Real-time disruption prediction in the plasma control system of HL-2A based on deep learning

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- Background
- Offline algorithm in HL-2A
- Real-time implementation
- Testing result in PCS without mitigation
- Testing result in PCS with mitigation
- Future works

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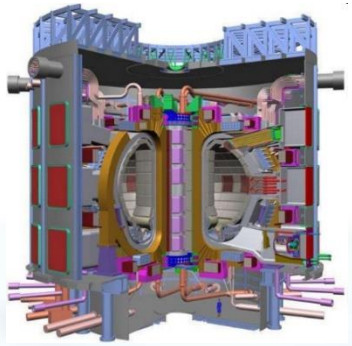
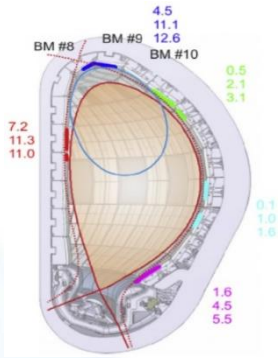
Background

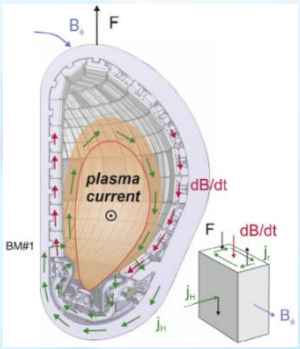
- Disruption→ 3 main harmful effects:
  - Thermal quench(TQ)
  - Current quench (CQ)
  - Runaway electrons(RE)
- The solution is:
  - Avoidance
  - Prediction → Machine learning algorithm
  - Mitigation
- Many algorithms are developed, but:
  - Cross-tokamak prediction
  - Real-time implementation
  - Interpretable algorithm



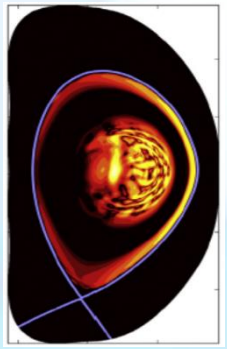
ITER



TQ



CQ



RE

Background

- Some ML-based algorithm have been implemented in real-time environment
  - APODIS: based on Support Vector Machine, implemented in JET
  - DPRF: based on Random Forest, implemented in DIII-D and EAST
  - How about the real-time implementation of deep learning-based algorithms?

- Difficulties
  - Complex data: low sample rate scalars → high sample rate 0D/1D/2D data
  - Complex software: interaction between python, C and deep learning framework
  - Complex hardware: calculation on GPUs

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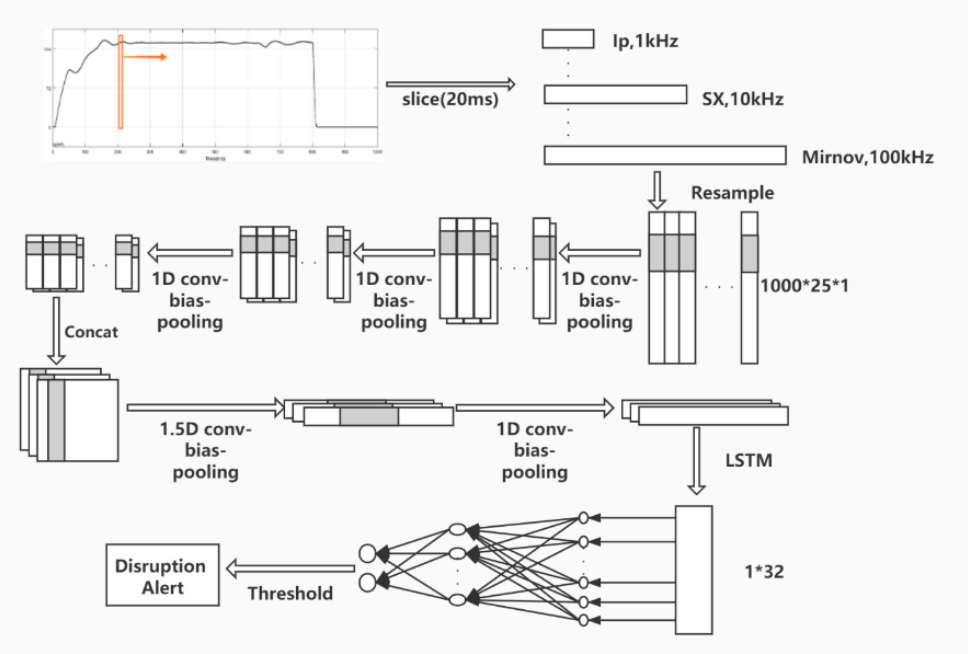
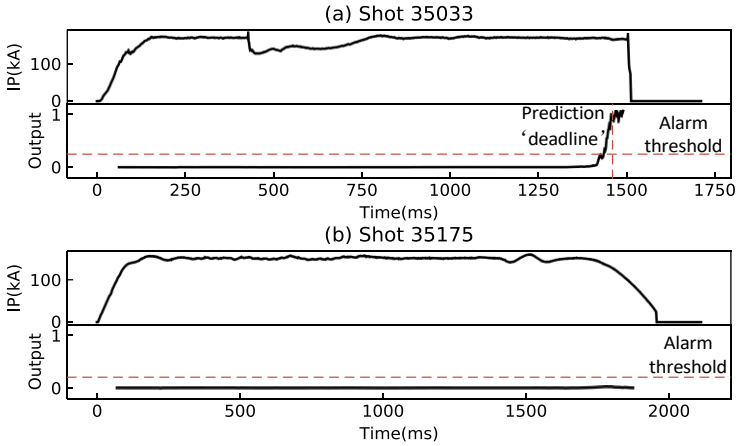
Deep learning model

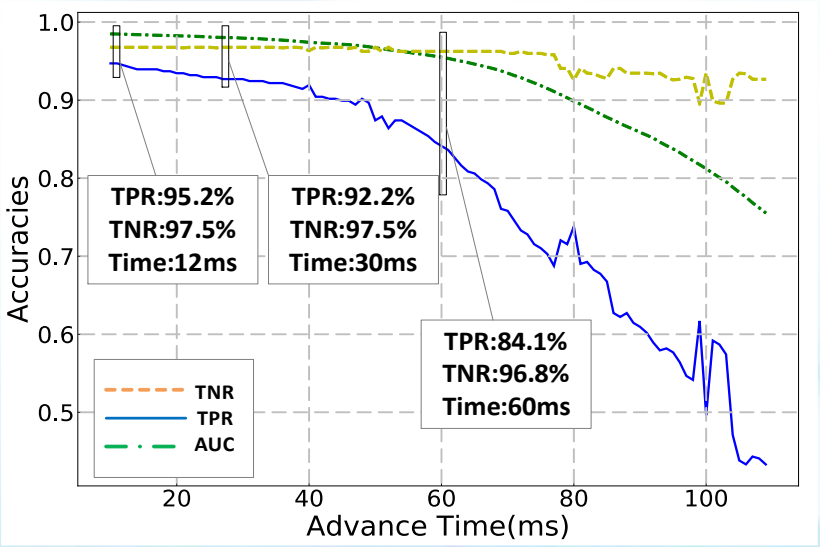
- Input
  - ✓ 25 channels
  - ✓ Sample rate: 1/10/100kHz (all resampled to 100kHz)
  - ✓ Window length: 20ms
  - ✓ Preprocessing: mean-std-truncate
- Model structure
  - ✓ Convolutional layers
  - ✓ 1.5-D convolutional layers
  - ✓ Long short term memory layers
  - ✓ Fully connected layers
- Output
  - ✓ Disruptivity: 0~1

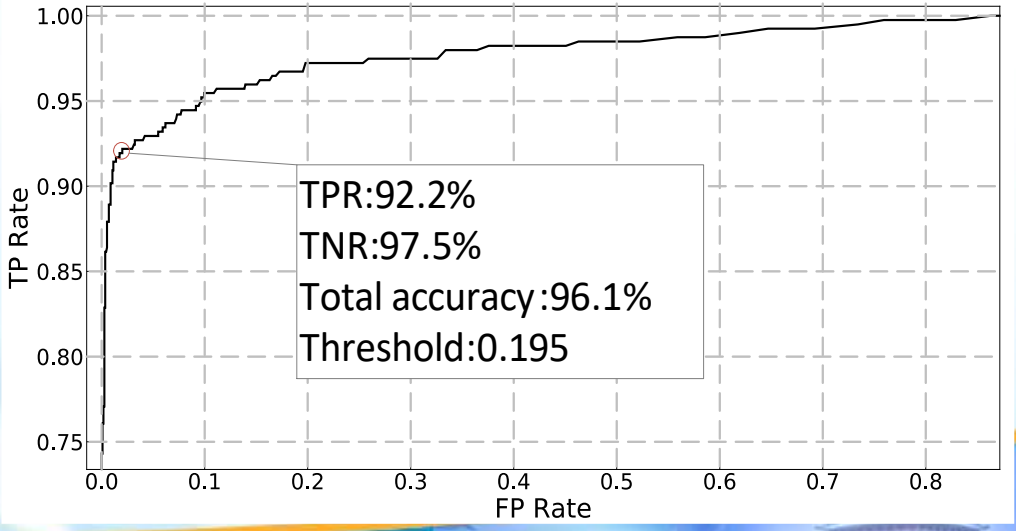


Testing Results

- Performance on testing set
  - ✓ True positive rate: 92.2%
  - ✓ True negative rate: 97.5%
  - ✓ Accuracy: 96.1%







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Input data provided by PCS

- Some input channels can't be real-timely obtained: EFIT data
- Local resources in PCS might be helpful

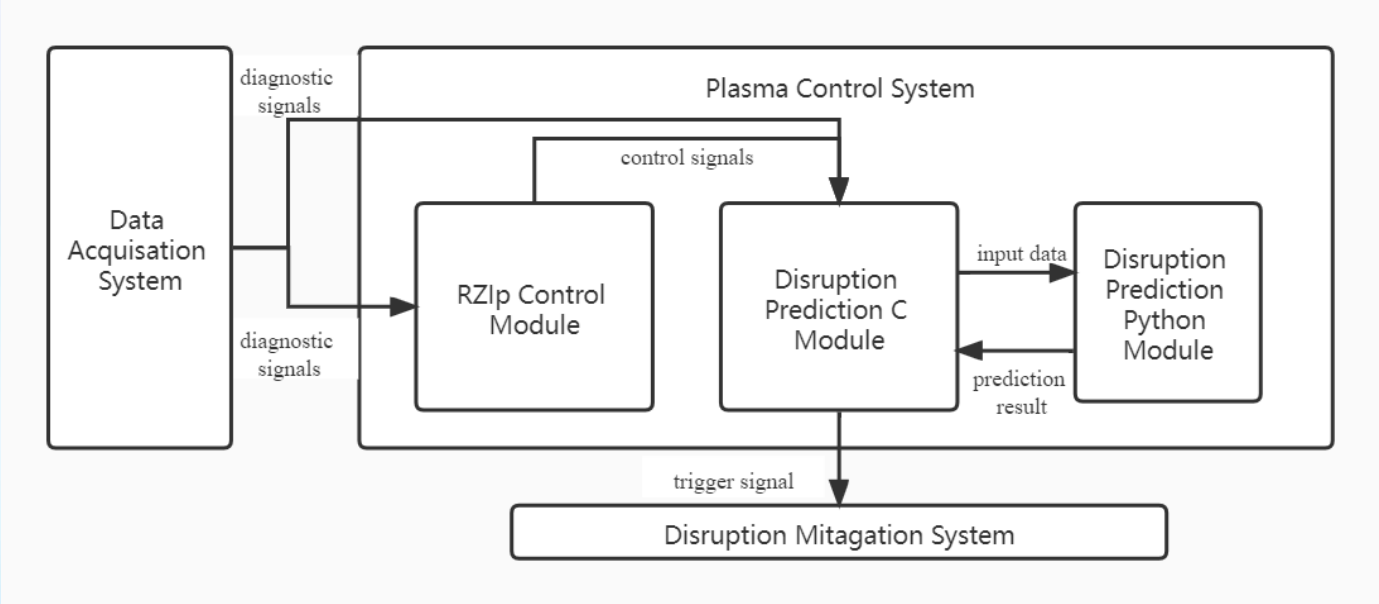
	Sample rate	Physical Meaning
IP_001~IP_009	1kHz	Plasma current measured by 9 Rokovski coils
Boh_EM	1kHz	Intensity of ohmic field
Bt_EM	1kHz	Intensity of toroidal field
Bv_EM	1kHz	Intensity of vertical field
MP1_EM	1kHz	Intensity of multipole field
MP2_EM	1kHz	Intensity of multipole field
Diam_TX_4	1kHz	Amplitude of diamagnetic measured by concentric coils
Density	1kHz	Density of electrons at the center of plasma
Vloop	1kHz	Loop voltage
Hx_1	1kHz	Power of hard-x-ray (0–5 MeV)
Hx_2	1kHz	Power of hard-x-ray (5–10 MeV)
BOLU10	1kHz	Power of radiation measured by the 10^{th} channel of upper bolometer array
Mpol_04	10kHz	A pair of toroidal probes located at symmetric positions
Mpol_13	10kHz	
Npol_04	10kHz	A pair of poloidal probes located at symmetric positions
Npol_09	10kHz	
I_Div_Imp2	10kHz	D-α ray at divertor
SX52	10kHz	Power of soft-x-ray, 52^{th} channel
FDh	1kHz	Horizontal displacement calculated by PCS
FDv	1kHz	Vertical displacement calculated by PCS

Accelerating

- Offline model takes 17ms to analyze an input slice, too long to serve in plasma control system, which calls for less than 1ms per slice.
- Reduce the model: 17ms → 2ms 😀
  - ✓ Input sample rate: 100kHz → 10kHz
  - ✓ Model structure: mainly CNN → mainly RNN
- Using inference framework: 2ms → 0.3ms 😀
  - ✓ TFLite: inference framework for Tensorflow models
- Cost of accuracies 😔
  - ✓ TPR0.922/TNR0.975 → TPR0.880/TNR0.879

Embedded into the PCS

- Software works
  - Cross language interaction between PCS and deep learning model
  - Real-time analysis of diagnostic data
- Hardware works
  - Updating the acquisition system
  - Connecting PCS to the Massive Gas Injection system



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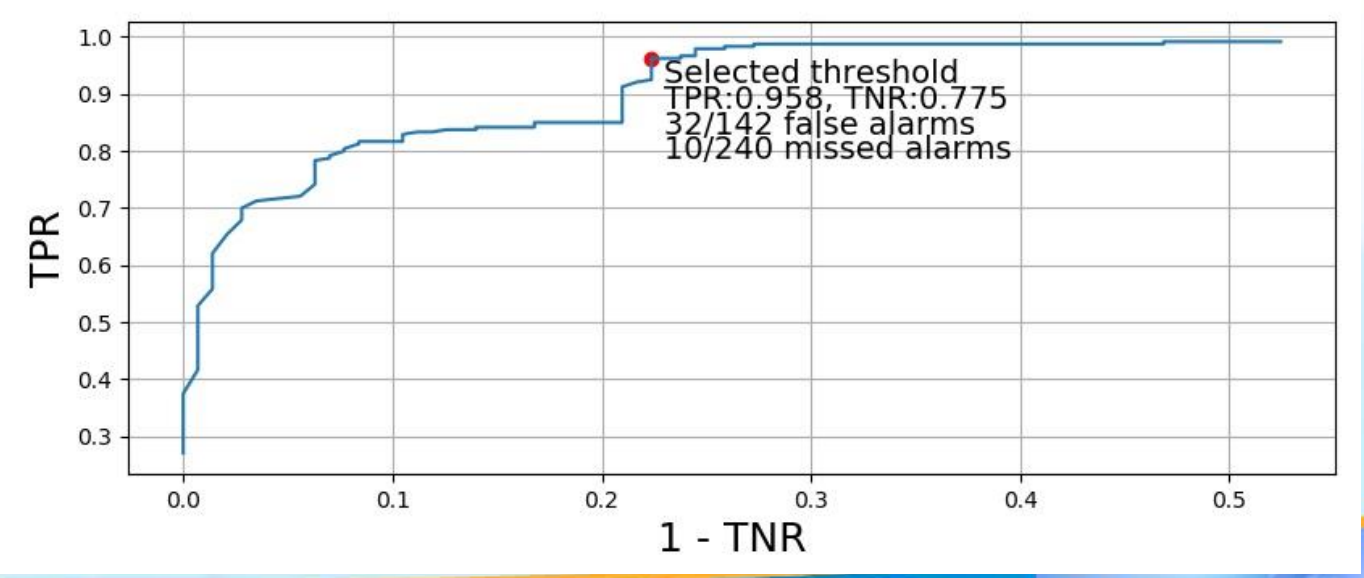
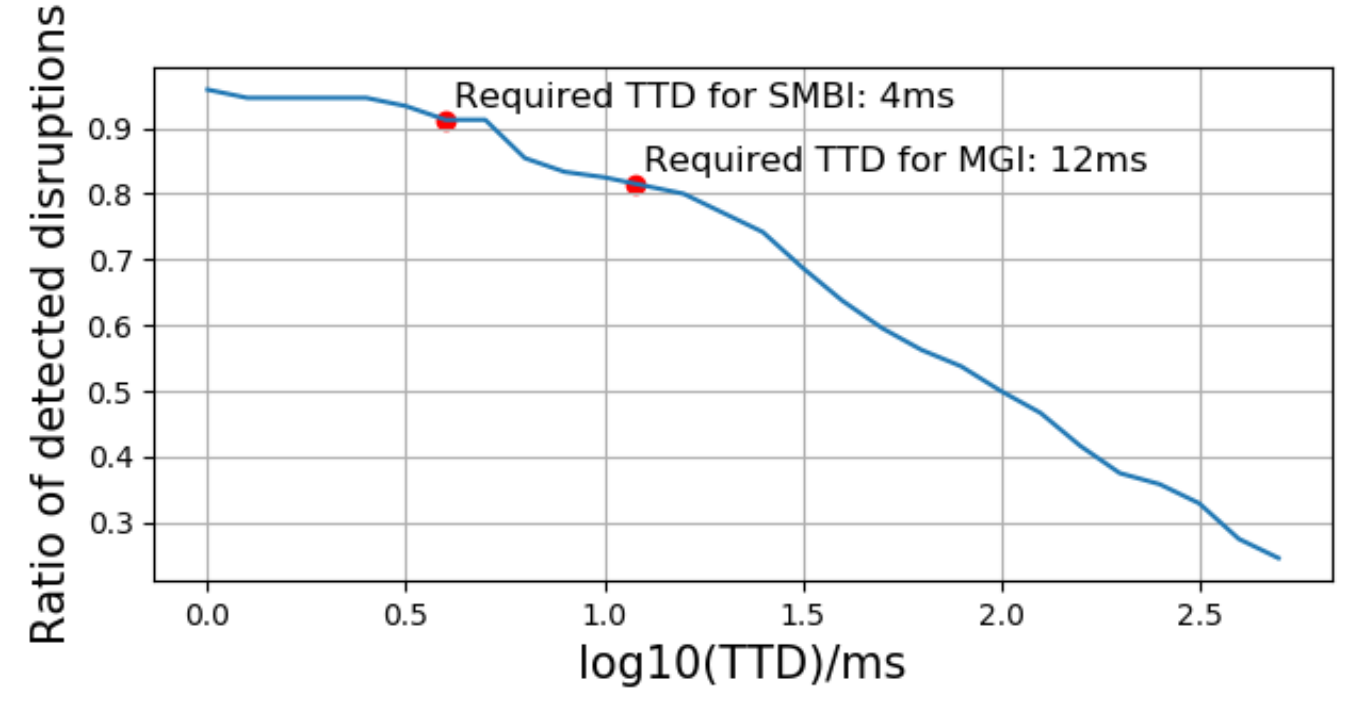
Accuracies

- Testing set: Shot Nos. 38650-39347 in HL-2A
  - TPR:0.958, TNR:0.775
  - 32/142 false alarms, 10/240 missed alarms
  - False alarms are mainly triggered by minor disruptions/internal disruptions/noise from data acquisition system



Advance time

- For SMBI, 91.3% of the disruptions can be timely mitigated
- For MGI, 81.5% of the disruptions can be timely mitigated



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Mitigated disruption: 39303

- Vertical displacement induced disruption, mitigated by SMBI
  - Trigger signal was sent at 1047ms
  - Plasma density started to increase at 1050ms
  - Mitigated disruption started at 1051ms

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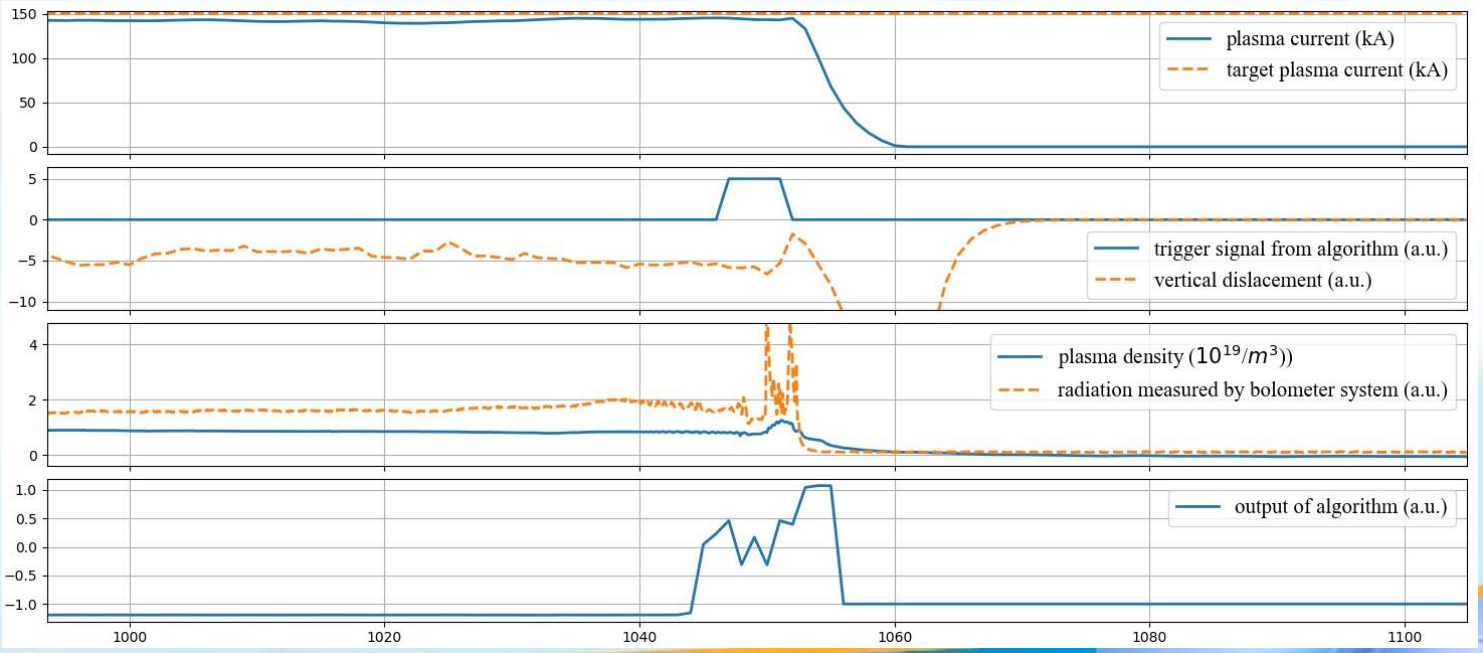
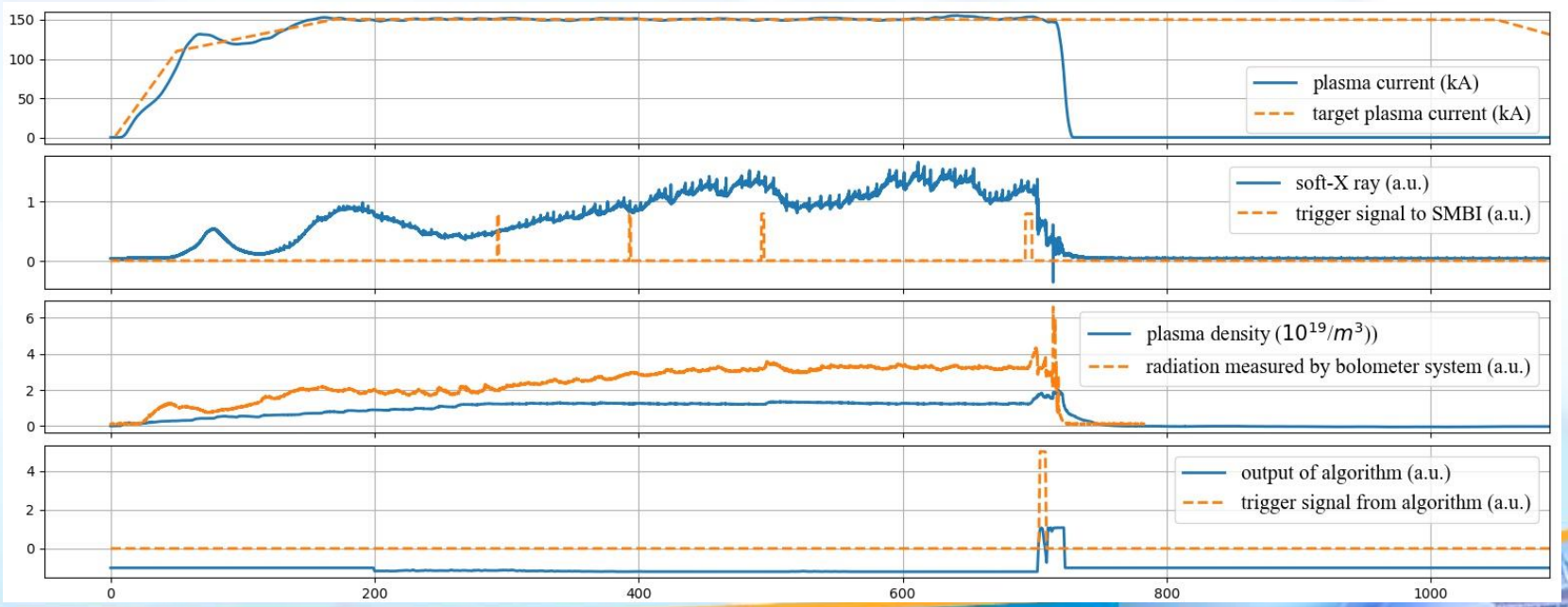


Mitigated disruption: 39346

- Cooling of core plasma induced disruption, mitigated by MGI
  - Trigger signal was sent at 704ms
  - Plasma density started to increase at 714ms
  - Mitigated disruption started at 716ms



Mitigated disruption: 39346

- Cooling of core plasma induced disruption, mitigated by MGI
  - Trigger signal was sent at 704ms
  - Plasma density started to increase at 715ms
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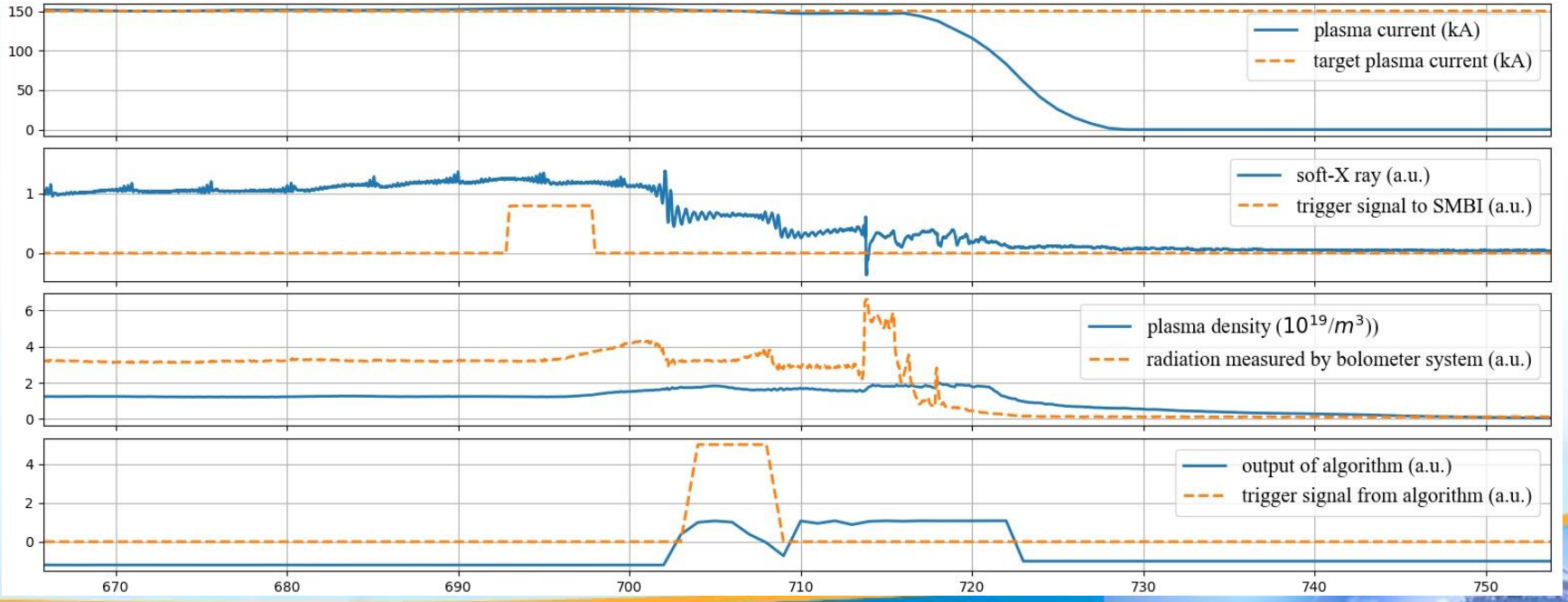

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Future works

- Deep learning models works well in PCS
- Future works
  - Real-time implementation: preliminarily solved in this research, keep optimizing
  - Interpretable algorithm: preliminarily answered by [2], keep optimizing
  - Cross-tokamak prediction: coming soon
- Related works

[1] Offline algorithm in HL-2A, *Zongyu Yang et al*, *Nuclear Fusion* 60, 016017

[2] Model optimization and interpretation, *Zongyu Yang et al*, *Nuclear Fusion* 61, 126042

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Thanks!