Update on GA Contributions and Plans for ARIES

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Outline

- **Update on analysis of ELM-free options for ARIES:**
  - Analysis of Li conditioned ELM-free option:
    - Discrepancies for analyzed NSTX discharges
    - Benchmark study initiated to resolve code discrepancies
  - Resolution plans:
    - Complete benchmarking
    - Resolve discrepancy with experiment
  - Future analysis of alternative ELM-free options:
    - QH-mode
    - RMP ELM-free option
- **New Work: Perform a Self-Consistent Analysis of ARIES Design Points:**
  - Proposed approach
  - New features

Small ELM and ELM-free Options in a Reactor Scenario Offer Significant Promise if They Can be Realized

- **ELM-free Scenarios:**
  - Enhanced D-alpha (EDA) Mode:
    - Observed in C-Mod
  - Quasi-H (QH) Mode:
    - Observed in DIII-D
  - Resonant Magnetic Perturbation (RMP) Discharges:
    - Observed in DIII-D with non-axisymmetric coils
  - Li Conditioned Discharges:
    - Observed in NSTX
- **Small ELM scenarios:**
  - Shaping:
    - Large squareness
  - Type II ("grassy") ELMs:
    - Mostly seen in JT-60
  - Type III ELMs

Propose to Study Possibility of Self-consistently Including Options for ELM-free and Small ELM Scenarios in ARIES

- **Take representative discharges for each regime in the respective machines and determine essential physics:**
  - Discharges from DIII-D, C-Mod, NSTX
  - Determine essential profiles and other characteristics
  - Utilize GATO to study n = 1 - 10, and ELITE for n > 3 modes
  - Characterize dependence of ELM type and size
- **Scale configurations to ARIES:**
  - Use profiles in ARIES configuration:
    - Density and temperature profiles from respective discharges with ARIES q profile
  - Adjust configuration as necessary:
    - Adjust q profile from bootstrap current self consistency
    - Modify shape as needed
    - Include other characteristics (eg. rotation)
- **Study low to intermediate n stability of scaled configuration:**
  - Characterize ELM type and size from GATO and ELITE

Essential Physics For ELM Onset: MHD Instability Driven by Steep Edge Gradients

- **Steep localized edge pedestal pressure gradient is both cause and consequence of improved confinement in H-mode:**
  - Local p’ drives local bootstrap current density j
  - Both p’ and j drive MHD instability
- **Instability observed as a precursor to ELM event:**
  - Typically low to intermediate n: $2 < n < 30$
- **ELM type is determined by different physics associated with varying:**
  - Specific mixture of drives from p’and j_{edge}
  - Pedestal width and height
- **EPED1.6 model predicts maximum edge pedestal height and width:**
  - Pedestal steepness largely set by MHD stability from low to intermediate n modes
  - Pedestal width largely set by Kinetic ballooning mode onset
  - But division is not ‘orthogonal’:
    - MHD stability also partly sets width

Lithium Conditioning Option for ELM-free Regimes Shows Promise But Understanding is Presently Limited

- **Discharges range from ELMing to infrequent ELMs to ELM-free:**
  - Depends on level of Li conditioning
  - Fully ELM-free apparently requires massive amounts of Li
- **Physics responsible is unknown:**
  - Change in the density profile from Li is thought to be the first step to ELM suppression
- **Key advantage over other ELM-free options:**
  - Continuous control over ELM frequency
  - Easy application from Li sprayers
- **Key disadvantage:**
  - Impurity accumulation
  - No control over ELM size:
    - Size depends on underlying regime
    - For large Type I ELMs Li conditioning increases ELM size as the frequency decreases

ELM-free regimes for ARIES Taken From Existing NSTX Experimental Equilibria:

- **Varying Li Conditioning led to varying ELM behavior:**
  - Discharge #129015: No lithium:
    - Type 1 ELMing H-mode
  - Discharge #129030: Much lithium:
    - Type 1 low frequency ELMing followed by ELM-free phase
  - Discharge #129031: Much lithium:
    - Type 1 low frequency ELMing followed by ELM-free phase
  - Discharge #129038: Massive lithium:
    - Completely ELM-free
- **Calculations with GATO, KINX, and ELITE showed all cases were stable to n = 1,2,…. 20 and higher:**
  - Discharge equilibrium reconstruction used an average of profiles over the ELM cycle
  - Instability is expected only right before the actual ELM !
- **Calculations with PEST showed instability in some cases:**
  - Seems to be due to PEST code cutting off edge:
    - Required for numerical reasons

Second Set of Equilibria Found Same Result: All Cases Stable to Low and Intermediate n Ideal Modes

- **Discrepancies between PEST and other codes and with experiment led to testing of other ELMing cases**
- **Second set used alternative reconstructions and new discharges:**
  - Discharge #129015: (Type 1 ELMing H-mode):
    - Edge current increased by 140% at constant edge P’
    - More data points in the fit
  - Discharge #129023: Closest to instability from ELITE
  - Discharge #129024: Highest growth rate from PEST
- **Calculations with GATO, KINX, and ELITE again showed all cases were stable to n = 1,2,…. 20 and higher:**
  - PEST result was again in conflict
- **Progress to resolve discrepancy with experiment requires either:**
  - Improved discharge reconstruction with data taken only right before the ELM
  - Arbitrarily increased edge current density to model the true profile right before the ELM
- **And a serious benchmark to resolve code discrepancies**

Benchmark Study Between GATO and ELITE Intended to Resolve Discrepancies Between Stability Codes

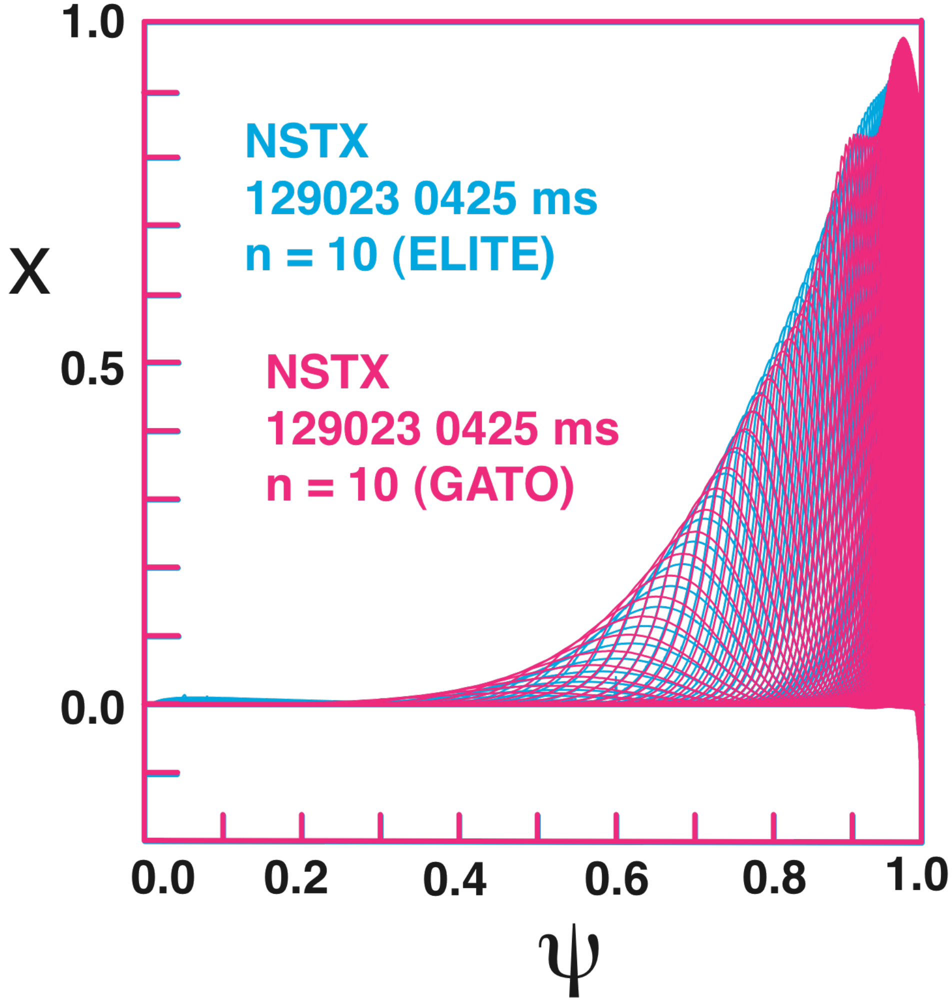
- **Benchmark requires an actually unstable case:**
  - Take discharge #129023:
    - Increase edge current using bootstrap current augmented arbitrarily to yield instability with ELITE
    - Edge cut off in both codes to match edge q value:
  - **Drawback:**
    Core profile is not well controlled producing unphysical $q_0 \sim 0.5$
- **GATO and ELITE are very different codes but should produce same result for an intermediate n range:**
  - GATO: full geometry finite element code valid up to n ~ 15
  - ELITE is specialized to edge modes for intermediate n > 3
- **Good agreement despite additional numerical issues due to low q_0:**
  - GATO finds multiple unrelated internal modes inside q = 1
    - Search procedure required to select edge instabilities
  - ELITE forces all modes to be edge modes
    - Finds most unstable modes to be unphysical modes that mimic edge modes
    - Difficult to converge on and select out physical edge modes

Growth Rates and Mode Structures From GATO and ELITE Agree for n = 9 and 10 Despite Numerical Issues

- **Growth rates:**
  - Normalized to toroidal Alfven time

n	GATO	ELITE
9	0.5677	0.5500
10	0.5853	0.5794

- **Mode structures:**



Alternative Benchmark Study Initiated With Higher Edge Current Density to Increase Edge Mode Growth Rates

- **Issue of unstable internal modes is a problem for ELITE:**
  - Convergence to physical edge mode takes significant hand adjustments and result is subject to interpretation
- **Numerical issues alleviated but not fully eliminated:**
  - Some n still have internal modes as most unstable mode
- **Benchmark is ongoing:**
  - GATO results completed:

n	Growth rate	n	Growth rate
1	0.53136E-01 (internal)	7	0.30623E+00 (2nd mode)
2	0.16278E+00 (internal)	8	0.31561E+00
3	0.56334E-01	9	0.34381E+00
4	0.13523E+00	10	0.29948E+00 (3rd mode)
5	0.43855E+00 (3rd mode)	11	0.39224E+00
6	0.24091E+00	12	0.37631E+00 (2nd mode)

  - ELITE results require more work to distinguish correct edge modes

Continuing Work Will Focus on Resolving Discrepancy And Then Other ELM-free Regimes

- **Resolve code discrepancies:**
  - KINX should yield same result as GATO (similar codes previously benchmarked)
  - Need to then resolve PEST discrepancy
- **Resolve discrepancy with NSTX experiment:**
  - Require reconstructions with more realistic edge current density
    - Not averaged over an ELM cycle
    - Bootstrap aligned
  - Require higher resolution equilibria to resolve outboard edge
- **ELM analysis of QH Mode discharges:**
  - DIII-D discharges with reconstructed equilibria have been selected
- **ELM analysis of RMP discharges:**
  - DIII-D discharges with reconstructed equilibria have been selected

Remaining Issue: How Do the ELM-free Profiles from Present the Discharges Scale to ARIES

- **ARIES has β_N ~ 5 but all these discharges have much lower β_N:**
  - How does pedestal width and height really scale if these operating modes are reproduced in an ARIES scale reactor
  - ELM losses are proportional to energy contained in the pedestal
- **ARIES has high internal q with flat low shear profile:**
  - How does this affect coupling of edge pedestal stability to core:
    - Likely to increase mode width
- **What is role of nearby wall:**
  - Coupling to wall will be quite different at high β_N with high bootstrap fraction:
    - Modes are generally much more global
- **What is the physics responsible for ELM suppression:**
  - Role of density profile seems especially crucial:
    - Pedestal density drop appears to be universal but edge temperature generally remains intact
    - Does recycling play a role

Proposal for Increased GA Efforts: Perform a Self-Consistent Analysis of ARIES Design Points

- **Similar analysis was done in the past for ARIES designs but:**
  - Design points have been updated with improved Systems Code modeling
  - Understanding of physics issues has also evolved considerably:
    - Particularly pedestal modeling and interaction with the core
- **Analysis will involve:**
  - Coupled equilibrium, transport, current drive, fuelling, and stability calculations to obtain a steady state solution
  - In a self consistent simulation using:
    - Latest core transport models
    - Coupled to edge pedestal models

The simulation would use the same tools as used to model DIII-D and FSNF, providing a consistent up-to-date set of models and tools across the spectrum of current and planned facilities

Proposal is Intended to Repeat Previous 2000 Effort For ARIES-AT With Improved Tools and Understanding

- **New optimized target configuration**
- **Self consistent steady state solution**
- **Transport model TGLF in place of GLF23:**
  - Real shaped geometry instead of GLF23 shifted circle model
- **Self consistent H-mode pedestal:**
  - Realistic pedestal height and width predictions with EPED1
- **Full-wave Lower hybrid modeling**
- **Improved resistive wall stability understanding:**
  - Stabilization at low rotation
  - Role of error fields in braking at low rotation
  - New angular momentum transport models
- **Key technical issue is that core transport is stiff:**
  - Largest leverage to improving confinement is from increasing pedestal height
  - Conversely, H-mode pedestal and ELM physics depends crucially on the heat and particle fluxes coming from the core