Beam transmutation in light-ion collisions

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Credits:

CTE simulations: Natalia Triantyfallou, Roderik Bruce

FLUKA/XSUITE simulations: Andre Donadon Servelle

AAMCC simulations: Savva Savenkov, Aleksandr Svetlichnyi, Ekaterina Vasyagina, Igor Pshenichnov,

RELDIS simulations: Igor Pshenichnov, Chiara Oppedisano

Useful discussions: Chiara Oppedisano, Spencer Klein, Jürgen Schukraft, Anthony Timmins, and others in ALICE, Maciej Supinski

Motivation

- We pointed out in 2021 that, since
  - the charge-to-mass ratios of ^{16}O and lighter nuclei with $A=2Z$ (^{14}N, ^{12}C, …, ^{4}He, ^{2}H) are identical and
  - the nuclear binding energies are small at the top of the Periodic Table

  any such nuclei produced in collisions with the same momentum per nucleon/charge would have a magnetic rigidity close to that of the beam and might circulate in the LHC rather than being lost in the dispersion suppressors or on momentum collimators.
- An effective transmutation, contaminating the ^{16}O or ^{20}Ne beams as the fill progresses
- Would not apply in Pb-Pb
- Such nuclei can be produced as spectators in electromagnetic dissociation (EMD) or hadronic fragmentation processes
- Quantitative estimates were previously given (LPC meetings) based on various models and luminosity scenarios

Rigidity shifts of outgoing spectator nuclei (if γ unchanged)

O-O

^{16}O	0.
^{14}N	0.0537726 %
^{12}C	0.0318025 %
^{10}B	0.161248 %
^{8}Be	0.0981555 %
^{6}Li	0.284 %
^{4}He	0.0969224 %
^{2}H	0.737309 %

Ne-Ne

^{20}Ne	0.
^{18}F	0.0430345 %
^{16}O	0.00601942 %
^{14}N	0.0597953 %
^{12}C	0.0378238 %
^{10}B	0.167277 %
^{8}Be	0.104181 %
^{6}Li	0.290036 %
^{4}He	0.102948 %
^{2}H	0.743373 %

Pb-Pb

^{208}Pb	0.
^{206}Tl	0.260842 %
^{204}Hg	0.527183 %
^{202}Au	0.801752 %
^{200}Pt	1.08196 %
^{198}Ir	1.37117 %
^{196}Os	1.66607 %
^{194}Re	1.97085 %
^{192}W	2.28194 %
^{190}Ta	2.60344 %
^{188}Hf	2.9321 %

But the collision products have some momentum distribution around these values …

LHC momentum acceptance in the light-ion runs

In order to circulate in the beam, fragments (Z_1,A_1) must have a fractional change of magnetic rigidity with respect to the central particle of the original beam (Z_0,A_0) smaller than the momentum acceptance of the LHC

$$"\left|\frac{\delta p}{p}\right|" = \left|\frac{|\mathbf{p}_1| Z_0}{|\mathbf{p}_0| Z_1} - 1\right| = \left|\frac{|\mathbf{p}_{N1}| A_1 Z_0}{|\mathbf{p}_{N0}| A_0 Z_1} - 1\right| < \sqrt{\frac{2ZeV_{\mathrm{RF}}}{\pi h \eta E_b}} = 0.34 \times 10^{-3}$$

In the light-ion runs, this value was defined by RF voltage (bucket) and was smaller than momentum cut from momentum collimation in IR3.

$$\boxed{\text{Magnetic rigidity} = \frac{|\mathbf{p}|}{Z} = \frac{|\mathbf{p}_N| A}{Z}}$$

Simulations of spectator fragment production

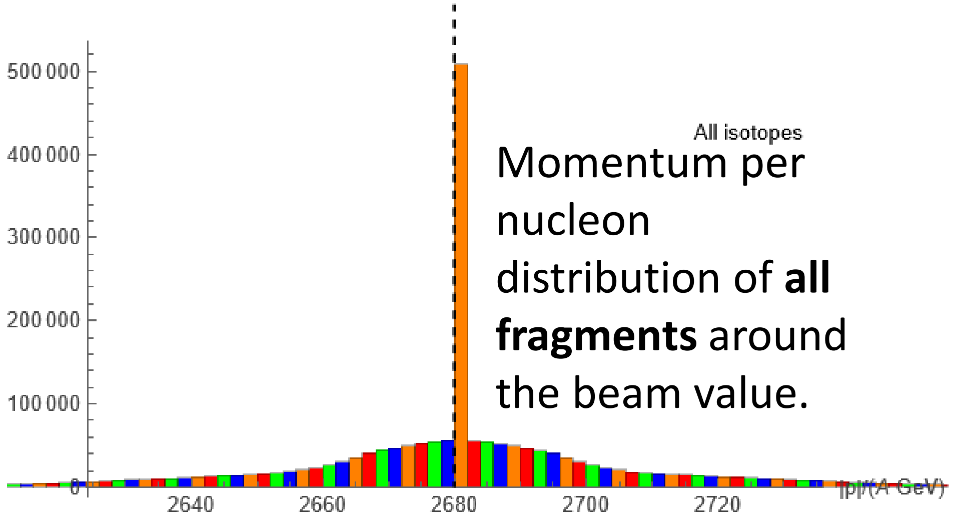
- Abrasion-Ablation Monte Carlo for Colliders (**AAMCC**) for hadronic fragmentation
  - Results from the authors (via Chiara Oppedisano) for 5.36 TeV O-O and Ne-Ne
- **RELDIS** for electromagnetic dissociation (EMD) processes
  - Previous use in ALICE and for early LHC collimation studies
  - Results from the authors (via Chiara Oppedisano) for 5.36 TeV O-O (*not* Ne-Ne)
- **FLUKA** for both hadronic and EMD processes
  - Past and present use for LHC collimation studies
  - Coupled to XSUITE for tracking in the accelerator lattice
  - Results for hadronic, EMD in 5.36 TeV O-O, Ne-Ne (also p-O) from ADS
- Collider Time Evolution (**CTE**) for beam intensity and luminosity evolution
  - Results from NT and RB for initial conditions of fills (also logged data from LHC)
- Similar results from Trajectum (see W. van der Schee talk)

Method

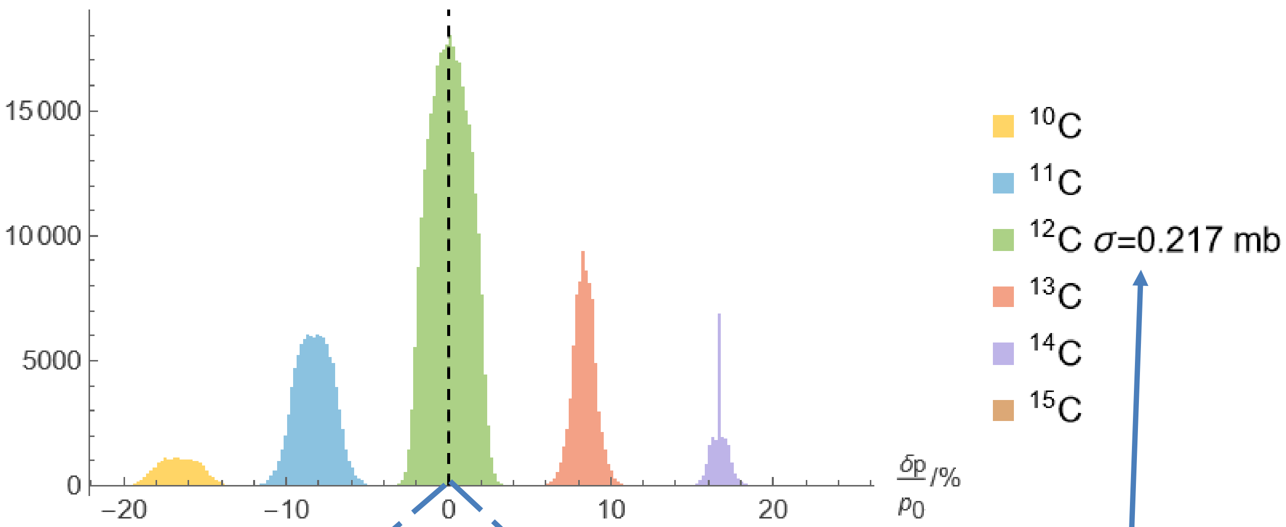
- Momentum distributions of fragments (> 10^6 events) for EMD and hadronic from selected Monte-Carlo simulations
- Momentum distributions are wide so some fragments are lost and do not circulate: we should not use inclusive cross-sections
- Compute rigidity-shift distribution to determine which stay in the beam momentum acceptance
- Normalised to overall hadronic cross-section, we compute effective cross sections for capture of each fragment to circulating beam
- Beam-capture cross-sections are combined with intensity and luminosity evolution of main beam to predict evolution of beam contamination by captured fragments

O-O PREDICTION EXAMPLE

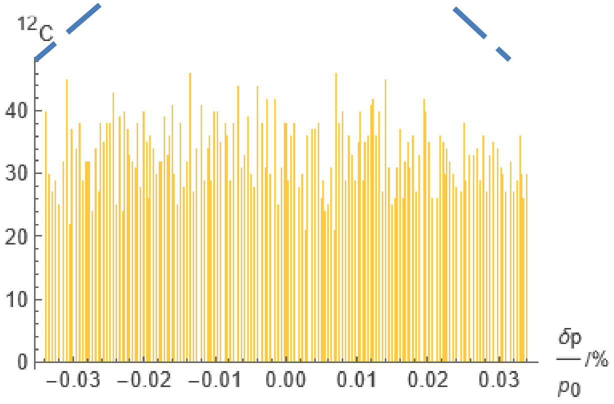
RELDIS: EMD fragments of ^{16}O, O-O 5.36 TeV



Momentum per nucleon distribution of **all fragments** around the beam value.



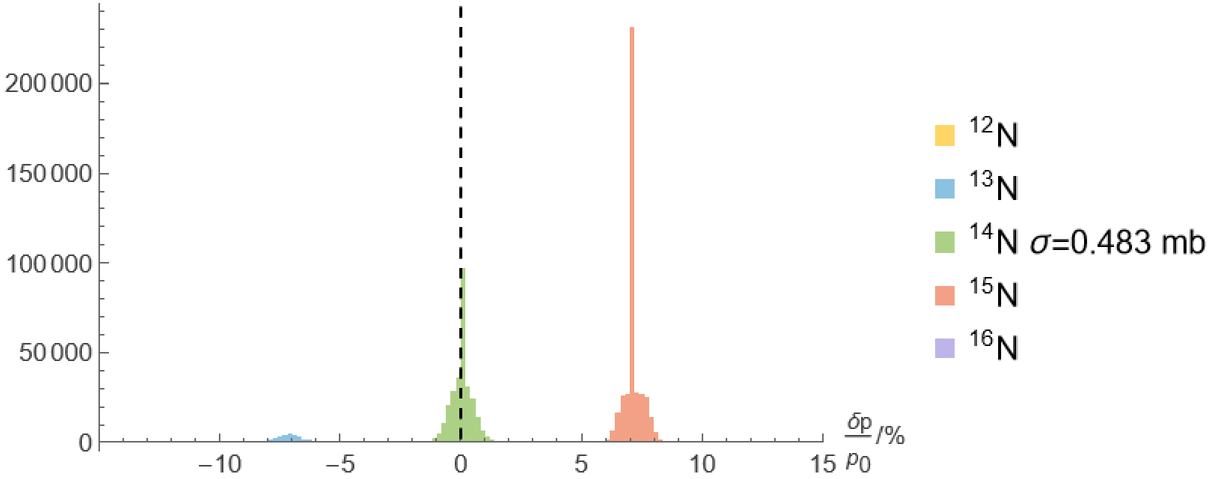
Beam capture cross-section

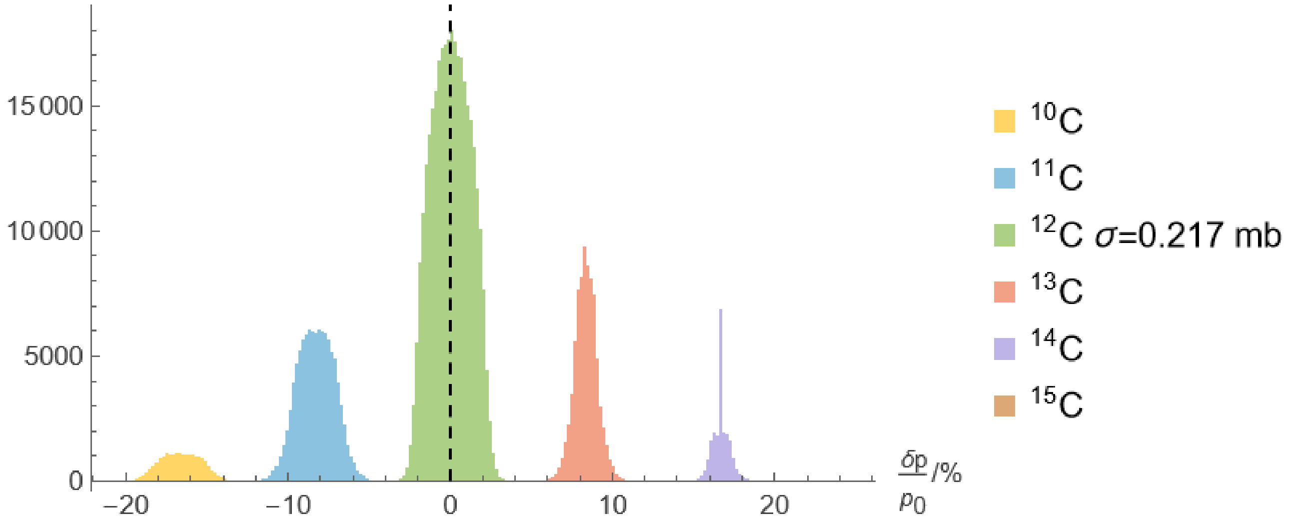


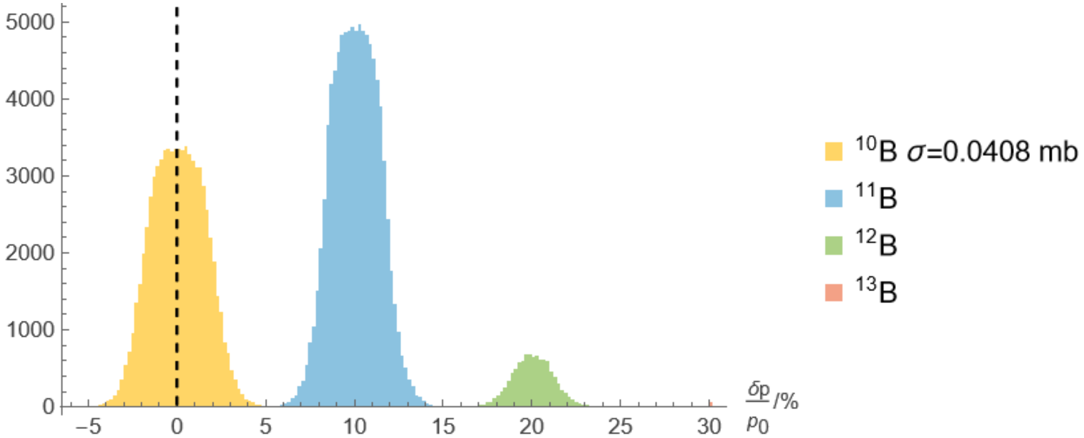
Rigidity shift distribution of the **carbon fragments**.

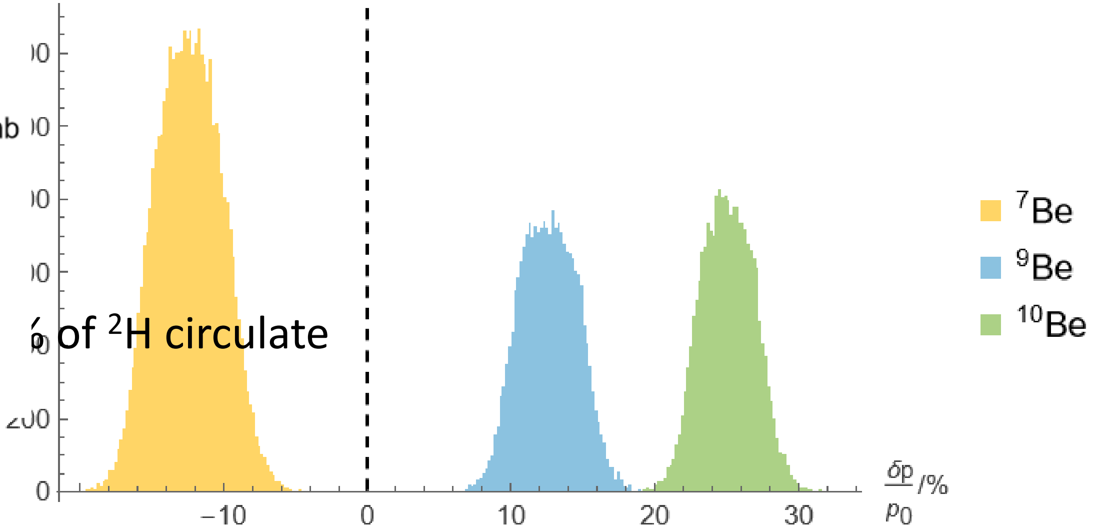
Only a small fraction of the ^{12}C fragments have a non-zero cross-section for capture to the beam.

RELDIS: rigidity of EMD fragments of ^{16}O, O-O 5.36 TeV

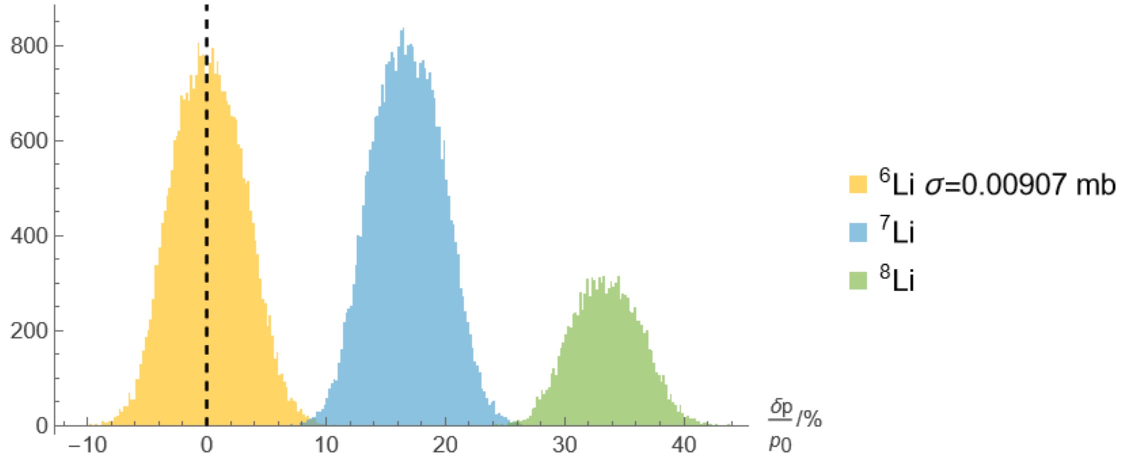


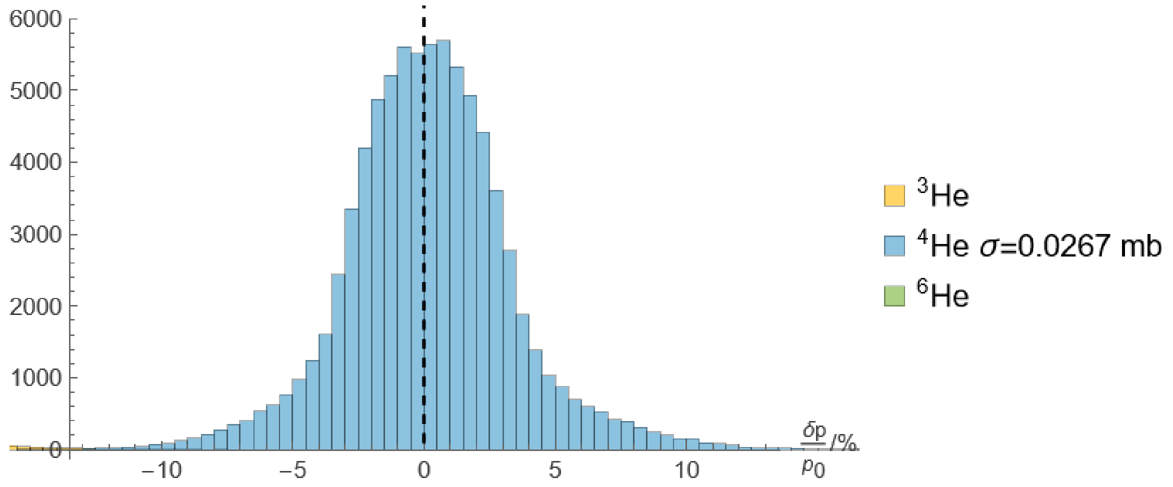




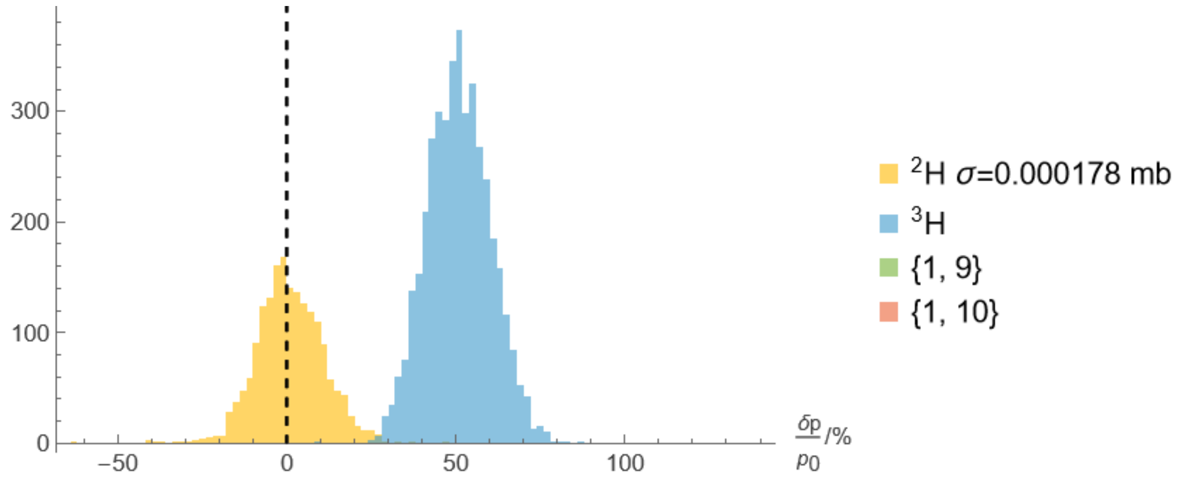


RELDIS: rigidity of EMD fragments of ^{16}O, O-O 5.36 TeV





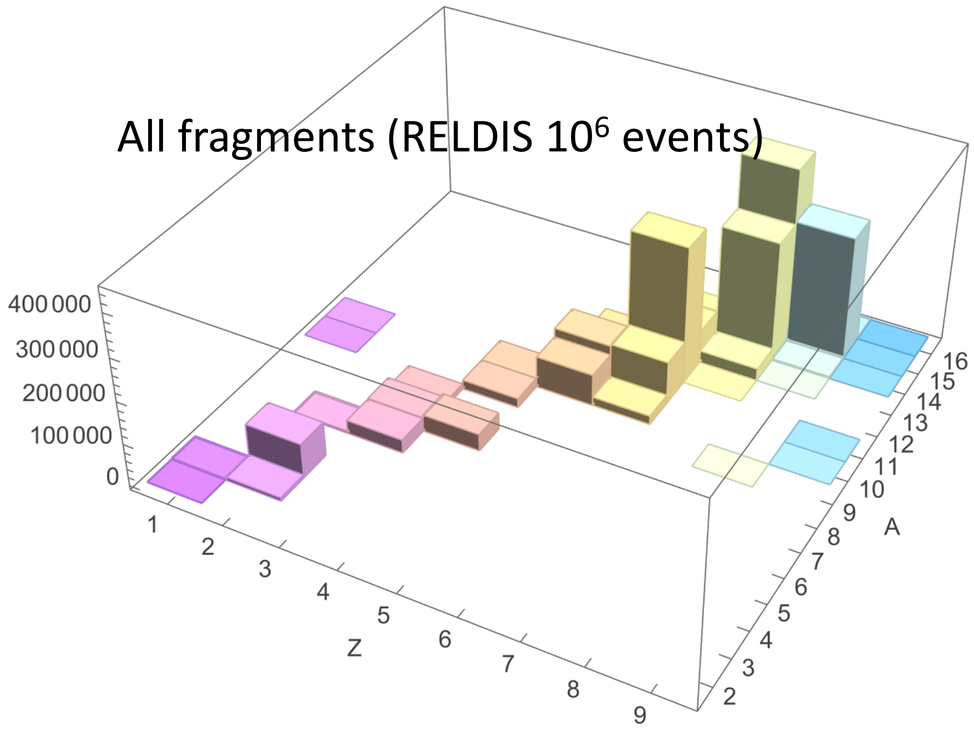
x% of ^{4}He circulate

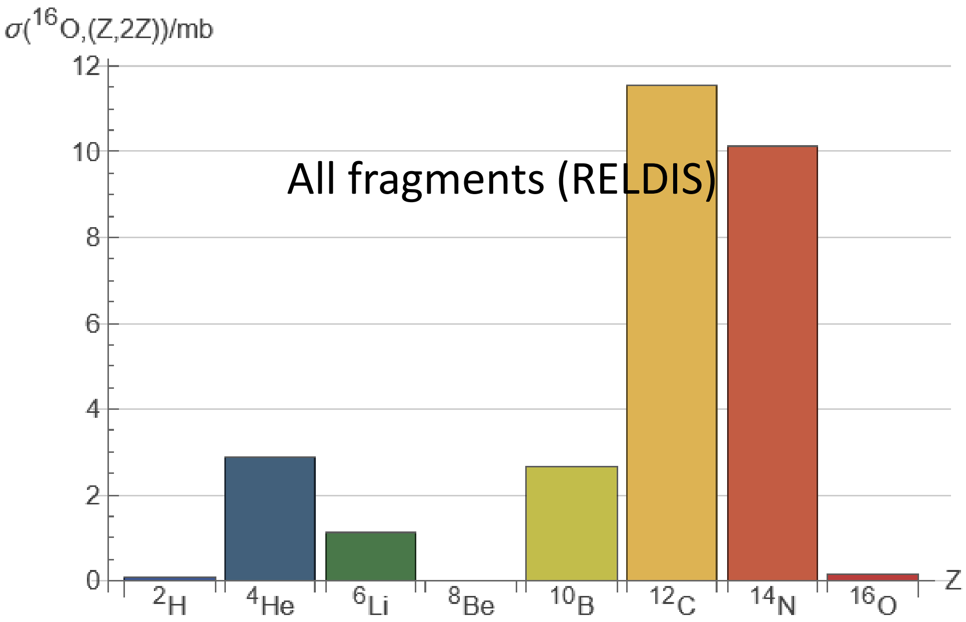


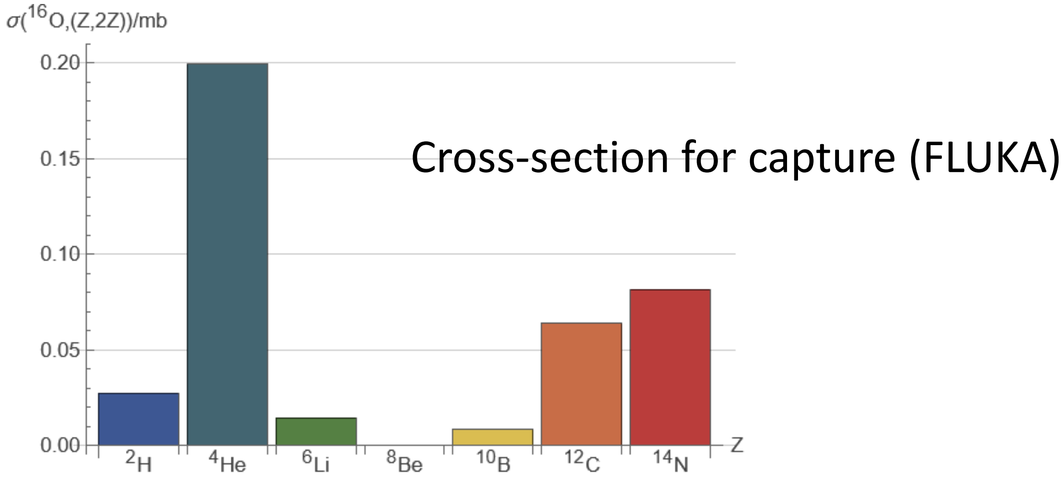
f ^{2}H circulate

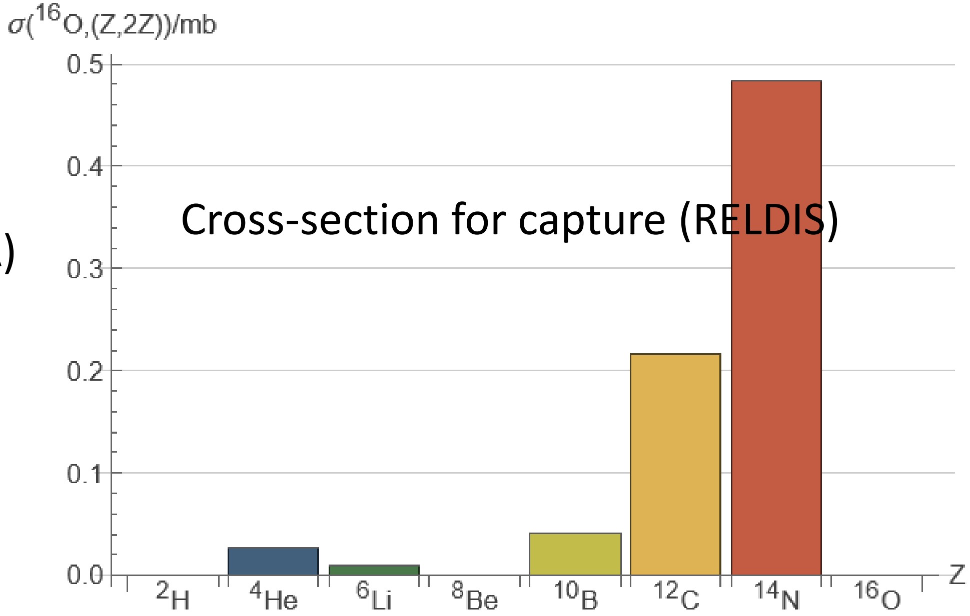
Only a small fraction of the isotopes can circulate. These are almost entirely those with A=2Z (except Be). α particles dominate!

RELDIS: EMD fragments of ^{16}O, O-O 5.36 TeV

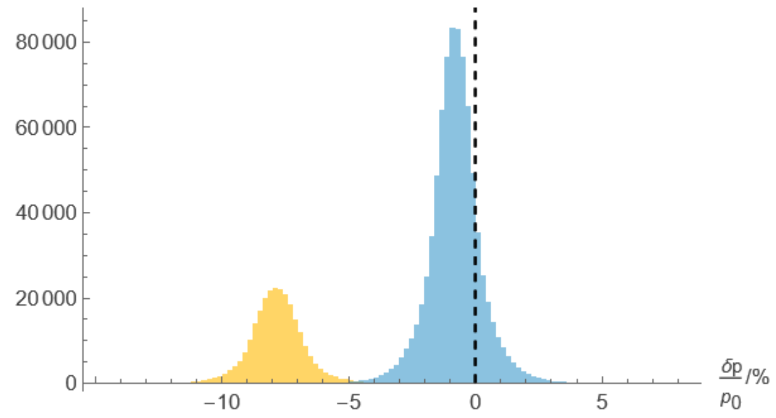


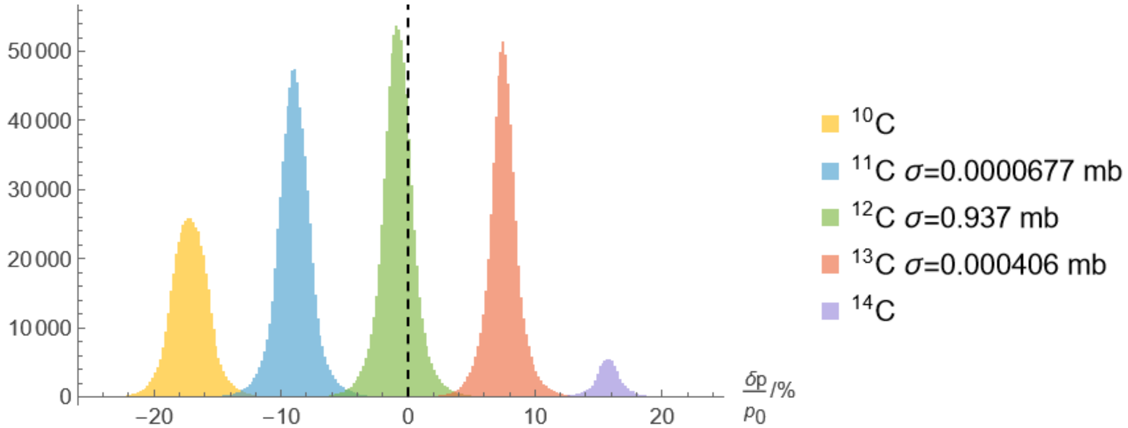


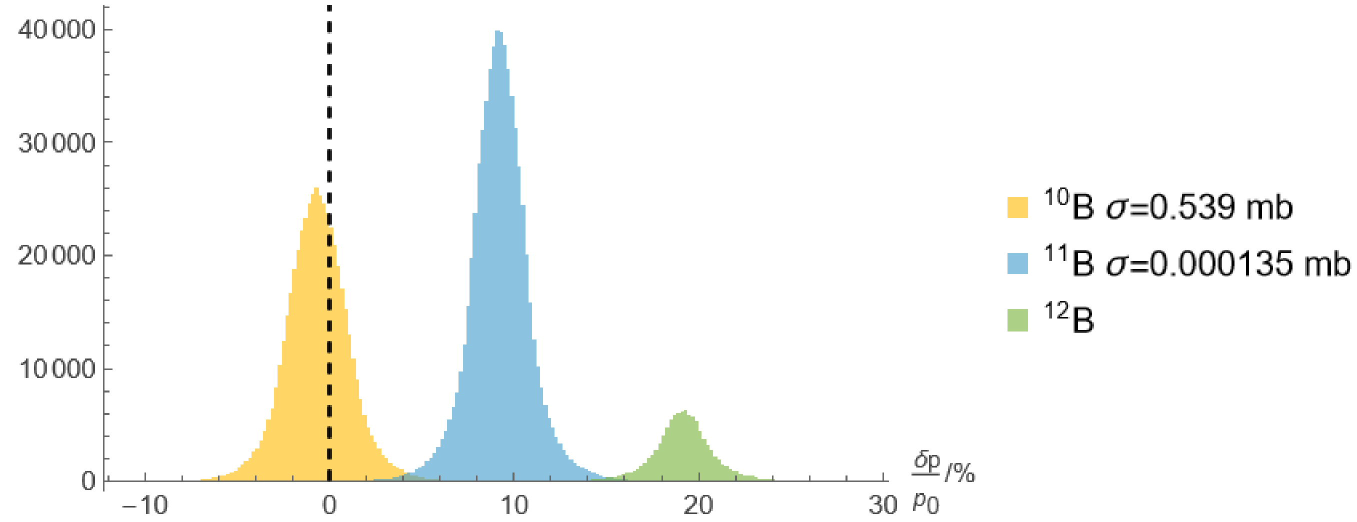


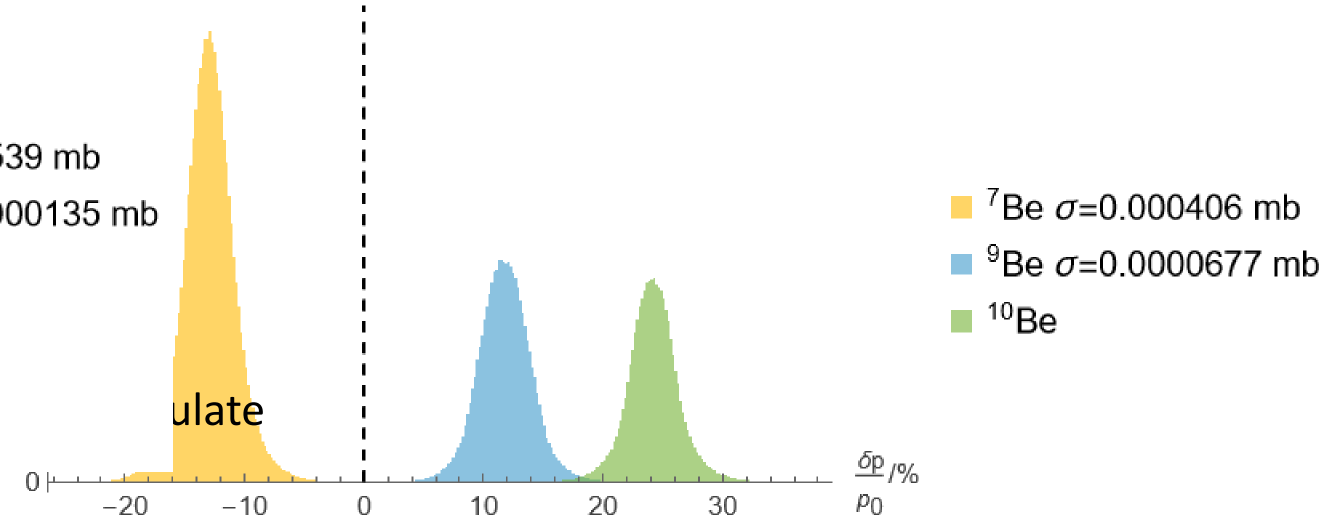


AAMCC: rigidity of hadronic fragments of ^{16}O, 30% α-clustering, O-O 5.36 TeV

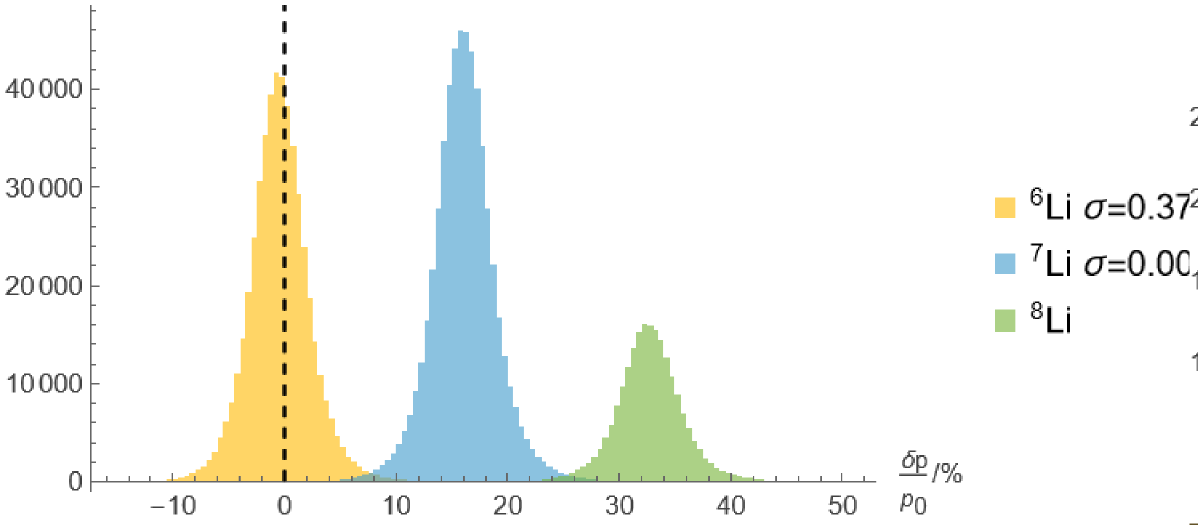


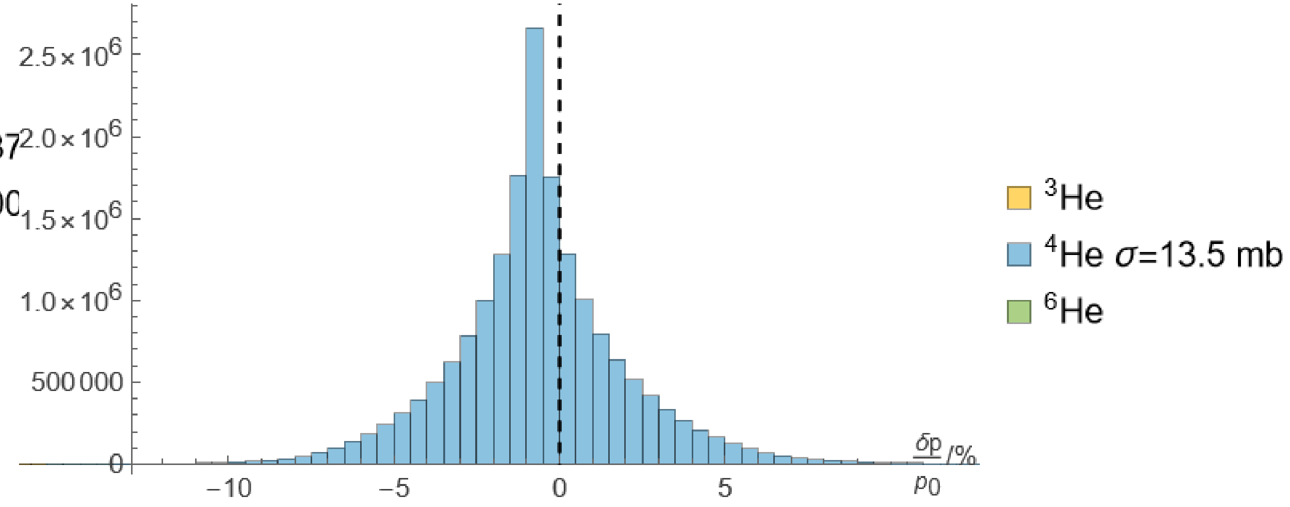




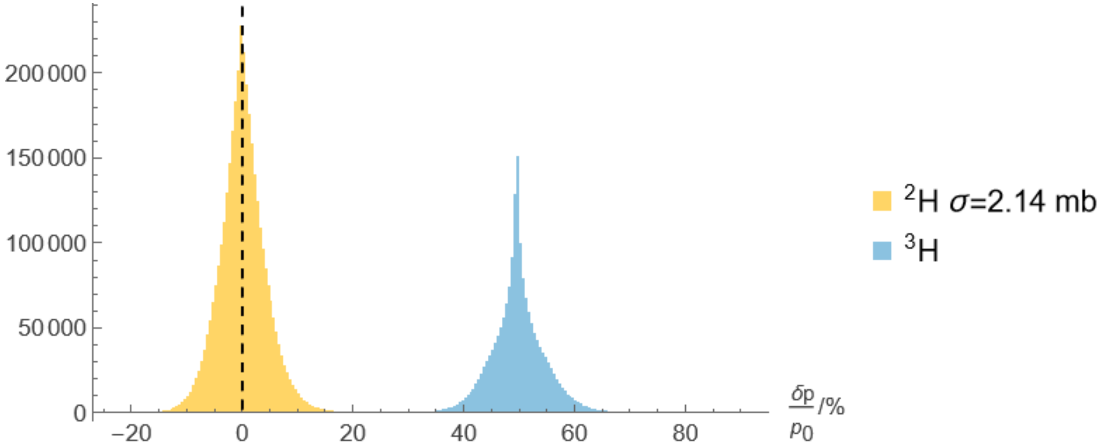


AAMCC: rigidity of hadronic fragments of ^{16}O, 30% α-clustering, O-O 5.36 TeV





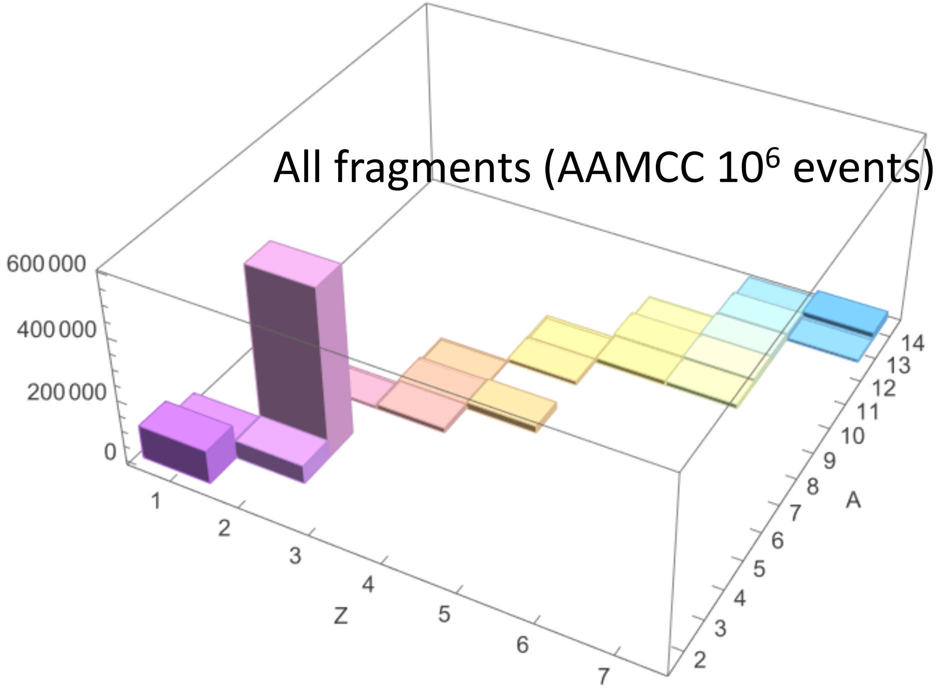
1% of ^{4}He circulate

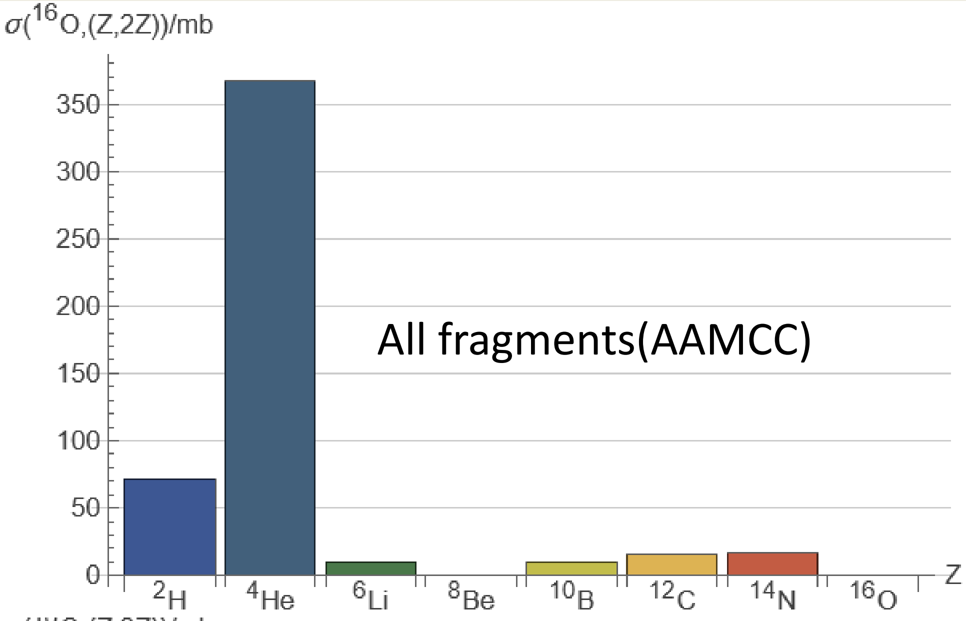


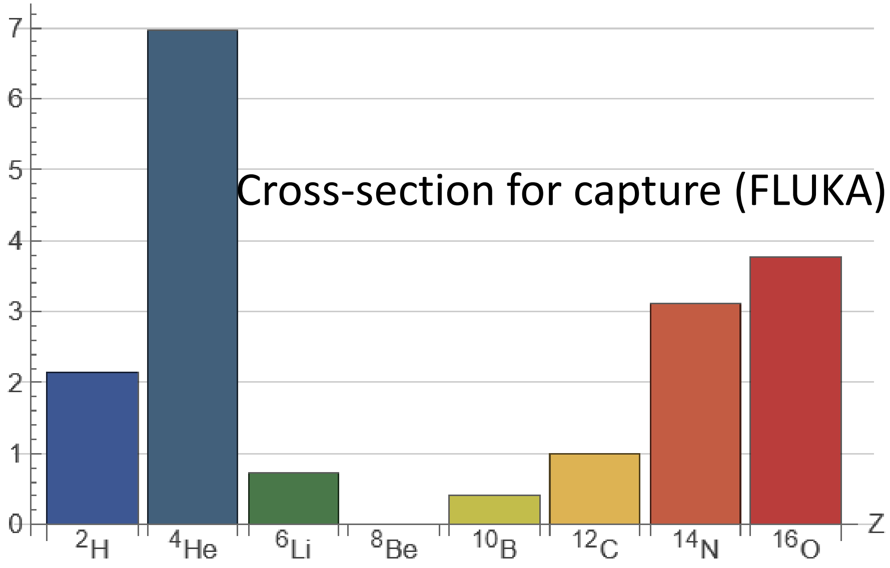
6% of ^{2}H circulate

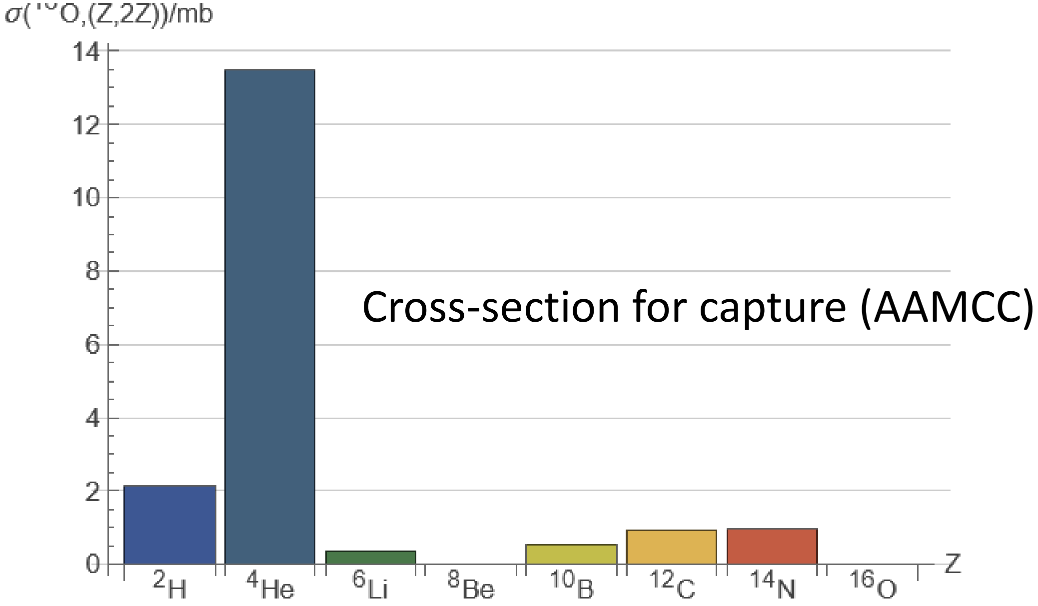
Only a small fraction of the isotopes can circulate. These are almost entirely those with A=2Z (except Be). α particles dominate!

AAMCC: hadronic fragments of ^{16}O, O-O 5.36 TeV

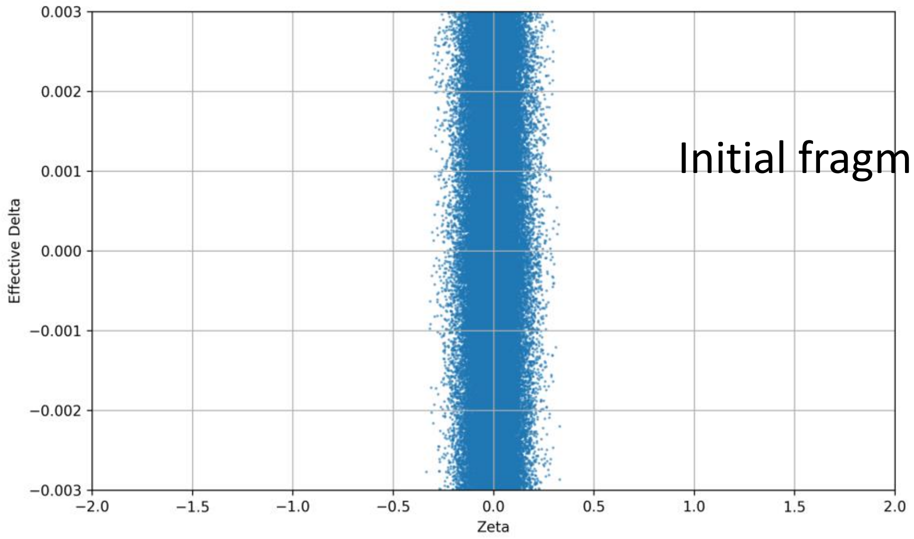




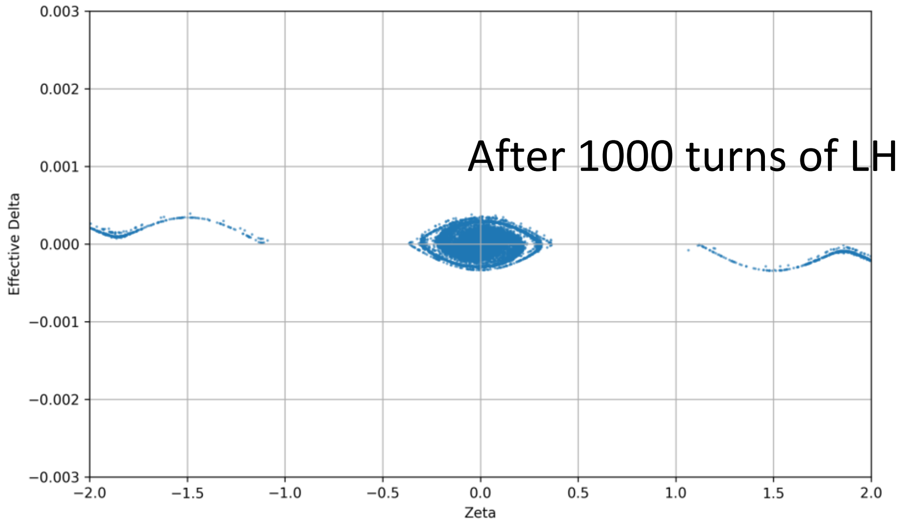




XSUITE tracking from FLUKA (had), longitudinal phase space

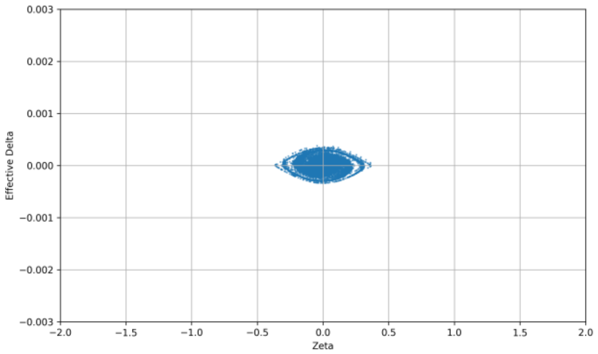


Initial fragments



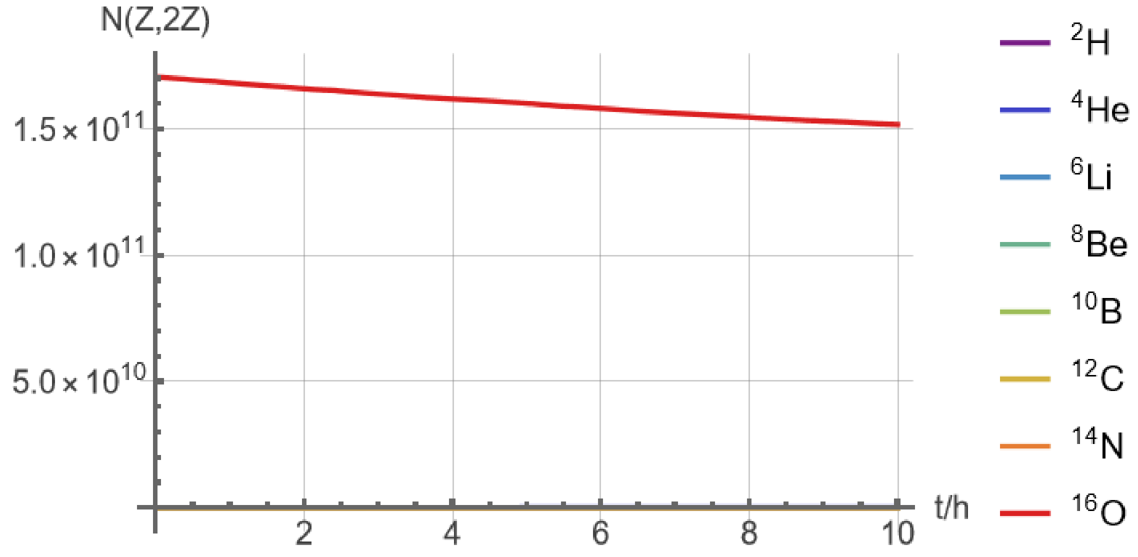
After 1000 turns of LHC

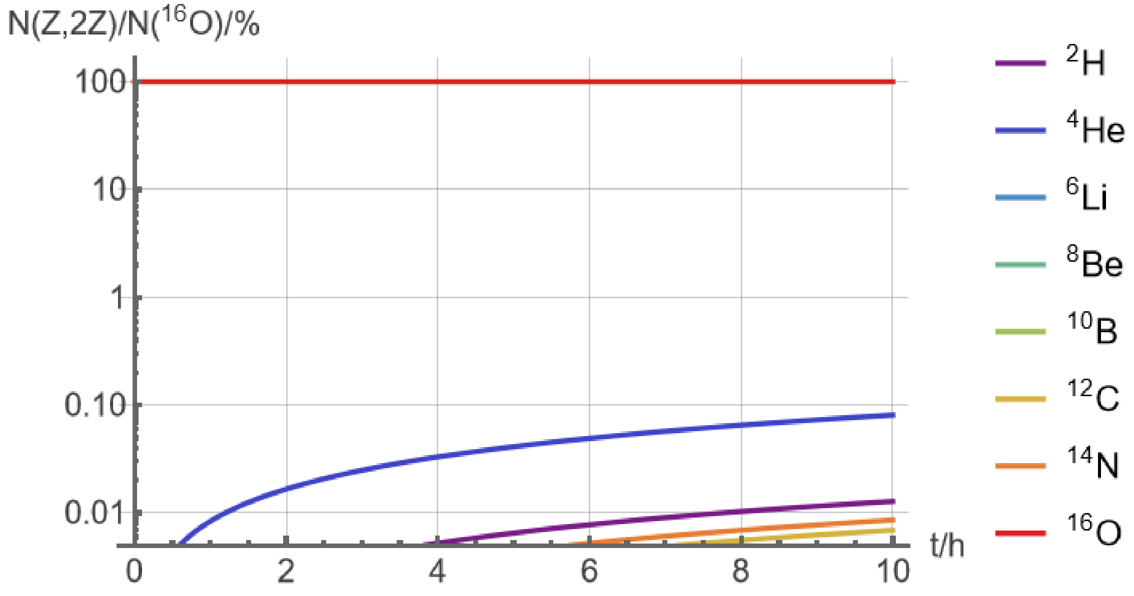
Plots show the rigidity shift “Effective Delta” vs. conjugate time coordinate (in m)



Manual cut on initial after 1000 turns

O-O RELDIS EMD, AAMCC had, scenario OO_62b_fill_10804_26Aug2025

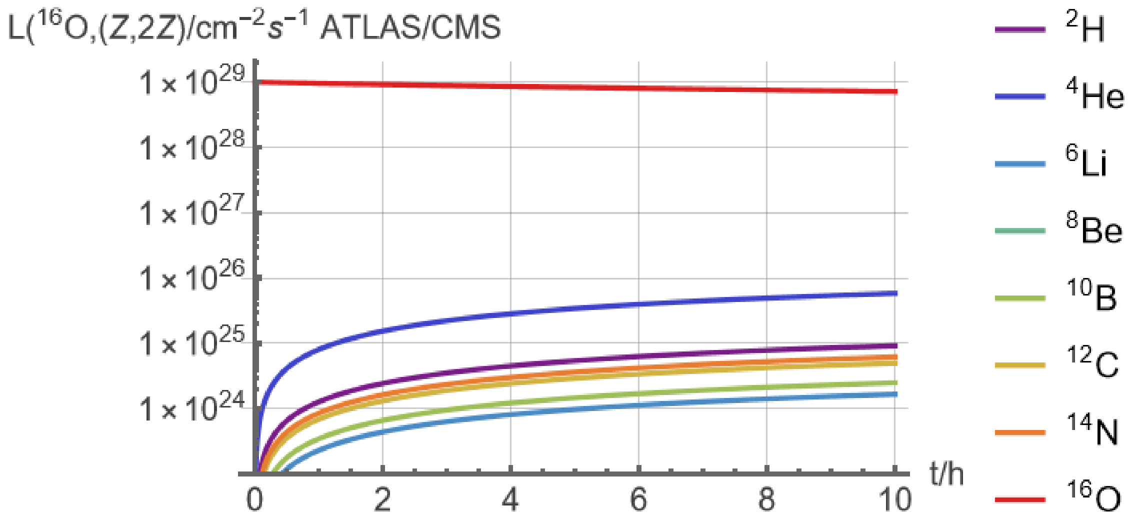


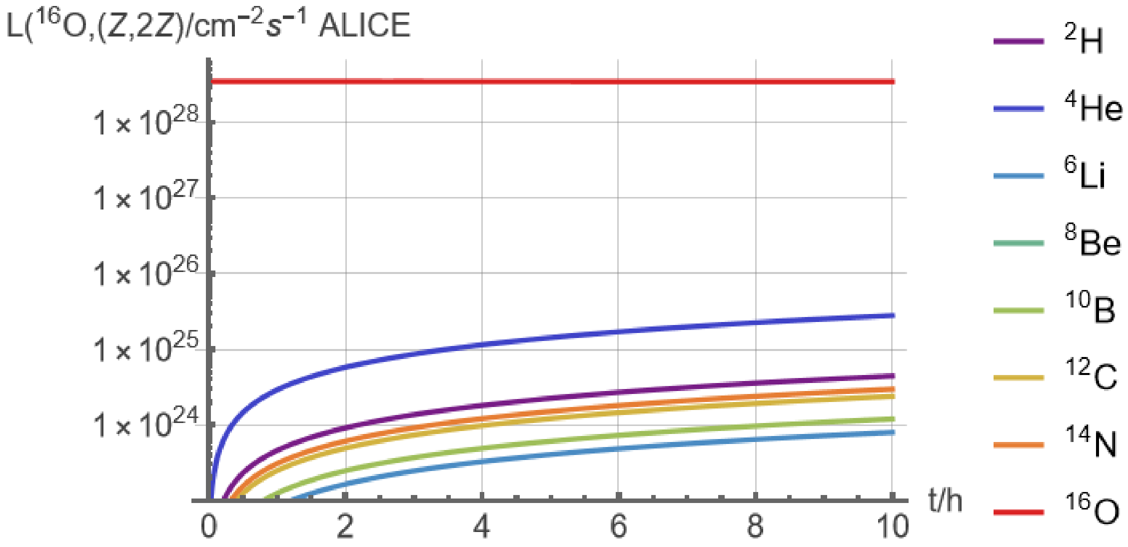


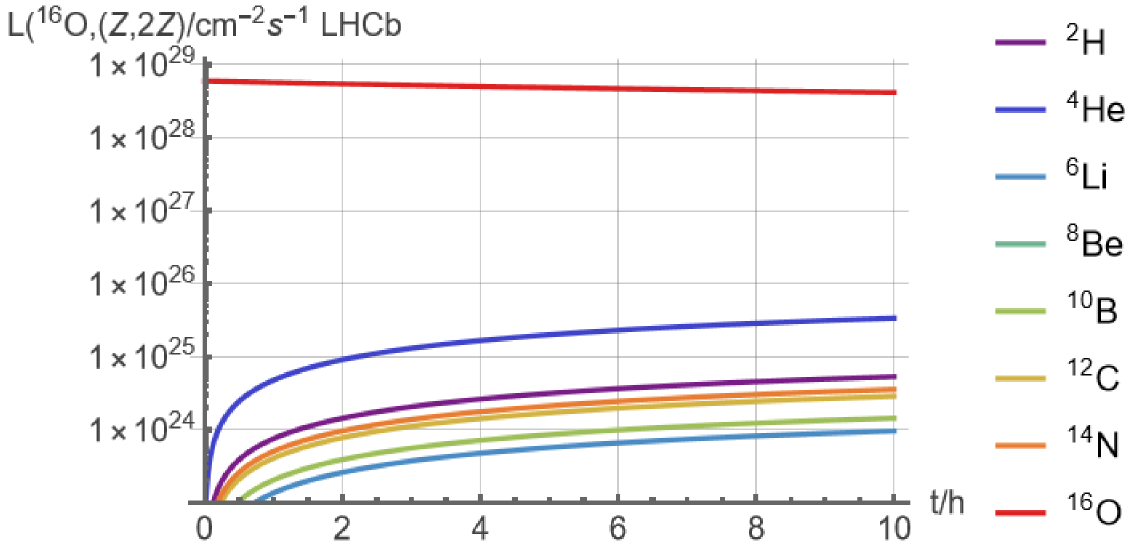
$$\left|\frac{\delta p}{p}\right| < 0.34 \times 10^{-3}$$

Total beam intensities,
same expressed as fraction of ^{16}O intensity

O-O RELDIS EMD, AAMCC had, scenario OO_62b_fill_10804_26Aug2025





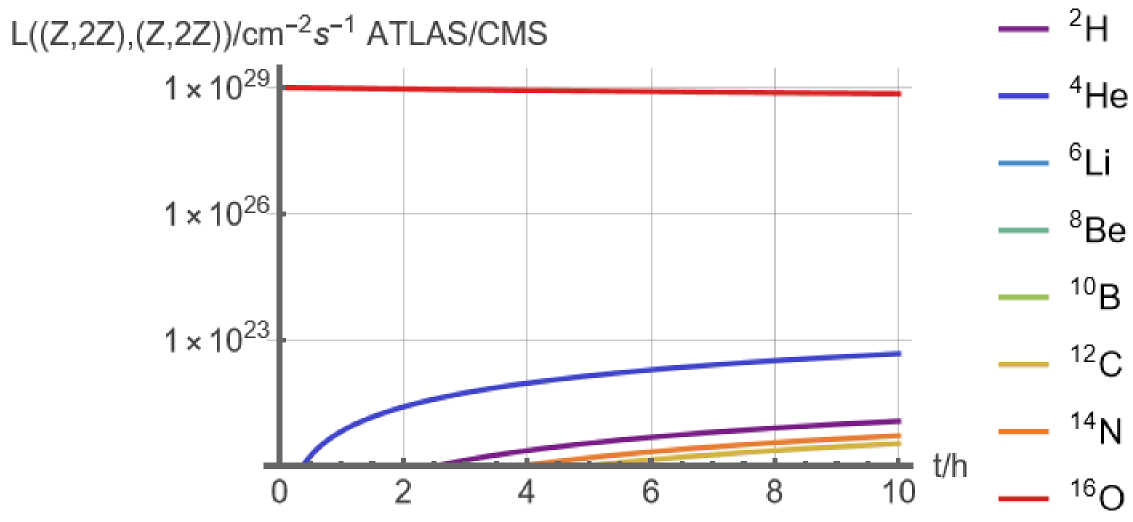


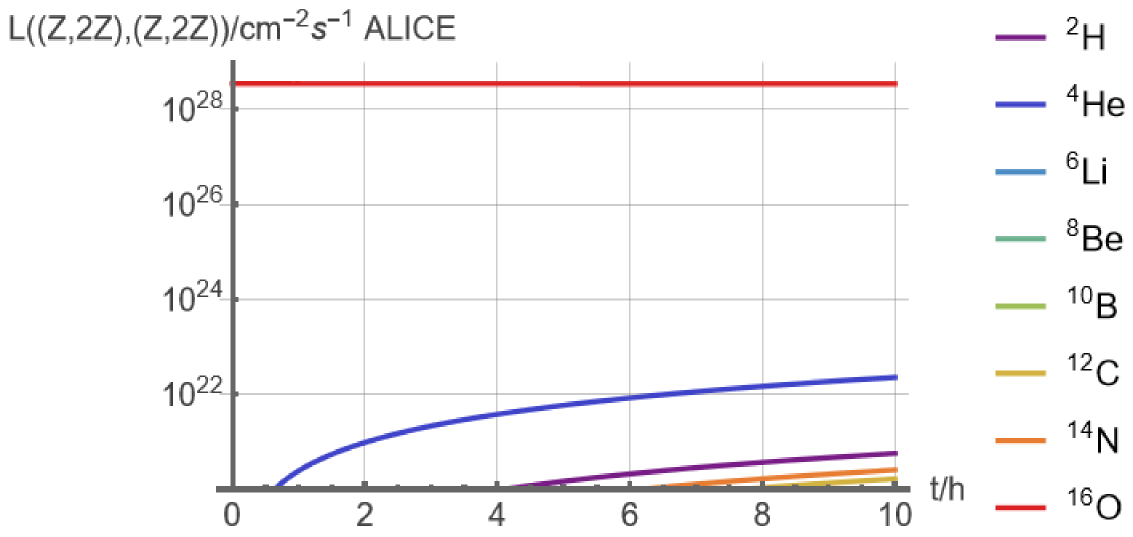
Hybrid collision luminosities in each direction with ^{16}O (total is twice this, except for O-O).

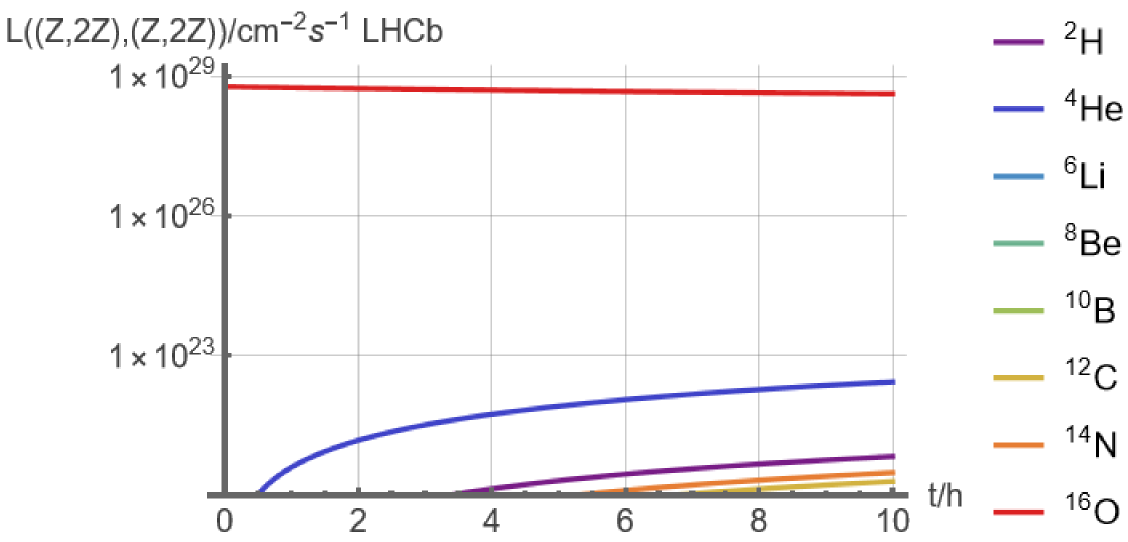
$$L((Z,2Z),\mathrm{O}) = L(\mathrm{O},(Z,2Z))$$

$$\left|\frac{\delta p}{p}\right| < 0.34 \times 10^{-3}$$

O-O RELDIS EMD, AAMCC had, scenario OO_62b_fill_10804_26Aug2025







Collision luminosities of A=2Z isotopes with themselves

$$\left|\frac{\delta p}{p}\right| < 0.34 \times 10^{-3}$$

O-O RELDIS EMD, AAMCC had, scenario OO_62b_fill_10804_26Aug2025

Hybrid integrated collision luminosities with ^{16}O as a **percentage** of integrated luminosity of ^{16}O - ^{16}O. Luminosities of Z-O and O-Z, although equal, are reported separately.

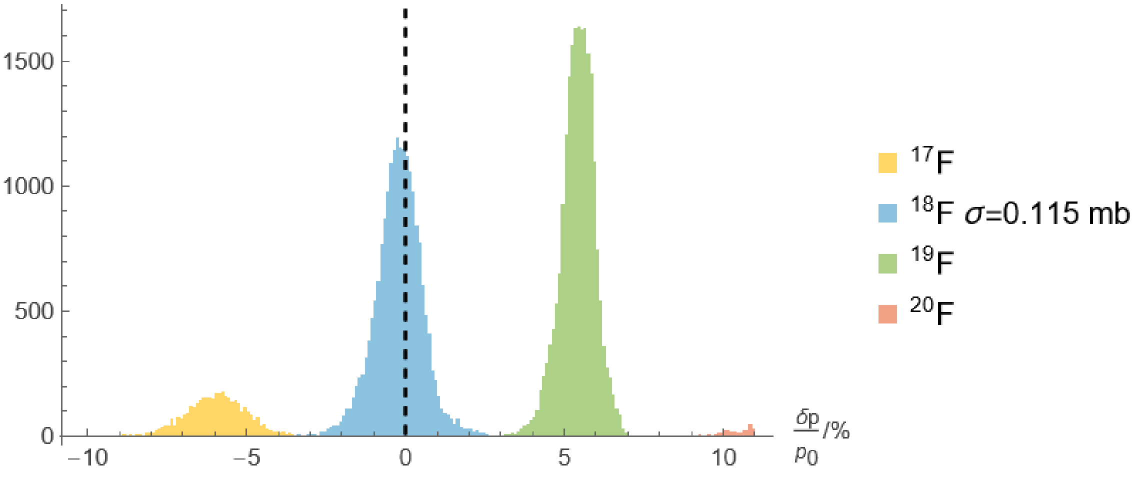
ALICE, fractional integrated luminosities at 10. h

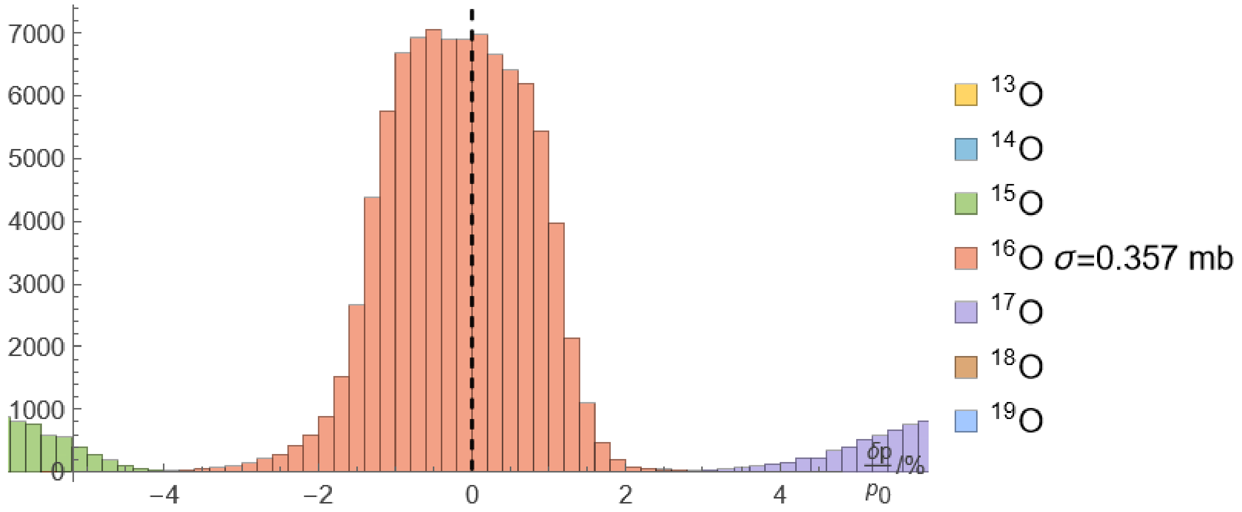
	^{2}H	^{4}He	^{6}Li	^{8}Be	^{10}B	^{12}C	^{14}N	^{16}O
^{2}H	5.5×10^{-7}	3.5×10^{-6}	$1.\times10^{-7}$	0.	1.5×10^{-7}	$3.\times10^{-7}$	3.7×10^{-7}	0.0065
^{4}He	3.5×10^{-6}	0.000022	6.3×10^{-7}	0.	9.5×10^{-7}	1.9×10^{-6}	2.3×10^{-6}	0.041
^{6}Li	$1.\times10^{-7}$	6.3×10^{-7}	1.8×10^{-8}	0.	2.7×10^{-8}	5.4×10^{-8}	6.7×10^{-8}	0.0012
^{8}Be	0.	0.	0.	0.	0.	0.	0.	0.
^{10}B	1.5×10^{-7}	9.5×10^{-7}	2.7×10^{-8}	0.	4.1×10^{-8}	8.1×10^{-8}	$1.\times10^{-7}$	0.0018
^{12}C	$3.\times10^{-7}$	1.9×10^{-6}	5.4×10^{-8}	0.	8.1×10^{-8}	1.6×10^{-7}	$2.\times10^{-7}$	0.0035
^{14}N	3.7×10^{-7}	2.3×10^{-6}	6.7×10^{-8}	0.	$1.\times10^{-7}$	$2.\times10^{-7}$	2.5×10^{-7}	0.0043
^{16}O	0.0065	0.041	0.0012	0.	0.0018	0.0035	0.0043	100.

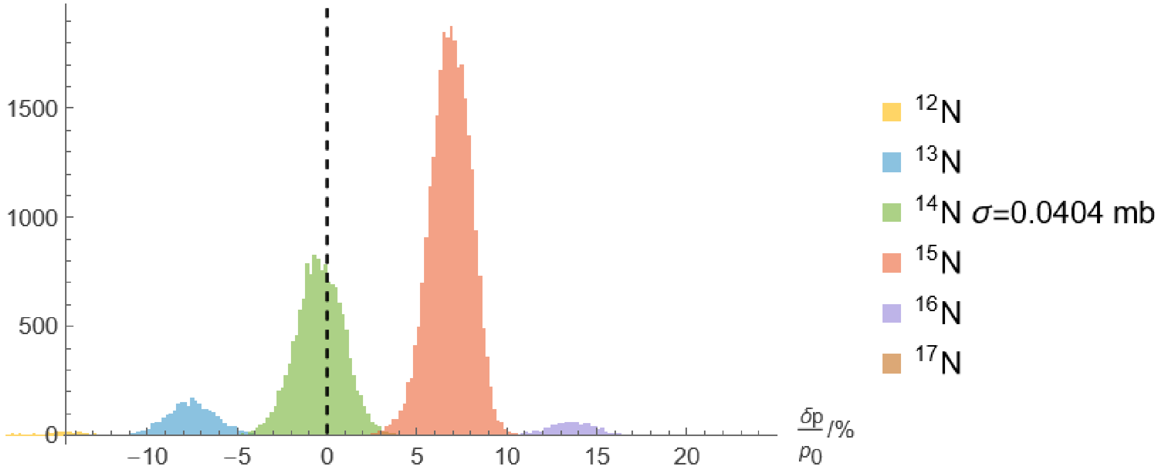
$$\left|\frac{\delta p}{p}\right| < 0.34\times10^{-3}$$

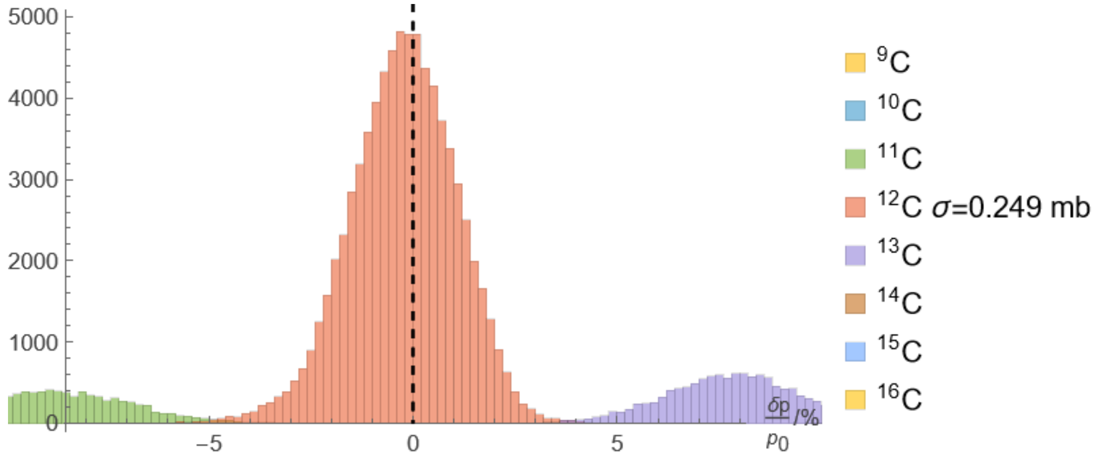
NE-NE PREDICTION EXAMPLE

FLUKA: rigidity of EMD fragments of ^{20}Ne, Ne-Ne 5.36 TeV

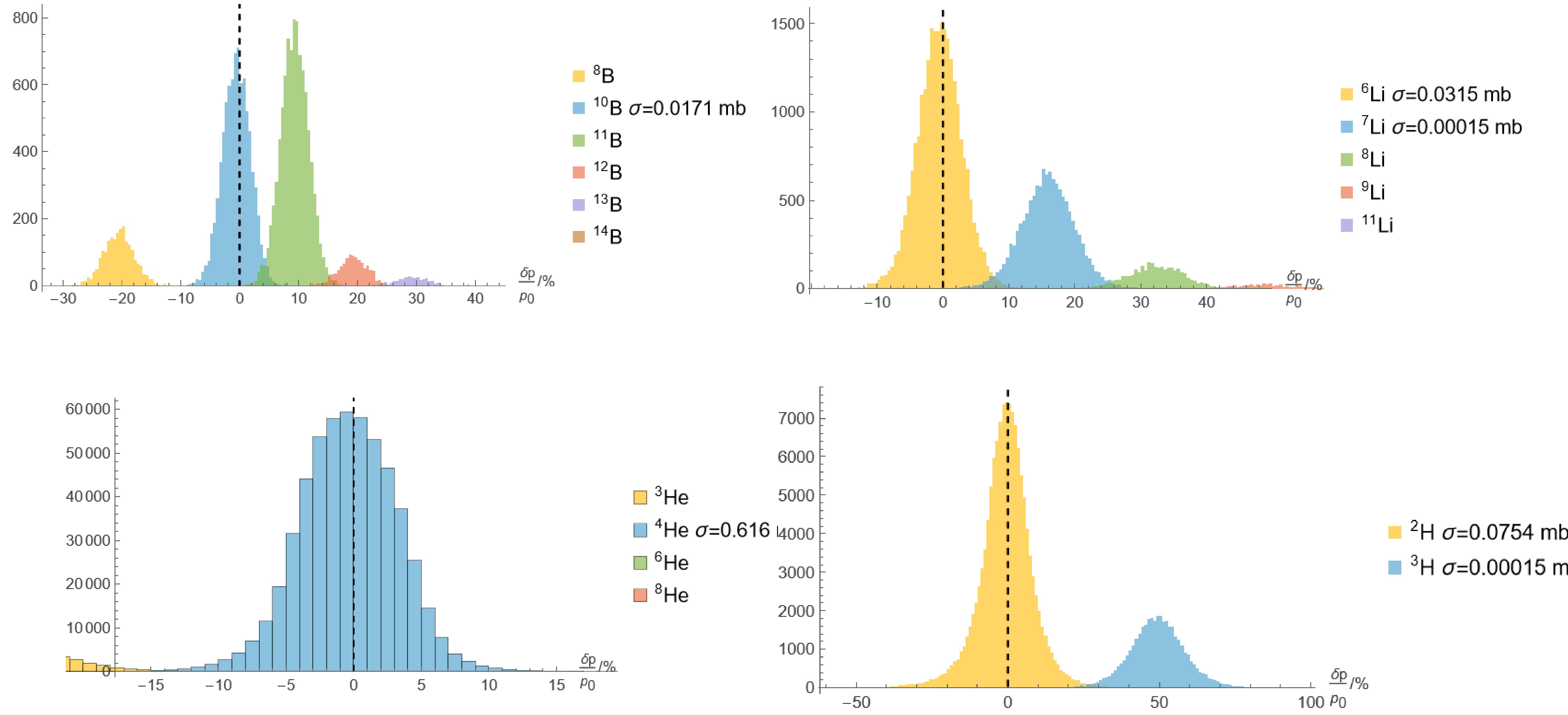








FLUKA: rigidity of EMD fragments of ^{20}Ne, Ne-Ne 5.36 TeV



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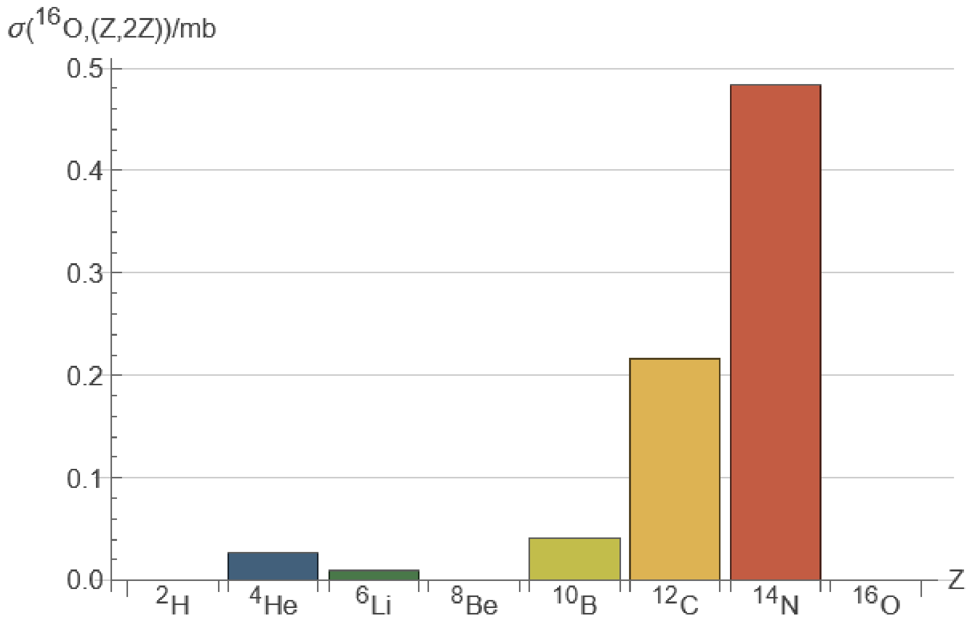
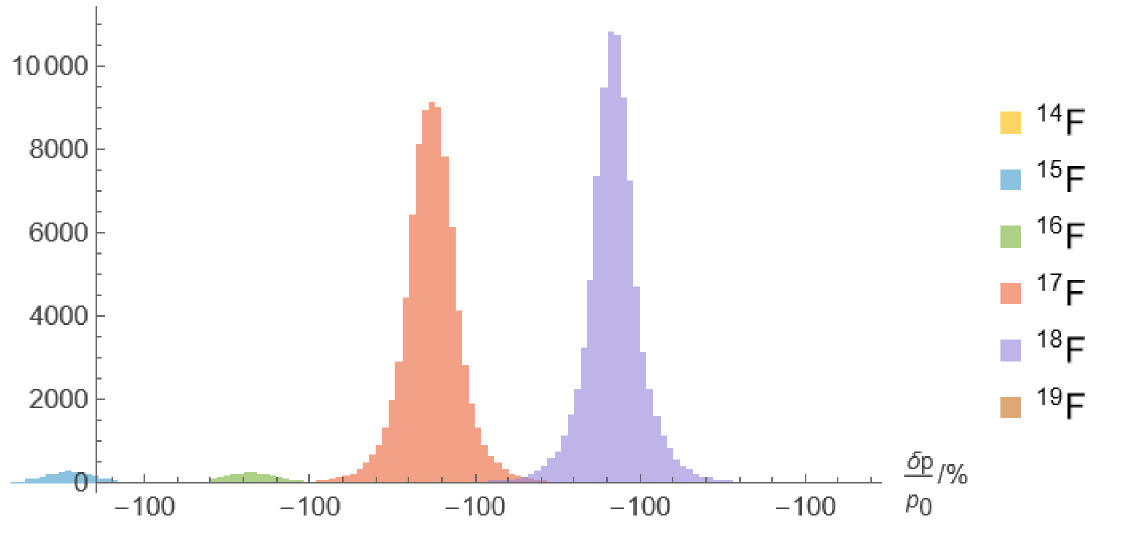
FLUKA: rigidity of EMD fragments of ^{20}Ne, Ne-Ne 5.36 TeV

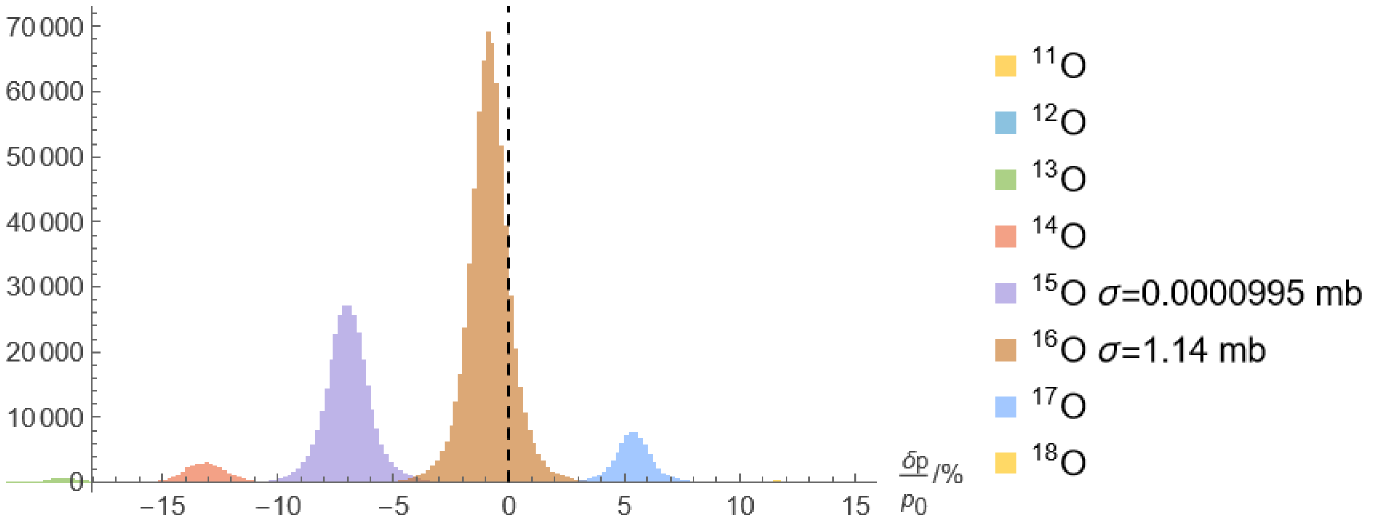


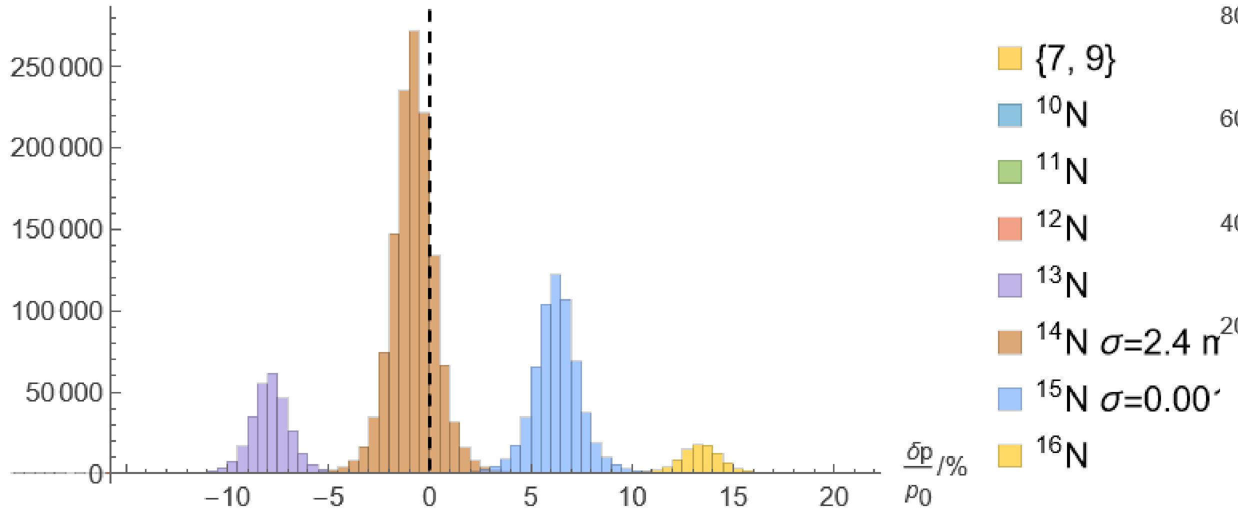
Cross-section for capture (FLUKA)

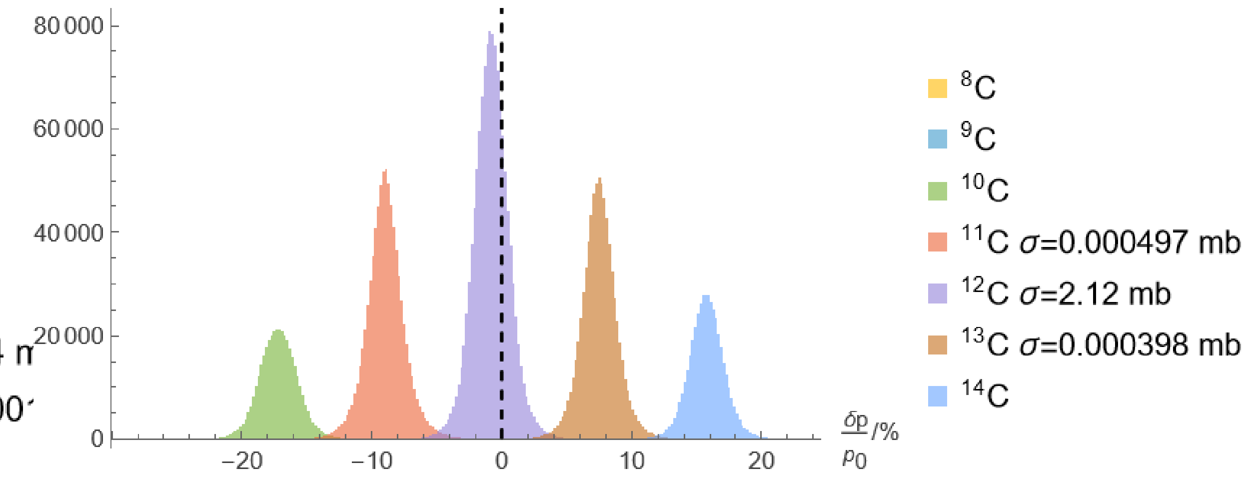
(no RELDIS data for Ne)

AAMCC: rigidity of had fragments of ^{20}Ne, 100% α-clustering, Ne-Ne 5.36 TeV

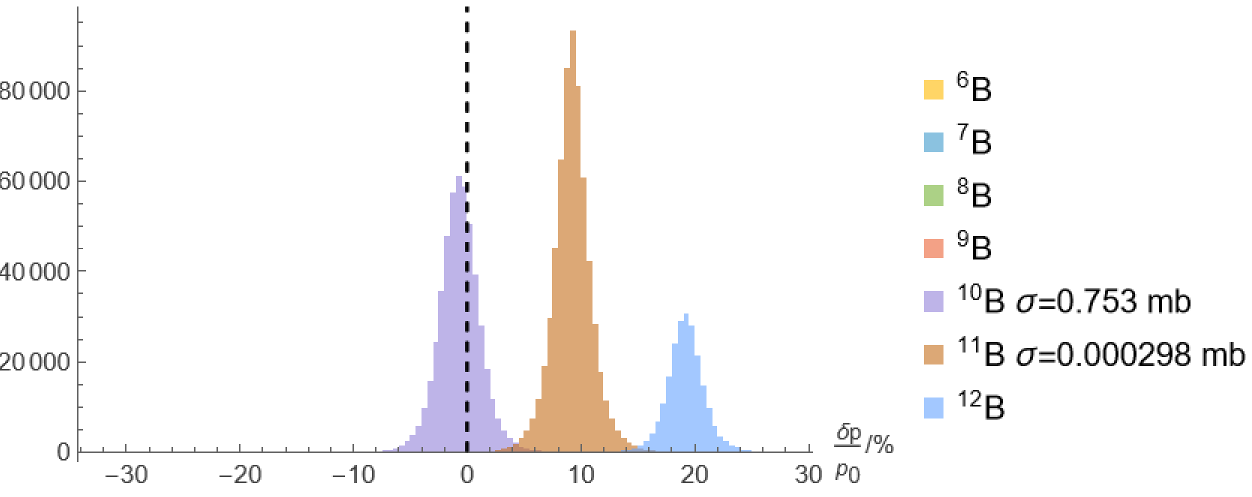


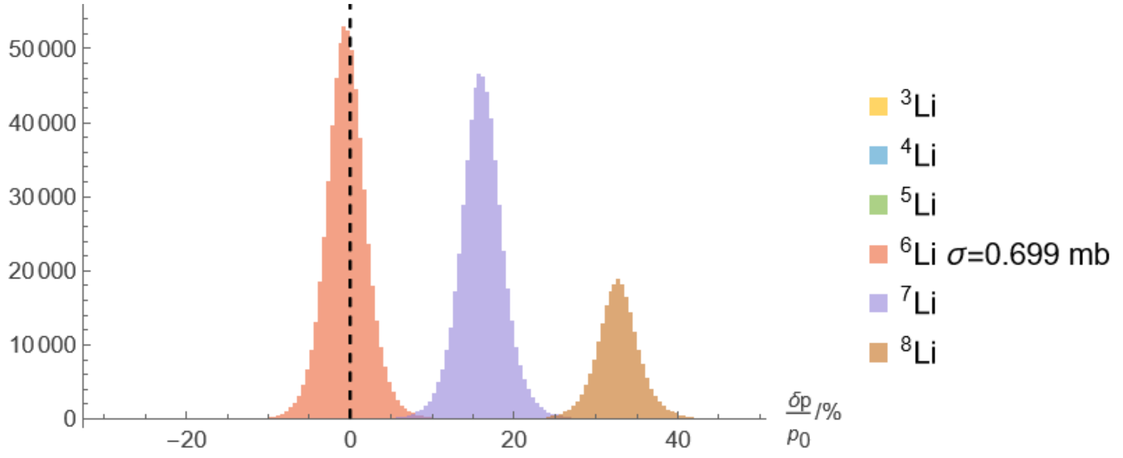


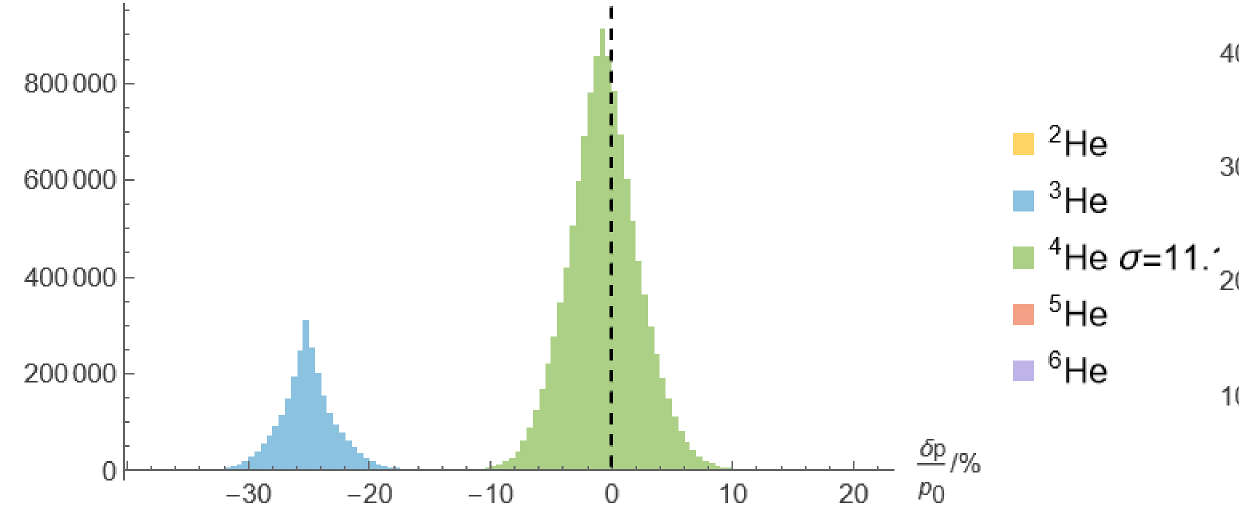


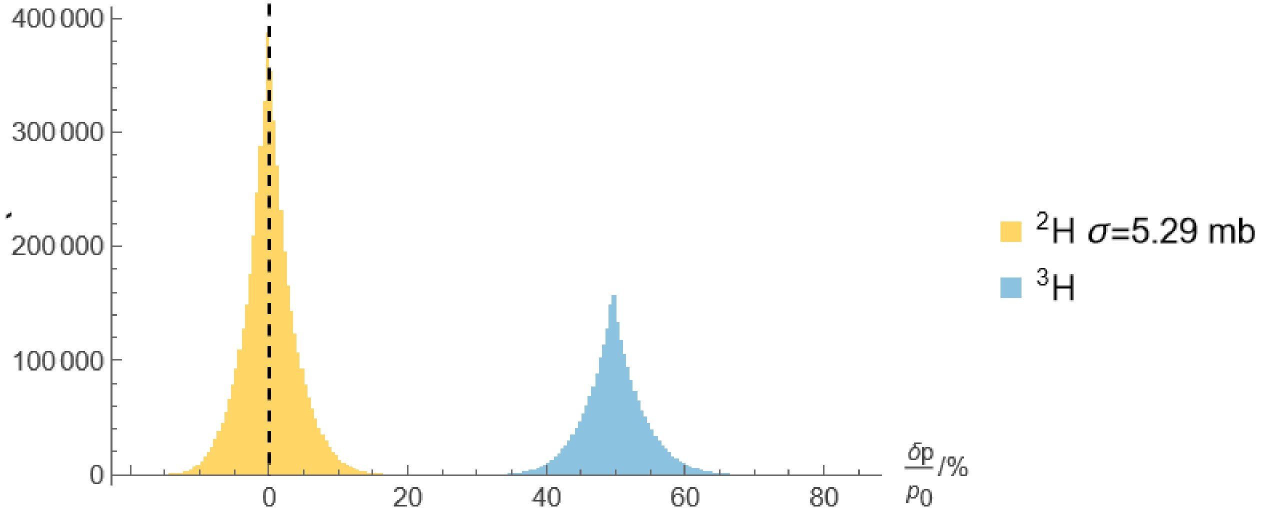


AAMCC: rigidity of had fragments of ^{20}Ne, 100% α-clustering, Ne-Ne 5.36 TeV









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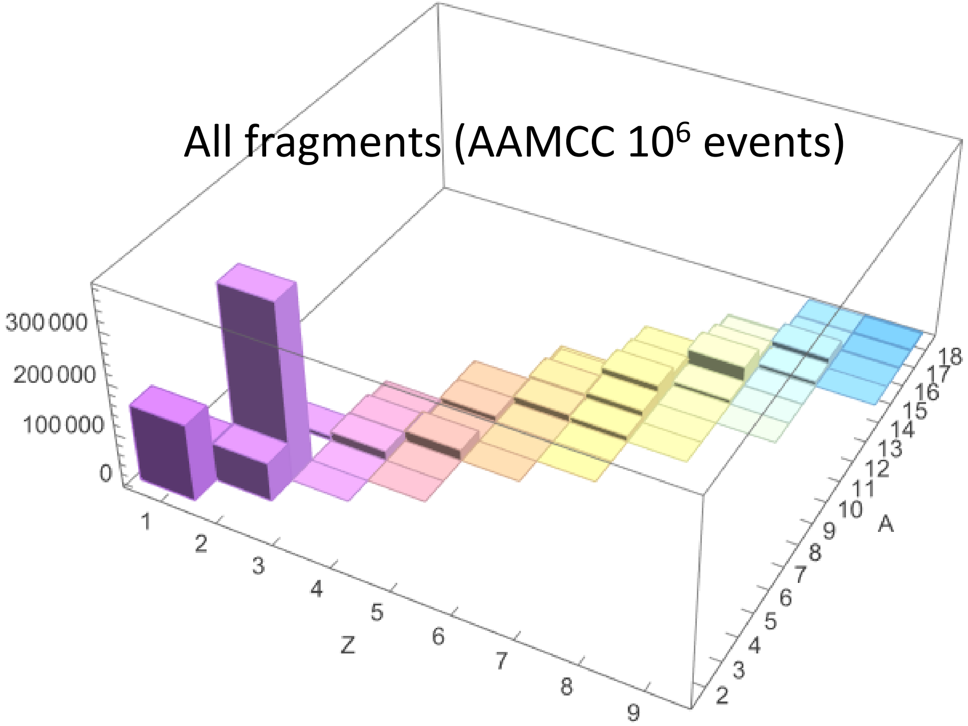
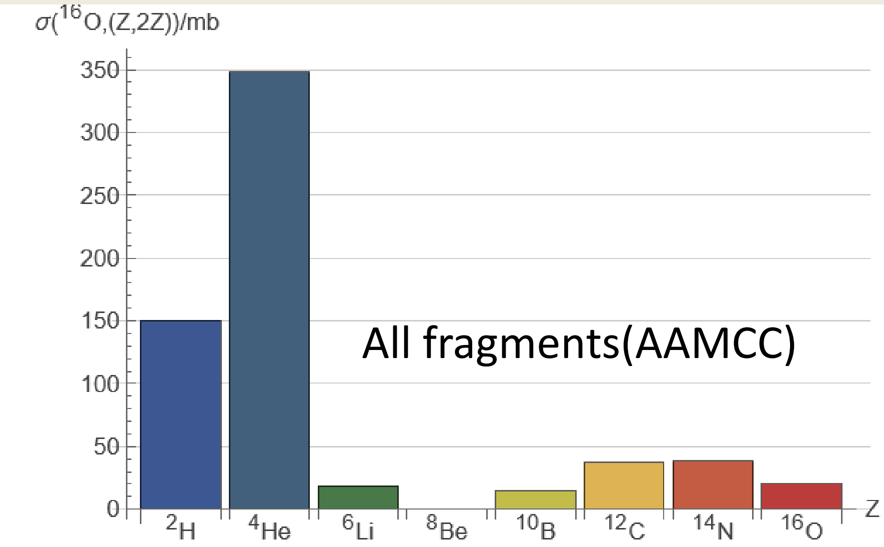
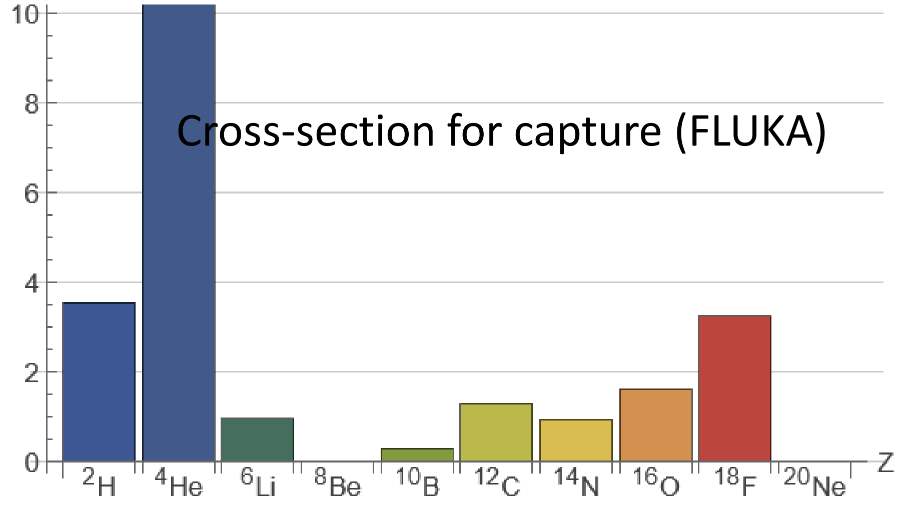
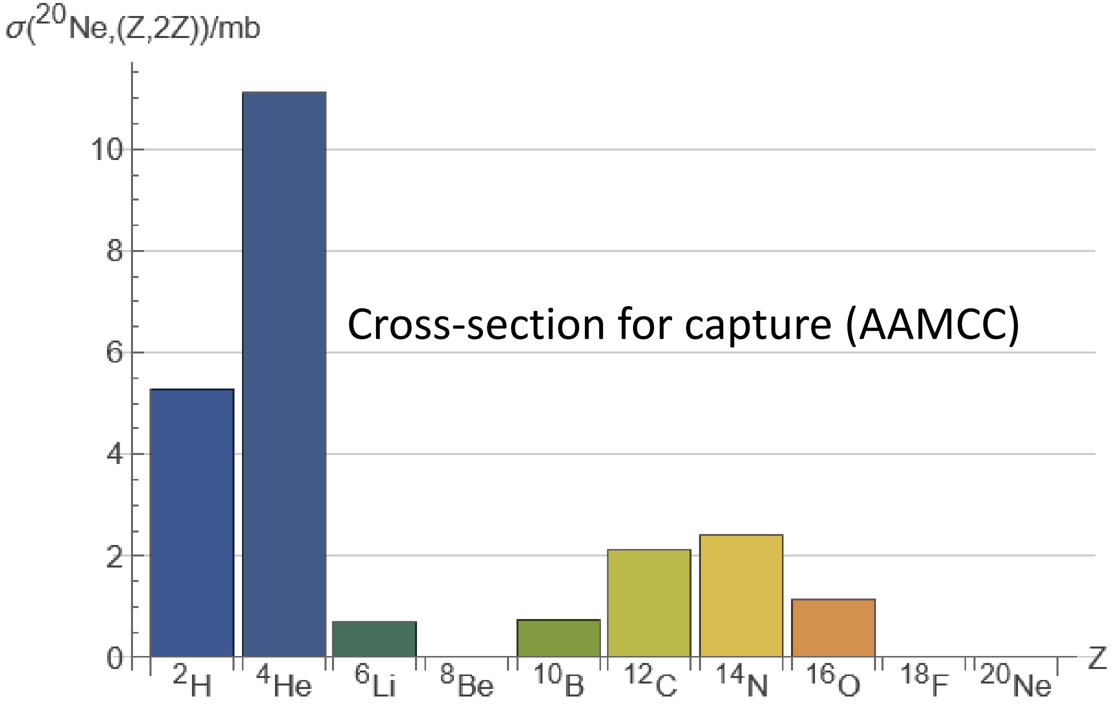
AAMCC: hadronic fragments of ^{20}Ne, Ne-Ne 5.36 TeV

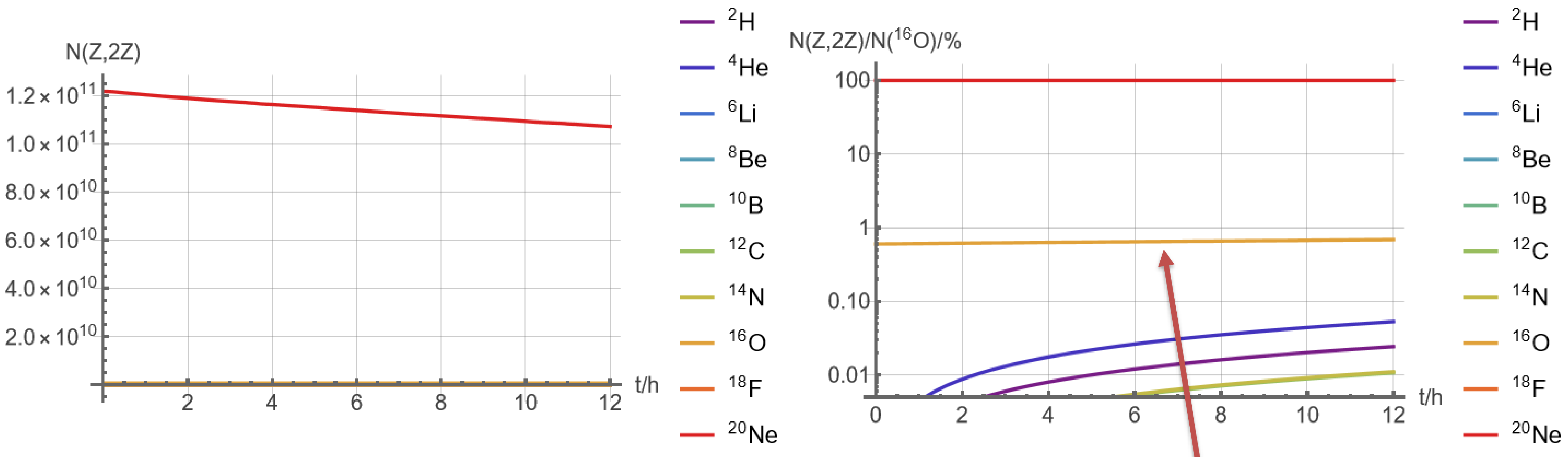








Ne-Ne FLUKA EMD, AAMCC clustering 100%, scenario NeNe_62b_fill_10813

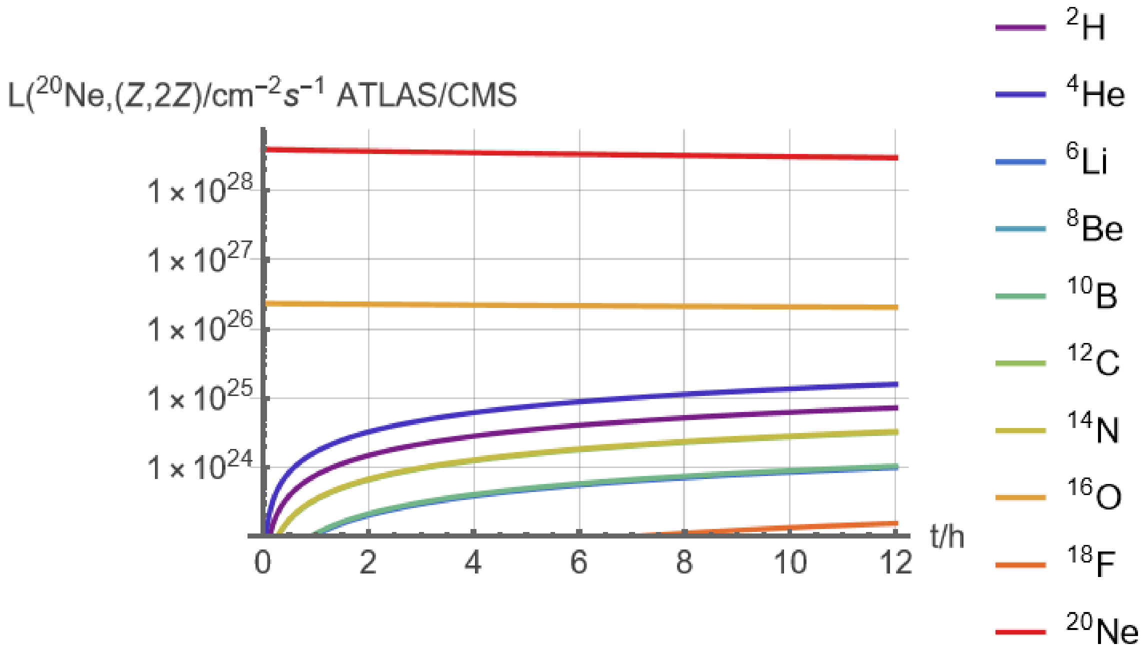


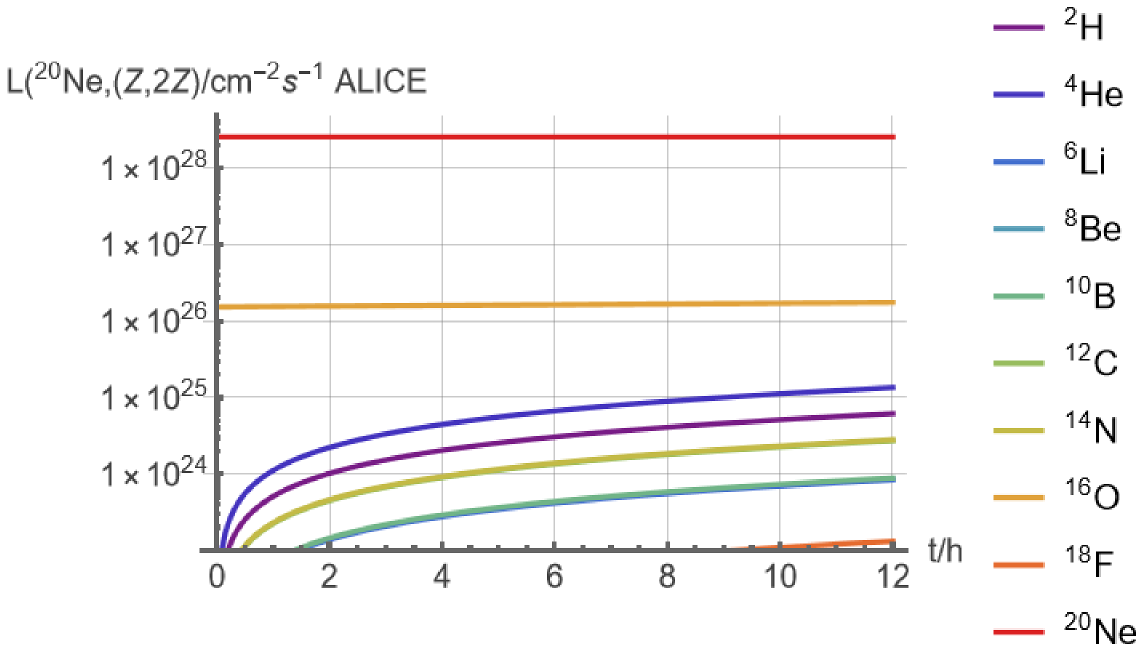
Including upper limit of O contamination of Ne beam from the ion source (Maciej Supinski)

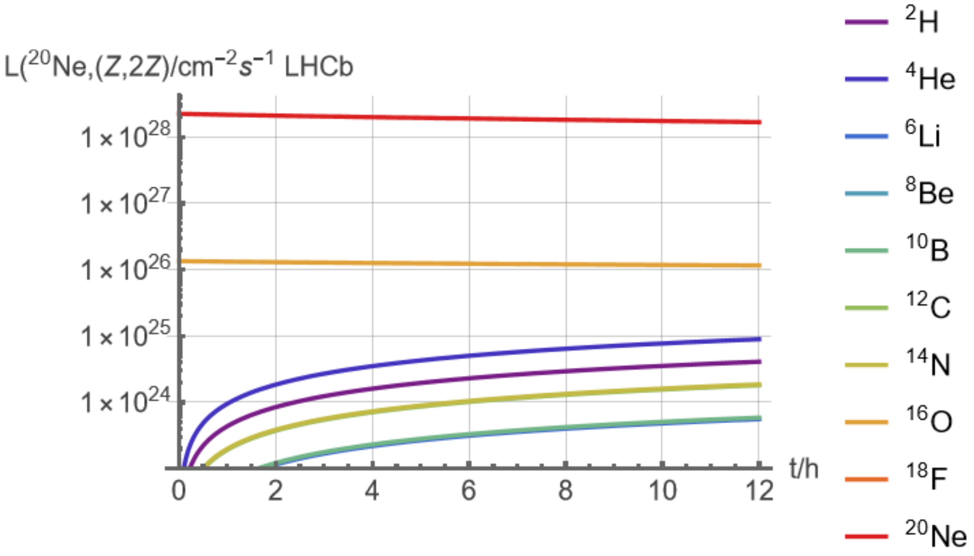
$$\left|\frac{\delta p}{p}\right| < 0.34\times 10^{-3}$$

Total beam intensities,
same expressed as fraction of ^{16}O intensity

Ne-Ne FLUKA EMD, AAMCC clustering 100%, scenario NeNe_62b_fill_10813







Hybrid collision luminosities in each direction with ^{16}O (total is twice this, except for O-O).

$$L((Z,2Z),\mathrm{O}) = L(\mathrm{O},(Z,2Z))$$

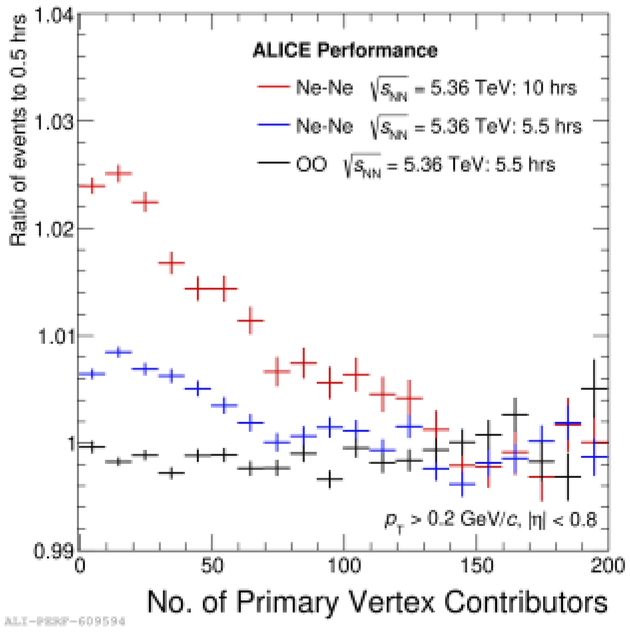
Ne-Ne FLUKA EMD, AAMCC clustering 100%, scenario NeNe_62b_fill_10813

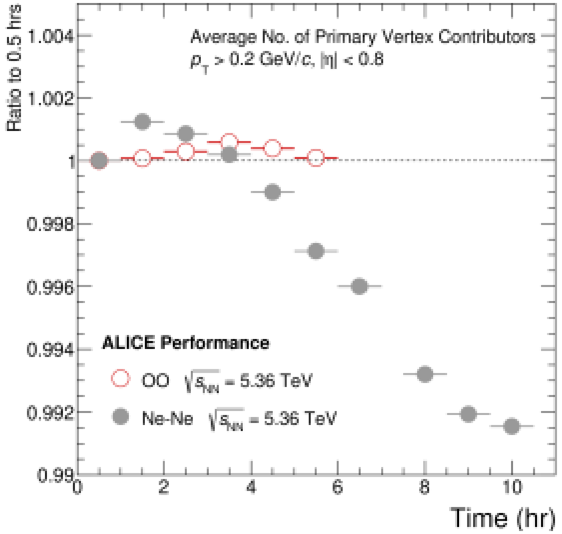
Hybrid integrated collision luminosities with ^{16}O as a **percentage** of integrated luminosity of ^{16}O - ^{16}O. Luminosities of Z-O and O-Z, although equal, are reported separately.

ALICE, fractional integrated luminosities at 10. h

	^{2}H	^{4}He	^{6}Li	^{8}Be	^{10}B	^{12}C	^{14}N	^{16}O	^{18}F	^{20}Ne
^{2}H	$2.\times10^{-6}$	4.3×10^{-6}	2.7×10^{-7}	1.1×10^{-10}	2.8×10^{-7}	8.6×10^{-7}	8.9×10^{-7}	0.00008	4.2×10^{-8}	0.012
^{4}He	4.3×10^{-6}	9.3×10^{-6}	5.8×10^{-7}	2.4×10^{-10}	6.1×10^{-7}	1.9×10^{-6}	1.9×10^{-6}	0.00017	9.2×10^{-8}	0.026
^{6}Li	2.7×10^{-7}	5.8×10^{-7}	3.6×10^{-8}	1.5×10^{-11}	3.8×10^{-8}	1.2×10^{-7}	1.2×10^{-7}	0.000011	5.7×10^{-9}	0.0016
^{8}Be	1.1×10^{-10}	2.4×10^{-10}	1.5×10^{-11}	$6.\times10^{-15}$	1.6×10^{-11}	4.8×10^{-11}	4.9×10^{-11}	4.4×10^{-9}	2.3×10^{-12}	6.7×10^{-7}
^{10}B	2.8×10^{-7}	6.1×10^{-7}	3.8×10^{-8}	1.6×10^{-11}	$4.\times10^{-8}$	1.2×10^{-7}	1.3×10^{-7}	0.000011	$6.\times10^{-9}$	0.0017
^{12}C	8.6×10^{-7}	1.9×10^{-6}	1.2×10^{-7}	4.8×10^{-11}	1.2×10^{-7}	3.8×10^{-7}	3.9×10^{-7}	0.000035	1.8×10^{-8}	0.0053
^{14}N	8.9×10^{-7}	1.9×10^{-6}	1.2×10^{-7}	4.9×10^{-11}	1.3×10^{-7}	3.9×10^{-7}	$4.\times10^{-7}$	0.000036	1.9×10^{-8}	0.0055
^{16}O	0.00008	0.00017	0.000011	4.4×10^{-9}	0.000011	0.000035	0.000036	0.0042	1.7×10^{-6}	0.64
^{18}F	4.2×10^{-8}	9.2×10^{-8}	5.7×10^{-9}	2.3×10^{-12}	$6.\times10^{-9}$	1.8×10^{-8}	1.9×10^{-8}	1.7×10^{-6}	$9.\times10^{-10}$	0.00026
^{20}Ne	0.012	0.026	0.0016	6.7×10^{-7}	0.0017	0.0053	0.0055	0.64	0.00026	100.

Comparison with experiment





Although there is no evidence of an enhancement of He–O induced low-multiplicity events as the O-O fill progresses, there is an apparent enhancement in Ne-Ne collisions.

This could be interpreted as due to ~ 2 % of ^{4}He nuclei in the ^{20}Ne beam.

This would be clearly inconsistent (factor ~ 20), with the model predictions shown in previous slides.

Would require much larger cross-section for ^{4}He fragment production *together with a drastic narrowing of their momentum distribution and shifting of its peak to the right rigidity value.*

Can this be explained by a better model of the bowling-pin structure of Ne ? One α-particle peeling off with just the right momentum shift (~ -0.1 %) ?

Conclusions and outlook

- Contrary to initial expectations, the predicted level of contamination of the oxygen and neon beams in the LHC runs with lighter isotopes is very small, according to the momentum distributions from the AAMCC, RELDIS and FLUKA event generators
- An exception is the possible initial contamination of the Ne beam with ^{16}O from the ion source.
- This appears to be incompatible with ALICE multiplicity measurements which indicate a potential contamination of about 2 % in the Ne-Ne fills

- *Thanks to all the contributors to this talk!*

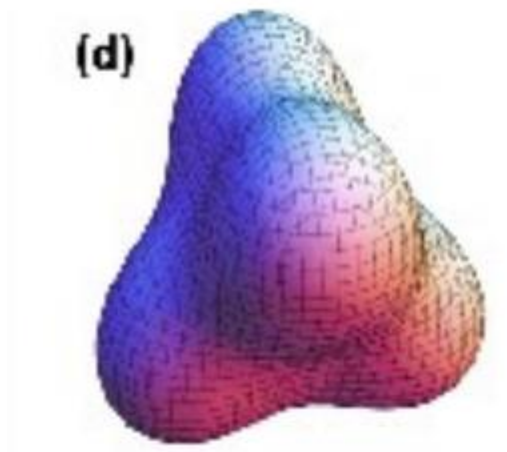
BACKUP SLIDES

Other nearby isotopes of Pb

^{208}Pb 0.	^{207}Tl 0.748344 %	^{206}Hg 1.51506 %	^{205}Au 2.30242 %	^{204}Pt 3.10919 %	^{203}Ir 3.93819 %
^{207}Pb −0.48129 %	^{206}Tl 0.260842 %	^{205}Hg 1.0214 %	^{204}Au 1.80226 %	^{203}Pt 2.60258 %	^{202}Ir 3.42478 %
^{206}Pb −0.962906 %	^{205}Tl −0.226842 %	^{204}Hg 0.527183 %	^{203}Au 1.30159 %	^{202}Pt 2.09526 %	^{201}Ir 2.91087 %
^{205}Pb −1.44383 %	^{204}Tl −0.713981 %	^{203}Hg 0.0339257 %	^{202}Au 0.801752 %	^{201}Pt 1.5891 %	^{200}Ir 2.39776 %
^{204}Pb −1.92544 %	^{203}Tl −1.20159 %	^{202}Hg −0.460123 %	^{201}Au 0.301465 %	^{200}Pt 1.08196 %	^{199}Ir 1.88405 %
^{203}Pb −2.4062 %	^{202}Tl −1.68856 %	^{201}Hg −0.953242 %	^{200}Au −0.198175 %	^{199}Pt 0.575942 %	^{198}Ir 1.37117 %

α-clustering in the nuclear structure of ^{16}O

- Nucleus can be regarded as 4 α-particles (^{4}He nuclei) arranged in a tetrahedral structure
- Enhances production of α-particles in hadronic fragmentation reactions
- Simulations have been done for three levels of clustering: 0, 30% and 100%
- The 30 % case is tentatively considered “realistic”
- See eg A. Svetlichnyi , [The 6th international co… on particle physics and astrophysics (29 Novemb… 2 December 2022)]



X.B. Wang et al. PLB 790 (2019) 498–501

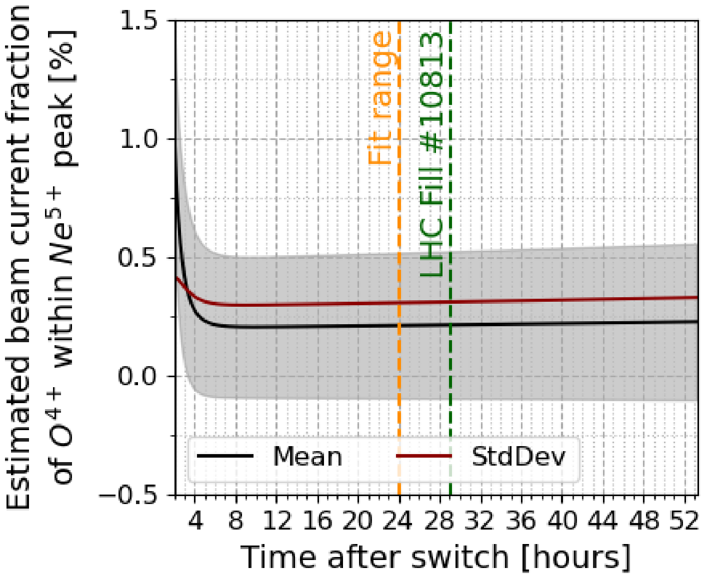
Clustering in Oxygen Nuclei and Spectator Fragments in ^{16}O–^{16}O Collisions at the LHC #9

Aleksandr Svetlichnyi (Moscow, ITEP and Moscow, INR), Savva Savenkov (Moscow, ITEP and Moscow, INR), Roman Nepeivoda (Moscow, ITEP), Igor Pshenichnov (Moscow, ITEP and Moscow, INR) (Apr 4, 2023)

Published in: *MDPI Physics* 5 (2023) 2, 381-390

https://doi.org/10.3390/physics5020027

Initial contamination of beam with 16O from ion source (Maciej Slupinski)



To sum up, when the LHC was filled, the O4+ contamination was between 0 and 0.6% (which is the uncertainty range of our instrumentation).

I take a pessimistic 0.6% of 16O in both LHC beams in the following.

References on RELDIS and AAMCC models

Nuclear multifragmentation induced by electromagnetic fields of ultrarelativistic heavy ions, I.A. PshenichnovI.N. MishustinJ.P. Bondorf, A.S. Botvina A.S. Ilinov, *Phys.Rev.C* 57 (1998) 1920-1926

+ many others

- Clustering in Oxygen Nuclei and Spectator Fragments in ^{16}O–^{16}O Collisions at the LHC, A. Svetlichnyi, S. Savenkov, R. Nepeivoda, I. Pshenichnov, MDPI Physics 5 (2023) 2, 381-390

+ others

Hadronic cross sections from AAMC, ^{20}Ne-^{20}Ne at 5.36 TeV

- From : <aleksandr.svetlichnyy@phystech.edu> Sent:Thursday,5 June 2025 21:59 Subject:Re:Transmutation of O beam and Ne beam Attachments:charge_0.9.png
  …
  Ekaterina tuned the AAMCC model to achieve reasonable agreement with the data.
- The main issue was the lack of high-quality data on relativistic ^{20}Ne projectile fragmentation. We therefore compared the AAMCC to the ^{22}Ne+emulsion data. The comparison is *on following slide*.
  Please note that the underestimation for Z=9 and 10 may be related to the EMD in the nuclear emulsion. As with oxygen, overestimation of He production can be seen. The clustered state of ^{22}Ne is represented by a clustered 20Ne plus two valence neutrons.
- Next, I prepared the production of the ^{20}Ne-^{20}Ne collision at the same energy as OO. Two types of nuclear density parameterisation were employed:deformed ^{20}Ne and clustered ^{20}Ne.Both were tuned to describe the nuclear density profile data for ^{20}Ne.
- These are new results which have not yet been reported. Ekaterina is currently preparing a report for the conference,after which we will prepare a paper on Ne fragmentation. If you need to cite something,please cite the same papers as for oxygen.
- …