COMPASS
INSTITUTE OF PLASMA PHYSICS ASCR

Overview of runaway electron physics presented at the REM 2018 and studies at the COMPASS tokamak

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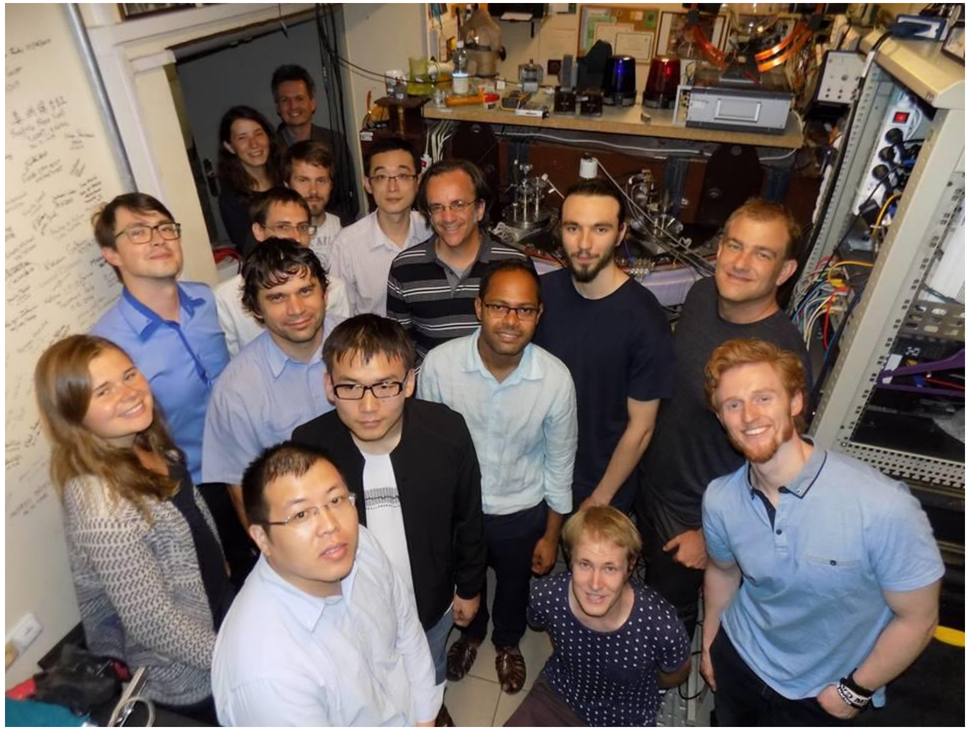
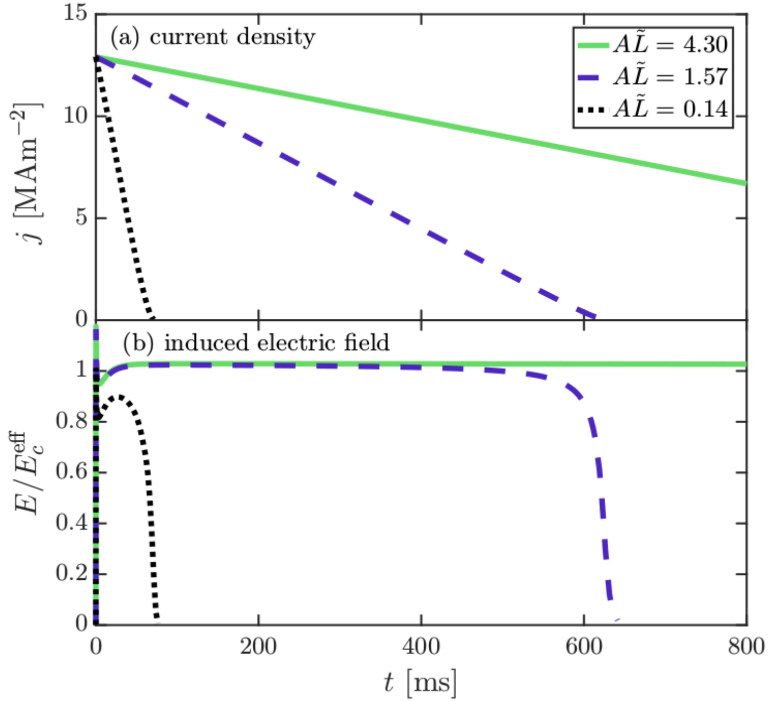
- Effects of the gas injection
  - MGI triggered disruptions in the current ramp-up phase
  - Gas injection in the current plateau phase
- RE in perturbed magnetic fields at COMPASS
  - Resonant magnetic perturbation (RMP)
  - Combined effects of RMP and gas injection
- Future plans



6th Runaway Electron Meeting - 28-30 June 2018 Prague (FNSE CTU)

Effect of partially ionized impurities and radiation on the effective critical field for runaway generation (hesslow@chalmers.se)

- Analytical expression for **effective critical field E_c^{eff}** – minimum field where force balance is possible
  - Screening (partially ionized collision operator), synchrotron & bremsstrahlung effects included
  - Agreement with kinetic simulations
  - Week dependence on ionic species
  - Weakly ionized impurities: $E_c^{eff} \geq E_c^{tot}$ (total e$^-$ density = free & bound e$^-$) >> E_c (Connor-Hastie formula)
- **Estimate of RE current decay rate**
  - **E** remains close to $\mathbf{E_c^{eff}}$
  - Influenced by induced electric field $\left(-\frac{L}{2\pi R}\frac{dIp}{dt}\right)$
  - Higher E_c^{eff} reduces the required amount of injected impurities



$A\tilde{L} \equiv \pi a^2 L/(\mu_0 R)$, $n_D = 10^{20}$ m^{-3}, $n_{Ar+} = 4n_D$ and $T = 10$ eV

Hesslow et al., PRL (2017); Hesslow et al. PPCF (2018)

Model comparisons with MST1 data & Latest results from TCV (MST1 campaign) (ppg@ipp.mpg.de)

RE decay rate for QRE AUG & TCV beams well described by screening model [Hesslow PRL 2017]

GO [Papp NF 2013] modelling - AUG RE shots

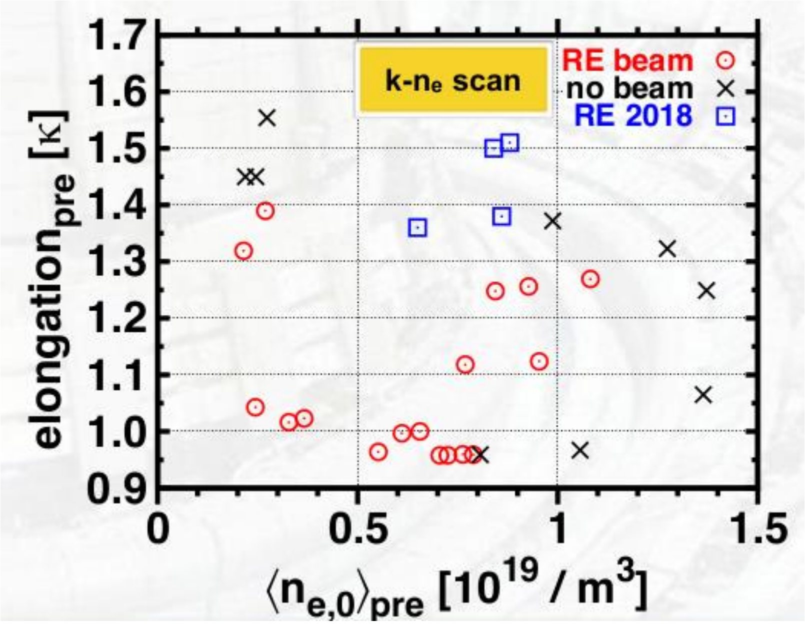
- Best match - at an assimilation rate < 30% (by the end of the quench), lower sensitivity to penetration speed
- Temperature dependence (or lack of) can only be explained if T dep of gas assimilation is modelled (-> ASTRA)

CODE simulations for FTU (QRE) and AUG (disruptions)

- FTU quiescent RE shots can only be described if RE transport is taken into account
- Full-f CODE (with self-consistent E-field) was run for a complete AUG CQ for the first time. On-axis RE current is overpredicted -> investigation of the effect of losses & argon interaction is ongoing

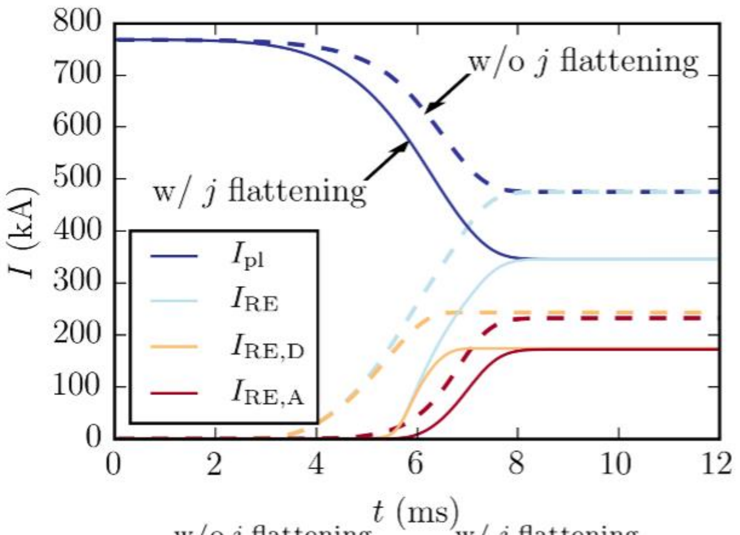
Predisruption seed is esssentiall -> scenario sensitive to n_e

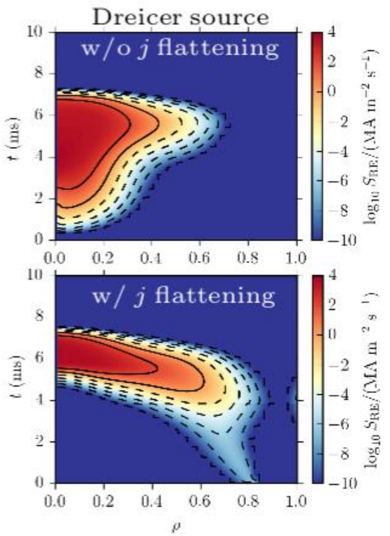
- Basic control is excellent - [Carnevale EPS 2018 + July 17 at 8:30]
- **New DMV** injects significantly more gas - possibility of extending the dissipation scan, wider operational space
- **Plasma vertical position no longer affects assimilation/dissipation**
- RE beams up to k ~ 1.5, nonmonotonic dependence
- Unlike AUG, no q_{95} = 3 threshold observed for RE beam formation

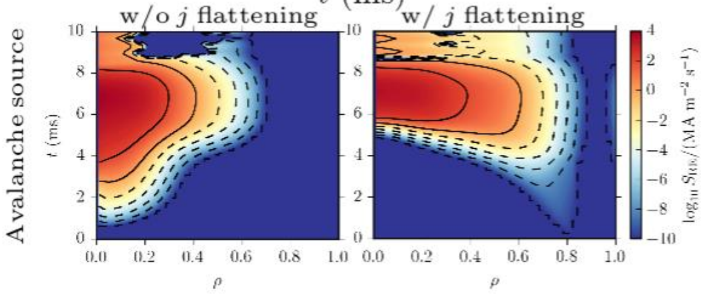


Self-consistent modelling of runaway electron generation in massive gas injection scenarios (oliver.linder@ipp.mpg.de)

- Coupling of transport solver ASTRA & impurity code STRAHL + equilibrium reconstructions -> **self-consistent modelling of RE in MGI scenarios**
- RE in ASTRA – evolution of plasma quantities
  - RE sources fluid description
  - j_{RE} coupled to evolution of electric field
- Validation against the GO code
- Current density flattening in MGI scenarios
  - Cold gas reached q = 2 -> formation of flat j_p profile & drop in l_i & increase in I_p (spike)







Flat q enhances E_{tor} around $q = 2$ location
$\Rightarrow$ RE generation starts off-centre

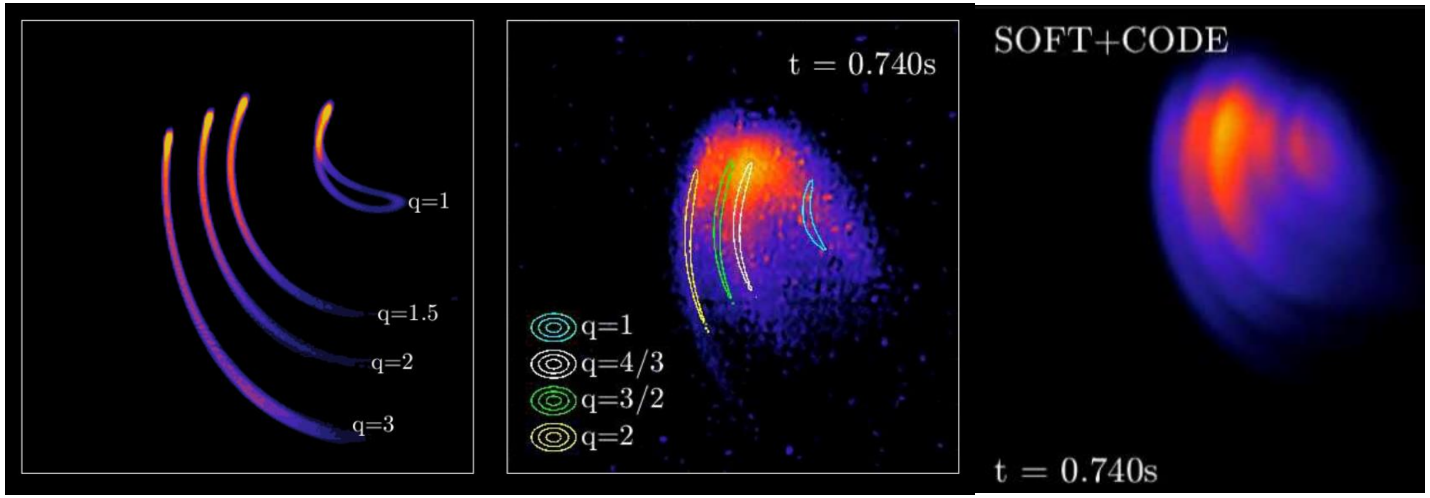
Another transport code METIS is coupled with FP solver LUKE -> self-consistent calculations of plasma and RE beam parameters

E Macusova et al., REM + 45th EPS, Prague, 2018

6th REM 2018: Alex TINGUELY & Mathias HOPPE

Using SOFT and CODE to study spatiotemporal dynamics of runaway electrons in Alcator C-Mod (rating@mit.edu)

- *Wide-angle camera* (60fps, visible & NIR, distortion-corrected, background and HXR removed)
- **SOFT + CODE** (full momentum-space distribution function) – image build from q-surfaces – **most accurate in spatial features reproduction**
- Effect of MHD (lock mode) on RE –> **'third leg' in SR pattern** -> Structures at rational q?
- First results with synchrotron polarization (10 channel system)



Tinguely R. A. et al., NF 58 082001 2018

Modeling the anisotropic radiation of runaway electrons: M. Hoppe (July 17 at 10:30)

SOFT - real(istic) magnetic geometry

- drift and radiation cone deformation corrections

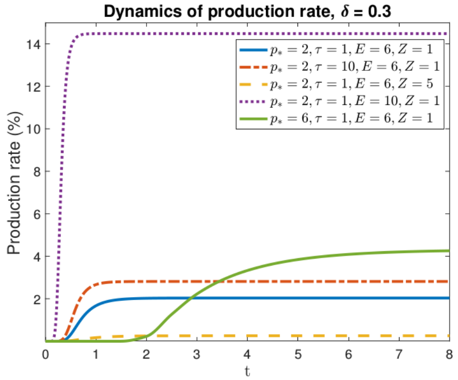
- SR & Bremsstrahlung – different part of the distribution function
- **Importance of geometric effects**

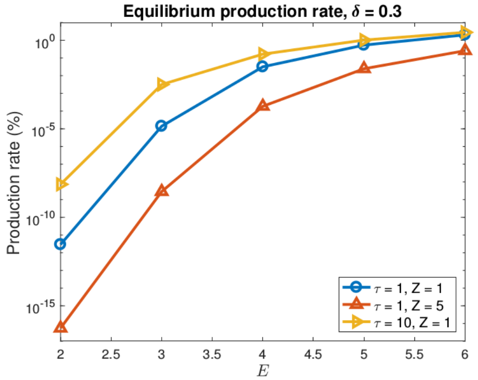
Hoppe M. et al., NF 58 026032 2018; Hoppe M. et al., NF 58 082001 2018

6th REM: Diego DEL-CASTILLO-NEGRETE & Chang LIU

Production rate of RE in dynamic scenarios: a probabilistic backward Monte Carlo method: D. del-Castillo-Negrete (July 16 at 16:10)

- **BMC method** – powerful tool (faster convergence; T_{RE}, T_{Loss} & production rate)





G. Zhang and D. del-Castillo-Negrete. Phys. Plasmas 24, 092551 (2017)

Synchrotron radiation of relativistic RE

- Synthetic diagnostic for the Kinetic Orbit Runaway electrons Code (**KORC**) SR developed – compute the full-orbit relativistic dynamics in the electric and magnetic fields **including radiation & collisions**

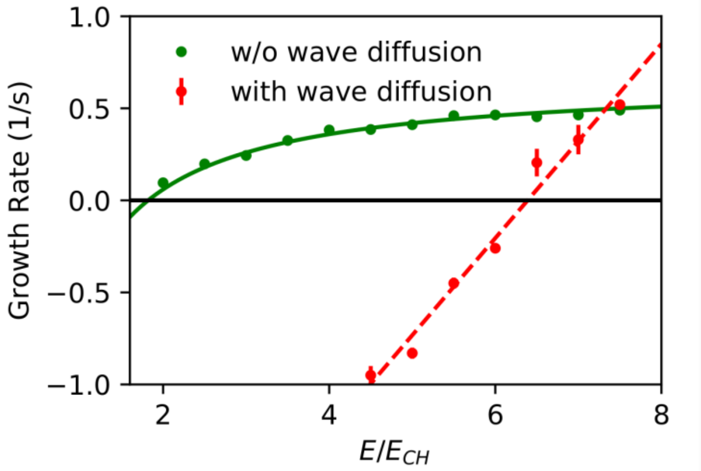
D. del-Castillo-Negrete et al., Phys. Plasmas 25, 056104 (2018)

Kinetic instabilities associated with runaway electrons: C. Liu (July 17 at 11:40)

Self-consistent quasilinear simulation model (whistler and extraordinary electron waves included) - **new E/E_{CH} threshold** -> avalanche & losses

- theory closer to experiment
- prompt growth of ECE signal explained

C. Liu et all., ArXiv:1801.01827 (2018)



A **new expression** of conservative magnetic moment of RE was introduced **C. Liu et all., ArXiv:1804.01971 (2018)**

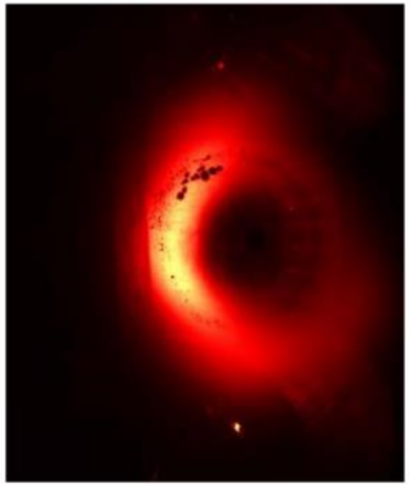
A **fluid-kinetic framework** for RE simulation **using the BMC** method presented

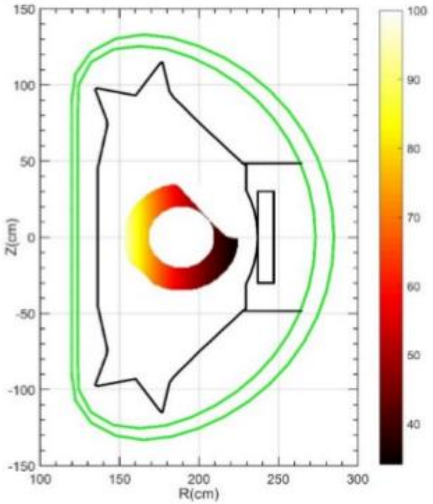
Recent Runaway Electron Investigations in EAST Tokamak (rjzhou@ipp.ac.cn)

- **RE diagnostics** (High Energy HXR System: CdTe+NaI(Tl)+BGO: 0.5-9 MeV & 1ms time resolution; Gamma Ray Spectroscopy: LaBr3(Ce), max. 1MHz; in development – fast IR cameras system & Cherenkov probe)
- Up to 60% of the pre-disruptive plasma current -> to I_{RE} in the disruption when a seed of fast electrons exist
- 1-D self-consistent model - evolution of radial profile of electric field and n_{RE} (diffusion <-> induced electric field)
- ½ of magnetic energy converted to RE kinetic energy during the disruption **R.J.Zhou NF 57 114002 2017**
- Analysis of synchrotron radiation (SR) spectra and pattern can supplement each other - **large orbit shift of REs can result to an asymmetrical SR pattern**

Synchrotron radiation intensity and energy of runaway electrons in EAST tokamak (ykzhang@ipp.ac.cn)

- Energy of RE from drift orbit shift
- **SR intensity and energy of runaway electrons do not reach the maximum at the same time**
- SR compared with Pankratov's analytical formula/SOFT **Pankratov, Plasma Phys. Rep. 22 (1996) 535**





E=35MeV θ_p=0.18 $R \in [20,35]$cm

Dynamic evolution of runaway electron energy distribution during tokamak disruptions (zenglong@ipp.ac.cn)

- 0D model describing RE energy distribution developed
- **Negative U_{loop}** applied on the post-disruption RE beam -> **de-acceleration of RE** and decrease of their energy in the medium-energy range + oscillations of HXR signal (not ECE), SXR, U_{loop} and magnetics
- MGI into the post-disruption RE beam (He & H) -> Non-monotonous dependence of bremsstrahlung on the injected amount of gas; Ar & Ne – stronger RE losses

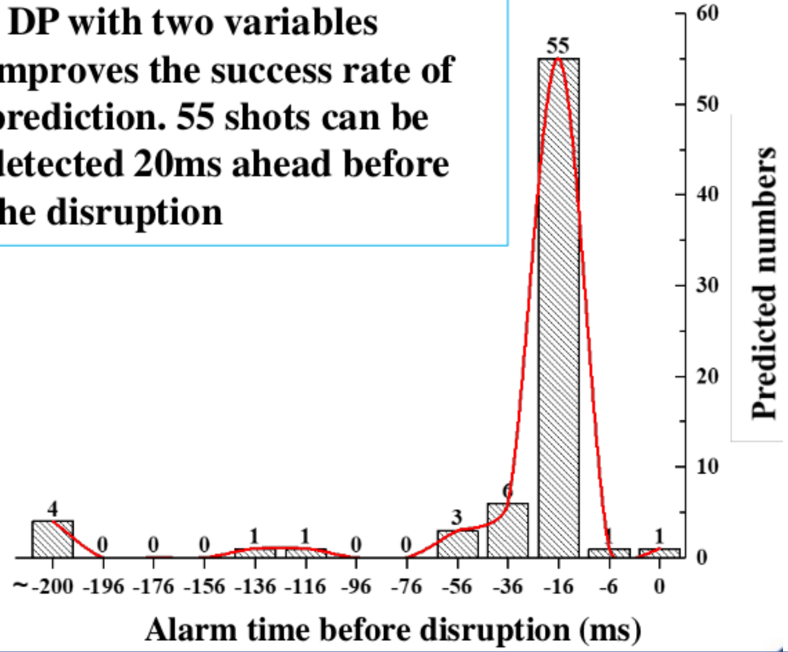
Statistic analysis of disruption induced by vertical displacement events on EAST tokamak (zhangyang@ipp.ac.cn)

- 60% of disruptions (Ip > 500kA) = VID (vertical instability disruption)
  - Triggered or accompanied by the impurity accumulation, MHD mode, minor D, ELM, physical perturbation -> more flatten current profile – reduced capability of control
  - enhanced halo current = enhanced electromagnetic force or uncontrollable loss of RE

Disruption prediction function constructed -> linear Support Vector Machine method used with 2 variables (ΔZ, $d\ln|\Delta Z|/dt$)

- 93% of VID predicted successfully
- **80 % VID detected 20 ms ahead** before disruption

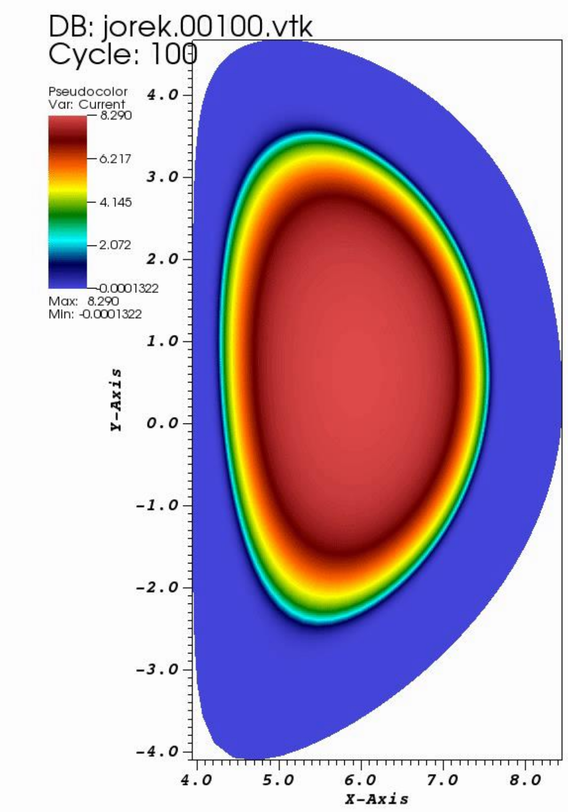
• DP with two variables improves the success rate of prediction. 55 shots can be detected 20ms ahead before the disruption



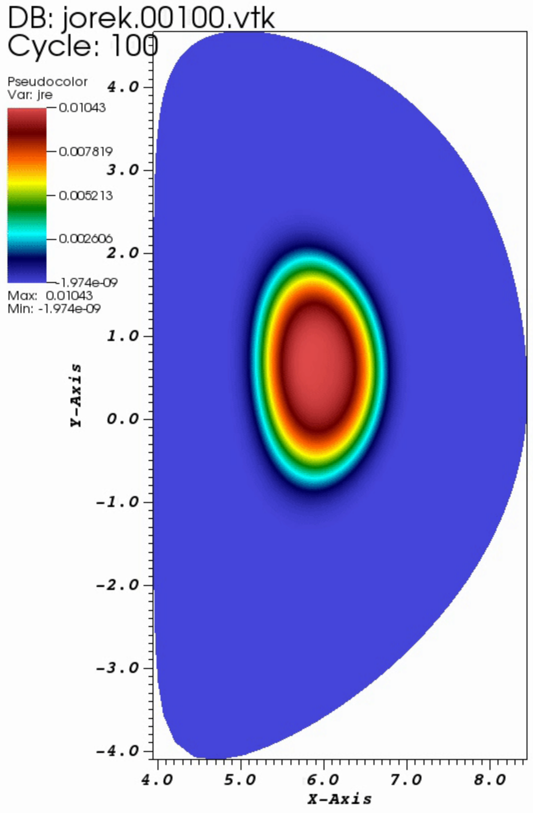
Runaway electron fluid model in JOREK (vkb@ipp.mpg.de)

ITER VDE with Runaways (axisymmetric)

Total current density



RE current density



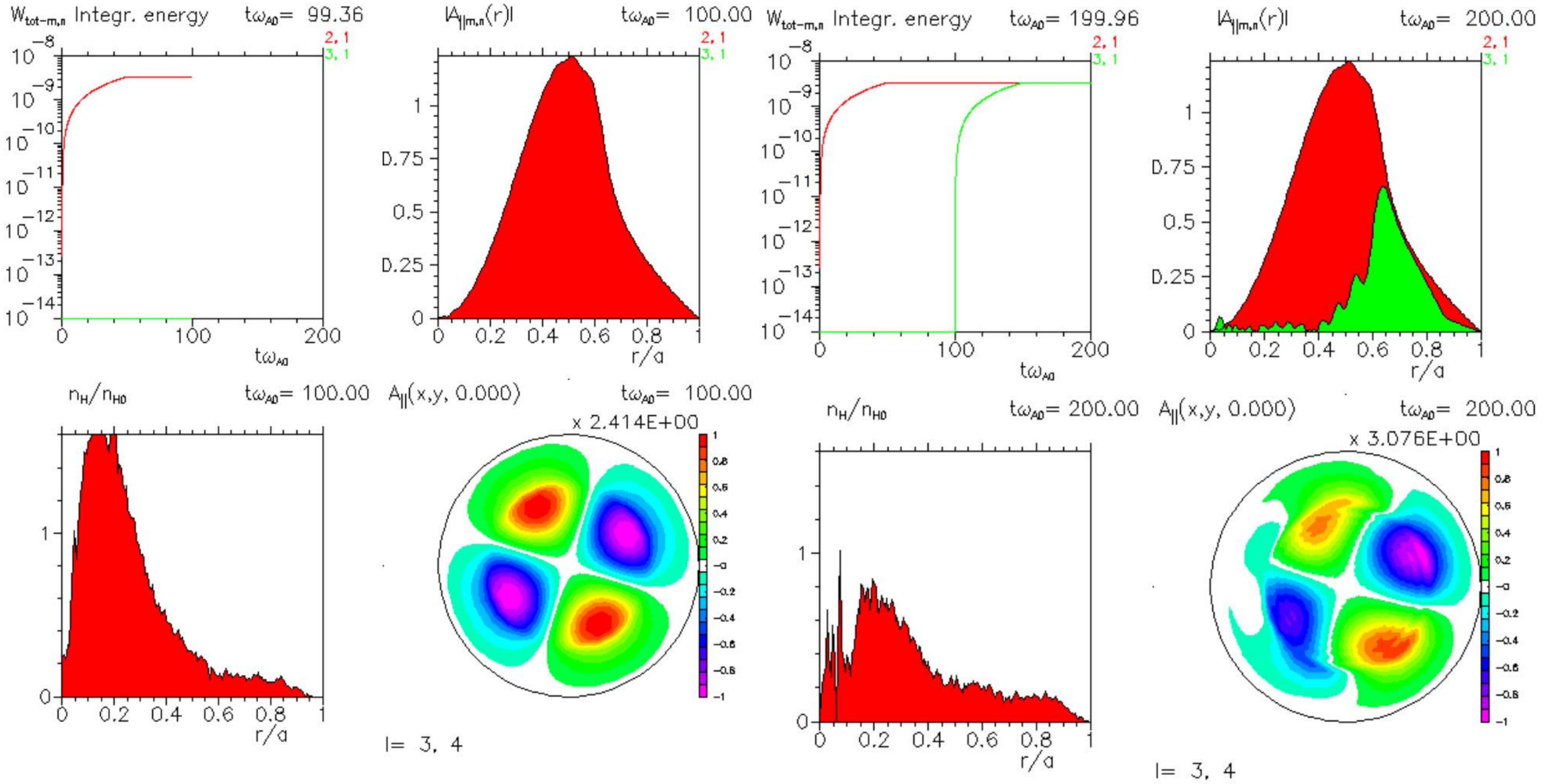
- RE fluid model implemented in to the 3D non-linear MHD code JOREK
  - RE separated fluid from plasma
  - RE generated during thermal quench
  - **RE effects the linear growth of resistive internal kink mode in circular plasma**

- ITER VDE simulations with RE

(V. K. Bandaru & F.J. Artola Such*)

* Aix-Marseille Université, CNRS, Marseille, France

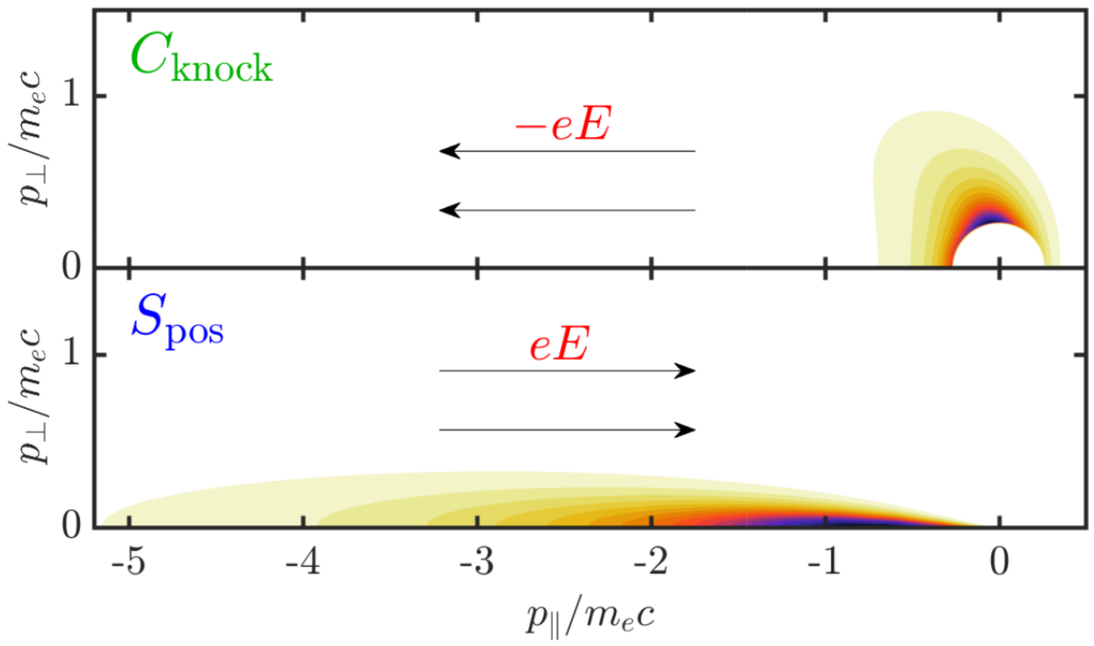
Study of transport of runaway electrons in the presence of MHD perturbations with the Hybrid MHD Gyrokinetic Code (casolari@ipp.cas.cz)



- n_e profile evolution from simulations compared with a purely diffusive model (based on the stochastic diffusion of magnetic field lines)
- effect of n=(1, 2) & (1, 3) tearing modes
- **flattening of n_e profile** when n = (1, 2) reached the max. amplitude (model) and when n=(1, 2) & (1, 3) were overlapping (simulation)

Dynamics of runaway positrons (embreus@chalmers.se)

- Positrons in systems with kinetic energy exceeding the pair-productions ($2m_ec^2$ ~ 1MeV)
- RE accelerated in the direction opposite to E (small pitch angles)
- Positrons remain thermalized or annihilate (small fraction accelerated)
- **Distribution function with positron collision operator derived** -> threshold for positrons pair production E_{PP} (increase with effective charge)
- $n_{RP}/n_{RE} = 10^{-7}$ -> very small synchrotron or HXR radiation, but annihilation radiation (peaked at 511 keV)



Embreus et al.,arXiv:1807.04460, 2018

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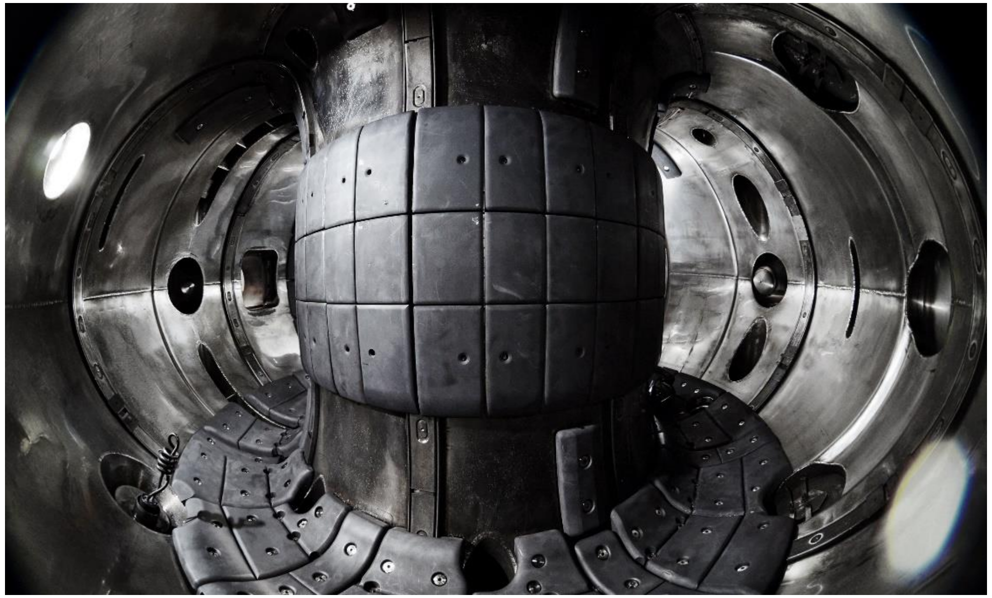
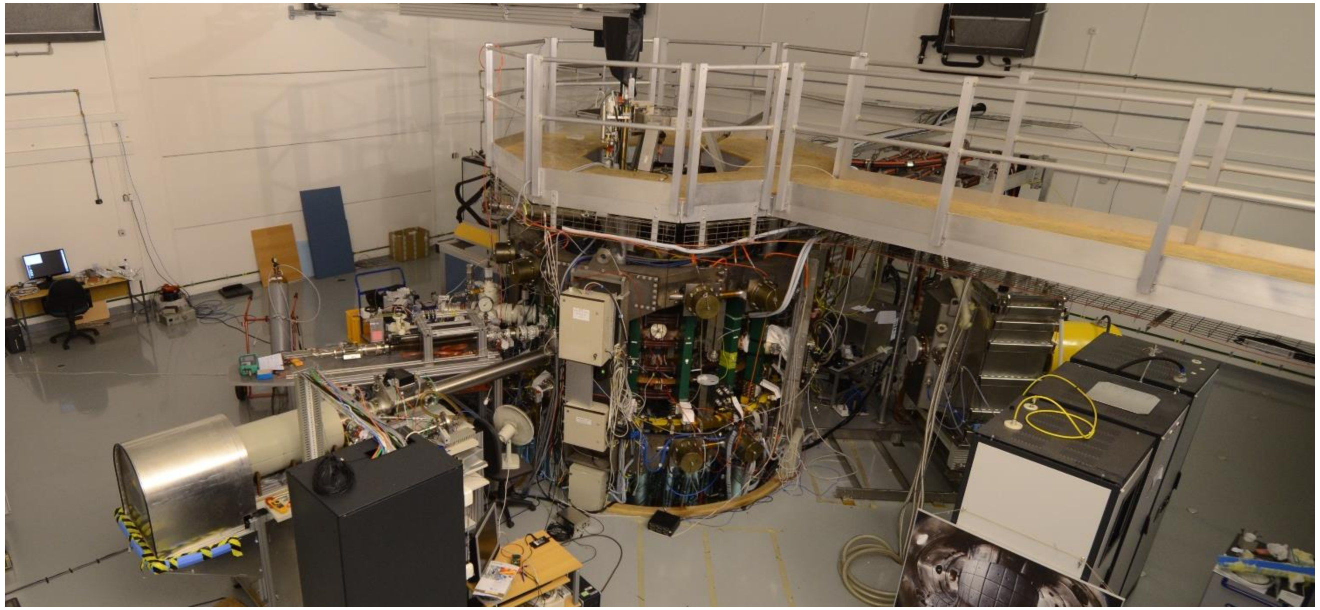
The COMPASS tokamak

- ITER-like plasma
- R_0/a = 0.56m/0.23m
- B_T = 0.9 T – 1.6 T
- $I_p \leq$ 350 kA
- P_{NBI} up to 600 kW
- **Full poloidal coverage by RMP coils**

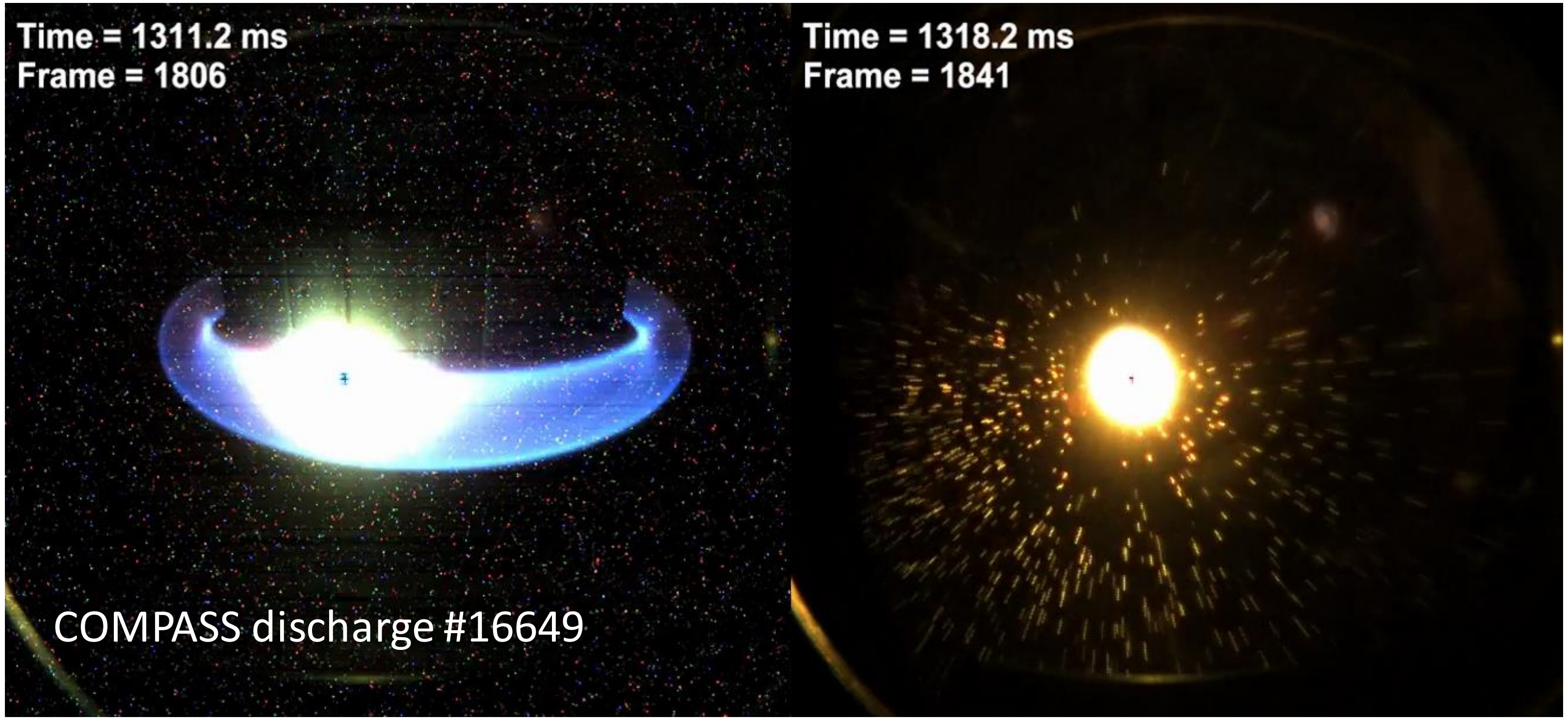


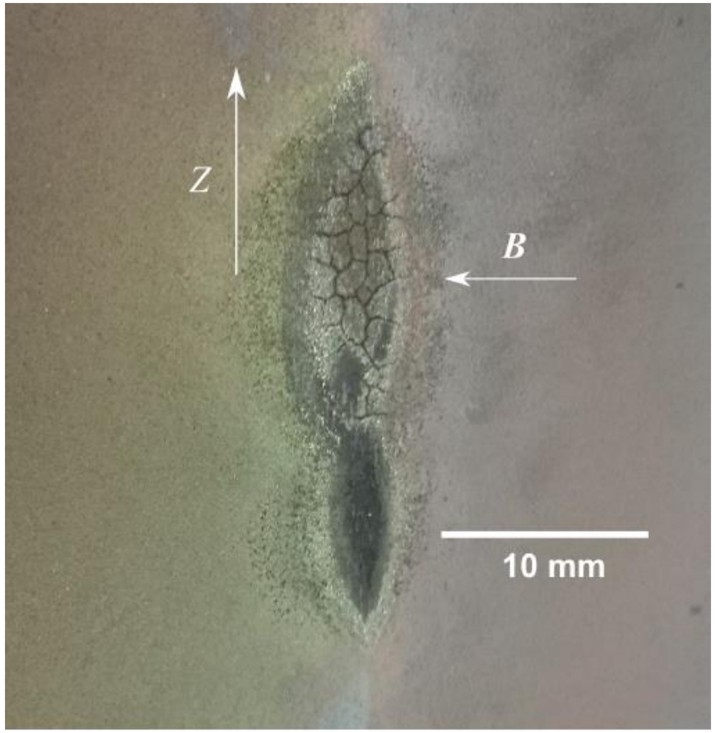


- Rich magnetic diagnostics
- Fast visible & infrared cameras
- Hard X-ray (HXR) and neutron diagnostics
- Thomson scattering; 2mm interferometer
- Dedicated diagnostics for RE - **SXR matrix detector MediPix**

V Weinzettl et al. 2011 Fusion Eng. Des. 86 1227; T Benka *et al* 2018 *JINST* 13

The COMPASS tokamak – fast cameras





Record from fast visible camera (1280 × 1024px @ 4 kfps; 640 × 8 px @ 800 kfps) at COMPASS (# 16649)

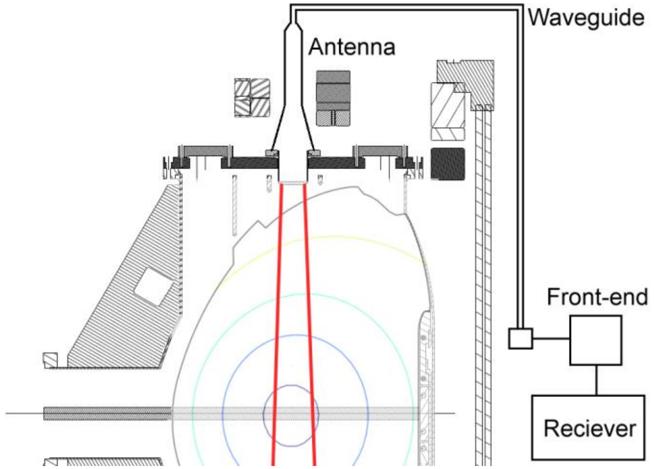
COMPASS protruding graphite inner limiter tile

A Havranek et al. 2017 *Fus. Eng. Des.* 123; Weinzettl et al. 2017 *JINST* 12

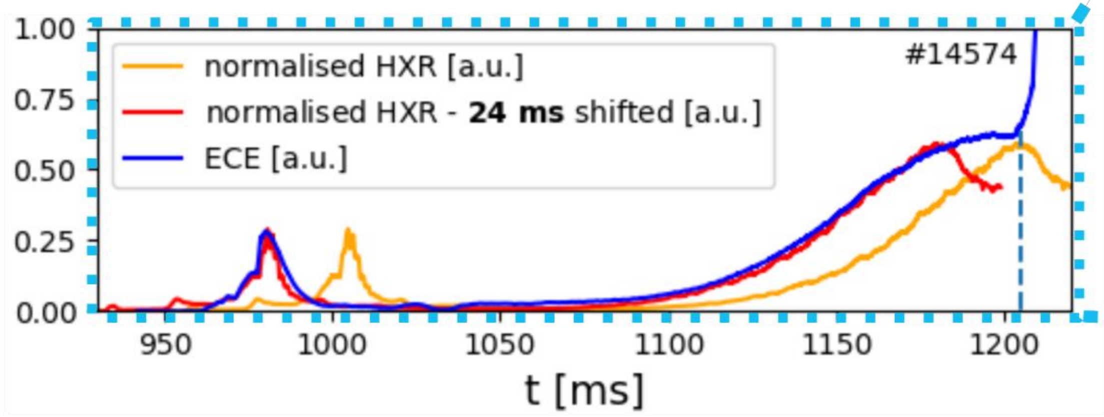
J Mlynar et al. 2018 PPCF, submitted

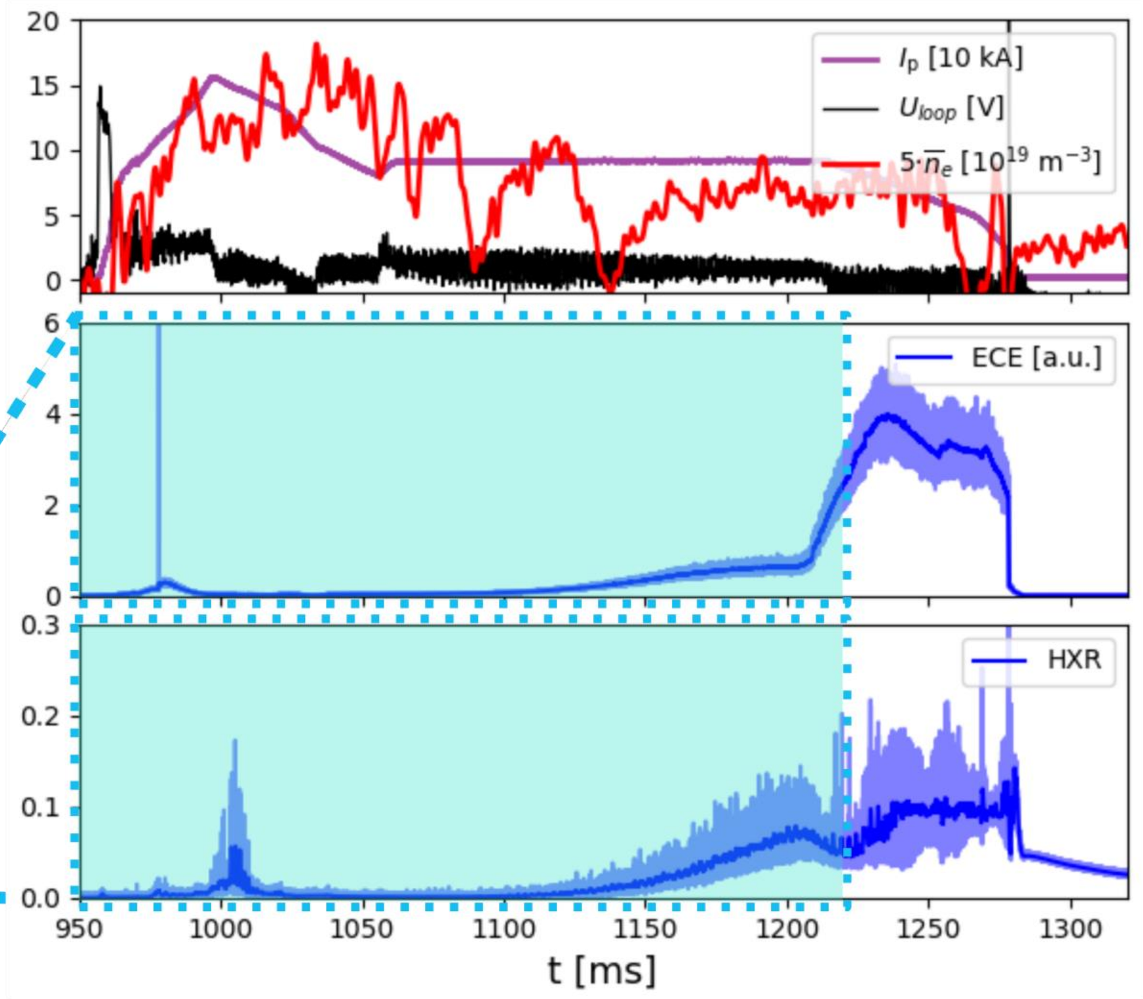
COMPASS – diagnostics development

Vertically placed ECE heterodyne radiometer (V-ECE)



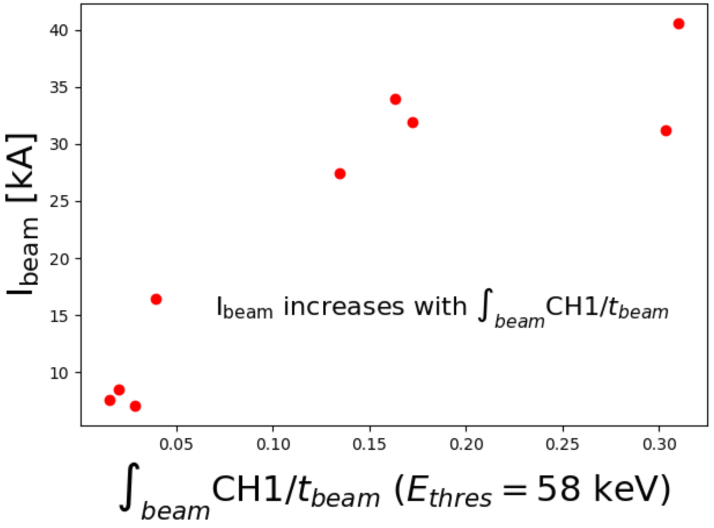
- 3rd harmonic
  -> (76 - 88 GHz)
- E = 50 - 140 keV
  -> initial seed
  -> primary generation
- Comparison with HXR
  -> "confinement time"



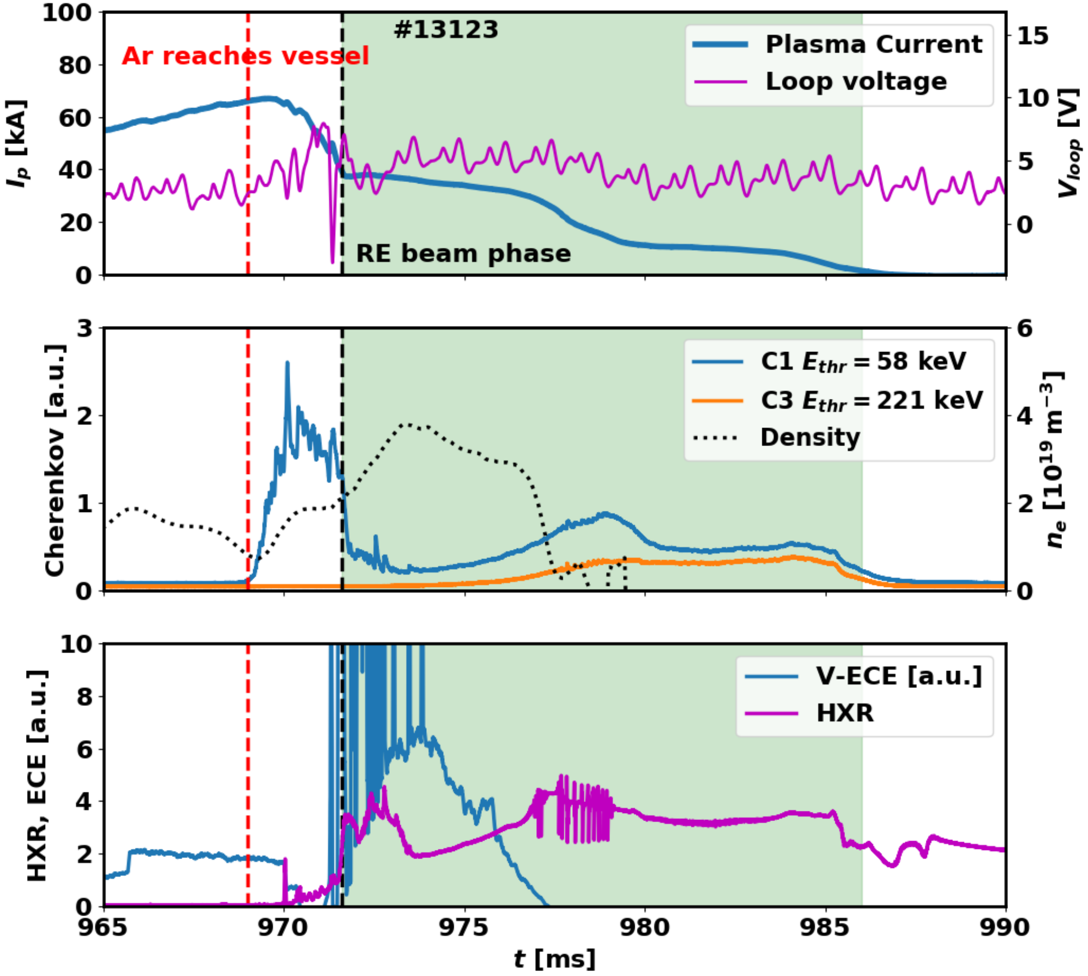


M Farnik et al., P 1.1010, 45th EPS, Prague, 2018 (farnik@ipp.cas.cz)

COMPASS – diagnostics development



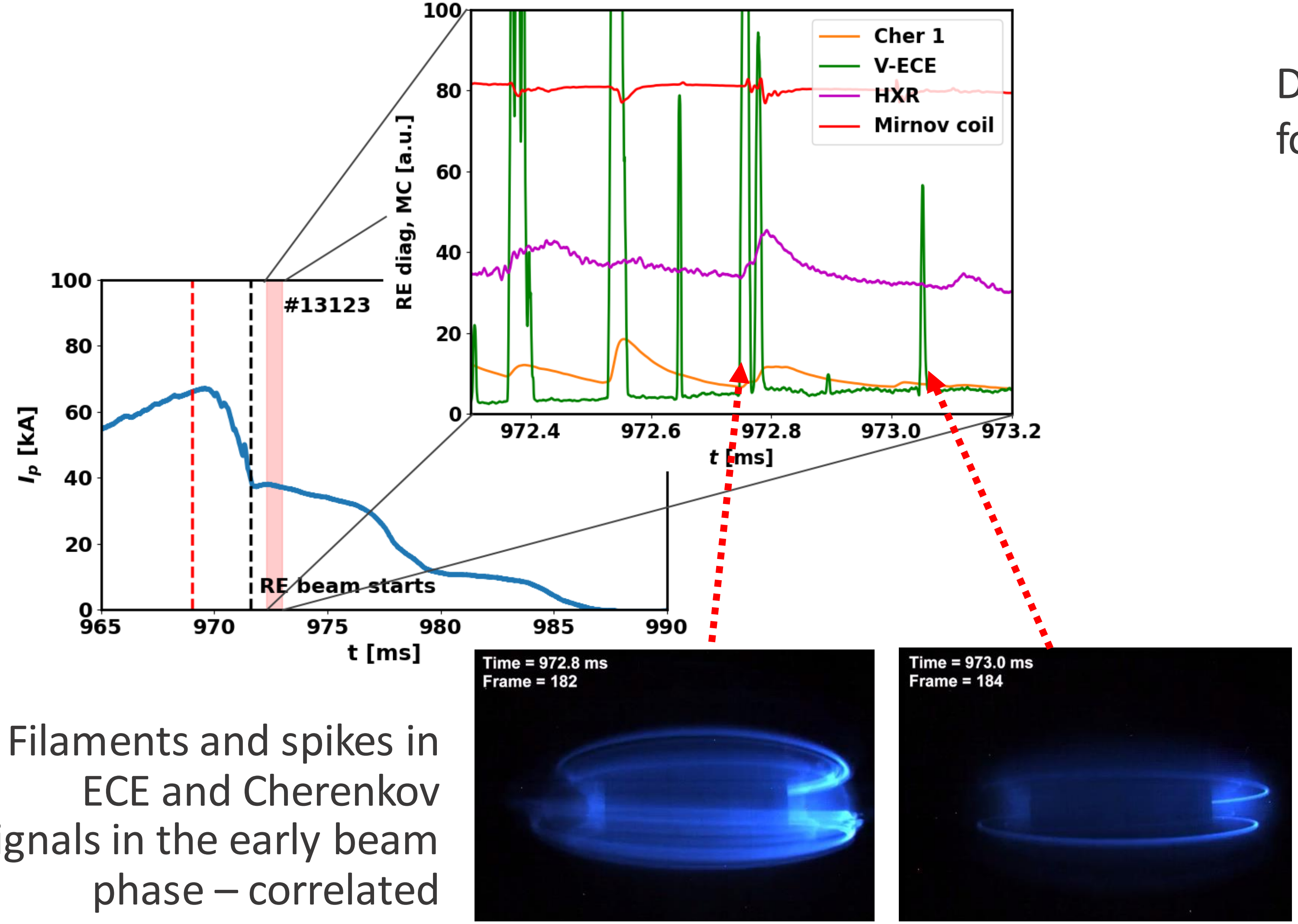
- B_T = 1.15 T, I_p = 70 kA, q_a > 5
- n_e = 10^{19} m^{-3}, Te = 500 eV



- Developed in NCBJ, Poland, EUROfusion support
- Direct detection of lost RE in CVD diamond
- 3 channels: ***E_{thr}*>58 keV, >145 keV, >211 keV**
- Outer midplane, slightly in shadow of the limiter
- Identifies the onset of Runaway Electrons

J Cerovsky et al., P 2.1006, 45th EPS, Prague, 2018
(cerovsky@ipp.cas.cz)

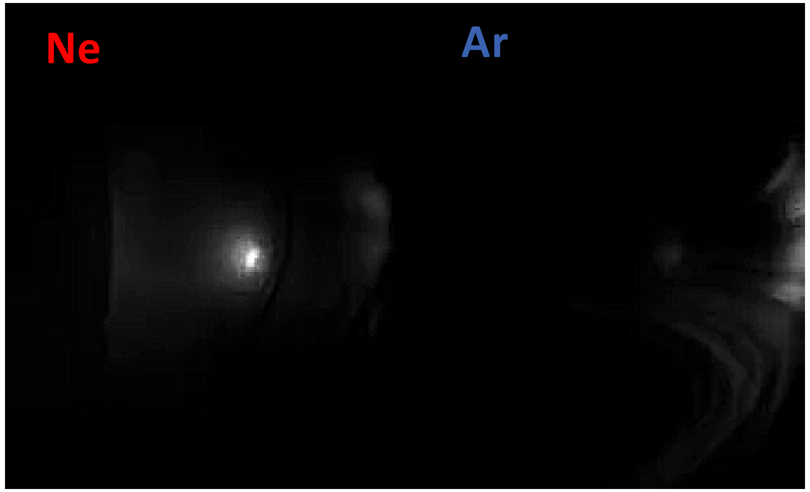
Current ramp-up: post-disruption RE beam



Filaments and spikes in ECE and Cherenkov signals in the early beam phase – correlated

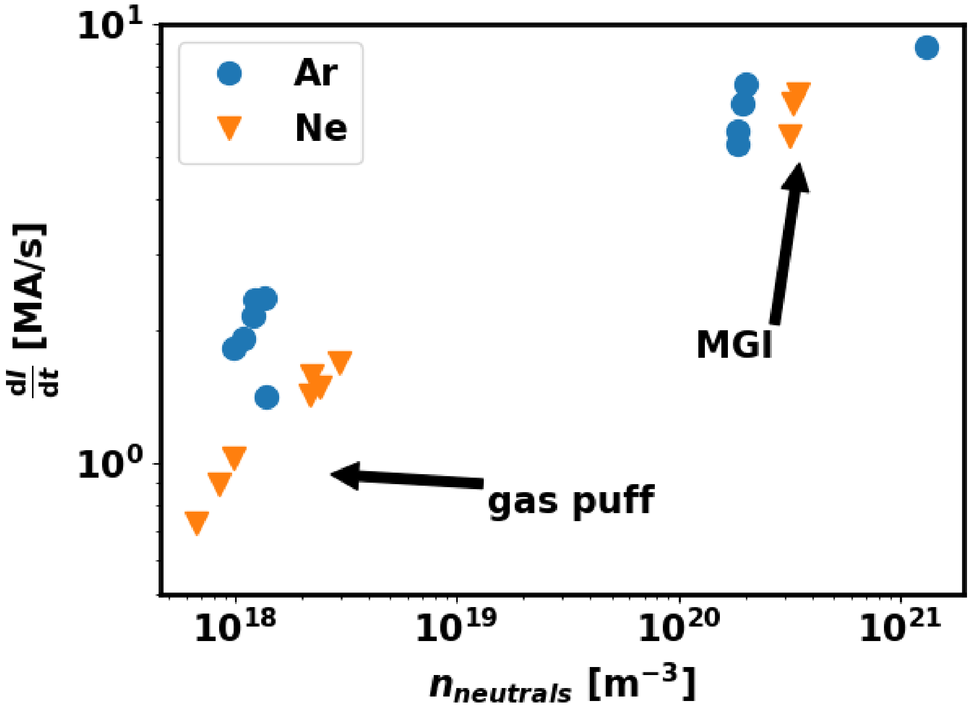
Difference between Ar and Ne behaviour following their injection

- Ne seems to penetrate as a blob (neutral particles)
- Ar spreads poloidally from the onset (ionised particles)



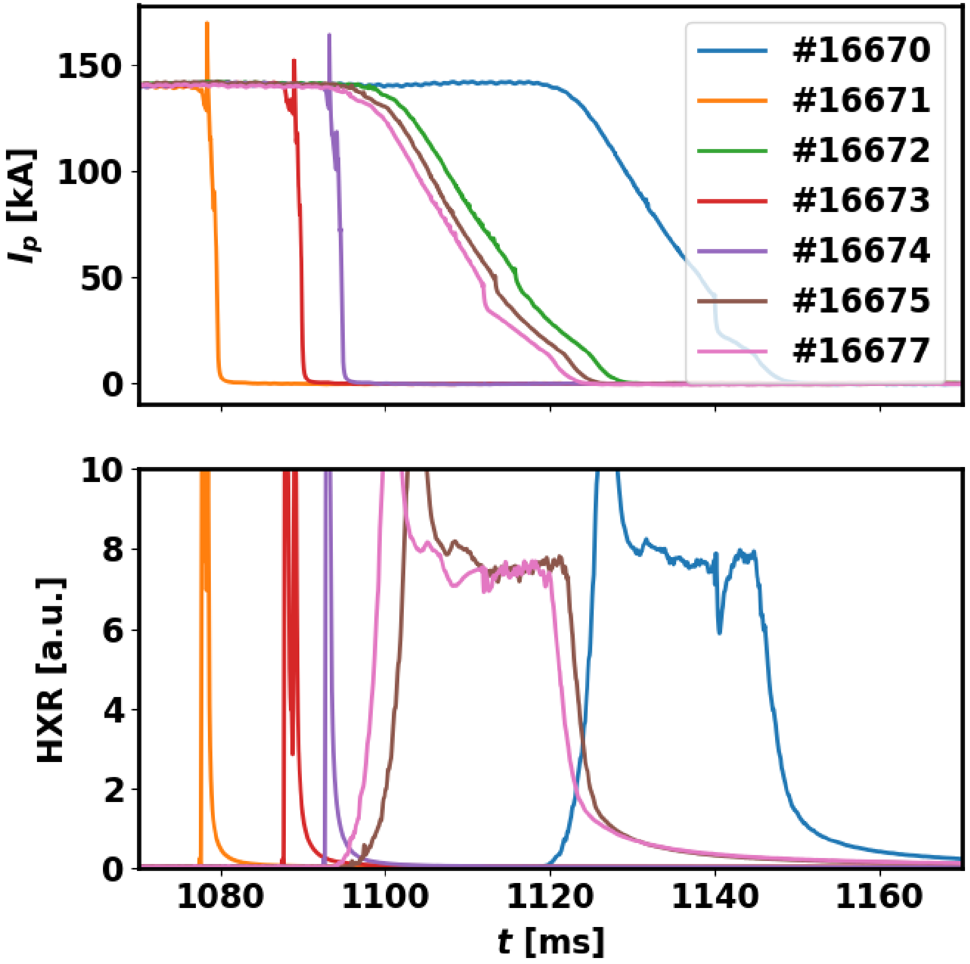
Current flat-top: The gas puff disruptions

Current decay rate in the gas amount scan

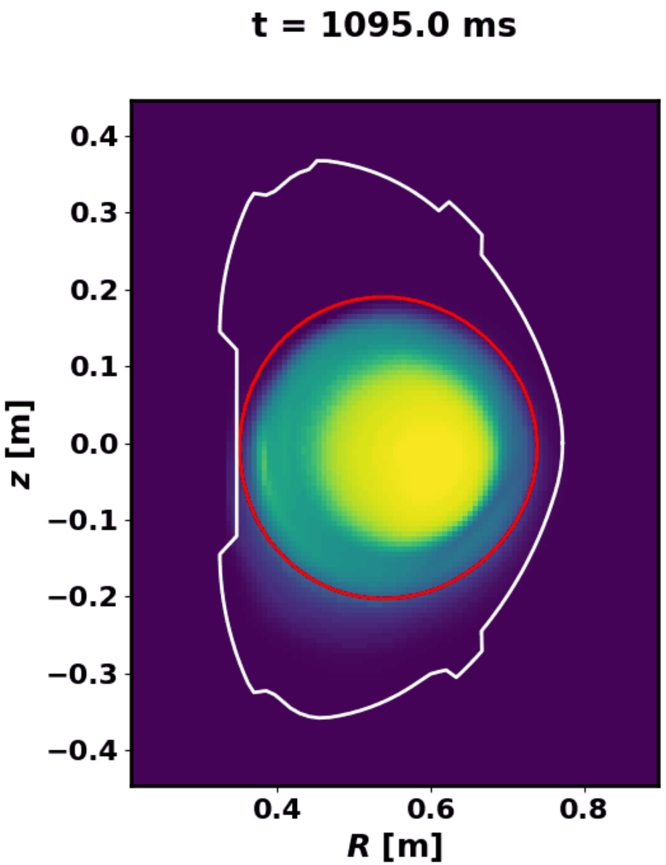


O Ficker et al., P 1.1062, 45th EPS, Prague, 2018
(ficker@ipp.cas.cz)

MGI timing scan - Ip flat-top scenario -> RE energy is decisive for the RE survival



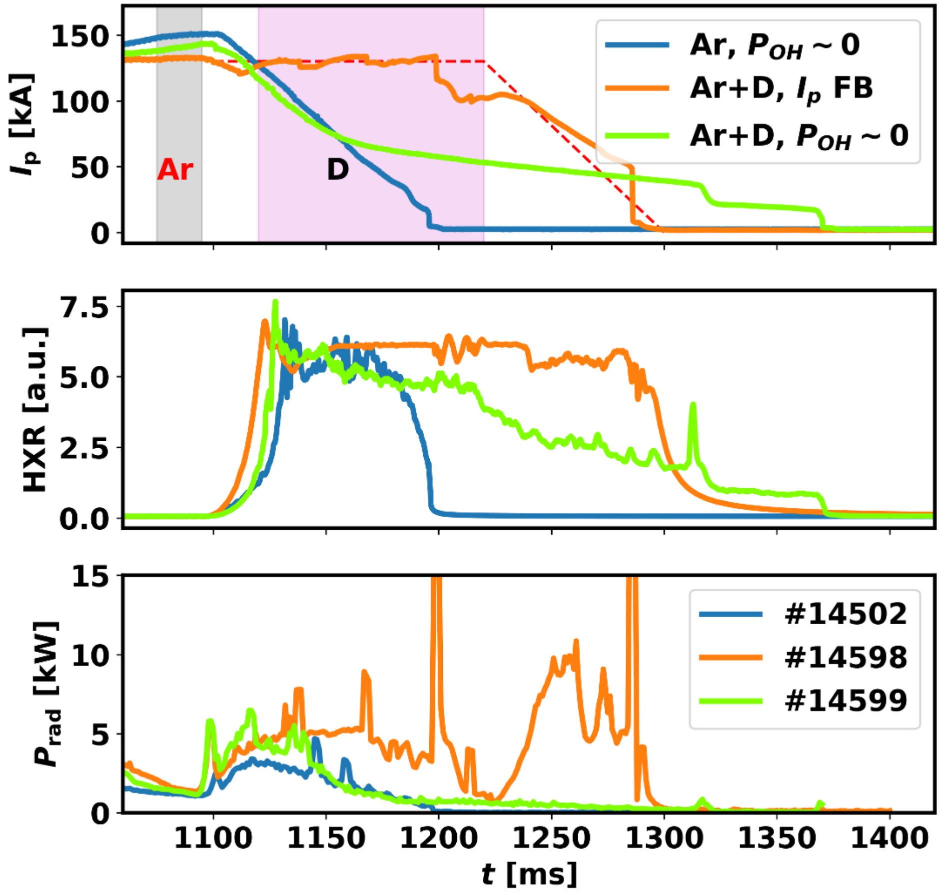
Current flat-top: Combined gas puff



O Ficker et al., P 1.1062, 45th EPS, 2018

- Motivated by JET - tomography
- Different behavior with the zero U_{loop} configuration
- **D injection** added– **slows decay** (Proposed interpretation: **D** cools down the background plasma- supported by data from minipectrometers)
- **Great interest** for **modellers**

Zero U_{loop} -> natural decay of I_{RE}



J Mlynar et al. 2018 PPCF, submitted

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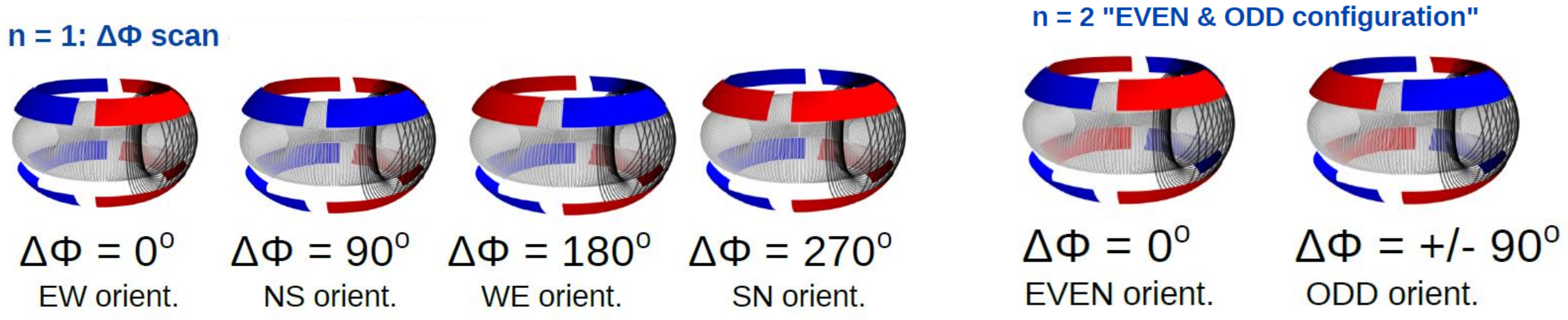
RMP II: Overview

Resonant Magnetic Perturbation (RMP): toroidally periodic (COMPASS, n = 1 or n = 2)

- Motivated by **AUG results:** RE losses increase with RMP, with higher efficiency for the resonant component.

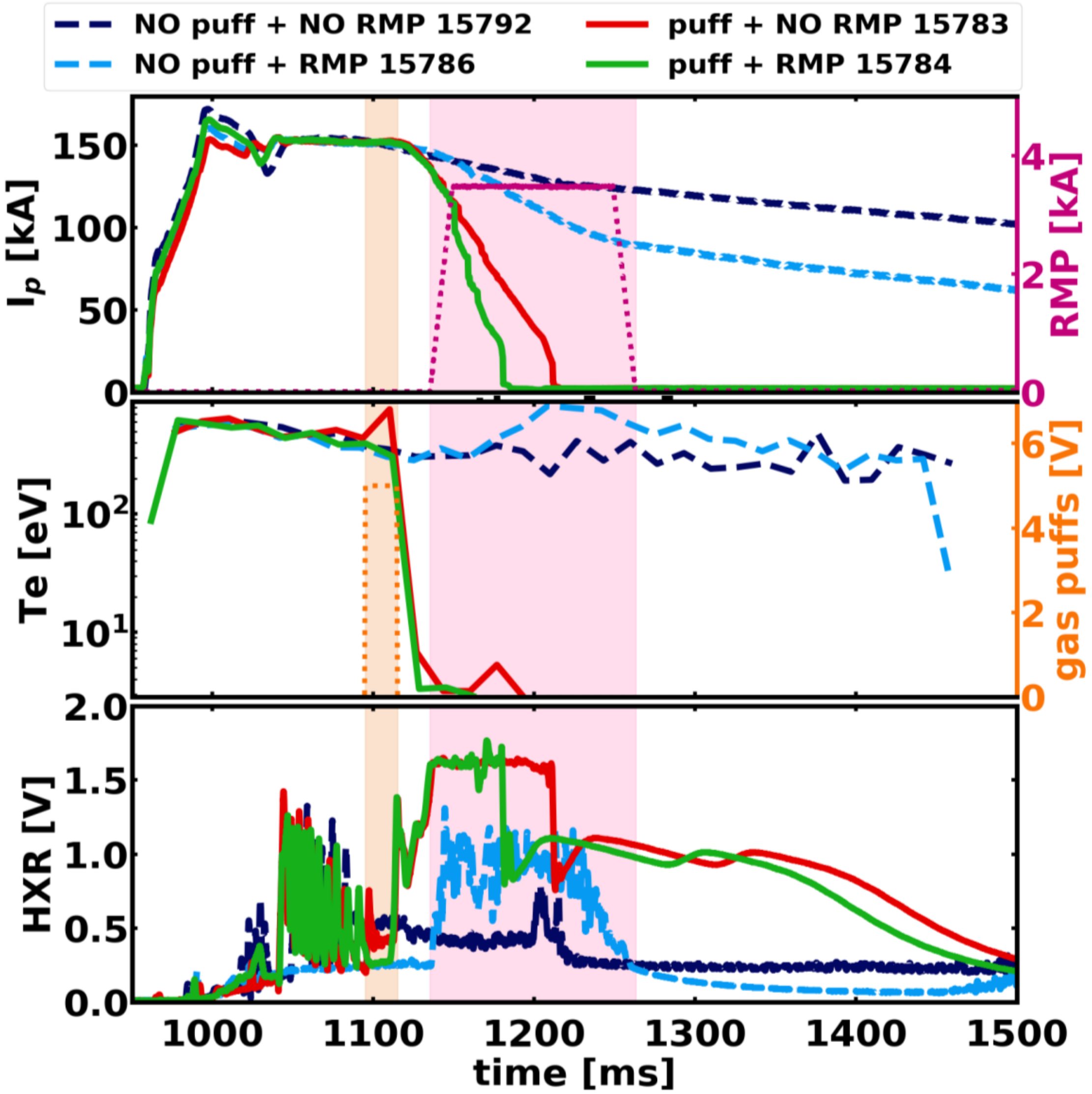
Gobbin M. et al., 2018 Plasma Phys. Control. Fusion 60 014036



- $B_{RMP} / B_T \sim 10^{-2}$ -> help understanding of RE dynamics
- **MARS-F** (resisitive MHD code) applied to interpret RMP experiments

Y. Liu, et al., Phys. Plasmas 7, 3681, 2000

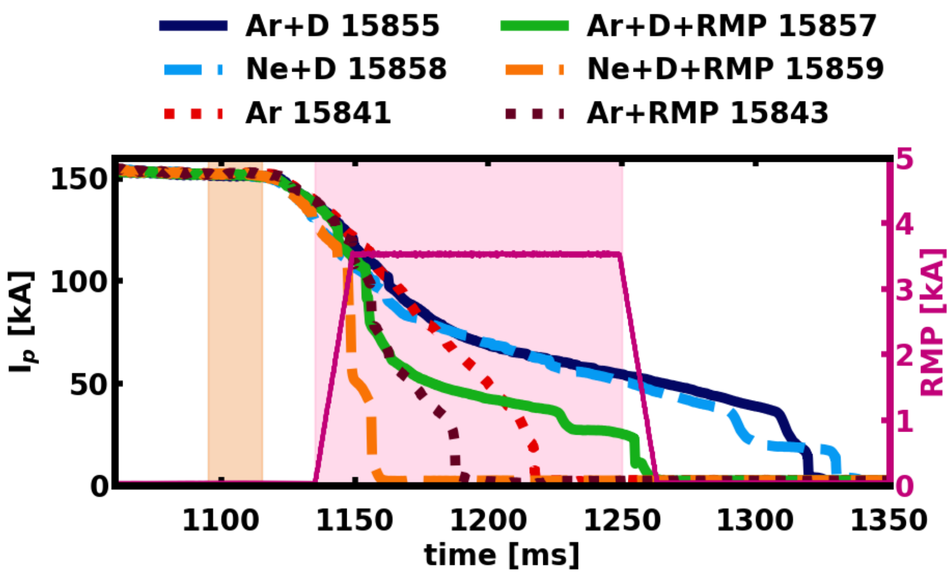
Gas puff & RMP on/off for n=1



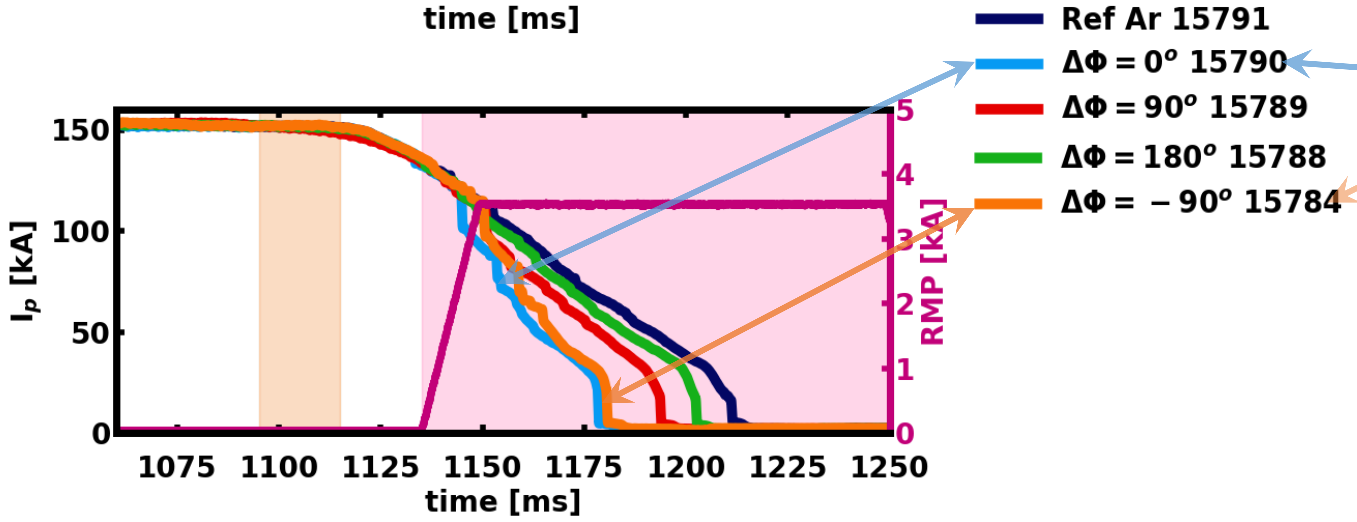
- **Zero U_{loop} configuration**
- Effect of gas puff - significant for the plasma and RE current decay rate
- RMP energized after the gas puff
- Effect of RMP clearly visible (even without gas puff) in both current decay rate and in HXR radiation
- The HXR scintillation detector (> 50 keV) suffers saturation in the case of the gas puff
- No gas puff, no RMPs -> RE confined

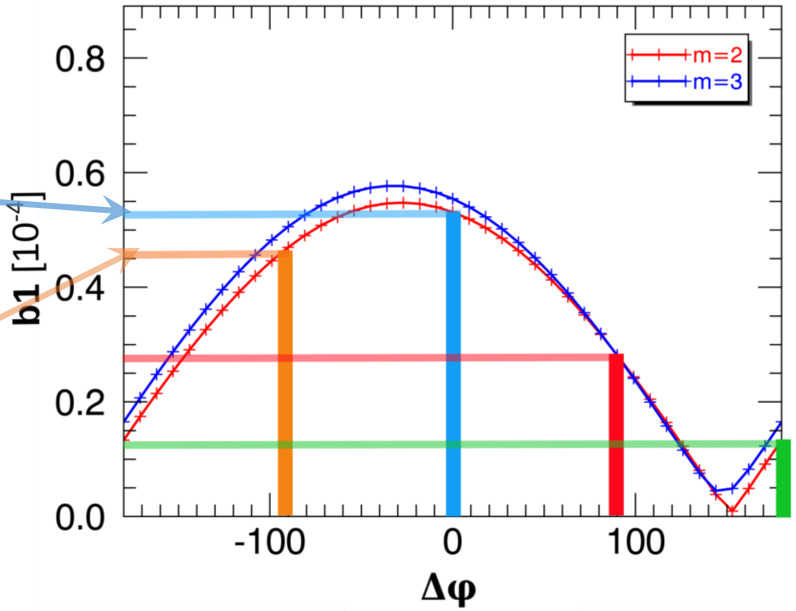
J Mlynar et al. 2018 PPCF, submitted

RMP & 2nd Gas puff / ΔΦ scan for n=1



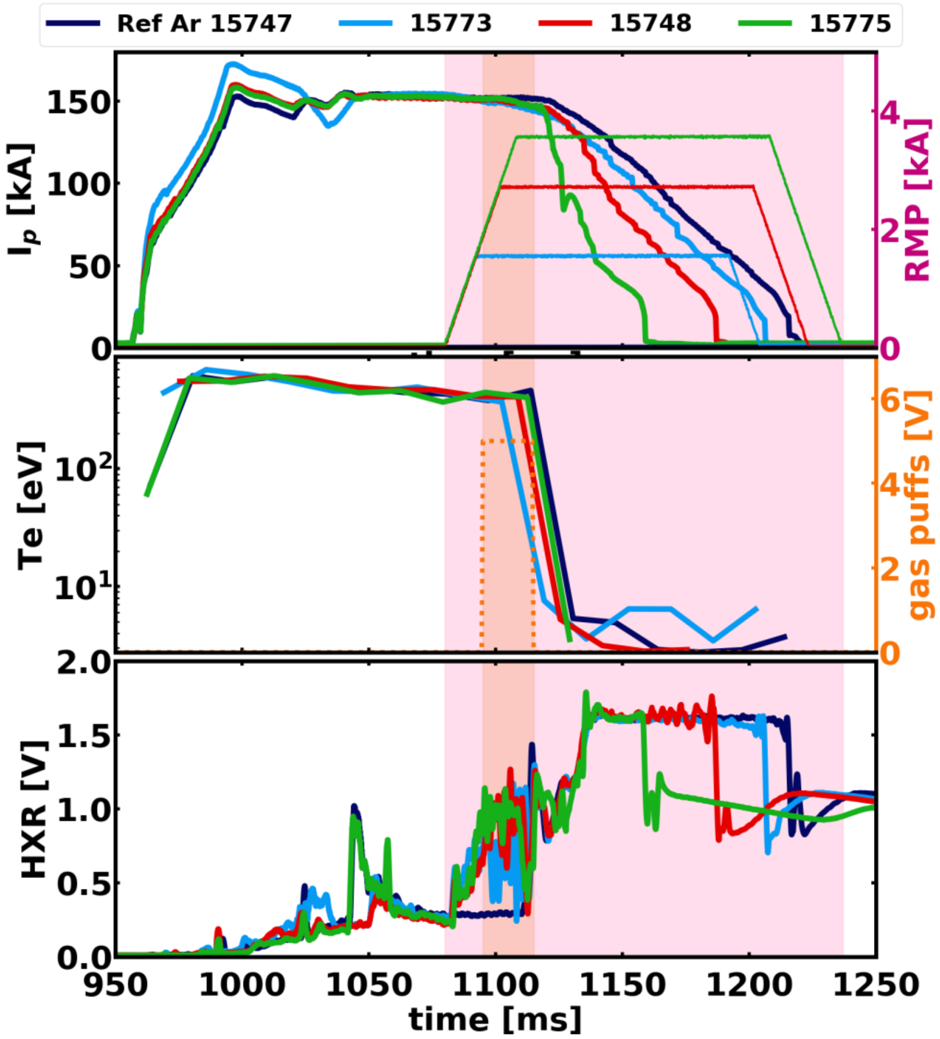
- **Zero U_{loop}** scenario
- Post-disruption RMP (**ΔΦ = 0º**)
- D injections – slows down the current decay
- Ne + D+ RMP faster current decay than Ar + RMP and Ar + D + RMP





Resonant component in plasma (MARS-F)

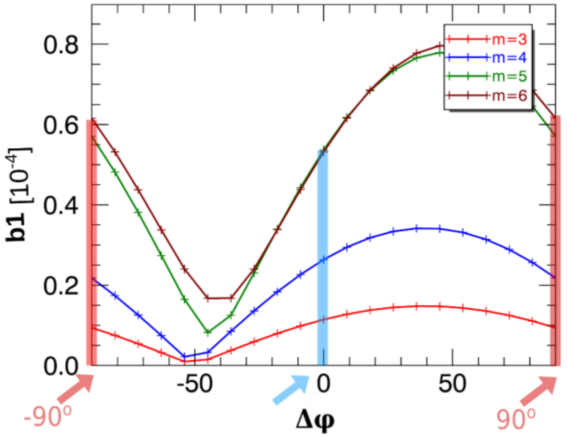
RMP amplitude scan & overview for n=1



- **Zero U_{loop} configuration**
- **RMP energised prior to the gas puff**
- **RMP amplitude scan for ΔΦ = -90°**
- The stronger the RMP, the faster the current decay
- The fast T_e quench (together with the HXR intensity) documents importance of the RE current
- The HXR scintillation detector (> 50 keV) show RE losses with the RMP onset, prior to the disruption

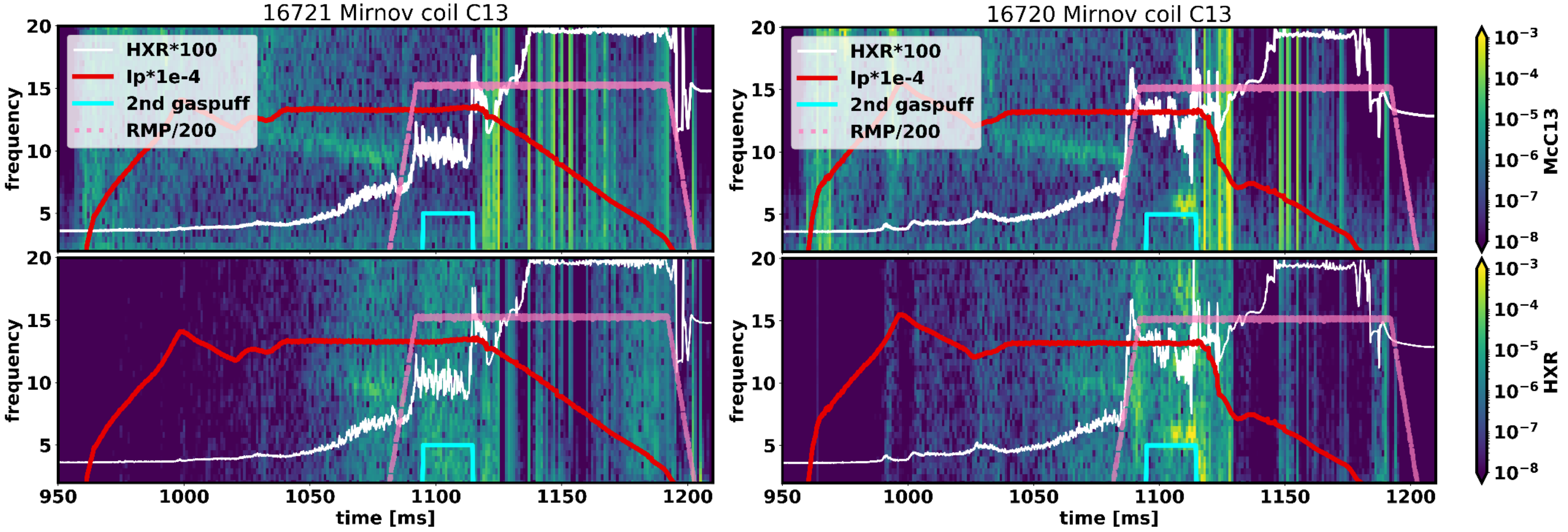
RMP ΔΦ scan for n=2

Resonant component in plasma (MARS-F)



Δϕ = 0º
EVEN orient.

Δϕ = +/-90º
ODD orient.



- Experiment stronger effect for Δϕ = 90º compared to Δϕ = 0º
- Spectrograms from Mirnov magnetic probe from the HFS and from HXR data demonstrate onset of the MHD mode in the Δϕ = +/-90º configuration

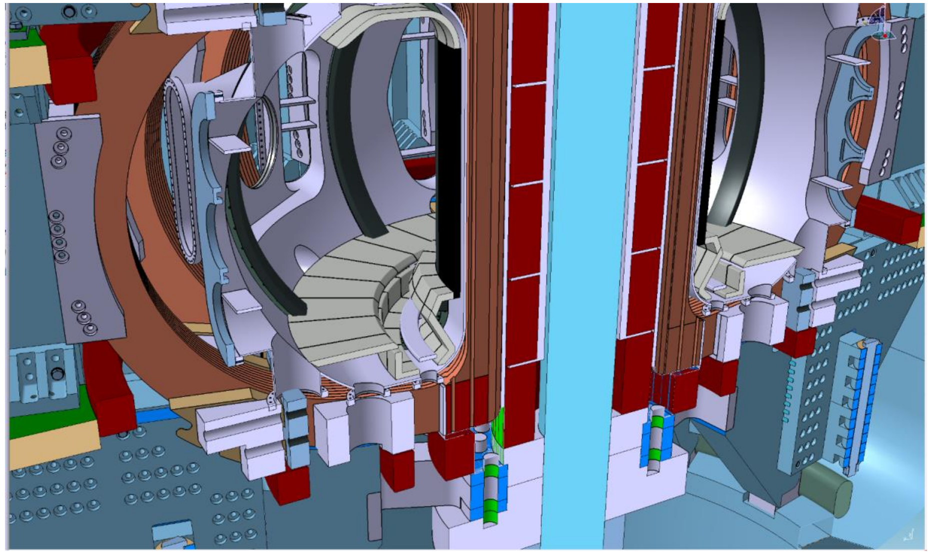
E Macusova et al. 29th SPPT, Prague, 2018

Outline

- Overview from the 6th REM – Prague
- The COMPASS tokamak & dedicated diagnostics for RE
- Effects of the gas injection
  - MGI triggered disruptions in the current ramp-up phase
  - Gas injection in the current plateau phase
- RE in perturbed magnetic fields at COMPASS
  - Resonant magnetic perturbation (RMP)
  - Combined effects of RMP and gas injection
- Future plans

- Solid pellet injector (2019-2020)
- **REIS** (RE infrared spectrometer, for SR) – collaboration with Università di Roma Tor Vergata, Italy
- RE control improvement
- **Advantageously high B_T for RE studies**

in the COMPASS Upgrade tokamak



View inside COMPASS-U

Basic dimensions and parameters of COMPASS- U:

R = 0,89 m

a = 0,3 m

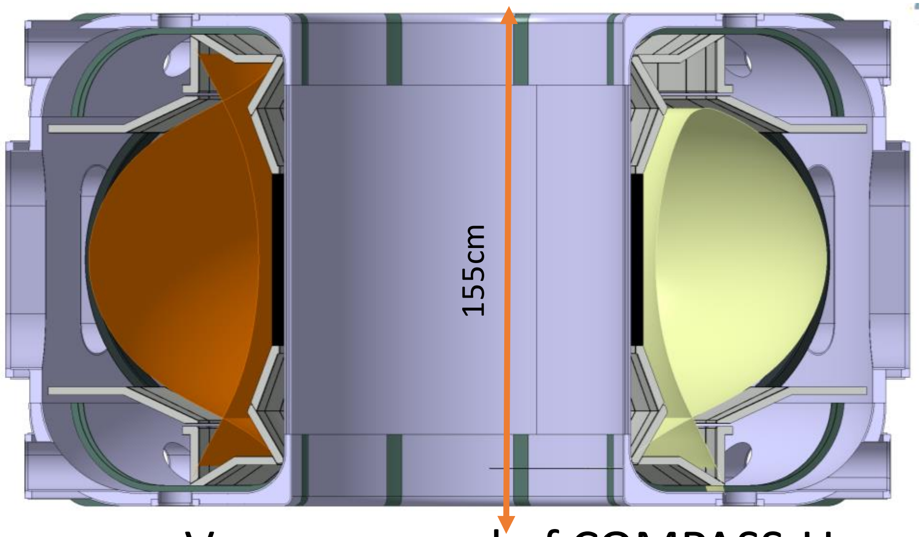
B_T = 5 T

Ip = 2 MA

P_{NBI} = 4-5 MW

P_{ECRH} = 4 MW (170 GHZ)

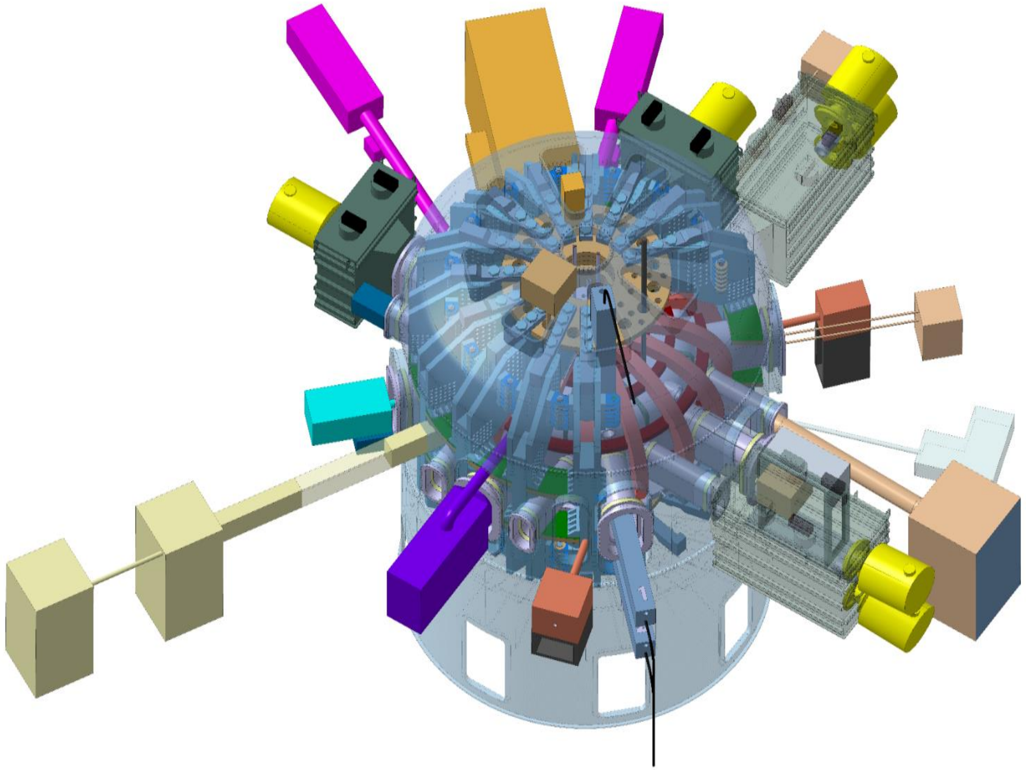
- ITER plasma shape
- Single and double null at high κ (up to 0.6)
- Single and double snow-flake geometry
- Plasma volume ~ 2 m^3
- Metallic first wall device
- High-temperature operation (~ 300 -500°C)



Vacuum vessel of COMPASS-U

- Two closed high density divertors
- High power fluxes in the divertor (λ_q ~ 1 mm => ≈ 15 - 20 MW/m2)
- Possibility to study physics of advanced modes (QH-mode, I-mode, EDA-mode, etc.)
- **Liquid metal divertor in later phase**

First plasma 2022
Full parameters 2023/2024



COMPASS-U and basic layout of auxiliary systems and large diagnostic systems