Overview of latest runaway electron experiments and analysis at COMPASS

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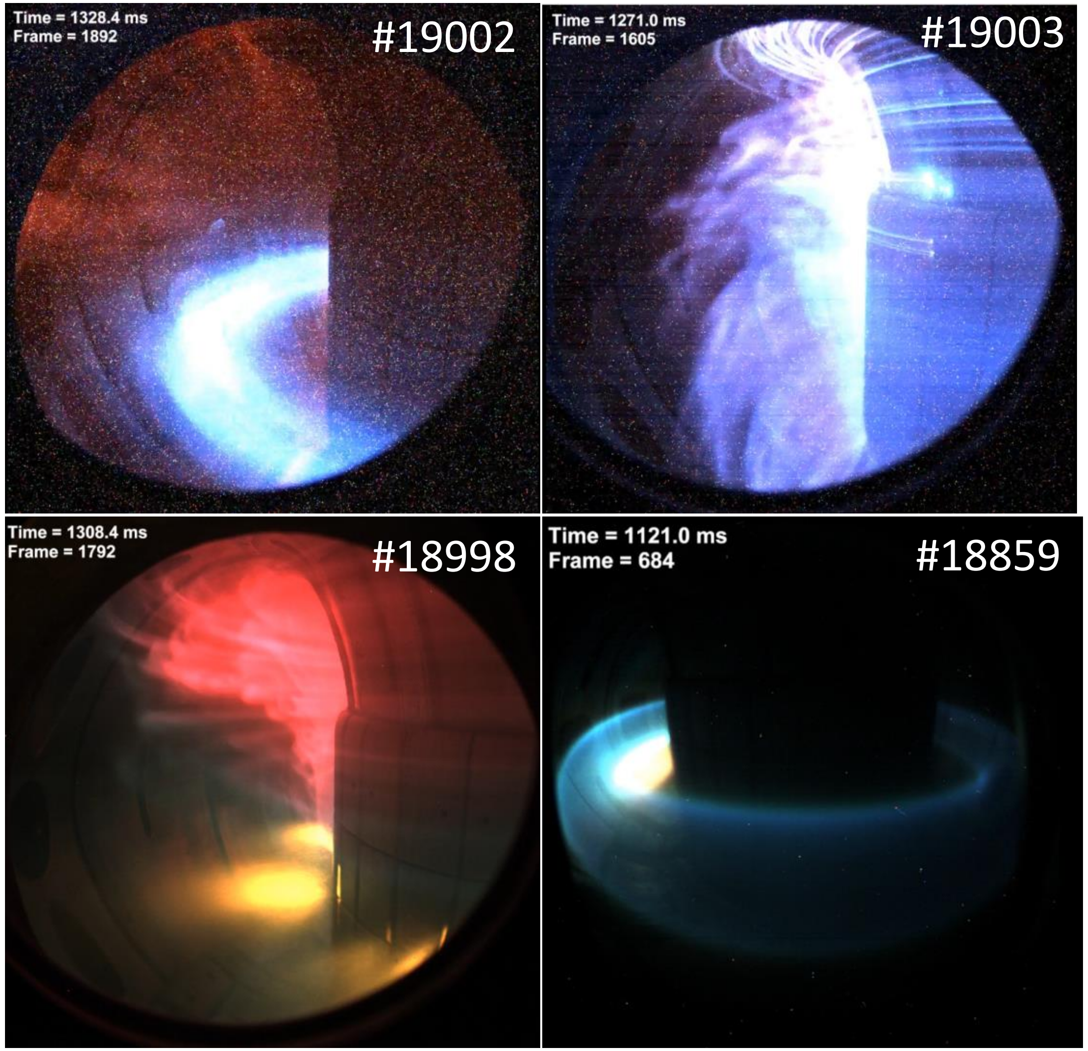
Outline

- RE campaigns during COMPASS life-time

- Special diagnostics + pellet injector used in the last campaigns
- High energy RE beam equilibrium in the experiment

- Gas injection experiments
- Solid state pellet injection experiments
- RMP experiments

- Calorimetric head measurements
- Measurements of high frequency waves during RE experiments



RE campaigns in COMPASS life time

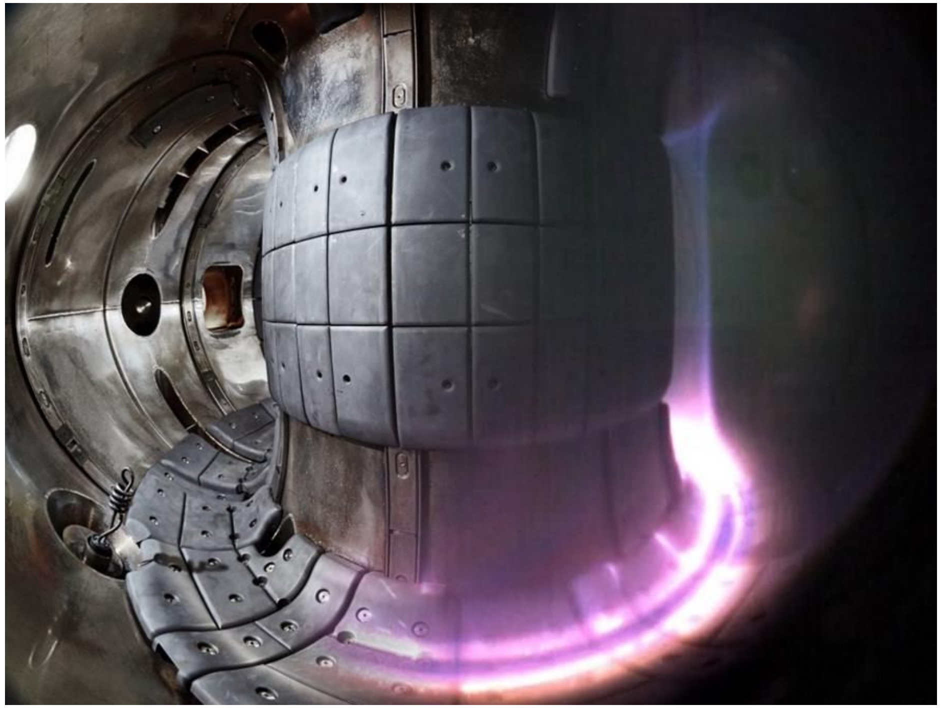
- **COMPASS** – ITER-like shaped plasmas with $I_{p,max}$ = 400 kA, $B_{t,max}$ = 1.5 T, 2x 400 kW NBI, flexible diagnostics setup

- Runaway experiments run 2014-2020
  within EUROfusion MST2-14, then MST1, MST1-Topic 8

2014-2015 – Low density discharges, MHD losses
2015-2016 – Massive gas injection into ramp-up
2017-now „Full conversion" RE beams flattop injection with secondary gas puffs, RMPs, pellet injection, enhanced diagnostics

Typical RE discharge

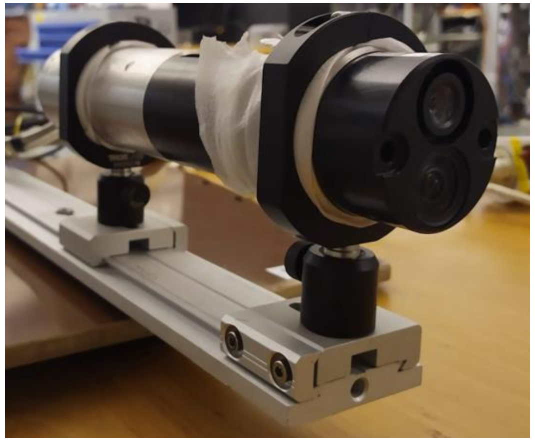
- Ar or Ne injection into 150 kA flattop of **low-density discharge (1-2e19 m^{-3})** with **significant RE seed**
- **Generation of RE beam than can be further accelerated or is sustained with zero external loop voltage**



Special hardware of last RE campagins

- **Room temperature solid state pellet injector** *(Čeřovský, J. et al. EPS 2021, P4.1006)*
    - **Single stage gas gun with carbon pellets** borrowed from AUG
    - Gas expansion system designed and built for COMPASS

- DIAGNOSTICS:
    - **REGARDS** – HXR spectrometer base on LaBr3(Ce) scintillator
    - **Other HXR detectors with spectrometric ability** or HXR/neutron discrimination – CeBr3, YAP, NaI(Tl), NuDET Neutron
    - **Tipex3-based matrix SXR detectors** - interaction at the HFS
    - **REIS 2** – spectrometers capturing synchrotron radiation – NIR region of interest on COMPASS
    - **Set of ex-vessel and in-vessel MHz – GHz antennas** – loop and log-periodic
    - **Active injection of 500 MHz, 50 W EM waves** via the loop antenna



Runaway electron beam equilibrium I

- Betatrons – high current, plasma assisted (charge dilution), modified betatrons (B_t for ideal MHD stability)
  - For current 10 kA – little spread in energy allowed, diamagnetic to paramagnetic transition, etc.
- Yoshida, NF 1990
  - tokamak geometry plasma + sum of elemental beams, total force balance, modified G.S. equation + equilibria shapes for different energies

$$\vec{j} \times \vec{B} - \sum_{b=1}^{N} n_b (\vec{v}_b \cdot \nabla) M_b \vec{v}_b - \nabla p = 0$$

- Application at COMPASS
  - RE energy estimated using very simplified formulation of the problem

$$E_\beta[\mathrm{MeV}] = 3.75\beta_N a B_t$$

$$E_{FB}[\mathrm{MeV}] = RcB_v^{an}/10^6$$

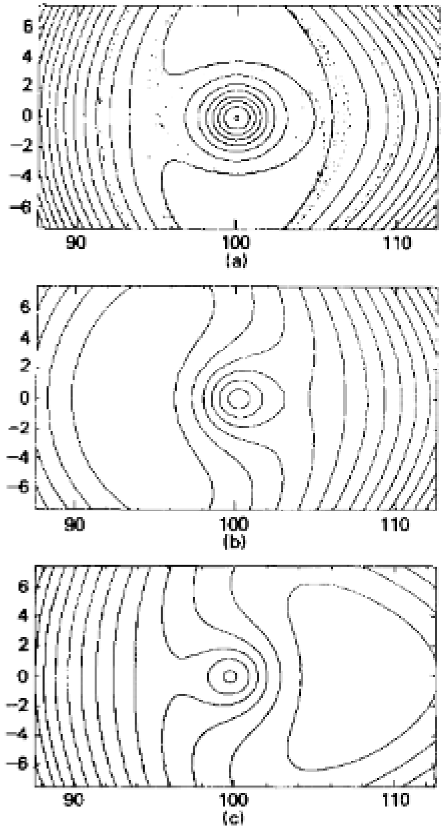
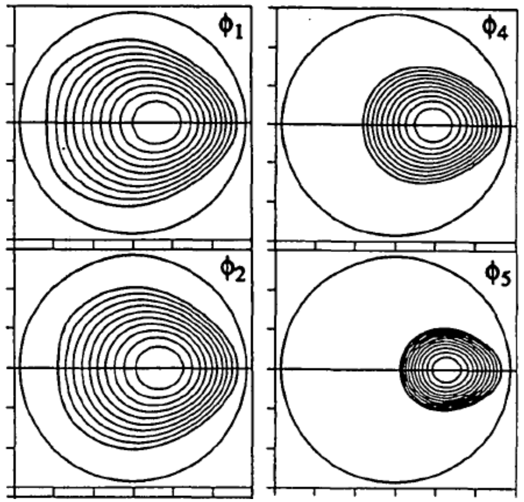


FIG. 4. Equilibrium with $\gamma_0 = 7.93$, 10 kA: (a) drift surfaces for the beam, and for test particles with (b) $\gamma_0 = 7.73$ and (c) $\gamma_0 = 8.13$.

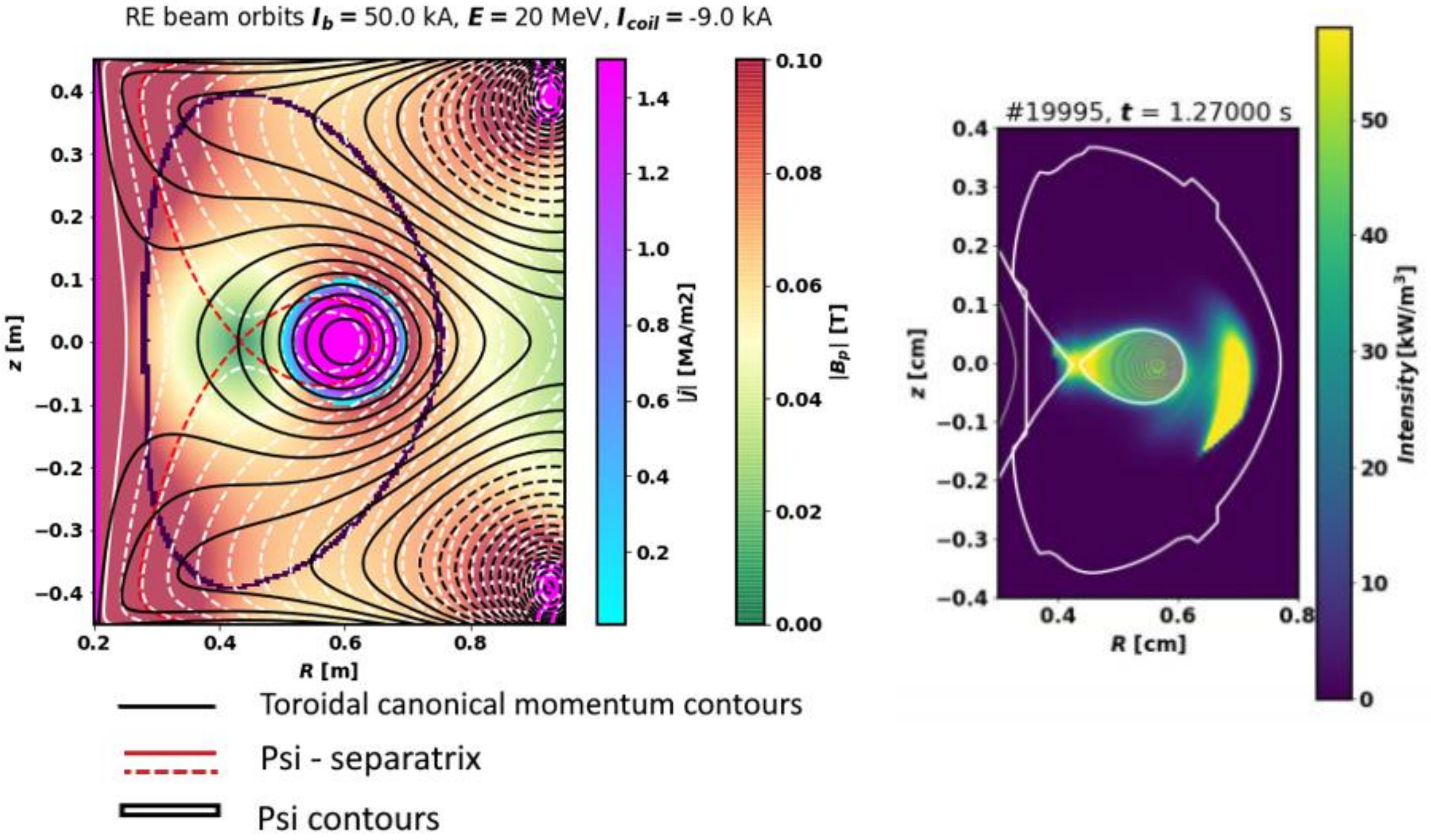
Finn and Mannerheim, Phys fluids 1988



Yoshida, NF 1990

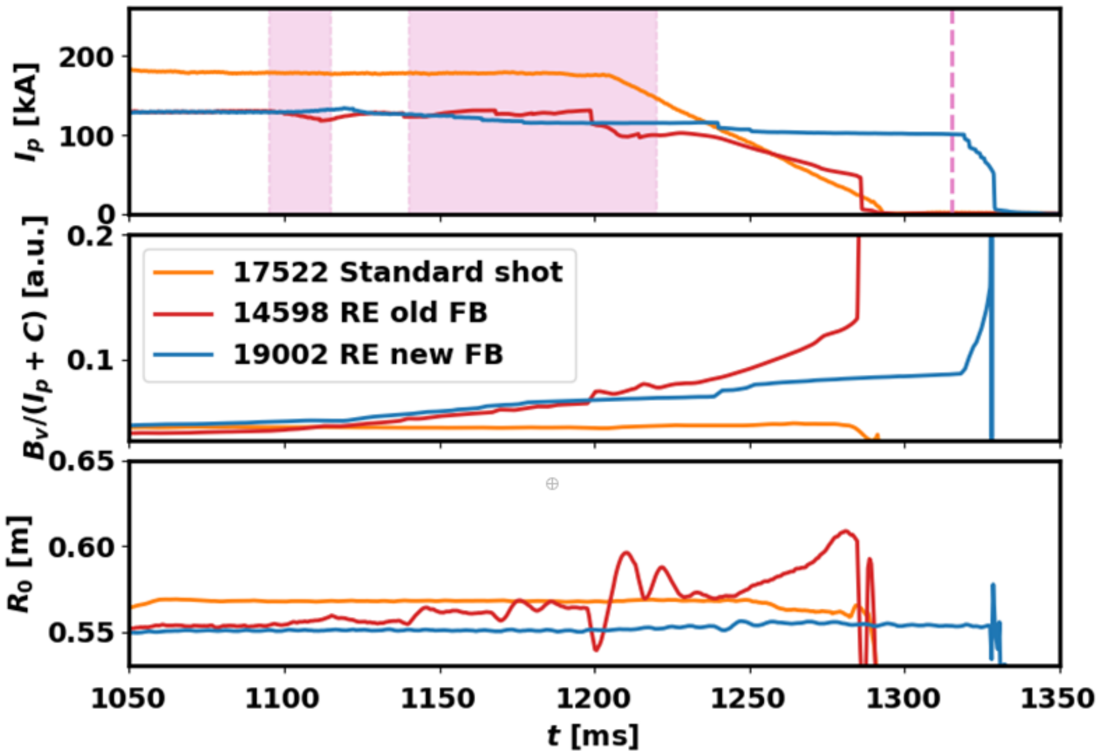
Runaway electron beam equilibrium II

- Plasma and equilibrium field coil geometry in Biot-Savart solver
- Experimental plasma + coil currents reproduce EFIT configuration well
- HFS X-point with RE beam
- AXUV tomography and calorimetry point to strong heating of LFS limiter already before RE beam termination
- High energy fraction of the beam indeed LFS limited based on drift surfaces

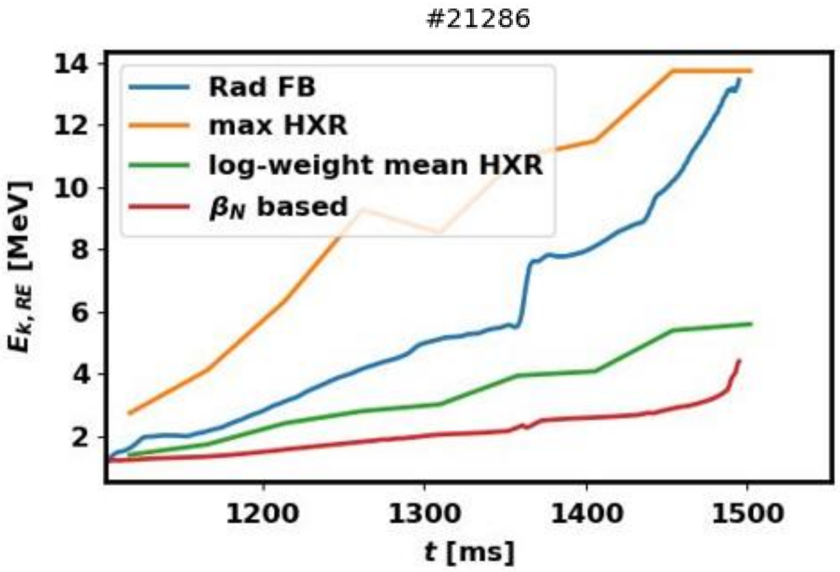


Ficker, O., et. al. EPS 2021, P3.1034

Runaway electron beam equilibrium III



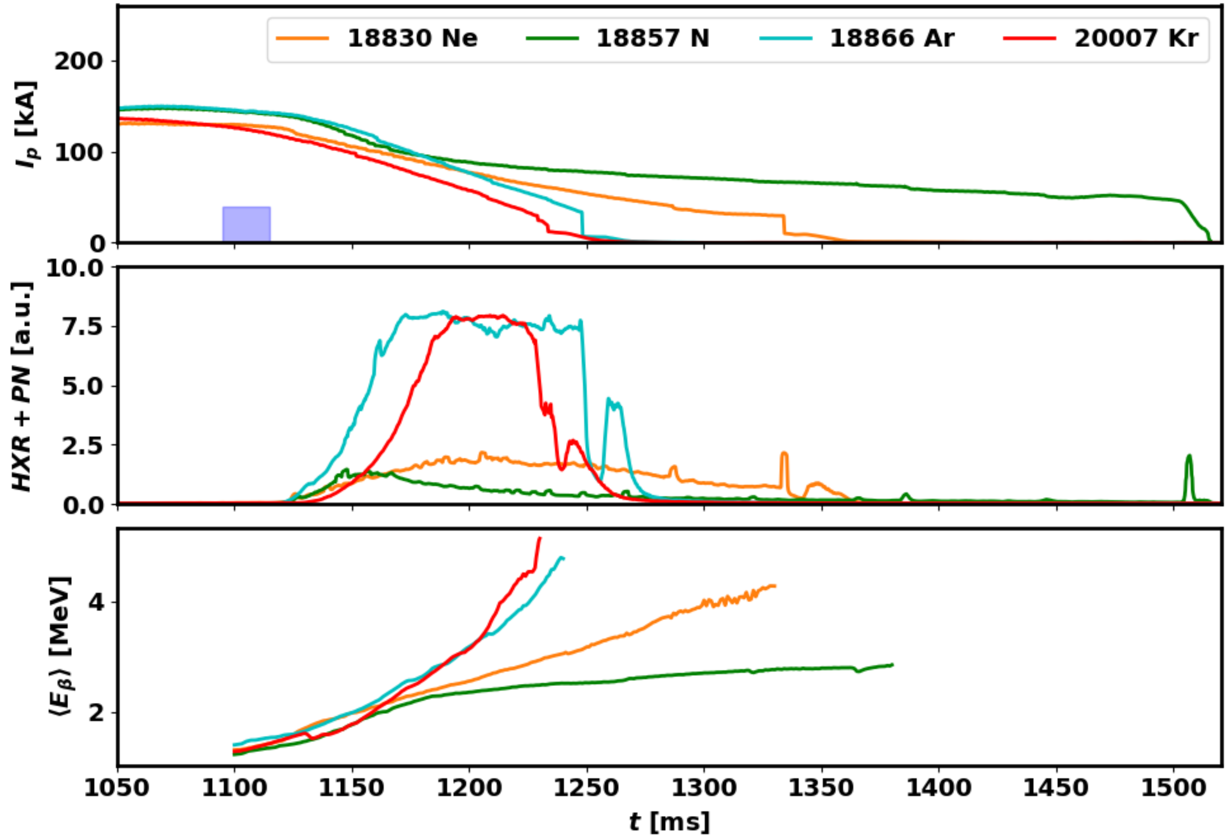
- Decreasing of I_p role in radial position control – increasing of the role of E_{RE} – secures control of the RE beam
- The β_N and FB-based estimates of RE energy seem to agree in trends with HXR PHA energy and synchrotron radiation

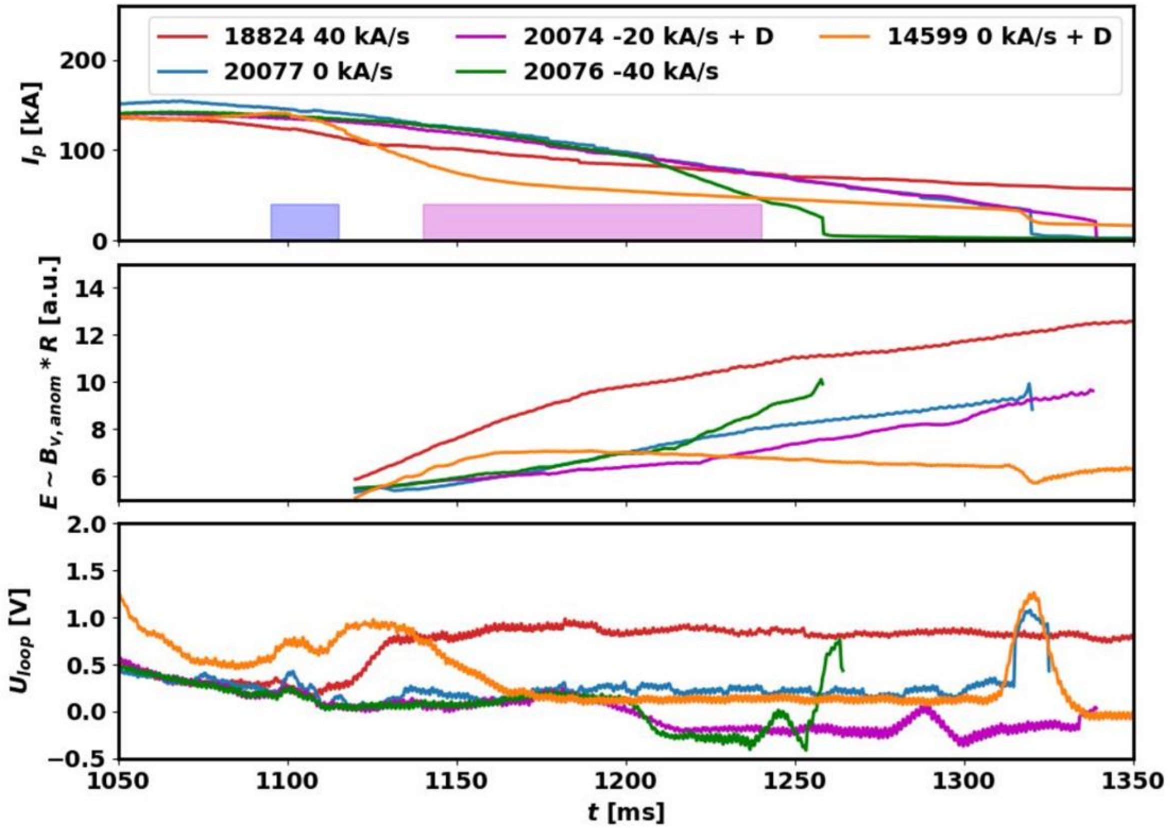


Ficker, O et. al. NF 2019

Gas injection results – Ar, Kr, Ne, N, Ar/D2

- Various noble gases and N for beam triggering tested – Ne and N produce significantly less HXR radiation and slower decay
- Intensive secondary D2 injection seems to stop the increase of RE energy, -U_{loop} only decreases current but increases energy





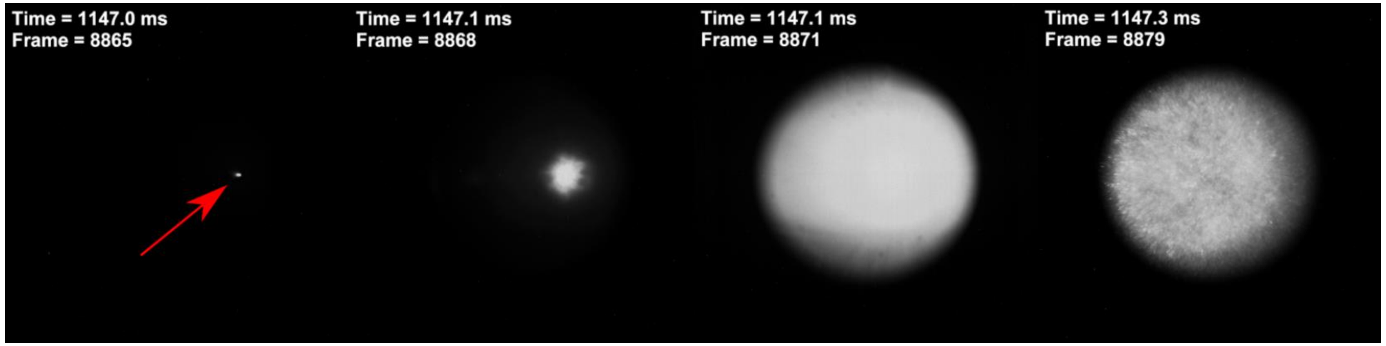
Room temperature solid state pellet injector results I – effect on the RE beam

RTSP

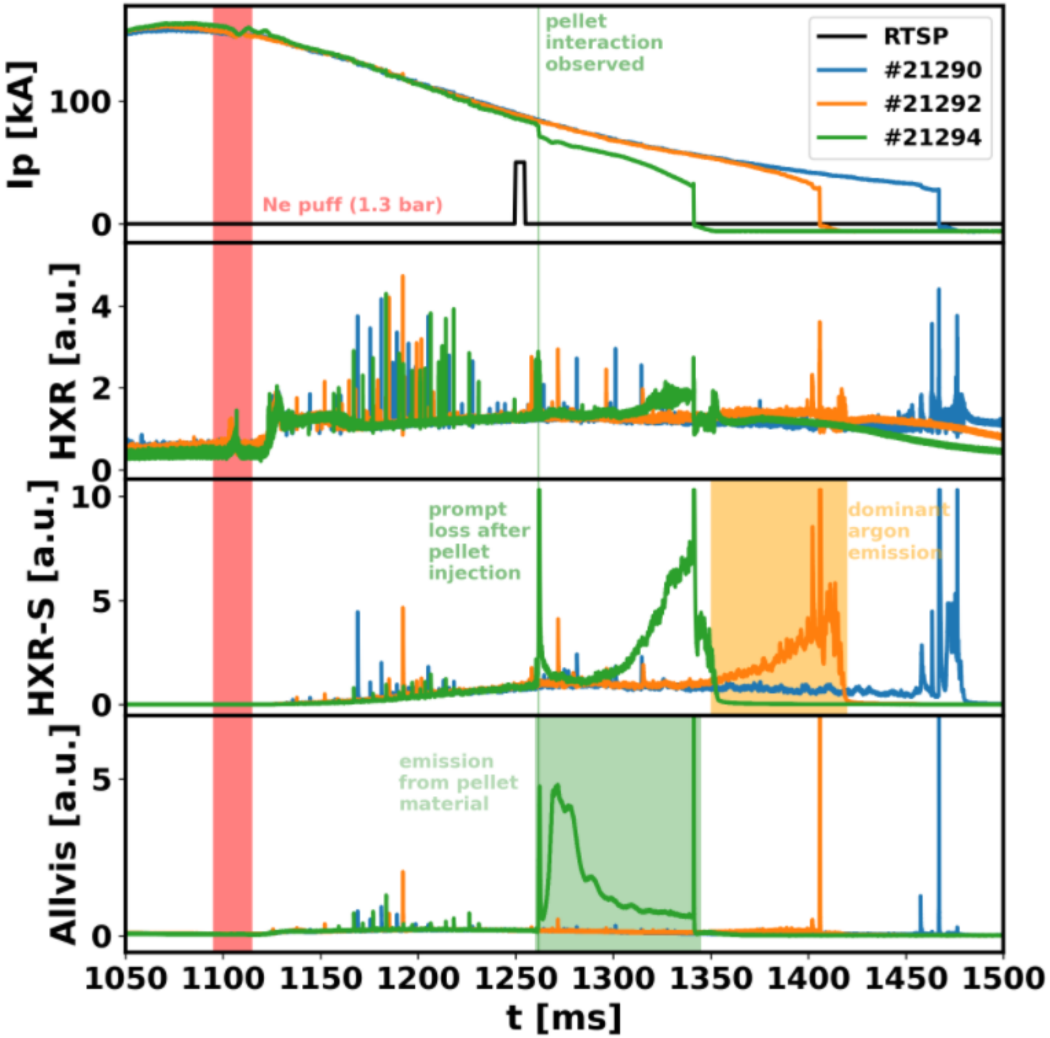
- **single stage gas gun from AUG**
- **mm-sized carbon pellets**
- **Ar-propelled, velocities 100-400 m/s**
- **gas expansion system designed at COMPASS**

#21290 - Ne generated RE beam reference
#21292 - Ne generated RE beam, without pellet injection (only propellant gas)
#21294 - Ne generated RE beam, with graphite pellet injection

Pellet ablates and then explodes

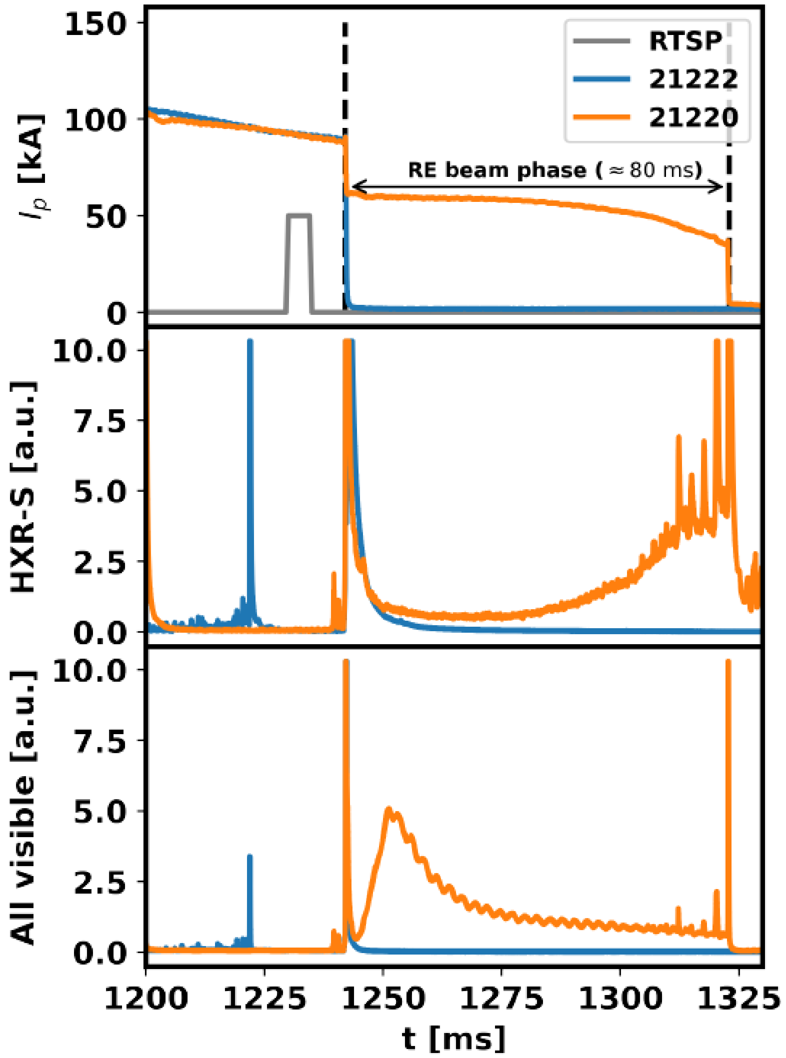


Video available here

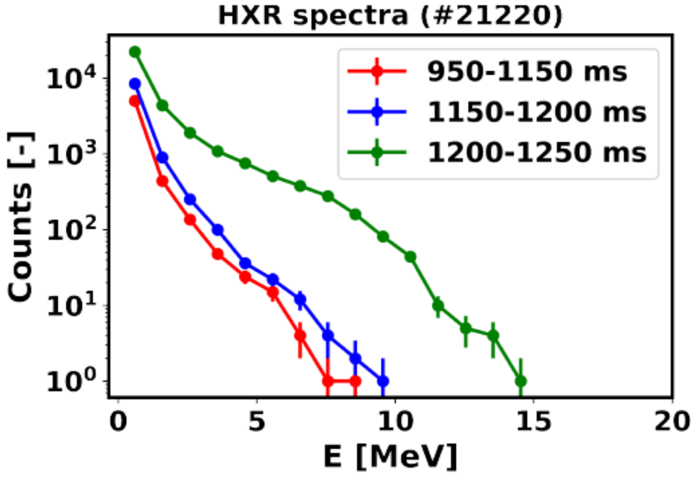


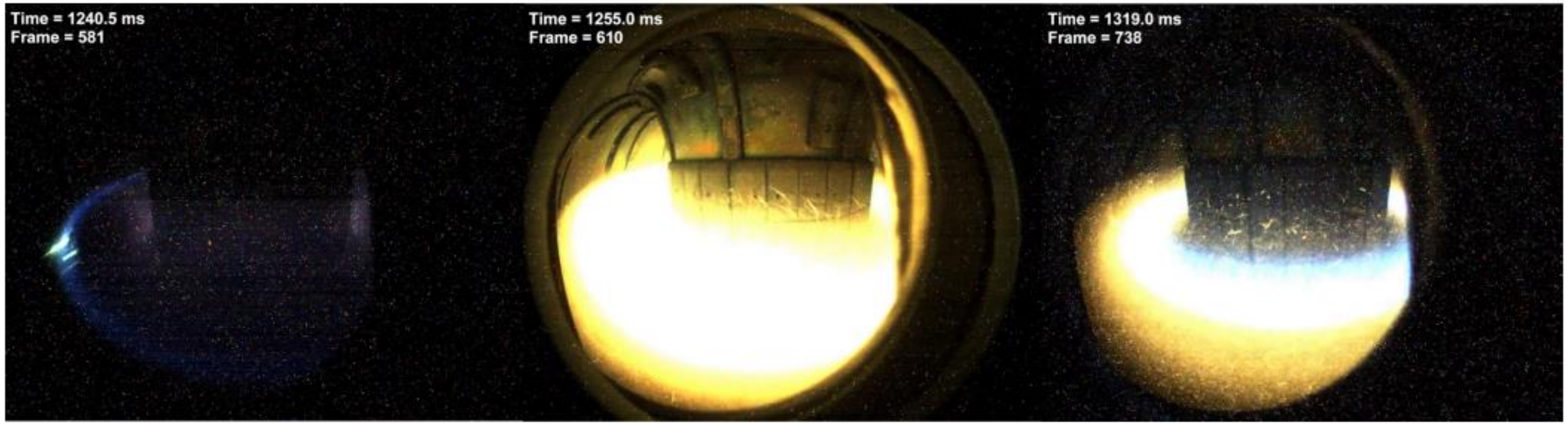
Cerovsky J. et al. EPS 2021 P4.1006, paper in preparation

Room temperature solid state pellet injector results II – RE beam triggered by pellet



- C pellet can generate RE beam from low density plasma
- Beam generated or not depending on the seed?
- Pellet dust distributed in the beam volume
- HXR counts and maximum energy significantly increased





Video available here

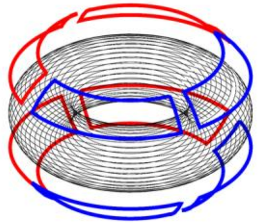
Cerovsky, J. et al. EPS 2021 P4.1006, paper in preparation

RMP effect on the RE beam I

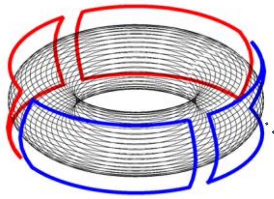
COMPASS RMP coils

- **4 toroidal sectors**
- **full poloidal coverage**
- **penetration time ~ 5ms**
- **$I_{RMP} \leqq 3.5$ kAt → $B_r/B_T \leqq 10^{-2}$**

n=1 LFS OFF midplane $\Delta\Phi$ large



n=1 LFS ON midplane large



Effect of the RMP timing

- **Pre-disruption = the early RE population**
- **Post-disruption = developed RE beam**

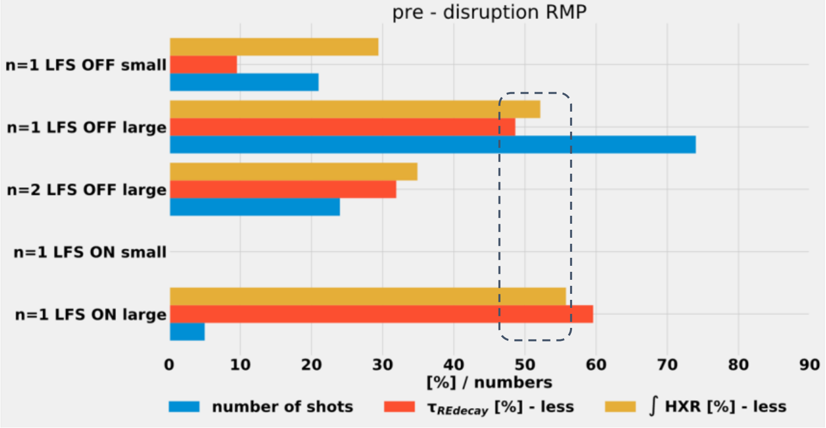
Observed quantities

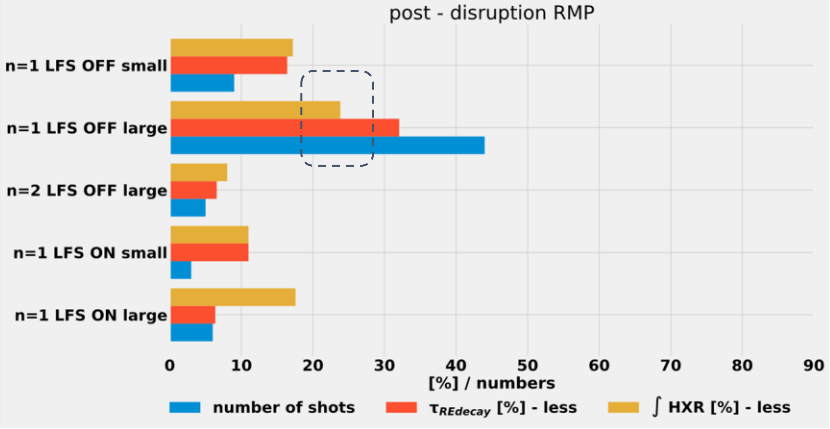
→ $\tau_{REdecay}$ RE current decay time **(I_{RE} 120 kA → I_{RE} 30 kA)**

→ ∫HXR*4 **(∫- over $\tau_{REdecay}$)**

Macusova, E. et al. EPS 2021, I2.106

% drops of $\tau_{REdecay}$ and ∫HXR - RMP configuration effect





Effect of the RMP setup

- n=1 LFS OFF-mid $\Delta\Phi$ (4 options)
  → large (all 4 toroidal RMP sectors used) or small (2 toroidal sectors of RMP coils used)

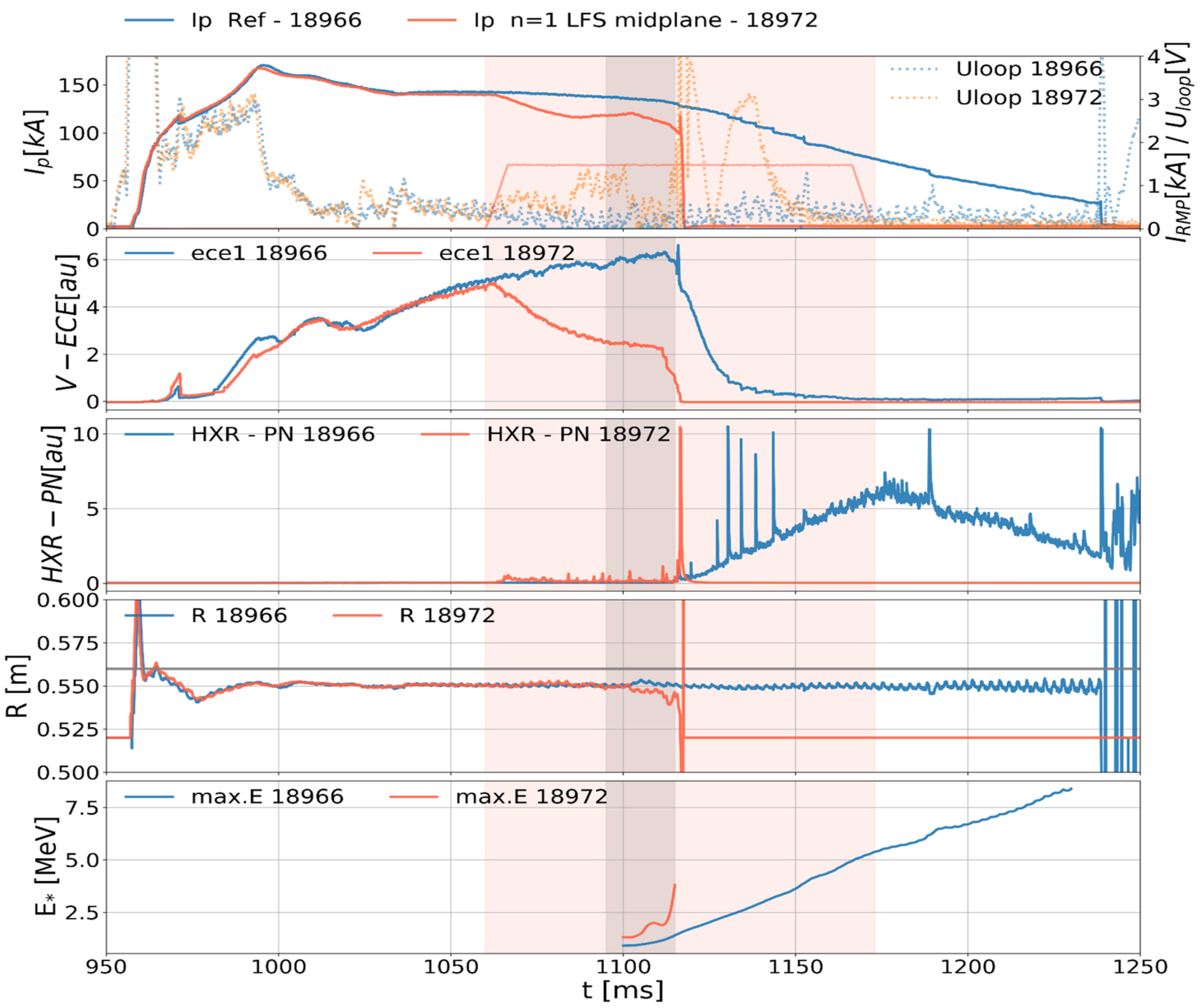
  → **the strongest phase** ($\Delta\Phi$=270°) identified experimentally and confirmed by MARS-F simulations

- n=1 LFS ON-mid
  → large (all 4 toroidal RMP sectors used) or small (2 toroidal sectors of RMP coils used)

  → **formation of non-rotating MHD** → $\delta B_r/B_T$ increased ~ 2 times

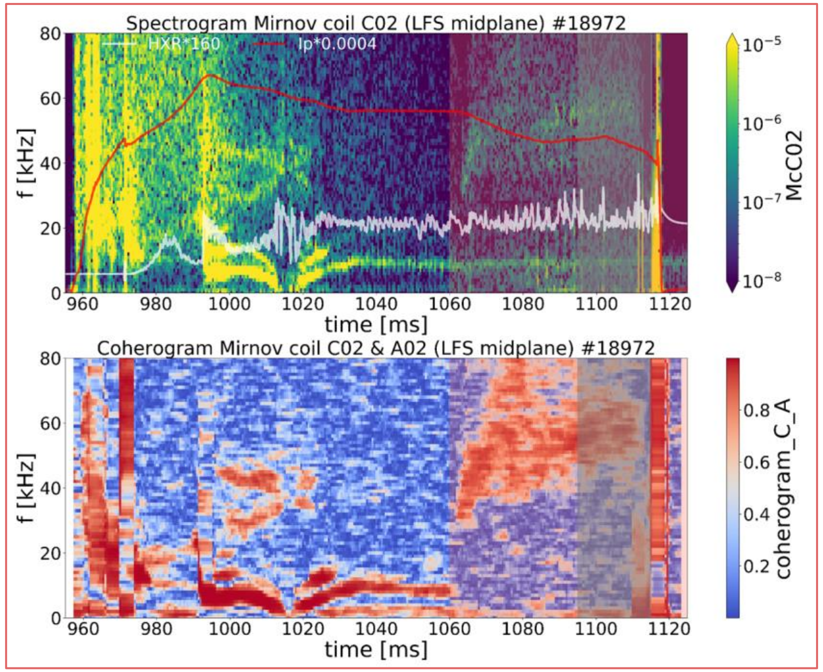
→ pre-disruption RMP - stronger effect
→ 2 most efficient RMP configurations identified

RMP effects on the RE beam II: n=1 LFS midplane – pre-disruption RMP



Macusova, E. et al. EPS 2021, I2.106

- similar effect as n=1 LFS off-midplane $\Delta\Phi$=270° → smaller RE energy and final RE impact
- formation of non-rotating MHD ("GAM") - small effect on RE losses
- I_{RE} ~ 15 kA deconfined despite Ip feedback



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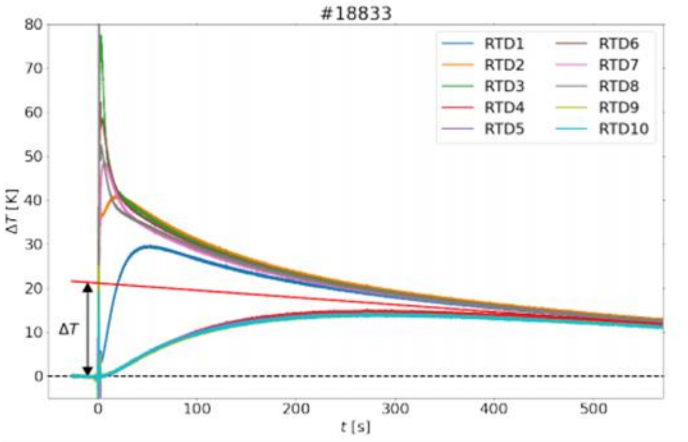
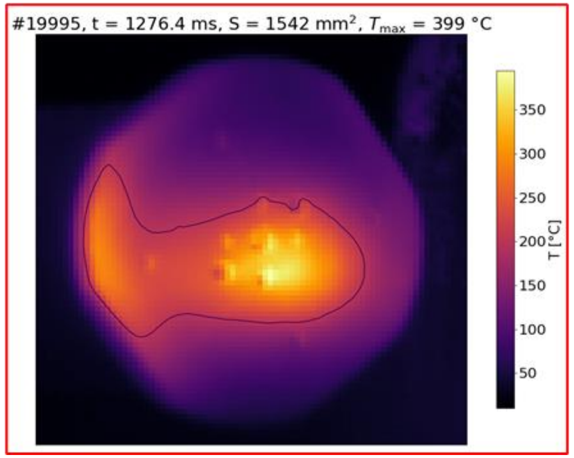
Calorimetry of the runaway electron beam

Typical evolution of temperature at sensors

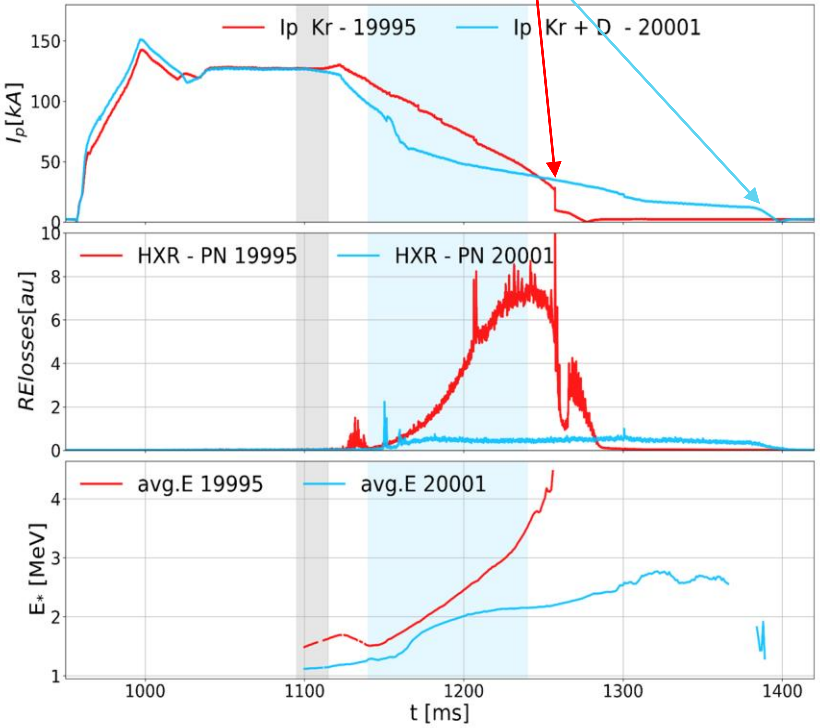




Calorimetry head measurements of RE beam in Kr and Kr+D2

E_{RE}(kJ)=7 ± 1 & P_{RE}(MWm^{-2})=32 ± 6

E_{RE}(kJ)=6 ± 1 & P_{RE}(MWm^{-2})=20 ± 4



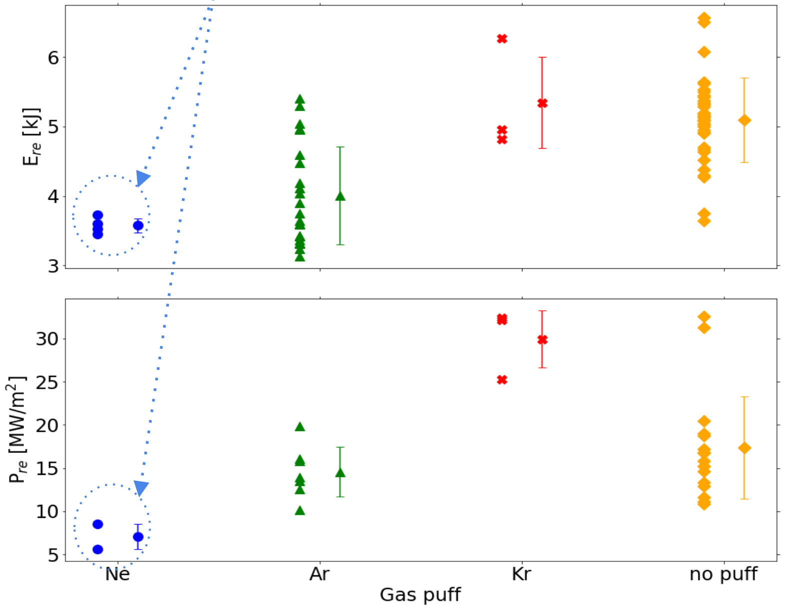
Čaloud, J, master thesis MU Brno, paper in prep.

1st puff - standard valve - high Z (< 10^{19} m^{-3})
calorimetry measurements*1, *2

- E_{RE} (kJ) - average RE energy
- P_{RE}(MWm^{-2}) - incident power on deposited area

Ne	**⟨E_{RE}⟩ = (3.6 ± 0.1) kJ**	**⟨P_{RE}⟩ = (7 ± 2) MW/m2**
Ar	⟨E_{RE}⟩ = (4.0 ± 0.7) kJ	⟨P_{RE}⟩ = (15 ± 3) MW/m2
Kr	⟨E_{RE}⟩ = (5.3 ± 0.7) kJ	⟨P_{RE}⟩ = (30 ± 3) MW/m2

Ne → lowest E_{RE} & lowest P_{RE}

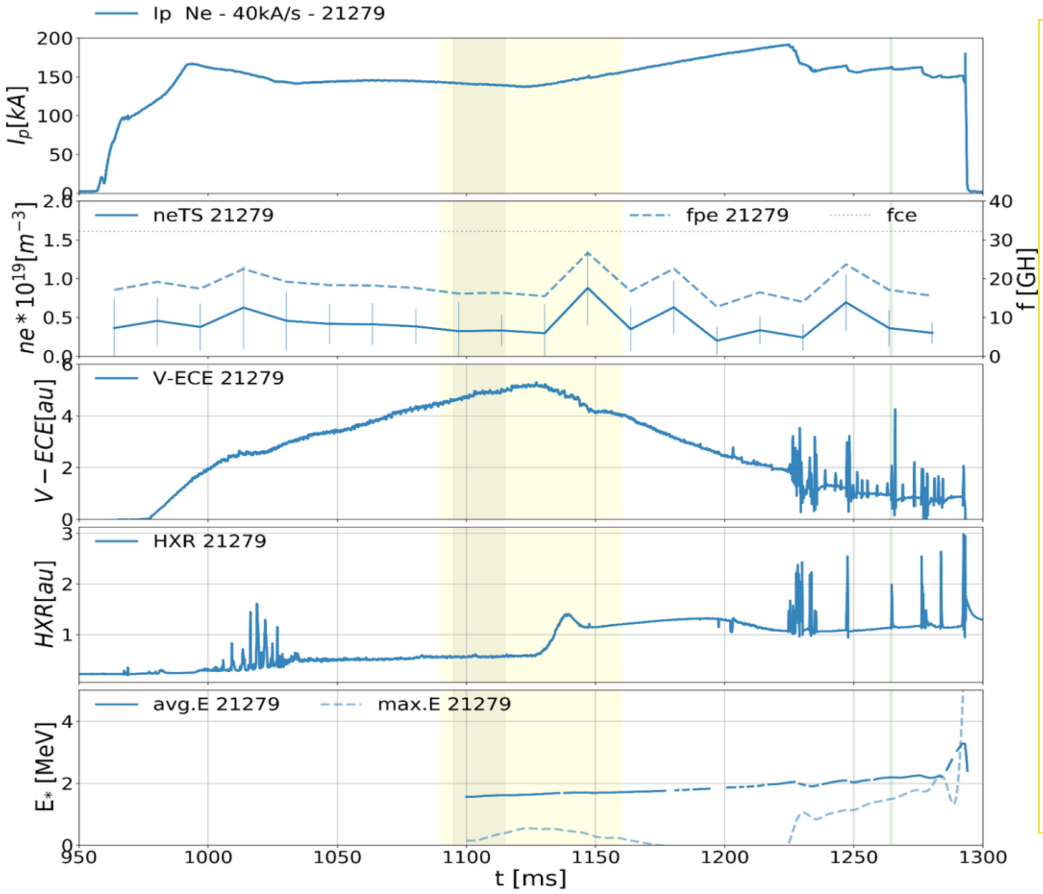


High frequency antenna measurements

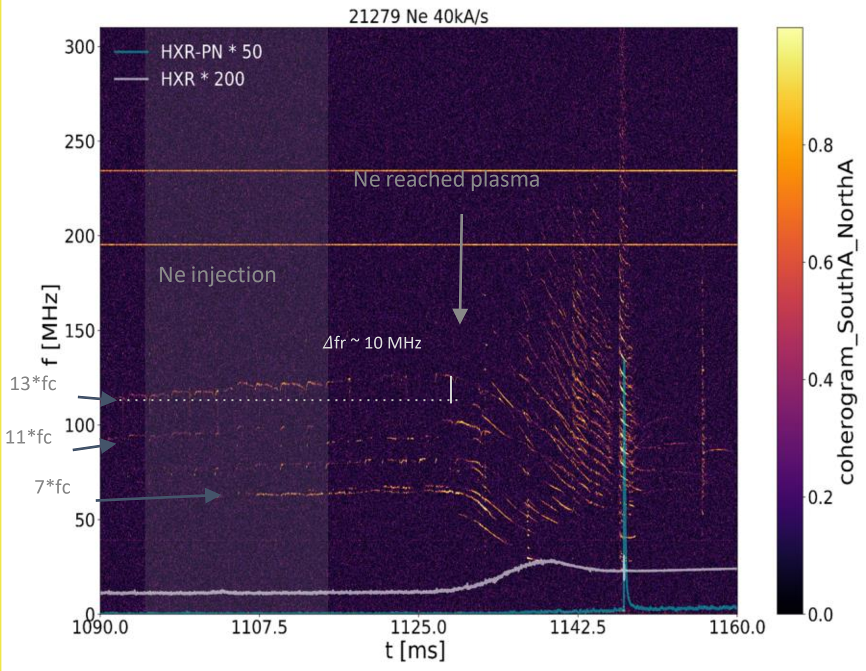
System of antennas

(collaboration with ENEA & CNR Italy)

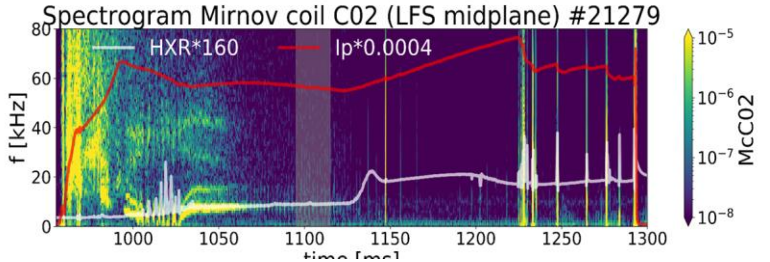
- **2 square loop in-vessel antennas (North and South midplane radial ports) - loop size (11x11 cm)**
  - **South loop (SL) - two regimes - receiving (R) and transmitting (T)**
    → T: low power EM waves (35-60W) at ~ 500 MHz
- **1 twin square loop ex-vessel antenna in South & 1 logarithmic ex-vessel antenna in North**
- **130 useful pulses acquired (whistler like, chirping, broadband HF emissions detected - as in DIII-D and FTU, KSTAR)**



Deuterium cyclotron frequency f_c=8.77 MHz at 1.15T



North & South in-vessels antennas used (SR: 625 Ms/s)

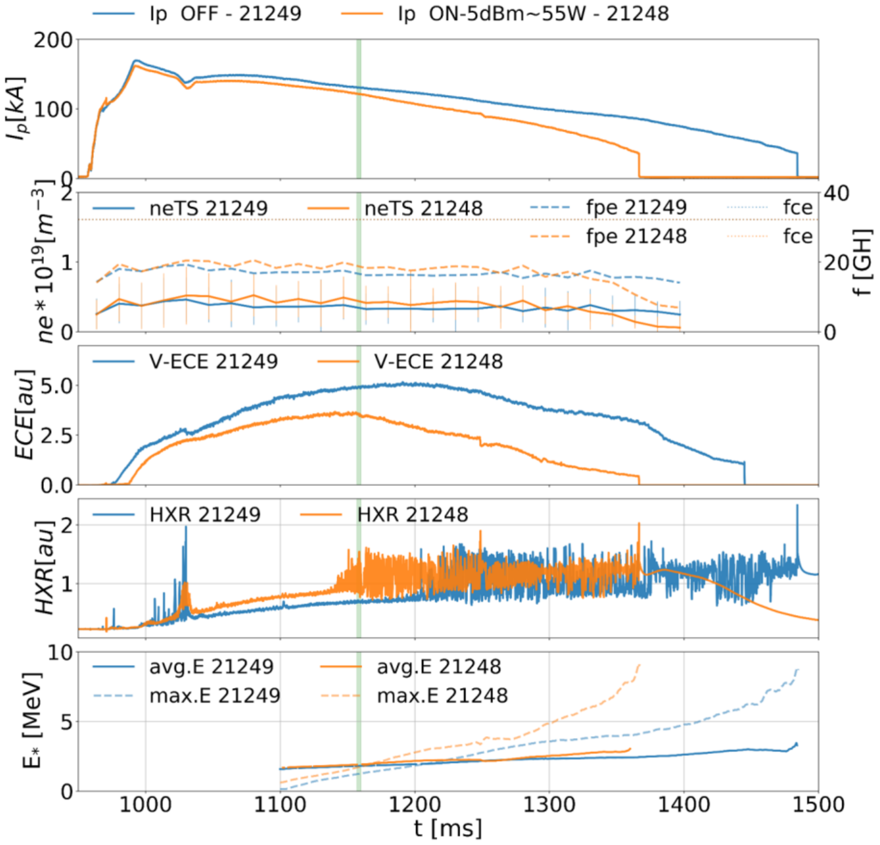


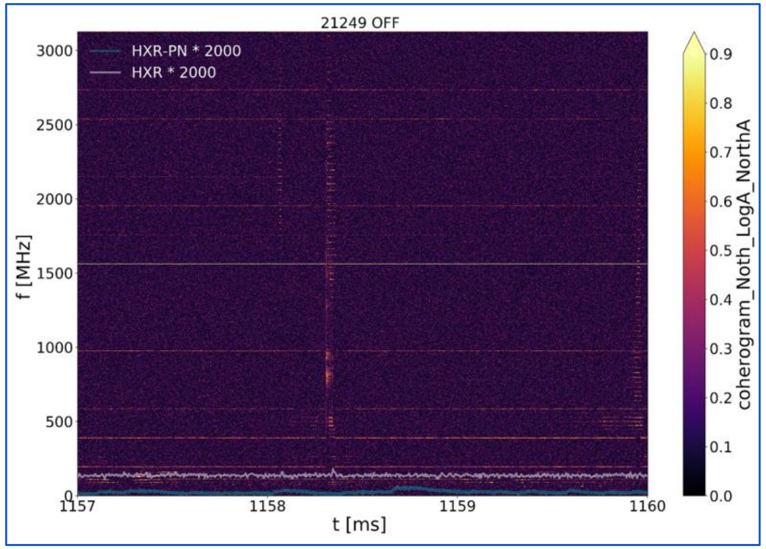
→ low fr. whistler like emissions
→ Ne injection = rapid change of fr. of KI when Ne reached the plasma (no low fr. MHD changes)
→ broadband RF emission followed by spikes on HXR and ECE signals, Ip drop

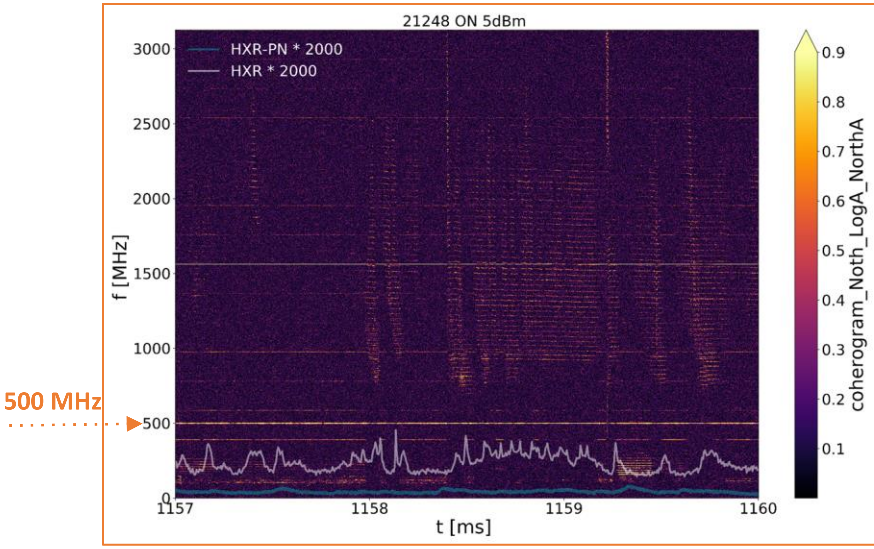
Macusova, E. et al. EPS 2021, I2.106

Active antenna experiment

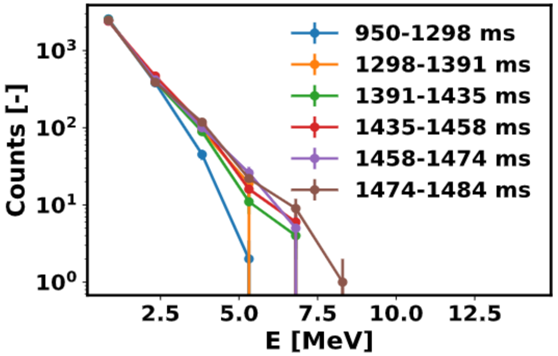
Transmitting antenna: functional prototype
(5dBm ≈ **55 W at 500 MHz**) OFF/ON **- entire shot**
→ enhanced activity at fr. > 750 MHz
→ change of HXR activity, V-ECE, Ip
→ E_{RE} remains similar



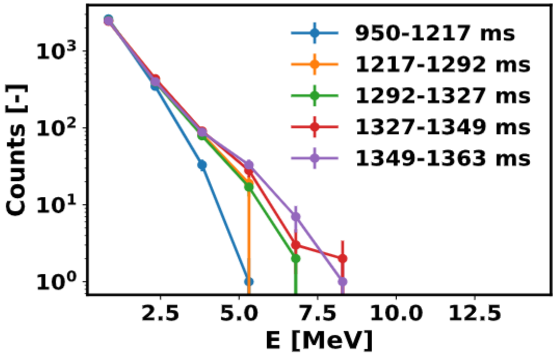




#21249 HXR spectra - **1*10⁴** counts/950-1298 ms



#21248 HXR spectra **2*10⁴** counts/950-1292 ms



Macusova, E. et al. EPS 2021, I2.106

Conclusions

- Runway experiments conducted at COMPASS for 6 years, experience to be brought to COMPASS-Upgrade
- Pellet injector, HXR and synchrotron radiation spectrometry and high frequency antenna measurements realised in the last RE campaigns
- The runaway electron energy seems to has a very strong effect on the RE beam equilibrium in COMPASS
- Injection of higher-Z gases results typically in higher HXR fluxes and higher RE energy (calorimeter measurement) than lower Z gases
- The carbon pellets can cause RE beam generation from low density plasma and change properties of RE beam if injected into a developed one, the pellets typically explode
- RMPs in suitable configuration strongly enhance losses of RE
- Various high frequency modes observed in the low frequency plasmas with RE presence, waves of 500MHz actively launched