Runaway Electron Studies and Plasma Restart from a RE Beam on TCV

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Presentation Overview

- **Overview of current TCV internal RE research program**
  - TCV capabilities
  - Baseline scenario for RE generation
  - Scan of injection gas species
    - Natural current decay rates
- **Explore heating of background plasma (“plasma restart”)**
  - Promote Ohmic current carrying channel
  - Secondary D_2 injection
    - Heat background plasma
  - Restart from clean RE beam (primary D_2 injection)
- Preliminary modelling

RE Beam Studies on TCV

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  - Range of shaping
    - Neg. triangularity, elongations up to 1.5
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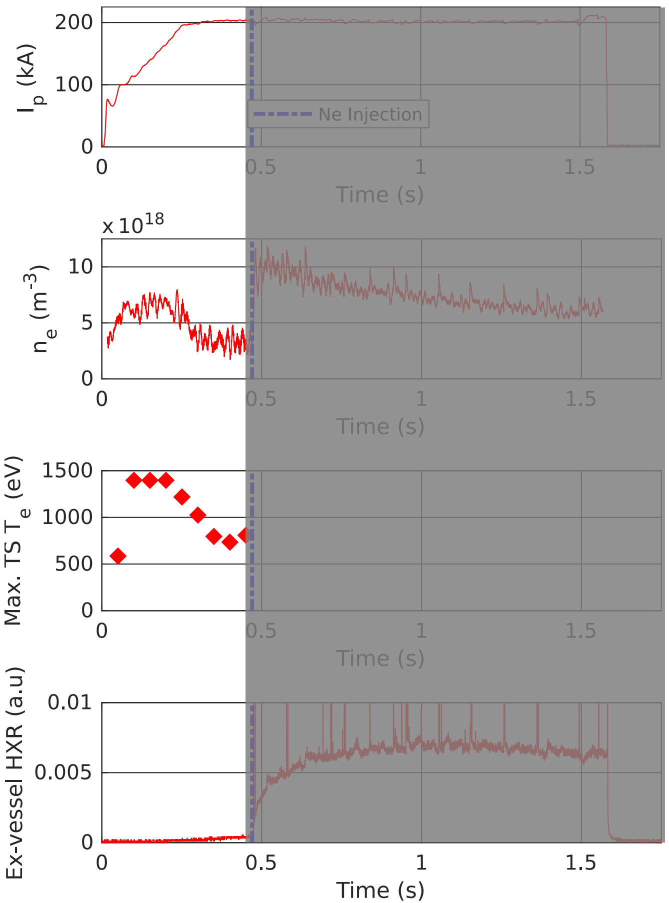
  - High pre-disruption electric field
    - ~20-40x classic critical electric field
    - Generate RE seed population
    - Disruptions induced by MGI



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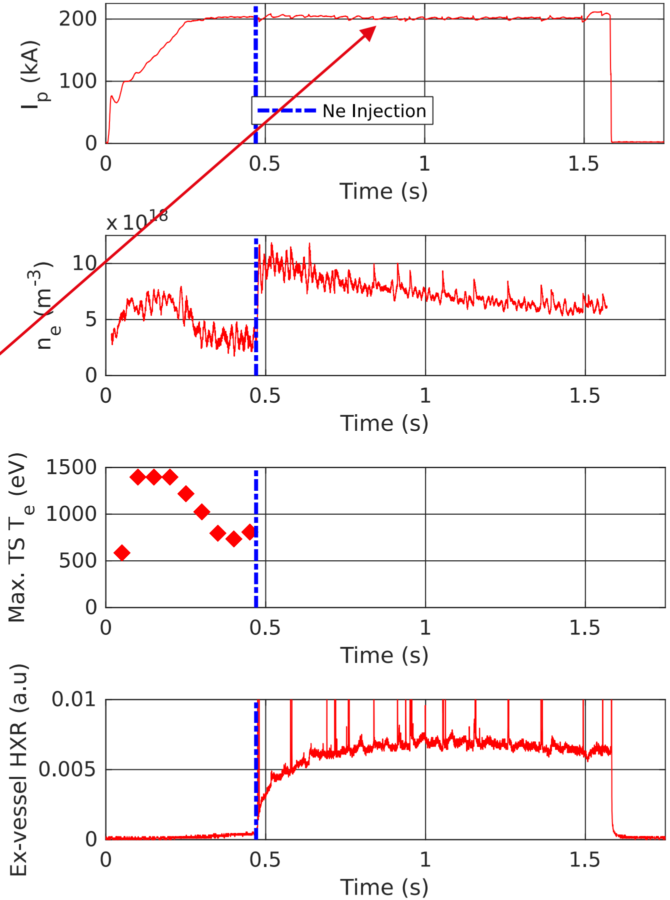
    - Generate RE seed population
    - Disruptions induced by MGI
- Consistently generate 200kA RE beams with over 1s of steady beam duration
- Tokamak magnetic configuration maintained by I_p



RE Beam Studies on TCV

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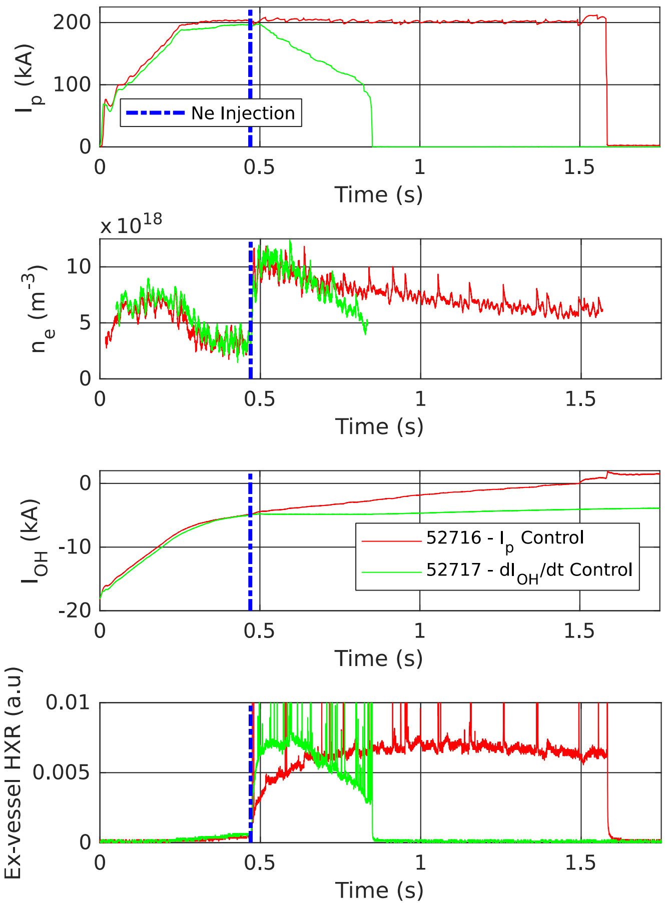
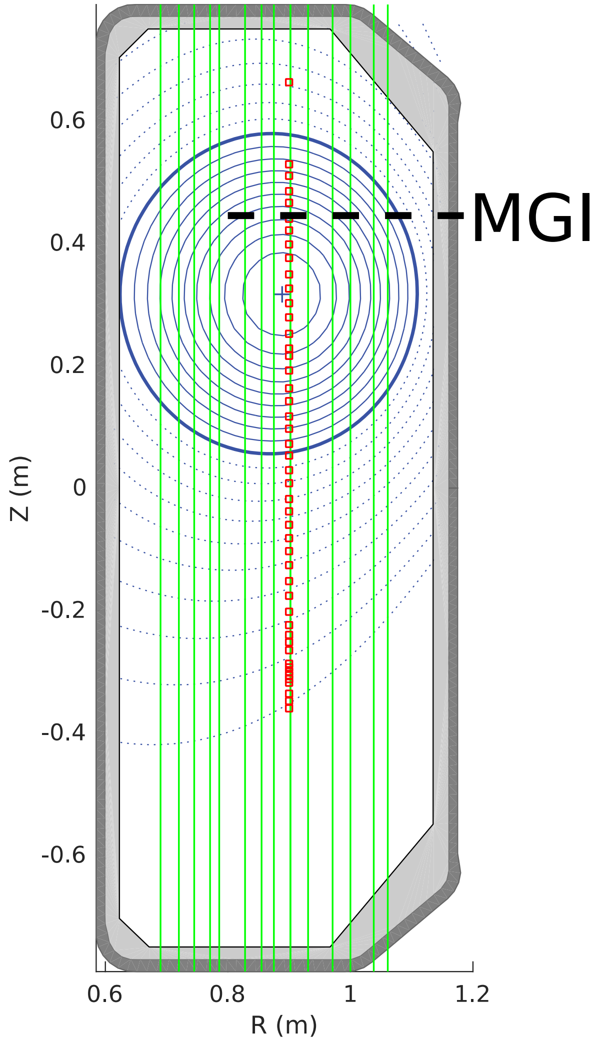
- Mature control system
  - RE beam in control down to 10kA
  - Position control of RE beam
    - z-movement of beam (Hoppe 2020)
  - Fixed I_p or dI_{OH}/dt
    - RT triggers to switch
- Versatile MGI system
  - 5 fast opening/closing valves
    - Multiple injections
    - Variations in species and quantity
    - Same location
  - D_2, He, Ne, Ar, Kr or Xe possible



RE Beam Studies on TCV

Diagnostics for this presentation

- Thomson scattering system (red squares)
  - 3 lasers that can operate in "burst"
  - Temperatures down to 6eV
- FIR interferometry (14 vertical chords) (green lines)
- Ex-vessel hard X-ray measurements
  - Min. photon energy: 150keV
- Filtered soft X-ray diodes for core T_e (xT_e)
  - 0.1ms temporal resolution

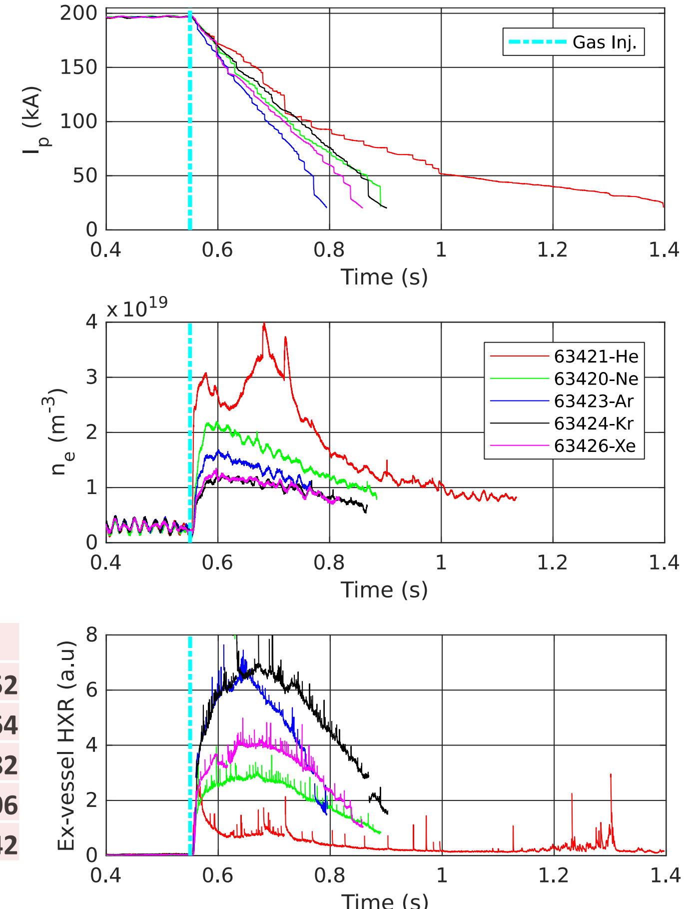


Scan of Injection Gas Species

Natural Decay Rates

Variation of Gas Species

- I_{OH} set constant at disruption
  - No external energy introduced to system
  - Measure natural current decay rate (τ_{CD})
- Dataset includes He, Ne, Ar, Kr, Xe
  - Fewer injected particles for higher Z



Injection Gas	Particles	mbar L	τ_{CD} (80-20%) (s)	τ_{CD} (190-100kA) (s)
He (2)	5.70E+19	2.35E+00	0.927	0.452
Ne (10)	5.63E+18	2.33E-01	0.459	0.364
Ar (18)	4.81E+18	1.99E-01	0.281	0.282
Kr (36)	2.10E+18	8.67E-02	0.413	0.406
Xe (54)	1.83E+18	7.57E-02	0.398	0.342

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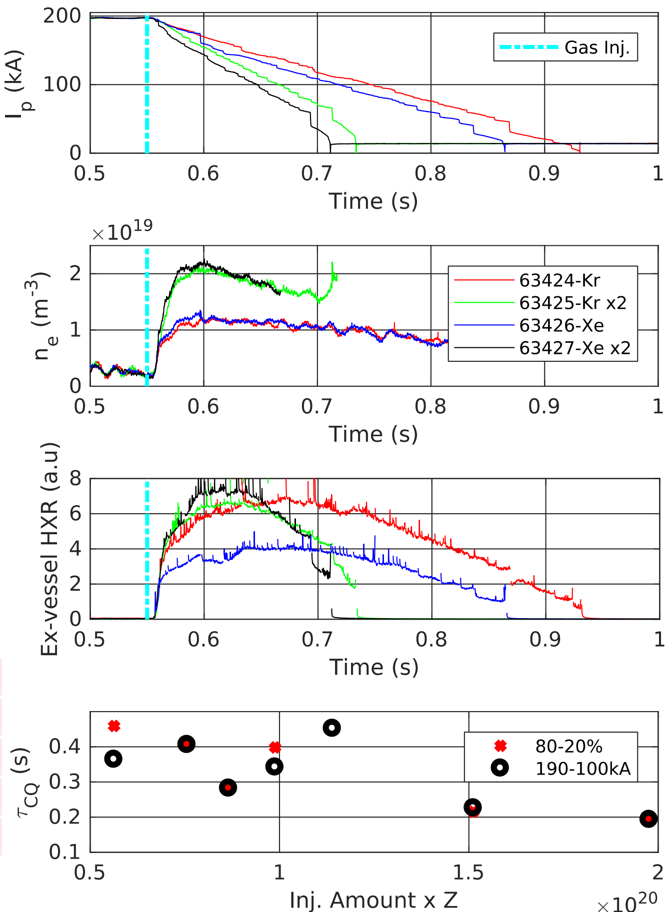
Variation of Injection Amount

- τ_{CD} and n_e proportional to amount injected
  - HXR photons doubled for doubled Xe
- Strong correlation of τ_{CD} with injection amount and Z
- Modelling on-going



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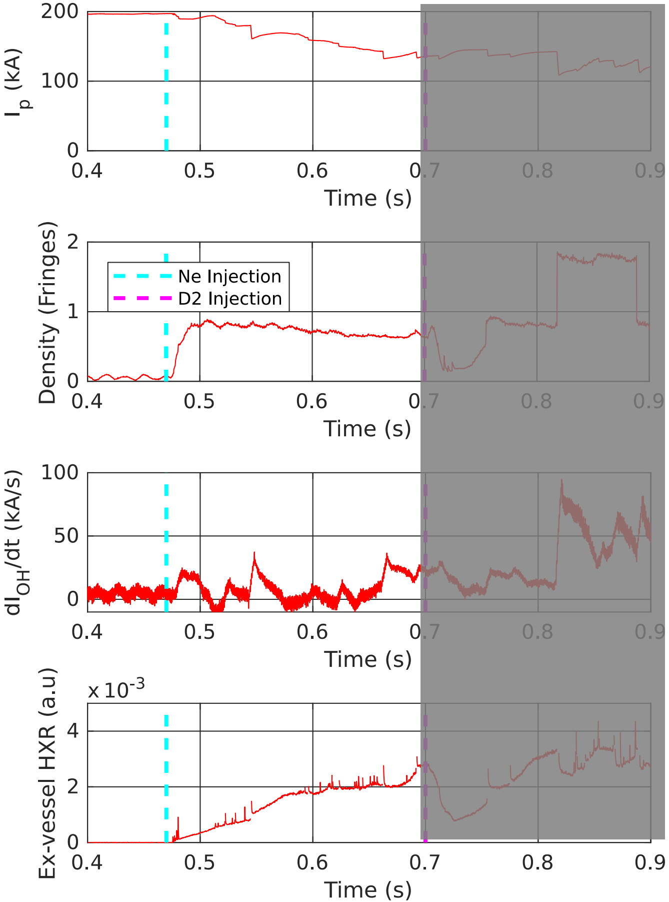
Kr (36)	2.10E+18	8.67E-02	0.413	0.406
Kr (36) x2	4.20E+18	1.73E-01	0.215	0.226
Xe (54)	1.83E+18	7.57E-02	0.398	0.342
Xe (54) x2	3.66E+18	1.51E-01	0.190	0.193

Secondary D_2 Injection

Neon Flushed With Second D_2 Injection

- Stable RE beam already created (Ne)
  - I_p @150kA for stability
  - Bulk of current carried by REs



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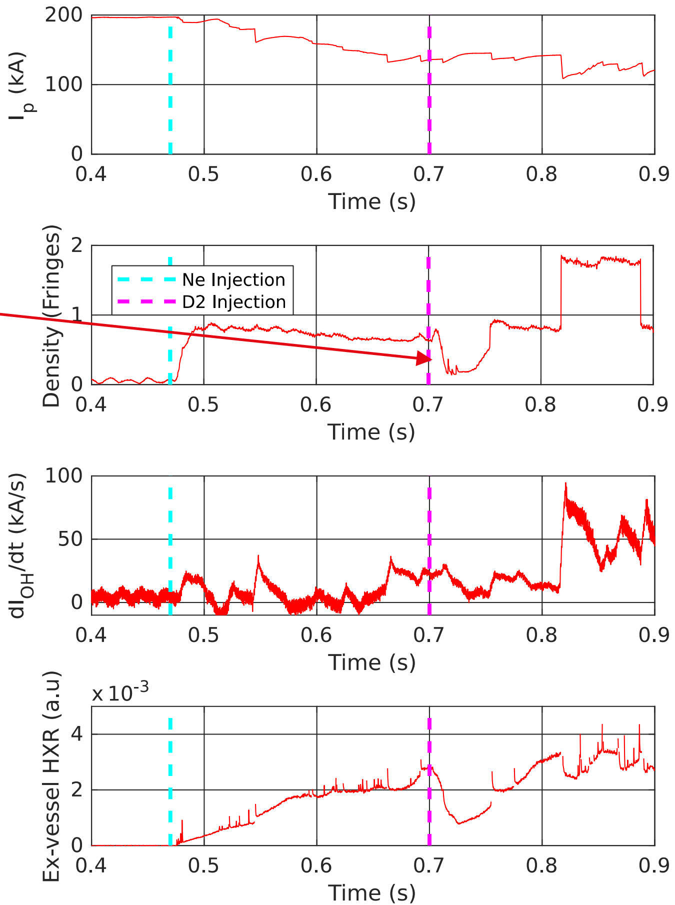
- D_2 injection (~20x Neon injection pcls)
  - Background plasma disappears
  - Remaining T_e < 1eV



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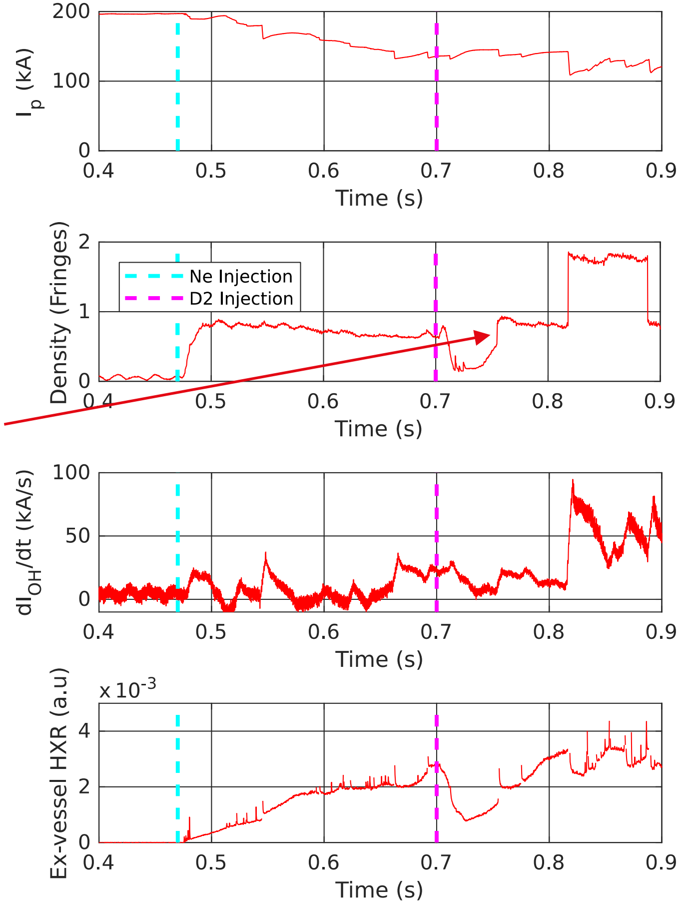
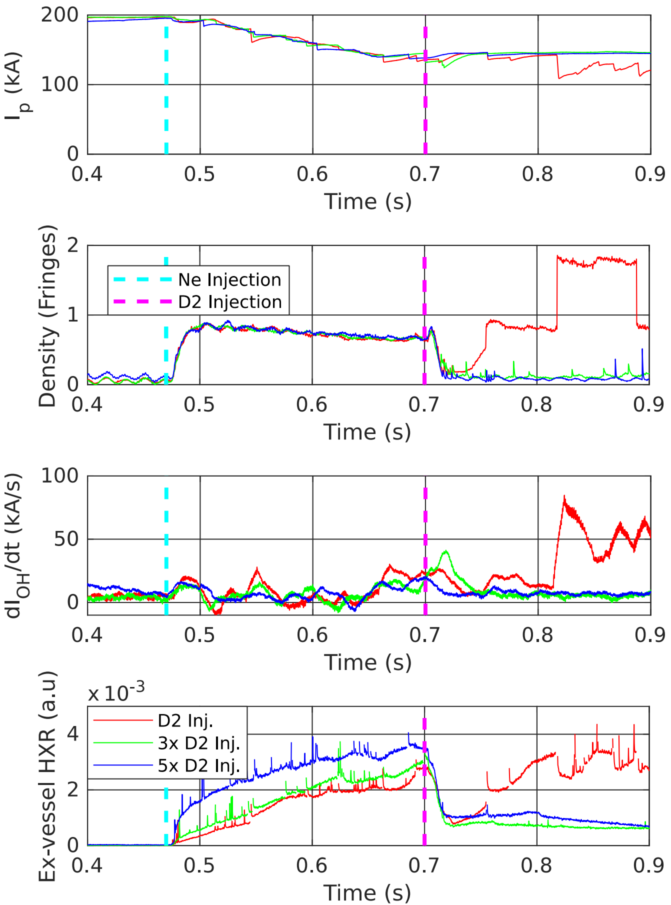
- D_2 injection (~20x Neon injection pcls)
  - Background plasma disappears
  - Remaining T_e < 1eV
- Background plasma reheats after 50ms
  - Pre-D_2 injection regime achieved
  - High generation of REs expected
    - Increase in dI_{OH}/dt
    - Sharp "drops" in I_p
  - High RE losses inferred from HXR
- Bulk of current still carried by REs



Increased D_2 Injection Maintains Low Density

- Sufficient D_2 injection prevents ionisation
- Background plasma disappears
  - T_e below 1eV maintained
- dI_{OH}/dt remains low
  - Low E_Φ maintained
  - **RE formation reduced**
- HXR reduced and maintained
- Bulk of current still carried by REs
  - Low T_e and n_e in background plasma

Injection Gas	Particles	mbar L
Neon	5.63E+18	0.23
D2 (Red)	9.90E+19	4.11
D2 (Green)	2.97E+20	12.33
D2 (Blue)	4.95E+20	20.55



Background Plasma Heated With NBH

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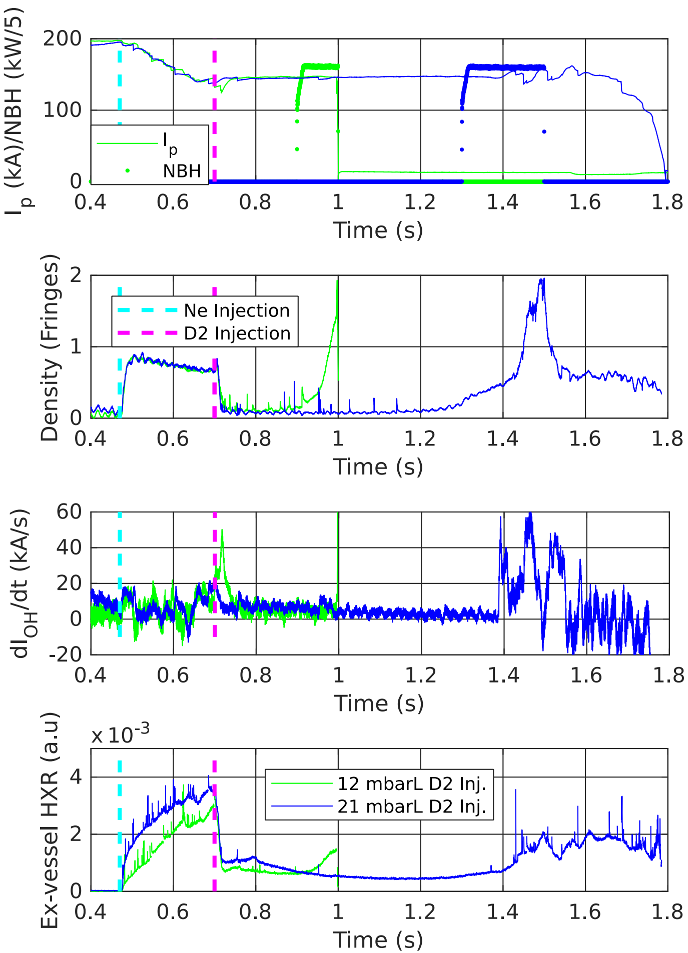
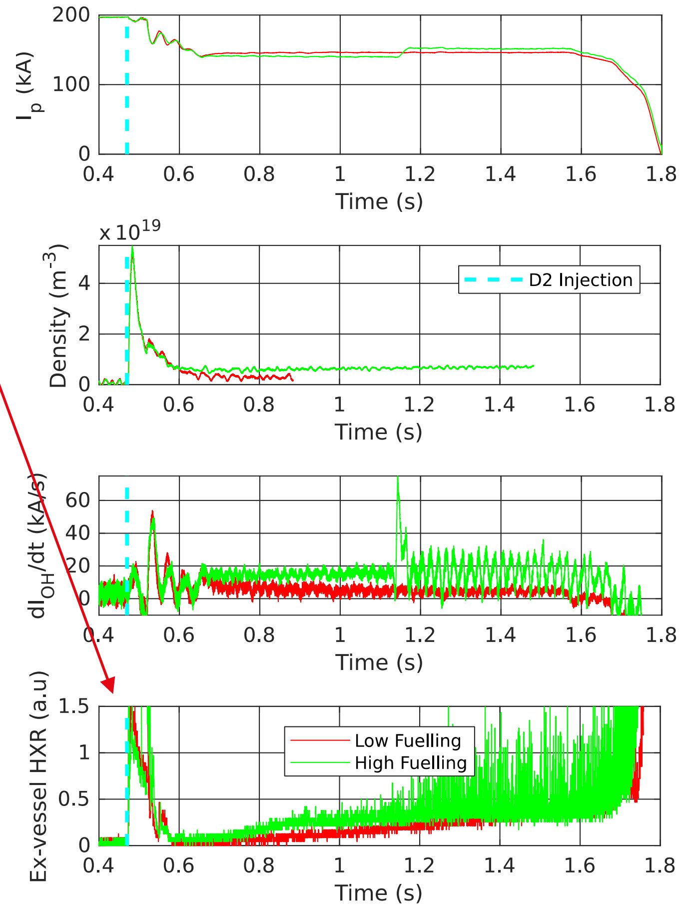
- 800kW injected into cold, low n_e plasmas
  - Poor absorption expected
- Goal: Heat/ionise a background plasma
  - Promote as current carrying channel
- n_e and T_e increase
  - Some power coupled
- Loss of REs, drop in I_p
  - High dI_{OH}/dt heats background plasma
- Radiation losses quickly cool plasma after beam
  - Similar n_e, dI_{OH}/dt and HXR to pre-D_2 injection levels
  - Bulk of current still carried by REs
- Similar results with Ar and He flushing



Primary D_2 Injection

Primary D_2 Injection Creates RE Beam and Restart

- D_2 injection => disruption @0.47s
  - Low temperature background plasma
  - HXR emission signalling RE ejection



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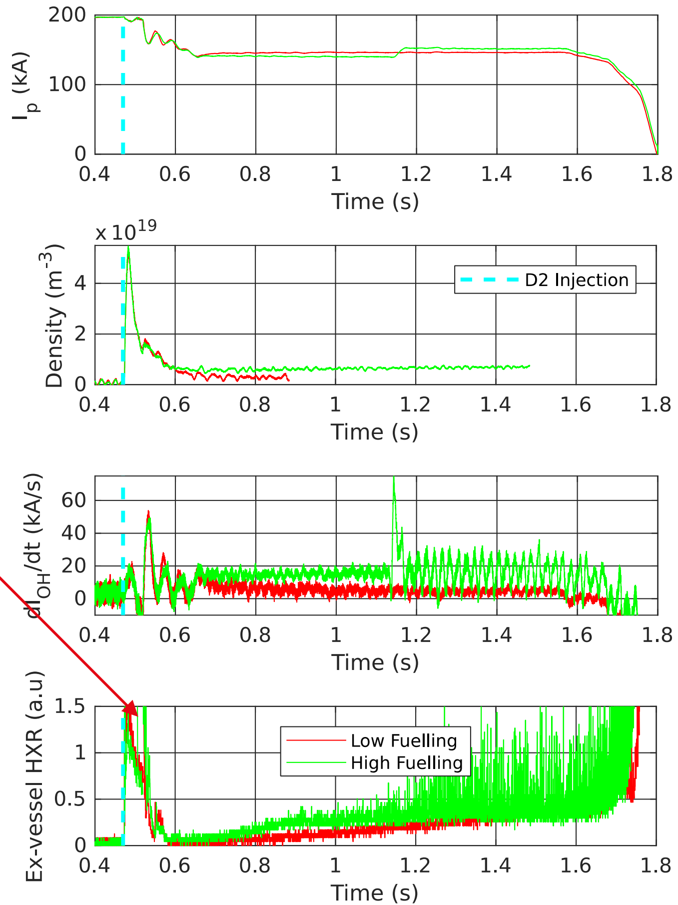
- Large HXR event at 0.52s
  - Expulsion of RE
  - Background plasma heated
- Low HXR and n_e ~0.5e19 maintained
  - V_{loop} remains below 1



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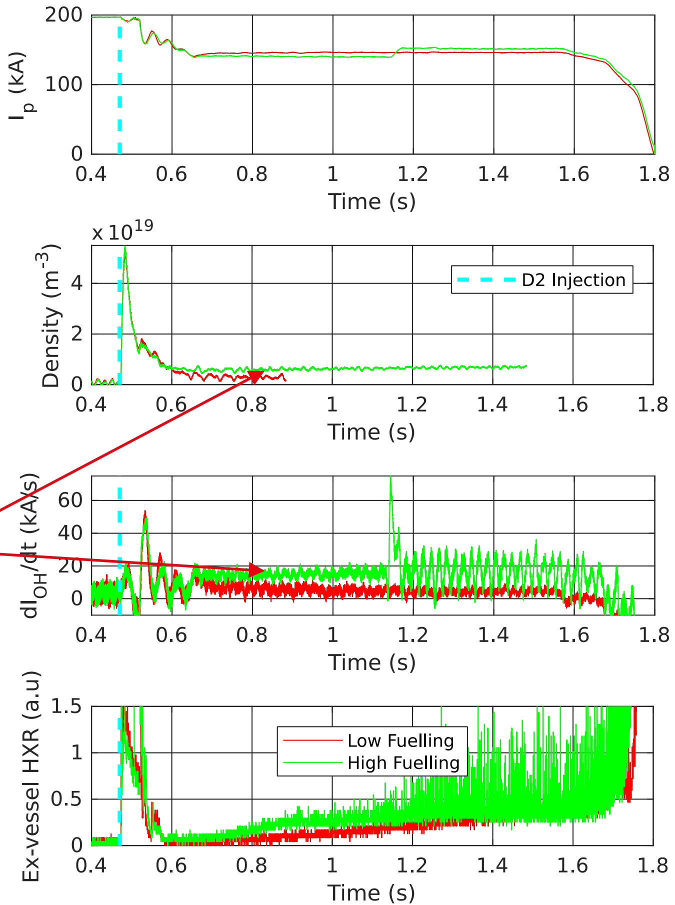
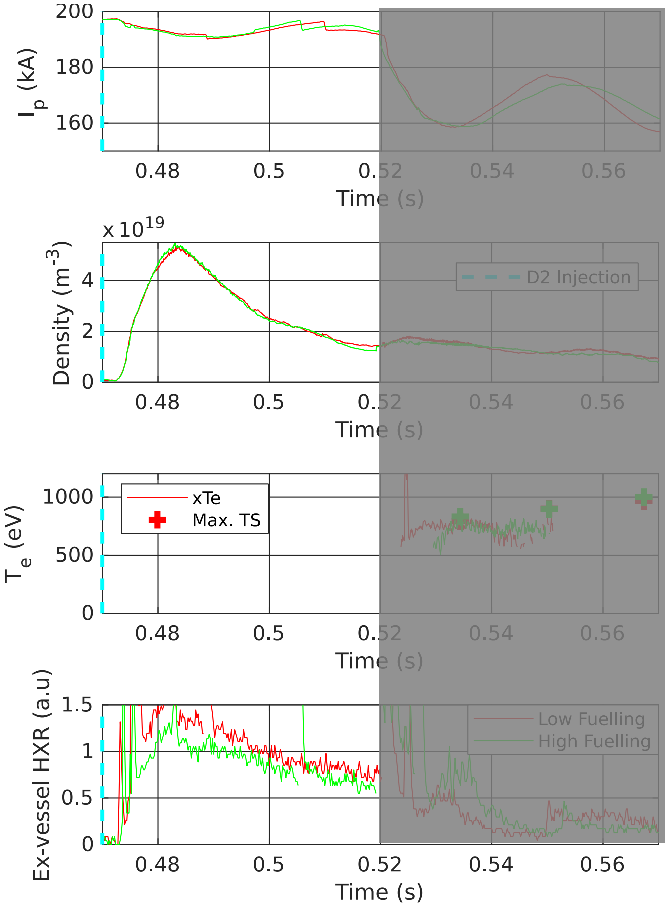
- Low HXR and n_e ~0.5e19 maintained
  - V_{loop} remains below 1
- Higher n_e and dI_{OH}/dt for high fuelling
  - Injection from standard fuelling valve
- OH spike @1.15s
  (TCV specificity)



Plasma Temperature Increased to 1keV

- No T_e measurements during RE phase
  - Standard spectroscopy too slow
  - Temperature too low for TS and xTe
    - TS suggests T_e < 5eV



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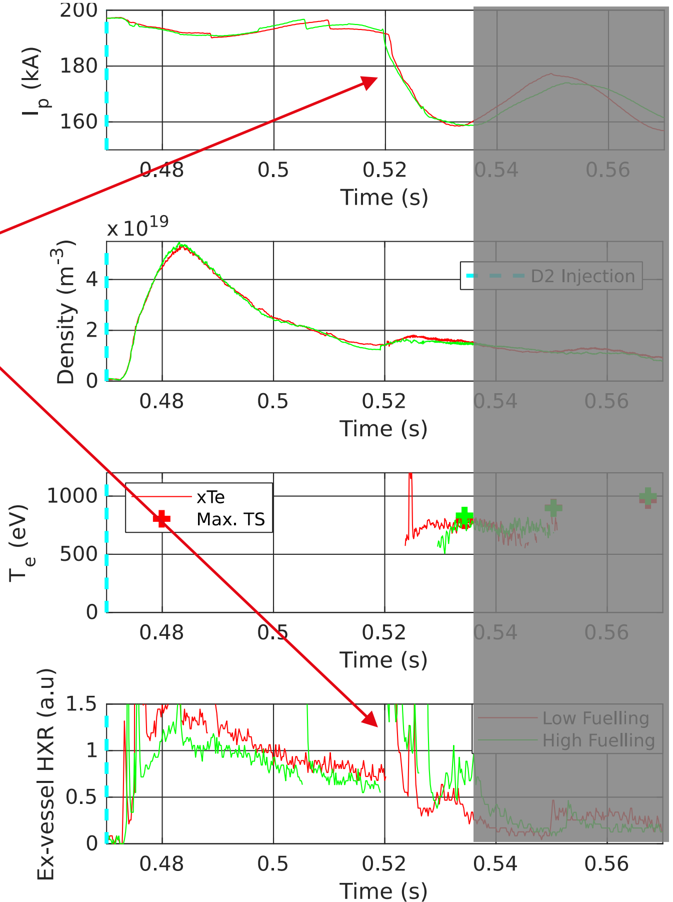

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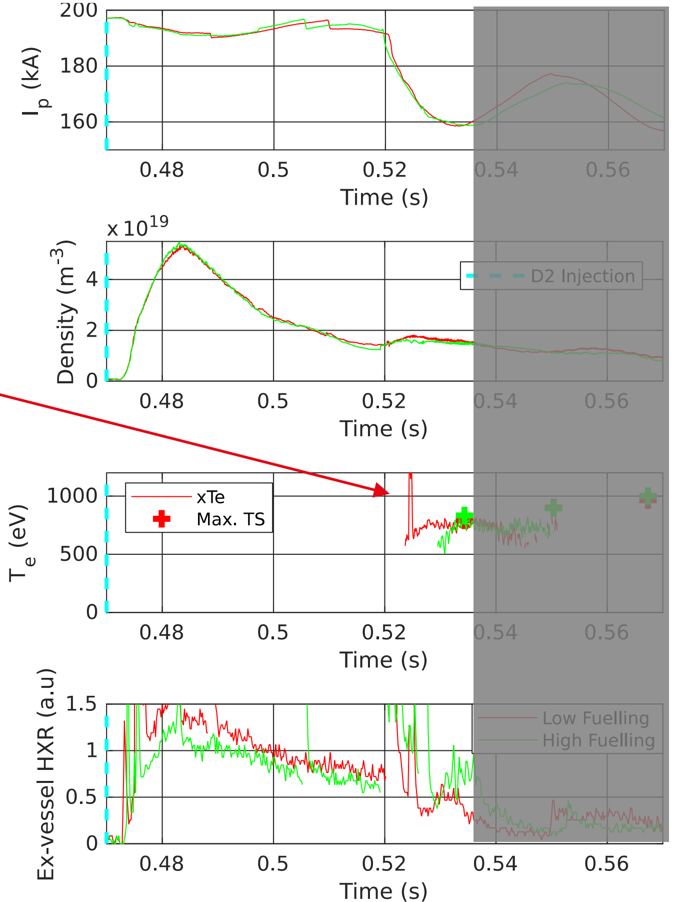
  - xTe (assumes Maxwellian distribution)
    - Good match with TS
  - Background plasma heating in 5-10ms
    - Flux surfaces already established



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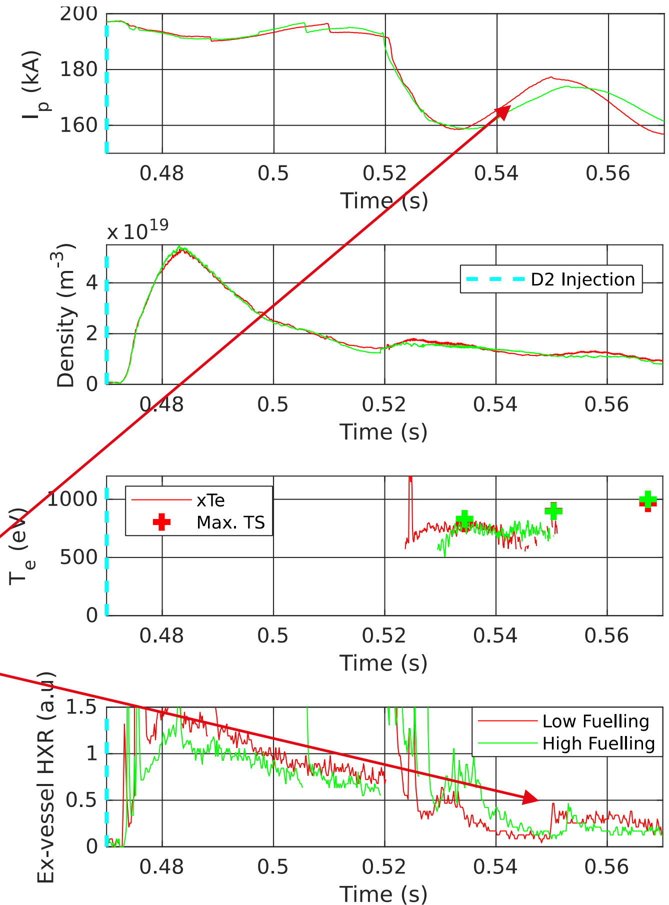
- Plasma current recovers and HXR emissions remain low
- Potential for current to be carried by background plasma - modelling

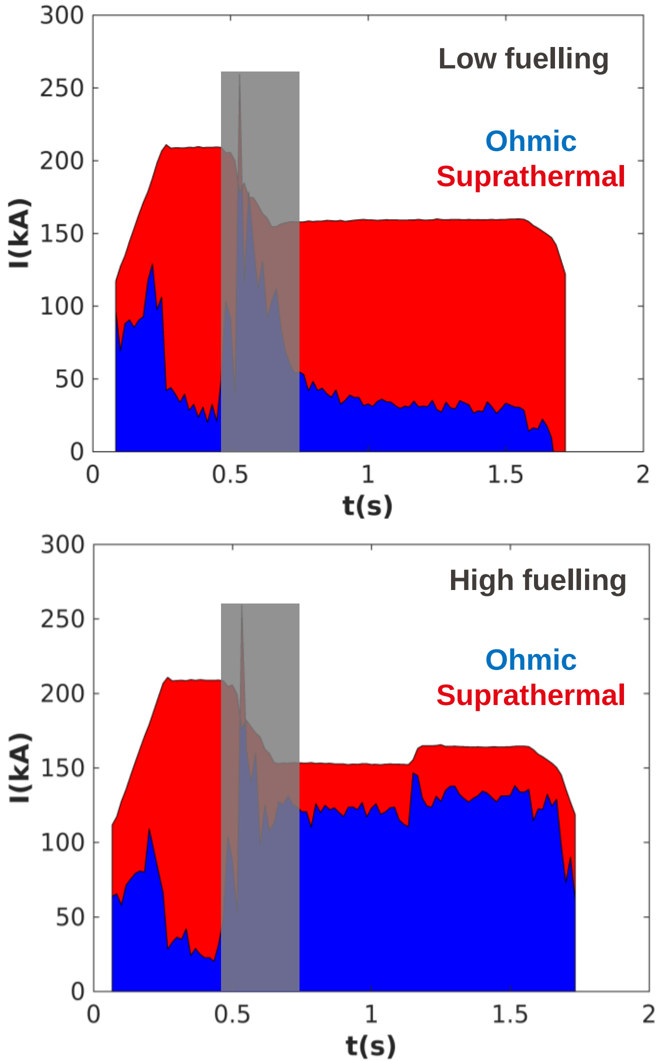


Preliminary Modelling

EPFL

Modelling with LUKE

- LUKE : relativistic guiding-center Fokker-Planck code (Decker 2008)
  - Current diffusion equation not solved
  - Only valid in quasi-steady phases
- Pre-disruption: suprathermal electrons (including REs) drive 80% of I_p
  - Towards slideaway regime?
- Post-disruption: Ohmic contribution is 4x higher with high fueling
  - Slightly higher T_e, much higher V_{loop}
  - Similar to pre-disruption Ohmic contribution with low fueling
- Higher n_e => lower RE generation vs transport => higher V_{loop} => larger Ohmic contribution
- Ongoing modelling to characterize RE population



Summary

- Confined RE beams reliably created on TCV via MGI
- Natural decay rates with He, Ne, Ar, Kr, Xe covered
- Flushing and background plasma heating demonstrated
- D_2 primary injection led to RE beam followed by background plasma re-established at 1keV
  - LUKE modelling predicts high post-disruption Ohmic contribution to I_p
- Only a small subset of full TCV RE database
  - Data available for model validation and collaboration

Merci

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