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# Complete Compensation of Criss-cross Deflection in a Negative Ion Accelerator by Magnetic Technique

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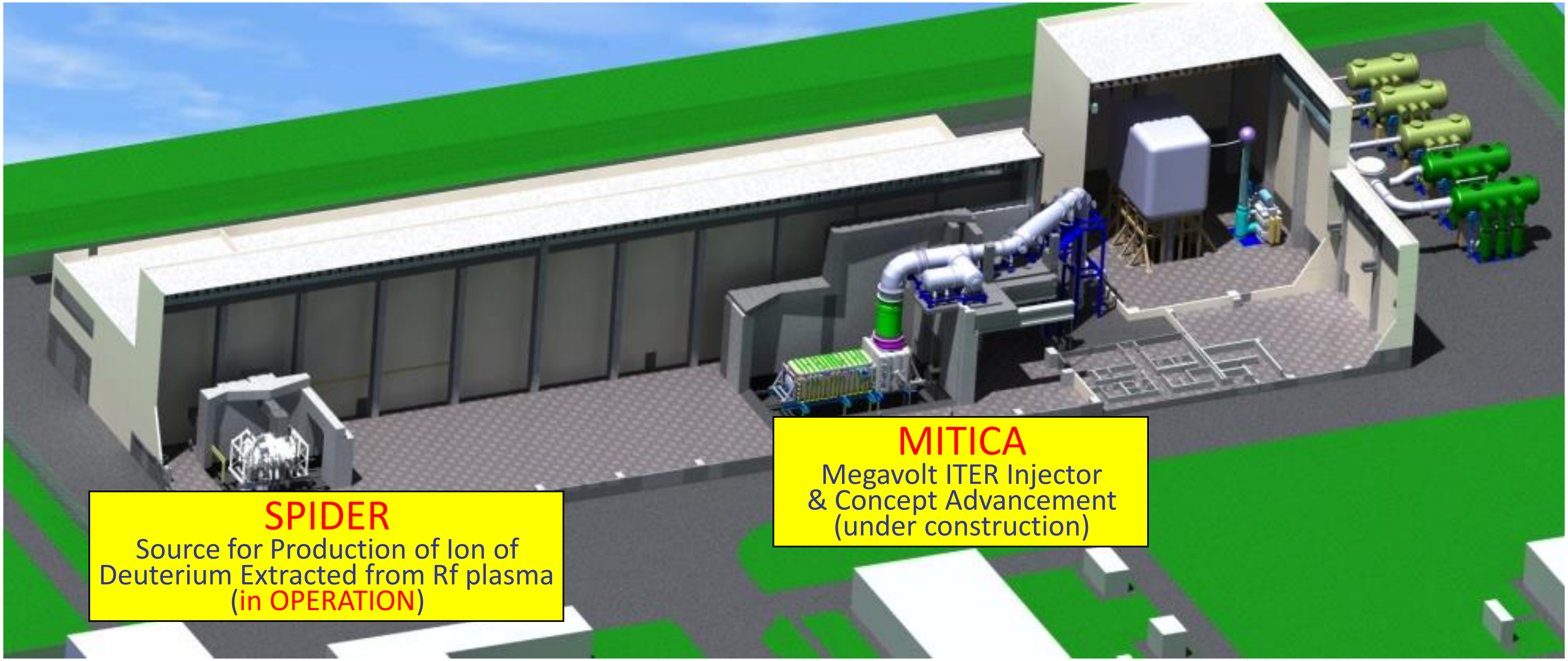
# Outline

- The Neutral Beam Test Facility
- Motivations of the QST – Consorzio RFX joint experiments
- Magnetic Technique for compensation of Criss-Cross deflection
- Summary of first joint experiments
- Summary of second joint experiments
- Analysis of the result
- Benchmark of numerical models
- Conclusions

# Neutral Beam Test Facility

NBTF is an essential step for the smooth operation of the ion source of ITER HNB, whose design is based on concepts developed in several collaborating labs (QST, IPP, CEA), but never tested at full performance at once in a single experiment.

- MITICA: full-scale prototype of ITER HNB, 46 A, 1 MV, 5 acceleration stages, 16.5 MW
- SPIDER: full-scale negative ion source and extractor having the same features and size as ITER HNB (and DNB), 46 A, 100keV. Operation started in June 2018.



# Motivations of the joint experiments

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1. Validation of the optics design for MITICA and ITER NBI
   - test of the magnetic technique for criss-cross deflection compensation
   - test of ITER-like extractor geometry (Plasma Grid, Extraction Grid, extraction gap size)

2. Benchmark and improvement of numerical tools for negative ion accelerator design
   - beamlet optics (2D): SLACCAD, design cross-check by QST using BEAMORBT
   - beamlet aiming (3D): OPERA (and recently COMSOL)

3. Improvement of the knowledge of negative ion extraction physics

# Criss-cross deflection: origin and solution

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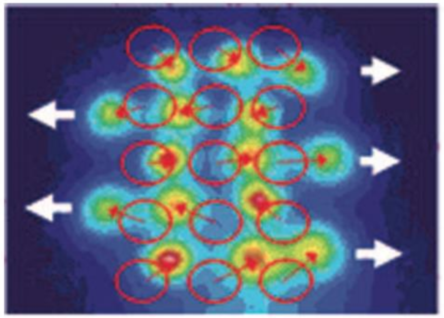
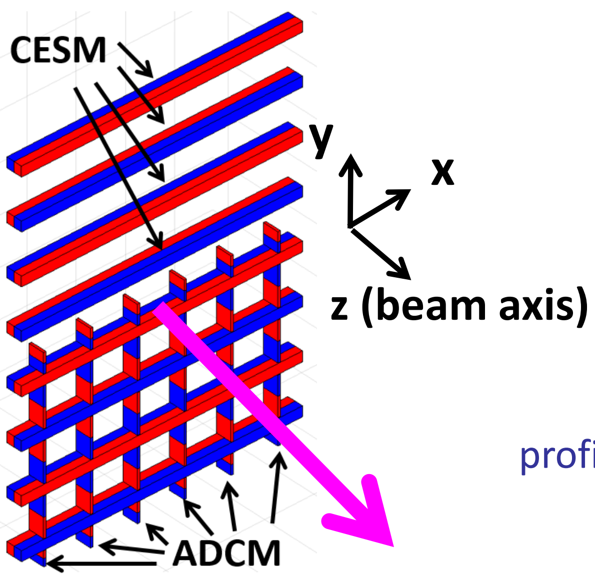
- Alternate shift of consecutive beamlet rows
- produced by Co-extracted Electron Suppression magnet
- it produces in turn a global beam divergence



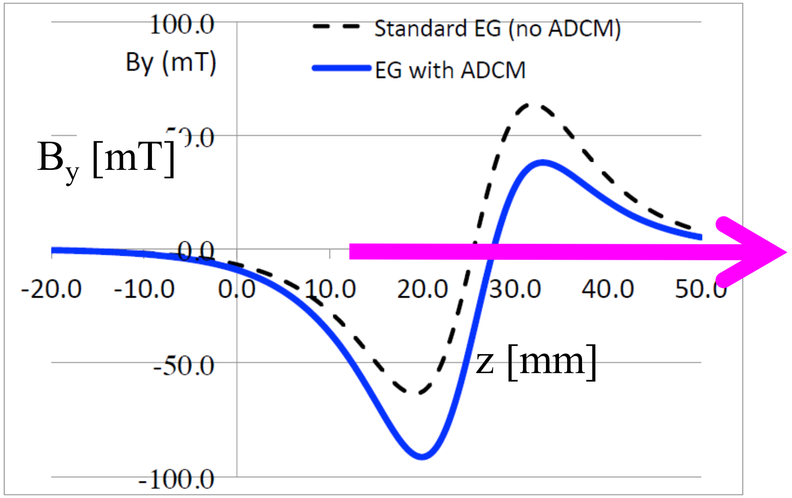
picture from M. Taniguchi et al, Rev. Sci. Instrum. 83, 02B121 (2012)

Beamlet deflection compensation by ADCM (Asymmetric Deflection Compensation Magnets) in the Extraction Grid:

- robust to beam energy variations
- easy to realize




magnet layout inside Extraction Grid

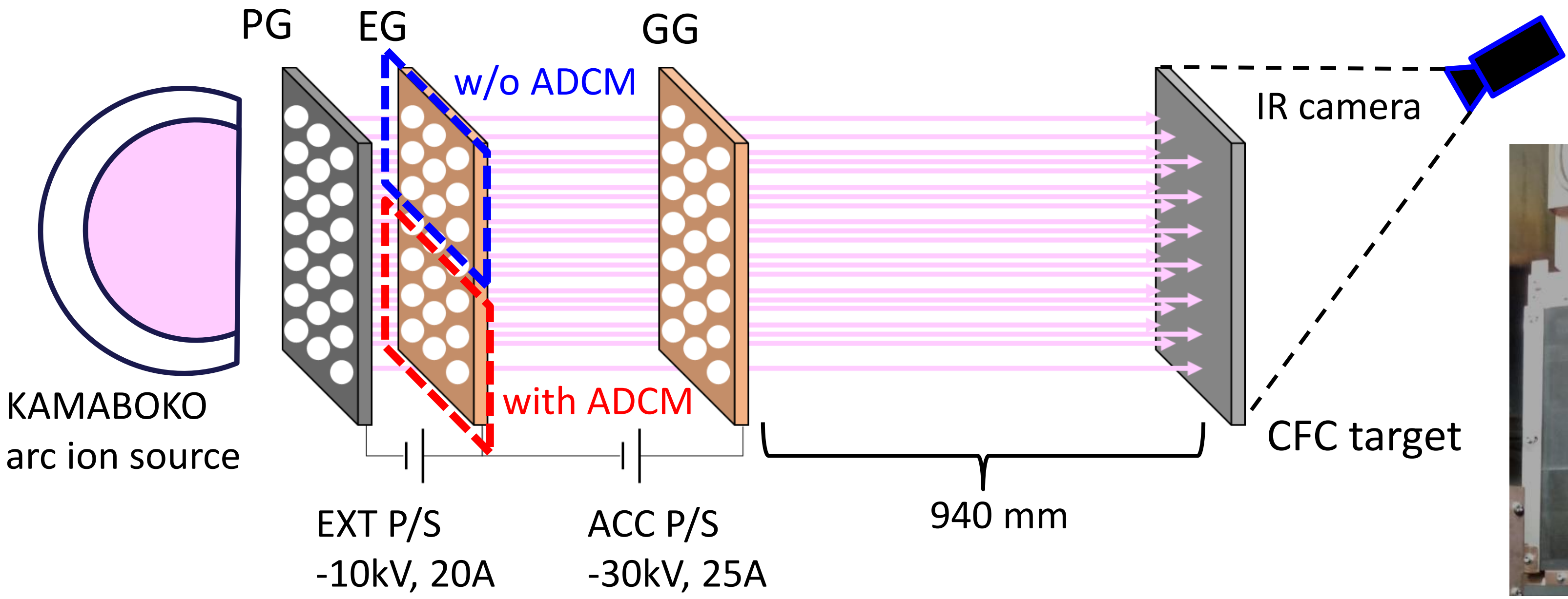



profile of vertical component of magnetic field $B_y$

# The Negative Ion Test Stand (NITS)

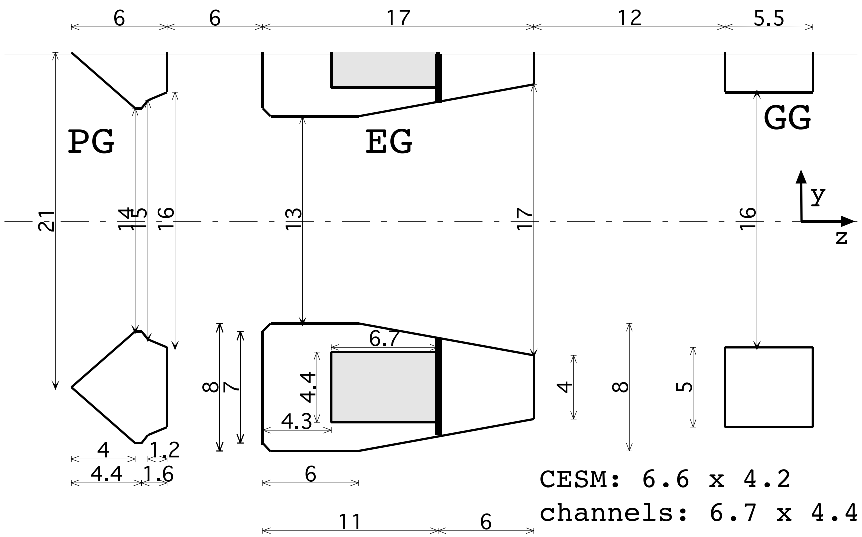
- “Kamaboko” arc source
- Single stage accelerator, 2 beamlet groups of 3x5 apertures
- Max $V_{EXT}$ = 10 kV, max $V_{ACC}$ = 30 kV
- Main diagnostics available:
  - ✓ CFC target (Mitsubishi MFC-1) with current measurement
  - ✓ IR camera (InfRec R500 with IRL-TX02D tele-lens)
  - ✓ power supply current measurements

PG

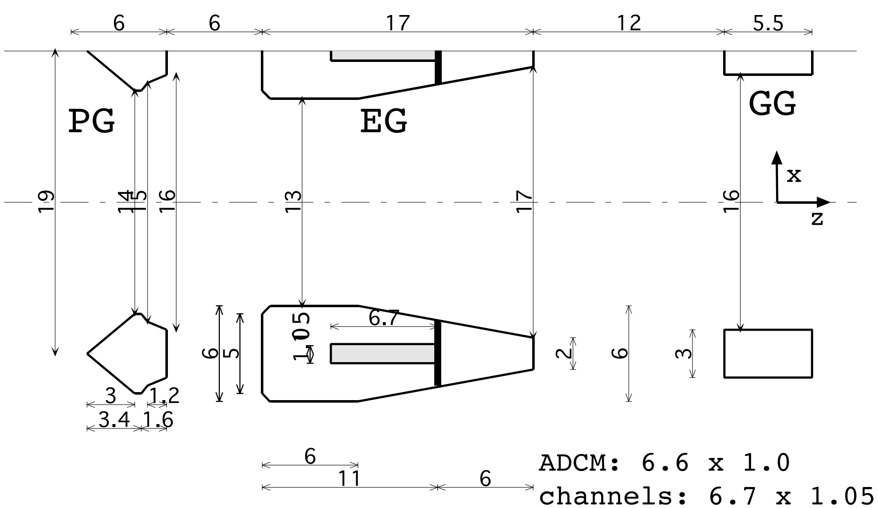



# NITS accelerator with ITER-like PG and EG

vertical cross-section



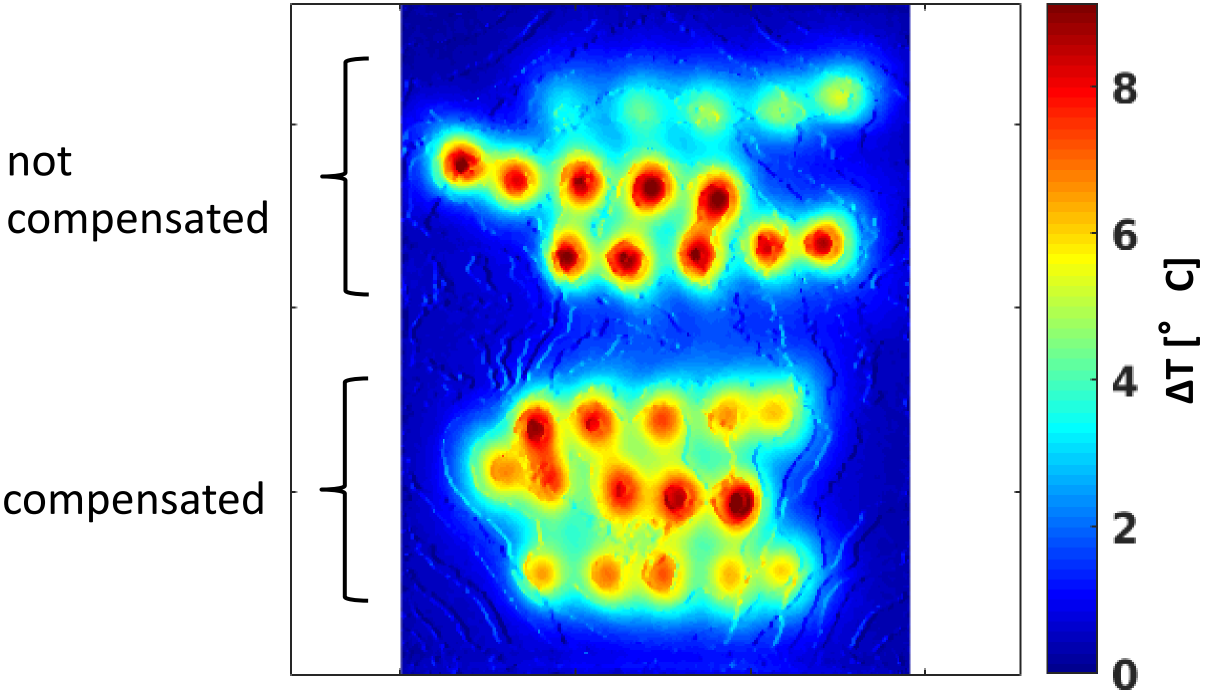

horizontal cross-section




- aperture pitch
  - vertical = 21 mm
  - horizontal = 19 mm
- ITER-like PG and EG profile
  - upstream aperture diam = 13 mm
  - downstream aperture diam= 17 mm
  - CESM 6.6x4.2x28.3mm Br=1.1 T
  - ADCM 6.6x1.0 x 16.4mm Br=0.88 T
- PG-EG_gap= 6mm
- EG-GG_gap= 12 mm
- Vacc= 30 kV

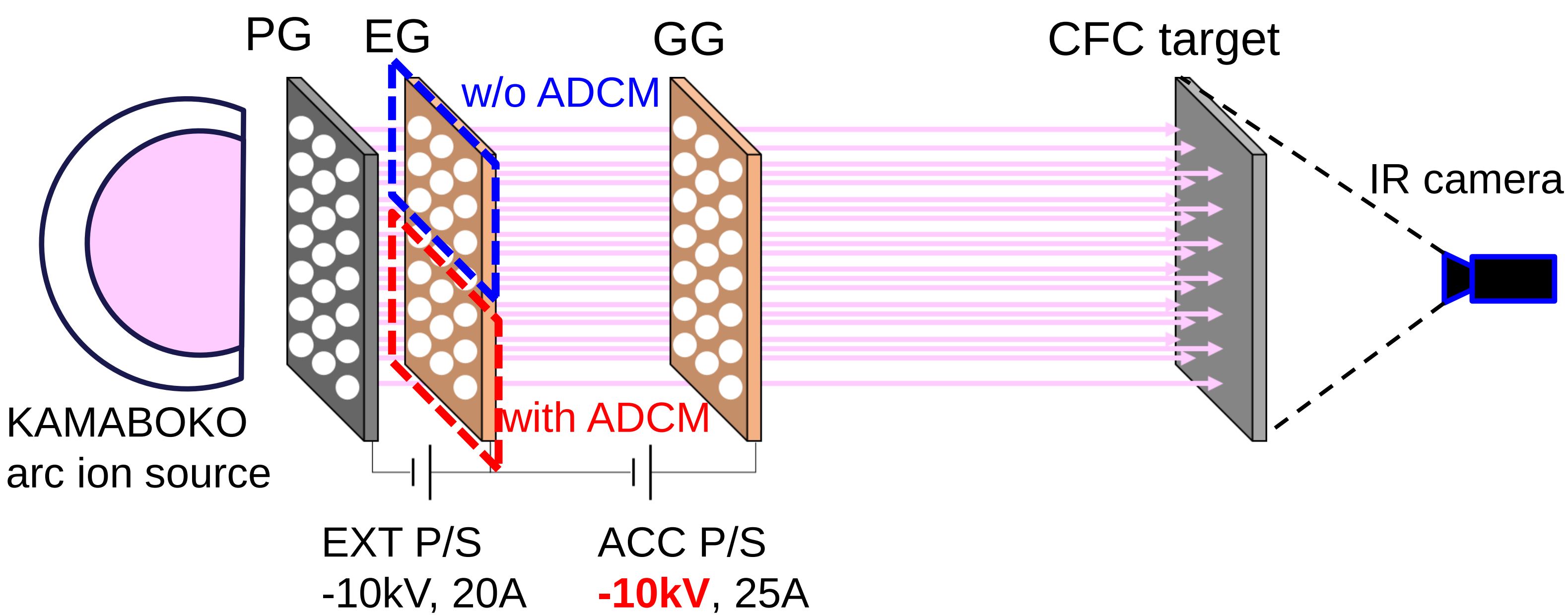
# Main results of first joint experiments

- Successful test of MITICA/HNB optics design, beamlet divergence < 10 mrad, up to 140 A/$m^2$ H- ion current
- compensation of beamlet deflection by ADCM experimentally confirmed
- discovery of a discrepancy between numerical models (OPERA) and experiments:
  - residual criss-cross deflection was underestimated
  - possible missing effects in the simulations



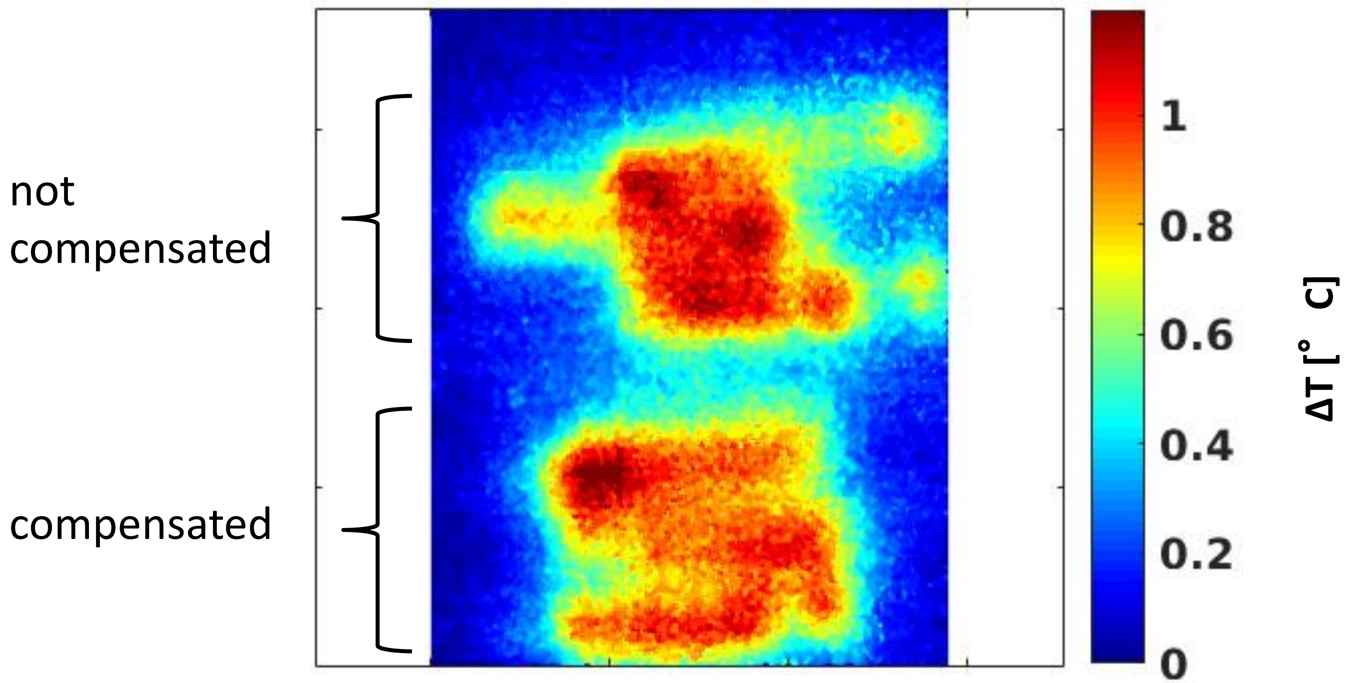
# Second joint experiments

- New combination of CESM and ADCM designed on the base of previous results (same geometry, but different remanent magnetic field)
- troubles with acceleration power supply: limitation of $V_{ACC}$ to 10 kV
- better IR camera positioning



# Main results of second joint experiments

- Complete criss-cross deflection compensation achieved
- numerical models further improved
- development of a general model correlating beamlet deflection with magnetic field and beam energy



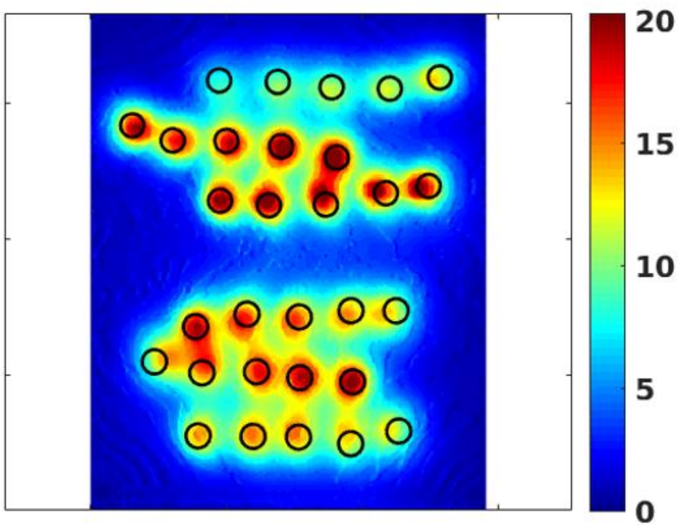
# IR image analysis

Noise reduction, then image fitting. Approximating function: sum of 30 Gaussians, one for each beamlet:

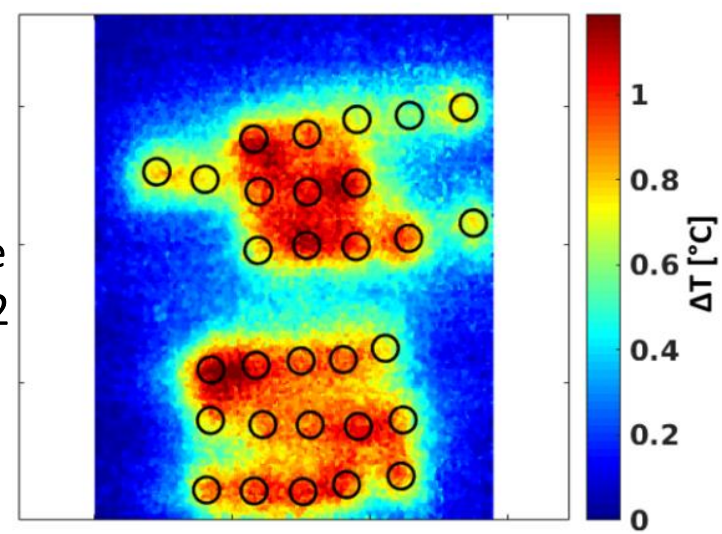
$$z(x,y)=\sum_{i=1}^{30} A_i \exp\left(-\left(\frac{x-x_i}{w_i}\right)^2-\left(\frac{y-y_i}{w_i}\right)^2\right)$$

| | |
|---|---|
| x,y | spatial coordinates |
| $x_i$, $y_i$ | coordinates of Gaussian centers (beamlet positions) |
| $w_i$ | Gaussian width (proportional to beamlet divergence) |
| $A_i$ | Gaussian amplitude (proportional to beamlet intensity) |

example from JT1




example from JT2




Criss-cross deflection at target (Δx) = average shift of consecutive rows / 2

# Typical experimental parameters

Typical parameters for first and second joint experiments (JT1 and JT2)

| Campaign | max $V_{ACC}$ [kV] | max $j_{EXT}$ [A/m$^2$] | best optics for | magnets | | not compensated deflection [mm] | compensated deflection [mm] |
|---|---|---|---|---|---|---|---|
| **JT1 (2016)** | 30 | 140 | $V_{ACC}$ = 22500 V<br>$V_{EXT}$ = 4500 V<br>ratio = 5 | part 1 | $Br_{CESM}$ = 1.1 T<br>$Br_{ADCM}$ = 0.88 T | 20 ÷ 22 | **7 ÷ 5** |
| | | | | part 2 | $Br_{CESM}$ = 1.1 T<br>$Br_{ADCM}$ = 1.1 T | | |
| **JT2 (2017)** | 10 | 20 | $V_{ACC}$ = 6000 V<br>$V_{EXT}$ = 1200 V<br>ratio = 5 | $Br_{CESM}$ = 0.77 T<br>$Br_{ADCM}$ = 1.1 T | | 18 | **-1.5** |

# Deflection vs beam energy

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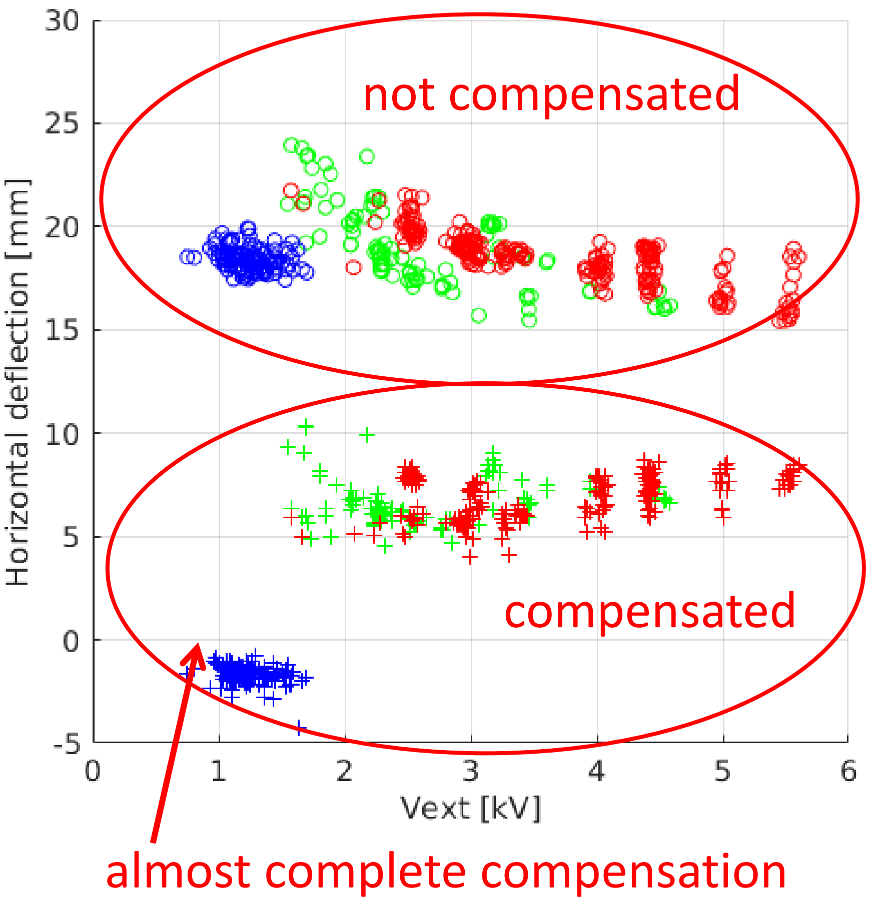
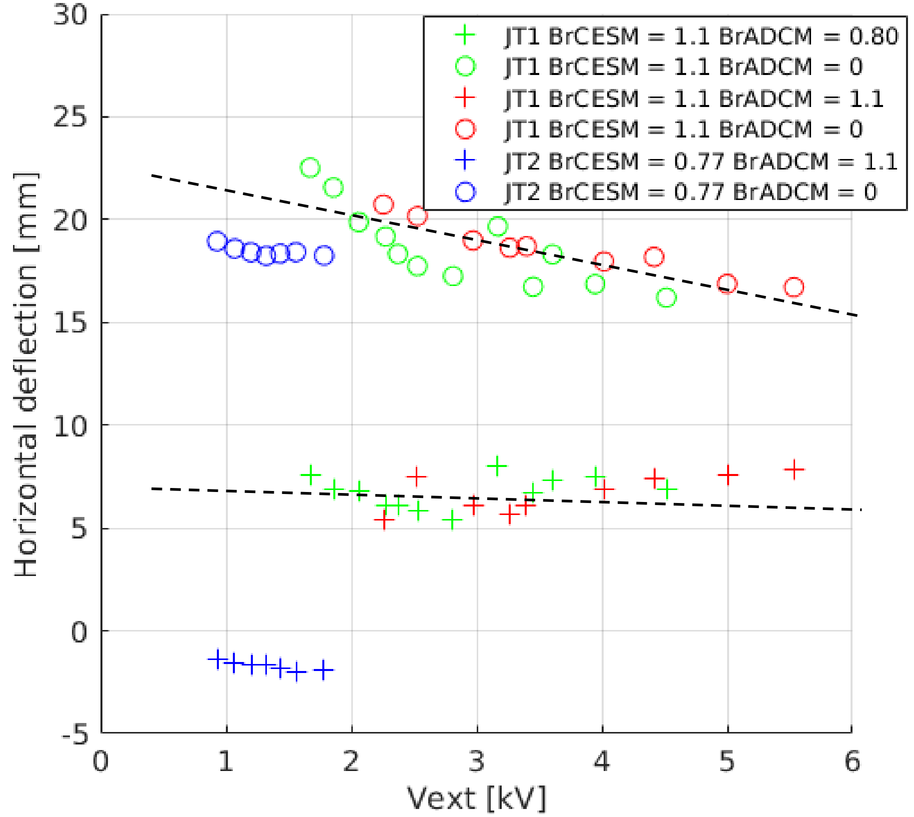
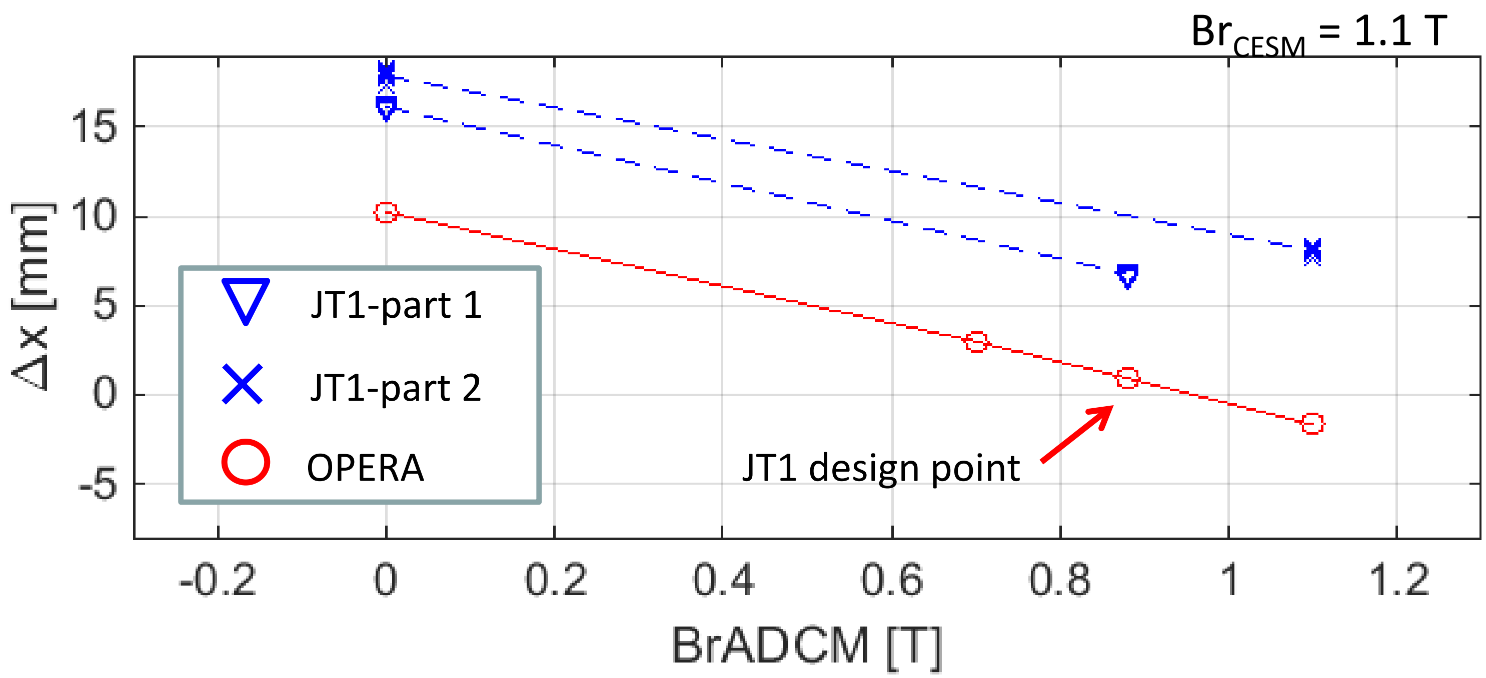
- compensated configurations less dependent on beam energy



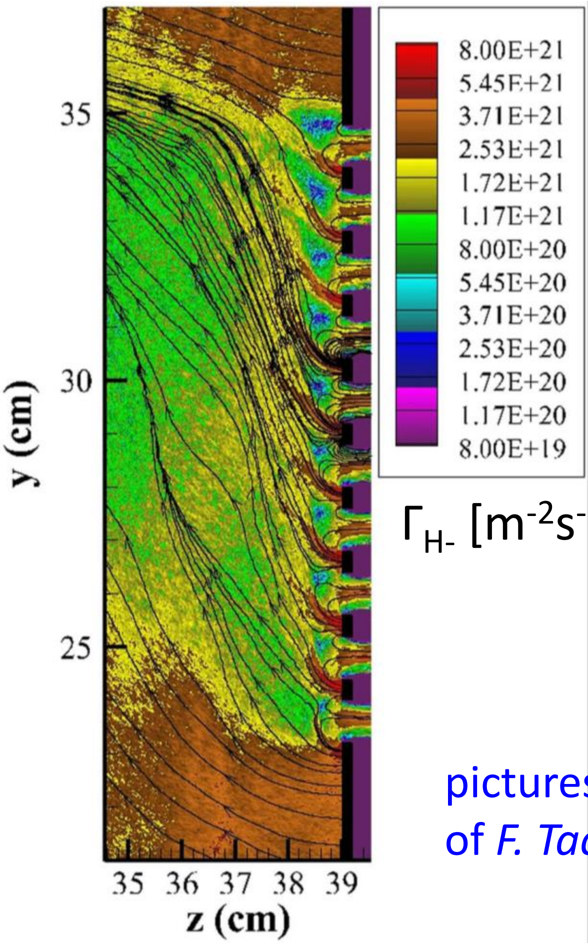
# Gap between experiments and simulations

- OPERA single beamlet model
- 5 mm shift in the result (deflection underestimated by ≈ 5 mrad)

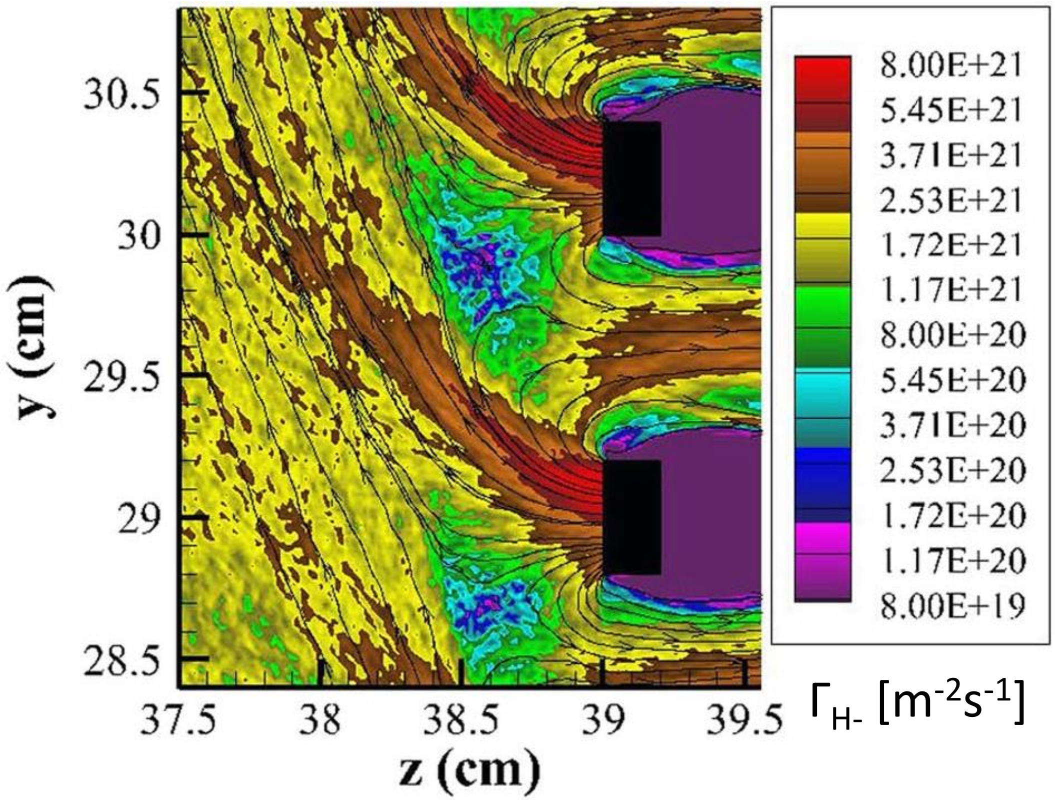


# Possible explanation

- Non-uniform current density extraction
- pointed out by *Veltri [1],* confirmed by PIC models of *Fubiani* [2] and *Taccogna* [3]
- caused by ***E*x*B*** drift inside the source




$\Gamma_{H-}$ [$m^{-2}s^{-1}$]

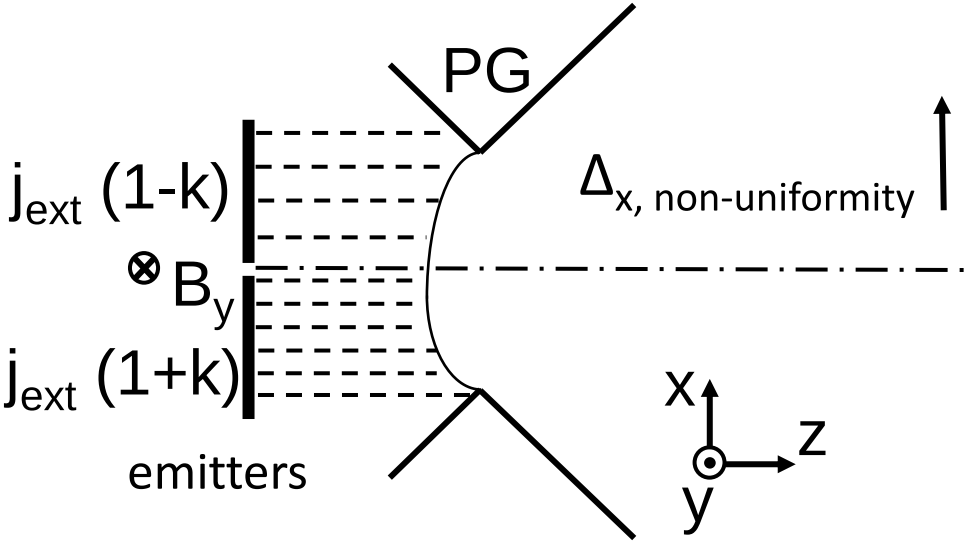


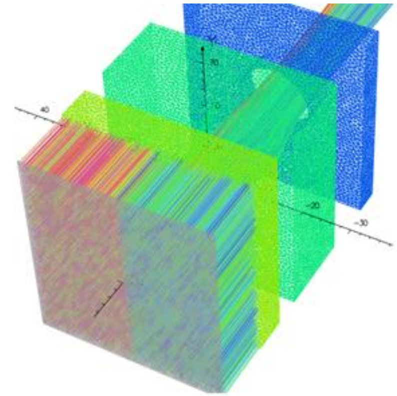

$\Gamma_{H-}$ [$m^{-2}s^{-1}$]

pictures by courtesy of *F. Taccogna* [3]


*[1] P. Veltri et al., Nucl. Fusion 57 016025 (2017)*
*[2] G. Fubiani et al, Physics of Plasmas 25, 023510 (2018)*
*[3] F. Taccogna and P. Minelli, New J. Phys. 19 015012 (2017)*

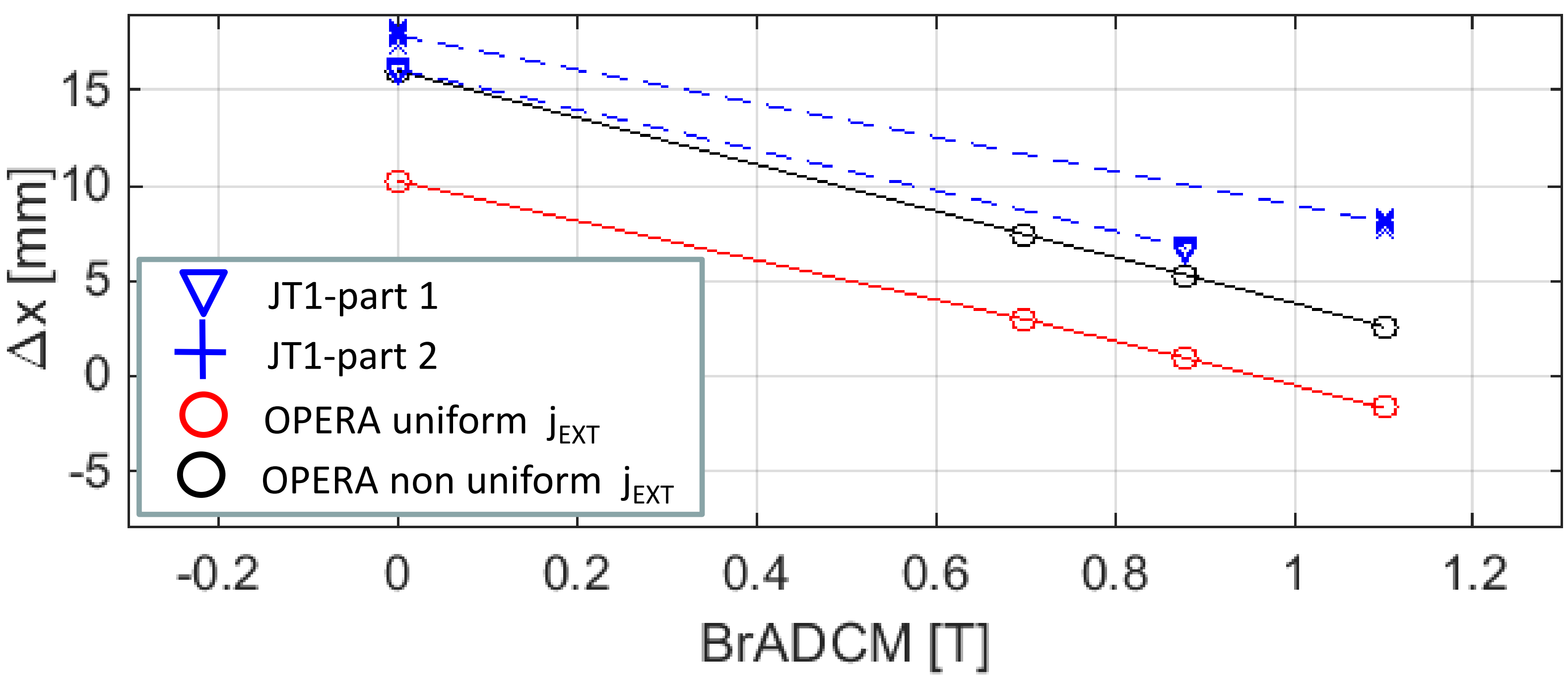
# OPERA model with non-uniform extraction



k = 17 %

$Br_{CESM}$ = 1.1 T

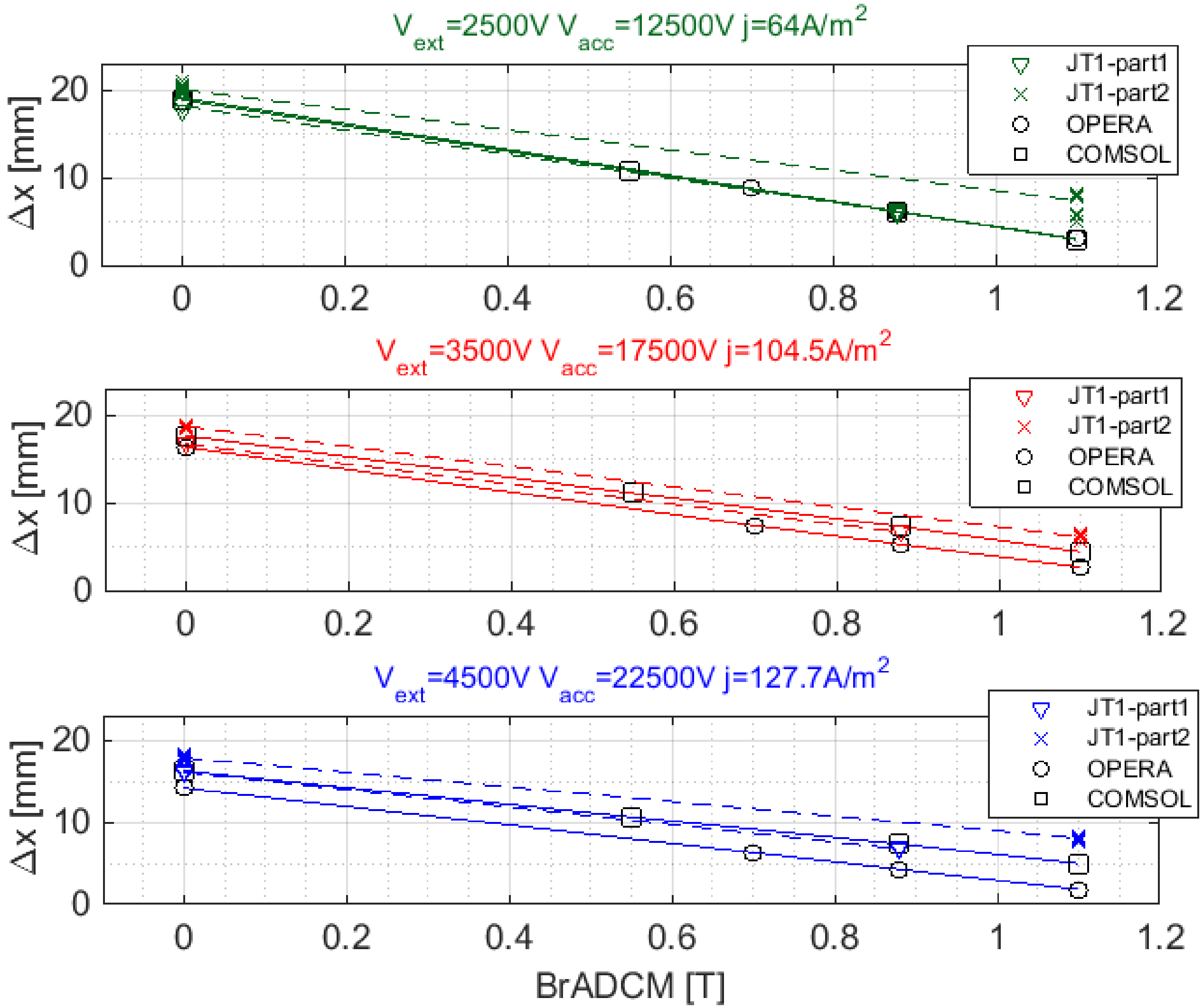


# A step further, variable non uniformity

- Non-uniformity proportional to $B_Y$ (consistent with the ***E*x*B*** assumption)
- COMSOL simulation added
- better agreement

$j_{EXT, RIGHT} = (1 + p*B_Y)$
$j_{EXT, LEFT} = (1 - p*B_Y)$

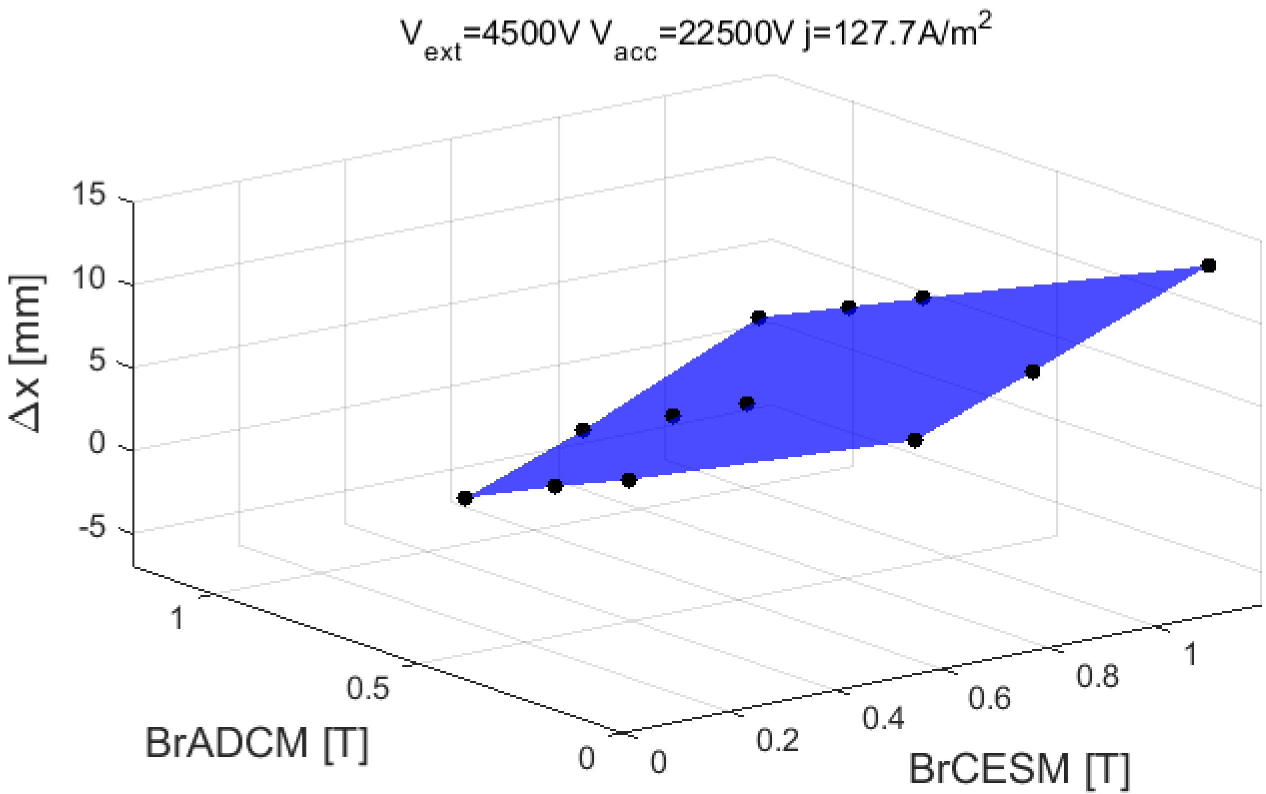
$Br_{CESM} = 1.1$ T
p = 0.5 % / mT



# Extensive OPERA simulations (I)

- Purpose: exploring the operative space
- extraction non uniformity included
- first set of simulations: constant V
- the effect of magnet strenght on the deflection is perfectly linear

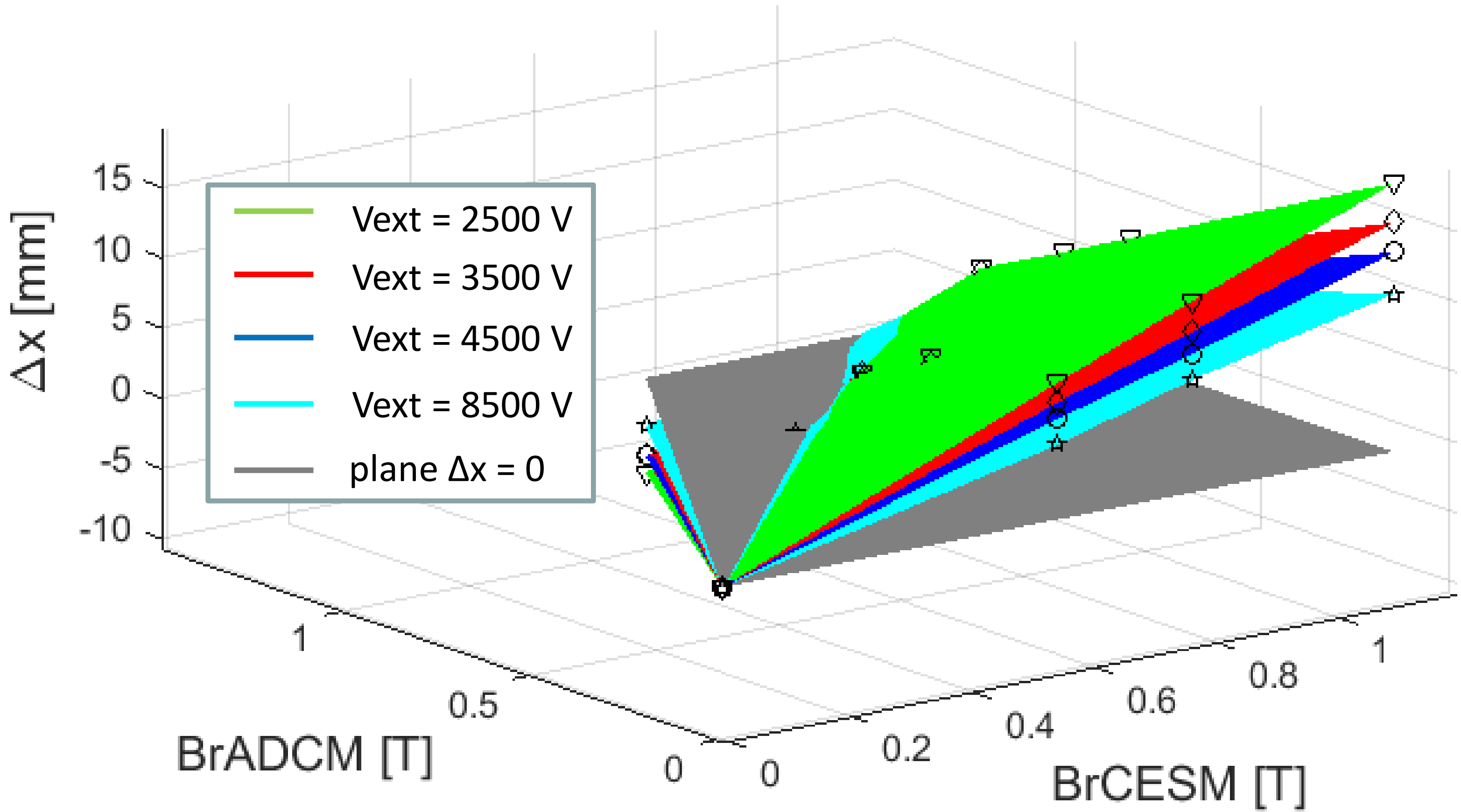
$$\Delta x = f(B_{r,ADCM}, B_{r,CESM}, V)$$



# Extensive OPERA simulations (II)

- Simulations with different Br and V
- general model derived:

$$\Delta x = \frac{a * B_{r,CESM} + b * B_{r,ADCM}}{\sqrt{V_{ext}}}$$



# Conclusions

- Three successful years of QST – Consorzio RFX collaboration
- Magnetic technique for criss-cross compensation validated
- Complete compensation of beamlet deflection achieved
- Clearer picture of negative ion extraction process
- Improvement of numerical design tools
- Large experimental database collected

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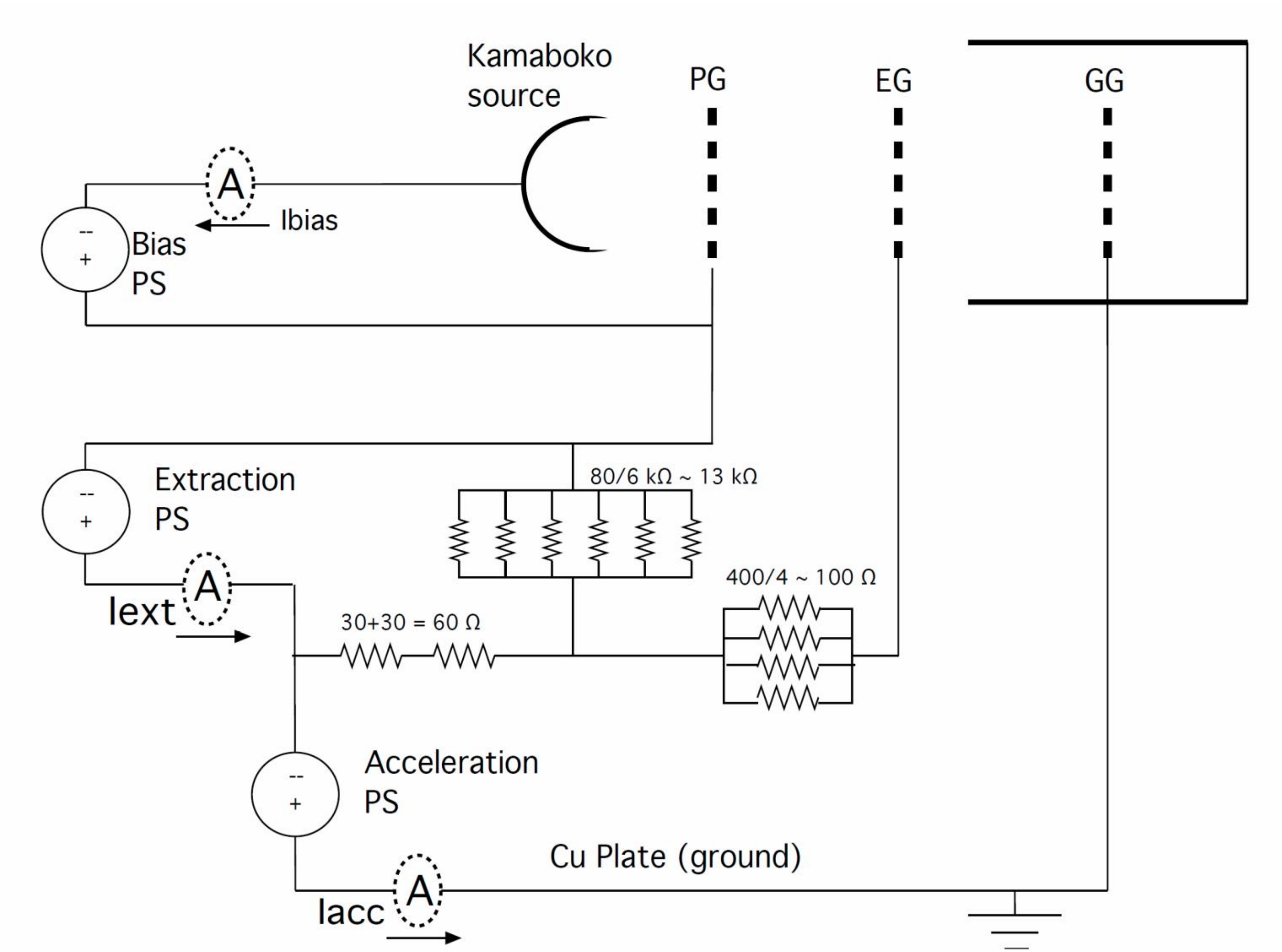
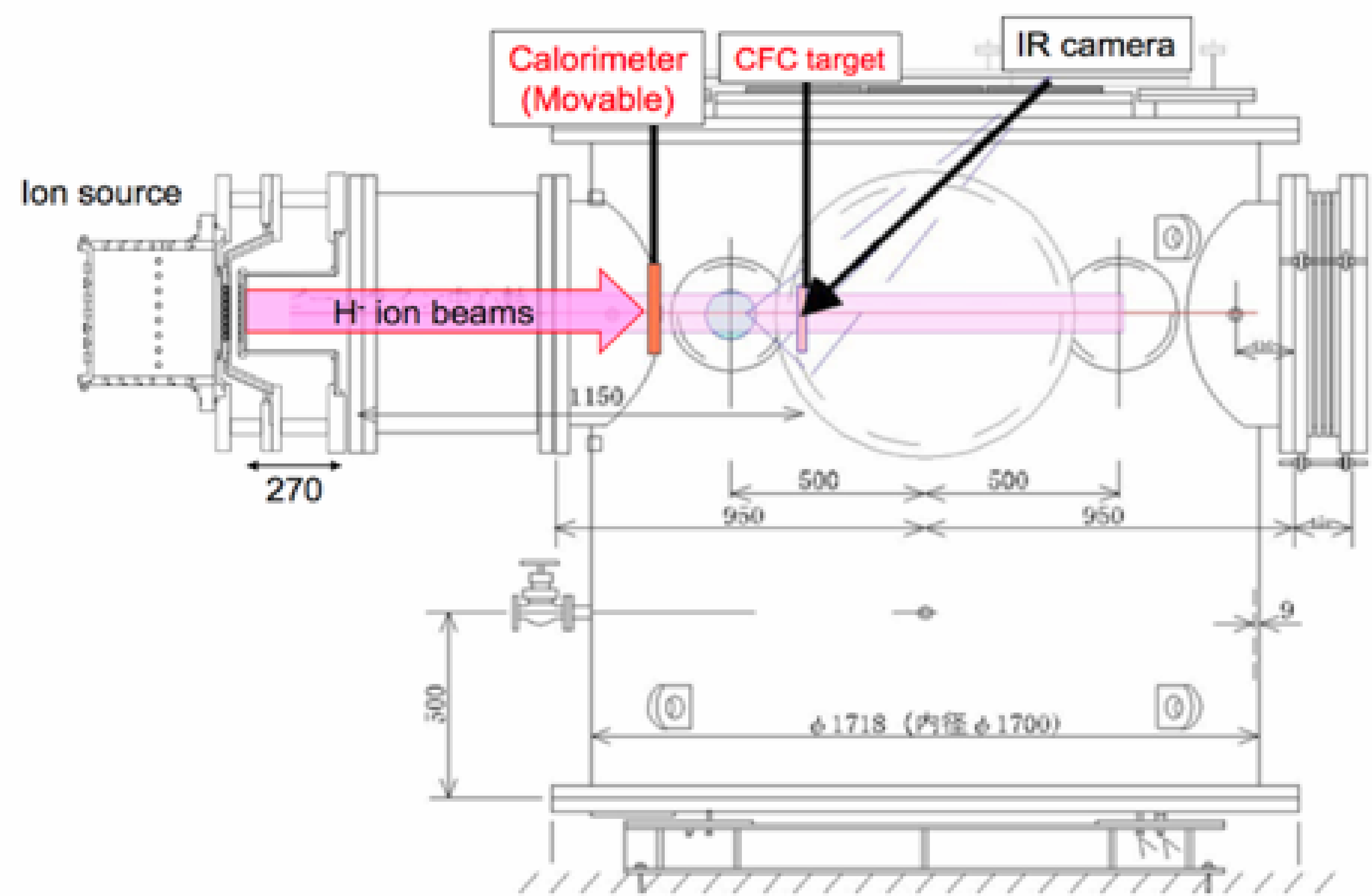
- Beneficial effects on the design of MITICA and future NBIs
- Hopefully, time will be saved on ITER NBI development schedule

# Spare slides

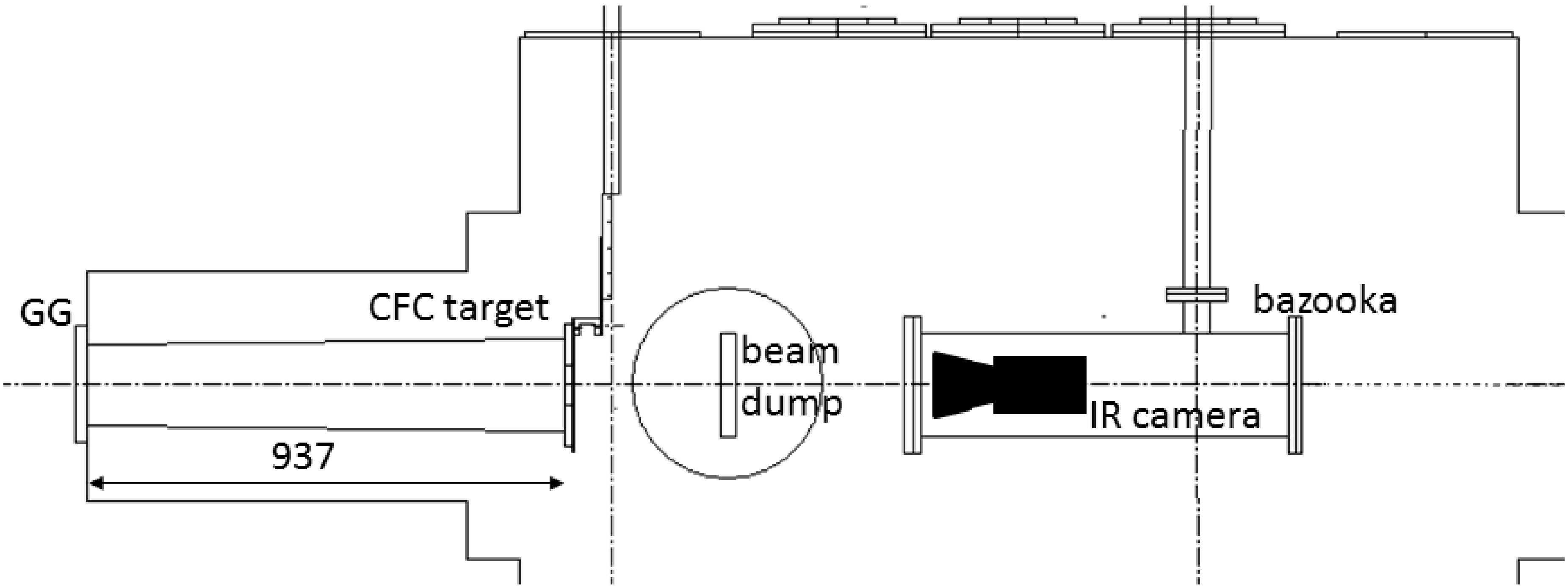
# NITS electrical scheme



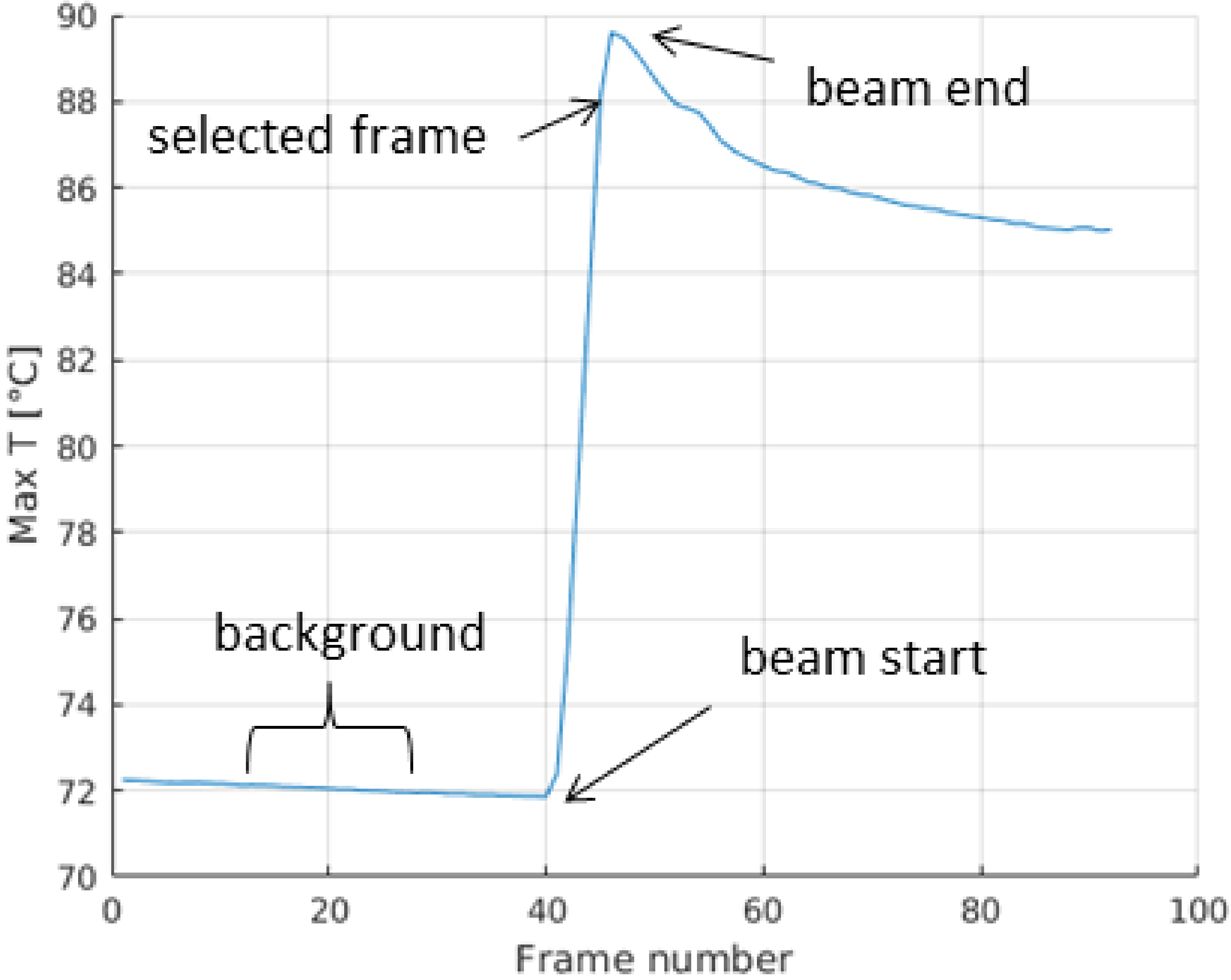
# NITS during JT1



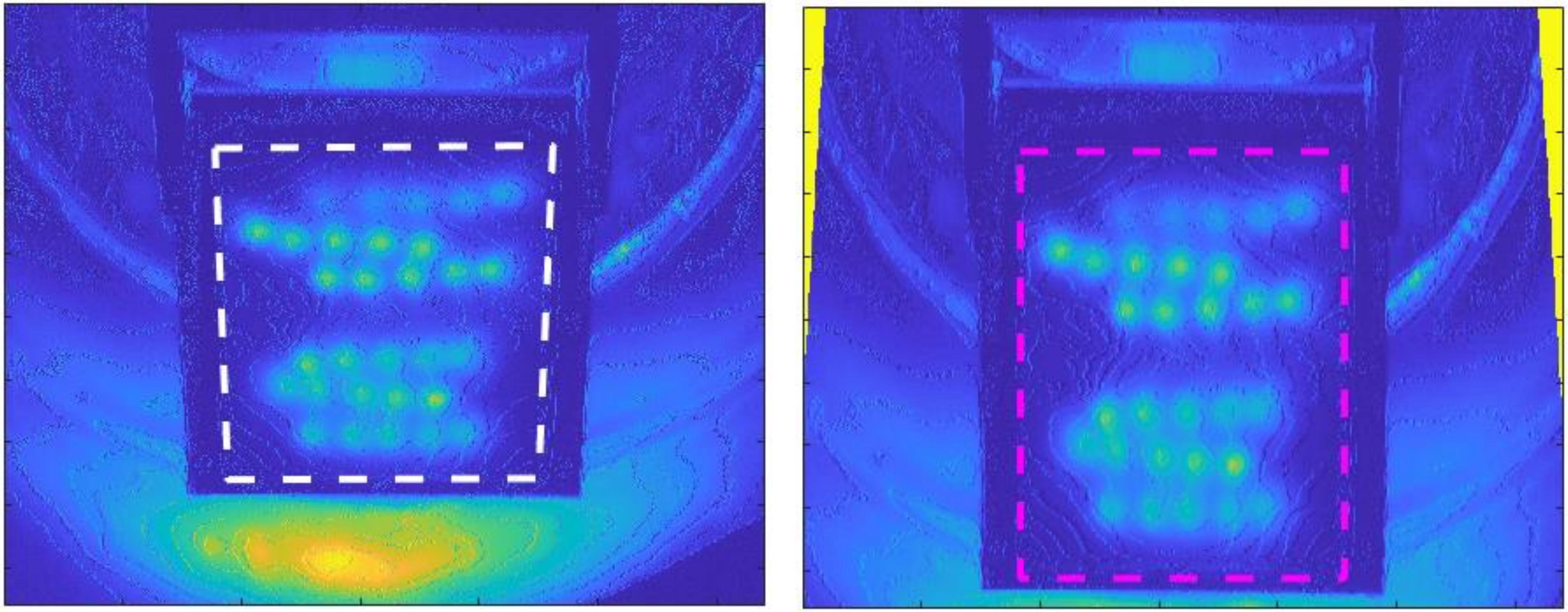
# NITS during JT2



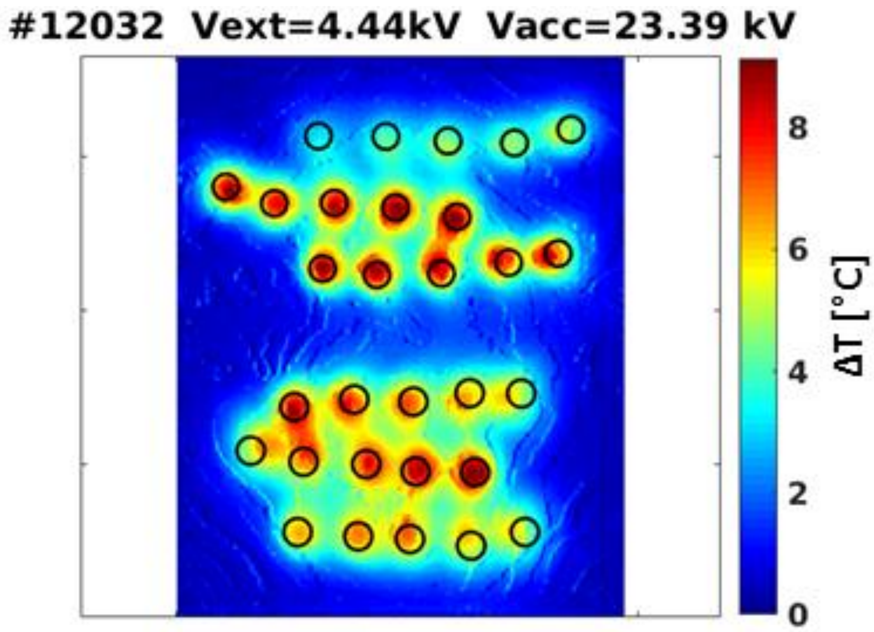
# Frame selection

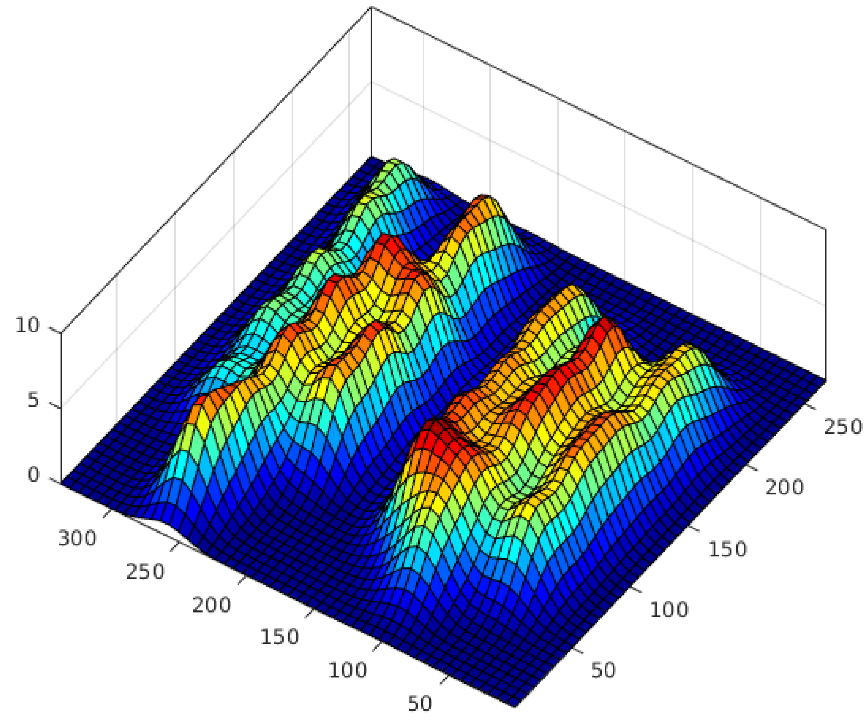


# Homography and cropping

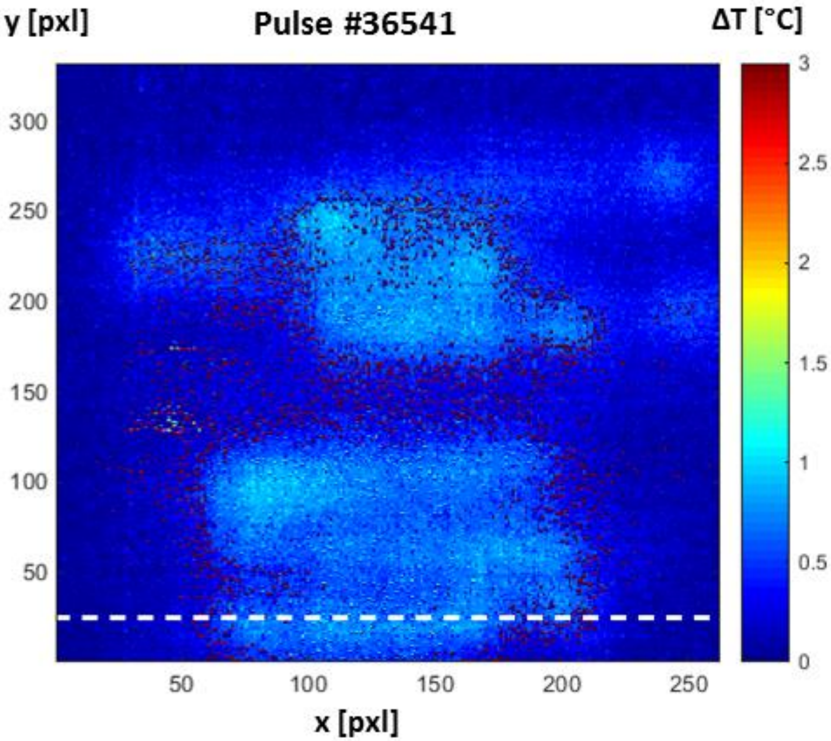


# Fitting and reconstruction

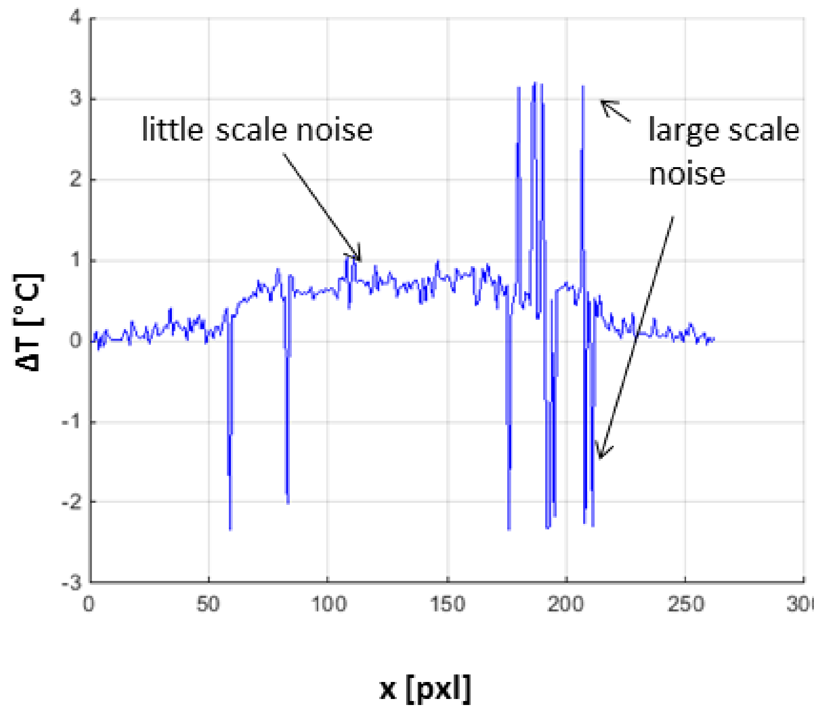


# Image noise

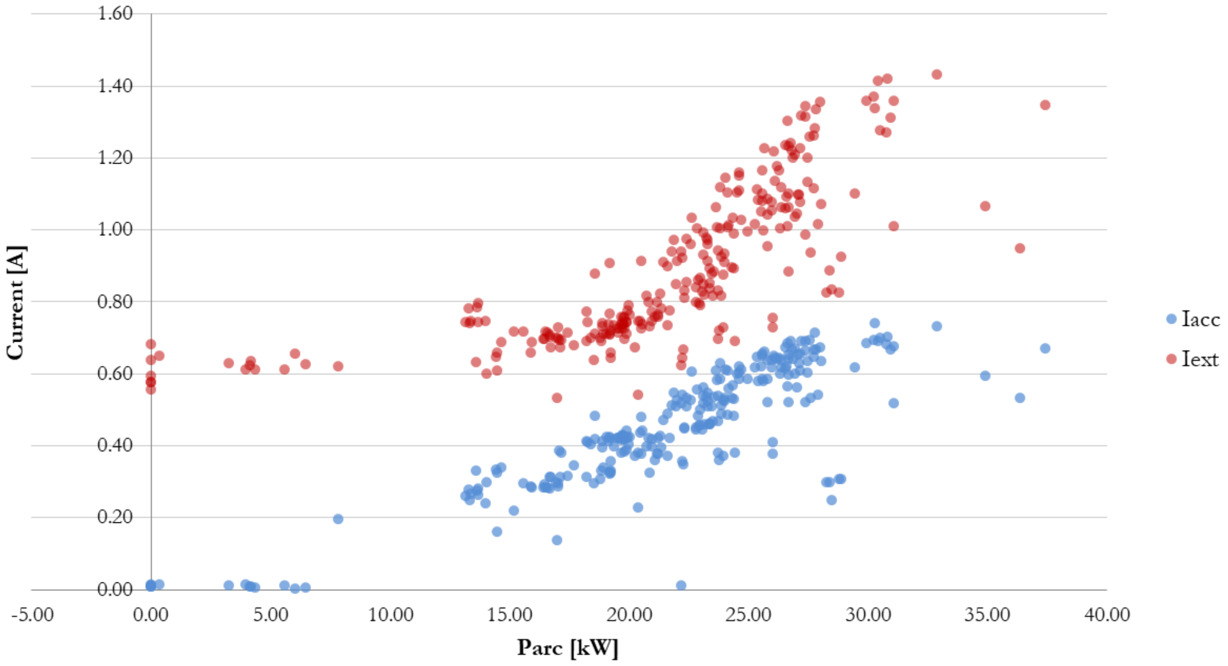


y [pxl]
Pulse #36541
ΔT [°C]
300
250
200
150
100
50
50
100
150
200
250
x [pxl]
3
2.5
2
1.5
1
0.5
0

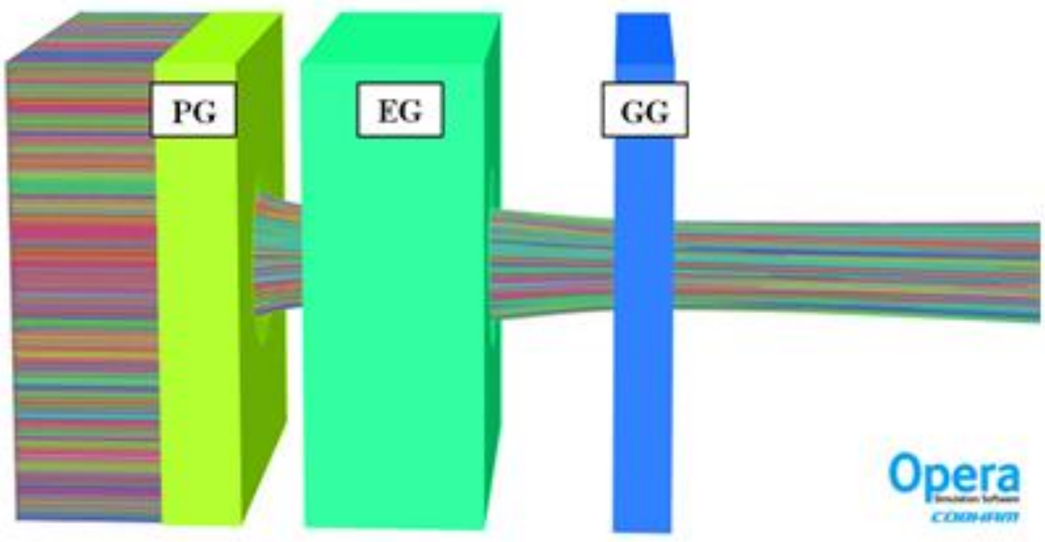
little scale noise
large scale noise
ΔT [°C]
x [pxl]
4
3
2
1
0
-1
-2
-3
0
50
100
150
200
250
300

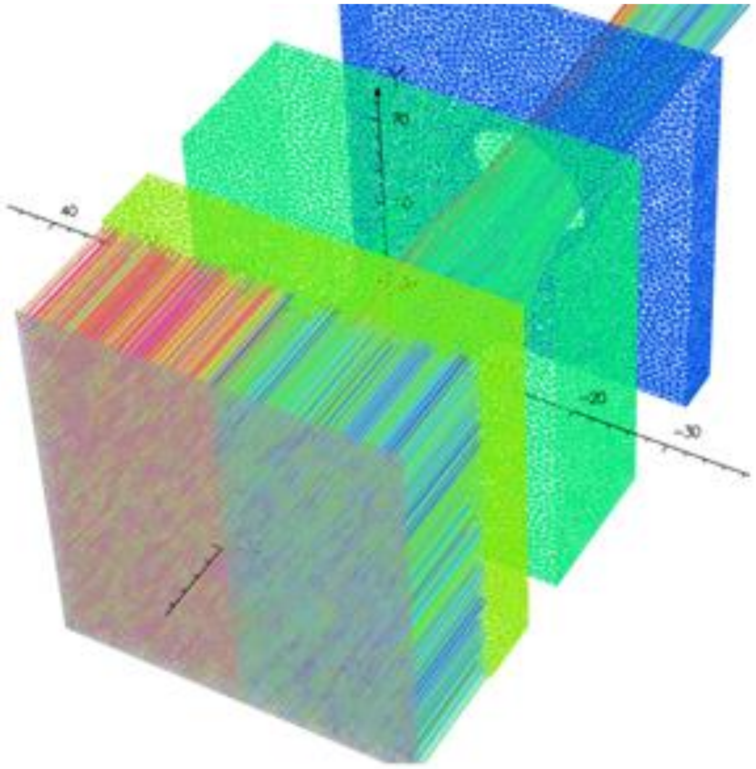
# Iext vs Parc



1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Current [A]
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Parc [kW]
Iacc
Iext

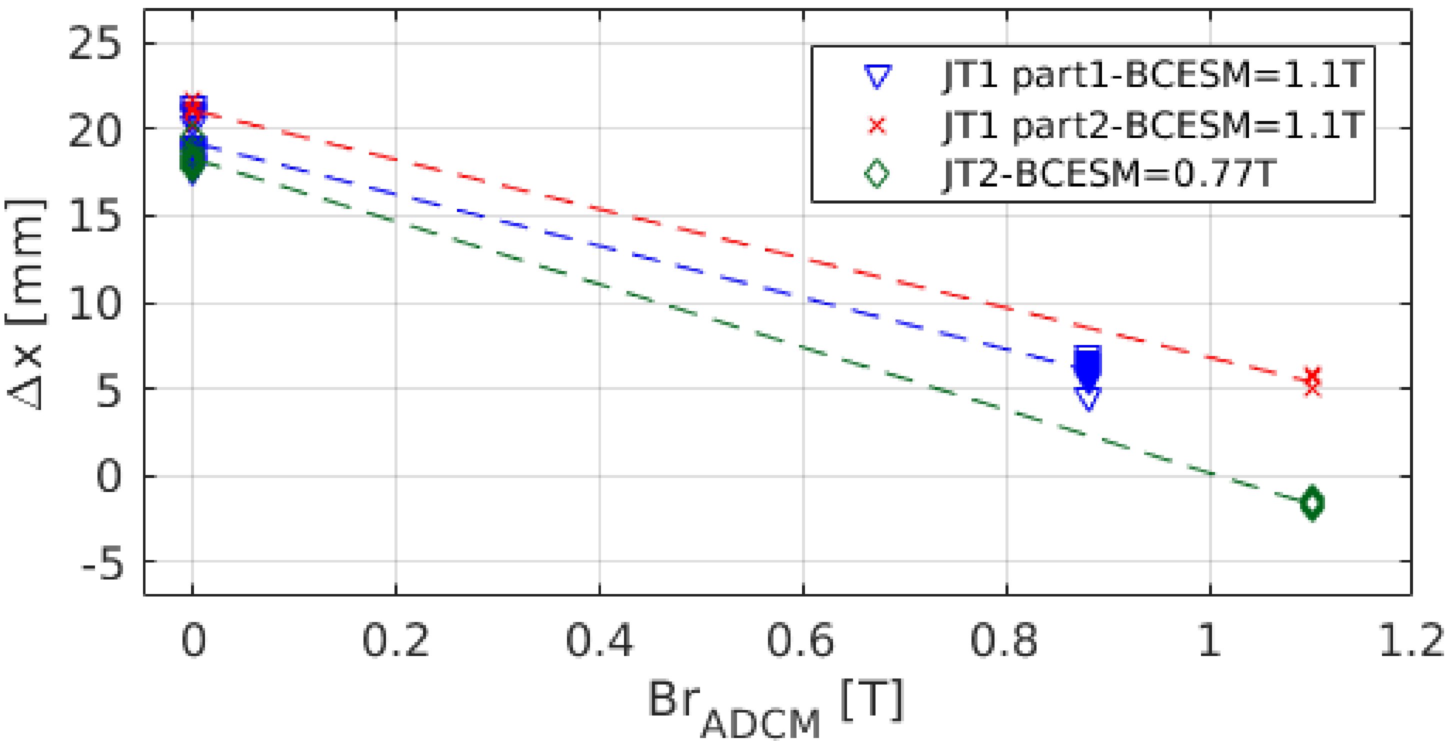
# OPERA non-uniform extraction



# Deflection vs magnet strength

- Shift between JT1 part 1 and 2 not yet understood
- linearity (not considering the shift) between deflection and magnet strength



# General model (scheme)