FRIB Estimated Rates

v 2.01

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This document describes the assumptions used to generate version 1.08 of the estimated FRIB fast, stopped, and reaccelerated beam rates.

Primary beams

A total of 47 primary beams were used for the FRIB yield analysis. These cover nearly 90% of the optimum primary beams for the production of all isotopes. Characteristics of the beams are given in Table 1. For PAC 1 beams a subset of these beams ^{238}U, ^{124}Xe, ^{82}Se, ^{78,86}Kr, ^{48}Ca, ^{36}Ar, ^{16,18}O. For PAC 2 additional beams of ^{92}Mo, ^{58,64}Ni, ^{22}Ne were added.

Table 1. *Preliminary list of primary beams for FRIB assuming the same maximum energy as for the NSCL ISF described in the FRIB Conceptual Design Report 2012. A beam power of 400 kW was used for each beam.*

Beam	A	Z	abund.	qin	qout	A/q	MeV/u
238U	238	92	99.30%	29	89	2.67	203
209Bi	209	83	100.00%	27	81	2.58	210
208Pb	208	82	52.40%	26	80	2.60	210
204Pb	204	82	1.40%	26	80	2.55	214
204Hg	204	80	6.90%	26	78	2.62	208
198Pt	198	78	7.20%	25	76	2.61	210
196Hg	196	80	0.15%	26	78	2.51	218
190Pt	190	78	0.01%	25	76	2.50	218
186W	186	74	28.40%	24	72	2.58	214
184Os	184	76	0.02%	24	74	2.49	220
180W	180	74	0.12%	24	72	2.50	220
176Yb	176	70	12.80%	23	69	2.55	216
174Hf	174	72	0.16%	23	70	2.49	221
170Er	170	68	14.90%	22	67	2.54	218
168Yb	168	70	0.13%	23	69	2.43	225
162Er	162	68	0.14%	22	67	2.42	227
160Gd	160	64	21.90%	21	63	2.54	219
156Dy	156	66	0.06%	21	65	2.40	228
150Nd	150	60	5.60%	19	59	2.54	219
144Sm	144	62	3.10%	20	61	2.36	233

136Xe	136	54	8.90%	18	54	2.52	222
130Te	130	52	34.10%	18	46	2.83	217
124Xe	124	54	0.09%	18	48	2.58	235
124Sn	124	50	5.80%	17	45	2.76	222
112Sn	112	50	0.97%	17	45	2.49	242
106Cd	106	48	1.25%	16	43	2.47	244
96Zr	96	40	2.80%	14	37	2.59	234
92Mo	92	42	14.80%	14	38	2.42	248
86Kr	86	36	17.30%	14	33	2.61	233
82Se	82	34	8.70%	14	32	2.56	237
78Kr	78	36	0.35%	14	34	2.29	260
76Ge	76	32	7.60%	13	30	2.53	239
64Zn	64	30	48.60%	12	28	2.29	261
64Ni	64	28	0.93%	11	27	2.37	253
58Ni	58	28	68.10%	11	27	2.15	275
48Ca	48	20	0.19%	8	19	2.53	240
40Ca	40	20	96.90%	8	19	2.11	280
40Ar	40	18	99.60%	8	18	2.22	268
36Ar	36	18	0.34%	8	18	2.00	293
36S	36	16	0.02%	8	16	2.25	265
32S	32	16	94.90%	8	16	2.00	293
30Si	30	14	3.10%	7	14	2.14	276
28Si	28	14	92.20%	7	14	2.00	293
22Ne	22	10	9.25%	6	10	2.20	271
20Ne	20	10	90.50%	6	10	2.00	294
18O	18	8	0.21%	6	8	2.25	266
16O	16	8	99.80%	6	8	2.00	294

Transmission and yield calculations

Transmission efficiency calculations were done with LISE^{++} v. 9.2.68 [1]. Calculation settings are given in Table 2. An approximation of the optimum production target thickness was chosen to speed the calculations. The use of a Li, Be, or C target changes the production by on average less than 30%.

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

Objects/characteristic	Parameter	Value / Model
Target	Material	C
	Thickness	30% of range of projectile in target
Angular acceptance after target	horizontal	80 mrad
	vertical	80 mrad
	Solid angle	5 msr
Momentum acceptance	dp/p	10 %
Momentum distribution:	Convolution model	[2] –Es (coef=3)

Charge states :	Yes	[0] – Winger
Energy loss model :		[2] – Atima
Secondary reactions in target :	Yes	

The optimal charge state combination through the various stages of separation was chosen, and then spectrometer has been tuned for maximum production of each isotope. The production cross sections for projectile fragmentation have been calculated using the EPAX 2.15 [2] parameterization for each beam from the list.

Fission

Production cross sections following projectile fission of ^{238}U have been calculated with the use of the LISE^{++} 3EER model [3]. The characteristics of excitation energy regions used in calculations are given in Table 3, and also can be retrieved through the file http://groups.nscl.msu.edu/frib/rates/FRIB/238U_FH.lpp.

Table 3.

Region	A Z	CS, mb	E*, MeV	dE, MeV
Low	^{236}U	200	23.5	11.2
Middle	^{226}Th	500	100.0	53.1
High	^{220}Ra	350	250.0	64.4

For each excitation energy region calculations were done assuming this excitation energy region as principal to tune a spectrometer. Then maximum yield has been chosen for the fission yield database.

Charge state transmission

We assumed the use of two wedges in the fragment-separator to provide good separation of secondary beams from background. In this case, after each dispersive block with material located there is an additional loss due to the charge state distribution after the material. In order to produce final fragment yield, the LISE^{++} yield has been multiplied twice by the optimum charge state fraction following the target. This is a close approximation to the charge state losses.

Stopping efficiency

If fragment is particle bound ($T_{1/2}$ > 1e-6 sec), then *Fast_beam_rates* (*FastBR*) is production of the LISE++ yield and the transport efficiency (*TraGS*), which was taken 80%. The stopped beam rate is calculated as:

$$\textit{Stopped beam rate} = \textit{StoppingEfficiency(Mass,Z)} \times \textit{FastBR} \times \textit{Survive}_{extraction} \times \textit{TraB},$$

Where TraB is the Gas stopper EBIT transport efficiency, which is determined by the cooler-buncher efficiency. This was taken as 80%. $Survive_{extraction}$ is part of nuclei which survived at extraction process. Extraction time in the case of isotopes was assumed to be 0.075 sec. In addition, an overall extraction efficiency of 25% is assumed. *StoppingEfficiency(Mass,Z)* Is taken as 0.158 for Z<5, 0.3834 for 4<Z<21, and 0.95 for Z>20.

The maximum beam rate was limited to $1x10^8$ pps for PAC1, $1x10^8$ pps for PAC2, and $1x10^{10}$ pps for the ultimate rates. Please note that rates above $1x10^8$ pps are very uncertain. A plan is in place to add a solid stopper at FRIB, which will provide rates of more than this limit.

Limited improvements in these values were assumed for the ultimate rates.

Charge State Breeding and Reacceleration

The reaccelerated beam rate is calculated by:

$$Reaccelerated\ beam\ rate = Stopped\_beam\_rate \times Survive_{breeding} \times Beps \times TraQA \times Reeps,$$

where *Reeps* is the Re-accelerator efficiency (80%), *TraQA* is the EBIT Gas stopper transport efficiency (80%), $Survive_{breeding}$ is part of nuclei which survived at breeding process, and *Beps* is the accumulation and breeding efficiency depended from mass region, show in Table 4.

Limited improvements in these values were assumed for the ultimate rates.

Table 4.

Z region	Accumulation and breeding efficiency, *Beps*	Breeding time [sec]
Z < 5	30%	0.1
5 ≤ Z ≤ 50	25%	0.1
Z > 50	10%	0.1

References:

[1] O.B.Tarasov and D. Bazin, NIM B 266 (2008) 4657-466.
[2] K. S¨ummerer and B. Blank, Phys. Rev. C 61 (2000) 034607.
[3] O.B. Tarasov, Tech.Rep. MSUCL1300, NSCL, Michigan State University 2005.