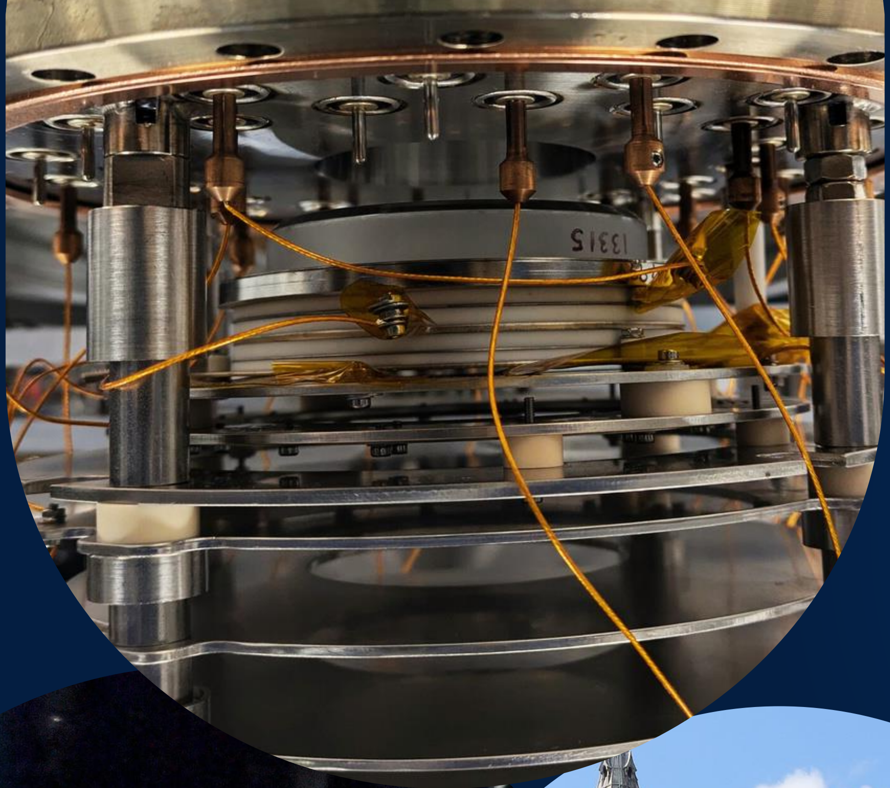
Novel end station, diagnostic and Instrumentation (gas-jet technology)

MILAAN PATEL

University of Liverpool



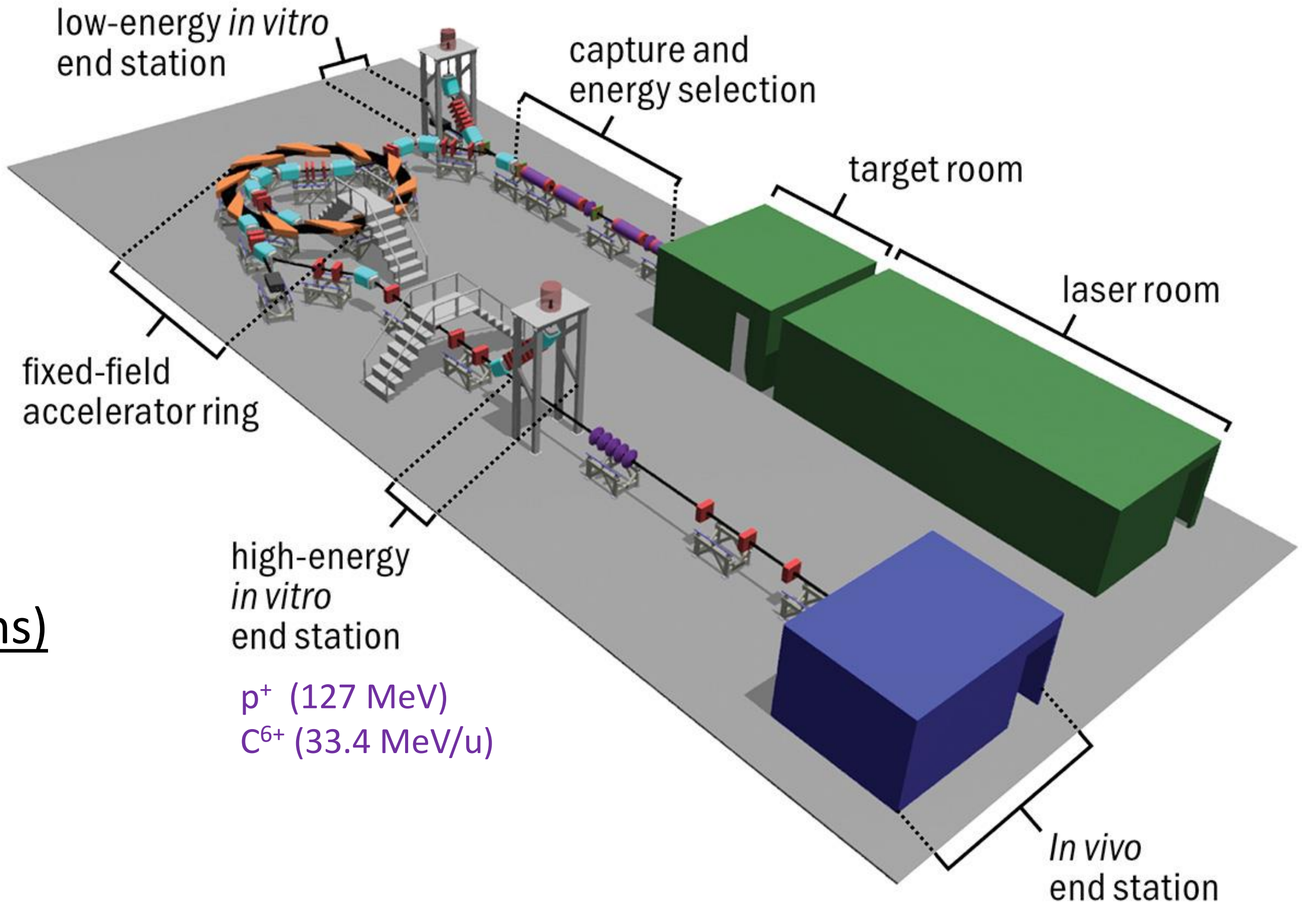
LhARA Collaboration Meeting #7
7-8, Apr 2025

The goal

Application of LhARA

- To monitor beam at end station: in-vitro (x2) and in-vivo (x1)
- **Beam Type** [a]: Laser driven beam at 10 Hz, ~10 ns bunches ~10^9 p^+ , C^{6+} per bunch
- Online (Single bunch) beam profile monitoring.
- **Parameters to monitor**: beam Profile, current also energy and dose (if possible)

p^+ (15 MeV)



p^+ (127 MeV)
C^{6+} (33.4 MeV/u)

Deliverables (Phase-1, 2 years) (Brg.P., ~10 months)

- **A detailed report on the dosimetry techniques.**
- **Feasibility of gas jet as profile monitor:**
  - **Experiments**
  - **Outline a path to realization**
- **Novel beam monitoring solutions (not gas jet).**

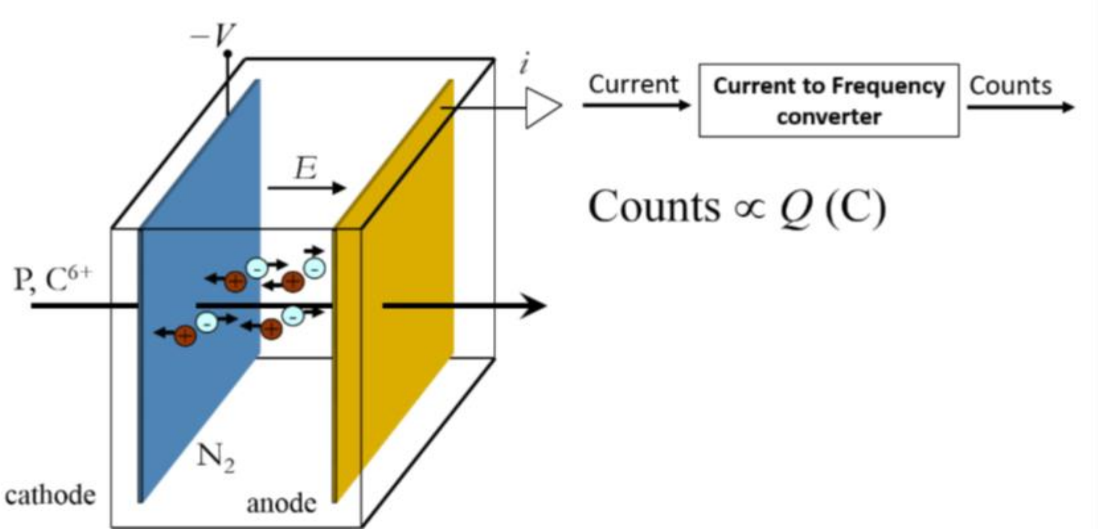
[a] Baseline for the LhARA design update. Technical Report CCAP-TN-11 Issue 1, The LhARA Collaboration (2022)

Review of Dosimetry techniques for End-Station

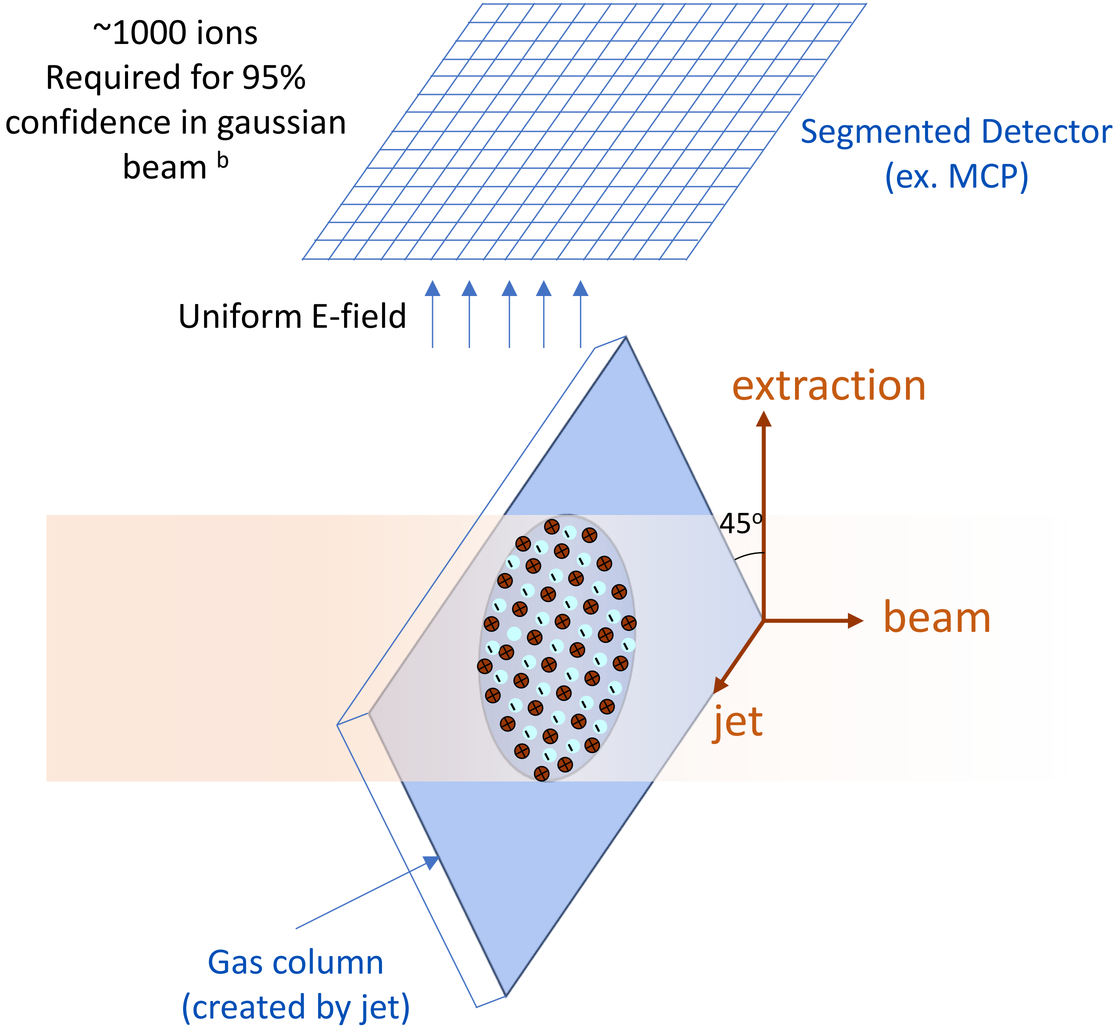
Details in CDR

Dosimeter	Absolute Dosimetry	FLASH dosimetry	Dose measurement	Spatial resolution	Response time	beam perturbation	Dose-rate dependence	Accuracy	Characteristics
Ionization chamber	Yes	p ,e	1D, 2D scanning	few mm	10-200us	Yes	significant > 1 Gy/pulse >80Gy/s	1% 80Gy/s, 15% at 1050Gy/s , 1% with recombination correction	Ion recombination at High dose rates
Diodes	N	C, ph	1D, 2D scanning	sub mm	ms	mask	Independent at 0.2 Gy/s	2-5%	Radiation damage at high dose rate, over-response at low dose rate
MOSFETs	N	ph	1D, 2D scanning	1mm	ms	mask			Temperature dependence
Diamod Detectors		p,ph,e	1D	1 mm	us	mask	> 1mGy/pulse, 50 mg/s	1% <1mGy/s, 9% for >50 mGy/s	
Faraday cup	N							up to 1%–2%	Measures total collected charge
Frikie	D	ph,e	1D	2mm	ns	Yes			High dose rate causes diffusion of radiation induced species.
Alanine	D	ph,e	1D	5mm	Passive	Yes	independent up to 3e10	<3% upto 1050Gy/s	Decreased accuracy for doses less than 10 Gy (minimum 2 Gy)
Radiochromic /Radiographic films	potentially	p, C, e	2D	<1um	Passive	partially transparent	independent up to 1.5e10	5-20% @ bragg peak , 25-35% for C	Underresponse in high LET field
Polymet gels			3D	1 um	Passive	Completely			Complex measurement and Complicated readout machinery
TLD	D	ph, e	1D, 2D array/scan	1 mm	Passive	mask	independent up to ~10^8	2% for ~10^9 Gy/s with corrections, ~15% without corrections	Energy dependence, time consuming, LET dependence
OSLD	D	ph	1D, 2D array/scan	1 mm	Passive	mask	Independent up to ~10^9 Gy/s)	3-5%	Energy dependence, time consuming, LET dependence
Scintillators	D	e, p	1D, 2D-film	1 mm	ns	partially transparent	Independent up to ~10^7 Gy/s	2% up to ~10^7 Gy/s	Real-time readout, water-equivalence, energy independence, dose-linearity and resistance to radiation damage,
Chernkov	D(e)	e, Ph	1D, 2D, 3D	1 mm	ps	partially transparent (energy)			Only applied to electron or Photon beams
Caloriemeters	Yes	p, e, ph				Completely	principally independent	<1% [90,91,93]	Bulky, not easy to use, correction factors, time consuming
Gas jet (under consideration)	potentially		2D	sub-mm		mostly transperent	principally independent		dose-rate independent, transparent to beam

Detection Concept

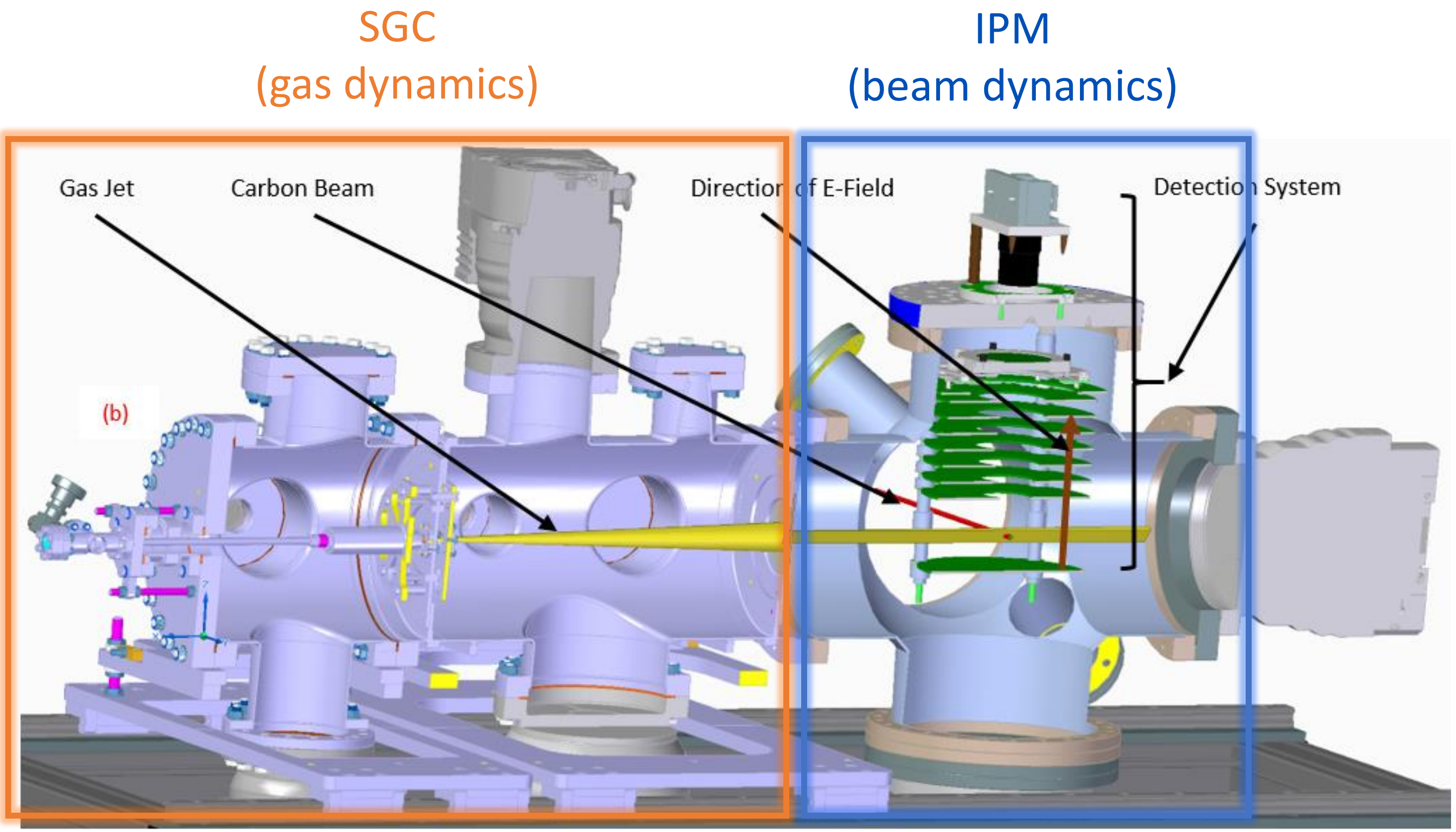


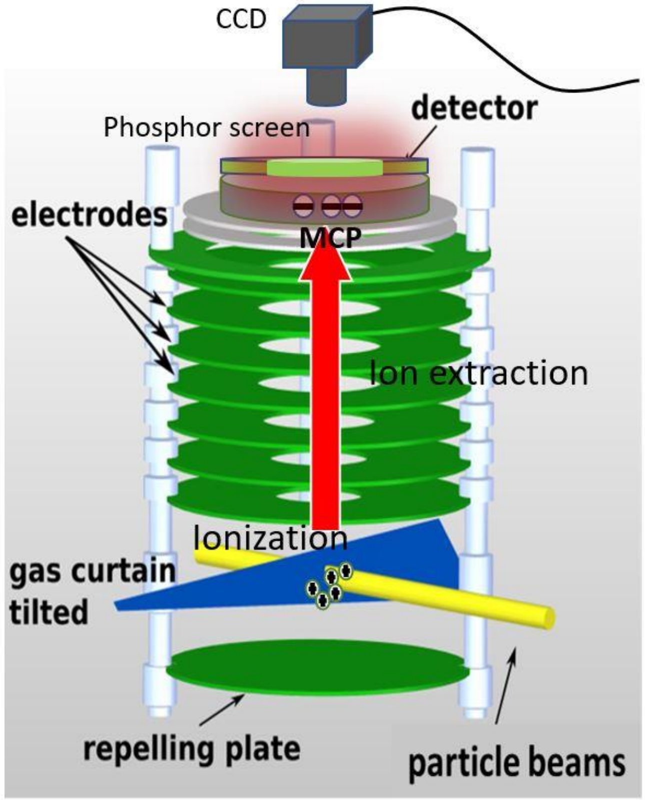
Detection principle of the Ionization chamber [a]



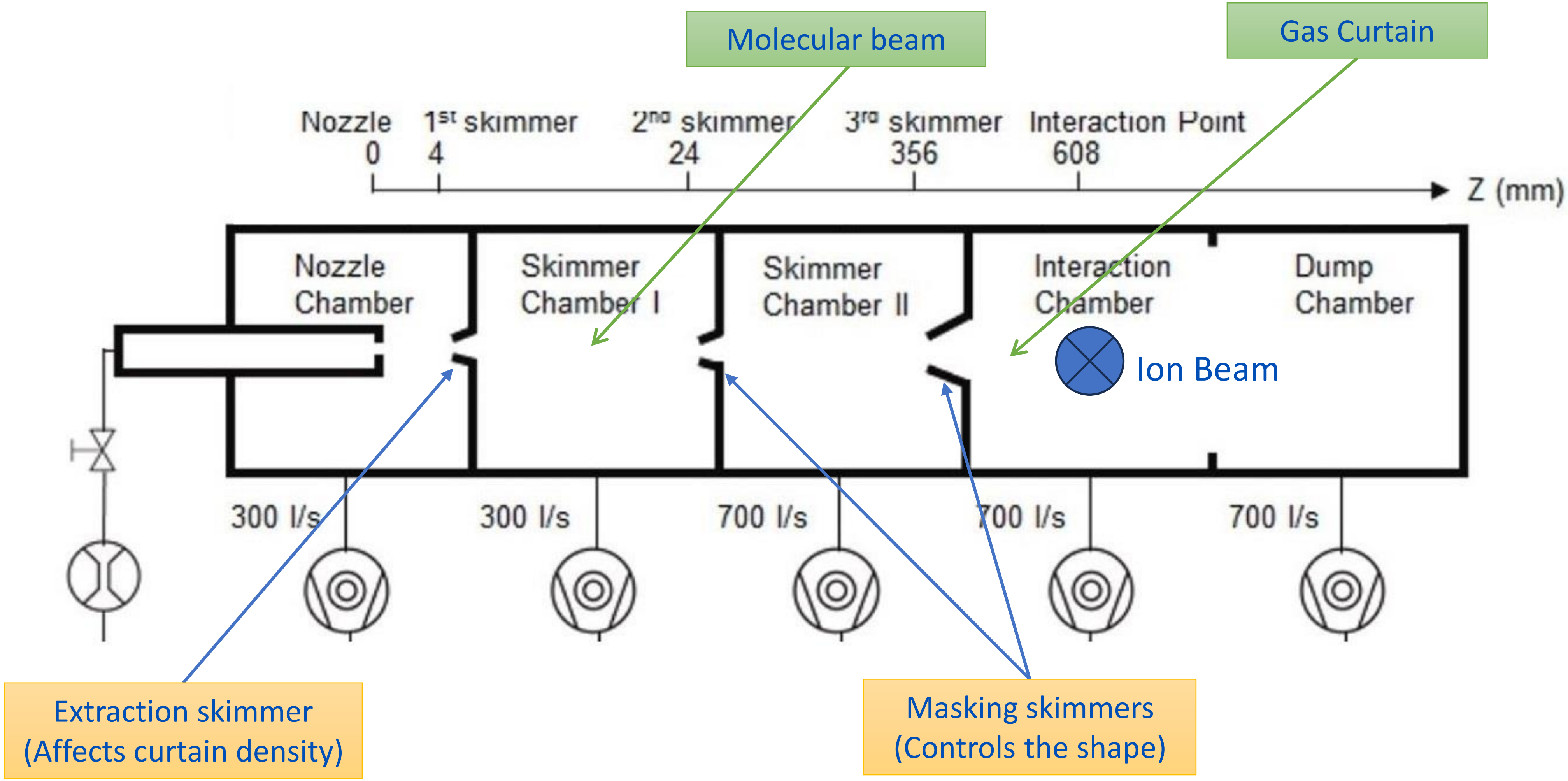
[a] Romano.F, et al., Med Phys. 2022; 49(7): 4912-4932
[b] N. Kumar et al, Physica Medica 2020; 73:173-178

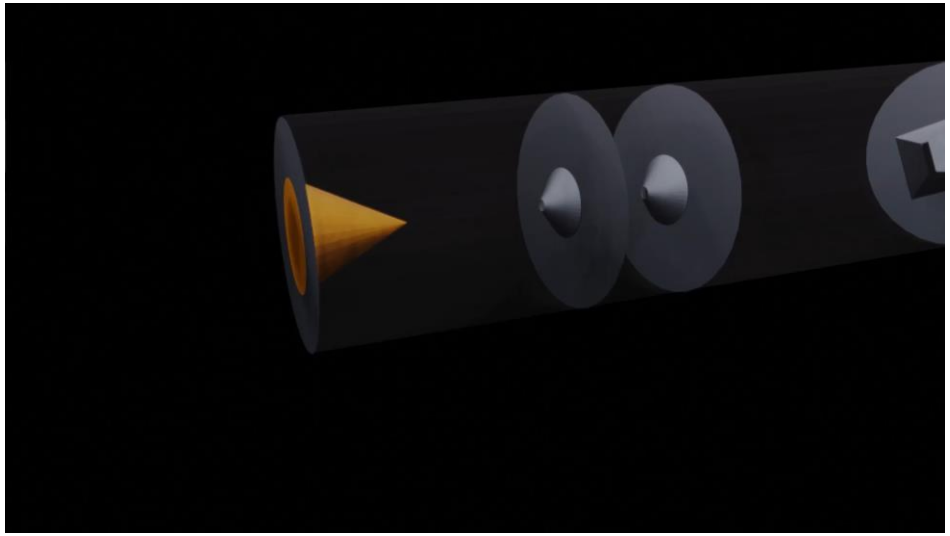
Supersonic gas curtain - Ionization profile monitor



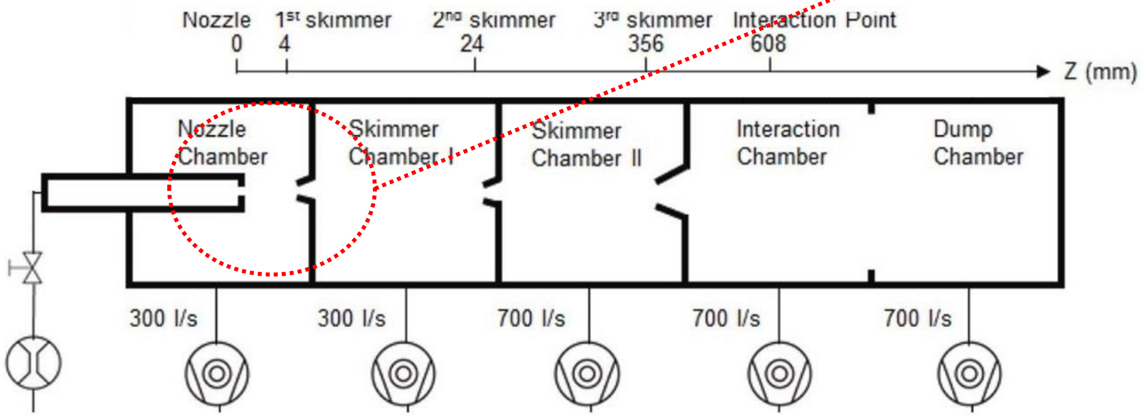


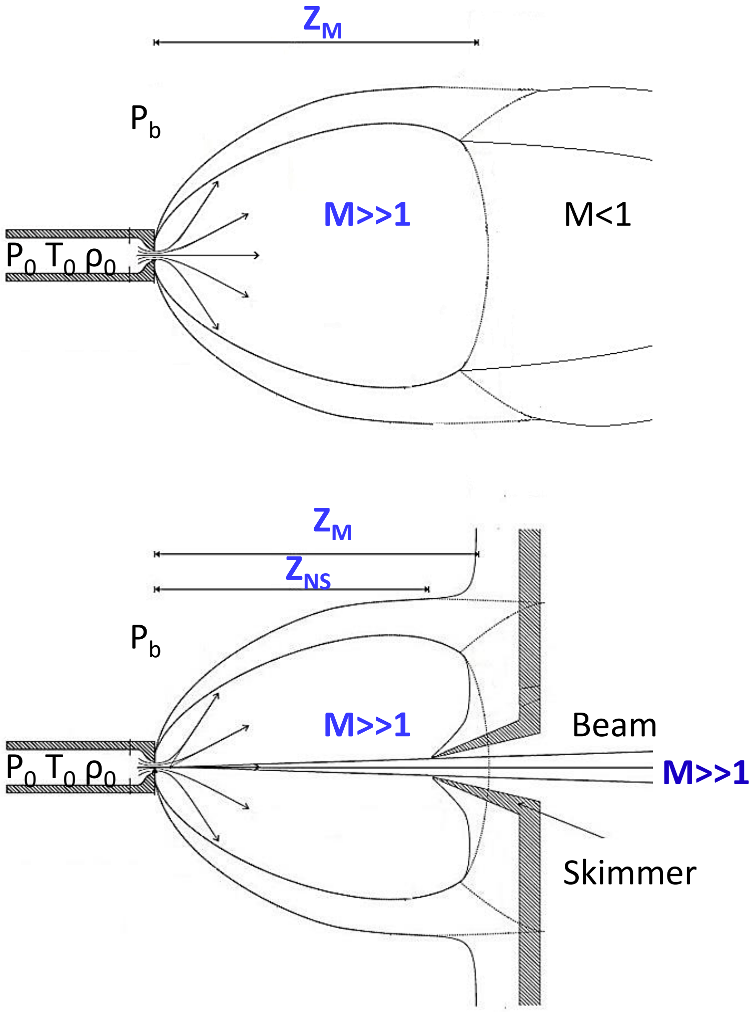
Gas curtain formation





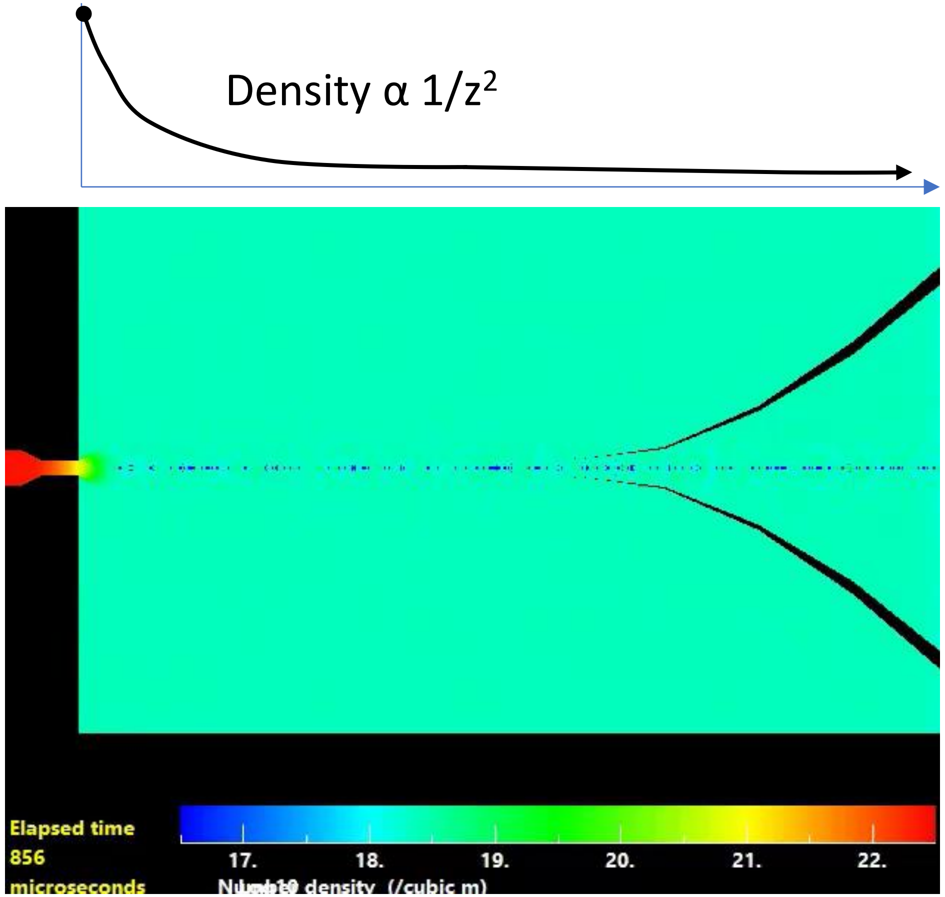
Artistic representation of gas curtain formation



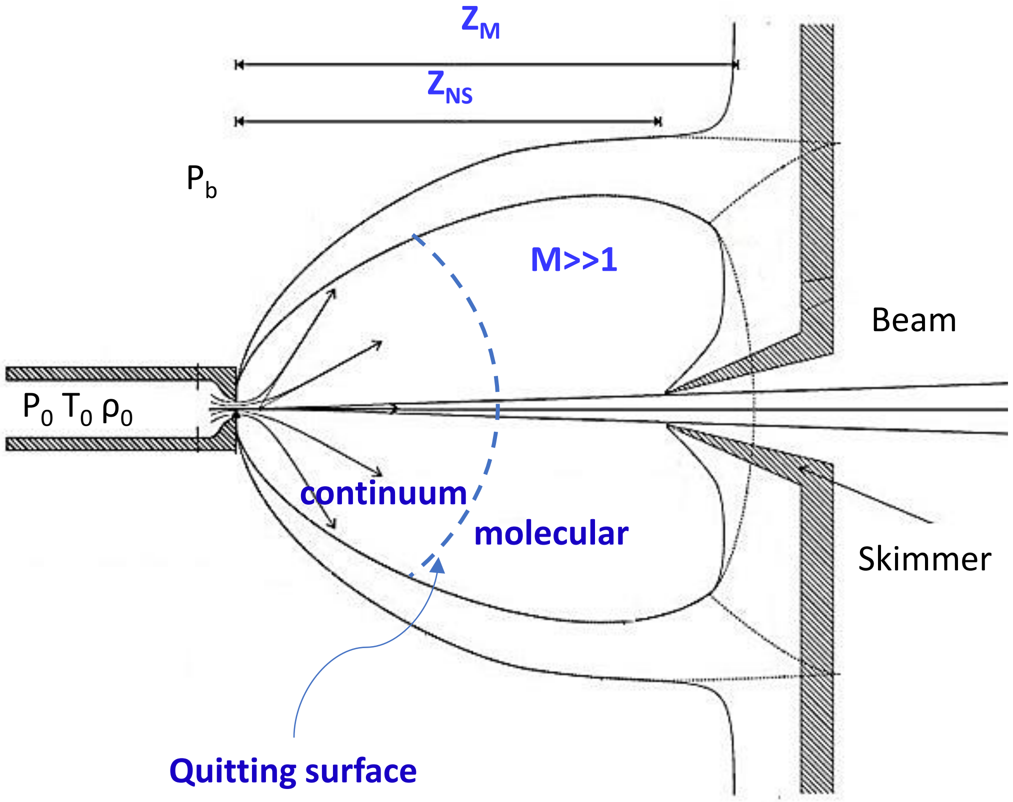


(Simplified) Mach Cell structure of a highly under-expanded supersonic jet with and without skimmer

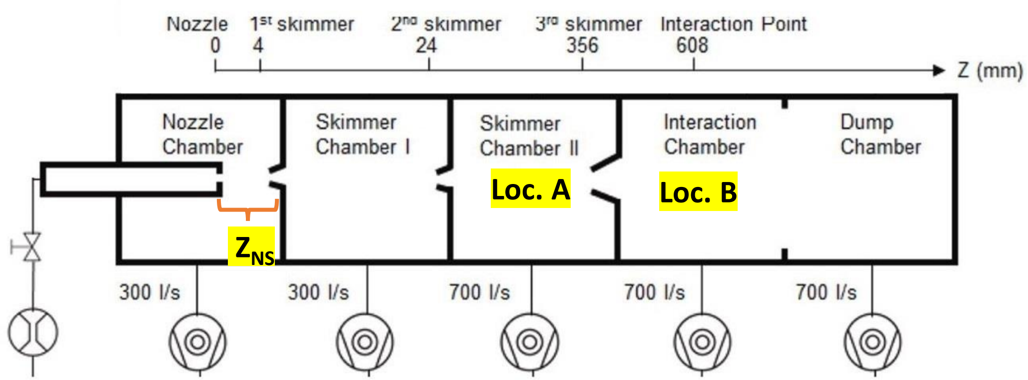
Gas curtain: governing theory



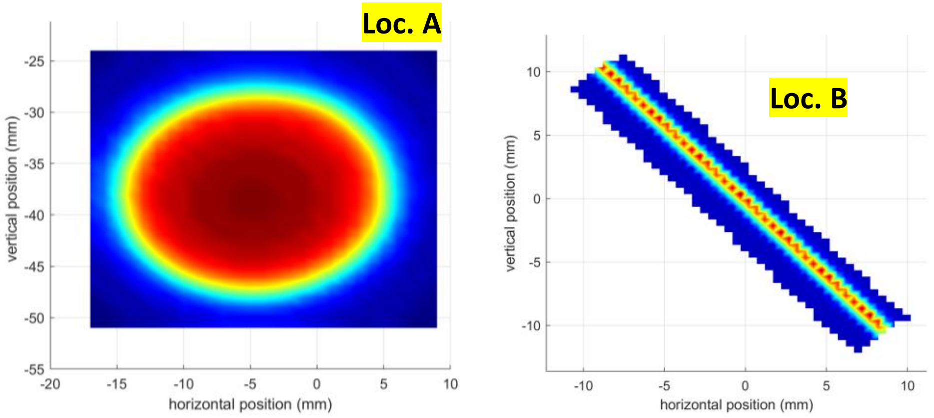
Direct Simulation Monte Carlo Code; 6 billion particles, ~50 hours

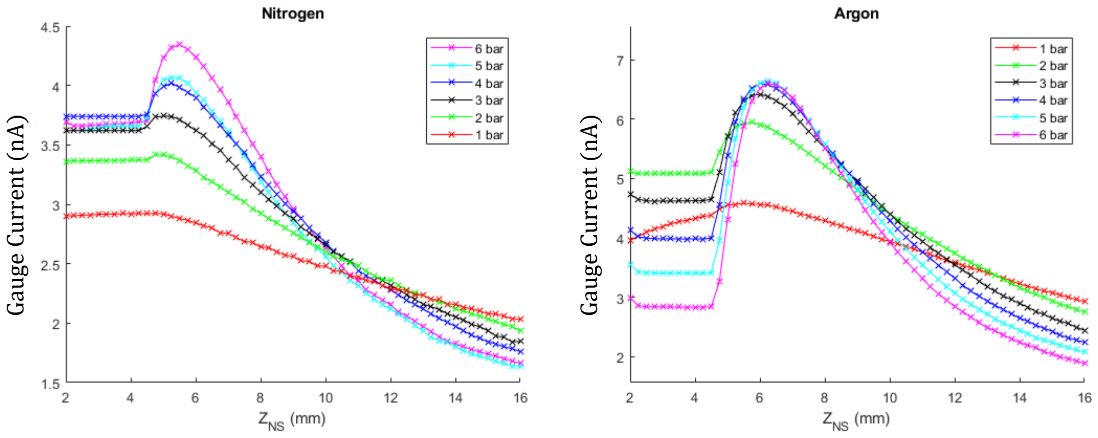


Gas curtain: optimizing density and shapes

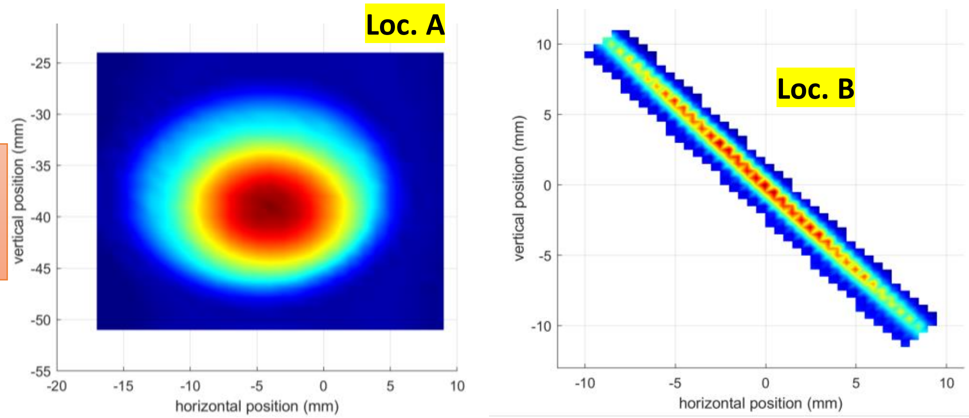


Argon
Z_{NS} = 6mm
(optimal)

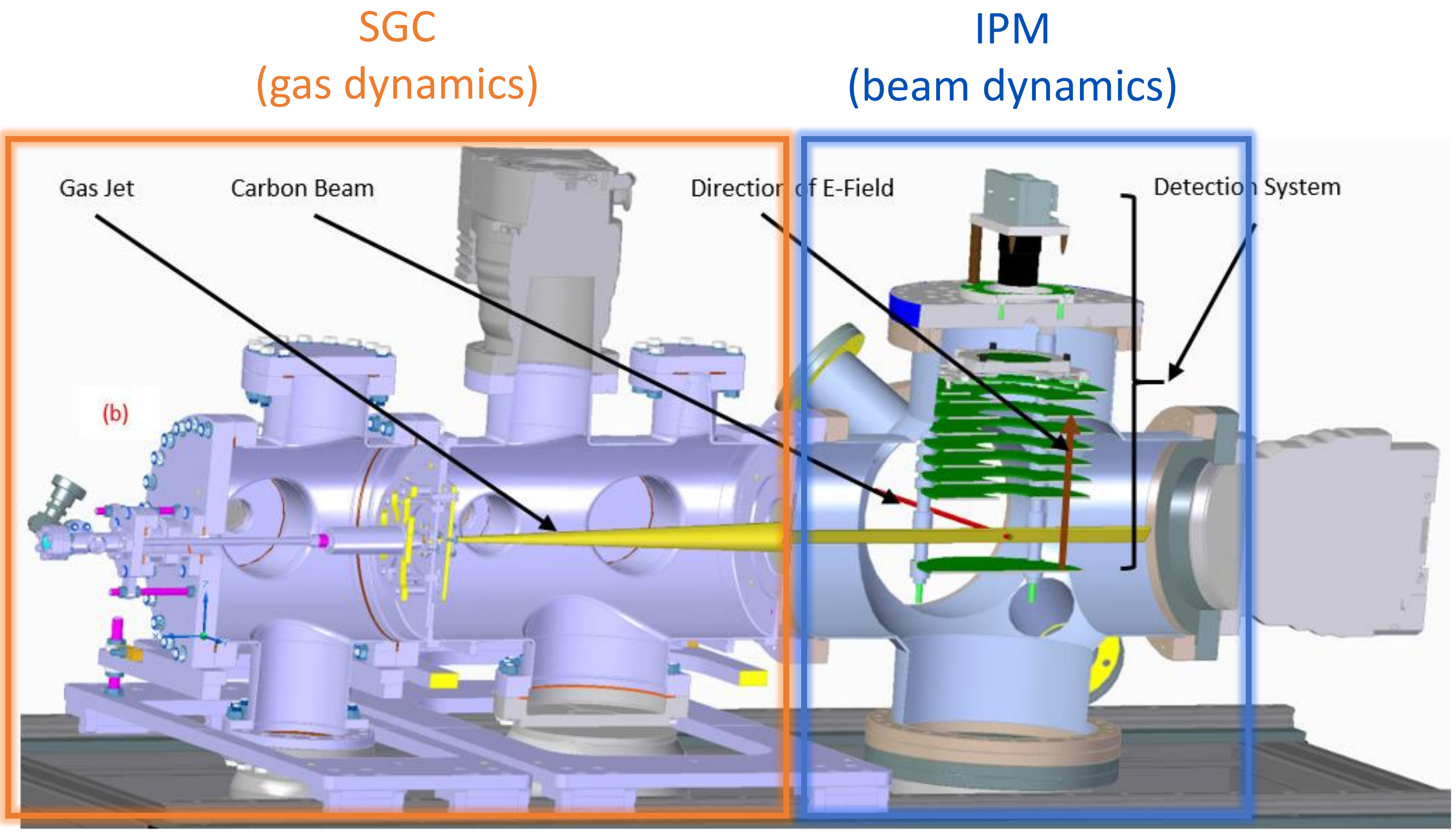


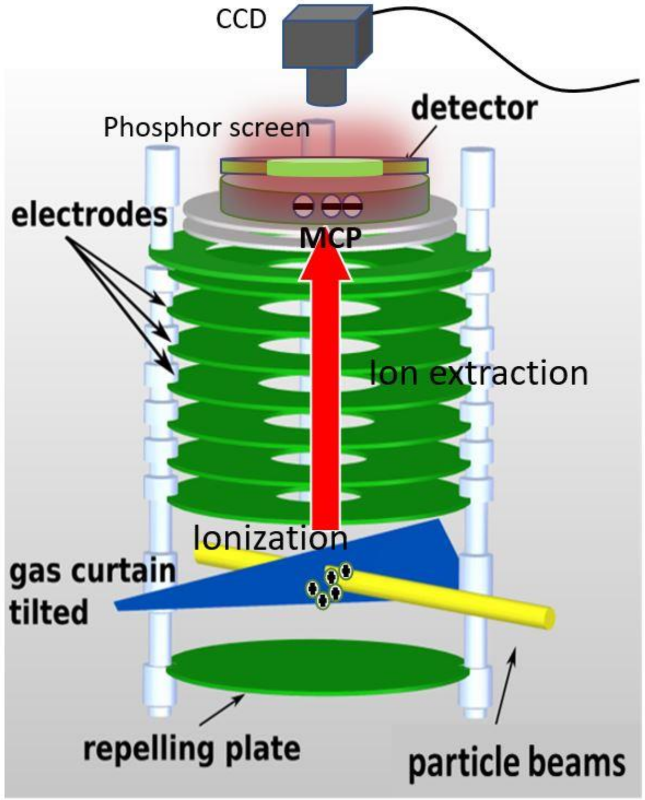


Argon
Z_{NS} = 14mm
(too far)

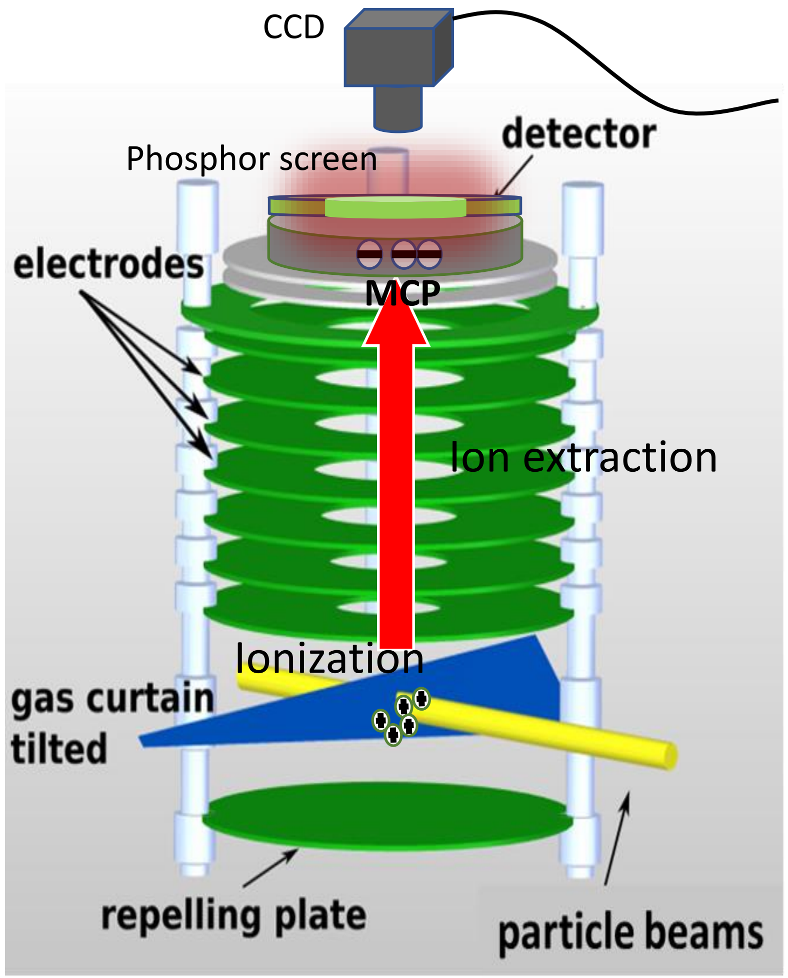


Supersonic gas curtain - Ionization profile monitor

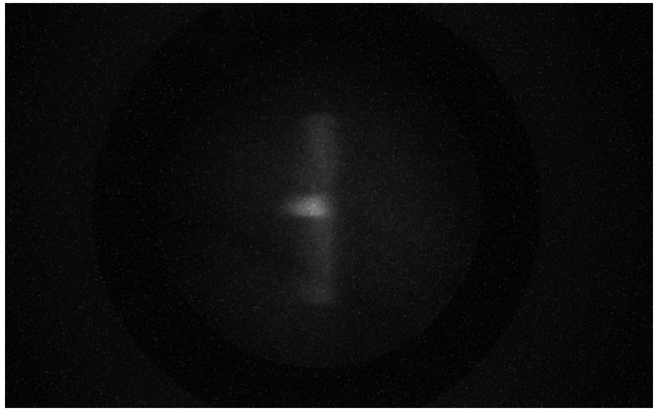




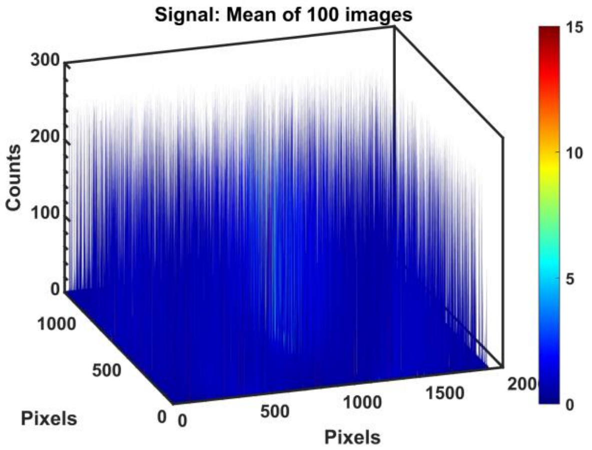
Ionization Profile Monitor



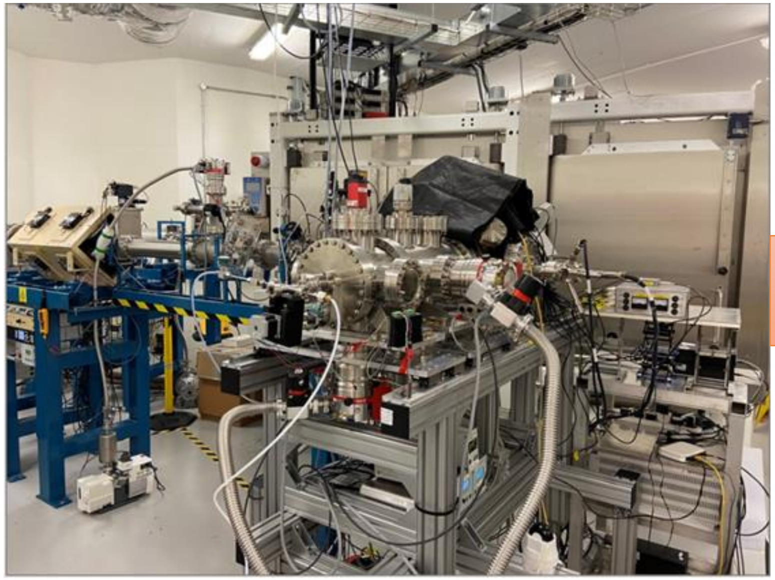
What camera sees



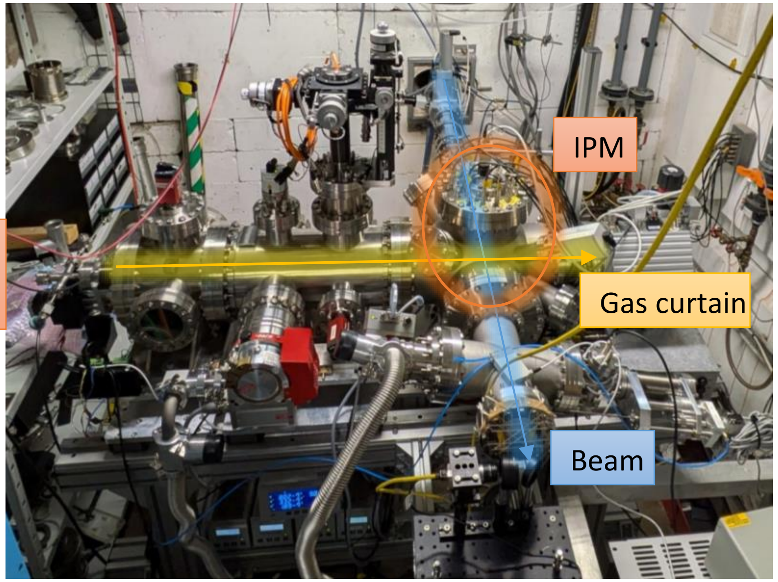
3D representation of the data



Beamtime



Dalton Cumbria Facility,
July 2023



University of Birmingham
August 2024

Proton Beam

	Energy (MeV)	Current (nA)						
Argon	4	10	98	99				**DCF**
	6	10	103	102	101			
	8	11	102					
Nitrogen	4	10	101					**DCF**
	6	10	102	102				
	8	10	99	100	102			
Argon	10.8	2.0	4.0	5.9				**UoB**
	16	5.1	10.3	15.5	20.6	30.9		
	20	6.4	12.8	19.3	25.8	38.7	51.7	
	28	9.1	18.0	26.9	35.8	53.6	71.4	
Nitrogen	28	9.1	18.0	26.9	35.8	44.7		**UoB**

Carbon Beam

Current (nA)	**2.35**	**10.50**	**11.31**	**99.00**	**103.75**	
12 MeV C^{2+}	1000 2000		300 1000		100	**DCF**
16 MeV C^{3+}		100 300	300 1000	100 300	100 x2 300	
20 MeV C^{4+}	1000 2000	1000	300 1000	30 300		
24 MeV C^{5+}					100 300 1000	

How does the measurements scales for LhARA beam?

	P+ (12MeV)		P+ (15MeV)		P+ (127MeV)	C6+ (33.4MeV/u)		
Instanteneous dose rate	1.00×10^{9}		1.80×10^{9}		1.56×10^{10}	9.70×10^{8}		
pulse length (ns)	7		7		41.5	75		← LhARA design baseline
Charge per laser shot (pC)	100		100		100	100		
ions per bunch (no.)	**6.24×10^{8}**		**6.24×10^{8}**		**6.24×10^{8}**	**1.04×10^{8}**		**← Calculated**
instantaneous beam current (mA)	**14.286**		**14.286**		**2.410**	**1.333**		
Square 35×35 mm (ions/sq.mm/bunch)	5.10×10^{5}		5.10×10^{5}		5.10×10^{5}	8.49×10^{4}		← Fluence for different field sizes
Circular 30 mm (ions/sq.mm/bunch)	8.83×10^{5}		8.83×10^{5}		8.83×10^{5}	1.47×10^{5}		
pencil 1 mm (ions/sq.mm/bunch)	7.95×10^{8}		7.95×10^{8}		7.95E $\times 10^{8}$	1.32×10^{8}		
Square: 35 by 35 mm	**64910**	**80439**	**80329**	**97514**	X	**12312**	**31367**	**← Number of bunches required to measure the beam profile**
Circular: 30 mm	**37455**	**46415**	**46352**	**56268**	x	**7105**	**18099**	
Pencil: 1 mm	**42**	**52**	**52**	**63**	x	**8**	**20**	

Set targets and improvements achieved

	Gain improvement			
	pessimistic	optimistic	Actual	
QE P43	1.2	1.4	1.3	← Manufacturers datasheet
MCP Double chevron	100	1000	80	← Operation limited by poor vacuum
Effective ions extraction	1	1-4	-	← New Design being manufactured
curtain thickness	2	5	-	← Unchanged
curtain density	2	5	3	← Z_{NS} optimization
	480	49700	240	

Tested at UOB Aug 2024

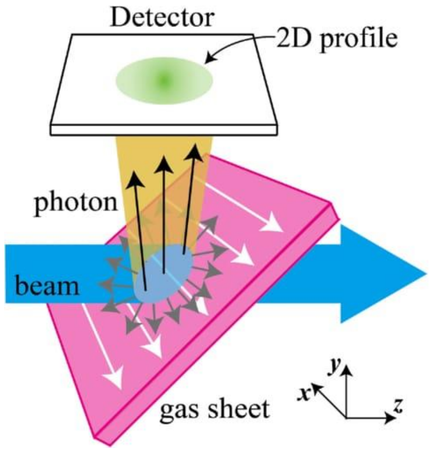
Size Reduction: 25% along beam, 50% lateral to beam
[M. Patel et al, in Proc. IPAC’24 WEPG097]

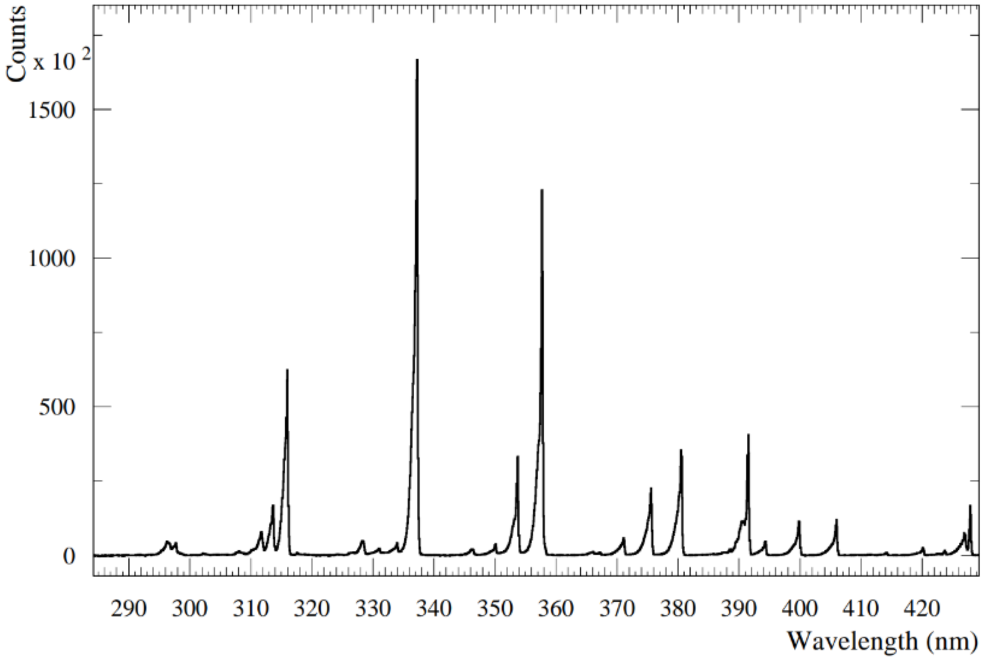
	P+ (12MeV)		P+ (15MeV)		P+ (127MeV)	C6+ (33.4MeV/u)	
Square : 35 by 35 mm	270	335	335	406	x	51	131
Circular: 30 mm	156	193	193	234	x	30	75
Pencil: 1 mm	0.17	0.21	0.21	0.26	x	0.03	0.08

Number of bunches required for beam profile measurement with upgrades

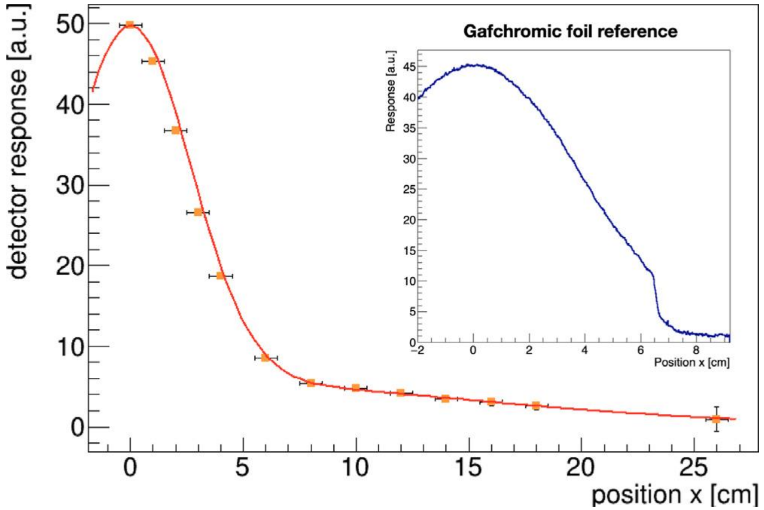
Beyond gas curtain beam profiler (Beam Induced Fluroscence)

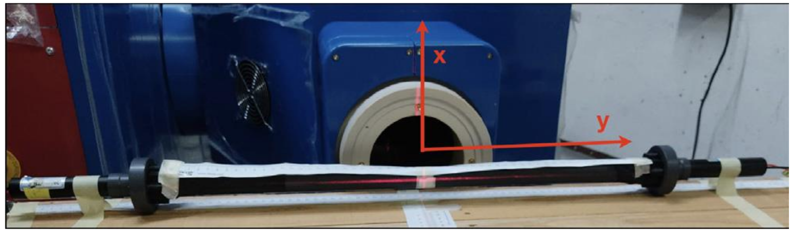
- SGC-IPM is detecting ions to measure the beam profile.
- However, interaction also excites the ions and neutrals which emit photons.
- The same phenomenon occurs when beam travels through air.





Fluorescence spectrum in Dry Air, (800hPa) from electron beam 200 MeV **[b]**

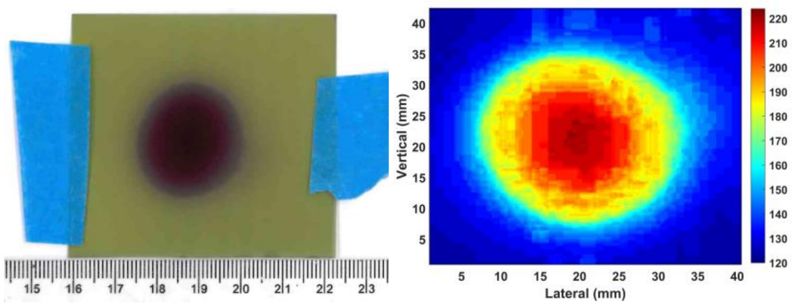




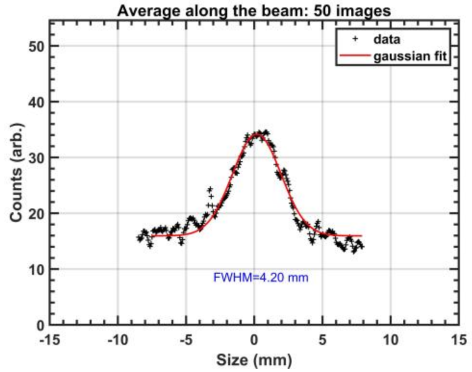
Fluorescence yield from air enclosed in black Tedlar: e- , 6 MeV, 10^{10} e/bunch at 10^6 Gy/s **[a]**

[a] Antonio T. et al., NIMS PR-A1041 (2022) 167334
[b] M. Ave et al., Astro Particle Physics 28, (2007) 41, 57

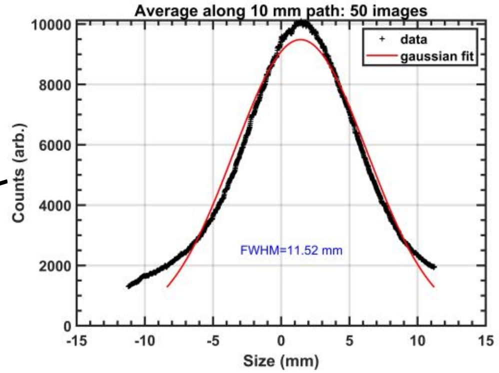
Beam size comparison for p+ 20 MeV,12.8 nA



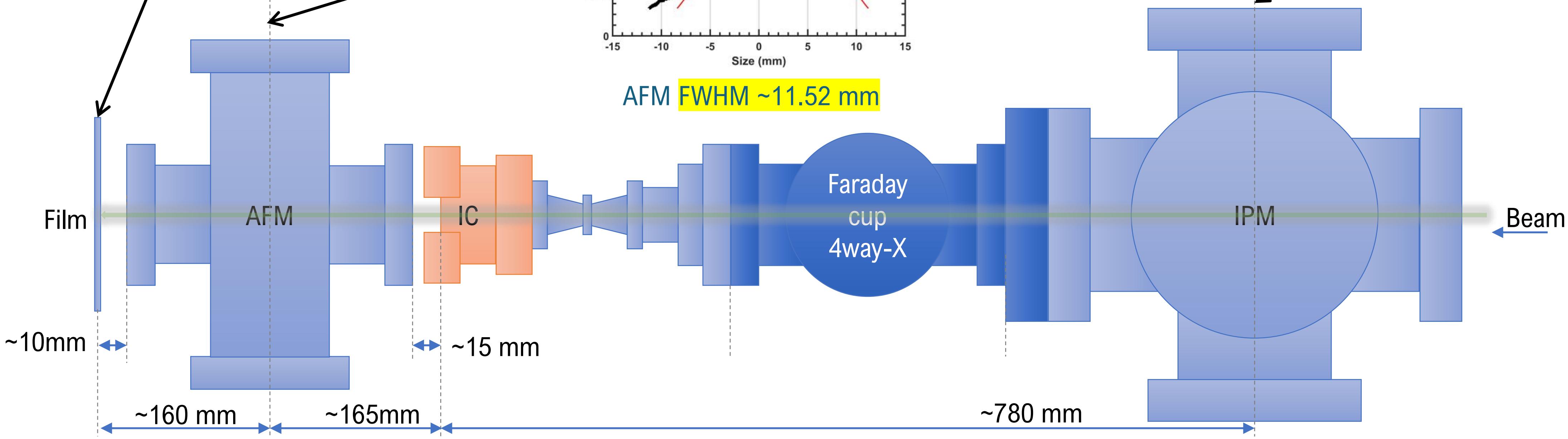
RCF(left) - Red channel (right), FWHM 16mm



IPM FWHM 4.2 mm



AFM FWHM ~11.52 mm



Summary and Future Plans

Summary

- Gas curtain density improved by a factor of 3 by changing nozzle skimmer distance (more studies using broader parameter sweep underway)
- Parameterization of IPM response with beam energy and current shows linear trend (atleast within measured range). Potential for dose prediction by calibration.
- Estimated detection threshold based on the beam fluence. The gas jet monitor with upgrades can measure the single (10^9) <1 mm bunch for LhARA p+ and C^{6+} beam parameters.
- New IPM being manufactured. Reduction in size by 25% longitudinal and 50% lateral to beam.
- New device, Air Fluorescence Monitor (AFM) test sucessful. Analysis shows linearity with beam current. Also potential for dose prediction following calibration.

Short Term Plans (<1 year)

- 4F spatial filter to operate AFM in well lit rooms.
- Potential beam time for systematic measurements using AFM.

Long term plans (>1 year)

- Optical setup for narrow band spectral filtering with 6F chromatic lens configuration. (To isolate spectral lines to study line intensity distribution for different beam energies.)
- Beam profile reconstruction with 4-axis and 6-axis observations using ML. Test setup at DITA Lab

Thank you

Work Package members

- Narender Kumar,
- Farhana Thesni,
- Tony Price,
- Ruth Mclauchlan,
- Carsten Welsch