MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

BATMAN Upgrade: general results from beam optics studies

Christian Wimmer,
M. Barnes, N. den Harder, A. Hurlbatt, G. Orozco, U. Fantz and the NNBI team

8th International Symposium on Negative Ions, Beams and Sources

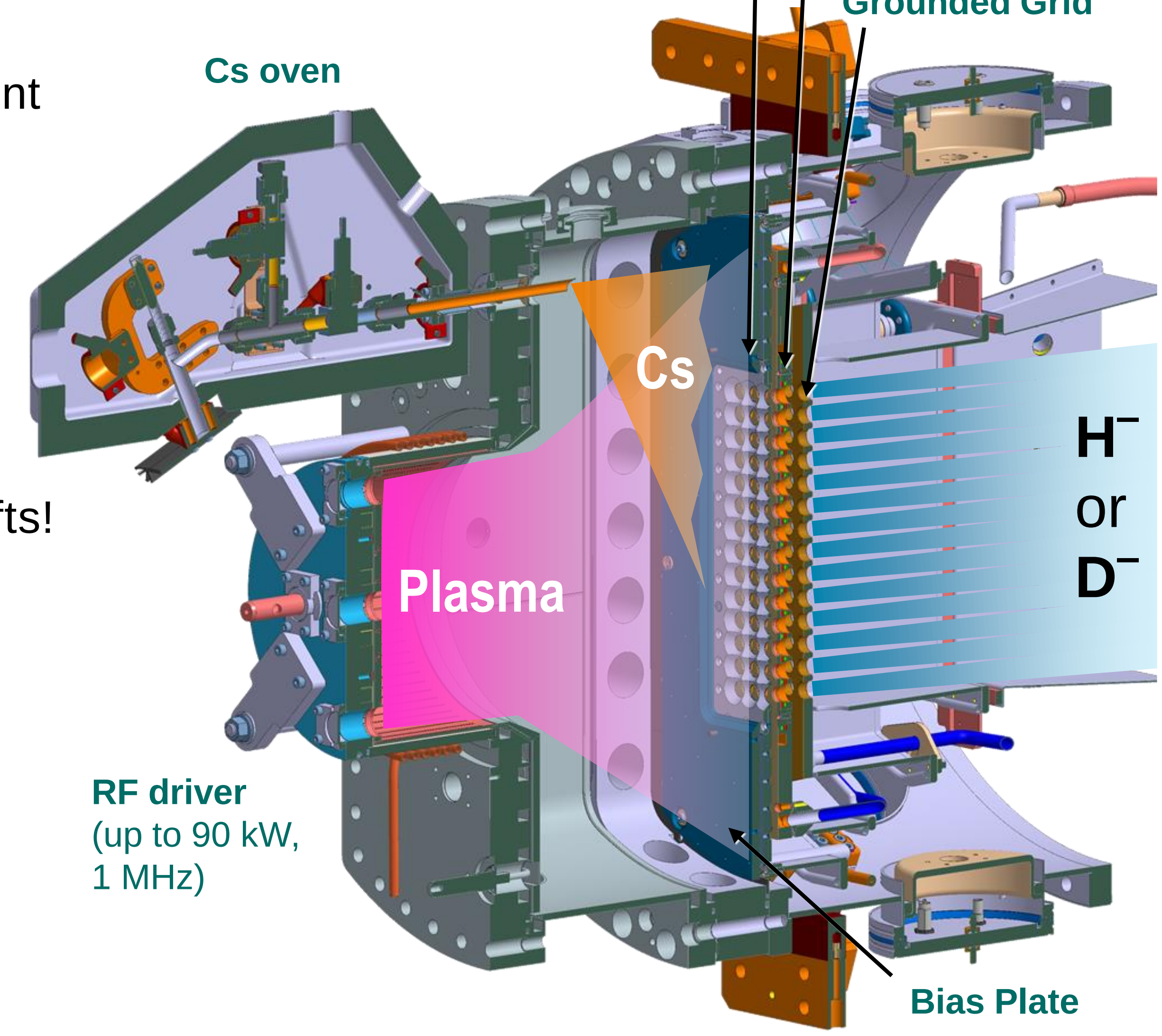
EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

BATMAN Upgrade: a well-diagnosed, flexible test facility

- 1/8 ITER source size, contributes to development of ITER NBI source & beyond
- H^- production on caesiated PG
- Magnetic filter field created either by vertical current through PG or by attached external magnets
  → vertical plasma asymmetry caused by xB drifts!
- Three-grid extraction system (up to 45 kV) (repeller grid removed in 2021)

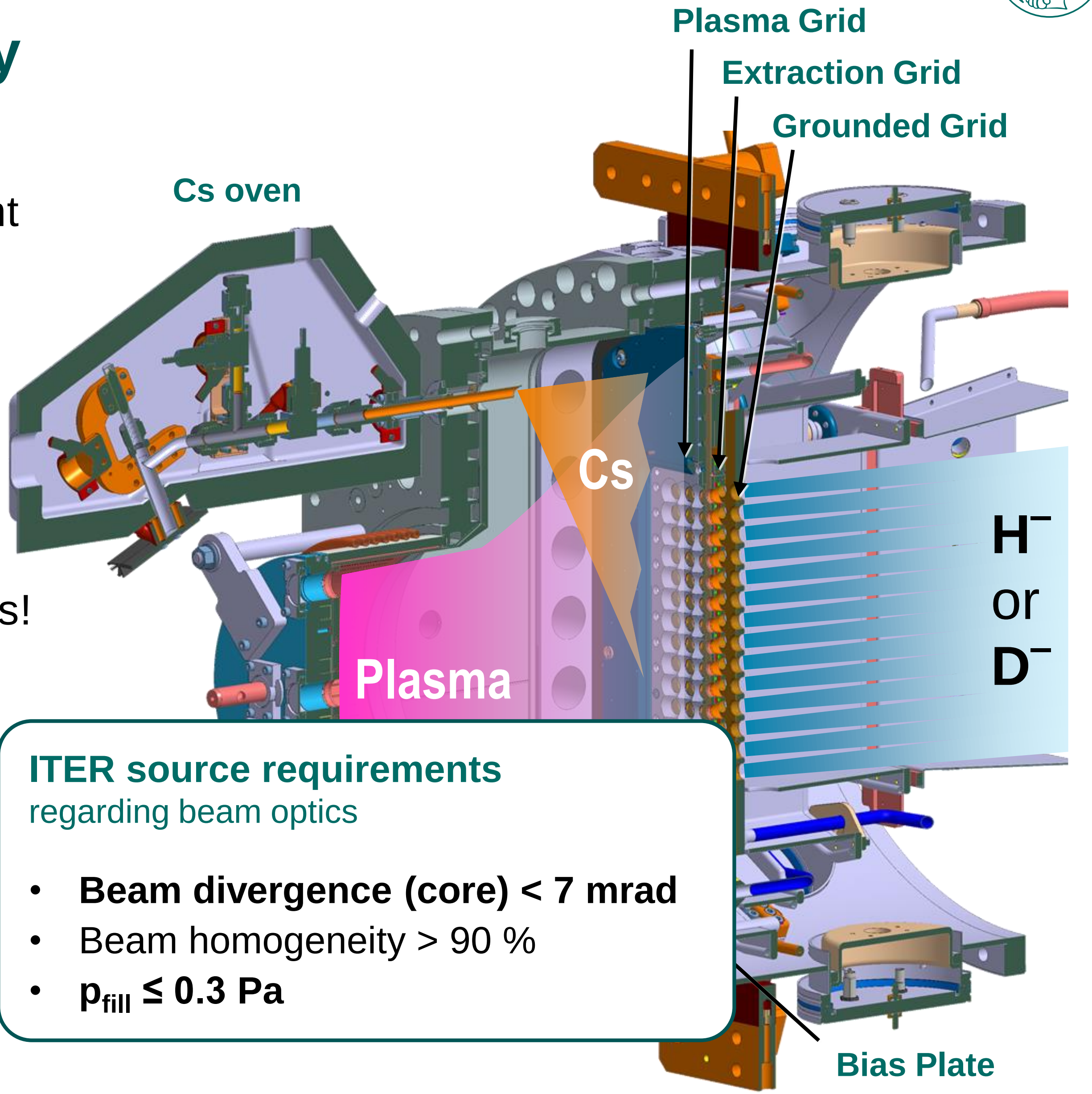
Best beam optics requires $U_{acc}/U_{ex} \approx 6.5$
→ **beam optics studies only possible for $U_{ex} \leq 6$ kV!**



BATMAN Upgrade:
a well-diagnosed, flexible test facility

- 1/8 ITER source size, contributes to development of ITER NBI source & beyond
- H^- production on caesiated PG
- Magnetic filter field created either by vertical current through PG or by attached external magnets
  → vertical plasma asymmetry caused by xB drifts!
- Three-grid extraction system (up to 45 kV) (repeller grid removed in 2021)

Best beam optics requires $U_{acc}/U_{ex} \approx 6.5$
→ **beam optics studies only possible for $U_{ex} \leq 6$ kV!**



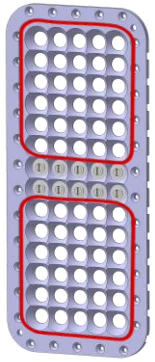
ITER source requirements
regarding beam optics

- **Beam divergence (core) < 7 mrad**
- Beam homogeneity > 90 %
- **$p_{fill} \leq 0.3$ Pa**

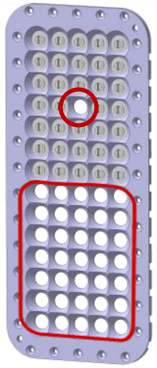
BATMAN Upgrade:
ADC magnets & grid masking

Grid mask

- PG can be masked flexibly using plugs
- Standard configuration for beam optics studies: single beamlet mask



two beamlet groups

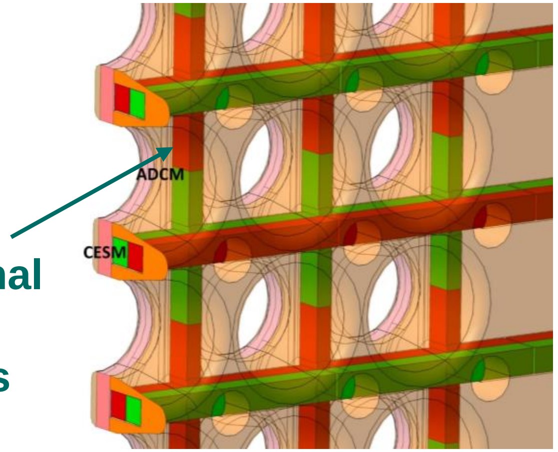


isolated beamlet

ADC magnets

- Row-wise zig-zag deflection created by alternating polarity of Co-extracted Electron Supression Magnets (CESM) in EG
- Additional asymmetric deflection compensation magnets (ADCM): harmonize vertical B-field & cancel out row-wise zig-zag deflection (pioneered by Consorzio RFX)
- Joint project with ITER (2021): Installation at BATMAN Upgrade, installed in upper grid half

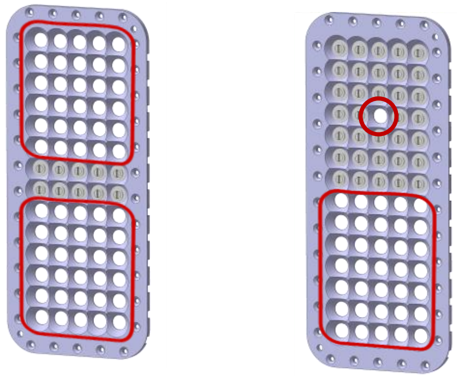
Additional ADC magnets



BATMAN Upgrade:
ADC magnets & grid masking

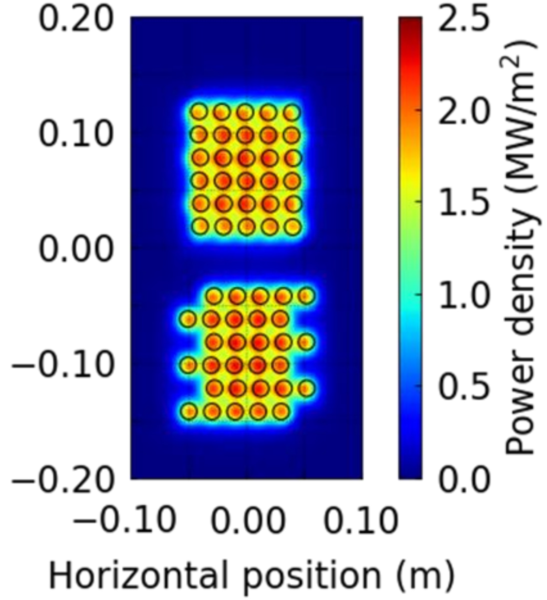
Grid mask

- PG can be masked flexibly using plugs
- Standard configuration for beam optics studies: single beamlet mask

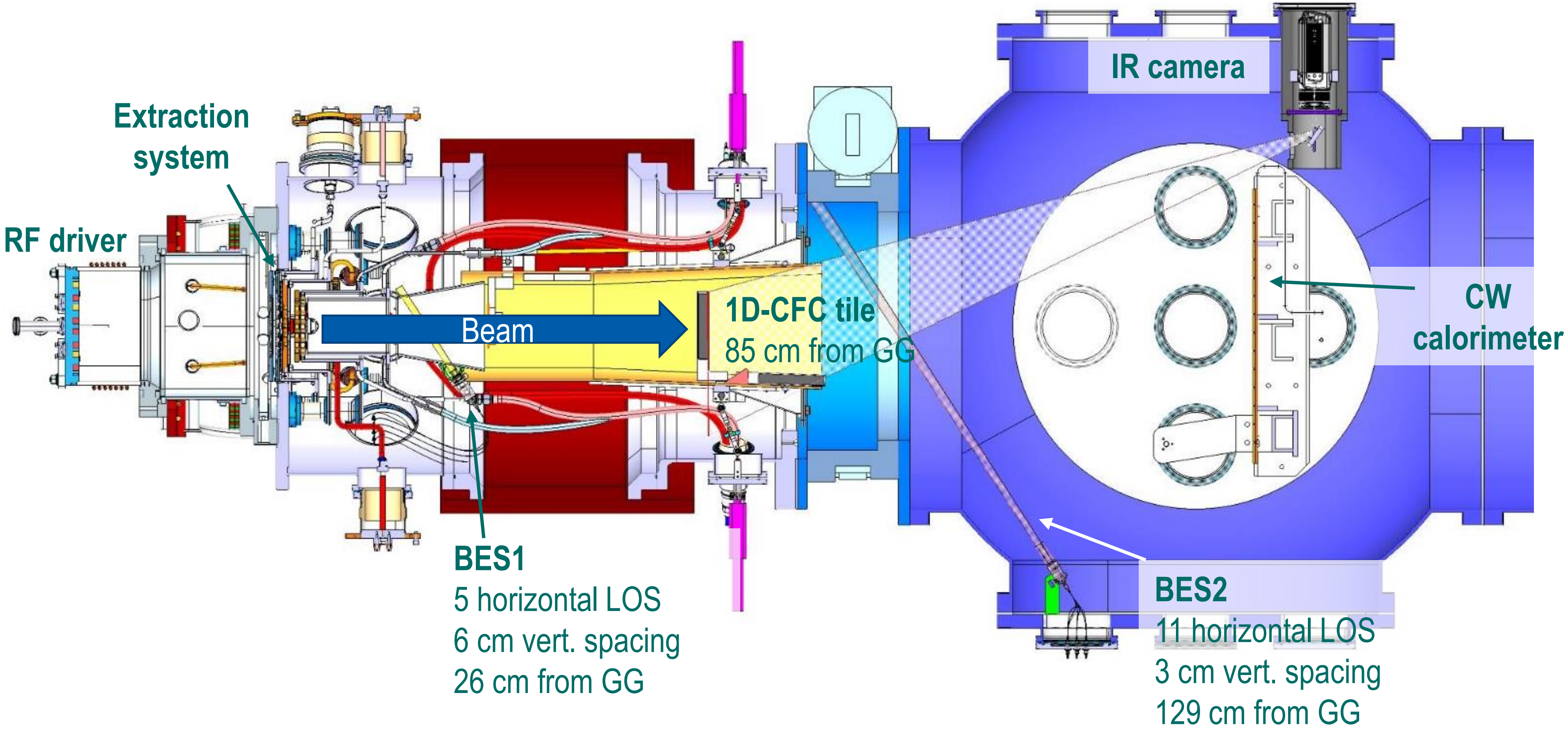


ADC magnets

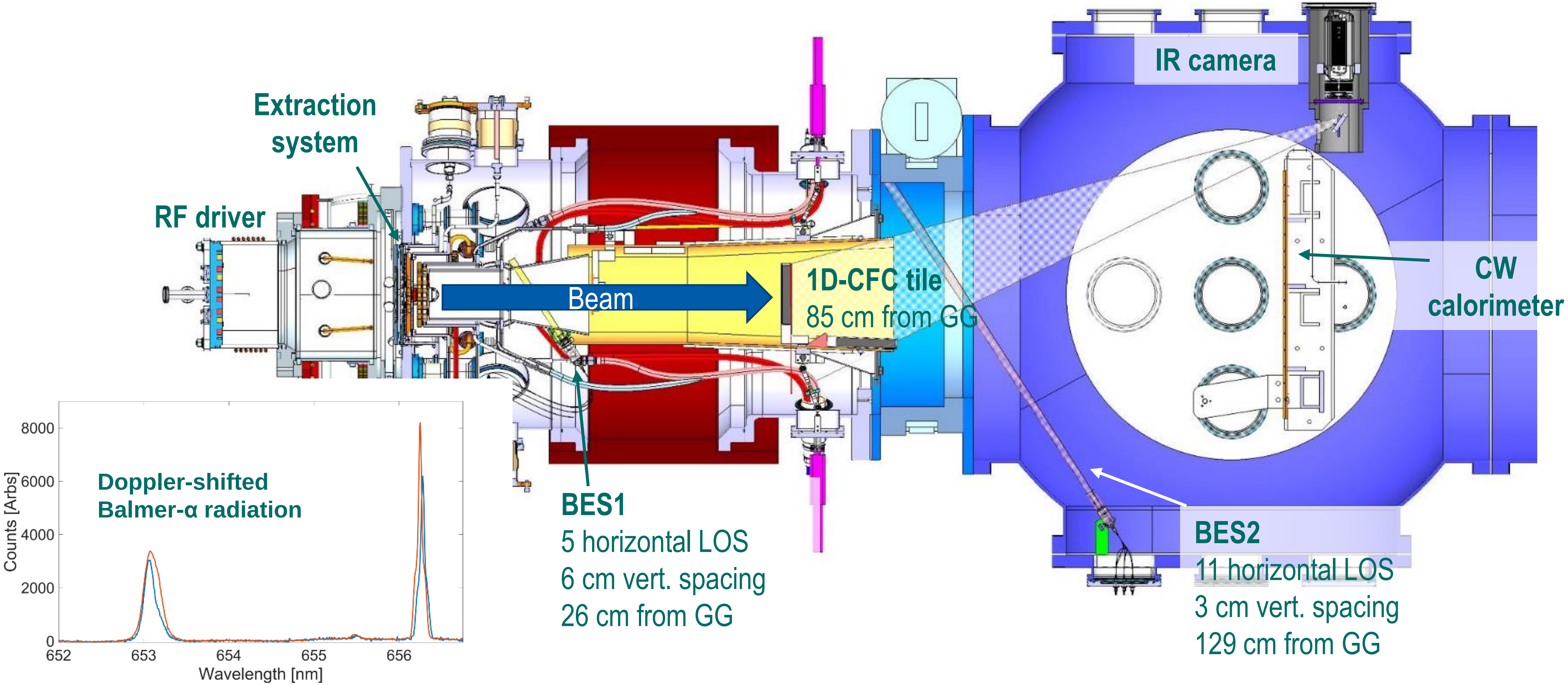
- Row-wise zig-zag deflection created by alternating polarity of Co-extracted Electron Supression Magnets (CESM) in EG
- Additional asymmetric deflection compensation magnets (ADCM): harmonize vertical B-field & cancel out row-wise zig-zag deflection (pioneered by Consorzio RFX)
- Joint project with ITER (2021):
  Installation at BATMAN Upgrade, installed in upper grid half



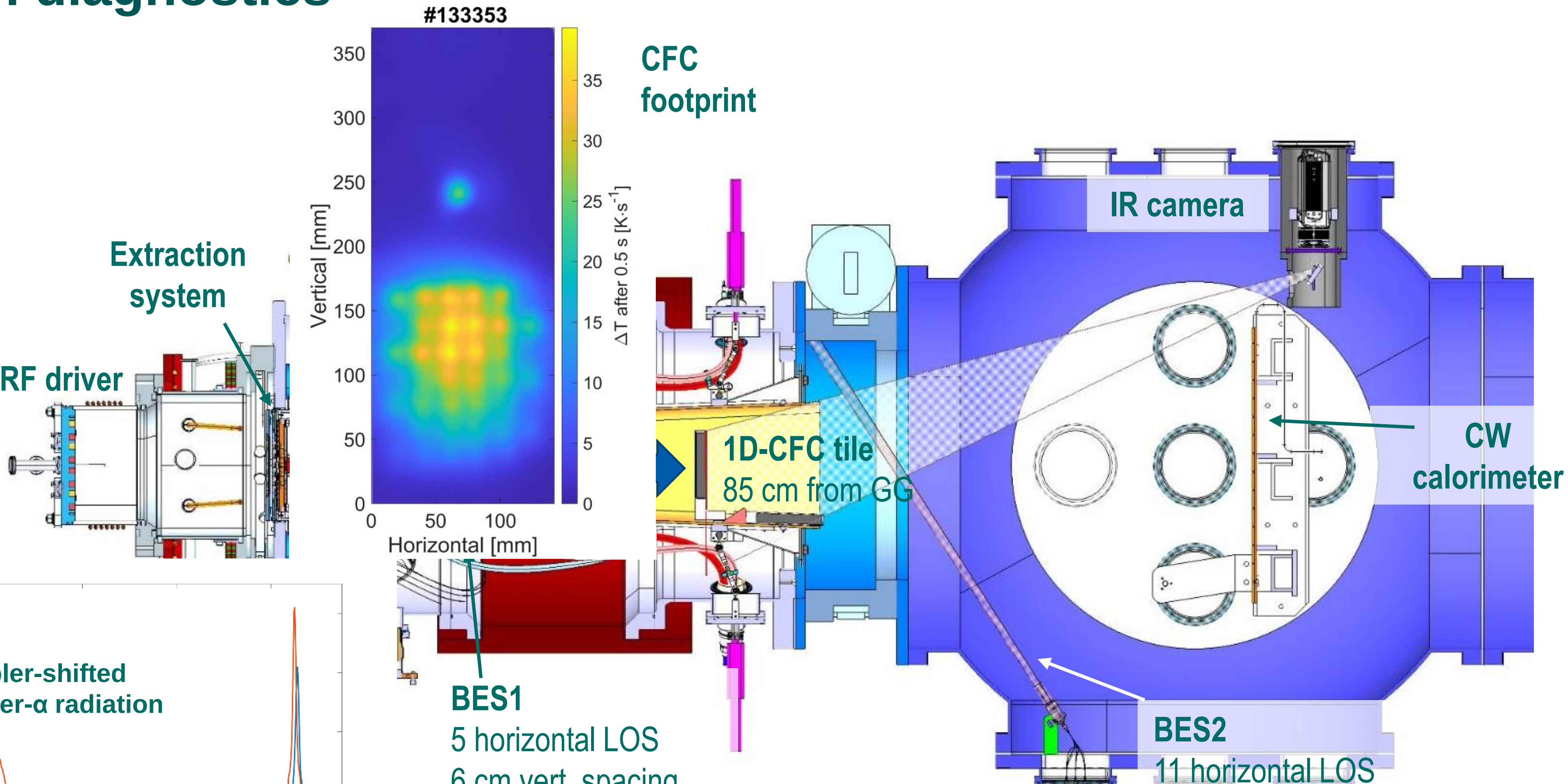
BATMAN Upgrade:
beam diagnostics

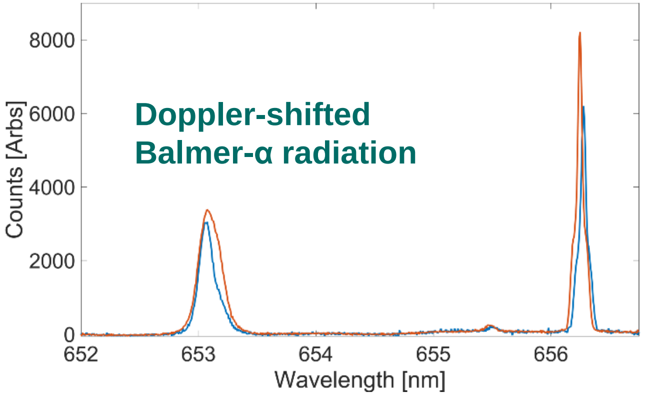


BATMAN Upgrade:
beam diagnostics

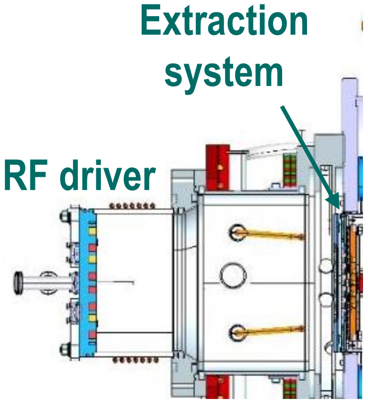


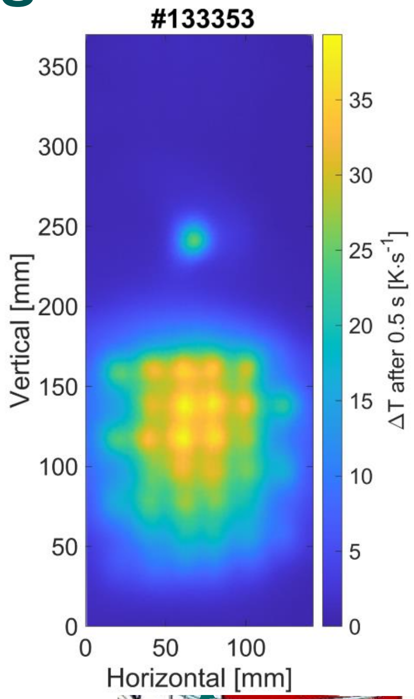
BATMAN Upgrade: beam diagnostics

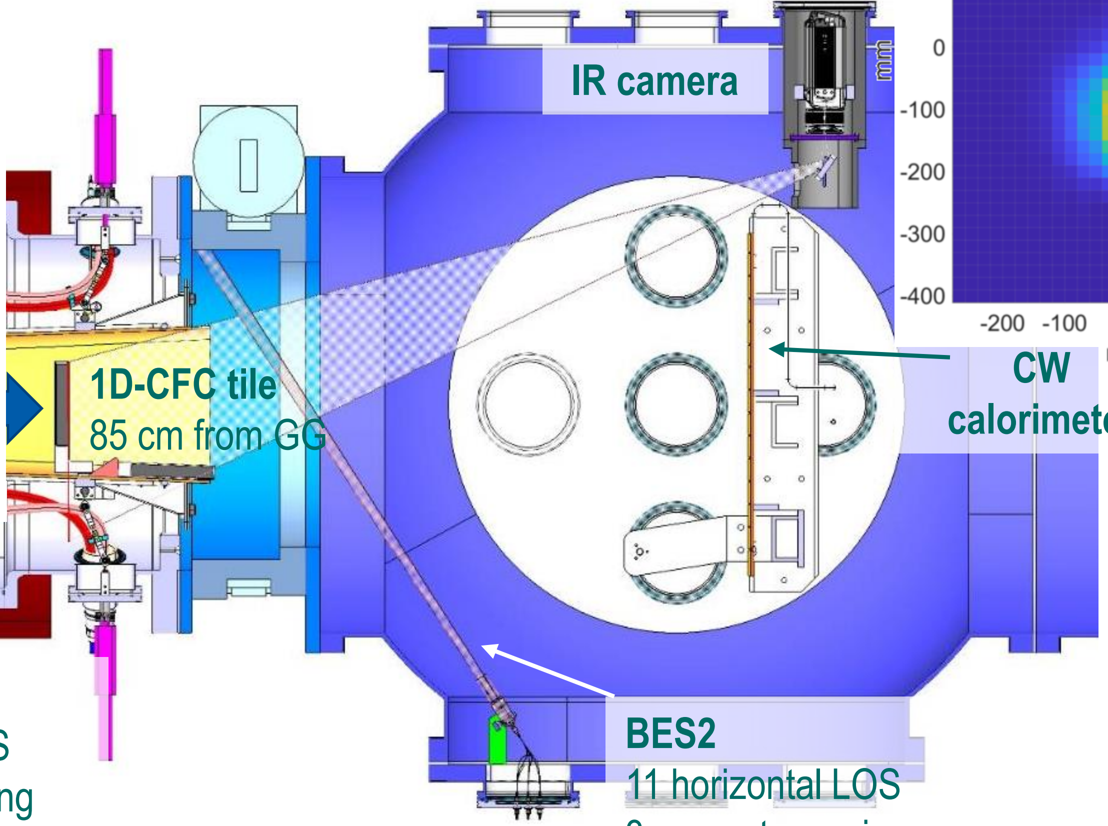


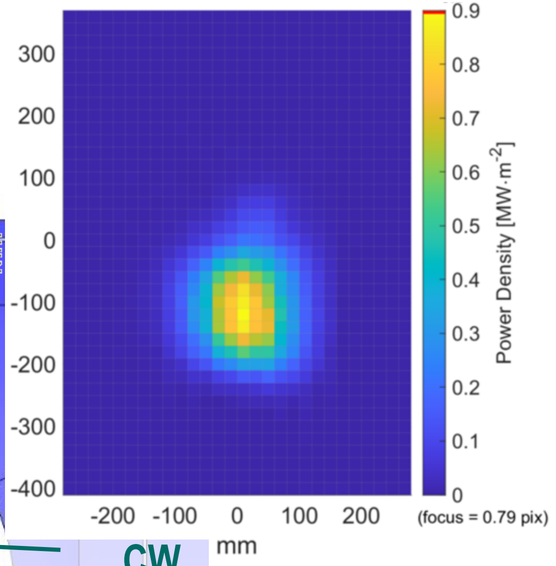


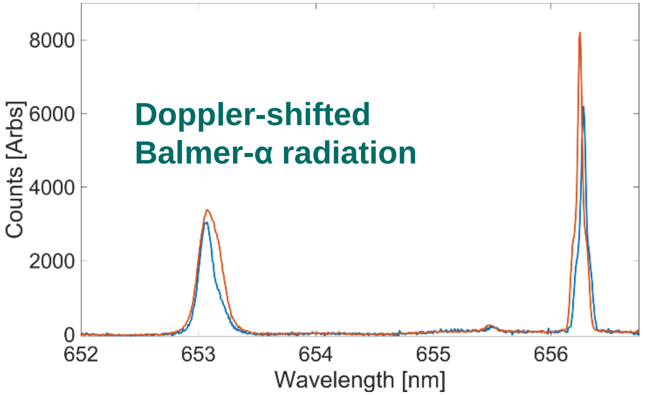
BATMAN Upgrade: beam diagnostics











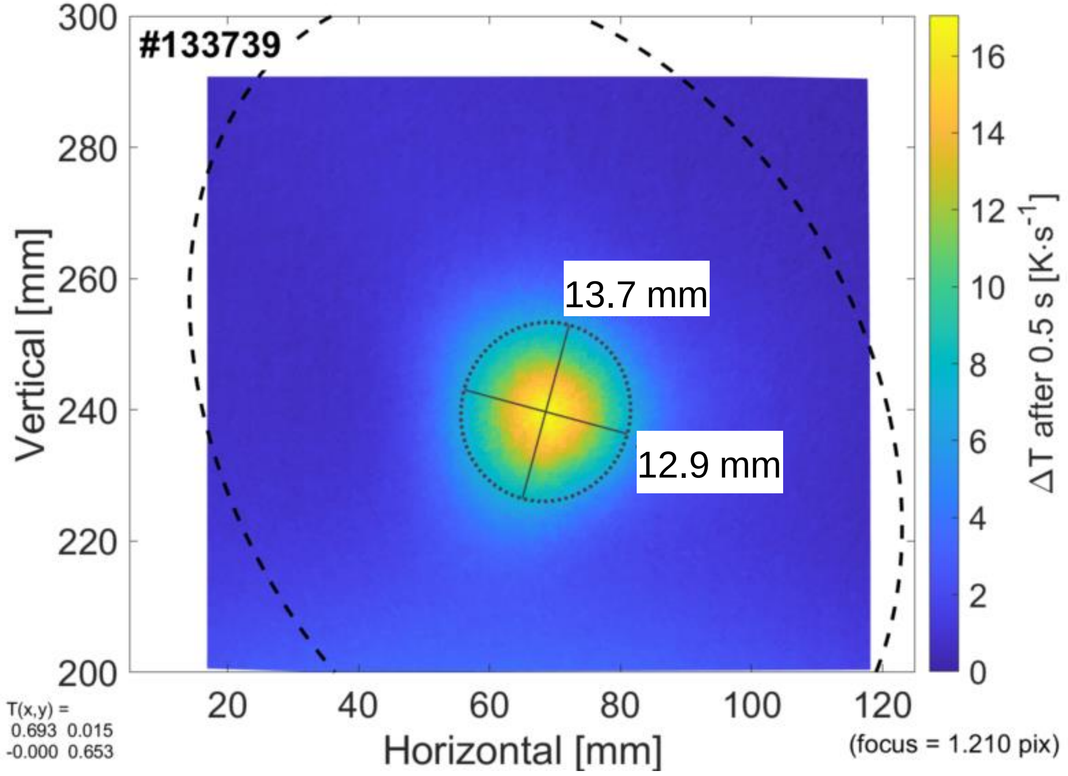
Evaluation of the CFC tile calorimeter

Size of single beamlet determined on CFC:

- 2D Double Rotatable Elliptical Gaussian fit
- Core size used to determine divergence

Divergence depends on initial beam size at GG & time frame (lateral heat conductance):

Shown shot:
0 mm initial beam diameter → 15.2 mrad divergence
5 mm initial beam diameter → 12.2 mrad divergence



0 mm diameter used in standard evaluation
& no lateral heat conductance is taken into account
→ **Evaluated divergence is upper boundary!**

Beam divergence task force initiated by ITER
→ see talk by P. Veltri

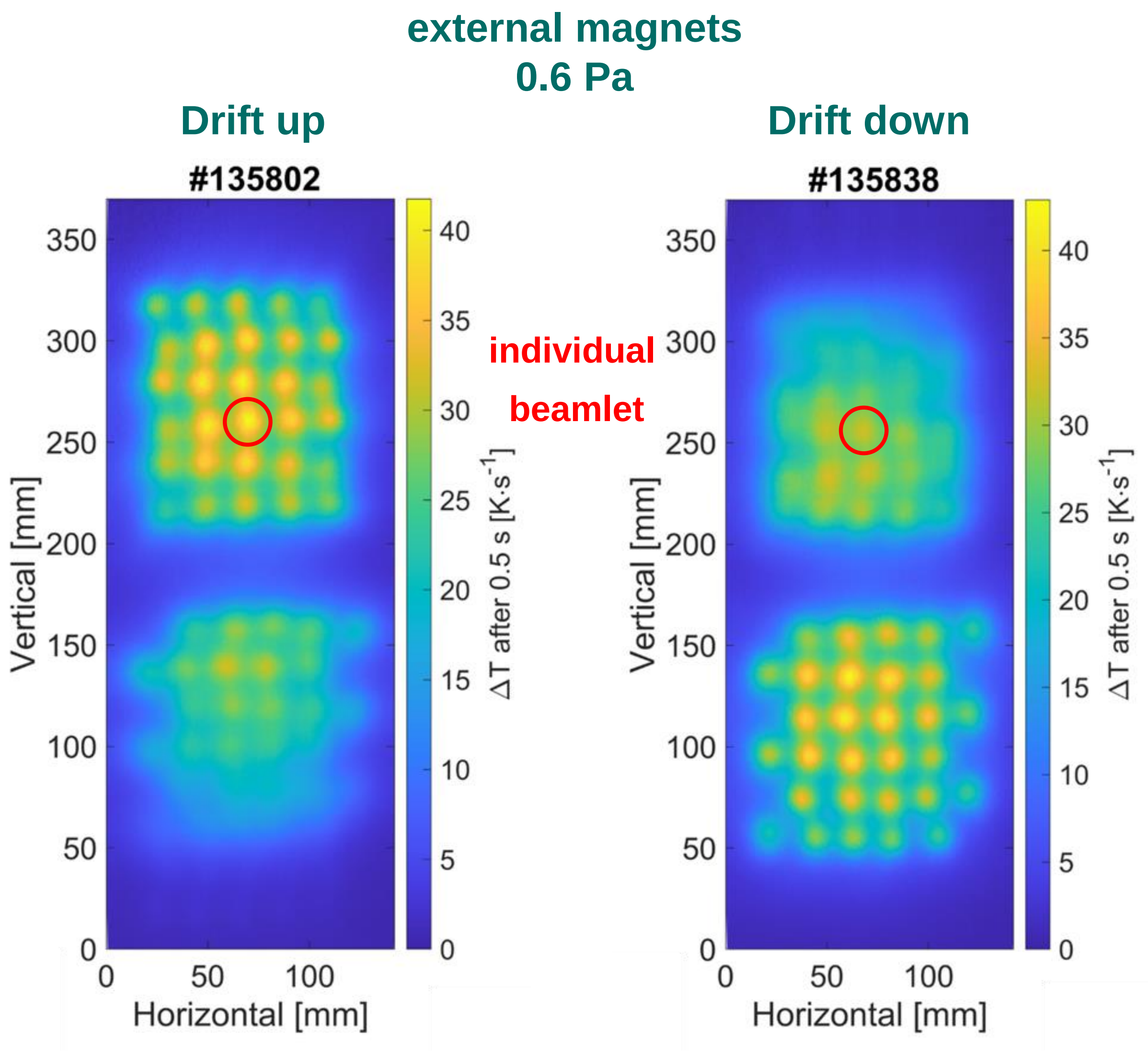
Beam asymmetry at BATMAN Upgrade

Significant vertical beam asymmetry at BATMAN Upgrade (smaller in larger sources!)

→ $j_{ex,beamlet} \neq j_{ex,total}$

no measurement available

Parameter variations:
Usually done two-dimensional (additionally varying P_{RF}) in order to compare perveance curves!

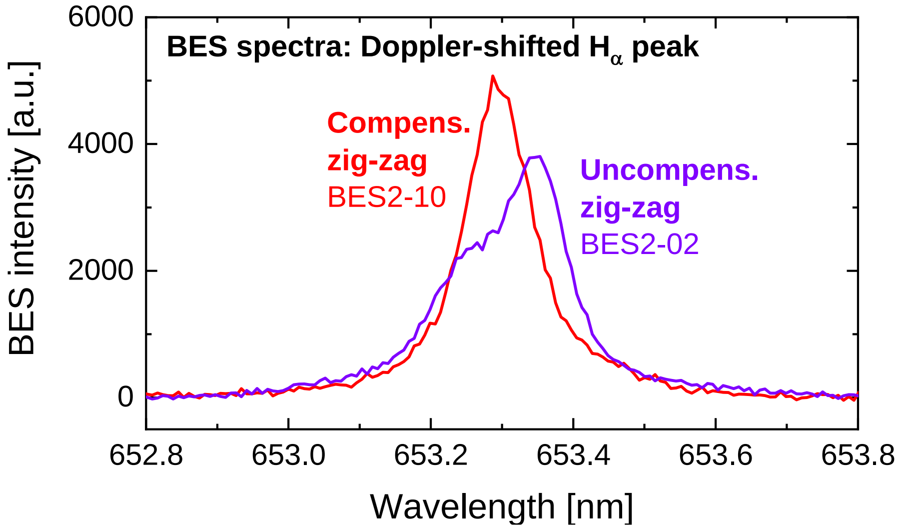


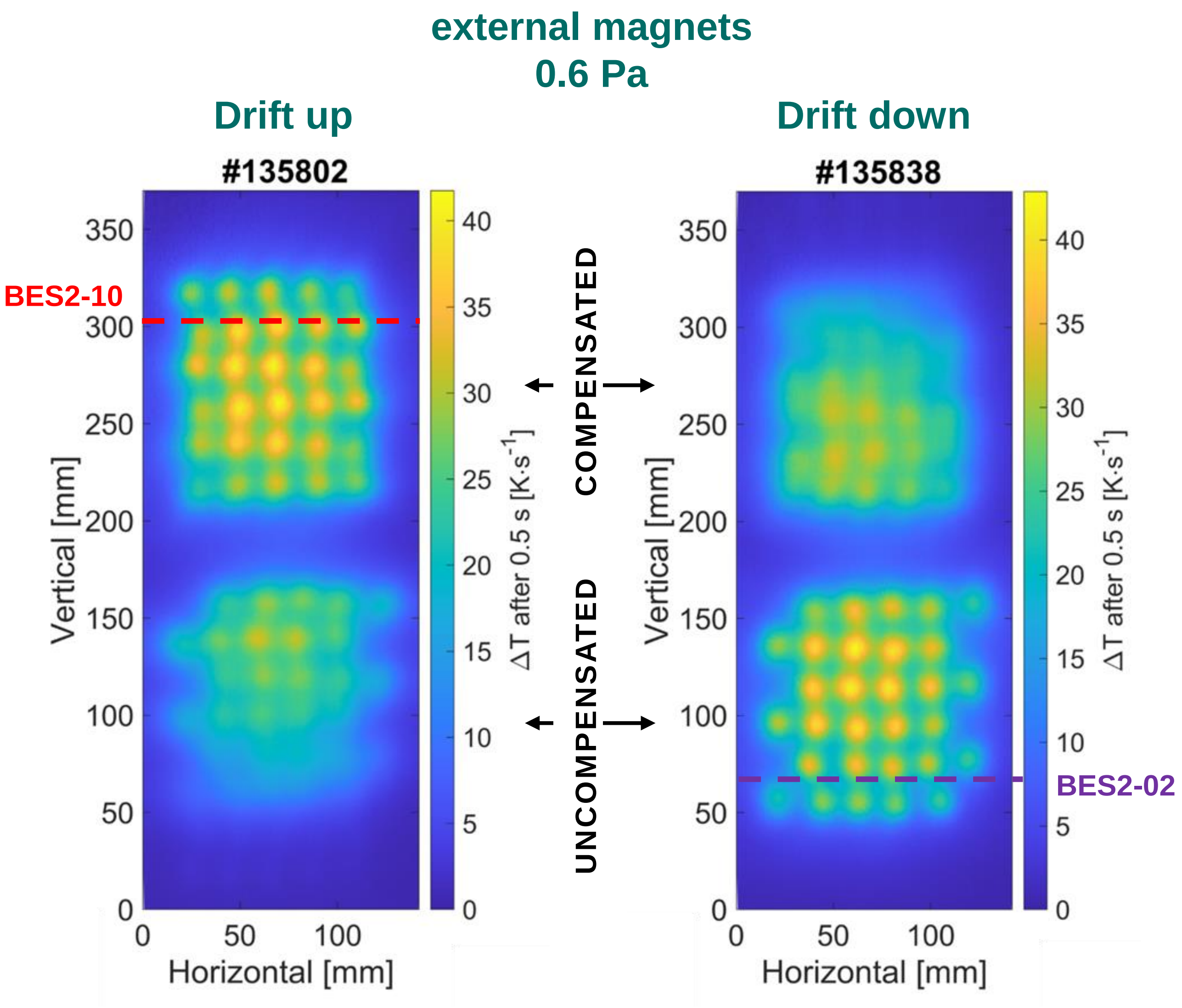
BES divergence on full beamlet group

Horizontal BES overestimates divergence for non-zig-zag-compensated grouped beamlets:

Compensated zig-zag (BES2-10):
12 mrad divergence

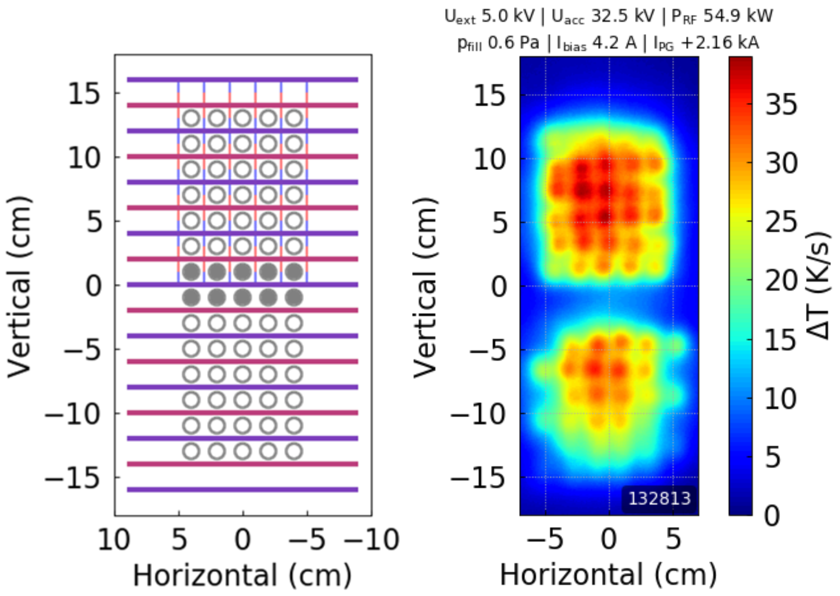
Uncompensated zig-zag (BES2-02):
28 mrad divergence

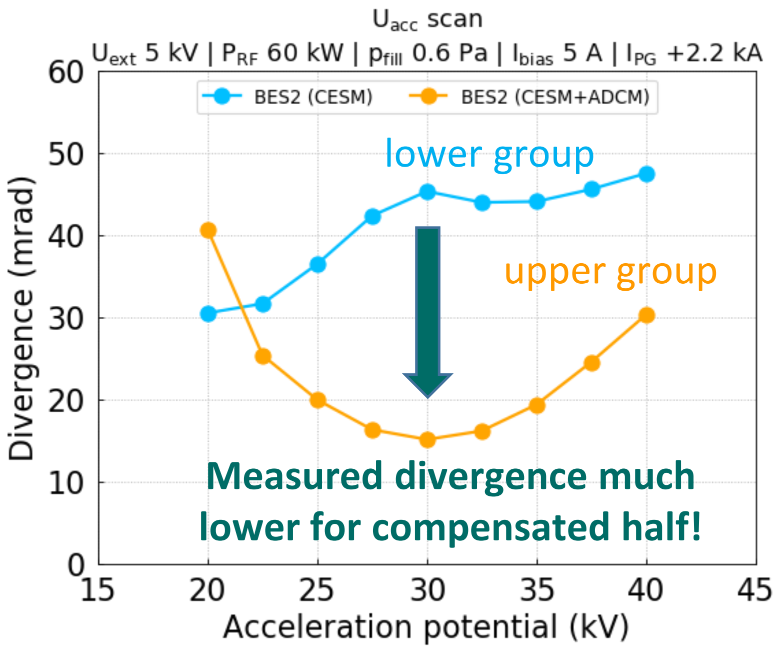


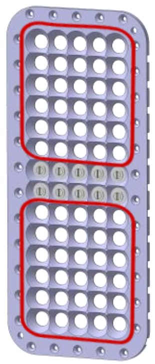


Compensation of zig-zag deflection

- CFC footprint: good compensation to be seen visually
- Lower BES2 divergence at compensated grid half
  (BES collects signal created by a manifold of beamlets!)
- Proof of IBSimu predictions



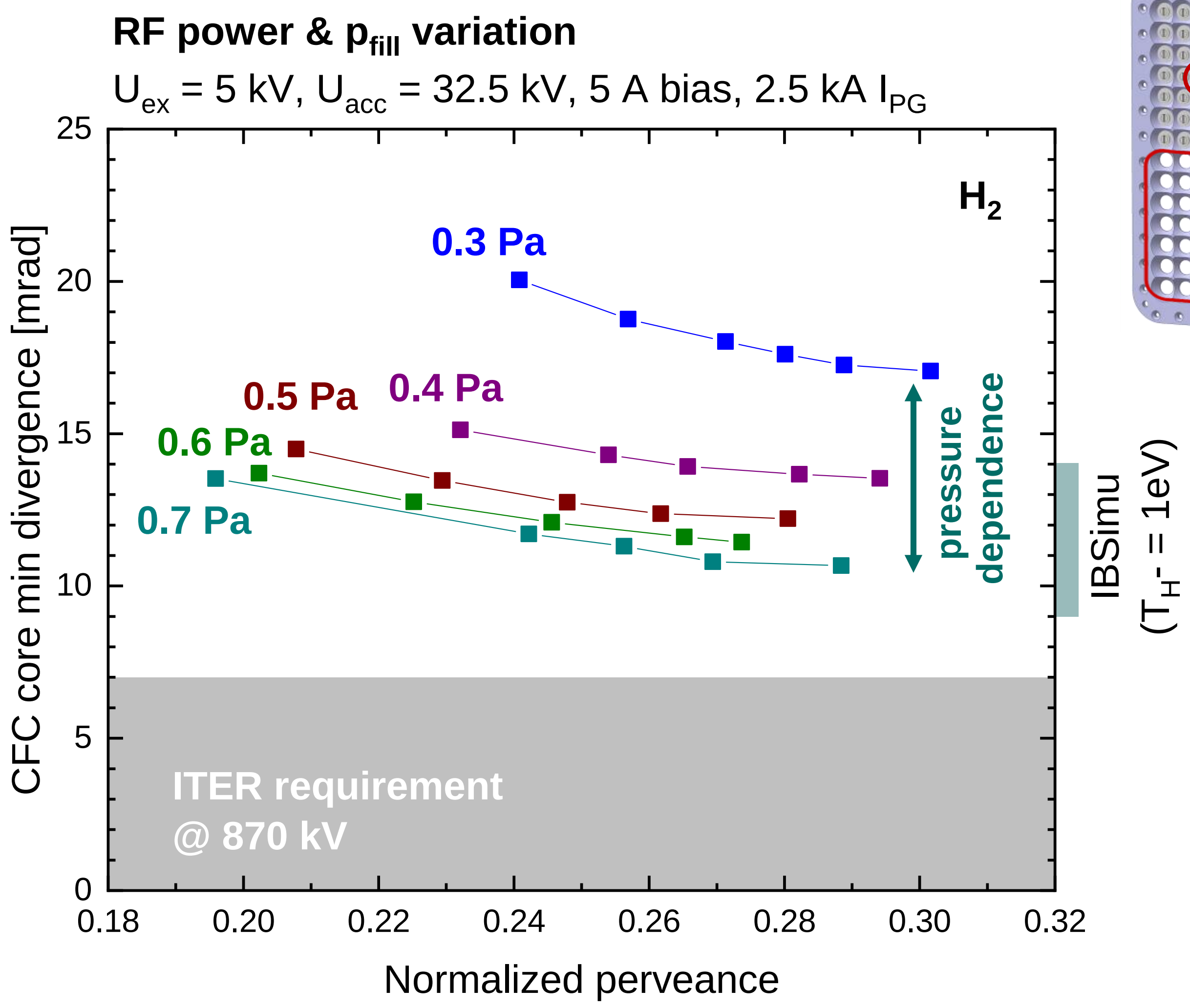


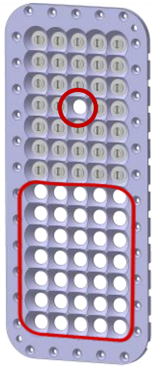


Niek den Harder et al 2022 *J. Phys.: Conf. Ser.* **2244** 012053

Dependence of divergence on filling pressure

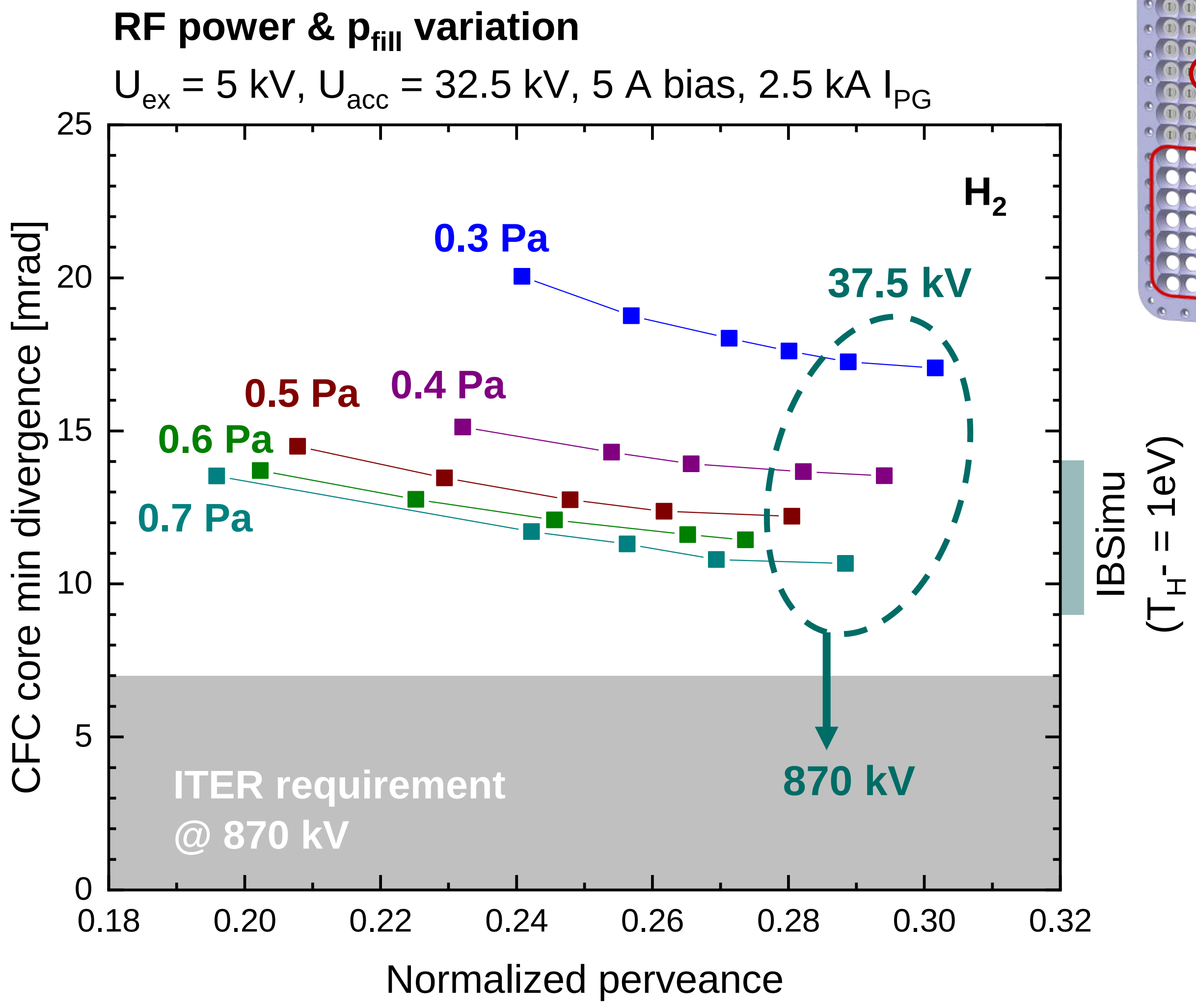
- Perveance curve: decreasing divergence for increasing norm. perveance (P_{RF} ↑)
- Strong dependence on filling pressure: **Divergence increases strongly for lower pressure** (biggest step 0.4 → 0.3 Pa)
- IBSimu simulations match divergence measured at higher filling pressure
- ITER requirements not achievable at **limited total U_{HV}**

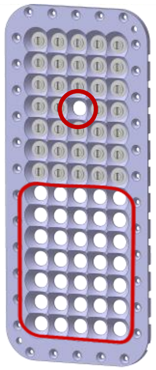




Dependence of divergence on filling pressure

- Perveance curve: decreasing divergence for increasing norm. perveance (P_{RF} ↑)
- Strong dependence on filling pressure: **Divergence increases strongly for lower pressure** (biggest step 0.4 → 0.3 Pa)
- IBSimu simulations match divergence measured at higher filling pressure
- ITER requirements not achievable at **limited total U_{HV}**





Dependence of divergence on filling pressure

Comparison of BES (single beamlet) & CFC core divergence:

Good agreement!
(taking into account weak signal/noise ratio of single beamlet BES)

Possible reasons for pressure dependence:

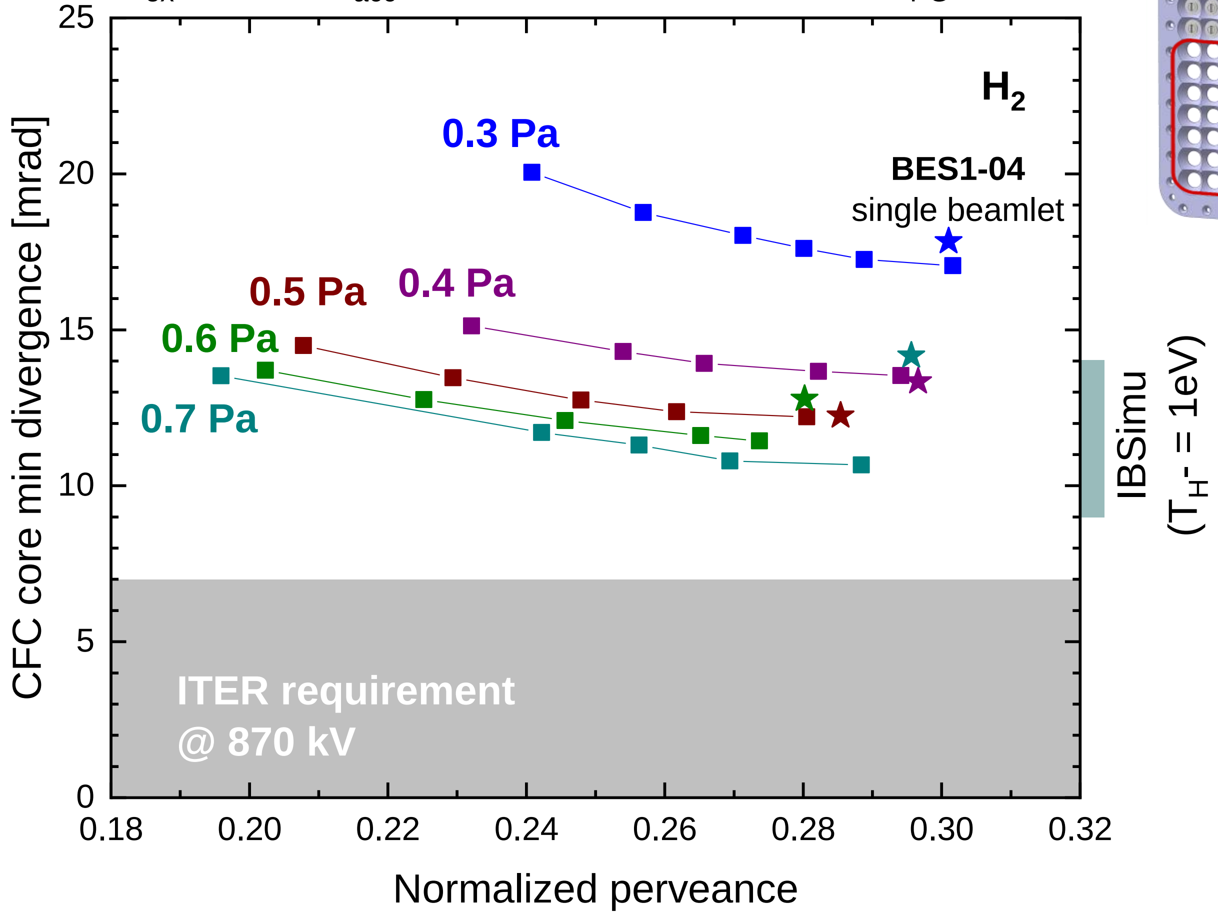
- T_H-? (energy of H atoms / positive ions)
- Meniscus shape?

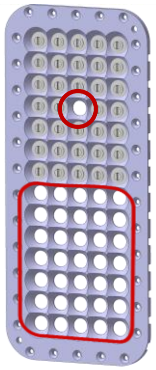
Comparison CFC & BES:

A. Hurlbatt et al., *AIP Advances* **11**, 025330 (2021)

RF power & p_{fill} variation

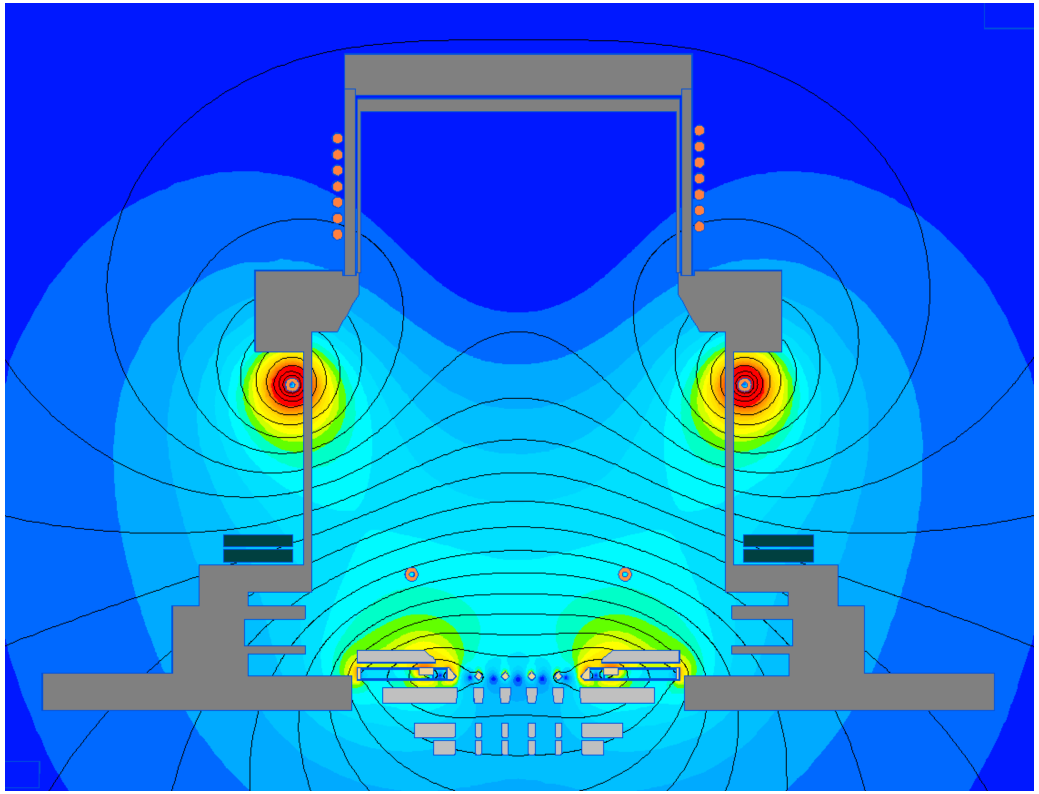
U_{ex} = 5 kV, U_{acc} = 32.5 kV, 5 A bias, 2.5 kA I_{PG}



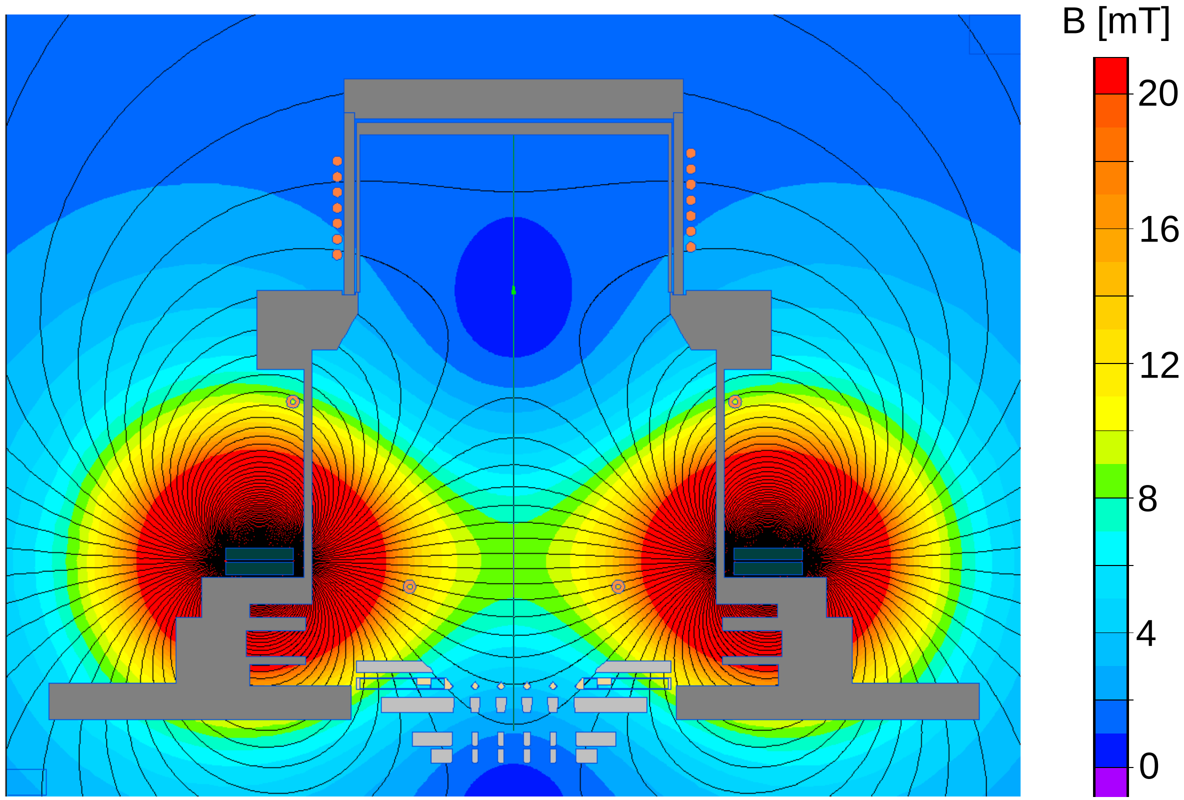


Dependence on magnetic filter field topology

Filter field topology differs strongly between vertical PG current & external magnets!



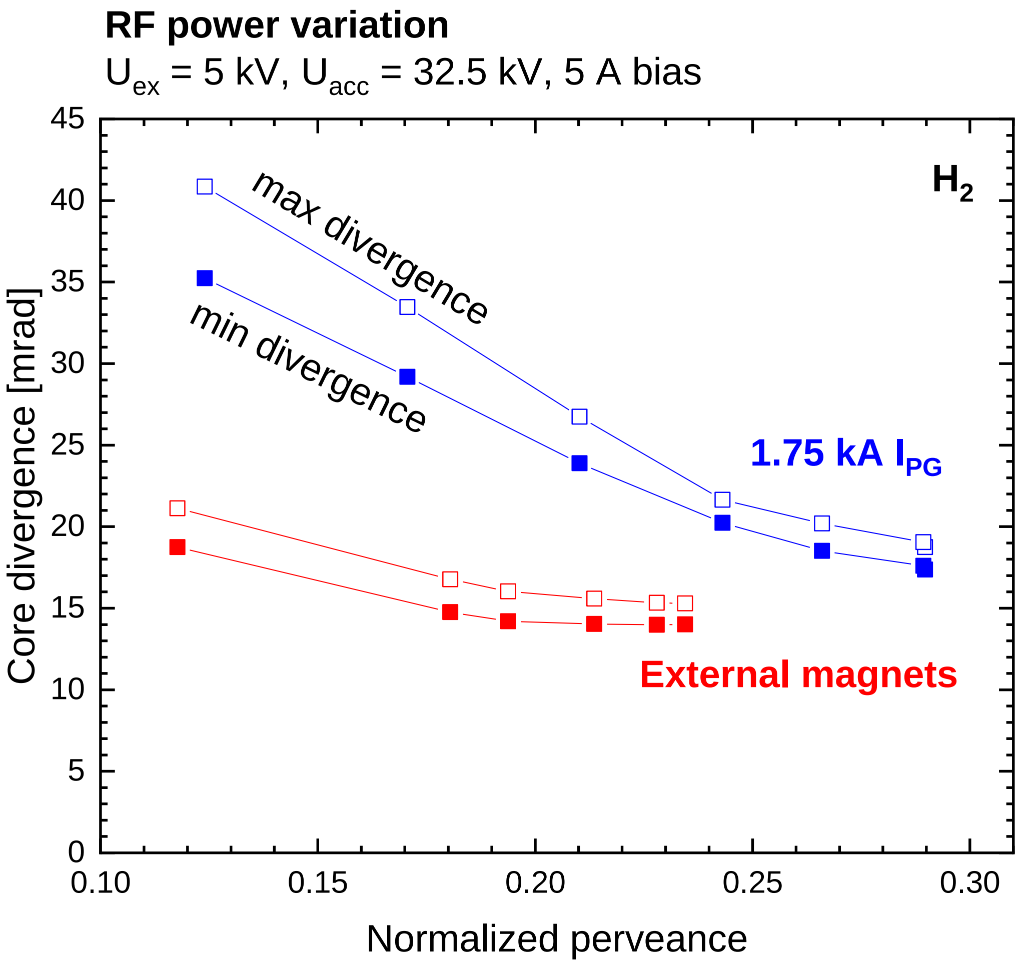
3 kA PG current

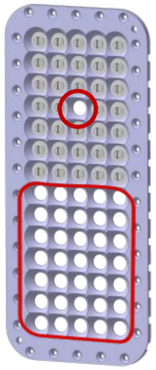


External magnets

Dependence on magnetic filter field topology

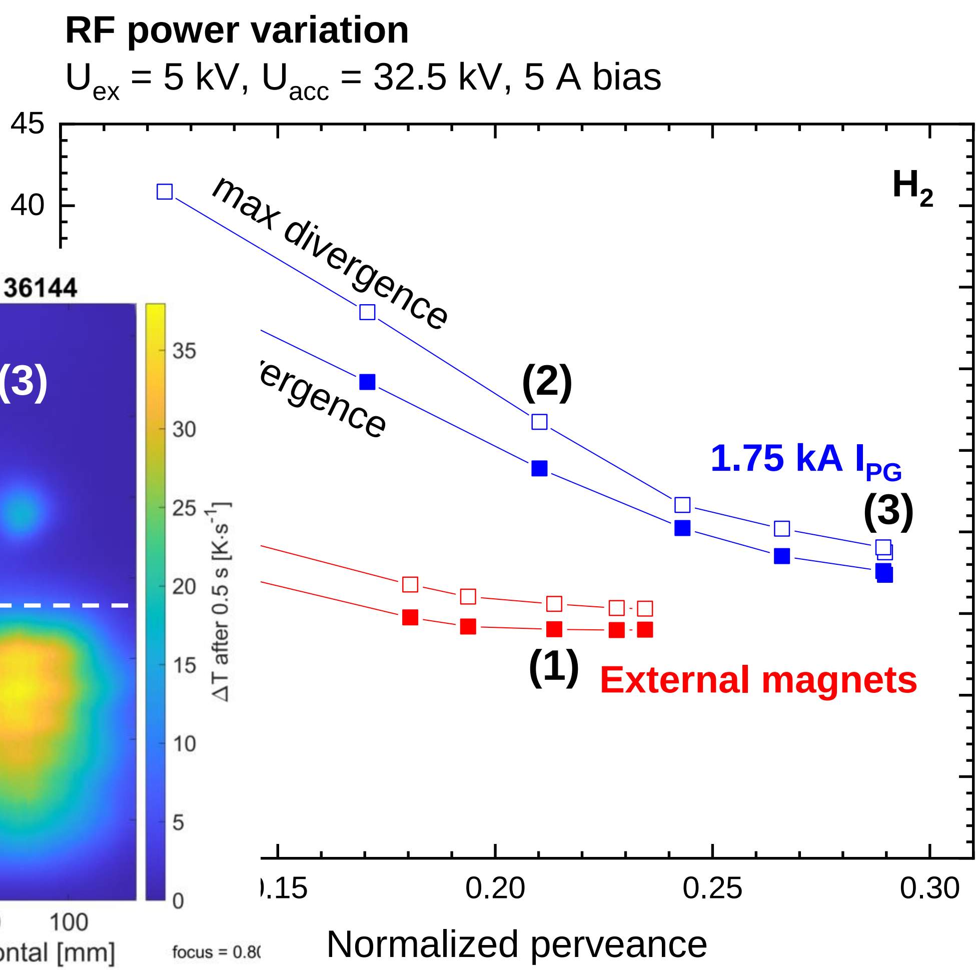
- 1st glance: divergence seems to be significantly lower with external magnets
- However: beam more asymmetric with external magnets
  → significant influence of higher local perveance!

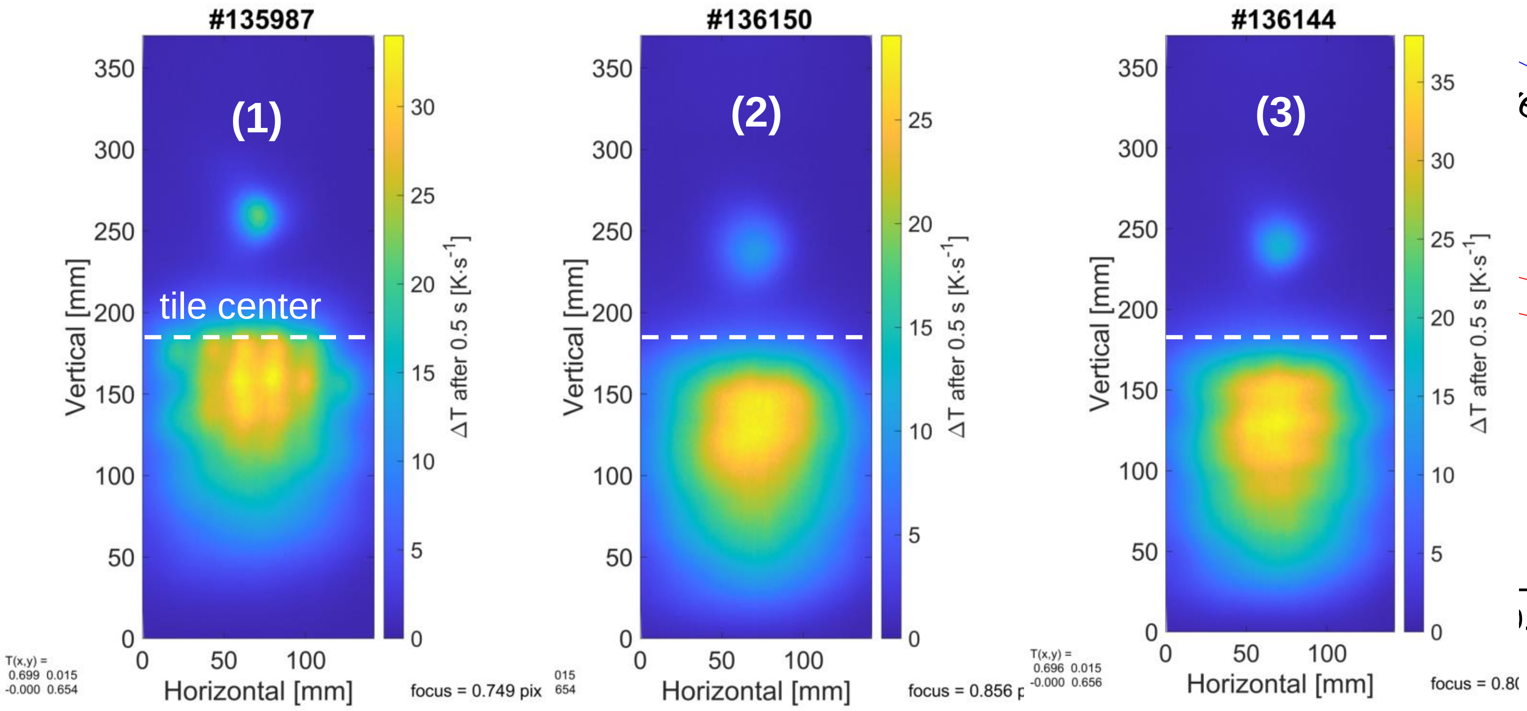


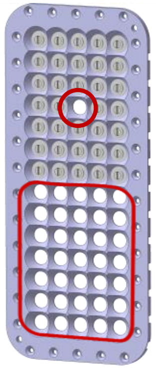


Dependence on magnetic filter field topology

- 1st glance: divergence seems to be significantly lower with external magnets

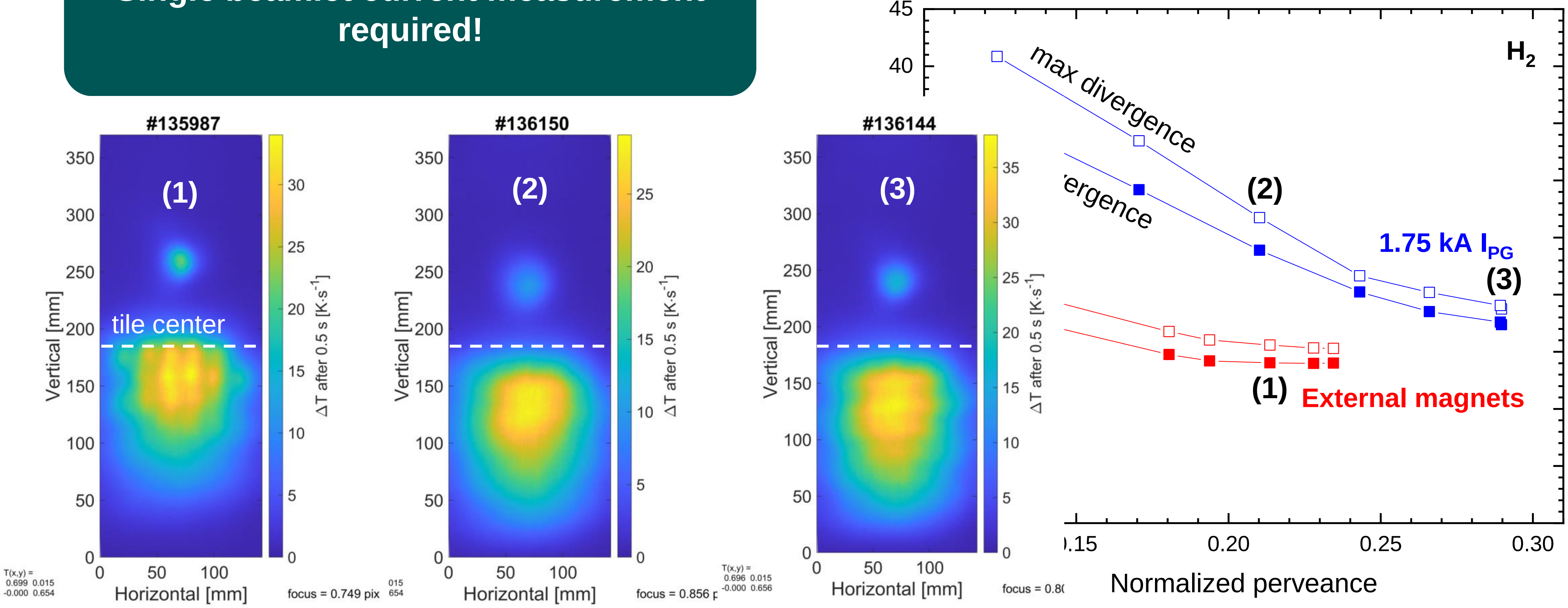


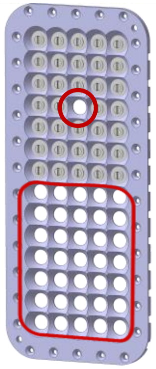




Dependence on magnetic filter field topology

Single beamlet current measurement required!

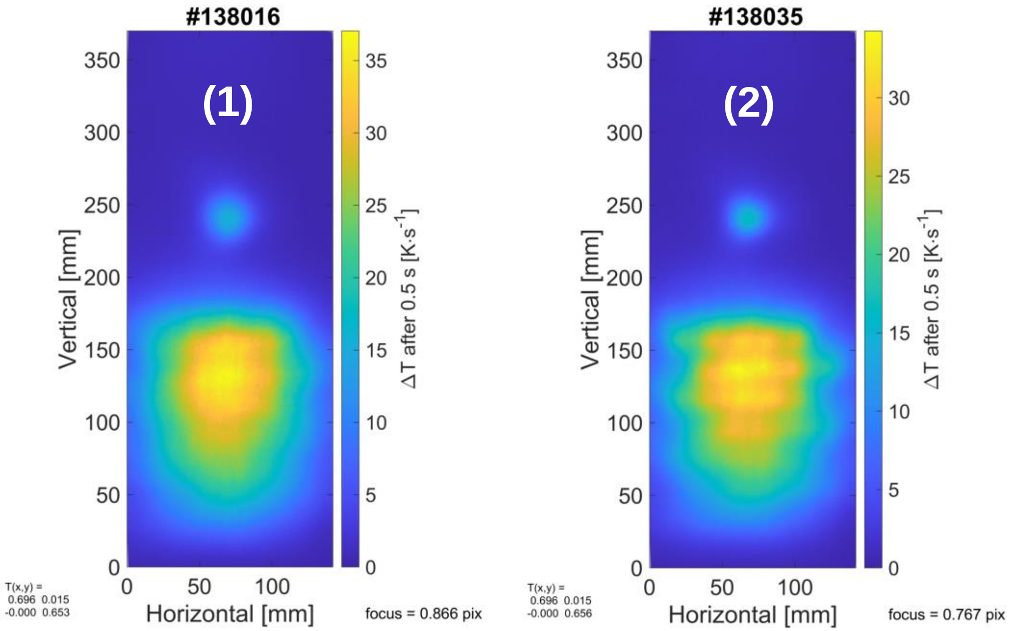


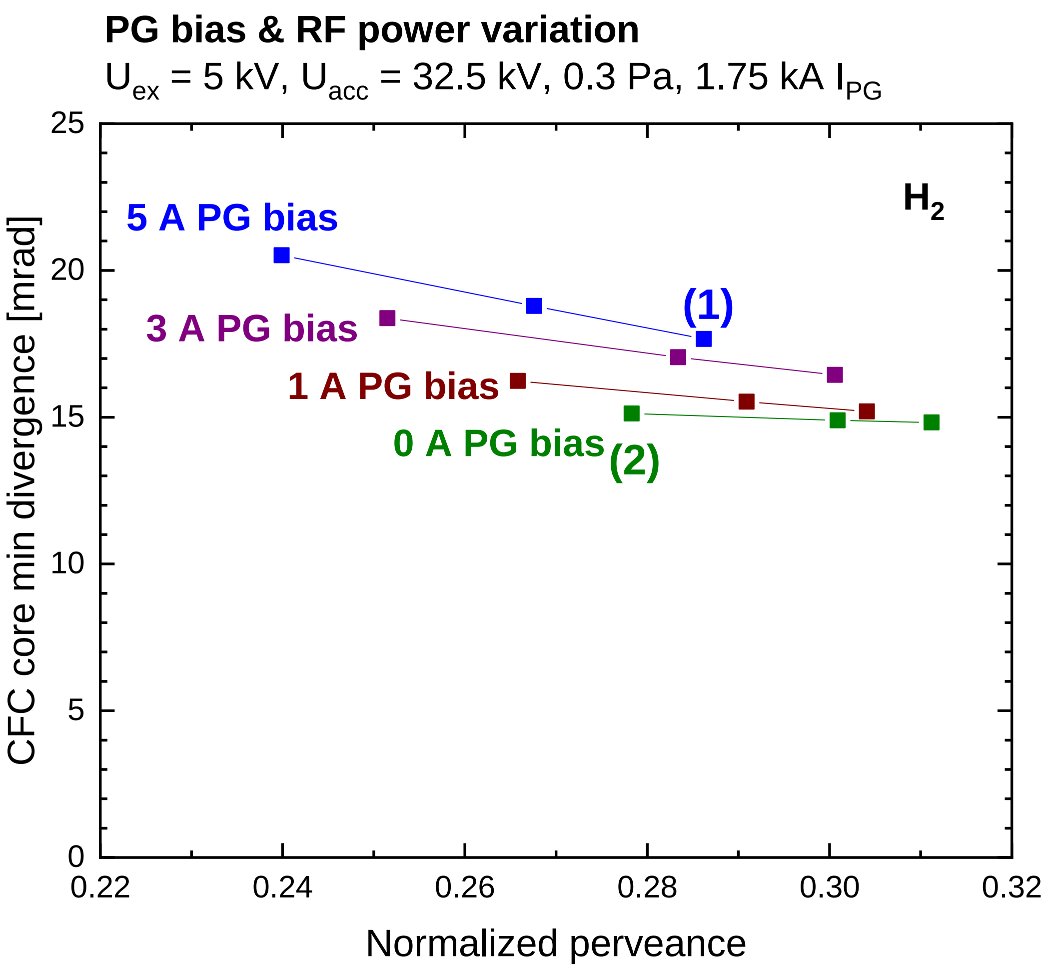


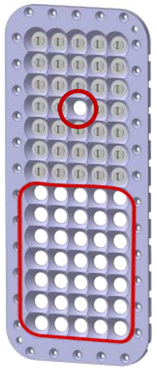
Dependence of divergence on PG bias

Divergence decreasing for lower PG bias
(less significant at high norm. perveance i.e. standard operation conditions)

→ **Effect of local perveance change (indirect effect) or starting energy of negative ions?**







Conclusion

- **BES & CFC calorimetry are valuable tools for beam optics studies at BATMAN Upgrade**
  (their individual drawbacks need to be taken into account!)
  CFC evaluation: conservative divergence estimation (upper boundary!)
- **Robust compensation of zig-zag deflection with ADC magnets**
- **Lower filling pressure strongly increases beamlet divergence (biggest step: 0.3 Pa → 0.4 Pa)**
  - Physics understanding on-going task
  - Ion source operation @ 0.4 Pa would be beneficial!
- **Measurement of ion current from single beamlet required** in order to clearly distinguish between influence of local perveance change and other parameter variations