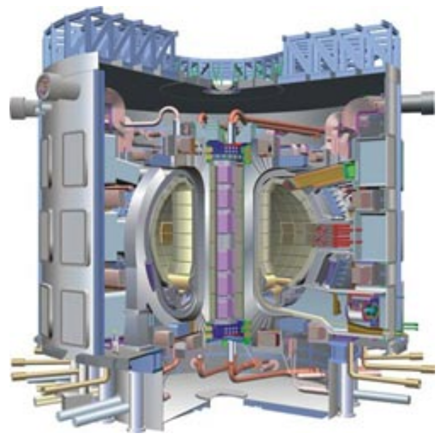


An ITPA joint experiment to study runaway electron generation and suppression

R. Granetz

with contributions from
C. Paz-Soldan, J. Wesley, R. Koslowski, M. Lehnen, B. Esposito,
J. Martin-Solis, T. Rhee, J.H. Kim, and ITPA MHD group

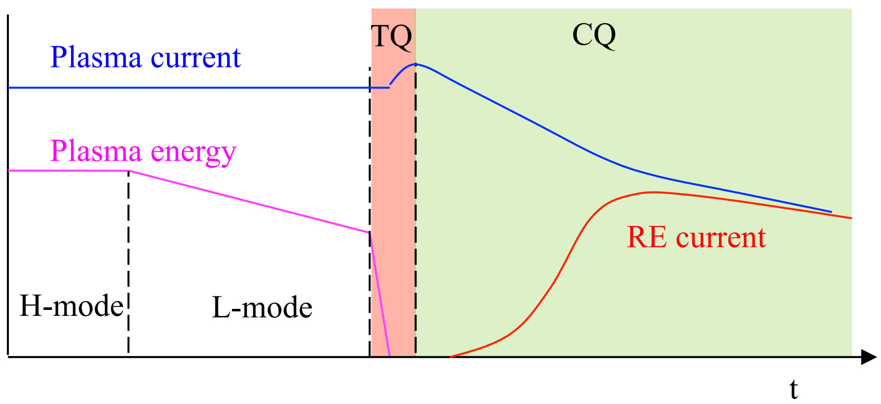
Disruption theory workshop
PPPL
2014/07/09-11

Paper will be in next month's (Aug) issue of Physics of Plasmas

Motivation for joint experiment:

Do we really have to get to the Rosenbluth density to quench runaway electrons in ITER?

Disruption runaways in ITER



$$V_{Loop} = -L_{plasma} \frac{dI_p}{dt}$$

Disruptions can generate very high loop voltage, which can create runaway electrons under some conditions

Modeling of ITER 15 MA disruptions leads to predictions of up to 10 MA of current carried by runaways, with 10-20 MeV energies

- Potentially very damaging to blanket modules

Runaways need to be mitigated, collisionally or otherwise

- ***Collisional-only*** mitigation requires electron densities in the mid-10^{22} m^{-3} range (Rosenbluth density)
- Severe implications for tritium-handling plant, cryopumps, etc.
- Experiments in ASDEX-U and DIII-D have been unable to surpass 25% of the required density

Primary (Dreicer) runaway generation

Consider collisional slowing down of an electron:

$$F_{coll} = m\frac{d\mathrm{v}}{dt} = -m\nu\mathrm{v} \qquad \text{where} \qquad \nu = \frac{n_e e^4 \ln \Lambda}{4\pi\varepsilon_0^2 m_e^2 \mathrm{v}^3}$$

Note that ν decreases like v^3, so fast electrons experience less collisional drag than thermal electrons.

Now consider force due to applied electric field: $F_E = eE$

If $F_E \geq F_{coll}$ the electron will gain energy indefinitely, i.e. run away *if there are no other energy loss mechanisms*.

Combining the above equations gives a condition for runaway generation:

$$E \geq \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0^2 m_e \mathrm{v}^2}$$

Notes about simple Dreicer picture of primary RE generation:

- Runaway electrons have no slowing down mechanism, and no loss mechanism. Each RE continues to gain energy indefinitely.
- Each electron that runs away eventually gets replaced by another electron from the bulk distribution, ensuring a steady supply of electrons available to runaway.
- The replacement rate limits the RE growth rate:

$$\frac{dn_{RE}^{primary}}{dt} = \text{replacement rate } = f(n_e, T_e, Z_{eff})$$

Not exponential, but sensitive to plasma parameters

- Non-relativistic: $E \geq \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0^2 m_e \mathrm{v}^2}$

No matter how small E is, there are always some electrons that can runaway

There is an upper limit to the electron velocity, $v = c$, and therefore a lower limit, i.e. a minimum E-field to generate any runaways. A fully relativistic treatment gives:

$$E_{\mathrm{crit}} = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

J.W. Connor and R.J. Hastie, Nucl.Fusion ***15*** *(1975) 415*

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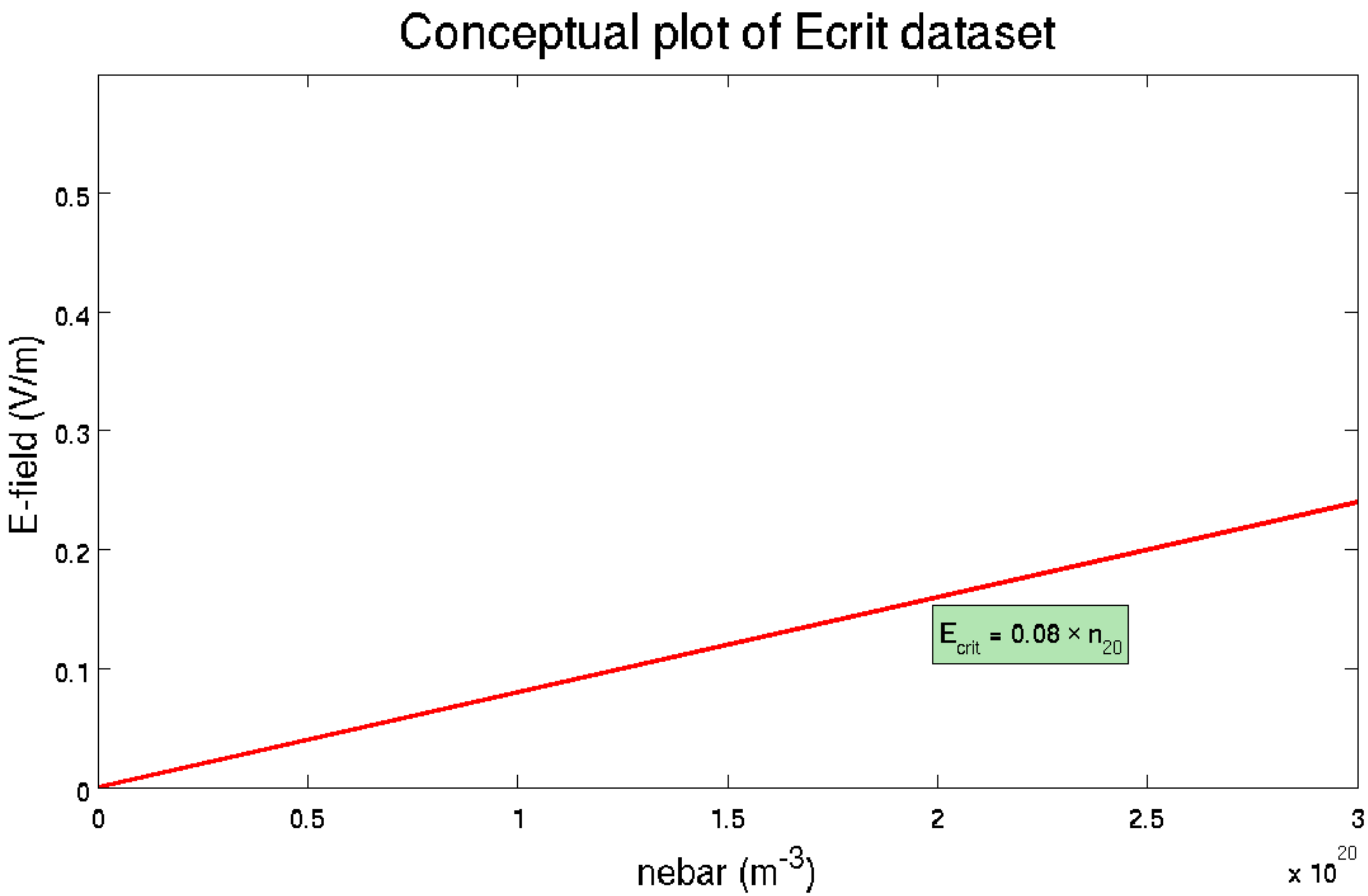
$$E_{\mathrm{crit}} = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2} = 0.08\, n_{20} \quad (\text{for } \ln\Lambda = 15)$$

J.W. Connor and R.J. Hastie, Nucl.Fusion ***15*** *(1975) 415*

Parameter space: runaway population vs E-field and density



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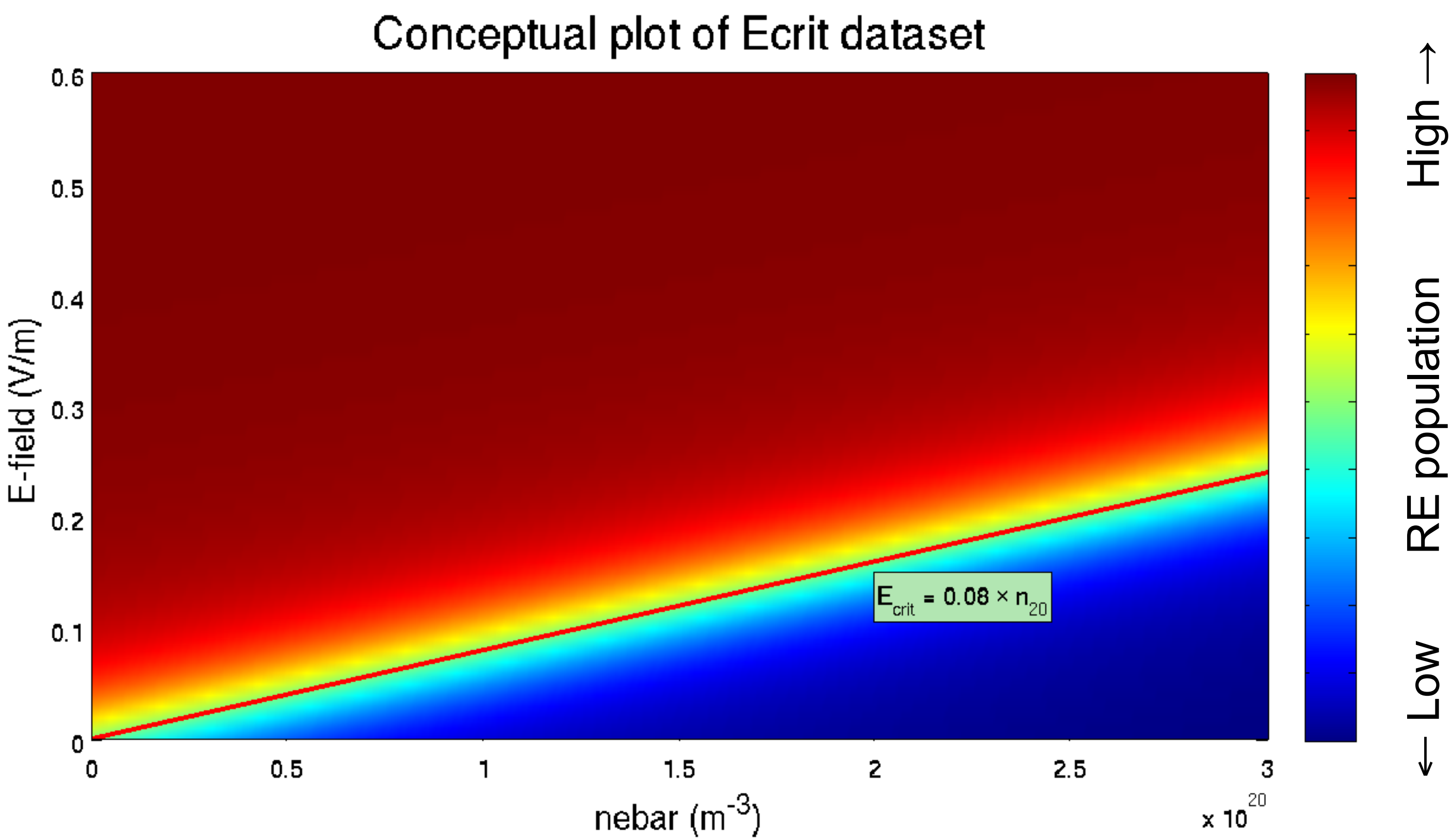


There is anecdotal evidence from many tokamaks that operation above E_{crit} is possible with no runaways

Suggests that other energy loss mechanisms in addition to collisional drag are important

Dreicer & Conner-Hastie derivations were done in unmagnetised plasmas

- No B-field $\Rightarrow$ no synchrotron emission losses from Larmor motion
- No toroidicity $\Rightarrow$ no synchrotron emission losses from toroidal motion; no drift orbit losses; no trapping
- No $\widetilde{B}$ $\Rightarrow$ no stochastic losses
- No beam instabilities $\Rightarrow$ no scattering in velocity space

Idea for ITPA joint experiment

Change this:

"There is anecdotal evidence from a number of tokamaks that operation above E_{crit} is possible with no runaways"

To this:

Measure threshold E-field in well-controlled and well-diagnosed conditions on a number of tokamaks, and compare with E_{crit}

MDC-16 joint experiment

Measure threshold E-field for RE production on a number of machines by one of the following methods:

- In the flattop of discharges that don't have runaways, lower the density until runaways are observed, either by ramping during a shot, or varying shot-to-shot.

or

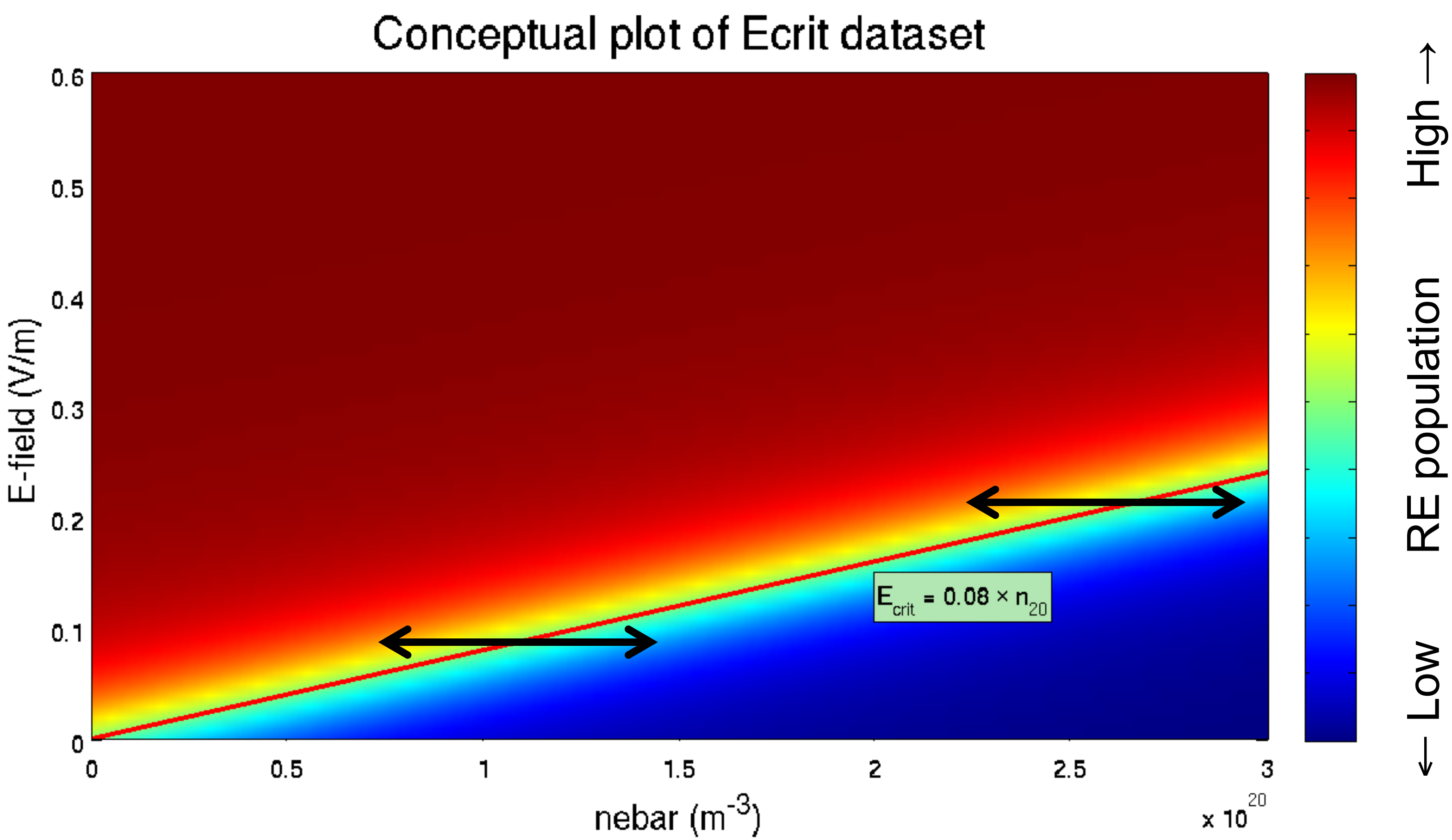
- In the flattop of discharges that already have runaways, increase the density until runaways are suppressed, either by ramping during a shot, or varying shot-to-shot

The flattop is desirable, rather than during disruptions, because the loop voltage, electron density, Z_{eff}, T_e, etc. can be accurately measured

To minimize confusing factors, exclude discharges with LHCD or ECCD, since these can distort the electron distribution

Note: method of detecting runaways is not specified

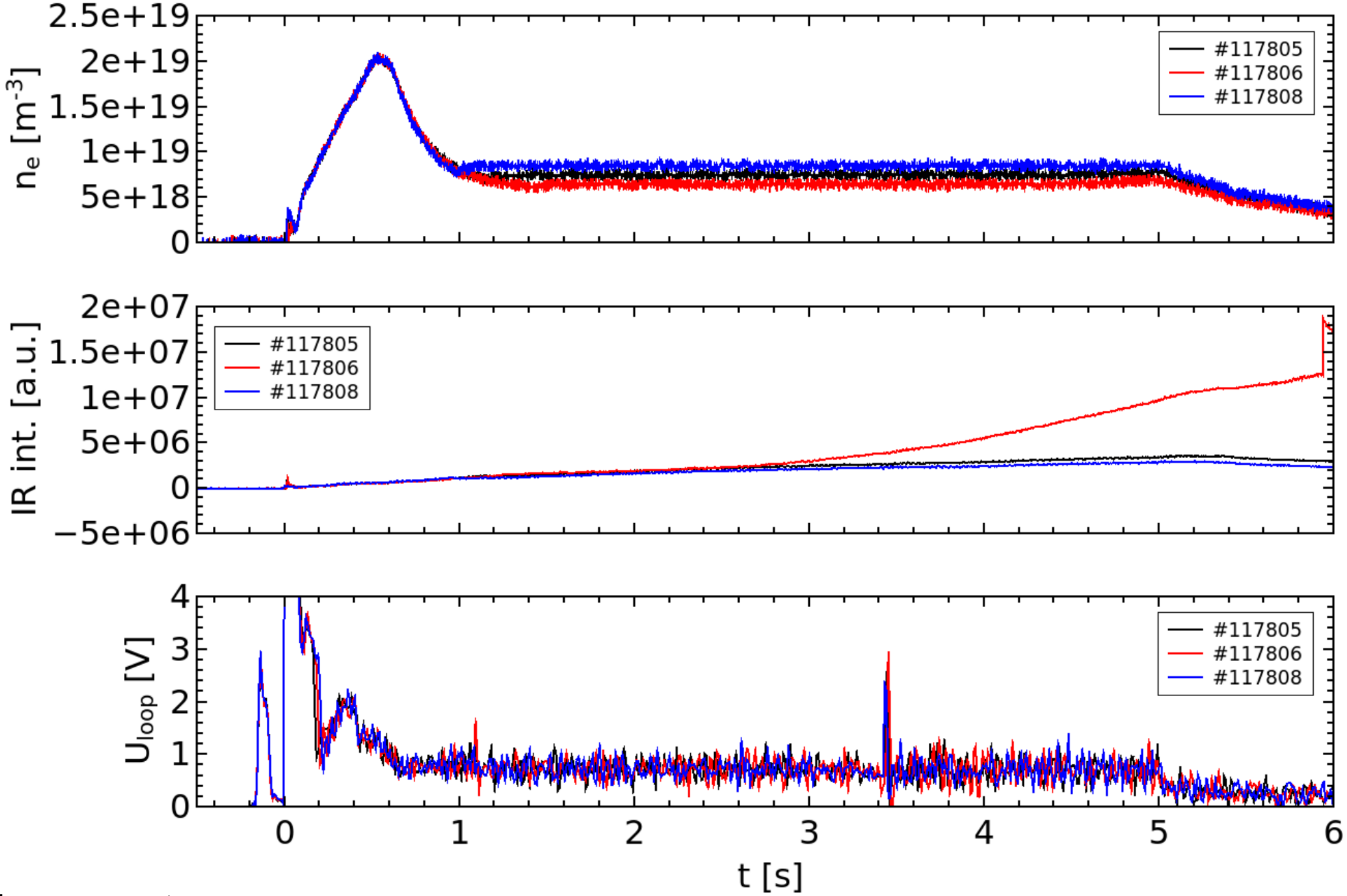
Parameter space: runaway population vs E-field and density



Participants in MDC-16 so far:

- FTU (dedicated experiments)
  - J. Martin-Solis, B. Esposito
- TEXTOR (dedicated experiments)
  - R. Koslowski, M. Lehnen
- Alcator C-Mod (data mining and dedicated experiments)
  - R. Granetz
- DIII-D (data mining and dedicated experiments)
  - J. Wesley, C. Paz-Soldan
- KSTAR (data mining and attempted experiments)
  - T. Rhee, J.H. Kim
- JET (data mining; *not during flattop*)
  - P. deVries

TEXTOR dedicated experiment



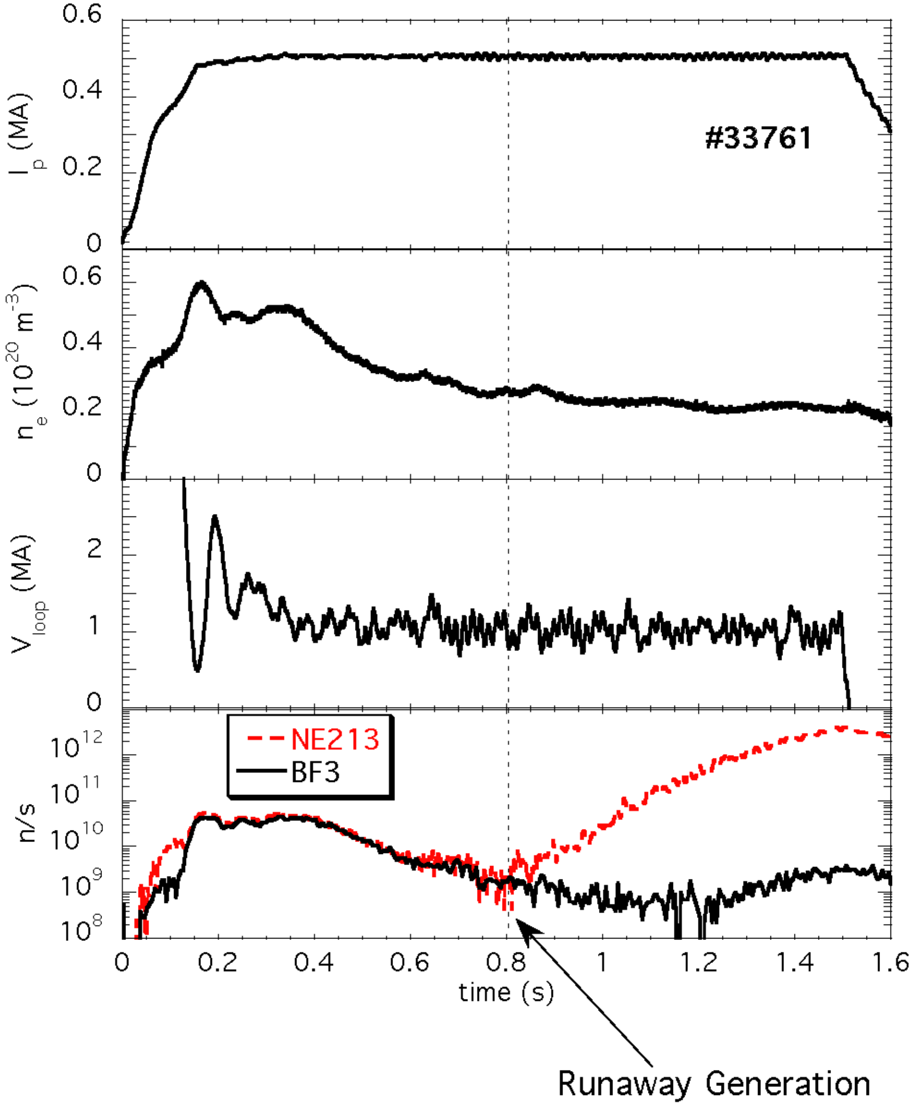
RE onset:

E = 0.066 V/m

$n_e = 0.07 \times 10^{20}$ m^{-3}

Rudi K: “very reproducible”

FTU dedicated experiment

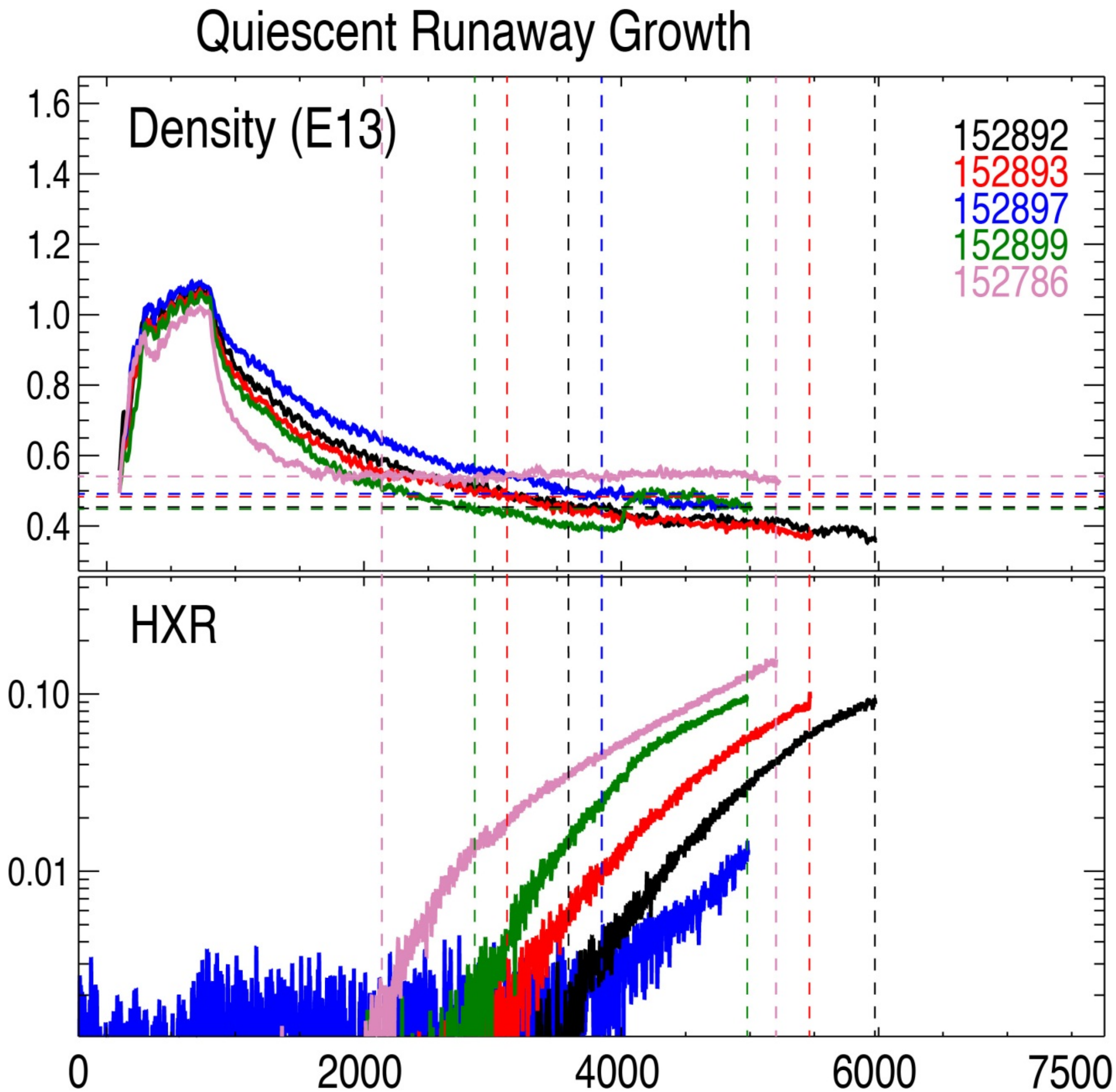


RE onset:

$E = 0.17$ V/m

$n_e = 0.25 \times 10^{20}\ m^{-3}$

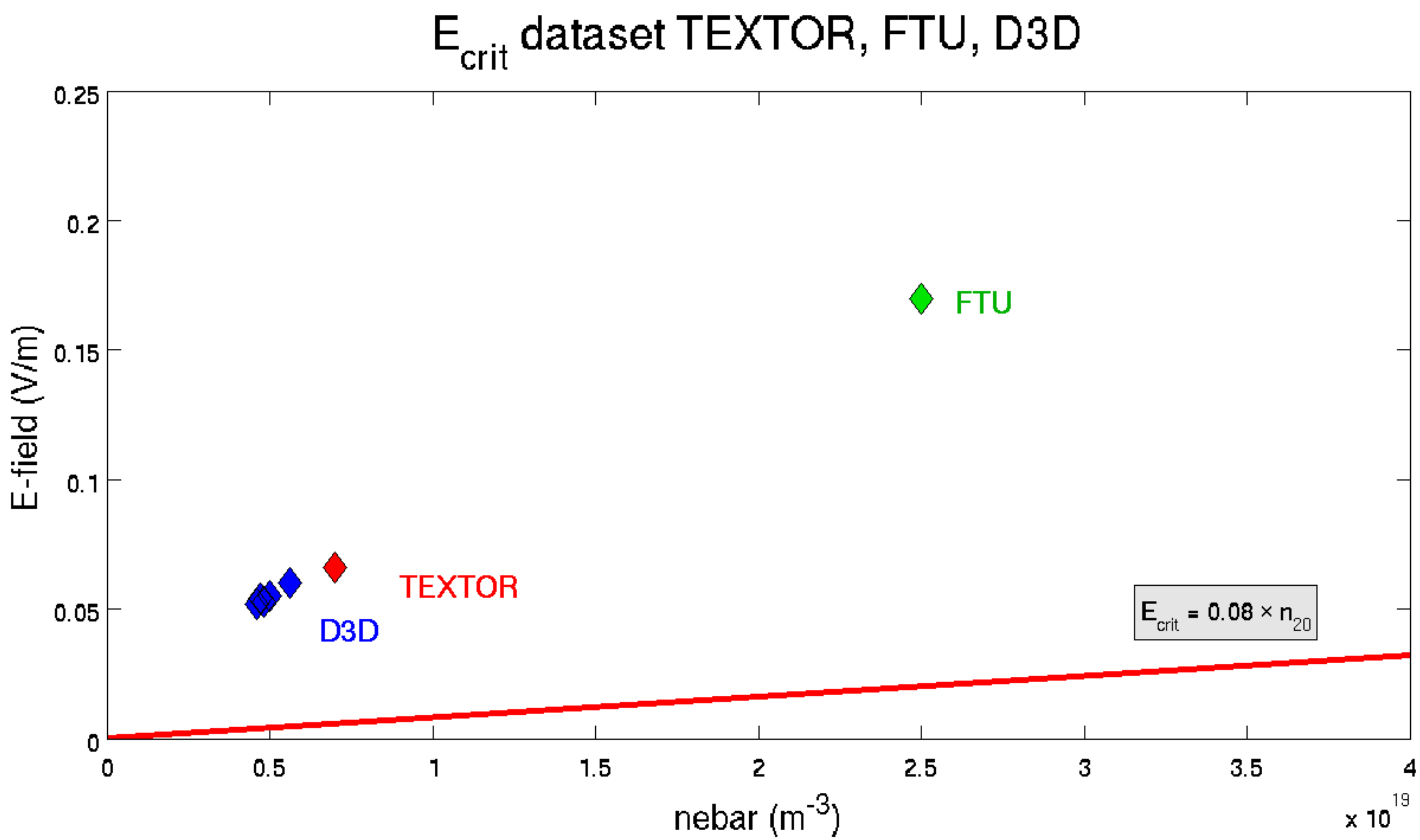
DIII-D dedicated experiments



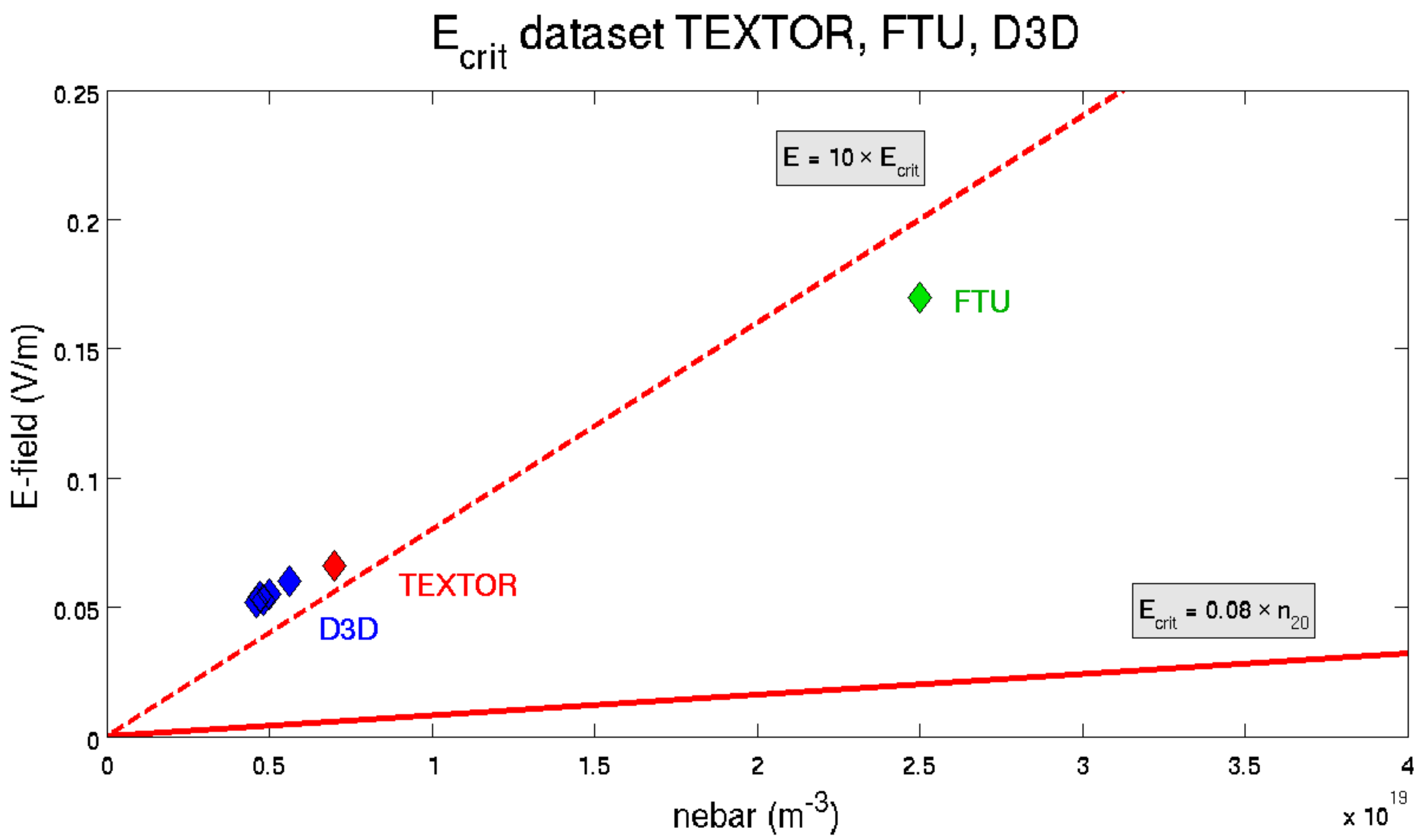
Shot	E (V/m)	n_e (10^{20} m^{-3})
152892	0.052	0.046
152893	0.055	0.050
152897	0.053	0.048
152899	0.054	0.047
152786	0.060	0.056

Note: intrinsic error fields must be carefully reduced to prevent locked modes at these low densities

E-field for RE onset



E-field for RE onset



Alcator C-Mod

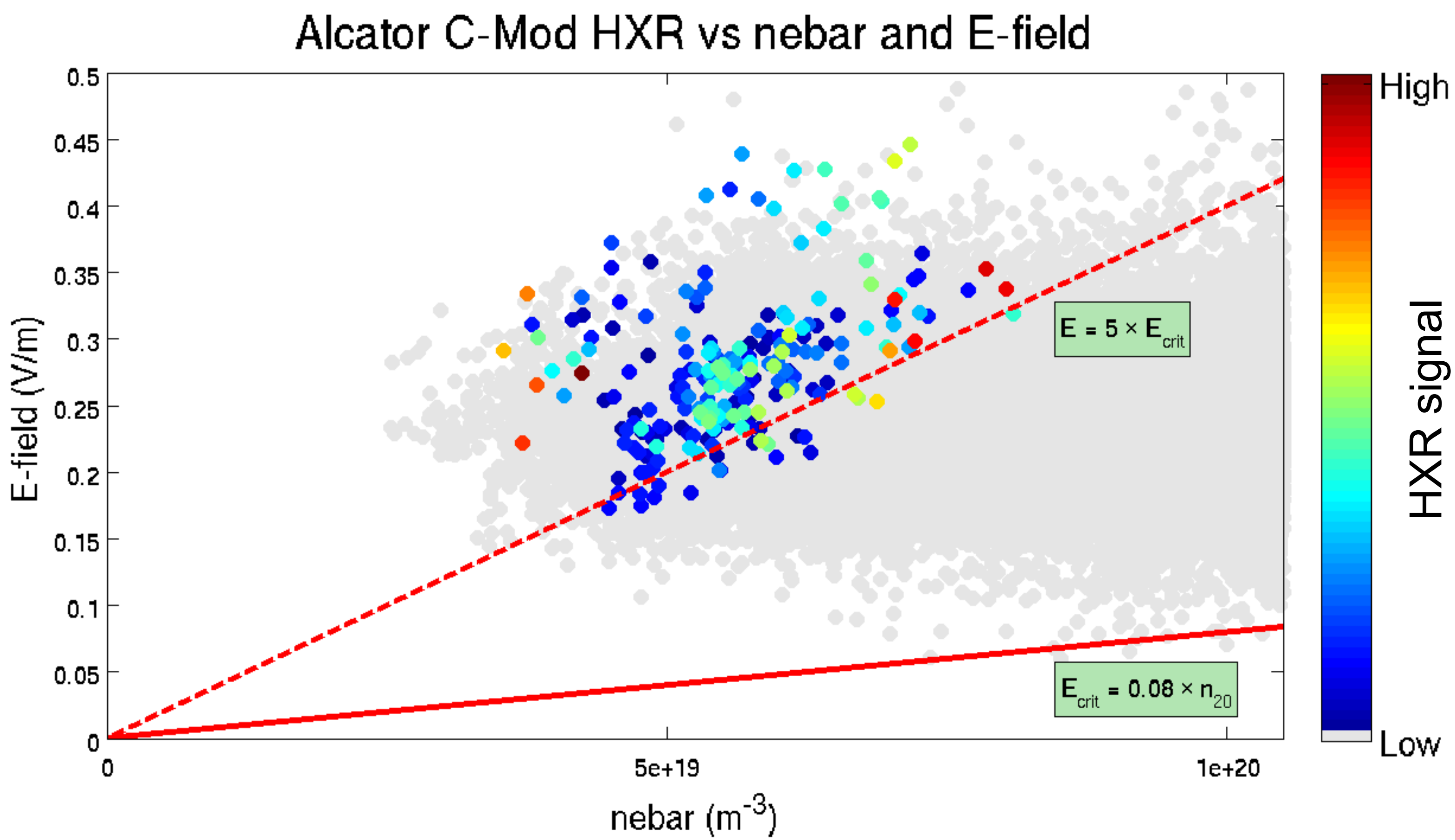
At the time this joint ITPA experiment began, Alcator C-Mod was not funded, so the only option was data mining:

Tabulate E, n_e, and HXR values from 150,000 time slices during flattop of 3000 non-disruptive discharges (2010-2012)

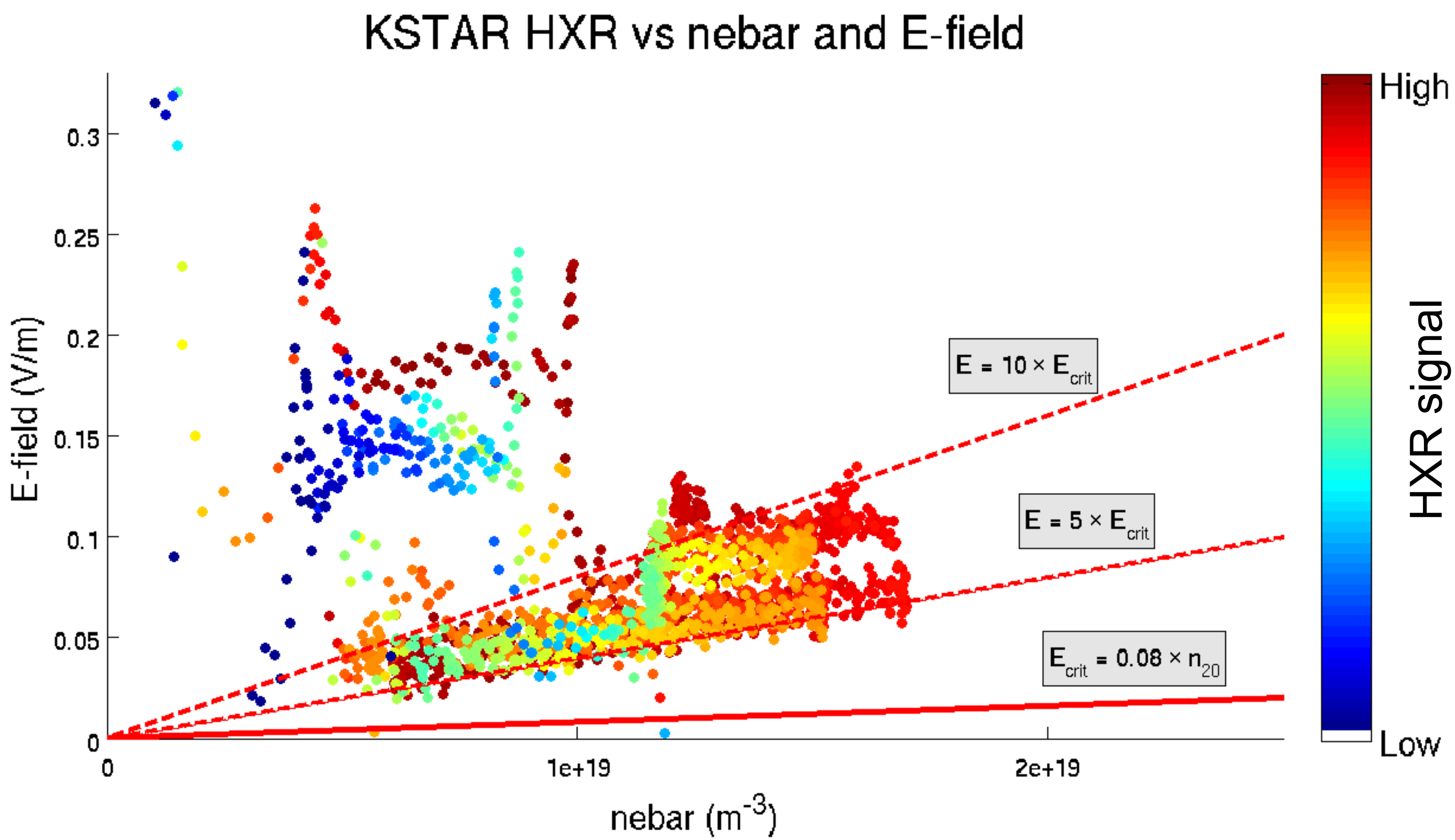
- LH discharges excluded, since they could have distorted electron distribution functions

- Discharges that begin in “slideaway” regime are automatically rejected, since C-Mod plasma control system terminates these early in ramp-up

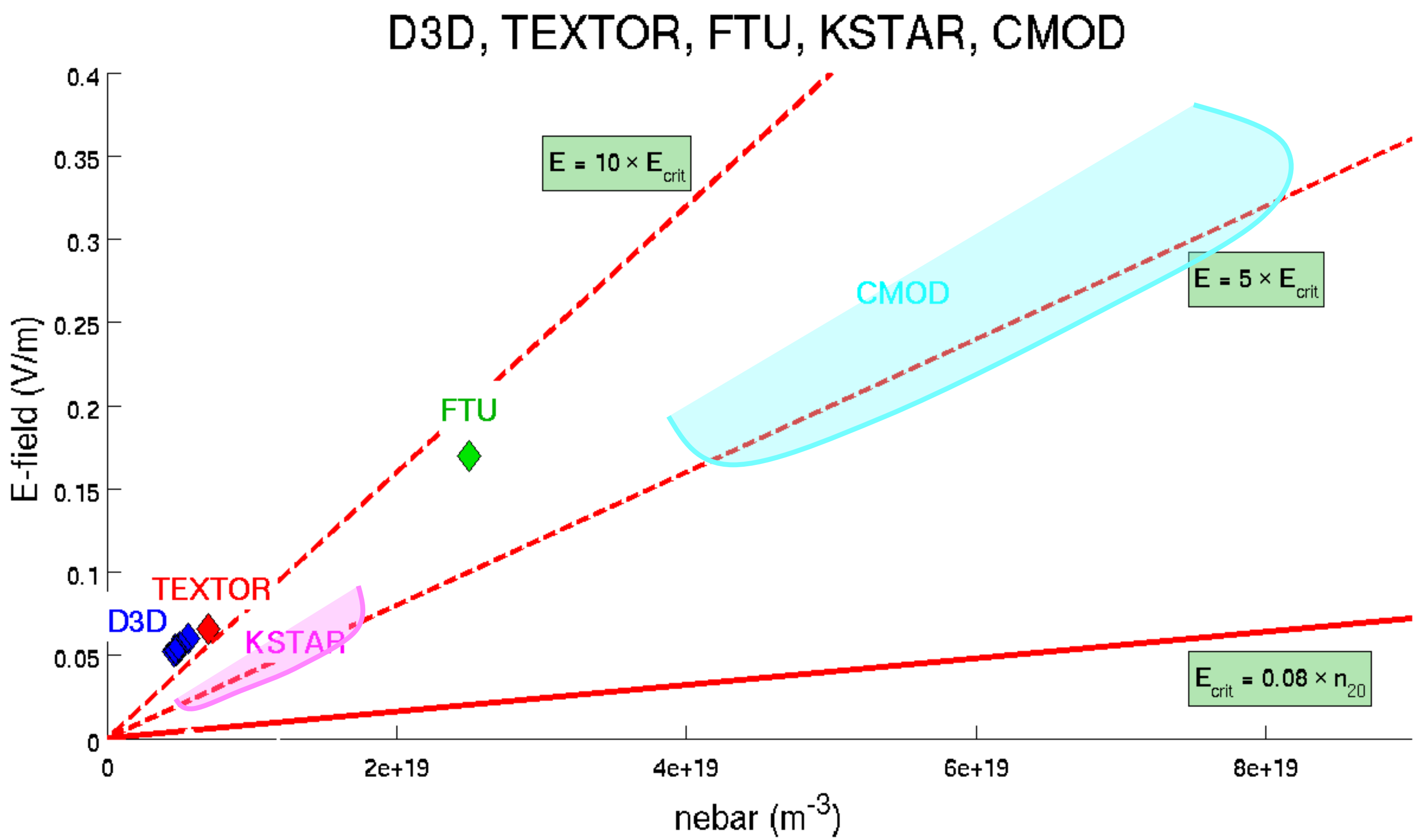
Alcator C-Mod (data mining)



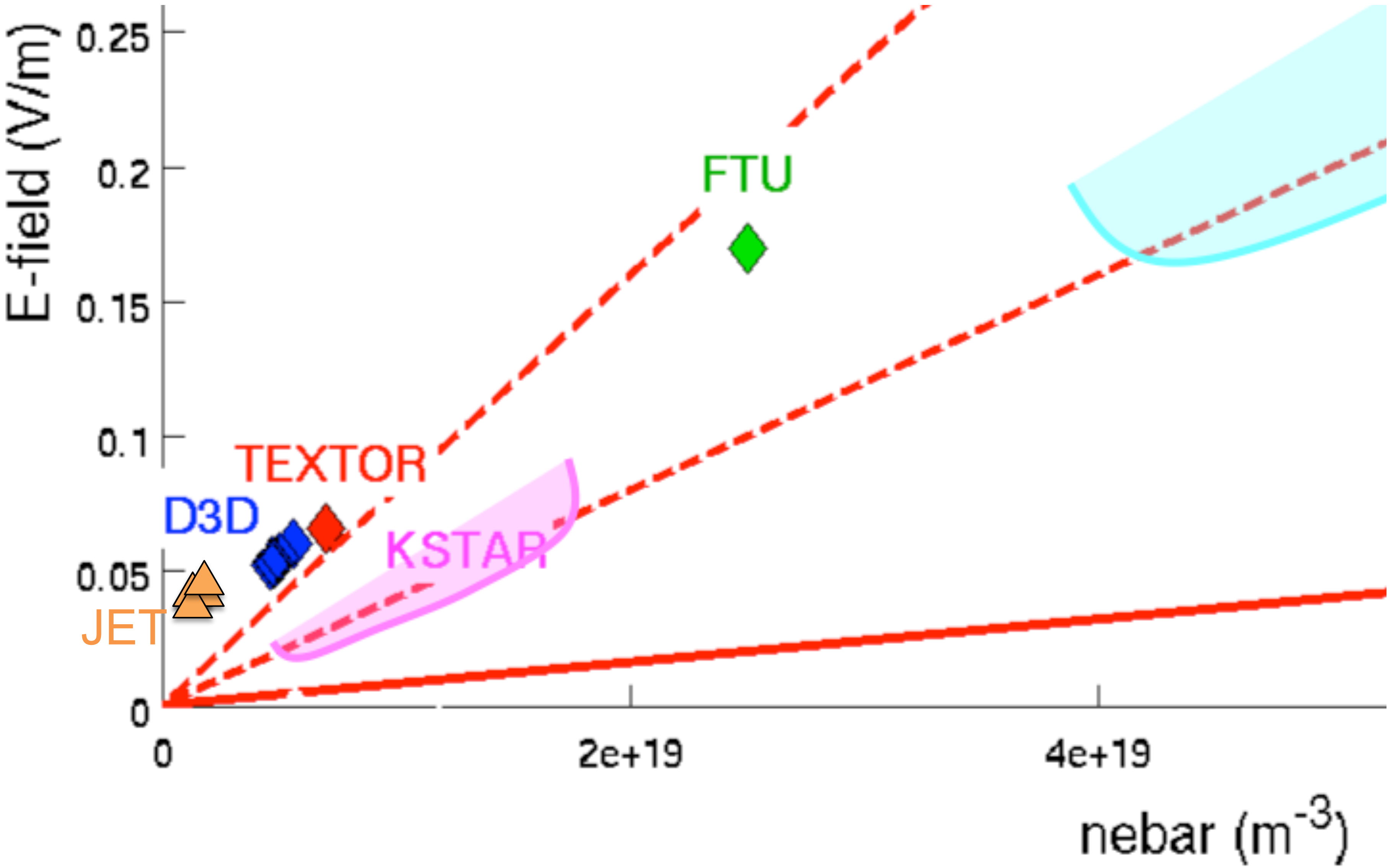
KSTAR (data mining)



Thresholds for RE onset on multiple machines



JET (data mining)



Summary of RE threshold study

The threshold E-field for runaway electrons appears to be 5-10 times higher than Connor-Hastie E_{crit}

- Data were obtained under well-controlled, well-diagnosed conditions, and are quite reproducible
- This implies that other RE loss mechanisms strongly dominate over collisional damping

Summary of RE threshold study

The threshold E-field for runaway electrons appears to be 5-10 times higher than Connor-Hastie E_{crit}

- Data were obtained under well-controlled, well-diagnosed conditions, and are quite reproducible
- This implies that other RE loss mechanisms strongly dominate over collisional damping

But, it turns out that this approach to measuring threshold E-field using the 'onset' method has some caveats

Caveats of using ‘onset’ method to determine threshold E-field

1) RE detectors (usually HXR) have finite sensitivity, i.e. a minimum detectable level of REs

2) In a Maxwellian of a few keV and ~10^{20} electrons, with V_{loop} ~ 1 volt, the initial number of runaways is well below detectable limits

Caveats of using 'onset' method to determine threshold E-field

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2) In a Maxwellian of a few keV and ~10^{20} electrons, with V_{loop} ~ 1 volt, the initial number of runaways is well below detectable limits

Therefore, in order to be detected, i.e. the "onset", the RE population must grow to a measurable size, which takes finite time. It depends on:

- the RE growth rate, which is actually relatively slow, and
- the initial, unmeasurable, number of runaways, which is presumably quite variable

Hence, it may be surprising that we get such a reproducible result

Detection threshold can be important

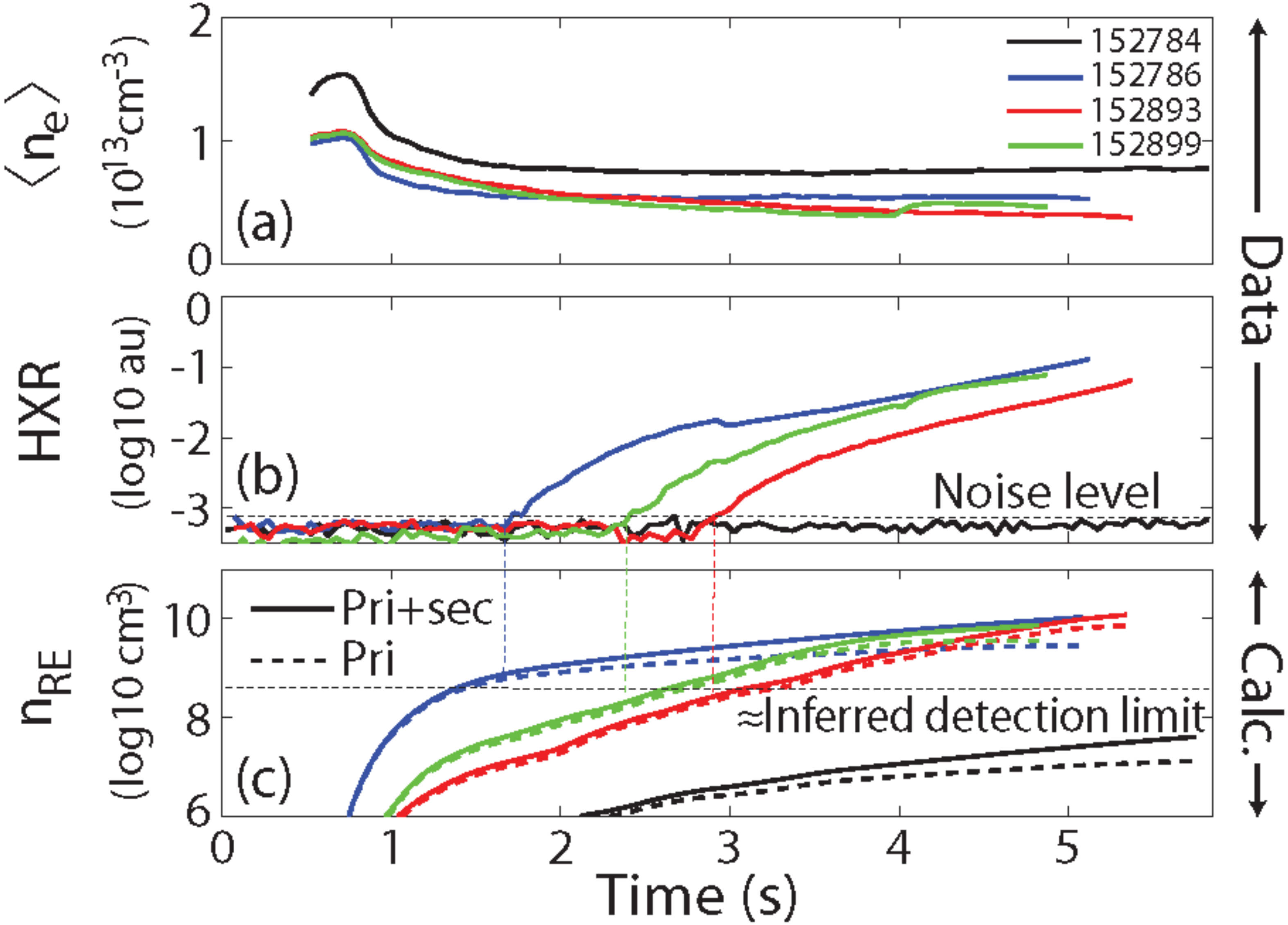


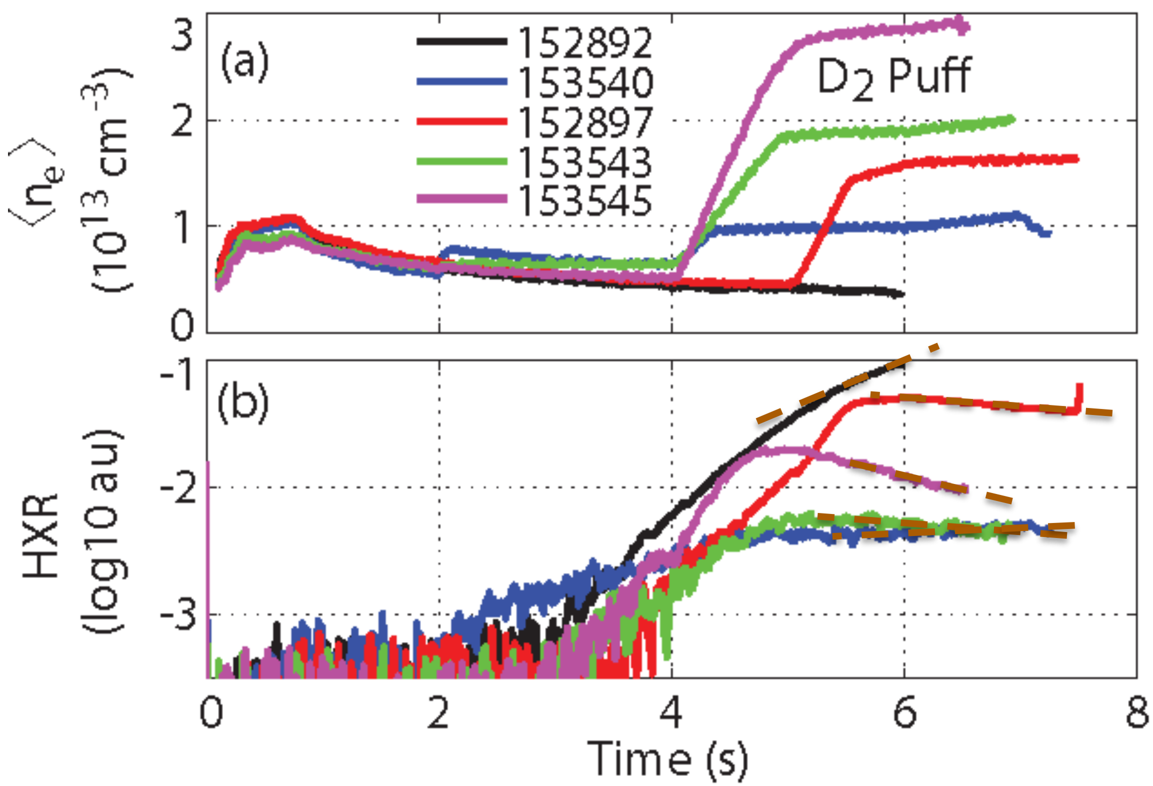
Figure courtesy of Carlos Paz-Soldan

Alternative to onset method

In the flattop of discharges that already have runaways, increase the density until runaway growth becomes runaway decay.

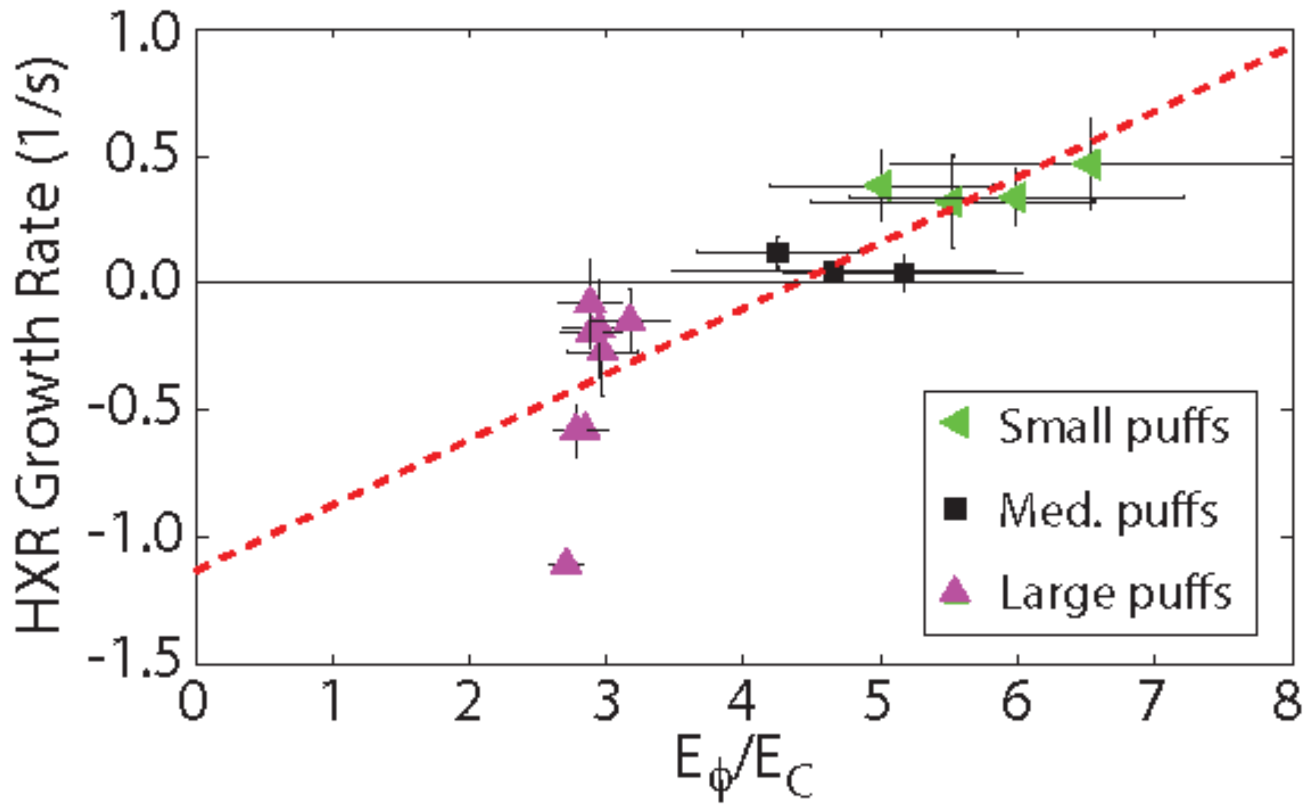
- The transition between growth and decay should occur at $E/E_{crit} = 1$, since below that level the collisional drag force dominates over the E-field acceleration force.
- Differentiating between growth and decay does not depend on detection threshold

Measuring RE growth & decay rates on DIII-D



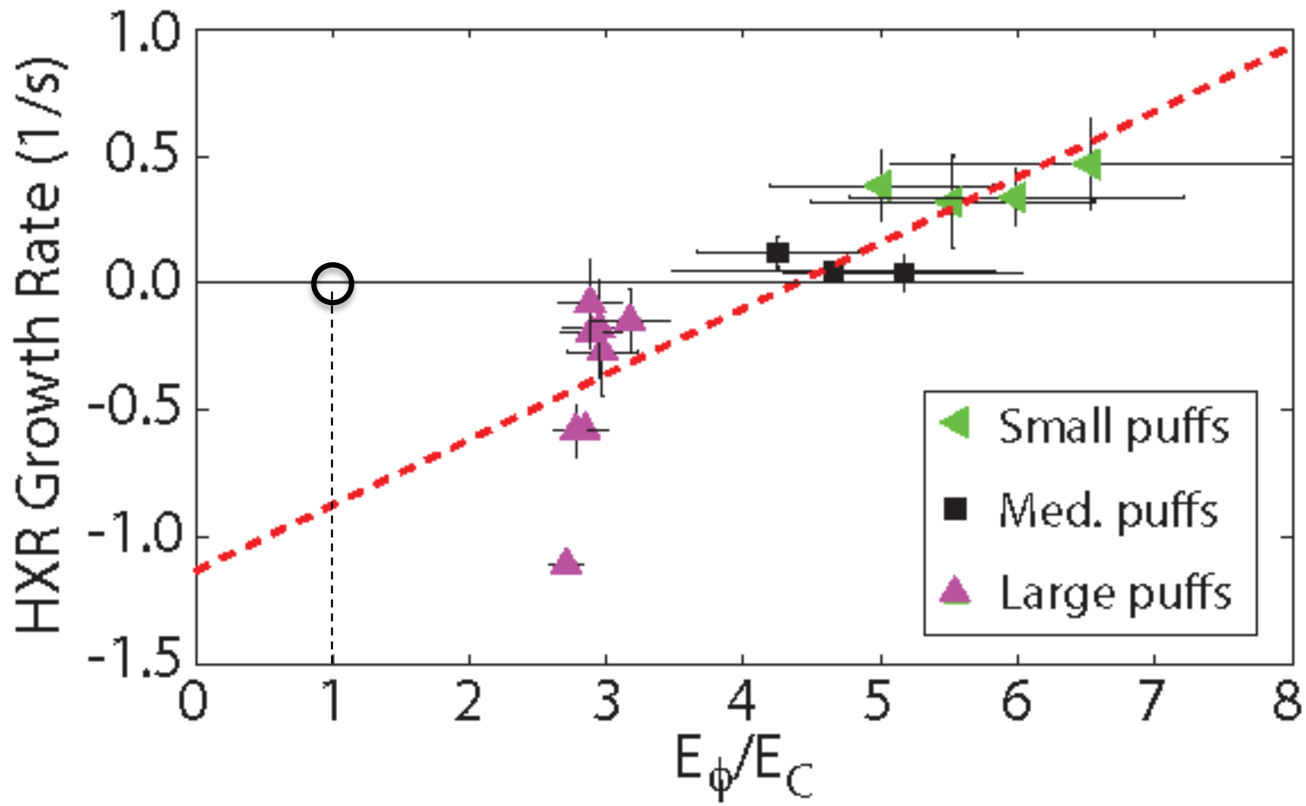
- First, get RE's by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine growth or decay rate

Measuring RE growth & decay rates on DIII-D



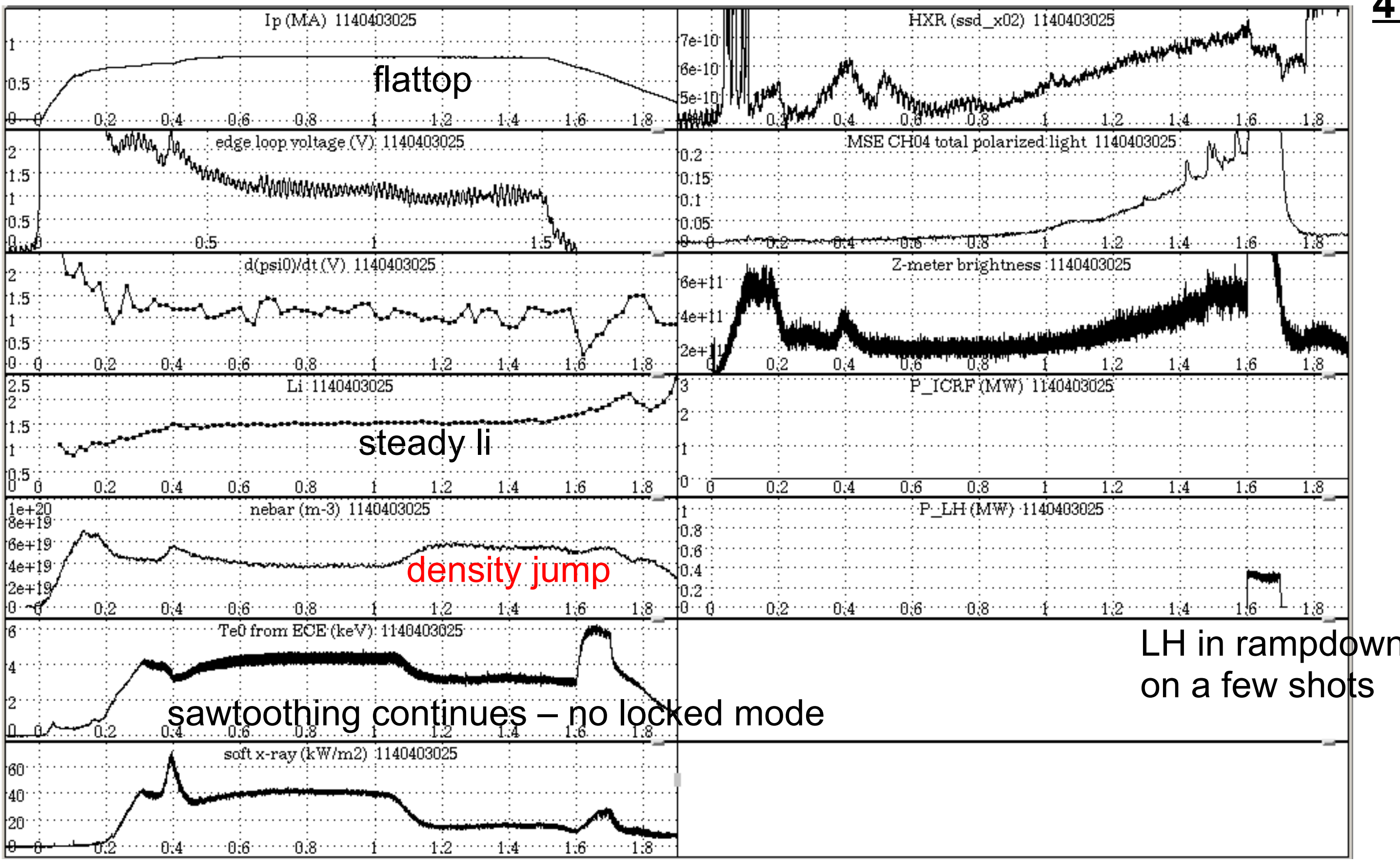
- Transition from growth to decay occurs at E/E_{crit} ~ 3 – 5

Measuring RE growth & decay rates on DIII-D



- Transition from growth to decay occurs at E/E_{crit} ~ 3 – 5
- Theory says this should occur at E/E_{crit} = 1
- *Hence, this method leads to similar conclusion as 'onset' method*

Measuring RE growth & decay on C-Mod



4 measures of RE's:

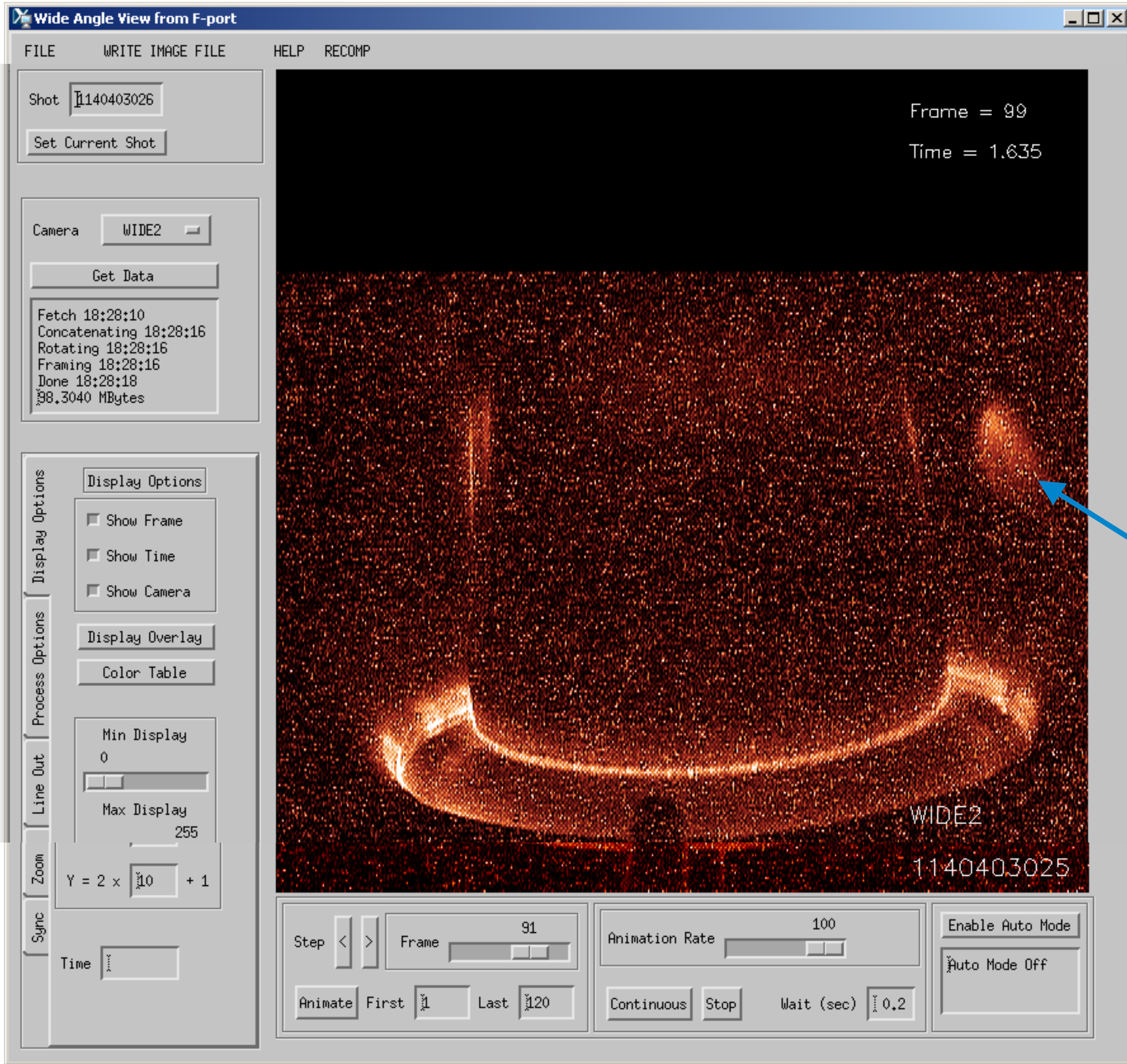
HXR (SSD_X02)

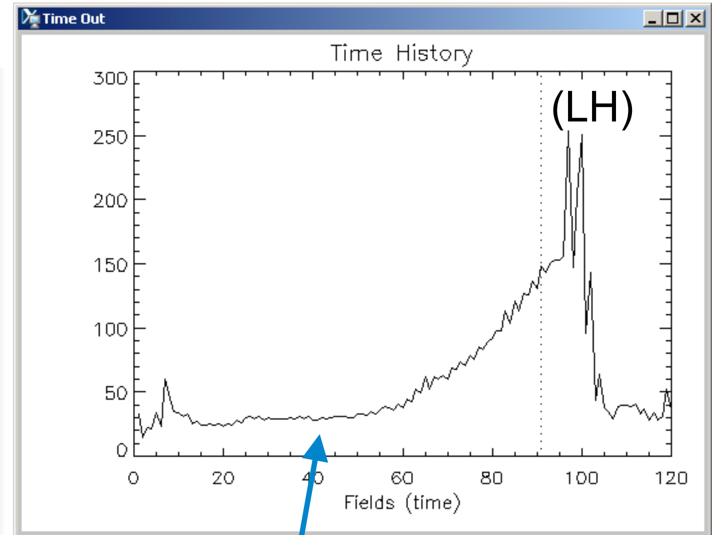
MSE polarized light

Z-meter brightness

(also line-out vs time from WIDE2; see next slide)

Measuring RE growth & decay on C-Mod

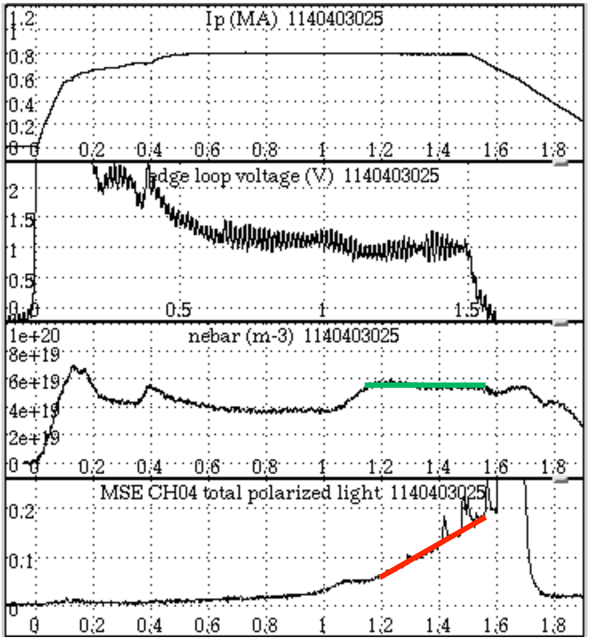




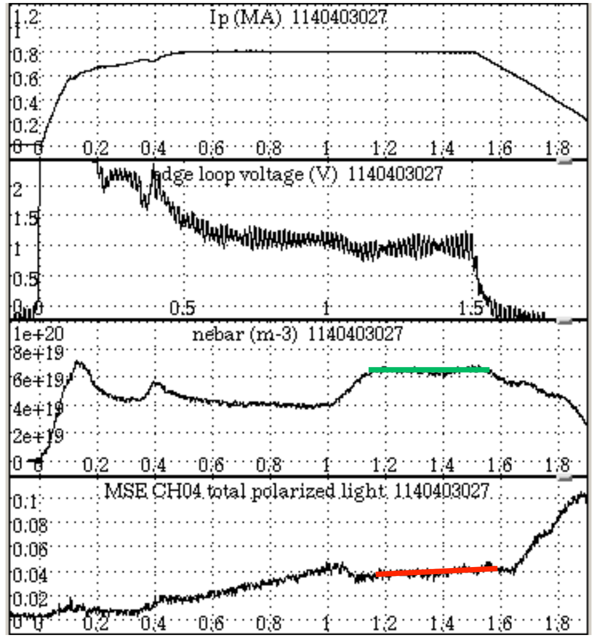
pixel brightness
vs time

Measuring RE growth & decay rates on C-Mod

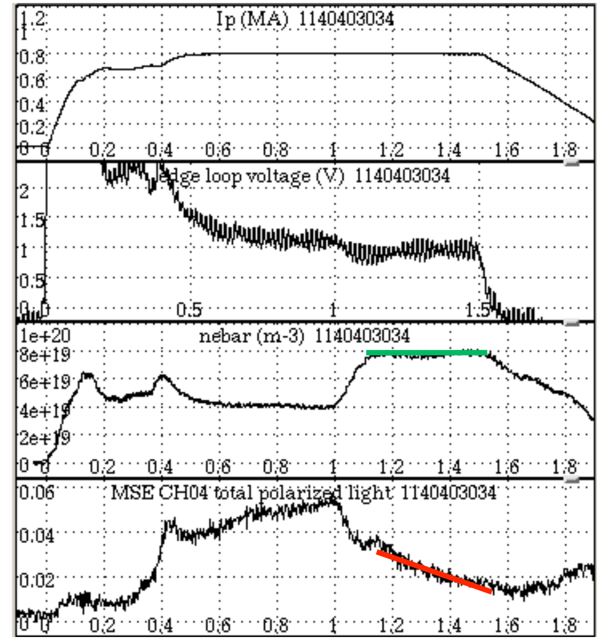
increasing RE’s



nearly steady RE’s

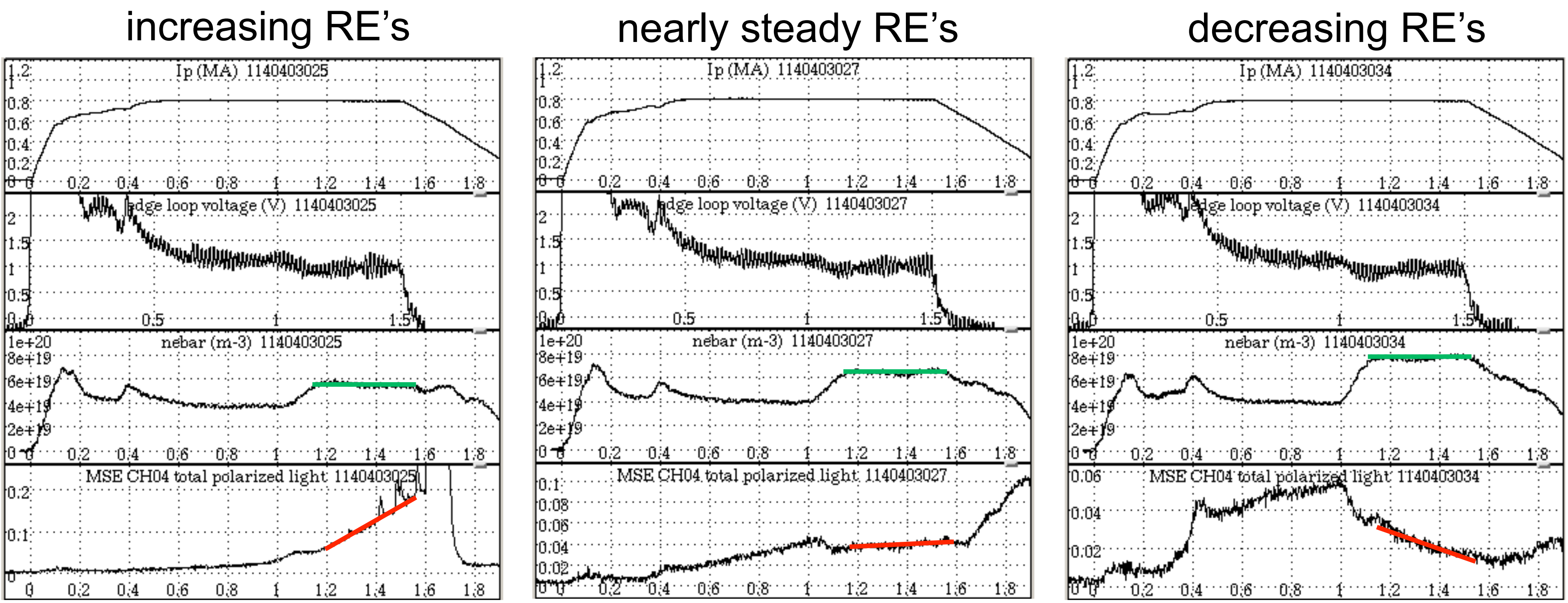


decreasing RE’s



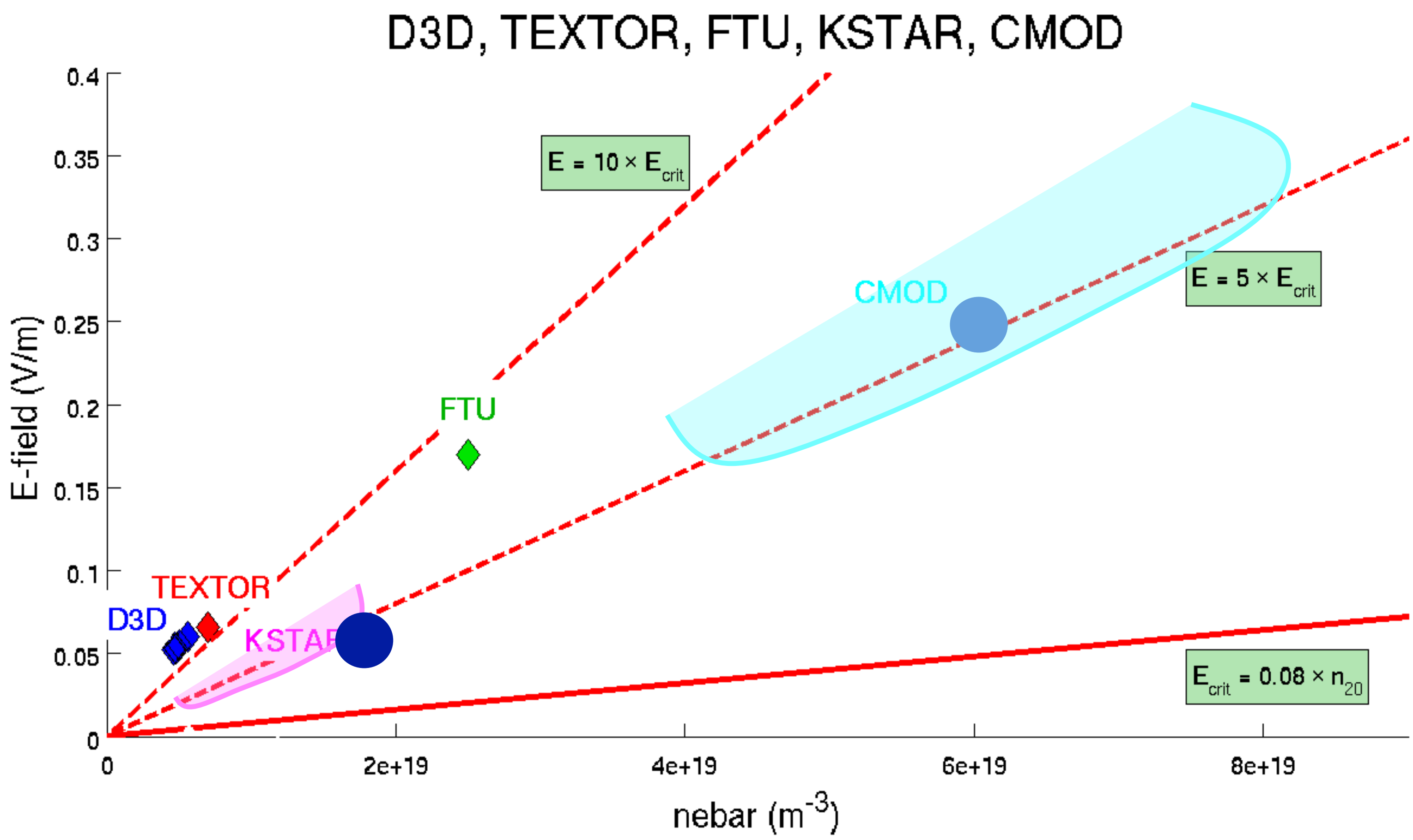
- First, get RE’s by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case

Measuring RE growth & decay rates on C-Mod



- First, get RE's by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case
- Center case has n_e=0.6×10^{20} m^{-3}, $E_{//}$=0.25 V/m

Thresholds for RE onset on multiple machines



Caveat on RE growth and decay measurements

RE population is measured by hard x-ray detectors and/or synchrotron light detectors. The signals from these diagnostics depend on both RE number AND RE energy spectrum. These two individual entities are not yet well-characterized in present experiments.

Summary

A study of runaway electrons under well-controlled, well-diagnosed conditions in a number of tokamaks finds that the threshold E-field for both onset and decay of RE signals is at least 4 – 5 times above the Connor-Hastie E_{crit}

– Conversely, the density at which runaways are suppressed for a given loop voltage is at least a factor of 4-5 less than theoretically predicted

This may imply that there are other significant RE loss mechanisms in addition to collisional damping, even in steady-state quiescent plasmas.