Northern Illinois University

Gas Sheet Beam Profile Monitor for IOTA

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(NIU: Swapan Chattopadhyay, PI and Bela Erdelyi, Co-PI)

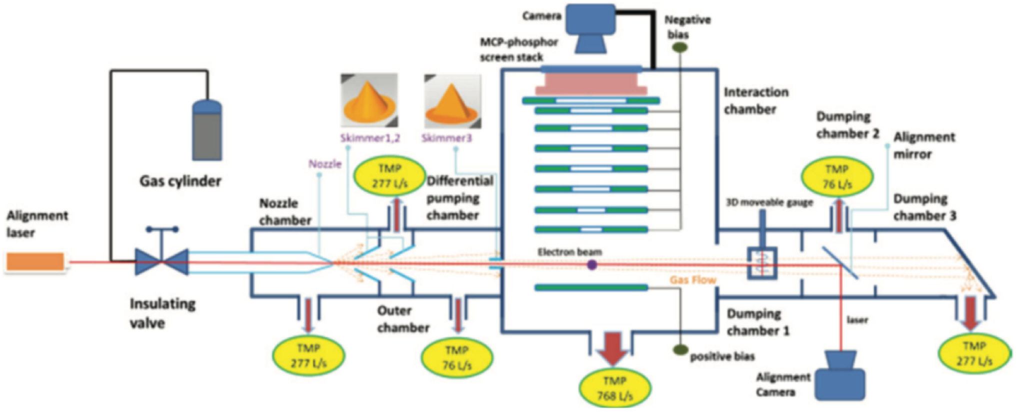
Gas Jet Monitor Motivation

- Turn-by-turn, two-dimensional transverse beam profile monitor to study time dependent collective instabilities and halo formation of a proton beam.

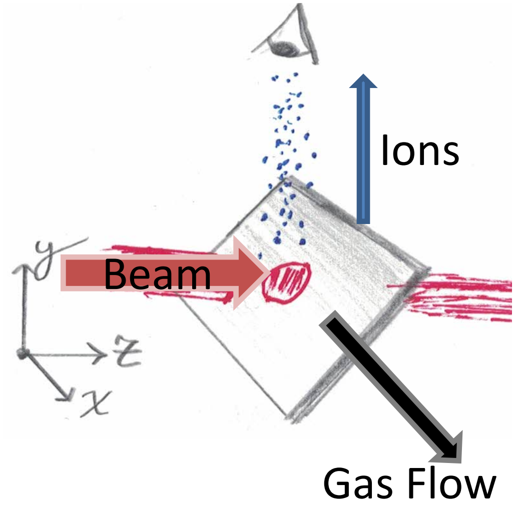
- Traditional profile monitors such as multiwires and scintillator screens are too destructive or measure one-dimensional such as residual gas monitors.

Concept

- Gas sheet formed transverse to beam direction
- Proton beam will ionize the gas
- Ions will be collected into a detector system, measuring 2D transverse profile.
- Previous groups have built Gas Jet Monitors

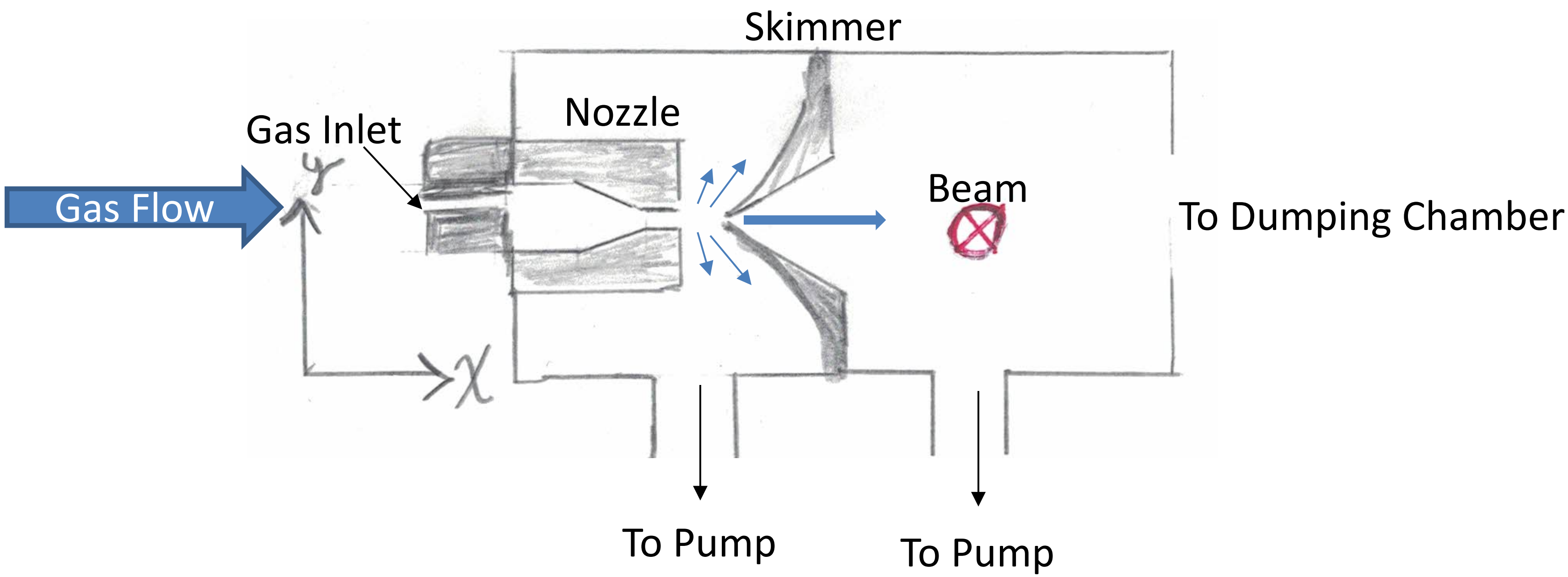


H.Zhang, IPAC16 (MOPMR046)



Injection/Sheet Formation

- Capillary or Nozzle to induce expansion of the gas so that the core of the flow can be selected
- Slit or Skimmer to form sheet

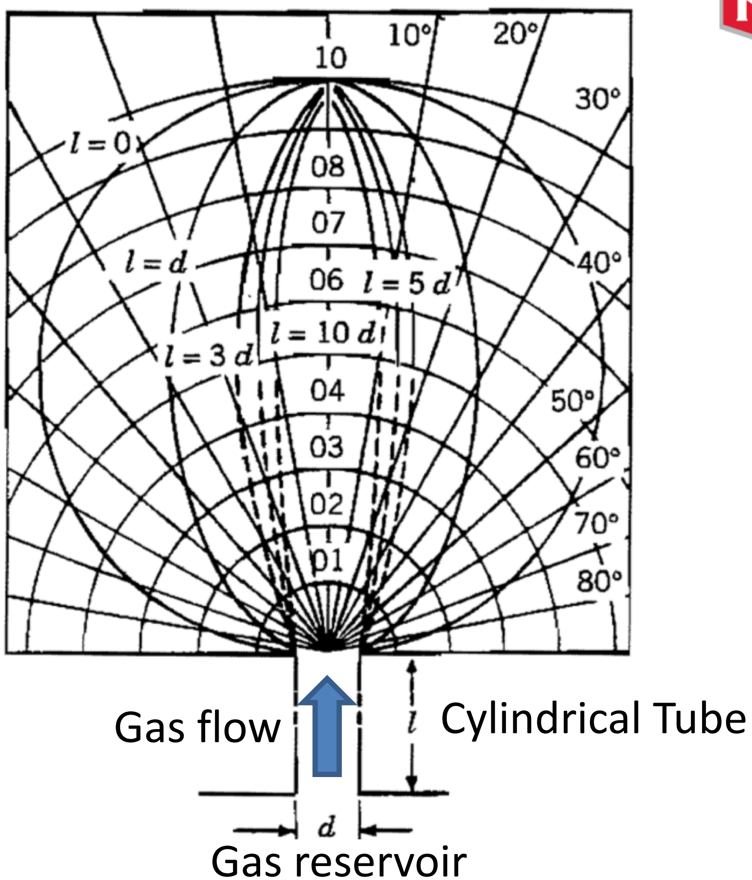


Injection – Cylindrical tubes

- The number of molecules leaving per unit time per solid angle is defined:

$$\frac{dN}{d\omega} = p_i d^2 C_o \cos\theta \sqrt{\frac{N_a}{32\pi k_B M T}}$$

p_i - partial pressure of the species
d – diameter of tube
C_o- Correction factor, ranges from 0 to 1
k_B- Boltzman Constant
M - species molecular weight
N_a - Avogadro's Number
T - Temperature



L. Valyi, Atoms and Ion Sources, p.86 (1977)

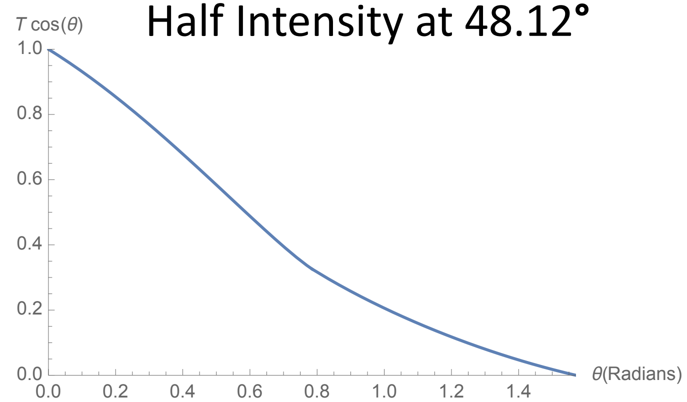
Distributions for various parameters after orifice

The angle at which the distribution falls to half the maximum intensity:

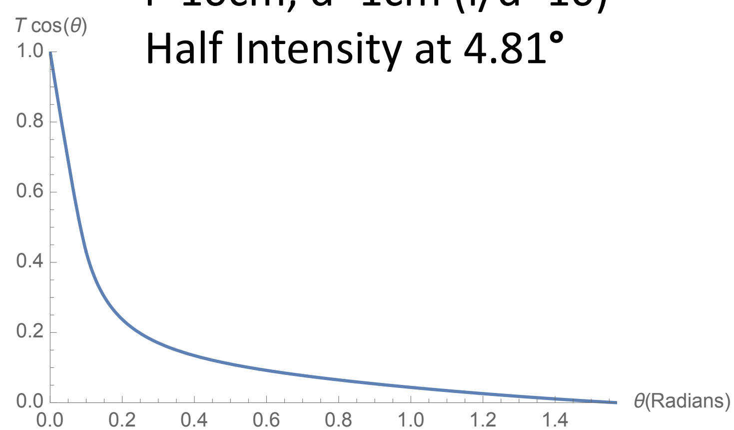
$$\theta_{\frac{1}{2}} = 0.84\frac{d}{l}$$

J.A. Giordmaine and T.C. Wang, "Molecular Beam Formation by Long Parallel Tubes", *J. Appl. Phys.*, **31**, pp. 463-471 (1960).

l=10cm, d=10cm (l/d=1),
Half Intensity at 48.12°

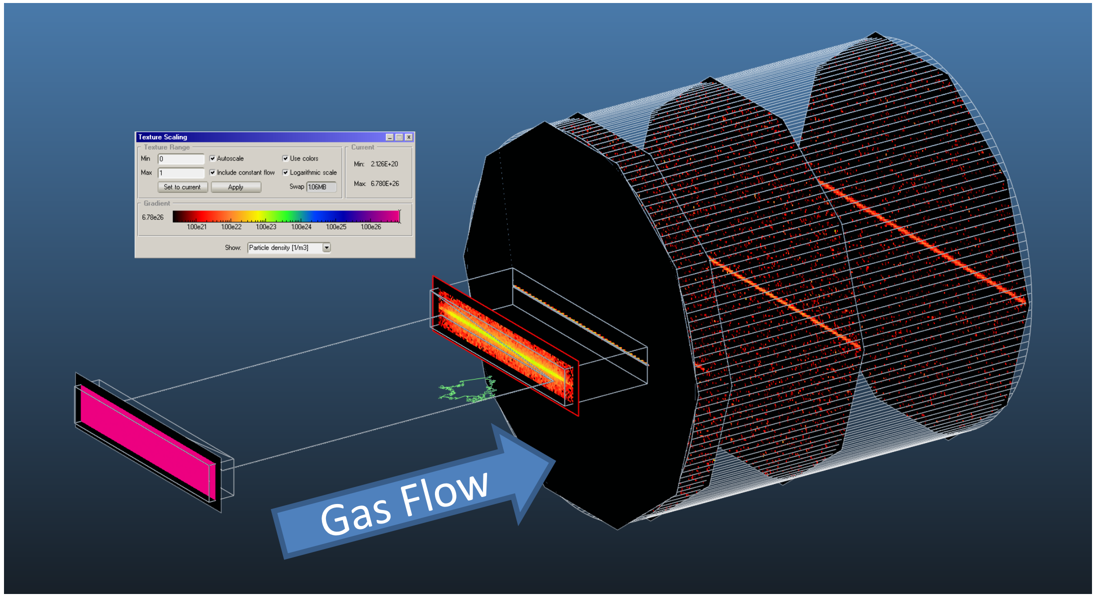


l=10cm, d=1cm (l/d=10)
Half Intensity at 4.81°



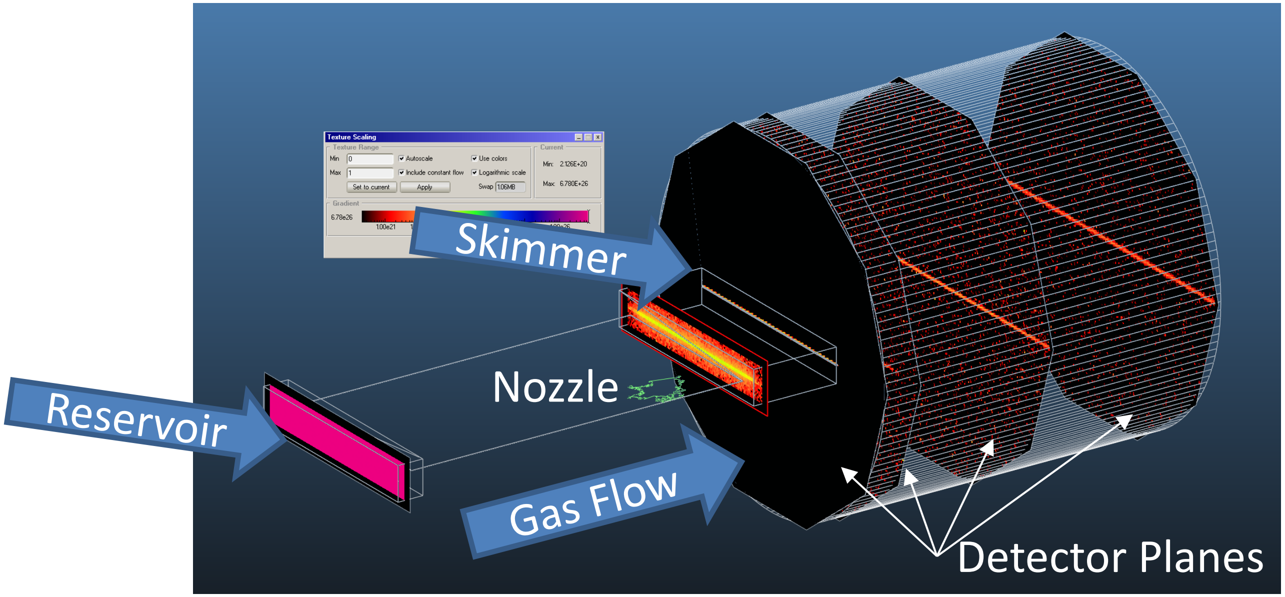
MolFlow+ (UHV Simulation)

- Monte Carlo simulation developed at CERN
  - Calculate steady-state pressure in system
  - Record gas distribution at various planes
- Simulated and studied gas sheet system in the RCS at J-PARC



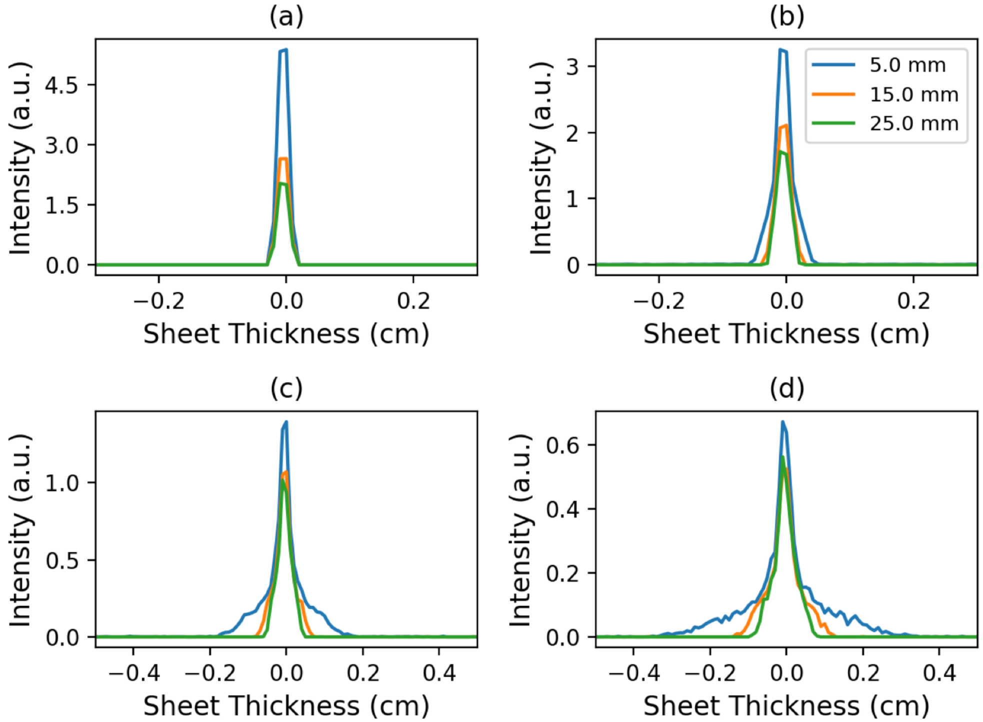
MolFlow+ (UHV Simulation)

- Gas Reservoir Volume 7.5 cm^3
- Rectangular Nozzle Dimensions (50x0.1x100 mm) (w*l*h)
- Rectangular Skimmer (60x0.3x0.5 mm)
- Virtual Detector planes located 0.1, 10, 50, 100 mm away from skimmer



Nozzle Skimmer Distance Varied

- Distance between nozzle skimmer varied by 5, 15, and 25 mm

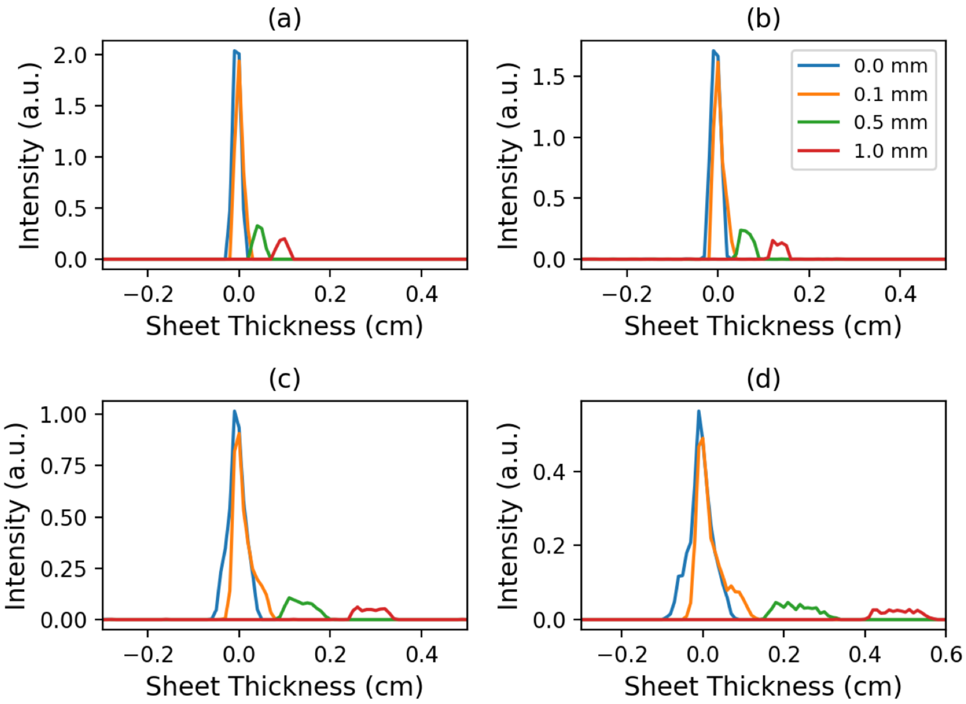


Distance	D1	D2	D3	D4	Units
5.0	0.22	0.25	0.31	0.42	mm
15.0	0.22	0.27	0.33	0.44	mm
25.0	0.22	0.28	0.33	0.41	mm

FWHM with various nozzle to skimmer distances.

Skimmer Offset

- Offset varied by 0.1, 0.5, 1.0 mm



Offset	D1	D2	D3	D4	Units
0.0	0.22	0.28	0.33	0.41	mm
0.1	0.19	0.21	0.28	0.36	mm
0.5	0.27	0.37	0.73	1.19	mm
1.0	0.29	0.38	0.82	1.32	mm

FWHM of nozzle-skimmer offsets.

Beam-Gas Interaction

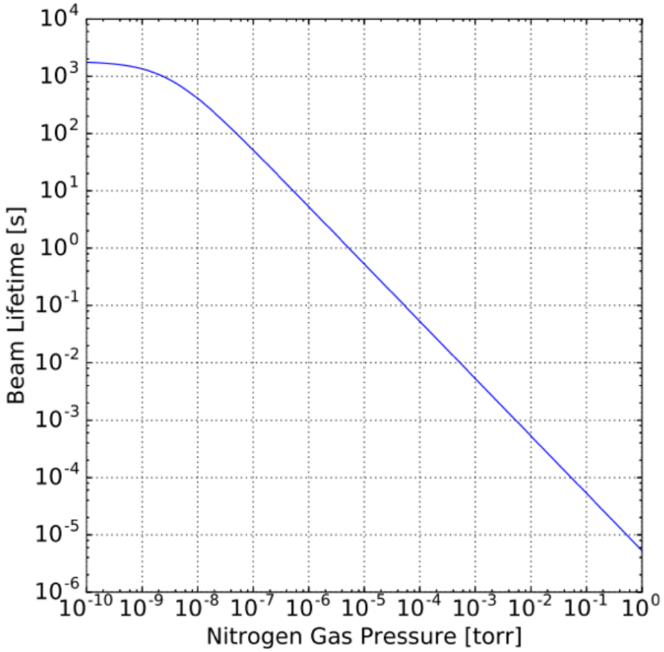
- Number of electron-ion pair produce defined as:

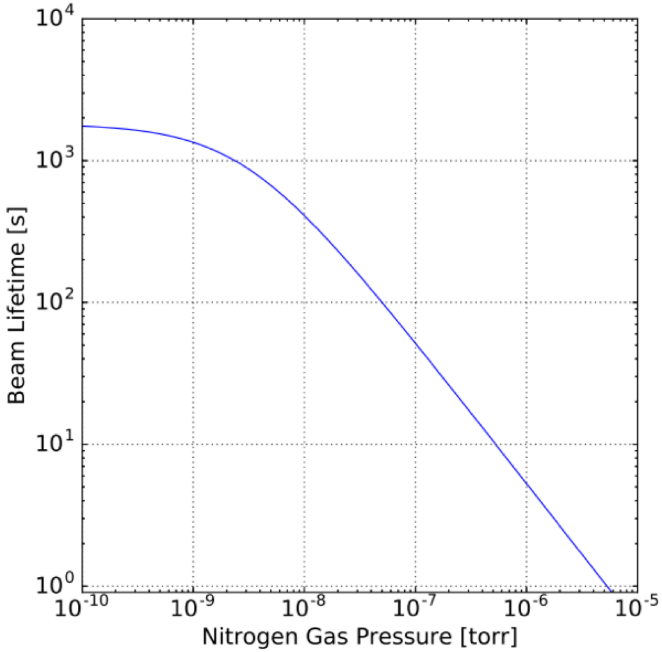
$$\dot{N} = \frac{dE}{dx}\frac{I_b}{q}\frac{\rho_g\, l}{W_i}$$

$\frac{dE}{dx}$: Stopping Power of protons
ρ : Mass density of the gas
W : Average energy required to ionize a gas
I_b : Beam current
q : proton charge
l : gas sheet thickness

For example with nitrogen gas: dE/dx = 118 MeV cm^2/g
Mass Density (at 1.2*10^-7 torr)= 1.98*10^13 g/ccm
W = 36 eV
I = 8 mA
At a sheet thickness of 0.2mm, 1.14 *10^3 pairs will be produced per turn

Beam Lifetime





(Calculations by Ben Freemire)

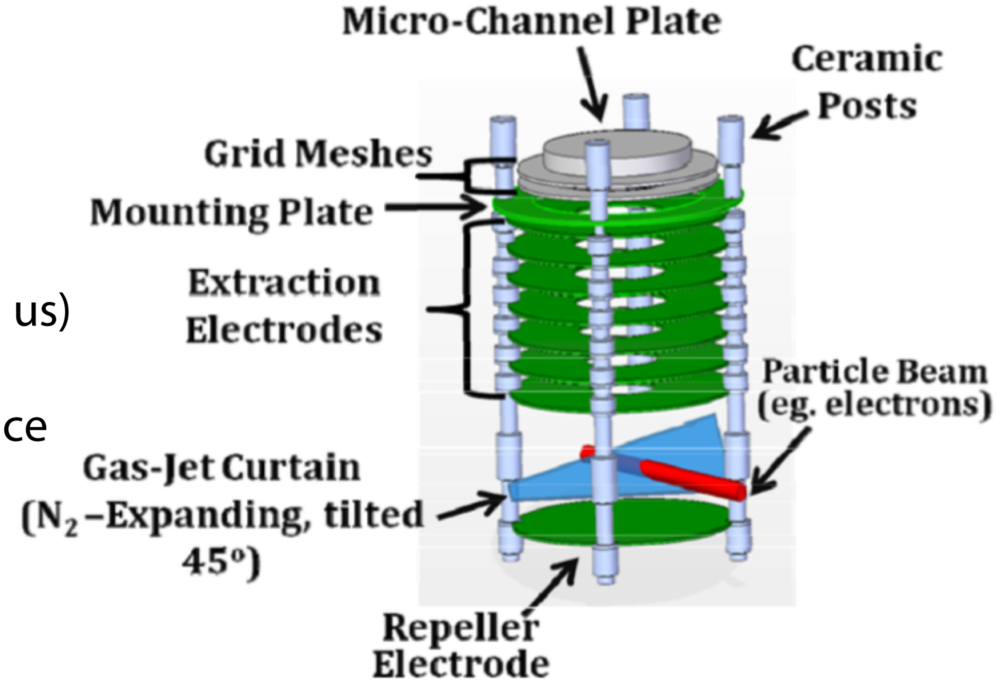
Proton Beam lifetime in IOTA due to Coulomb scattering off nitrogen gas over a 1 meter long segment. Residual gas pressure assumed 1*10^-10 torr.

- Lifetime with only residual gas is ~30min
- Operating at 1*10^-8 torr in interaction chamber lifetime is ~6min

Detector System

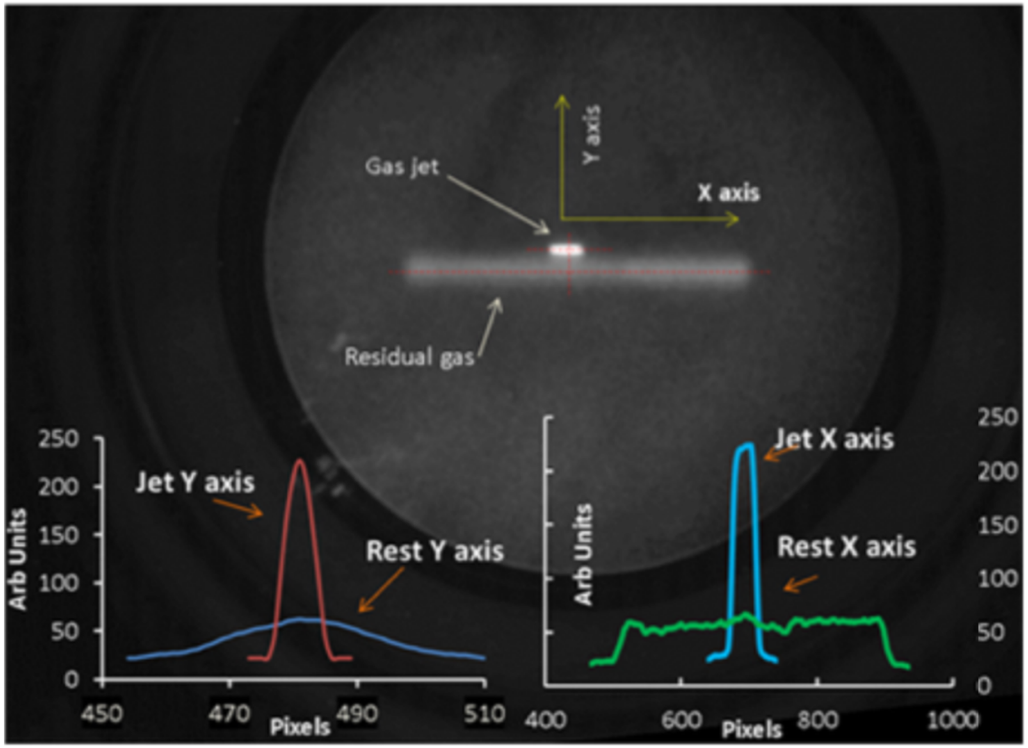
- Ions are accelerated by array of electrodes
- Followed by a stack of Microchannel plates and phosphor screen, followed by a CCD
- Time resolution limited by phosphor screen material, CCD capabilities
  - P43 Screen (Decay 90% to 10%-> 1ms)
  - CCD (25 us exposure, triggering 2 us)
- Spatial resolution limited by MCP orifice size.
  - MCP (10um channel Diameter)
  - CCD (3.45x3.45 um Pixel Size)

B.B.D. Lomberg, IPAC14, (THPME135)



Cockcroft Institute Signal

- At Cockcroft Institute, used a 5keV electron gun, with a 1024x768, 8bit CCD camera (10um Pixel)



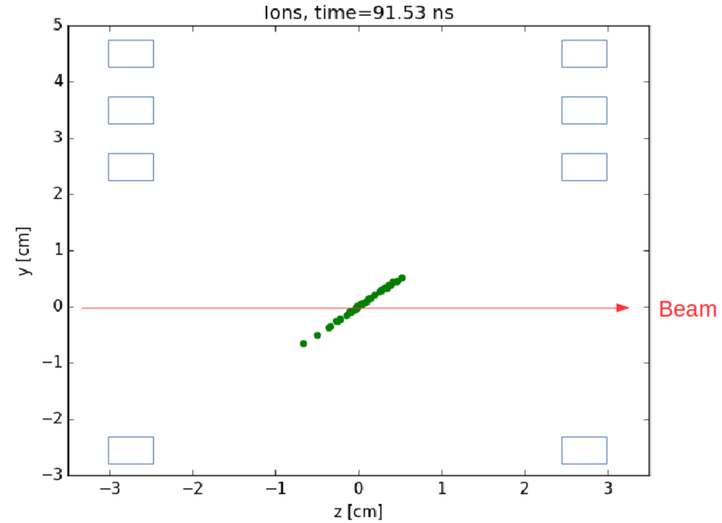
V. Tzoganis, Appl. Phys. Lett. **104**, 204104 (2014)

N2 Gas Sheet
Density = 2.5 * 10^10 cm^-3
Thickness = 0.4mm
Width = 4mm

We are targeting a density of 4*10^11 cm^-3 to compensate shorter integration time

WARP Simulation

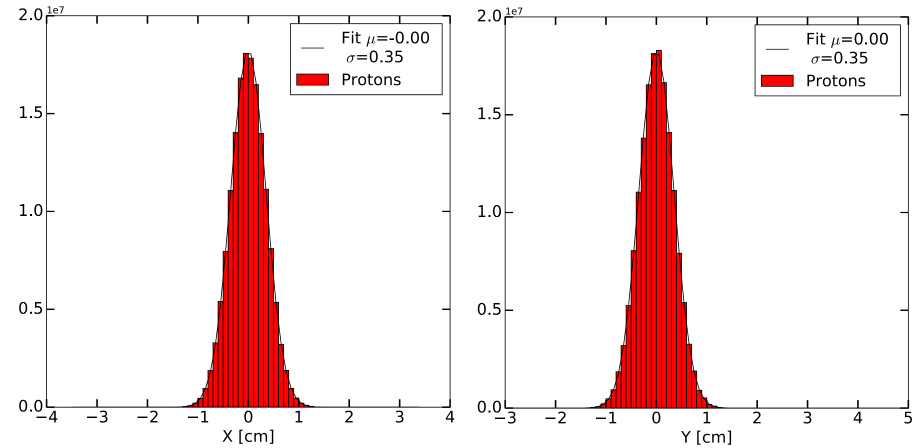
- Simulate IOTA proton beam interacting with nitrogen gas.
  - Gaussian Beam distribution σ=3.5 mm
  - Four annular electrodes
    - Biased at +500, -500, -1000, -1000 V at -2.5, 2.5, 3.5, 4.5 cm, respectively
  - Look at particle/molecule distribution



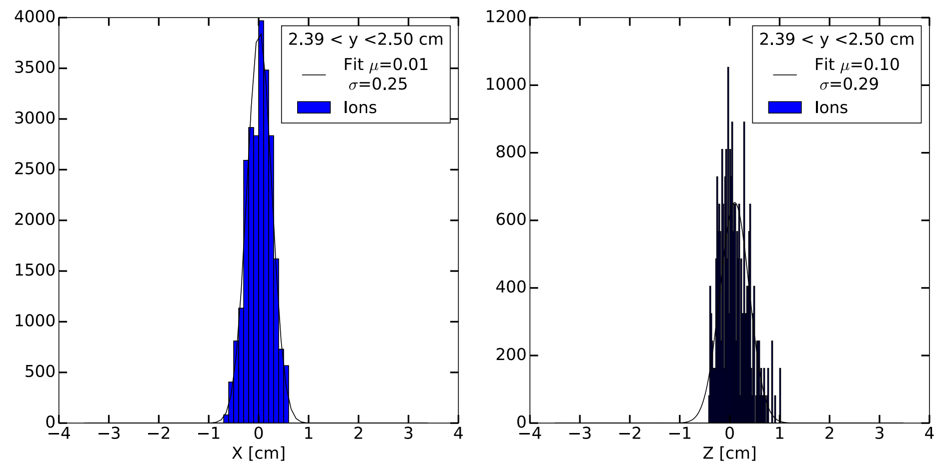
Simulation domain in the y-z plane. The green dots are ion macroparticles generated by the beam. The cross section of the electrodes are outlined in blue. This snapshot was recorded 91.53 ns into the simulation.

(Simulations by Ben Freemire)

WARP Results



Transverse distribution for the proton beam



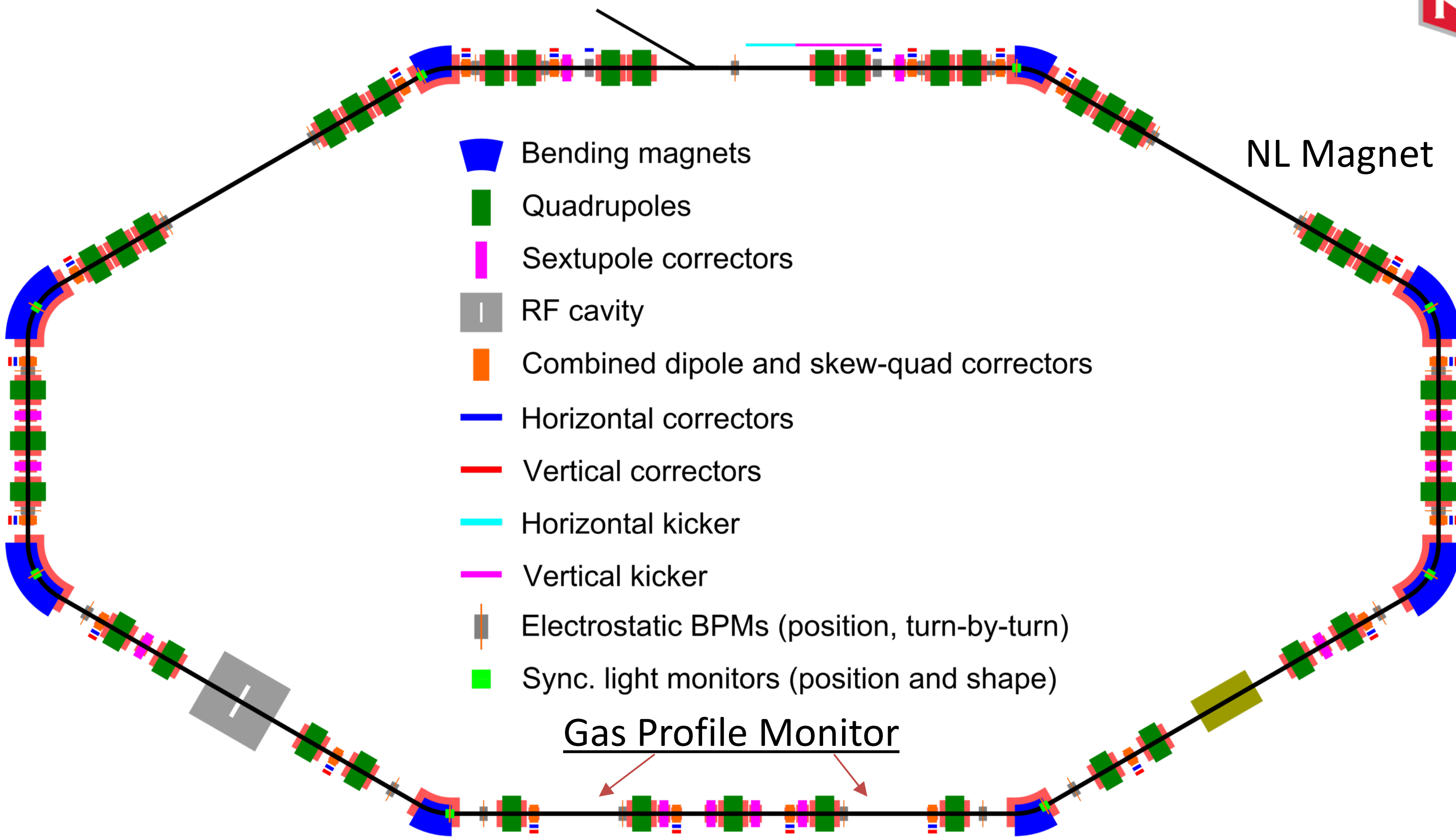
Transverse distribution all ions passed through a slice in y between 2.39 and 2.50 cm

Vacuum Consideration

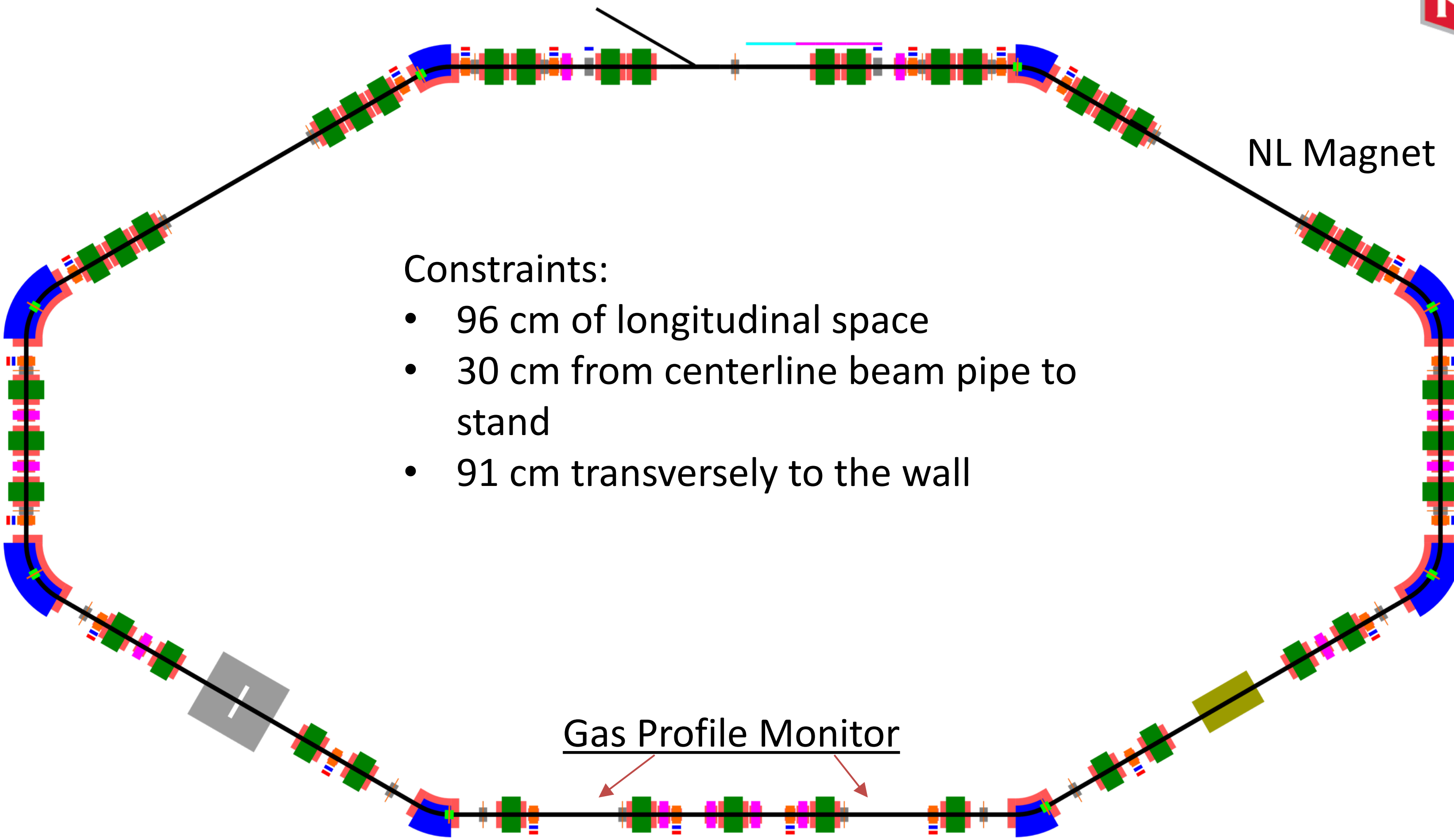
- Maintain UHV in rest of the ring
  - Optimize Gas density and sheet divergence
  - Turbo-pumps and titanium sublimation pump
  - For IOTA want to achieve a background pressure no more than 10^-8 torr in monitor region in the one meter length.

Cockcroft institute was able to achieve vacuum:
Outer Jet Chamber: 2.43 * 10^-8 torr
Experimental Chamber: 3.15 * 10^-8 torr
Dump chamber: 1.63 * 10^-9 torr
12%- 29% Pressure rise with gas injection
(V. Tzoganis, Vacuum **109** (2014) 417-424)

Proposed Location in IOTA



Proposed Location in IOTA



Constraints:

- 96 cm of longitudinal space
- 30 cm from centerline beam pipe to stand
- 91 cm transversely to the wall

Interaction Chamber

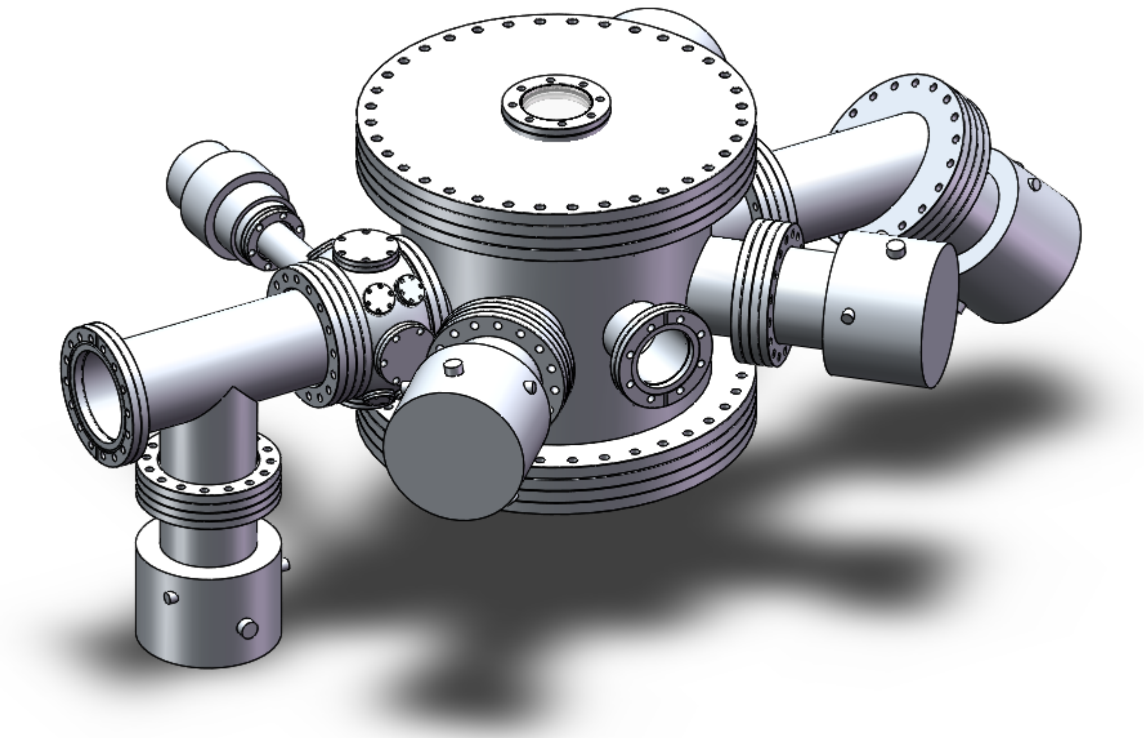


Image courtesy of Tara Campese

Interaction Chamber

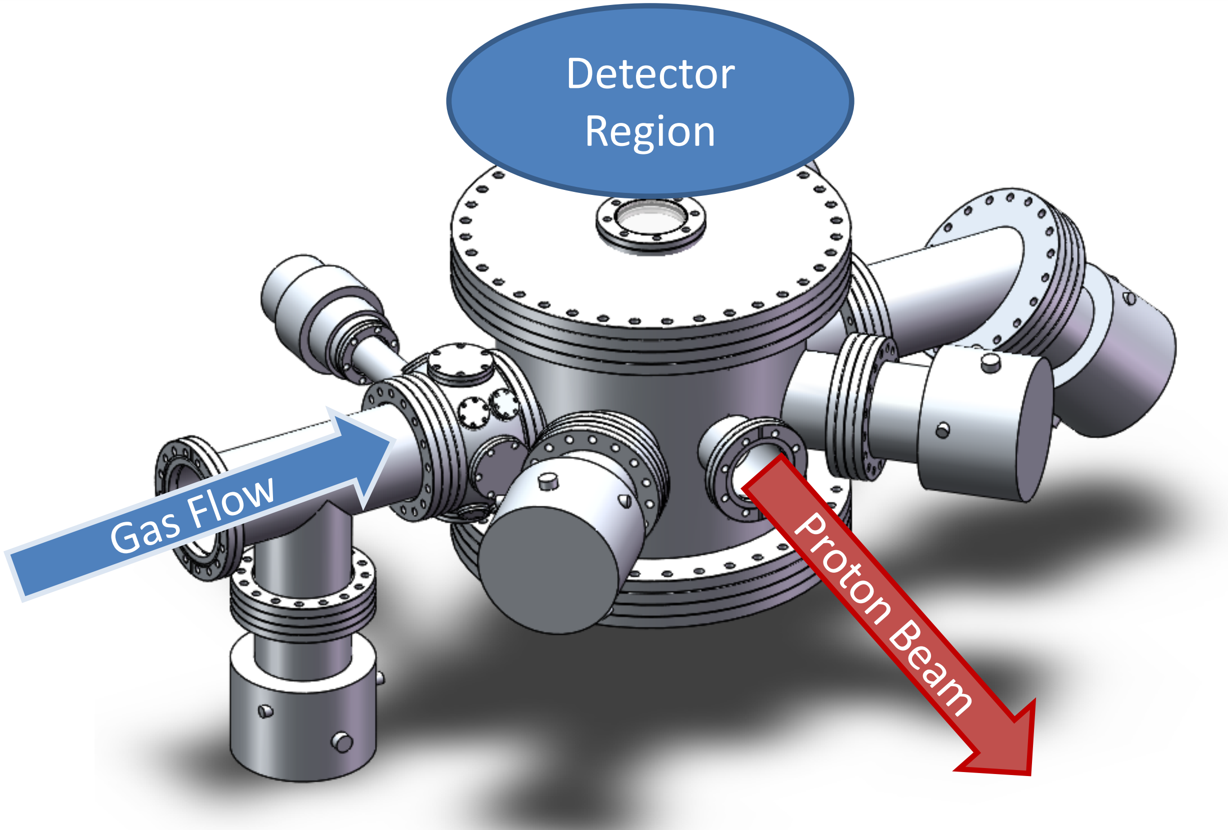
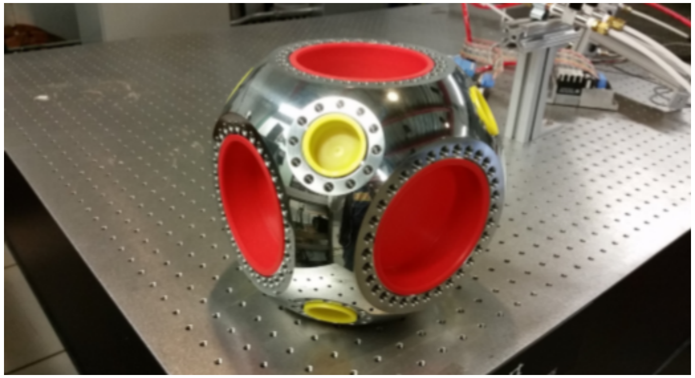


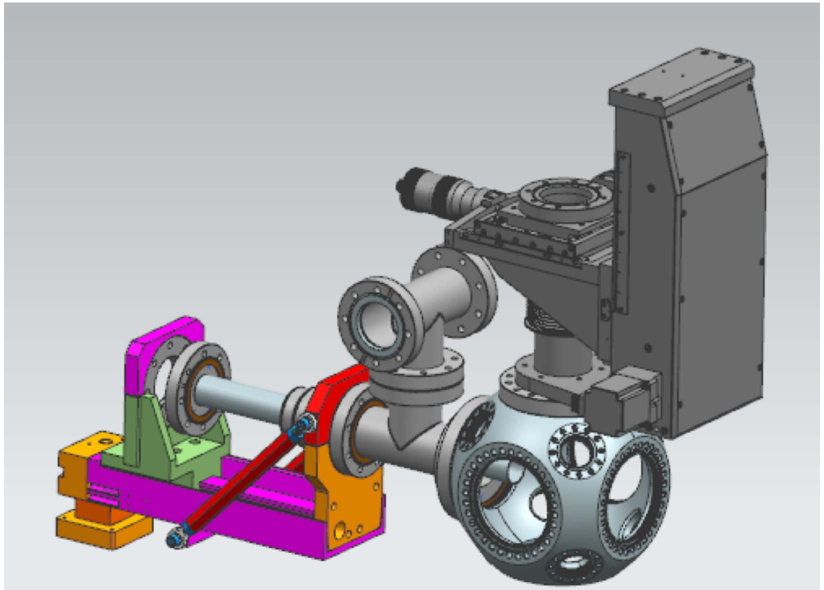
Image courtesy of Tara Campese

radiabeam TECHNOLOGIES

Test Stand

- Characterize Gas Sheet density and shape
- Investigate various skimmer and Nozzle configurations
- Design of interaction chamber in progress
- Will be testing at NML





(Image courtesy of Tim Hamerla)

Summary

- Want to monitor the evolution of the transverse profile in IOTA
- Improve design to minimize the number of pumps, compact design to meet IOTA design
- Optimize gas density in order to have a decent resolution and beam life time
- Investigating faster acquisition and higher resolution in detector system
- Further studies to optimize the strength of extraction electrodes and quantify the effect of space-charge
- Test stand is being set up to finalize gas injection design

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Backup Slides

- Back up slides

Backup - Correction Factor

- Let $p = \frac{l}{d}\tan\theta$, where l is the tube length and d is its diameter

$$C_0(p \leq 1) = 1 - \frac{2}{\pi}(1-\alpha)(\arcsin(p) + p\sqrt{1-p^2}) + \frac{4}{3\pi p}(1-2\alpha)[1-(1-p^2)^{3/2}]$$

$$C_0(p \geq 1) = \alpha + \frac{4(1-2\alpha)}{3\pi p}$$

The general expression of α for a cylindrical tube:

$$\alpha = \frac{u\sqrt{u^2+1} - v\sqrt{v^2+1} + v^2 - u^2}{\frac{u(2v^2+1)-v}{\sqrt{v^2+1}} - \frac{v(2u^2+1)-u}{\sqrt{u^2+1}}}$$

$$u = \frac{l}{d} - v$$

$$v = \frac{l\sqrt{7}}{3l + d\sqrt{7}}$$

B.B.Dayton, *Trans. 3rd Nat. Vac. Symp.*, pp. 5-11 (1956).