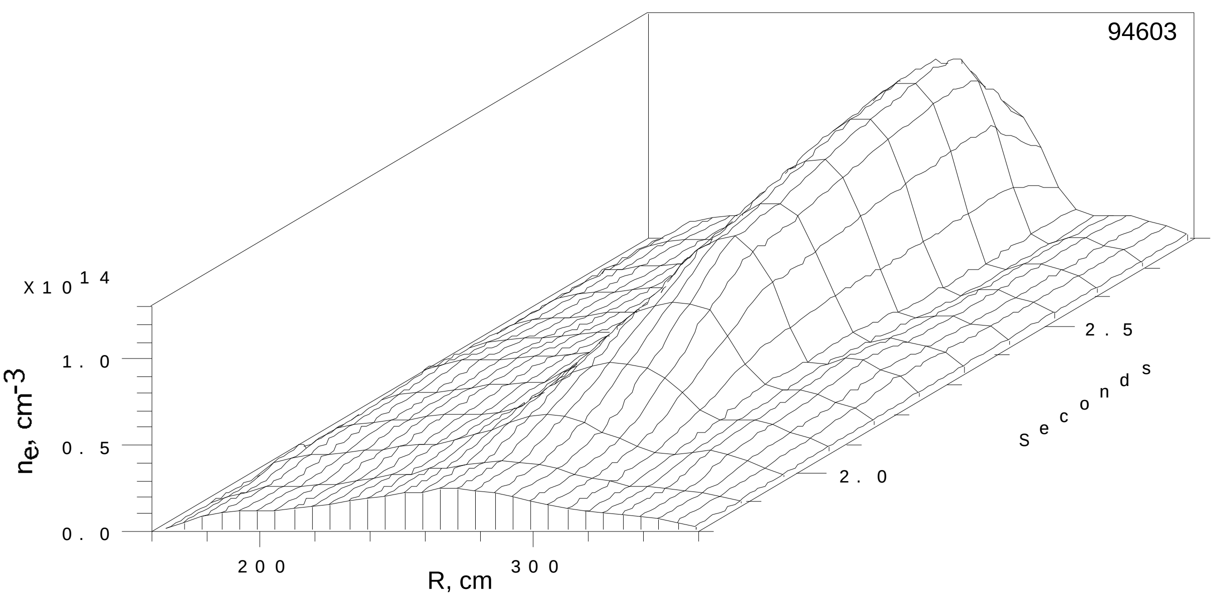


4 Here's the resulting Z_{eff} profile of the ERS shot, compared with the RS shot of the pair. They sure look a lot alike. Does this mean anything? We know that transport in the ERS shot is different; why shouldn't there be a difference in impurity transport, too? This clearly needs more study.

Profiles in the Postlude Phase of ERS Shots

4 We'll look now at a very interesting ERS shot, after the high power beams turn off. Note the beam timing, then look at the electron density profile:

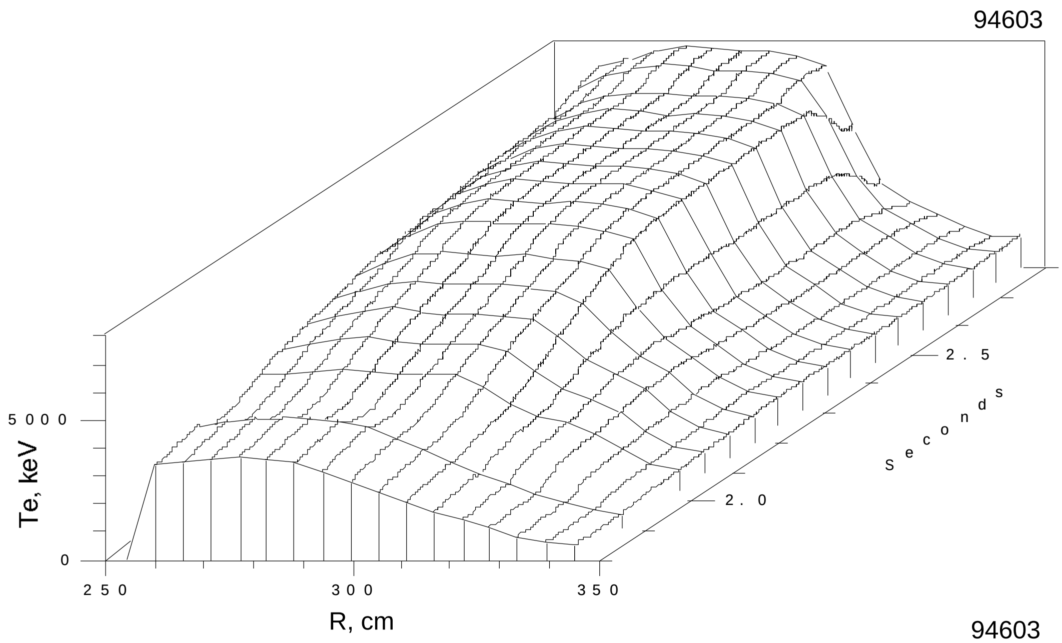


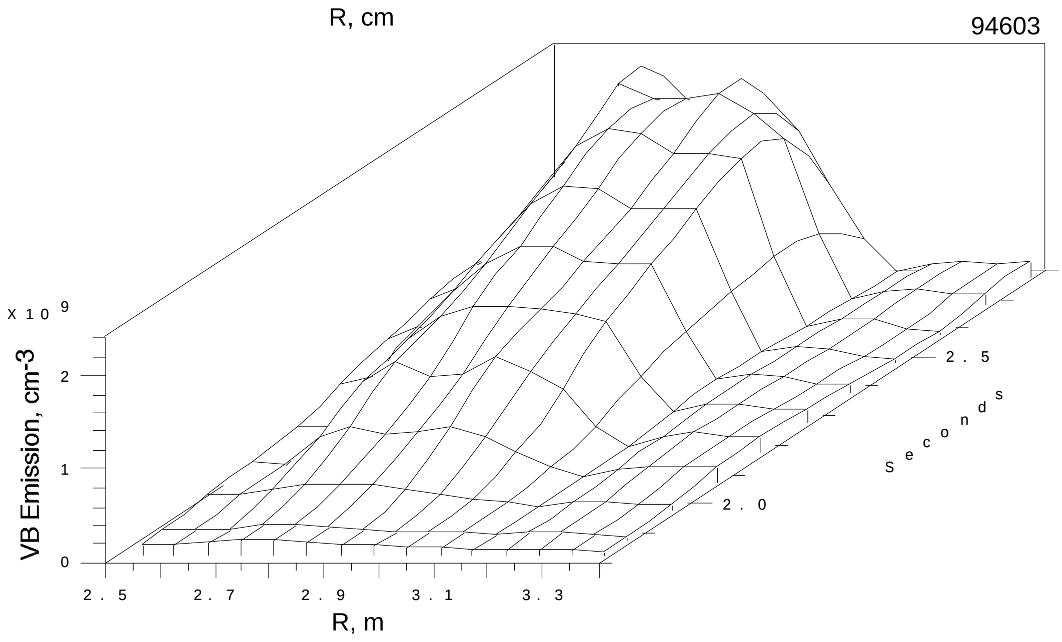


4 Even though the high power phase of beam injection ends at 2.2 s, the density continues to rise in the postlude phase. What are the other profiles doing?

T_e and VB Profiles Continue to Evolve:

4 Here are the T_e and the VB profiles. The high power beam phase ends at 2.2 s:

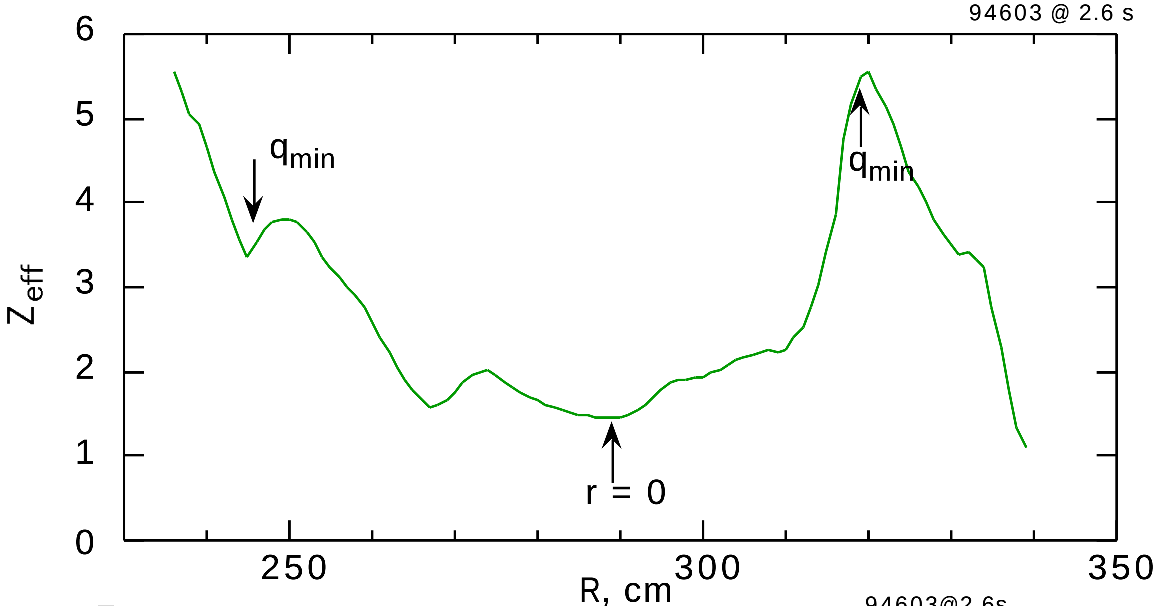


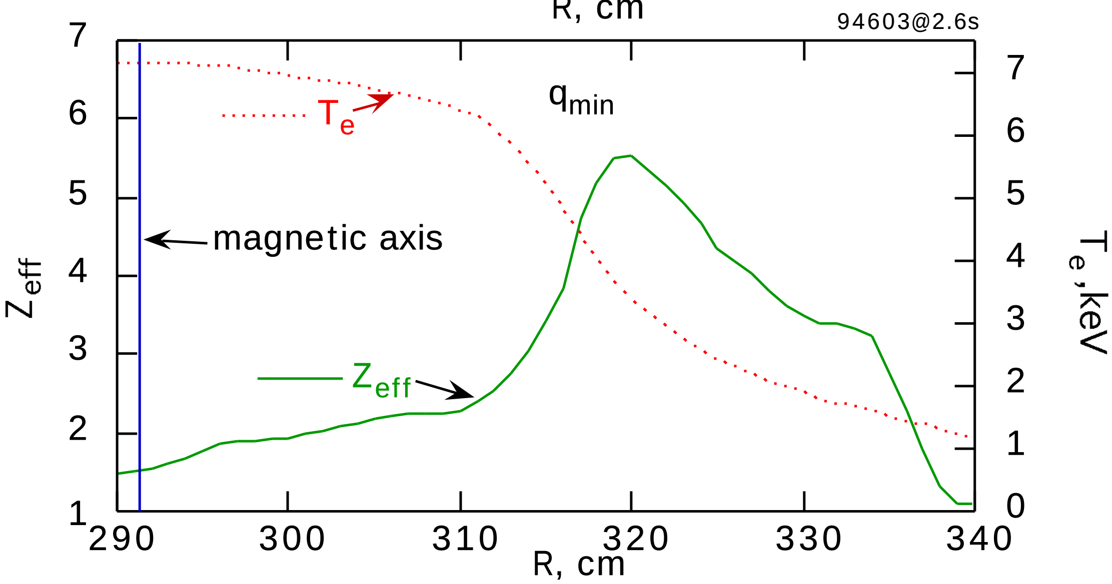


4 Both profiles continue to flatten and grow well into the postlude. Notice the steepening of the outboard edge of the profiles.

Z_{eff} and T_e at the q_{min} Surface

4 Here is the Z_{eff} profile of the shot near the end of the postlude where the profiles are nearly in equilibrium. Below it is the same curve on an expanded scale around the measured q_{min} surface, with the T_e profile overlaid.

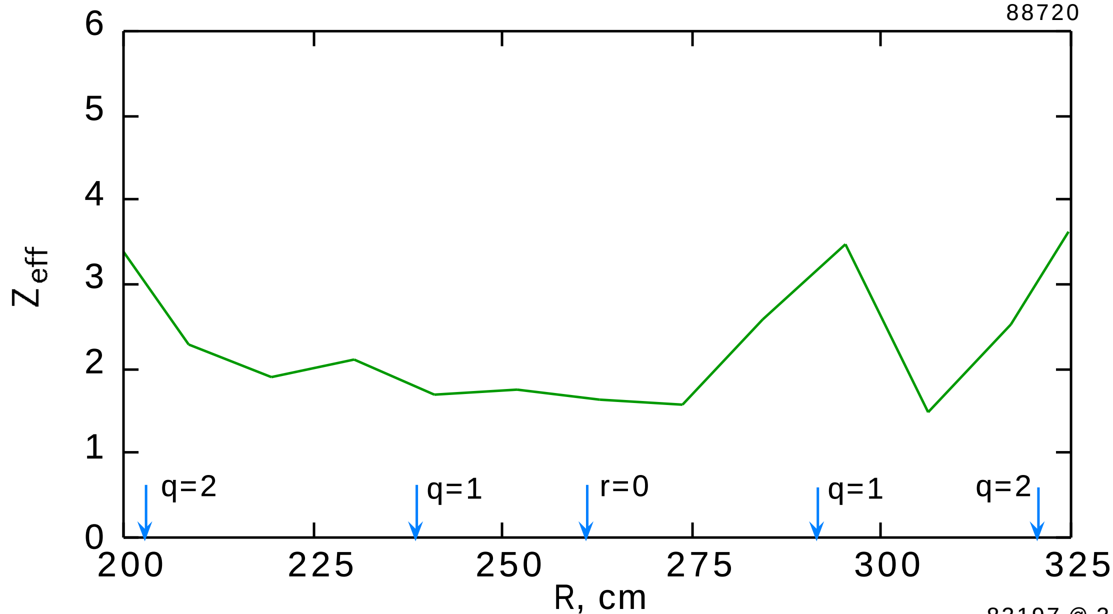


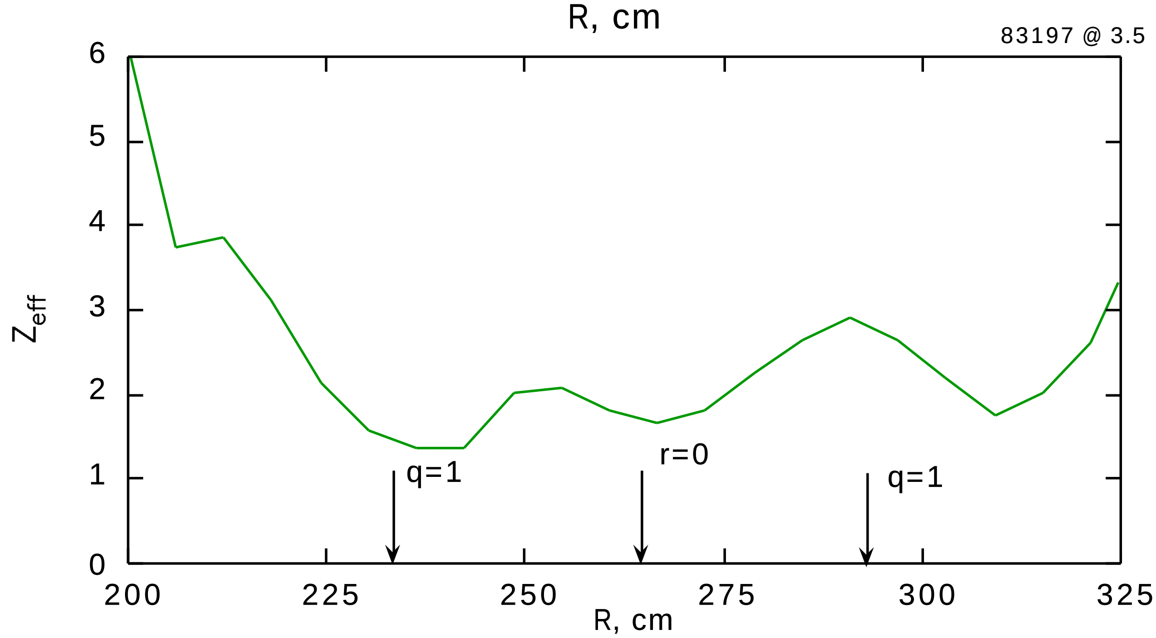


4 It seems quite clear that impurities are piling up at the edge of the q_{min} surface exactly at the point that the barrier in the T_e profile appears. This does not answer the barrier *vs* region question, however. The accumulation of impurities outside the q_{min} surface is not inconsistent with a hollow Z_{eff} profile in the core; but what do we make of the peaked profiles in the RS phase?

Is History a Help?

4 Let's look at some shots where the magnetic axis didn't fall into the pf coil gap. Here are a low-mode and a super shot at 2.5 m. Both are at I_p=2 MA and about 20 MW injected power - similar to plasmas above.

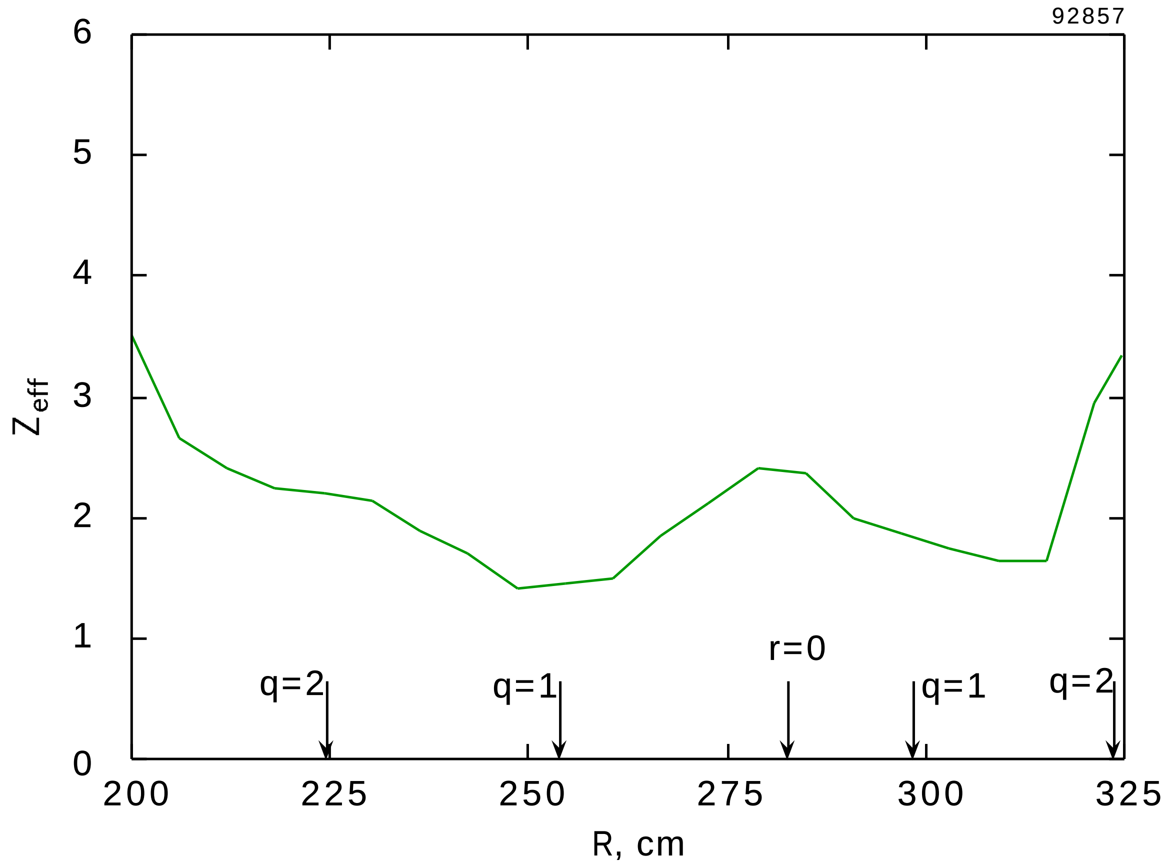




4 Both shots show what we have historically seen: The Z_{eff} profiles are flat in the core, with some bunching up near the q=1 surface - sometimes between the q=1 and q=2 surfaces.

What's $Z_{eff}(r)$ of a Large Radius Super Shot?

4 For comparison with the shots just above, here's a super shot done recently at 2.6 m. The magnetic axis falls into the blind spot of the density measuring system.



4 Unlike small radius supershots, which have flat Z_{eff} profiles in the core, this shot show a peak similar to the RS shots at the same radius. An explanation?

- Large radius supershots are different?
- An artifact of the VB inversion process?
- A systematic under-peaking of large radius density profiles in the inversion process? This leads to peaked Z_{eff} profiles in RS shots, which disappears when the VB profile broadens in ERS shots, while the density stays (mostly) the same shape.

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