Gas jet diagnostics for hollow electron lens

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for the

BGC Collaboration

9th HL-LHC Collaboration meeting, Fermilab, USA, 15th October 2019

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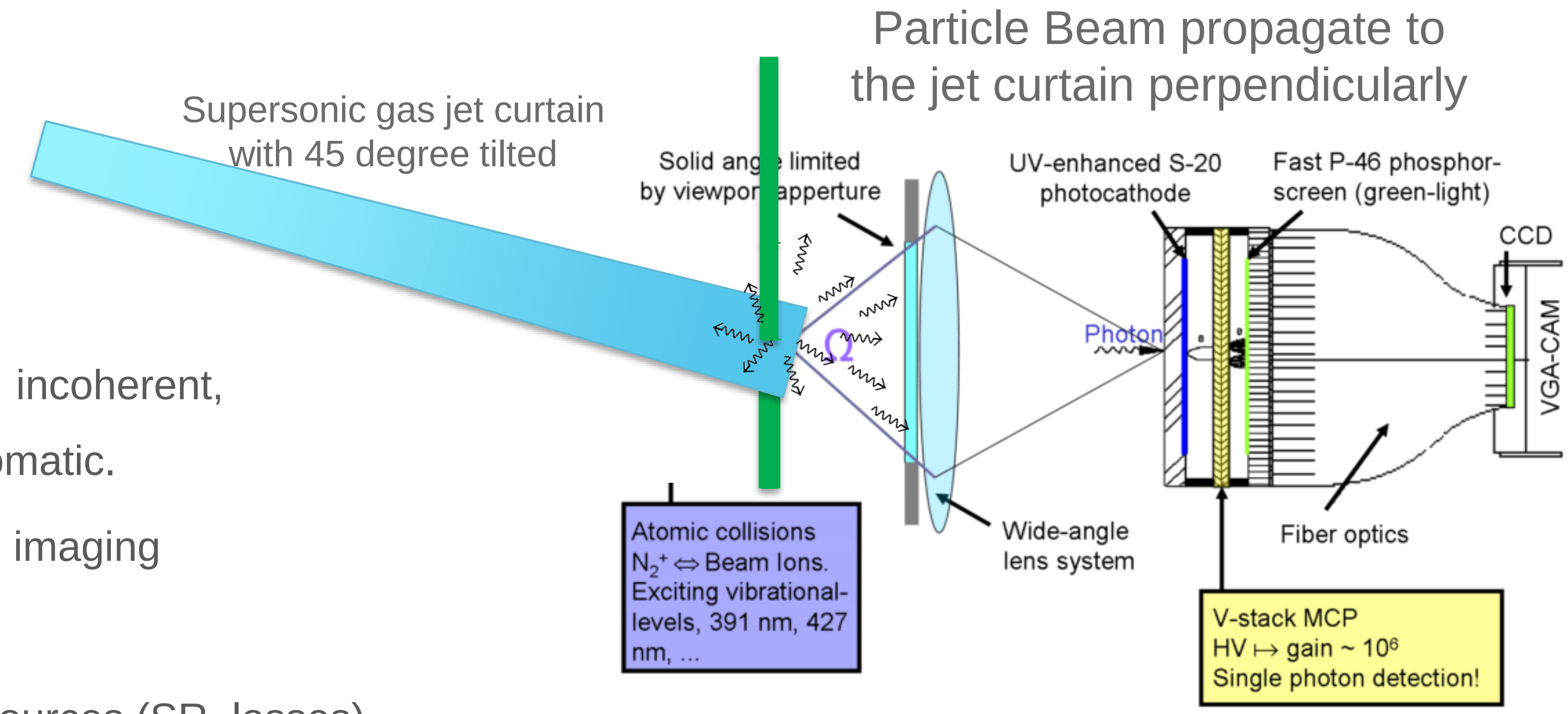
Outline

- Motivation
- Principle of the supersonic gas jet beam profile monitor in beam induced fluorescence (BIF) mode.
- Experimental program in CI with prototype setup
- Ongoing v3 setup for HEL test stand
- *HL-LHC-UK phase II* proposal and plans

Motivation

- **Problem**: HLLHC aims to increase the luminosity by 10 times than current LHC condition. There is no mature diagnostics for continuous, non-invasive 2D profile monitoring for such condition.
- Hollow e-lens (HEL) requires a diagnostic for on-line monitoring of the overlap between proton and electron beams in high magnetic field region.
- A **solution** was developed during *HL-LHC-UK phase I* where it was successfully demonstrated through a prototype setup at the Cockcroft Institute that a supersonic gas jet in fluorescence mode can measure the 2D transverse beam profile online with sufficiently short integration times.

Beam induced fluorescence using gas jet



*Credit: GSI, http://www-bd.gsi.de/dokuwiki/doku.php

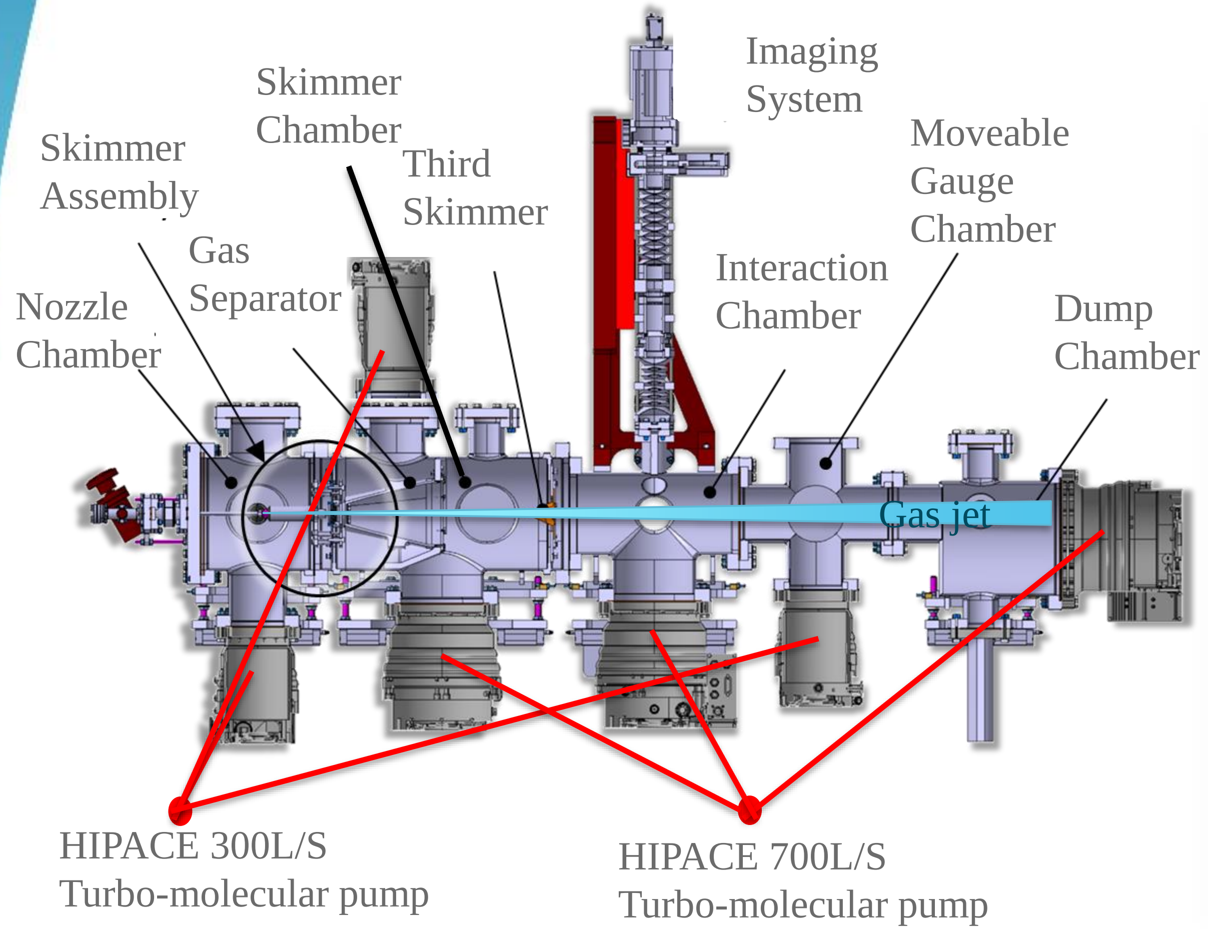
- PROS:
  - Very simple source: incoherent, isotropic, monochromatic.
  - Detection is simple: imaging
- CONS:

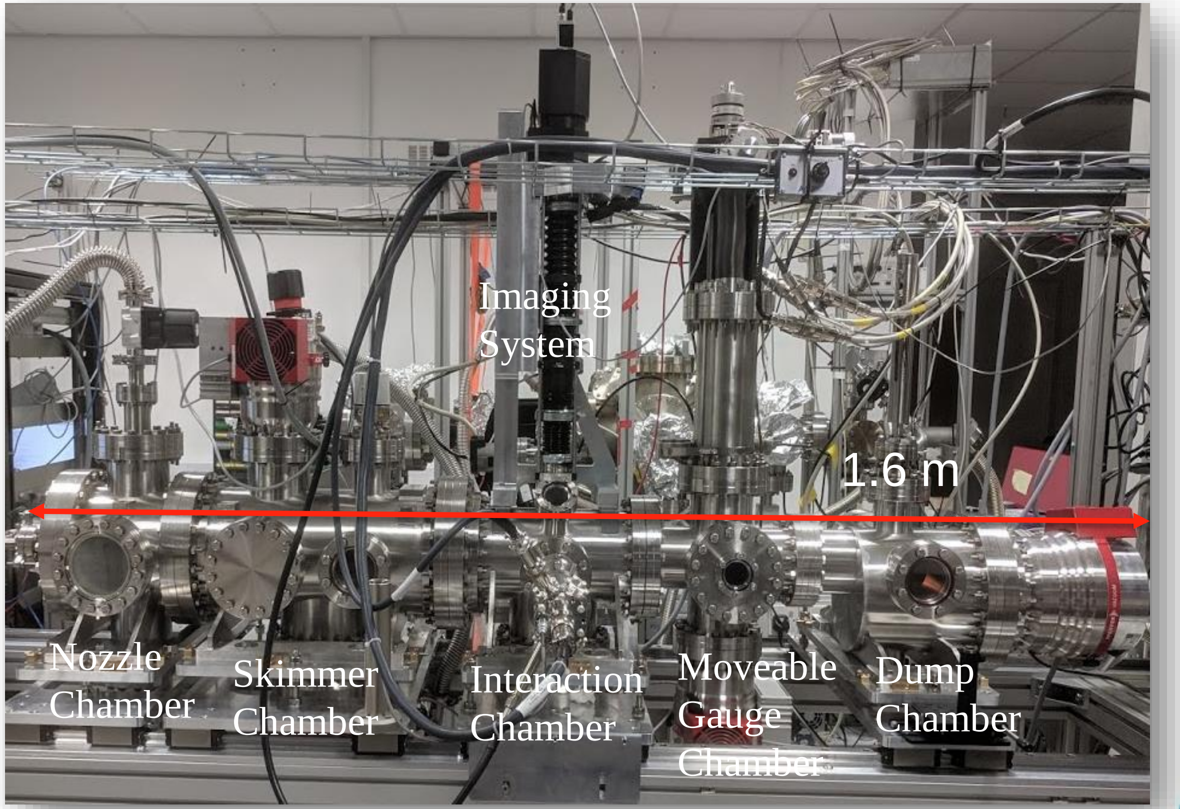
  Low light yield, noise sources (SR, losses).

$$T(Integration\ time) \propto \frac{1}{\sigma}(Cross\ section)\ \frac{1}{n}\,(Jet\ number\ density)$$

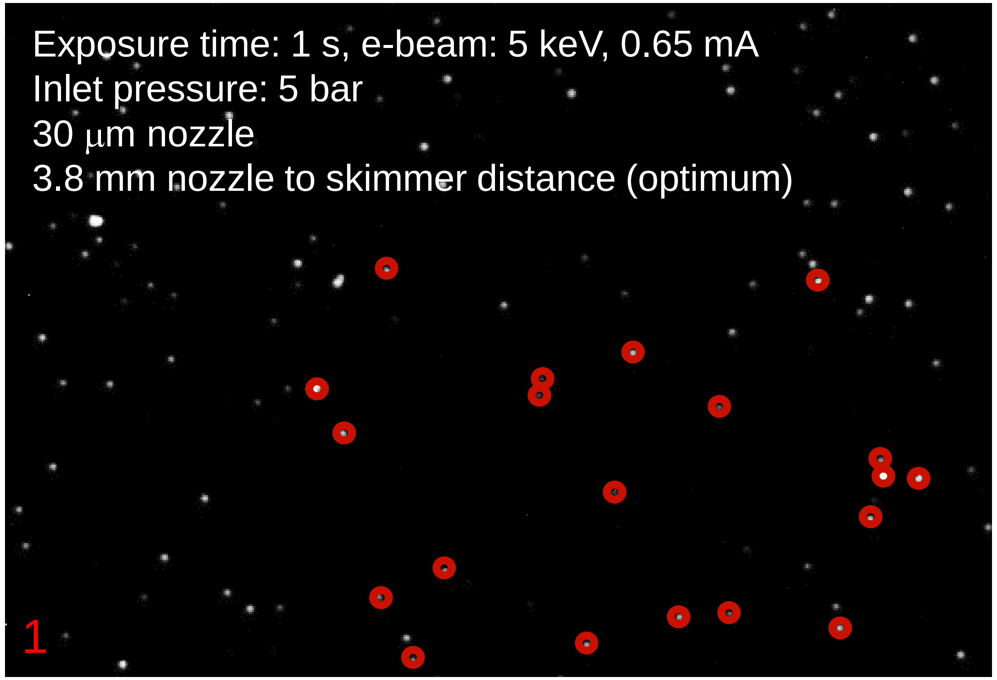
Key: Increase gas jet density
test working gases

Prototype (v2) at the Cockcroft Institute





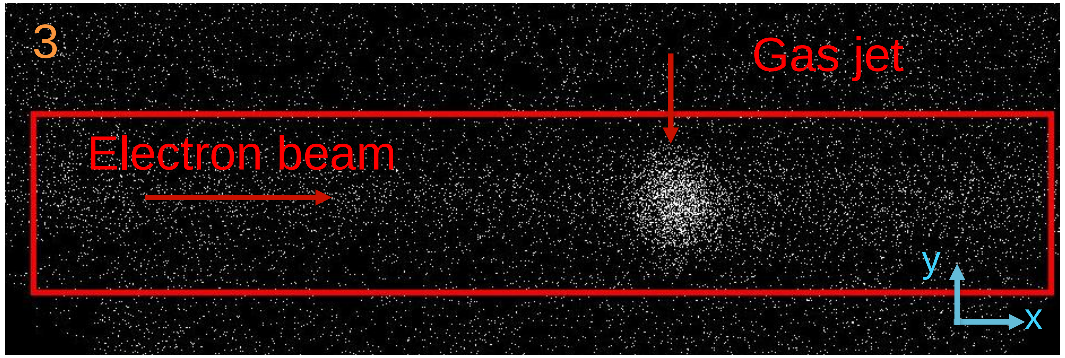
Photon counting method



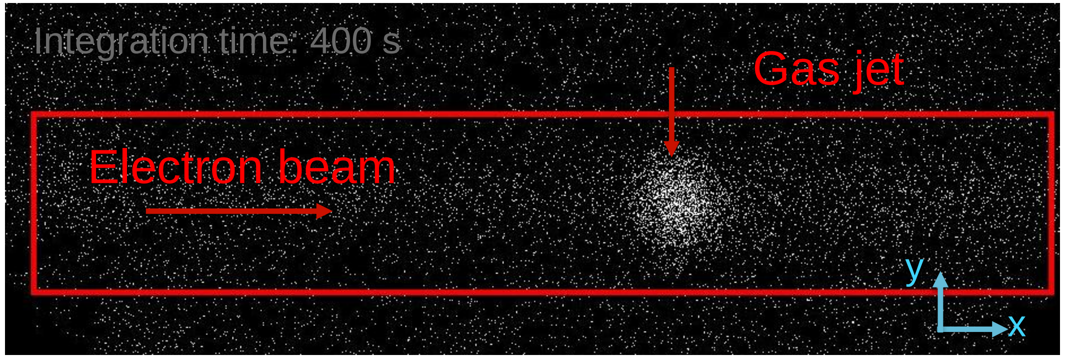
1. Identify location of each dot. Each dot is a photon (either signal or noise)
2. Repeat this for all frames
3. Integrate all frames to form a photon count matrix. The total integration time will be exposure time * frame number.

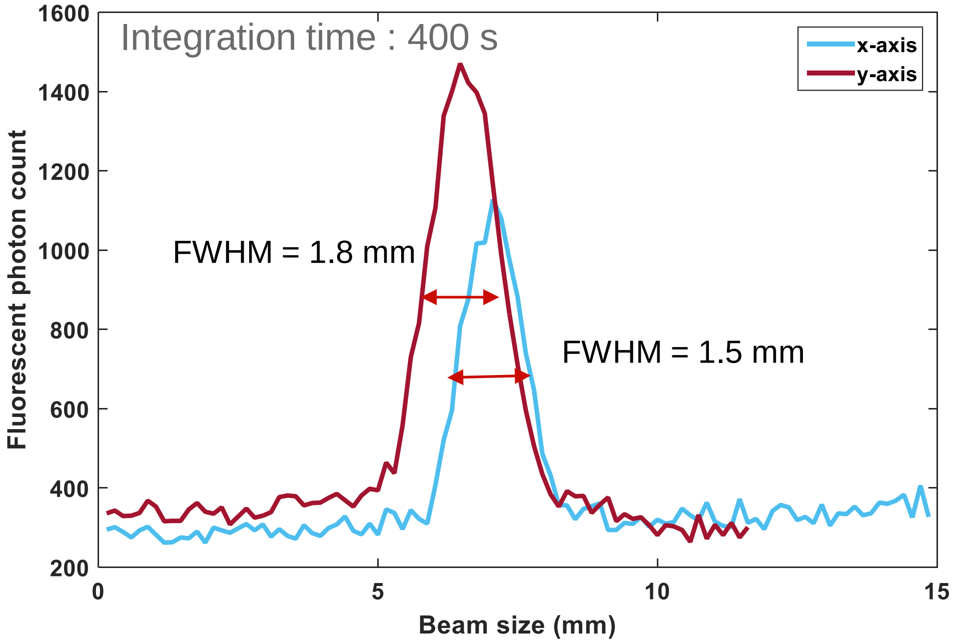
2

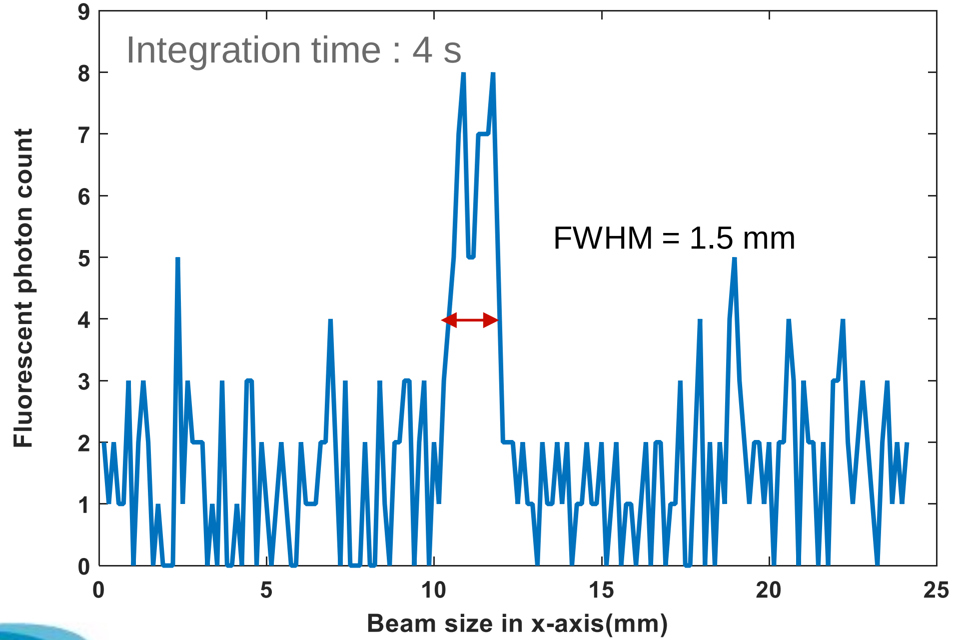
	X	Y
1	879	485
2	585	1114
3	332	381
4	1275	448
5	461	950
6	1605	388
7	484	732
8	1355	732
9	242	12
10	1089	288
11	1121	636



Working gas test: Nitrogen gas jet







Filter used for Nitrogen: 391 nm with 10 nm bandwidth

Number of photons per second from the jet: ~ 17

Electron beam signal is visible in just 4 s via binning.

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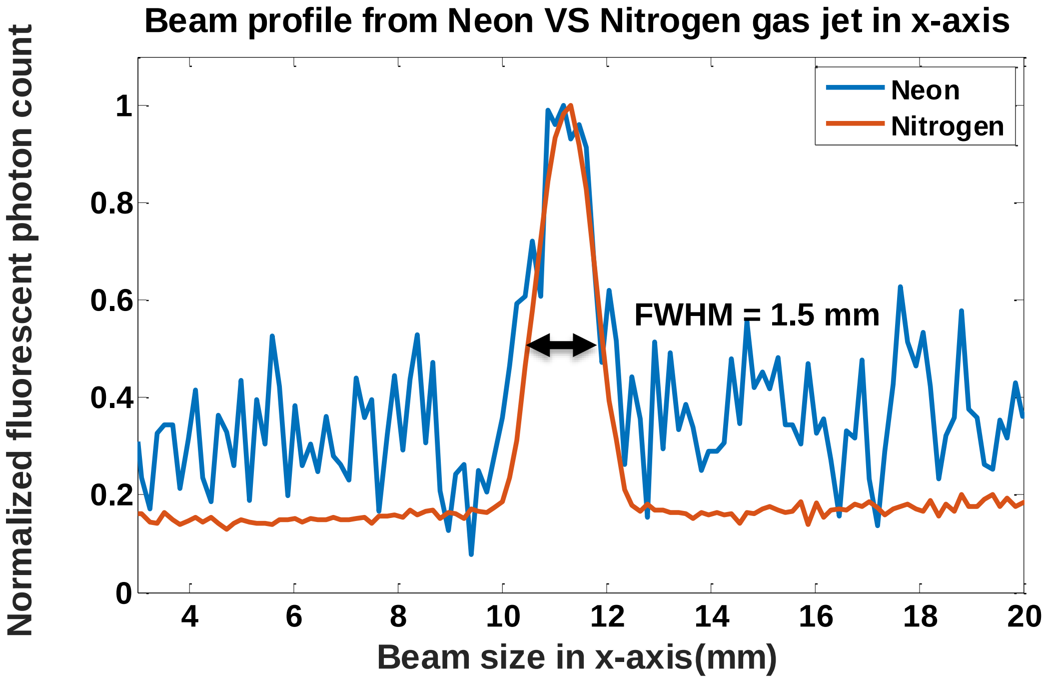
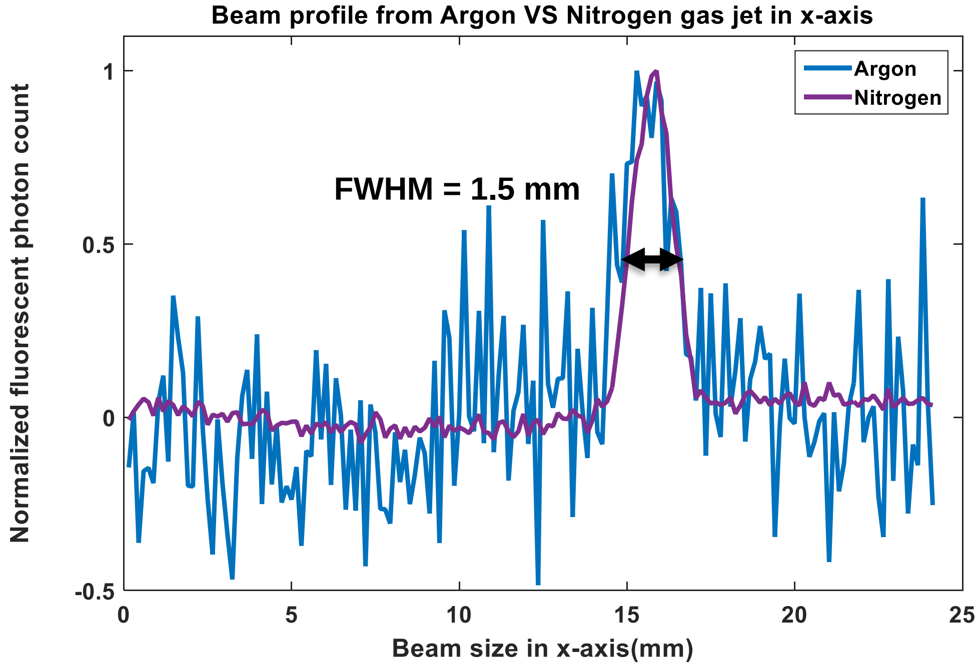
Neon and Argon gas-jet

- Integration time: 4,000 s (+ 4,000 s for background);
- Good agreement between normalised profiles of neon and nitrogen;
- Filter used for Neon: 585 nm with 10 nm bandwidth
- Number of photons per second from jet: 1.6 per second



- Integration time: 4,000 s (+ 4,000 s for background);
- Filter used for Neon: 476 nm with 10 nm bandwidth
- The background was subtracted from the gas jet image
- Number of photons per second from jet: 1.3 per second.



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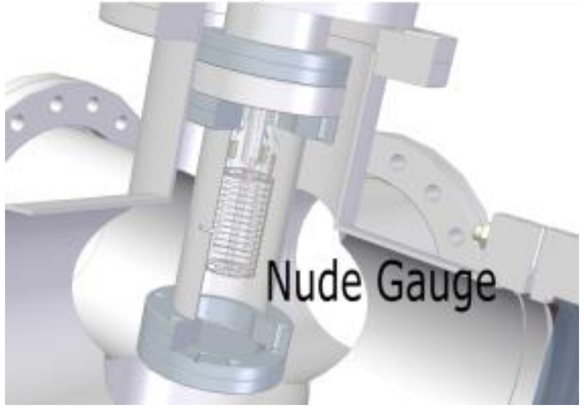
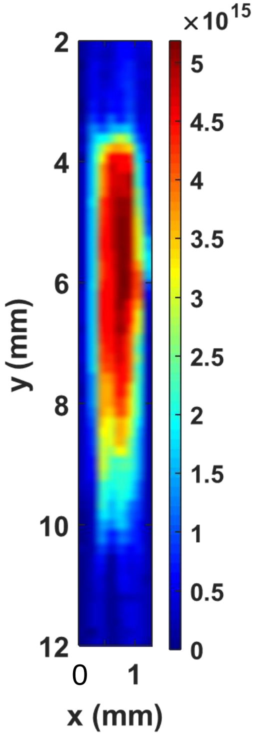
Density measurements with pin-hole gauge

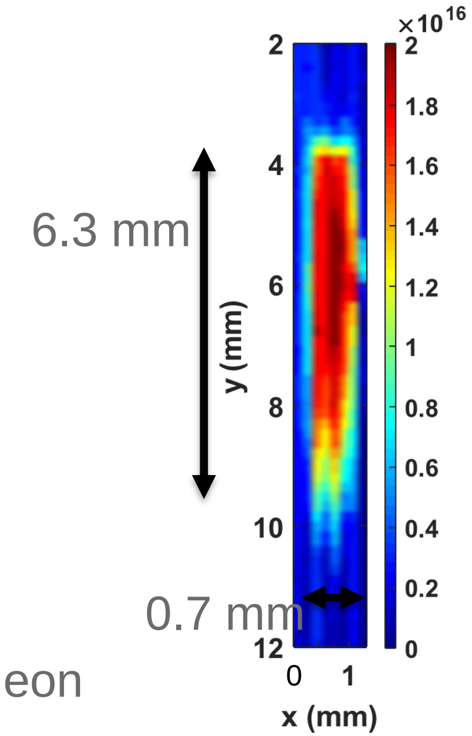
- A scan was taken using the pin-hole opening for nitrogen, neon and argon under similar experimental conditions. (30 μm nozzle at optimum nozzle-skimmer distance and third skimmer set vertically).
- Density measured by :

$$\rho = \frac{\frac{I_{ion}}{I_e} * S * < v >}{4Q * k_B * T * v_{jet}}$$

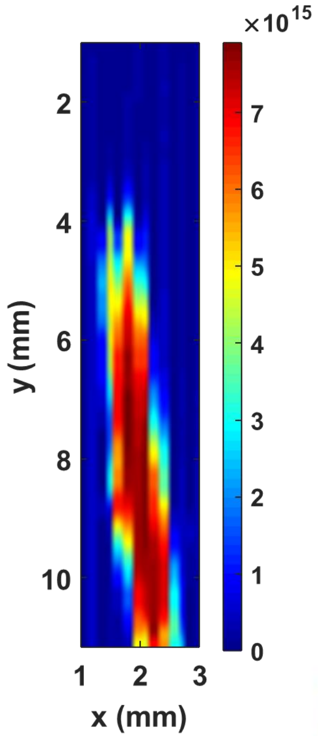




Nitrogen



Neon



Argon

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Summary: working gases in lab condition

	Experimental Photon Number/s	Advantages	Disadvantages
N_2 N_2^+ emitter 391.4 nm	17	• Higher photon rate, shorter integration time. • lower dark counts rate for the photocathode • Higher quantum efficiency of photocathode	• Ion emitter with 60 ns lifetime, potential distortion due to space charge and external EM field on the N_2^+ • Need further vacuum approval
Neon Ne emitter 585.4 nm	1.6	• Fluorescence due to neutral Ne (yellow line), not affect by space charge of the primary beam and external EM field • LHC vacuum compatible	• Lower photon rate, longer integration time • Higher dark counts rate for the photocathode • Lower quantum efficiency of photocathode • Background light from lab e-gun
Argon Ar^+ emitter 476.5 nm	1.3	• Short decay time, less affected by space charge or external EM field • Higher quantum efficiency of photocathode	• Lower photon rate, longer integration time • Background light from lab e-gun
Argon Ar^+ emitter 420±75 nm	4		

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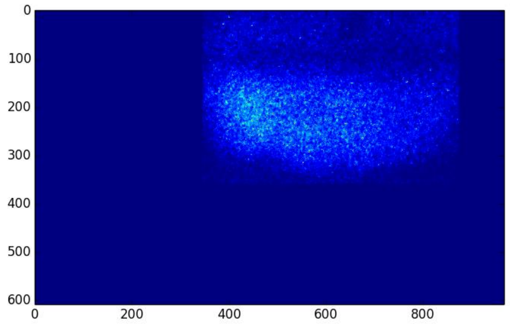
Estimation for HEL condition

- Based on a gas jet with N=2.5e10 cm^{-3}, d=0.5 mm.
- Cross section data for 7 TeV proton beam is extrapolated from references. Tests are required for LHC condition.
- $\langle t_i \rangle_{mcp}$ is the expected time to detect one photon. A few hundred photons are required for the proton beam and 10^4 for the HEL electron beam.
- Expected integration time
  - Electron: sub second
  - Proton: few or few tens of seconds

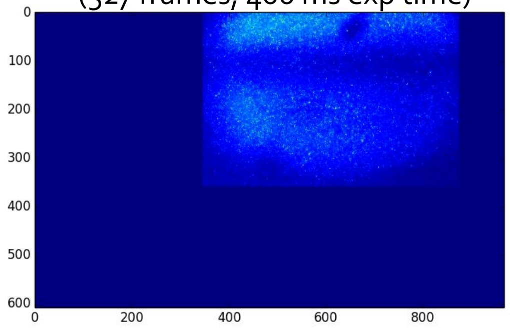
Projectile	Emitter	λ [nm]	σ [cm²]	I [A]	$\langle t_i \rangle_{MCP}$
electron	N_2^+	391.4	$9.1\cdot10^{-19}$	5	$2.9_{0.51}^{10608}\cdot10^{-7}$
proton	N_2^+	391.4	$3.7\cdot10^{-20}$	1	$3.6_{0.59}^{14330}\cdot10^{-5}$
electron	Ne	585.4	$1.4\cdot10^{-20}$	5	$4.0_{0.71}^{23475}\cdot10^{-5}$
proton	Ne	585.4	$4.7\cdot10^{-22}$	1	$5.9_{0.97}^{37760}\cdot10^{-3}$
electron	Ar^+	454.5	$4.2\cdot10^{-21}$	5	$5.4_{0.97}^{19389}\cdot10^{-5}$
electron	Ar^+	476.5	$5.7\cdot10^{-21}$	5	$4.6_{0.82}^{16826}\cdot10^{-5}$
electron	Ar^+	454 & 476	$9.9\cdot10^{-21}$	5	$2.5_{0.45}^{9072}\cdot10^{-5}$
proton	Ar^+	454.5	$7.3\cdot10^{-22}$	1	$1.6_{0.27}^{6256}\cdot10^{-3}$
proton	Ar^+	476.5	$9.9\cdot10^{-22}$	1	$1.3_{0.21}^{5174}\cdot10^{-3}$
proton	Ar^+	454 & 476	$1.7\cdot10^{-21}$	1	$7.4_{1.2}^{29315}\cdot10^{-4}$

BIF test during Run 2

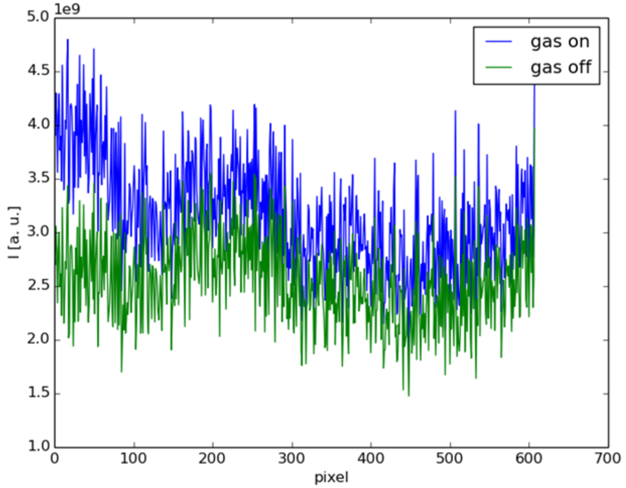
- Pb$^+$ at injection



585 nm, gas **OFF**, beam **ON**
"photon counting" over 210.8 s
(527 frames, 400 ms exp time)

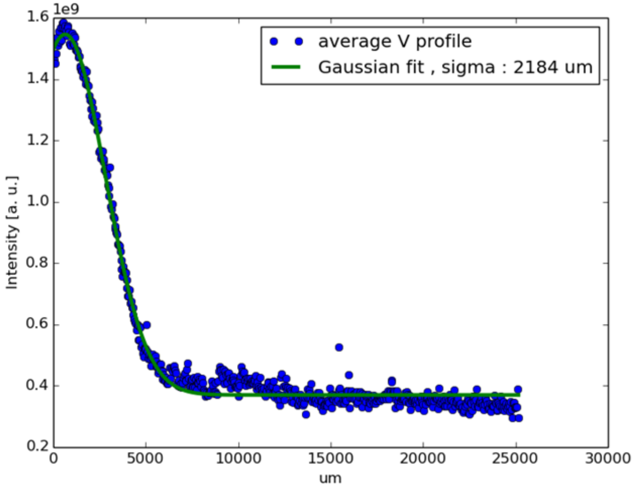


585 nm, gas ON, beam ON
"photon counting" over 1286.4 s
(3216 frames, 400 ms exp time)



V Profiles from sum of

- 3215 images (gas on)=> 1285 s integration time
- 1443 images (gas off)=> 577 s i.t.



Difference corrected for different integration time, no other adjustable parameter.

Sigma 2.2 mm

- Proton test => Noises from SR

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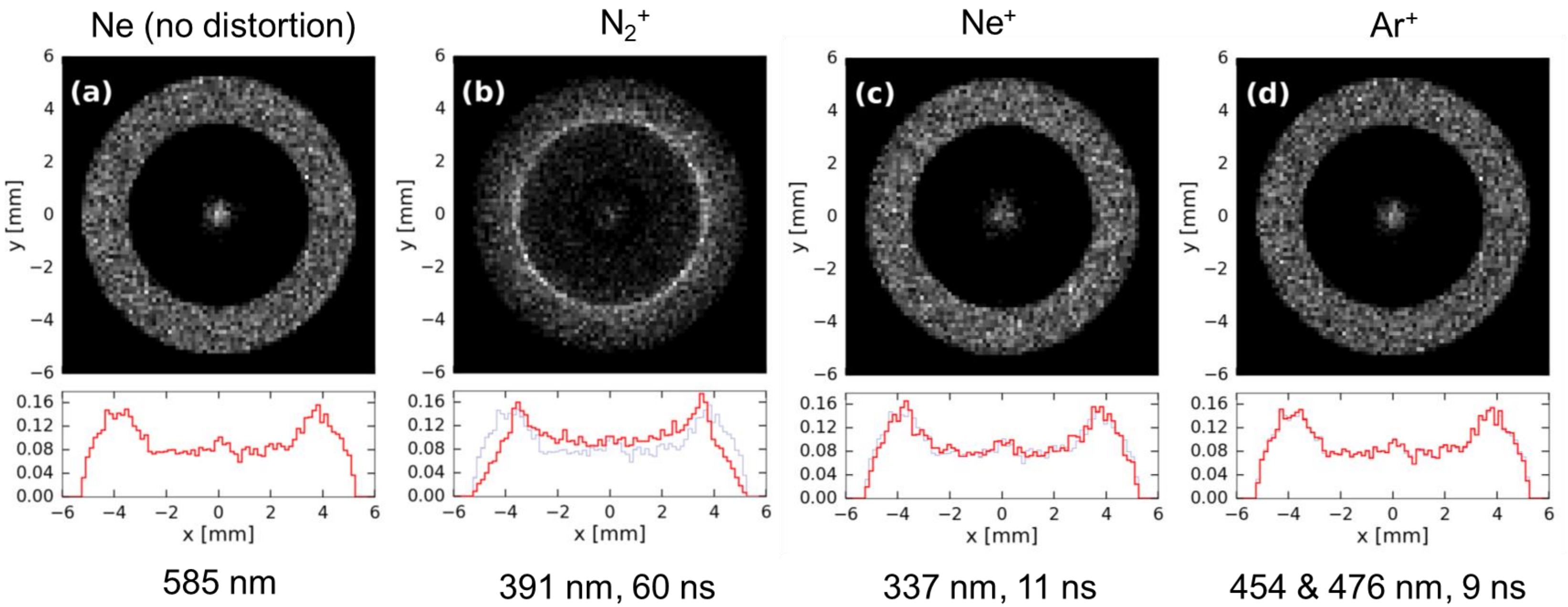
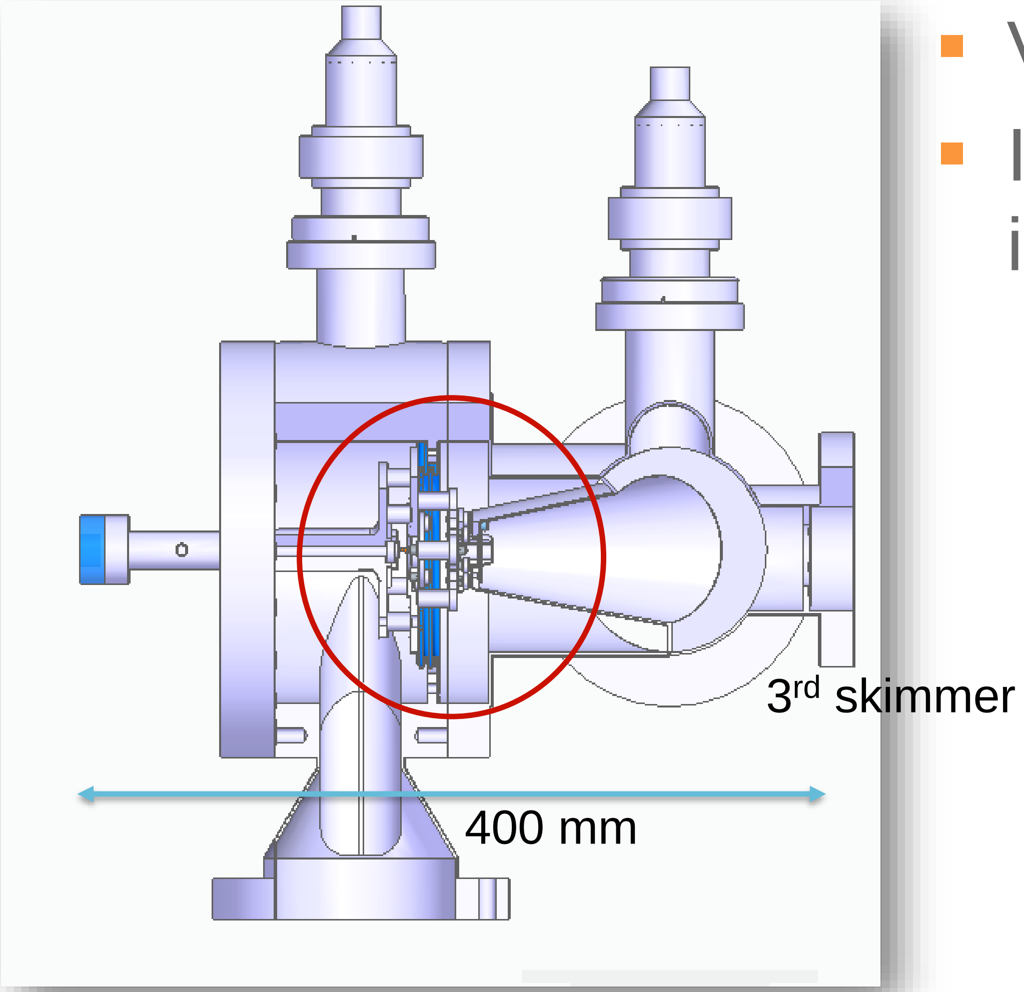
Challenge of BGC for HEL

- Gas choice (distortion due to space charge)

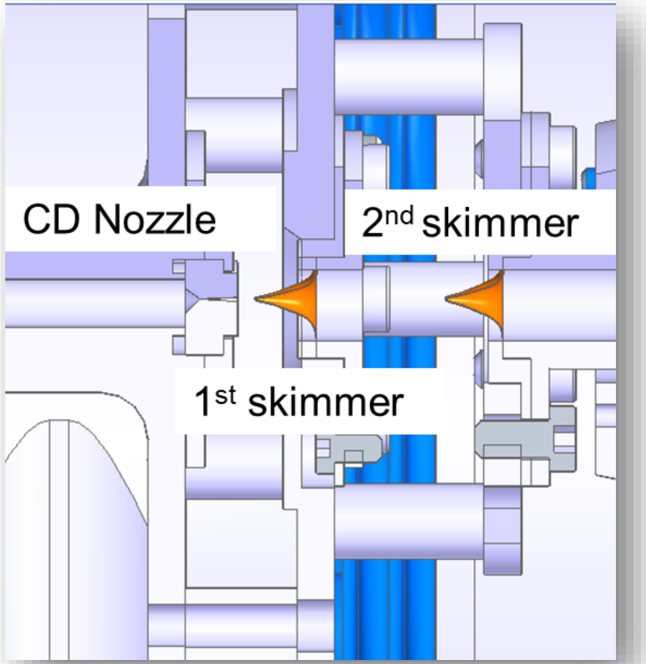


- Light pollution (SR, stray light) => Black coating, filtering
  - NEG on Cu (R = 44.3%) vs. Polyteknik black coating (R = 0.12 % @ 585 nm)
- Shorten the integration time => Increase jet density.

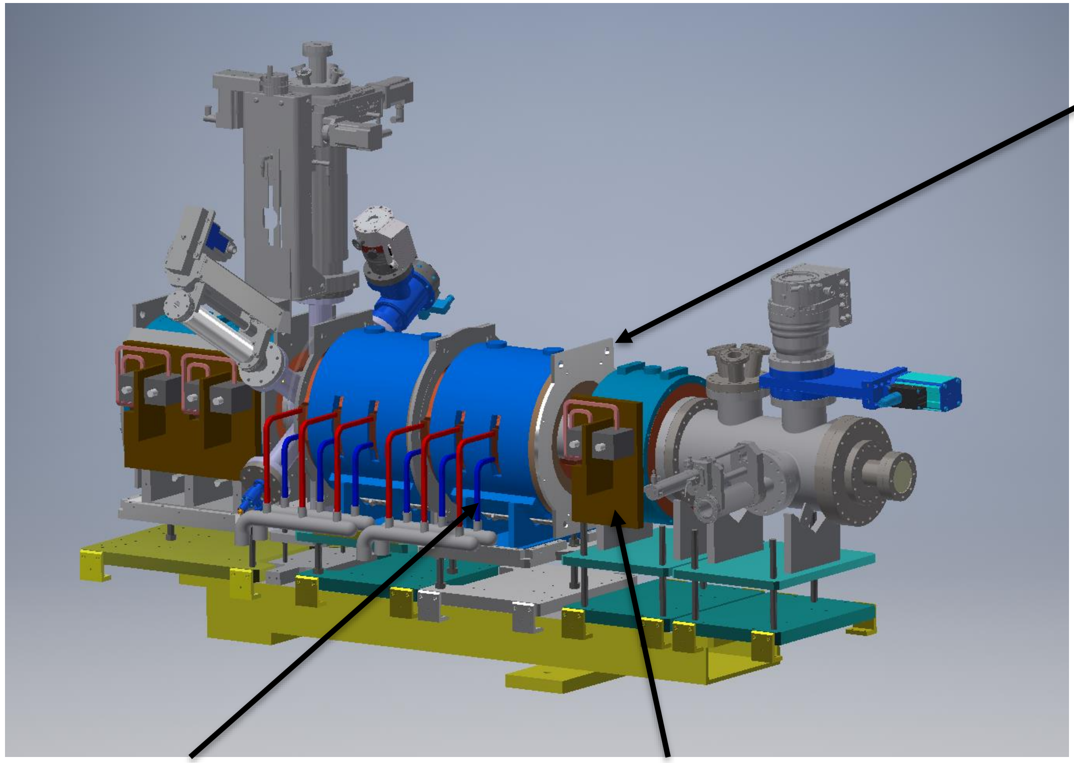
Compact design for gas jet generation

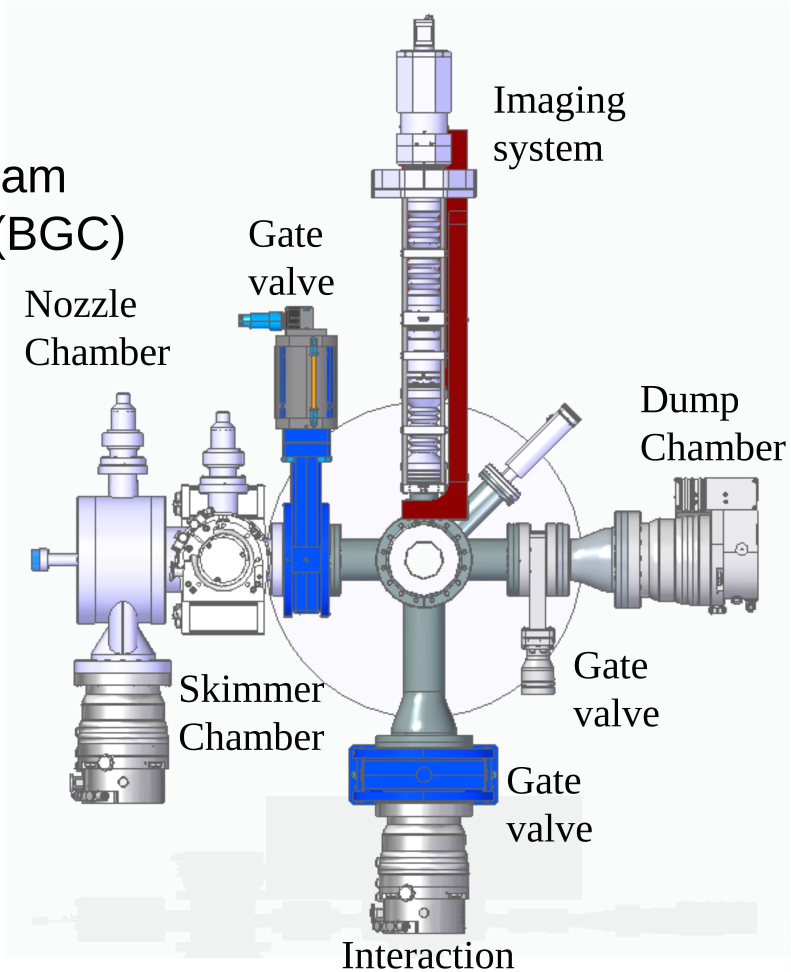


- Versatile for space limitation
- Increase gas jet density at the interaction chamber.



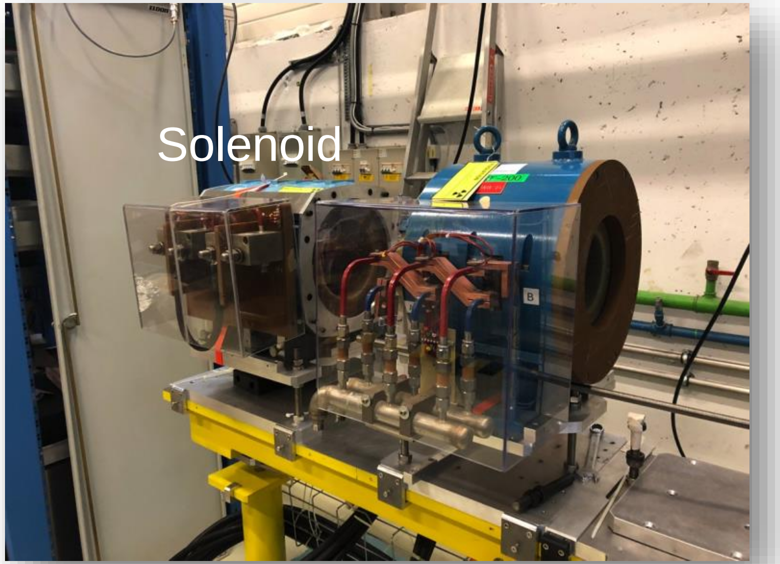
V3 gas jet setup for HEL test stand





Plans for v3 gas jet for HEL test stand

- Procurement ongoing
- By end of March 2020: v3 gas jet system delivered and commissioned at CI;
- Connected to June 2020 milestone: ARIES e-gun and modulator measurements



HL-LHC-UK Phase II

- Gas jet beam profile monitor (BGC) is strongly supported by CERN for LHC as a general non-invasive profile measurement diagnostic and the baseline instrument for on-line monitoring of the overlap between proton and electron beams for HEL;
- We will carry out R&D into minimum-invasive transverse profile monitoring and deliver two supersonic gas jet-based monitors based on beam-induced fluorescence
- The specific objectives are
  - Build and commission two gas jet monitors; deliver the instruments to CERN for integration in HL-LHC and contribute to commissioning and operation;
  - Optimize optical imaging and acquisition system through simulation and experiments;
  - Fully characterize different jet formation schemes and their impact on density at interaction point;
  - Study options for gas jet wire scanner and achievable resolution.

HL-LHC-UK Phase II

- This work is a direct continuation of our previous studies in HLLHCUK – phase I.
- Large parts of the monitors will be manufactured by UK industry through established contacts from phase I. Opportunities for further commercialization of the monitor will be exploited with the help of experts from *D-Beam*, STFC-CERN BIC alumni.
- Phase II work will make this profile monitor a versatile solution for essentially any high energy, high intensity accelerator.

- Research and installation plan
  - **Stage 1**
    - Install interaction chamber assembly in LHC include blackened chamber, gate valves, supports, optical calibration target during LS2. **01/04/20-24/12/20**
  - **Stage 2**
    - M3.2.1: Commission and optimize gas-jet design based on Phase I final deliverable both at CI and at HEL test stand. **01/04/20-31/11/21**
    - Carry out investigations into the adaptation of the current scheme to a gas jet wire scanner. **01/01/21-31/11/21**
    - D3.2.1: Get-jet monitor engineering design: show that proposed design meets all specifications. **31/12/21**

Interaction chamber

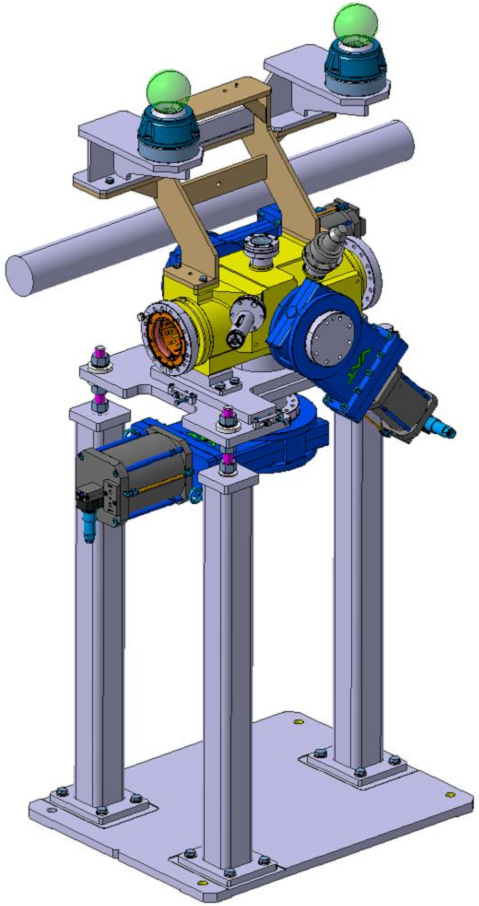
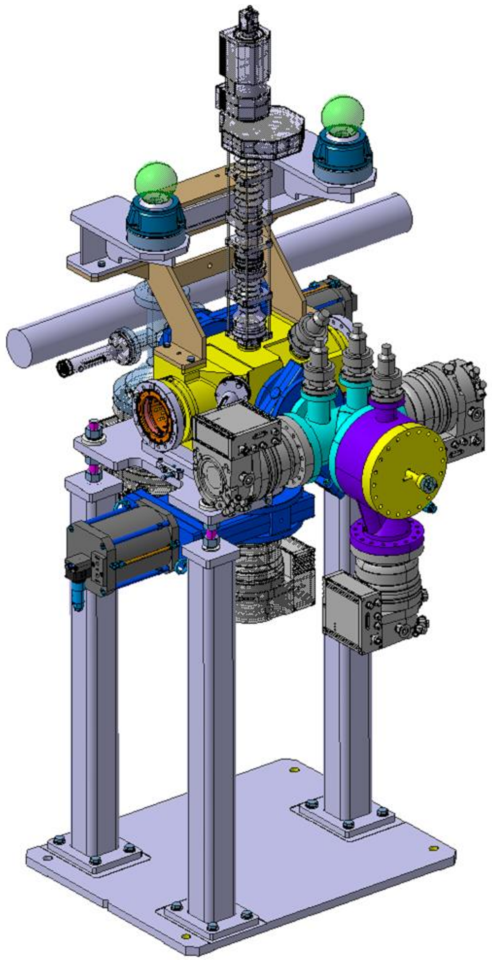


Image Courtesy: J. Glutting

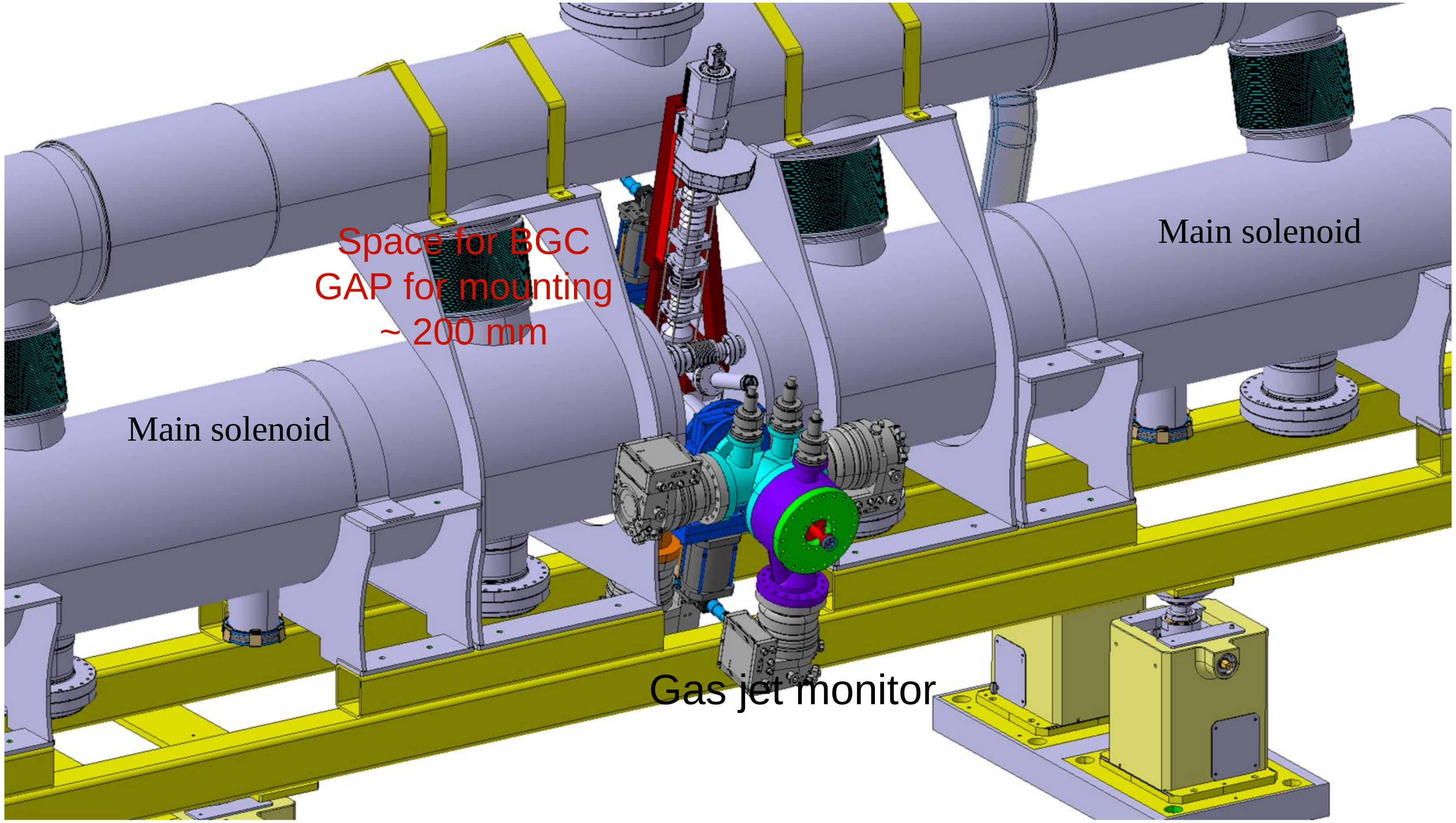
HL-LHC-UK Phase II

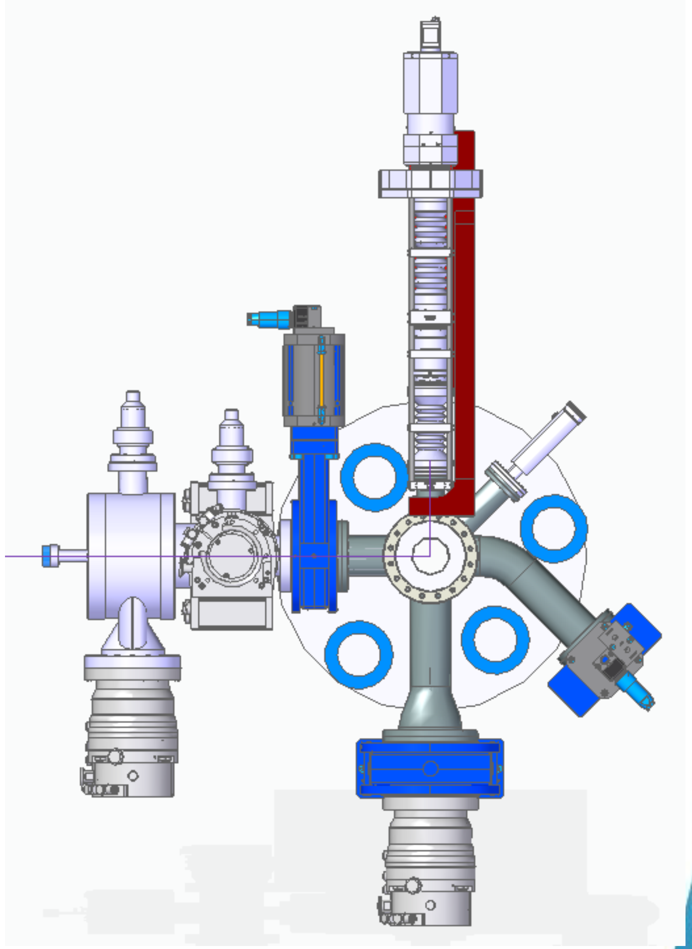
- Research and installation plan - continued
  - **Stage 3**
    - Prototype monitor installed during LHC technical stop **01/12/22-28/02/22**
    - M3.2.2: Finalize design and production drawings. **01/03/22-30/06/22**
    - Review of gas-jet drawings to launch production completed **01/03/22-30/06/22**
    - Prototype monitor commissioning and study of 7 TeV proton fluorescence **01/03/22-31/08/22**
    - D3.2.2: Final design: report with final drawings, integration and commissioning plan **01/09/22-31/10/22**
  - **Stage 4**
    - Manufacture interaction chambers and delivery to CERN for HEL setup **30/06/22-28/03/23**
    - D3.2.3: Delivery of interaction chambers for integration in HEL **31/03/23**
    - M3.2.3: Orders placed for major gas-jet unit 1 components:
      - Manufacture and delivery of gas jet monitor unit 1 **28/03/23-26/03/24**
      - Manufacture and delivery of gas jet monitor unit 2 **26/03/24-17/12/24**
    - D3.2.4: Delivery of gas-jet monitor unit 1, pre-tested at CI, for integration in HEL. Participation in commissioning **28/03/23-31/03/20**
    - D3.2.5: Delivery of gas-jet monitor unit 2 for integration at CERN, pre-tested at CI **31/12/2024**
    - M3.2.4: Production of gas-jets completed and shipped to CERN **02/01/25**



Preliminary image of BGC integrated with LHC.
Image Courtesy: J. Glutting

HEL integration with gas jet monitor





Summary

- In *HL-LHC-UK phase I*, we successfully demonstrated 2D minimum invasive transverse profile monitor based on beam-induced fluorescence, using supersonic gas jet;
- Various options of gases were studied in terms of achievable gas jet density and integration time;
- Key technologies required to produce a working instrument in the LHC have been identified and development is well under-way
- V3 monitor is being progressed and will be tested in HEL test stand;
- For *HL-LHC-UK phase II*, primary goal will be delivery of two working monitors, but R&D into gas jet wire, BGV and monitor simplification will continue.

Thanks for your attention!

Work presented on behalf of the BGC collaboration:
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C.P. Welsch, H. Zhang *(U Liverpool / Cockcroft Institute)*
P. Forck, S. Udrea *(GSI)*
M. Ady, N. Chritin, T. Doddington, J. Glutting, R. Jones, R. Kersevan, S. Mazzoni,
A. Rossi, G. Schneider, R. Veness, *(CERN BE-BI, TE-VSC, EN-MME)*

9th HL-LHC Collaboration meeting, 15th October 2019