Disruption Avoidance and Prediction: Session Summary

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Introduction and content

- yesterday's session motivates this session
- division between "disruption avoidance/prevention" and "disruption prediction" is artificial
- 10 invited talks + 10 oral talks; all excellent (clear and interesting) contributions; this summary cannot replace *watching/reading* contributions
- some threads behind summary; summary index
- summary

Scenario development

Plasma control

Theory, Modeling, extrapolating

Data analysis, ML tools, statistics, physics

Disruption avoidance/prevention
Prediction (A&P)
DMS trigger generation

Scenario development

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Data analysis, ML tools, statistics, physics

Disruption avoidance/prevention
Prediction (A&P)
DMS trigger generation

Evolving disruption A&P needs

existing device → ITER half I_p and B_t → ITER high I_p → DEMO and FPP)

e.g. allow/plan disruptions;
experiment and expand PCS;
training NN on one device w dimensioned variables for device protection;
data analysis and education;

complex PCS with several layers of decisions/ competences

few diagnostics survive neutron environment;
no disruptions allowed → scenario must be controllable and stable (existance?);
stripped-down PCS and device

Index

ITER scenario development, plasma control, physics

F. Turco. Scenario optimization and instability monitoring to reach Q=10 ITER mission without disruptions

Plasma control, disruption avoidance, scenario development, data analysis

D. Humphreys. Design of the ITER PCS for disruption prevention and mitigation

A. Pau. Off-normal event-detection and NTM-control for integrated disruption avoidance and scenario control

J. Barr. Control solutions supporting disruption free operation on DIII-D and EAST

M. Maraschek. Prevention of the H-mode density limit by various heating schemes through control of the plasma state *space*

Scenario development towards DEMO and FPP

F. Janky. Controlling a burning plasma in the DEMO tokamak away from disruptive events

L. Zakharov. Does a tokamak have a chance to avoid disruptions?

Data analysis, methods and tools, physics

Steven Sabbagh. Progress on tokamak disruption event characterization

Suite of tools

E. Kolemen. RT prediction and avoidance of fusion plasma instabilities using feedback control

C. Rea. Interpretable data-driven disruption predictors to trigger avoidance and mitigation actuators on different tokamaks

J. Zhu. A hybrid deep learning architecture gor general disruption prediction across tokamaks

K. Montes. Accelerating disruption database studies with semi-supervised learning

Event identification

M. Fontana. Real-time applications of ECE interferometry for disiption avoidance in JET

D.R. Ferreira. Identifying disruption precursors by anomaly detection on bolometer tomography

Locked mode phase

M.J. Choi. 2D Te patterns of various disruptive events

R. Nies. RF current condensation with self-consistent ray-tracing and application to ITER

A. Reiman. Magnetic island suppression and disruption avoidance via RF current condensation

A. Murari. Investigating the physics of the tokamak operational boundaries using ML tools

Learning whole operational space

M. Gelfusa. On the potential of adaptive predictors and their transfer between different devices for both mitigation and prevention of disruptions

E. Aymerich. Continuous update of machine learning disruption prediction and prevention models at JET

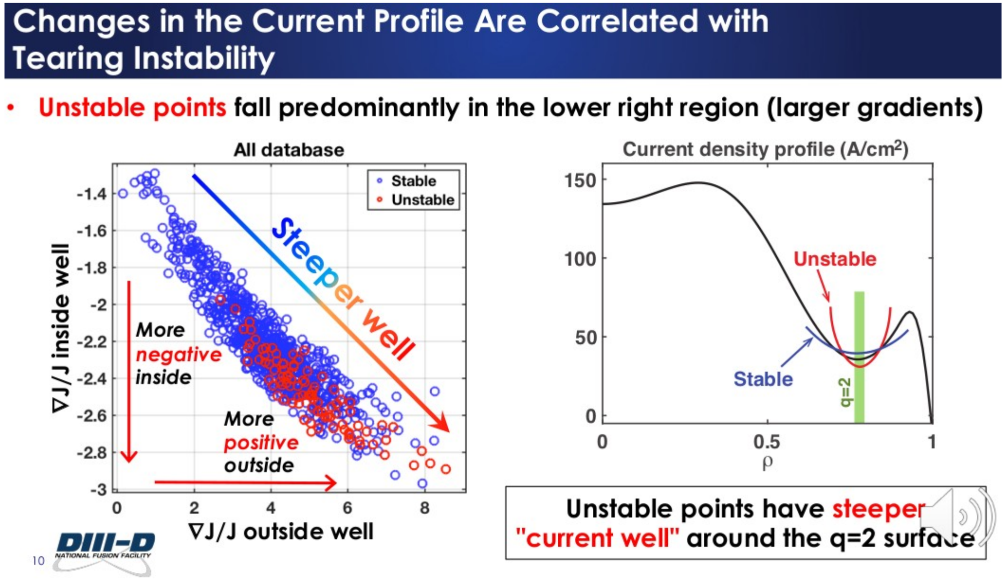
ITER scenario development, plasma control, physics

F. Turco et al., Scenario optimization and instability monitoring to reach the Q=10 ITER mission without disruptions

- More than a decade dedicated to IBS (Q=10) development
- IBS DIII-D scenario matches most of target parameters, q_{95}~ 3 and q=2 @ rho=0.8; many discharges suffer of growth of 2,1 mode (noNTM, no beta dependence) followed by disruption: why?
- equilibrium/current profile reconstruction show well at q=2; found that steeper well has high probability of generating 2,1 (figure)
- mostly inductive and bootstrap current → NI drive and ECCD (low T_e and j_{CD}) are ineffective
- modification of ramp-up (*slower* I_p *ramp, later heating, lower* $T_{e,ped}$*, modest gas flow*) allows for passively stable scenario (next slide)

Mission:
- 500 MW for 400 s, Q = 10 (G=0.42)
- Full Bt, Ip=15 MA, I_N=1.415 → q_{95}=3
- Expected T<0.7 Nm, low rotation

DIII-D demonstration discharges:
- ITER shape+ϵ, q_{95}=2.9-3.3
- H_{98}=1, β_N=1.7-2.25 → G=0.38-0.43
- T=-0.5-5 Nm

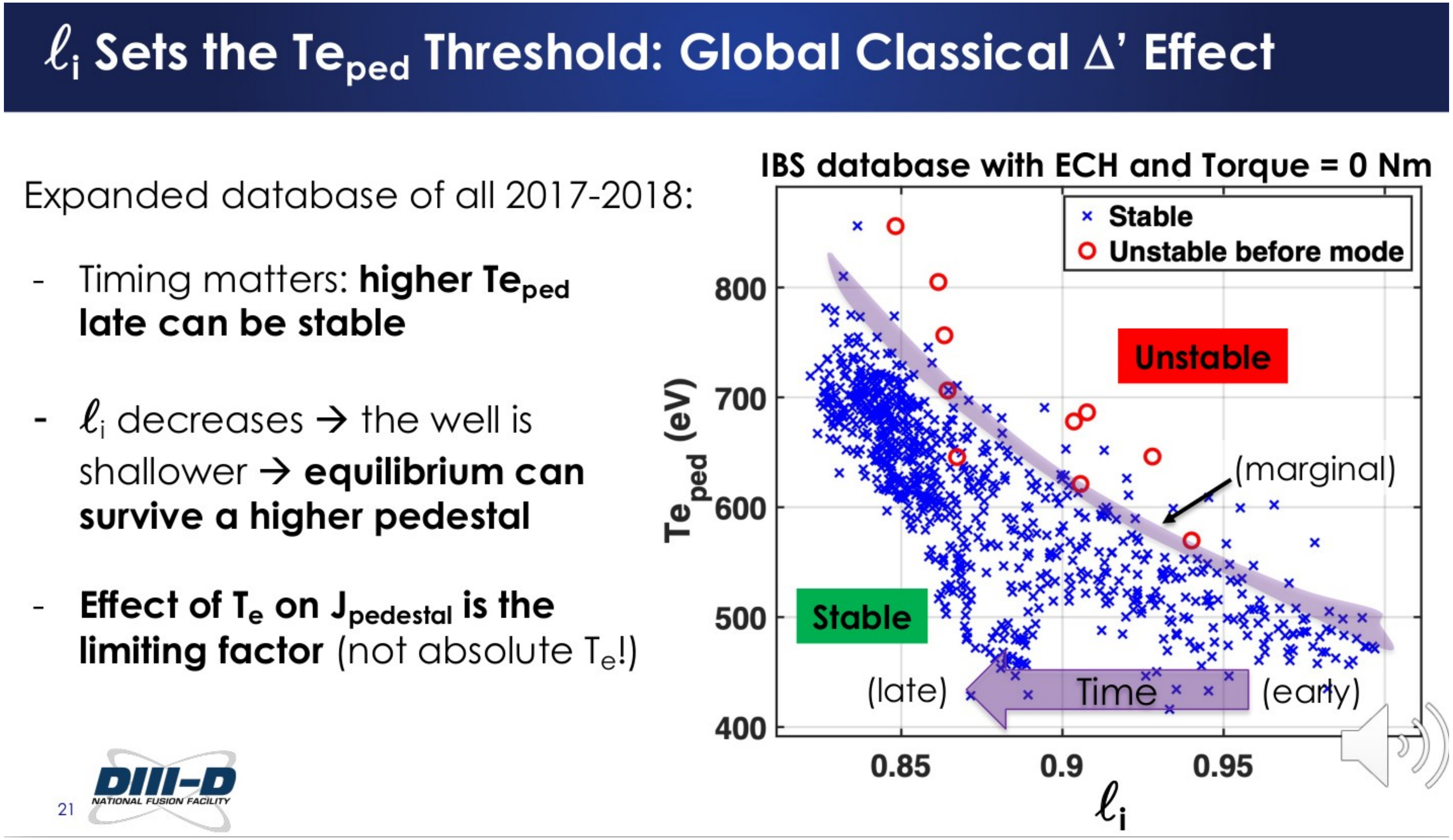


Changes in the Current Profile Are Correlated with Tearing Instability

- **Unstable points fall predominantly in the lower right region (larger gradients)**

Unstable points have steeper "current well" around the q=2 surface

F. Turco (continue)



ℓ_i Sets the Te_{ped} Threshold: Global Classical Δ' Effect

Expanded database of all 2017-2018:

- Timing matters: **higher Te_{ped} late can be stable**
- ℓ_i decreases → the well is shallower → **equilibium can survive a higher pedestal**
- **Effect of T_e on $J_{pedestal}$ is the limiting factor** (not absolute T_e!)

More in talk: MHD spectroscopy; preview of effect of shaping on current density and stability

Plasma control, disruption avoidance, scenario development, data analysis

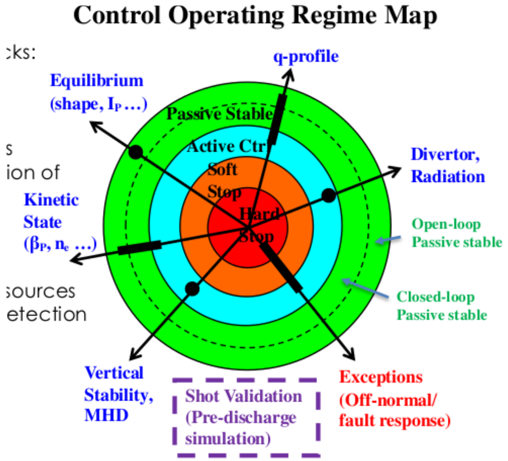
D. Humphreys et al., Design of the ITER plasma control system for disruption prevention and mitigation

- **The ITER PCS plays a central role in preventing and managing ITER disruptions**

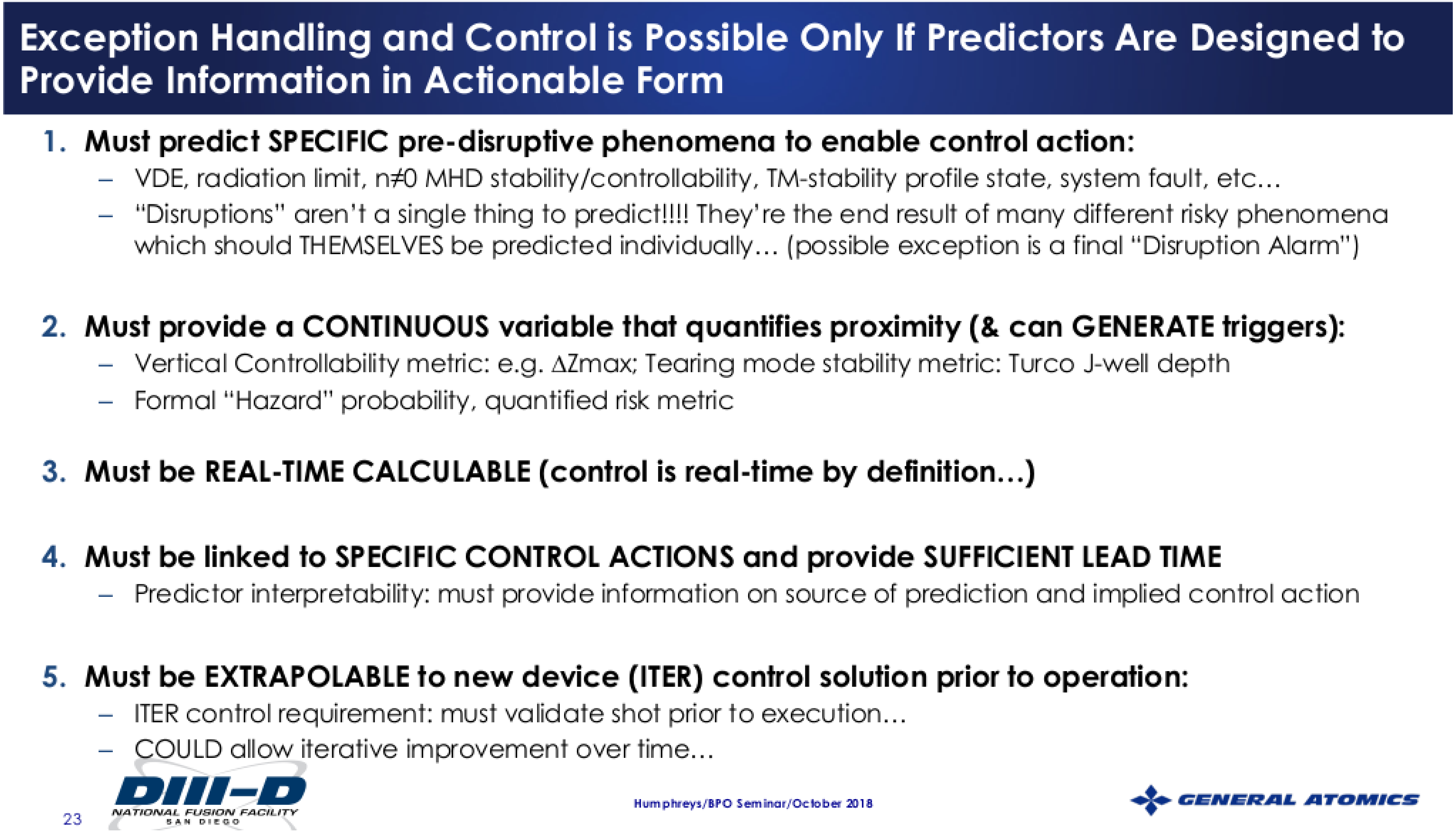
- **Key PCS functions for disruption management include:**
  - Shot validation through control simulation verification: mitigate human error
  - Robust control algorithms: tolerate expected noise/disturbances
  - Proximity control: prevent approach to disruptive states, continuously minimize risk
  - Effective Exception Handling: respond to system faults to avoid disruptive states
  - FRTS Forecasting and effective predictors: avoid potential disruptive states
  - DMS triggering (maybe) and effective mitigation scenarios: mitigate effects

- **Novel elements needed for ITER PCS are now subject of active research:**
  - Proximity control, controllability assessment/prediction, disruptivity risk assessment
  - ITPA Joint Activity between IOS and MDC TG's: disruption-free operation

(see description of Exception Handling in Dave's slides)



D. Humphreys (continue)



Exception Handling and Control is Possible Only If Predictors Are Designed to Provide Information in Actionable Form

1. **Must predict SPECIFIC pre-disruptive phenomena to enable control action:**
   - VDE, radiation limit, n≠0 MHD stability/controllability, TM-stability profile state, system fault, etc…
   - "Disruptions" aren't a single thing to predict!!!! They're the end result of many different risky phenomena which should THEMSELVES be predicted individually… (possible exception is a final "Disruption Alarm")

2. **Must provide a CONTINUOUS variable that quantifies proximity (& can GENERATE triggers):**
   - Vertical Controllability metric: e.g. ΔZmax; Tearing mode stability metric: Turco J-well depth
   - Formal "Hazard" probability, quantified risk metric

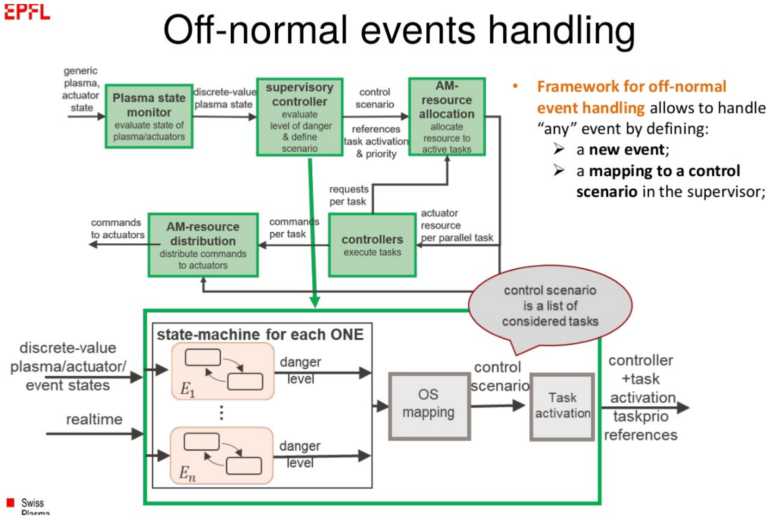
3. **Must be REAL-TIME CALCULABLE (control is real-time by definition…)**

4. **Must be linked to SPECIFIC CONTROL ACTIONS and provide SUFFICIENT LEAD TIME**
   - Predictor interpretability: must provide information on source of prediction and implied control action

5. **Must be EXTRAPOLABLE to new device (ITER) control solution prior to operation:**
   - ITER control requirement: must validate shot prior to execution…
   - COULD allow iterative improvement over time…

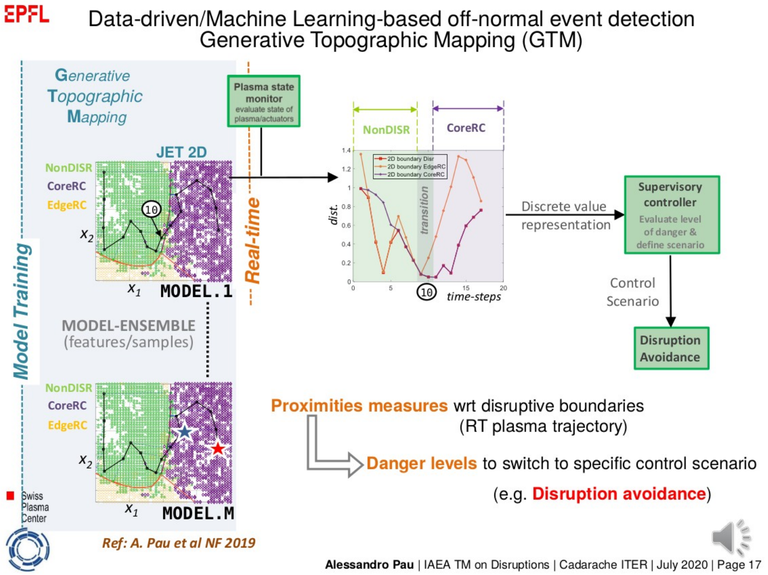
- **A. Pau et al., Off-normal event-detection and NTM-control for integrated disruption avoidance and scenario control**

- Generic Framework for PCS must easily accommodate new algorithms for PCS evolving tasks
- different task simultaneously, need for actuator sharing, actuator management
- particularly true for off-normal event handling
- event detection and characterization, e.g NTM rotating amplitude, frequency
- long tradition of NTM and beta RT integrated control
- off-normal events can be detected with data-driven algorithms (pre-disr states w high edge oder core radiation, GTM →)



Off-normal events handling

- **Framework for off-normal event handling** allows to handle "any" event by defining:
  - a **new event**;
  - a **mapping to a control scenario** in the supervisor;



Data-driven/Machine Learning-based off-normal event detection
Generative Topographic Mapping (GTM)

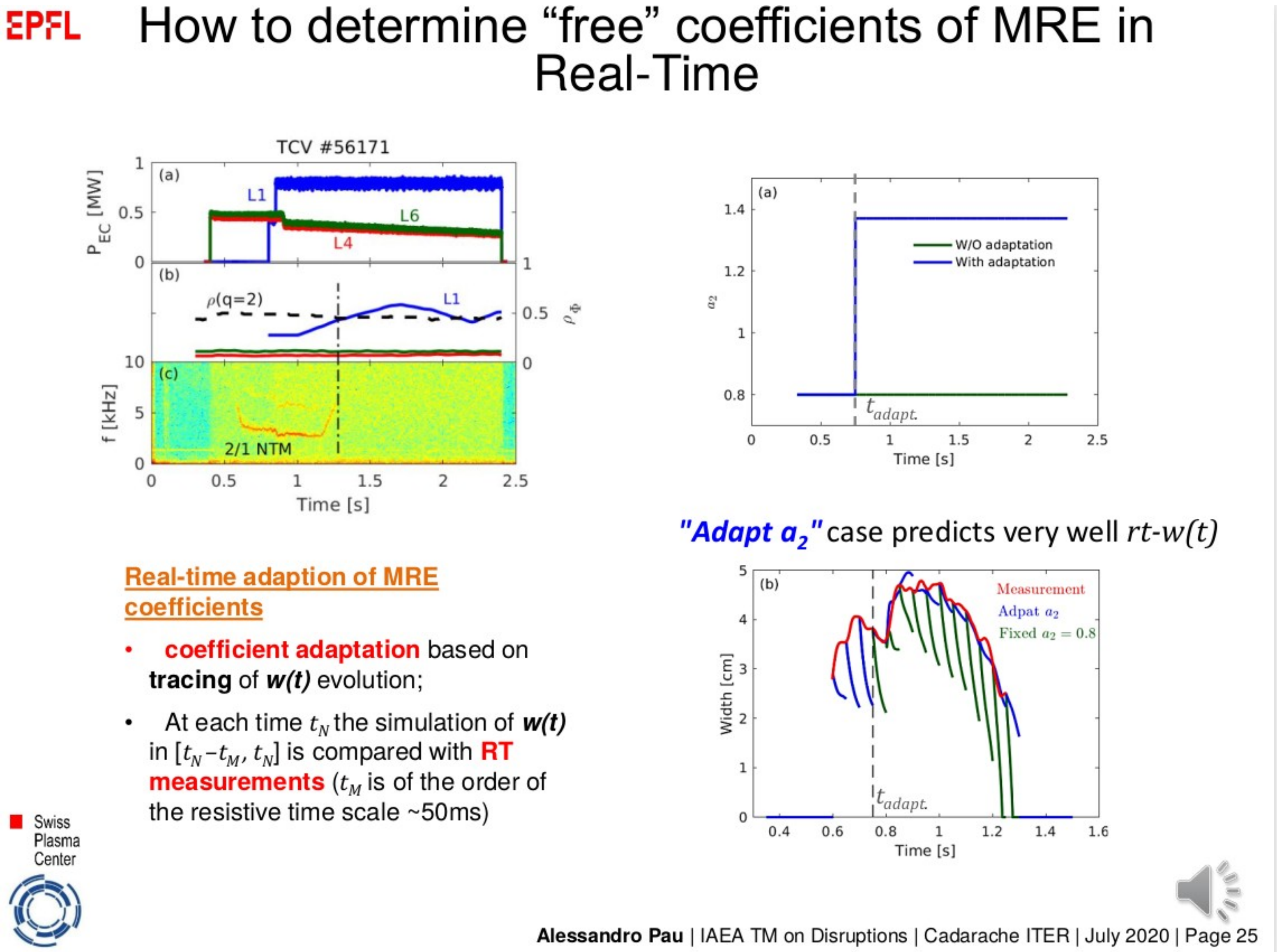
Proximities measures wrt disruptive boundaries (RT plasma trajectory)

Danger levels to switch to specific control scenario (e.g. **Disruption avoidance**)

Ref: A. Pau et al NF 2019

Alessandro Pau | IAEA TM on Disruptions | Cadarache ITER | July 2020 | Page 17

A. Pau (continue)



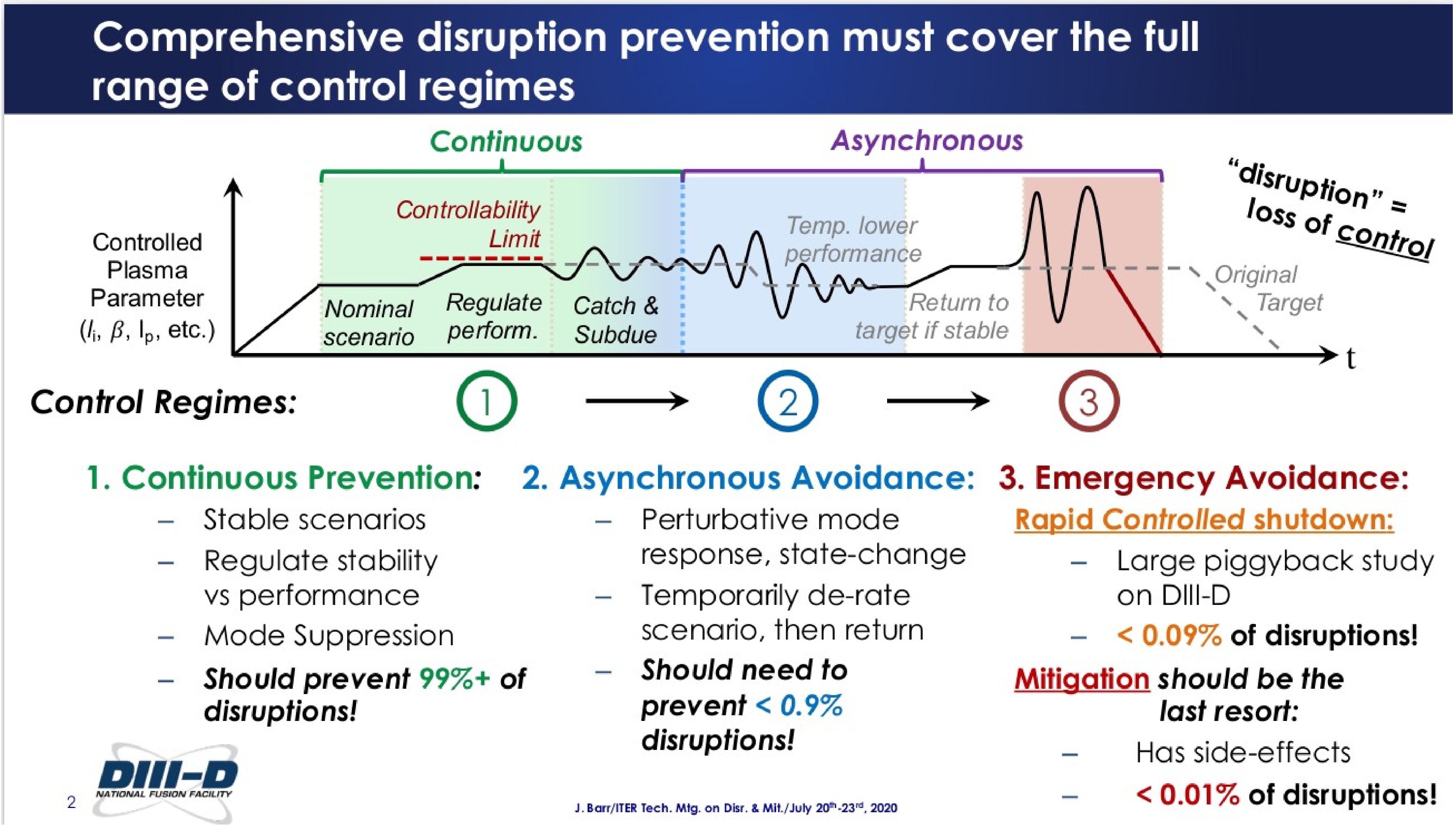
How to determine “free” coefficients of MRE in Real-Time

"Adapt a_2" case predicts very well rt-$w(t)$

Real-time adaption of MRE coefficients

- **coefficient adaptation** based on **tracing** of ***w(t)*** evolution;
- At each time t_N the simulation of ***w(t)*** in $[t_N - t_M, t_N]$ is compared with **RT measurements** (t_M is of the order of the resistive time scale ~50ms)

J. Barr et al., Control solutions supporting disruption free operation on DIII-D and EAST



Comprehensive disruption prevention must cover the full range of control regimes

1. Continuous Prevention:

- Stable scenarios
- Regulate stability vs performance
- Mode Suppression
- ***Should prevent 99%+ of disruptions!***

2. Asynchronous Avoidance:

- Perturbative mode response, state-change
- Temporarily de-rate scenario, then return
- ***Should need to prevent < 0.9% disruptions!***

3. Emergency Avoidance:

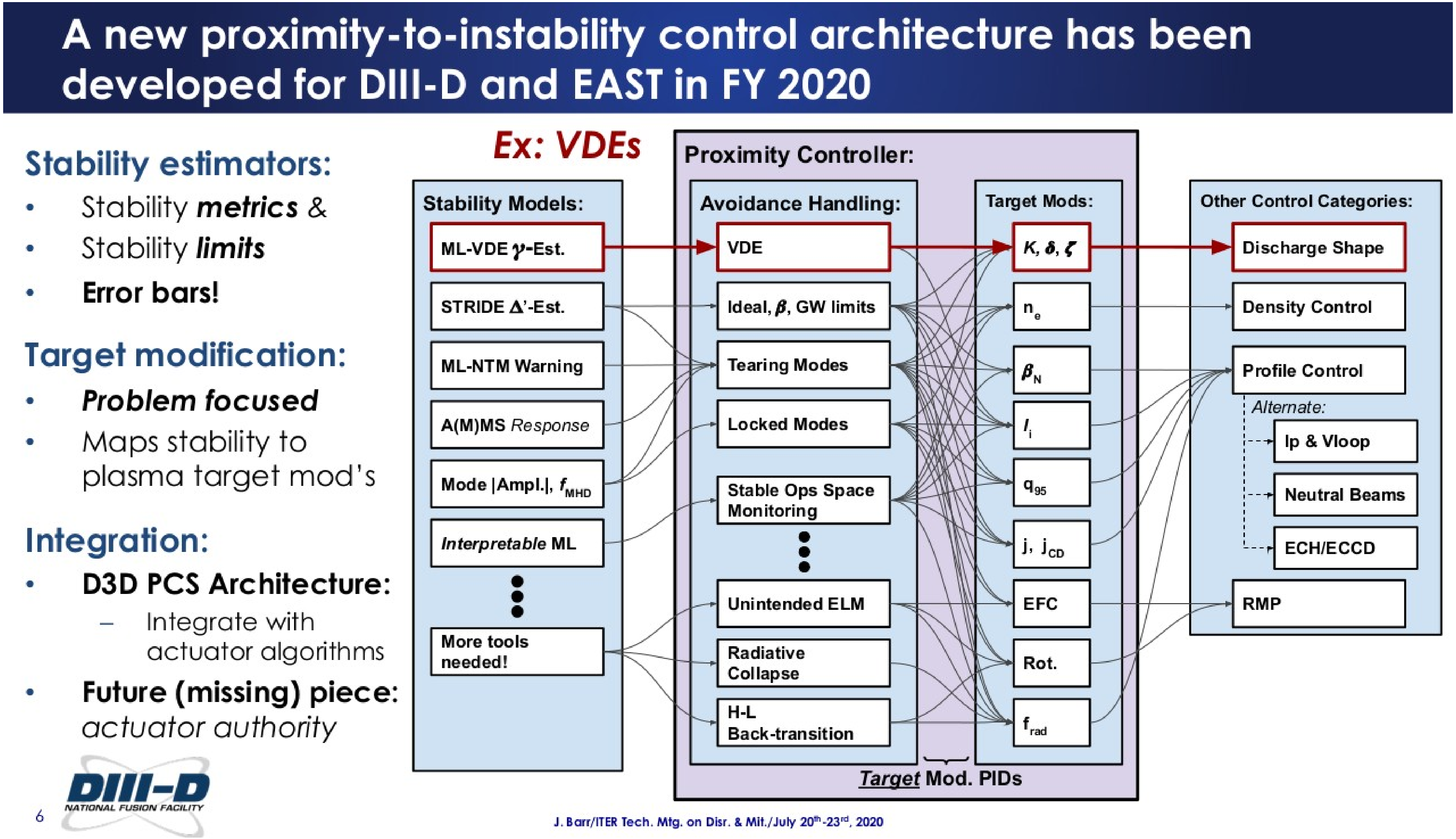
Rapid Controlled shutdown:

- Large piggyback study on DIII-D
- **< 0.09% of disruptions!**

Mitigation should be the last resort:

- Has side-effects
- **< 0.01% of disruptions!**

J. Barr (continue)



A new proximity-to-instability control architecture has been developed for DIII-D and EAST in FY 2020

Stability estimators:

- Stability ***metrics*** &
- Stability ***limits***
- **Error bars!**

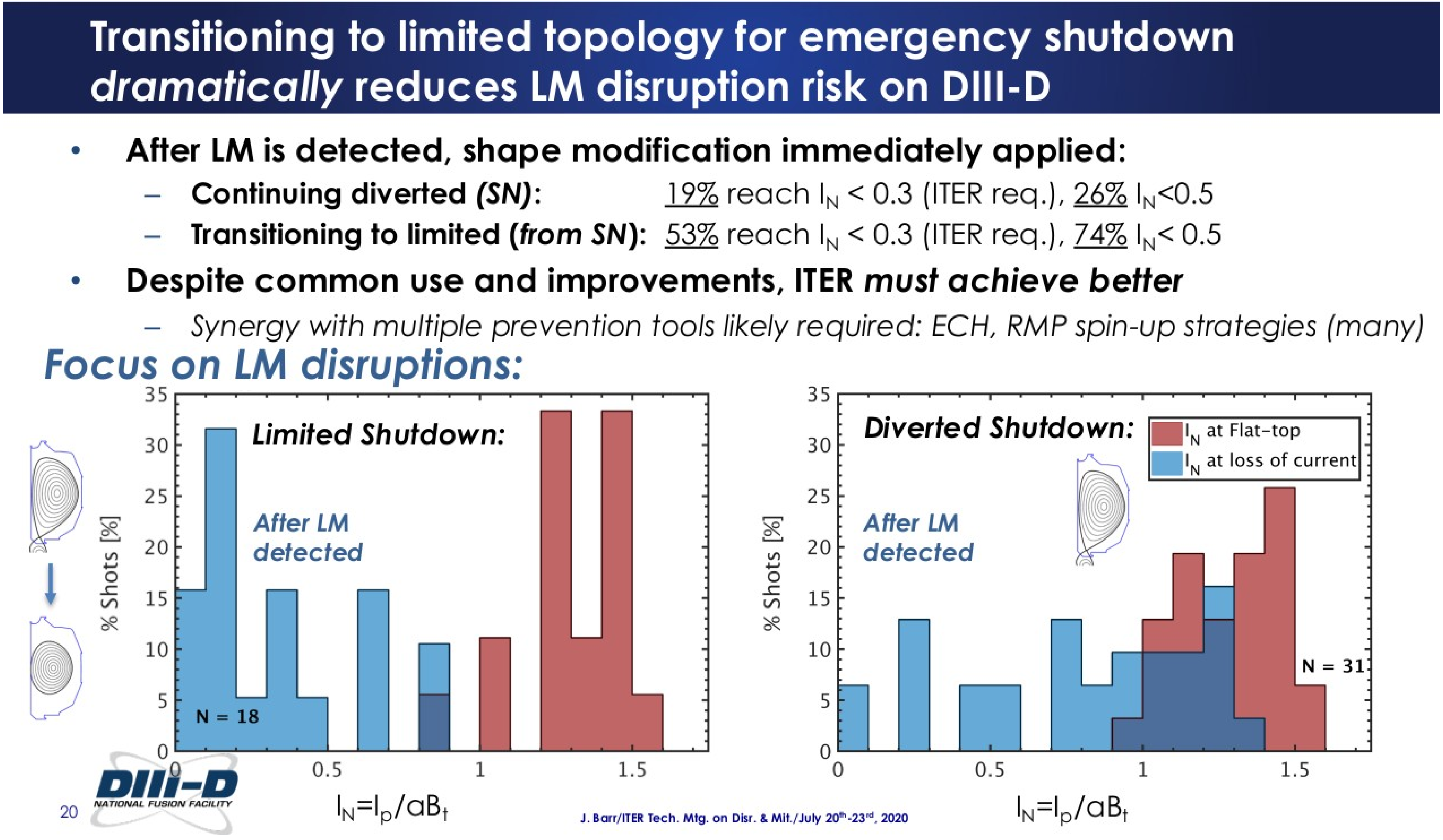
Target modification:

- ***Problem focused***
- Maps stability to plasma target mod's

Integration:

- **D3D PCS Architecture:**
  - Integrate with actuator algorithms
- **Future (missing) piece:** *actuator authority*

J. Barr (continue)



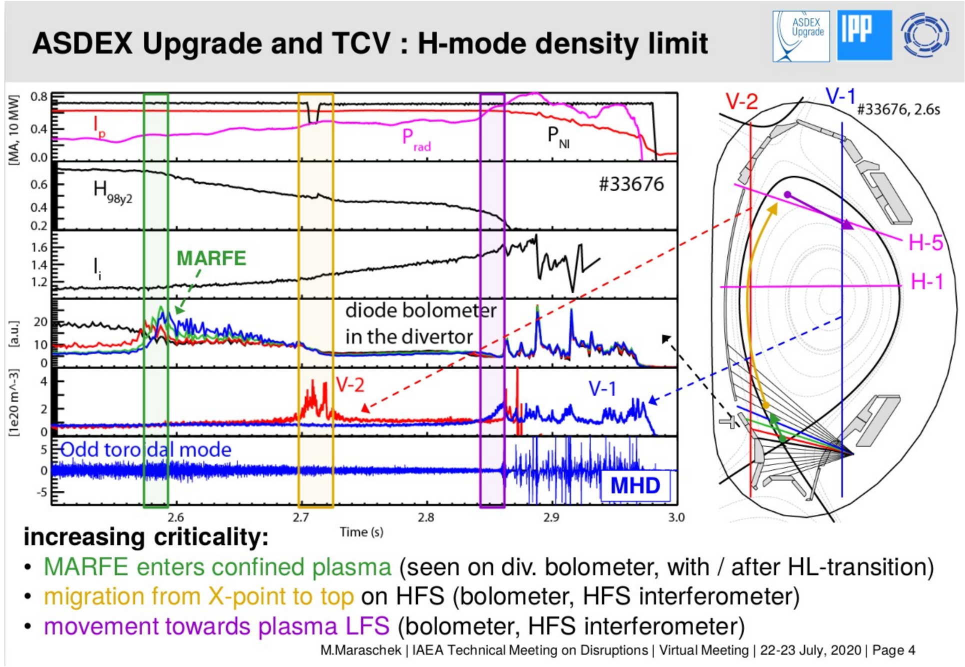
Transitioning to limited topology for emergency shutdown *dramatically* reduces LM disruption risk on DIII-D

- **After LM is detected, shape modification immediately applied:**
  - **Continuing diverted *(SN)*:** 19% reach $I_N < 0.3$ (ITER req.), 26% $I_N<0.5$
  - **Transitioning to limited (*from SN*):** 53% reach $I_N < 0.3$ (ITER req.), 74% $I_N< 0.5$
- **Despite common use and improvements, ITER *must achieve better***
  - *Synergy with multiple prevention tools likely required: ECH, RMP spin-up strategies (many)*

Focus on LM disruptions:

M. Maraschek et al., Prevention of the H-mode density limit by various heating schemes through control of the plasma state … space

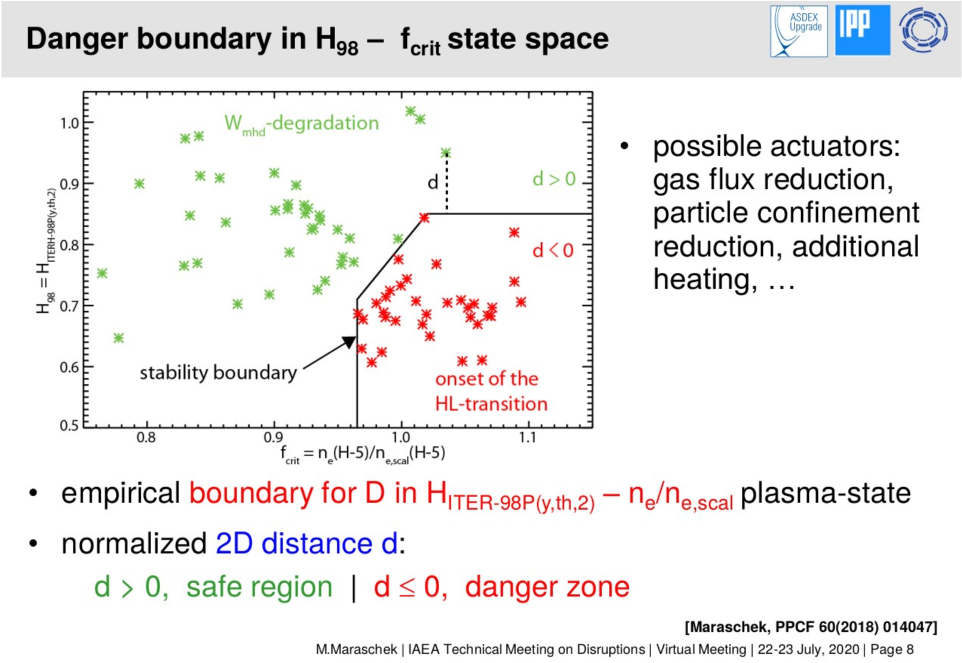
- Learning to control H mode high density scenario close to HDL: it can end in a disruption
- precursors: continuous increase of P_{rad}, li, confinement deterioration → MARFE → HL transition → MHD modes, LM (figure left)
- plasma state evolution can be followed on H-f_{crit} space (figure right); green points indicate confinement degradation start; H-L transition boundary in read; possible actuators: gas valves, aux heating (effect depends on type)



ASDEX Upgrade and TCV : H-mode density limit

increasing criticality:

- MARFE enters confined plasma (seen on div. bolometer, with / after HL-transition)
- migration from X-point to top on HFS (bolometer, HFS interferometer)
- movement towards plasma LFS (bolometer, HFS interferometer)



Danger boundary in H_{98} – f_{crit} state space

- possible actuators: gas flux reduction, particle confinement reduction, additional heating, …

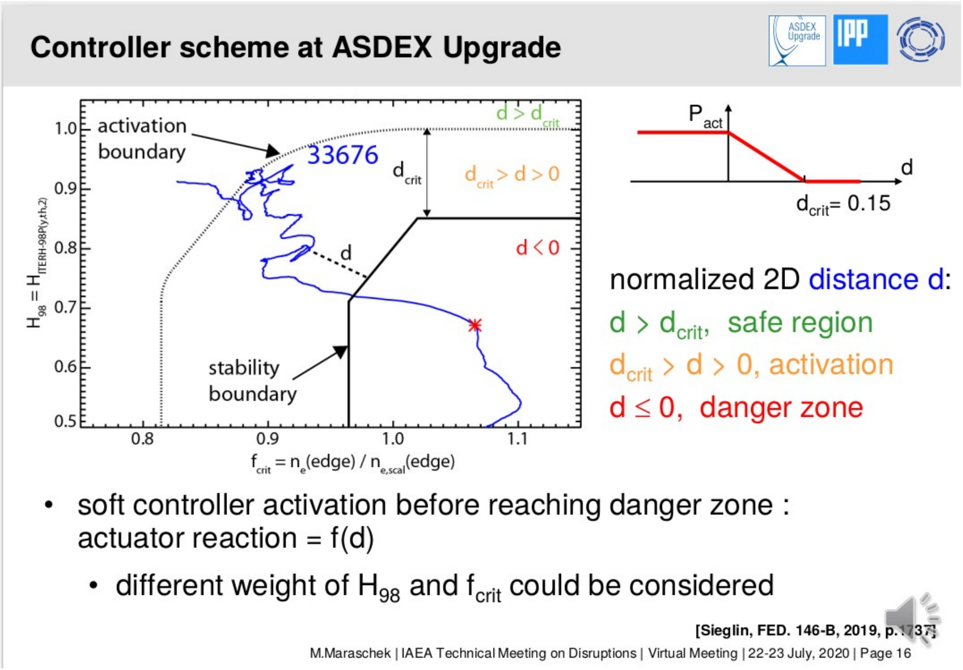
- empirical boundary for D in $H_{ITER-98P(y,th,2)}$ – $n_e/n_{e,scal}$ plasma-state
- normalized 2D distance d:

$d > 0$, safe region | $d \leq 0$, danger zone

[Maraschek, PPCF 60(2018) 014047]

M. Maraschek (continue)

- Control by heating = maintain plasma in green region (figure left); different heating systems have different effect
- if N2 added to plasma, different plasma trajectory and MARFE formation conditions observed
- this calls for different sensors, control algorithms and plasma state definition



Controller scheme at ASDEX Upgrade

normalized 2D distance d:

$d > d_{crit}$, safe region

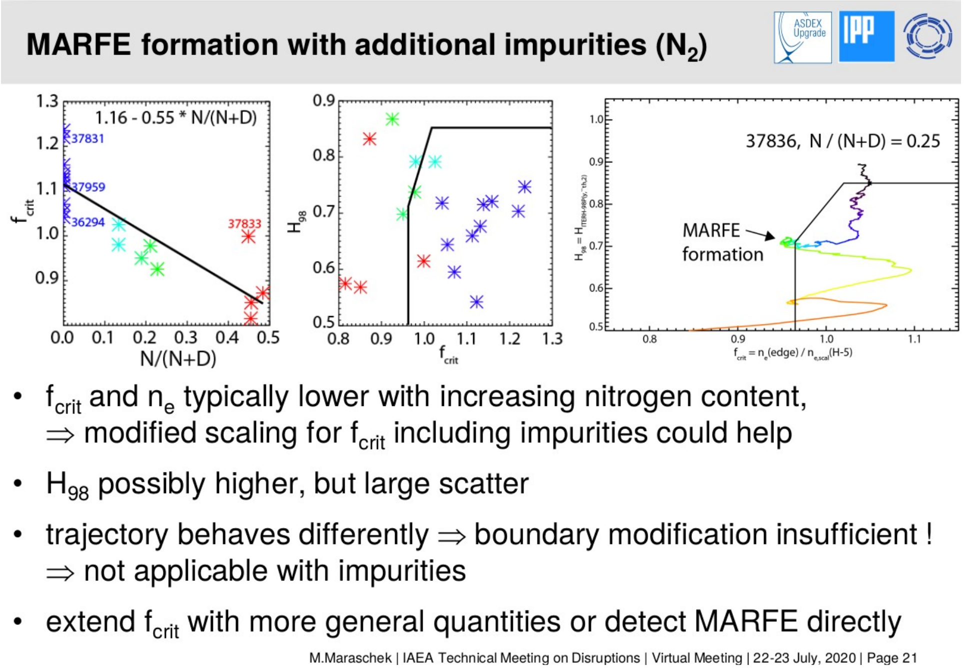
$d_{crit} > d > 0$, activation

$d \leq 0$, danger zone

- soft controller activation before reaching danger zone : actuator reaction = f(d)
  - different weight of H_{98} and f_{crit} could be considered

[Sieglin, FED. 146-B, 2019, p.1737]

M.Maraschek | IAEA Technical Meeting on Disruptions | Virtual Meeting | 22-23 July, 2020 | Page 16



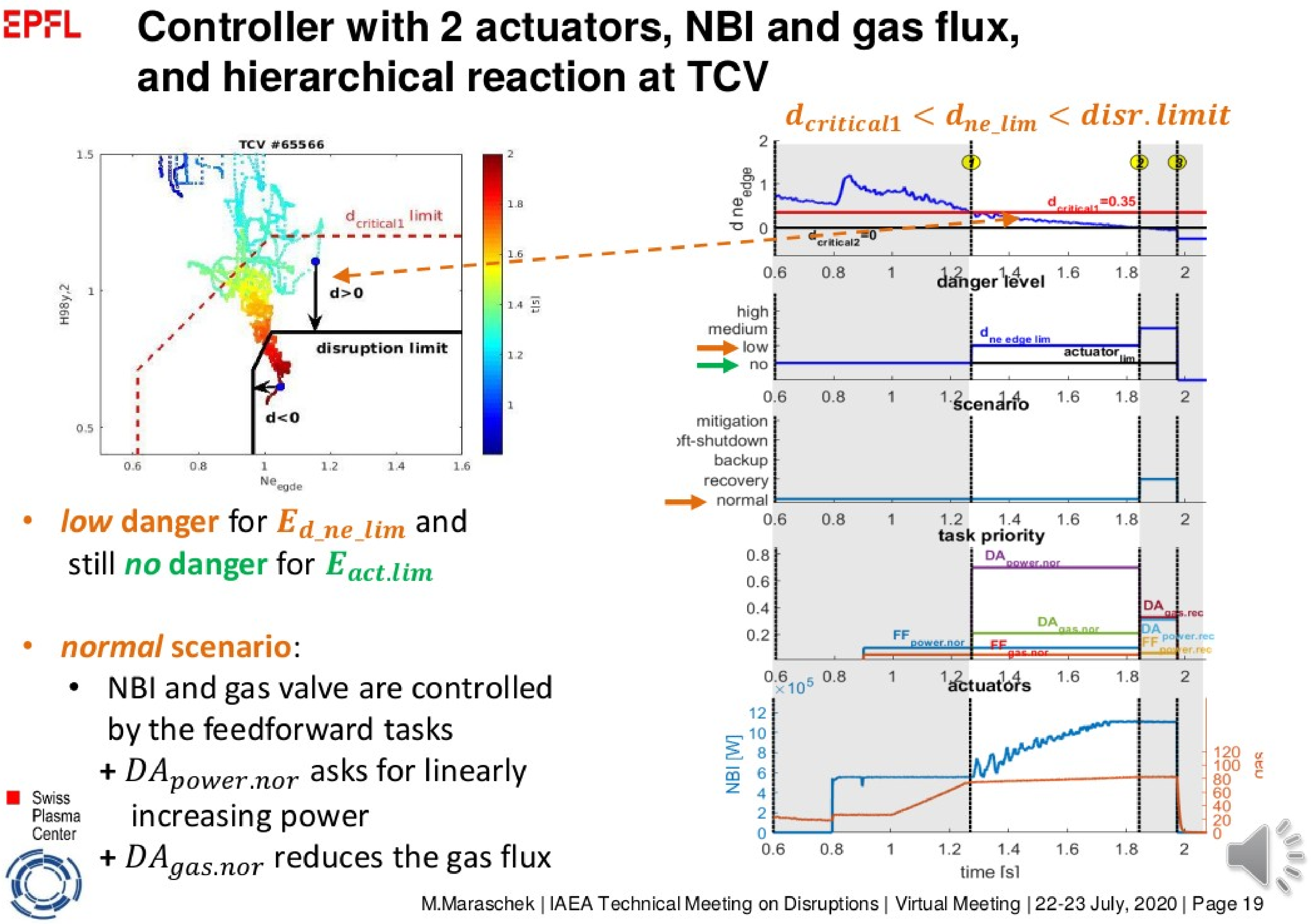
MARFE formation with additional impurities (N_2)

- f_{crit} and n_e typically lower with increasing nitrogen content, $\Rightarrow$ modified scaling for f_{crit} including impurities could help
- H_{98} possibly higher, but large scatter
- trajectory behaves differently $\Rightarrow$ boundary modification insufficient ! $\Rightarrow$ not applicable with impurities
- extend f_{crit} with more general quantities or detect MARFE directly

M.Maraschek | IAEA Technical Meeting on Disruptions | Virtual Meeting | 22-23 July, 2020 | Page 21

M. Maraschek (continue)

- Similar exp.s carried on on TCV; exception handling and use of 2 actuators



EPFL

Controller with 2 actuators, NBI and gas flux, and hierarchical reaction at TCV

$d_{critical1} < d_{ne\_lim} < disr.limit$

- *low* **danger** for $E_{d\_ne\_lim}$ and still *no* **danger** for $E_{act.lim}$

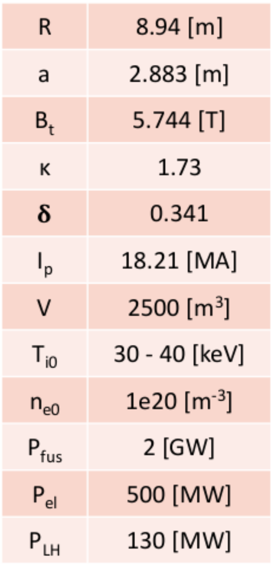
- *normal* **scenario**:
  - NBI and gas valve are controlled by the feedforward tasks
    + $DA_{power.nor}$ asks for linearly increasing power
    + $DA_{gas.nor}$ reduces the gas flux

Swiss Plasma Center

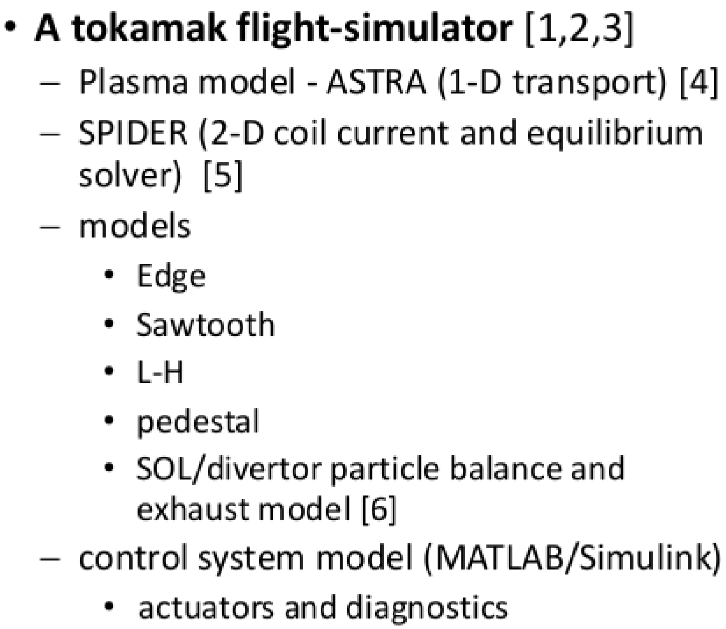
Scenario development towards DEMO and FPP

F. Janky et al., Kinetic control of a tokamak burning plasma away from disruptive events

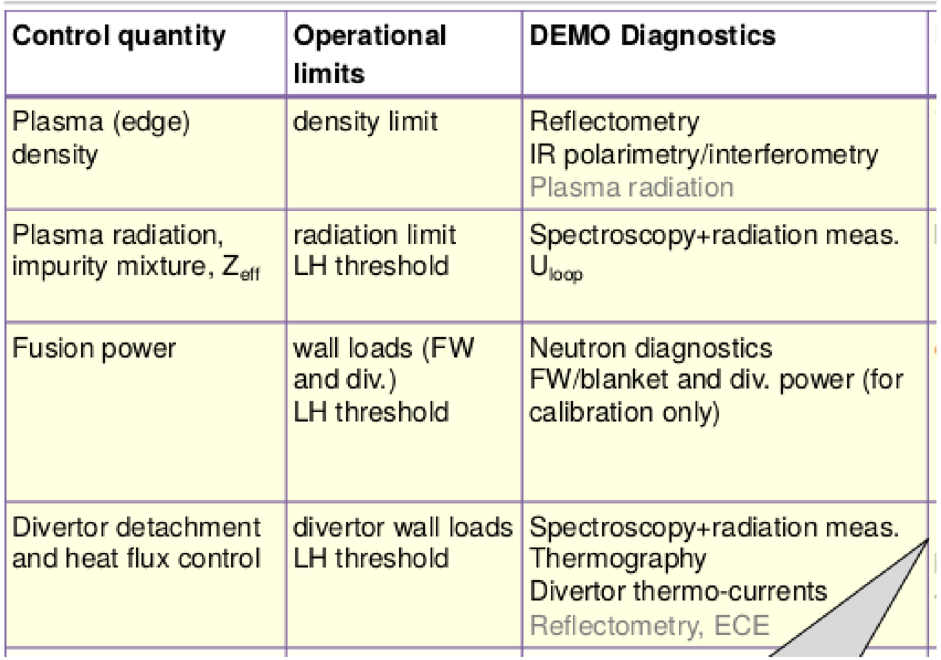
- **EU DEMO 2019 standard ELMy H-mode scenario requirements**: no disruptions and required electric power
- **PCS requirements**: continuous plasma magnetic and kinetic control (ramp up and down, flattop, L-H-L transition); plasma parameters anomaly is detected (Prad, li and ne); control of unexpected events (ufo, loss of actuator) or shut-down w/o disruption
- Simulations are required to design PCS and scenario
- **Fenix** – tokamak flight simulator for physics and control studies – is used for AUG and DEMO



R	8.94 [m]
a	2.883 [m]
B_t	5.744 [T]
κ	1.73
δ	0.341
I_p	18.21 [MA]
V	2500 [m^3]
T_{i0}	30 - 40 [keV]
n_{e0}	1e20 [m^{-3}]
P_{fus}	2 [GW]
P_{el}	500 [MW]
P_{LH}	130 [MW]



- **A tokamak flight-simulator** [1,2,3]
  - Plasma model - ASTRA (1-D transport) [4]
  - SPIDER (2-D coil current and equilibrium solver) [5]
  - models
    - Edge
    - Sawtooth
    - L-H
    - pedestal
    - SOL/divertor particle balance and exhaust model [6]
  - control system model (MATLAB/Simulink)
    - actuators and diagnostics



Control quantity	Operational limits	DEMO Diagnostics
Plasma (edge) density	density limit	Reflectometry IR polarimetry/interferometry Plasma radiation
Plasma radiation, impurity mixture, Z_{eff}	radiation limit LH threshold	Spectroscopy+radiation meas. U_{loop}
Fusion power	wall loads (FW and div.) LH threshold	Neutron diagnostics FW/blanket and div. power (for calibration only)
Divertor detachment and heat flux control	divertor wall loads LH threshold	Spectroscopy+radiation meas. Thermography Divertor thermo-currents Reflectometry, ECE

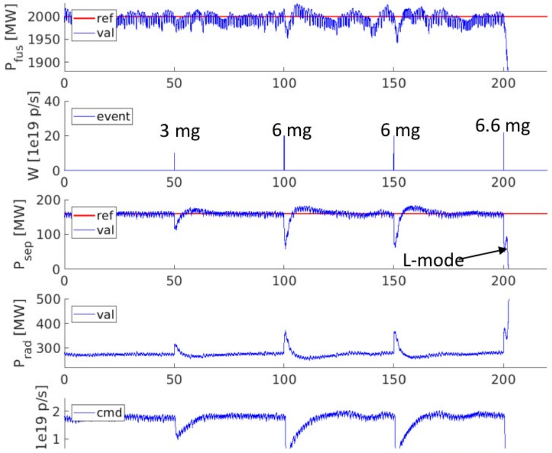
F. Janky (continue)

Causes for disruptions in DEMO

- **During different phases of the discharge:**
  - ramp-up: breakdown, variation of internal inductance, *li*, (avoid vertical displacement event - VDE), L-H transition
  - flat-top: burn control, detachment, keep the plasma inside limits
  - ramp-down: li control (avoid VDE), H-L transition
- **During the flat top phase:**
  - Sawteeth: core events, not dramatic per se, but can trigger NTMs
  - Impurity accumulation: not dramatic in a low-collisionality hot plasma
  - NTMs: need to be controlled or pre-emptively avoided
  - Pedestal events: ELMs (ELM-free scenario or very small), radiation anomalies
  - Density limit: keep density below limits at pedestal top AND separatrix
  - Loss of detachment: avoid divertor damage
- **Technical issues**
  - Failure of actuators: need redundancy as much as possible
  - Failure of diagnostics: strategy to detect it and stop plasma safely

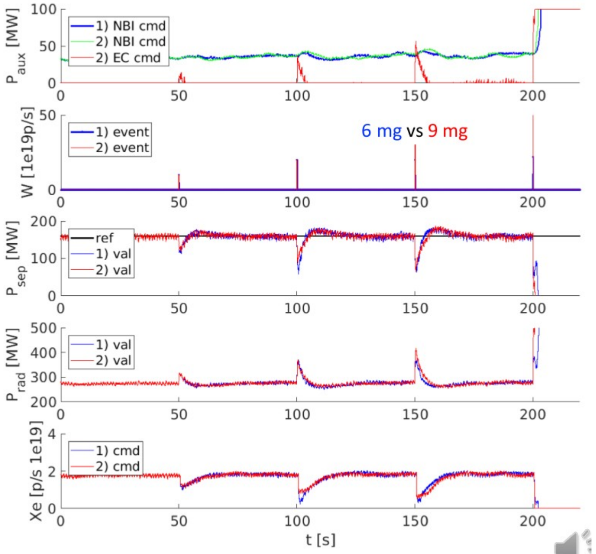
Unexpected radiation from W influx

- **Tungsten influx for from 1e19 to 2.2e19 particles/seconds (3 mg, 6 mg, 6 mg, 6.6 mg)**
- **E.g. Tungsten flake falling from the upper tiles or erosion from divertor**
- **Separatrix power controlled by Xe puff from "top" Psep (ref) = 160 MW**
- **Heuristic finding 6.6 mg**
  - W puff at the separatrix (model)
  - No rocketing effect
- **Technical and control aspects to avoid disruptions**
  - Pipes length
  - Diagnostic latencies
  - Control of pumping speed and pumping impurities is not possible
  - Stop injecting xenon is slow



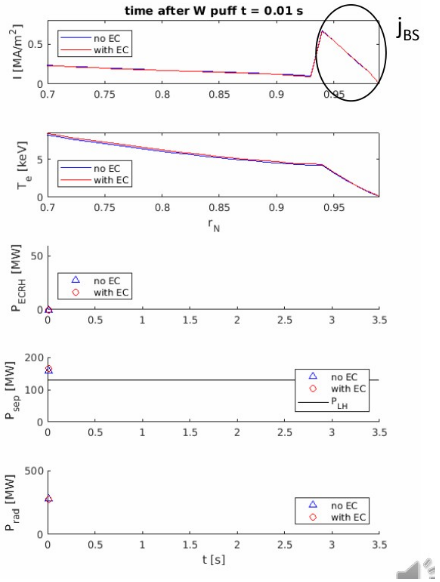
Controlled tungsten radiation event with ECRH

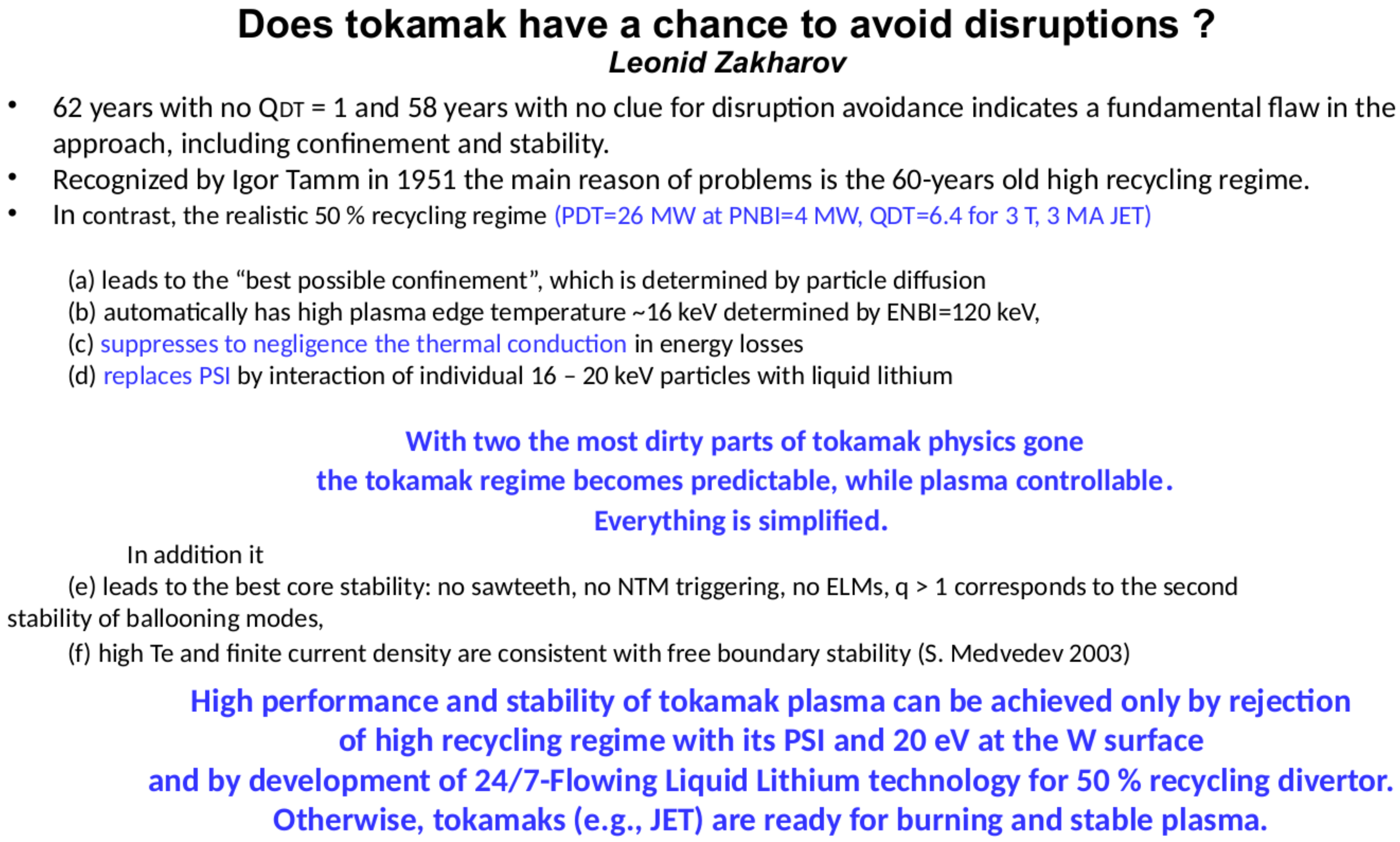
- **Tungsten influx for from 1e19 to 50e19 particles/seconds (3 mg to 6.6 mg, 3 mg to 15 mg)**
- **1) Psep controlled only from "top"**
  - *Xe puff, P_{sep} target = 160 MW*
  - Max 6 mg of tungsten
- **2) Psep control as 1) plus**
  - *Xe puff, P_{sep} target = 160 MW*
  - Max ECRH power = 100 MW
  - ECRH @ r_N 0.8 (close NTM location)
  - P_{sep} target = 140 [MW]
  - Max 9 mg of tungsten
  - Surviving ~ 50 % bigger tungsten influx



Current density and T_e profile tungsten case analysis

- **Comparison of two cases with and without ECRH control**
  - 6.6 mg vs 9 mg of tungsten
  - 0 MW ECRH vs 50 MW of ECRH at $r_N = 0.8$ if $P_{sep} < 140$ MW
  - P_{sep} controlled with xenon puff if $P_{sep} > 160$ MW in both cases
  - $P_{LH} = 130$ MW
  - $P_{sep} = P_\alpha + P_{aux} - P_{rad} - dW/dt$
    - In foreseen P_{sep} diagnostic there is missing plasma thermal stored energy derivative term
    - It is advantage for control





Does tokamak have a chance to avoid disruptions ?

Leonid Zakharov

- 62 years with no $Q_{DT} = 1$ and 58 years with no clue for disruption avoidance indicates a fundamental flaw in the approach, including confinement and stability.
- Recognized by Igor Tamm in 1951 the main reason of problems is the 60-years old high recycling regime.
- In contrast, the realistic 50 % recycling regime (PDT=26 MW at PNBI=4 MW, QDT=6.4 for 3 T, 3 MA JET)

(a) leads to the "best possible confinement", which is determined by particle diffusion
(b) automatically has high plasma edge temperature ~16 keV determined by ENBI=120 keV,
(c) suppresses to negligence the thermal conduction in energy losses
(d) replaces PSI by interaction of individual 16 – 20 keV particles with liquid lithium

With two the most dirty parts of tokamak physics gone
the tokamak regime becomes predictable, while plasma controllable.
Everything is simplified.

In addition it

(e) leads to the best core stability: no sawteeth, no NTM triggering, no ELMs, q > 1 corresponds to the second stability of ballooning modes,

(f) high Te and finite current density are consistent with free boundary stability (S. Medvedev 2003)

High performance and stability of tokamak plasma can be achieved only by rejection
of high recycling regime with its PSI and 20 eV at the W surface
and by development of 24/7-Flowing Liquid Lithium technology for 50 % recycling divertor.
Otherwise, tokamaks (e.g., JET) are ready for burning and stable plasma.

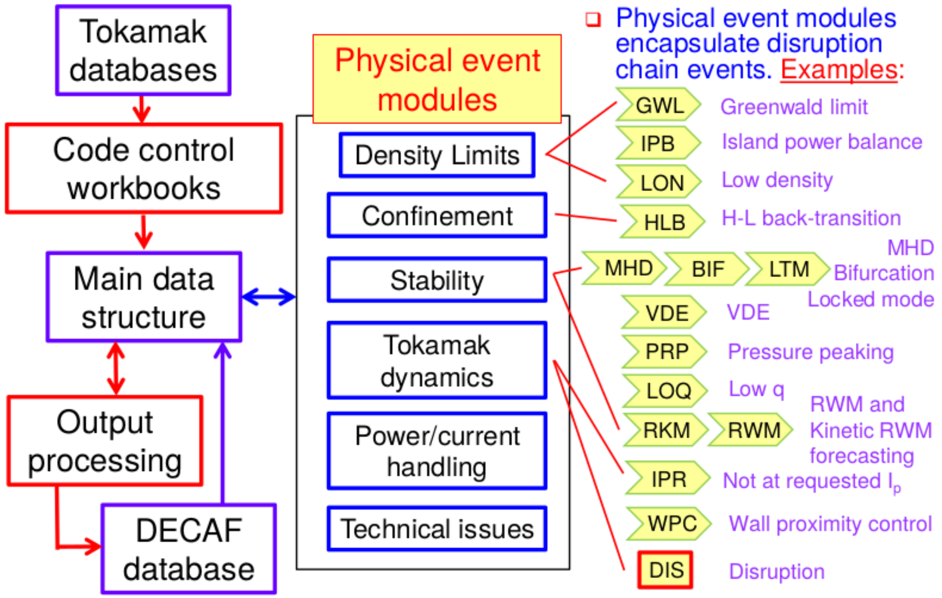
Leonid Zakhharov suggests a low recycling tokamak. Recycling is controlled to low level by Li PFCs. It is anticipated that this plasma would be free of MHD, turbulence and disruptions.

Are there turbulence calculations, MHD analysis and Tritium balance calculations in support of these theses? → discussion session

Data analysis, methods and tools, physics

S. Sabbagh et al., Progress on tokamak disruption event characterization and forecasting research and expansion to real-time application

- DECAF code: suite of routines to study pre-disruption phase (and not only)
- Originally inspired by deVries' JET disruption classification
- Routine functions
  - access to data of several devices (AUG, KSTAR, MAST-U, NSTX-U)
  - database assembly and analysis
  - event and event chain identification
  - evaluation of disruption forecasting and performance
  - use of ML tools for event analysis and building models
  - MHD mode analysis
  - stability analysis
  - rt application on KSTAR

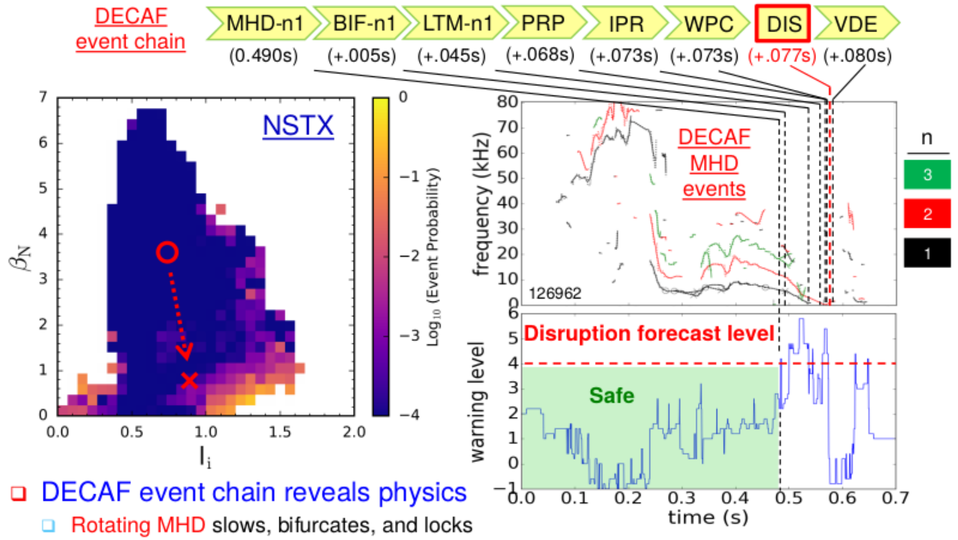


❑ Physical event modules encapsulate disruption chain events. Examples:

Tokamak databases
Code control workbooks
Main data structure
Output processing
DECAF database

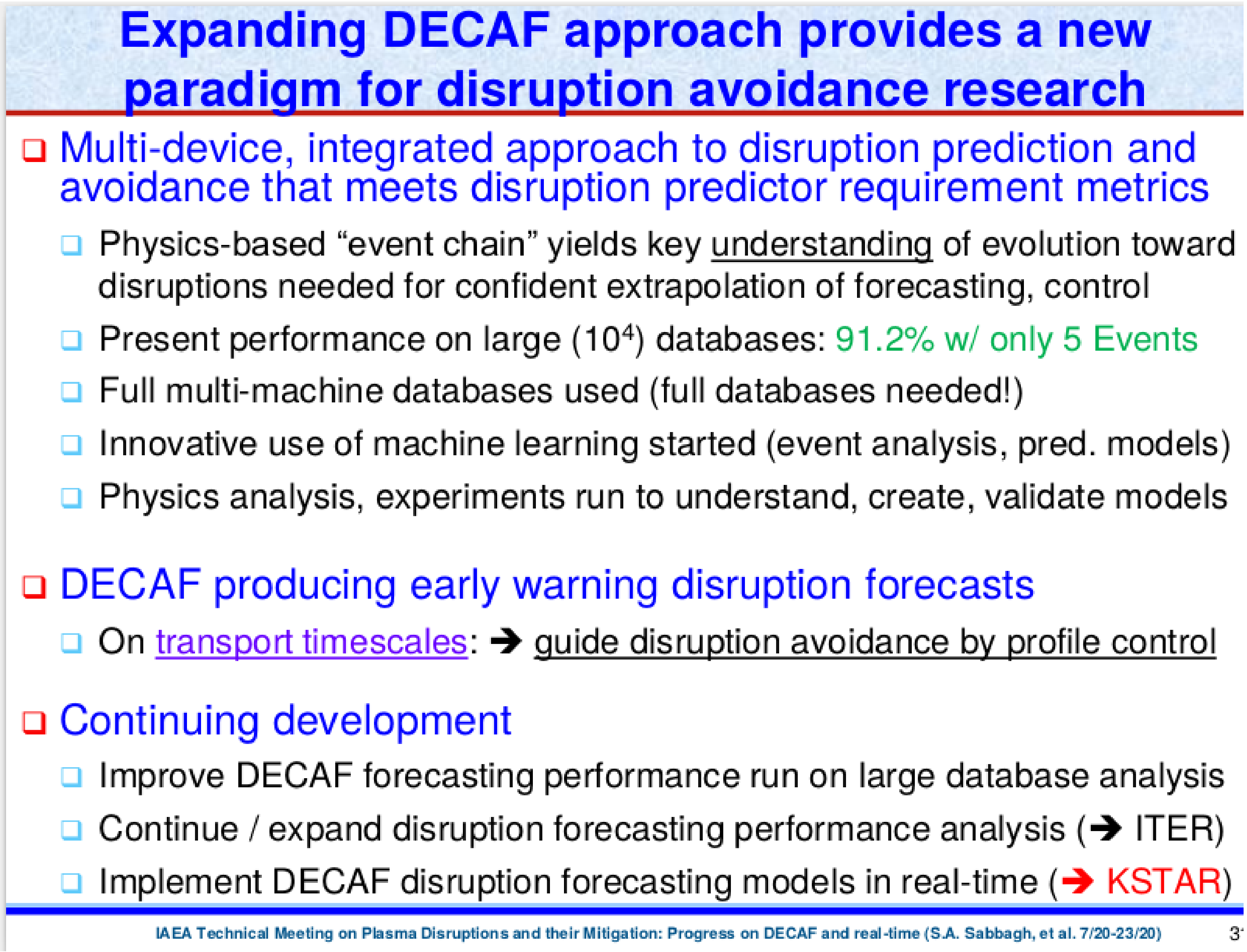
Physical event modules
Density Limits
Confinement
Stability
Tokamak dynamics
Power/current handling
Technical issues

GWL Greenwald limit
IPB Island power balance
LON Low density
HLB H-L back-transition
MHD BIF LTM MHD Bifurcation Locked mode
VDE VDE
PRP Pressure peaking
LOQ Low q
RKM RWM RWM and Kinetic RWM forecasting
IPR Not at requested I_p
WPC Wall proximity control
DIS Disruption



- ❑ DECAF event chain reveals physics
  - ❑ Rotating MHD slows, bifurcates, and locks
  - ❑ Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - ❑ Important: Early warning occurs in apparently SAFE region of operating space!

S. Sabbagh (continue)



Expanding DECAF approach provides a new paradigm for disruption avoidance research

- ☐ Multi-device, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics
  - ☐ Physics-based "event chain" yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting, control
  - ☐ Present performance on large (10^4) databases: 91.2% w/ only 5 Events
  - ☐ Full multi-machine databases used (full databases needed!)
  - ☐ Innovative use of machine learning started (event analysis, pred. models)
  - ☐ Physics analysis, experiments run to understand, create, validate models
- ☐ DECAF producing early warning disruption forecasts
  - ☐ On transport timescales: ➔ guide disruption avoidance by profile control
- ☐ Continuing development
  - ☐ Improve DECAF forecasting performance run on large database analysis
  - ☐ Continue / expand disruption forecasting performance analysis (➔ ITER)
  - ☐ Implement DECAF disruption forecasting models in real-time (➔ KSTAR)

IAEA Technical Meeting on Plasma Disruptions and their Mitigation: Progress on DECAF and real-time (S.A. Sabbagh, et al. 7/20-23/20) 3

E. Kolemen et al., Real-time prediction and avoidance of fusion plasmas instabilities using feedback control

PORTFOLIO approach to disruption avoidance

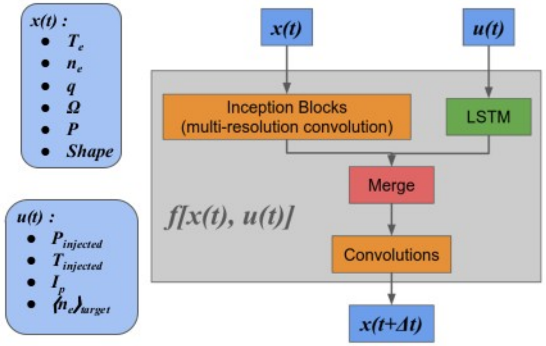
- **Automated plasma equilibrium from diagnostic**
  - automatic kinetic equilibrium reconstruction (CAKE kinetic EFIT) workflow robustly generates quality equilibria; RT Thomson + MSE and RT CER constrains current and pressure profiles → RT version running on DIII-D = basis for stability analysis

- **Tearing and disruption prediction**
  - STRIDE: RT calculation of deltaW for ideal stability calculation; STRIDE GPU implementation under development, projected to achieve 20 ms calculation time
  - STRIDE: Delta prime calculation, < 100 ms (CPU only); planned to incorporate into real time
  - Physics + ML: “Tearibility” predicting TM onset; it may allow prevention

- **ML control for disruption avoidance**
  - Using NN profile predictor for control: given plasma state and actuator imputs, predict future state and energy confinement

- **RT adapting ML prediction and control**
  - Reservoir computing network: a recurrent NN with random and sparsely connected early layers (can process temporal information, much faster and easier training procedure than DNN)

E. Kolemen (continue)

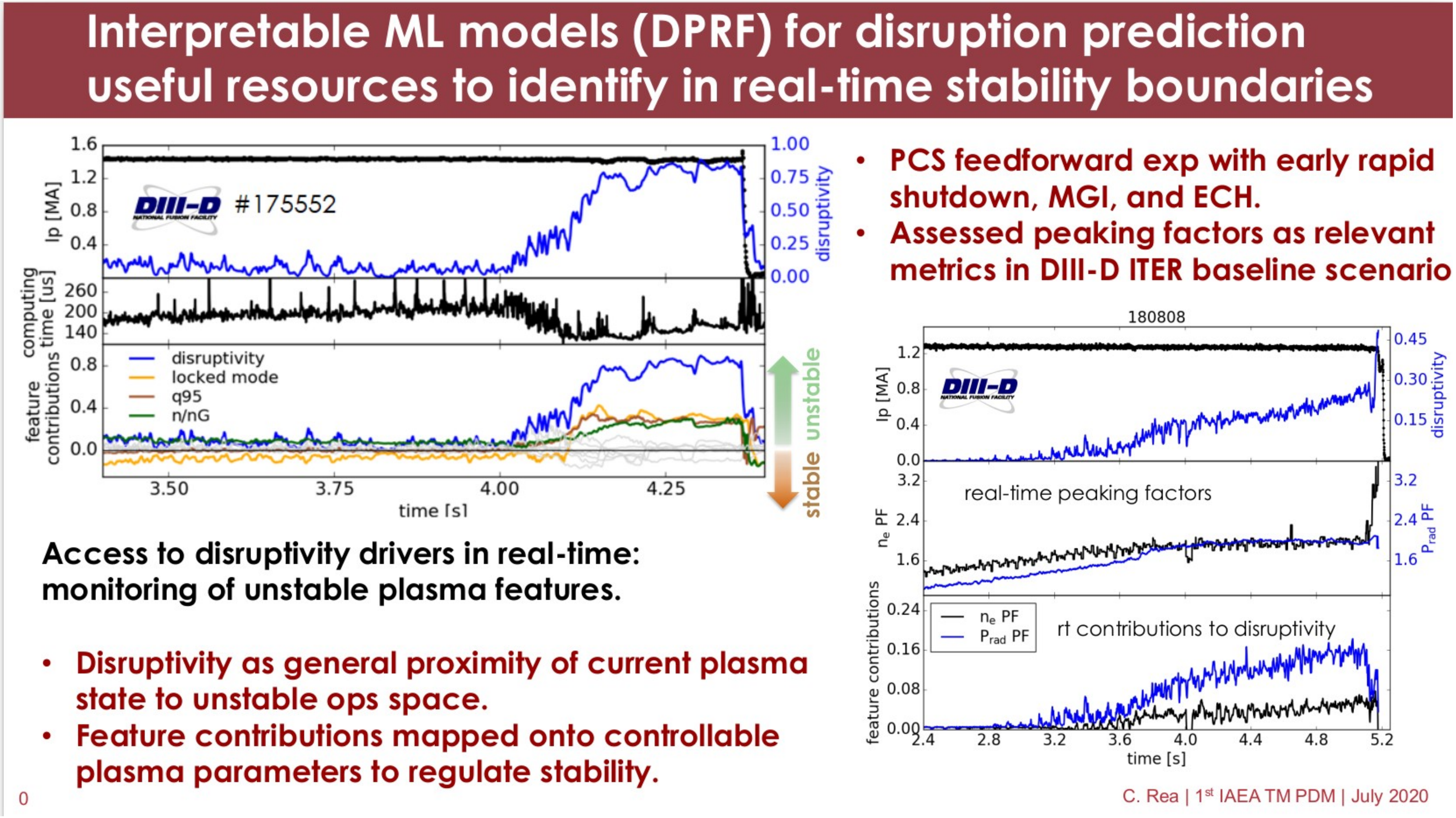


(Abbate, Conlin, NF, submitted)

Big Updates for 2020: For the people who know our research already

1. ML-based plasma evolution predictor/controller running on DIII-D
2. Real-time kinetic EFIT is functional and being tested on DIII-D
3. Keras2c ➔ Automatic NN to PCS code conversion functional
4. Real-time δW running at ~200 ms at DIII-D: Offline tests projecting to ~20 ms is using GPU, RT-Δ' in development
5. Dynamic Mode Decomposition gives good plasma evolution models
6. Big Highlight: RT-Adaptive ML proof-of-concept shown using reservoir learning. So fast ~20 ms that for ML profile predictor/controller, we can update the ML online as new data comes in

C. Rea et al., Interpretable data-driven disruption predictors to trigger avoidance and mitigation actuators on different tokamaks



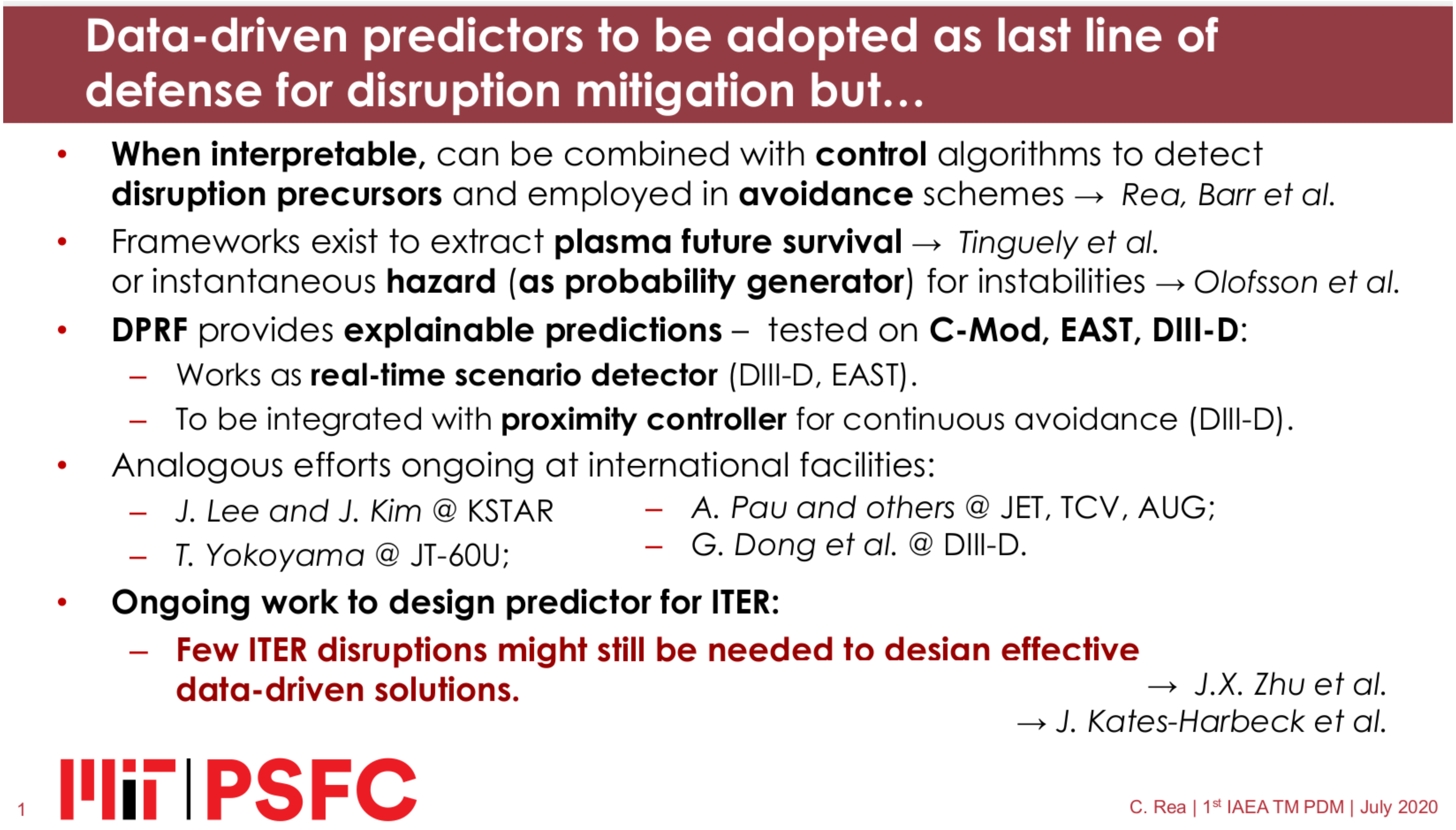
Interpretable ML models (DPRF) for disruption prediction useful resources to identify in real-time stability boundaries

- PCS feedforward exp with early rapid shutdown, MGI, and ECH.
- Assessed peaking factors as relevant metrics in DIII-D ITER baseline scenario

Access to disruptivity drivers in real-time: monitoring of unstable plasma features.

- Disruptivity as general proximity of current plasma state to unstable ops space.
- Feature contributions mapped onto controllable plasma parameters to regulate stability.

C. Rea (continue)



Data-driven predictors to be adopted as last line of defense for disruption mitigation but…

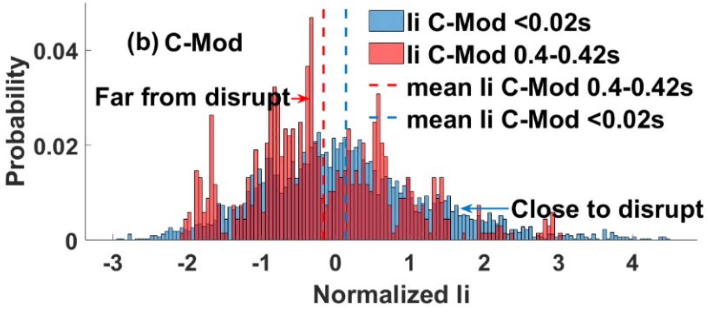
- **When interpretable**, can be combined with **control** algorithms to detect **disruption precursors** and employed in **avoidance** schemes → *Rea, Barr et al.*
- Frameworks exist to extract **plasma future survival** → *Tinguely et al.*
  or instantaneous **hazard** (**as probability generator**) for instabilities → *Olofsson et al.*
- **DPRF** provides **explainable predictions** – tested on **C-Mod, EAST, DIII-D**:
  - Works as **real-time scenario detector** (DIII-D, EAST).
  - To be integrated with **proximity controller** for continuous avoidance (DIII-D).
- Analogous efforts ongoing at international facilities:
  - *J. Lee and J. Kim* @ KSTAR
  - *T. Yokoyama* @ JT-60U;
  - *A. Pau and others* @ JET, TCV, AUG;
  - *G. Dong et al.* @ DIII-D.
- **Ongoing work to design predictor for ITER:**
  - **Few ITER disruptions might still be needed to design effective data-driven solutions.**

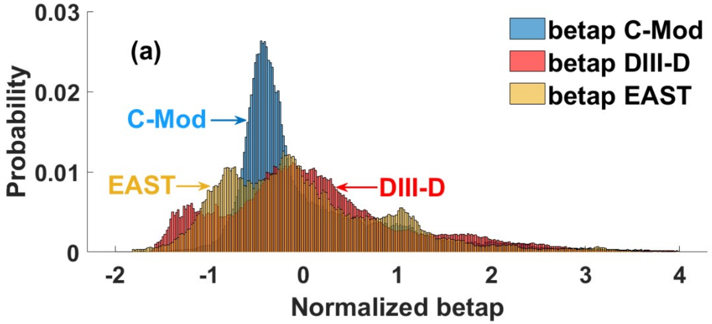
→ *J.X. Zhu et al.*
→ *J. Kates-Harbeck et al.*

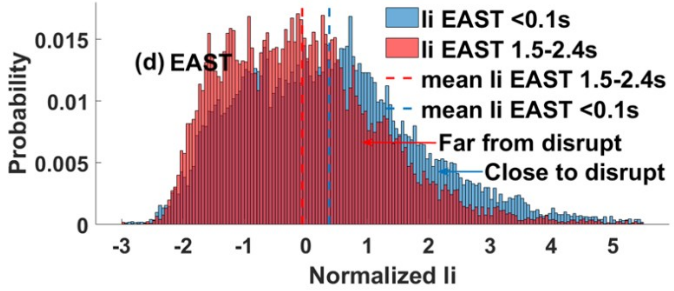
Deep Learning extracts general representations of disruptive behavior across devices

J.X. Zhu et al, "A new Deep Learning architecture for general disruption prediction across tokamaks", *this meeting*

- Numerical experiments with aggregated **DIII-D**, **C-Mod**, and **EAST** data show DL learns disruptive characteristics: **device-independent knowledge**.
- Non disruptive data results **device-specific**, not improving performances.
- **Limited disruptive** data from target device still needed for prediction, as well as **all available non-disruptive** data.



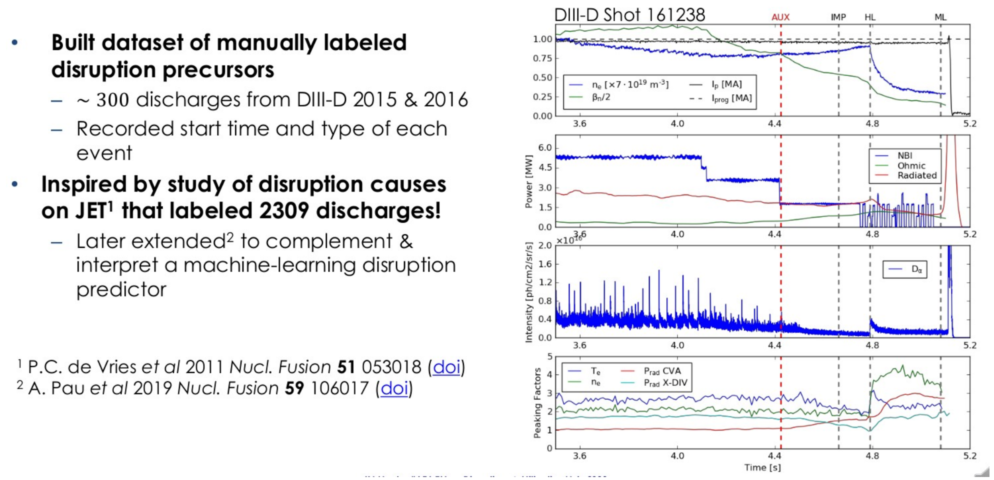




Data analysis, methods and tools, physics: Event identification

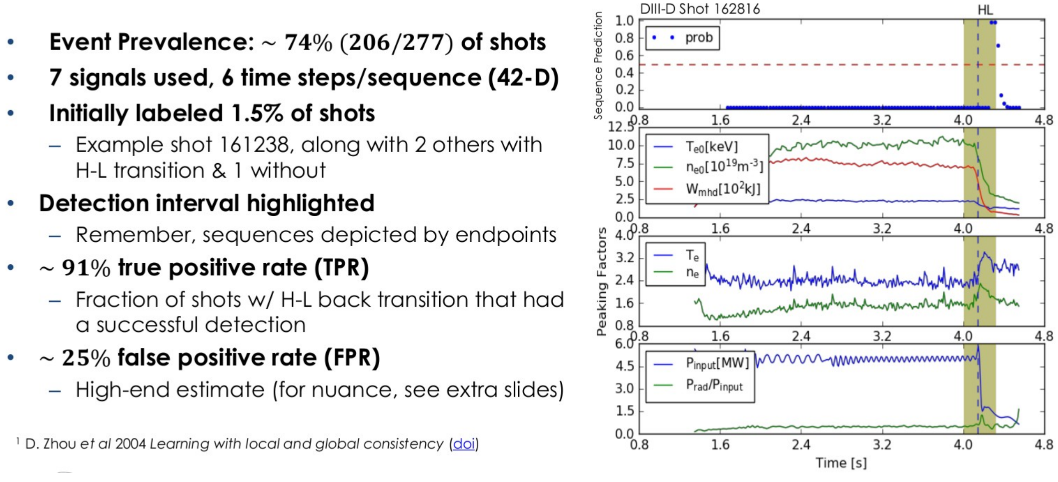
K.J. Montes et al., Accelerating Disruption Database Studies with Semi-Supervised Learning

- Algorithms able to recognize events can contribute to progress in disruption avoidance
- preparation of input for data-driven/ML algorithms is tedious
- **label spreading** allows to learn identifying event with few examples (*but proper variables*)
- requires **samples (time sequences of proper signals) some of which classified;** application uses only 1-5% of samples with *classified* labels; performance increases as labels are added
- algorithm infers classes of unclassified samples; success with H-L transition, initially rotating LM, core radiative collapses (figures show examples of events, left, and H-L event study, right)



- **Built dataset of manually labeled disruption precursors**
  - ~ 300 discharges from DIII-D 2015 & 2016
  - Recorded start time and type of each event
- **Inspired by study of disruption causes on JET[1] that labeled 2309 discharges!**
  - Later extended[2] to complement & interpret a machine-learning disruption predictor

[1] P.C. de Vries *et al* 2011 *Nucl. Fusion* **51** 053018 (doi)
[2] A. Pau *et al* 2019 *Nucl. Fusion* **59** 106017 (doi)

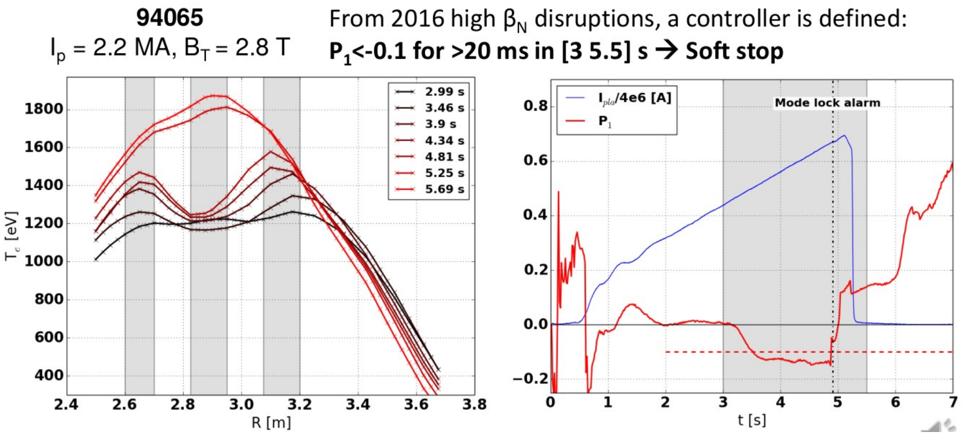


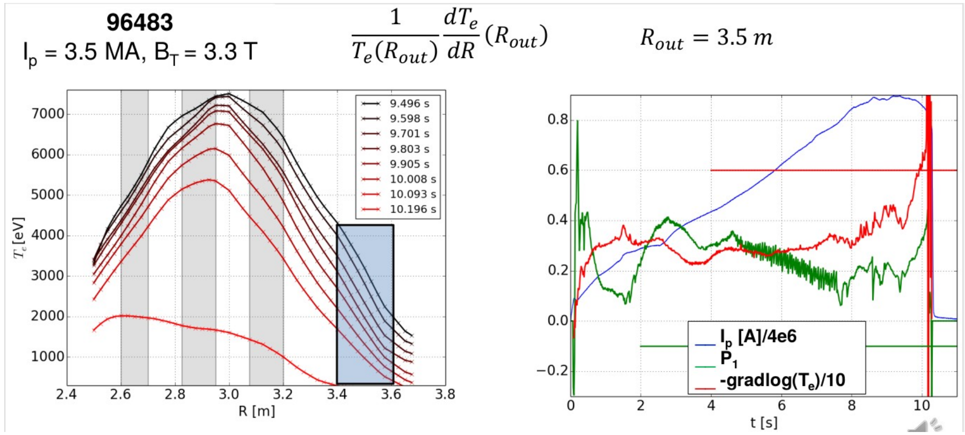
- **Event Prevalence: ~ 74% (206/277) of shots**
- **7 signals used, 6 time steps/sequence (42-D)**
- **Initially labeled 1.5% of shots**
  - Example shot 161238, along with 2 others with H-L transition & 1 without
- **Detection interval highlighted**
  - Remember, sequences depicted by endpoints
- **~ 91% true positive rate (TPR)**
  - Fraction of shots w/ H-L back transition that had a successful detection
- **~ 25% false positive rate (FPR)**
  - High-end estimate (for nuance, see extra slides)

[1] D. Zhou *et al* 2004 *Learning with local and global consistency* (doi)

M. Fontana et al., Real-time applications of electron cyclotron emission interferometry for disruption avoidance at JET

- JET ECE X-mode interferometer delivers T_e in RT
- T_e profile correlated with disruption occurrence (*proxy for current profile);* fast current ramp and impurity accumulation → hollow current profile → 2,1 TM, LM → disruption
- RT monitoring of T_e profile, peaking and edge gradient
  - $P_1 = (T_{core} - T_{edge})/T_{edge}$ → (control) → $P_1 > 1$ → safe termination
  - **P_1<-0.1 for >20 ms in [3 5.5] s → Soft stop**
  - gradlog(T_e) indicate edge cooling
- Future: combine with radiation measurements *(uncorrelated? Added information?)*

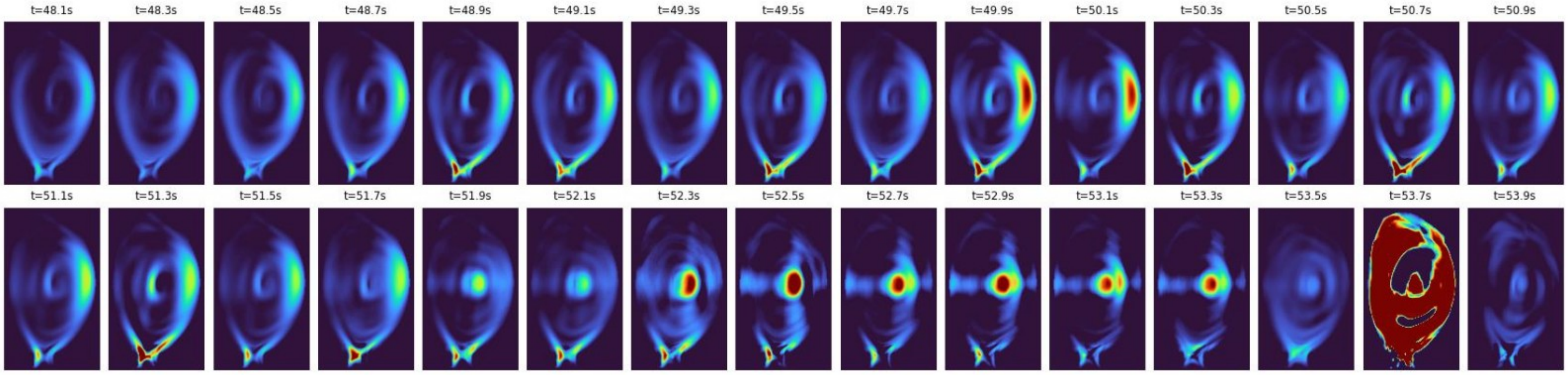




D.R. Ferreira et al.

- Impurity accumulation and core radiation, strong edge cooling w marfe, radiation collapse can precede disruptions
- can be detected e.g. fast tomographic method + ML methods for anomaly detection
- method speed matters in RT

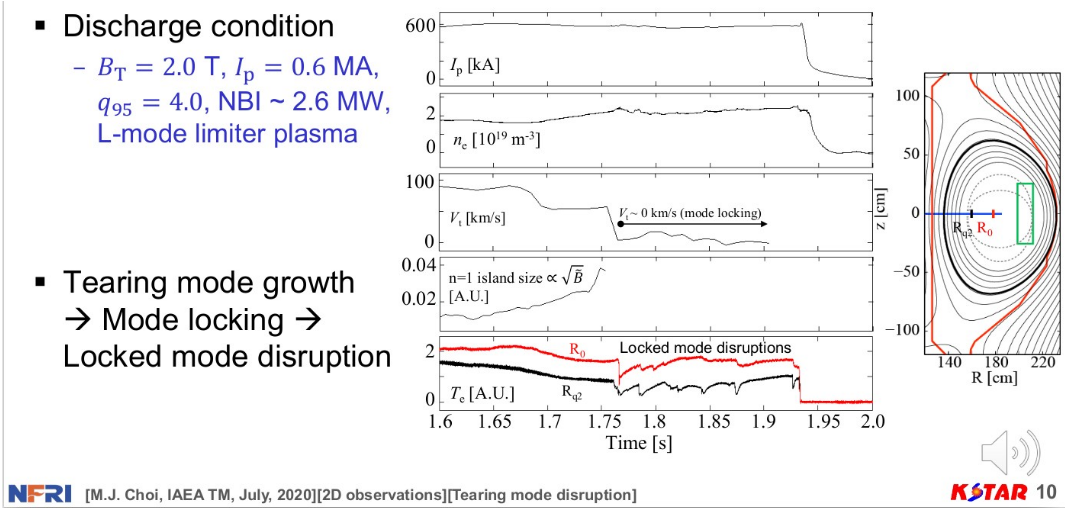
- *question to PCS: which information would be more useful for control?*



Data analysis, methods and tools, physics: locked mode phase

Minjun J. Choi et al., 2D Te patterns of various disruptive events and retardation of turbulence-associated disruption with non-resonant magnetic field

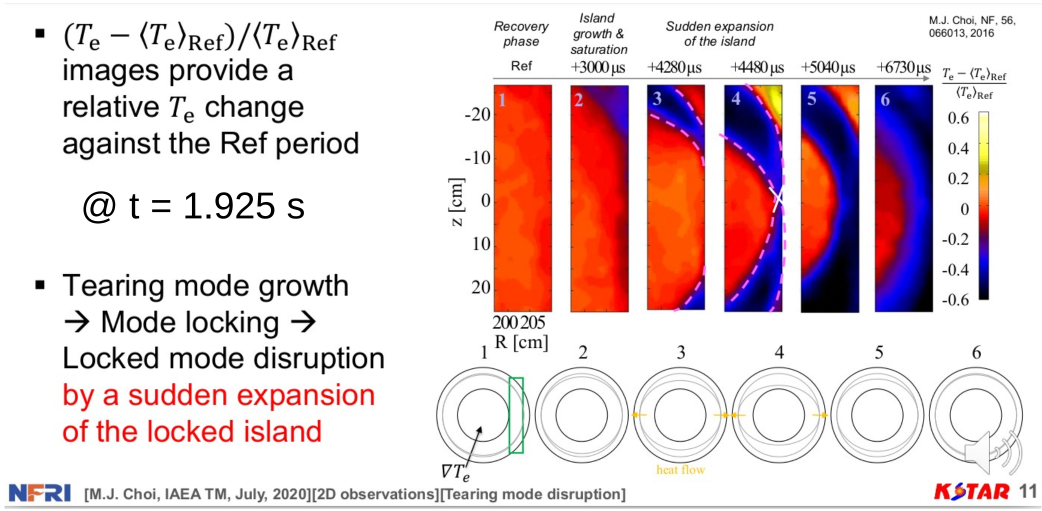
- Disruptions are caused by growth of MHD instabilities
- KSTAR has 3 ECEI (2D) systems at two toroidal positions, 2 cm and 1 micros resolution
- Observations of various disruptive events: sawtooth crash, tearing and interchange mode, king+tearing+interchange, cold bubbles, ballooning fingers, turbulence-modes-NRMP interaction
- Figures below: sudden expansion of island during LM phase
- *Physics understanding + application: TQ onset, LM phase duration (dwelling), mode structure evolution during LM are not known ↔ ITER low rotation and DMS trigger generation*



- Discharge condition
  - $B_T = 2.0$ T, $I_p = 0.6$ MA, $q_{95} = 4.0$, NBI ~ 2.6 MW, L-mode limiter plasma
- Tearing mode growth → Mode locking → Locked mode disruption

[M.J. Choi, IAEA TM, July, 2020][2D observations][Tearing mode disruption]

KSTAR 10



- $(T_e - \langle T_e \rangle_{Ref})/\langle T_e \rangle_{Ref}$ images provide a relative T_e change against the Ref period

@ t = 1.925 s

- Tearing mode growth → Mode locking → Locked mode disruption by a sudden expansion of the locked island

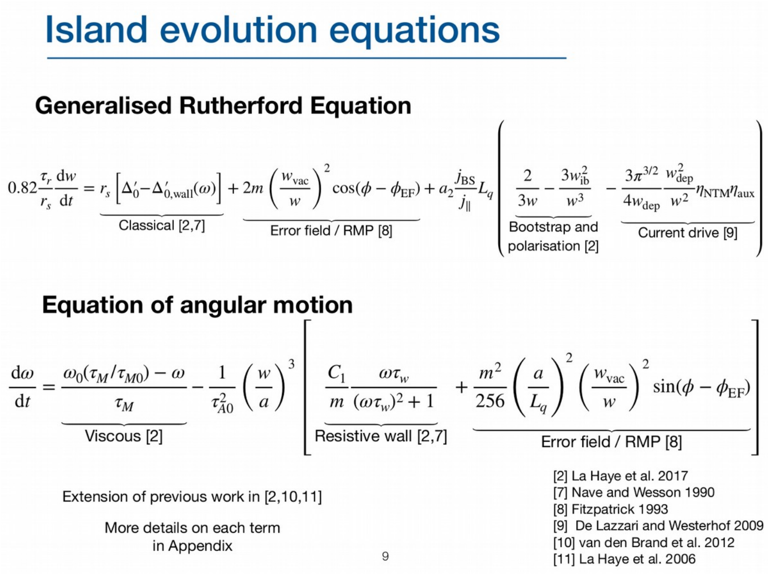
[M.J. Choi, IAEA TM, July, 2020][2D observations][Tearing mode disruption]

KSTAR 11

A. Reiman et al., Electron-cyclotron current drive stabilization of large islands could play an important role in reducing disruption frequency in ITER. RF cirrent condensation can facilitate this.

- Disruptions are preceded by large MHD modes, which lock wall (deVries et al.)
- Most large islands arises from off-normal events other than NTMs *(NTM control is not enough)*
- Fast ramp-down w LM can trigger disruption
- Need to investigate use of ECCD to stabilize large islands: **nonlinear effects can facilitate suppression**
- Sensitivity to current drive and power deposition to small Te changes can give rise to **“current condensation”** and increased stabilization efficiency
- RF current condensation motivates reevaluation of lower hybrid CD for stabilizing islands
- Simulation for use in ITER
- Need experimental study

R. Nies et al., RF current condensation with self-consistent ray-tracing and application to ITER



Island evolution equations

Generalised Rutherford Equation

$$0.82\frac{\tau_r}{r_s}\frac{\mathrm{d}w}{\mathrm{d}t} = \underbrace{r_s\left[\Delta_0' - \Delta_{0,\mathrm{wall}}'(\omega)\right]}_{\text{Classical [2,7]}} + \underbrace{2m\left(\frac{w_{\mathrm{vac}}}{w}\right)^2\cos(\phi - \phi_{\mathrm{EF}})}_{\text{Error field / RMP [8]}} + a_2\frac{j_{\mathrm{BS}}}{j_{\|}}L_q\left(\underbrace{\frac{2}{3w} - \frac{3w_{\mathrm{ib}}^2}{w^3}}_{\text{Bootstrap and polarisation [2]}} - \underbrace{\frac{3\pi^{3/2}}{4w_{\mathrm{dep}}}\frac{w_{\mathrm{dep}}^2}{w^2}\eta_{\mathrm{NTM}}\eta_{\mathrm{aux}}}_{\text{Current drive [9]}}\right)$$

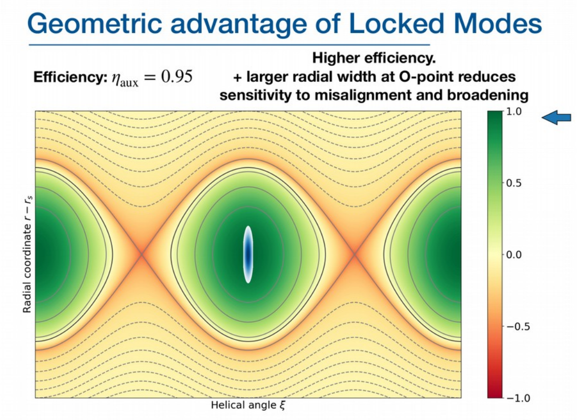
Equation of angular motion

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \underbrace{\frac{\omega_0(\tau_M/\tau_{M0}) - \omega}{\tau_M}}_{\text{Viscous [2]}} - \frac{1}{\tau_{A0}^2}\left(\frac{w}{a}\right)^3\left[\underbrace{\frac{C_1}{m}\frac{\omega\tau_w}{(\omega\tau_w)^2 + 1}}_{\text{Resistive wall [2,7]}} + \underbrace{\frac{m^2}{256}\left(\frac{a}{L_q}\right)^2\left(\frac{w_{\mathrm{vac}}}{w}\right)^2\sin(\phi - \phi_{\mathrm{EF}})}_{\text{Error field / RMP [8]}}\right]$$

Extension of previous work in [2,10,11]

More details on each term
in Appendix

[2] La Haye et al. 2017
[7] Nave and Wesson 1990
[8] Fitzpatrick 1993
[9] De Lazzari and Westerhof 2009
[10] van den Brand et al. 2012
[11] La Haye et al. 2006



Geometric advantage of Locked Modes

Efficiency: $\eta_{\mathrm{aux}} = 0.95$

Higher efficiency.
+ larger radial width at O-point reduces sensitivity to misalignment and broadening

- Advantages of LM stabilisation: dynamical (fast locking ⇒ rotating island stabilisation is hard + w_{lock} is small) and geometrical (higher stabilisation efficiency, less sensitive to misalignment and broadening).

- Stabilisation of small LMs is efficient (lower EC power) and robust (no problem with large w_{seed}, detection threshold).

- A lot of attention on rotating island stabilisation, comparatively little for locked modes [4, 5, 12]. Let us correct that.

- Open questions: are small LMs a problem for confinement? Optimisation for ITER and beyond - launching angles, combined strategies, low rotation scenarios, …? Importance of current condensation (See also presentation by A.H. Reiman)? How reliable for disruption avoidance in experiment?

[4] Volpe et al. 2015
[5] Nelson et al. 2020
[12] Yu and Guenter 2008

A. Murari et al., Investigating the physics of the tokamak operation boundaries using machine learning tools

- Critical introduction on past and future use of ML tools for disruption P&A.
- Revisiting pre-TQ LM amplitude. Formula → (P. de Vries et al.) does not perform well: why?

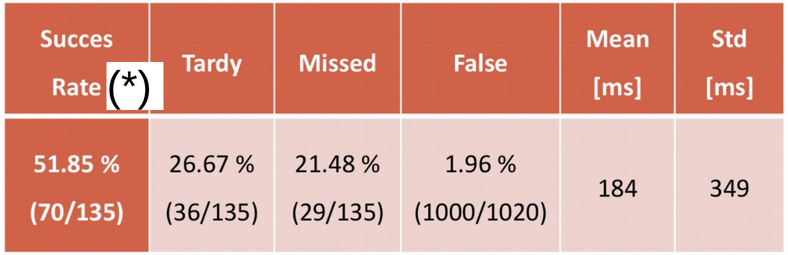
$$B_{ML}(r_c) = c \cdot I_P^{a_I} \cdot a^{a_a} \cdot q_{95}^{a_q} \cdot li(3)^{a_{li}} \cdot \rho_c^{a_\rho}$$

- Method: probabilistic SVM (→ right figure) + symbolic regression via genetic programming
- Variables are informative but $\mathrm{LM} = 0.475 - 0.017 \cdot y^{0.95} - 0.014 \cdot x^{1.00}$ (no power law)
- *Physics interpretation? ↔ ITER low rotation and DMS trigger generation*

$x = li[H]$

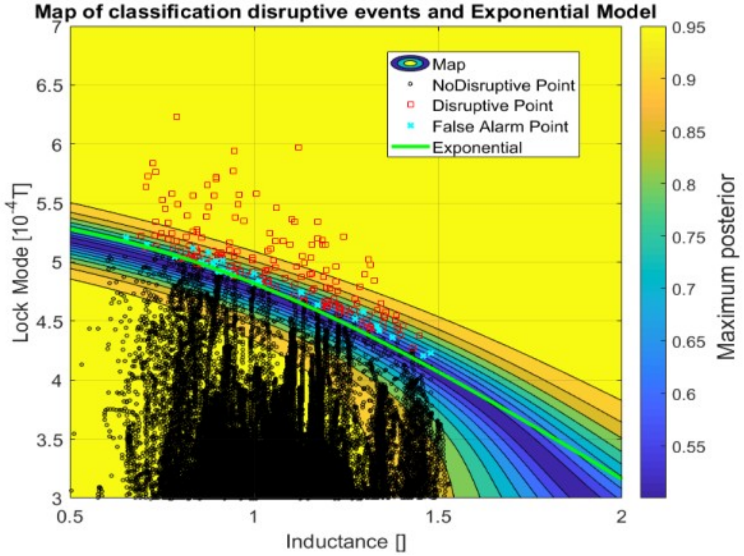
$y = \mathrm{q95}$

$z = \mathrm{LM[mT]}$



Succes Rate (*)	Tardy	Missed	False	Mean [ms]	Std [ms]
51.85 % (70/135)	26.67 % (36/135)	21.48 % (29/135)	1.96 % (1000/1020)	184	349

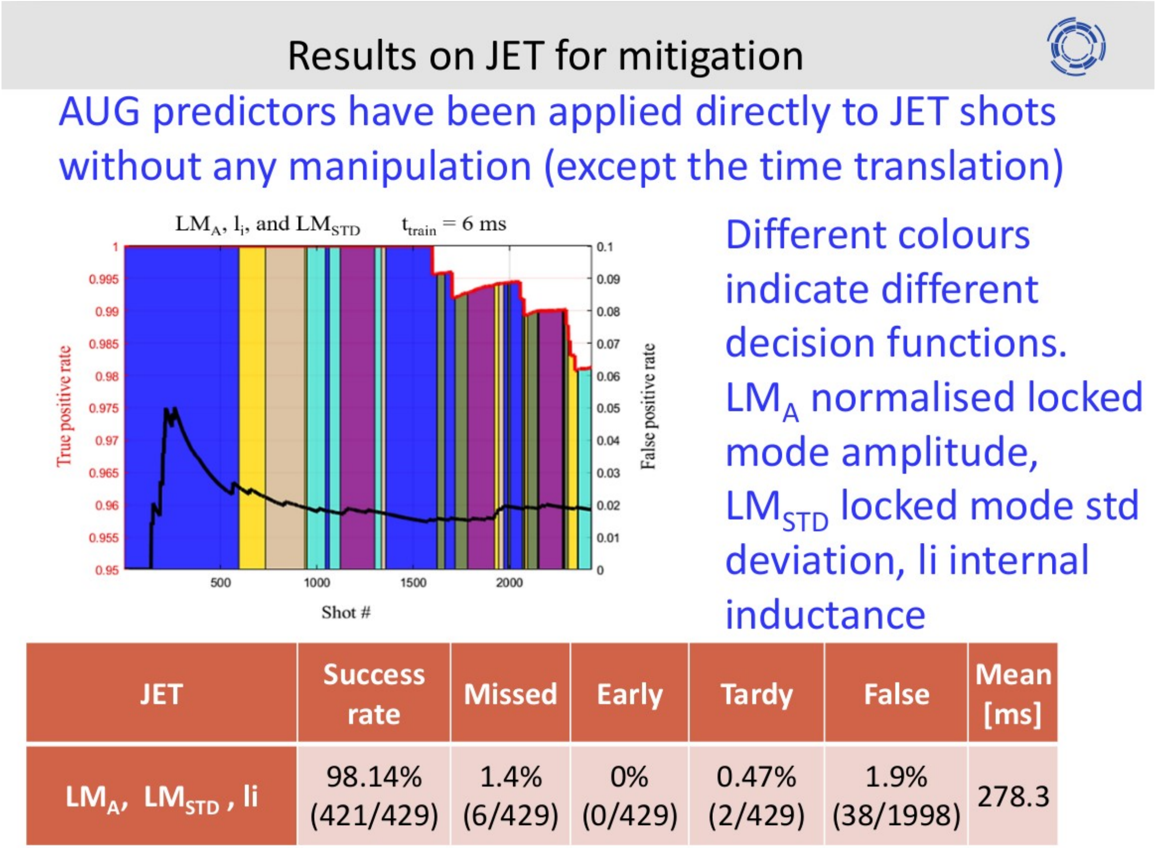
Method	Success Rate	Missed	Early	Tardy	False
SVM and SR via GP	91.7% (156/170)	1.2% (2/170)	0% (0/170)	7.1% (12/170)	2.3% (23/987)



Data analysis, methods and tools, physics: learning whole operational space

M. Gelfusa et al., On the potential of adaptive predictors and their transfer between different devices for both mitigation and prevention of disruptions

- She uses methods of **adaptive learning** and has been quite successful in predicting ILW JET disruptions after training on ASDEX Upgrade. Good fall-back solution for ITER.
- Types of adaptation: trajectory learning during discharge; updates of training set (error in output or obsolete sample) and modification of decision functions between discharges
- Different decision functions are run in parallel and one with best (?) results generates alarm
- Variables used →



Results on JET for mitigation

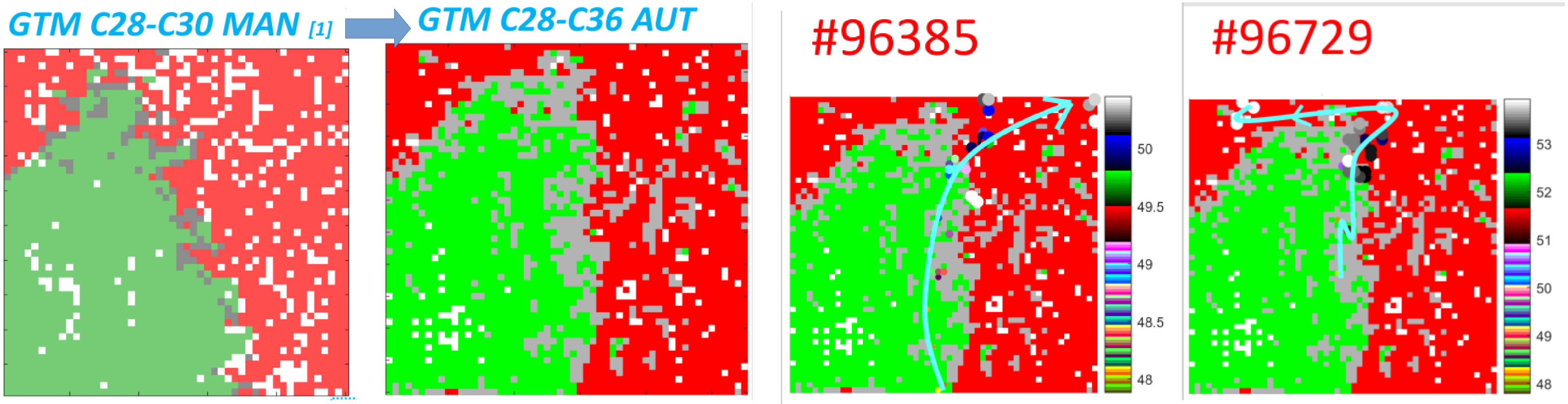
AUG predictors have been applied directly to JET shots without any manipulation (except the time translation)

Different colours indicate different decision functions. LM$_A$ normalised locked mode amplitude, LM$_{STD}$ locked mode std deviation, li internal inductance

JET	Success rate	Missed	Early	Tardy	False	Mean [ms]
LM$_A$, LM$_{STD}$, li	98.14% (421/429)	1.4% (6/429)	0% (0/429)	0.47% (2/429)	1.9% (38/1998)	278.3

E. Aymeric et al., Continuous update of machine learning disruption prediction and prevention models at JET

- GTM (generative topographic map) is used to 2D-map non-disruptive and pre-disruption phases of JET discharges
- Evolving operational space suggests updating of maps (done, fig.s below); large fraction of recent disruptions are preceded by impurity accumulation; pre-disruption phase chosen automatically → **continuous update**
- Variables: $T_{e,pf}$, $n_{e,pf}$, $Rad_{pf\text{-}CVA}$, $Rad_{pf\text{-}XDIV}$, li, PFRAC
- *Possible use in PCS to trigger JET DMS? Suitable for avoidance? Extrapolation to other devices?*



[1]: A.Pau et al., Nucl. Fusion 2019, 106017 (22pp)

Discussion follows