Exposure due to activated air from accelerator operation: Comparison of internal and external exposure exemplified at recent air activation studies for selected facilities in the CERN PS accelerator complex

R. Froeschl (CERN)

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Motivation

Generic comparison for the most relevant radionuclides

Selected facilities in the CERN PS accelerator complex

Constraints on operation due to committed effective dose due to inhalation

Motivation

- Operation of high energy particle accelerators leads to activation of surrounding air
- Exposure of people
  - Inside the facility: Personnel during interventions (focus of the presentation)
  - Outside of the facility: Personnel and members of the public due to release
- Radionuclide concentrations depend also on the characteristics of the ventilation system
- Different exposure pathways:
  - External
  - Internal (mainly inhalation for intervening personnel)

Exposure of Personnel during Interventions

- External exposure due to γ-radiation well monitored for personnel during interventions
- Internal exposure
  - Not directly monitored
  - Design constraint on committed effective dose due to inhalation:
    $\leq 1\,\mu$Sv for 1 hour access
- Goal is to assess the ratio of internal and external exposure

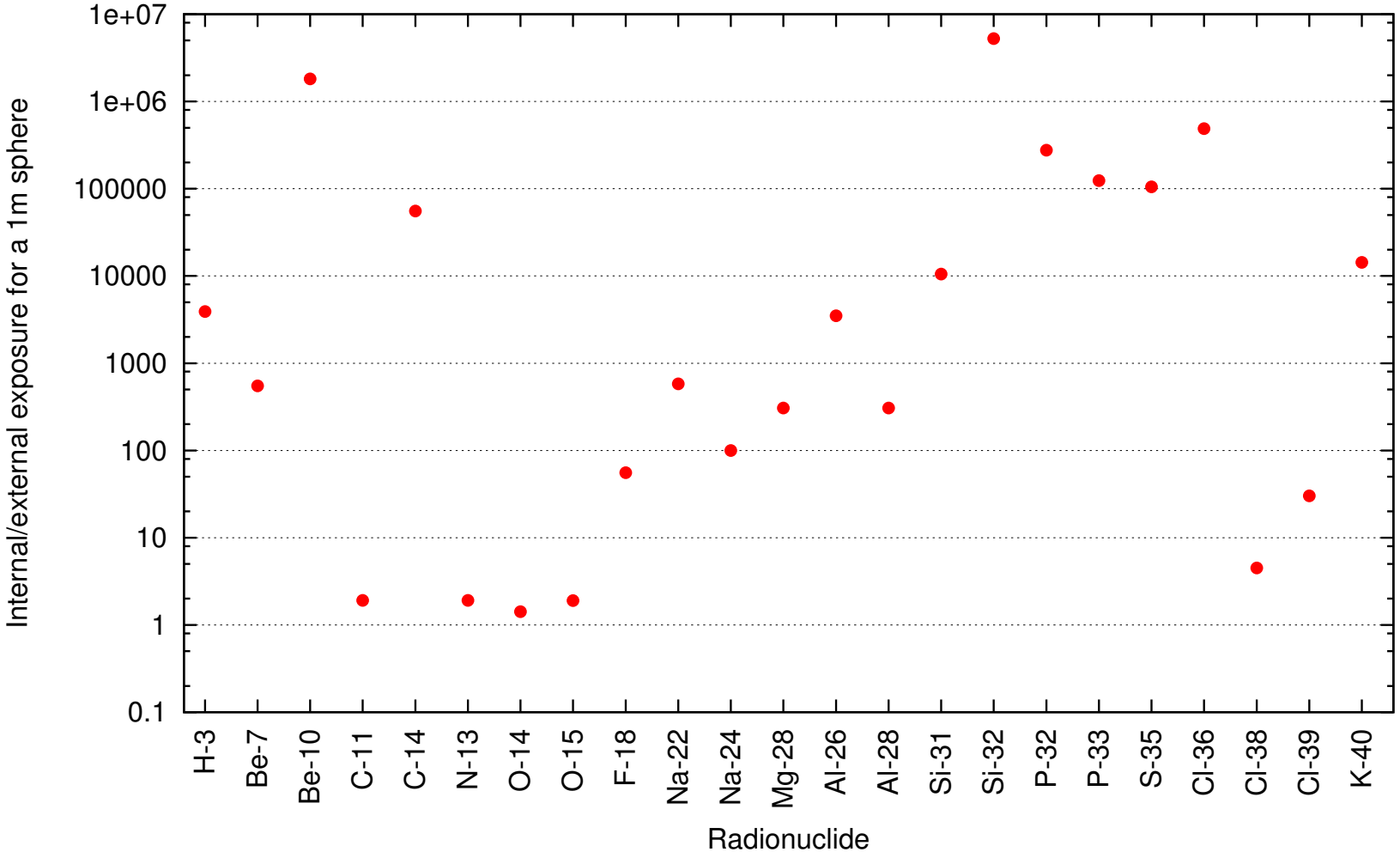
Generic comparison for most relevant radionuclides

- Radionuclides that are produced directly on C, O, N, Ar
- Internal exposure
  - Breathing rate of $1.2\,\mathrm{m}^3/\mathrm{h}$ from ICRP 66
  - Conversion coefficients to committed effective dose from Swiss legislation (slightly different from ICRP 72)
- External exposure
  - Ambient dose equivalent at 1 meter distance
  - Point kernel integration
    - Sphere of radius 1 meter for generic comparison
    - More realistic geometries for facilities examples
- Ratio of internal and external exposure for 1 hour long access

Comparison

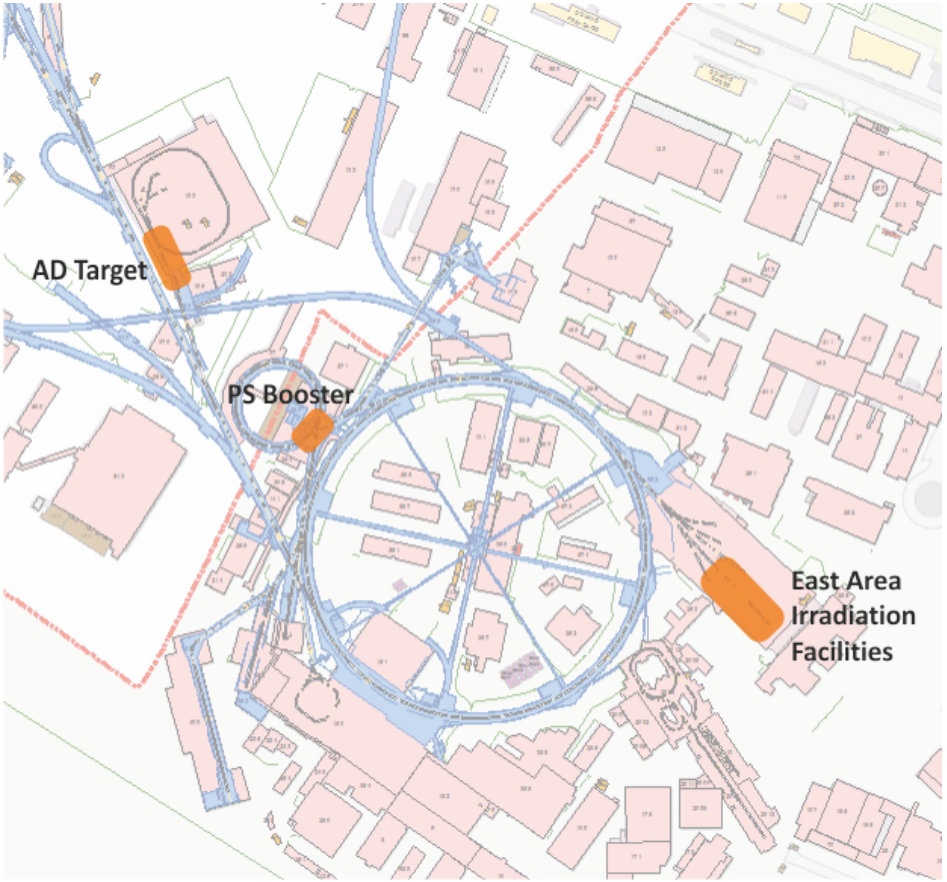
Nuclide	Half-life	Exposure coefficient $h_{10,r}$ [pSv/(h · Bq)]	Inhalation coefficient $e_{inh,r}$ [Sv/Bq]	Effective dose for 1 hour access [Sv/(Bq/m^3)] External	Internal	Ratio Internal/External H_{int}/H_{ext}
H-3	12.33y	<0.001	4.1e-11	<1.257e-14	4.92e-11	>3915
Be-7	53.22d	0.008	4.6e-11	1.005e-13	5.519e-11	549.1
Be-10	1.6e+06y	<0.001	1.9e-08	<1.257e-14	2.28e-08	>1.814e+06
C-11	20.37m	0.16	3.2e-12	8.572e-13	1.637e-12	1.91
C-14	5700y	<0.001	5.8e-10	<1.257e-14	6.96e-10	>5.539e+04
N-13	9.967m	0.16	3.2e-12	4.743e-13	9.059e-13	1.91
O-14	1.177m	0.45	3.2e-12	7.690e-14	1.093e-13	1.42
O-15	2.041m	0.161	3.2e-12	9.911e-14	1.881e-13	1.898
F-18	1.829h	0.16	9.3e-11	1.674e-12	9.289e-11	55.51
Na-22	2.603y	0.33	2e-09	4.147e-12	2.4e-09	578.7
Na-24	14.96h	0.506	5.3e-10	6.214e-12	6.215e-10	100
Mg-28	20.9h	0.529	1.7e-09	6.539e-12	2.007e-09	306.9
Al-26	7.17e+05y	0.382	1.4e-08	4.8e-12	1.68e-08	3500
Al-28	2.241m	0.529	1.7e-09	3.58e-13	1.099e-10	306.9
Si-31	2.62h	<0.001	1.1e-10	<1.104e-14	1.16e-10	>1.05e+04
Si-32	132y	<0.001	5.5e-08	<1.257e-14	6.6e-08	>5.252e+06
P-30	2.498m	0.371	-	2.801e-13	-	-
P-32	14.27d	<0.001	2.9e-09	<1.255e-14	3.476e-09	>2.769e+05
P-33	25.38d	<0.001	1.3e-09	<1.256e-14	1.559e-09	>1.241e+05
S-35	87.32d	<0.001	1.1e-09	<1.256e-14	1.32e-09	>1.05e+05
Cl-36	3.01e+05y	<0.001	5.1e-09	<1.257e-14	6.12e-09	>4.87e+05
Cl-38	37.2m	1.551	7.3e-11	1.174e-11	5.274e-11	4.495
Cl-39	55.6m	0.241	7.6e-11	2.132e-12	6.422e-11	30.11
Ar-41	1.827h	0.188	-	1.966e-12	-	-
K-38	7.61m	0.48	-	1.103e-12	-	-
K-40	1.265e+09y	0.022	3e-09	2.765e-13	3.6e-09	1.432e+04

Comparison


Internal/external exposure for a 1m sphere
1e+07
1e+06
100000
10000
1000
100
10
1
0.1
H-3
Be-7
Be-10
C-11
C-14
N-13
O-14
O-15
F-18
Na-22
Na-24
Mg-28
Al-26
Al-28
Si-31
Si-32
P-32
P-33
S-35
Cl-36
Cl-38
Cl-39
K-40
Radionuclide

Selected facilities in the CERN PS accelerator complex

- PS Booster
  - Protons from 50 MeV to 1.4 GeV
  - Injection/ejection losses and beam dump
- AD target area
  - 26 GeV/c proton beam
  - Thin target and beam dump
- EAIF
  - 24 GeV/c proton beam
  - Very thin samples and then thick target for mixed fields

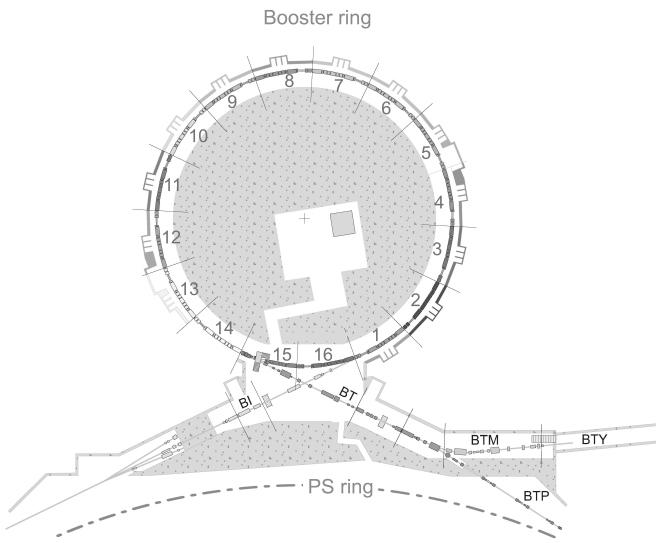


Methodology and Constraints

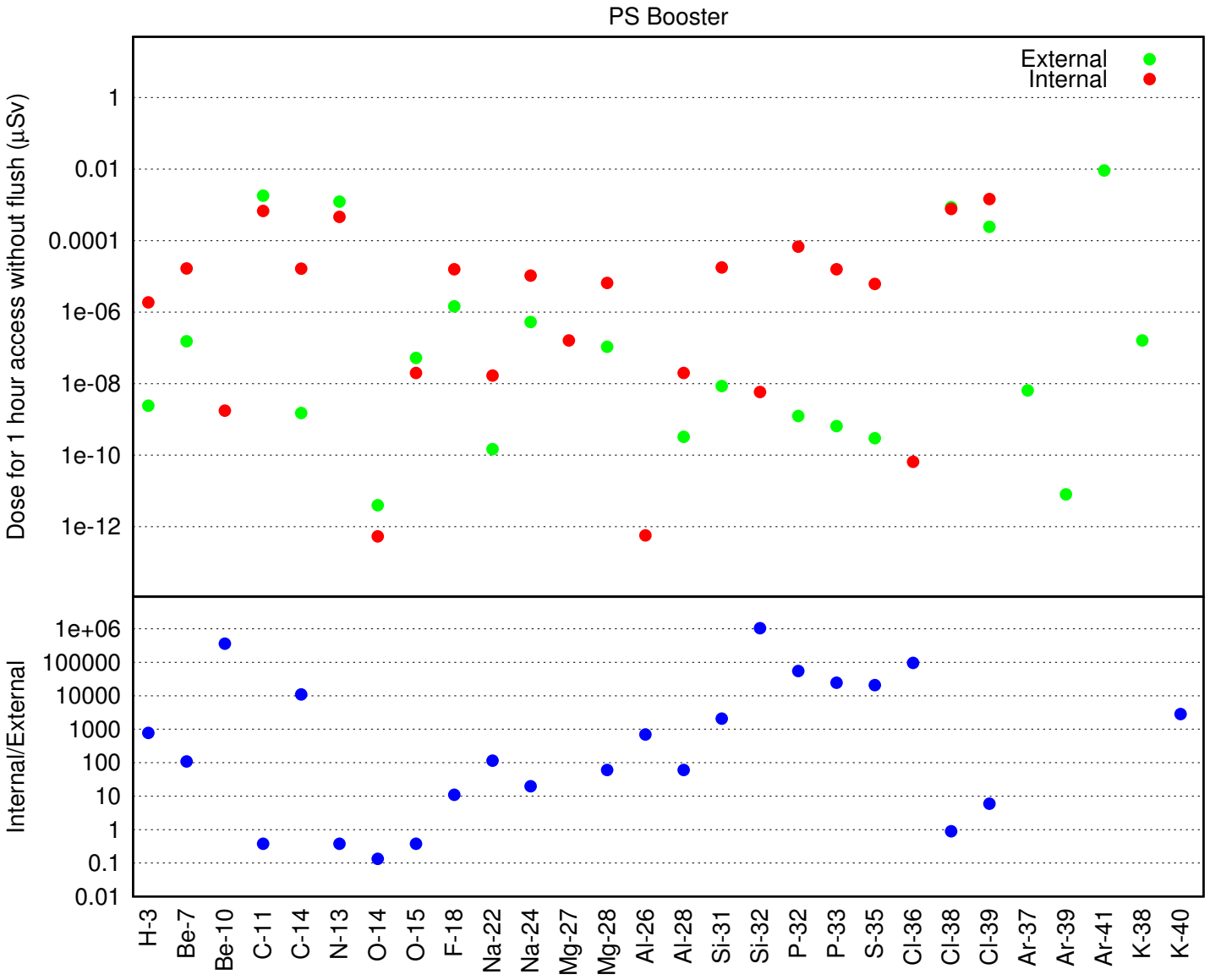
- Radionuclide concentrations and resulting exposure
  - Track-length spectra scored in air volumes in FLUKA simulations
  - Radionuclide production yields by weighting of spectra with dedicated air activation cross–sections
    - evaluated data set for n, p, π^+ and π^-
    - γ with JEREMY code using data from TENDL 2010
  - Confinement characteristics (dynamic/static) and time evolution to obtain radionuclide concentrations
  - External effective dose and the internal committed effective dose by integrating over the 1 hour exposure time after a cool-down period of 30 minutes without flush before access
  - No filtering of the recirculated air has been taken into account
- Design constraint
  - Committed effective dose due to inhalation:
    $\leq 1\,\mu$Sv for 1 hour access

PS Booster

- Ring accelerator in the PS complex
- Protons from 50 MeV to 1.4 GeV
- Injection/ejection losses and beam dump
- Air exchange rate: $2.1\,\mathrm{h}^{-1}$
- Dimensions: 20 m x 10 m x 5 m

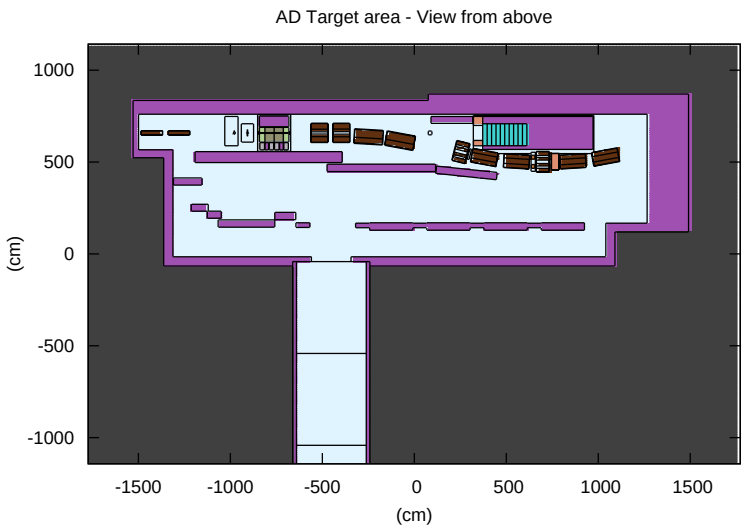


PS Booster

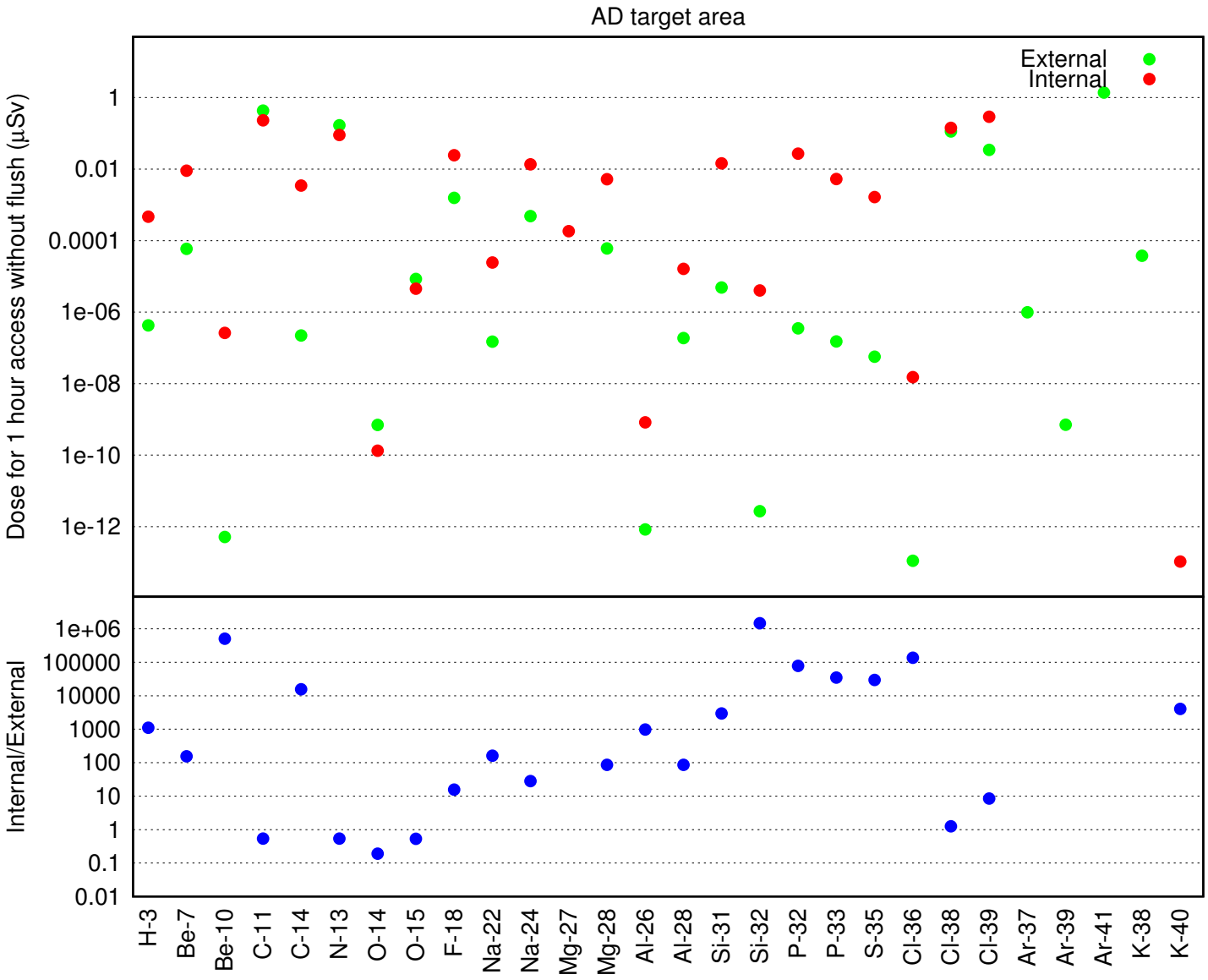

PS Booster
External
Internal
Dose for 1 hour access without flush (µSv)
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
Internal/External
1e+06
100000
10000
1000
100
10
1
0.1
0.01
H-3
Be-7
Be-10
C-11
C-14
N-13
O-14
O-15
F-18
Na-22
Na-24
Mg-27
Mg-28
Al-26
Al-28
Si-31
Si-32
P-32
P-33
S-35
Cl-36
Cl-38
Cl-39
Ar-37
Ar-39
Ar-41
K-38
K-40

AD target area

- Production of anti-protons for the Anti-proton Decelerator
- 26 GeV/c proton beam
- Thin target and beam dump
- Air exchange rate: $1.7\,\mathrm{h}^{-1}$
- Dimensions: 25 m x 7 m x 3 m

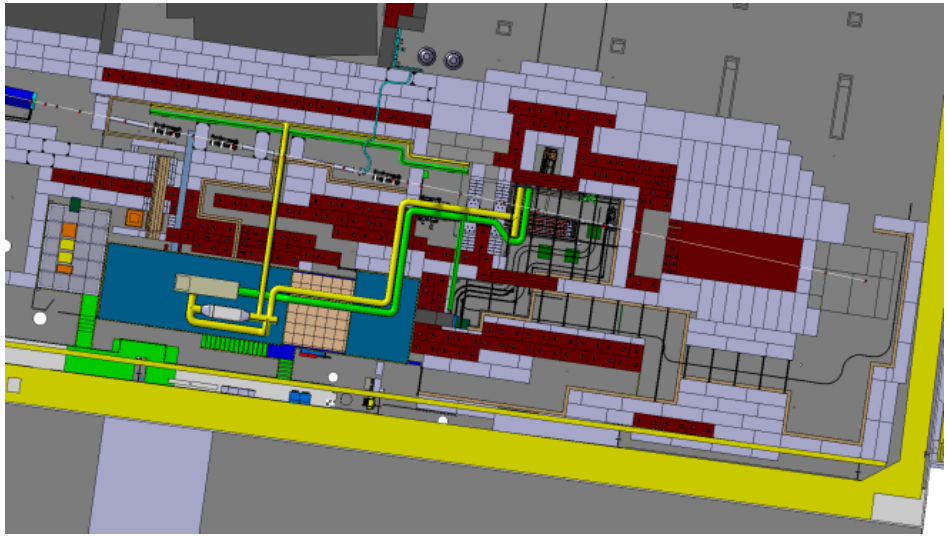


AD target area

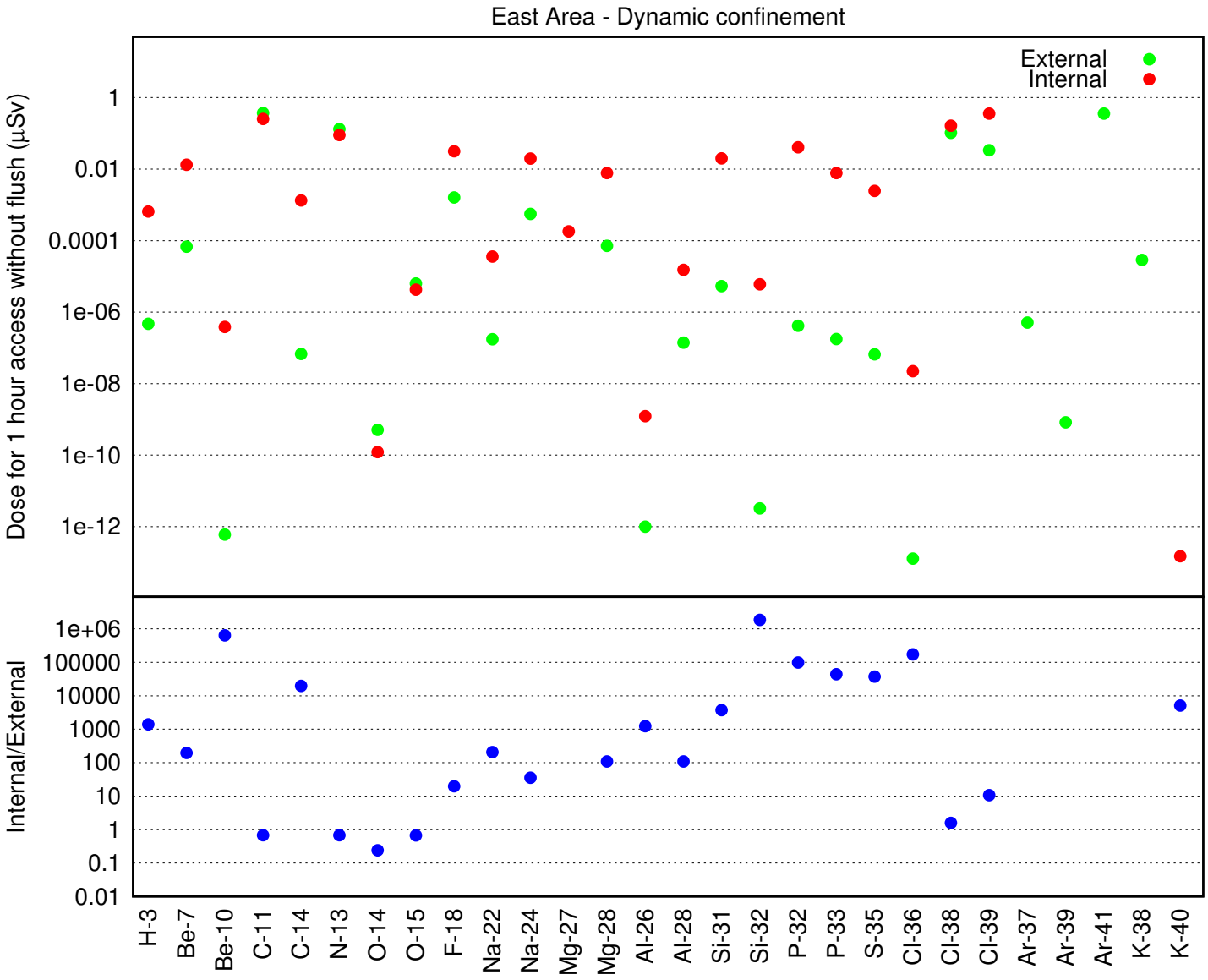


East Area Irradiation Facilities (EAIF)

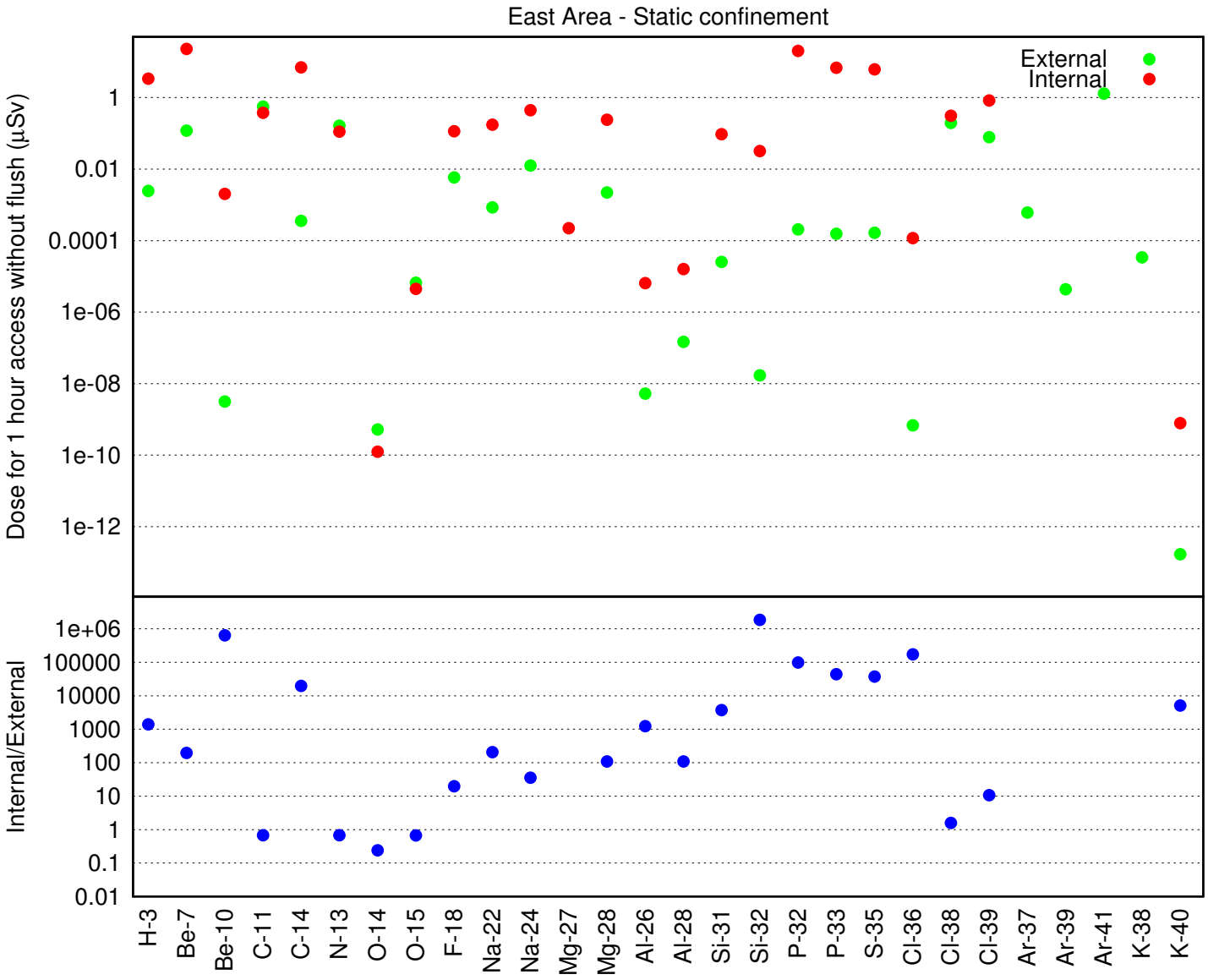
- Irradiation Facilities
- 24 GeV/c proton beam
- Maximum design average beam intensity 6.6E10 p/s
- Very thin samples and then thick target for mixed fields
- Long beam trajectory in air
- Air exchange rate:
  - $1\,\mathrm{h}^{-1}$ as design goal
  - different values realized
- Dimensions: 8 m x 5 m x 3.1 m



EAIF


East Area - Dynamic confinement
External
Internal
Dose for 1 hour access without flush (µSv)
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
Internal/External
1e+06
100000
10000
1000
100
10
1
0.1
0.01
H-3
Be-7
Be-10
C-11
C-14
N-13
O-14
O-15
F-18
Na-22
Na-24
Mg-27
Mg-28
Al-26
Al-28
Si-31
Si-32
P-32
P-33
S-35
Cl-36
Cl-38
Cl-39
Ar-37
Ar-39
Ar-41
K-38
K-40

EAIF


East Area - Static confinement
External
Internal
Dose for 1 hour access without flush (µSv)
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
Internal/External
1e+06
100000
10000
1000
100
10
1
0.1
0.01
H-3
Be-7
Be-10
C-11
C-14
N-13
O-14
O-15
F-18
Na-22
Na-24
Mg-27
Mg-28
Al-26
Al-28
Si-31
Si-32
P-32
P-33
S-35
Cl-36
Cl-38
Cl-39
Ar-37
Ar-39
Ar-41
K-38
K-40

Facility examples summary

- External effective dose and the internal committed effective dose for 1 hour exposure after a cool-down period of 30 minutes without flush before access

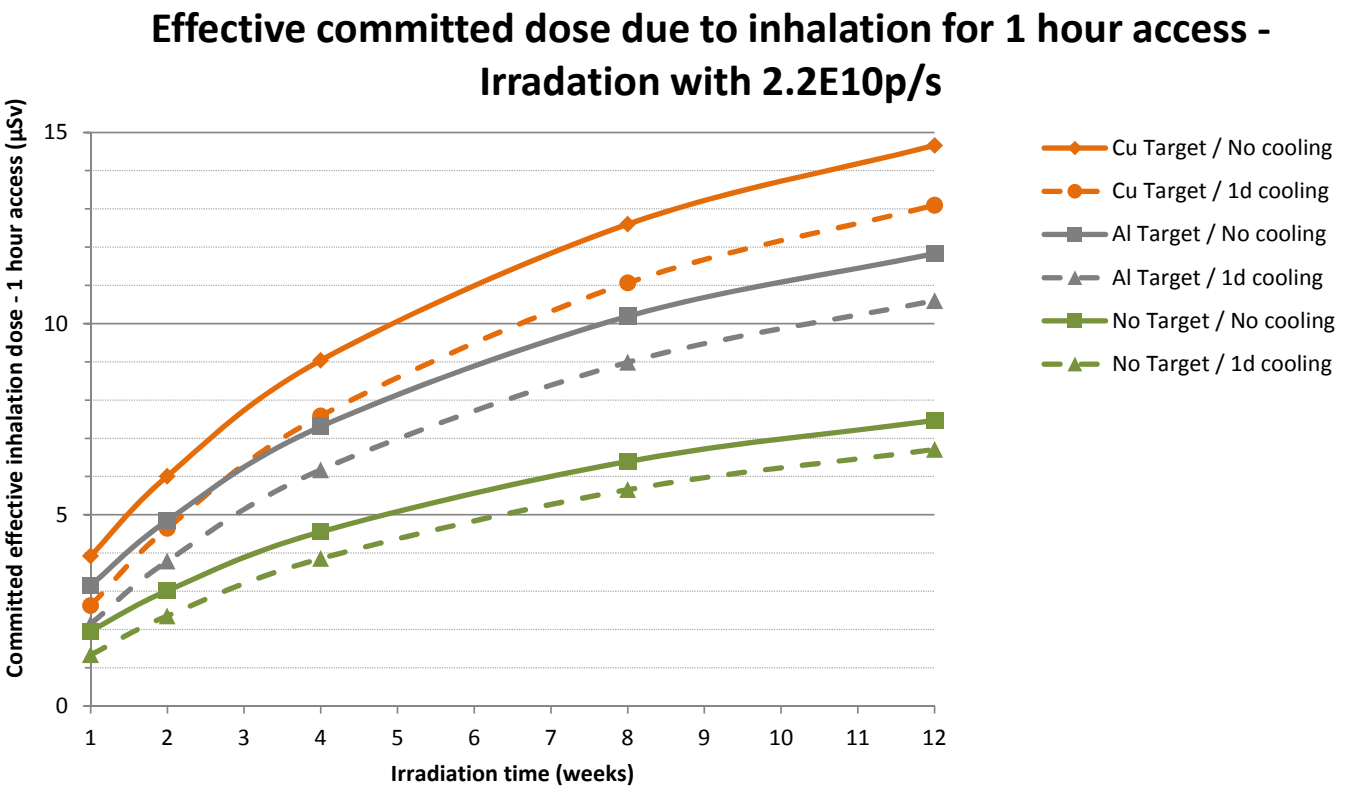
Scenario	Confinement type	Air exchange rate [h^{-1}]	Effective dose for 1 hour access# [μSv] External	Internal	Ratio Internal/External H_{int}/H_{ext}
PSB tunnel Injection Region	dynamic	2.1	0.01327	0.003532	0.2661
AD Target Area	dynamic	1.7	2.128	0.8604	0.4044
East Area Irradiation Facilities	dynamic	1	1.003	1.006	1.004
East Area Irradiation Facilities	static	-	2.441	69.29	28.39

hypothetical values for dynamic confinement: flush will always be performed before access

East Area Irradiation Facilities

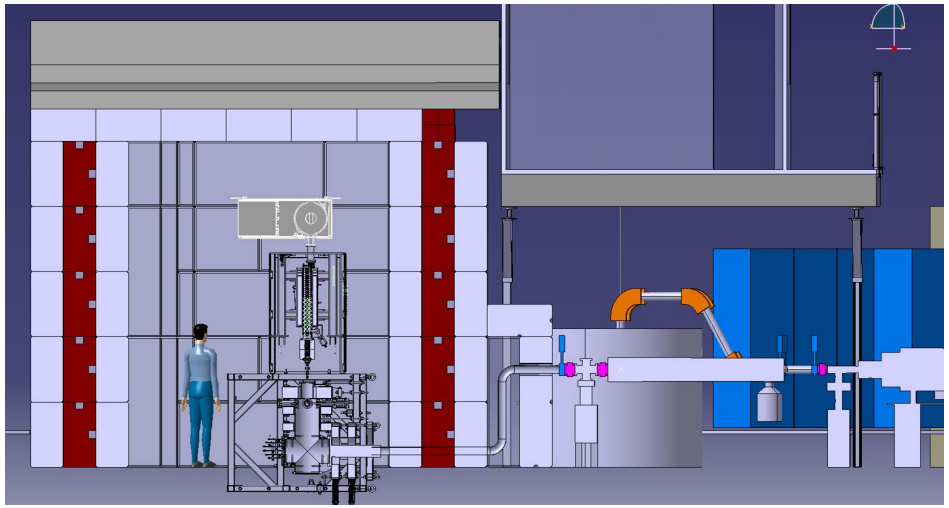
- Ventilation system had not been operational during start-up phase
  - No flush before access possible
  - No extraction during beam operations
    - Different build-up of the radionuclides (effective half-life changed)
- Reduction of average beam intensity or restriction on target choice as a function of the operation time to respect design constraint on committed effective dose due to inhalation

East Area Irradiation Facilities



GBar Electron LINAC

- Electron LINAC for positron production via Tungsten target
- Proposed electron energies
  - 20 MeV
  - 9 MeV
- Average beam current 200 μA
- Enclosed in small shielding bunker
- Requirements for ventilation system among the most critical points for the project



GBar Electron LINAC

- Internal committed effective dose for 1 hour exposure without cool-down time and without flush before access

Electron Energy MeV	Confinement type	Committed Effective dose due to inhalation for 1 hour access# μSv	Main contributors
20	static	60.4	C-14 (33.6 μSv), N-13 (26 μSv)
20	dynamic	21.4	N-13 (21 μSv), Cl-39 (0.22 μSv), O-15 (0.15 μSv)
9	static	0.036	C-14 (0.036 μSv)
9	dynamic	7.6e-06	C-14 (7.6e-06 μSv)

hypothetical values for dynamic confinement: flush will always be performed before access

Conclusions

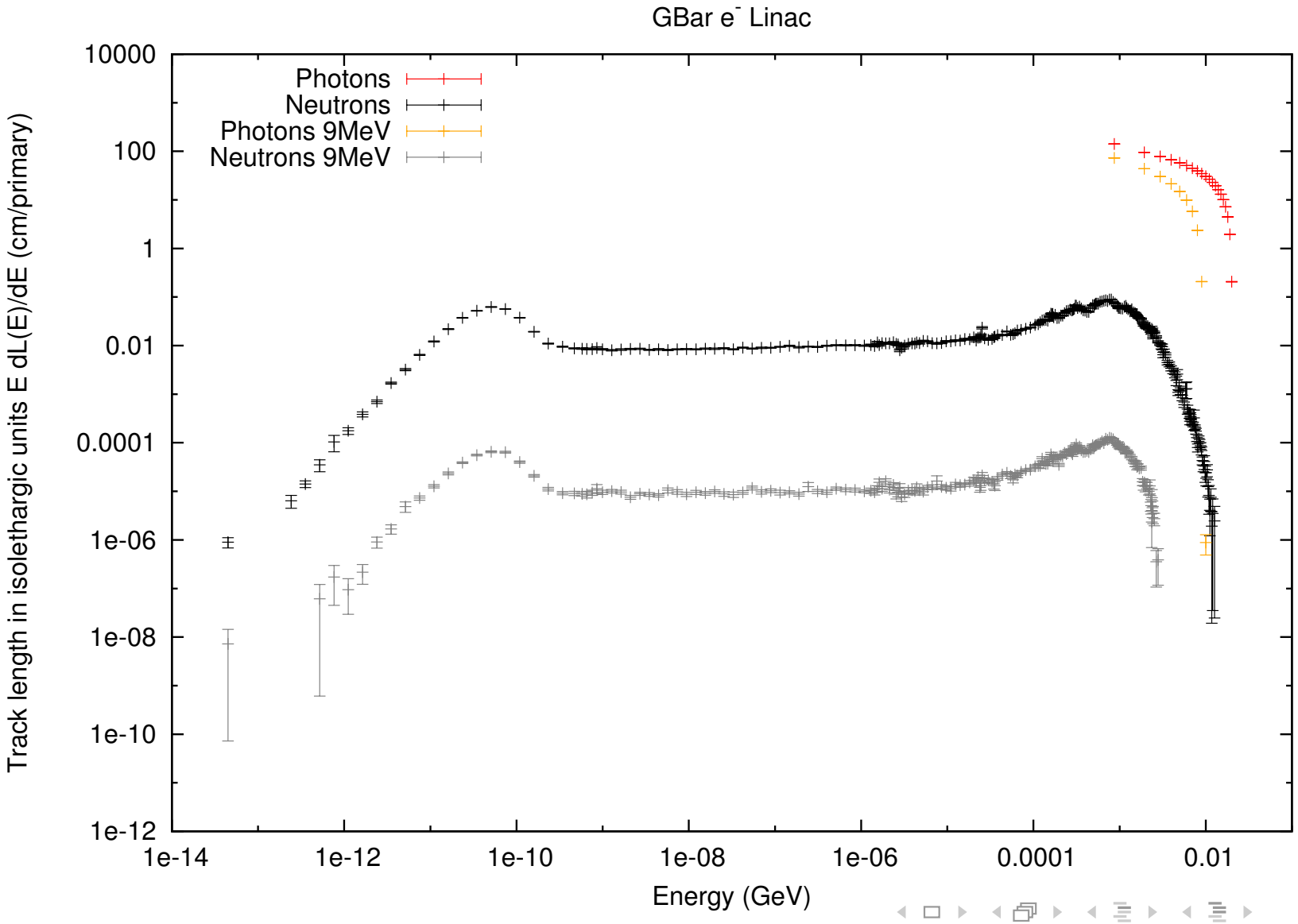
- Internal exposure not directly monitored
- Large variation of ratio of internal/external exposure for 1 m sphere, e.g.
  - C-11, N-13, O-14, O-15: 1.5-2.0
  - P-isotopes: higher than 1e5
- Confinement types
  - **Dynamic** with air exchange rate $O(1\,h^{-1})$: internal exposure not larger than external exposure
  - **Static**: internal exposure higher than external exposure from activated air, i.e. larger non-monitored fraction of the exposure
- Design constraint on committed effective dose due to inhalation can lead to
  - operational constraints
  - significant requirements on ventilation system

Thank you for your attention!

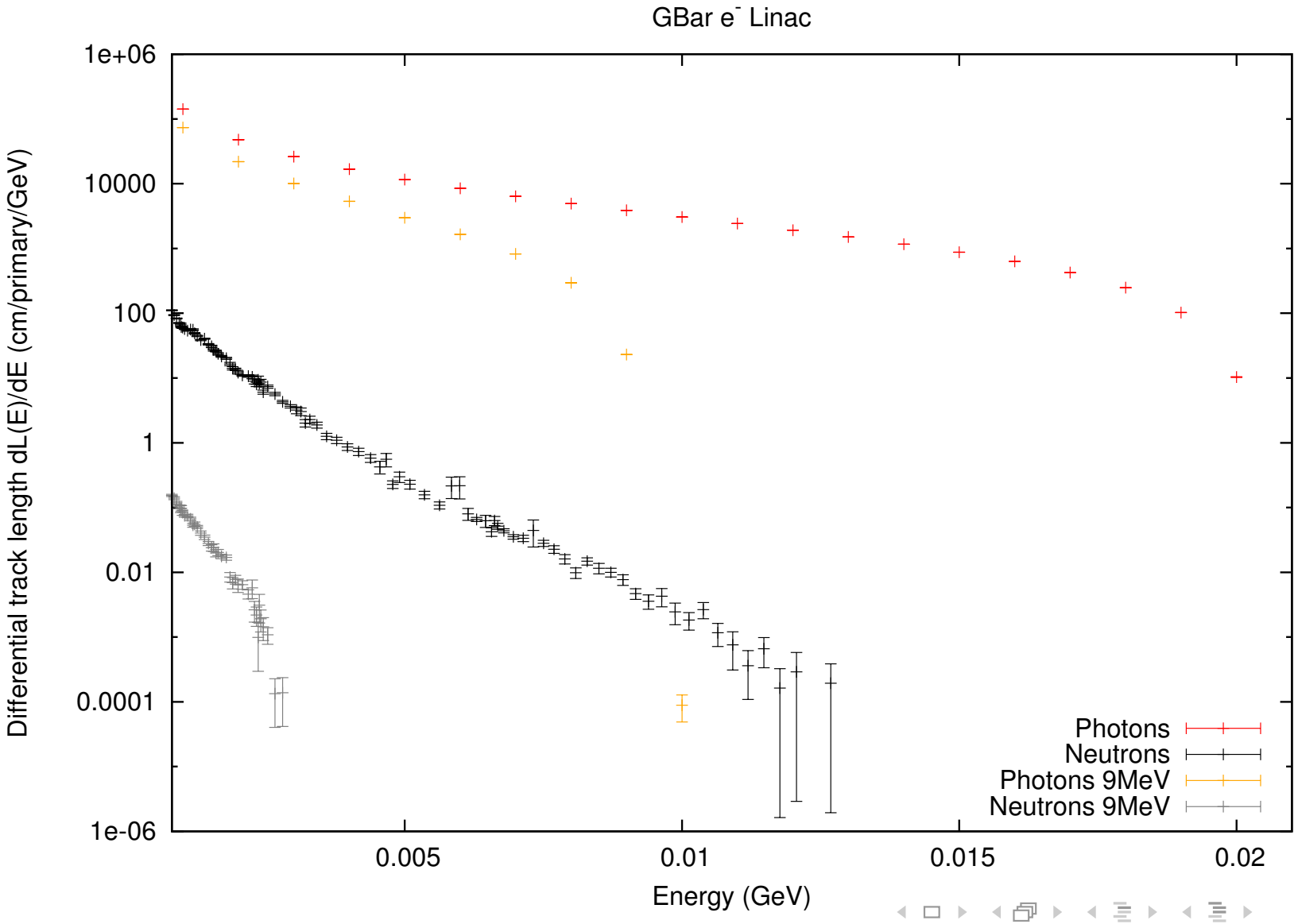
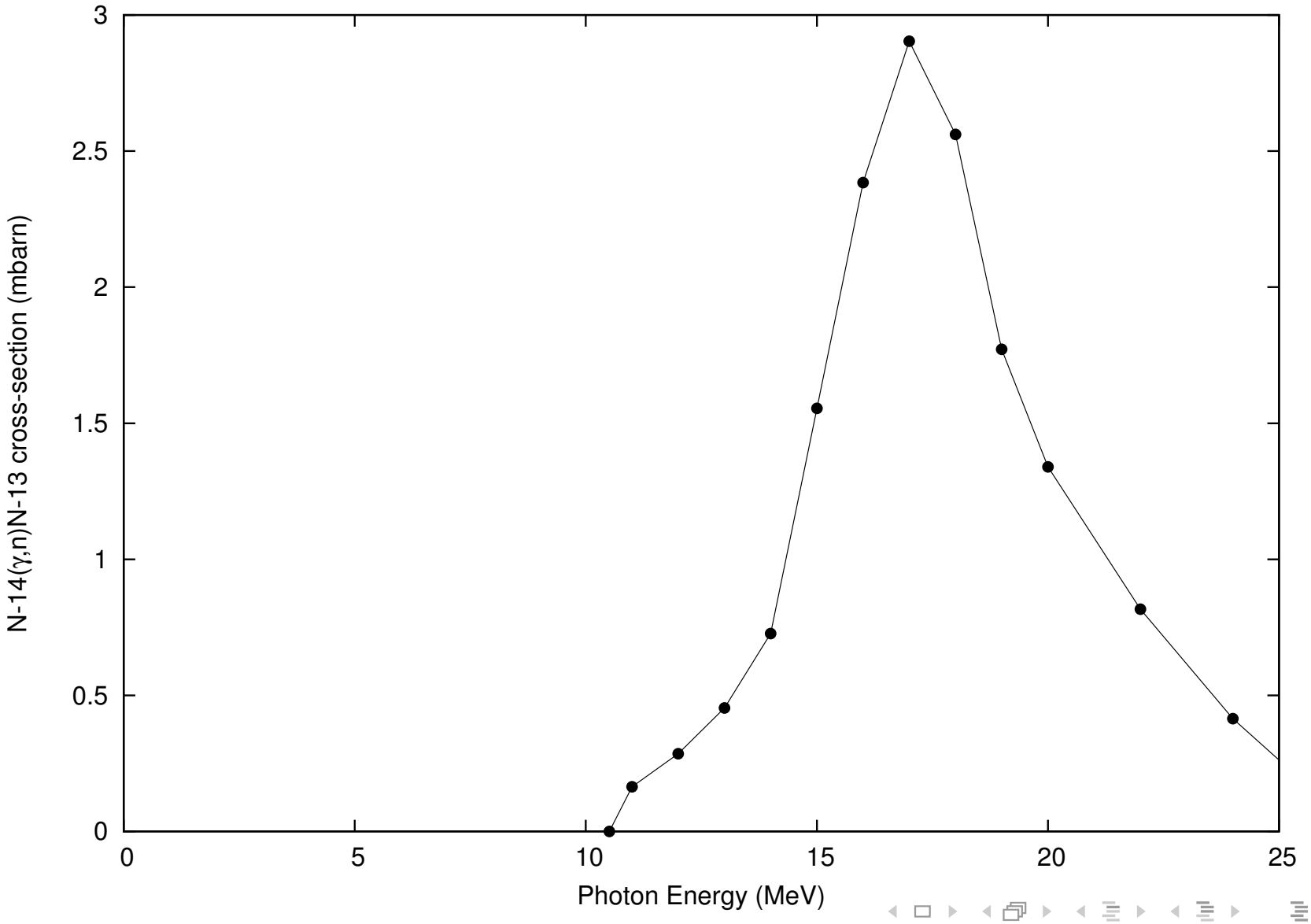
Backup

Backup

GBar - Spectra in Air



GBar - Spectra in Air



GBar - N-14(γ,n)N-13