Numerical investigation of the early operational phase of the negative ion test facility SPIDER: beam features

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Abstract

The ITER tokamak requires two injectors of neutral beams resulting from the neutralisation of accelerated negative hydrogen/deuterium ions. To optimise the source operation, a specific test facility ("PRIMA") was established in Padova, comprising the experiment SPIDER (full-size negative ion source with 40A beam, 100keV particle energy). The design of SPIDER accelerator was based on the most advanced numerical codes available for the investigation of the expected beam properties. Several diagnostic systems will characterise source and beam during the experiments. In view of the operation, this paper describes the preparation of the experiments by means of numerical simulations of the accelerator. The simulations provide also estimates of the current and power deposited onto the accelerator grids and will be the basis for further work aimed at computing the expected measurements by the various beam diagnostics.

SPIDER:
Ion source and extractor prototype for ITER HNB

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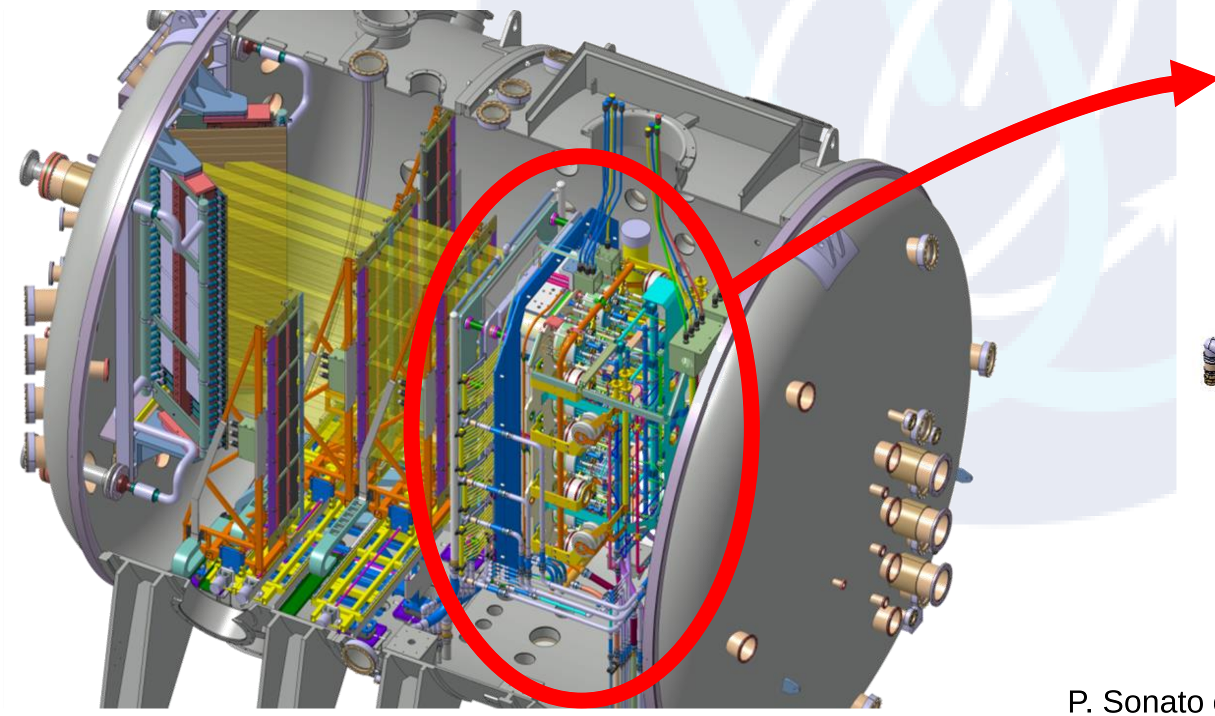
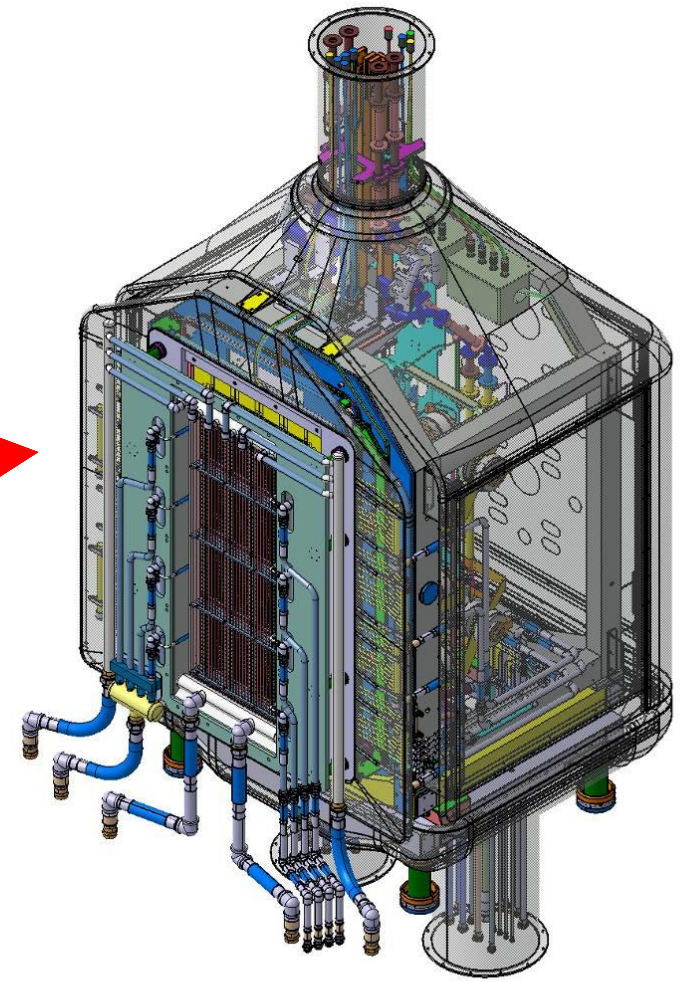
Parameter	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density (1.52x0.56 m^2)	A/m^2	>350	>290
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^- or e^-/D^-)		<0.5	<1



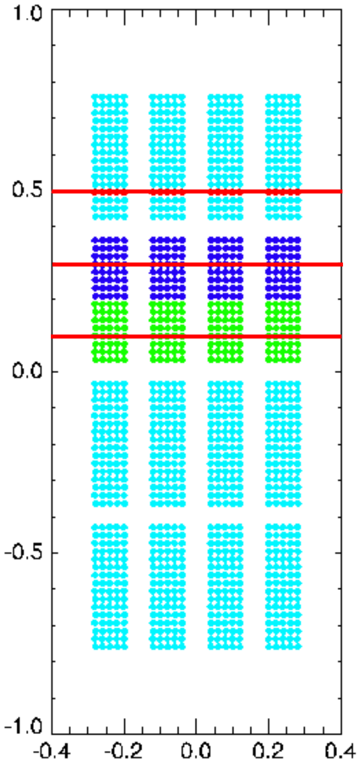


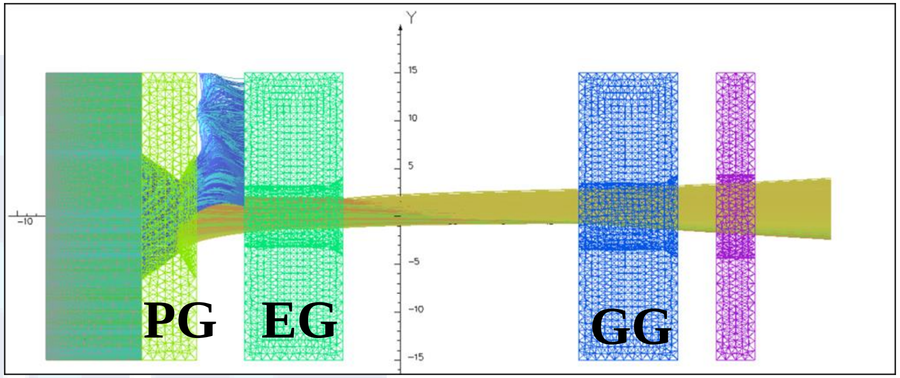
P. Sonato et al., Fusion Eng. Des. **84**, 269 (2009)

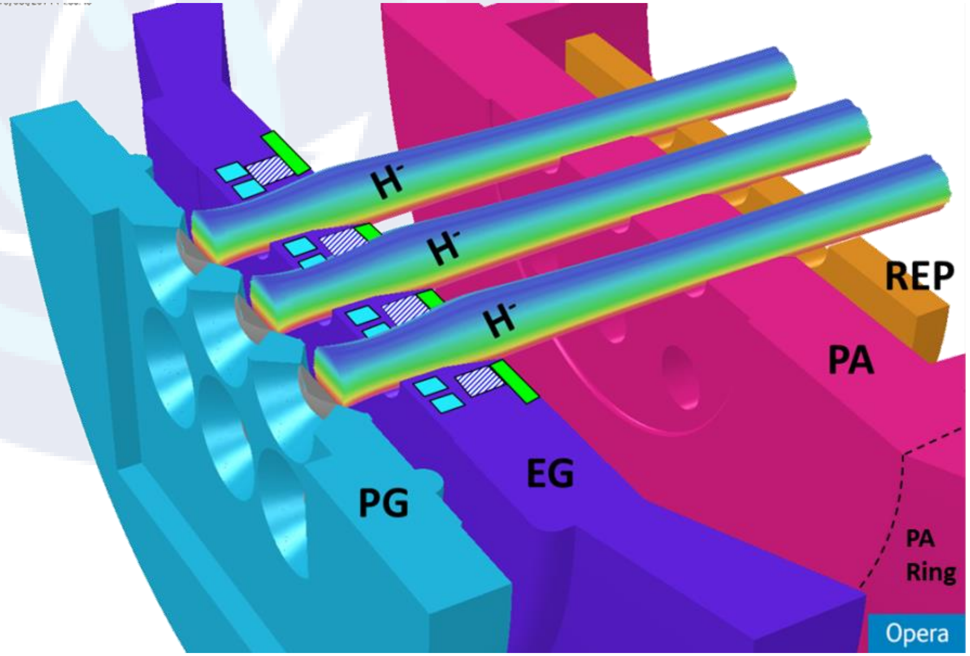
Compensation of magnetic deflection in SPIDER

- S4 = CESM field only (no compensations)
- S5 = Magnetic Compensation
- S6 = Electrostatic Compensation

Lines-of-sight







Case 1: div 4.5 mrad (best optics)

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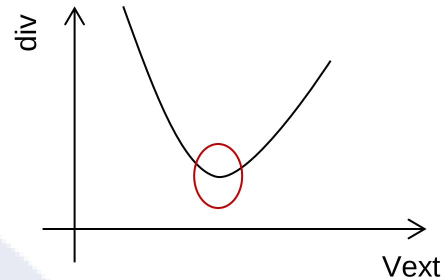
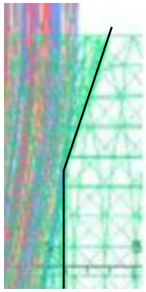
Vext = 1.2 kV
Vacc = 12.2 kV

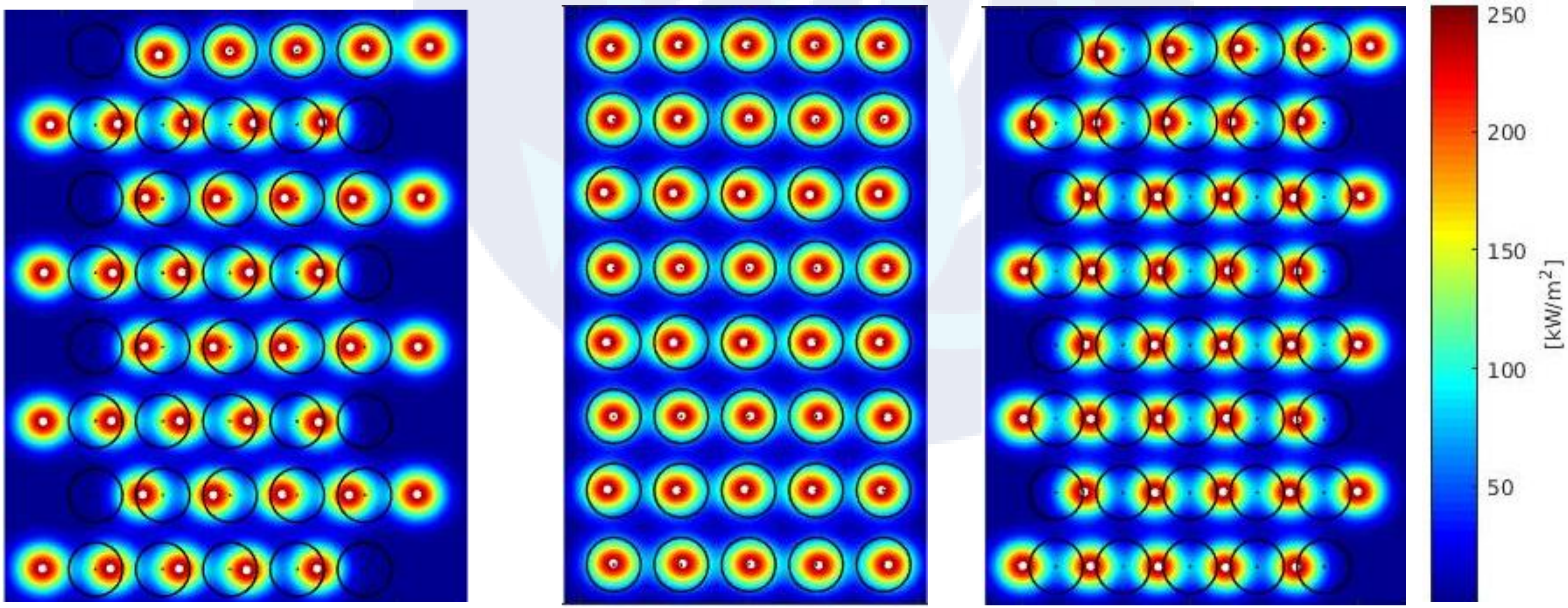




Small over compensation
due to very low j

B_{eamlet} power = 37 W

X-def = → 19.3 S4 → 20 (8) S5 → 13.8 S6 → 14.4 (4)



Case 2: div 8.5 mrad

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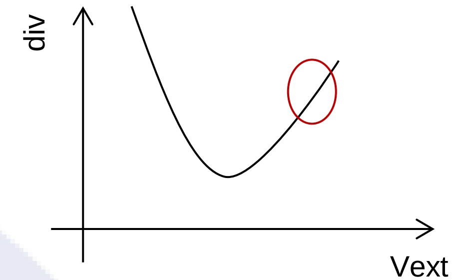
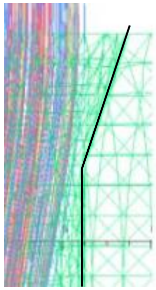
Vext = 1.4 kV
Vacc = 12.2 kV

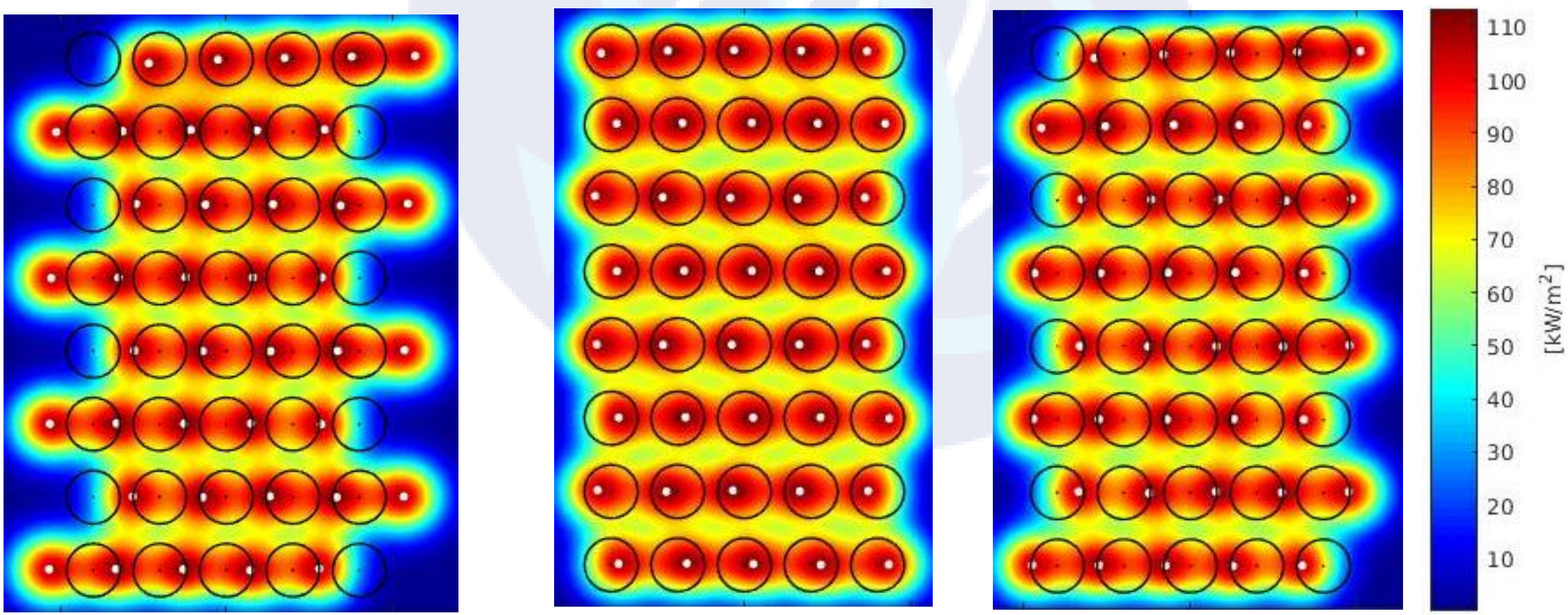




Small over compensation
(more visible due to higher div)

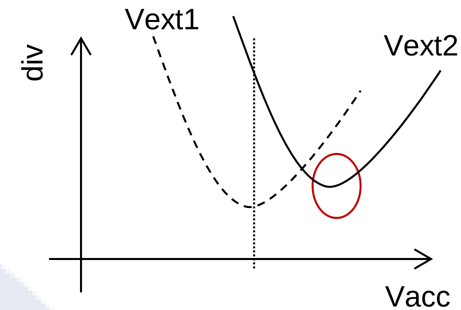
B_{eamlet} power = 38 W

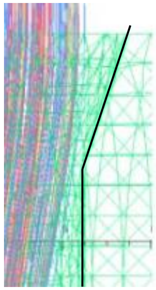
X-def = → 17.2 S4 → 17.3 S5 → 11.7 S6 → 11.8



Case 3: div 6 mrad (best optics)

Vext = 1.35 kV
Vacc = 15.9 kV

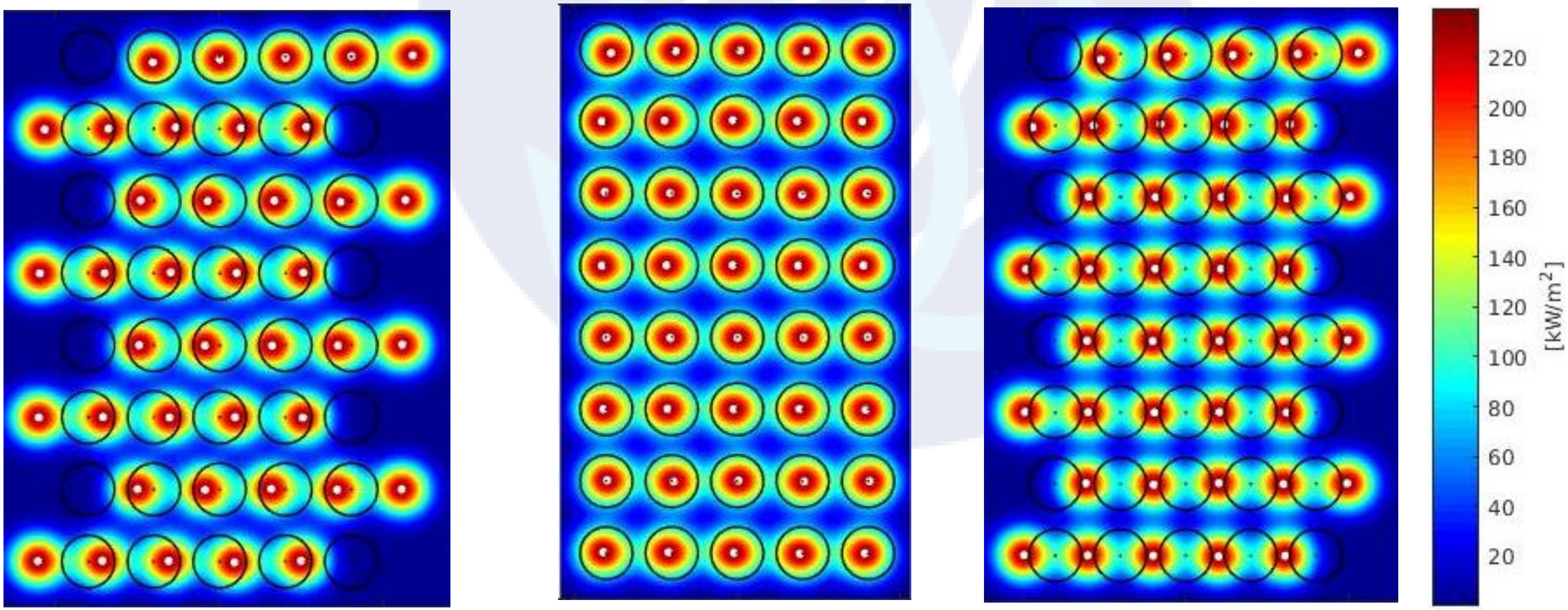




Over compensation disappears due to different optics (V_{acc})

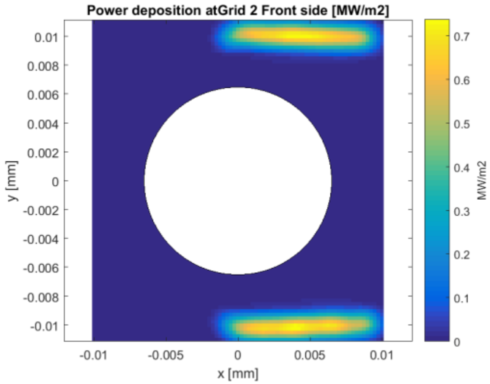
B_{eamlet} power = 44 W

X-def = → 20 S4 → 19.1 S5 → 14.4 S6 → 13.6



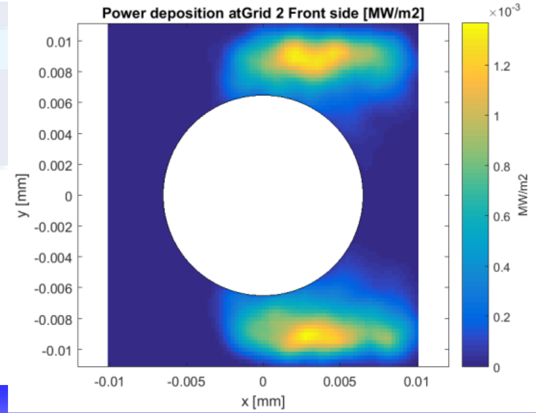
Power and current over accelerator grids

			Power [W]				Current [A]			
Vext [kV]	compens.	particle	PG	EG	GG	transm.	PG	EG	GG	transm.
1.2	none	total	1.32	25996.8	302.1	39552	-1.50	-20.31	-0.03	-2.96
	electrost.	total	5.75	26004.5	290.6	39552	-1.50	-20.31	-0.04	-2.94
	magnetic	total	1.04	25935.4	558.1	39936	-1.50	-20.31	-0.17	-2.84
1.4	none	total	1.78	25929	281.6	40704	-1.50	-20.31	-0.03	-3.00
	electrost.	total	5.16	25936.6	277.8	40576	-1.50	-20.31	-0.04	-2.98
	magnetic	total	0.37	25932.8	537.6	40704	-1.50	-20.31	-0.17	-2.85
1.35	none	total	0.74	25908.5	316.2	47360	-1.50	-20.31	-0.02	-3.02
	electrost.	total	5.06	25912.3	326.4	47232	-1.50	-20.31	-0.03	-3.00
	magnetic	total	1.82	25907.2	586.2	47488	-1.50	-20.31	-0.15	-2.89



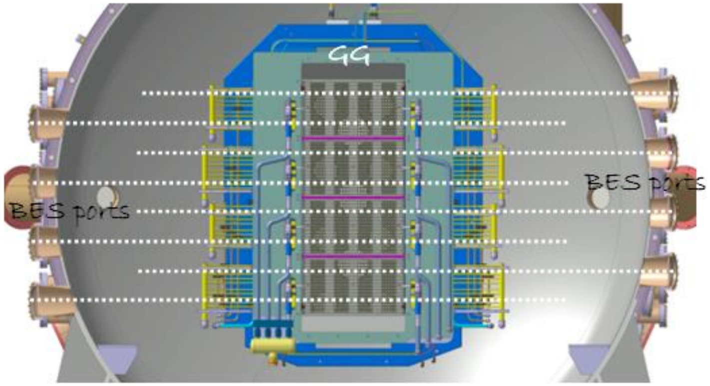
electrons

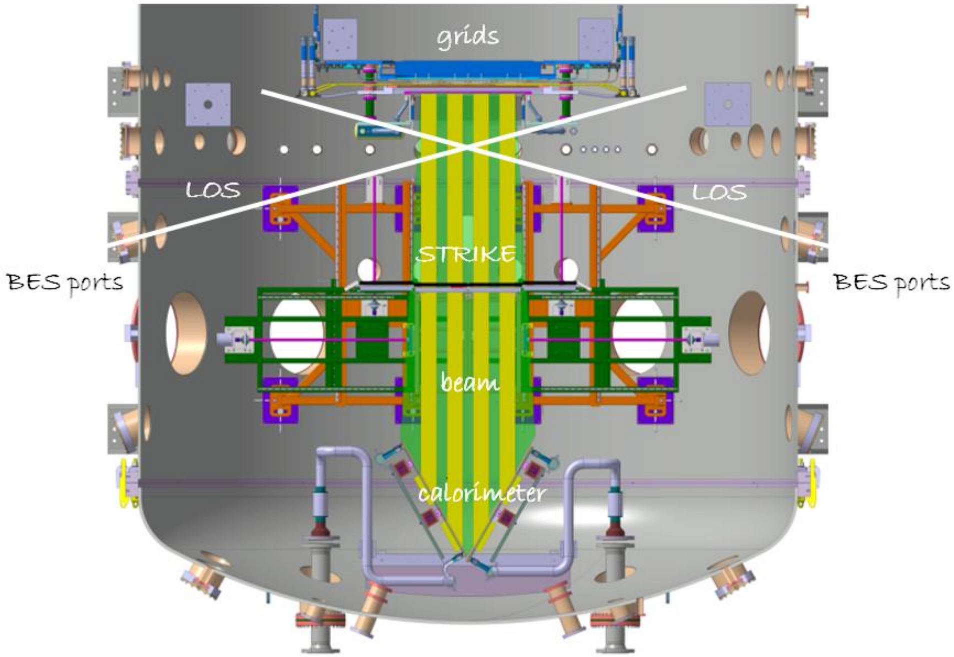
ions



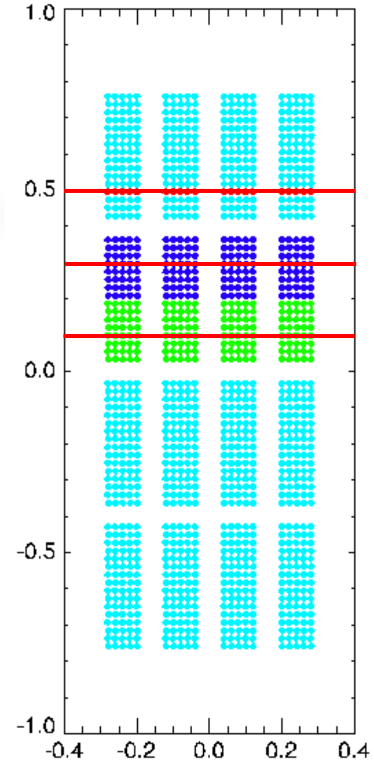
Beam Emission Spectroscopy

- S4 = CESM field only (no compensations)
- S5 = Magnetic Compensation
- S6 = Electrostatic Compensation



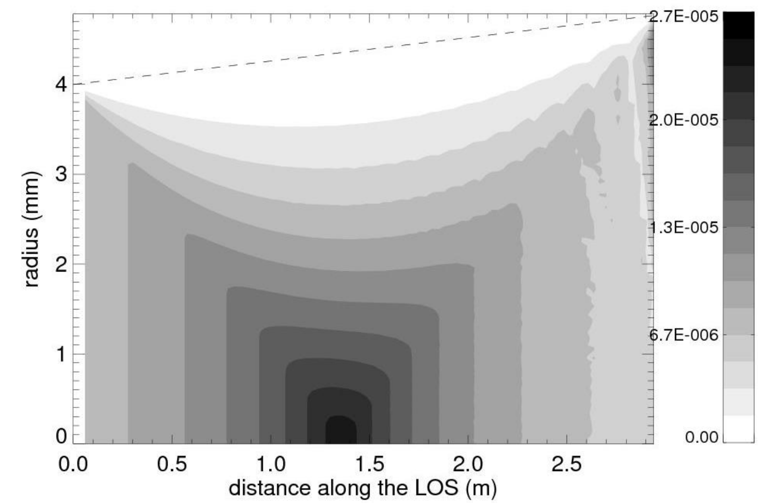


Simulated Lines-of-sight



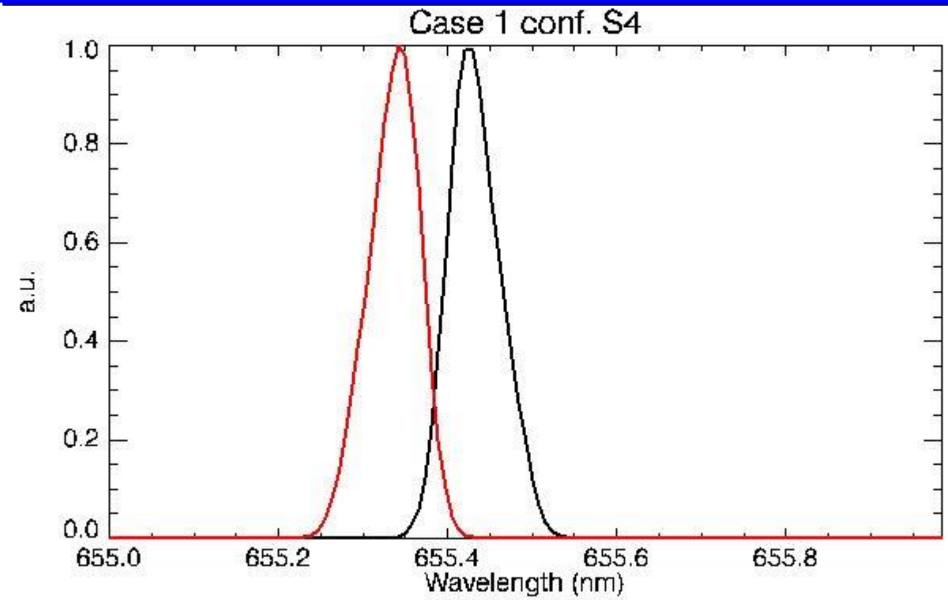
Beam Emission Spectroscopy: basic operation

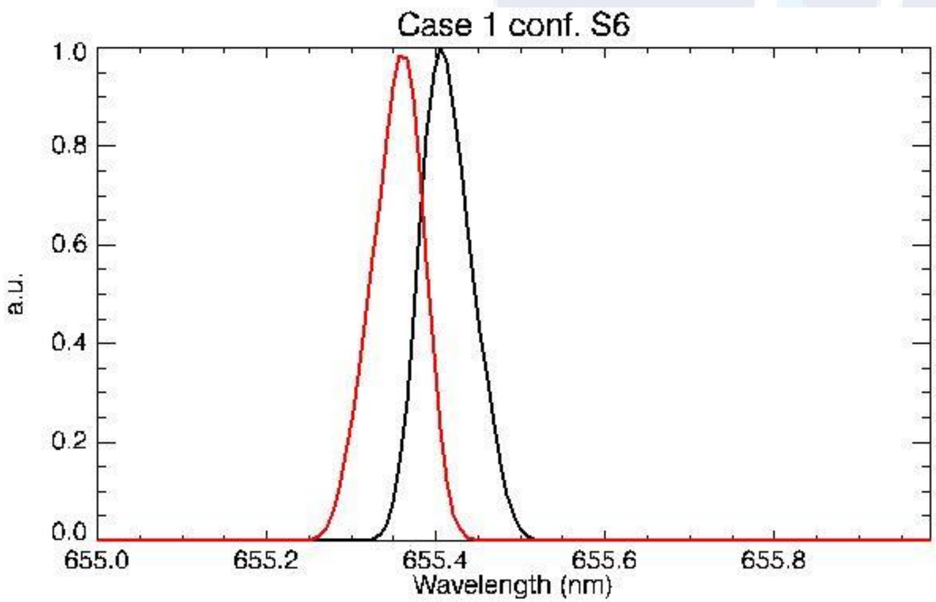
- Simulated spectra analysed to retrieve beam-LOS direction and beam divergence
- Input data covering half beamlet group per deflection compensation type. Data replicated to cover full SPIDER grid
- If any, segment of each particle trajectory inside LOS volume calculated
- For each segment, 10 equidistant points calculated. For each point Gaussian curve added to final spectrum
- Gaussian centre depending on angle between particle trajectory and LOS axis, and on particle energy (ripple ~0,1%)
- Integral of Gaussian curve proportional to solid angle of observation of optic head lens from selected point, to current of specific particle and to length of observed segment of particle trajectory
- Gaussian width depending on: spectrometer instrumental width, H_α intrinsic width, energy ripple, observation angle of optic head lens from emission point
- At low divergence (like considered cases) each LOS intercepting just 1 beamlet row

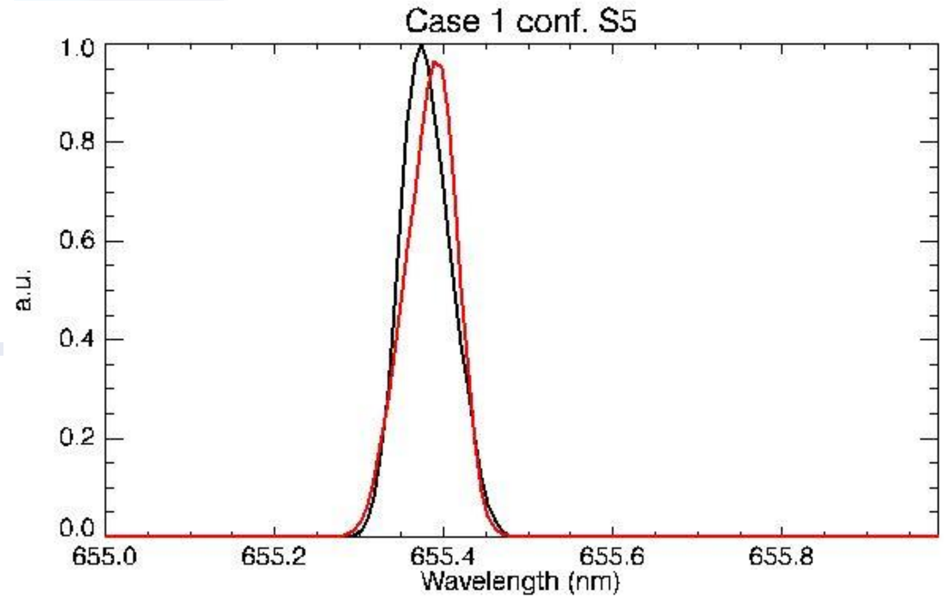


M. Barbisan, Rev. Sci. Instrum. 85 (2014) 11E430

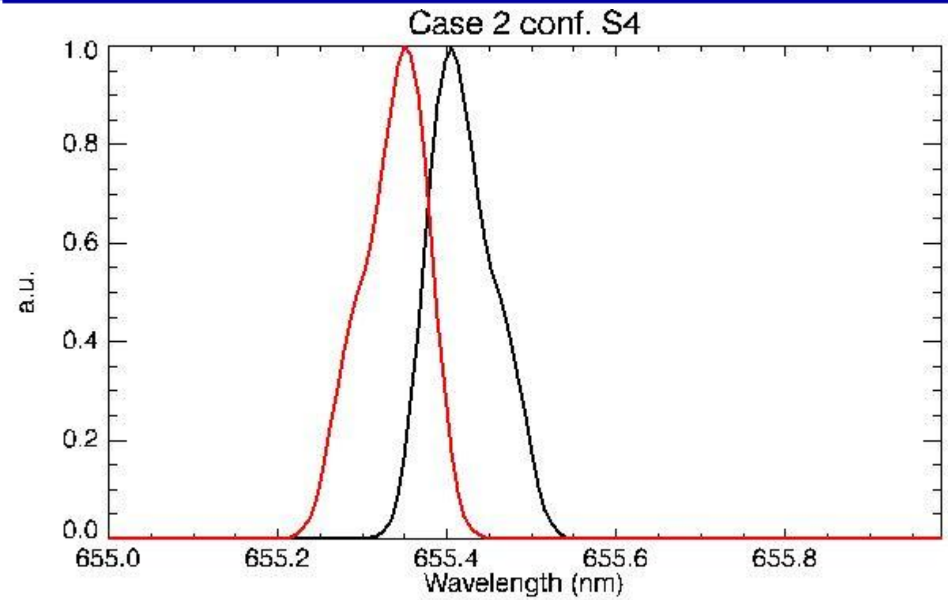
Case 1 (V_{ext}=1.2kV): alternate BES LoSs

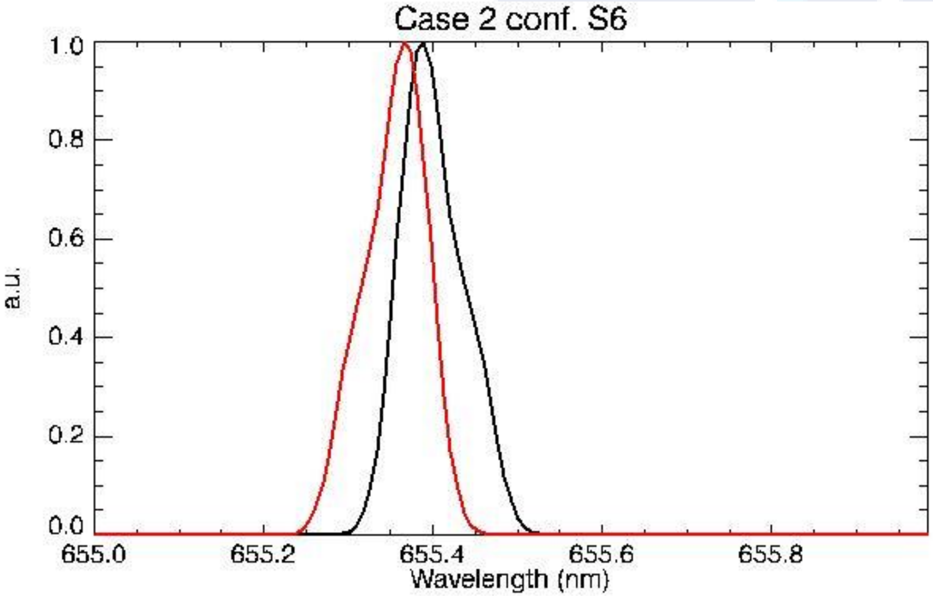


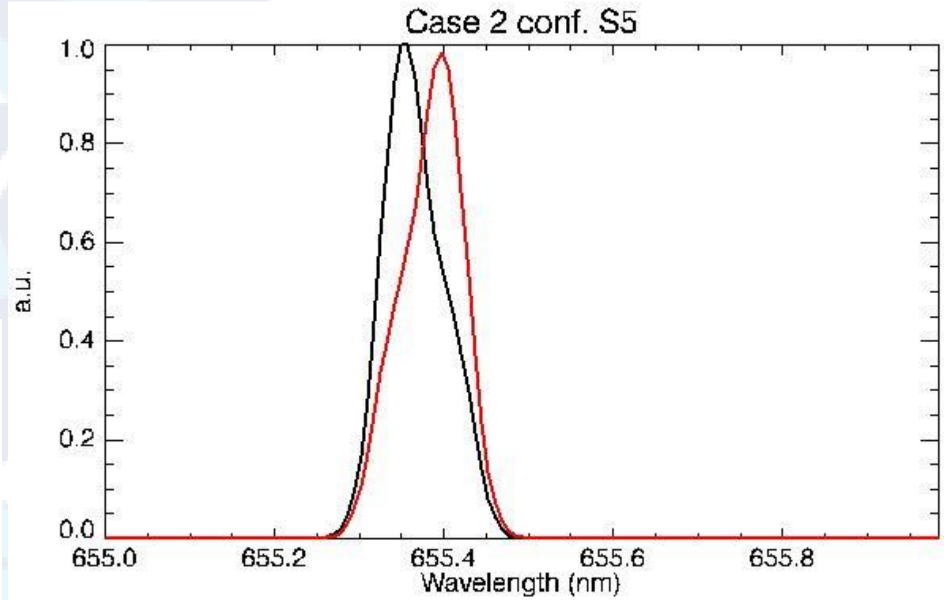




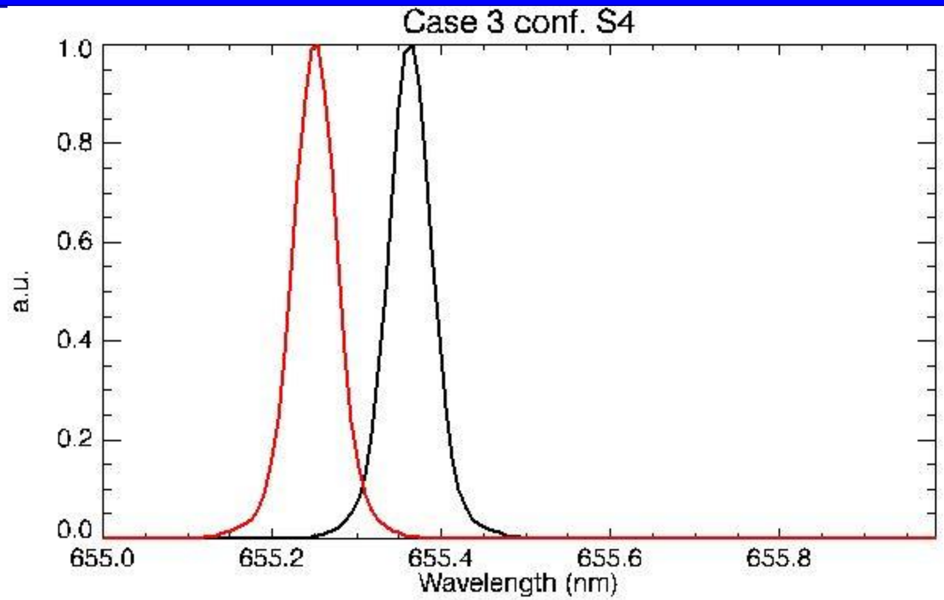
Case 2 (V_{ext}=1.4kV): alternate BES LoSs

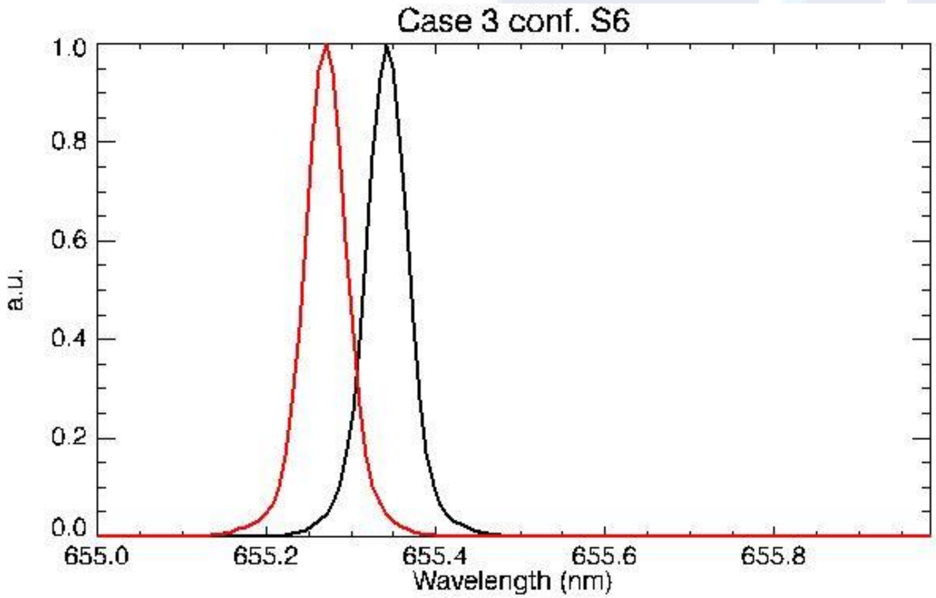


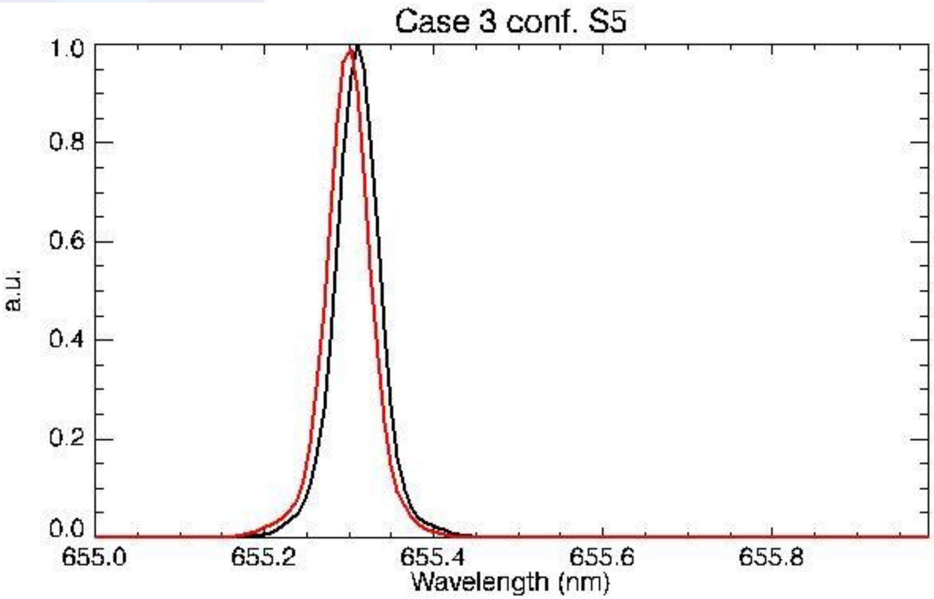




Case 3 (V_{ext}=1.35kV): alternate BES LoSs







Summary of BES results

- Values obtained with LOS in standard position/1 row upwards

Case	Expected e-folding divergence (mrad)	Divergence - S4 (mrad)	Divergence – S5 (mrad)	Divergence – S6 (mrad)
1	6,4	9,9/10,1	10,0/10,0	9,9/10,0
2	12	14,6/14,8*	13,8/13,7*	13,7/13,7*
3	8,5	6,1/6,3	5,5/5,6	5,5/5,5

Case	Expected direction (deg)	Direction - S4 (deg)	Direction – S5 (deg)	Direction – S6 (deg)
1	75	75,8/74,2	74,9/75,1	75,5/74,5
2	75	75,6/74,3*	74,7/75,2*	75,4/74,7*
3	75	76,4/74,7	75,7/75,5	76,2/75,1

*strong asymmetry of Doppler peak

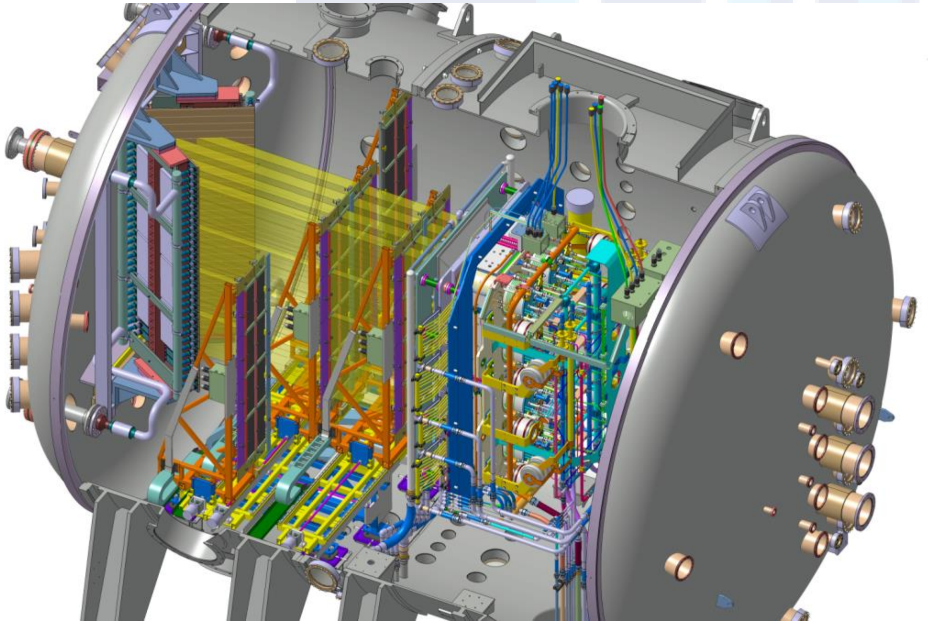
STRIKE

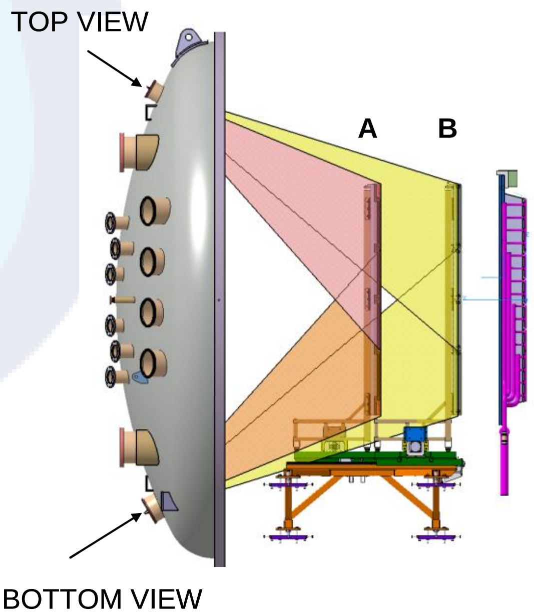
– Two panels of 1-D CFC tiles with large thermal conductivity ratio, to preserve image from front to back

– Two IR cameras from behind: 2D temperature map of entire beam :

  - beam uniformity
  - resolution ≤2 mm (640x480), frame rate ≥25 frames/s

– Two measurement positions: beam divergence





Expected STRIKE results

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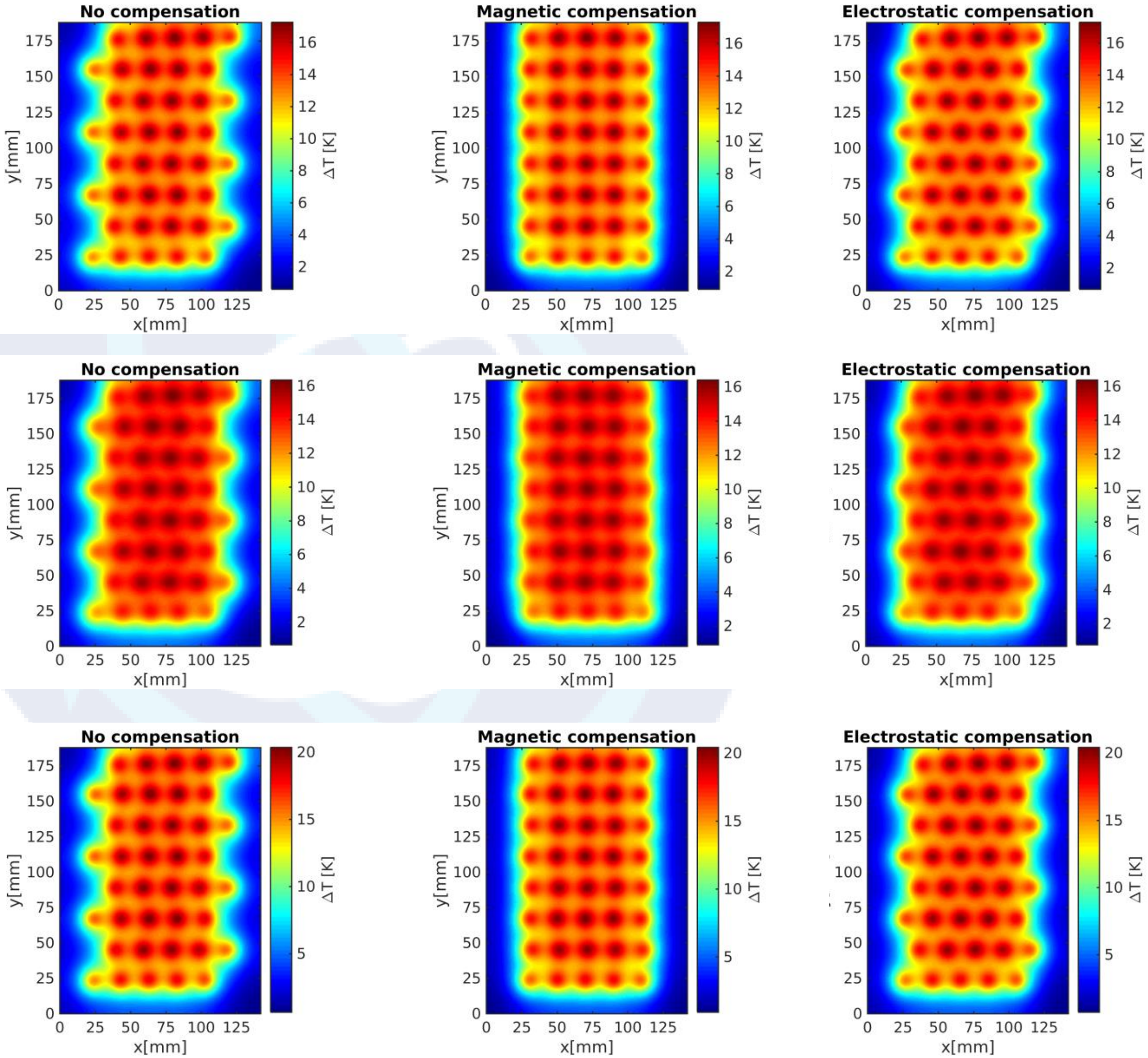
Vext = 1.2 kV
Vacc = 12.2 kV

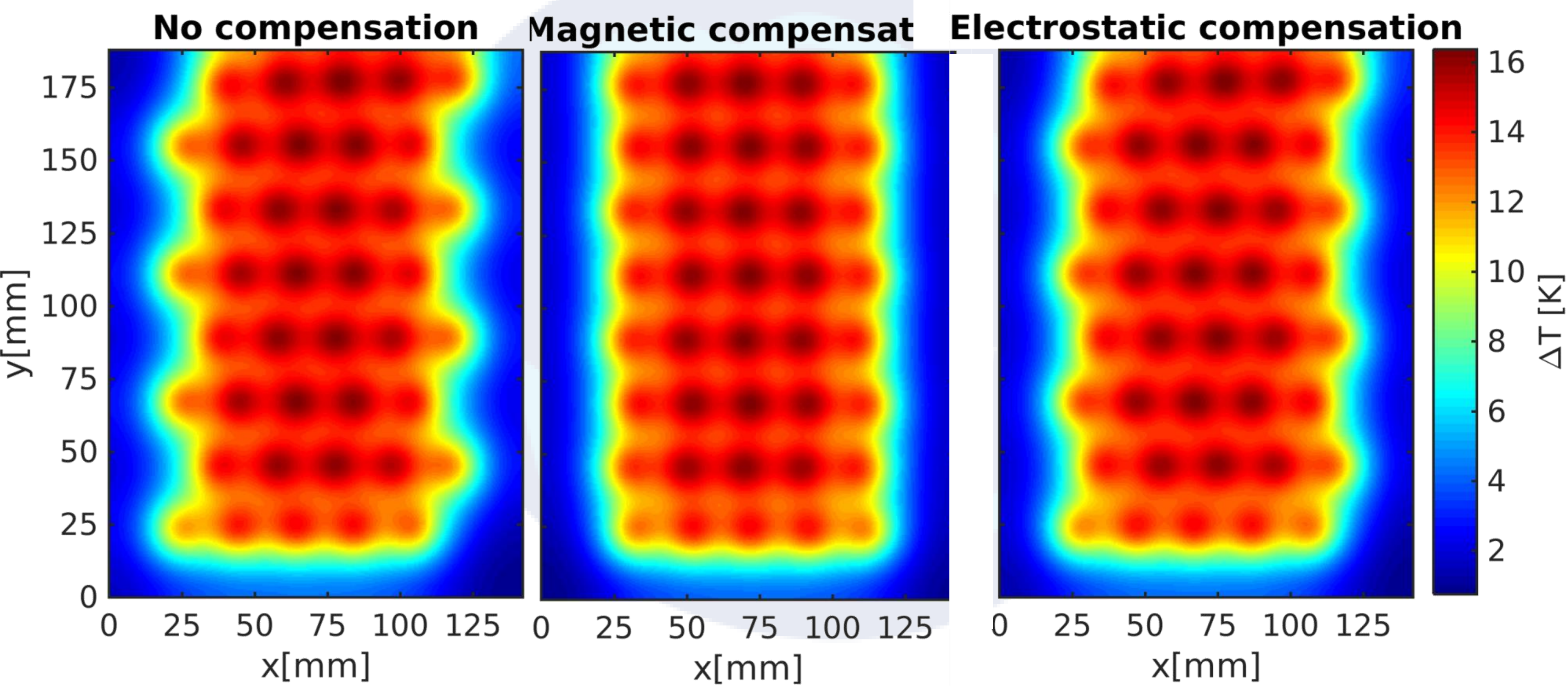
Vext = 1.4 kV
Vacc = 12.2 kV

Vext = 1.35 kV
Vacc = 15.9 kV



STRIKE

- Capability of distinguishing the pattern: largest divergence



Summary

- Various cases of early SPIDER operation simulated:
  - negative ions at low particle energy deflected by extraction grid magnets
  - raising extraction voltage straightens particle trajectories but detrimental for beam optics
  - hence, increase of voltage in second gap to optimise electrostatic lenses
- Multi-beamlet simulations confirm possibility
  - two-dimensional effects are accounted for
  - power and the current deposited onto each grid are also computed
- Expected measurements by SPIDER diagnostics can be computed