EC angle dependence of pre-ionization plasmas

by
J. Yang[1], A.C.C. Sips[2], M. Walker[2], P. De Vries[3], J. Sinha[4], H.T. Kim[5], F. Glass[2], M. Austin[6], M. Van Zeeland[2], J. Herfindal[7], M. Shafer[7], A. Nelson[8], C. Marini[9], A. Hyatt[2], F. Turco[8], R. Pinsker[2]

1 Princeton Plasma Physics Laboratory
2 General Atomics
3 ITER Organization
4 Tokamak Energy Ltd
5 Culham Centre for Fusion Energy
6 University of Texas at Austin
7 Oak Ridge National Laboratory
8 Columbia University
9 University of California at San Diego

Presented at the
NSTX-U Science Meeting

April 3, 2023

This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under DE-AC02-09CH11466 and DE-FC02-04ER54698.

Contents

- **Introduction: ITER needs more data on “pre-plasma” for modeling**
- **Method**
  - Isolation of pre-plasma
  - EC and diagnostic configuration
- **Result**
  - Cross check of profile measurements
  - Angle dependence of EC pre-plasma
- **Discussion**
- **Conclusion: Acquired good data for ITER multi-pass EC modeling**

ITER needs more data on “pre-plasma” for modeling

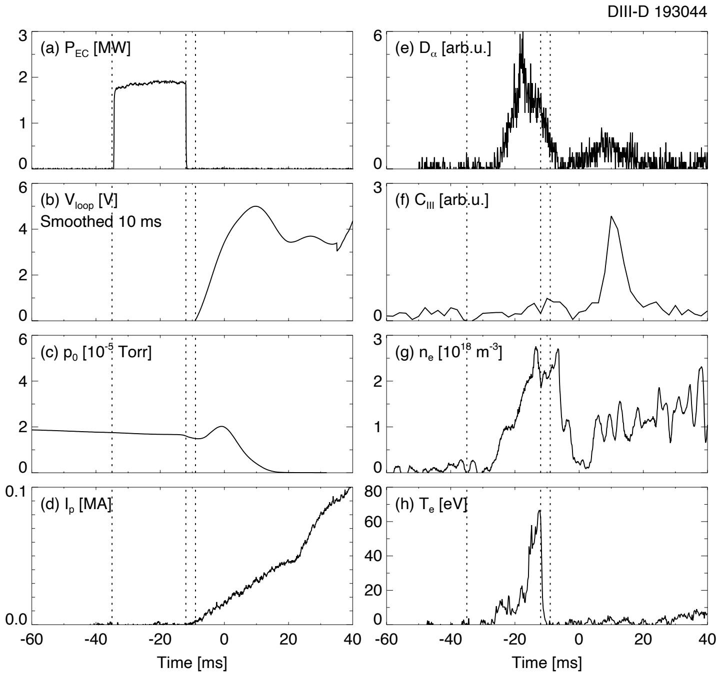
- **EC assisted startup consists of three phases [1]**
  - Pre-plasma
  - Burn through the radiation barrier
  - Current ramp-up

- **Level of our understanding is different for each phase**
  - Latter two phases are relatively well understood [2]
  - Theoretical basis for the pre-plasma phase is being developed [3]
  - Experimental data will help improve and validate the modeling effort [4]

[1] Jackson *et al*., Nucl. Fusion **47** 257 (2007)
[2] Kim *et al*., Plasma Phys. Control. Fusion **55** 124032 (2013)
[3] Farina, Nucl. Fusion **58** 066012 (2018)
[4] De Vries and Gribov, Nucl. Fusion **59** 096043 (2019)

Pre-plasma can be isolated by ending EC pulse early

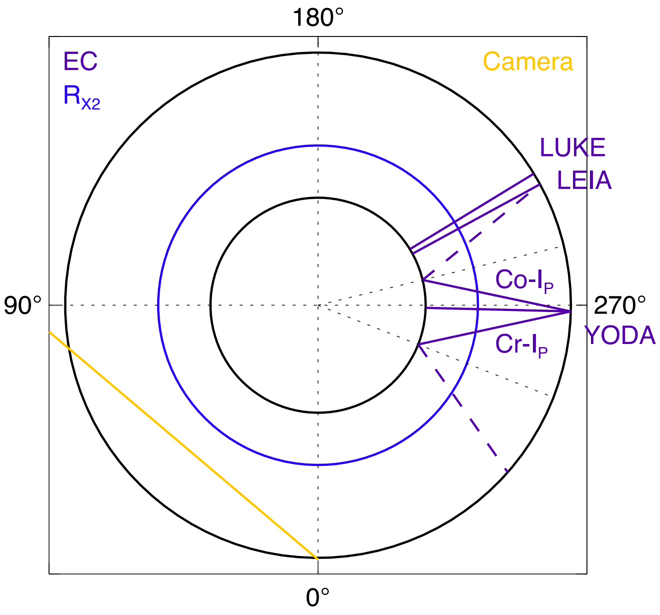
- **EC is often left *on* during OH [1]**
  - This helps burn through
  - This does not help modeling
- **Here, EC is turned *off* before OH**
  - Post turn off, n_e remains high
  - Post turn off, T_e drops quickly
  - This builds on previous work [2]

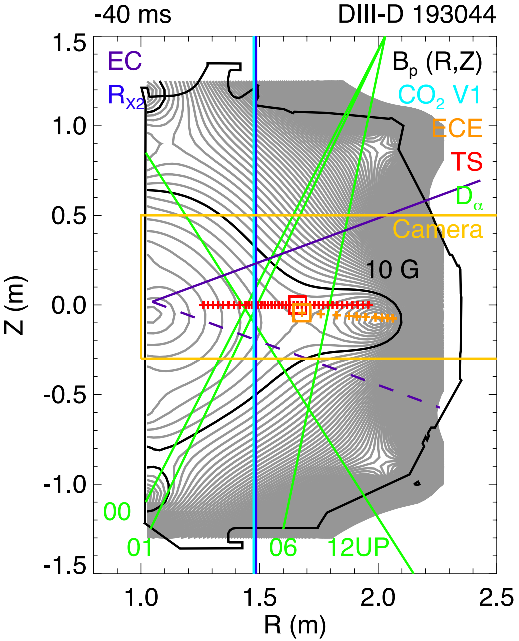


[1] Jackson *et al.*, Nucl. Fusion **47** 257 (2007)
[2] Sinha *et al*, Nucl. Fusion **62** 066013 (2022)

DIII-D EC and diagnostic system are used

EC: 110 GHz, X mode





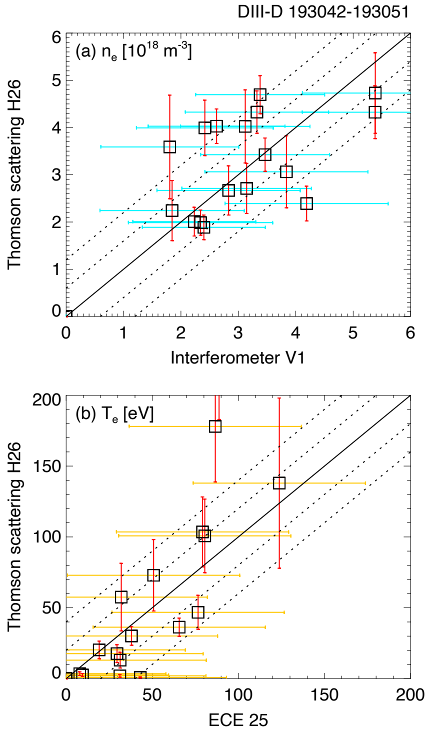
Azimuthal angles are approximations
Dashed lines are "pass 2" paths assuming vacuum

Channels in square (TS, ECE) are used for cross check

Profile measurements have good intercorrelation

- **Pre-plasma can be characterized by (n_e, T_e)**
  - TS [1] has limited time resolution of 50 ms†
  - CO2 [2] has bad spatial resolution (three chords)
  - ECE [3] has limited accuracy for pre-plasma

- **ECE & CO2 have *reasonable* correlation with TS**
  - Profiles of (n_e, T_e) are largely flat at -2 ms [4]
  - ECE error bars may be reduced with modeling [5]

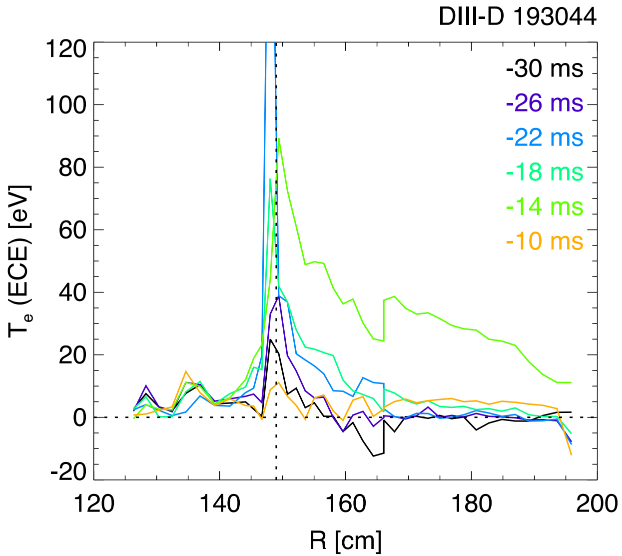


† Midplane TS has two lasers only. Pre-plasma exists for 25 ms < 50 ms

[1] Glass *et al.*, Rev. Sci. Instrum. **87** 11E508 (2016)
[2] Van Zeeland *et al.*, Rev. Sci. Instrum. **77** 10F325 (2006)
[3] Austin and Lohr, Rev. Sci. Instrum. **74** 1457 (2003)
[4] Jackson *et al.*, Nucl. Fusion **51** 083015 (2011)
[5] Luna *et al.*, Rev. Sci. Instrum. **74** 1414 (2003)

Growth of plasma column is observed in T_e profiles

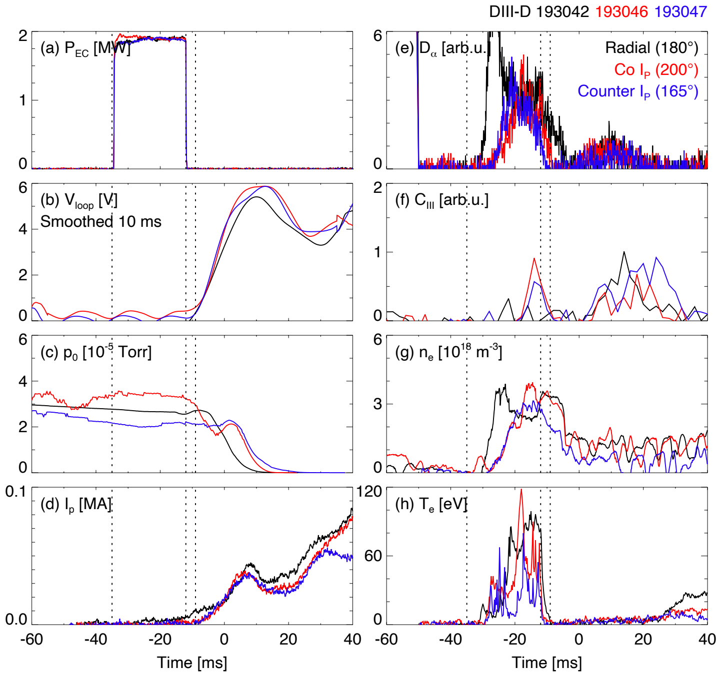
- **ECE shows time evolution of T_e profile**
  - EC power is applied from -35 to -12 ms
  - ECE has 40 channels, ΔR = 1.5 – 3.0 cm
  - T_e increase is clear near resonance†
- **Phases of pre-ionization are identified**
  - Breakdown ends before -30 ms
  - Local burn-through ends at -18 ms (D_α)
  - Radial expansion is ongoing at -14 ms
  - Plasma cools down within 2 ms of EC off



† It is, however, reasonable to assume interference with injected EC near the resonance

D_α emission [1] shows plasma response to EC angle

- **Radial injection is more efficient**
  - Earlier peak of D_α emission
  - Means faster local burn-through
  - From shorter pass 2 path length [2]
- **In oblique injection, angle matters**
  - Co-I_P is 20° off from radial injection
  - Counter-I_P is 15° off
  - Co/counter-I_P is likely unimportant†

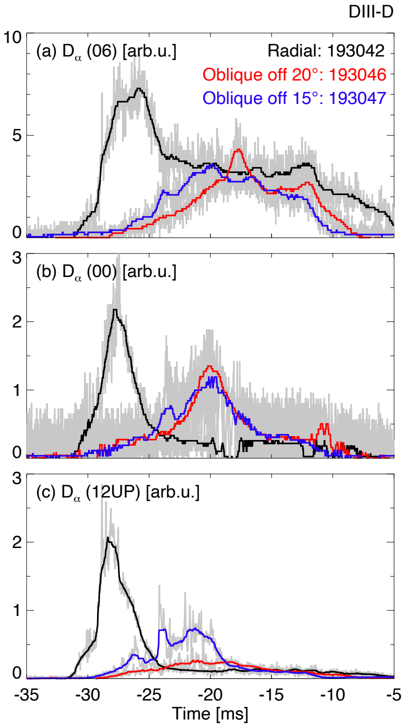


† $I_P < 1$ kA during the pre-plasma phase

[1] Colchin *et al*., Rev. Sci. Instrum. **74** 2068 (2003)
[2] Sinha *et al*, NF **62** 066013 (2022)

D_α brightness drops for pass 2 with 5° tilt of EC

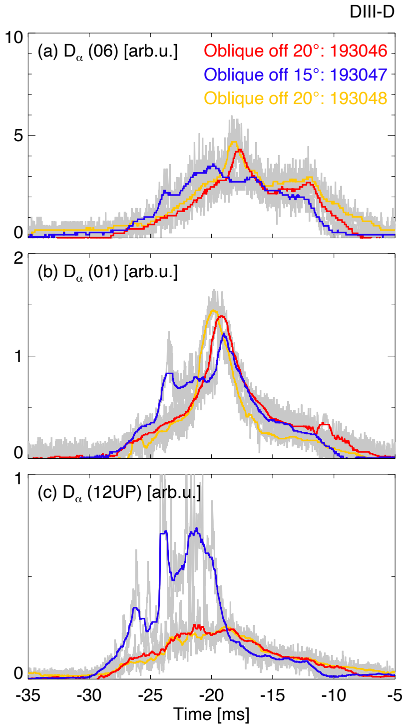
- **D_α signals from three line of sights are highlighted**
  - Signal baselines are removed
  - Signals are smoothed for clarity
- **Each line of sight sees different part of EC beam**
  - FS06 does not pass R_{X2}† (sees diffusion)
  - FS00 passes R_{X2} at $Z > 0$ (sees pass 1)
  - FS12UP passes R_{X2} at $Z < 0$ (sees pass 2)
- **Pass 2 D_α brightness drops as EC is tilted**
  - Emissivity: Radial > Oblique 15° off > Oblique 20° off



† Radius of second harmonic resonance for EC 110 GHz

Prefill gas is *not* causing pass 2 D_α brightness drop

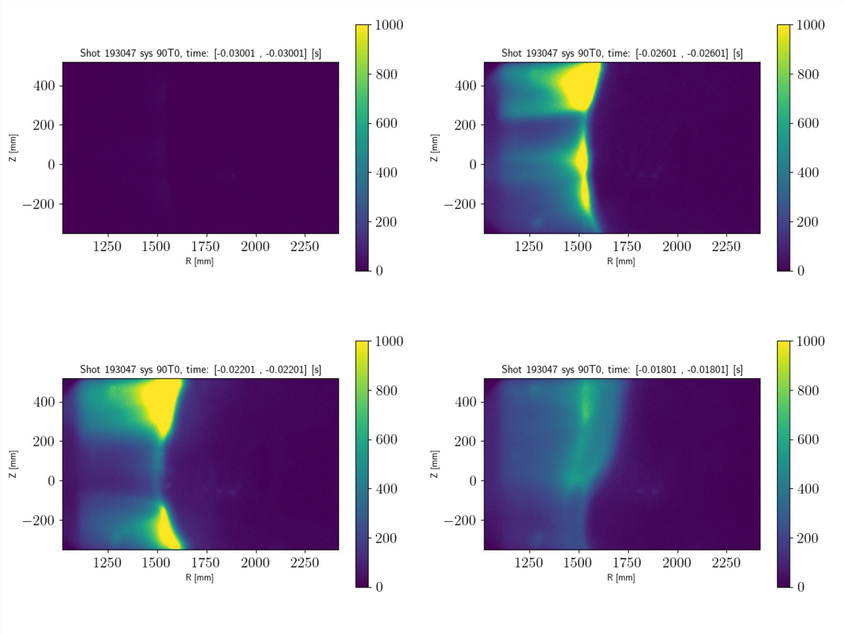
- **Several factors affect prefill gas pressure**
  - Wall condition can be different yet irrelevant
  - Gas valve flow rate and open time are controlled
- **More prefill gas is injected in repeat discharge**
  - Repeated oblique 20° case
  - Prefill gas pressure is higher by 30%
  - D_α signals remain the same, especially for pass 2
  - Note: Used FS01 for pass 1 D_α signal†



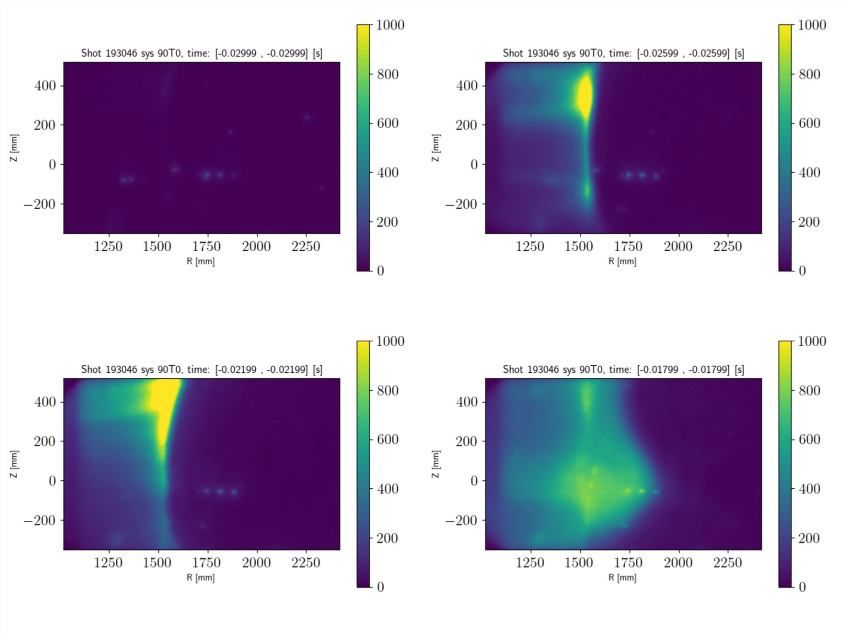
† LOS closer to pass 2, used due to unavailability of FS00 for 193048

Fast camera captures pass 2 D_{α} brightness drop

Shot 193047 (Oblique off 15°)



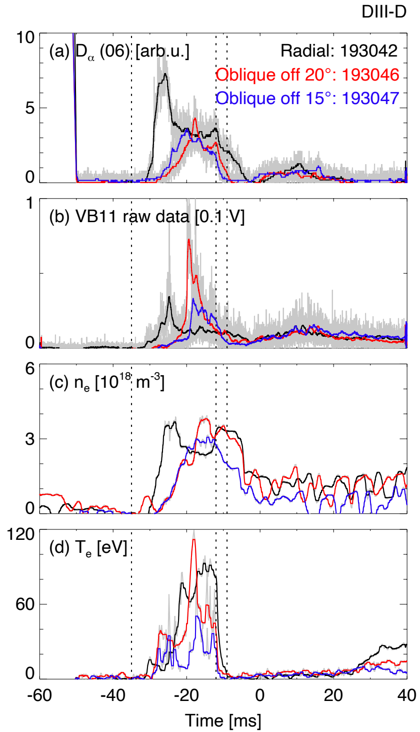
Shot 193046 (Oblique off 20°)



Same color scale using unfiltered visible light, seen at same time slices for both cases (-30, -26, -22, -18 ms)

As pass 2 D_α brightness drops, (n_e, T_e) become higher

- **Plasma is likely pure Deuterium (Z_{eff} = 1)**
  - Visible bremsstrahlung† [1] depends on (n_e, T_e) [2]
  - Off 20° oblique injection results in higher peak
  - Agrees with density and temperature
- **Some modeling is desired for the interpretation**
  - Visible bremsstrahlung signal is uncalibrated‡
  - Error bars are large for density and temperature
  - Off radial tilt means less heating, more current drive



† Taken at R = 1.52 m, near ECE25 and CO2 V1 location
‡ Planned back calibration in Summer 2023

[1] Colchin *et al*., Rev. Sci. Instrum. **74** 2068 (2003)
[2] Ramsey and Turner, Rev. Sci. Instrum. **58** 1211 (1987)

Acquired good data for ITER multi-pass EC modeling

- **Pre-plasma (n_e, T_e) can be measured with reasonable accuracy**
  - Good correlation is found between TS/ECE and TS/interferometer
- **Dependence of pre-plasma on EC injection angle is clearly observed**
  - Oblique injections with 5° difference result in different "pass 2" brightness
  - This provides attractive target data set for pre-plasma modeling
- **Future work**
  - Follow up experiment was performed on March 27: Finer angle scan
  - ECE modeling to improve signal to noise ratio
  - EC ray tracing for quantitative modeling of EC assisted startup

Discussion 1

Backup

- **Non-Maxwellian distribution of pre-plasma**
  - Can we improve ECE error bar?
    - Assume ne, Te
    - Calculate distribution
    - Calculate ne, Te
    - Iterate steps 2-3

Discussion 2

Backup

- **EC beam paths at DIII-D**
  - Can we use TORAY (Xi) or PETRA-M (Masa)?
  - Pass 1 absorbed power can depend on beam angle against B field
  - Pass 2 absorbed power is nonlinearly dependent on beam relative angle
    - Beam width and polarization changes
    - Both changes depend on beam angles, toroidal *and* poloidal

Processing of ECE, CO2, and TS data using IDL

Backup

- **ECE**
  - Take *tece25* using gadat2 [keV]
  - Take *terr* using get_ece [keV]

- **CO2**
  - Take *denv1f* using gadat2 [m/cm3] and divide† by 4.68 (path length)
  - Take max. med. smoothed (width = 4) abs. *denv1f* from -1000 to -100‡ ms

- **TS**
  - Take *tete_lh26* using gadat2 [eV] and *tsne_lh26* using gadat2 [m-3]
  - Take *temp_err* using get_ts [eV] and *dens_err* using get_ts [m-3]

† Assumed uniform ne along the path length, i.e., $n_{co2} = \int n_e dl \approx \langle n_e \rangle L$
‡ Taken instead of 0 ms because EC power was injected at times as early as -55 ms

Processing of Da, CIII and VB data using IDL

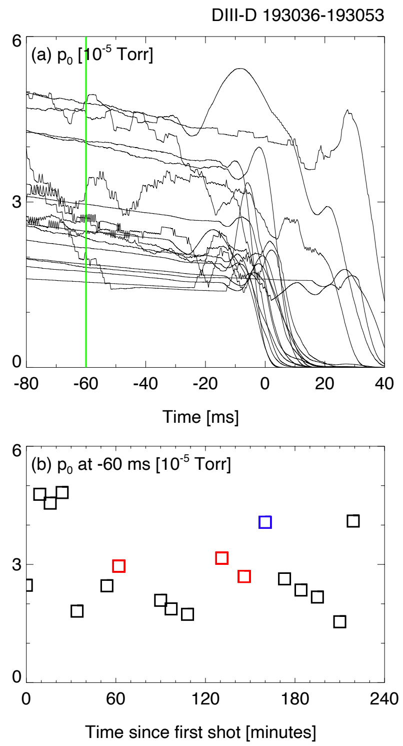
Backup

- **Da**
  - Take *fs06* using gadat2, resample every 0.01 ms
  - Take max. med. smoothed (width = 4) from -40.1 to -39.9 ms (baseline)
- **CIII**
  - Take *ciii_977* using gadat2, resample every 0.1 ms
- **VB**
  - Take *phdmidvb12* using gadat2 (*vb12* unavailable until Summer vent)

Prefill pressure may be changing within a day

Backup

- **Pressure range is at low end for measurement [1]**
  - Discharges with similar p_0 is taken for analysis (red)
  - Repeat discharge had higher p_0 (blue)
- **Comments from Morgan**
  - Discharges with oscillating p_0: 193046, 49, 52

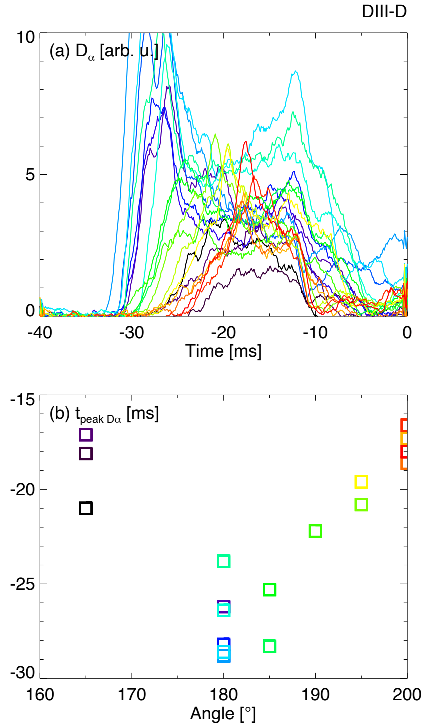


[1] Shafer *et al.*, Nuclear Mater. Energy **19** 487 (2019)

Ionization is delayed for oblique EC injection

Backup

- **Peaking of Da signal indicates breakdown [1]**
  - Commonly associated with 50% ionization
  - FS06 measures diffused pre-plasma
- **Oblique EC injection results in delayed Da peak**
  - Linear dependence is found
  - No directional dependence (co/ctr-I_P)
- **Future work**
  - Scatter of data: From prefill gas pressure?

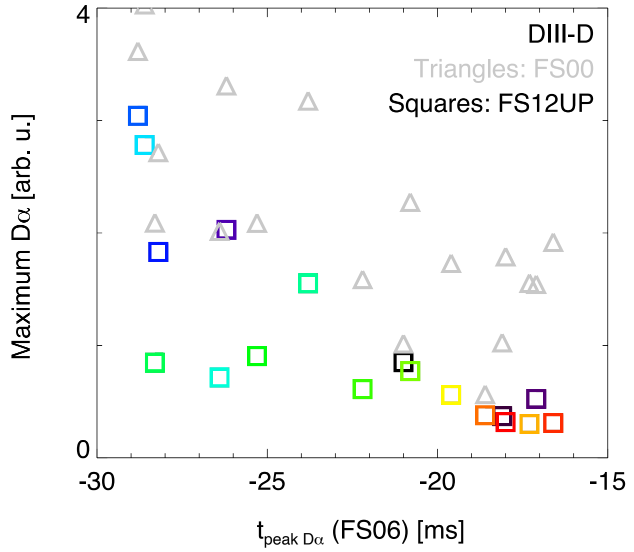


[1] Lloyd *et al.*, Nucl. Fusion **31** 2031 (1991)

Pass 2 is more relevant than Pass 1

Backup

- **Pass 1 & 2 brightness can be compared**
  - FS00 focuses on pass 1
  - FS12UP focuses on pass 2
  - Significant “noise” pickup is inevitable
- **Is Da peak time related more w/ Pass 2?**
  - Preliminary data suggests “maybe”
- **Future work**
  - What does fast camera with Da filter say?



It is still early to report these data

Backup