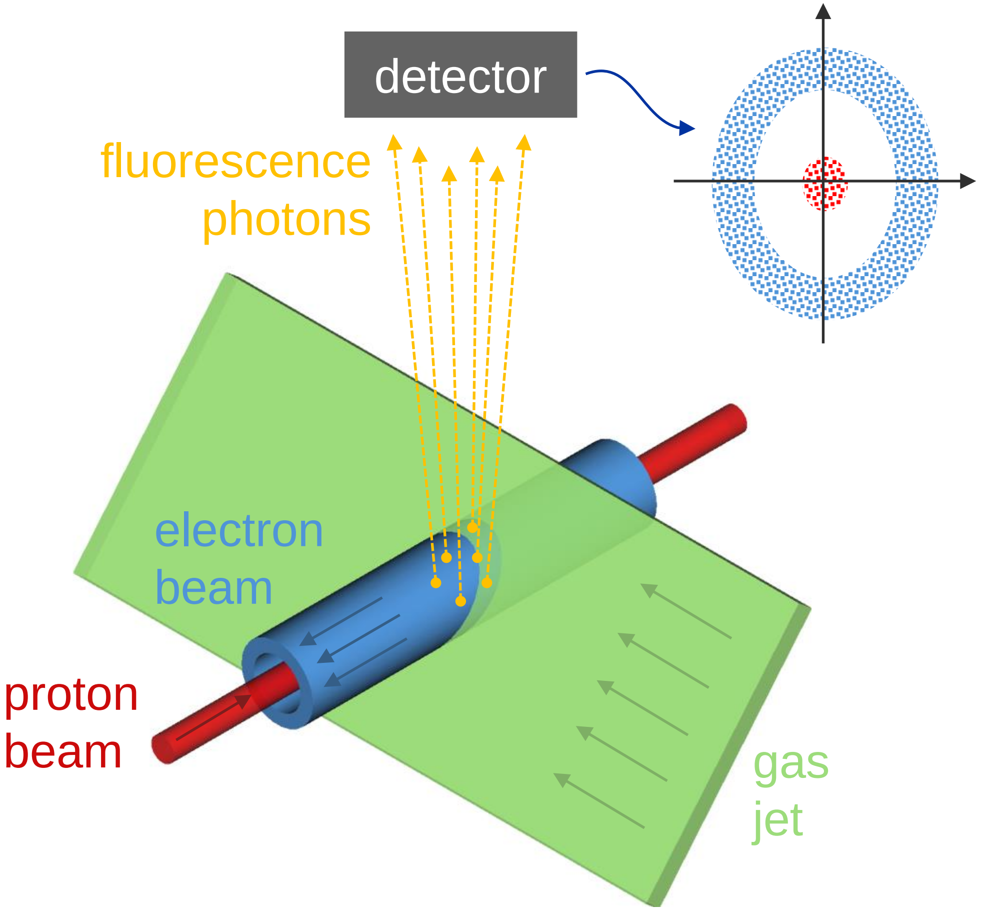
Results from the BGC in 2024

LBOC meeting 171 – 24th September 2024

D. Butti on behalf of the BGC collaboration

Beam Gas Curtain



Conceived as overlap monitor for the Hollow Electron Lens

After HEL descoping, **reproposed as beam size monitor** for the main LHC beam:

- ✓ **non-invasive**
- ✓ simple beam imaging
- ✓ only option for Pb @INJ

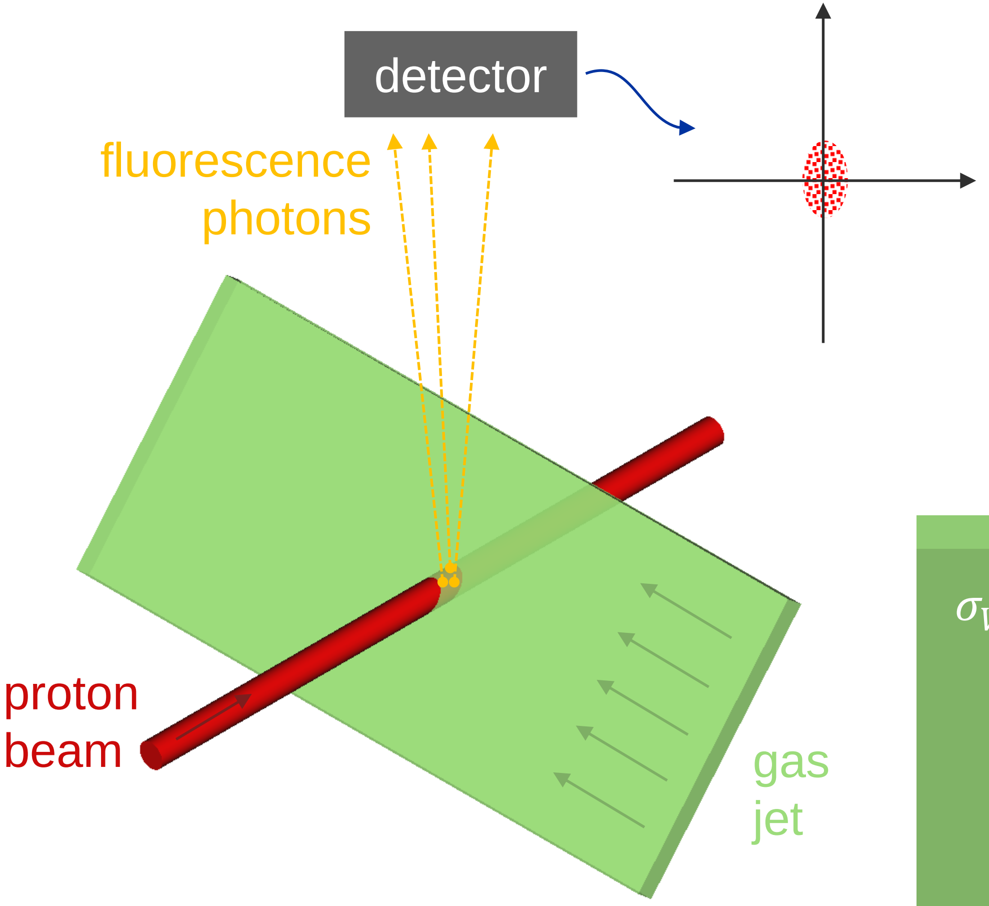
- × **weak fluorescence signal**, only suitable for avg measurements
- × jet thickness affects measurement in vertical direction

Promising measurements during 2023 run (with ions)*
→ **ongoing effort to move towards an operational device**

BGC animation on YouTube

*O. Sedlacek, LBOC meeting 156

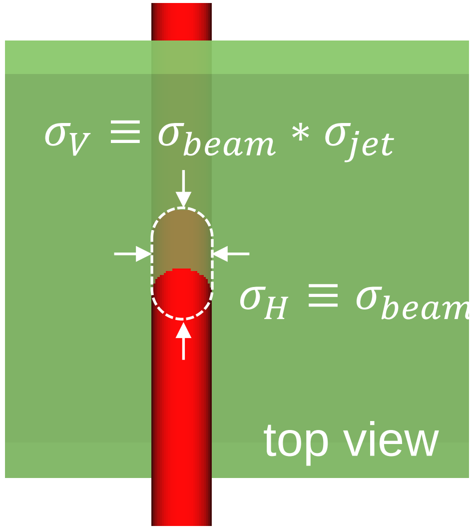
BGC as beam size monitor



Because of the gas jet finite thickness,
the **BGC output is different in the two directions**

Horizontal projection is unaffected
→ used as indicator of data quality

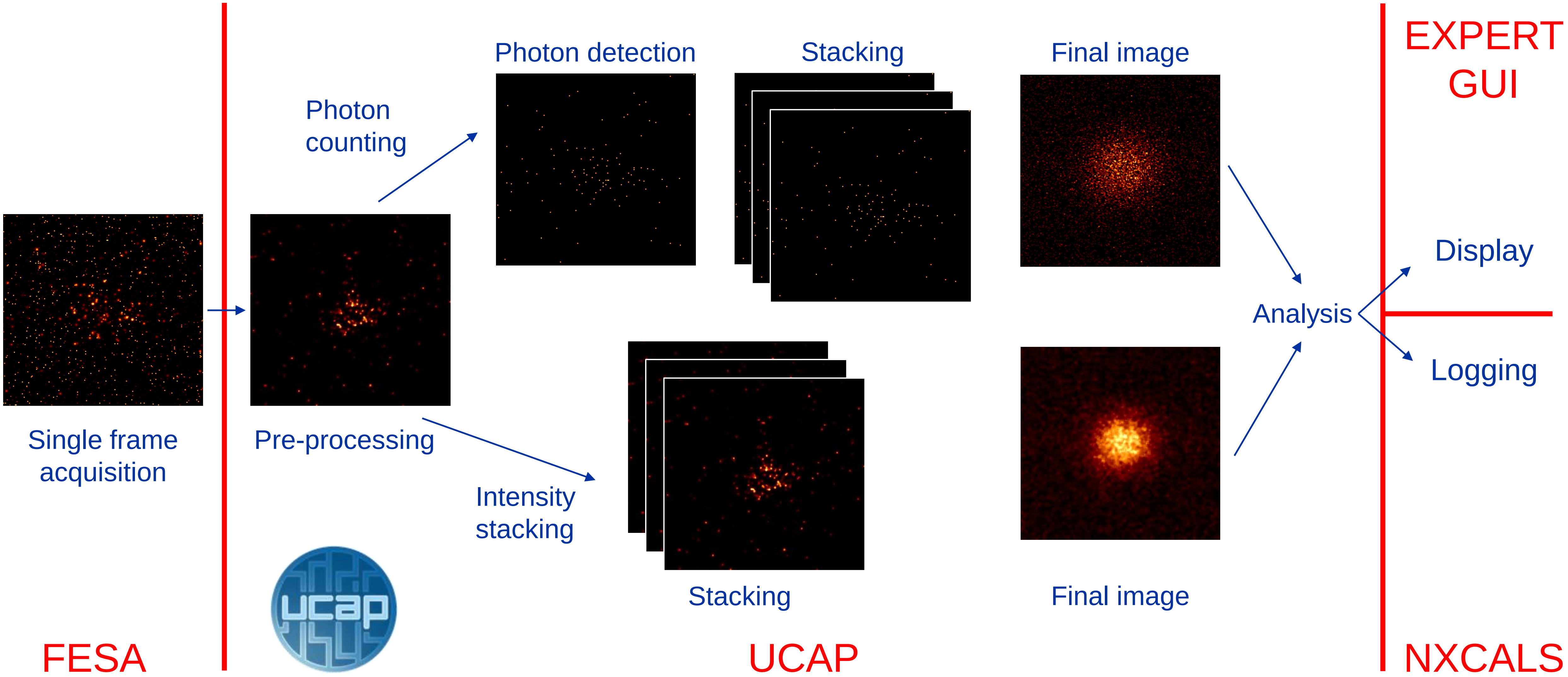
Vertical projection includes jet distribution
→ retrieving accurate beam size is more challenging



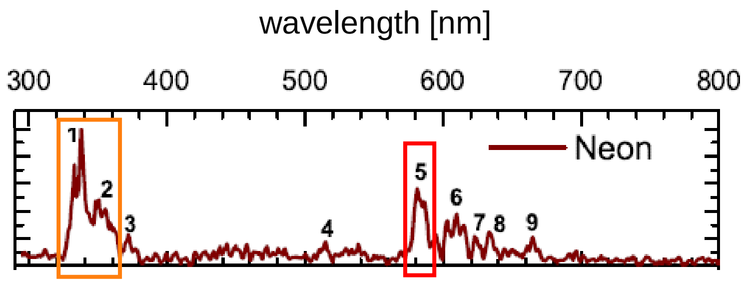
Horizontal
light profile = beam profile

Vertical
light profile = convolution of beam and jet profiles

Image processing



Fluorescence signal



Non-destructive profile measurement of intensive heavy ion beams,
F. Becker 2010

BGC currently operates in two **spectral domains**

BGC VIS: visible line 585 nm

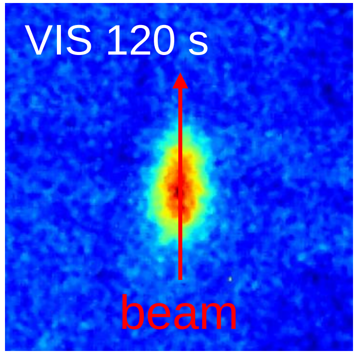
- lower light yield → longer integration times
- neutral transition Ne* → better resolution

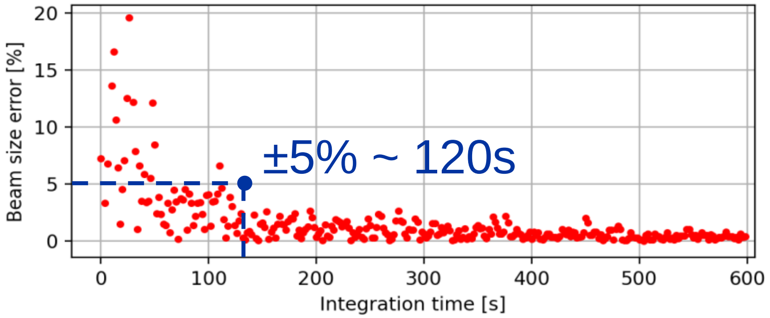
→ best option for **accurate absolute measurements**

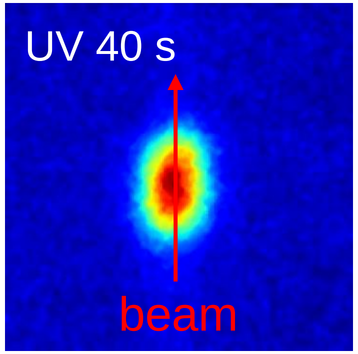
BGC UV: ultra violet lines

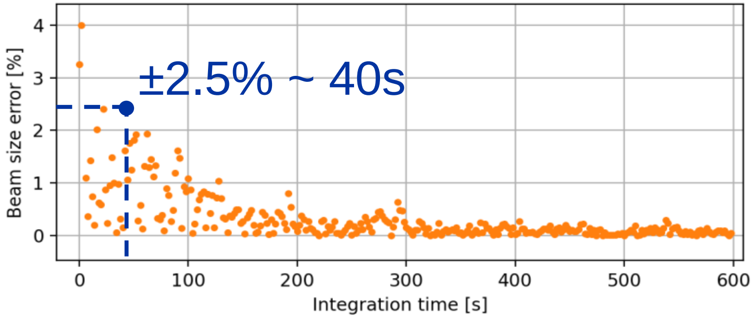
- better light yield → shorter integration times
- ionic transition Ne^+ → worse resolution

→ best option for **precise relative measurements**









Resolution

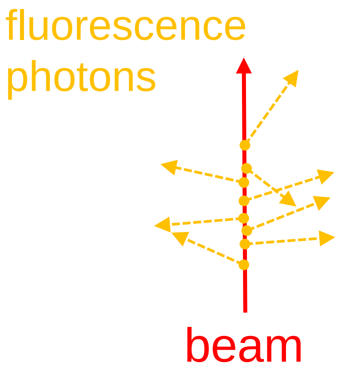
Beam size inferred from image size, correcting for resolution

$$\sigma_{beam}^2 = \frac{\sigma_{img}^2}{M^2} - \sigma_{res}^2$$

M = magnification
σ_{beam} = beam size
σ_{img} = fitted size
σ_{res} = resolution

<u>BGC VIS</u>

- neutral transition Ne* unaffected by beam field
- resolution only given by optics

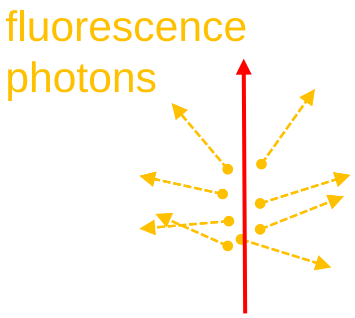


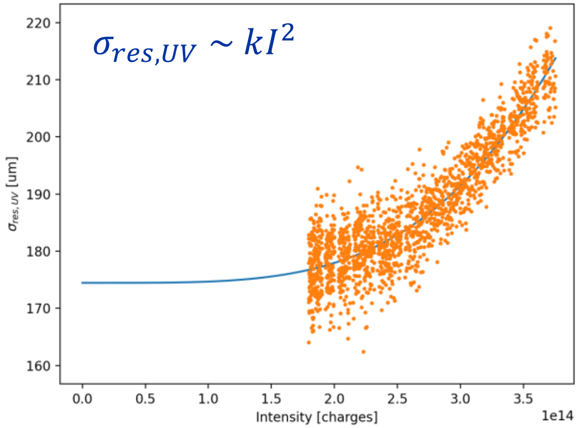
$\sigma_{res,VIS} \simeq 65\ \mu m$

- measured a priori
- much smaller than any beam size

<u>BGC UV</u>

- ionic transition Ne^+ affected by beam field
- semi-empirical correction including beam current





BGC self-calibration → assume "true" value provided by BGC VIS and derive correction for BGC UV

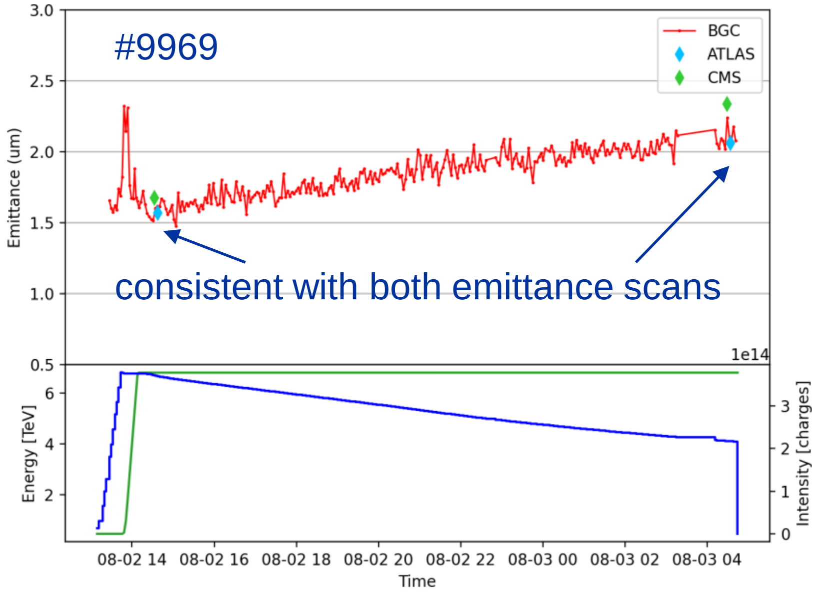
Accuracy of BGC VIS

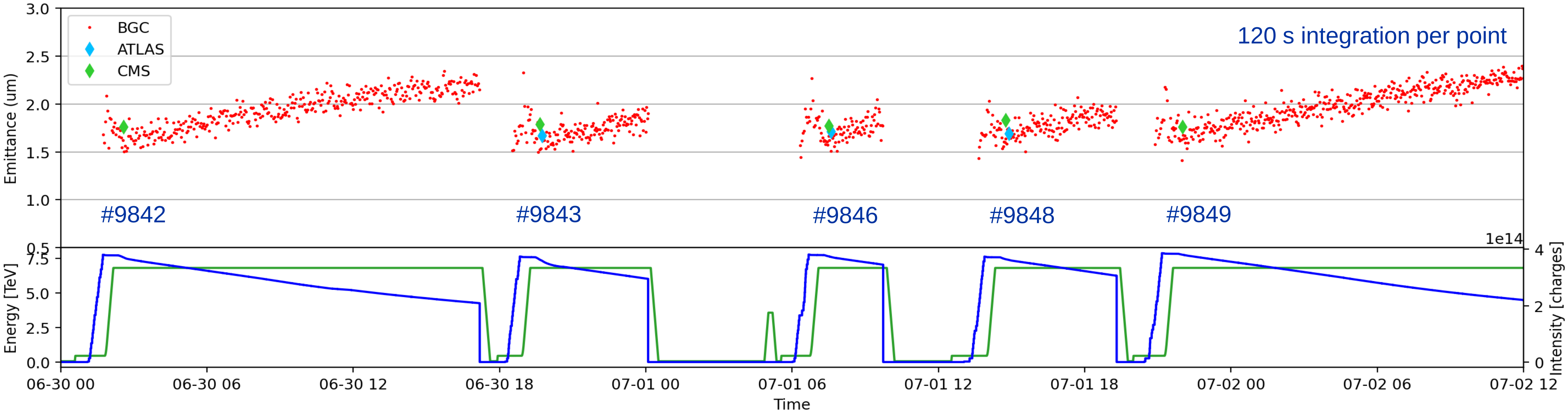
Resolution much smaller (~1/3) than beam size

→ measurements look **accurate and reproducible** at flat-top

Low light yield with visible line

→ measurements **quite noisy** (±10% peak-to-peak in emittance)



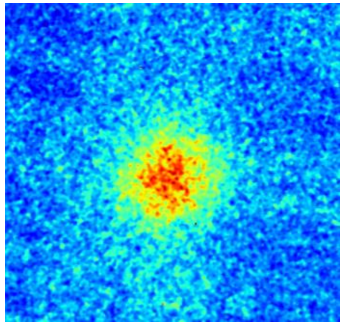


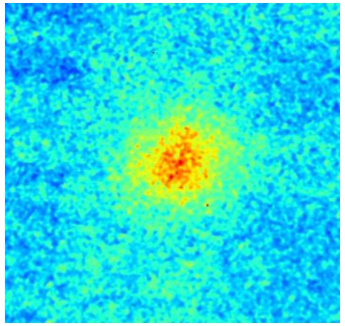
BGC VIS results during machine cycle

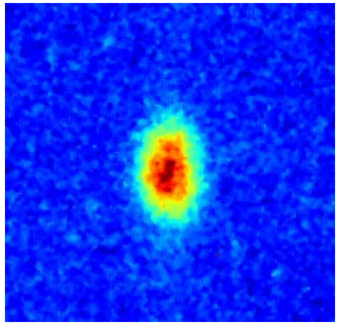
Some issues affect the measurement

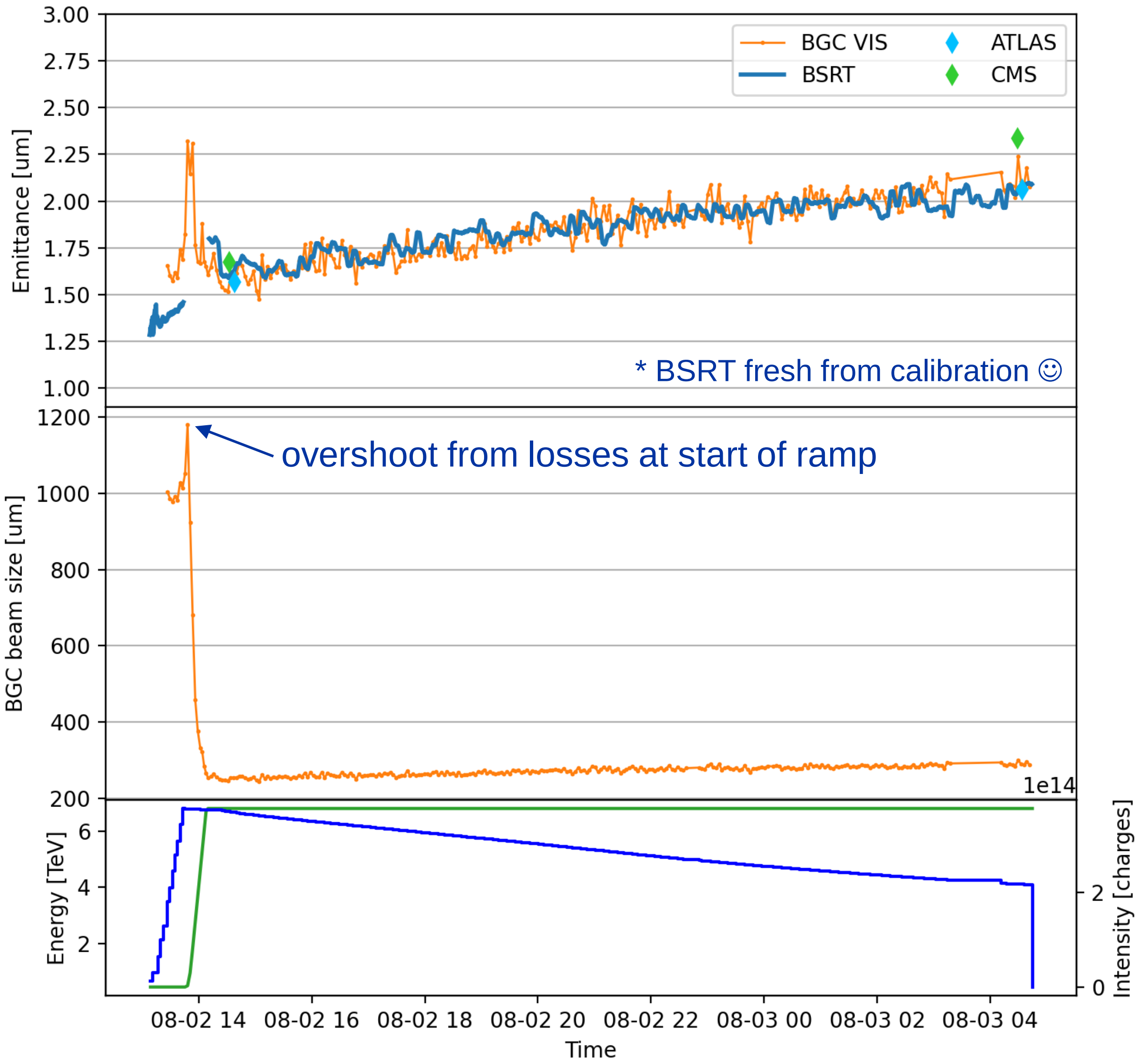
- overestimation of injection size due to poor signal
- fluorescence easily overwhelmed by losses
- long integration time implies very few points

BGC VIS reliable reference in stable beams but not ideal to track beam size evolution


Injection


Start of ramp


Stable beams

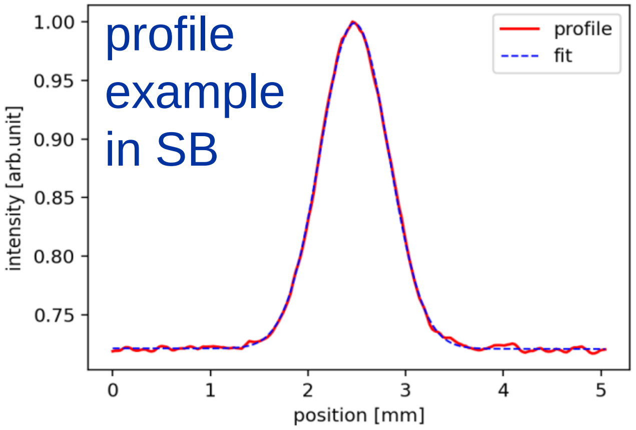


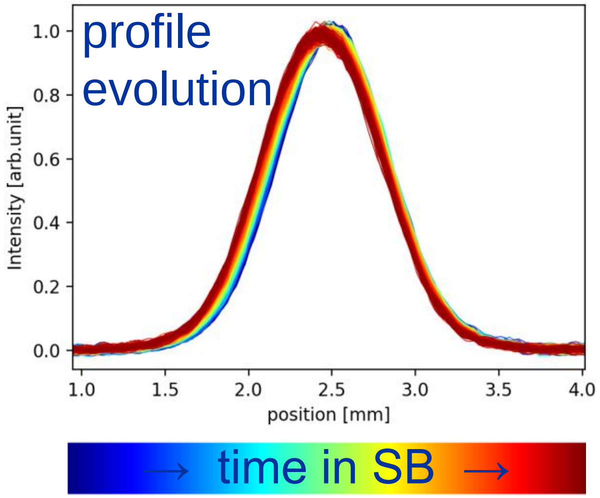
Horizontal direction

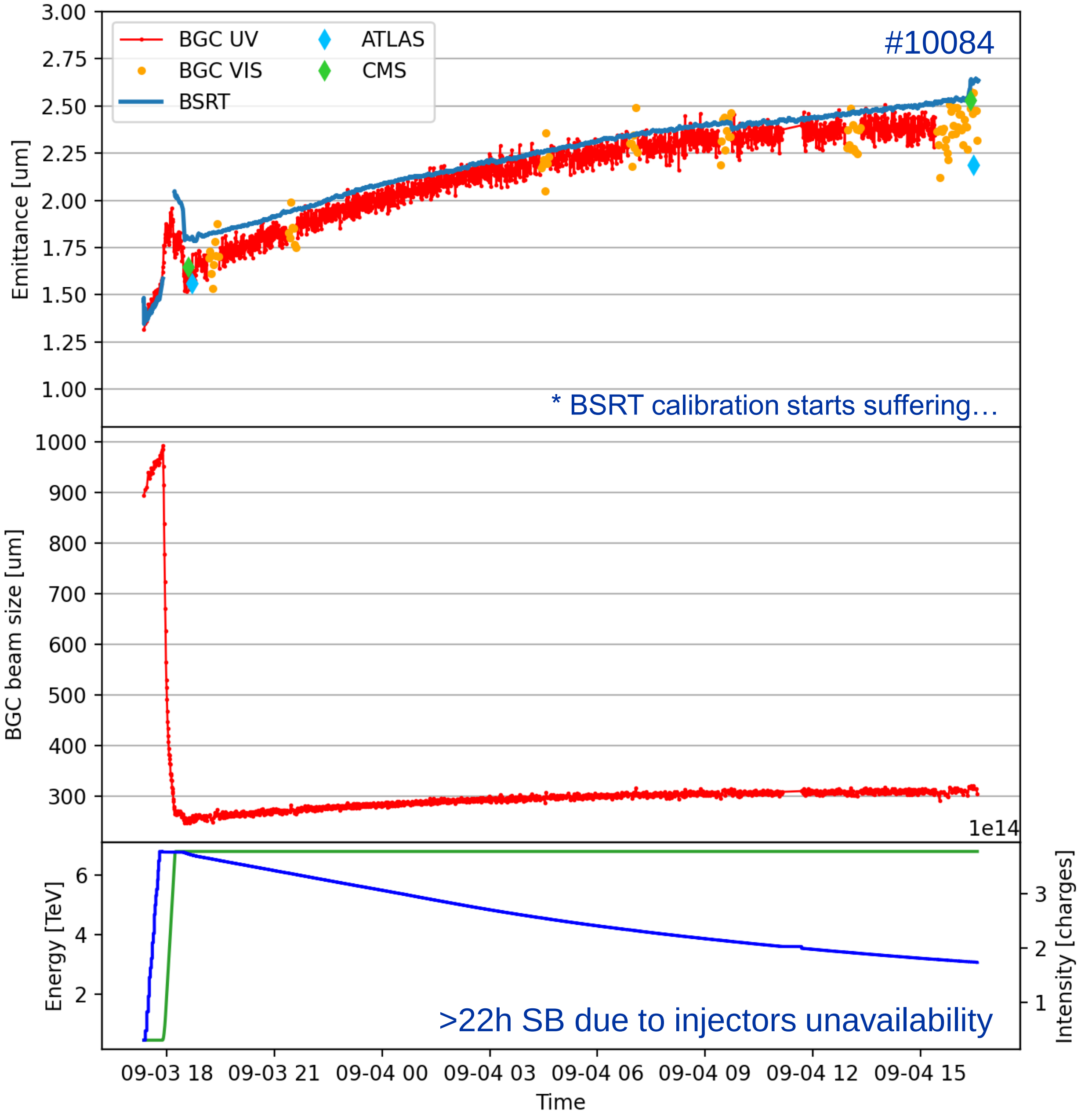
Measure fill using BGC UV, switching to BGC VIS for accuracy cross-checks

Fluctuations of BGC UV within ±5% in emittance

Trend from combined **BGC VIS+UV compatible with emittance scans** at start and end of fill



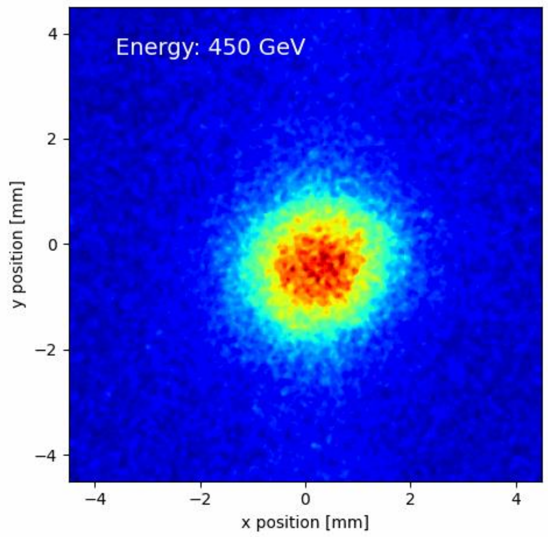




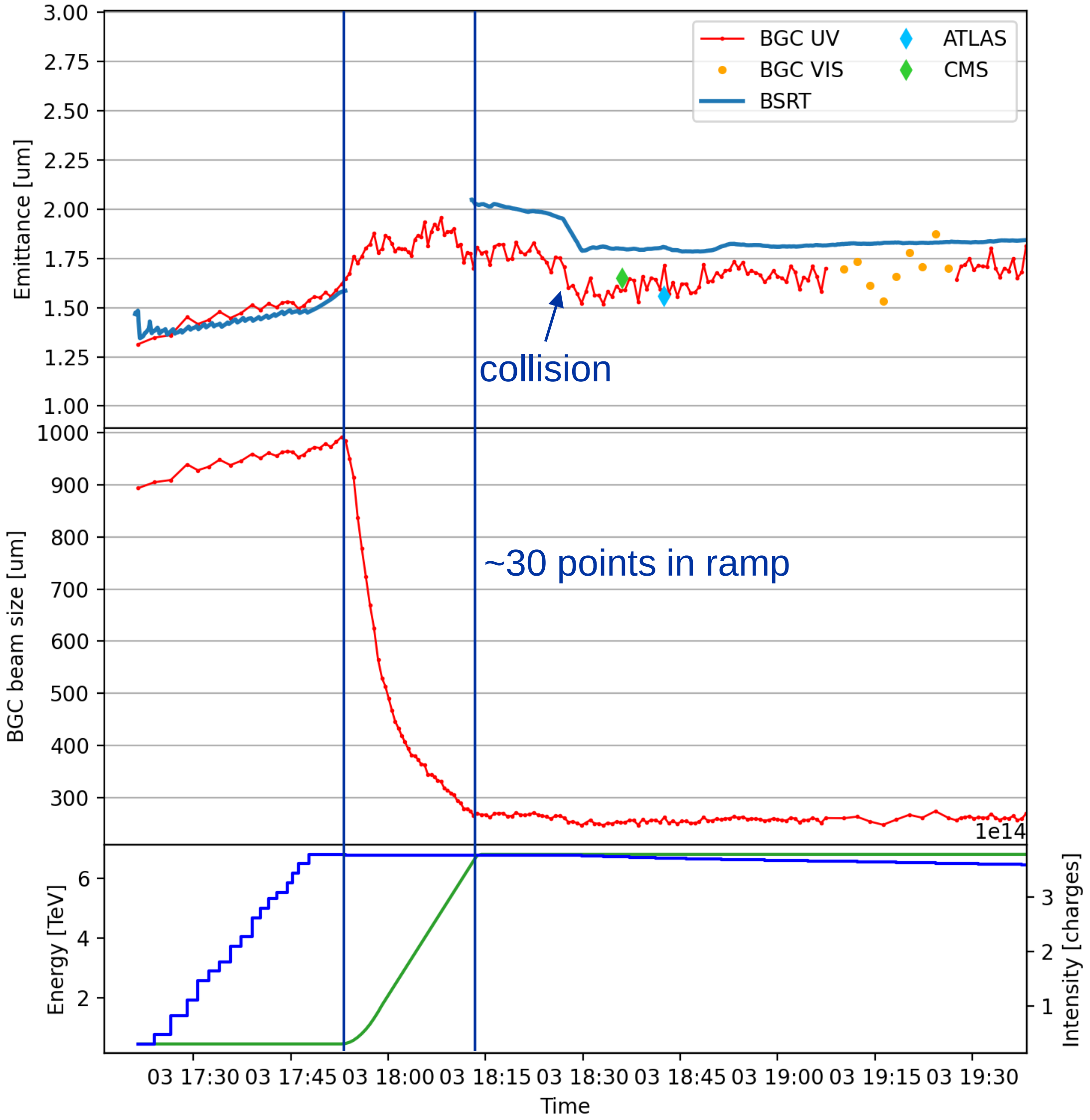
Horizontal direction during ramp

Overall **positive results**

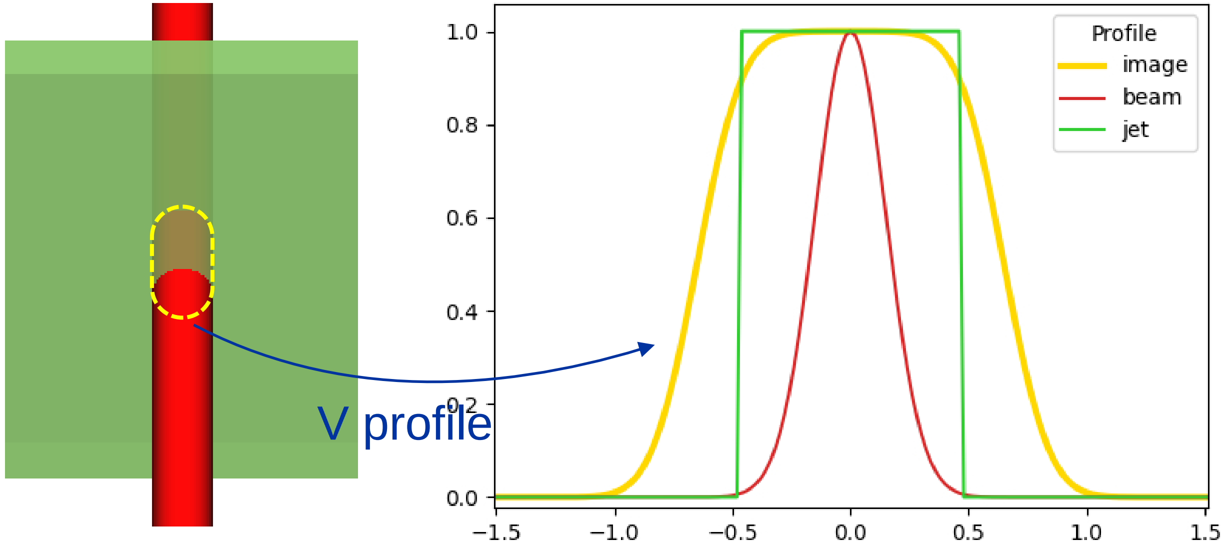
- quantitative agreement with BSRT at injection
- “smooth” behavior in ramp
- qualitative agreement with BSRT at FT
  (e.g. dynamic beta effect on collision)
- quantitative agreement with emittance scan



BGC UV images
during energy ramp
(ROI follows beam size)



Vertical direction (perpendicular to jet)



Ideally, the vertical profile of the image has

- intensity plateau from uniform jet distribution
- Gaussian edges from beam distribution

→ beam size information only encoded in the edges, retrievable from **deconvolution**

If jet thin enough, deconvolution can be replaced by simple Gaussian fit and correction in quadrature

In reality,

- deconvolution works with low-noise profiles → only BGC UV usable
- real jet profile not perfectly rectangular → jet edges further correction to beam size

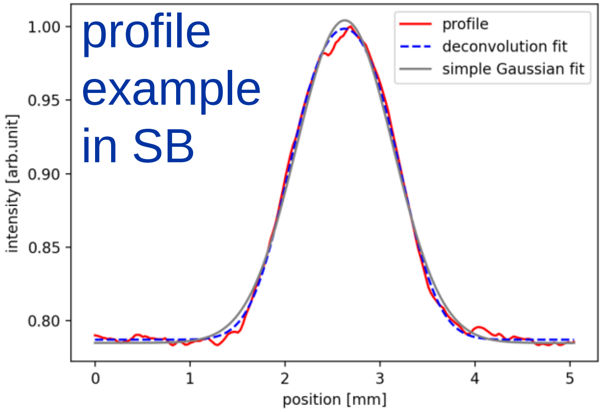
... these issues are mitigated **if beam size is larger** (low energy)

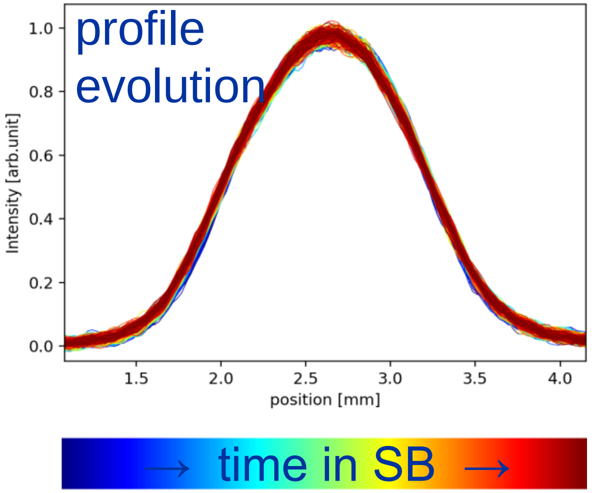
Vertical direction

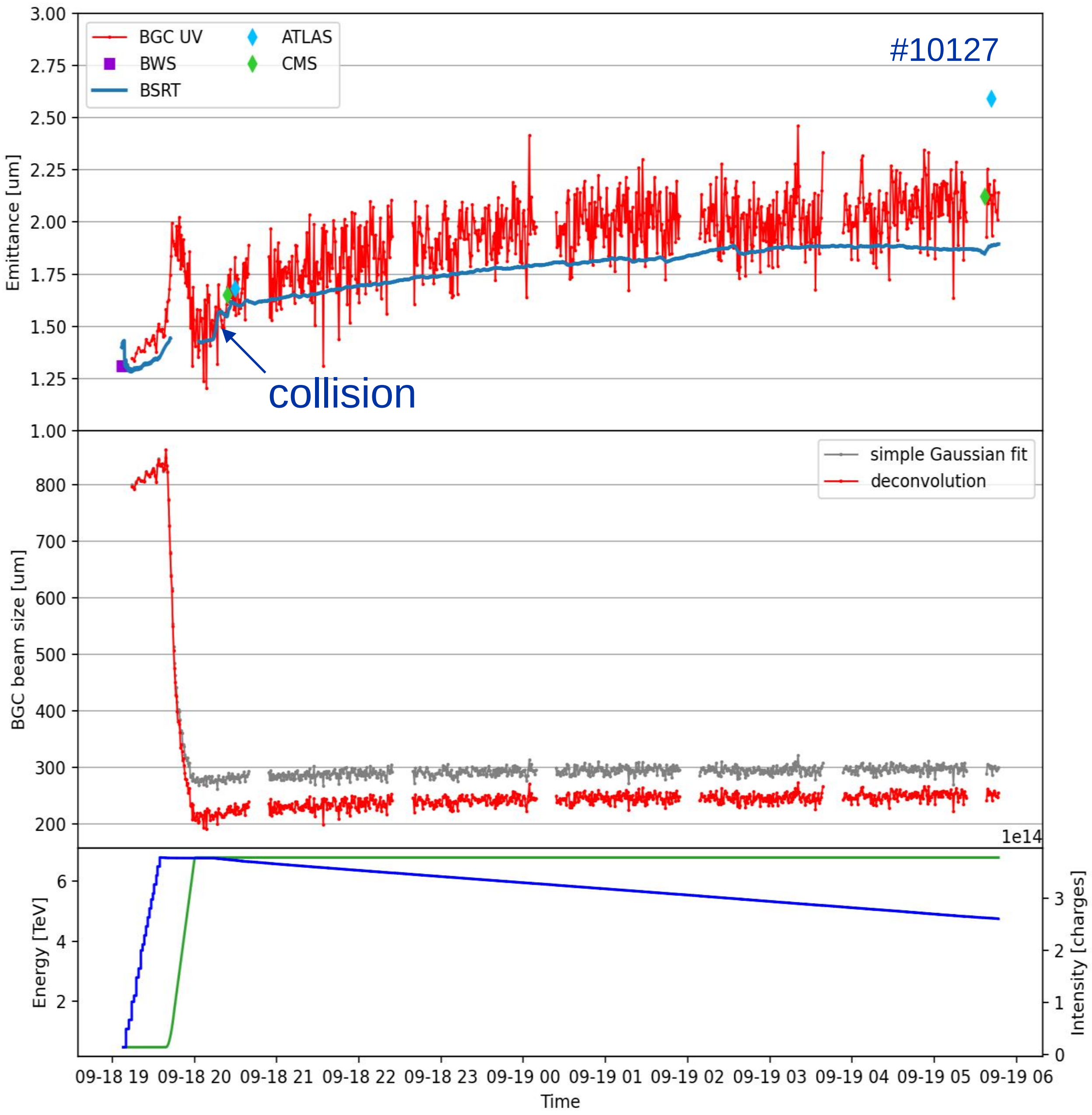
Deconvolve BGC UV profiles to assess beam size

Larger fluctuations at flat-top than horizontal, ±15% emittance, due to extra correction for jet thickness

No accurate reference from BGC VIS.
Deconvolution seems to match emittance scans but reproducibility to be assessed…







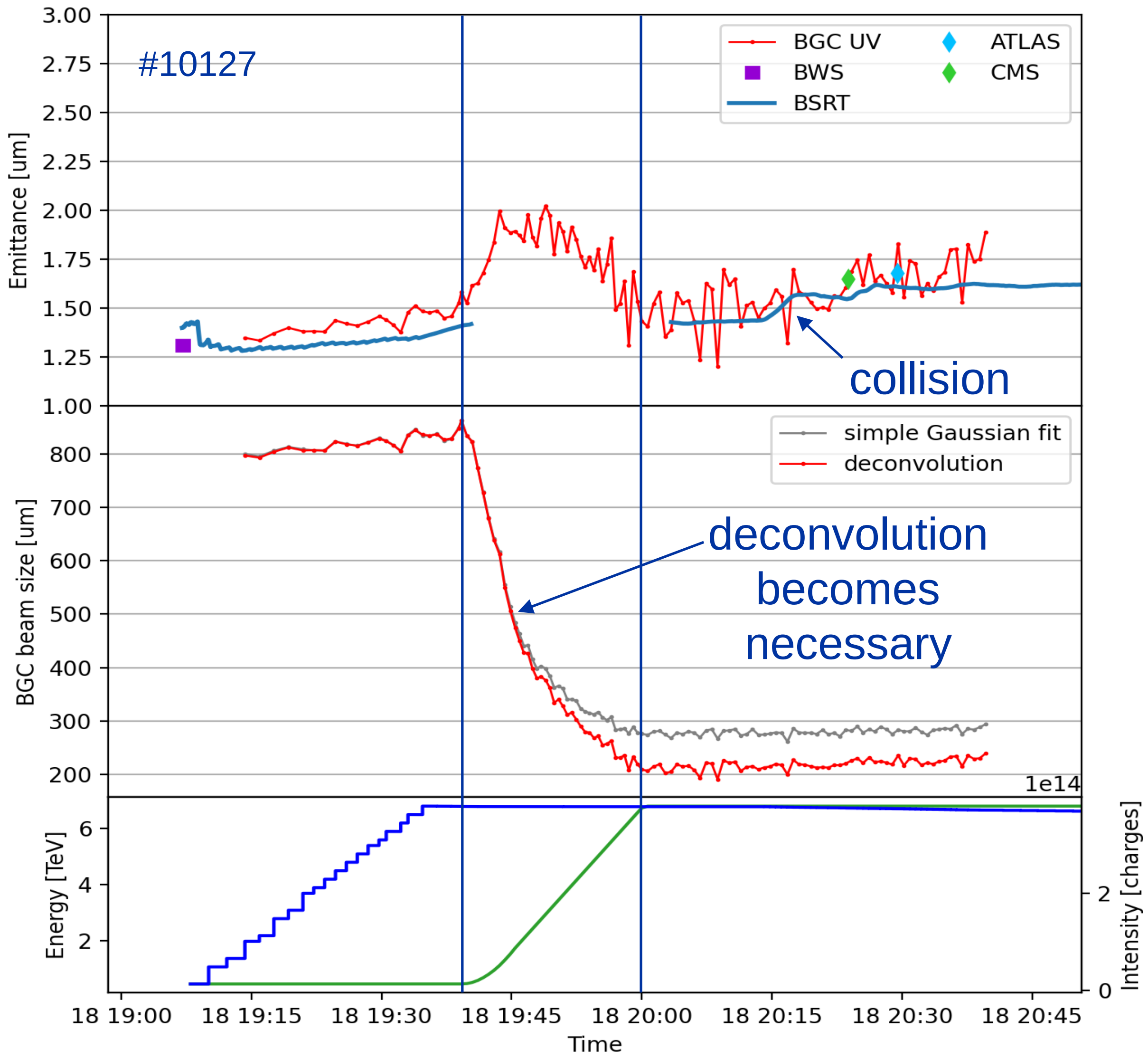
Vertical direction during ramp

Still **some positive results**:

- BGC, BSRT and BWS are compatible within 10% at injection
- “smooth” behavior in ramp, not so different from horizontal case
- within larger BGC fluctuations, good agreement with BSRT and emittance scan at FT

As size decreases, **effects of jet thickness** appear

- simple Gaussian fit v from deconvolution
- measurements become noisier



Conclusion

If HEL comes back, BGC certainly works as **overlap monitor**

Horizontal measurements (i.e. parallel to jet)

- BGC VIS configuration provides accurate and reproducible measurements in stationary beam conditions
- BGC VIS and BGC UV combined best option for beam size monitoring over full machine cycle

Vertical measurements

- BGC UV still OK at injection, at flat-top performance affected by jet thickness.

Promising measurements from last year's **Pb-run**

- re-commission BGC for ions and validate results

A **few options for the future**

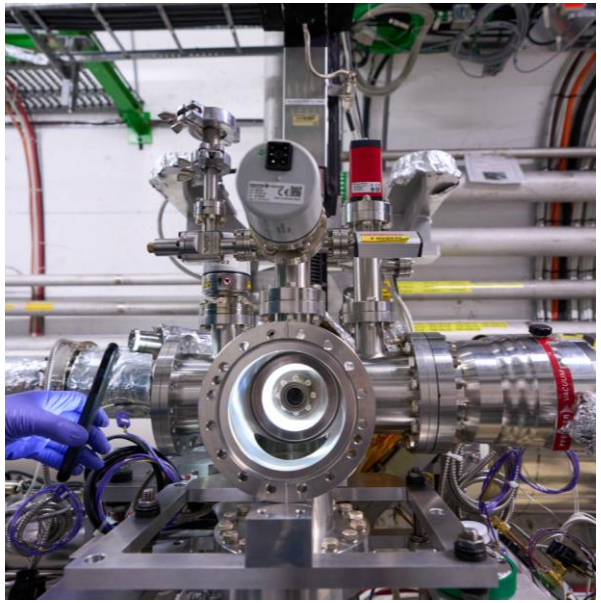
- test N_2 as jet gas to increase signal
- reduce jet thickness to improve vertical sensitivity at flat-top
- test diagnostics based on jet-induced losses instead of fluorescence

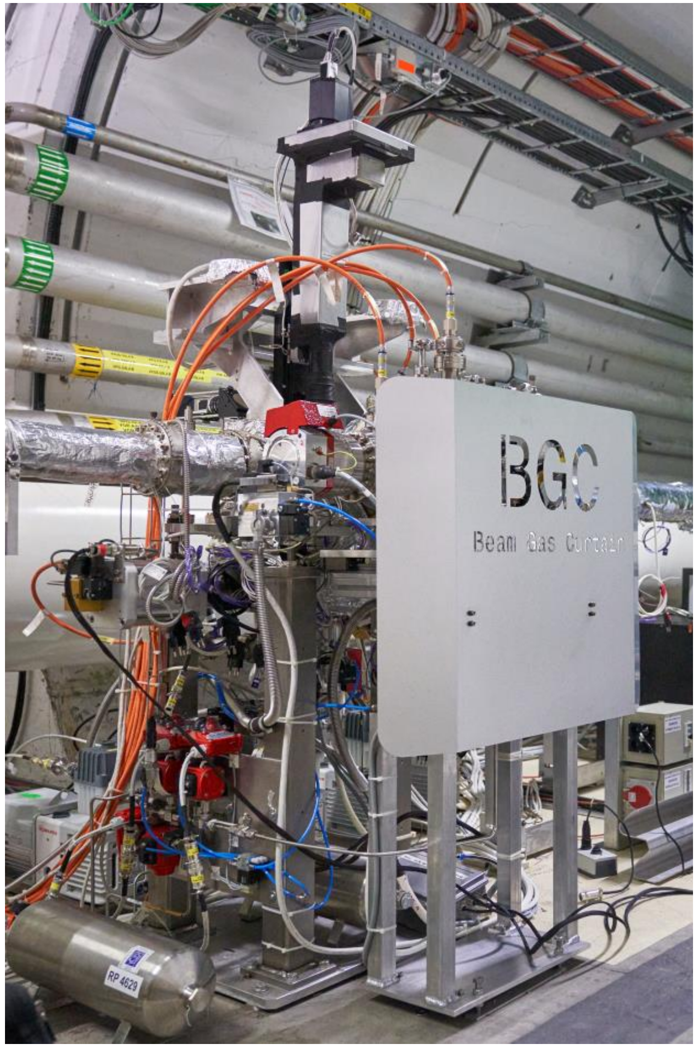
Thank you!

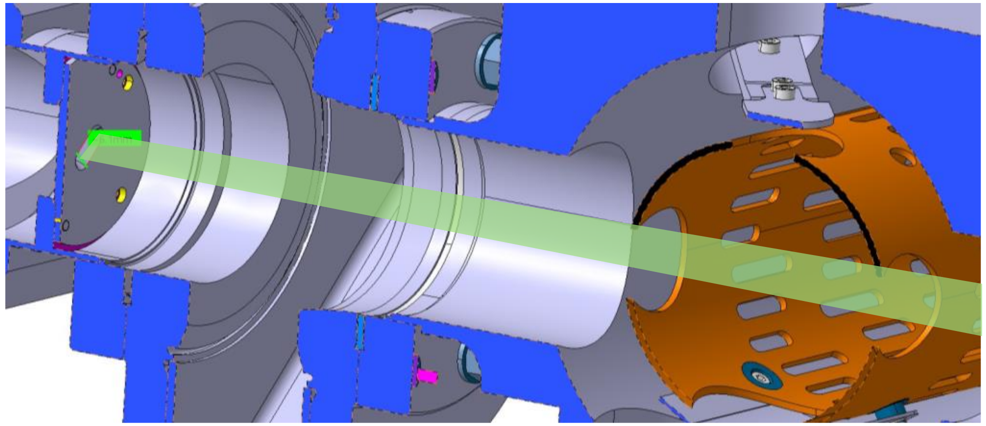
Thank you!

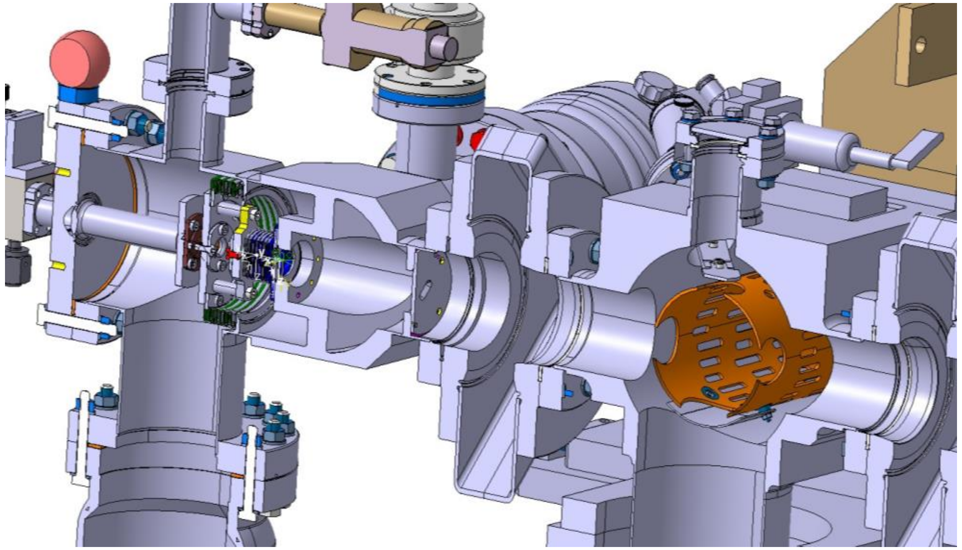
home.cern

Beam Gas Curtain instrument







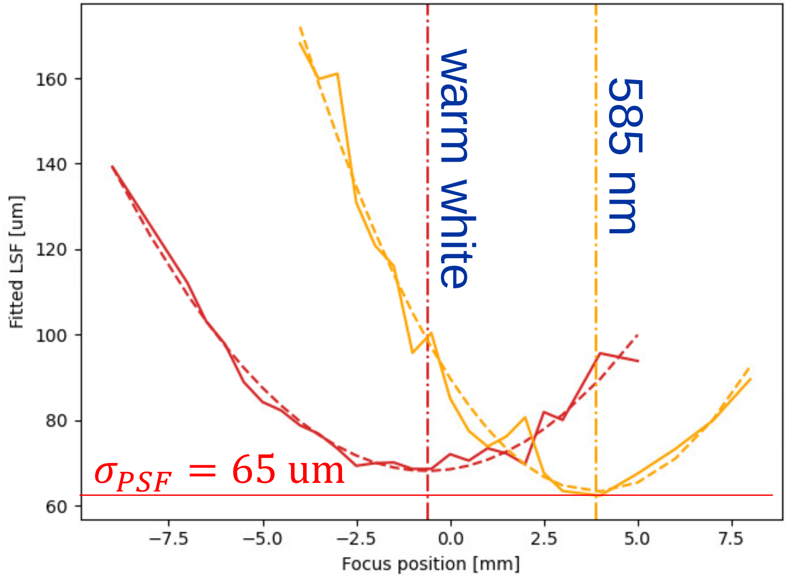


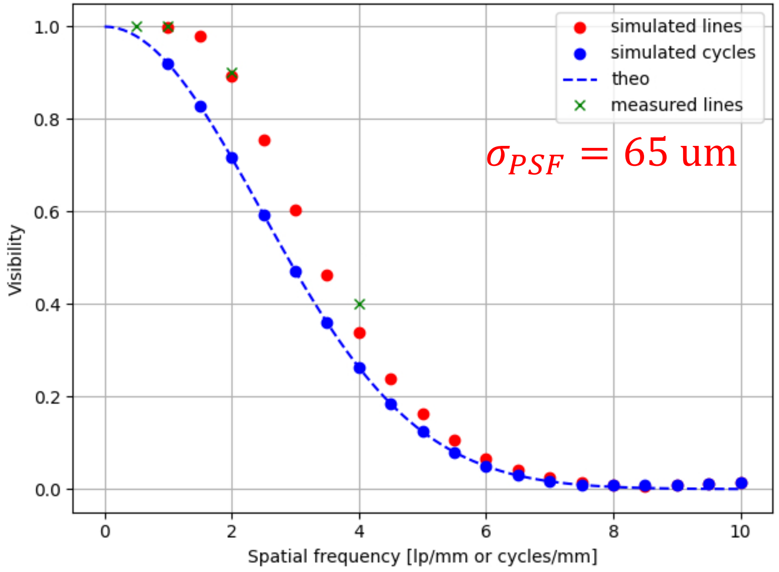
Focusing and resolution assessment

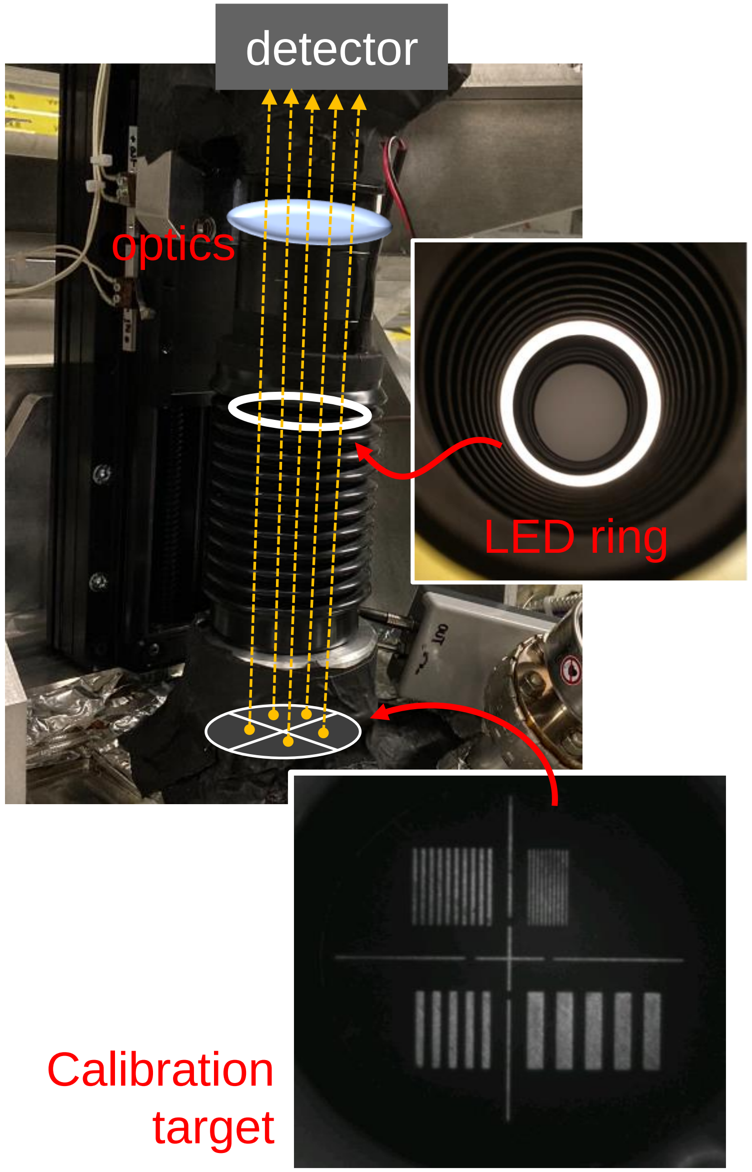
Magnification and resolution of the optics needed to get beam size from the image size

$$\sigma_{image} = \boldsymbol{M}\sqrt{\sigma_{source}^2 + \boldsymbol{\sigma_{PSF}^2}}$$

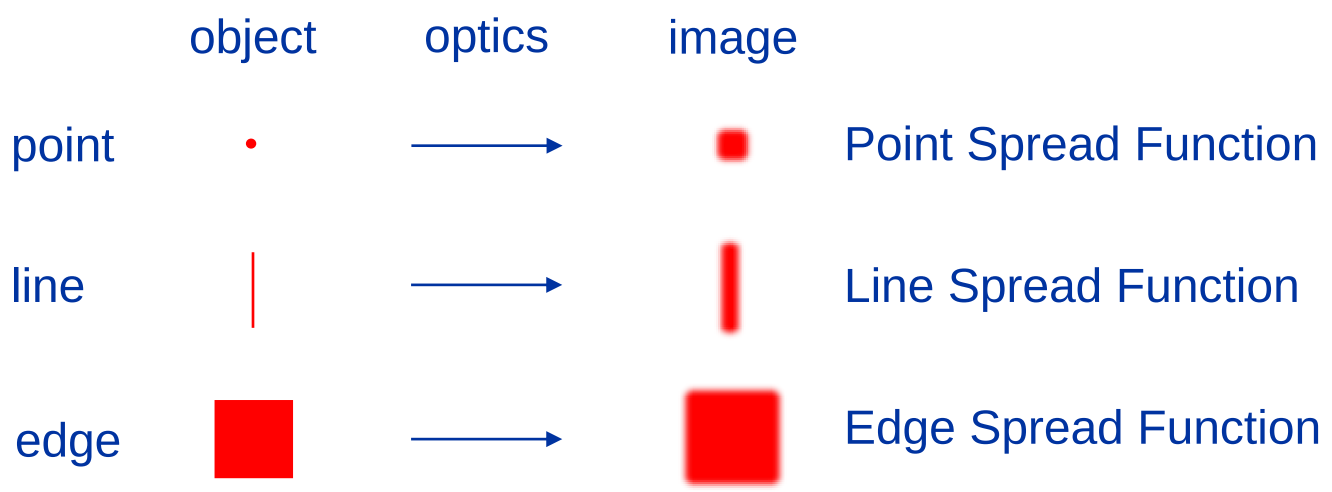
Several tests during YETS
→ independent techniques yield consistently ~**65 um resolution**







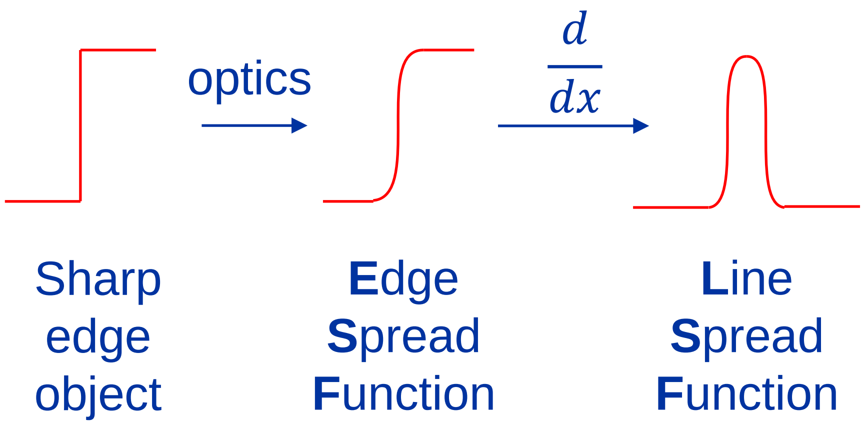
Resolution assessment

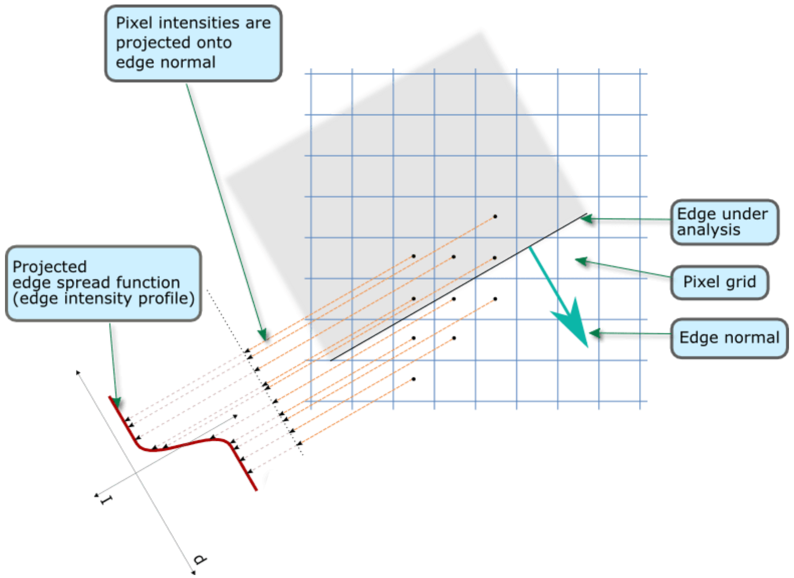


sharp spread functions ↔ better resolution

All valid estimators, **edge spread function (ESF) is often the most practical** to measure

Slanted edge method





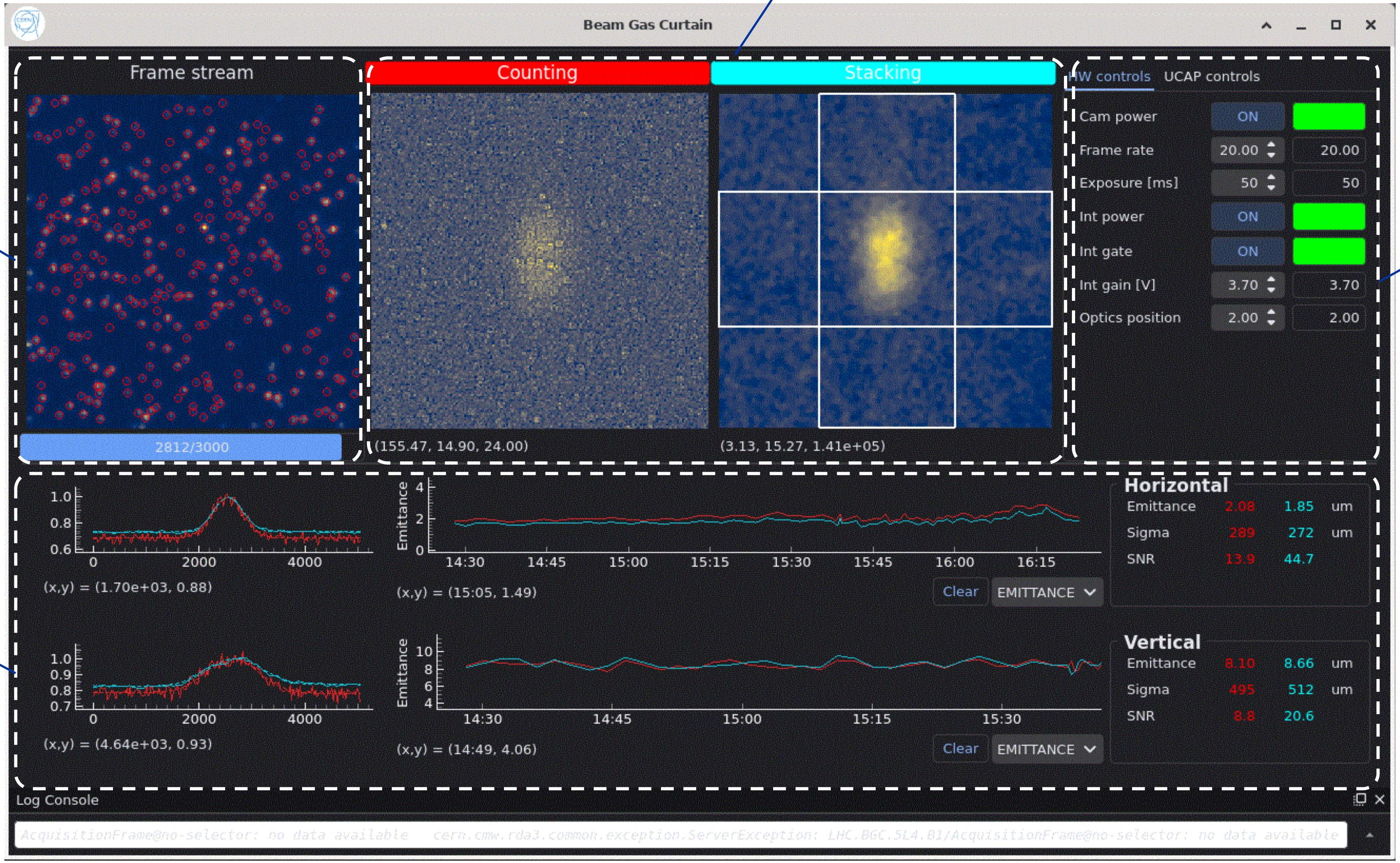
Real-time display

Single frames with photon detection

Integrated images

HW and analysis controls

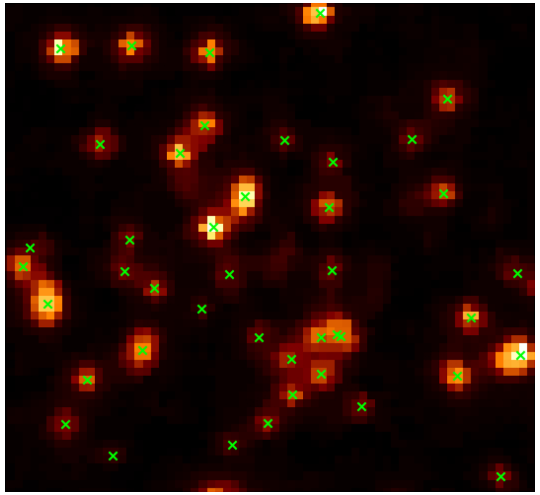
Profiles and fit results



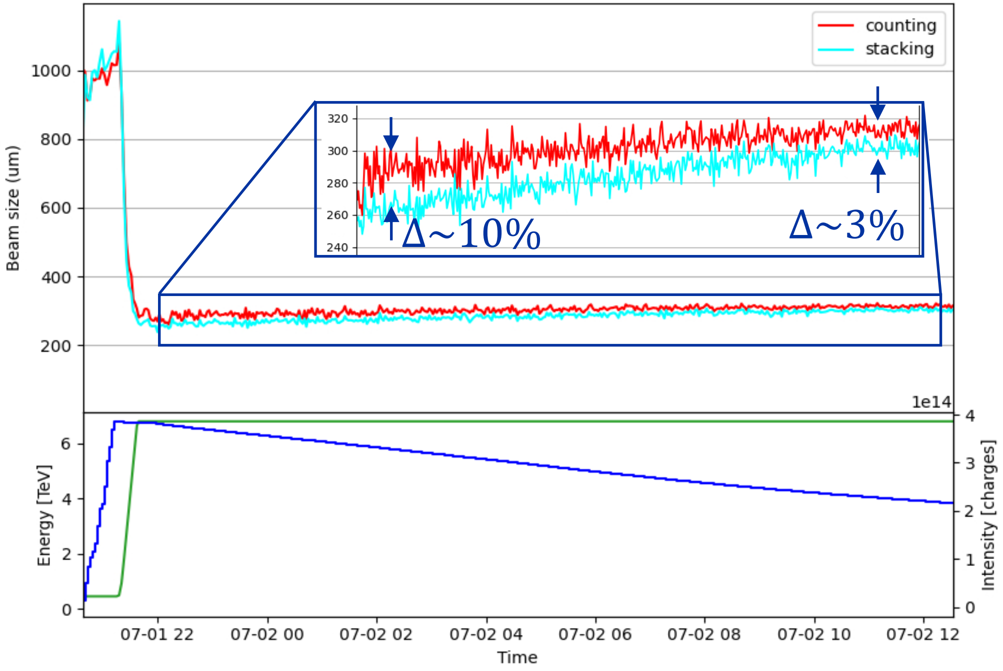
Photon counting vs intensity stacking

Given the long exposure time required, two possible strategies to create image

- **photon counting:** necessary for fluorescence cross-section measurements and, in principle, less affected by noise
- **intensity stacking**: straightforward implementation but more susceptible to noise



Example of photon detection in a single frame of 50ms exposure



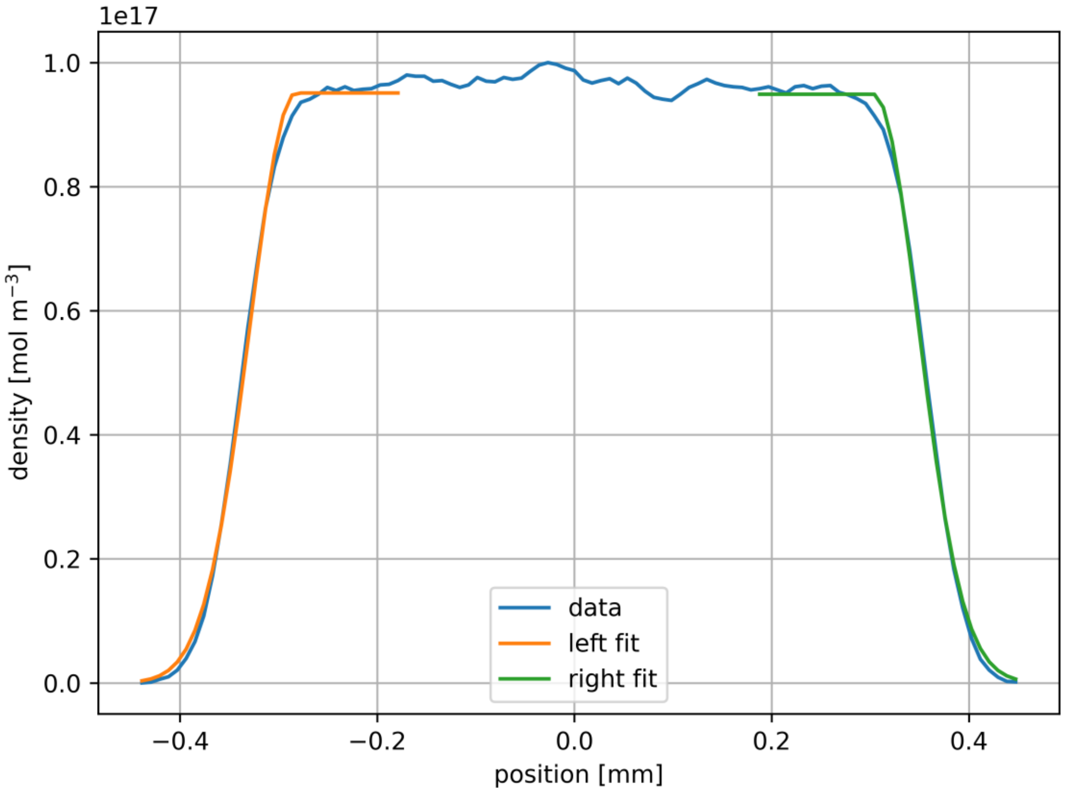
Counting and stacking coincide for large beams (e.g. at injection energy)

For small beams, counting is systematically larger, and the delta decreases with time at flat-top.
Likely due to a failure of photon counting at high photon density (small beams and beginning of SB with high losses).
→ frame rate faster than current 20Hz probably needed

Impact of jet sharpness on resolution

BGC resolution in vertical direction limited by **sharpness and uniformity** of jet profile

Current jet has edges with $\sigma \approx 45\ \mu\text{m}$ width and 5% peak-to-peak uniformity in central plateau



Impact of long integration time during ramp

BGC is integrating a beam size that changes

We assume to use the average energy within the integration time to get the emittance

$$\varepsilon = \frac{\bar{\gamma}\sigma^2}{\beta}$$

For reasonable integration times (<2 min), this simple assumption does not give a big error