PRINCETON PLASMA PHYSICS LABORATORY

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Introduction for the KSTAR project
"Integrated 3D-edge Long-pulse Tokamak Scenarios – Extended with Core Instability and Transport Control"

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On the behalf of collaborators in
Columbia University, Princeton University,
Lawrence Livermore National Laboratory, General Atomics,
University of Wisconsin – Madison, University of California – San Diego

Magnetic Fusion Meeting
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Project Objectives

- Integrate the predictive capabilities of non-axisymmetric (3D) field physics into core scenario optimizations
- Demonstrate the scientific feasibility of 3D magnetic perturbations for transport and instability control in long-pulse high-performance tokamak plasmas
  - Will leverage 2020-2022 progress on RMP ELM suppression
  - Will utilize many predictive simulations
    - GPEC, MARS, TM1, JOREK, M3D-C1, NIMROD, BOUT++, EMC3-EIRENE, GTC
  - Will collaborate on DIII-D, AUG, EAST as well for universal physics validations
  - Will use KSTAR as a focus device for core-edge integration and demonstration
    - KSTAR as a testbed for 3D TRANSP

Project will follow 3 thrusts with PPPL taking main part of KSTAR collaborations

AUG, EAST, DIII-D collaborations, ITER applications

Thrust 1: 3D field physics basis for ELM control (database, model, validation)

Thrust 2: Integrated 3D tokamak scenario (3D TRANSP, transport and flux optimization)

Thrust 3: ELM-free H-mode demonstration (long pulse up to 300s, high performance β_N>2.0)

Centered around KSTAR with tungsten divertors

- PPPL will be the main counterpart of KSTAR
  - By providing profile and equilibrium reconstructions for simulations
  - By providing diagnostic data in collaborations with KSTAR
  - By optimizing scenarios under 3D fields and conducting experiments

Upgraded long-pulse capabilities in 2023-2025 will be valuable to US

2008 — *Phase I* → **2017**

First plasma (ECH 84 GHz)

Long-pulse H-mode (NBI~5.5 MW) (ECH~1 MW)

Long-pulse H-mode research
- *Long pulse H-mode (>70s)*
- *ELM research & control (>30s)*
- *Alternative operation modes (ITB, low q, ..)*

2017 — *Phase II* → **2021**

Heating & CD Upgrade (NBI~12 MW) (ECH~6 MW)

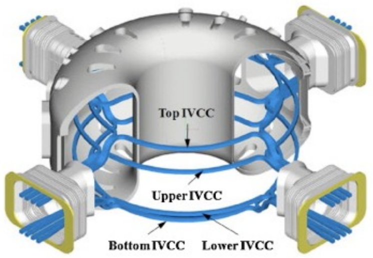
Advanced scenario & MHD research
- *Core-Edge Integrated high-beta operation*
  - *ELM control with cool divertor*
  - *β_N>3.0, T_{ion} ~ 10 keV, active profile control)*
- *MHD & disruption control (AEs, TMs)*
  - *Model-based adaptive control (DECAF & AI)*
- *Explore advanced scenario (Hybrid, low-q ITB)*

2021 — *Phase III* → **2025 ~**

Divertor upgrade (Tungsten divertor)

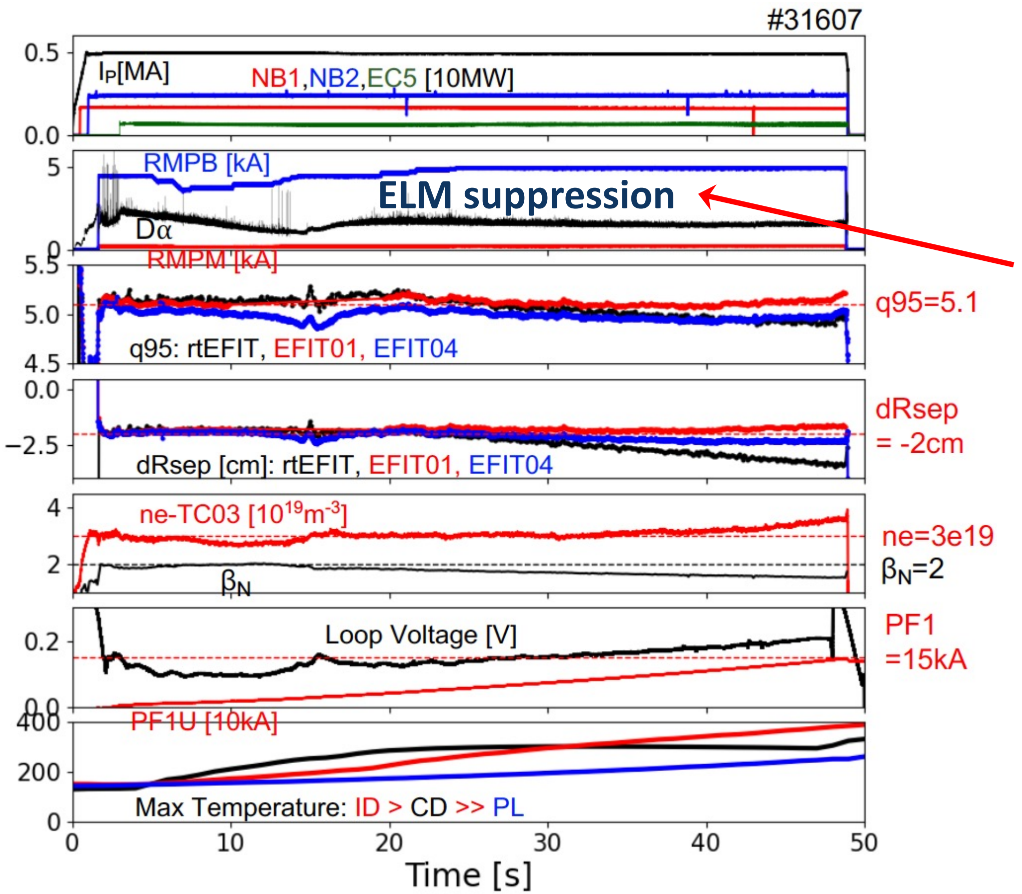
Advanced current drive (4 MW of LHCD or Helicon-CD)

Reactor relevant scenario research
- *Actively cooled metal divertor (ITER grade)*
- *Advanced current drive under test (HFS LHCD & Helicon CD)*
- *Steady-state (β_N>3.0) operation (~300s)*



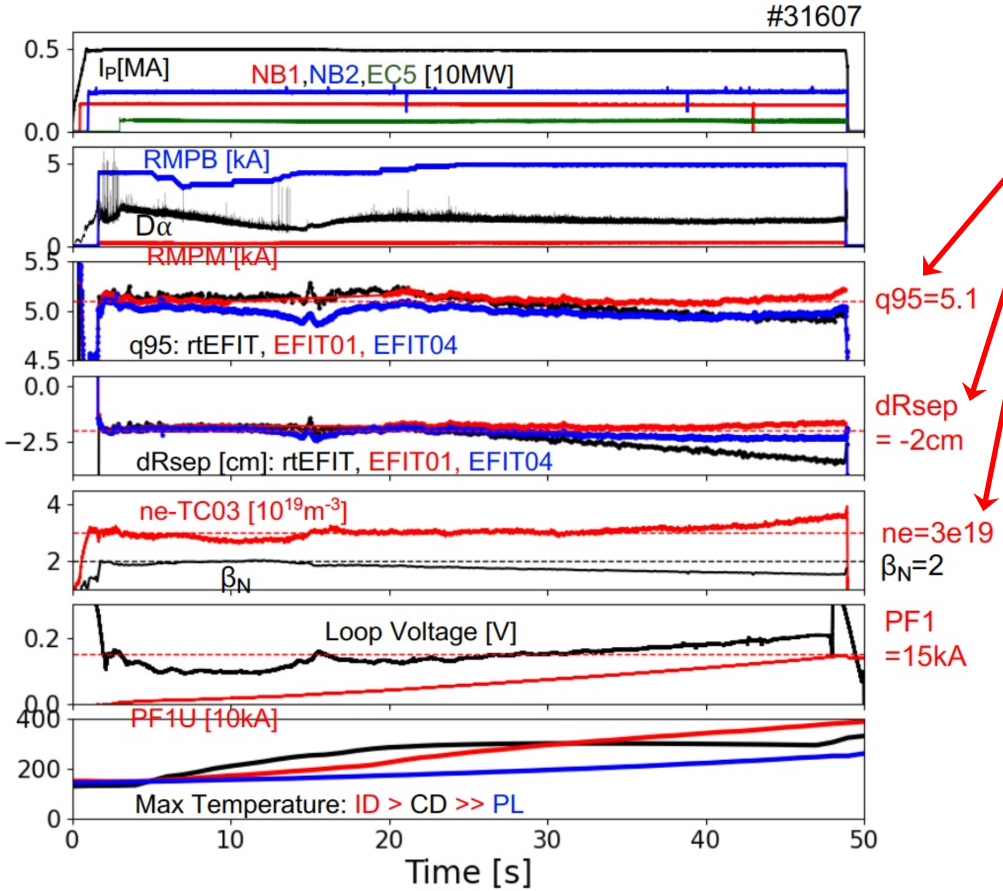
KSTAR plans to complete upgrade next year and have 2023 campaign, and 2024, 2025 campaigns

RMP ELM suppression in long pulse requires strong scheme integration



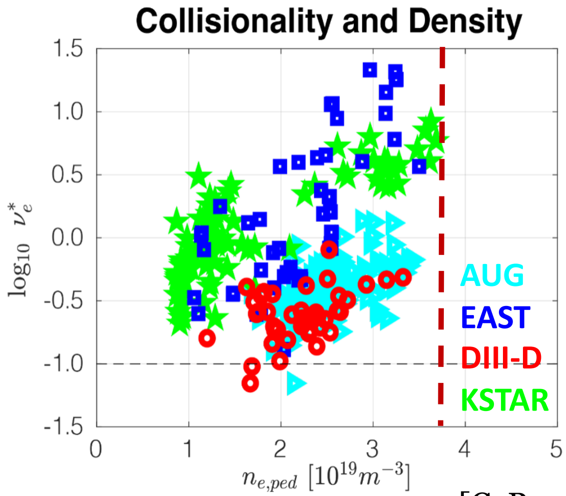
- 2020-2022 KSTAR project progress has been highlighted by
  - 45s long pulse
  - with ELMs suppressed or mitigated
  - in entire H-mode period
  - using many RMP schemes

RMP ELM suppression in long pulse requires strong scheme integration



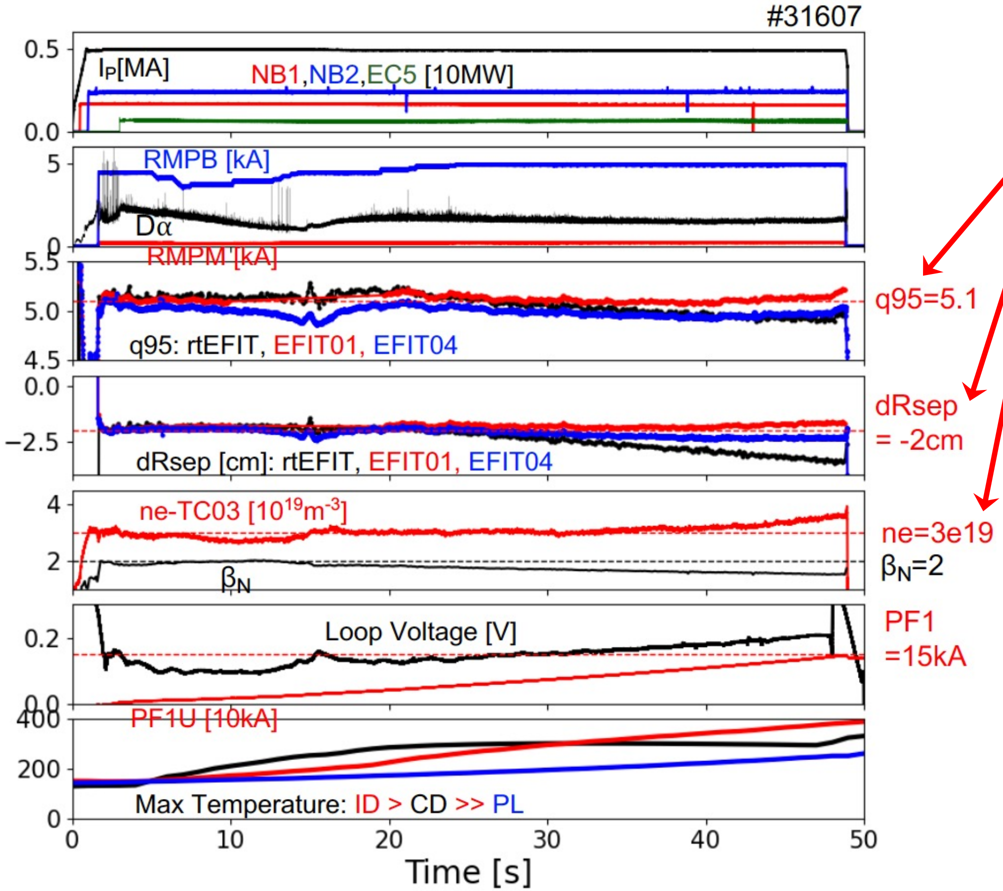
- It is critical to match and maintain accessibility conditions
  - q95, shape, density, rotation

Ex) 2020-22 project and CU shows



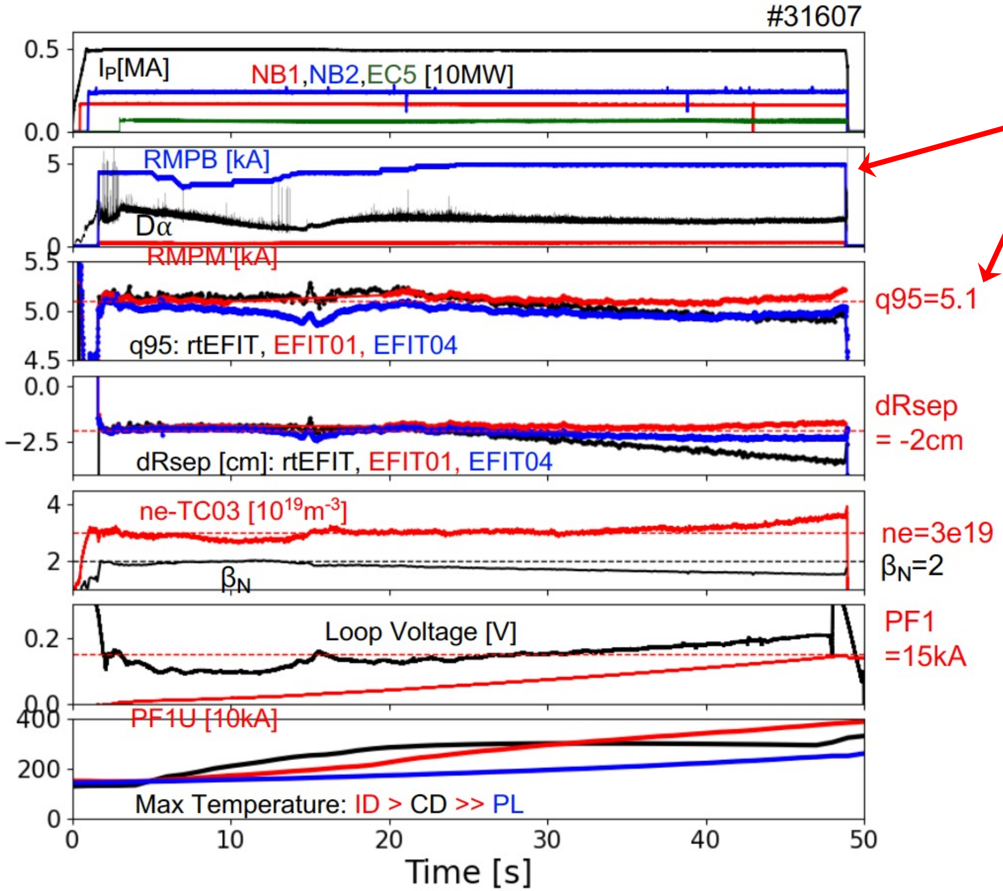
[C. Paz-Soldan]

RMP ELM suppression in long pulse requires strong scheme integration



- It is critical to match and maintain accessibility conditions
  - q95, shape, density, rotation
- Thrust 1: Continue to develop international RMP database to understand and predict accessibility (CU, PPPL)

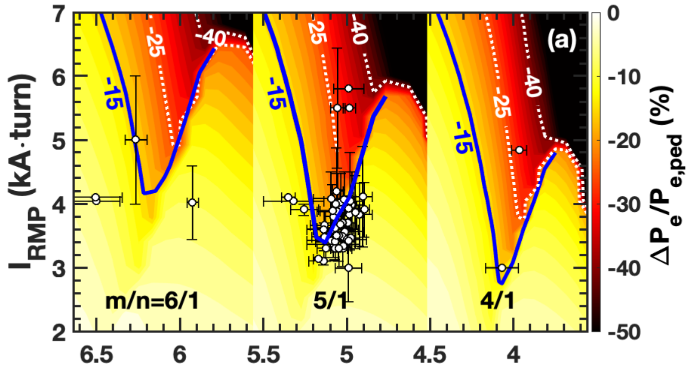
RMP ELM suppression in long pulse requires strong scheme integration



- Needs to predict RMP thresholds for ELM suppression in the optimized target

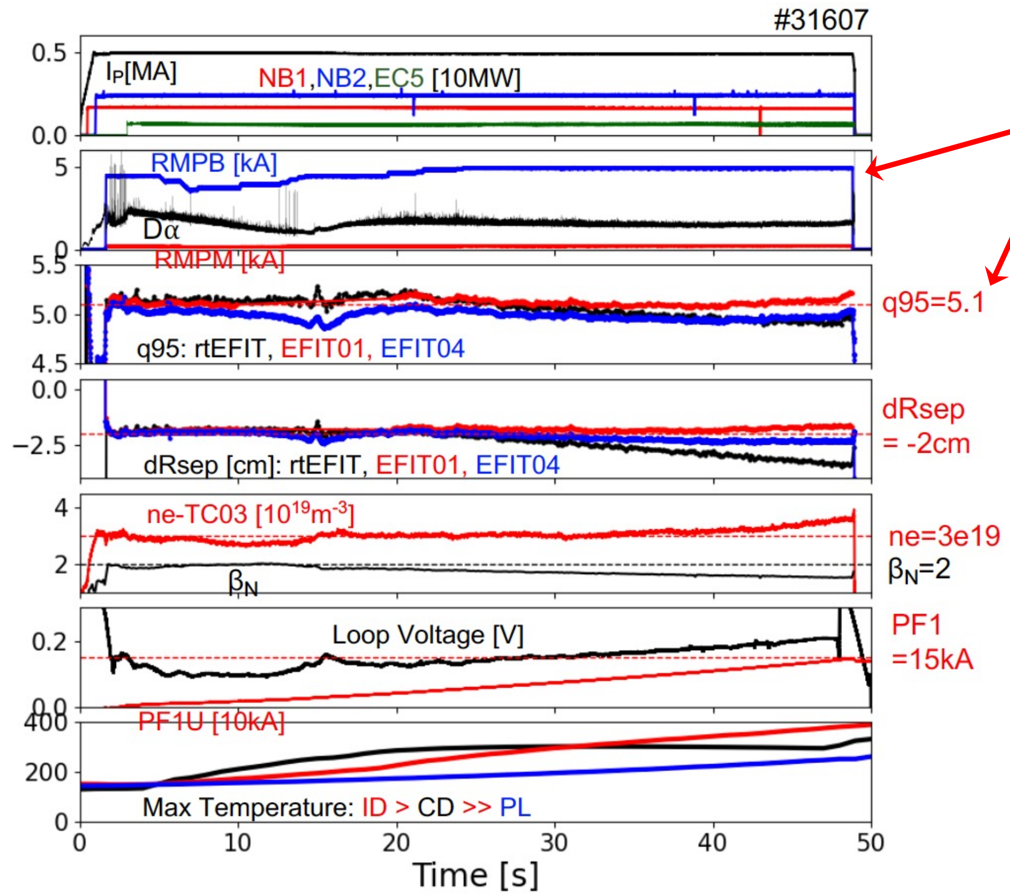
Ex) 2020-22 project and PPPL shows

$$\frac{\delta B_{51}}{B_{T0}} \propto n_e^{0.62} B_{T0}^{-1.05} T_e^{0.6} \omega_E$$



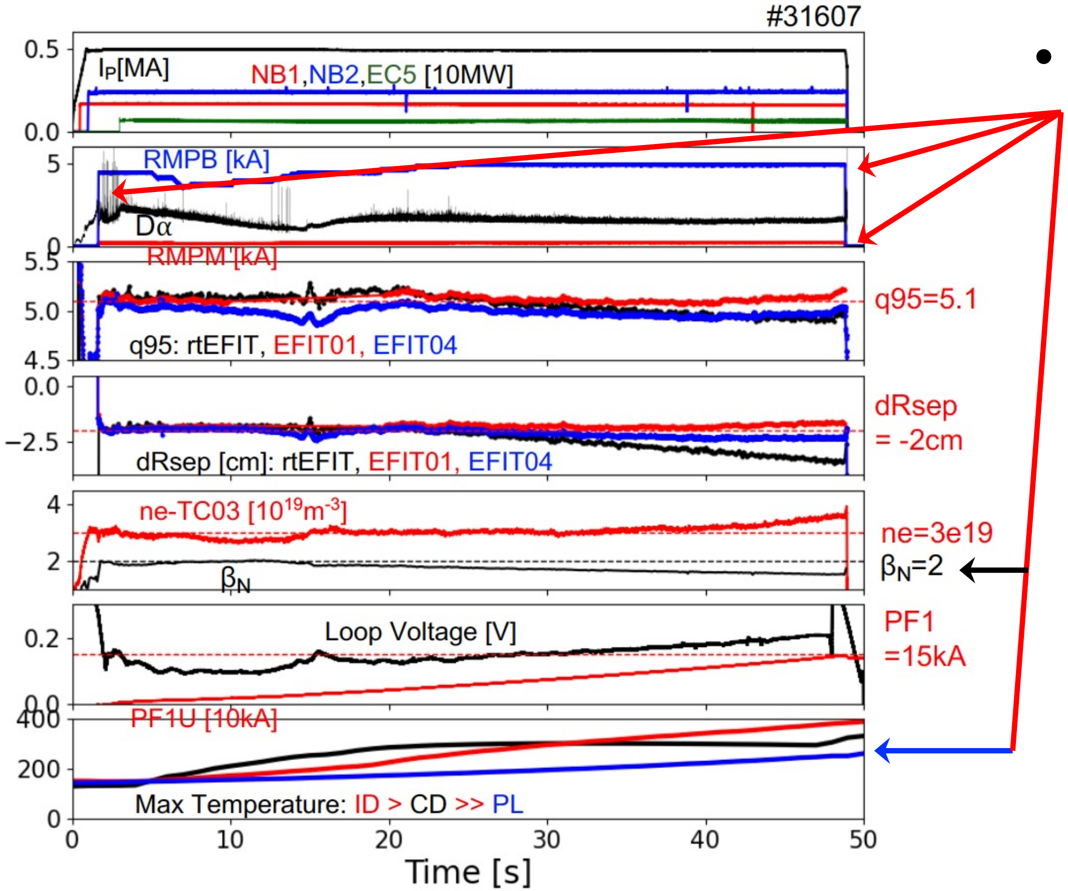
[Q. Hu, TM1]

RMP ELM suppression in long pulse requires strong scheme integration



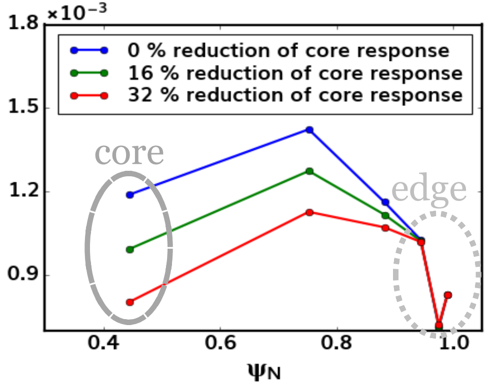
- Needs to predict RMP thresholds for ELM suppression in the optimized target
- Thrust 1: Modeling and validation in hierarchy (PPPL and GA)
  - Use GPEC and MARS to test threshold metric on RMP database along with Machine Learning
  - Use TM1, MARS-Q, JOREK, M3D-C1 to verify and validate field penetration, classical and neoclassical transport
    - With KSTAR imaging diagnostics

RMP ELM suppression in long pulse requires strong scheme integration



- Needs to optimize RMP spectrum to make it safer and reduce unnecessary transport
  - Especially considering possible profile evolutions in long pulse

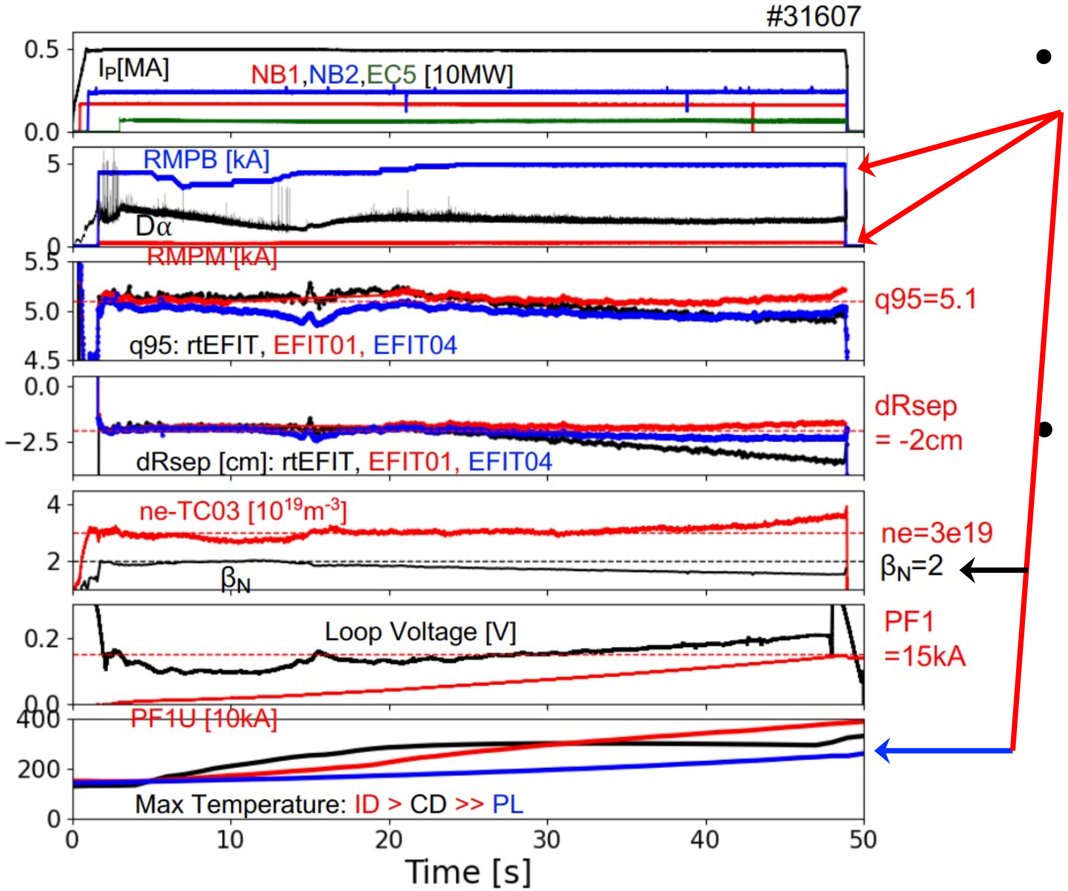
Ex) 2020-22 project and PPPL shows



[S. Yang]

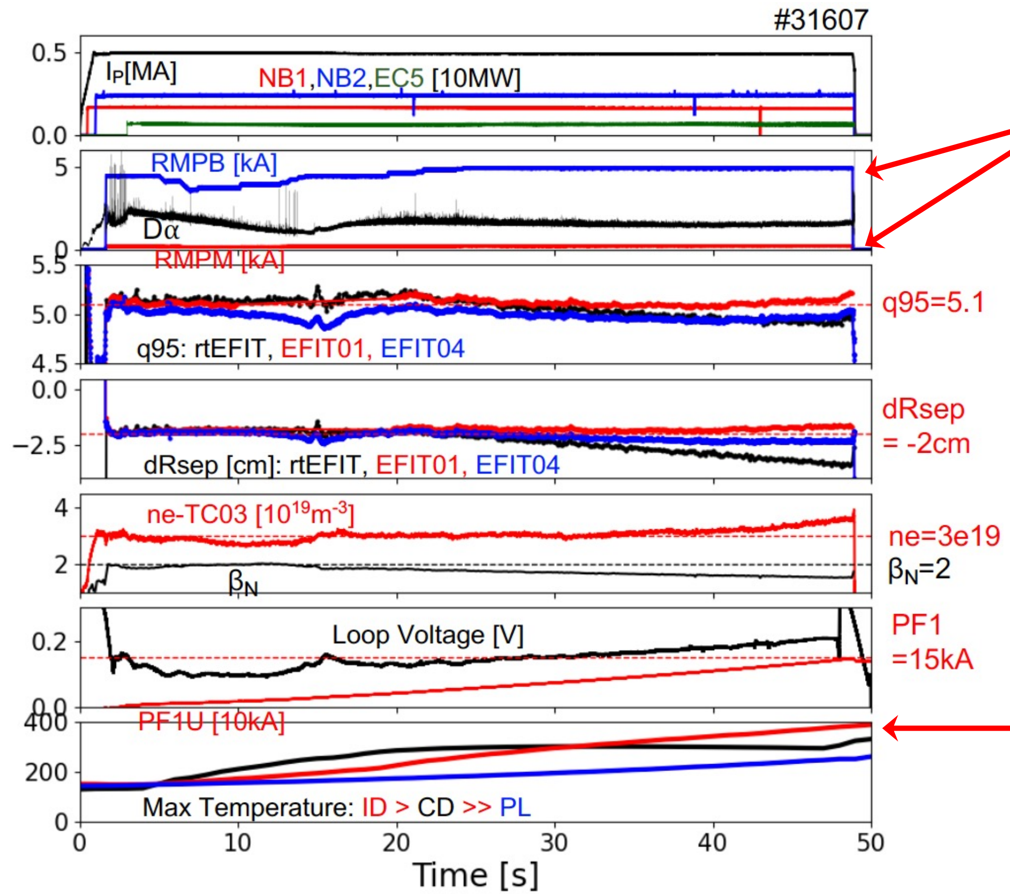
Optimization can lead the reduction of fast ion losses and **poloidal limiter heating**

RMP ELM suppression in long pulse requires strong scheme integration



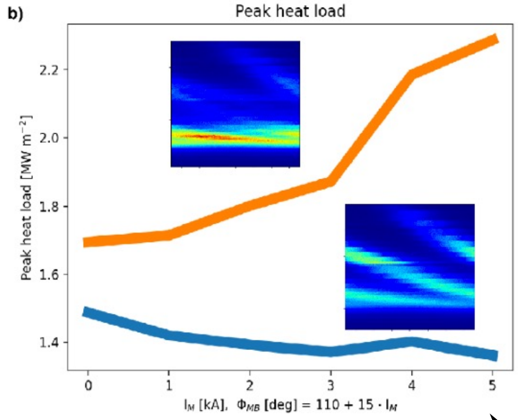
- Needs to optimize RMP spectrum to make it safer and reduce unnecessary transport
  - Especially considering possible profile evolutions in long pulse
- Thrust 2: Model and optimize fast ion losses (e.g. ORBIT or REORBIT) and kinetic transport under 3D fields (PPPL, UCSD, UCI, GA)
  - And validate modeling with profile, FIDA diagnostics

RMP ELM suppression in long pulse requires strong scheme integration



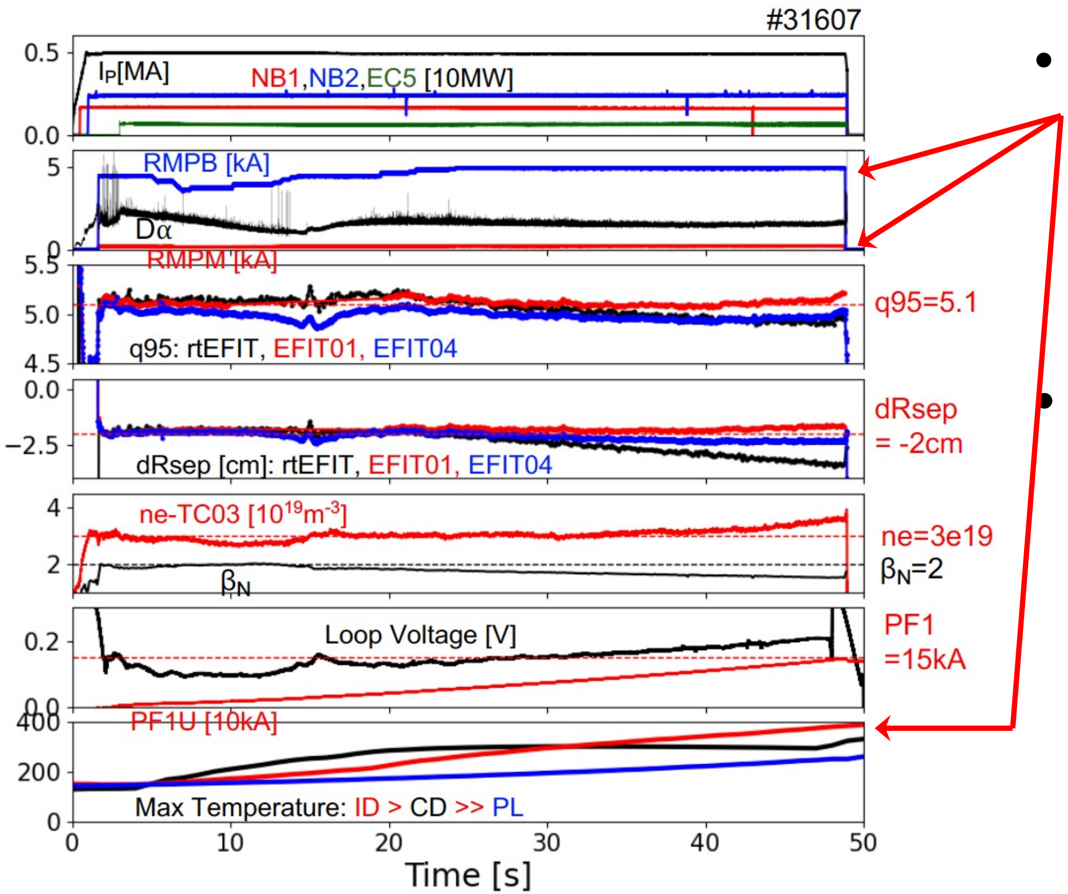
- Needs to optimize divertor heat loads
  - It was a limiting factor for long pulse
    - 400C is the hard limit for operation
  - Tungsten divertor will allow us to go beyond 50s but maybe not 100s-300s

Ex) 2020-22 project and UW shows



Phasing (under ELM suppression window)

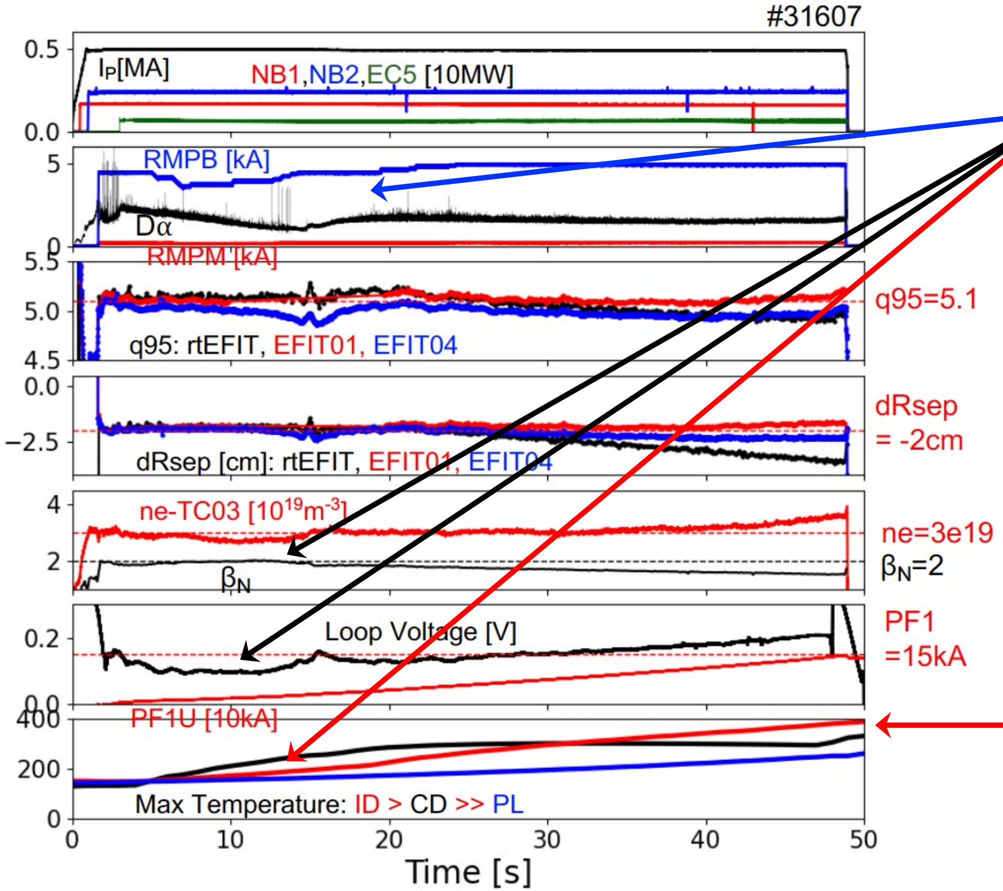
RMP ELM suppression in long pulse requires strong scheme integration



- Needs to optimize divertor heat loads
  - It was a limiting factor for long pulse
    - 400C is the hard limit for operation
  - Tungsten divertor will allow us to go beyond 50s but maybe not 100s

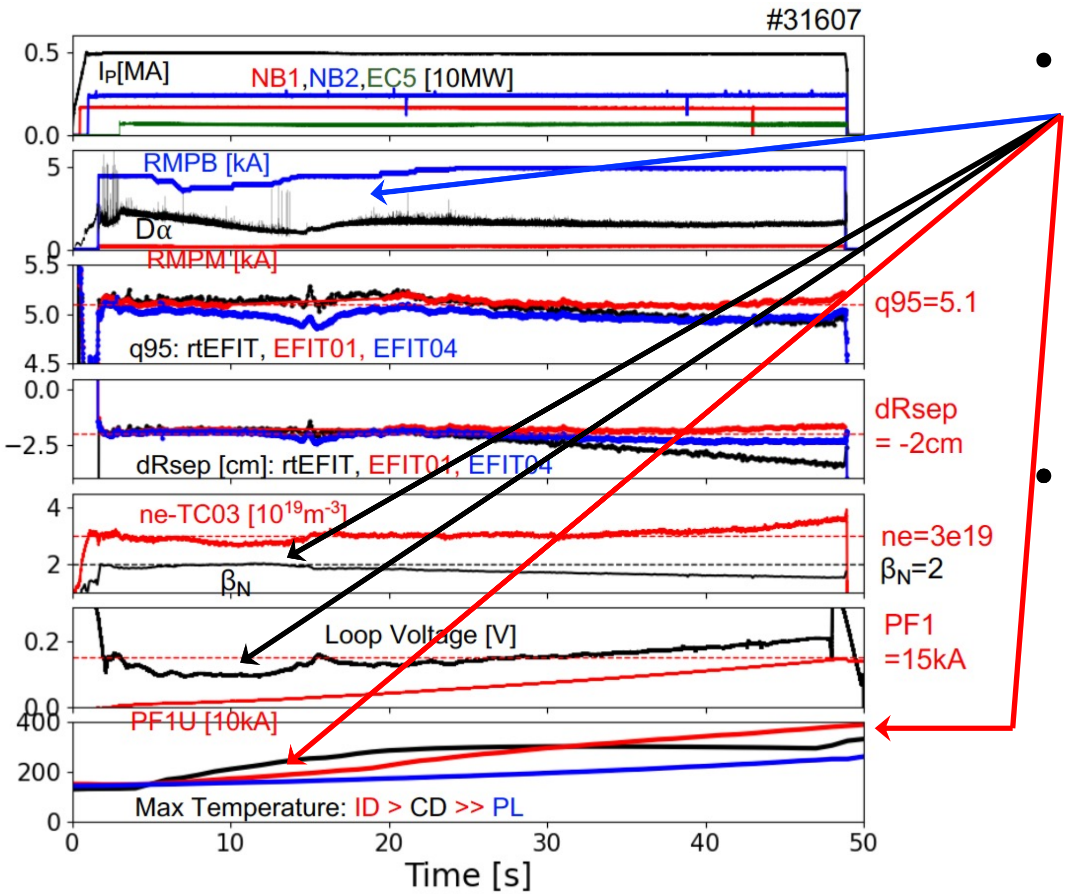
- Thrust 2: Predictively optimize divertor heat loads using EMC3-EIRENE and BOUT++, along with impurity or gas puffing, strike point sweeping (UW, LLNL)

RMP ELM suppression in long pulse requires strong scheme integration



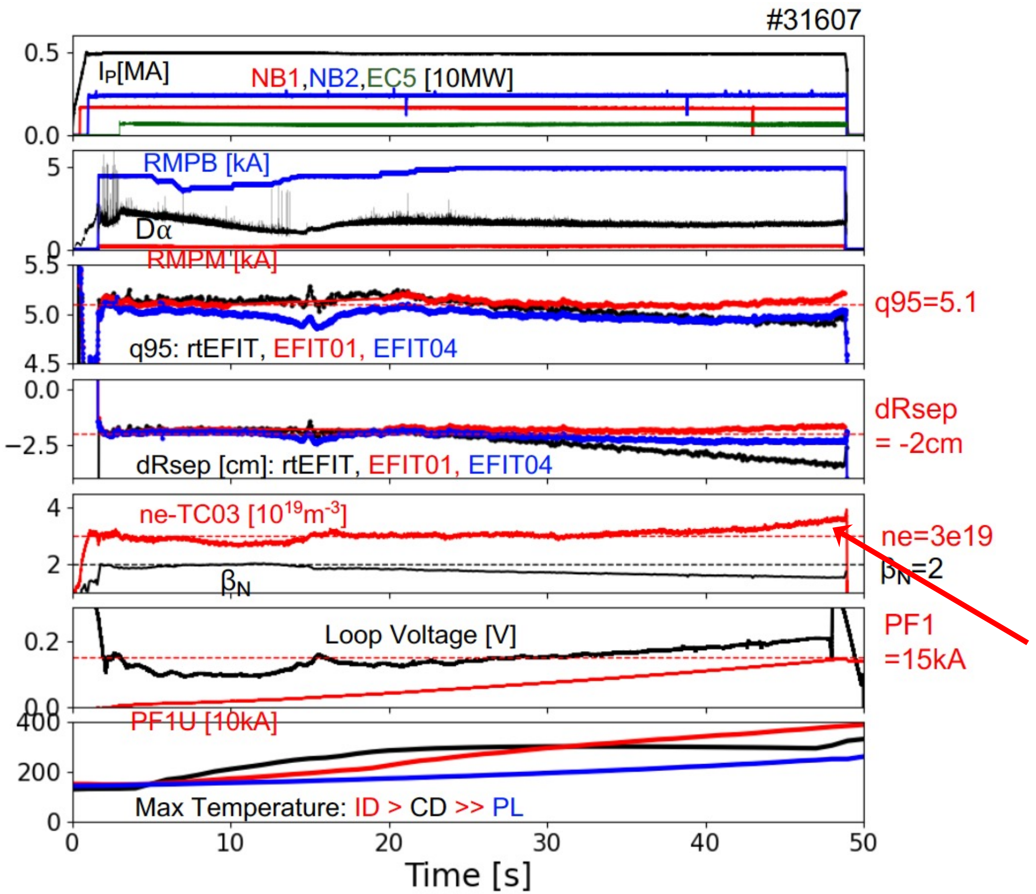
- Needs adaptive RT RMP control to restore confinement, reduce inductive current drive and heat loads
  - Inductive flux consumption is another critical limiting factor for long pulse
- 2020-22 project and PU successfully implemented real-time adaptive control in KSTAR (and DIII-D)

RMP ELM suppression in long pulse requires strong scheme integration



- Needs adaptive RT RMP control to restore confinement, reduce inductive current drive and heat loads
  - Inductive flux consumption is another critical limiting factor for long pulse
- Thrust 3: Make the controller smarter in long pulse, in full knobs, with MLs, with active probing (led by PU)

RMP ELM suppression in long pulse requires strong scheme integration



- With all these schemes, 300s may not be feasible unless we make RMP ELM control compatible with non-inductive scenarios

- Thrusts 1-3: 3D TRANSP (PPPL)
  - With ELM suppression predictor, particle pump-out and rotational damping predictors, and integrated core stability modules
- Thrusts 1-3: Collaborative experiments (all group and KSTAR)
  - Understanding long pulse issues with metal wall

Concluding remarks

- PPPL will lead this international collaborative project on RMP ELM suppression in the next 3 years

- KSTAR will provide good opportunities for PPPL to learn long pulse physics with 3D fields (also without 3D fields)

- This project will be a good venue for PPPL to validate 3D MHD responses and transport, and integration to whole device modeing