First Operations with Caesium of the Negative Ion Source SPIDER

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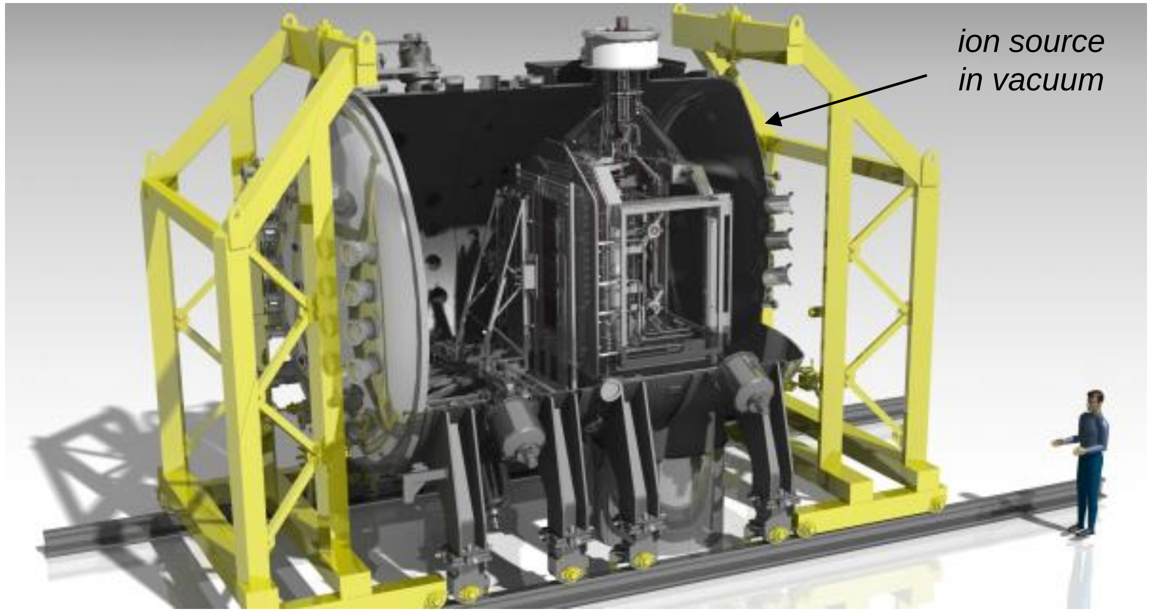
SPIDER full-size prototype source for ITER HNB



Full scale **plasma source** of ITER Heating Neutral Beams;
RF plasma source based on IPP design, 2x ELISE

Targets: optimisation of

- Extracted current density (355 A/m^2 H^-, 285 A/m^2 D^-)
- Uniformity over 1280 apertures (within 10%)
- Stability (1 h beam)
- Co-extracted electron fraction (<0.5 H^-, <1 D^-)

2018

first plasma

influence of vessel pressure on RF discharges clarified

2019

first extracted beam, masking most extraction apertures

source plasma studied with movable probes

2020

Improving availability and reliability [1h/day plasma on]

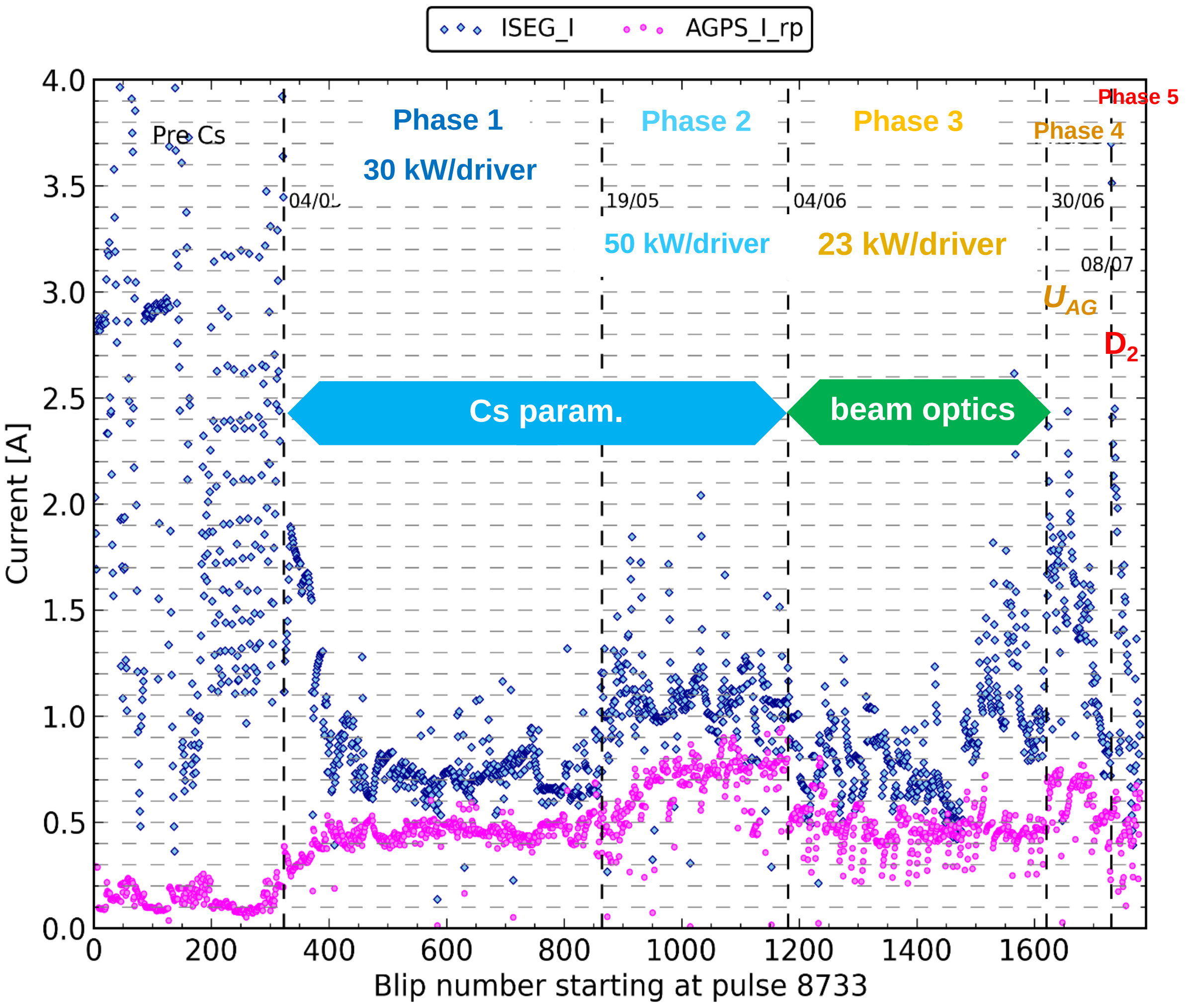
HV >30kV available

2021

First operation with caesium

shutdown for improvements

First Operations with Caesium of the Negative Ion Source SPIDER

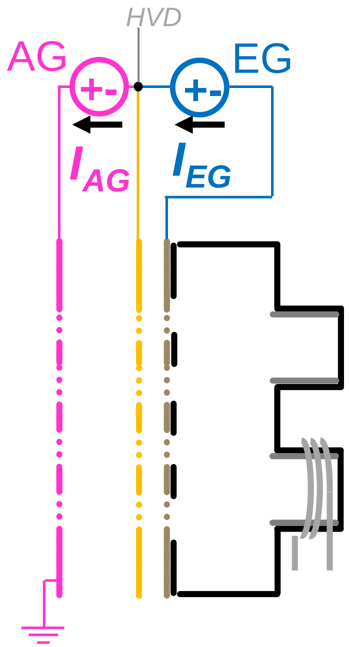


- Short-pulse operation (~30s plasma, ~15s beam on) about 1500 blips with Cs
- Investigation of
  - parameters influencing caesiation
  - beam optics [at low RF power]
  - HV-related technical issues

At sufficiently high U_{EG}, extracted ions and electrons:

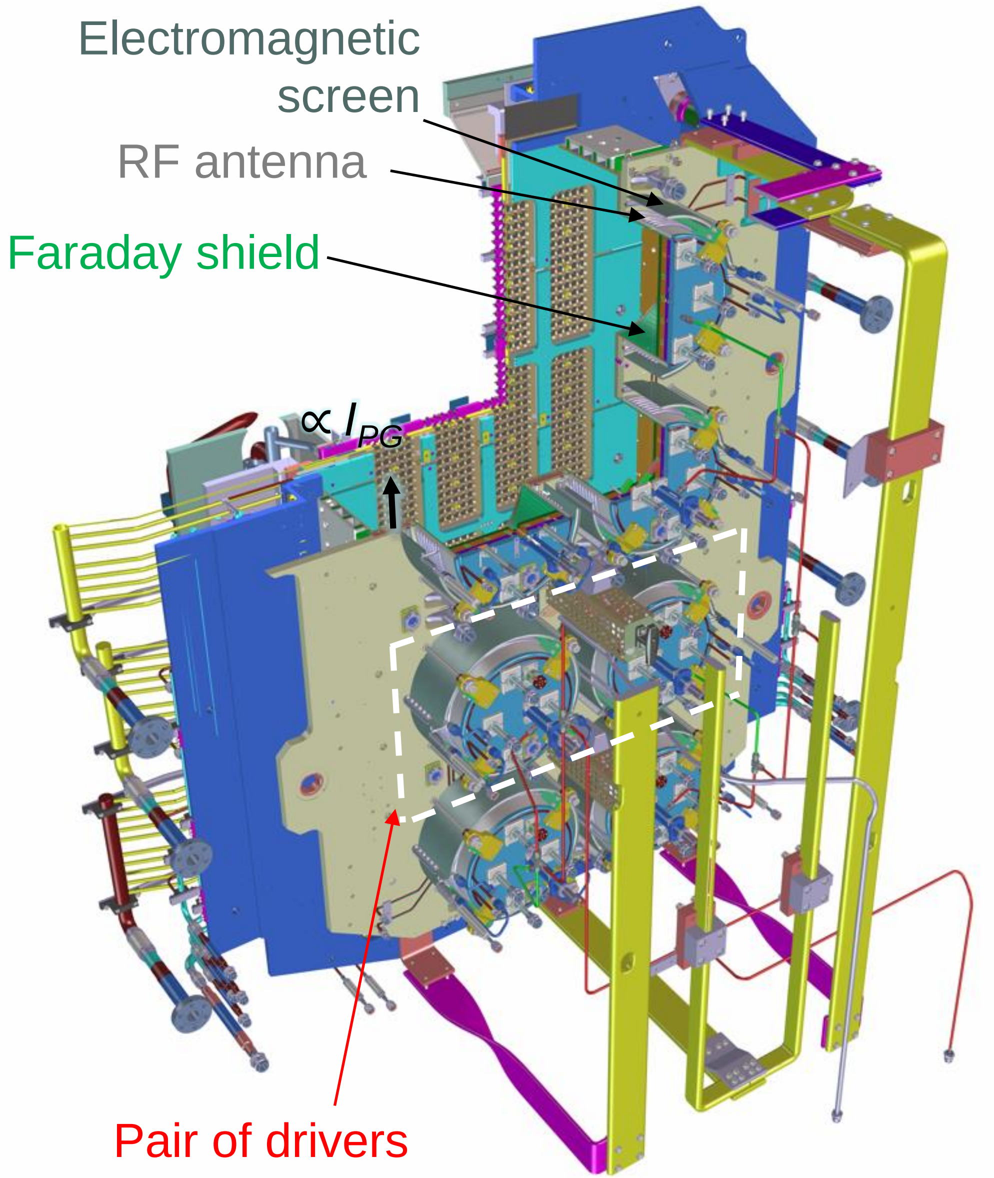
$$I_- \sim I_{AG}$$

$$I_e \sim I_{EG} - I_{AG}$$



Outline

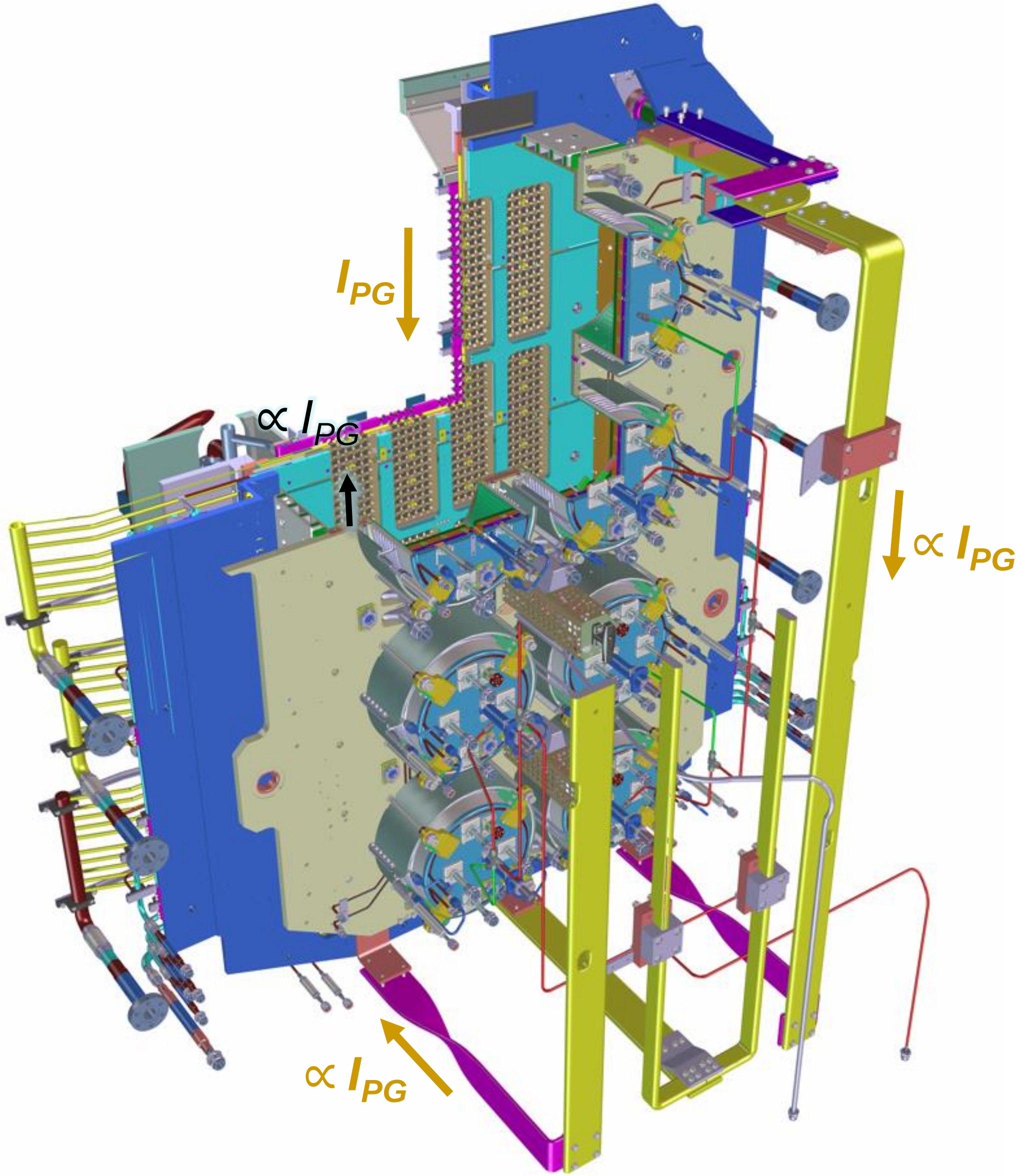
- SPIDER full-size prototype source for ITER HNB
- Effect of caesiation parameters
  - Cs evaporation rate, pulse repetition time, PG temperature
- Main beam features
  - Single beamlet optics at low energy
  - Tuned RF power to compensate non uniformities
  - Stability in deuterium
- Conclusions: performance throughout campaign



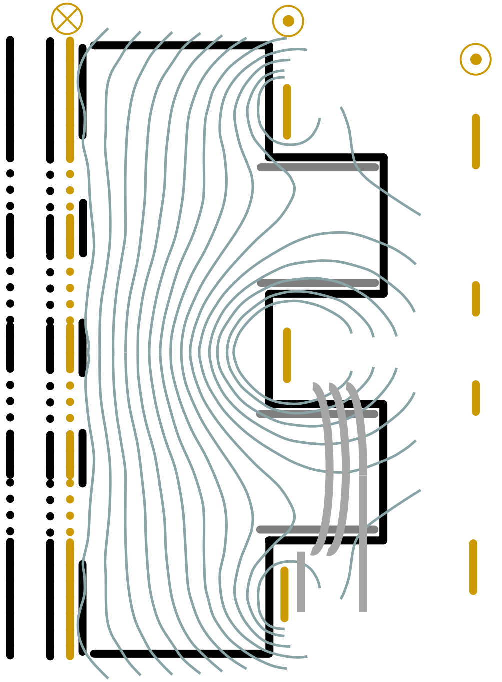
- 4 horizontal pairs of RF drivers
- Present **limit** for reliable beam operation **50 kW/driver**
- Pulse **duration limit** due to power on defective passive element (i.e. < 40s @ 50kW/driver)

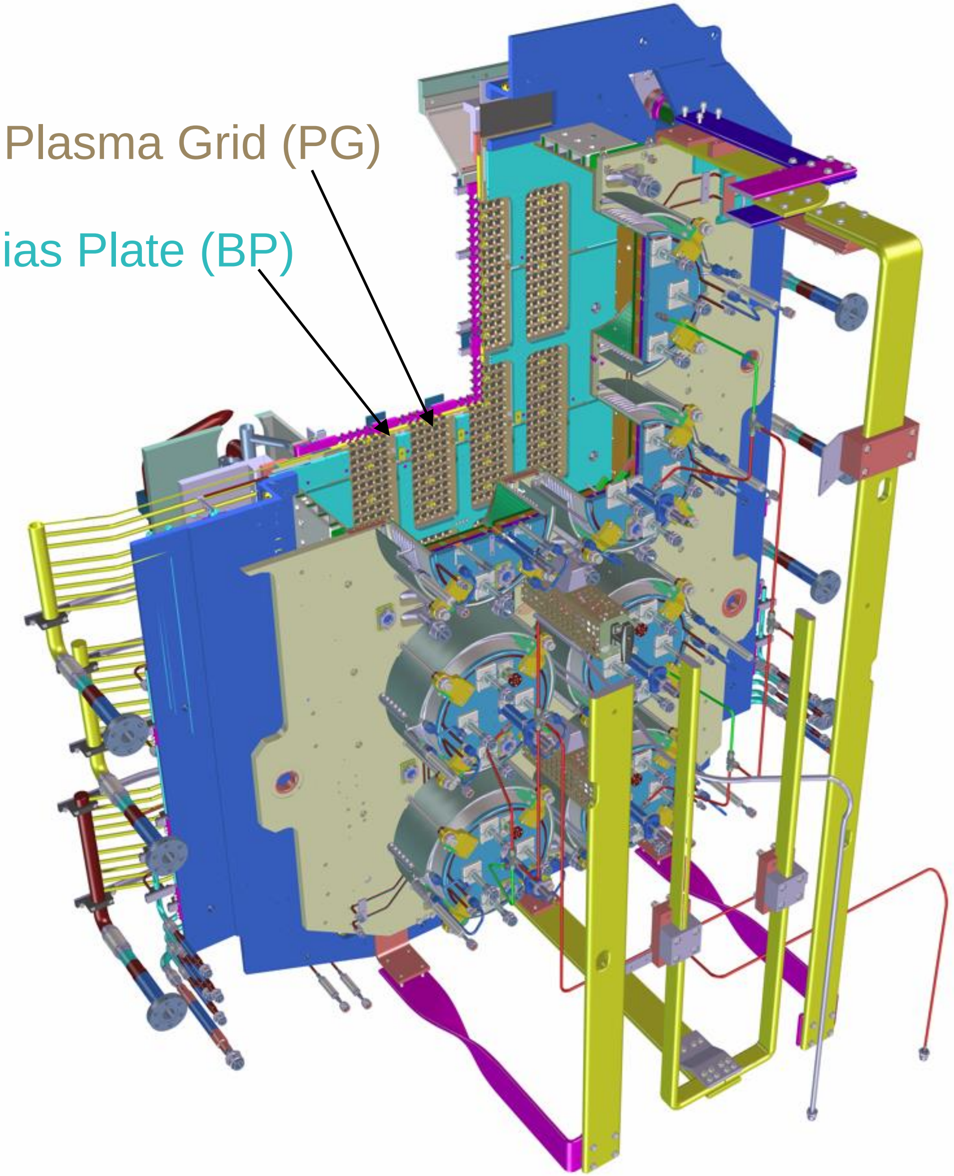
P. Jain, poster #142: Experimental investigation of RF driver equivalent impedance in the inductively coupled SPIDER ion source

R. Casagrande, Techniques to widen the operational space of SPIDER radio frequency driven plasma source



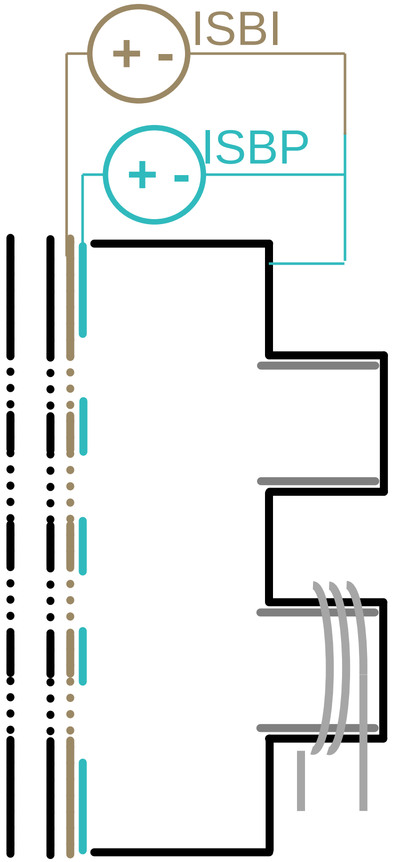
- I_{PG} creates horizontal filter field (before PG, about 1.6mT/kA)

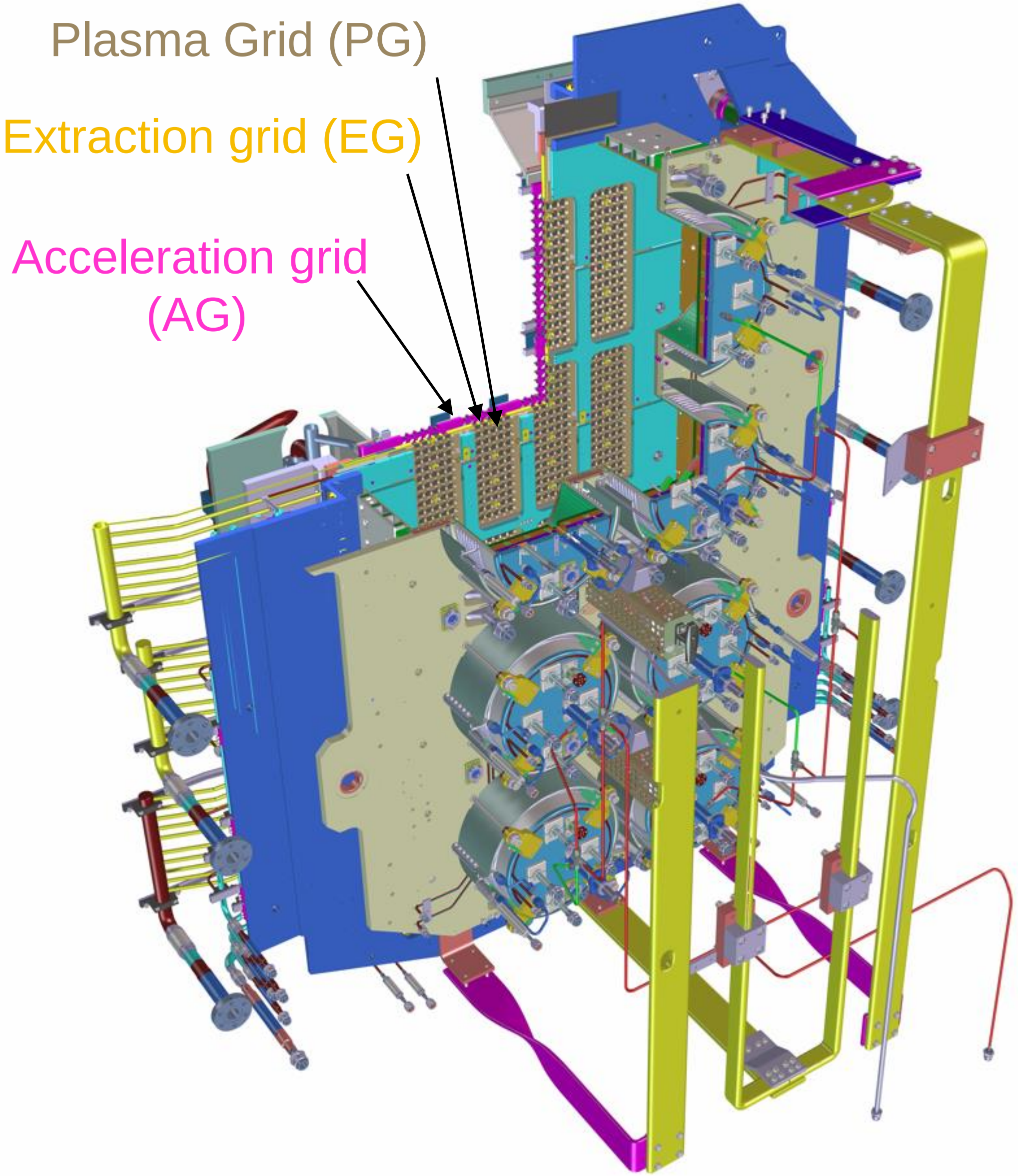




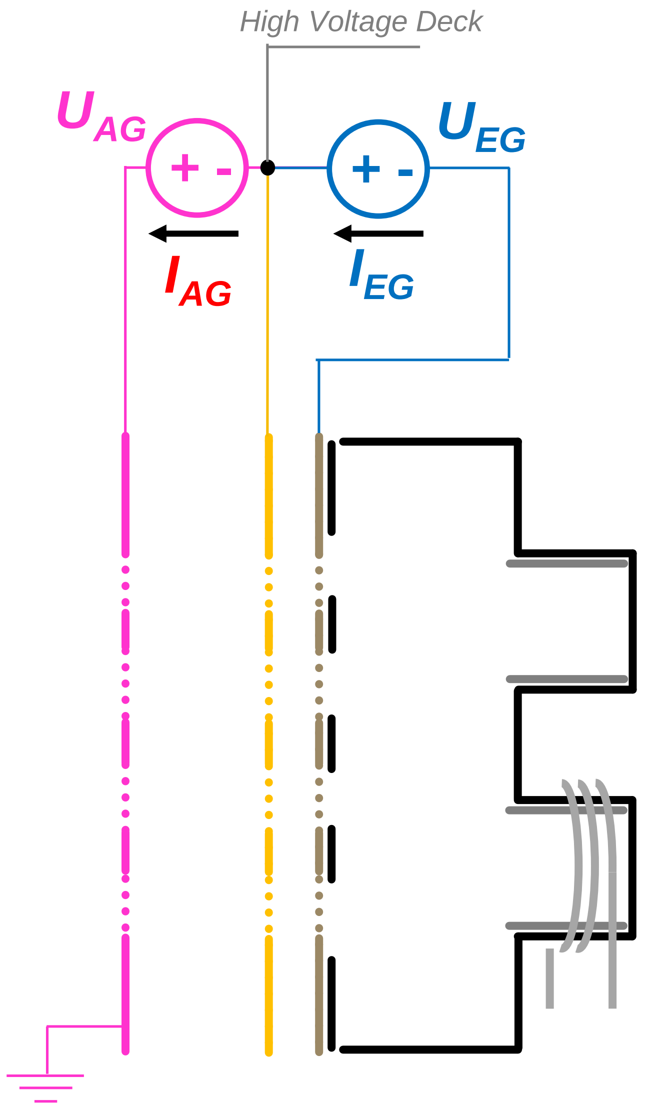
- I_{PG} creates horizontal filter field (before PG, about 1.6mT/kA)
- Bias of Plasma Grid (PG)
- Bias of Bias Plate (BP)

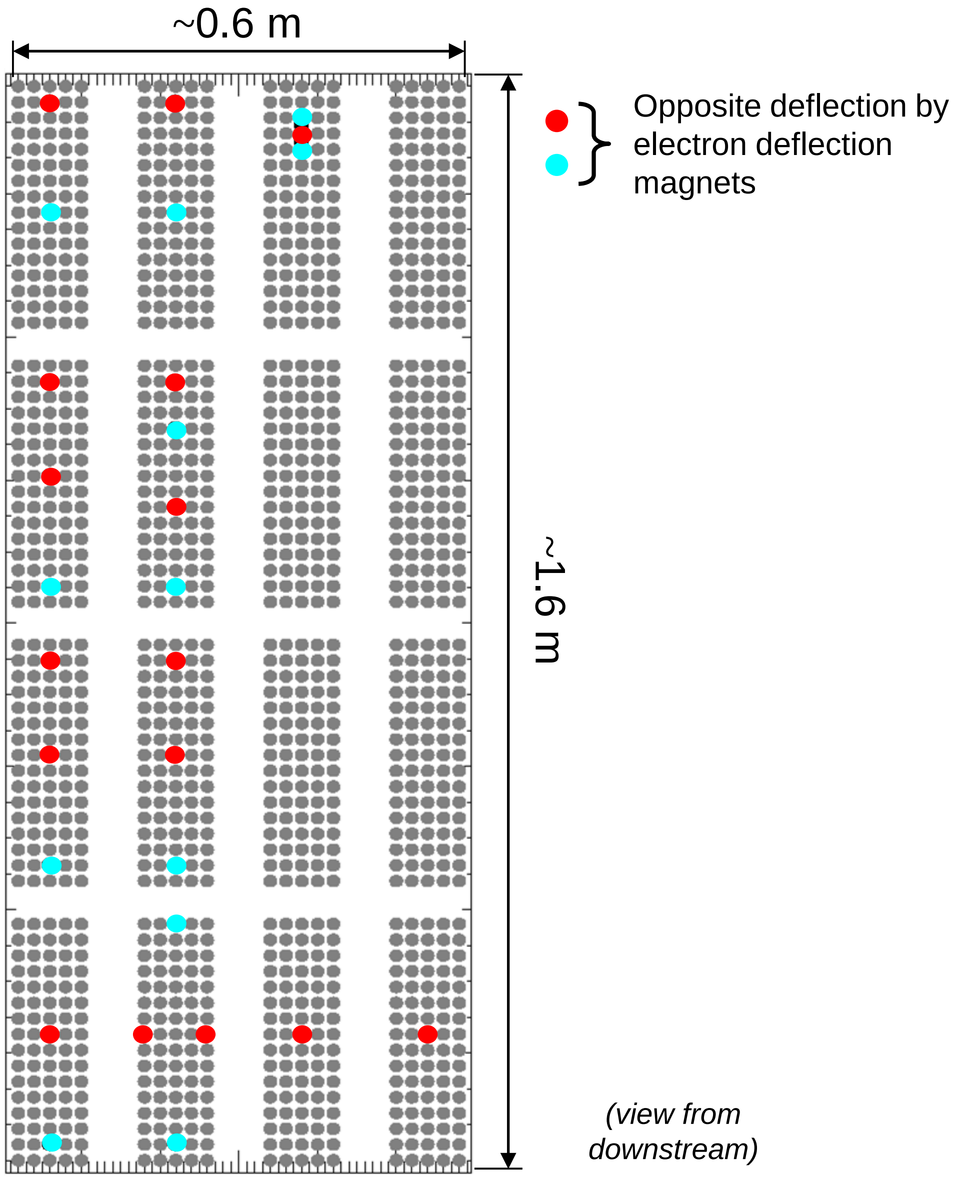
(either current- or voltage-controlled)





- I_{PG} creates horizontal filter field (before PG, about 1.6mT/kA)
- Bias of Plasma Grid (PG)
- Bias of Bias Plate (BP)
- **EG power supply**: 0-12kV
- **AG power supply: limited to about 45 kV**
- Nominal ratio U_{AG}/U_{EG} = 9.5





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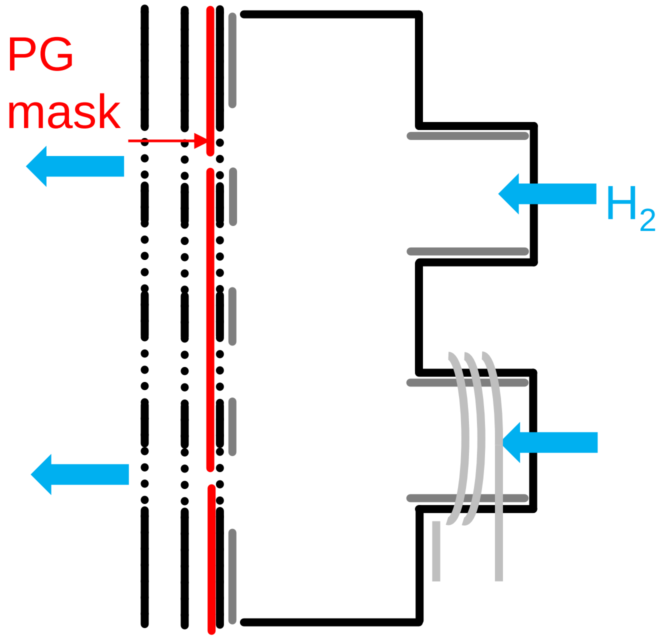
- **EG power supply**: 0-12kV
- **AG power supply**: **limited to about 45 kV**
- Nominal ratio U_{AG}/U_{EG} = 9.5
- **mask covering most apertures at PG:**
  - Limit on vessel pressure (45mPa)
  - Limit on gas load to cryopumps (40 bar L / day)
  - Choice of beamlet



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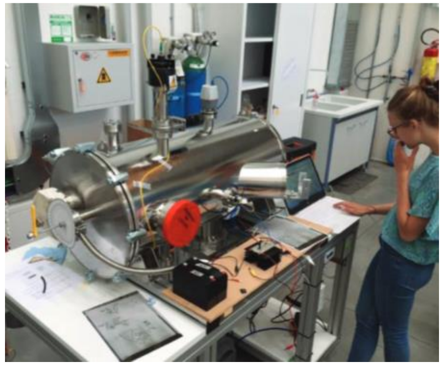
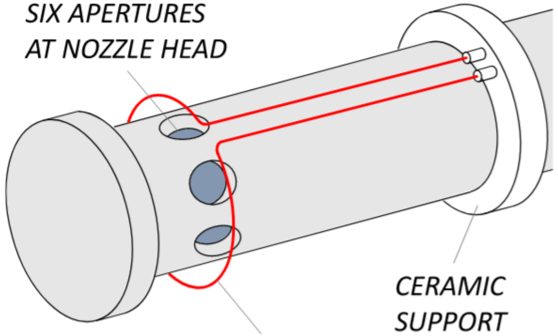
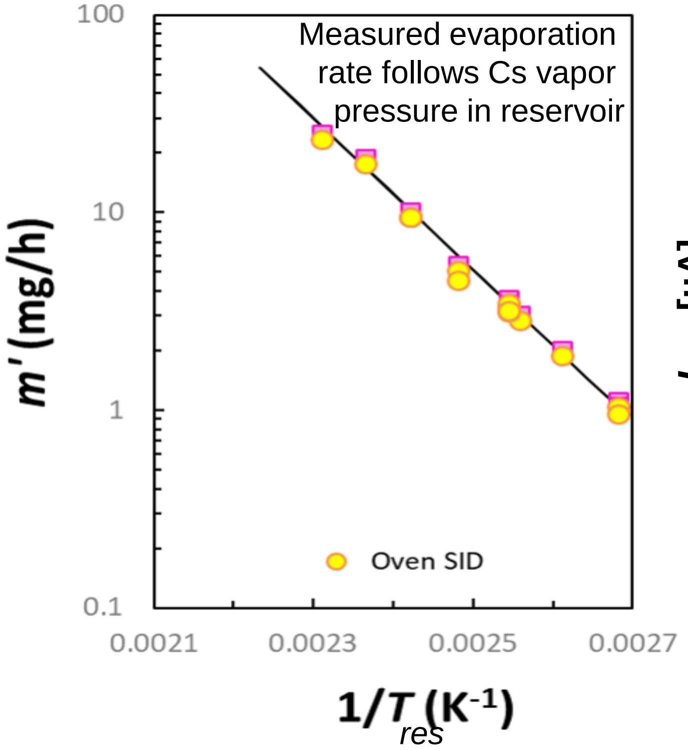
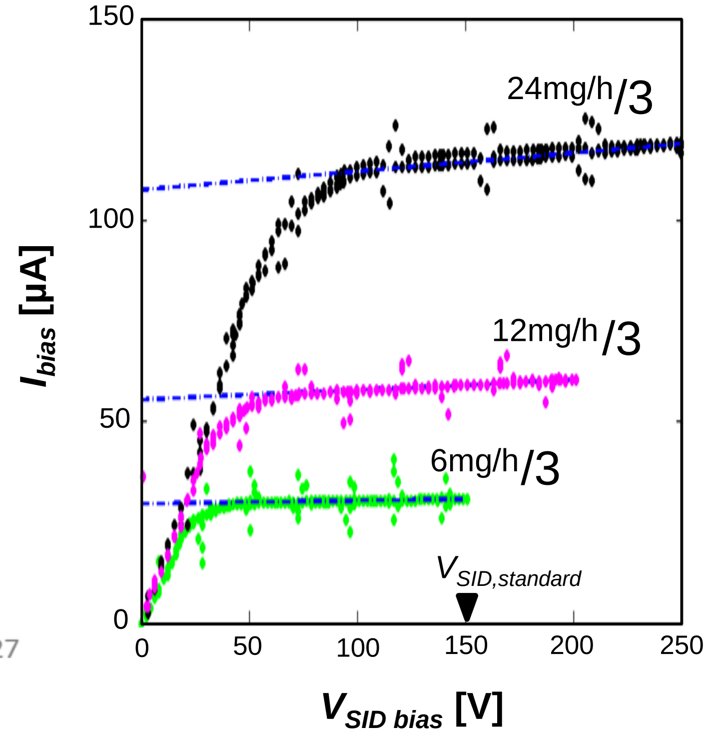
1) Caesium injection rate



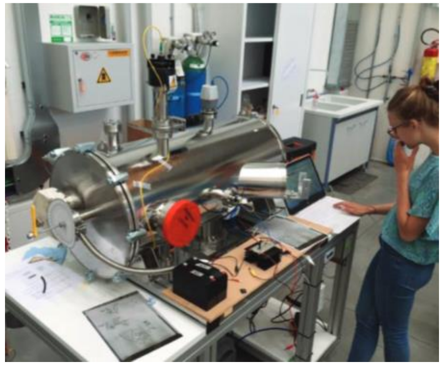


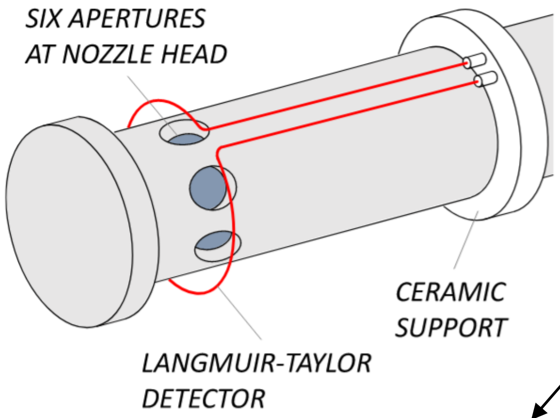
- 3 Cs ovens installed in vacuum
- characterised in dedicated test stand
- control of Cs evaporation rate
  - repeatability
  - affects source operation
  - affects voltage holding of accelerator





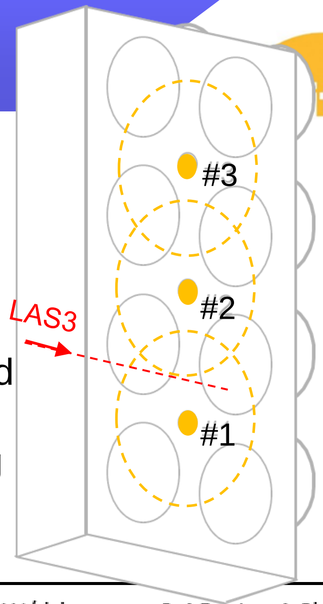
1) Caesium injection rate

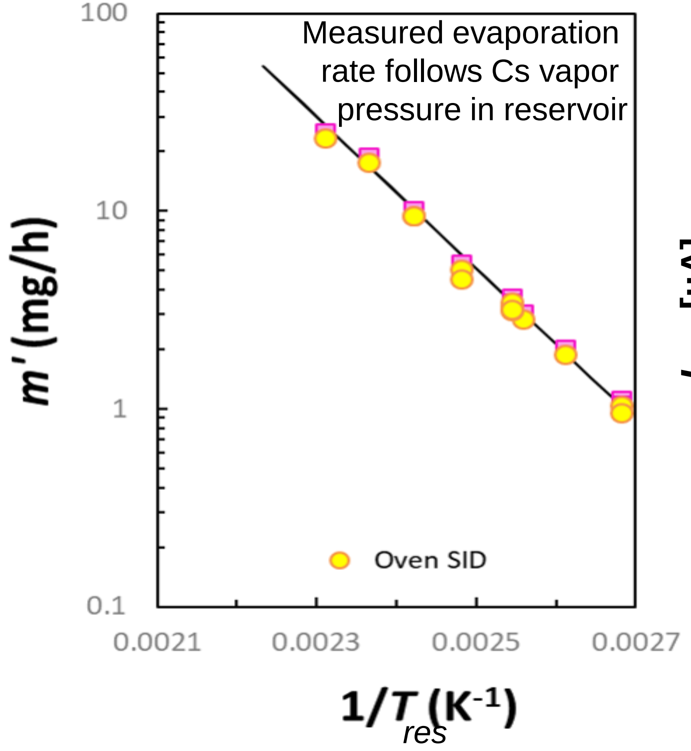


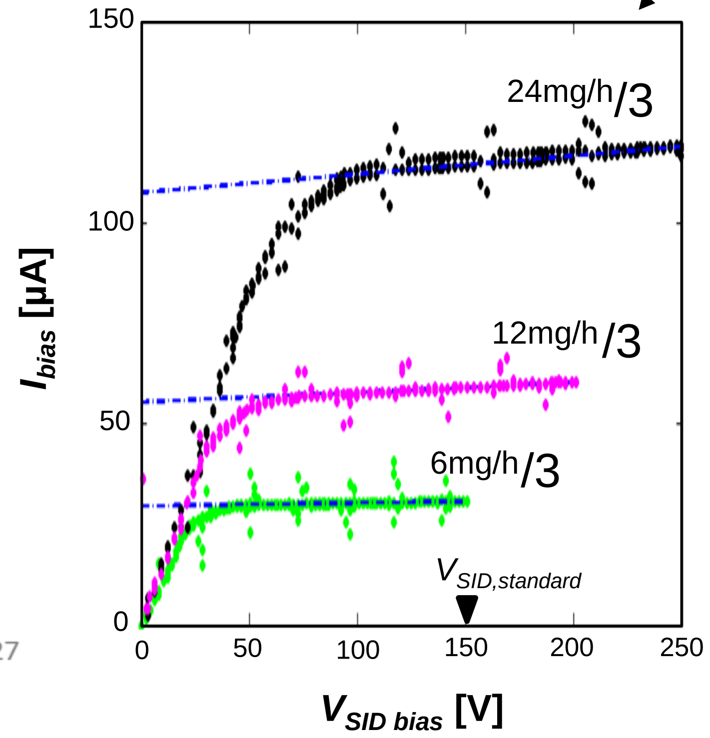


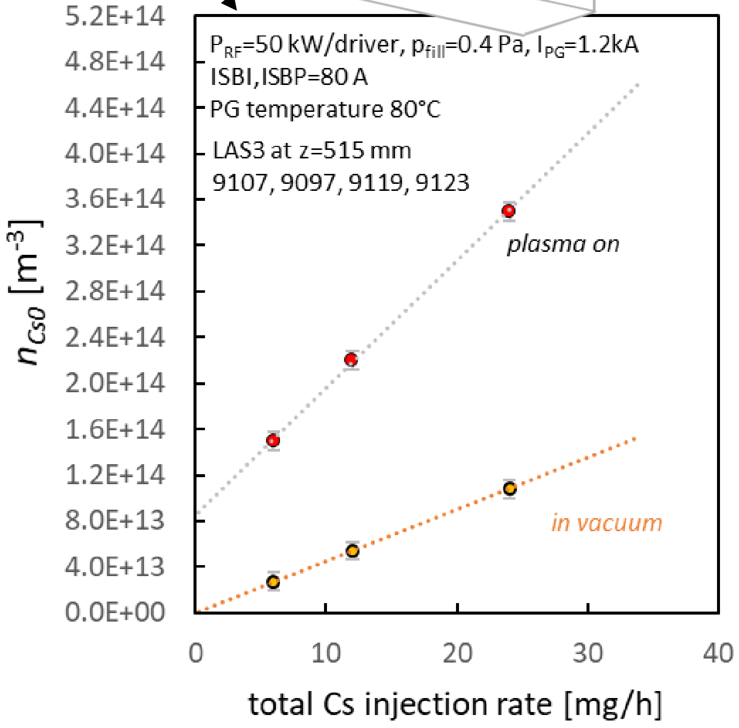
Cs evaporation (measured between plasma pulses)

Cs density measured at extraction region (between and during plasma)

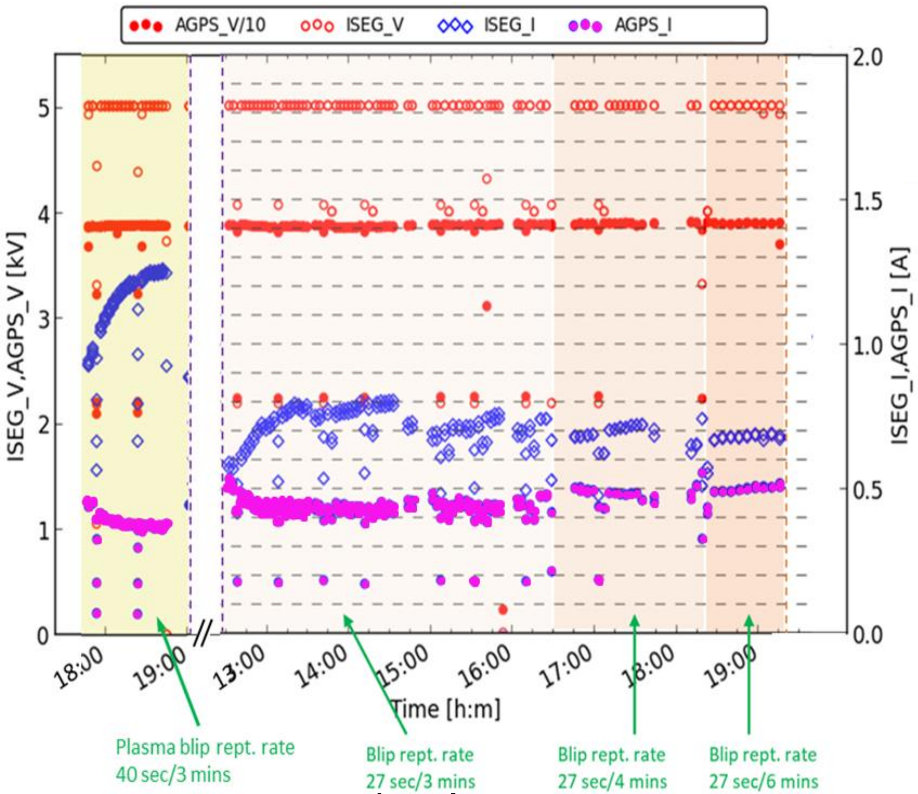








2) Repetition rate of plasma pulses

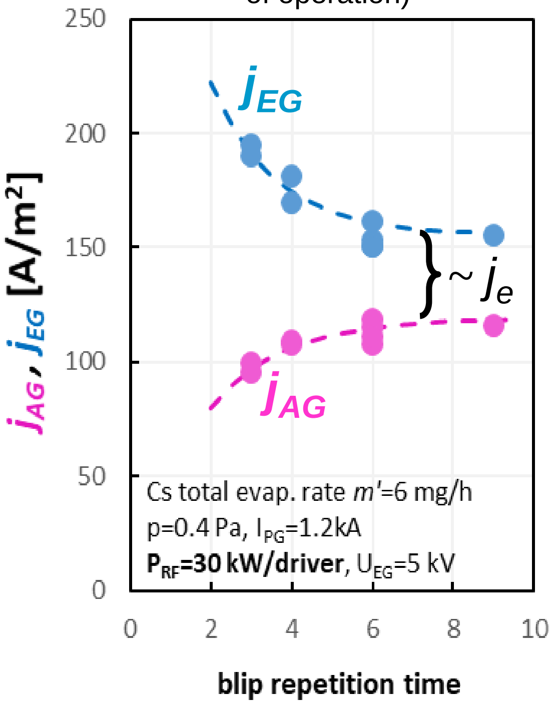


27sec/3min

27sec/4min

27sec/6min

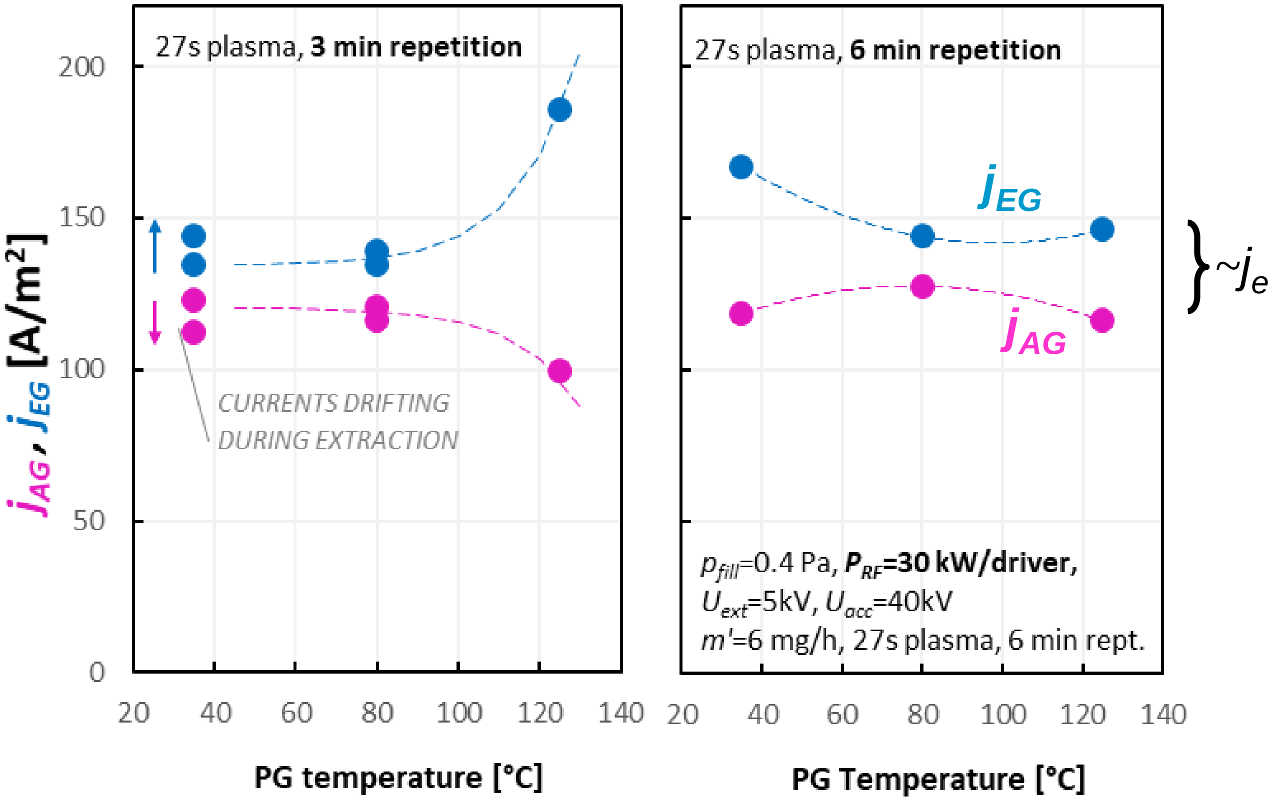
(saturation currents; one point requires hours of operation)

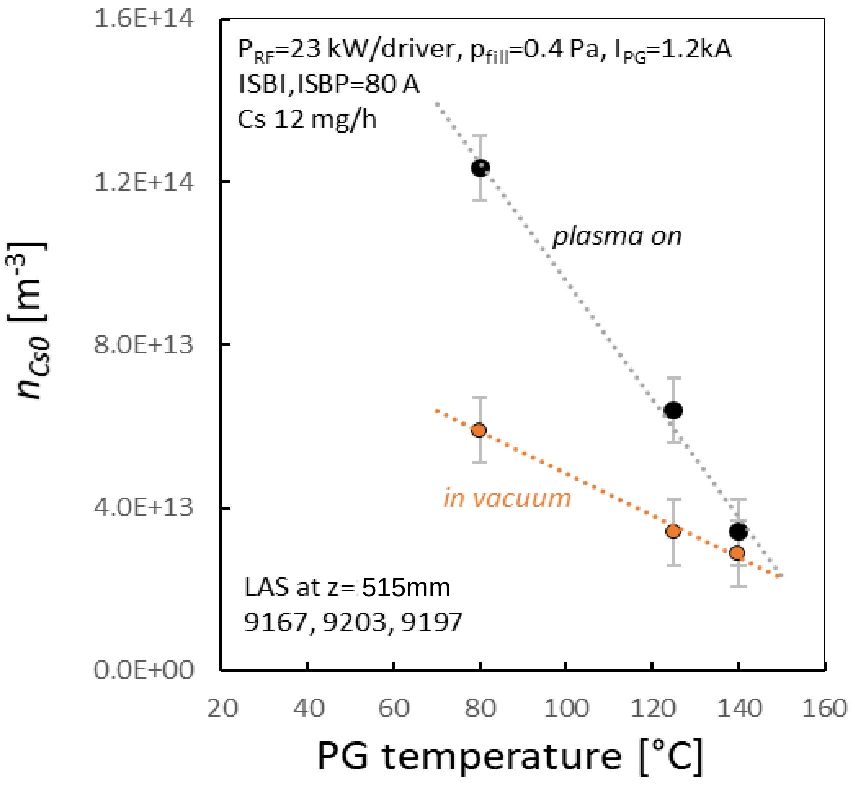


- For given Cs injection rate and source parameters:
  - Longer time between plasma, better performance
  - Shorter plasma-on time, better performance
- Equilibrium between *positive* and *negative fluxes* of Cs to converter surface
- During plasma, two possible mechanism (competing)
  - Plasma removes Cs from converter surface
  - Plasma increases Cs transport towards converter and/or reactivate Cs layer
- During vacuum phases, sticking to converter surface of Cs

3) Dependence on plasma grid temperature

- Thermal desorption at converter is a further contribution to balance of Cs at converter
- PG temperature: can be controlled between 35°C and about 150°C
- steady-state extracted and accelerated currents: in general, beam performances decreases above PG temperature of 80°C
- Cs density at extraction region decreases with PG temperature, both in vacuum and plasma phases





Influence of caesiation parameters in SPIDER, short-pulse op.

- Build-up of Cs layer at converter is a balance of competing processes
- Normalisation: "duty cycle/evap. rate"

$$\nu = \frac{t_{plasma}}{t_{rept} \cdot \boldsymbol{m'}}$$

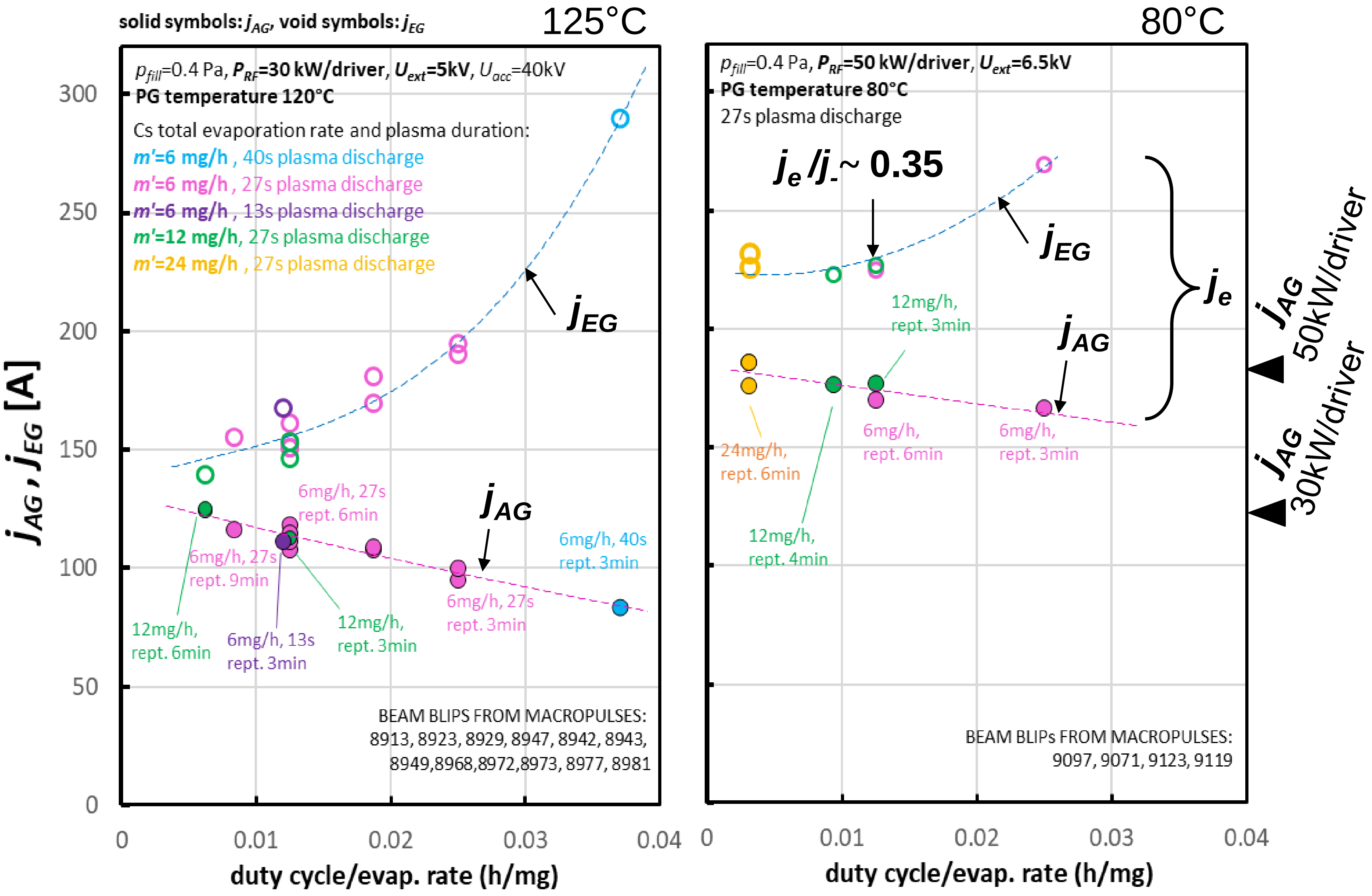
- In the plot, saturation values of j_{EG} and j_{AG} for various plasma duration, pulse repetition time, and caesium injection rate
- PG temperature has large influence, not included in this normalisation

Example:

at 50kW/driver, $j_{electrons}/ j_{H-}$= 0.35 at ν = 0.013

Target: 4 min every 16 min → duty cycle 0.25

Cs evaporation: duty cycle / ν =19 mg/h



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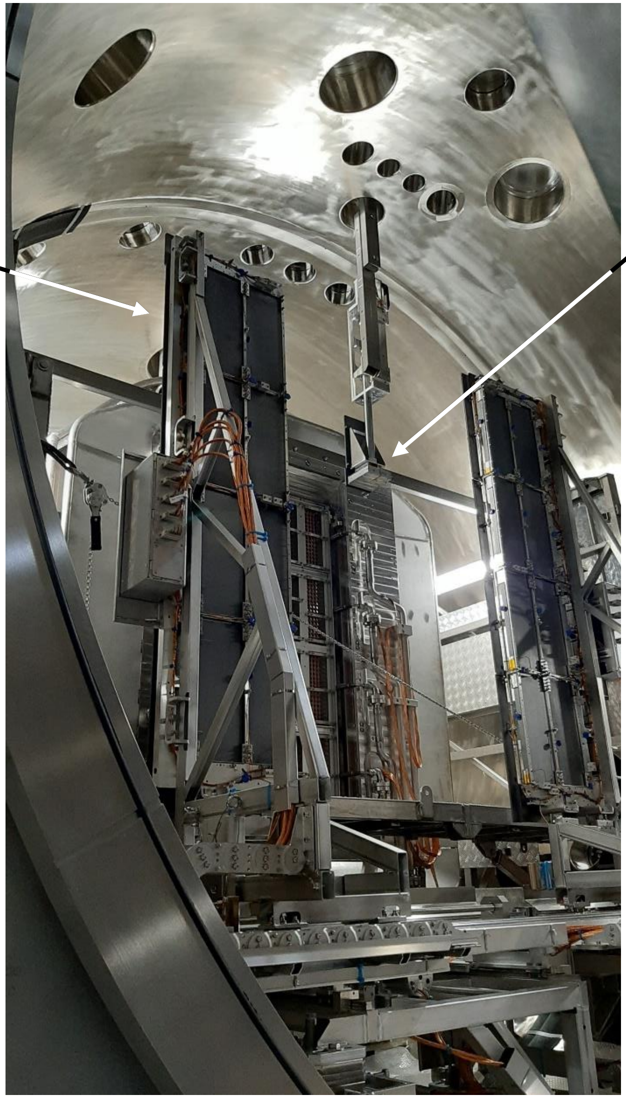
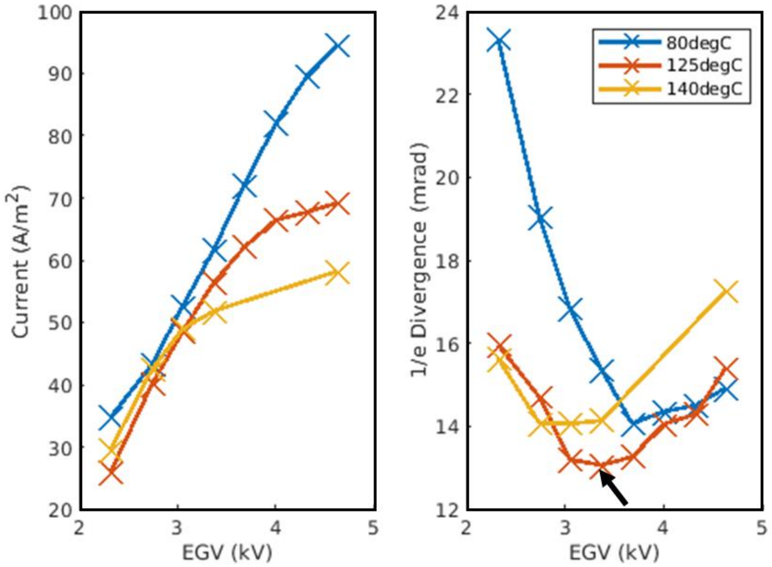


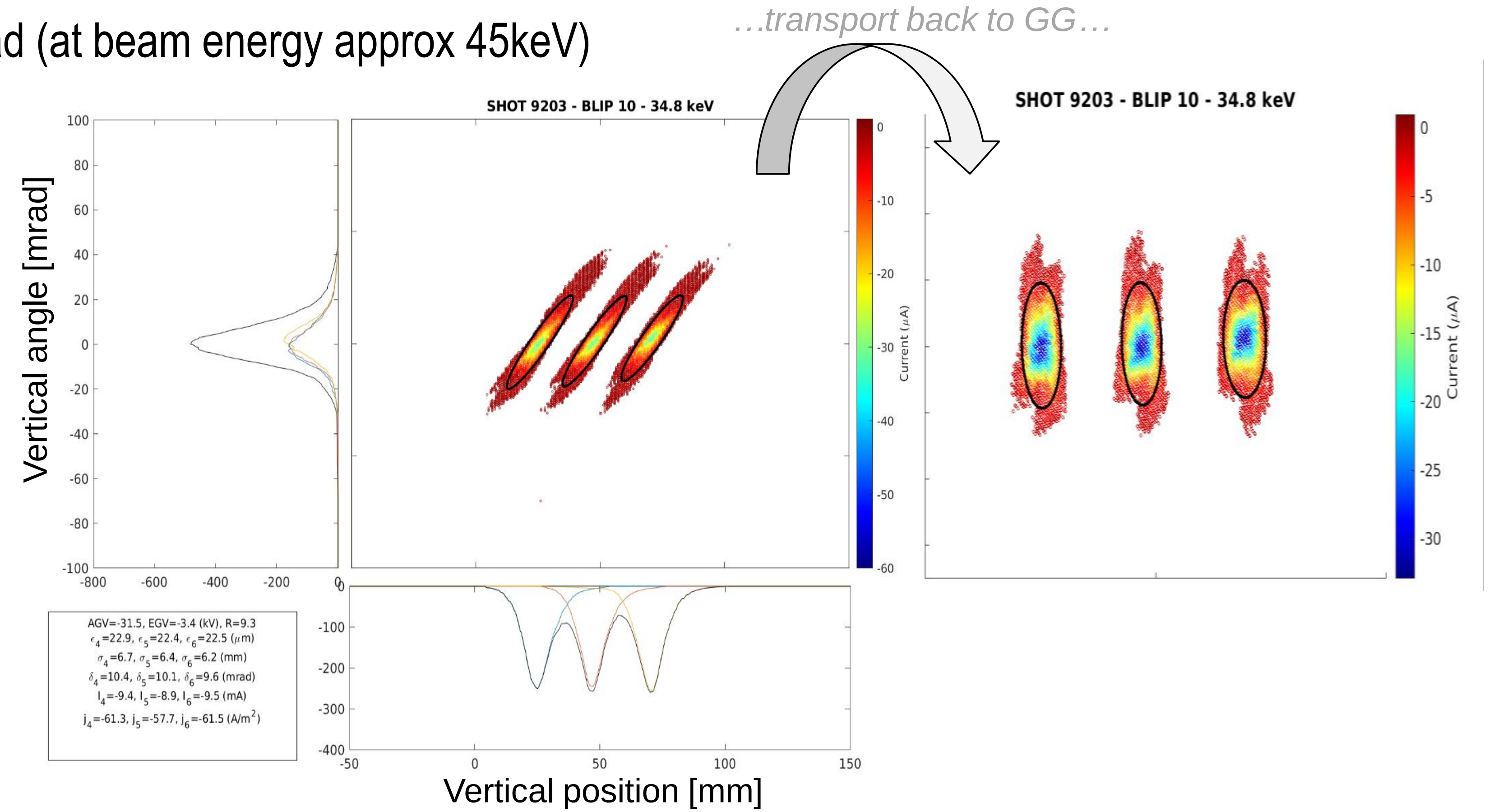
Multibeamlet optics at 23 kW/driver: 3 adjacent beamlets

- Either usign IR imaging at CFC tiles or **Allison type Emittance scanner**
- Emittance scanner intercepts **three adjacent beamlets** along its vertical run
- Optimal divergence about 13 mrad (at beam energy approx 45keV)

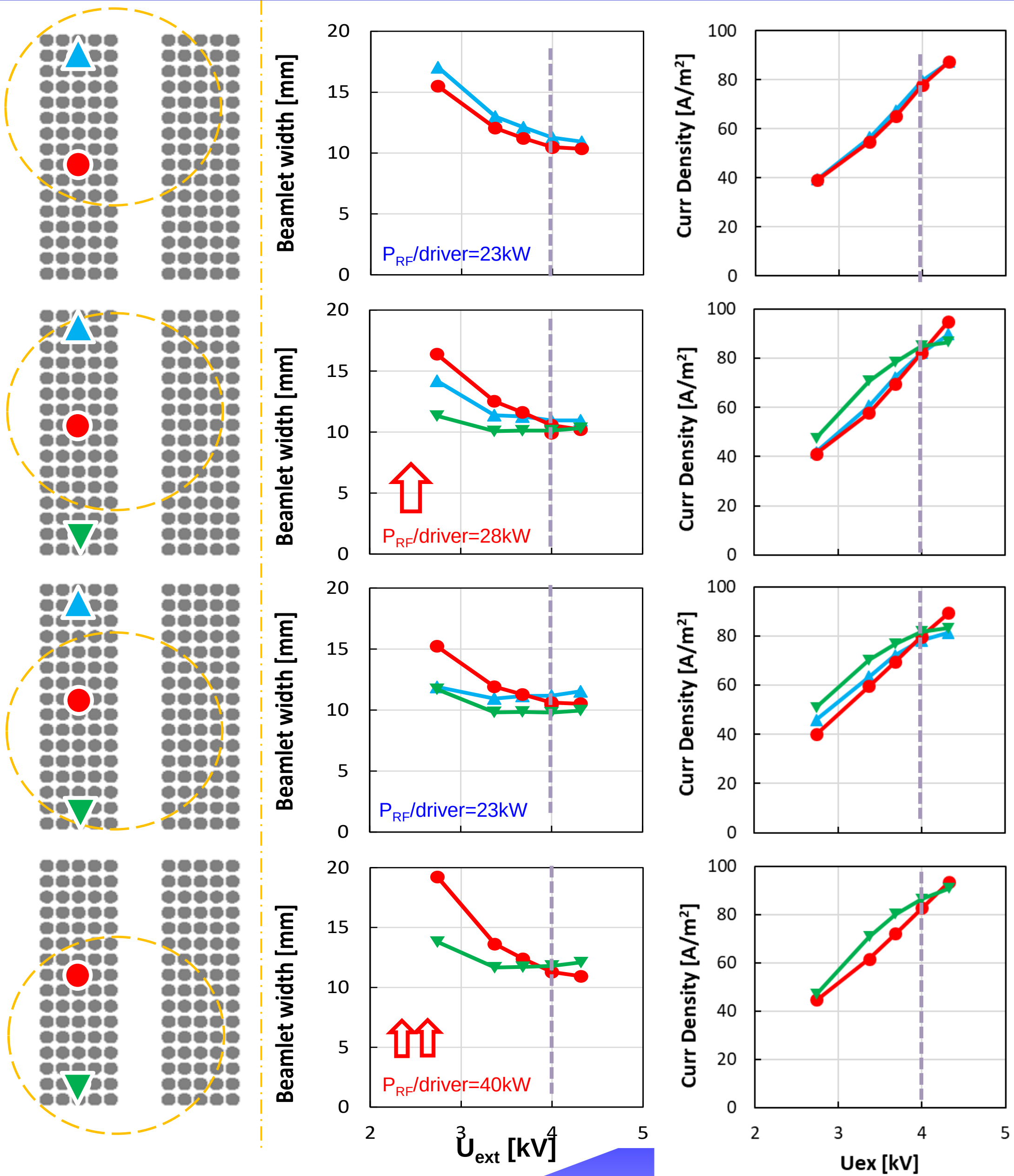
C. Poggi, poster "Phase-space characterization of SPIDER beam using an Allison type emittance scanner", (session 2 tomorrow)



Example:
center beamlet, current and divergence
U_{EG} scan with varying PG temperature



Multibeamlet operation at 23 kW/driver

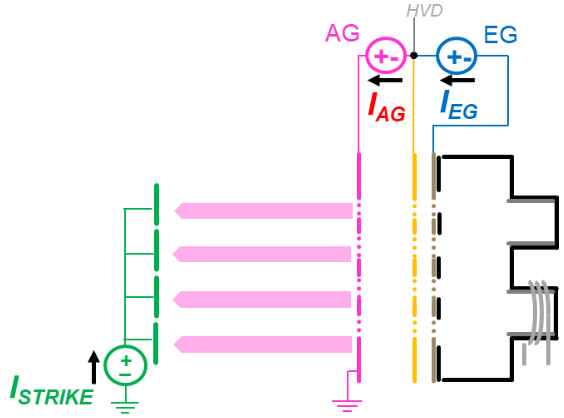


- **High filter field, high PG bias** improves electron to ion ratio; however vertical uniformity becomes poorer
- **Balancing RF power**, the beam vertical profile can be tuned
- Example: **beam optimised for 4kV extraction**
- Minima of beamlet divergence rather flat on the underperveant side: nonuniformities on the scale of the beamlet group can be dealt with

macropulse 9281, 9282
U_{ext} scan, U_{acc}/U_{ext}=9.5
p_{fill}~0.35 Pa,
I_{PG}=1.05kA (1.6mT)
23kW<P_{RF}/driver<40kW,
$j_e/j_{-,acc}$ ~ 1 @4kV
STRIKE at 0.5m, width 1/e

Beamlet current density based on current collected at calorimeter (I_{STRIKE} < 0.85 I_{AG})

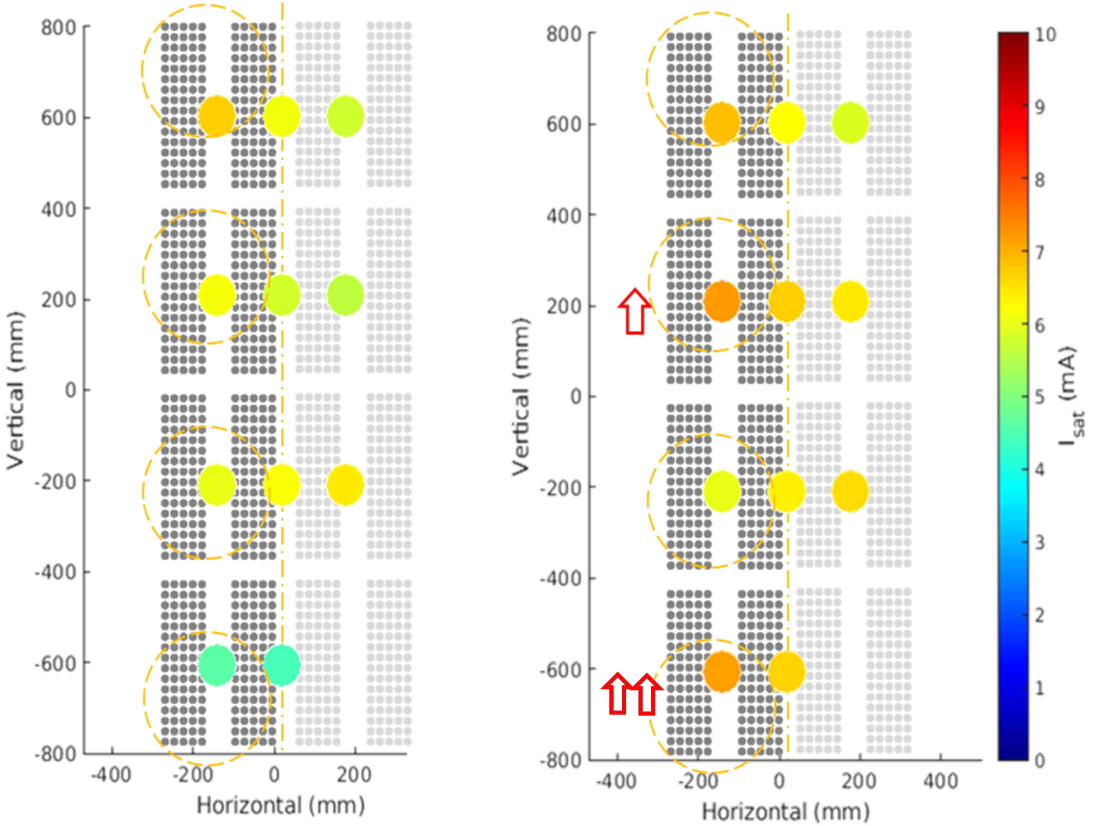
Purpose: optimise current density for 4 kV extraction voltage



Multibeamlet operation at 23 kW/driver

Positive saturation current at PG probes 9280

Positive saturation current at PG probes 9282



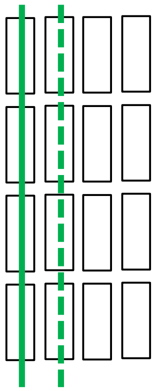
P_{RF}/driver=23kW
P_{RF}/driver=23kW
P_{RF}/driver=23kW
P_{RF}/driver=23kW

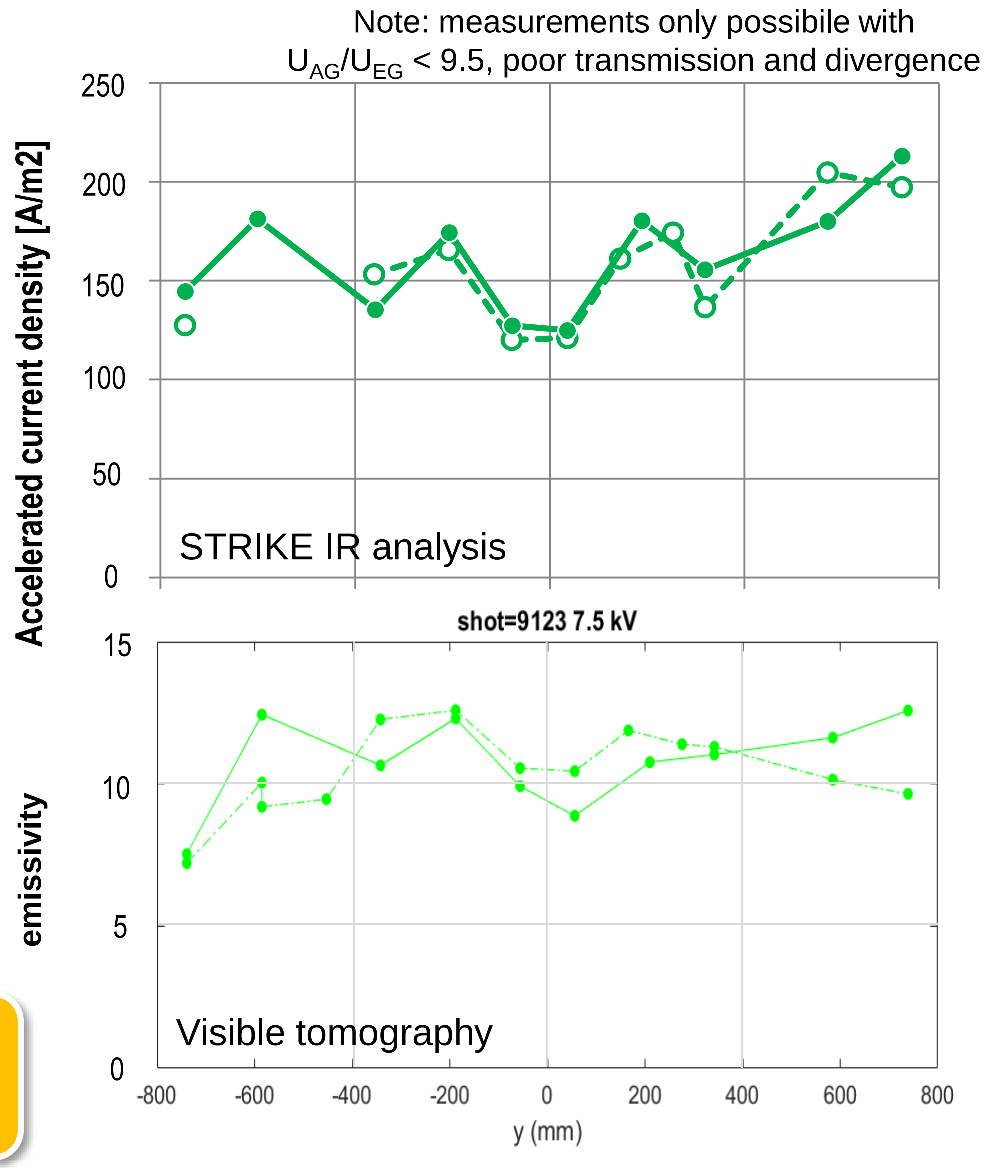
P_{RF}/driver=23kW
P_{RF}/driver=28kW
P_{RF}/driver=23kW
P_{RF}/driver=40kW

- High filter field, high PG bias improves electron to ion ratio; however vertical uniformity becomes poorer
- Balancing RF power, the beam vertical profile can be tuned
- Example: beam optimised for 4kV extraction
- Minima of beamlet divergence rather flat on the underperveant side: nonuniformities on the scale of the beamlet group can be dealt with
- Positive saturation current at PG shows same improvement of vertical uniformity

Multibeamlet operation at 50 kW/driver

- Structure within each beam segment is visible (beamlet group dimension, or projection of RF driver)
- Qualitative agreement of IR analysis and visible tomography



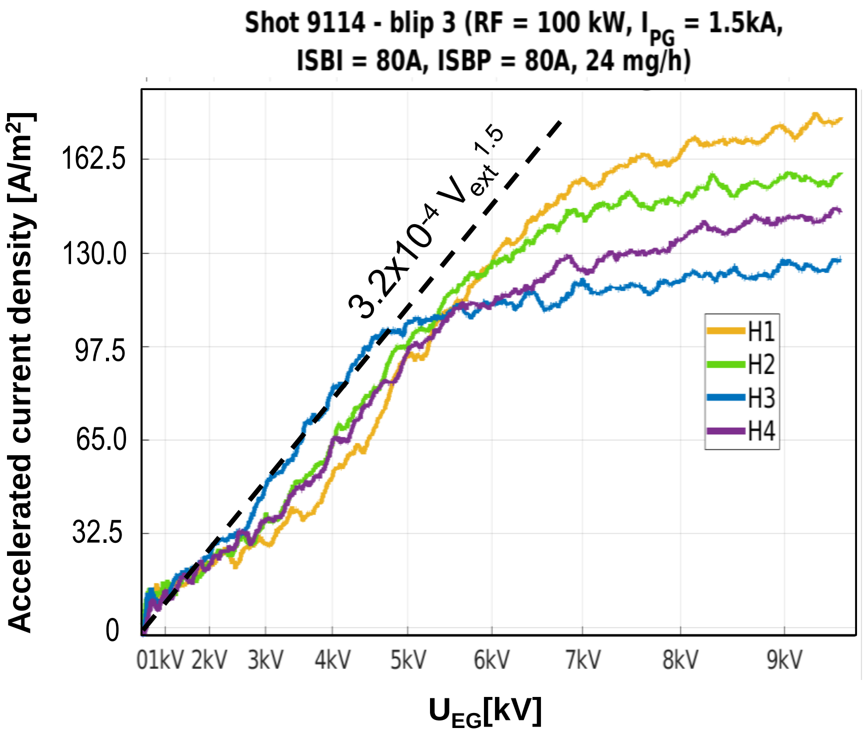


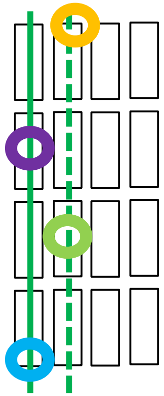
M.Ugoletti, poster "Study of SPIDER beam current through visible light measured by beam imaging diagnostic"

M. Agostini, poster " Characterization Of Spider Beam Optics With Visible Cameras "

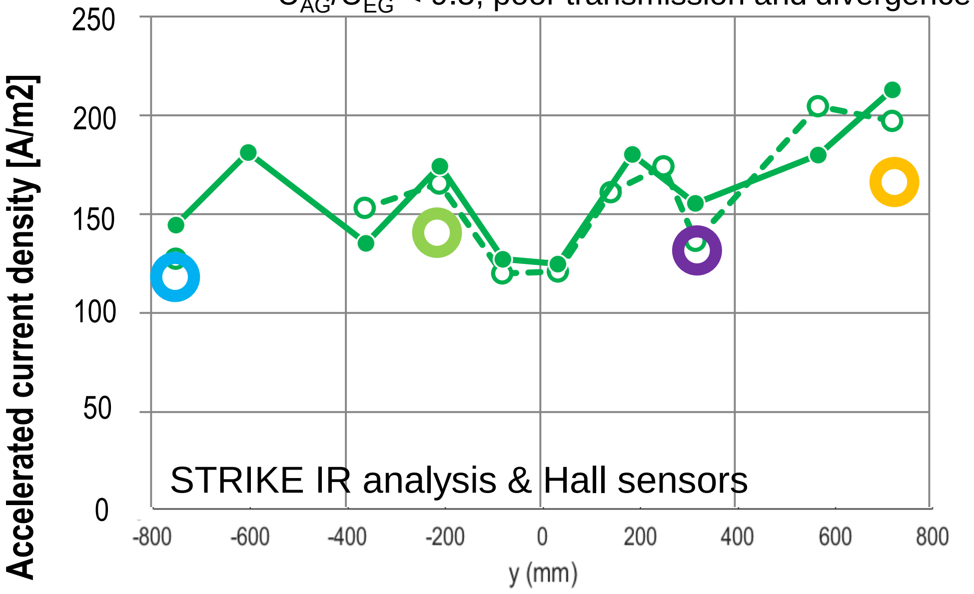
Multibeamlet operation at 50 kW/driver

- Structure within each beam segment is visible (beamlet group dimension, or projection of RF driver)
- Non uniformity depends on extraction voltage:





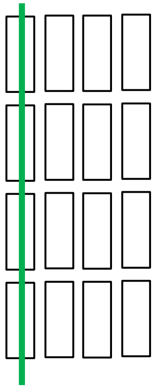
Note: measurements only possibile with U_{AG}/U_{EG} < 9.5, poor transmission and divergence

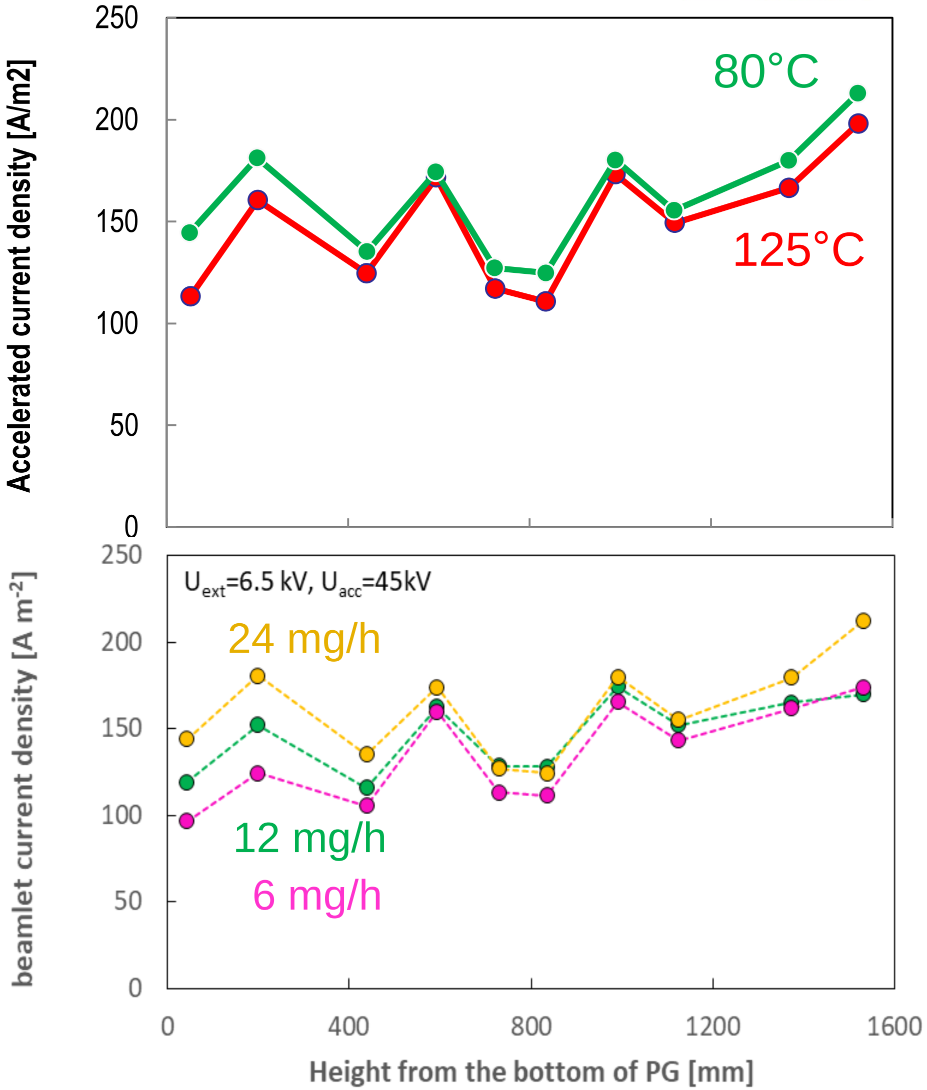


Hall sensors (LEM)
[with repeller]

Multibeamlet operation at 50 kW/driver

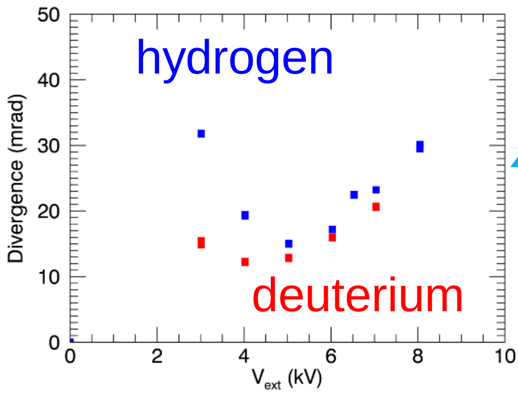
- For the **same source parameters**, by **improving caesium condition**, *j-* see an increase especially at beamlets with lower current, improving the overall **uniformity**
(in this example, either by reducing PG temperature from 125°C to 80°C or by increasing the Cs evaporation rate, the overall uniformity improves)

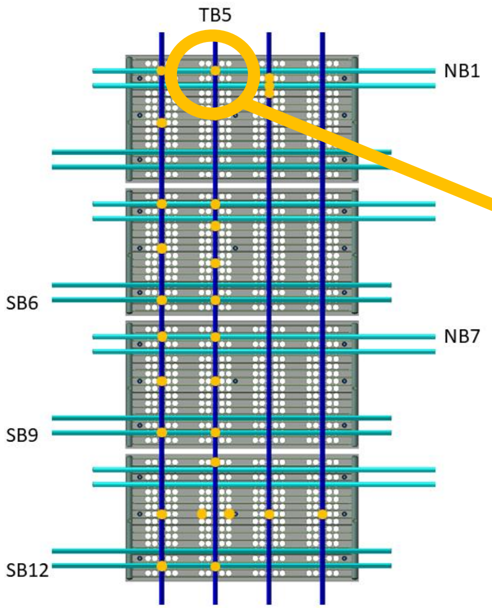


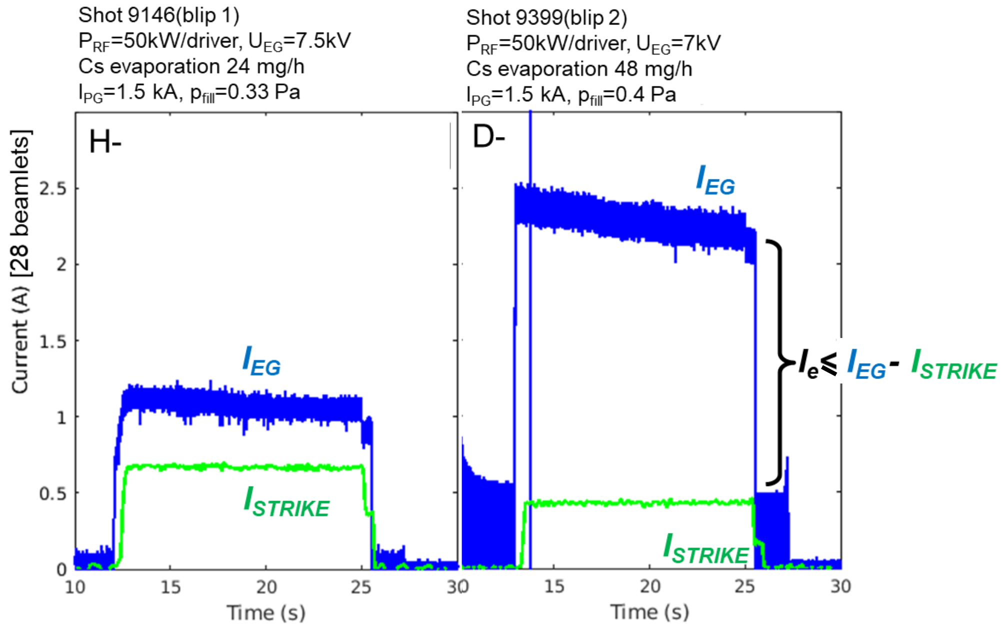


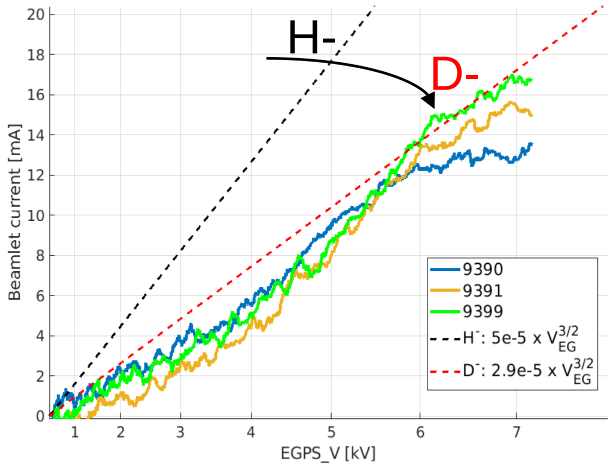
Beam stability and operation with deuterium

- Only two experimental days dedicated to deuterium
- One example of blip stability at 50 kW/driver is reported for comparison against hydrogen
- Hall sensor measurments correctly indicate the lower perveance in deuterium
- with PG mask, no indications of «overcaesiation» up to 48 mg/h
- Example of BES divergence: (broad component in deuterium)

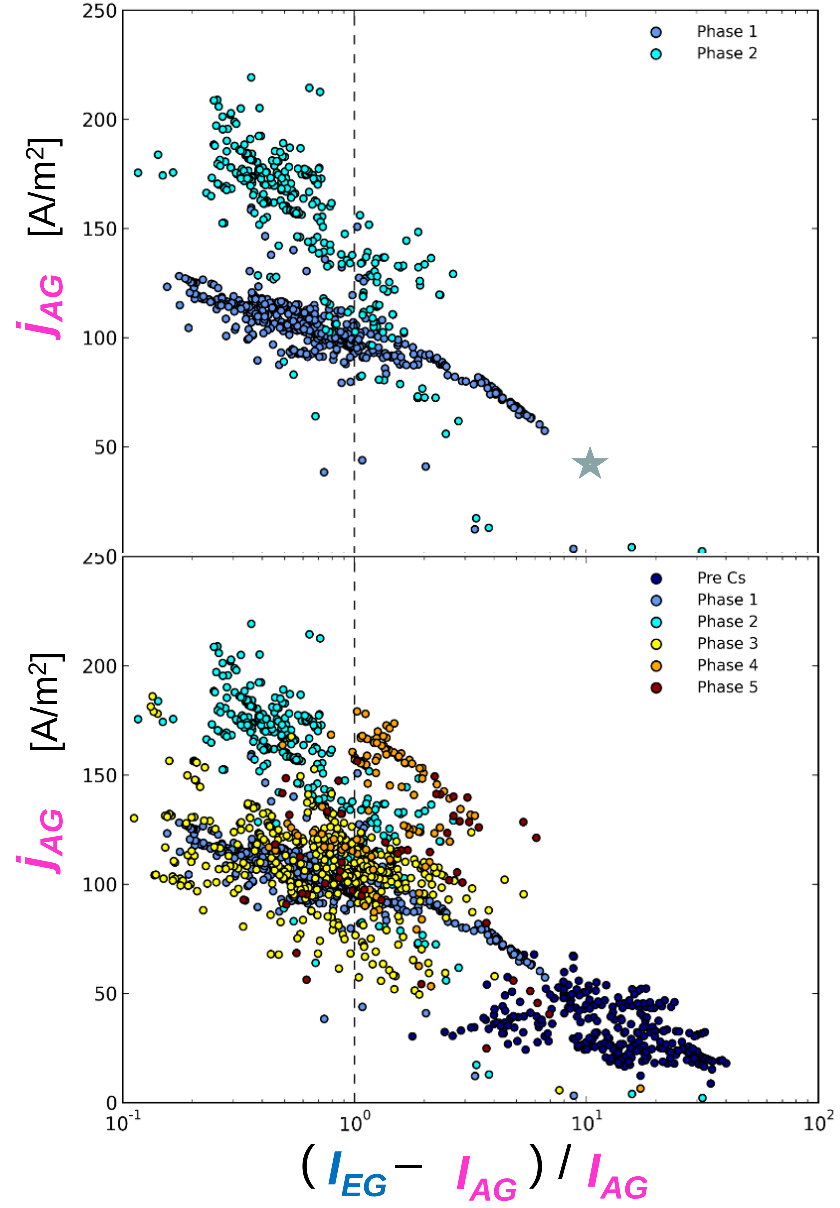


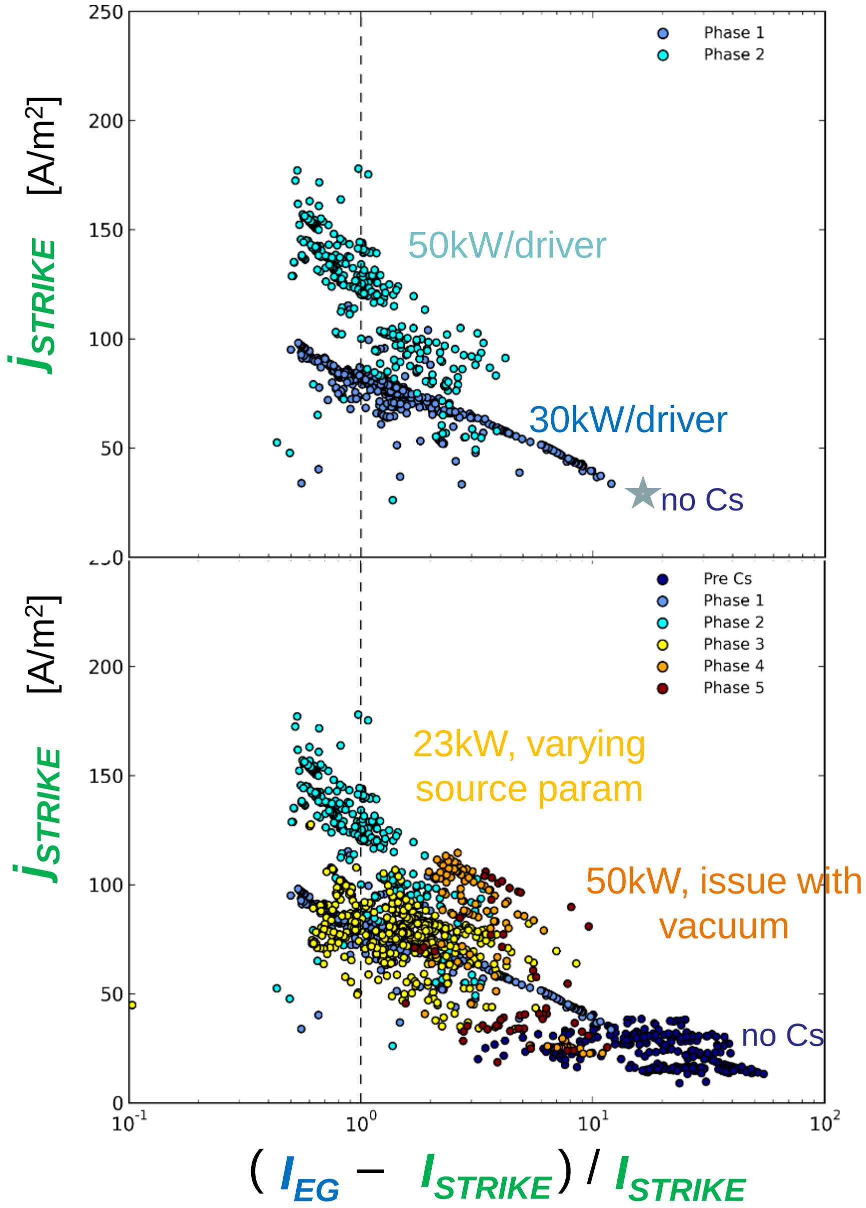






Conclusions: performance throughout campaign





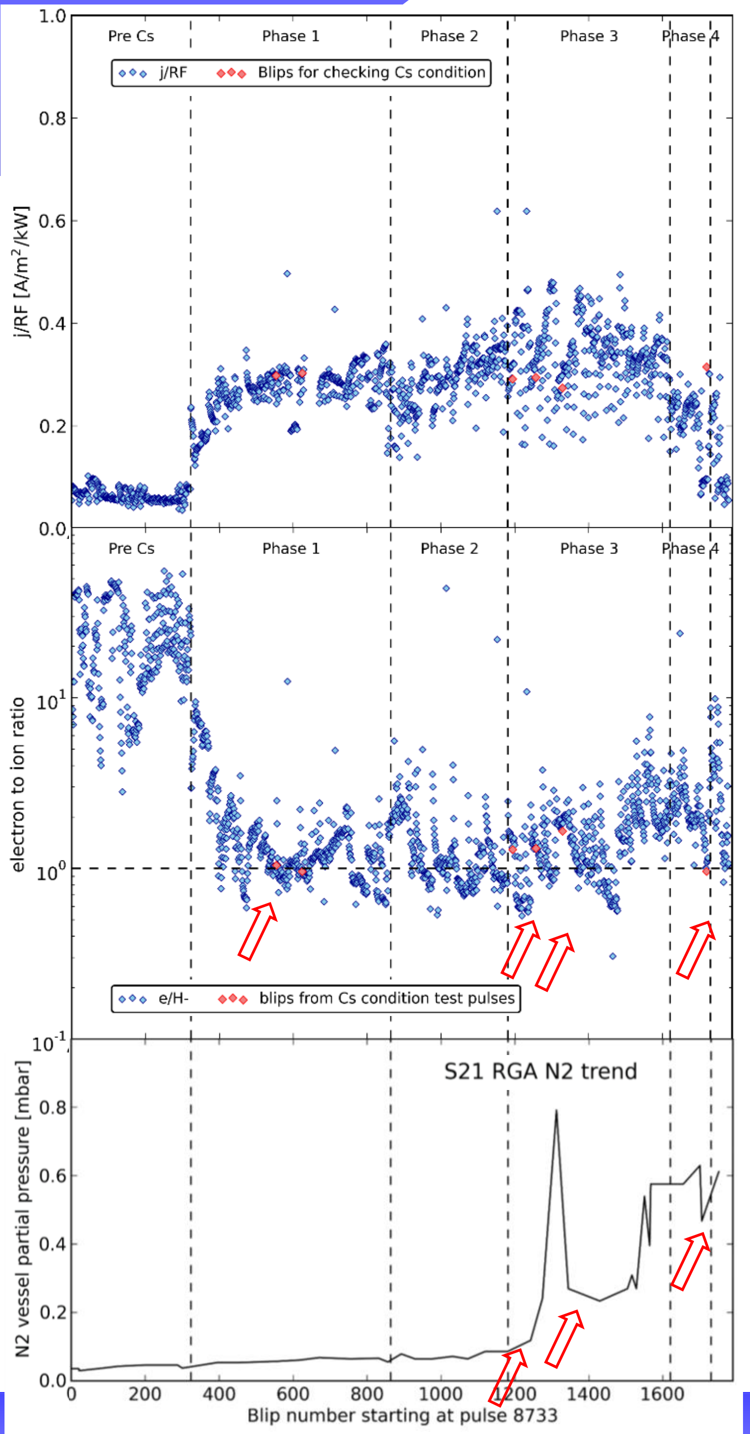
- Effect of caesiation parameters explored in the SPIDER giant source
- Extracted negative ion current density in the range of 150-200 A/m^2 at 50 kW/driver in hydrogen, with electron to ion ratio below 0.5
- Beamlet divergence as good as 13 mrad, at beam energy of 45 keV (23 kW/driver with approx 0.32 Pa)

AG power supply current is well below nominal value and it is affected by large noise/signal ratio.

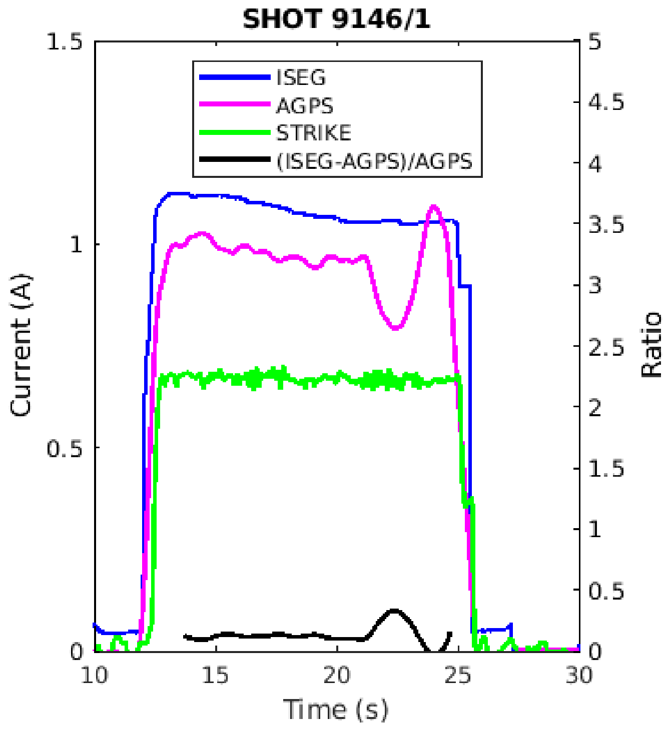
SPARE

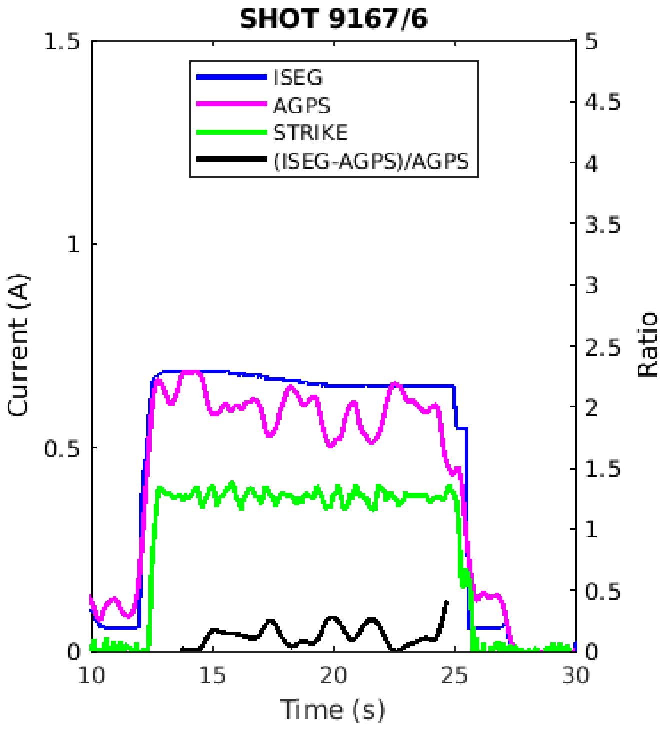
Beam ion efficiency

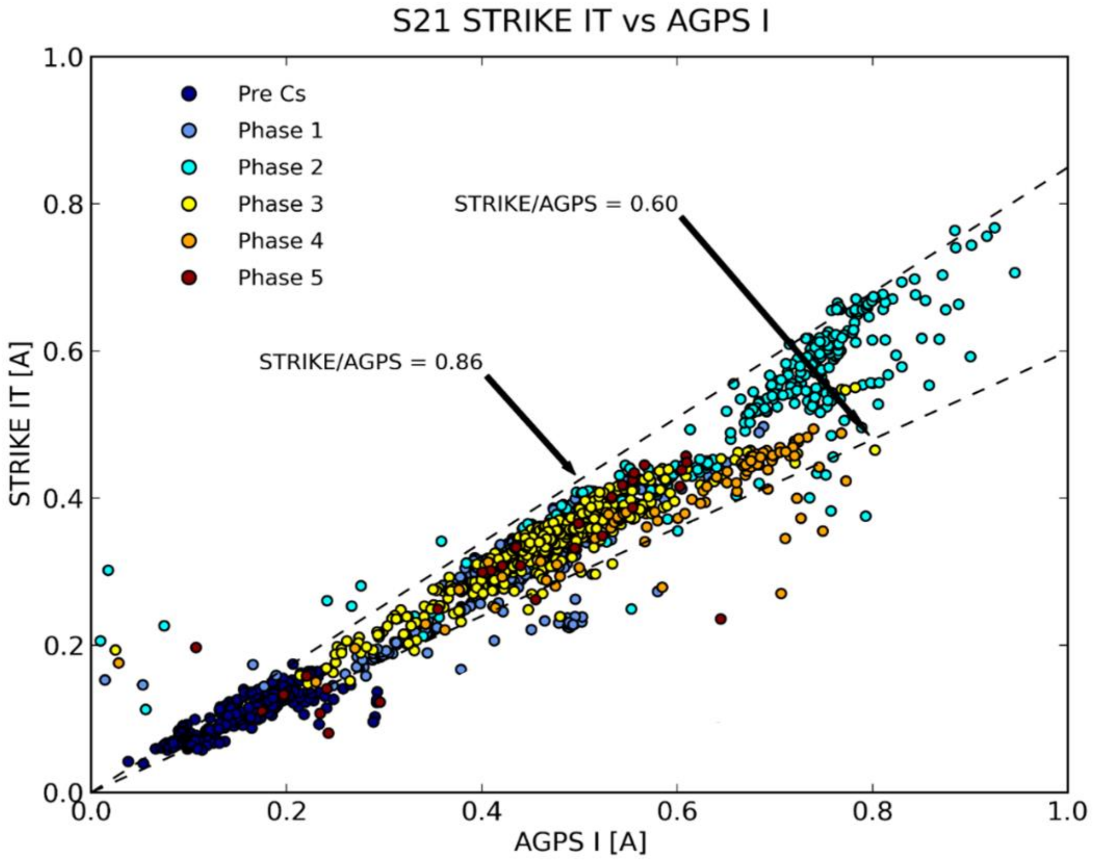
- Phase 1 and 2: good vacuum conditions and caesium effectiveness but insufficient acceleration voltage
  - accelerated current lower than extracted current (ion transmission <1)
- Phase 3: reduction of extracted current by reducing RF power for beamlet optics investigation around perveance match
  - Deterioration of vacuum and caesium effectiveness
- Phase 4: impossibility of raising acceleration voltage above 45kV and of recovering caesium effectiveness of phase 2
  - Investigation of breakdown-related issue by circuitry modifications
  - air leak; temporary recovery after total regeneration
- Phase 5: operation in deuterium
  - commissioning of neutron diagnostics



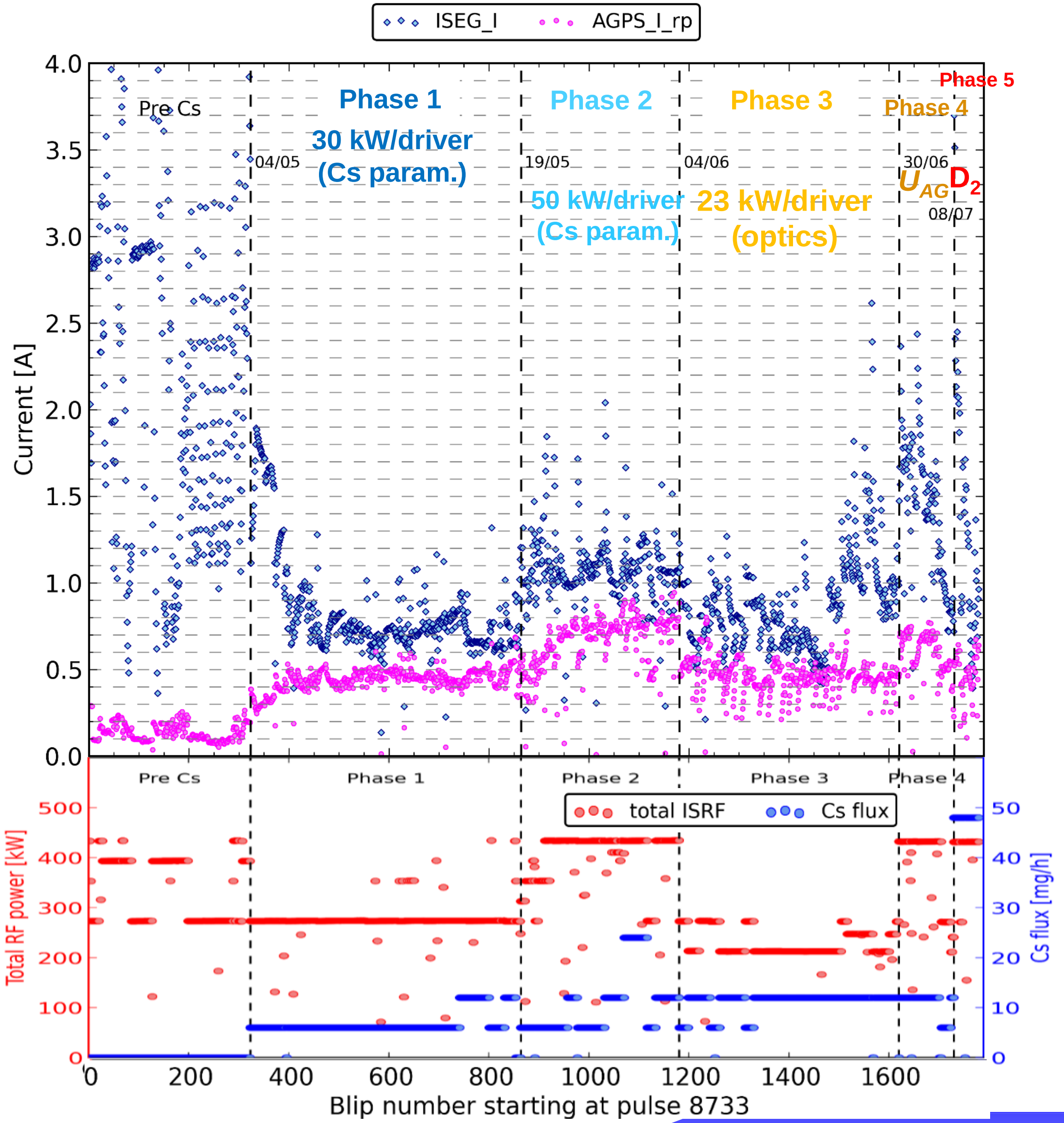
AG current and STRIKE current







First Operations with Caesium of the Negative Ion Source SPIDER



Beam properties vs plasma properties at 23 kW/driver

- All parameters vs PG bias and BP bias
- Determining role of PG bias in j_e → monotonously decreased with bias current
- Positive ion density at BP decreases with bias current
- Positive ion density and temperature at rear wall increases with biases