Alfvén-eigenmode-related proposal ideas for OP2.x (involving MHD and fast ions)

Christoph Slaby and Kian Rahbarnia

Motivation and high-level goals

Main Objectives Task Force I

Main Objective	Scientific Goal	Measures of success / deliverables
Exploration of reduced turbulence / high performance scenarios w.r.t. stationary plasma conditions, kinetic-, density-, and impurity-profile control	▪ Demonstrate steady-state viability of increased performance scenarios after pellet / impurity injections as well as low ECRH/NBI heated plasmas ▪ Qualify actuators for the control of profiles and impurities	▪ High plasma performance in the order of seconds, including • T_i above clamping limit (1.5 keV) • τ_E equal or better to ISS04 scaling ▪ Avoidance of impurity accumulation ▪ Assess density profile control
Exploration of heating scenarios using upgraded plasma heating capabilities (ECRH, NBI, ICRH)	▪ Extension of NBI operation space and preparation of fast ion diagnostics ▪ Observation and prediction of fast ion losses for machine safety and validation of simulations tools	▪ Demonstrate effective ion heating ▪ Exhaustive operational map of the W7-X configuration space incl. operation limits ▪ Safe operation w.r.t. NBI/ICRH induced fast ion losses ▪ Validation of fast ion loss simulation tools
Develop high beta plasma scenario by means of low field operation	▪ Development of a plasma startup scenario @ B=1.7 T employing X3 / ICRH / NBI heating ▪ Fast ion confinement at high plasma-beta	▪ Reliable plasma startup scenario @ 1.7 T ▪ Demonstration of improved fast ion confinement of W7-X at high beta ▪ Develop capability to extrapolate B-field dependency to high-field reactor operation

27.09.2020 Program Planning OP2.1 & OP2.2 | W7-X Physics Meeting | O. Grulke 14

Motivation and high-level goals

Main Objectives for OP2.1/2.2 – TF-III

Main objective

- **Complete the core transport and stability physics basis in the extended operational space**

Scientific goals

- *Identify fundamental heat and particle transport mechanisms*
- *Continue the assessment of W7-X optimization*

Deliverables

- Documentation of relevant plasma profiles for detailed transport analysis and modelling.
- Assessment of the effects of heating and fueling actuators (profile shaping, fast ions) and magnetic configuration on turbulent transport.
- Documentation of core impurity profiles and perturbative experiments for detailed impurity transport analysis and modelling.
- Confirmation of neoclassical optimization at increased ion temperatures.
- Confirmation of reduced equilibrium currents at higher betas and different magnetic configurations.
- Documentation of MHD stability and limits and fast-particle driven MHD modes within the magnetic configuration space.

27.10.2021 2

Characterizing AE activity and fast-ion losses in a wide range of configurations

Main idea	Characterize new configurations with NBI blips • 100-200 ms / longer than slowing-down time • Can be at the end of discharge to not disturb other experiments (maybe partly also embedded in reference discharge) • Learn about fast-ion losses, but also characterize (unexpected) AE activity • Short ICRH pulses might also be an idea
Magnetic configurations	No preference
Required heating systems	ECRH + NBI / ICRH blips
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	C. Slaby, S. Lazerson, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies
Possible number of proposals	1

AE activity for reduced-field operation

Main idea	Characterize AE activity and fast-ion losses at reduced field • Alfvén speed scales linearly with |B|, hence it decreases for 1.7 T • This makes it easier for our “slow” fast ions from NBI to resonantly interact with these modes (backed by LGRO simulations) • Increases the ratio v_{beam} / v_A
Magnetic configurations	No preference
Required heating systems	ECRH + NBI and/or ICRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
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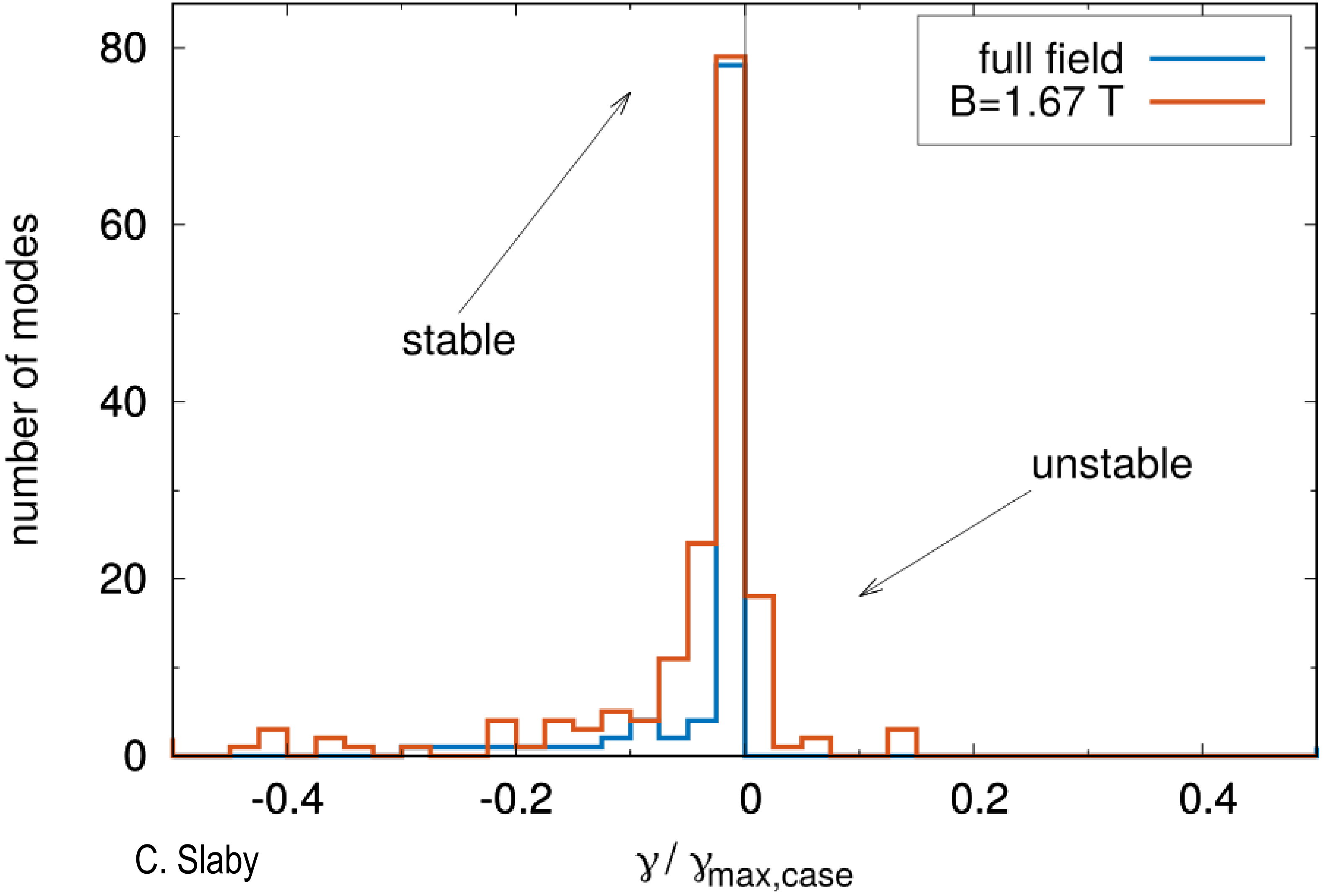
AE activity for reduced-field operation



C. Slaby

- **Simplified LGRO simulations for AEs destabilized by fast ions from NBI**
- **Most modes marginally stable**
- **Reduced field can push some modes over the stability boundary**

AE activity for reduced-field operation

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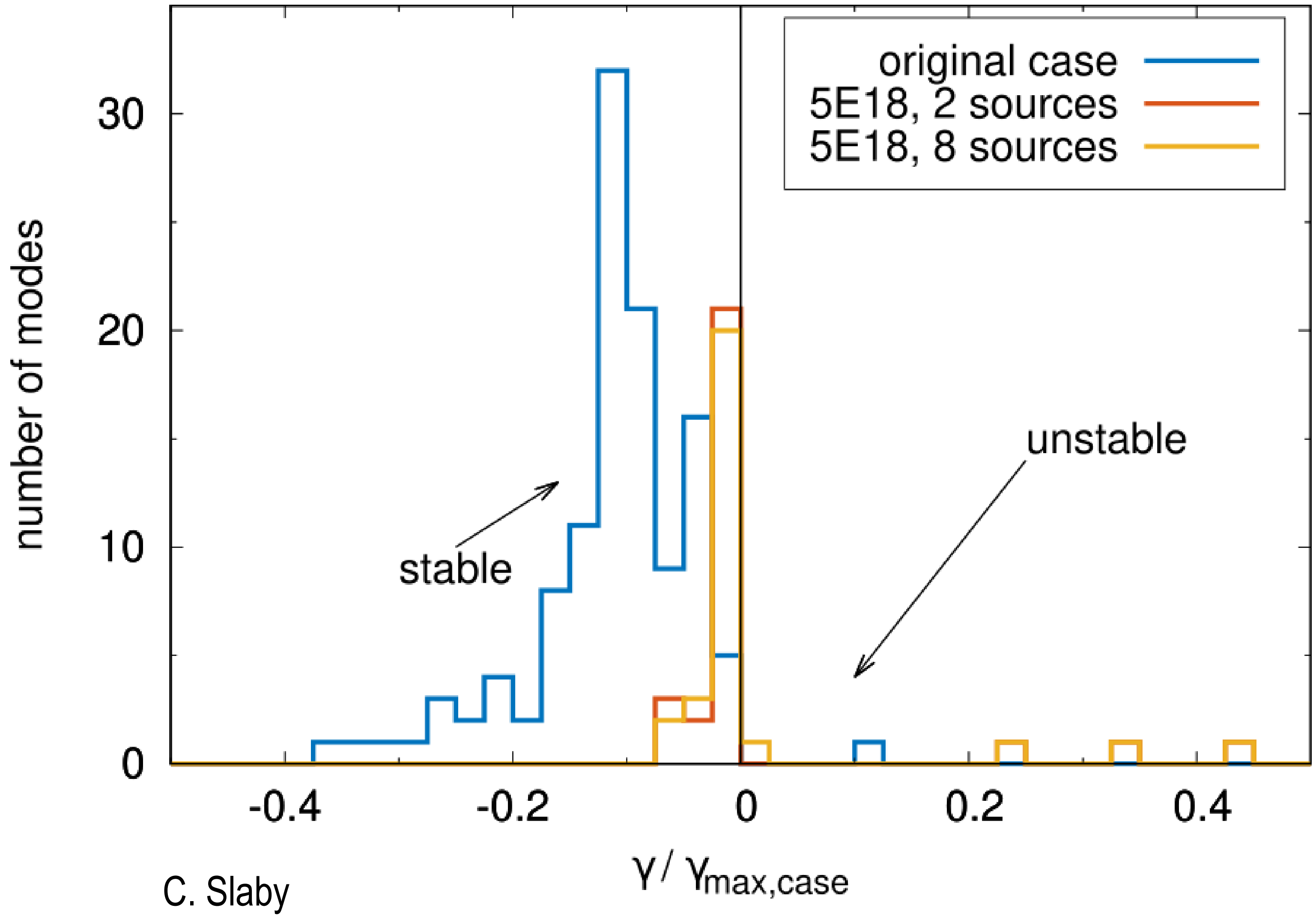
Possible number of proposals	1

AE activity in low-density plasmas

Main idea	**Leverage a low-density plasma to assess if fast-ion-driven modes can be triggered** • **Lowering the density shifts β_{fast} / β_{bulk} in a more favourable direction** • **Backed by LGRO simulations** • **NBI shine-through may impose lower bound on n_e** • **Lowering n_e leads to an increase of the v_A and therefore also f**
Magnetic configurations	No preference
Required heating systems	ECRH + NBI and/or ICRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, <u>possible proponents</u>)	<u>S. Lazerson</u>, C. Slaby, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies
Possible number of proposals	1

AE activity in low-density plasmas



C. Slaby

- original case: W7-X experimental program 20180823.020@5.2s
- on-axis density: $n_{e,0}$ = 7.4e19 m^{-3}
- study based on BEAMS3D and LGRO simulations

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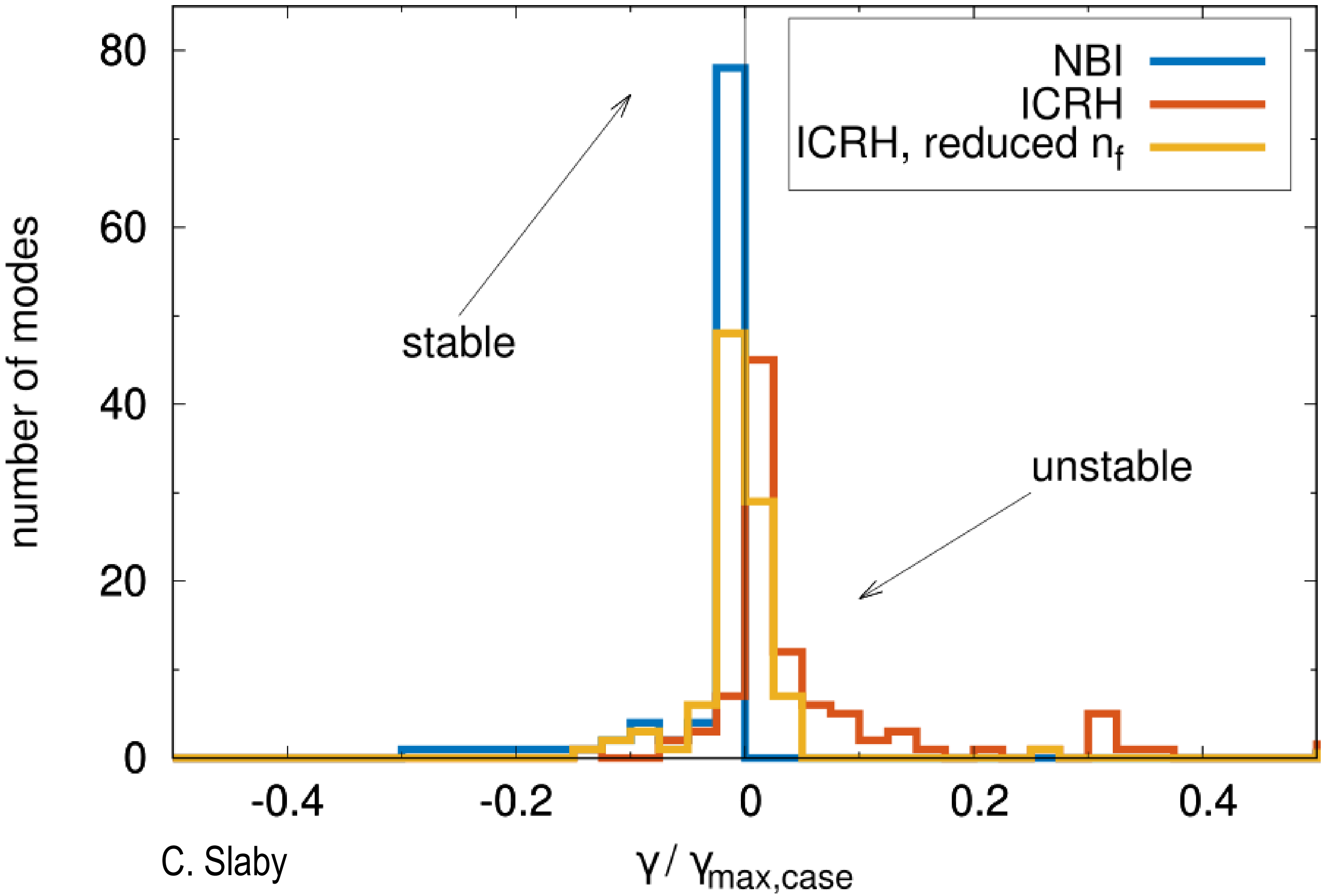
Involved people (list incomplete and in no particular order, possible proponents)	S. Lazerson, C. Slaby, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies
Possible number of proposals	1

AE activity under ICRH conditions

Main idea	Characterize AE activity in the presence of fast ions generated by ICRH • ICRH heats predominantly the perpendicular velocity component • Interaction of AEs with fast particles is a parallel resonance → Question how quickly distribution function becomes isotropic • ICRH can generate higher-energy particles than NBI → higher-energy resonances are reachable • Try different methods of fast-ion generation (minority / 3-ion scheme) • LGRO simulations available (assuming a high-energy Maxwellian)
Magnetic configurations	No preference
Required heating systems	ECRH + ICRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	C. Slaby, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, S. Lazerson, D. Hartmann, M. Machielsen, J. Graves, Y. Kazakov. J. Ongena
Possible number of proposals	2

AE activity under ICRH conditions



C. Slaby

- Simplified LGRO simulations comparing AEs destabilized by NBI and ICRH
- Blue and red curve have the same β_{fast}
- ICRH distribution function approximated roughly by high-energy Maxwellian (MeV)

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AE activity in combined NBI / ICRH heating scenarios

Main idea	**Characterize AE activity when using our full set of ion-heating systems** • **SCENIC simulations have shown synergistic effects of combining NBI and ICRH** • **Fast ions can be accelerated to energies > 55 keV** • **This may populate additional resonances in velocity space and excite modes that were previously "inaccessible"**
Magnetic configurations	No preference
Required heating systems	ECRH + NBI and ICRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	C. Slaby, M. Machielsen, J. Graves, Y. Kazakov, J. Ongena, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies, D. Hartmann
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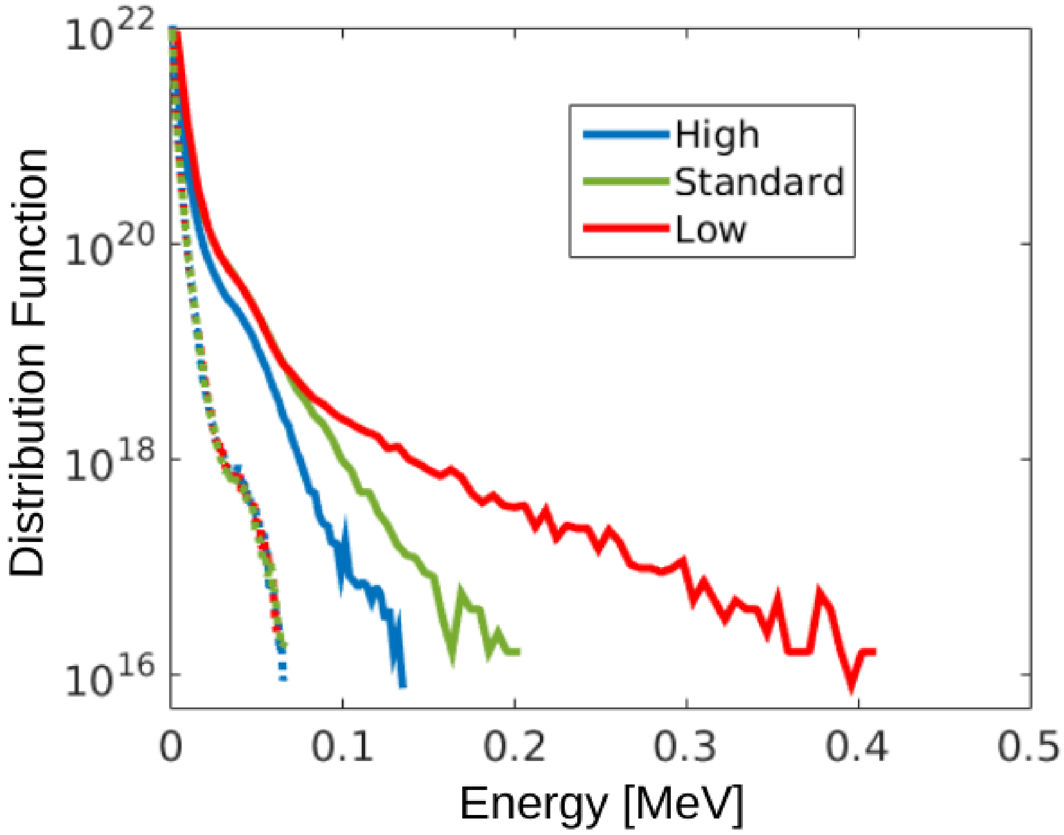

H. Patten, Workshop on Fast-Ion Physics, 22.01.2018

- **Fast-ion distribution functions calculated with the SCENIC code package**
- **Dashed lines: NBI only**
  - At most E = 55 keV can be reached
- **Full lines: NBI combined with ICRH**
  - Particles can be accelerated to higher energies
  - Resulting distribution function depends on the magnetic configuration

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Possible number of proposals	1

Impurity seeding to trigger AEs

Main idea	Try lowering β_{bulk} via deliberate impurity seeding • W-accumulation combined with off-axis NBI used in AUG to generate plasmas with $\beta_{fast} \approx \beta_{bulk}$ • In these scenarios: $T_{fast} \approx 100\ T_{bulk}$ • Relatively large β_{fast} then triggers AEs (TAE / RSAE / EGAM in AUG) • W-accumulation lowers T_{bulk}, β_{bulk}, and reduces Landau damping • NLED-AUG case based on ASDEX Upgrade discharge
Magnetic configurations	No preference
Required heating systems	ECRH + NBI
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	C. Slaby, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies, impurity group
Possible number of proposals	1

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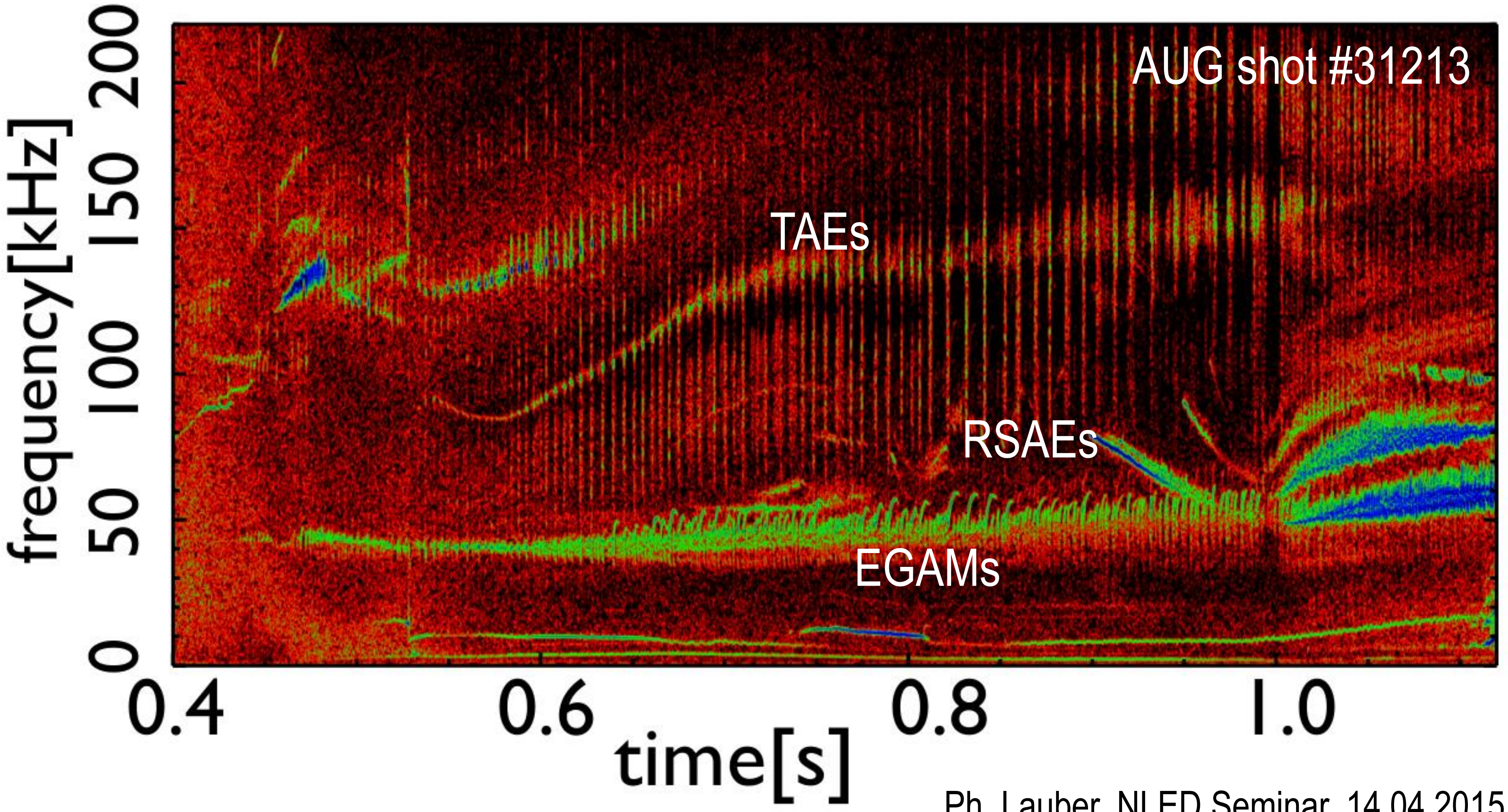

Ph. Lauber, NLED Seminar, 14.04.2015

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Possible number of proposals	1

Mode activity associated with ECCD (with fast ions)

Main idea	How do ECCD-induced crashes affect fast-ion confinement or are affected by the fast-ions themselves? • Effects of core ECCD crashes on fast-ion confinement (S. Lazerson) • Fast-ion stabilization of sawteeth • More about ECCD crashes in the absence of fast ions in second part of the talk
Magnetic configurations	All (specifically for fast-ion confinement studies: AIM, EIM, KJM, FTM or KJM001)
Required heating systems	ECRH + ECCD, NBI (specifically for fast-ion confinement studies: NBI blips 50% at 2.5 Hz)
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, FILDs, FIDA, LBO/Tespel (for impurity control studies), basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	K. Rahbarnia, K. Aleynikova, C. Slaby, S. Lazerson, S. Mendes, C. Brandt, H. Thomsen, A. Könies, A. Zocco, M. Zanini
Possible number of proposals	2

AE activity associated with ECCD (no fast ions)

Main idea	**Study use ECCD for strike-line control, impurity control, control of net toroidal current, and edge iota control** • **More systematic ECCD experiments necessary in different magnetic configurations** • **Dependency on global plasma parameters (heating scenario, density, temperature, current, …)** • **ECCD crashes could be used to improve the pellet fueling efficiency (M. Zanini)** • **Machine safety (control of the crash amplitude)**
Magnetic configurations	All
Required heating systems	ECRH + ECCD
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, LBO/Tespel (for impurity control studies), basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	K. Rahbarnia, K. Aleynikova, C. Slaby, S. Lazerson, S. Mendes, C. Brandt, H. Thomsen, A. Könies, A. Zocco, M. Zanini
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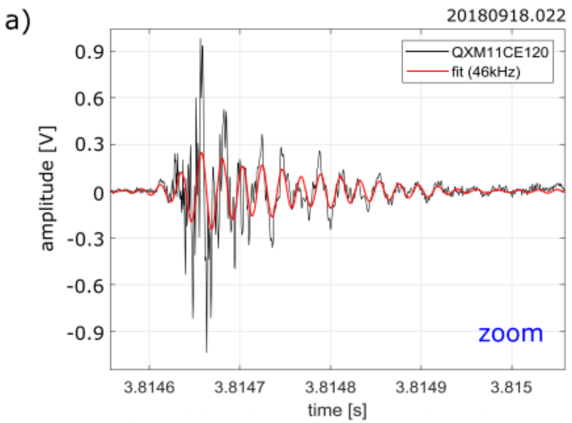
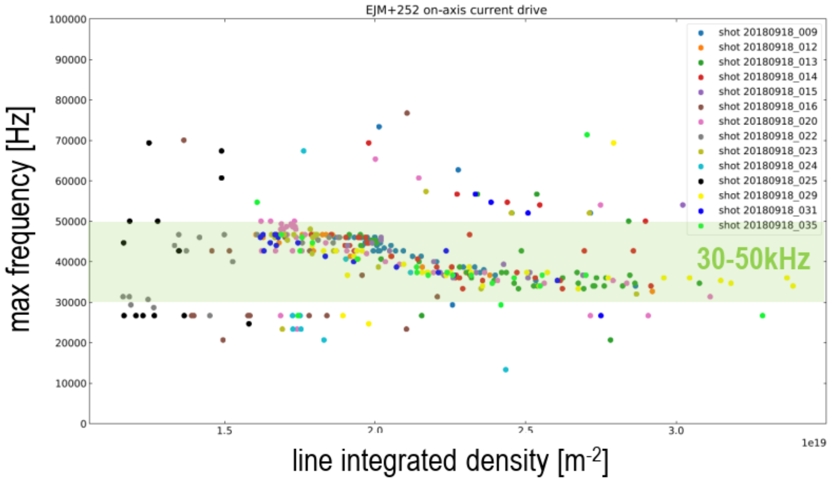
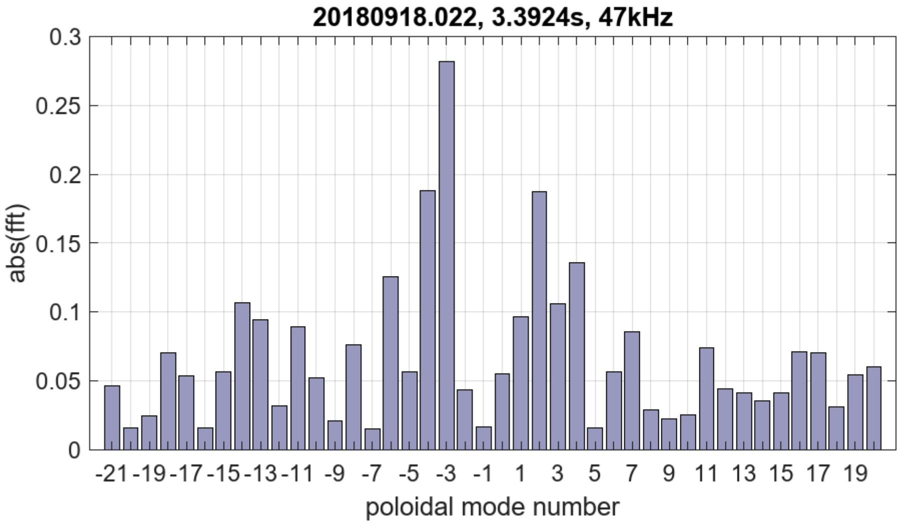
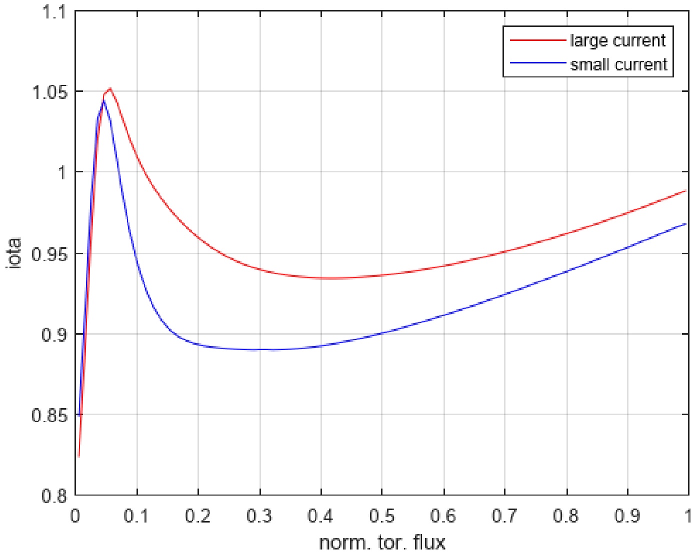
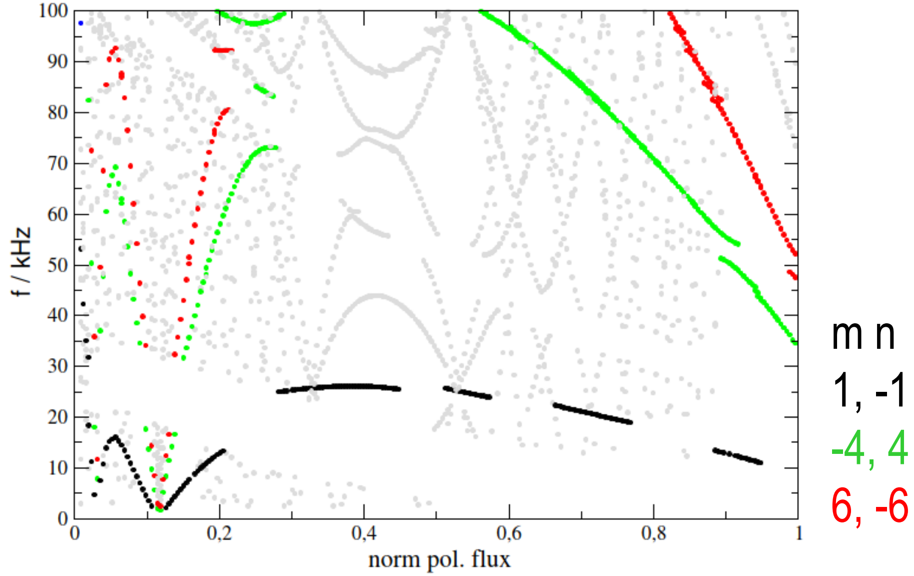
AE activity associated with ECCD











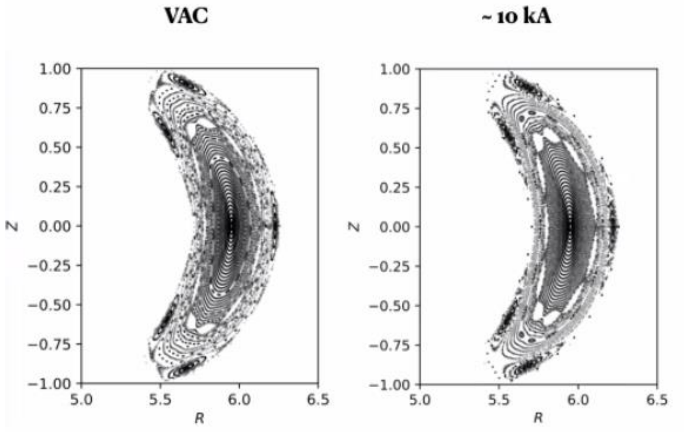
→ systematic comparison of expected mode activity with predictions

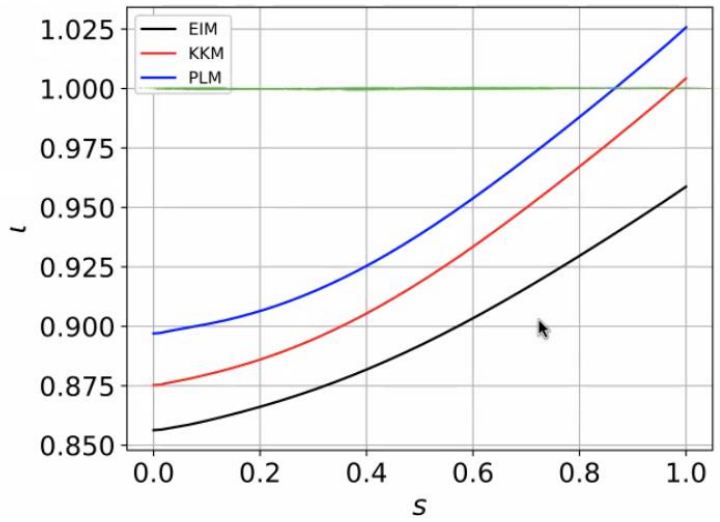
[K. Rahbarnia]

ECCD induced plasma collapses

Main idea	Study mechanism for ECCD induced plasma collapses • develop ECCD scenario to easily provoke total plasma collapse • initiate thermal quench followed by fast toroidal current decay • lower current sufficient → machine safety given
Magnetic configurations	t.b.d.
Required heating systems	ECRH + ECCD
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	K. Aleynikova, K. Rahbarnia, C. Slaby, J. Geiger, S. Mendes, C. Brandt, H. Thomsen, A. Könies, A. Zocco, M. Zanini, T. Stange
Possible number of proposals	1

ECCD induced plasma collapses

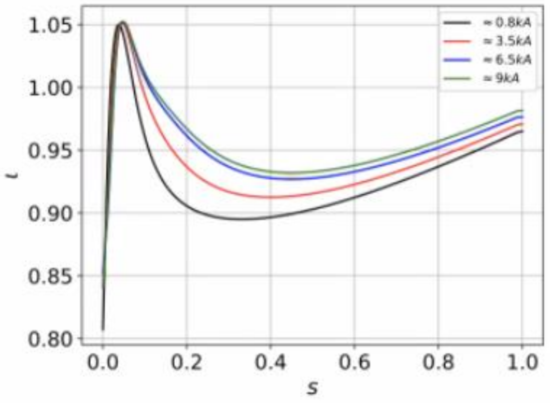


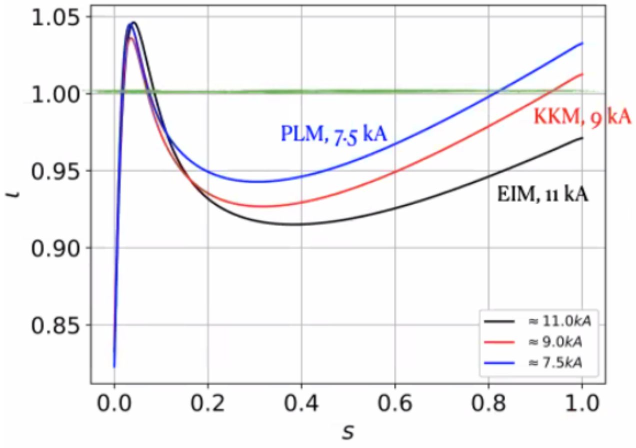


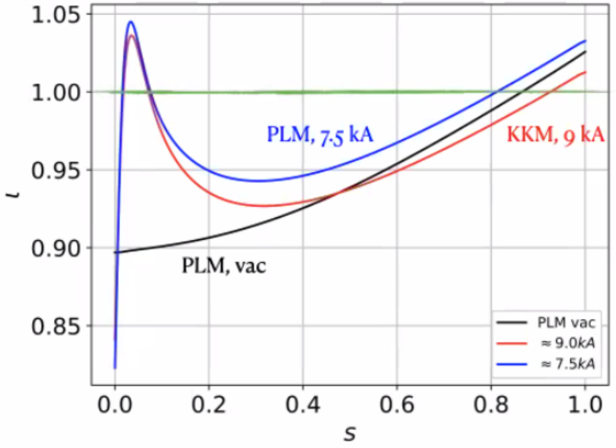
				iota					
I	[0.075	-	0.085)	[0.8425	-	0.8575)	[-0,675	-	-0.525)
J	[0.085	-	0.095)	[0.8575	-	0.8725)	[-0,525	-	-0.375)
K	[0.095	-	0.105)	[0.8725	-	0.8875)	[-0,375	-	-0.225)
L	[0.105	-	0.115)	[0.8875	-	0.9025)	[-0,225	-	-0.075)

> What if two outer crosses of iota = 1 becoming closer to each other while total current is getting larger? (can be modelled) thus providing a mechanism for a heat “transport” (from the core) => drop of the temperature => current drop

Something like F(E?)L(K)M with less then ~5kA?..



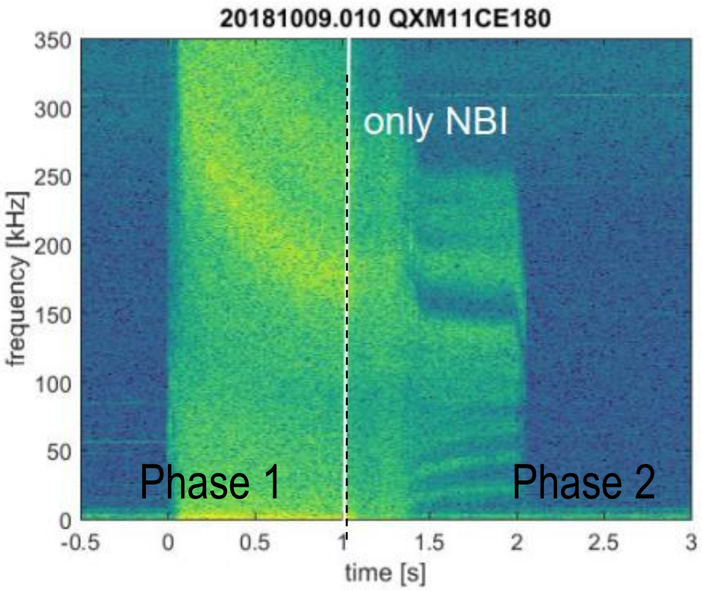


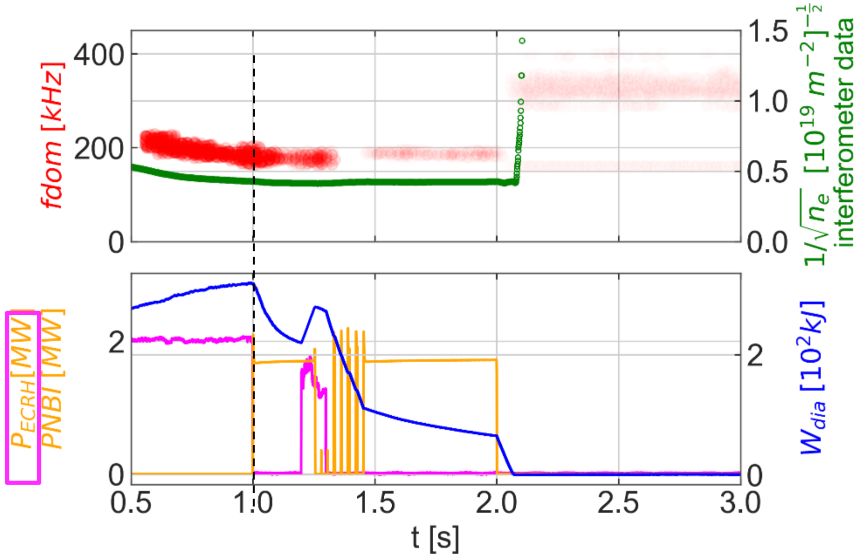


AE activity in ECRH-only scenarios

Main idea	Characterize AE activity in the absence of fast ions • Continue previous studies regarding driving mechanisms of AEs in the absence of fast ions • Role of turbulence (interplay of TAE and ITG turbulence) • Investigate profile effects (steep vs. flat density) on AE activity
Magnetic configurations	No preference
Required heating systems	ECRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, <u>possible proponents</u>)	C. Slaby, <u>K. Rahbarnia</u>, <u>S. Mendes</u>, C. Brandt, H. Thomsen, A. Könies, turbulence group
Possible number of proposals	1

AE activity in ECRH-only scenarios – mode drive in 200 kHz range still unclear

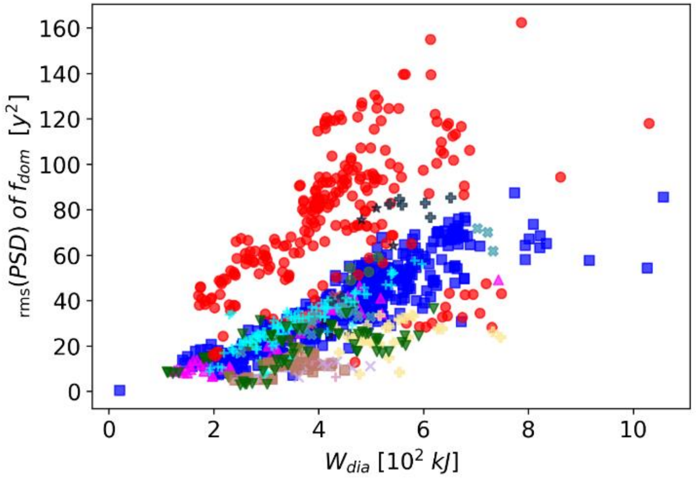


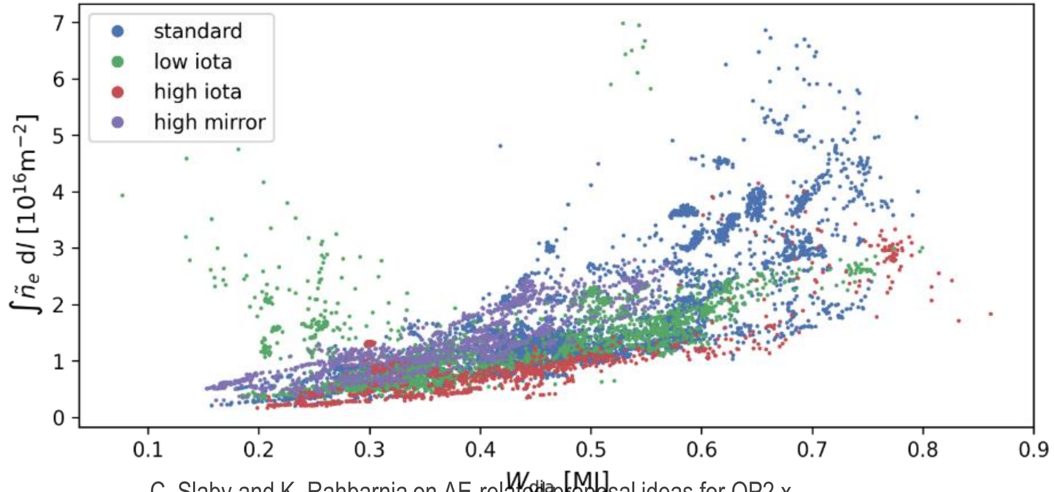


Generally poloidal mode number range

$$||m|| \lesssim 4$$

→ Simulations using Conti, CKA, Euterpe still not conclusive concerning driving mechanism





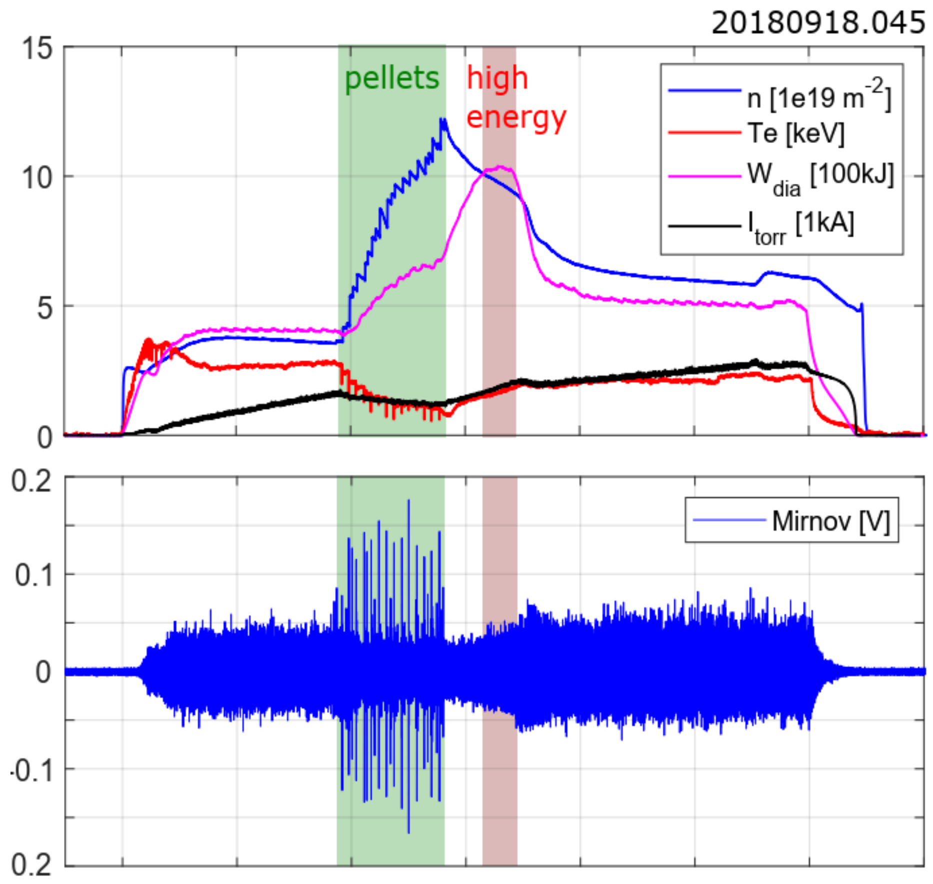
Correlation of magnetic fluctuations to turbulence?

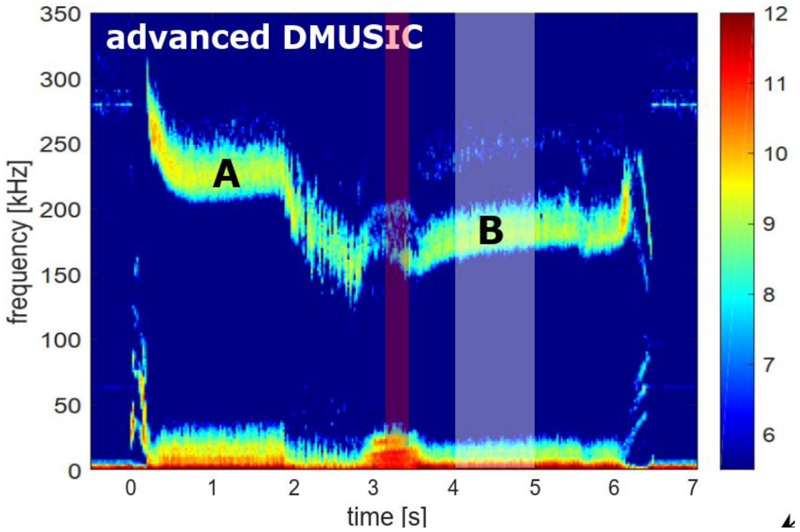
[S. Mendes, J.P. Bähner]

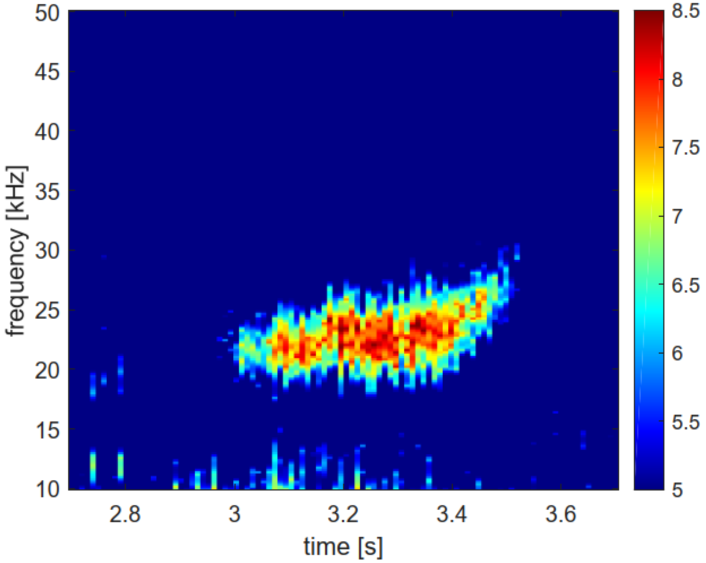
AE activity after pellet injection (potentially up to high performance)

Main idea	**Characterize AE modes in different phases of high-performance experiments: transient density increasing phase, high-performance plateau, re-heat phase** • **Study of mode activity in the re-heat phase after pellet injection** • **Impact on confinement** • **Connection to transport processes (heat?, particle?)** • **Confirm predictions (KBM, MHD-mode-induced crashes)** • **20-30 kHz mode potentially ending high-performance phase?**
Magnetic configurations	No preference
Required heating systems	ECRH
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	K. Rahbarnia, K. Aleynikova, M. Dreval, C. Slaby, S. Mendes, C. Brandt, H. Thomsen, A. Könies, A. Zocco, J. Baldzuhn, transport group
Possible number of proposals	2

AE activity after pellet injection (potentially up to high performance)







→ systematic comparison of expected mode activity with predictions

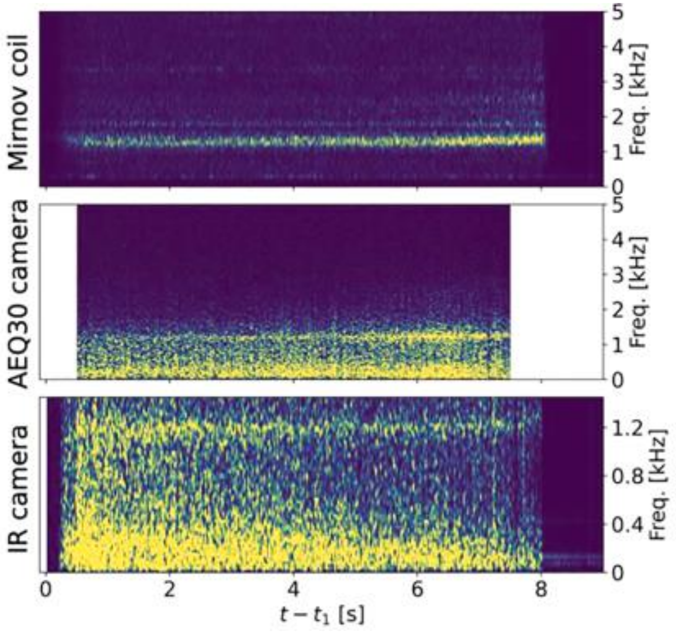
[K. Rahbarnia]

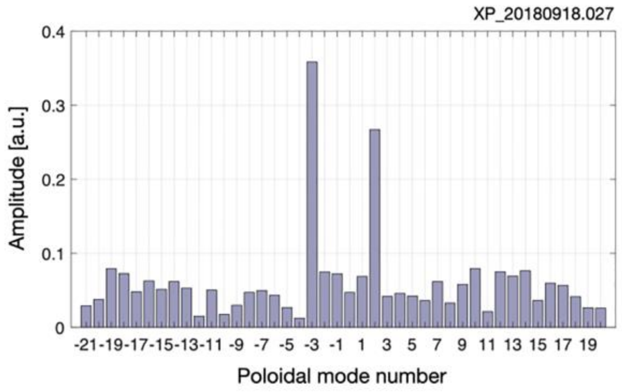
Low-frequency mode activity ~1 kHz

Main idea	Characterize AE activity previously observed • Study ILMs in configuration scans (evtl. island rotation) • Connection to zonal flows / zonal flow oscillations/turbulence?
Magnetic configurations	No preference
Required heating systems	ECRH (evlt. + NBI and ICRH)
Desired diagnostics	Mirnov, ECE, PCI, XMCTS, (FILDs), basic diagnostic to reconstruct equilibrium and profiles, MSE
Involved people (list incomplete and in no particular order, possible proponents)	A. Tancetti, J.P. Bähner, S. Ballinger, T. Andreeva, G. Wurden, C. Slaby, K. Rahbarnia, S. Mendes, C. Brandt, H. Thomsen, A. Könies, A. Krämer-Flecken
Possible number of proposals	1

Low-frequency mode activity ~1 kHz

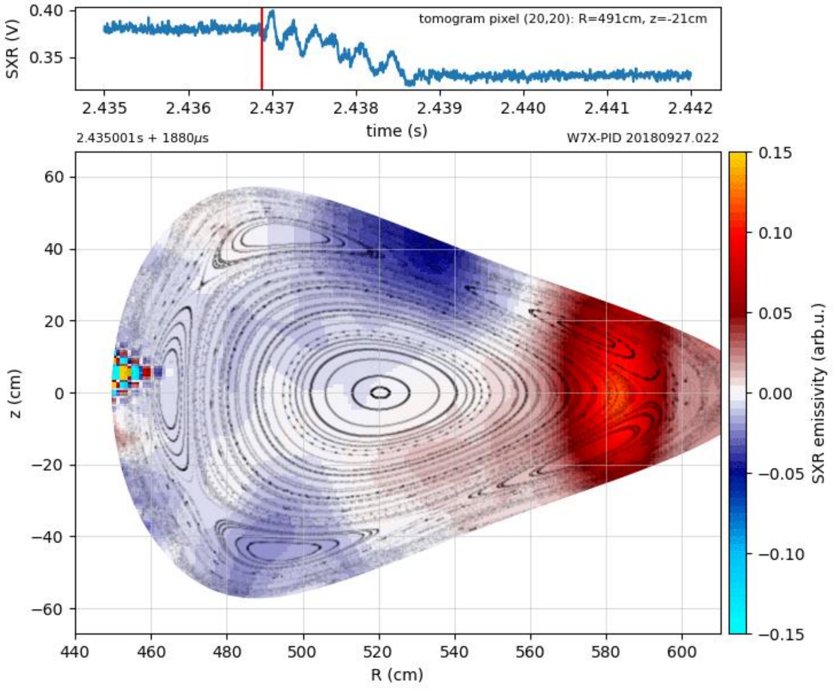
~1-2 kHz observed in many diagnostics
(example 20181010.008)





[S. Ballinger, K. Rahbarnia]

ILM dynamics in FMM+252



- SXR tomograms (each pixel normalized to mov. avg.); plotted to VMEC - LCFS
- dominated by m=1-like mode structure in the edge

[C. Brandt]

Appendix

Numerical tools at our disposal

Table 1: Numerical codes related to the proposals

code	purpose	model	cost
EUTERPE	kinetic interaction of AEs and (fast) particles turbulence can be added	fully gyrokinetic / 3 species	high (days to weeks)
CKA-EUTERPE	kinetic interaction of AEs (fixed mode structure) and (fast) particles	perturbative ideal-MHD/kinetic	medium (one day)
LGRO	very simplified kinetic interaction of AEs and (fast) particles	radially local	cheap (seconds)
CKA	eigenvalue code for finding AEs	usually ideal-MHD	medium (hours)
CONTI	Alfvén and sound continuum	local on a flux surface	medium (hours)
SCENIC	code package for ICRH physics	various codes included	high (days to weeks)
MISHKA	calculation of AE (contact: M. Dreval)	incompressional ideal-MHD	?