Power and Voltage Limits in the NSTX Ion Cyclotron System*

David Swain

NSTX Results Review Meeting

PPPL

September 9 – 11, 2002

* This research was sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract DE-AC05-00OR22725 with Oak Ridge National Laboratory managed by UT-Battelle and under contract DE-AC02-76CH03073 with Princeton Plasma Physics Laboratory.

Introduction - what are we trying to do?

Observation:

- During vacuum conditioning (no plasma or field)
  - HHFW antennas can operate with peak voltages over 20 kV without breaking down
  - (High voltages are obtained at low rf power, since no plasma means loading on antennas is very low) [$P \sim R_{load} V^2$]
- During plasma operation
  - antenna operating voltages *rarely* exceed 15 kV without arcing
  - more typical operation is around 10 – 12 kV

Enquiring minds want to know:

WHY?

WHAT'S GOING ON?

If we can understand what's causing the lower breakdown voltage in the presence of plasma, we may be able to figure out how to improve it.

How have we tackled the problem?

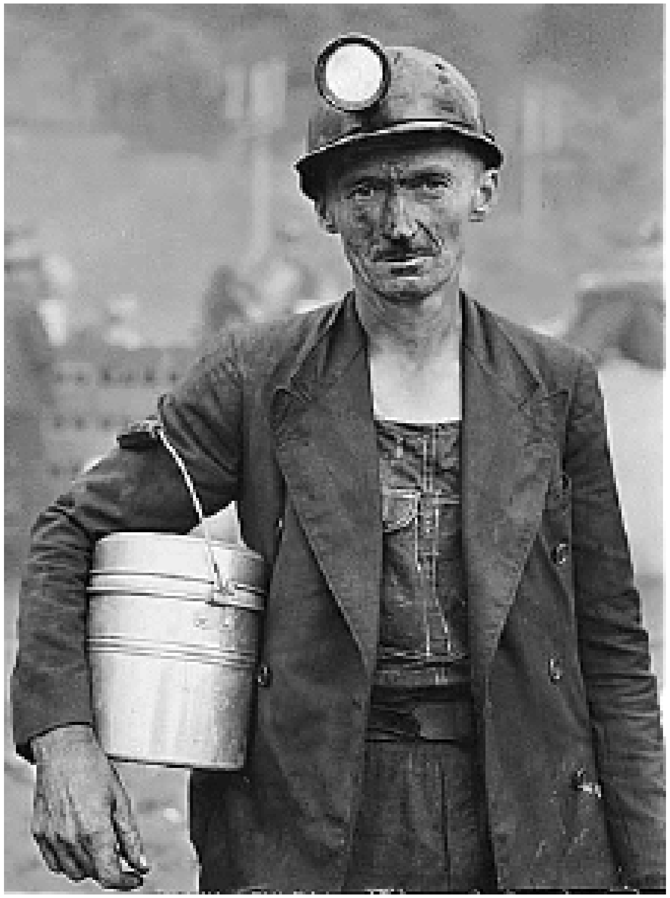
We have tried to do some data-mining using

- HHFW data (forward and reflected power,voltage in the resonant loop,…)
- Plasma data (density, temperature, position,…)

The idea is to look for correlations of breakdown voltage in antenna lines with various plasma parameters:

- Separatrix distance from antenna - “gap”?
- Plasma density?
- Diverted or not?
- Plasma current?
- Toroidal field?
- Gas pressure measured behind antenna?
- Phase of rf signals (symmetric, co-CD, ctr-CD)?

Oak Ridge data miner



Methodology

Select shots with

- HHFW power *and*
- transmitter arc signals (these indicate which transmitter(s) tripped)

• Shots 107888 (April 19) to ~109000 (end of run in June)

- 265 shots with HHFW during this period

Construct a database of rf and plasma parameters vs. time

• Select times corresponding to Thomson scattering (TS) times, before and during rf pulse

- TS data point every 17 ms
- 8128 time points in database (≈ 40 data points per shot on average)

Find arcs, evaluate rf and plasma parameters *just before* arc

- 287 arcs occurred, in 122 shots

Find shots with *no arcs*, look at maximum voltage achieved *without* breaking down

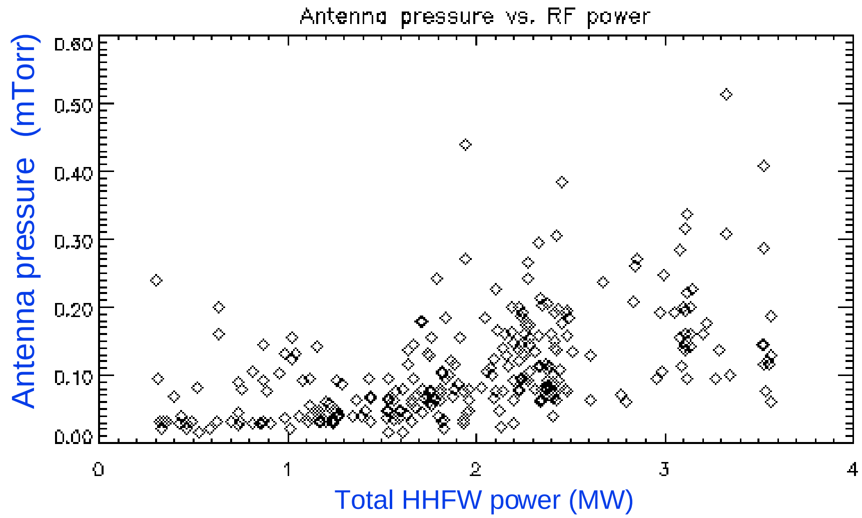
- 143 shots with *no* arcs

Look for correlations between breakdown voltages in lines and various parameters (B_0, I_p, gap, antenna pressure, phase, ….)

Cross-correlation in data makes for few “independent” variables

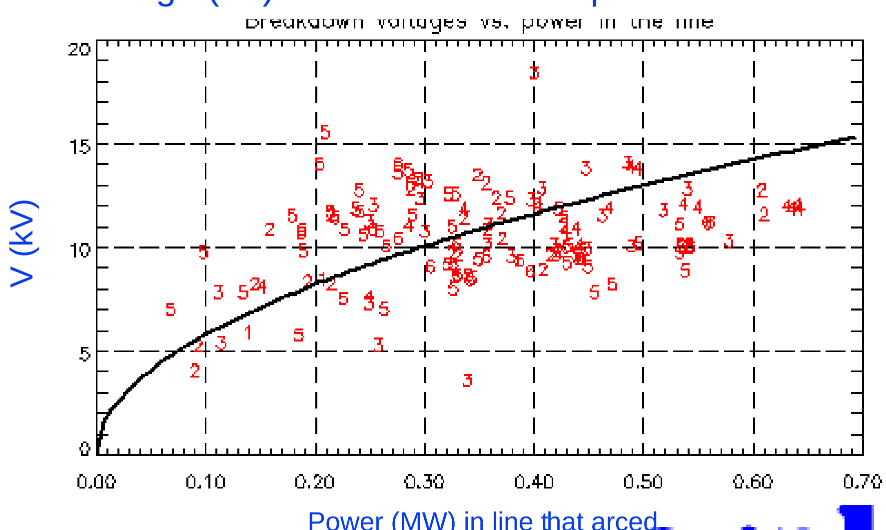
Examples:

- Antenna pressure (actually the pressure measured *behind* antennas 10 - 11) generally increases with HHFW power.



- Voltage on antenna increases with HHFW power

Voltage (kV) in line with arc vs. power in the line



N.B.: V_j = voltage measured at the junction of transmission line *j* with the resonant loop (i.e., at the cube) *just before* an arc occurred. This is (approximately) the high-voltage point in the line

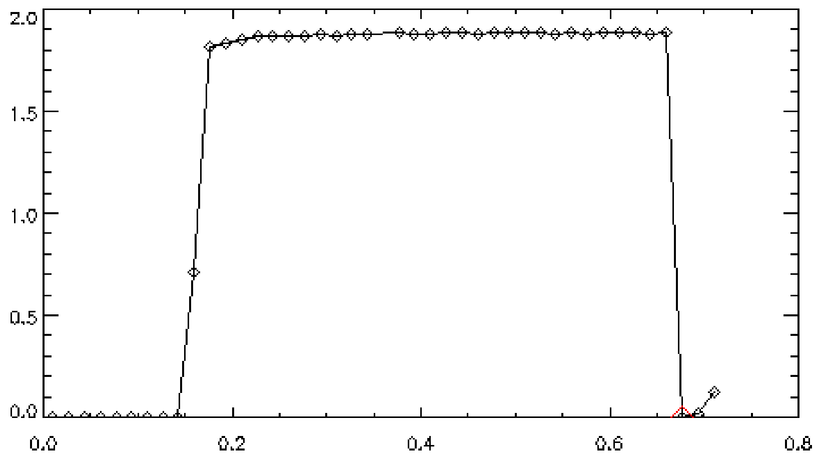
= “the voltage in the line”

Typical shots with arcs

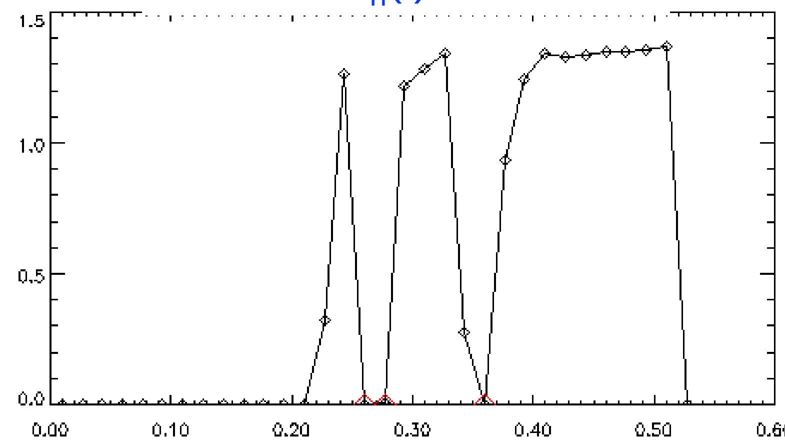
Algorithm identifies arcs:

- $P_{HHFW} \approx 0$, followed by $P_{HHFW} \geq 0.3$ MW

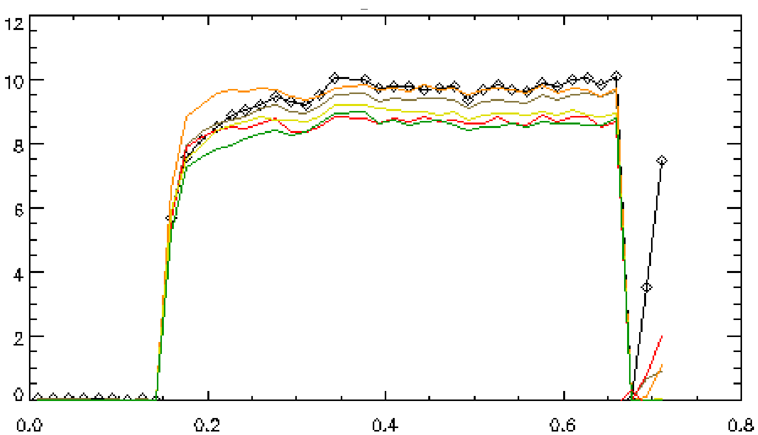
108888 $P_{rf}(t)$ - one arc



107895 $P_{rf}(t)$ - two arcs

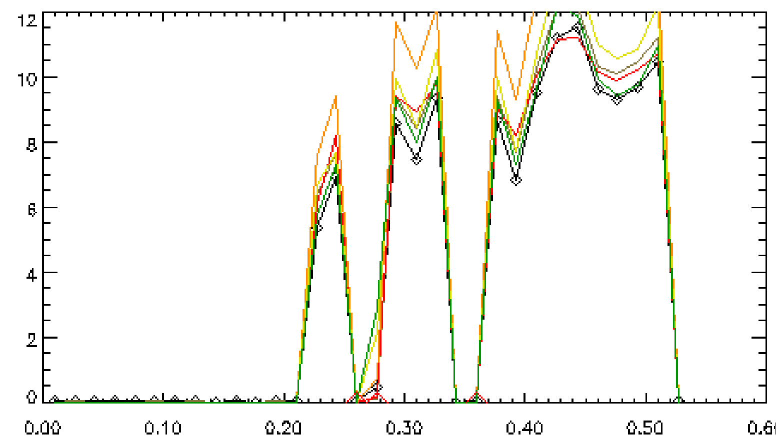


V(t) on each line



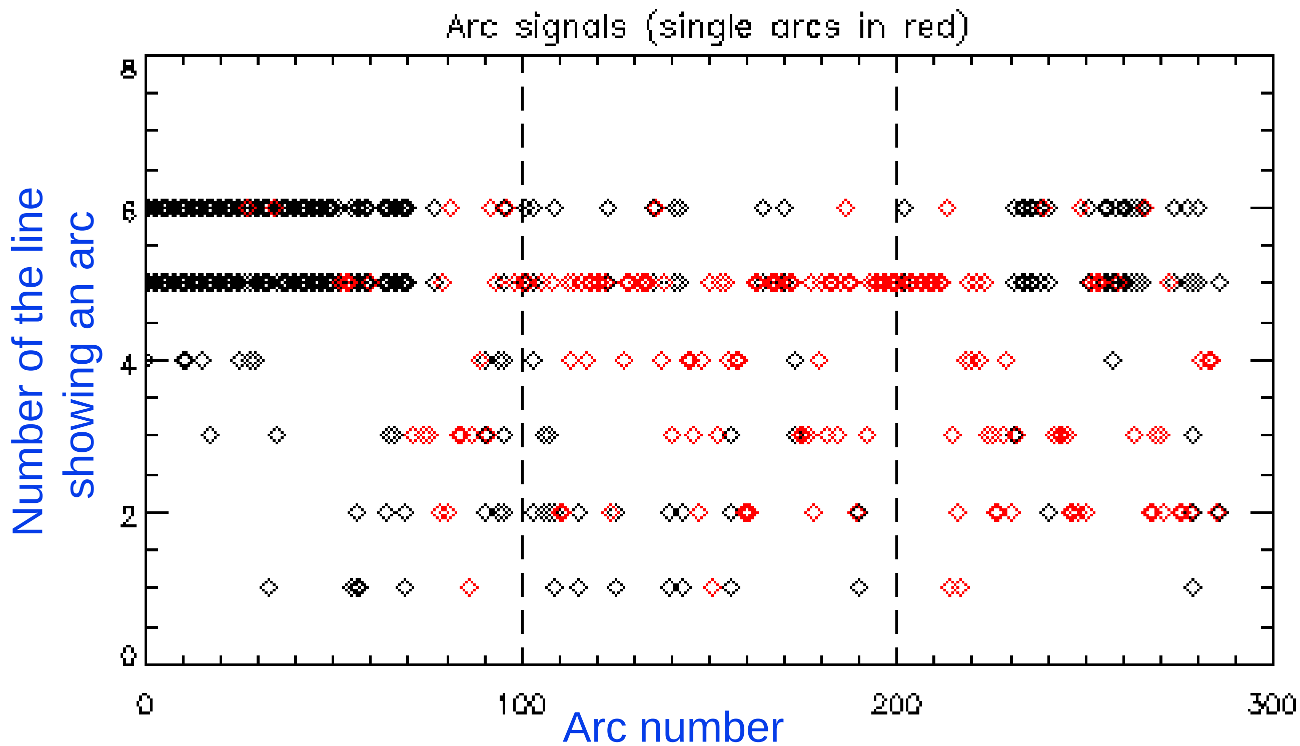
Colors correspond to different lines:
1-black
2-brown
3-red
4-orange
5-yellow
6-green

V(t) on each line



Which lines arced the most?

Of 287 arcs, 156 had a transmitter trip signal on only one transmitter. The other 131 arcs showed transmitter trips on multiple lines



line	arcs	single arcs
1	17	4
2	45	26
3	40	28
4	32	19
5	166	68
6	107	11

Lines 5 and 6 were primary culprits, but line 6 may have been tripping *because* line 5 went off. However, all lines tripped on occasion.

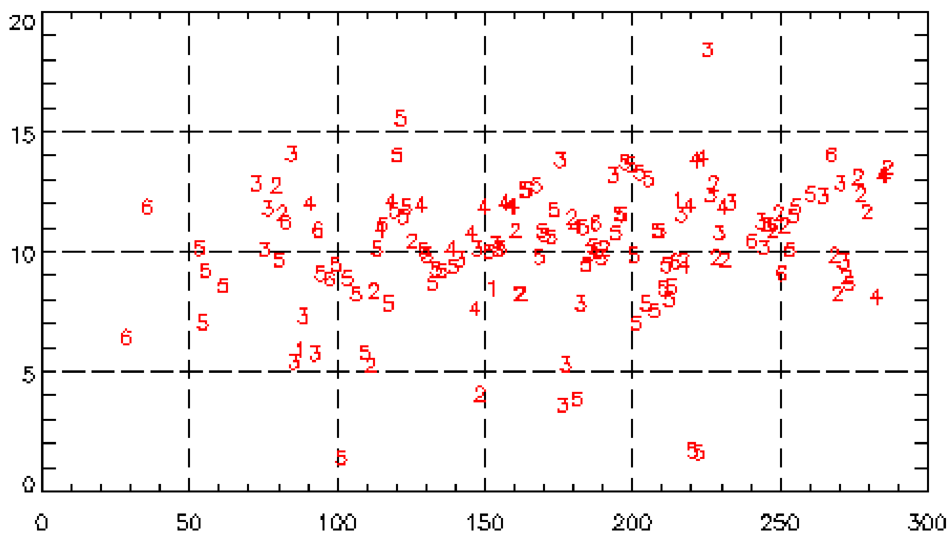
When arcs occurred, breakdown voltage was *about the same* on all lines

Interesting observation:

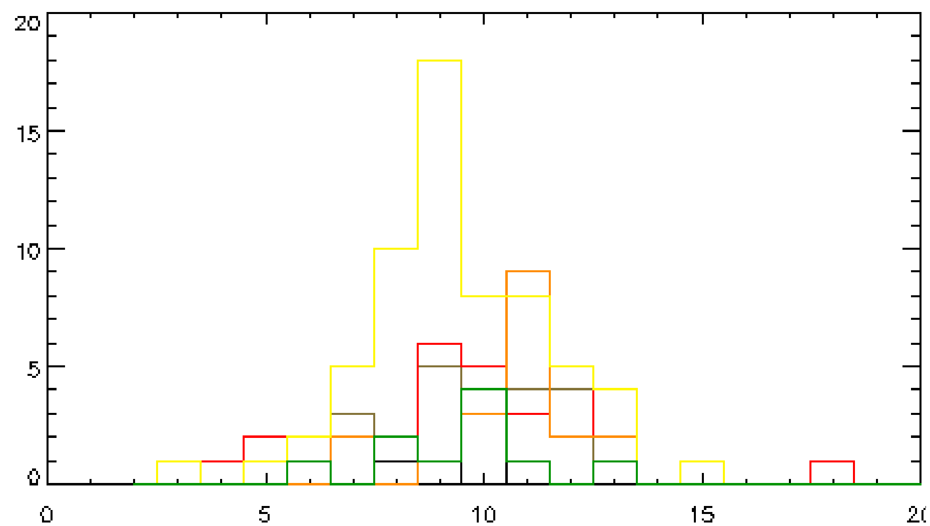
- Although line 5 arced the most, *when* the other lines had arcs they all occurred at about the same voltage.

Line	$\langle V_{bkdwn} \rangle$
1	8.9
2	10.38
3	10.41
4	11.31
5	10.09
6	10.51

V_{bkdn} (kV) vs. arc no. for arcs in only one line
Number = line with arc



Histogram - no. of single arcs in each line binned by V_{bkdn}

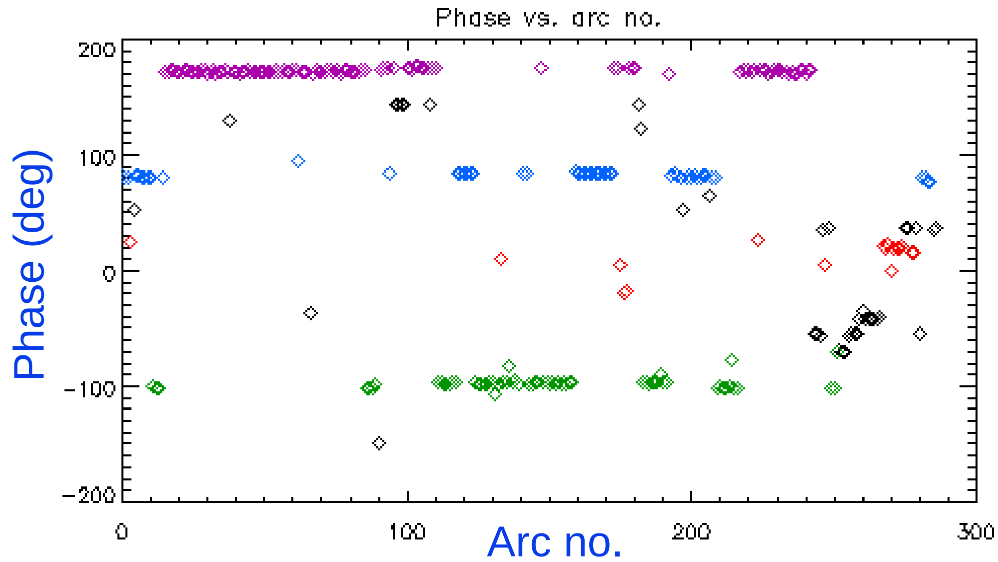


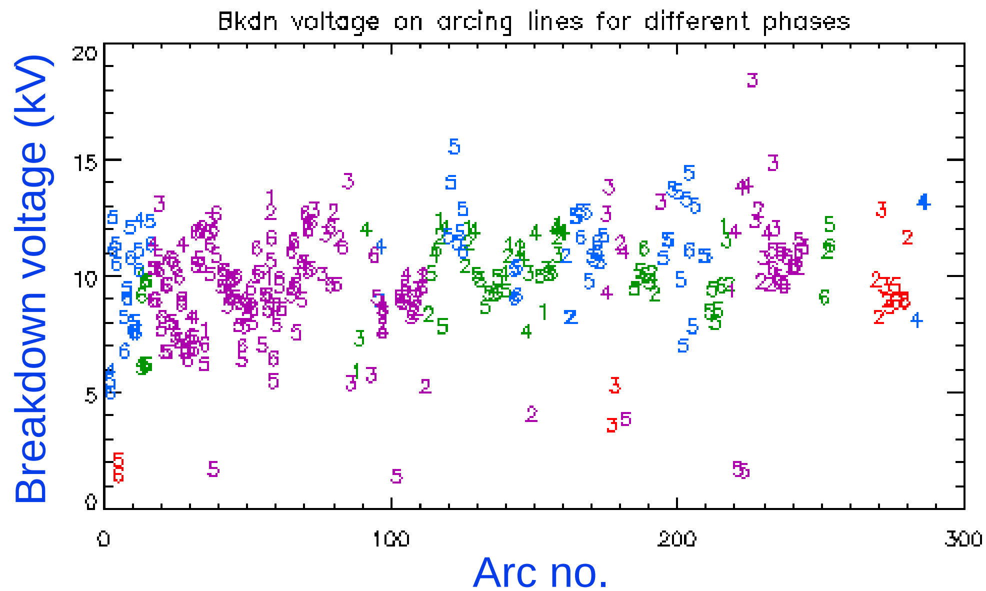
Does breakdown voltage depend on antenna phasing?

- Top plot shows the phase between lines 1 and 2 for the shots where arcs were detected
- Data binned into four phase groups:
  - Red = fast symmetric (~ 0°)
  - Green = co-CD (~-90°)
  - Blue = ctr-CD (~+90°)
  - Violet = slow symmetric (~180°)

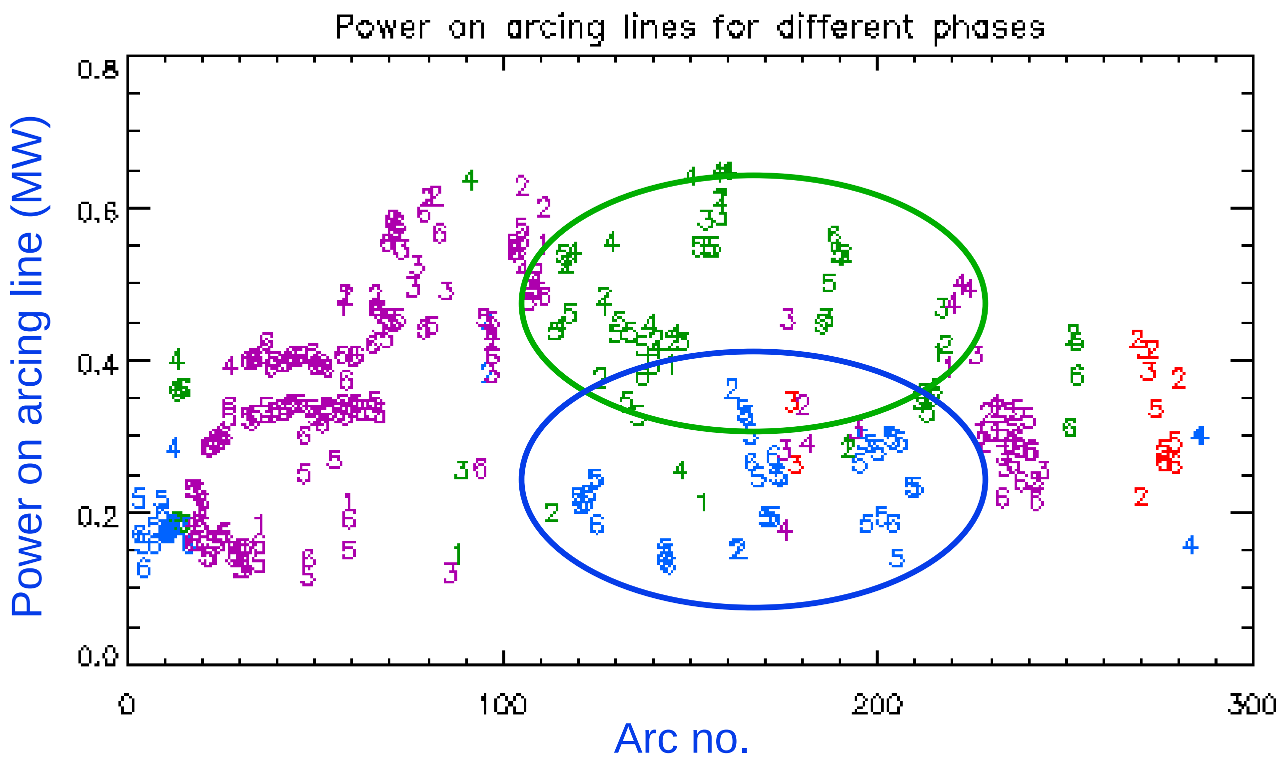
- Bottom plot shows the breakdown voltage on the lines that arced. Arcing line is indicated by the number, phase is indicated by the color.

No apparent correlation of breakdown voltage with phase.





Does breakdown power depend on antenna phasing?



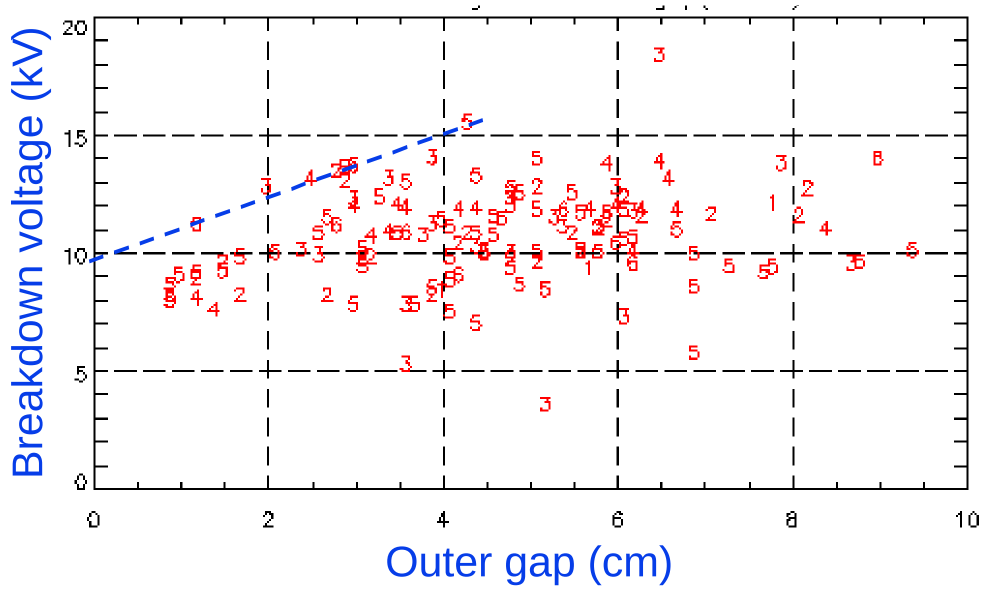
Yes. There's a systematic difference in breakdown POWER between co-CD (green points) and ctr-CD (blue points) shots.

- This is expected, since antenna loading by the plasma changes by about a factor of 2 going from co- to ctr-CD.

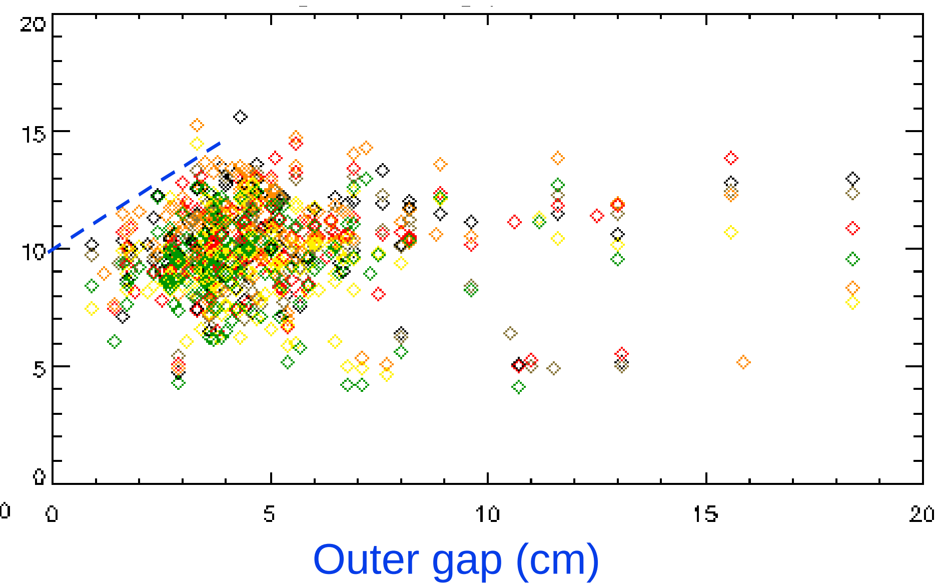
Conclusion: Breakdown is determined by Voltage, not Power

Does V_{bkdn} depend on outer gap?

V_{bkdwn}(kV) vs. outer gap (cm)
Number = line with trip (single arcs only)



Max. voltage (kV) in each shot for shots with no arcs vs. outer gap (cm)

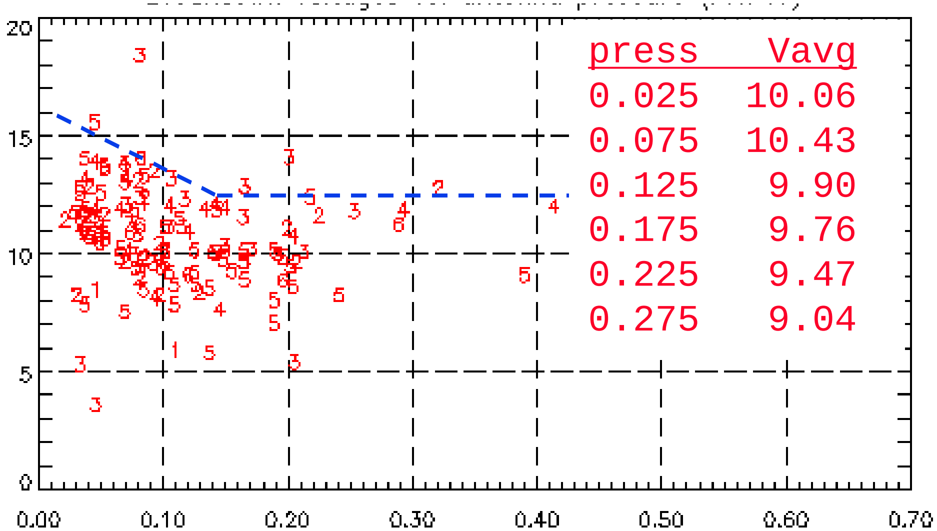


For shots with arcs and without arcs, the *maximum* voltages observed *in the shots in the database* appear to increase with gap for 0 ≤ gap ≤ 4 cm.

Conclusion: Maybe for small gaps.

Does V_{bkdn} depend on pressure behind antennas?

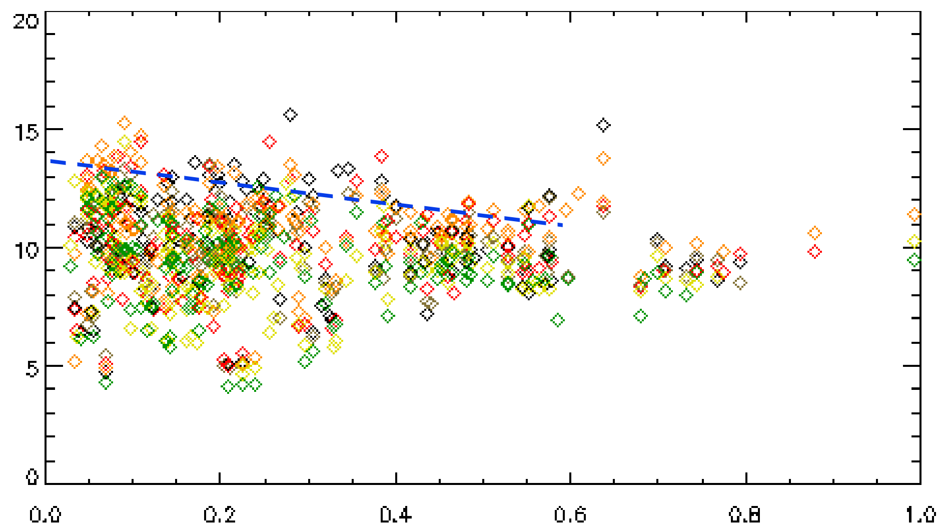
V_{bkdn}(kV) vs. antenna pressure (mTorr)
Number = line with trip (single arcs only)



press	Vavg
0.025	10.06
0.075	10.43
0.125	9.90
0.175	9.76
0.225	9.47
0.275	9.04

Pressure (mTorr)

Max. voltage in each shot for shots with no arcs vs. antenna pressure (mTorr)



Pressure (mTorr)

- Maximum V_{bkdn} observed drops as pressure increases to ~ 0.2 mTorr
- But comparable voltages vs. antenna pressure are obtained in shots when *no arc* occurred.
- Average breakdown voltage shows statistically insignificant drop

Conclusion: Maybe a correlation between maximum breakdown voltage and measured gas pressure, but not average breakdown voltage.

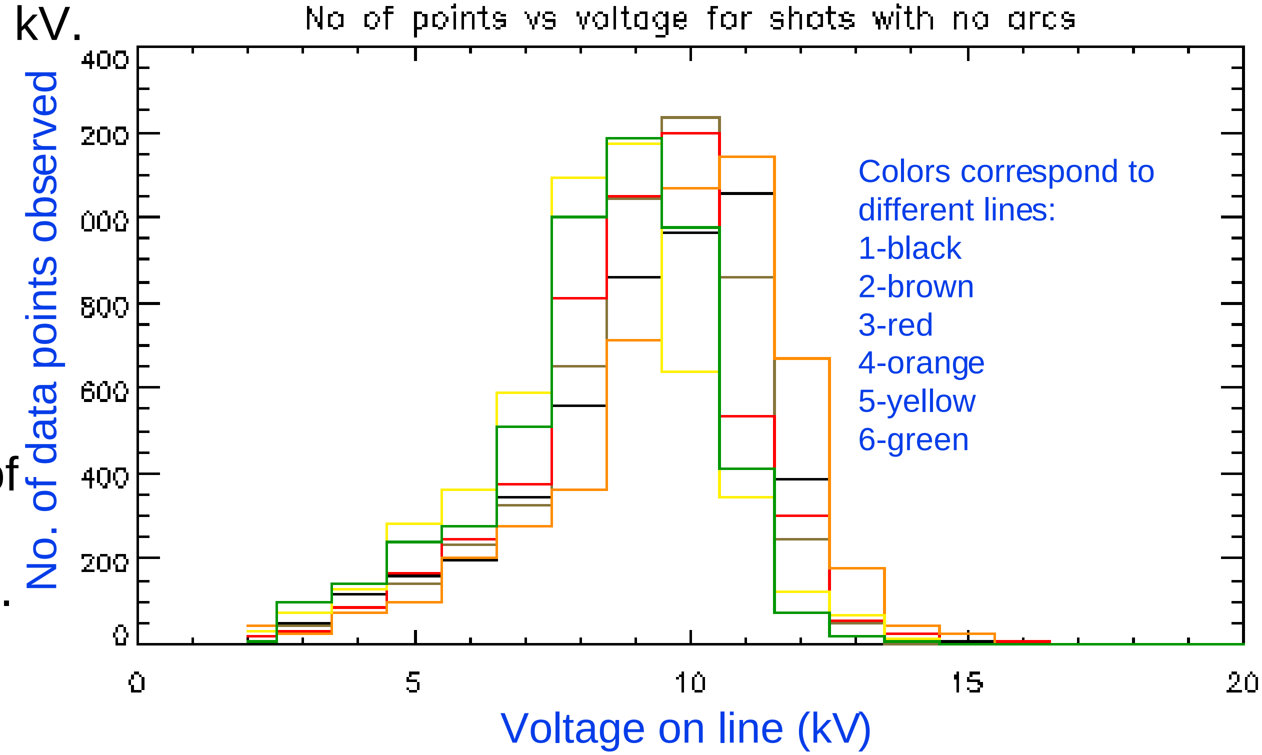
For reliable arc-free operation, usually need to operate around 10-12 kV

Below is a histogram of all the data points with no arcs (~ 6000 observations).

- Points are binned by voltage on each line, in 1 kV bins
- Most shots have 9 to 12 kV on loops
- Very few data points > 13 kV.

Arcs observed near vacuum feedthroughs appear likely culprit.

If breakdown is caused by electric field > E_{max}, then new feedthrough geometry should decrease field to about 60% of earlier value, so V_{bkdn} should go to about 1.7x the old value.



This should increase Power to the plasma from present 2.5 MW (where we can run comfortably) up to comfortable 6 MW.

We've gone to extraordinary lengths to try to understand drop in operating voltage in the presence of plasma

ORNL data miners invoking traditional E. Tenn method of obtaining enlightenment.

Also developing

New ORNL technology idea

- VTLI
  - Viper Transmission Line Inspection

Summary

Bottom line: No obvious cause for degradation of operating voltage with plasma

- No single variable that correlates with reduced breakdown voltage
  - Keeping gap > 3 cm may be a "good thing"

- Don't understand the pressure rise behind the antenna
  - M*ay* not be a contributor to degradation, but its getting close to values where we have seen breakdown voltage degradation in off-line experiments
  - Need to have measurement of pressure in antenna cavity
    - being installed this opening (?)

Looking forward to operation with new feedthrough geometry!

Addendum: Database software and IDL

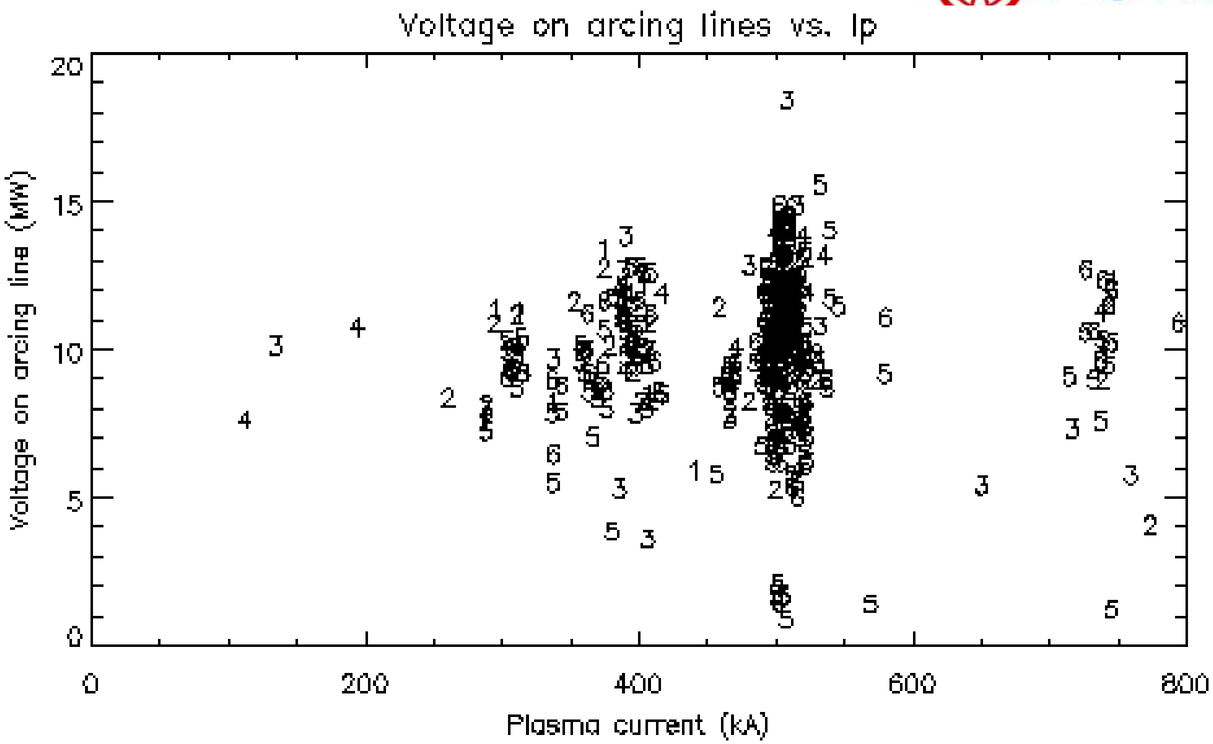
I'm using a suite of IDL routines from NASA for creating editing, searching, and displaying database information:

- IDL Astronomy Library (http://idlastro.gsfc.nasa.gov/).
- "Flat" (as opposed to a relational or object-oriented) database system.
- Useful because it uses IDL programming, plotting, and image display.
- Versatile and easy to learn for those already familiar with IDL programming.
- Can be run on any computer with IDL (Unix, Windows, MacOS, or VMS).

Works pretty well. I wrote a routine to pick up data from TS, EFIT, HHFW, and other data from the MDSplus tree, and wrote it to ASCII files:

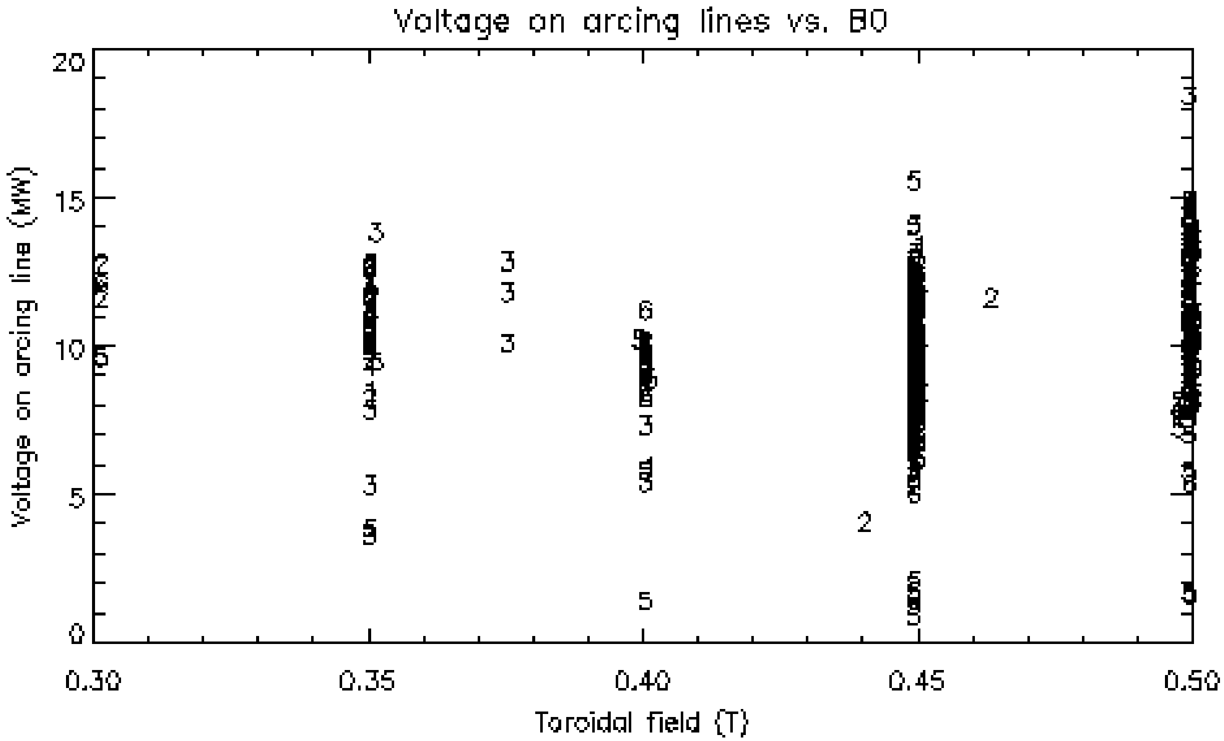
- ~ 40 variables, 8128 time points
- Used the NASA database software to store the data
- Can easily search on complex criteria (e.g., all points with $P_{HHFW} > 0.3$ MW AND $3 < gap \leq 5$ cm AND $600 \leq Ip \leq 800$ kA)

No apparent correlation of V_{bkdn} with plasma current



Lots of variation in breakdown voltage for one value of Ip masks any trend, *if* there is one.

No apparent correlation of V_{bkdn} with toroidal field



Lots of variation in breakdown voltage for one value of B0 masks any trend, *if* there is one.

No apparent correlation of V_{bkdn} with average density