# Investigation of X-ray Crashes in a Transient Coaxial Helicity Injected Spherical Tokamak

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## 1. Introduction

General Fusion is developing Magnetized Target Fusion (MTF) for electric power generation through the compression of a spherical tokamak (ST) plasma [1]. Plasma Injector 3 (PI3) (shown in Figure 1) was General Fusion's largest testbed to study pre-compression ST targets [2] and produced its plasmas via transient coaxial helicity injection (CHI) using a plasma injector [3]. Magnetohydrodynamic (MHD) activity is observed in PI3 plasmas and is often associated with significant thermal energy losses. To reach fusion conditions in MTF, optimization of temperature, density, and thermal energy confinement is crucial before and during compression. Understanding the nature of these MHD events and mechanisms for their avoidance is essential for producing fusion-ready MTF plasma targets.

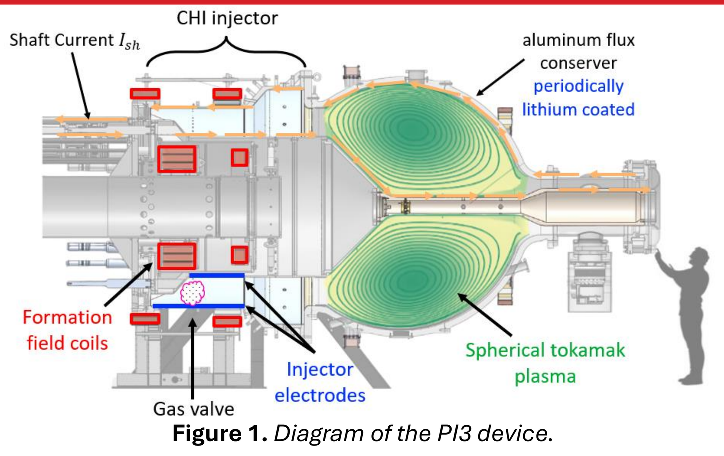


**Figure 1.** *Diagram of the PI3 device.*

**Table 1.** *Machine Parameters for the PI3 device.*

| Parameter | | Value range |
|---|---|---|
| Major radius | R | 0.6 – 0.7 m |
| Minor radius | a | 0.3 – 0.4 m |
| Poloidal flux | $\Psi_{CT}$ | 0.15 – 0.25 Wb |
| Plasma current | $I_{pl}$ | 0.3 – 0.5 MA |
| Shaft current | $I_{sh}$ | 0.8 – 1.2 MA |
| Plasma density | $n_e$ | $2\times10^{19}$ – $6\times10^{19}$ m$^{-3}$ |
| Temperature | $T_e \sim T_i$ | 100 – 500 eV |
| Thermal confinement time | $\tau_E$ | 5 – 15 ms [3] |

### Plasma formation in PI3

Plasma formation through transient CHI proceeds as follows (see Figure 3).

1. Formation coils in the plasma injector are fired to produce the injector flux ($\psi_{inj}$)
2. Deuterium is puffed in the plasma injector
3. Capacitor banks are discharged, and high voltage ($\sim$20 kV) is applied to the electrodes to ionize the gas, driving plasma current between the electrodes
4. When the resulting force $\vec{F} = \vec{J} \times \vec{B}$ exceeds the magnetic tension of the vacuum field, the plasma is accelerated out of the injector
5. The field lines stretch into the vacuum vessel until a reconnection process occurs, producing closed magnetic flux surfaces in the flux conserver

CHI typically produces plasmas with hollow current density profiles [4].

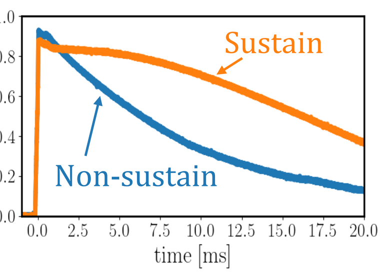


**Figure 2.** *Time-traces of the shaft current ($I_{sh}(t)$), responsible for the vacuum toroidal field in the flux conserver. The current can be sustained with an additional capacitor bank to prevent a fast drop of the q profile.*

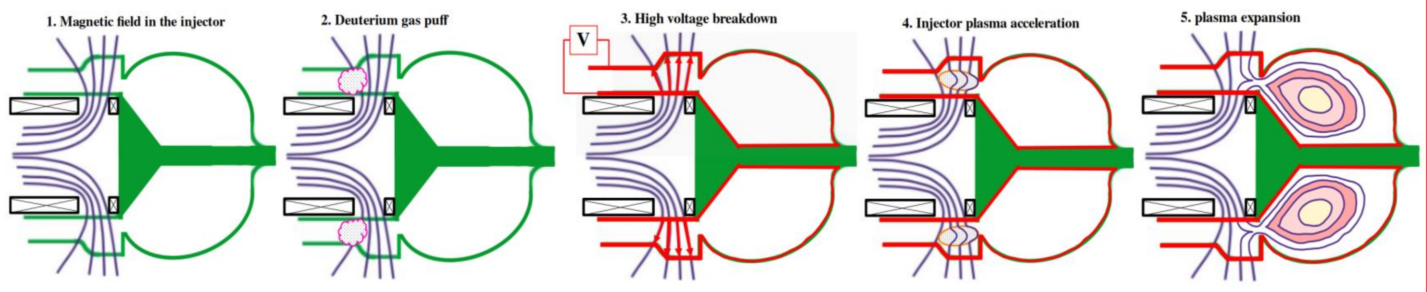


**Figure 3.** *Coaxial Helicity Injection in PI3. Adapted to PI3 from the SSPX figure in [5].*

## 2. Theory and Background

### DOUBLE TEARING MODES

- Requires a hollow $q$ profile in the plasma
- Two magnetic flux surfaces in the plasma have rational values of $q = {}^{m}/_{n}$
- Magnetic islands form in adjacent resonant magnetic flux surfaces with same value of $q$
- If modes are sufficiently close, as they grow, magnetic reconnection occurs inducing enhanced radial heating and particle transport, and rapid current penetration in the plasma
- DTMs are typically observed in tokamaks during the current ramp-up phase (or during high $\beta$ operation which can create a hollow $q$ profile). If current rise is faster than the resistive diffusion time, a skin current is formed, producing a hollow $q$ profile [6]
- Slowing down the current rise rate and increasing the plasma density (to reduce the electron temperature and hence the diffusion time) are typical strategies for avoiding DTMs [7]

$$\tau_R \sim \frac{\mu_0 a^2}{\eta}$$

Resistive diffusion time; Plasma minor radius; Plasma resistivity

$\tau_R \sim 100$ ms (For typical PI3 values of $a \sim 0.35$ m and $\eta \sim 3$ µΩm)

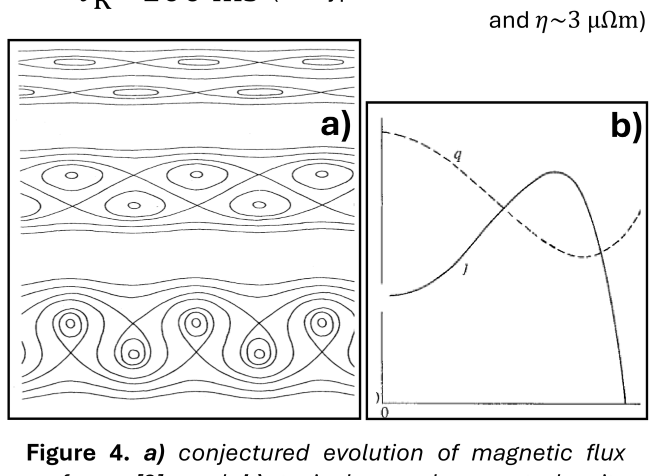


**Figure 4.** ***a)*** *conjectured evolution of magnetic flux surfaces [8], and* ***b)*** *typical q and current density profiles that lead to DTMs [6]*

### INTERNAL RECONNECTION EVENTS

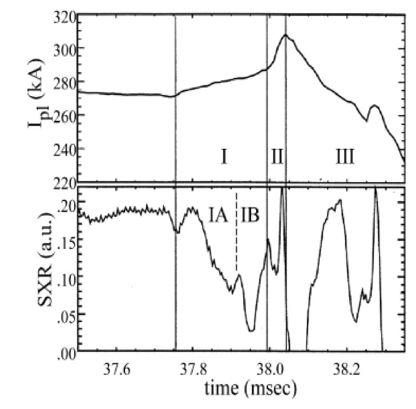


**Figure 5.** *Evolution of the plasma current (top) and SXR emitted by the plasma(bottom) during an IRE (figure adapted from [9]).*

- Typical of spherical tokamak (ST) plasmas
- IREs are a relaxation mechanism. Relaxation theory predicts that a plasma seeks a constrained minimum in magnetic energy and this process is associated with a broadening of the current profile
- Plasmas are resilient to IREs, and are not terminated by them
- IREs usually proceed in three stages [10] (see Figure 5):
  - I. Thermal quench
  - II. Current increase
  - III. Current quench
- Typical effects associated with IREs [10]:
  - I. Plasma distortion and increase in plasma elongation
  - II. Loss of plasma thermal energy
  - III. Current spike
  - IV. Generally accompanied by low m and n modes

## 3. Diagnostics and Methods

Figure 6 shows the diagnostics available on PI3. Alongside diagnostic measurements, other parameters (safety factor, current density profile, internal inductance, elongation, …) are estimated using Bayesian equilibrium reconstruction [2].

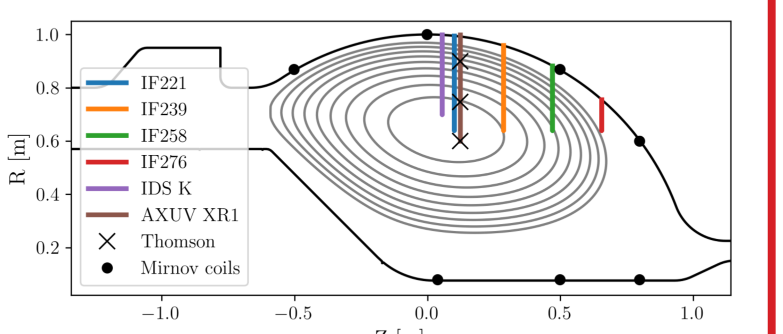


**Figure 6.** *IF are interferometer chords, IDS is Ion Doppler spectroscopy, and B-probes are Mirnov coils for $B_{pol}$ and $B_{tor}$. Only $T_e$ is measured with Thomson scattering.*

### X-ray crash detection

Sudden decreases in the soft X-ray emissions of the plasma, as measured by the central Absolute eXtreme Ultra-Violet (AXUV) chord pointing at the core of the plasma, will be referred to as "X-ray crashes". These events are simultaneously observed by several other systems and are thus associated with MHD activity.

A method has been developed to automatically detect X-ray crashes using filtered soft X-ray data alongside its first and second time derivative (shown in Figure 7 and Figure 8); this method allows for bulk analysis of X-ray crashes. When analyzing a transient CHI plasma, crash phase ($ph_{cr}(t)$) is a very useful parameter. Phase is defined as $ph_{cr,i}(t_i) = i$ for the $i^{th}$ X-ray crash (where for a shot with $n$ crashes, $\{ph | 0 \leq ph \leq n, ph \in \mathbb{R}\}$). The integer values of phase are shown in Figure 8.

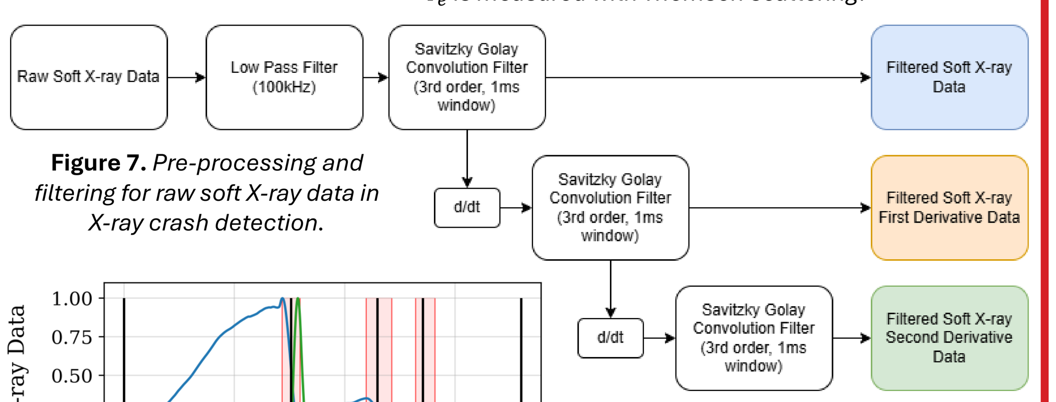


**Figure 7.** *Pre-processing and filtering for raw soft X-ray data in X-ray crash detection.*

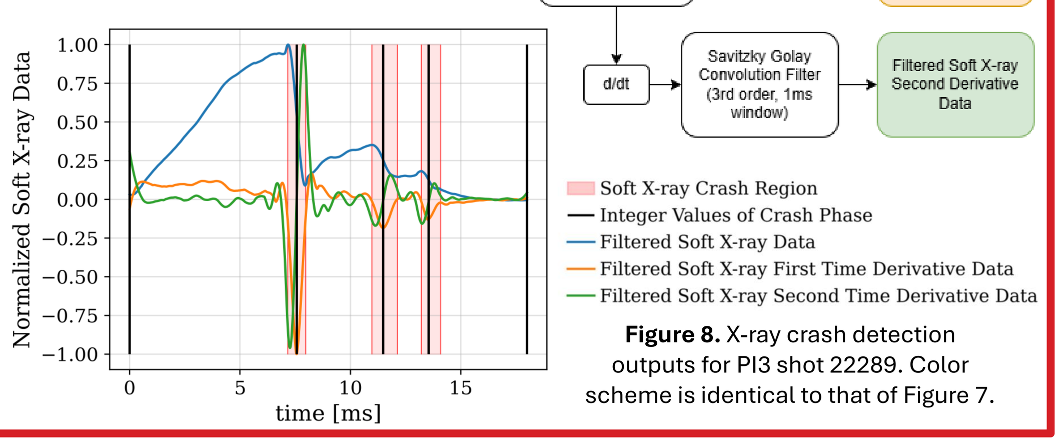


**Figure 8.** X-ray crash detection outputs for PI3 shot 22289. Color scheme is identical to that of Figure 7.

**References**

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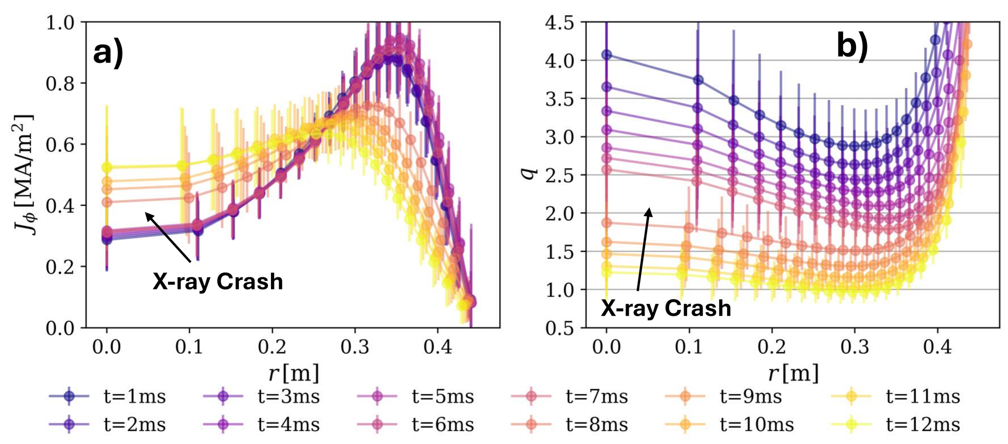
## 4. Results and Discussion

### Double Tearing Modes (DTMs) in PI3 Plasmas

DTM-like events are observed in PI3 non-sustained shots (see the blue curve in Figure 2). The hollow toroidal current density ($J_\phi(r)$) profile and reversed shear in the safety factor ($q(r)$) caused by CHI can be seen in Figures 9.a and 9.b. Crashes in the soft X-ray emissions of the plasma are linked to the time evolution of these profiles and cause large decreases in thermal energy (see Figure 9.c, where density drops by ~50% and core temperature drops by ~20%).

Typical $J_\phi(r)$ and q($r$) profiles associated with DTMs are shown in Figures 9.a and 9.b. The initially hollow $J_\phi(r)$ profile resulting from CHI is made more hollow by the decay in $I_{sh}$ that occurs in non-sustain shots (see Figure 2). As $I_{sh}$ decays, $B_\phi$ decays with it, causing a reduction in $q$ which eventually leads to a double crossing of some rational $q$ surface (seen at $q = 2$ in Figure 9.b for $t =$ 7ms), and a current penetration event that reduces the plasma thermal energy (seen in Figure 9.c).



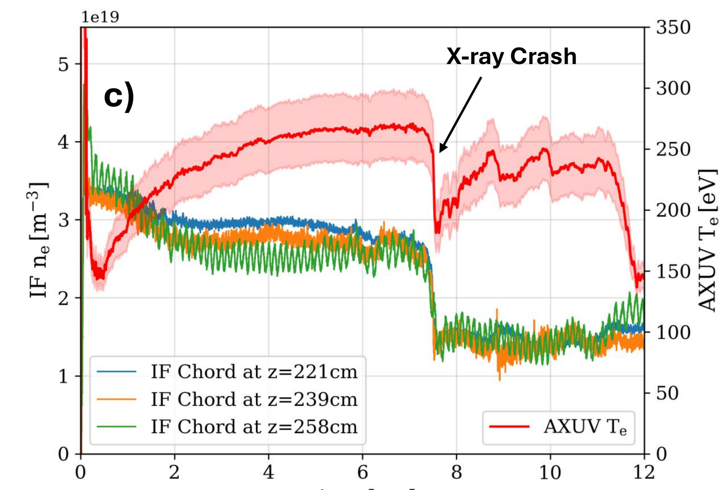




**Figure 9.** ***a)*** *$J_\phi(r)$ profiles,* ***b)*** *$q(r)$ profiles, and* ***c)*** *number density and electron temperature over time. These outputs show an example of a plasma with a hollow $J_\phi(r)$ profile and low injector flux $\psi_{inj}$ (PI3 shot 22289).*

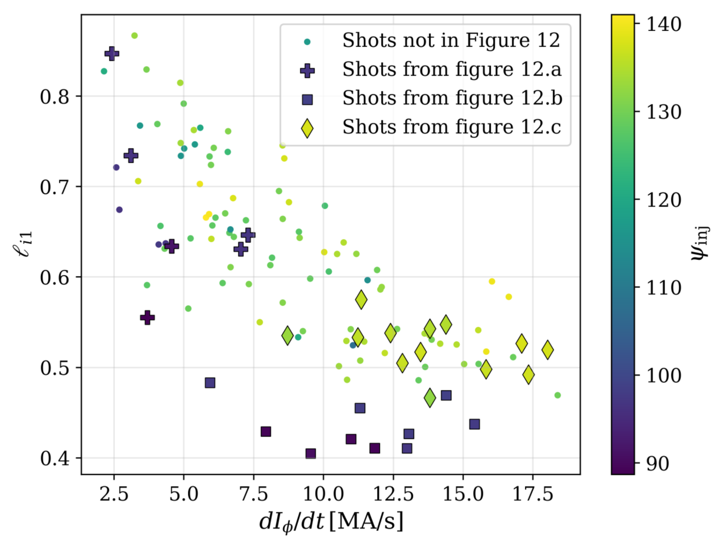



**Figure 10.** *$\ell_{i1}$ at the maximum of $I_{pl}(t)$ over the average current ramp between $t_{formation}$ and $t_{Ipl,max}$.*

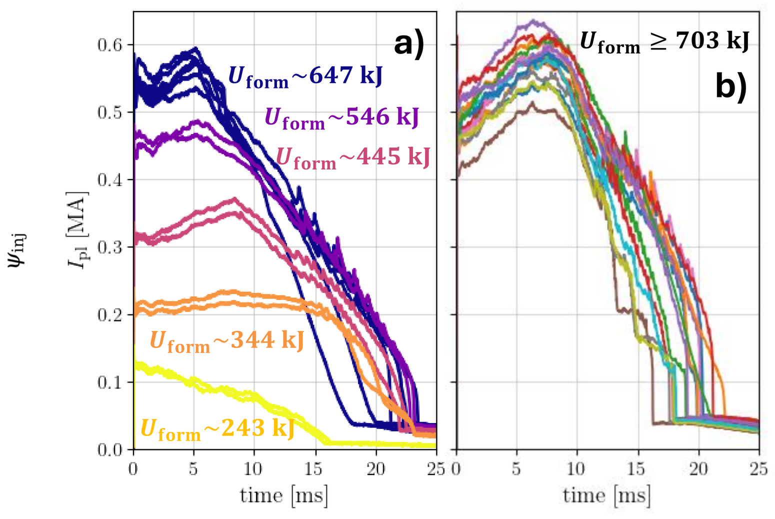



**Figure 11.** *$I_{pl}(t)$ for* ***a)*** *shots with $\psi_{inj}$~97 mWb and a variety of different formation capacitor bank energies, and* ***b)*** *shots with $\psi_{inj}$~135 mWb.*

The greater the rate of current rise, the lower the internal inductance ($\ell_{i1}$) is at the time of maximum plasma current (shown in Figure 10). This is due to skin current formation; once the rate of current rise exceeds the capacity of the plasma to diffuse current, then current is only driven in the edge, which lowers $\ell_{i1}$. The two factors that impact current ramp up rate are $\psi_{inj}$ and the amount of energy in the formation capacitor banks ($U_{form}$). If $\psi_{inj}$ is too low at formation, the plasma forms with no room for the decrease in $\ell_{i1}$ that accompanies an increase in plasma current, and if $U_{form}$ is too low, then there is not sufficient energy to drive more current into the system after formation. These effects are shown in Figure 11 where the effect of $\psi_{inj}$ can be seen by comparing Figures 11.a and 11.b, and the effect of $U_{form}$ can be seen by comparing the different groups of traces Figure 11.a.

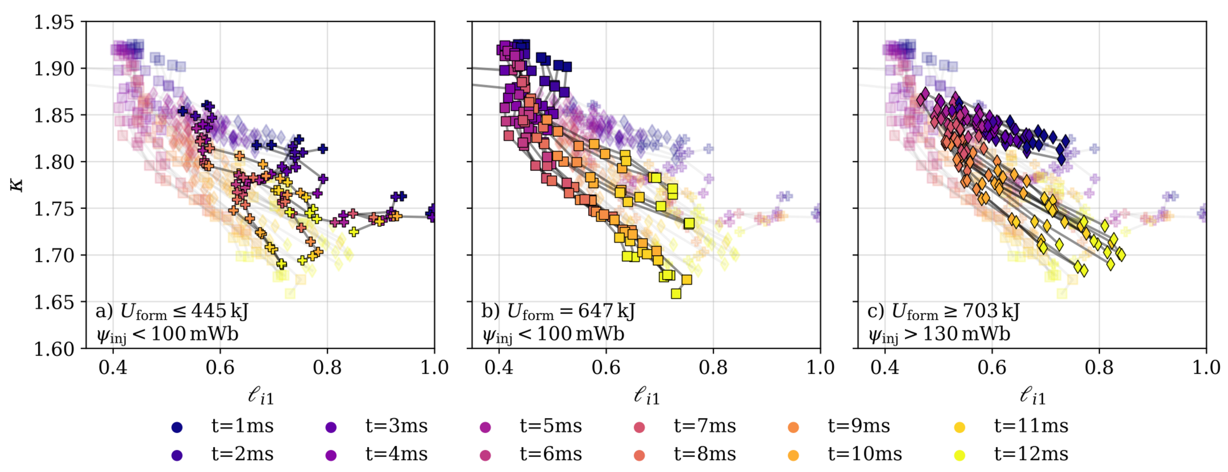



**Figure 12.** *Evolution of plasmas in the κ-$\ell_{i1}$ space over time. The shapes of markers in this plot correspond to the same marker shapes in Figure 10, showing the three cases of non-sustain shots.*

Using $\ell_{i1}$ and elongation ($\kappa$) to describe the plasma, the differences in evolution for varied plasma injector settings can be observed (shown in Figure 12). In shots with higher $\psi_{inj}$, the plasma forms with a higher $\ell_{i1}$; and in shots with a lower $\psi_{inj}$, plasmas form with a higher $\kappa$, filling the entirety of the internal volume of the flux conserver. This formation character relating to the value of $\psi_{inj}$ means shots with higher injector flux during the CHI process must slowly evolve to a hollower $J_\phi(r)$ profile before a DTM is required to facilitate anomalous current redistribution, delaying the X-ray crash. This current evolution can be seen in Figure 11, where the ramp up of $I_{pl}$ primarily drives current in the edge. This current driven in the edge decreases $\ell_{i1}$ and forms a strong skin current alongside a high $\nabla J_\phi$ (shown in Figure 9.a), which necessitates anomalous current penetration (shown in Figure 9 for 7ms $\leq t \leq$ 8ms), causing a DTM.

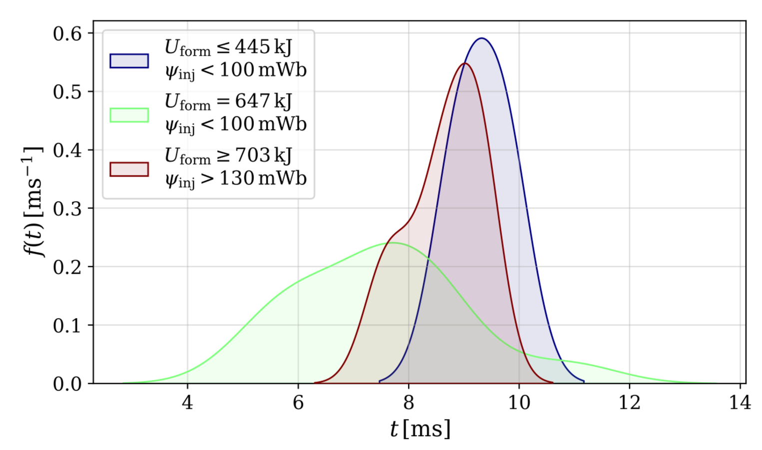



**Figure 13.** *Probability density functions $f(t)$ of the timing of the first X-ray crash for different plasma injector settings matching those from the groups in Figure 12.*

In Figure 13, probability density functions of the first crash timings of expanded versions of shot groups with the same settings as those in Figure 12 are shown. This bulk analysis confirms that double tearing modes typically take longer to develop for shots with higher $\psi_{inj}$ and provides a possible mechanism for delaying DTMs until after peak MTF compression in non-sustained shots. This effect also changes which modes are most likely triggering the DTM (seen in Table 2).

**Table 2.** Tabulation of which $q$ surfaces likely caused the DTMs for shots from Figures 12.b and 12.c.

| Input Settings | q=3/2 | q=2 | q>2 |
|---|---|---|---|
| $\psi_{inj} < 100$ mWb, $U_{form} = 647$ kJ | 0% ($^{0}/_{12}$) | 75% ($^{9}/_{12}$) | 25% ($^{3}/_{12}$) |
| $\psi_{inj} > 130$ mWb, $U_{form} \geq 703$ kJ | 92% ($^{12}/_{13}$) | 8% ($^{1}/_{13}$) | 0% ($^{0}/_{13}$) |

### Internal Reconnection Event (IRE)-like Activity in PI3 Plasmas

IRE-like activity is most common in PI3 sustained shots. In these cases, current drive in the plasma due to the decay of the vacuum toroidal field (shaft current) generally plays a minor role. The evolution of the system is dominated by plasma relaxation; during this process, X-ray crashes can occur which suggests plasma re-organization through relaxation phenomena such as IREs. Immediately after the crash, a spike in the plasma current is visible, as shown in Figure 14.a for shot 22605, and in Figure 15 for shots 21111 and 21174. The event induces a simultaneous reduction in the soft X-ray and TS $T_e$ measurements as well as in the reconstructed particle inventory ($N_p$) (see Figure 14.b). In particular, the drop in the core TS points implies flattening of the $T_e$ profile within the range 5ms $< t \leq$ 7ms.

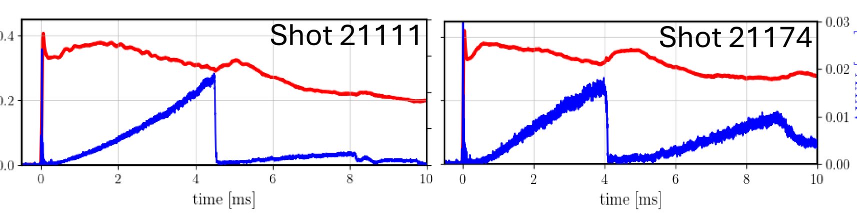



**Figure 15**. *X-ray crash and consecutive spike in the plasma current.*

The evolution of the plasma elongation ($\kappa$) and internal inductance ($\ell_{i1}$) for shot 22605 is shown in Figure 14.d for 0ms $\leq t \leq$ 10ms of the plasma's magnetic lifetime. Figure 14.d clearly shows that the event at $t$~6ms produces a slight growth in $\kappa$ and a sharp drop in $\ell_{i1}$. A flattening of the plasma current profile at the same time is also indicated by the sudden increase in $q_0$ and $q_{min}$ (see Figure 14.e). Interestingly, the core safety factor is locked around $q_0$~ $^{3}/_{2}$ from $t$~5ms until the time of the MHD event at $t$~6ms. This condition suggests that an $m = 3$, $n = 2$ mode may be formed in proximity of the plasma core and may contribute to the instability. Expanding the set of available core diagnostics in future machines will allow for more detailed conclusions to be reached.

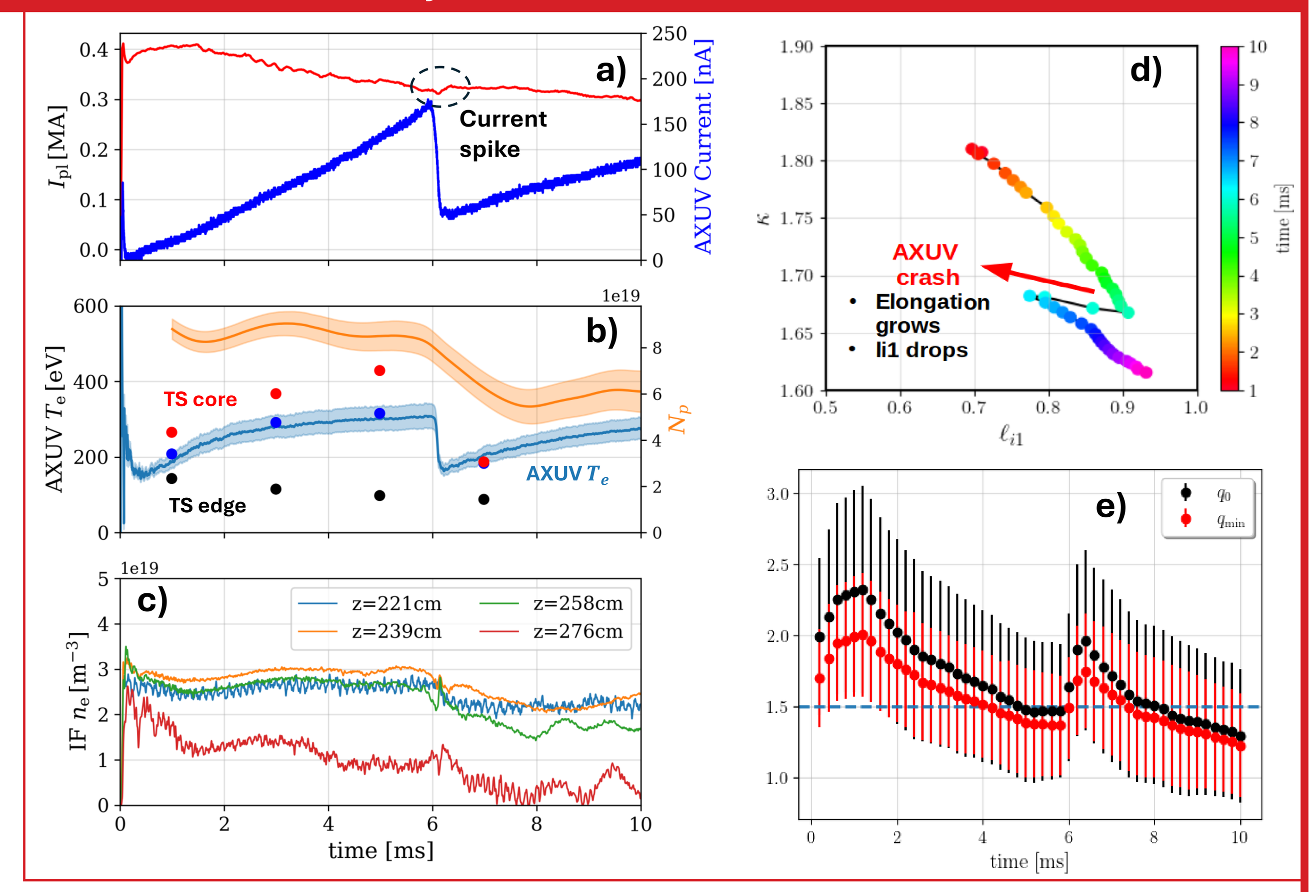



**Figure 14.** *Typical IRE-like activity in PI3 (from sustained shot 22605).*

The kink in the trajectory of shot 22605 in $\kappa$-$\ell_{i1}$ space shown in Figure 14.d at the time of the X-ray crash is shown to be a common trend during X-ray crashes by the analysis of 55 sustained shots, plotted in Figure 16. The major MHD event in these shots (normalized to occur at $ph_{cr} = 1$) is often accompanied by a distortion in the plasma geometry and a flattening of the current profile.

In general, despite the rapid and bursty nature of the process, the plasma partially recovers until another event occurs.

Even though we are still working on defining the set of precise conditions responsible for IRE-like events, the time of the first event is substantially delayed by coating the aluminum vessel of the machine with lithium (see Figure 17).

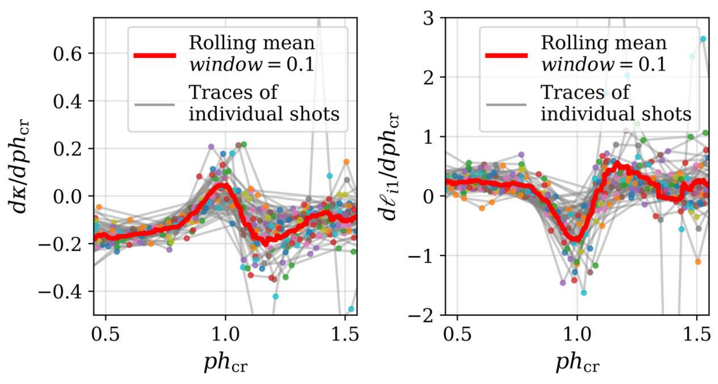
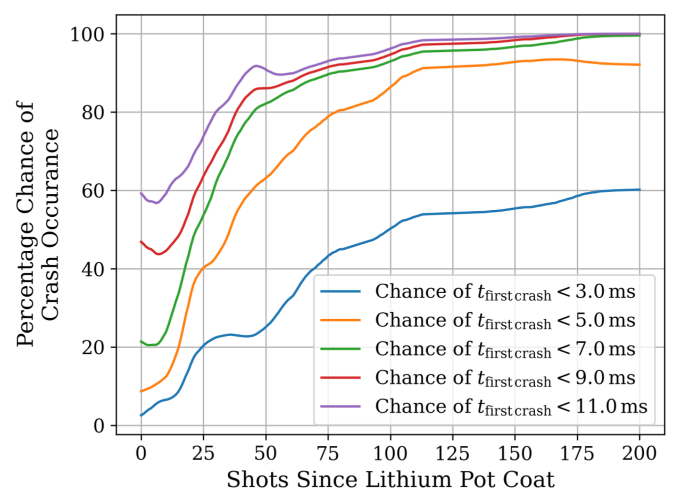



**Figure 16.** *Derivatives of κ and $\ell_{i1}$ over phase for 55 sustained shots in PI3.*

**Figure 17.** *Probability of X-ray crash for sustained PI3 shots as a function of the number of shots since lithium coating.*




## 5. Conclusions

1. The first X-ray crash in a PI3 shot is indicative of a MHD event that induces thermal energy losses
   - The success of MTF relies on high thermal confinement and good MHD stability of the MTF plasma target [11], meaning these crashes must be avoided
2. DTMs are present in non-sustain shots due to double crossings of $q = {}^{m}/_{n}$ rational surfaces driven by the decay of $I_{sh}$
3. IRE-like activity is present primarily in sustained shots and happens progressively earlier as the machine's lithium coat degrades
4. Mechanisms for preventing or delaying the first X-ray crashes in PI3 have been explored
   - Increasing plasma injector flux in a CHI fueled ST can delay a DTM since the initial $J_\phi(r)$ profile must become hollower ($\ell_{i1}$ must decrease) before it is energetically viable, and changes what surface triggers the DTM
   - Lithium coating the machine (both in the pot and plasma injector) delays the onset of IREs, suggesting that IREs may be driven by edge resistivity in PI3 even though the thermal energy lost in IREs typically occurs in the core of the plasma (similar to [10])
5. The following concepts for X-ray crash avoidance and IRE investigation should be explored
   - Double tearing modes can likely be avoided in their entirety by changing the character of the ramp up of $I_{pl}$ so no skin current is formed
   - The driving mechanism of IREs is still undetermined, but experiments with high spatial resolution edge temperature measurements could provide insight
   - The link between condition of the wall lithium coat and IREs should be explored further as it could help to explain the physical mechanism of IREs in STs