Lessons Learned from the DIII-D ICRF Program 1988-1999

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General Atomics

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Confession of Ignorance

- We have no data on localization of arcs on the vacuum side of the antennas, except in very rare cases (catastrophic damage, occasional arcs on FS)
- We have no data whatsoever acquired at a faster rate than 5 kHz, and the vast majority of our data was at 1 or 2 kHz
- We have never had any fast camera viewing any of our antennas (faster than 30 Hz frame rate)
- We have almost no data on power limits as a function of phasing/degree of symmetry

Gross power handling problems can be caused by activity on the plasma facing surface

- These MUST be solved in order for operation of the antenna to be acceptable to the rest of the community, or in some cases, even in order that the antenna be allowed to remain in the vacuum vessel
- Even the slow video camera or conventional IR camera is extremely helpful in diagnosis of such problems
- Gross metallic impurities from melting, drips, radiative collapse, etc.
- These events are not invariably associated with arcs, and in fact can occur during NBI heating without any rf power applied to the antenna
  - Often these events do cause an arc to occur subsequently
- Generally caused by heat concentrations due to poor thermal conductivity to cooling reservoirs/actively cooled surfaces

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Examples of these gross problems on plasma facing side

- Flaking of overly thick boron carbide FS coating, due to low conductivity of plasma sprayed material
  - Solution: improved, very thin CVD coating
- Heat buildup and melting of corners on “new” antenna’s Faraday shield clips
  - Solution: redesign of FS elements, returning to original molybdenum arched rod

Pressurized transmission line breakdowns MUST be prevented at all costs

- Since these problems will always lead to confusion, extremely poor reliability, and they can always be solved, there is hardly any excuse for problems in an environment which is under our control!
- We found that these arcs are (almost?) always associated with distinct audible sounds
- Strongly recommend the rule originally promulgated by JET – absolutely NO organic materials (e.g. Teflon) in regions that have rf fields:
  - Obviously, spacers in transmission lines
  - Less obviously, inside tuning elements, power splitters, dc breaks, switches, gas breaks, etc., etc.
- There is no such thing as too much overhead as far as rf standoff goes
- There is no simple translation of dc (hi-pot) standoff to rf standoff
- Anything less than the best possible transmission line is a foolish economy

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A fixed maximum voltage is NOT a good predictor of breakdown threshold!!!

- Vmax appears to be correlated with loading (!)
  - This must mean that that both local density profile and the power-limiting breakdown phenomenon both are affected by some unmeasured parameter – neutral pressure??
- Tendency is for low loading (H-mode with infrequent ELMs, VH-mode) to be associated with higher values of Vmax – tends in the direction of constant power rather than constant voltage
- Means that projecting power handling based on some predicated Vmax is a futile exercise
- Antenna designs that project increased power density based on increased effective loading are extremely suspect

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Very difficult to couple power with E parallel to B_o

- This despite reasonably high loading observed in this case
- Clearest case ever, probably – history of IBW antenna, and its replacement 4-strap antenna

Long connection lengths make power handling difficult

- Long connection length in front of the antenna straps at low toroidal field yields relatively high density at the straps
- Most obvious result of DIII-D Faraday shieldless operation was the degraded power handling of the shieldless antenna cf. power handling of the same antenna with a (far-from-optimal) FS
  - — Load resistance dependence on power at low power was explained by sheath dissipation and relatively high density at straps with no shield
- Wide antennas are difficult, especially at low toroidal field

The “balanced fault” was discovered and protected against

- The application of a transmission line configuration with a 90 deg hybrid junction led to the discovery of the balanced fault, in which the antenna loading on all four straps symmetrically jumps to a high value
- Never obvious whether this really corresponded to a damaging localized arc or not, though it was clear that the balanced fault often did constrict and turn into such an arc
- We felt that it should be avoided, since it was very easy to deposit all of the transmitter power into the local plasma thereby formed
- It is distinguishable from ‘legitimately’ high loading due to ELMs, etc., by its magnitude – protection circuit based on real time estimate of antenna loading was easy to prepare

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Good power handling does not necessarily correlate with good heating efficiency

- Just as antenna loading in large devices does not have anything to do with the global absorptivity, but is in fact a locally determined quantity, neither is there any necessary connection between coupling with good efficiency and good central heating efficiency
- Unfortunately, often the plasmas to which power could be most readily coupled were the most difficult to heat
  - — We understand this in terms of the weak single pass absorption in many of our heating scenarios competing with a loss mechanism at the edge of the plasma
  - — Somewhat painful reciprocity!

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Summary of most important points

- Voltage standoff of an antenna in vacuum often has little correlation with peak voltage standoff in the presence of plasma
- Peak voltage standoff in the presence of plasma can easily vary by about a factor of two, depending on some “hidden variable” that is correlated in some cases with antenna loading in such a direction as to tend towards a fixed maximum power coupled nearly independent of loading resistance!
- In the present state of ignorance about the relevant breakdown mechanisms, we cannot even know whether the power handling in a given situation would be improved by increasing or decreasing a given electrode spacing, for example, or what materials choices are smart or stupid
- Hence, our credibility when we attempt to predict the power handling/achievable power density/etc. of a future antenna in a future machine is negligible

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Recommendations (my personal views)

- Rather than to attempt to design more innovative, flexible and elaborate antennas, the performance of which cannot be credibly predicted, a better use of limited resources would be to design, build and test on an existing “real” device the simplest possible antenna that is designed from the start to be diagnosed to the maximum extent possible with FAST diagnostics, and the possibility of varying a number of possibly important local parameters (gas puffing, local pumping, for example)
- The ability to efficiently heat the plasma with this test antenna is not important – so even a single strap antenna might be perfectly adequate
- Determine the exact nature of the power limiting mechanism(s), and demonstrate a really substantial improvement in power handling with the knowledge so gained
- In my view, only by this kind of careful research and development can we begin to gain some credibility in the plasma heating community

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