HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Max-Planck-Institut
für Plasmaphysik
IPP

Uniformity of the Large Beam of ELISE during Cs Conditioning

F. Bonomo, I. Mario, D. Wünderlich, U. Fantz and the NNBI Team

6th International symposium on Negative Ions, Beams and Sources
3 – 7 September 2018
Budker INP, Novosibirsk, Russia

NIBS 2018

Motivation
A large beam for ITER

ITER NBI:

- Accelerated current of 40 A in D @1MeV / 46 A in H @870keV - 0.3 Pa filling pressure
- Electron – ion ratio < 1
- Long pulses (3600 s for D, 1000 s for H)
- Large beam:
  - source of ≈ 2 m x 1 m; extraction area: 0.2 m^2
  - uniformity better than 90% (beamlets)
  - beam core divergence smaller than 7 mrad (0.4 deg)

ELISE test facility:

- Half size of the ITER-NBI source in vertical direction
- Large beam:
  - source of ≈ 1 m x 1 m; extraction area: 0.1 m^2
  - so far, the only large source with extraction in operation

→ ***what can we learn about a large beam for the ITER NBI?***

Outline

- ELISE test facility
  - Beam diagnostics

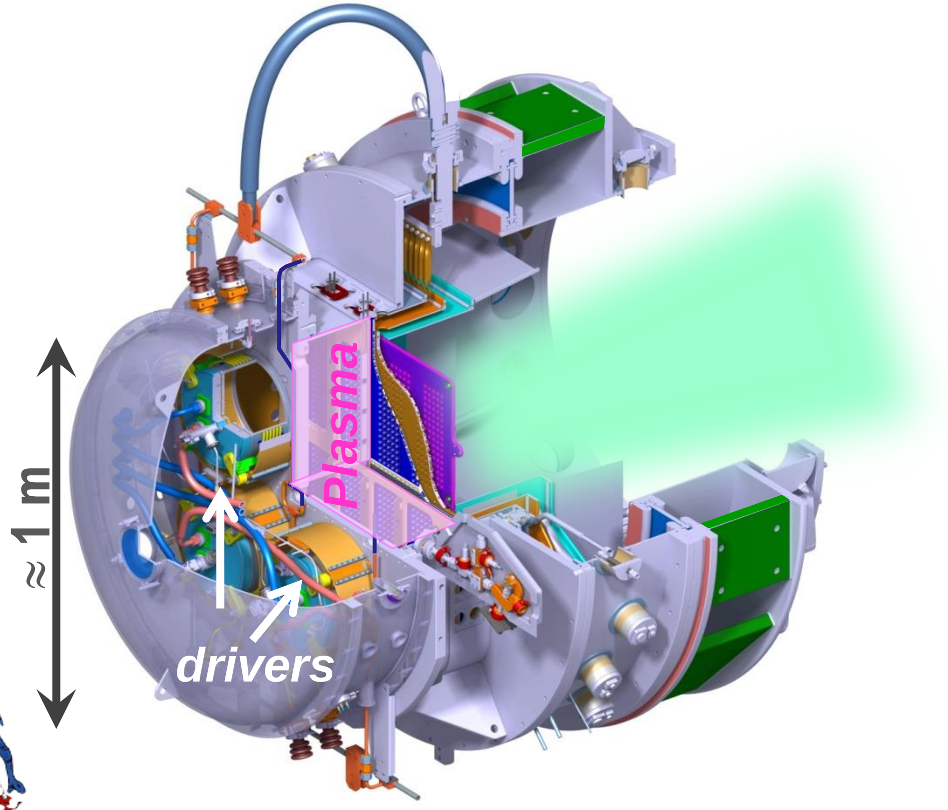
- Large beam features during Cs conditioning process of the source (**short pulses, H**)
  - Volume operation
  - Cs conditioning phase

- Beam optimization
  - Global beam uniformity better than 90%
  - Beam optics tuning

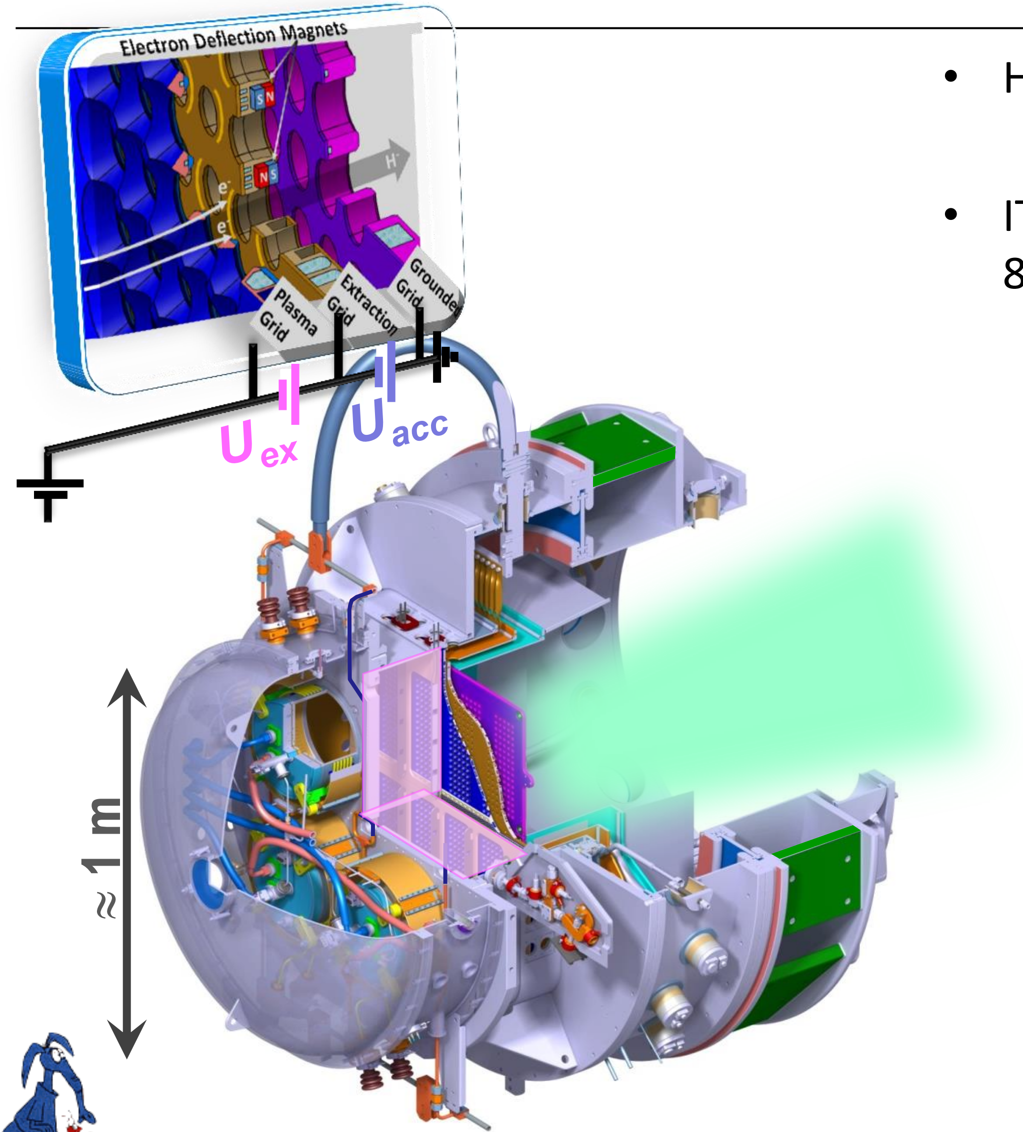
- Summary

ELISE test facility
NNBI source

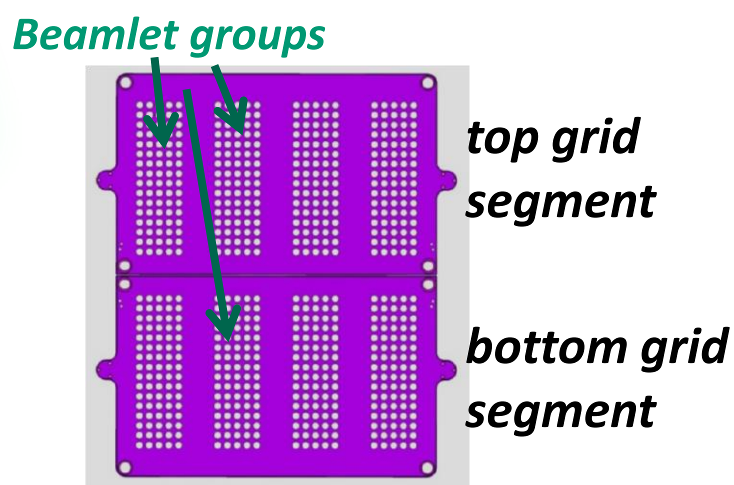
- Half of the ITER NBI in vertical direction
  - 4 drivers up to 75kW/driver



ELISE test facility
NNBI source

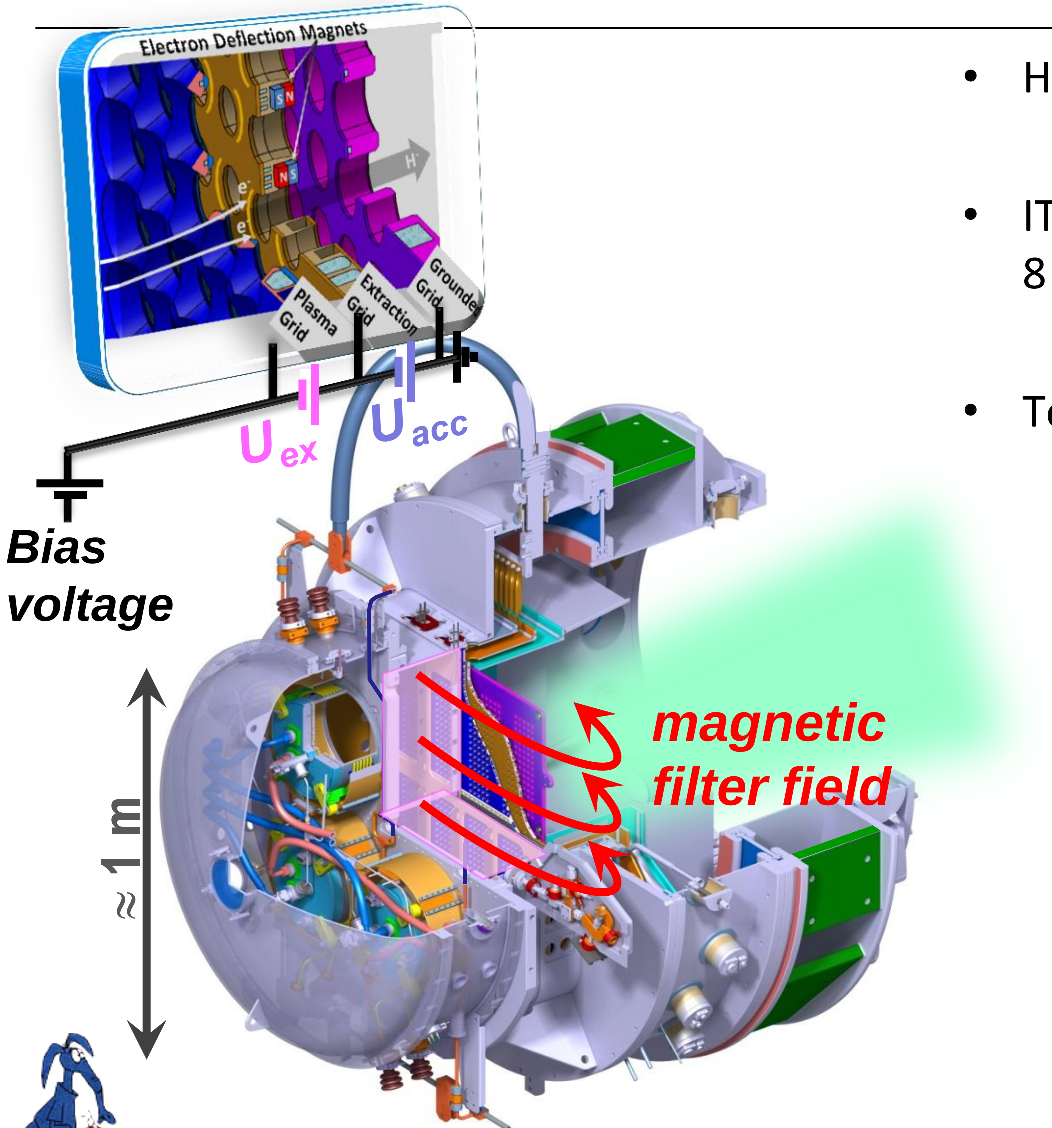


- Half of the ITER NBI in vertical direction
- ITER-like 3-grid system (640 beamlets / 8 rectangular beamlet groups)
  - HV power supply limited to 60 kV
  - 10 s extraction each 150 s
  - deflecting magnets in the extr. grid



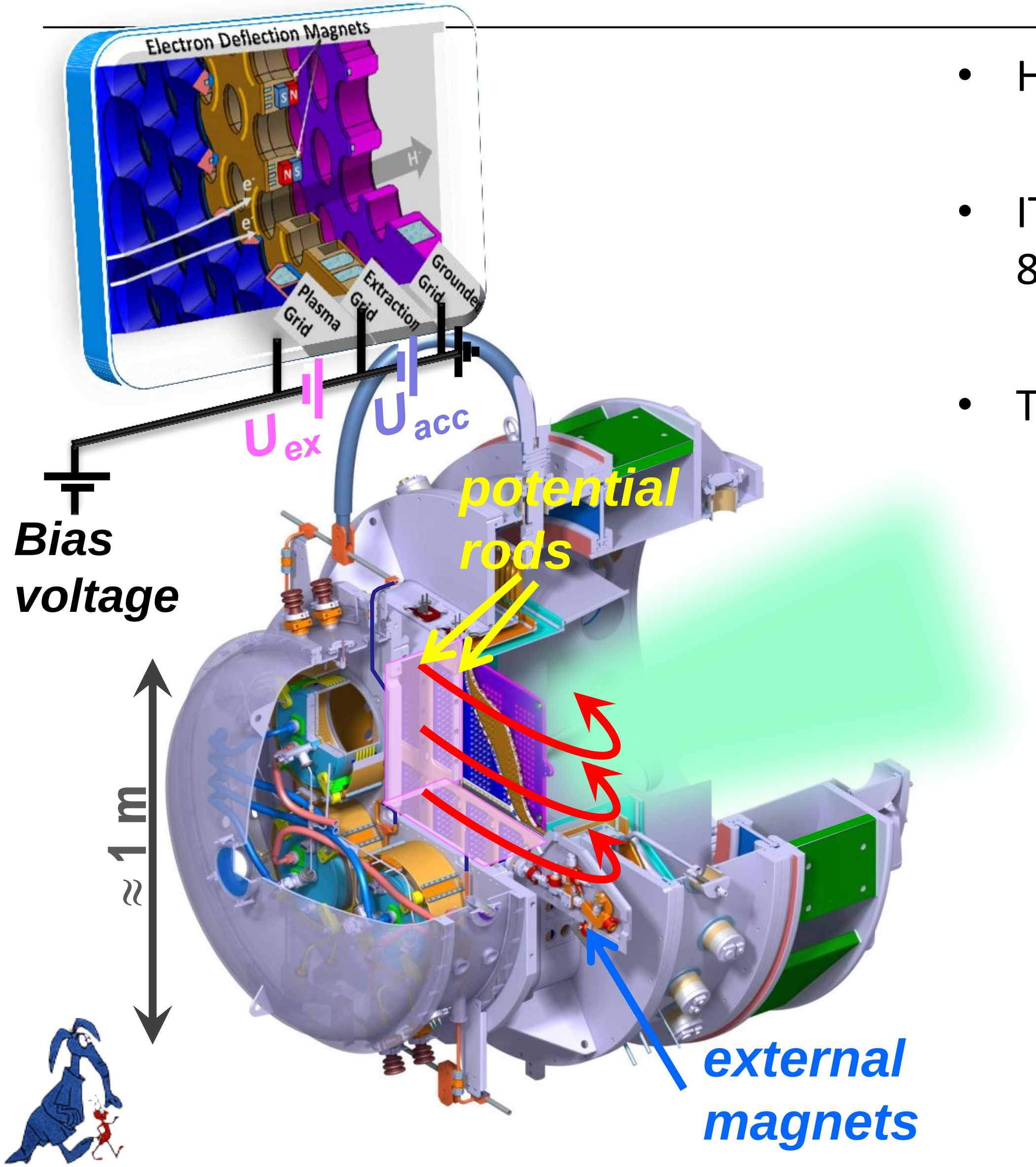
ELISE grid system

ELISE test facility
NNBI source



- Half of the ITER NBI in vertical direction
- ITER-like 3-grid system (640 beamlets / 8 rectangular beamlet groups)
- To limit the co-extracted electrons:
  - Filter Field (FF) to limit the co-extracted electrons (*I_{PG} current)*
  - Bias potential (PG positively biased versus the source wall)

ELISE test facility
NNBI source



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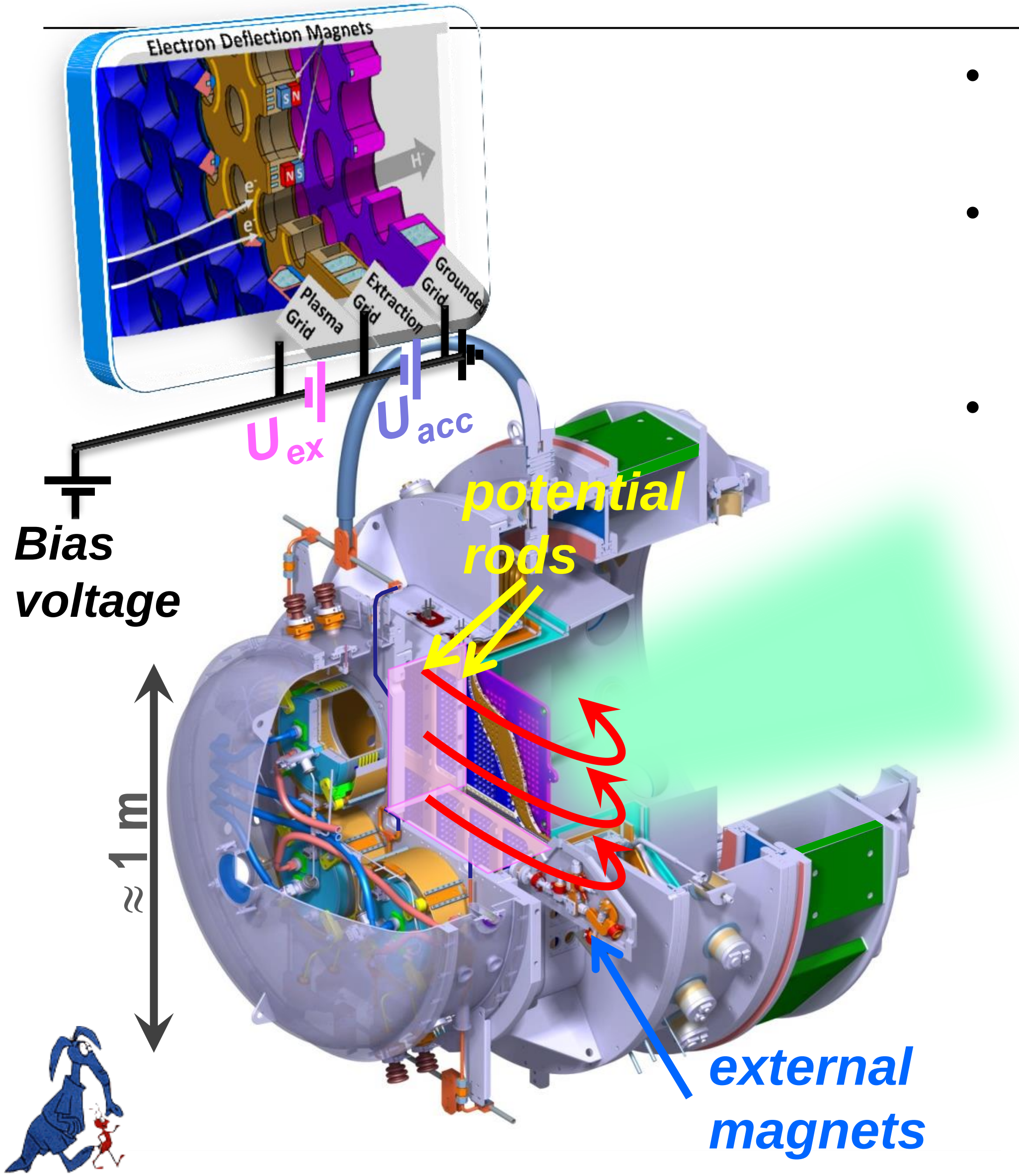
- ITER-like 3-grid system (640 beamlets / 8 rectangular beamlet groups)
- To limit the co-extracted electrons:
  - Filter Field (FF) to limit the co-extracted electrons (*I_{PG} current)*
  - **External magnets**
  - Bias potential (PG positively biased versus the source wall)
  - **Potential rods**

ELISE test facility
NNBI source



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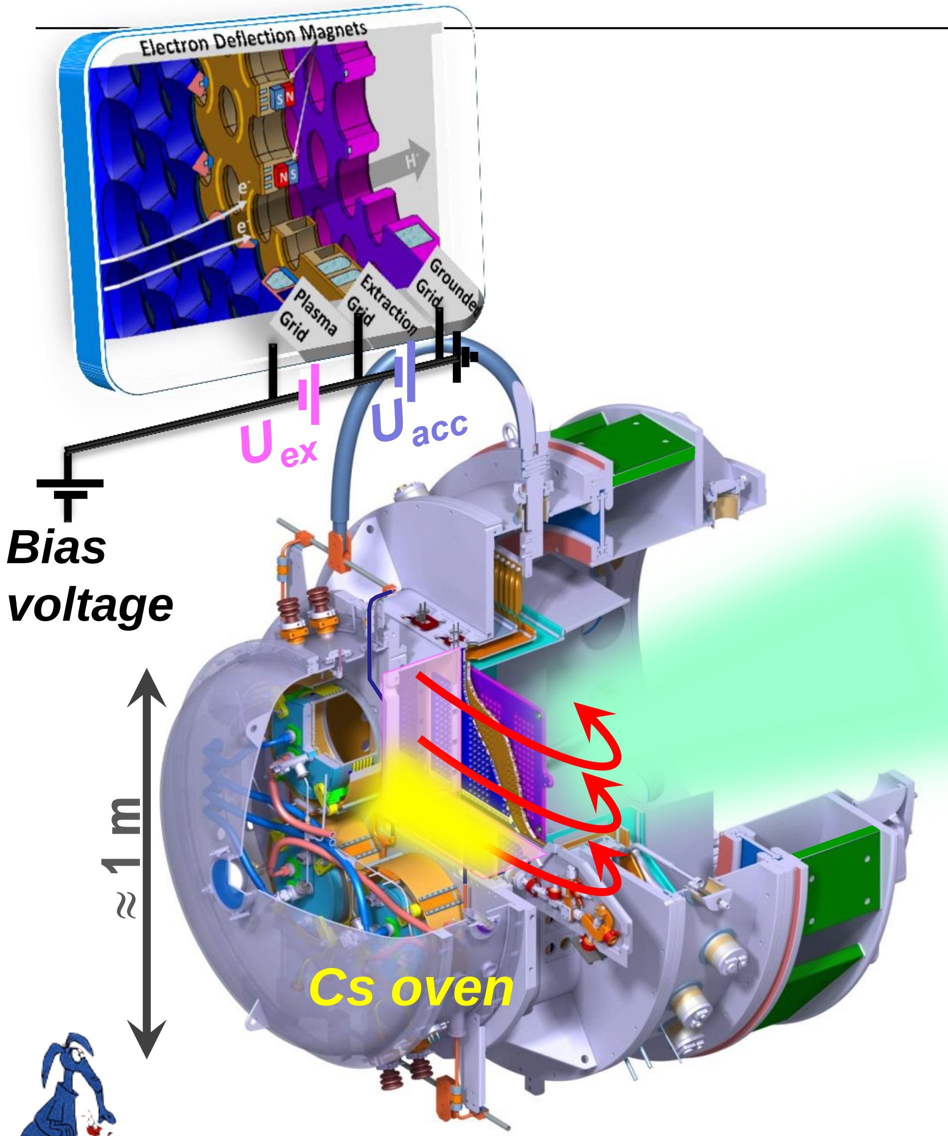
C. Wimmer
3rd Sept 2018 @ 11:40

ELISE test facility
NNBI source



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  - **External magnets**
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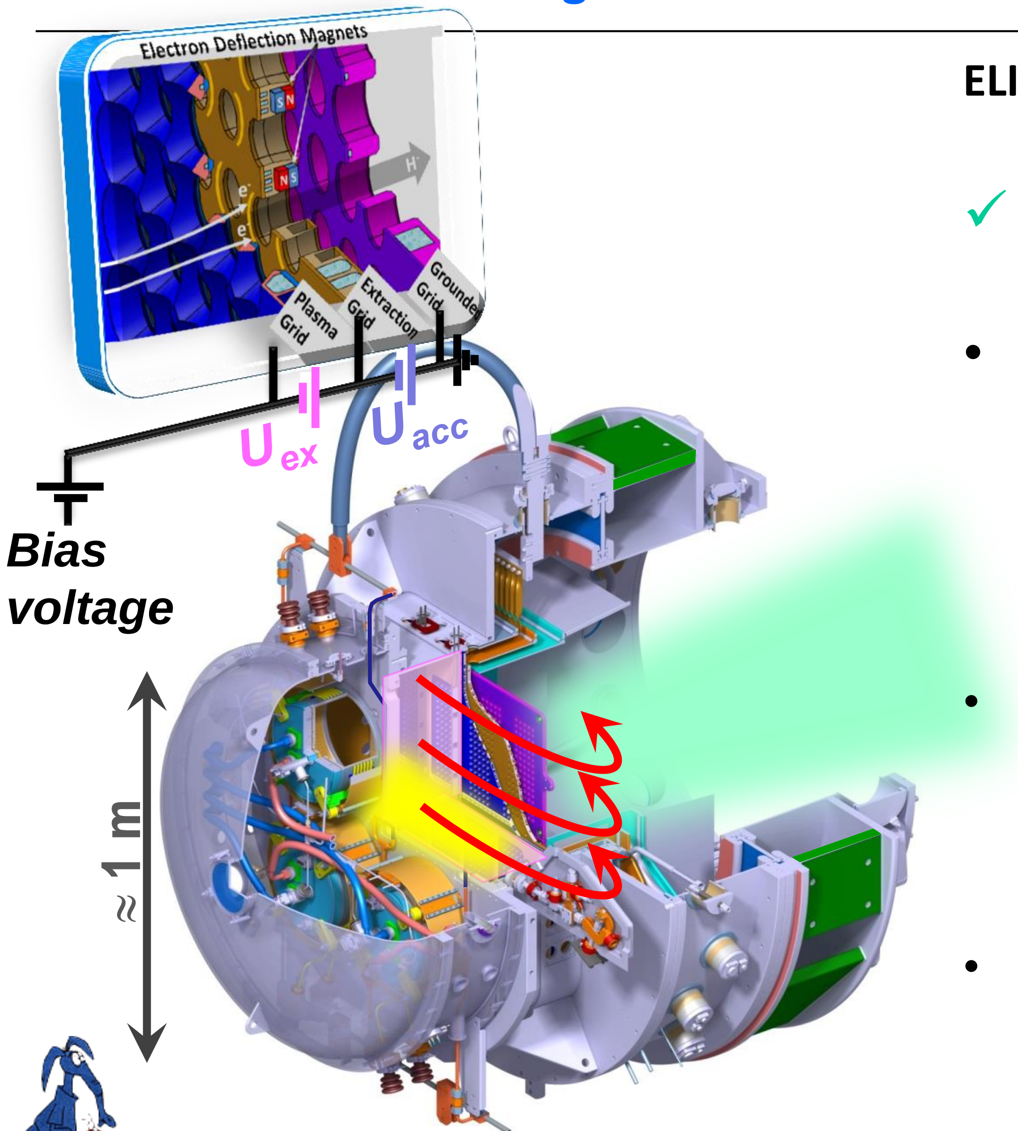
  - **Potential rods**
- Two liquid Cs ovens (left/right)

A. Mimo
Today @ 10:00

ELISE test facility
NNBI source & ITER targets



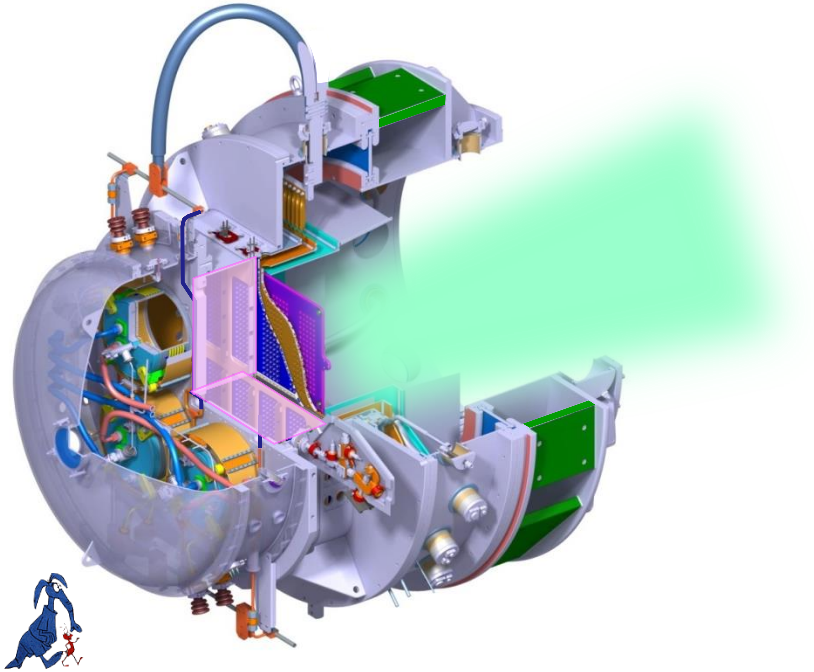
ELISE ITER targets:

D. Wünderlich
3th Sept 2018 @ 11:10

- ✓ Plasma duration (3600s D & 1000s H)
- Extracted & Accelerated currents:
  - ✓ for H (1000 s)
  - For D (3600 s) - only 65%
  - ✓ Ratio co-extracted electrons/ions <1
- Uniformity
  - top/bottom beam segments or beamlet groups
- Beam divergence
  - no ITER divergences (> 1 deg) ***BUT*** large beam investigation

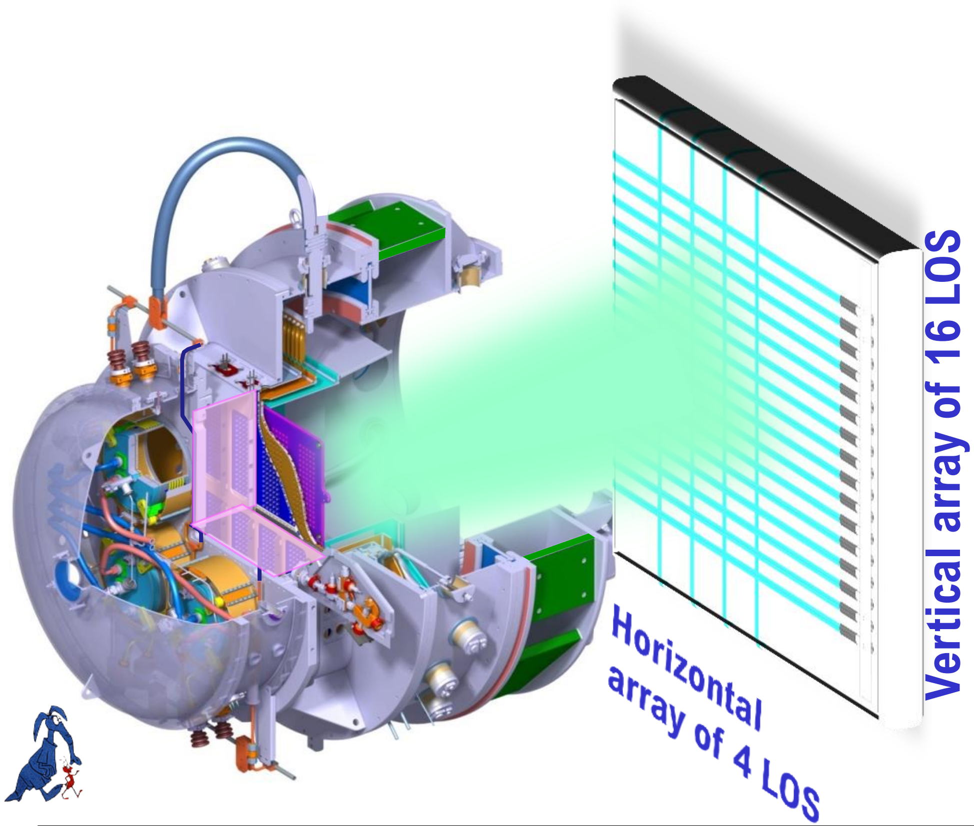
Electrical current measurements

- Electrical measurements of currents
  - Total extracted negative ion current (I_{ex})
  - Top/bottom currents on EG (mostly electrons)
  - Top/bottom currents on GG

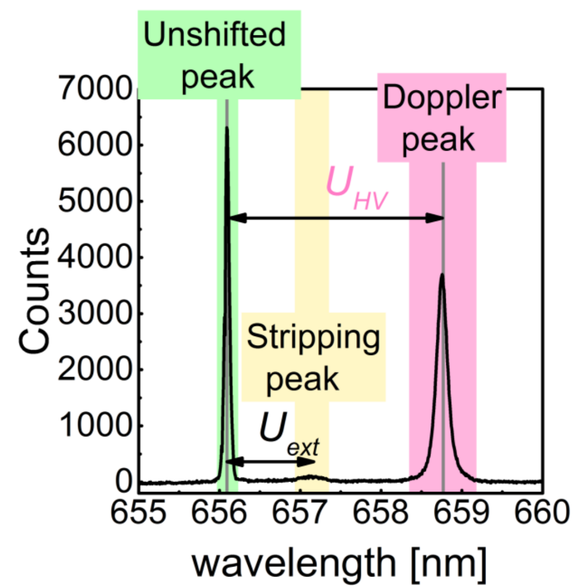


Beam Emission Spectroscopy

- Electrical measurements of currents
- Beam Emission Spectroscopy diagnostic (BES)



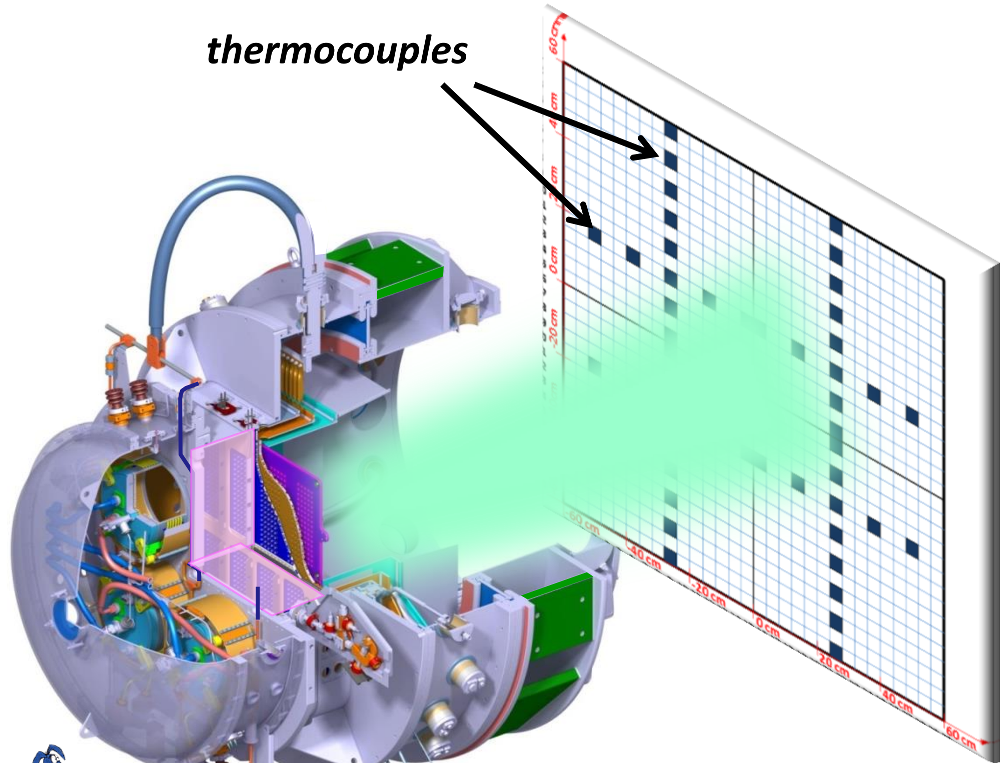
- Beam intersection: 2.7 m from GG
- 50 deg angle between LOS & beam
- H_α Doppler peak spectra analysis
  - Beam divergence from Doppler peak
  - Stripping losses
  - Vertical beam intensity profile



ELISE Beam Diagnostics

Diagnostic calorimeter

- Electrical measurements of currents
- Beam Emission Spectroscopy diagnostic (BES)
- Diagnostic calorimeter



- 3.5 m from GG
- Water calorimetry
- 30 x 30 inertially cooled blocks (4 cm x 4 cm)
- 48 thermocouples embedded

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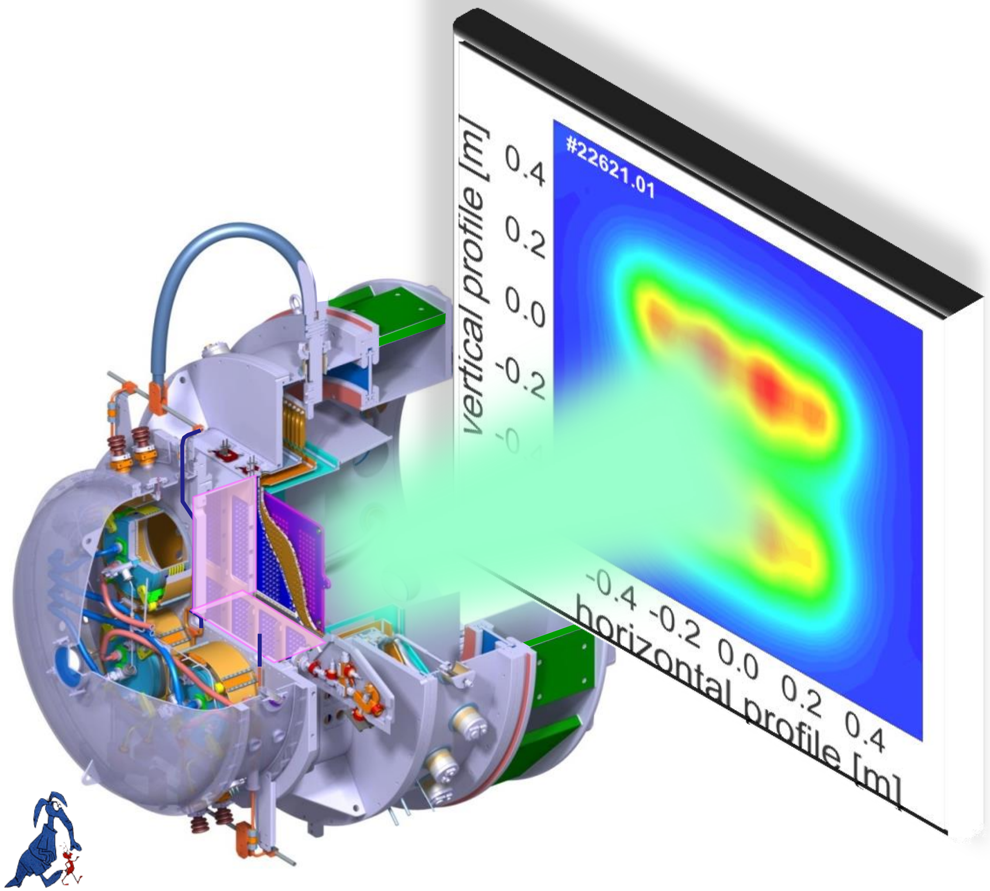

- 3.5 m from GG
- Water calorimetry
- 30 x 30 inertially cooled blocks (4 cm x 4 cm)
- 48 thermocouples embedded
- Black coating for Infra-Red (IR) analysis
  - Absolutely calibrated (thermocouples)
  - 2D map of the beam power
    - accelerated current (global & local) via 8 2D-gaussian fitting, one for each beamlet group
      → j_{acc} for the top/bottom grid segments

ELISE large beam features

Volume operation (hydrogen, 0.3 Pa)

- no Cs into the source

volume | Cs evaporation | caesiated source

ELISE large beam features
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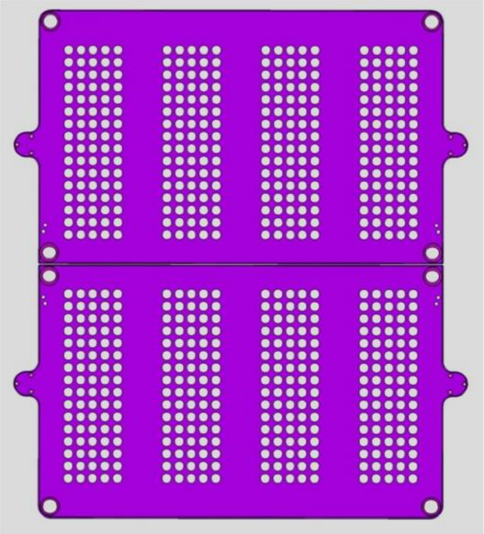

ELISE grid system

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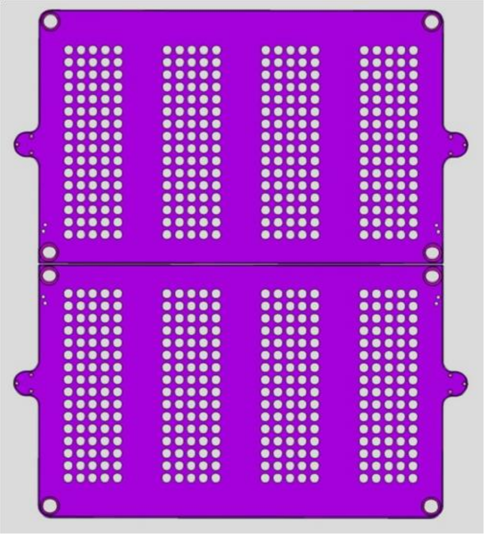

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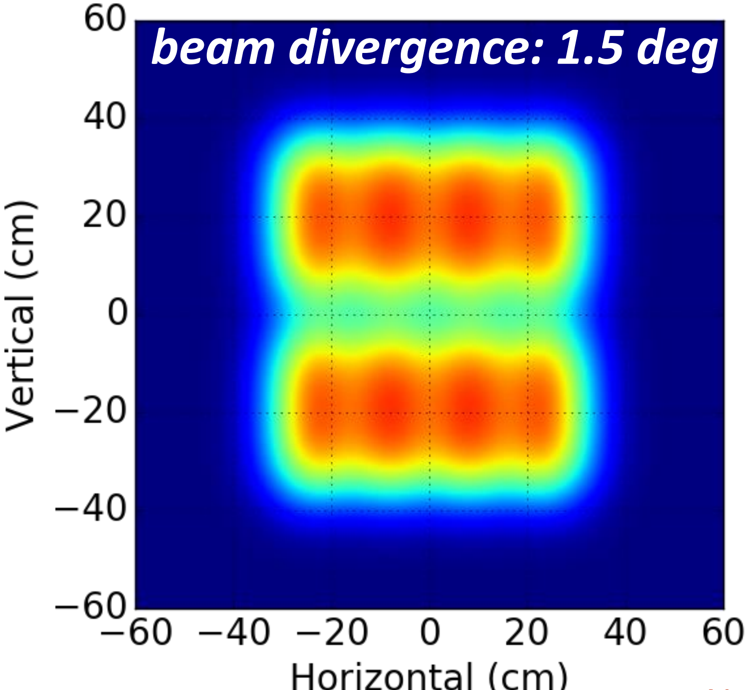
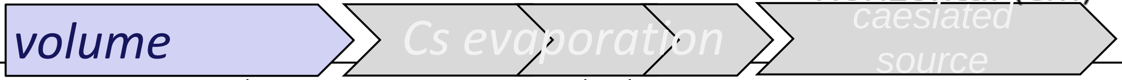


Courtesy of N. Den Harder



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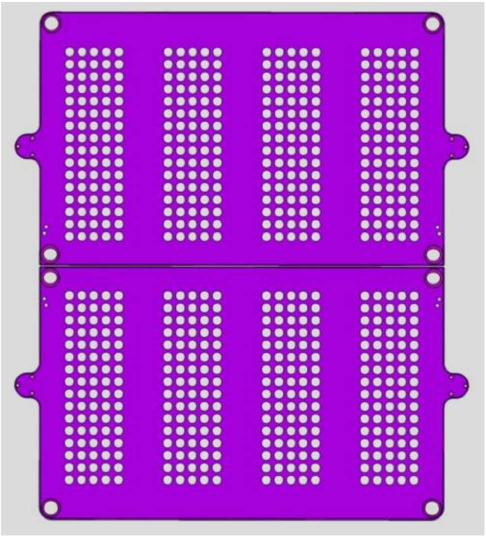
- To reduce the co-extracted electrons:
  - reduced parameters (low U_{ex} & RF power) → j_{ex} = 1 - 3 mA/cm²



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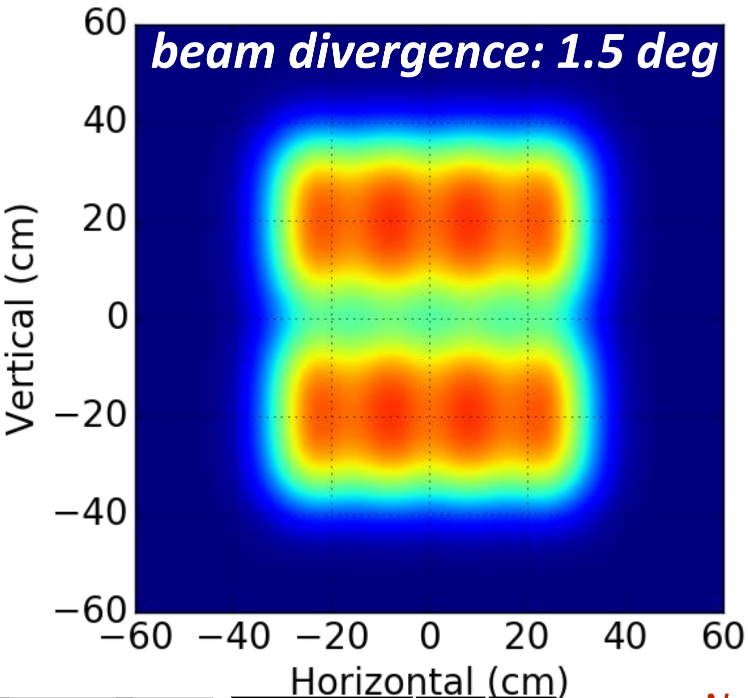

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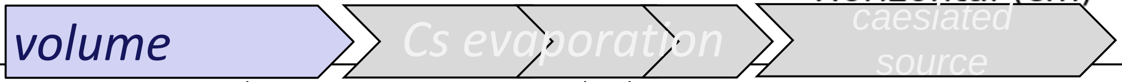

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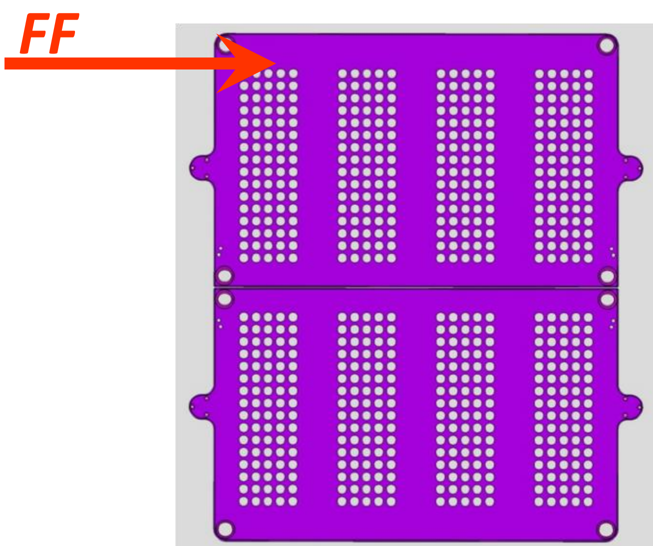
Volume operation (hydrogen, 0.3 Pa)

- no Cs into the source
- To reduce the co-extracted electrons:
  - reduced parameters (low U_{ex} & RF power) → j_{ex} = 1 - 3 mA/cm²
  - high *FF* + high bias potential
    - → large upward vertical drift in the plasma
    - → FF: downward beam deflection



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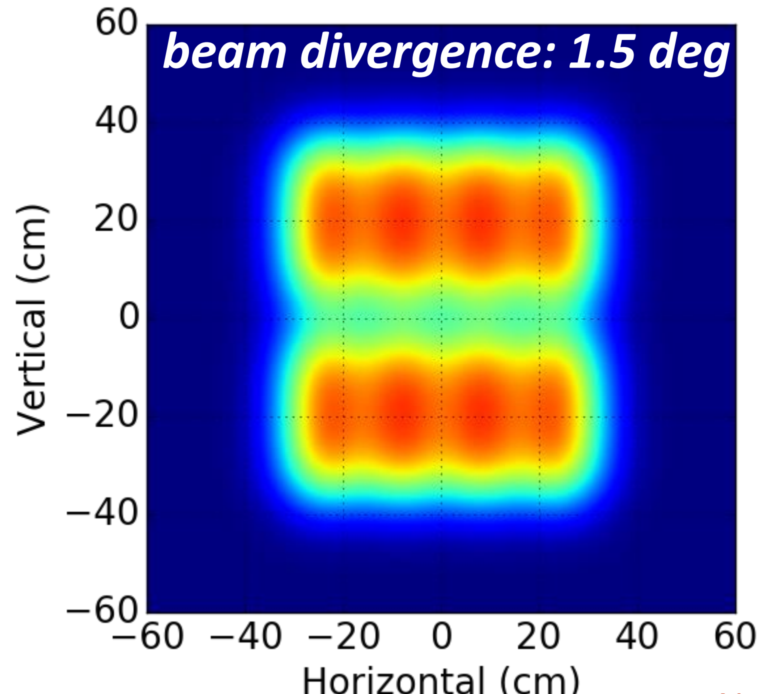

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volume → Cs evaporation → caesiated source

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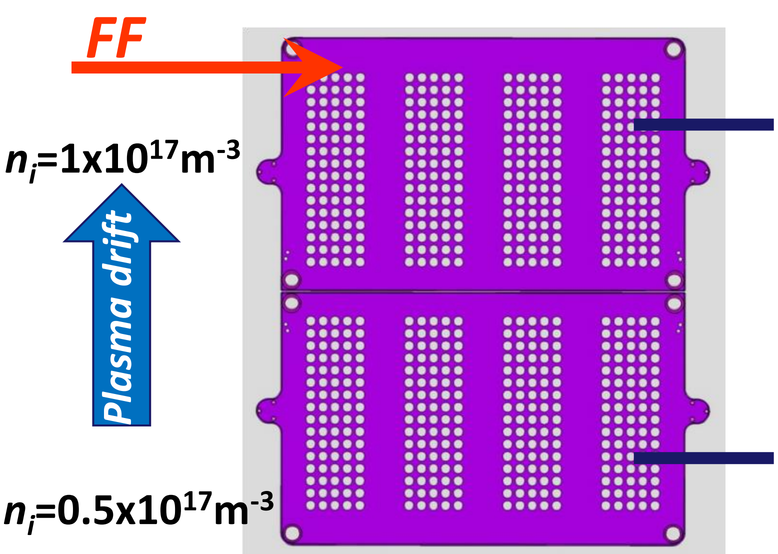

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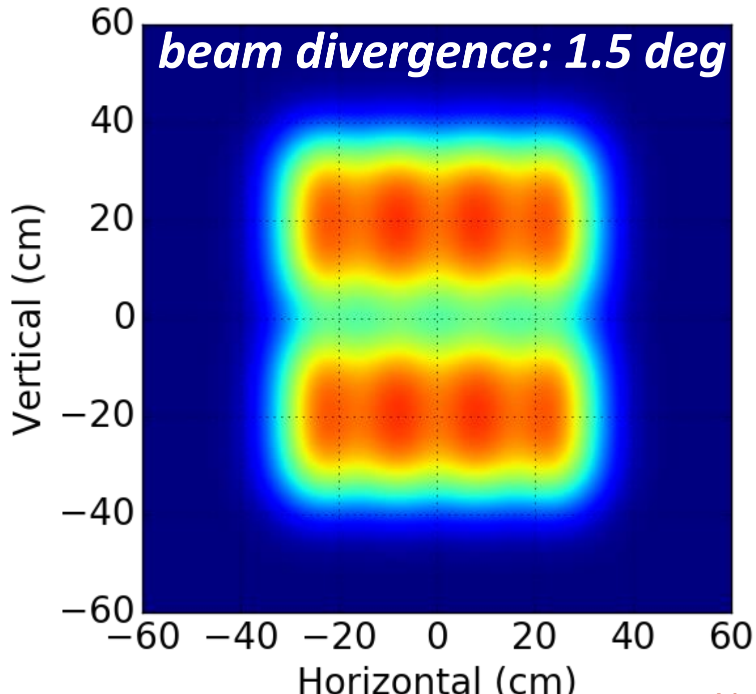

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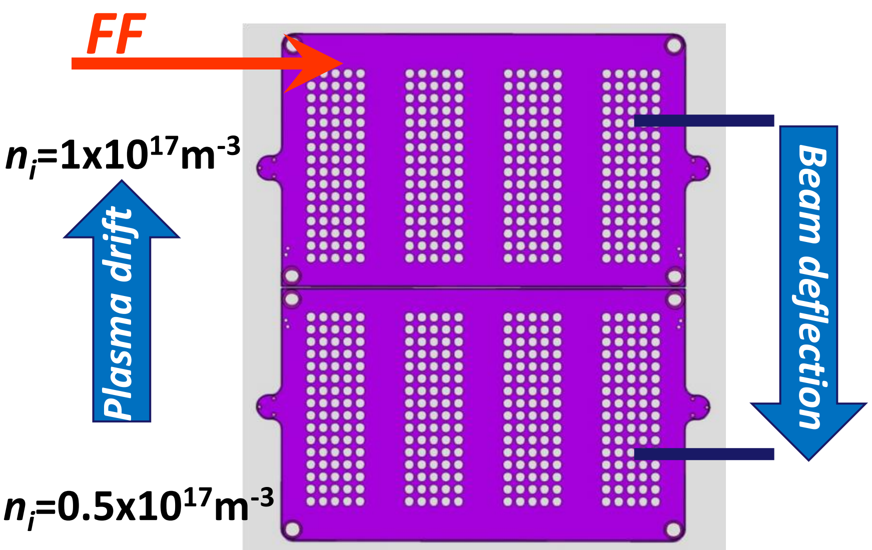

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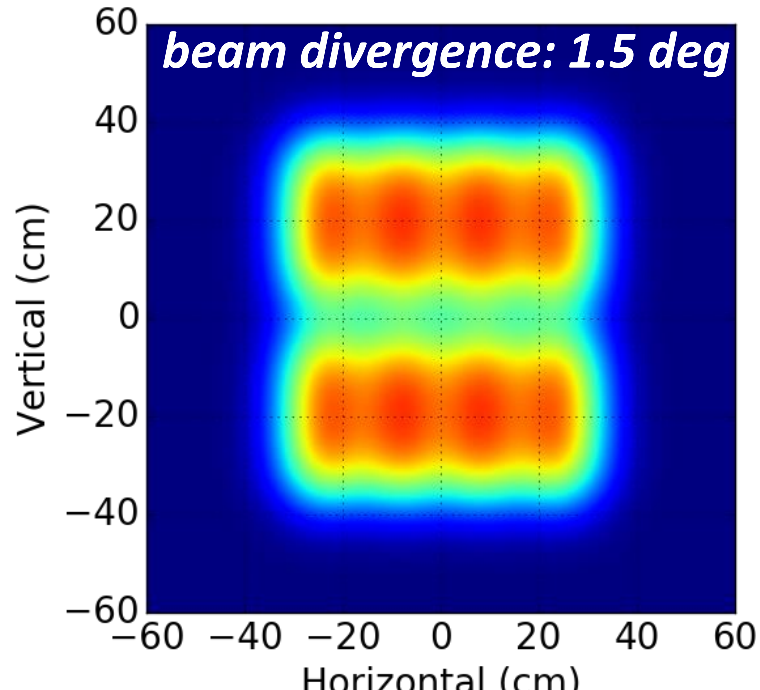

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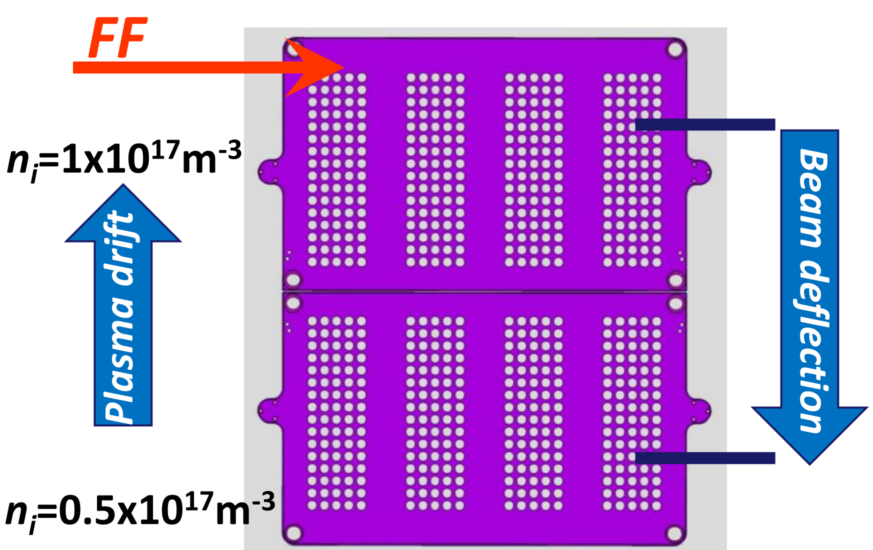

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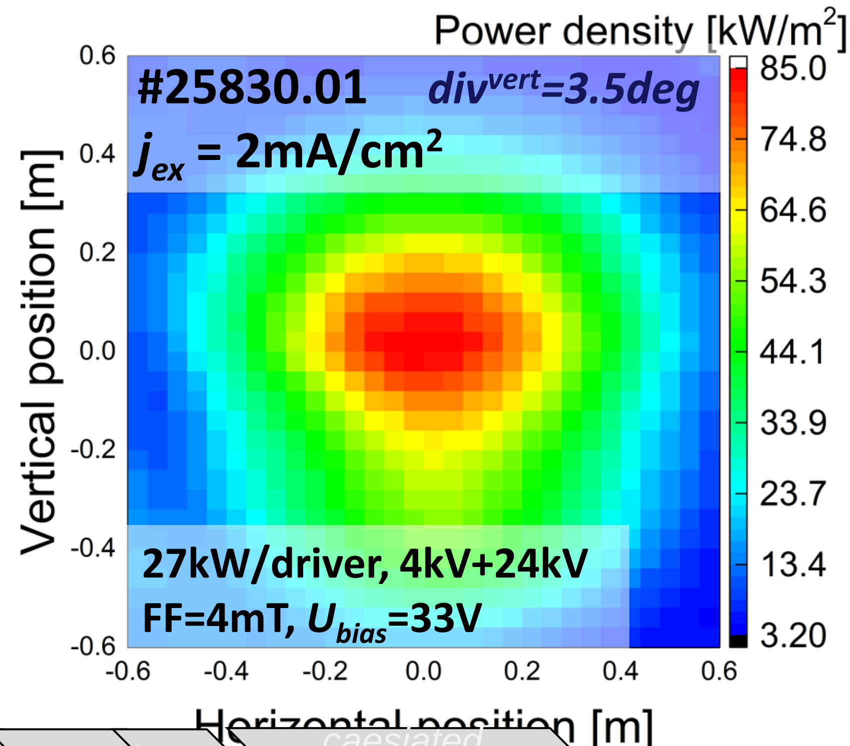
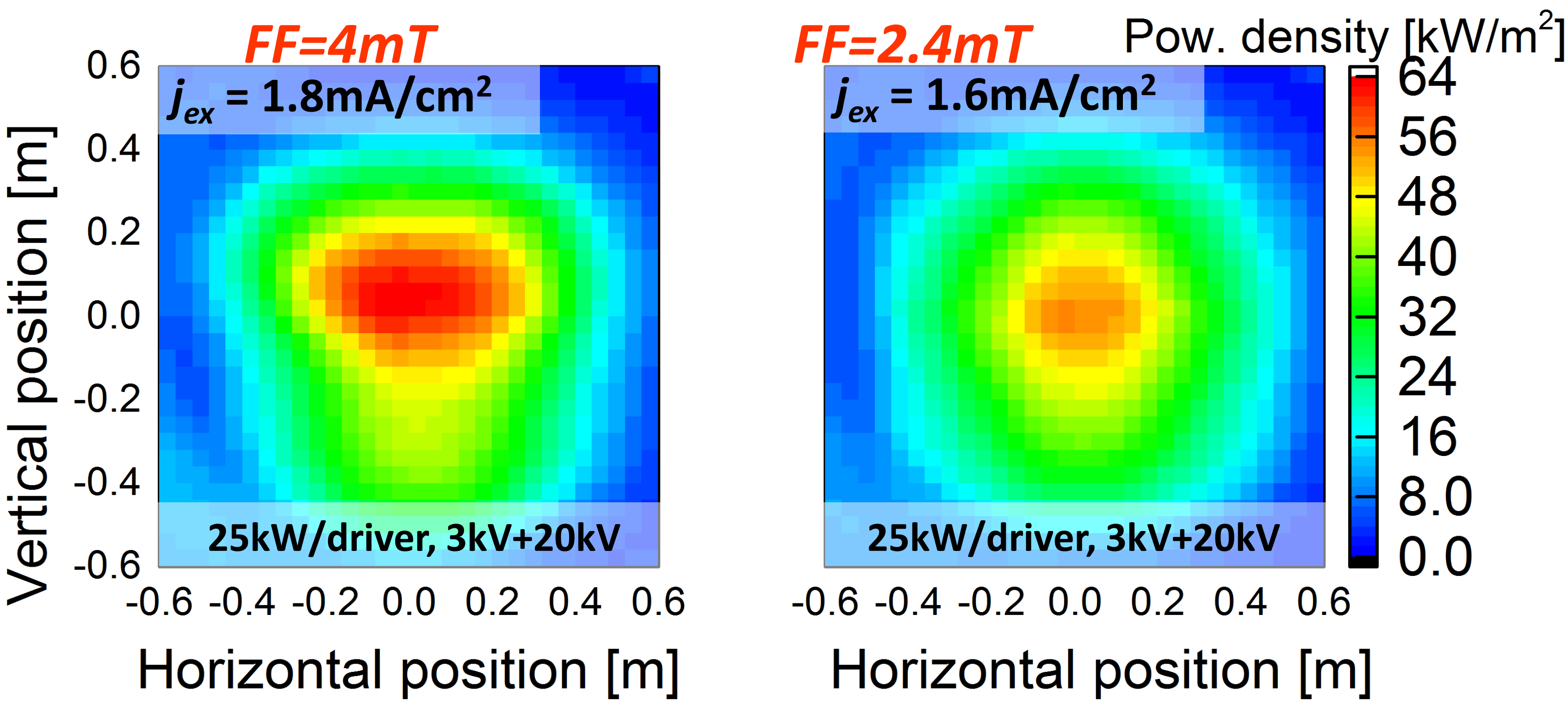


volume | Cs evaporation | caesiated source

Can the beam be vertically uniform during volume operation?

- smaller FF → more uniform beam…



n_i^{top}= 1.7 x n_i^{bot}

n_i^{top}= 1.2 x n_i^{bot}

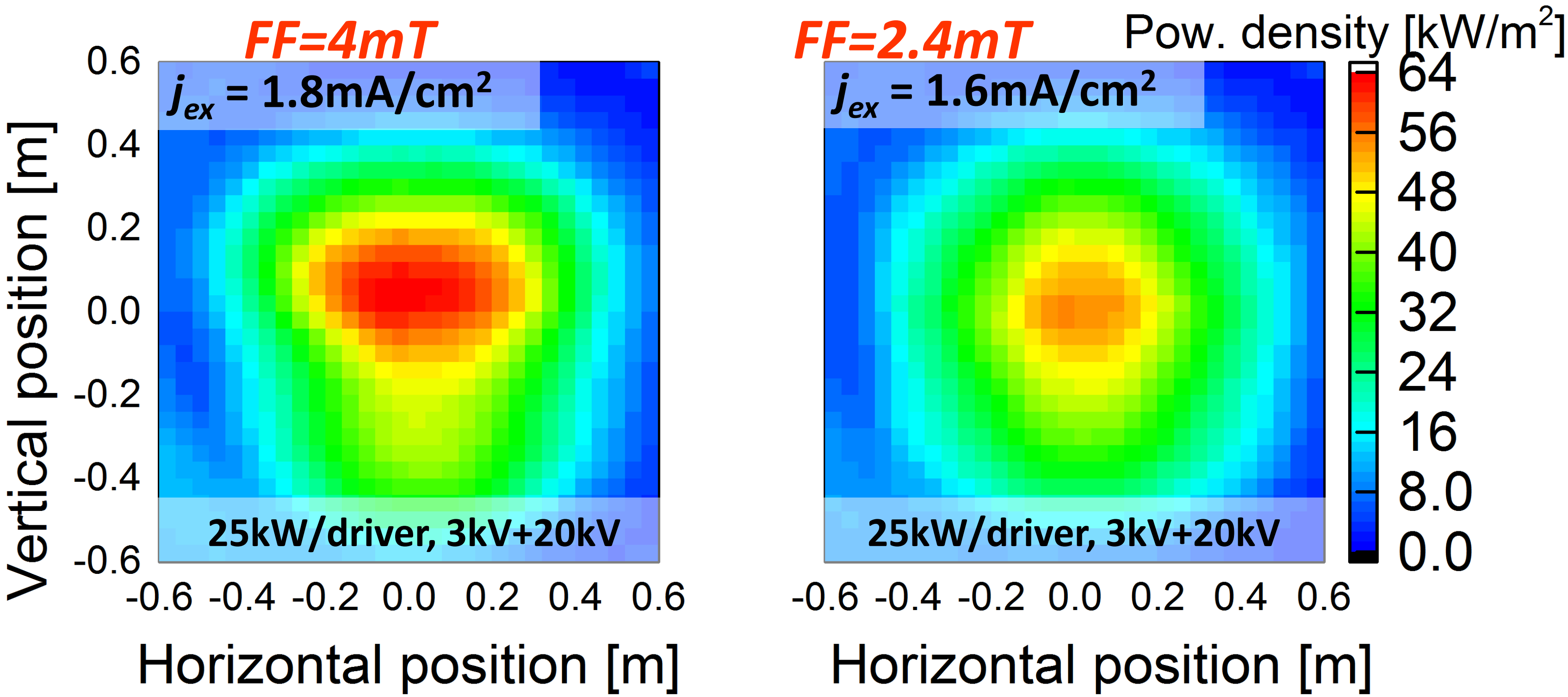
volume | Cs evaporation | caesiated source

Volume operation /2

Can the beam be vertically uniform during volume operation?

- smaller FF → more uniform beam…

…BUT not possible to get rid of the FF: too much co-extracted electrons!



$n_i^{top} = 1.7 \times n_i^{bot}$

$n_i^{top} = 1.2 \times n_i^{bot}$

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Volume operation /2

Can the beam be vertically uniform during volume operation?

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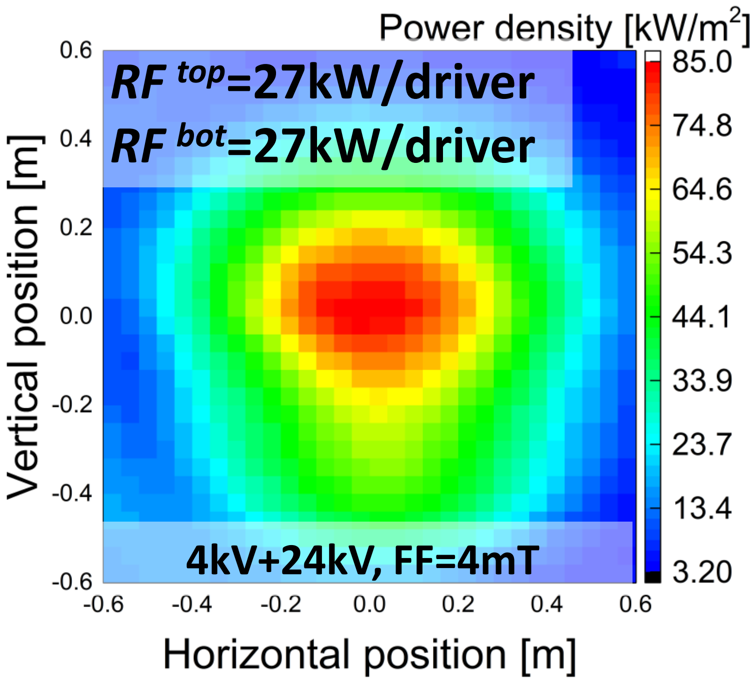
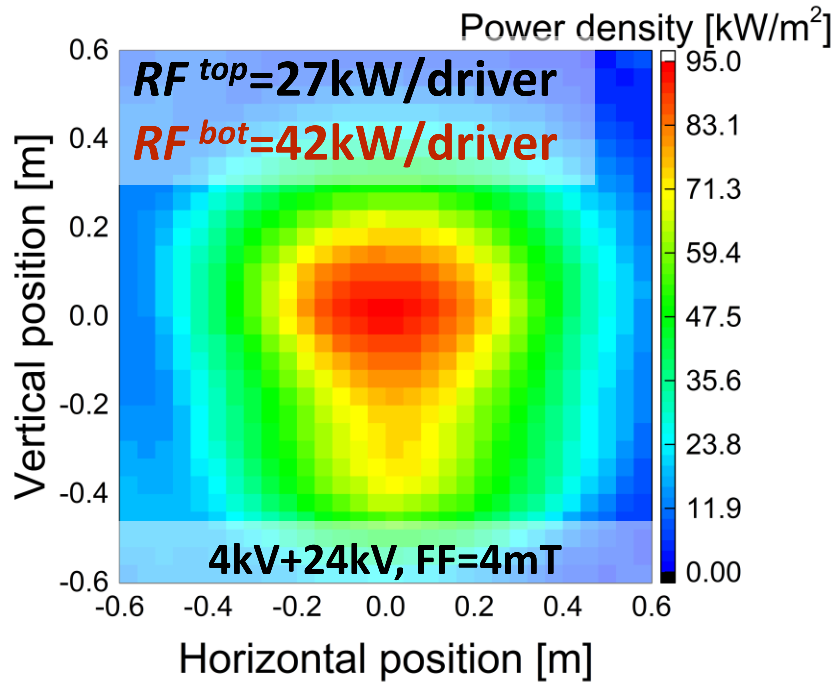
- independent settings of the RF power in the top/bottom generators





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ELISE large beam features
Volume operation /2

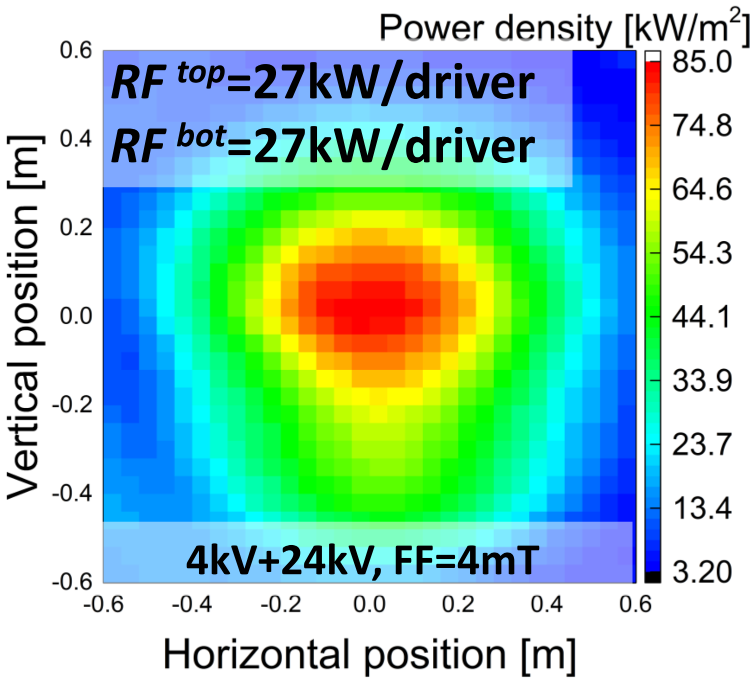
Can the beam be vertically uniform during volume operation?

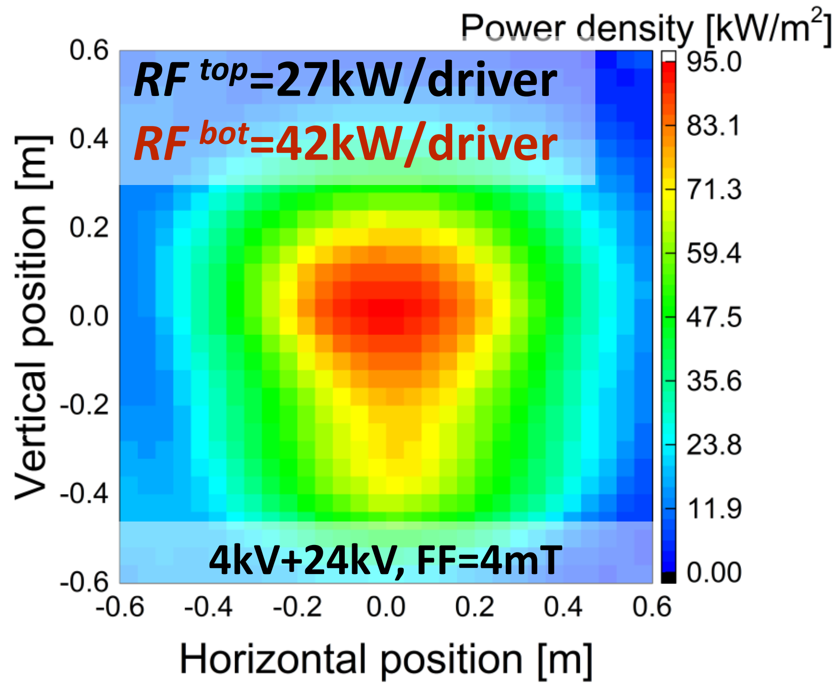
- smaller FF → more uniform beam…

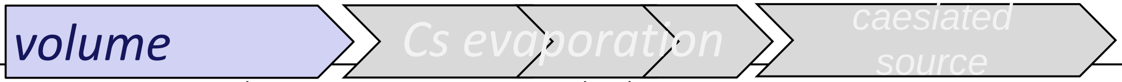
  …BUT not possible to get rid of the FF: too much co-extracted electrons!

- independent settings of the RF power in the top/bottom generators

  …BUT RF power limited to keep the co-extracted electron at a tolerable value!







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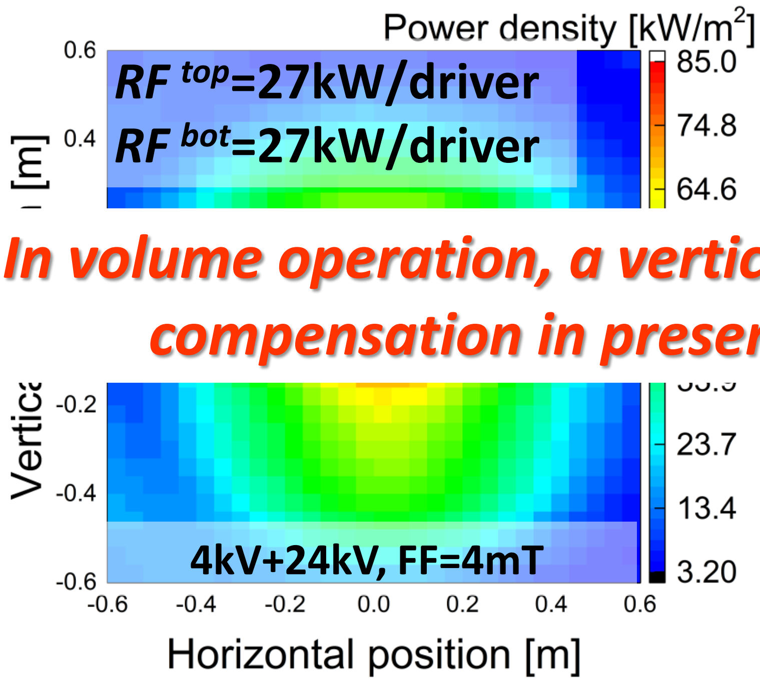
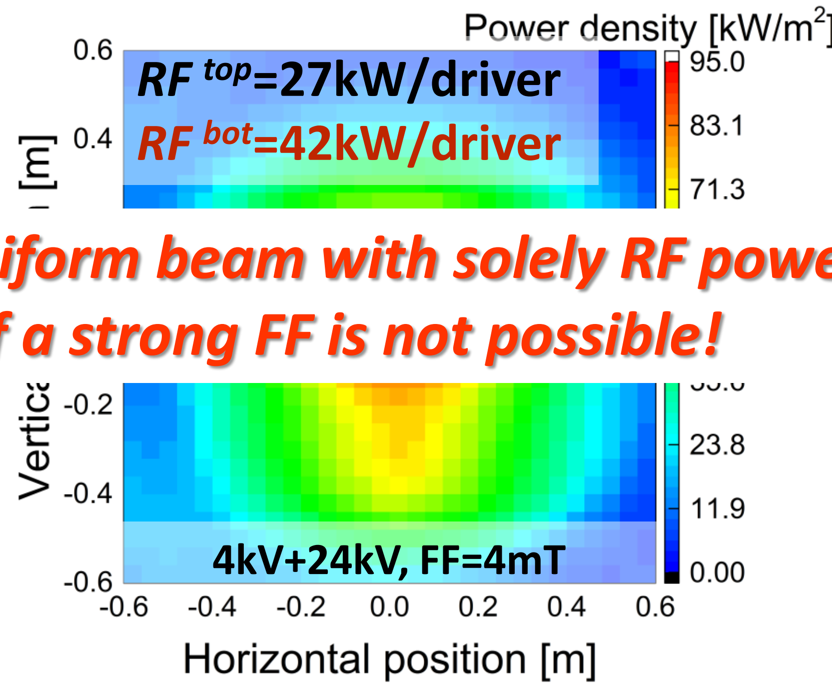


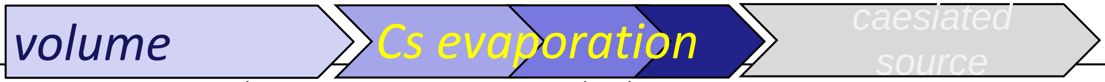


In volume operation, a vertical uniform beam with solely RF power compensation in presence of a strong FF is not possible!

volume → *Cs evaporation* → *caesiated source*

ELISE large beam features
Cs conditioning process

- Constant Cs evaporation rate for both ovens
- Steps of “constant parameters” from volume to higher performances
- Short pulses in hydrogen (9.5 s beam into a 20 s plasma pulse)



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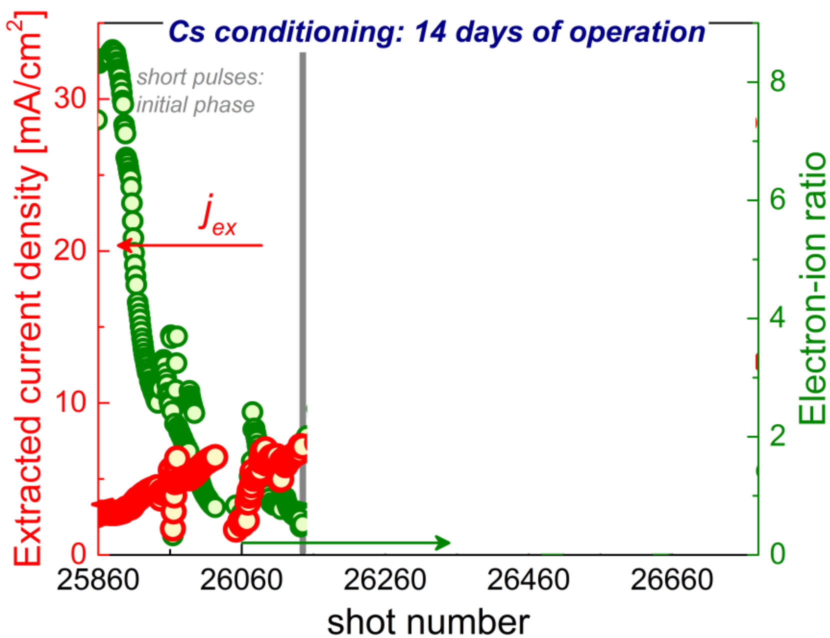
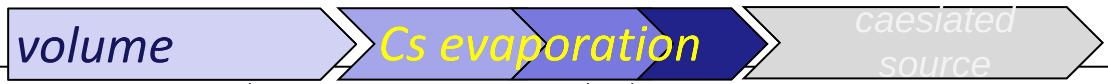


- **After 4 days (1.5h plasma-on time)**
  j_{ex} from 2 to 7 mA/cm^2
  $j_e / j_{ex} < 1$



- Constant Cs evaporation rate for both ovens
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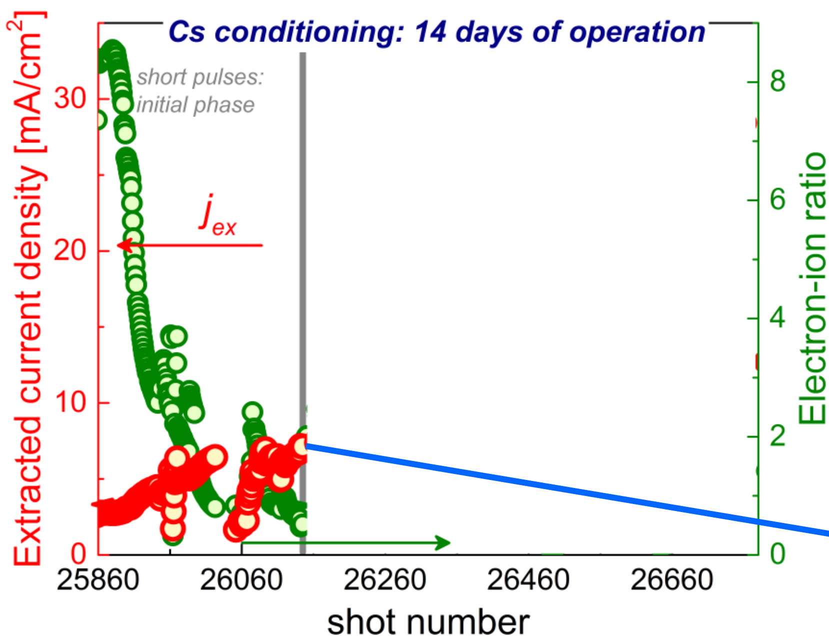
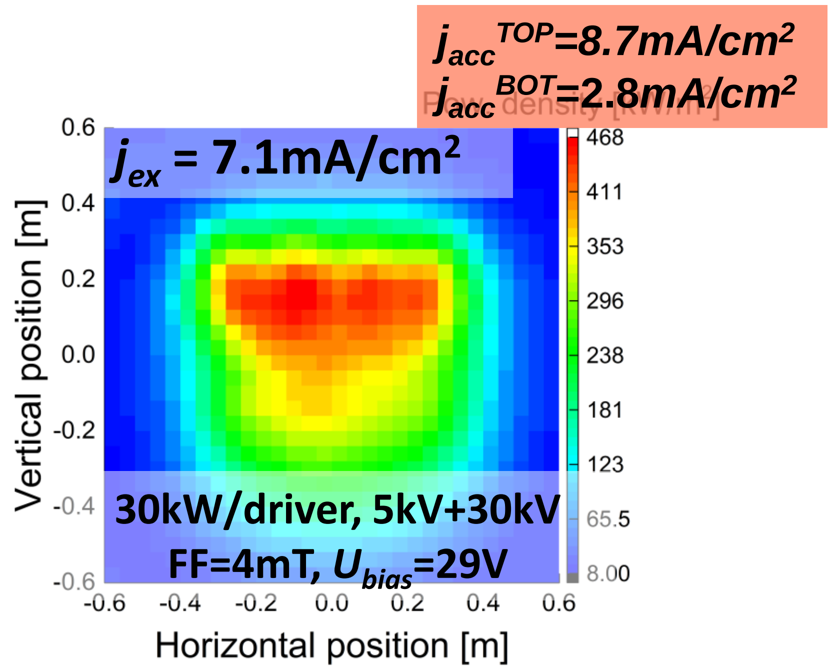
- **After 4 days (1.5h plasma-on time)**
  j_{ex} from 2 to 7 mA/cm^2
  $j_e / j_{ex} < 1$





volume → Cs evaporation → caesiated source

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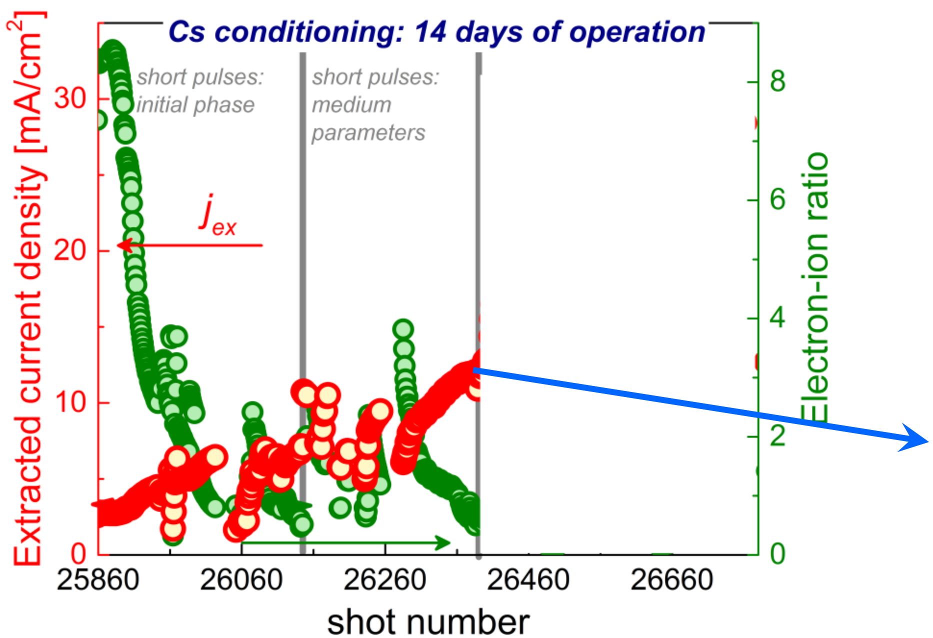
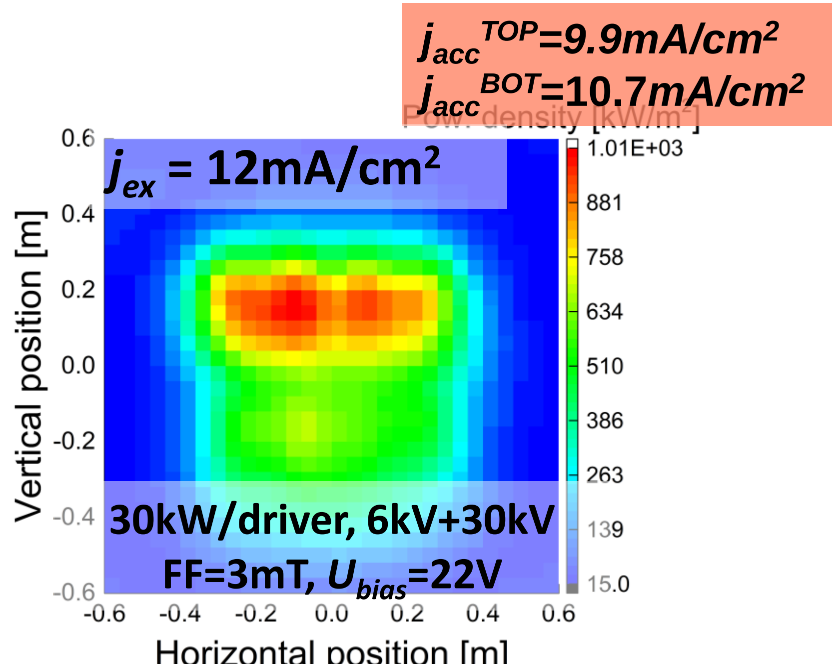


- **After 7 days (2.3h plasma-on time):**
  j_{ex} up to 12 mA/cm²; $j_e/j_{ex} < 1$
  $j_{acc}^{BOTTOM} \approx j_{acc}^{TOP}$ but different optics



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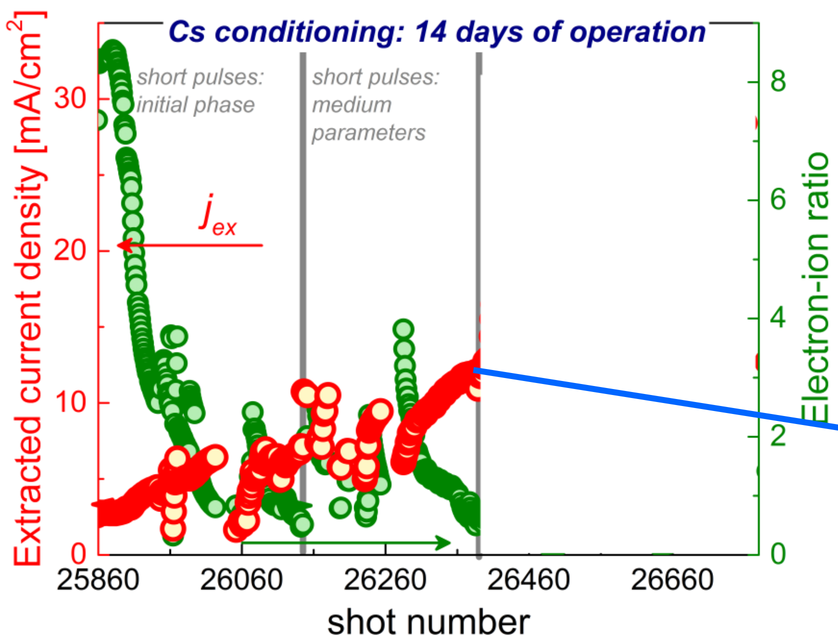

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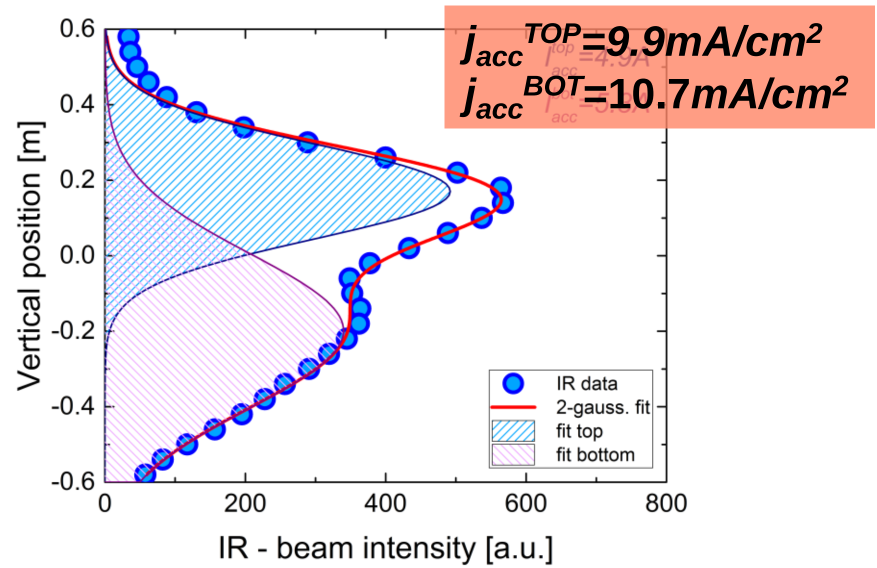

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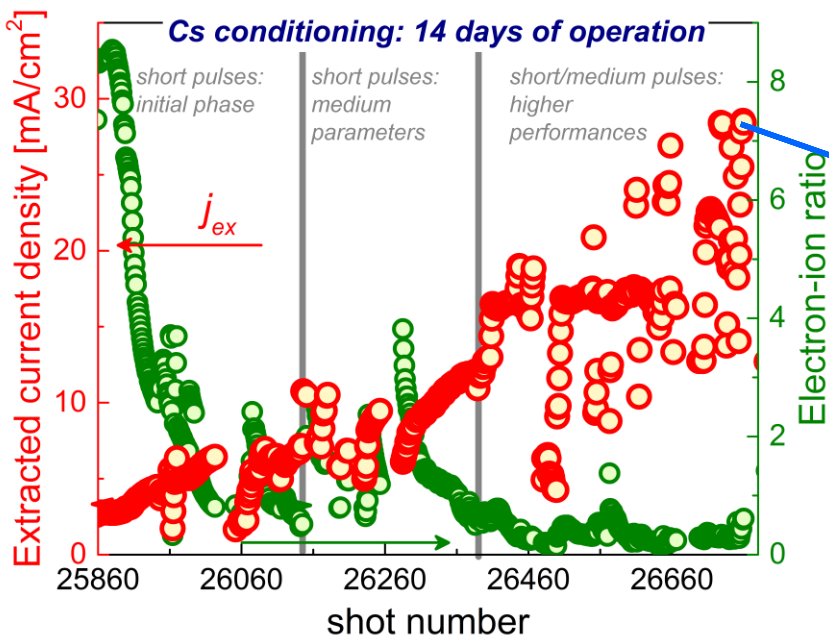
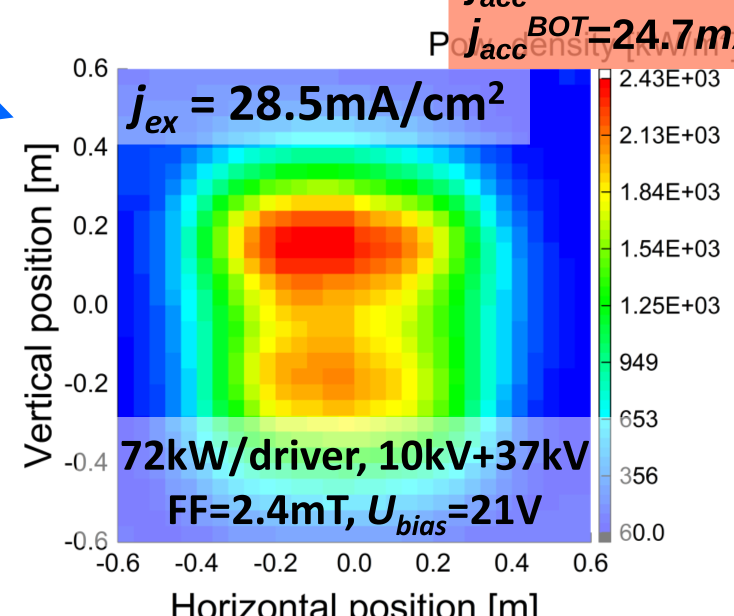


- **After 14 days (9 h plasma-on time):**
  j_{ex} up to 28.5 mA/cm²; $j_e/j_{ex} < 1$
  $j_{acc}^{BOTTOM} \approx j_{acc}^{TOP}$, but different optics

j_{acc}^{TOP}=24.9mA/cm²
j_{acc}^{BOT}=24.7mA/cm²



volume → *Cs evaporation* → caesiated source

ELISE large beam features
Cs conditioning process

- Constant Cs evaporation rate for both ovens
- Steps of “constant parameters” from volume to higher performances
- Short pulses in hydrogen (9.5 s beam into a 20 s plasma pulse)

- **After 14 days (9 h plasma-on time):**
  j_{ex} up to 28.5 mA/cm^2; $j_e/j_{ex} < 1$
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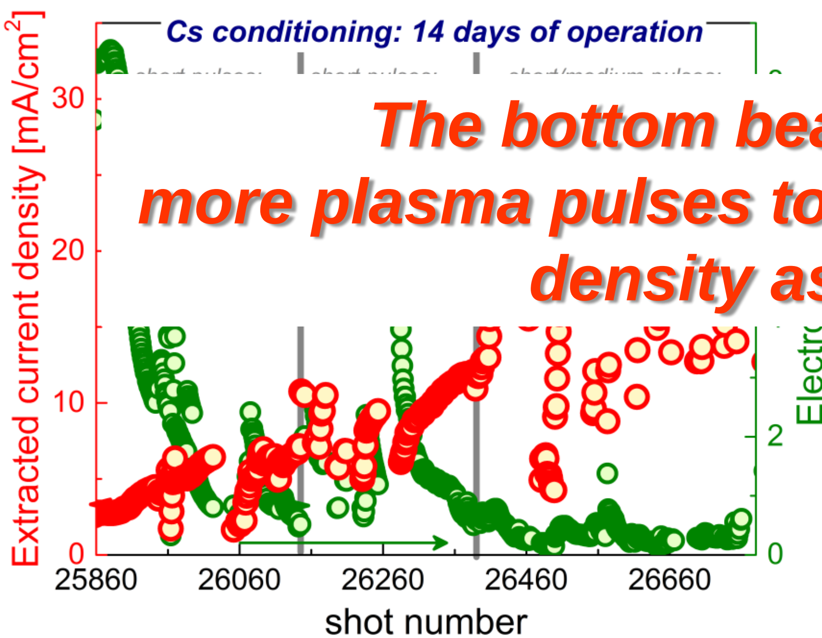
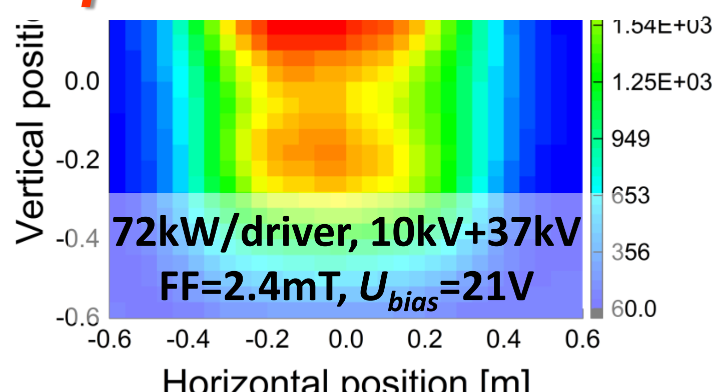
j TOP=24.9mA/cm²
mA/cm²



The bottom beam segment needs more plasma pulses to achieve the same current density as the top one!

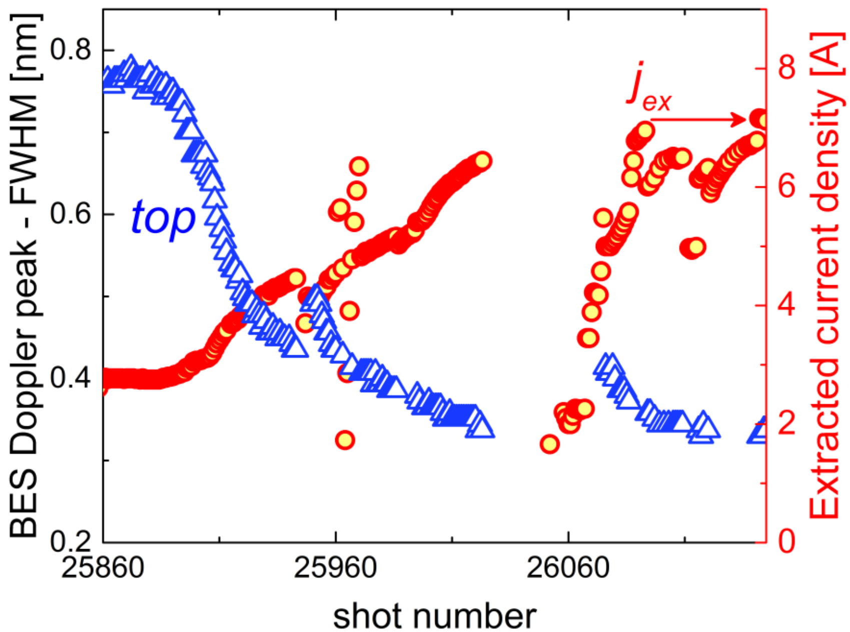


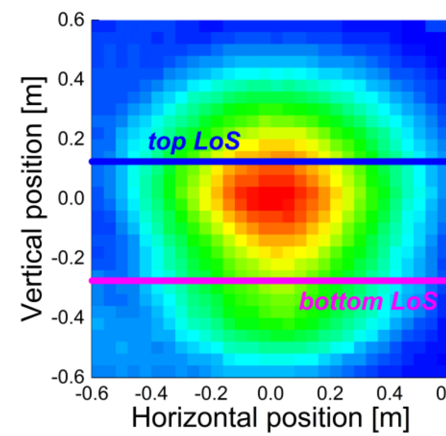
volume → Cs evaporation → caesiated source

BES measurements during Cs conditioning

- beam width decreases while j_{ex} increasing (divergence – perveance correlation)

First 4 days of operation:





volume → Cs evaporation → caesiated source

BES measurements during Cs conditioning

- beam width decreases while j_{ex} increasing (divergence – perveance correlation)
- **top & bottom beam width decreases with different time scales**

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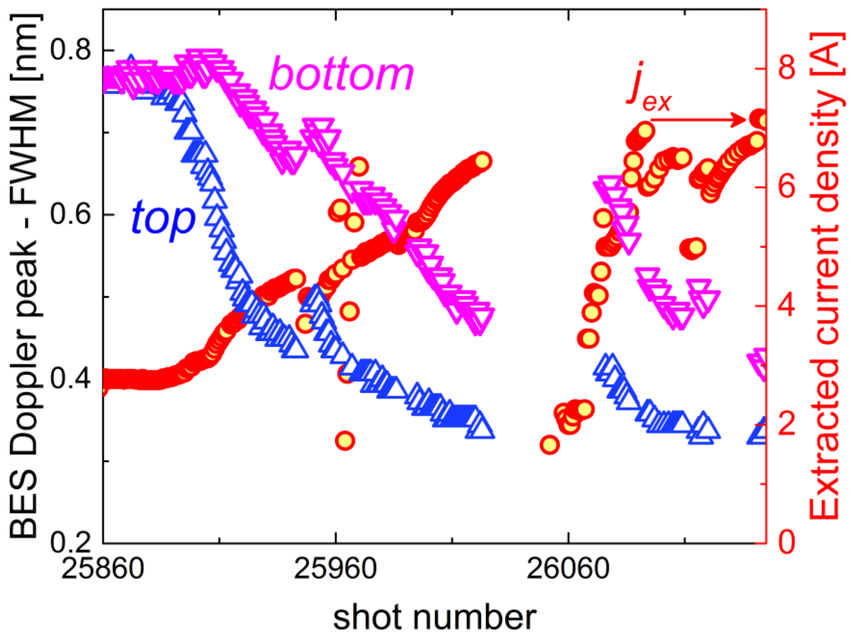

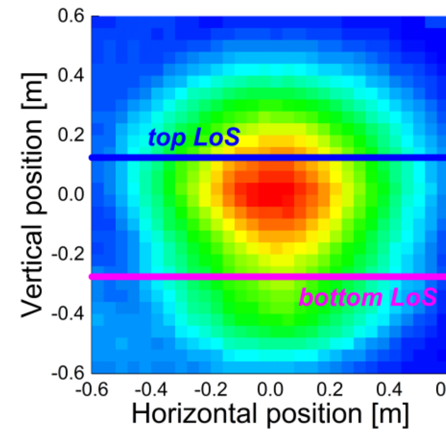

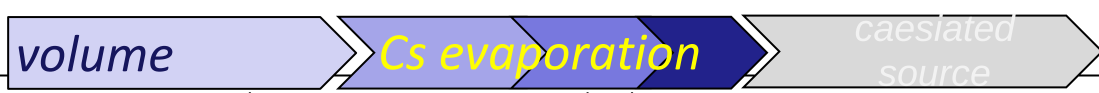

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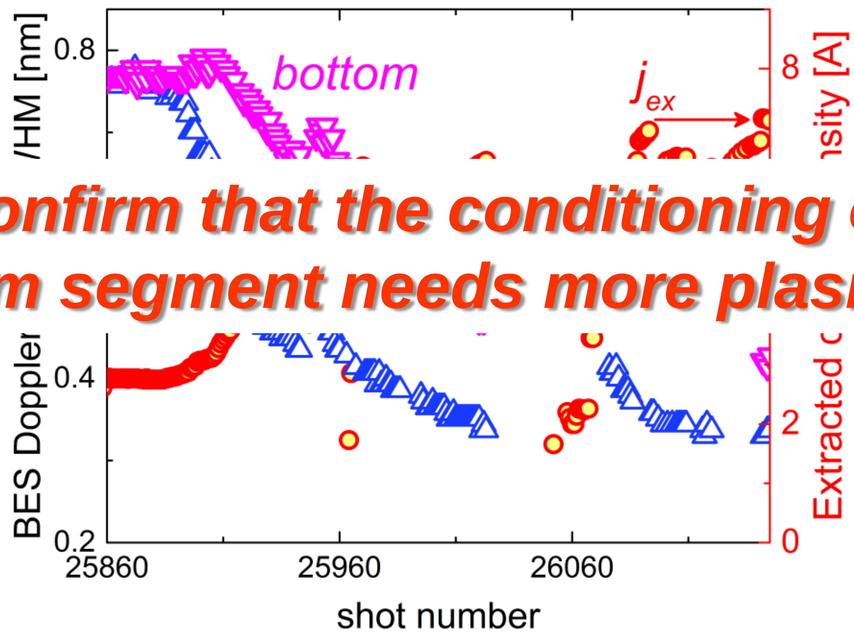
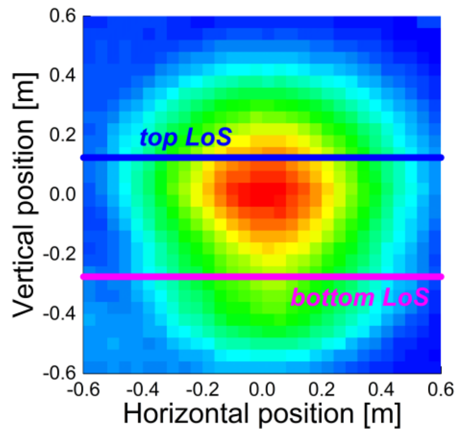
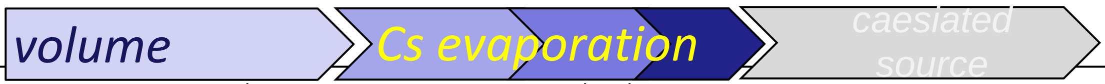


BES confirm that the conditioning of the bottom beam segment needs more plasma pulses!





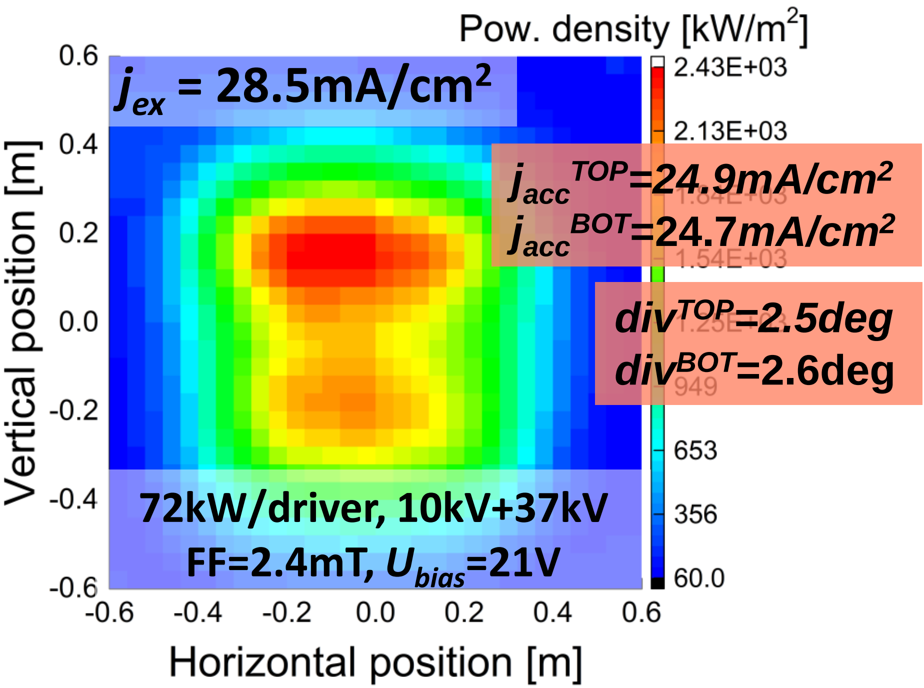
ELISE large beam
Beam optimization

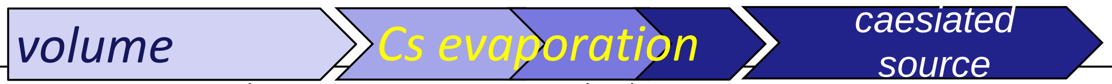
- ELISE: **global** homogeneity in terms of **top/bottom beam segments**
  - top/bottom accelerated current I_{acc} at the calorimeter (via IR analysis)
  - top/bottom beam divergence (BES)

In a good Cs conditioned source:

1. top/bottom accelerated currents are usually well within the 10%

2. similar top/bottom beam divergence is instead more tricky to get

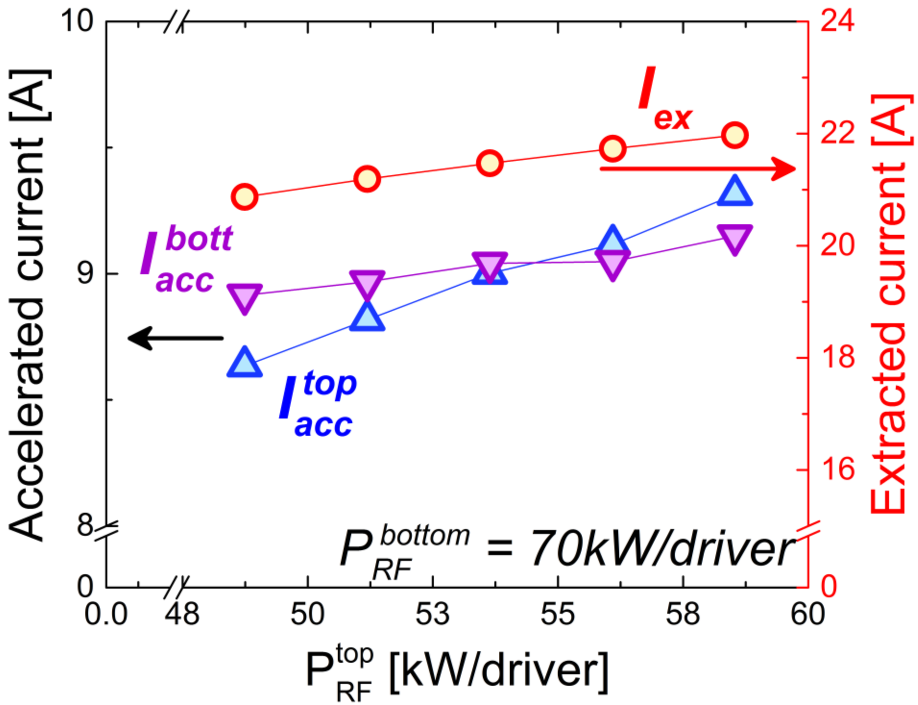


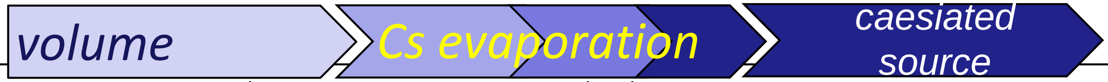


ELISE large beam
Beam optimization /2

1. Independent top/bottom RF power settings (RF top < RF bottom)

→ $I_{acc}^{TOP} = I_{acc}^{BOTTOM}$





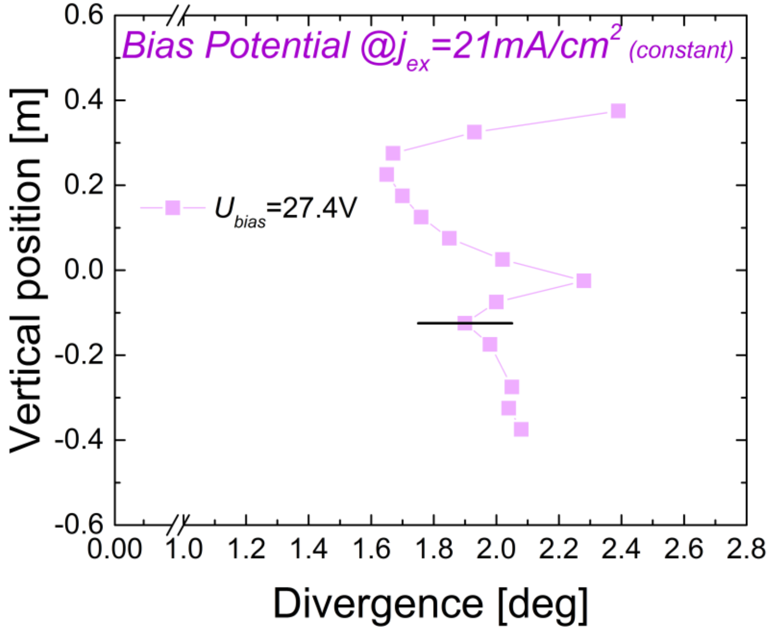
Beam optimization /2

1. Independent top/bottom RF power settings (RF ^{top} < RF ^{bottom})

   → $I_{acc}^{TOP} = I_{acc}^{BOTTOM}$

2. Effect of the bias potentials on the beam divergence profile

   → ***bias potentials change the flatness of the vertical divergence profile***



volume → Cs evaporation → caesiated source

ELISE large beam
Beam optimization /2

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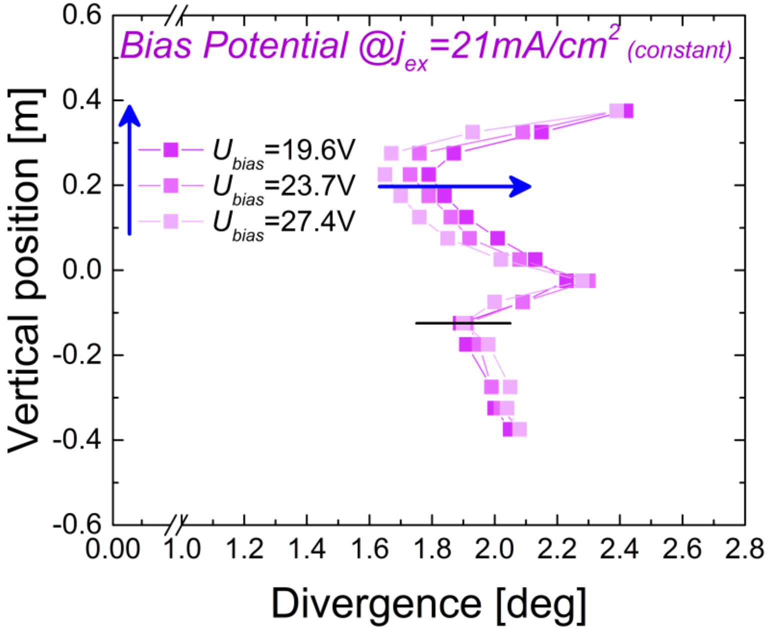

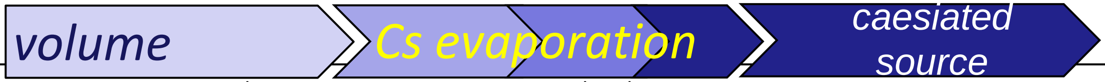

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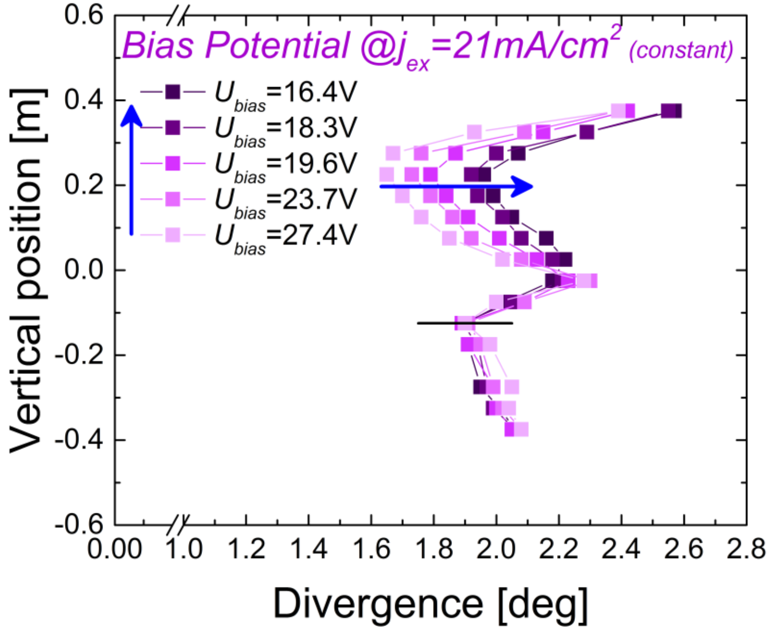

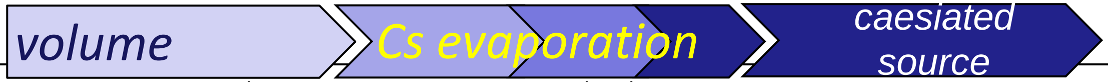

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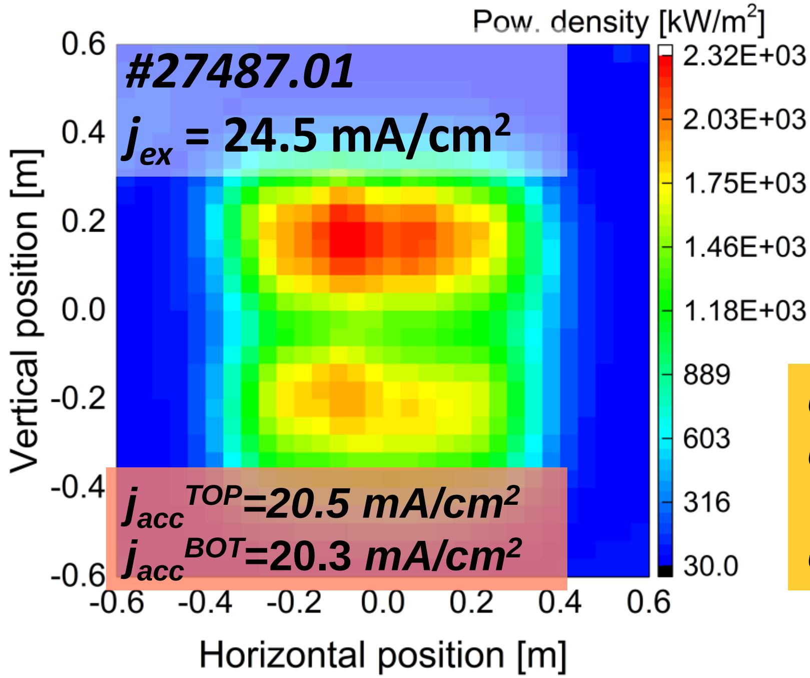
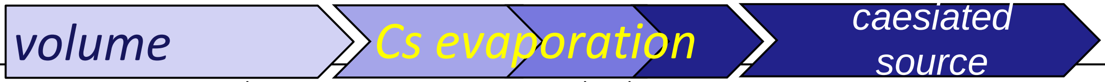


div^{TOP}=1.86deg
div^{BOT}=1.92deg

div^{VERT}=1.6deg



What have we learned so far?

- In **volume :**

  Beam uniformity not possible by simply RF tuning

- In the **Cs conditioning phase**:
  - **Long conditioning phase because of the potential rods**
  - **Top/bottom beam segments have different time-scales of conditioning**
    - bottom beam segment needs more plasma pulses

- **Large beam optimization** in a well conditioned source:
  - **Very good uniformity for the top/bottom accelerated currents**
    - fine tuning by independent RF power settings for different segments

      → very useful knob for ITER
  - **Some difficulties to keep the same top/bottom beam optics**
    - bias potentials help to change the vertical profile of the beam divergence

      → very useful knob for ITER