Development of the RF funnel for Ba^{+}-ion transportation with CFD calculations

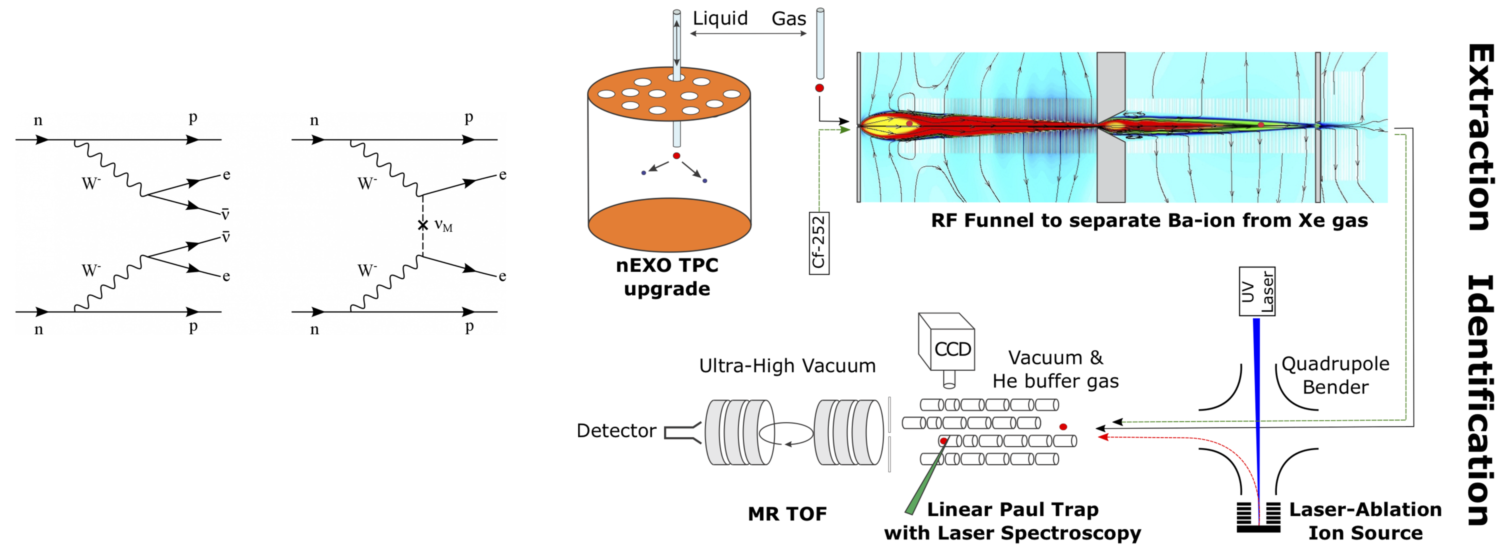
Yilin Wang, Lucas Darroch, Thomas Brunner

McGill nEXO

CINP ICPN Canadian Institute of Nuclear Physics / Institut canadien de physique nucléaire; NSERC CRSNG; Arthur B. McDonald Canadian Astroparticle Physics Research Institute; TRIUMF; Fonds de recherche sur la nature et les technologies Québec; INNOVATION.CA Canada Foundation for Innovation / Fondation canadienne pour l'innovation

Background: Ba^{+}-ion Tagging for the nEXO Collaboration

- **Next generation Enriched Xenon Observatory (nEXO):** developing a multi-ton $\beta\beta$-decay experiment with liquid xenon (LXe) isotopically enriched with ^{136}Xe [2].
- **Neutrinoless double beta decay ($0\nu\beta\beta$):** hypothesised, lepton-number violating nuclear process, the detection of which would demonstrate the Majorana nature of neutrinos. The process difference from $2\nu\beta\beta$ as illustrated [4].



- **Ba^{+}-ion tagging**: identification of ^{136}Ba, the $\beta\beta$-decay daughter of ^{136}Xe

$$^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^{-} \qquad (1)$$

- Detection of rare decay events requires extremely low background. Ba^{+}-tagging discriminates against all non-$\beta\beta$ events and would **drastically reduce background.**
- Associating the Ba^{+}-tagging technique with decay energy and event topology would discriminate $0\nu\beta\beta$ and $2\nu\beta\beta$.
- Traditional Ba^{+}-ion beam extraction methods from gas cells to vacuum: radiofrequency quadrupole (RFQ) or sextupole ion guide (SPIG) [3].
- Recent development of **RF-only ion funnel**: achieves **high-efficiency ion transport** via carrier gas flow, instead of DC-drag potentials [2].

Workflow in ANSYS Workbench

- **CAD Software** — Geometry creation in CAD software such as SolidWorks.
- **DesignModeler** (ANSYS) — Import into DesignModeler for face split to create meshing zones.
- **Mesh** (ANSYS) — Create mesh grids for CFD calculations.
- **Fluent** (ANSYS) — Computational calculation of coupled PDEs governing fluid dynamics.
- **CFX (CFD-Post)** (ANSYS) — Post calculation result processing.

Solving the Governing PDEs

- **Compressible ideal gas** with constant C_p is characterised by its static pressure and temperature (Eq. 2, 3), providing estimation of exit Mach number.

$$\frac{p_0}{p} = (1 + \frac{\gamma - 1}{2} M^2)^{\gamma/(\gamma-1)} \qquad (2)$$

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 \qquad (3)$$

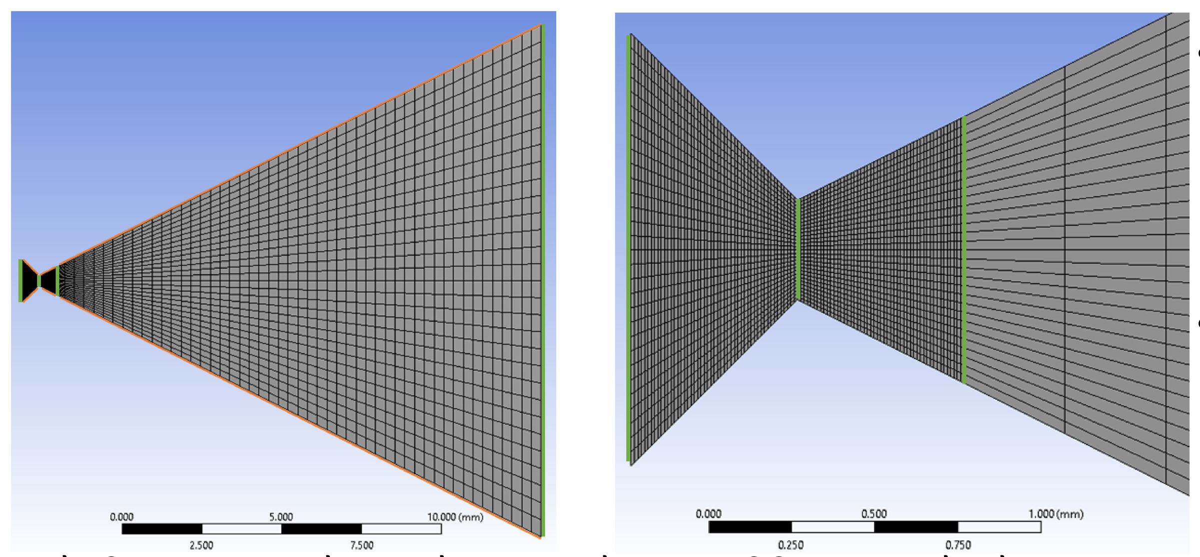
- The effects of compressibility are dependent on the Mach number (Eq. 4): negligible in subsonic cases (M < 0.1); extremely important in supersonic cases (M > 1), and may cause shock waves that impact flow pattern.

$$M = \frac{u}{c_s} \qquad (4)$$

- Equations for **mass conservation (continuity)** and **momentum conservation** in an inertial reference frame are solved for all flows; an additional equation for **energy conservation** is also solved, due to the compressibility of modelled flow. [1]
- The cylindrical symmetry of the funnel geometry allows the usage of the **2D axisymmetric model** of the conservation equations.

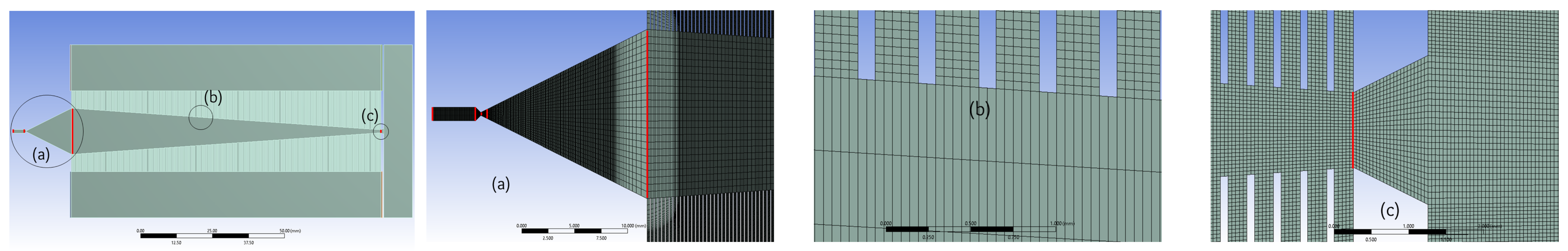
c_s: speed of sound	M: Mach number
C_p: specific heat (constant pressure)	p: pressure
C_V: specific heat (constant volume)	p_0: total pressure
γ: ratio of C_p:C_V	T: temperature
u: velocity	T_0: total temperature

Mesh Grids for CFD Calculations: Single Funnel



Mesh grids for CD nozzle, and zoomed view of finer mesh elements around throat area.

- CD nozzle:
  - 4 vertical edges: 30 divisions
  - 6 wall edges: 50 divisions
  - All faces: face mesh, quadrilateral
- Single funnel:
  - 6 vertical elements: 24 divisions
  - All faces: face mesh quadrilateral
  - Element size = 0.0508 mm



Single funnel geometry, and zoomed view of mesh grids at important contact faces.

Results: Single Funnel Design

- Velocity magnitude contour plot of converging-diverging nozzle, xenon compressible ideal gas, with 10 bar inlet, and various outlet settings.
- Compression of expansion fan as inlet-outlet pressure gradient decreases.
  - Solver settings: density-based steady state, laminar flow, 1000 iterations.

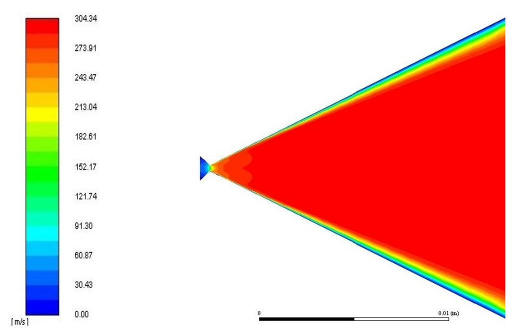


Fig. 4: 8 μbar outlet.

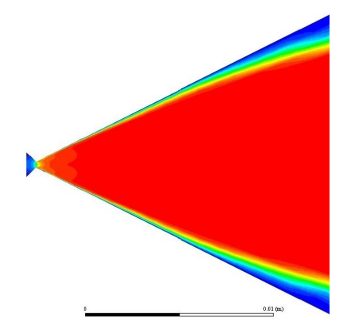


Fig. 5: 10 mbar outlet.

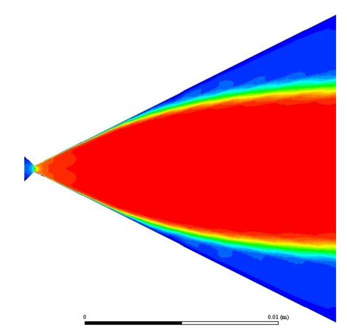
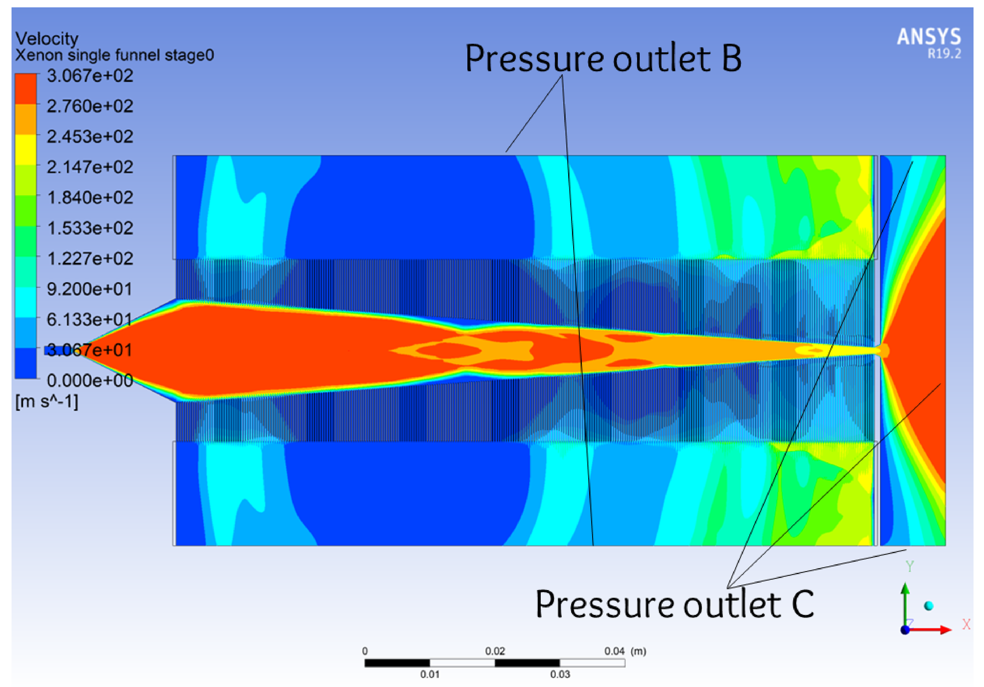
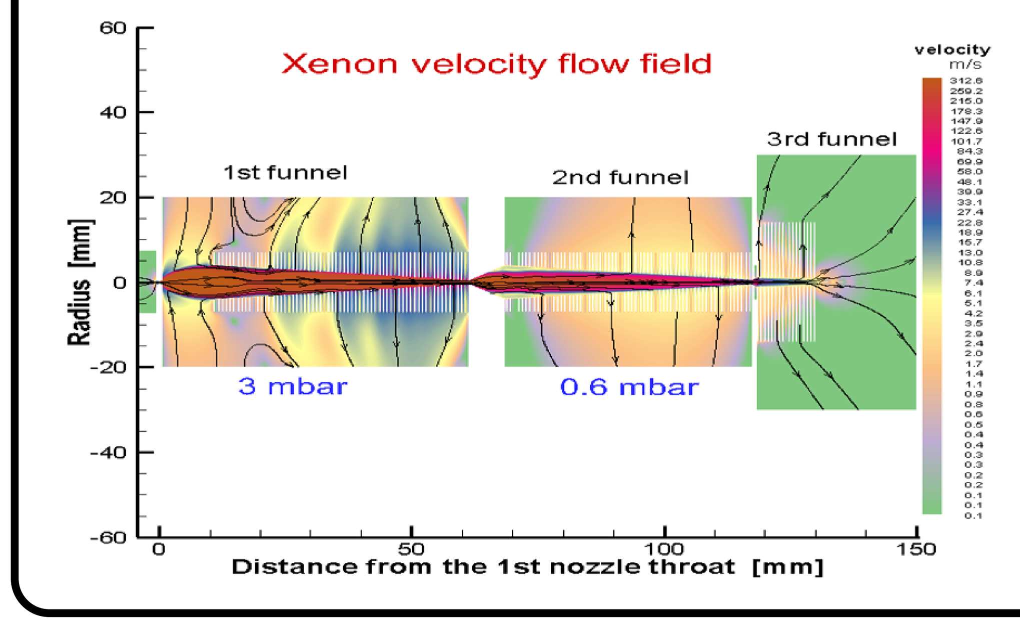


Fig. 6: 40 mbar outlet.



- Velocity magnitude contour plot of single funnel, with 10 bar inlet, 10 mbar outlet B, and 3.5 μbar outlet C.
- Shock wave formed at set boundary conditions.
  - Solver settings:
    density-based transient state
    laminar flow
    courant number = 4
    time step size = 50 μs
    100 time steps
    75 iterations / time step

Ongoing & Future Work



- ANSYS Fluent verification of triple funnel velocity profile [5].
- Variations of nozzle design to optimise gas flow.
- Incorporation of SIMION simulations of ion transmission onto ANSYS Fluent model of gas flow.

References

[1] *ANSYS FLUENT 12.0 Theory Guide*.

[2] *International Journal of Mass Spectrometry*, 379, 12 2014.

[3] *Scientific Reports*, GSI SCIENTIFIC REPORT 2014 FG-SFRS:503–504, 01 2015.

[4] Could dark energy be caused by frozen neutrinos?, Jul 2016.

[5] Victor Varentsov. Conceptual design of a triple-funnel system for ba ions extraction from 10 bar xenon gas. 10 2016.