Status of the FRIB Driver Linac Vacuum Calculations

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Abstract

The Facility for Rare Isotope Beams (FRIB) is a superconducting heavy ion linear accelerator that is to produce rare isotopes far from stability for low energy nuclear science. In order to achieve this, its driver linac needs to achieve a very high beam current (up to 400 kW beam power), and this requirement makes vacuum levels of critical importance. Vacuum calculations have been carried out to verify that the vacuum system design meets the requirements. In this paper, we present an overview of the methods used for FRIB vacuum calculations and simulation results for some interesting sections of the accelerator.

1 Introduction

The Facility for Rare Isotope Beams (FRIB) is a heavy ion fragmentation facility to produce rare isotopes far from stability for low energy nuclear science. The facility will utilize a high-intensity, superconducting heavy-ion driver linac (Figure 1) to provide stable ion beams from protons to uranium at energies greater than 200 MeV/u and at a beam power of up to 400 kW. The beam will be fragmented on a multi-layer high power fragmentation target and separated in a high resolution fragment separator.

Two ECR ion source injectors will provide highly charged ions for the superconducting linac for efficient acceleration. In order to transport the heavy ions at the low velocities of the injection beam the vacuum systems need to be carefully designed to avoid beam losses due to charge exchange. For U33+, for example (one of the commissioning beams), the cross-section for electron capture from the residual gas is so large at low energies (∼12 keV/u in the low energy beam transport section – LEBT) that a residual gas pressure of ≳ 10−6 Torr would lead to unacceptable beam losses.

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Figure 1: FRIB driver linac

Similarly, in the warm section of the superconducting linac, beam losses due to interaction of the beam with residual gas need to be minimized in order to keep the average uncontrolled beam loss well below 1 W/m as required for maintainability of the accelerator and safety considerations.

These beam loss requirements, as well as the need for managing vacuum levels in high loss regions such as beam stripping and collimation areas, led to the establishment of minimum baseline vacuum requirements for all areas of the accelerator system. In addition, the superconducting radio frequency (srf) cavities must be protected from contamination that could possibly migrate from the stripper region, collimator systems, or target systems.

CAD vacuum models of each area are made based upon the accelerator lattice file, and Monte Carlo simulations of vacuum levels are performed using MolFlow+ to help determine or validate the vacuum hardware configuration needed to meet the baseline requirements. This paper describes the FRIB facility vacuum requirements, and reports on the methods and status of the FRIB vacuum calculations, with emphasis on some challenging sections of the driver linac.

2 Vacuum requirements

The operation of the FRIB driver linac requires a sufficiently high vacuum, which is critical for several reasons:

- limit beam losses,
- keep the radiation induced thereby within safe levels,
• prevent contamination of superconducting cavities by residual gas.

These criteria have been translated into vacuum requirements in terms of average residual gas pressures across different linac sections, as laid out in FRIB Driver Linac Vacuum Requirements [1] and summarized in Table 1.

<table>
<thead>
<tr>
<th>Location in driver linac</th>
<th>Average Pressure [Torr]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE Ion Source Injection Region</td>
<td>$&lt; 3 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>FE Ion Source Extraction Region</td>
<td>$&lt; 1 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>FE Charge Selection System</td>
<td>$&lt; 3 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>FE LEBT</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>FE RFQ</td>
<td>$&lt; 5 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>FE MEBT</td>
<td>$&lt; 1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>LS1</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td>In the warm regions</td>
</tr>
<tr>
<td>FS1 Charge Stripping section</td>
<td>$&lt; 1 \times 10^{-8}$</td>
<td>Near the matching CMs</td>
</tr>
<tr>
<td>FS1 Charge Stripping section</td>
<td>$&lt; 1 \times 10^{-6}$</td>
<td>Near the Li stripper</td>
</tr>
<tr>
<td>FS1 Beam Bending Section</td>
<td>$&lt; 5 \times 10^{-8}$</td>
<td>After the second 45° dipole</td>
</tr>
<tr>
<td>FS1 Matching Section</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>LS2</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td>In the warm regions</td>
</tr>
<tr>
<td>FS2</td>
<td>$&lt; 1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>LS3</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td>In the warm regions</td>
</tr>
<tr>
<td>LS3 Beam Transport Section</td>
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<td></td>
</tr>
<tr>
<td>BDS</td>
<td>$&lt; 1 \times 10^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: FRIB driver linac vacuum requirements: beam line vacuum pressure during operation [1]. The Charge Stripping section requirements are based on lithium charge stripping. (FE=Front End, LS=Linac Segment, FS=Folding Segment, BDS=Beam Delivery Segment)

Vacuum calculations are a part of the overall vacuum system design. This is an iterative process, where the calculations, which are used to check how the proposed system design compares with the vacuum requirements outlined above, provide a feedback loop.

3 Methods

The requirements above specify pressure levels during operation, i.e. in stationary state. It is therefore assumed that the residual gas is in the molecular flow regime. CAD models of the beam line vacuum chamber were made based on the FRIB lattice files, and these models provided the geometry for test-particle Monte Carlo simulations using MolFlow+ [2] [1]. In parts where simple analytical models were possible (e.g., constant diameter cylindrical beam tube between

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two pumps), the results obtained from the simulations were compared against estimates from such models, and were validated to a satisfactory degree of accuracy.

3.1 Pressure profiles

MolFlow+ calculates the pressure on each planar facet of the model by keeping track of the number of hits received by it in the ray-tracing sequence [2]. Following [3], facet $i$ gets and impingement rate $z_i$ given by

$$z_i = \frac{v_i Q}{A_i N k T},$$

where $A_i$ is the area of facet $i$, $v_i$ is the number of collisions on facet $i$ during the simulation, $N$ is the total number of molecules generated, $Q$ is the gas load, $k$ is Boltzmann constant, and $T$ the absolute temperature. The relation between the pressure $P_i$ and the impingement rate $z_i$ is

$$P_i = \frac{4kT z_i}{c} = \frac{4Qv_i}{cA_i N},$$

where $c$ is the average thermal molecular velocity given by $c = \sqrt{8RT/(\pi M)}$, with $M$ the molar mass of the gas species which is simulated. For mixtures of different gas species, the pressure is obtained by running separate simulations and linearly combining via proper weights the individual pressure of each gas species.

3.2 Sampling

The pressure was sampled on square test-facets 2 cm in size. At each sampling point along the beam axis, three such test facets were positioned: one in the cross section plane (with normal vector along the beam axis, the $z$-direction), and two other with normal vectors in the $(x,y)$ plane (i.e. one extending along the beam axis vertically, and the other horizontally). The pressure shown in plots was averaged over all three orientations. Variations in pressure between the three planes were within a few percent at most locally, and at most a fraction of a percent in terms of average pressure along the beam axis.

3.3 Desorption rates

The vacuum chamber walls of the FRIB driver linac will be made almost exclusively of stainless steel. The desorption rate for stainless steel varies considerably (by several orders of magnitude) depending on the surface treatment. We consider two baseline treatment options, that we refer to as the “non-baked” and the “baked” one. The desorption rate for non-baked stainless steel used in calculations is $q_{\text{nonbaked}} = 4.0 \times 10^{-11}$ Torr L s$^{-1}$ cm$^{-2}$. It was largely based on measurements taken from an existing beam line in the ReA3 reaccelerator. For the desorption rate of baked stainless steel, a value that is one order of magnitude lower is used, $q_{\text{baked}} = 4.0 \times 10^{-12}$ Torr L s$^{-1}$ cm$^{-2}$. 

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3.4 Gas composition

The simulations are “nitrogen equivalent,” i.e. it is assumed that the (room temperature) thermally desorbing gas has molar mass 28 g/mol, and the pumping speeds used are the ones for molecular nitrogen. Other than thermal desorption, there are areas where specific gasses are expected, such as molecular oxygen diffusing from the ion source, oxygen ions in the beam (support gas) dumped on the analyzing magnet in the Charge Selection Section (Front End), and lithium diffusing from the Charge Stripper (Folding Segment 1). Simulations for these gas sources use the molar mass of the corresponding gas, and the nitrogen pumping speeds are scaled appropriately (taking into account the molar mass as well as the temperature if different from room temperature).

3.5 Valves and cryomodules

The two most important detrimental effects of vacuum contamination are (1) its effect on the beam and (2) its effect on the cryomodules. Therefore, away from cryomodules and unless otherwise indicated, we assume the beam is running and we leave all valves open along the beam line in the models. Near cryomodules, however, the main concern being cavity contamination, the valves in the models are closed, in order to ensure that the beam line can be pumped down to within requirements without relying on the pumping effect of the cryomodules. The cryomodules themselves were not included in the models.

3.6 Pumps

In these calculations, a pump is solely characterized by its nominal pumping speed (in L/s). Even though pumps may be referred to as ion pumps or turbo-molecular pumps, we do so only because the chosen pumping speeds correspond to data for selected specific pumps available from manufacturers. (Ion pumps: 65 L/s, 240 L/s; Turbo-molecular pumps: 280 L/s, 700 L/s, 2050 L/s) The calculations are independent of pump technology used.

3.7 Transmission rate calculations

In the Front End, we considered transmission rates in conjunction with required pressure levels. The main source of beam loss is charge exchange (electron pickup from residual gas) \( X^q + R \rightarrow X^{q-1} + R^+ \), where \( X^q \) is the accelerated beam ion (in charge state \( q \)), and \( R \) designates the residual gas. The beam transmission is given by

\[
T = \exp \left( - \int_0^L n \sigma_{q,q-1} \, dz \right),
\]

where \( z \) is the length coordinate along the beam axis, \( L \) is the beam line length, \( n = n(z) \) is the residual gas concentration, \( \sigma_{q,q-1} \) is the charge exchange cross
section given by Salzborn and Müller [4]:

\[ \sigma_{q,q-1} = 1.43 \times 10^{-12} q^{1.17} \left( \frac{I}{1V} \right)^{-2.76} \text{cm}^2, \]  

(4)

and \( I \) is the first ionization potential of the residual gas. The charge pickup cross section decreases with energy if energy is higher than a few tens keV, but the beam energy up to the radio frequency quadrupole (RFQ) is low enough that this formula applies.

4 Front End model

The first vacuum model we present here is the part of the Front End stretching from the extraction point to the RFQ entrance. It includes three sections that have different average pressure requirements (cf. Figure 2):

1. Extraction Region (er – from extraction point to beginning of first bending magnet),
2. Charge Selection Section (css - from beginning of first to the end of the second bending magnet),
3. Low Energy Beam Transport (lebt - from end of second bending magnet to RFQ entrance).

4.1 Boundary conditions

Both the upstream and the downstream end had open boundary conditions with a source term, i.e. the end facets were set as sticky (particles leaving the vacuum chamber through the boundary) and desorbing (particles entering the vacuum chamber through the boundary). The pressure profile for the boundary sources were scaled to set values of the pressure at the boundaries. At the upstream end, the model included the 8 mm diameter orifice at the exit of the Venus source extraction box, and the pressure inside the box was set to \( 2 \times 10^{-7} \) Torr, based on worst-case measured data [5]. At the downstream end of lebt, an orifice of diameter 25 mm was included near the RFQ entrance, and the boundary condition was set to the RFQ requirement value of \( 5 \times 10^{-8} \) Torr (cf. Table 1).

4.2 Gas sources

In the model of this part of the Front End, the following sources of outgassing have been included:

(1) Thermal desorption from room-temperature walls,
(2) Oxygen ions dumped on the walls of the analyzing magnet,
(3) Beam line boundaries:
   (a) Upstream end: diffusion of molecular oxygen from ion source
   (b) Downstream end: diffusion from RFQ

4.2.1 Thermal desorption
Thermal desorption is significant in the Front End due to the presence of many
quadrupole doublets and triplets, where the desorbing surface area per unit
beam line length is significantly increased (electrodes, supports, hardware). In
the calculations, non-baked stainless steel walls ($q = 4.0 \times 10^{-11} \text{ Torr L s}^{-1} \text{ cm}^{-2}$)
were assumed throughout.

4.2.2 Oxygen in the analyzing magnet
In a uranium beam, the oxygen support gas comprises 90% of the total beam
particle current (Venus measurement: 965 $\mu$A [5]). We assume that all of these
oxygen ions will be dumped on the walls of the analyzing magnet. We further
assume that, after an initial transient period where the dumped beam might
interact with the wall, oxygen ions would just scatter off the walls, recombine
into O$_2$, and diffuse through the beam line. Although it is possible that the
throughput in this initial period (beam-induced desorption) could be higher
than for the diffusing O$_2$ alone, it should remain within the same order of
magnitude due to the low beam energy (12 keV/u) [6].

We therefore estimate the outgassing source of molecular oxygen on the
analyzing magnet as follows. We assume that the temperature of the water-
cooled walls of the analyzing magnet is 350 K. At this temperature, the oxygen
ions particle current of 965 $\mu$A = 6.02 × 10$^{15}$ particles/s, corresponds to a
throughput of $Q_{O_2} = 1.09 \times 10^{-4}$ Torr L/s. In the simulation, this throughput
was uniformly distributed across the area of the side walls of the second part of
the analyzing magnet.

4.3 Requirements
The average pressure required over the three sections is:
   • ER: $1 \times 10^{-7}$ Torr,
   • CSS: $3 \times 10^{-8}$ Torr,
   • LEBT: $5 \times 10^{-9}$ Torr.

4.4 Pumping configuration
In the simulation the results of which are shown below, 700 L/s pumps were
used throughout except for the first pump after the extraction point (2050 L/s).
4.5 Results

The pressure profile obtained in the simulation is shown in Figure 3. The magnet and Venus graphs show pressure profiles for molecular oxygen, while the thermal and RFQ plots are for molecular nitrogen. The combined pressure profile in purple was averaged over the three sections.

Comparing the combined pressure averaged over the three sections with respective requirements:

- *ER* is within requirements at $2.34 \times 10^{-8}$ Torr.
- *CSS* is not within requirements at $7.08 \times 10^{-8}$ Torr.
- *LEBT* is within requirements at $4.99 \times 10^{-9}$ Torr.

4.6 Discussion

The peak at the analyzing magnet is due to a large load of oxygen dumped on the magnet and inadequate pumping in that area, leading to a high pressure average over the CSS. The vacuum chamber inside the magnet is only 10 cm high, and the conductance of the pumping port on the outer wall of the magnet chamber shown in Figure 4 was calculated from a MolFlow+ simulation to be $2200 \text{ L/s}$.

As it was apparent that the average pressure requirement in the CSS would be hard to reach, we considered the overall transmission rate from the extraction point to the RFQ entrance, with a goal of maximizing beam transmission over this region, preferably reaching a 90% beam transmission for a $\text{U}^{34+}$ beam. The transmission rate achieved in the simulation plotted in Figure 3 is 88.9%. Breaking down the pressure profile into oxygen (magnet and Venus profiles) and nitrogen (thermal and RFQ profiles), the transmission rate on nitrogen is 97.4%, while the transmission rate on oxygen is 91.2%. This points to the oxygen dumped on the analyzing magnet as the major obstacle in maximizing the transmission rate.

We attempted to address the analyzing magnet source by confining it with apertures. Simulations were carried out with a 5 cm aperture added after the analyzing magnet. However, the differential pumping effect was not significant due to inadequate pumping on the magnet. The pressure profile was somewhat improved (0.3% increase in overall transmission rate), but this size of the aperture may be too small from beam dynamics point of view.

We tested how much the situation can be improved by stronger pumping. Increasing pumping from 700 L/s to 1500 L/s throughout the CSS, as well as on the boxes before the analyzing magnet and after the second magnet, the average pressure achieved in simulations was $3.88 \times 10^{-8}$ Torr (requirement is $3 \times 10^{-8}$ Torr), while the overall transmission rate was 91.2%. This is a satisfactory result. However, we are currently exploring less expensive alternatives, such as adding a second pumping port on the opposite wall of the analyzing magnet, and/or widening the existing pumping port to a rectangular shape.
These solutions require magnet redesign, and are currently being evaluated for possible detrimental effects on the magnetic field.

5 Lithium Charge Stripper model

This is a part of the beam line located between Linac Segment 1 and Folding Segment 1, bounded by two matching cryomodules. The model of the vacuum chamber walls is shown in Figure 5. Located at the middle is the Charge Stripper, a liquid lithium film (cf. Figure 6) that is to strip electrons from the ions in the beam passing through it. The main concern in this section is the presence of liquid lithium, hence a relatively high pressure of lithium vapors (estimated at $1 \times 10^{-5}$ Torr in the cylinder containing the film, colored orange in Figure 5), in a proximity of cryomodules, which must be protected from contamination. The issue is addressed with

- differential pumping: two pairs of apertures surrounding the Charge Stripper cylinder, combined with strong pumping (two pairs of 2050 L/s turbo pumps),
- chicanes near the cryomodules that prevent the direct line of sight from the stripper into the cryomodules (shown in blue in Figure 5).

5.1 Lithium diffusion

Lithium sticks to the vacuum chamber walls at room temperature with very high probability. This was modeled by setting the sticking coefficient to unity outside the charge stripper module (enclosing the charge stripper cylinder and located between the two innermost diagnostic boxes with 65 L/s). In addition to this simulation, a second simulation was carried out without assuming sticky walls, and relying exclusively on pumps (blue graph in Figure 7). The latter case is unrealistically pessimistic, and the actual pressure profile is expected to be very close to the former.

5.2 Requirements

Requirements in this section are not expressed in terms of an overall average pressure, but in terms of pressure near the matching cryomodules: $p < 1 \times 10^{-8}$ Torr, and near the lithium stripper: $p < 1 \times 10^{-6}$ Torr (cf. Table 1).

5.3 Results

The pressure profiles for the two lithium diffusion simulations are shown in Figure 7. The cases where the walls are sticky and non-sticky are shown in

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2The charge stripper module is not shown in the vacuum chamber schematic in Figure 5 but its position is hatched in the pressure profile plots below.
green and blue, respectively. The lithium pressure profile in the sticky walls case (the more realistic one), combined with the non-baked thermal desorption from walls, is shown in Figure 8, while Figure 9 shows the combined plot in the pessimistic non-sticky walls case.

The combined plot in Figure 8 satisfies both requirements above: the pressure throughout the chicanes is below the required level in the proximity of cryomodules of $1 \times 10^{-8}$ Torr, while the pressure just outside the charge stripper module (hatched region in the graph) drops sharply (due to the stickiness of lithium to the walls) to below the $1 \times 10^{-8}$ Torr level, which is well within the requirements ($1 \times 10^{-6}$ Torr).

Even considering the unrealistically pessimistic case of no lithium sticking to walls at all, shown in Figure 9, the simulation results are within requirements near the cryomodules (chicanes still below $1 \times 10^{-8}$ Torr), while the pressure levels near the charge stripper module are just slightly above the required $1 \times 10^{-6}$ Torr.

6 Summary

The Facility for Rare Isotope Beams is to be the world’s leading heavy-ion accelerator, with breakthrough beam power. To achieve the desired beam intensity, beam line vacuum levels are critical in order to limit beam losses by charge exchange with residual gas. Vacuum calculations, largely based on MolFlow+ simulations, are used to validate the vacuum system design by ensuring that the simulated vacuum levels are within requirements. At this stage, the simulations are meeting the requirements in virtually all segments, while a few issues are still being addressed, as illustrated by the analyzing magnet pressure peak in the Front End (cf. Section 4.6). As the final issues are being resolved, the FRIB vacuum system design is near completion.

Acknowledgments

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The CAD models for the vacuum simulations were provided by Paul Guetschow and Glenn Morgan. The layout schematics pictures were made by Glenn Morgan.

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References


Figure 2: Front End: Model of the beam line vacuum chamber from the Venus source to the RFQ entrance. Yellow: quadrupoles, blue: bending dipoles.
Figure 3: Pressure profile from Venus extraction point to RFQ entrance. Thermal desorption rate: $4.0 \times 10^{-11}$ Torr L s$^{-1}$ cm$^{-2}$, throughput of oxygen dumped on analyzing magnet: $1.09 \times 10^{-4}$ Torr L/s, boundary conditions: Venus: $2 \times 10^{-7}$ Torr, RFQ: $5 \times 10^{-8}$ Torr (shading: colors from Figure 2).

Figure 4: Front End: vacuum chamber (inner) walls around the analyzing magnet with the pumping port. (Beam direction: right to left)
Figure 5: Charge Stripper: Schematic of the beamline around the Charge Stripper module, from the upstream matching cryomodule to the one downstream.

Figure 6: Charge Stripper: liquid lithium film
Figure 7: Charge Stripper: lithium pressure profile. Two cases are shown, the optimistic one (green curve), where the lithium sticks to the walls with 100% probability outside of the Charge Stripper Module (hatched region), and the pessimistic one (blue curve), where the sticking probability on the walls is 0% throughout. Apertures are located at dashed red lines.
Figure 8: Charge Stripper, combined plot (black curve) of thermal desorption (non-baked walls, blue curve) and lithium vapor diffusion (optimistic/realistic case with lithium sticking to walls at 100% probability outside of Stripper Module, green curve).
Figure 9: Charge Stripper, combined plot (black curve) of thermal desorption (non-baked walls, blue curve) and lithium vapor diffusion (pessimistic case with no sticking to walls, green curve).