FRIB Estimated Rates

v 4.0

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This document describes the assumptions used to generate version 4.0 of the estimated FRIB fast, stopped, and reaccelerated beam rates.

Primary beams: PAC4

The current list of FRIB primary beams and intensities is available at:
https://frib.msu.edu/users/beams

The online rates assume that the beam powers listed in Table 1 will be available during the PAC4 period of validity. The primary beams used are listed in Table 1.

Table 1. *List of primary beams, maximum BDS energies, and beam powers assumed in the ARIS beam-rate calculations.*

Beam	A	Z	Maximum Energy [MeV/u]	Intensity [pnA]	Beam Power [kW]
16O	16	8	165	9470	25
18O	18	8	165	8418	25
20Ne	20	10	175	7143	25
22Ne	22	10	175	6494	25
28Si	28	14	255	3501	25
30Si	30	14	255	3268	25
36Ar	36	18	255	2723	25
40Ar	40	18	255	2451	25
40Ca	40	20	255	2451	25
48Ca	48	20	240	2170	25
58Ni	58	28	250	2414	35
64Ni	64	28	235	2327	35
64Zn	64	30	250	2188	35
70Zn	70	30	230	2174	35
70Ge	70	32	246	1742	30
76Ge	76	32	228	1558	27

Beam	A	Z	Maximum Energy [MeV/u]	Intensity [pnA]	Beam Power [kW]
82Se	82	34	227	1880	35
78Kr	78	36	247	1817	35
86Kr	86	36	228	1785	35
92Mo	92	42	238	457	10
124Xe	124	54	240	840	25
144Sm	144	62	222	1095	35
195Pt	195	78	190	405	15
198Pt	198	78	188	403	15
208Pb	208	82	188	1023	40
209Bi	209	83	188	891	35
232Th	232	90	181	357	15
238U	238	92	177	1068	45
238U	238	92	193	435	20

Transmission and yield calculations

Transmission efficiency calculations were performed with LISE^{++} v.18.4 [1,2] using the "Distribution" analytical method. The calculation settings are given in Table 2. An approximate optimum production target thickness was used to speed up the calculations.

Table 2. *Fragment-separator characteristics, physical models, and assumptions used in LISE^{++} transmission calculations:*

Object/characteristic	Parameter	Value / Model
Target	Material	C
	Thickness	40% of projectile range in target
Angular acceptance after target	horizontal	80 mrad
	vertical	80 mrad
	Solid angle	5 msr
Momentum acceptance	ΔP/P	4 %
Momentum distribution	Convolution model [3]	#2 – Es (s0=160, coef=1.25, shift=-1)
Charge states	Yes (4: target, PS wedge, DB2 wedge, DB3 PPAC)	Global
Energy loss model		Atima 1.4
Primary reactions in target		NP=64; EPAX 3.1
Secondary reactions in target	Yes	NP=64; EPAX 3.1

The optimal charge-state combination through the various stages of separation was chosen, and then the spectrometer was tuned for maximum production of each isotope. The production cross sections for projectile fragmentation were calculated using the EPAX 3.1 parameterization [4] for each beam listed in Table 1.

Fission

Production cross sections following projectile fission of ^{238}U were calculated using the LISE++ 3EER model [5,6]. The characteristics of the excitation-energy regions used in the calculations are given in Table 3 and can also be retrieved from the corresponding LISE^{++} input file.

Table 3. *Excitation-energy regions used in the LISE^{++} 3EER projectile-fission calculations for ^{238}U. The table lists the representative fissioning systems, production cross sections, and excitation energies assigned to the low-, middle-, and high-excitation components.*

Region	A, Z	CS, mb	E*, MeV
Low	^{238}U	297	32
Middle	^{232}Th	401	101
High	^{225}Fr	340	340

BigRIPS tabulated user cross sections were used. For each excitation-energy region, calculations were performed assuming that region to be the principal one for spectrometer tuning. The maximum yield was then selected for the fission-yield database.

Stopped Beams

Beam rates for experiments in the stopped-beam areas and for delivery to ReAccelerator (ReA) have been estimated based on the observed performance of the Advanced Cryogenic Gas Stopper (ACGS). The estimates assume optimal conditions and are intended only to provide a rough indication of experiment feasibility. Actual rates will likely be lower. The rate estimates take into account the transport efficiency for fast beams from the ARIS separator to the gas stoppers and the stopping efficiency calculated with LISE^{++} assuming optimum fast-beam momentum-compression settings. The estimates also include a parametrization of the extraction efficiency from the gas stopper as a function of the ion mass and the incoming fast beam rate. Stopping efficiencies range from a maximum of 95% for heavy ions to 10% for low atomic numbers. Extraction efficiencies vary from 20% for mass numbers $A > 6$ to near unity for $A > 70$. Decay losses are considered using measured extraction times that vary from 15 ms for light ions to 60 ms for heavy ions. The possible effect of radio-molecule formation, which can lead to lower delivered beam rates, is not taken into account. Atomic numbers lower than four were excluded from rate estimates.

Reaccelerated beams

Beam intensities in the reaccelerated beam areas have been estimated using the stopped beam intensities multiplied by efficiencies for the Beam-Cooler-Buncher (BCB), the Electron Beam Ion Trap (EBIT) charge breeder, and the ReA-linac. The efficiencies are based on data from experiment runs and beam tests. The BCB efficiency ranges from 15% for ions with $A < 12$ to 60% for heavier ions up to $A = 133$. EBIT breeding efficiencies into a single charge state vary from 30% for atomic numbers $Z < 5$ to 10% for $Z > 50$. Decay losses in the EBIT are considered assuming an average breeding time of 100 ms. The ReA-linac and beamline transport efficiencies are assumed to be 60%.

References:

[1] O.B. Tarasov and D. Bazin, NIM B 266 (2008) 4657-4664.

[2] O.B. Tarasov *et al.*, NIM B 541 (2023) 4-7.

[3] O.B. Tarasov, Nuclear Physics A 734 (2004) 536-540.

[4] K. Sümmerer, Phys. Rev. C 86 (2012) 014601.

[5] O.B. Tarasov, Tech.Rep. MSUCL1300, NSCL, Michigan State University 2005.

[6] M. Bowry, O.B. Tarasov *et al.*, Phys. Rev. C 108 (2023) 034604.