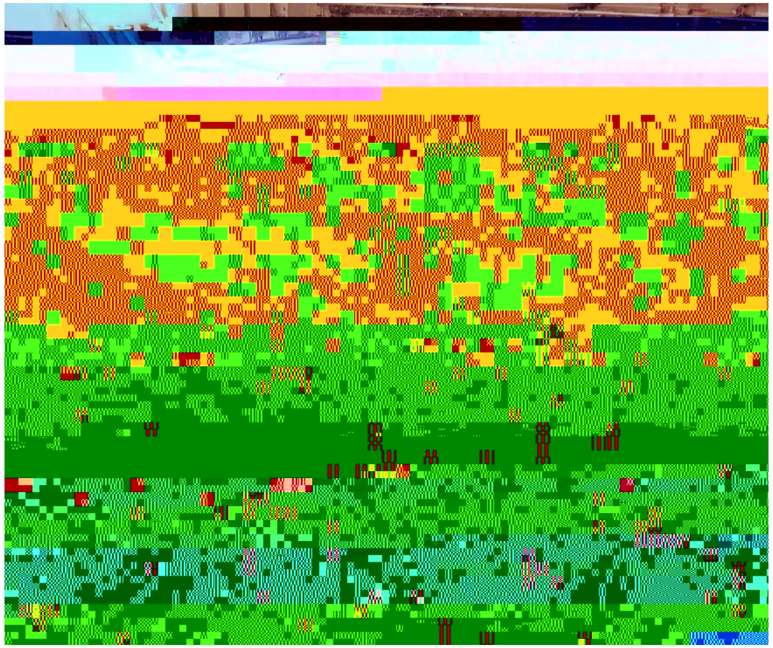
Disruption research on Alcator C-Mod

Three topics:

1) High resolution halo current measurements using Langmuir probes
2) Runaway electron synchrotron emission
   – Spectra and energy at 2.7, 5.4, & 7.8 tesla
   – Synthesizing images of RE beams
3) Databases for disruption warning analysis, including applications of machine learning

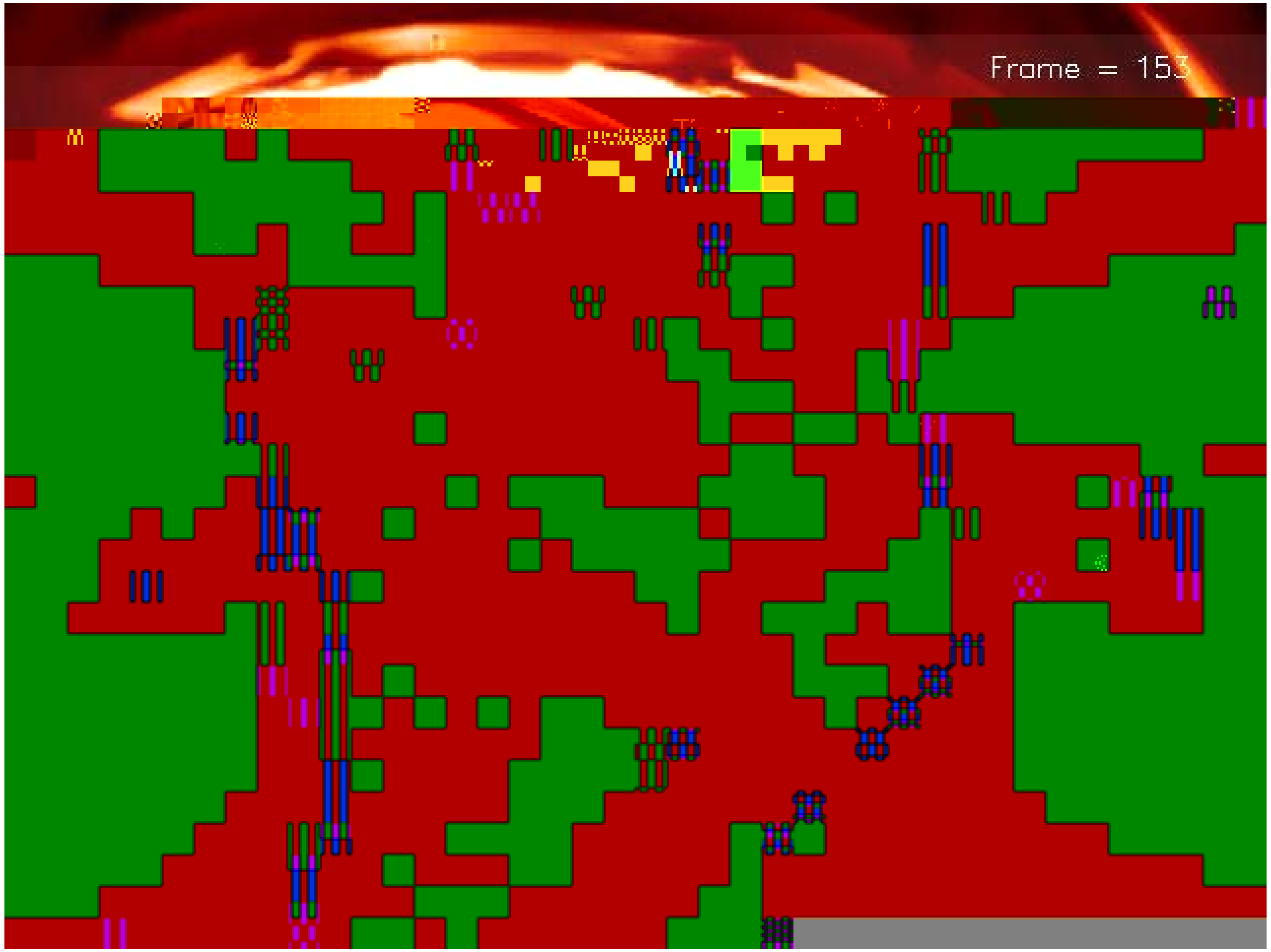
ITER school on disruptions and control
Aix-en-Provence
2017/03/20-25

Alcator C-Mod

- High field ($B \leq 8$ T), high current ($I_p \leq 2$ MA), high energy density ($W_{th}/Vol \leq 0.3$ MJ/m^3, $\langle p \rangle \leq 2$ atm), compact size ($R_0 = 0.68$ m)
- These characteristics greatly exacerbate disruption effects
  - Equipped with extensive disruption-relevant diagnostics
  - Equipped with two massive gas injection (MGI) systems for disruption mitigation studies
- C-Mod permanently shut down last year

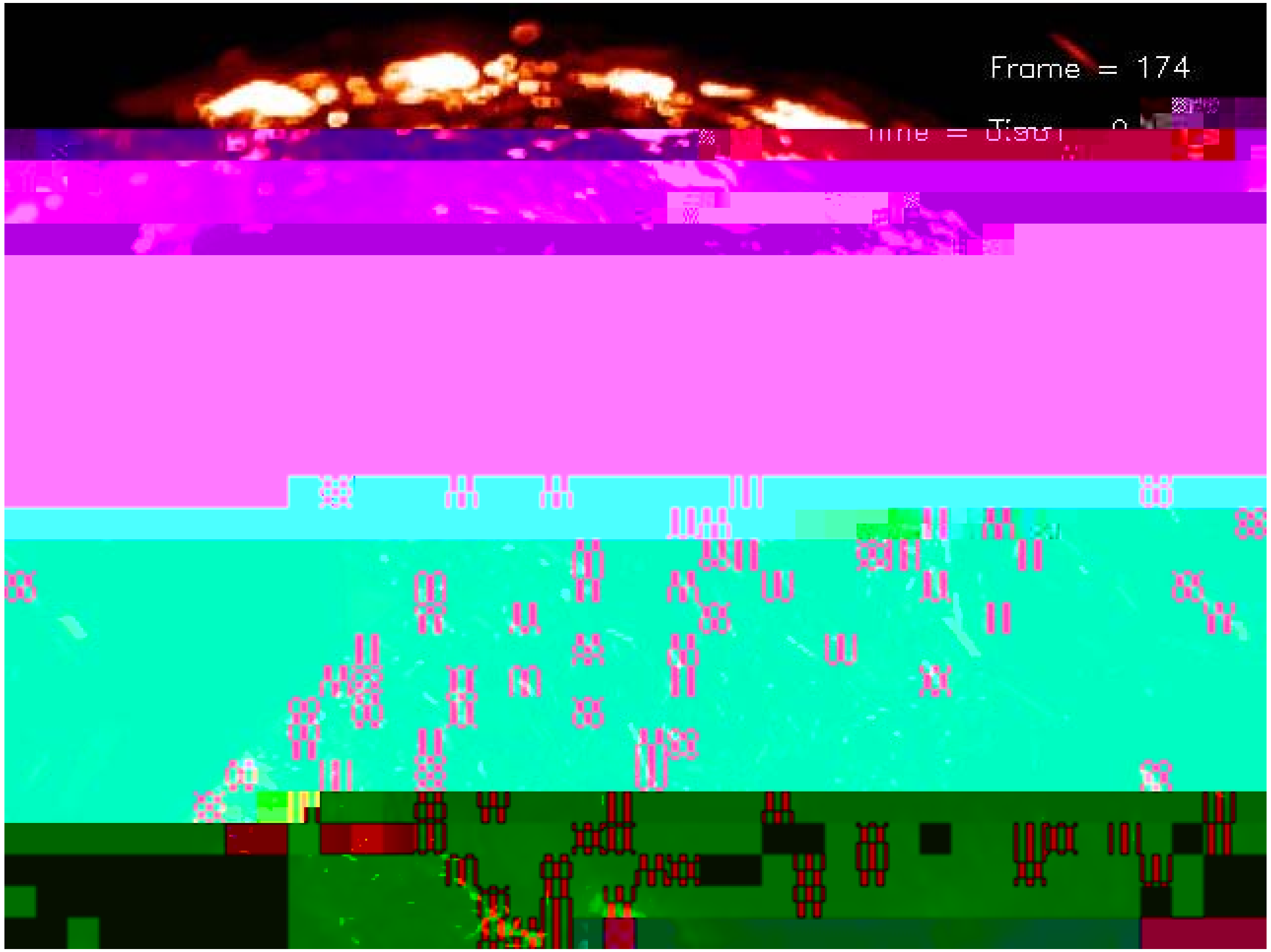
Images from a typical C-Mod disruption



Video from a typical

Images from a typical C-Mod disruption

Images from a typical C-Mod disruption



Disruption research on Alcator C-Mod

Three topics:

1) High resolution halo current measurements using Langmuir probes

High Resolution Halo Current Measurements using Langmuir Probes in Alcator C-Mod

R. Granetz, A. Tinguely, A. Berg,
A. Kuang, D. Brunner, B. LaBombard

MIT Plasma Science and Fusion Center

Halo currents have traditionally been measured with Rogowski sensors and/or current shunts

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R. Granetz, et al, Nucl. Fusion **36**, 1996

New SOL diagnostic: Langmuir rail probes

- 21 flush-mounted Langmuir rail probes give SOL profiles from bottom to top of outboard divertor plate with fast time resolution

New SOL diagnostic: Langmuir rail probes

- 21 flush-mounted Langmuir rail probes give SOL profiles from bottom to top of outboard divertor plate with fast time resolution
- Primarily intended to measure I-V characteristics to provide T_e(%), n_e(%), and V_f(%) in the SOL at the outboard divertor plate

New SOL diagnostic: Langmuir rail probes

- When run in “grounded” mode, the probes appear to the plasma to just be part of the divertor plate surface (almost)
- Current flowing in/out of the probes can be measured while in grounded mode.

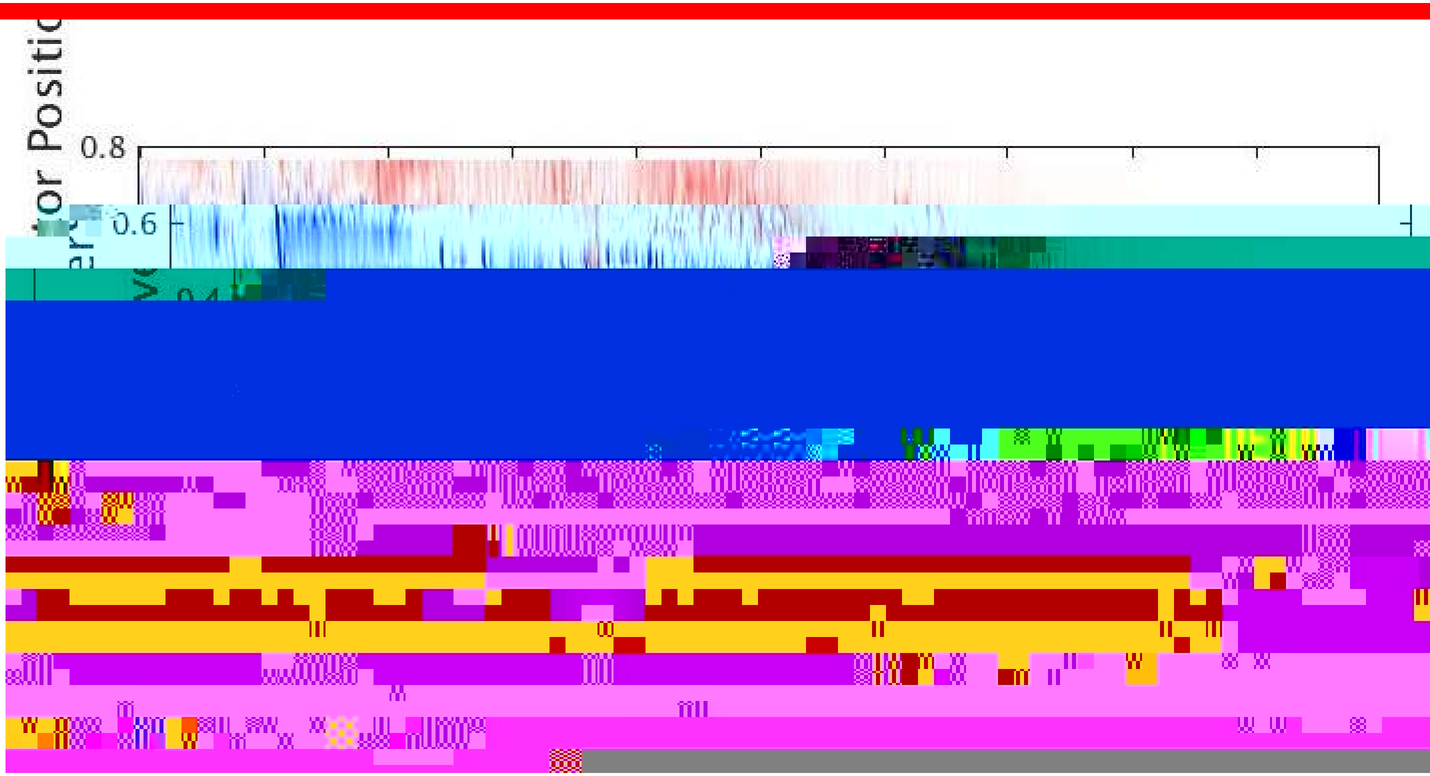
New SOL diagnostic: Langmuir rail probes

- When run in “grounded” mode, the probes appear to the plasma to just be part of the divertor plate surface (almost)
- Current flowing in/out of the probes can be measured while in grounded mode. During disruptions, halo currents can be measured.

New SOL diagnostic: Langmuir rail probes

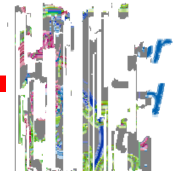
- When run in “grounded” mode, the probes appear to the plasma to just be part of the divertor plate surface (almost)
- Current flowing in/out of the probes can be measured while in grounded mode.

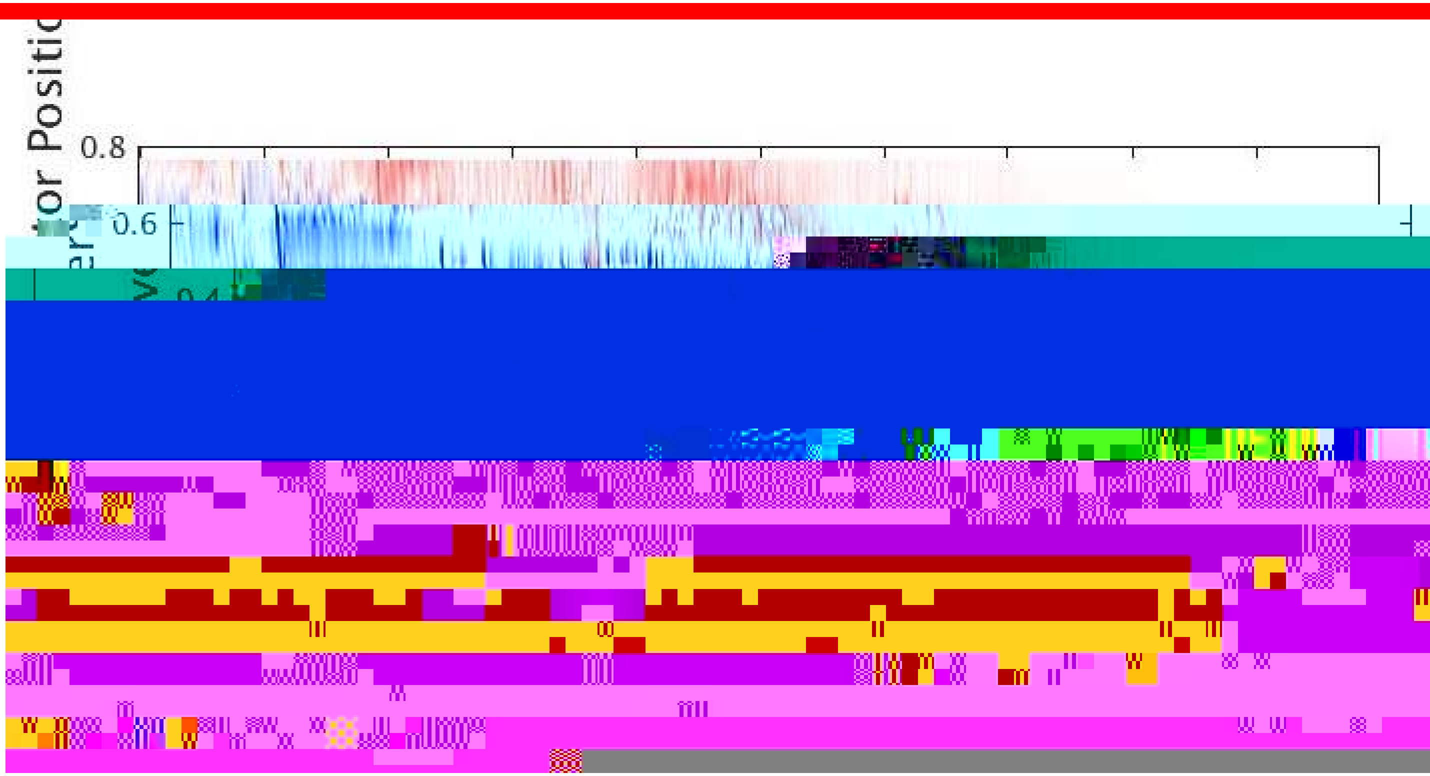
Spatially-resolved halo currents are measured during disruptions



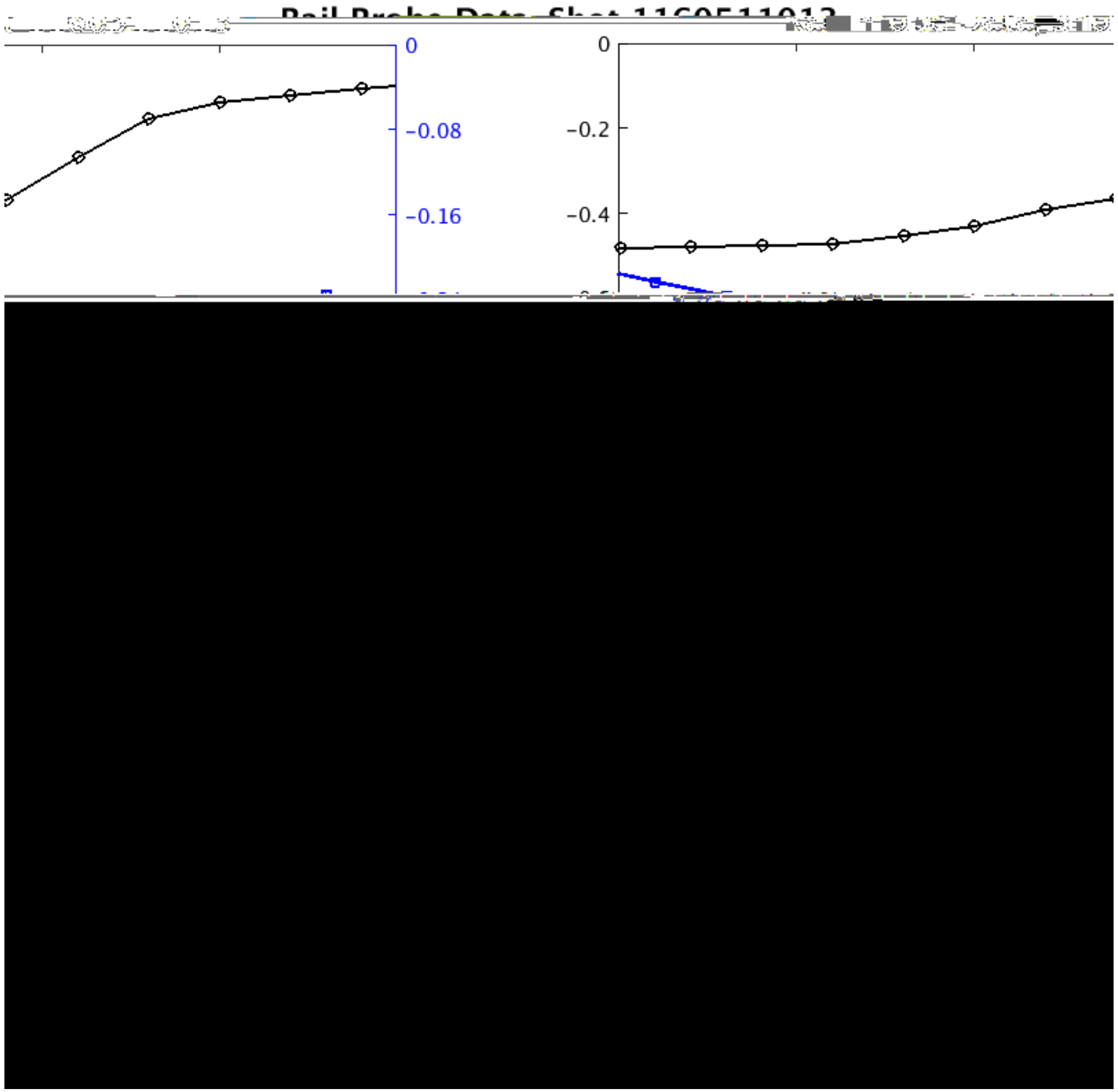
Division between + and – currents slides down the divertor face during the current quench

Spatially-resolved halo currents are measured during disruptions





Plasma contact point vs time compared to +/- halo boundary



On many disruptions there is good correspondence between contact point and +/- halo boundary vs time

$I_p(t)$ and $Z_c(t)$ are also shown

Contact point is obtained from flux reconstructions using fixed filament model

Plasma contact point vs time compared to +/- halo boundary

Resistance of measuring circuit makes a difference

- Halo current measurements with 3 different circuit resistors have been obtained for several of the rail probes, i.e. at several spatial positions in the scrape-off layer
  - At the lowest resistance, we measure total halo current that matches our scaling from 20+ years ago (measured with Rogowski sensors)

is dependent on the total ... path.

2) The V ... g%nerated in each d ... supposedly identical di ... uption shots (two shots with each resistor valt%) is reprod ...

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0HWKRG

6HOHFW VXLWDEOH WLPH UDQJH IRU HDFK V

I_{halo} $ $ $ UHVSHFWLYHO\ IRU UDLO SUR

3ORW V_{halo} YHUVXV I_{halo} IRU HDFK FDVH

,I FXUYHV FURVV DW VLQJOH SRLQW V_{halo} DQG I_{halo} WKDW

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Summary

- Divertor Langmuir rail probes provide unprecedented poloidally-resolved measurements of disruption halo currents in the SOL
  - Allows detailed comparison of quenching plasma geometry with halo current structure
  - We have also correlated halo currents with edge q of quenching plasma
- Dependence on measurement resistors yields information on SOL resistivity and structure
  - Should be useful " –p < Seen p T p ɔ M

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^Çv ZŒ}šŒ}v u]••]}v
]v o š}Œ rD}

A. Tinguely[1], R. Granetz[1], M. Hoppe[2], A. Stahl[2], O. Embréus[2]

Thursday, 3 November 2016

Research in Support of ITER

APS DPP, San Jose, CA

[1]Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA

[2]Chalmers University of Technology, Gothenburg, Sweden

Supported by USDoE award DE-FC02-99ER54512.

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Consider an electron with energy E = 40 MeV and pitch = 0.1 in three different magnetic fields.

[3]

[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

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u • µ Œ • Ç v Z Œ } š Œ } v u] • •] } v } v í D }

- RE densities are difficult to reproduce, so we are not interested in the absolute amplitude.
- Instead, we are interested in the spectral shape.

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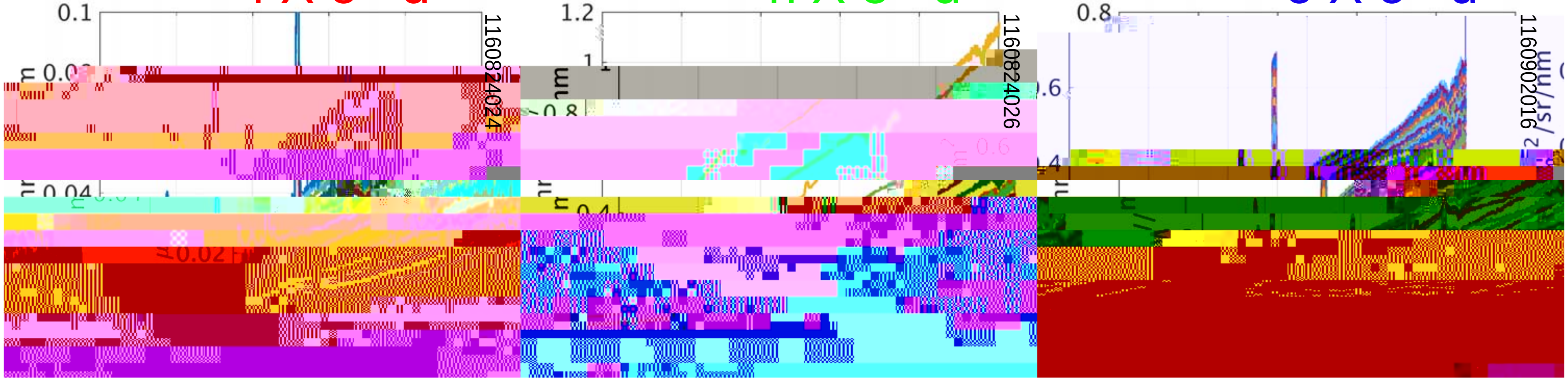

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E = 28 MeV
pitch = 0.1

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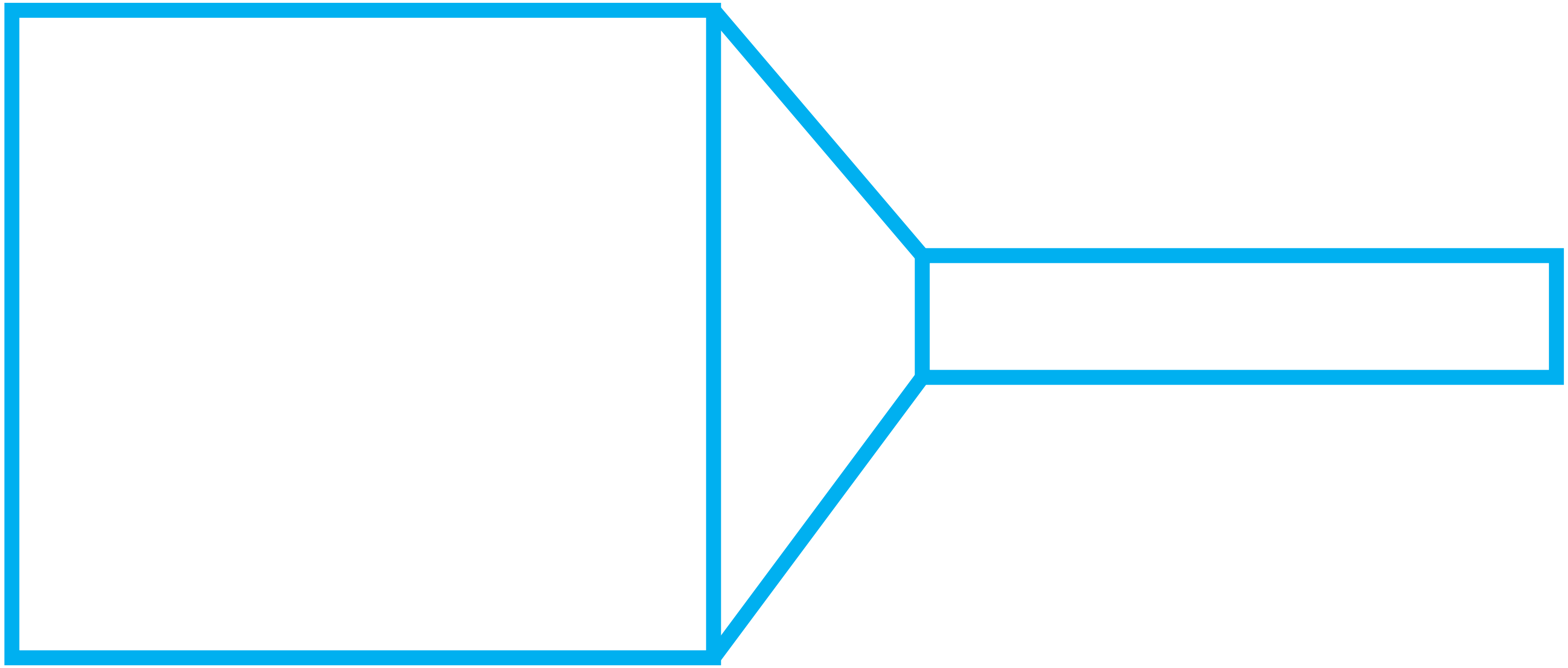
B = 5.4 T, pitch = 0.1

[3]

Æ To keep the brightness the same, an increase in magnetic field requires a decrease in energy.

[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

^Çv ZŒ}šŒ}v u]••]}v o]u]š• šZ u}v}r v



- Per particle, synchrotron emission increases and shifts toward shorter wavelengths with increasing magnetic field and energy (for fixed pitch).
- Measured synchrotron brightnesses at three magnetic fields (2.7 T, 5.4 T, and 7.8 T) have similar spectral shapes.
- Assuming a mono-energetic RE beam at a fixed pitch, an increase in synchrotron emission per particle (from an increase in magnetic field) reduces the energy.
  - ÆSynchrotro Ą

Z (Œ v •

[1] V.V. Plyusnin, et al. NF 46, 277-284 (2006).

[2] R.S. Granetz, et al. PoP 21, 072506 (2014).

[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

[4] J.H. Yu, et al. PoP 20, 042133 (2013).

[5] M. Hoppe, Chalmers Plasma Physics Group (private communication, 2016).

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:K\ /DUJH 'DWDEDVHV $UH 8VHI

'HYHORSLQJ 'LVUXSWLRQ :DUQLQ

:H ZDQW WR DQVZHU WKH IROORZLQJ W

- :KLFK SDUDPHWHUV DUH FRUUHODWHG ZLWK GLVUXSWLRQ" :KDW DUH WKHLU WKUHVKROG GLVUXSWLRQ and QXPEHU RI IDOVH SRVLWLYHV"
- :KDW LV WKH ZDUQLQJ WLPH YV WKUHVKROG
- 'R WKH GHWDLOV GHSHQG RQ ZKHWKHU WKH IODWWRS UDPSGRZQ RU UDPSXS"
- $UH WKHUH FRPELQDWLRQV RI SDUDPHWHUV
- Are the same parameters useful on different tokamaks?

$GGLWLRQDOO\ ZH GHVLUH D GLVUXSW ZRUNV LQ QHDU UHDO WLPH HPEHGGHG V\VWHP

¾ 7KHUHIRUH WKH RQ RXU GDWDEDVH SDUDPHWHUV DUH LQ WKH W LQ SULQFLSOH FDQ EH DYDLODEOH LQ QHDU

The Databases We Are Constructing

We have created databases consisting of candidate parameters sampled at many times during disruptive and non-disruptive shots on several tokamaks:

C-Mod 2015 campaign (~2000 shots; > 165,000 time slices)
EAST 2015 campaign (~3000 shots; > 117,000 time slices)
DIII-D 2015 campaign (~2100 shots; > 500,000 time slices)

– Non-uniform time slice sampling:

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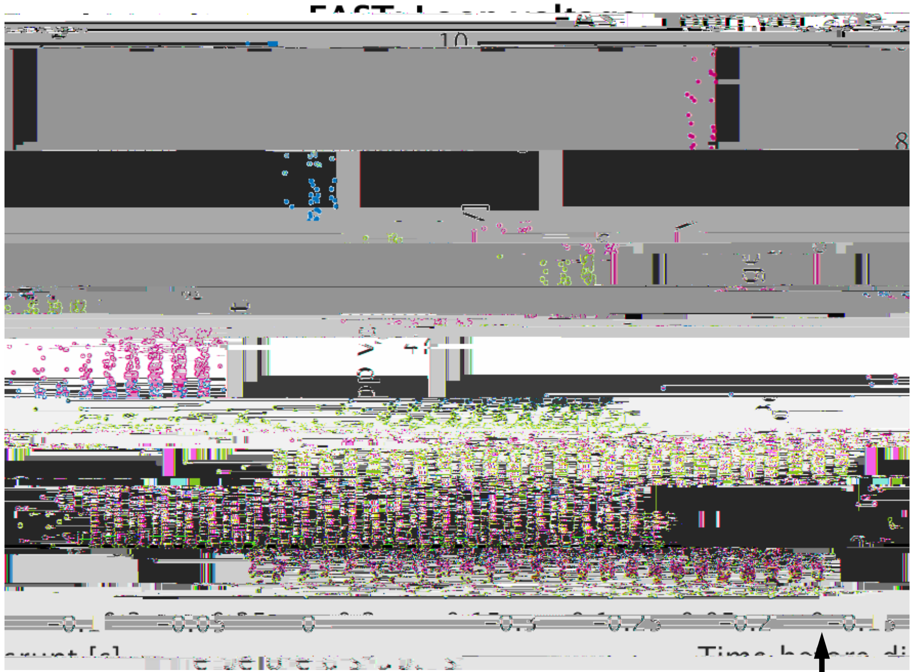
Parameter: Loop voltage
Tokamak: EAST

Non-disruptions

Disruptions



Disrupt time

Parameter: Loop voltage
Tokamak: EAST

Non-disruptions

Disruptions

If we declare: ($V_{loop} \geq 1.5$ or $V_{loop} \leq -0.7$) is threshold for disrupt:

47.8% of disruptions are predicted with ≥ 30 ms warning time

0.7% false positive rate

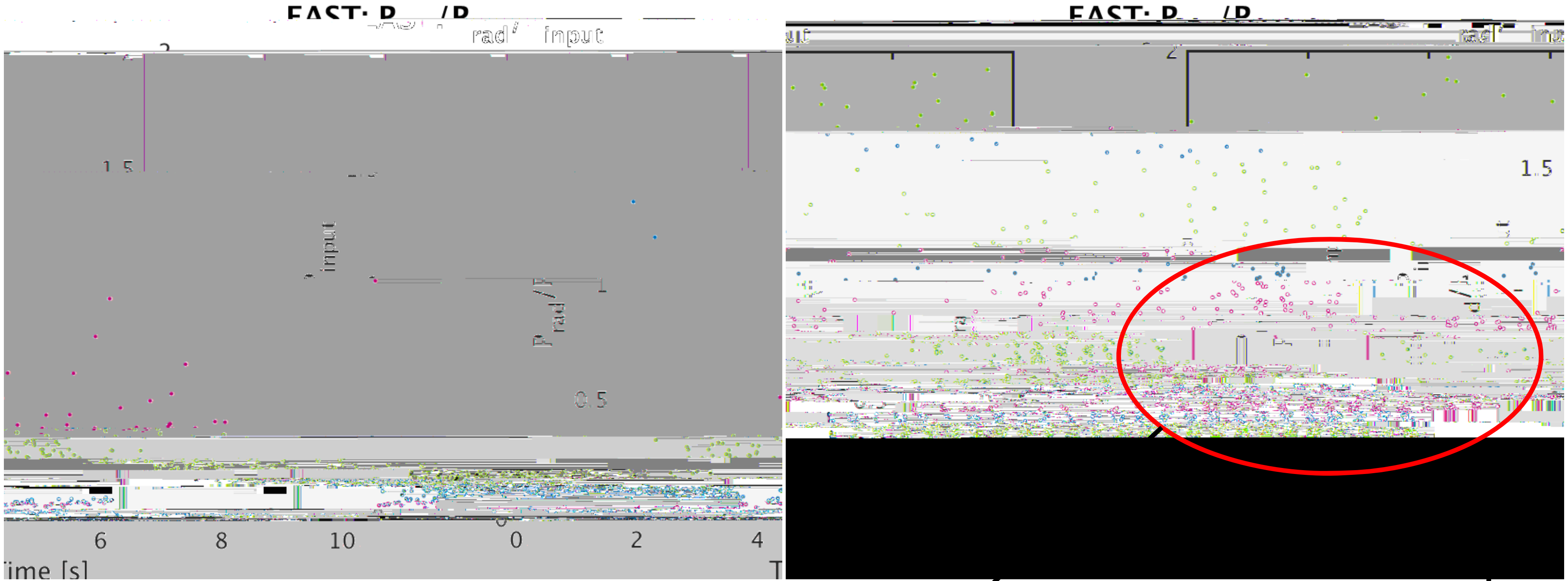
C. Mod: Loop voltage

Parameter: Loop voltage
Tokamak: C-Mod

Parameter: P_{rad} fraction
Tokamak: EAST

Non-disruptions

Disruptions



Disrupt time

A significant number of P_{rad} fraction values increase during the ~150 ms before disruptions occur

Parameter: P_{rad} fraction
Tokamak: EAST

Non-disruptions

Disruptions

If we declare: P_{rad} fraction ≥ 0.35 is threshold for disrupt:

24.9% of disruptions are predicted with ≥ 30 ms warning time

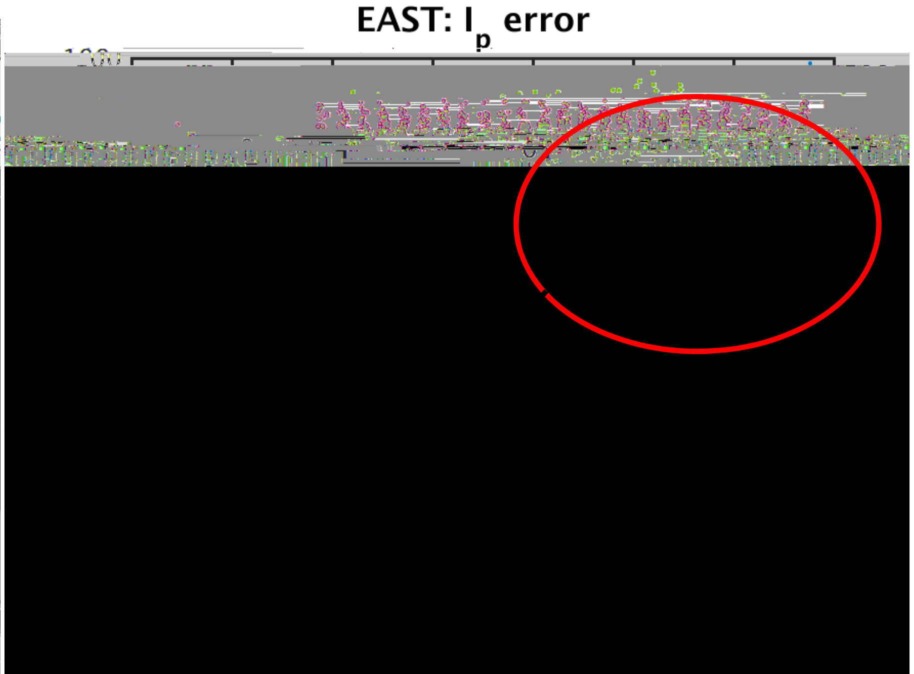
1.0% false positive rate

Parameter: P_{rad} fraction

To j l D í

Parameter: I_p error
Tokamak: EAST

Non-disruptions	Disruptions



Disrupt time

A significant number of I_p error values increase in magnitude during the ~100 ms before disruptions occur

Parameter: I_p error
Tokamak: EAST

Non-disruptions

Disruptions

If we declare: Ip error ≤ -30 kA is threshold for disrupt:

34.2% of disruptions are predicted with ≥ 30 ms warning time

0.9% false positive rate

Parameter: I_p error
Tokamak: C-Mod

Summary and Conclusions

We have examined several disruption parameters using our C-Mod and EAST disruption warning databases. More relevant parameters are still being added (locked mode signals, etc.)

- So far, our studies show that these parameters provide a useful warning of impending disruptions on EAST, with t 30 ms warning time
- But these parameters do a poor job of predicting disruptions on Alcator C-Mod with useful warning time

The faster timescales could be partly due to small size. But C-Mod “control room” expes   MAlca/beض

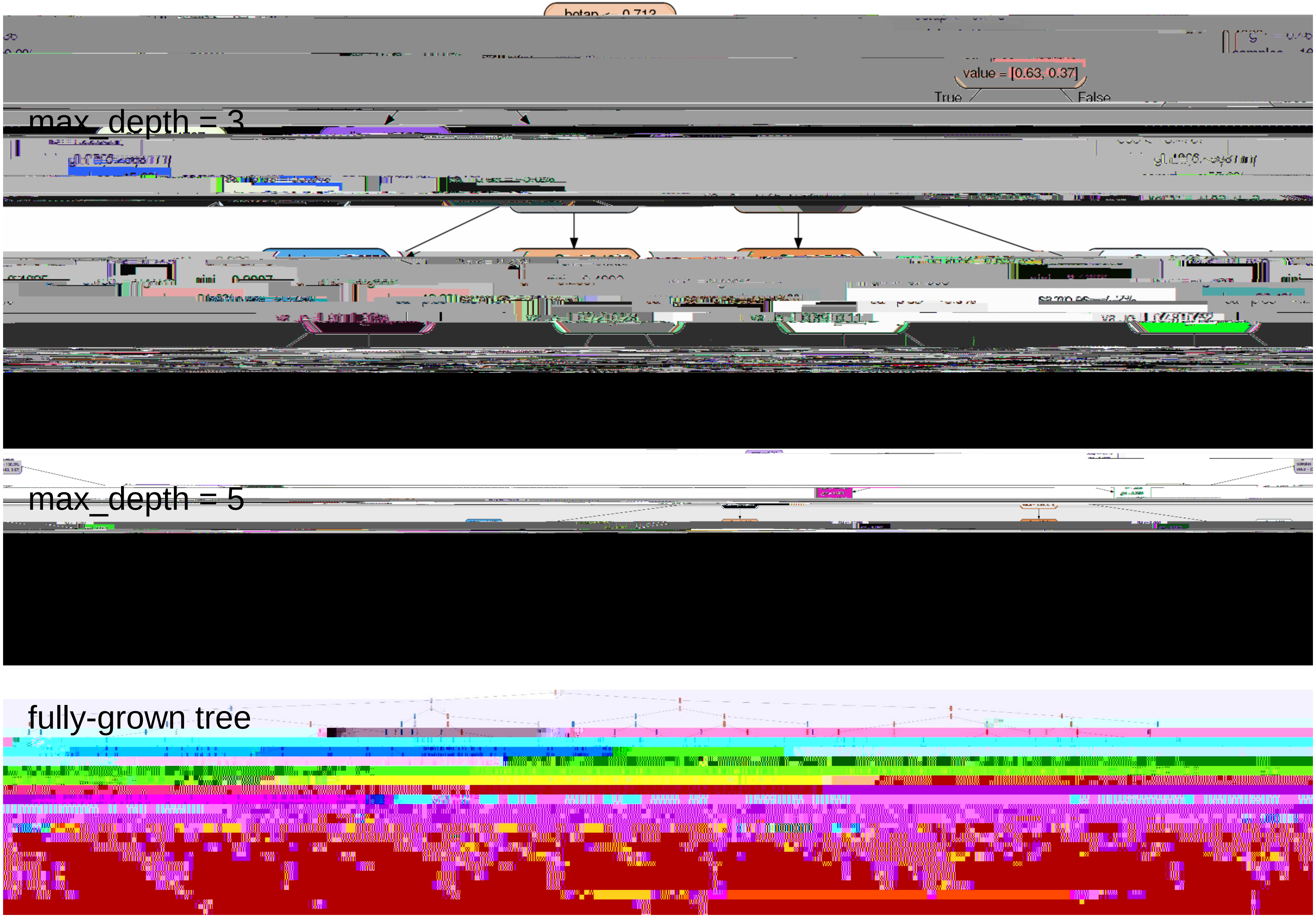
Application of machine learning techniques to our DIII-D disruption warning database

C. Rea, R. Granetz

MIT Plasma Science and Fusion Center

- statistical analysis of disruptions

- to obtain a


max_depth = 3
value = [0.63, 0.37]
True
False
max_depth = 5
fully-grown tree

- q95 probability distributions show major differences between the disrupted and non-disrupted discharge data
- while for the n=1 amplitude data, disr   egarding the peak at zero, it's true that the difference between disruptions and safe discharges does exist but it is very slim

blue : safe discharges, time slices during flattop
red : disruptions during flattop

blue : safe discharges, time slices during flattop
red : disruptions during flattop

[T]

binary classification

the dataset is composed of 59% non-disruptive time slices and 41% disruptive time slices

multi-class classification

the dataset is composed of only disrupted time slices

“far from disr” : time_until_disrupt > 1s
“in-between” : 0.1s < time_until_disrupt < 1s
“close to disr” : time_until_disrupt < 0.1s

the dataset is composed of
disruptive time slices;
non-disruptive time slices populate
the far from disr category

only the dataset is composed of
disrupted time slices