Some Notes on the Window Frame Method for Assessing the Magnitude and Nature of Plasma-Wall Contact

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1. Fig. 1 shows an example of a suitable magnetic configuration for application of the Window Frame Method. (Thanks, Adam McLean, for creating this fig.) It is a schematic and does not represent an actual DIII-D shot. The method exploits the presence of the toroidally symmetric 'nose' at the top of DIII-D, i.e. the set of tiles that protect the upper-outer pump. Thus the SOL is divided into 3 sub-SOLs, as shown:

1. The **Divertor SOL**, where the target solid surfaces terminate the flux tubes and provide the parallel sink. This sub-SOL extends radially from the separatrix out to the flux surface which touches the tip of the toroidally-symmetric nose limiter at the top (thus from the thick black line to the green line). It extends along **B** from target to target.

2. The **Symmetric Wall SOL**, which extends from the tip of the nose limiter out to the flux tube which makes the first contact with the toroidally-unsymmetric wall elements, such as the antennae, i.e. the radially most inward-protruding 3D wall component (thus from the green line to the orange line). Here we have shown this element - the "3D Wall Starting Point", 3DWSP - to be at the outer midplane but it may be elsewhere. The sinks for the flux tubes in this sub-SOL are the toroidally symmetric surfaces at the sides of the nose limiter at the top, and at the inner wall, and (for the example shown here) on the top of the outer-lower pumping plenum. Thus this sub-SOL is separated into 2 parts by the nose limiter – the **Outer Symmetric Wall SOL** and the **Inner Symmetric Wall SOL**.

3. The (toroidally) **Unsymmetric Wall SOL**, which then extends out 'indefinitely', i.e. at each toroidal and poloidal location out to the first solid contact point (thus from the orange line outward). The fig shows a definite termination of this sub-SOL (at the mauve line) but this is not really correct. While the other lines in the fig are meaningful, since they are projections onto the poloidal plane of surfaces which are toroidally symmetrical, the outer boundary of the 3rd sub-SOL is not toroidally symmetrical and so it's poloidal projection is not meaningful. The sink action in this sub-SOL is geometrically complicated, consisting of the plasma-wetted sides of the various 3D structures in this region. The 3D structures shadow each other in a complicated way which changes with q. From a practical viewpoint it is not possible to analyse the sink action in this region with any accuracy, although it may be possible to make upper-bound estimates (which are needed to assess the validity of the window frame method, below).

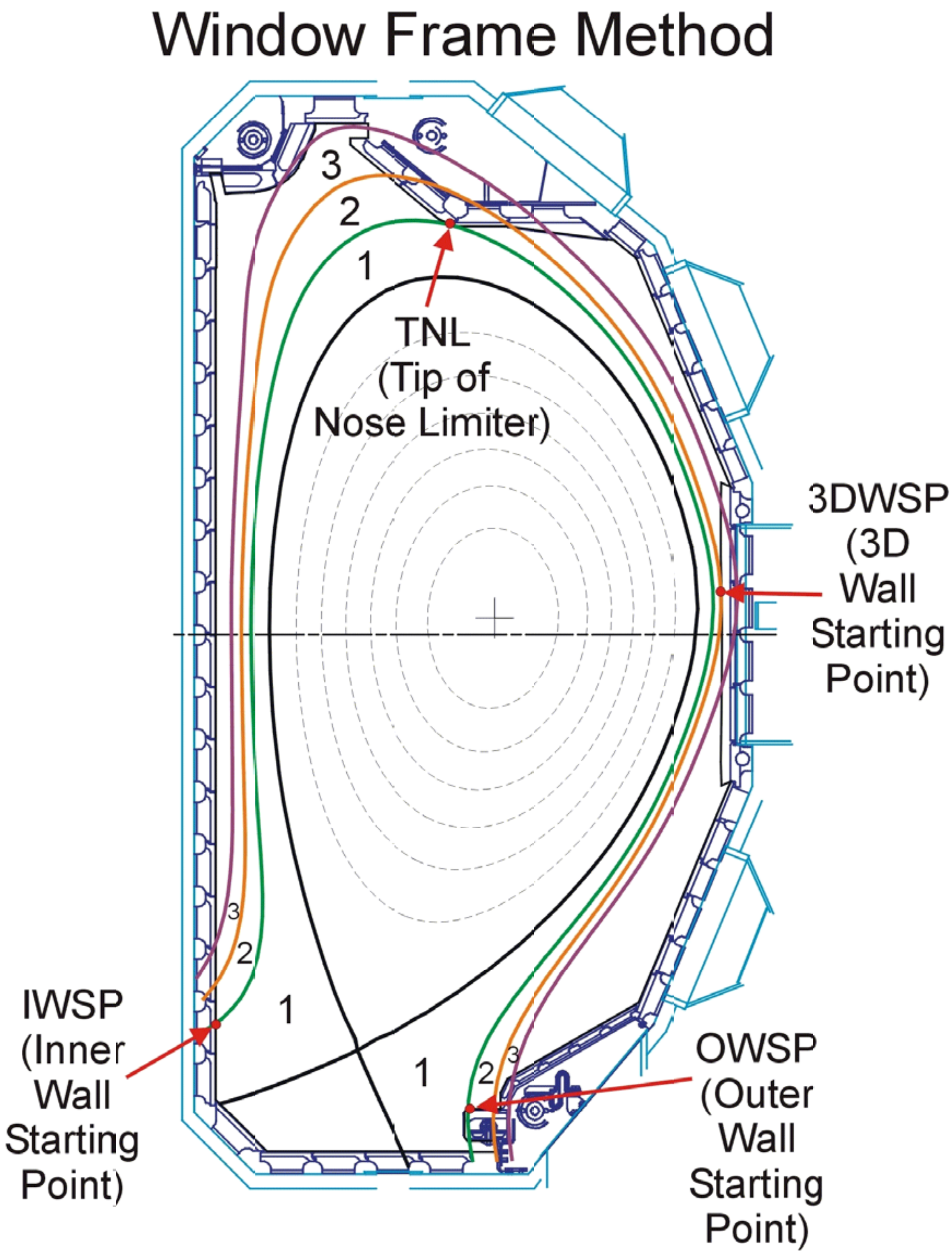


Fig. 1 Example of configuration for application of the Window Frame Method.

2. The definition of the locations where the "divertor targets" stop and the "walls" start is arbitrary, of course. Here, the obvious definitions are the points shown in the fig. where the green line intersects the inner wall/divertor-target structure at the "Inner Wall Starting Point", IWSP, and similarly at the "Outer Wall Starting Point", OWSP.

3. We define the "ionic wall flux" to be the total ionic flux going to solid surfaces lying outside the green line, while the "ionic target flux" is the total ionic flux to the solid surfaces lying between the green line and the separatrix, i.e. for the **Divertor SOL** (one may also choose to include the ionic flux to the Private Flux Zone, PFZ, wall in the latter).

4. We are in a good position to measure the ionic wall flux for the **Symmetric Wall SOL**, i.e. to the toroidally symmetrical wall surfaces which subtend this sub-SOL, but we are not in a good position to measure the ionic wall flux for the **Unsymmetric Wall SOL**, i.e. to the toroidally non-symmetrical wall surfaces which subtend this sub-SOL. Application of the Window Frame Method, therefore, requires that the total ionic wall flux occurring outside the orange line is a small fraction, say < 10%, of the total ionic wall flux, thereby justifying its neglect.

5. Measuring the ionic wall flux for the **Symmetric Wall SOL**: this can be done in several ways, in principle:

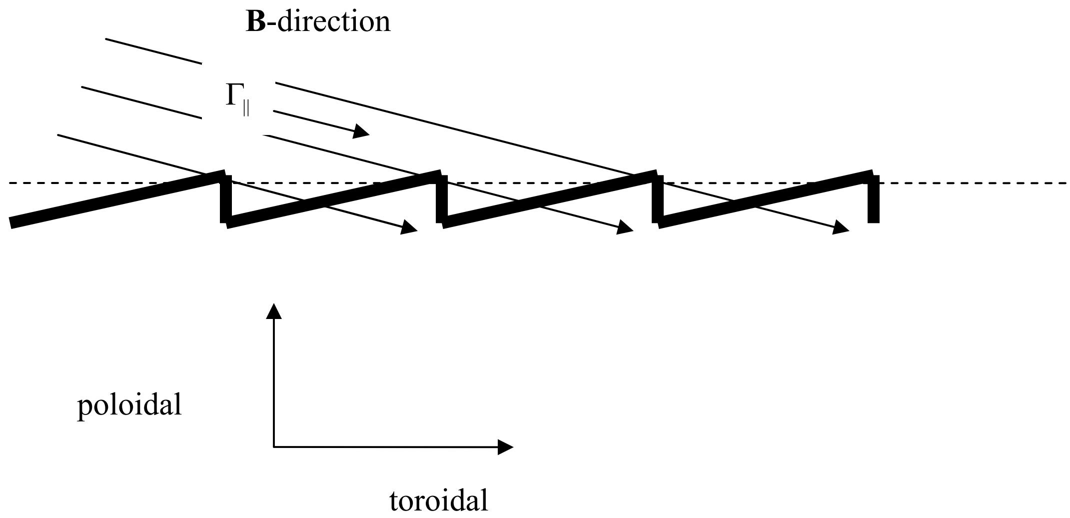
(a) The ideal method requires a radial array of built-in Langmuir probes, of a similar type to the ones in the divertor targets, extending radially outward from the Tip of the Nose Limiter, TNL, along the inner and outer sides of the nose limiter. Assuming toroidal symmetry, the array can be placed at any convenient toroidal location. An array on the outer-facing side of the nose limiter will provide a measure of the ionic wall flux for the **Outer Symmetric Wall SOL**, while a similar array on the inner-facing side will measure of the ionic wall flux for the **Inner Symmetric Wall SOL**. Since the plasma-wetted area involved is so simple and well-defined it is a straightforward job to calculate the total ionic flux to the each side of the nose limiter for the entire torus from the probe data. Assuming that the Symmetric Wall SOL is *simple*, i.e. is in the sheath-limited regime (negligible parallel temperature gradients), then it can be assumed that the ionic wall flux going to the lower ends of the Symmetrical Wall SOL - to the inner (outer) walls between the green and orange lines - is the same as to the inner (outer) sides of the nose limiter. In that case, the total ionic wall flux for the torus is just double that to the nose limiter. It would be valuable, however, to have radial arrays of probes near the IWSP and OWSP to check this assumption. It is likely that the Symmetrical Wall SOL is in the sheath-limited regime since T_e in this SOL is typically ~ 10 eV and the density is low.

(b) Assuming that the Symmetric Wall SOL is in the sheath-limited regime then it is adequate to measure the radial profiles of n_e and T_e at any toroidal and poloidal location, such as at the location of the Thomson Scattering System or the Reciprocating Probe. The ionic fluxes can then be calculated to the 2 ends of the

Outer Symmetric Wall SOL. This approach does not, however, give any values for the Inner Symmetric Wall SOL since at present no radially-scanning edge measurements are made on the inside

6. Checking that the ionic wall flux to the Unsymmetric Wall SOL is small enough to be neglected: this flux cannot be measured with precision, of course, but all that is required here is an estimate for an upper bound. One starts with the measured radial profiles of I_{sat}, n_e and T_e in the Symmetric Wall SOL, and extrapolates them into the Unsymmetric Wall SOL. This will overestimate the fluxes since shorter radial decay lengths should exist, on average, in this outer region with its larger number of sinks. What to assume for the plasma-wetted area for this outer region? Again, we cannot calculate this with precision but we can start with an estimate that it is somewhat greater than it would be if the localized 3D structures were absent and the toroidally symmetrical surfaces at the top and bottom of the machine were the only sinks. Since the flux densities for this region are over-estimated, while the plasma-wetted area is under-estimated, an approximate cancellation is indicated and so as a first estimate for the total flux to the Unsymmetrical Wall, one would simply extrapolate the flux received by the Symmetrical Wall to this outer region. It would be valuable to install Langmuir probes on the most protruding 3D structures in order to further refine the estimate of ionic wall flux for this outer region.

7. It is not essential that the plasma contact with the nose limiter (nor the walls near the IWSP and OWSP) be perfectly toroidally symmetric. If the tile alignment is not perfect, or if they are mounted in a faceted way, such that the tiles do not conform to a perfect toroidal circle, then the plasma-footprint will not be toroidally constant and continuous, but will be concentrated at one side of each tile, with only part of each tile then being plasma-wetted. Consider the following example for an “orthogonal target” (where the poloidal magnetic field at the target is perpendicular to the target):



By considering the flux passing through the surface represented by the dashed line, it can be seen that the total ionic outflux for the whole torus, i.e. sink rate, is still $\phi_{total} = \Gamma_{||} \sin\theta \, 2\pi R \, \lambda_{\Gamma}$ where θ is the magnetic pitch angle and it has been assumed that the radial profile extends out radially (direction into the page of the fig) to infinity, characterized by radial decay length λ_{Γ}. (Of course, so far as particle and heat *loading* of the solid surface is concerned, this is increased for the portions that actually receive particles and heat, since the shadowed regions of the tiles are not carrying their share of the load – but that is not of interest here.) The built-in Langmuir probes have to be designed so that they stand sufficiently proud of the surface that they are not effected by any shadowing, and therefore measure the value of $\Gamma_{||} = I_{sat} / e$. When Thomson or reciprocating probe data are used to calculate $\Gamma_{||}$, this is still given by $\Gamma_{||} = \frac{1}{2} n_e c_s$, where n_e is the value measured at the Thomson or reciprocating probe location (and where the sheath-limited regime is assumed).

The reason that the plasma-contact with these surfaces need not be perfectly toroidally symmetrical is that the parallel sink strength of the SOL is $\frac{n}{\tau_{SOL}} = \frac{n}{L_{||} / c_s}$, where $L_{||}$ is the parallel connection length. The introduction of grossly non-symmetrical structures into the edge changes $L_{||}$ substantially, and this is the reason – together with the complicated plasma-wetted area - that it is impractical to calculate the parallel sink action for the Unsymmetric Wall SOL. The very small variations in $L_{||}$ associated with imperfect or faceted tile alignment, however, has negligible effect on the parallel sink action.

8. We are therefore able to calculate the total ionic fluxes to the divertor targets, ϕ_{div}, to the outer wall, ϕ_{wall}^{outer}, and perhaps to the inner wall, ϕ_{wall}^{inner}. Such information is useful as a zeroth order indication of the importance of plasma wall contact, compared with divertor contact, regarding recycle refueling of the plasma and impurity sources.

9. We may, if certain conditions are met, proceed further and calculate the value of the cross-field particle flux density, $\Gamma_{\perp}$, "to the wall" - specifically across the green line – actually the value averaged over the poloidal extent of the outer wall (from TNL to OWSP), and perhaps also the value averaged over the extent of the inner wall (from TNL to IWSP). Assuming that the particle source supplying the particles to the outer wall i.e. providing $\phi_{wall}^{outer} = 2\Gamma_{\parallel}^{outer} \sin\theta \, 2\pi R \, \lambda_{\Gamma}^{outer}$ is entirely due to $\Gamma_{\perp}^{outer}$ across the outer green line, then we have from particle balance that $\Gamma_{\perp}^{outer} A_{wall}^{outer} = \phi_{wall}^{outer}$, where $A_{wall}^{outer} \approx 2\pi R L_{pol}^{TNL/OWSP}$ and $L_{pol}^{TNL/OWSP}$ is the poloidal length of the line from TNL to OWSP. Similarly for $\Gamma_{\perp}^{inner}$ if $\phi_{wall}^{inner} = 2\Gamma_{\parallel}^{inner} \sin\theta \, 2\pi R \, \lambda_{\Gamma}^{inner}$ has been measured.

The condition which has to be met for this to hold is that a negligible fraction of $\phi_{wall}^{outer} = 2\Gamma_{\parallel}^{outer} \sin\theta \, 2\pi R \, \lambda_{\Gamma}^{outer}$ is due to ionization occurring within the outer wall SOL. More accurately, it is required that no more than a small fraction of the ionization of the neutrals recycling from the outer side of the nose limiter (and the facing surface at the bottom of the vessel) occurs outboard of the green line. Since T_e is typically ~ 10 eV and n_e is typically also low in the wall SOL, it is likely that most of these recycling neutrals will not ionize until they have penetrated some distance into the Divertor SOL or even across the separatrix. As a first estimate one can use hand-calculations, together with the measured radial profiles of T_e and n_e, to estimate if this condition is satisfied. For a better handle one needs to employ a 3D Monte Carlo neutral hydrogen code such as EIRENE or DEGAS, below.

10. Do we really need the Nose Limiter? Suppose the Nose Limiter didn't exist. One would still be free to (now arbitrarily) choose 2 points for IWSP and OWSP and proceed as above. There would now be a single Symmetric Wall SOL, running from outer wall to inner wall. This would, however, result in loss of information: one could not distinguish ϕ_{wall}^{outer} from ϕ_{wall}^{inner} nor $\Gamma_{\perp}^{outer}$ from $\Gamma_{\perp}^{inner}$, but would average them together. This would be an unfortunate loss of information since we are rather sure that these numbers are very different from each other – with outflow strongly favoring the outside of the tokamak. We would like to be able to measure such differences.

A potentially more serious loss of information relates to the possibility that the wall ionic outflux is in some way induced by the very presence of the wall, and to its close proximity to the separatrix. The driving mechanisms of cross-field plasma transport are not fully understood. It may be influenced by the presence of neutrals. In this case, plasma-wall contact may be self-reinforcing to some degree. If the only plasma contact with the “wall” is actually right near the divertor targets (near IWSP and OWSP) – where large neutral populations are already present due to recycling from the divertor targets – then the magnitude of the plasma-wall contact may be quite different than if a solid surface exists near the separatrix far from the divertor – i.e. a “wall” as more usually understood. In this regard it is most valuable that the nose limiter is available in DIII-D. It is about as far removed from the divertor as a “wall” can be, while it is also toroidally symmetrical.

Another benefit of using the nose limiter as the main wall relates to the interpretability of D_α measurements, below.

11. D_α measurements. When plasma-wall contact is primarily 3D, involving the toroidally non-symmetrical structures, it is difficult to quantitatively interpret the D_α measurements in the main chamber. If the plasma-wall contact is 2D, or even just approximately so (point 7.), then quantitative interpretation is greatly facilitated. An additional benefit of concentrating the plasma contact with the wall onto a relatively small region – the nose limiter – is that the local intensity of D_α emission may be fairly high – thereby reducing the interpretation problem caused by photon reflection from the walls: the strength of the divertor D_α source is so great that even if the wall reflectivity for photons is small, reflections can dominate over local wall emission.

Another advantage of using the nose limiter as the “wall” – rather than employing a magnetic configuration where the Symmetric Wall SOL is defined by contact with the parts of the walls near IWSP and OWSP – is that the D_α emitted near the IWSP and OWSP may have significant contributions from divertor recycling, and so be hard to interpret. By contrast, D_α emission at/near the nose limiter is likely to be mainly due to “main chamber recycling” and may be fairly straightforward to interpret quantitatively as an additional way to measure ϕ_{wall}.

12. Modeling is made practical for edges where plasma-wall contact is important. If the plasma-wall contact is 3D then edge modeling is impossible, practically speaking. The situation where plasma contact occurs simultaneously with 2D toroidally symmetrical divertor targets and 2D toroidally symmetrical walls certainly poses some development challenges for edge codes such as UEDGE and OEDGE, but this situation does not appear to be intractable. In the case of OEDGE this development is fairly well along. So long as the *plasma* and the plasma-solid contact is 2D, the plasma modeling appears tractable.

What about the *neutral hydrogen* part of the edge modeling? For some purposes it should be adequate to do this with the 2D versions of the Monte Carlo neutral hydrogen codes, EIRENE and DEGAS, and approximating the wall structures as 2D, toroidally symmetric. For example, for the interpretation of the total D_α emitted near the nose limiter as a measure of ϕ_{wall}, such 2D neutral hydrogen modeling may be adequate – in fact, one scarcely needs any modeling at all for this interpretation, but can simply use some estimate of the Johnson-Hinnov factor (the photon efficiency for D_α). There are, however, other important questions that we are interested in where the details of the spatial distribution of the D_α emission can, in principle, help us sort things out. For example, we would like to know when/if neutral recycling from the walls is more important for fueling the confined plasma than the divertor recycling and when/if wall recycling sources are important in the formation of the density pedestal. This may require detailed analysis of the neutral hydrogen behavior, in which case we have to address the reality that the neutrals will 'explore' the complicated 3D wall structures as the bounce around the main vessel. That is, even if the plasma itself is 2D, the experience of the neutrals is 3D. Fortunately, 3D versions of EIRENE and DEGAS are available for such interpretive analysis. It is tedious, but straightforward to specify the complicated 3D wall structures as input to these codes.

By using a toroidally symmetrical wall – so far as the *plasma* is concerned - even if the wall is not toroidally symmetrical so far as *neutral* contact is concerned – we have what appears to be a tractable analysis situation, and one where we have a reasonable chance of being able to sort out the role of the walls in plasma re-fueling, pedestal formation, etc. This would also appear to be a tractable analysis situation regarding the equivalent impurity questions.

13. Quantitative interpretation of main chamber pressure gauges is facilitated. Pressure gauges in the main chamber are hard to interpret quantitatively since they reflect local conditions, i.e. the problem is 3D. Following the same considerations as in point 12., however, this problem may be made tractable. The neutral hydrogen modeling would be powerfully constrained by information from an array of pressure gauges distributed around the main chamber, increasing confidence in other outputs of the analysis.

The neutral hydrogen quantities that we are most interested in – the spatial distribution of neutral density and of ionization in the plasma – are not directly measurable. These quantities are, however, outputs of neutral hydrogen code like EIRENE. Why should we believe what EIRENE calculates for these quantities? Well, if what EIRENE calculates for the neutral hydrogen quantities that we *can* directly measure – the spatial distributions of D_α emission and pressure gauge data from various locations around the vessel – matches well with the measured data, then we can have some confidence in what the code calculates for these neutral hydrogen quantities which are not directly measurable.

14. Measuring plasma-wall contact due to ELMs. It may be that in H-modes plasma-wall contact may occur mainly during ELMs. If a radial array of built-in Langmuir probes is installed in the nose limiter, then this could be used to measure ϕ_{wall} during ELMs by biasing these probes constantly into ion saturation, where they could then measure the radial profile of I_{sat} during the ELMs.