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Beam Optics for the Isotope Target Beamline at the LERF

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Abstract

In this note we describe the design and performance of a dedicated isotope target beamline in Jefferson Laboratory's Low Energy Recirculator Facility (LERF) in preparation for tests of radioisotope generation using high power electron beams. The solution provides ease of operation and meets the beam size specifications to maintain the structural integrity of the Beryllium window.

Introduction

The DOE recently approved project funding to test a novel way of generating radioisotopes using high energy electron beams. Specifically, the proposal aims to demonstrate useful yields of ^{67}Cu by photo-production using bremmsstrahlung photons [1]. The experiment involves directing a low energy, high power electron beam onto a high-Z radiator to generate photons which are incident on a Gallium target. The target will then be sent off-site for radiochemical separation where the extraction efficiency and the yield of ^{67}Cu will be quantified.

Requirements

The crux of the proposal is the irradiation of a Gallium target with a high power electron beam in the Low Energy Recirculator Facility (LERF) at Jefferson Laboratory, removing the target and then chemically separating the ^{67}Cu offsite at VCU. There are two beam energies of interest, 18.5 and 40 MeV, delivering 1 kW of beam power for each. Additionally, a run at 40 MeV with 5 kW of beam power is planned.

Due to LCLS-II cryomodule testing in the LERF vault and the removal of 2 of the 3 cryomodules from the linac, a re-design of the linac region was required. The result is documented in Ref. [2] and consists of installing two additional quadrupole triplets to yield a robust solution that provides lossless transport of different energy beams to the target while providing sufficient operational tunability. The target will be part of an isotope beamline whose design is the subject of this note. The advantages of a dedicated beamline include: (1) allowing easier access for target removal after irradiation (2) leveraging the existing shielding from the 1G beam dump and (3) allowing other experiments to utilize the LERF – particularly in the backleg.

The isotope target apparatus consists of an electron beam exit window made of Beryllium (Be), a Tungsten radiator followed by the Gallium target. The Be window must withstand the current density of the beam while maintaining its thermal and structural integrity. This places constraints on the size of the electron beam which in turn inform the design choices for the beamline itself. An initial analysis concluded that a 4 mm diameter uniform beam would be sufficiently large so as to avoid damage to the 0.015" thick window [3].

The transverse beam distribution in the LERF is not uniform. So we consider a Gaussian distribution with a 1 mm rms spot size giving a full beam size of 6 mm (6σ). This is larger than the 4 mm assumed in the analysis, but compensates for the non-uniform power deposition from the Gaussian distribution. To achieve a 1 mm rms spot size on the window, and assuming transverse (normalized) emittances of 10 mm-mrad, it follows that the beta functions for 18.5 and 40.0 MeV are 4 m and 8 m, respectively.

Lattice Solution

As a reminder, recall the nominal IR FEL Upgrade configuration and the nomenclature used. Figure 1 shows a schematic of the FEL layout with labels for the relevant regions and modules. The electron beam is generated and formed in a DC photocathode gun, accelerated in a quarter-cryomodule and merged onto the linac axis – all of which is denoted as the 0F region. The linac region which is comprised of a single cryomodule and three intervening quadrupole triplets is the 1F region. The extraction chicane – which sends an energy recovered beam to the dump and the recirculating beam back onto the linac axis – marks the beginning of the 2F region (and which extends through the first recirculation arc but is not shown in the figure).

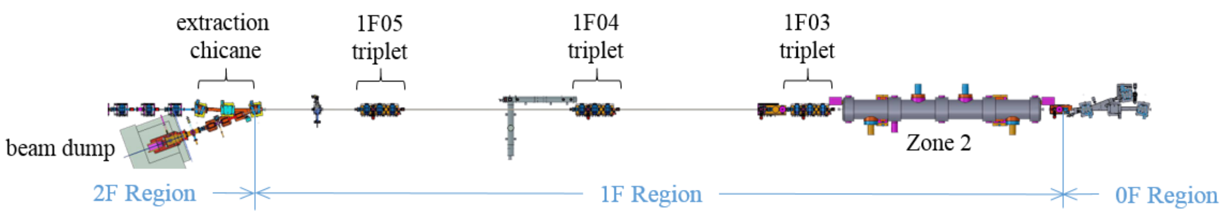

Figure 1: Schematic of the 0F, 1F and beginning of the 2F region in the LERF. Beam is generated in the injector (0F region) and is transported from right to left in the figure.

Following the extraction chicane there are six quadrupoles (QX2F01 through QX2F06). To accommodate the isotope beamline, the fourth quadrupole (QX2F04) will be removed and a DQ-style dipole will be installed in its place. The dipole was formerly used as a reverse bend in the IR FEL Demo Bates bend. It has a bend angle of 29.38°, has 6.4° pole face rotations and provides focusing in both transverse planes. (Note that the QX2F04 quadrupole nominally runs at 0 G for LERF operations so its removal does to preclude beam transport to the backleg).

To maintain simplicity, the beamline is comprised of a single quadrupole 0.925 m downstream of the DQ dipole with an additional 0.925 m drift to the Be window. This provides enough room for the usual suite of diagnostics, namely a BPM and corrector pair upstream of the quadrupole and a viewer downstream. The viewer serves several important functions; it is used to verify the presence of beam during initial tune-up, to center the beam on the window and to measure the beam size. A drawing of the 2F region and the new isotope beamline is shown in Fig. 2. (Note the isotope beamline is denoted as the 1X region e.g. using this nomenclature the single quadrupole in the line is named QX1X01). Hardware layout and coordinates are given in Appendix A.

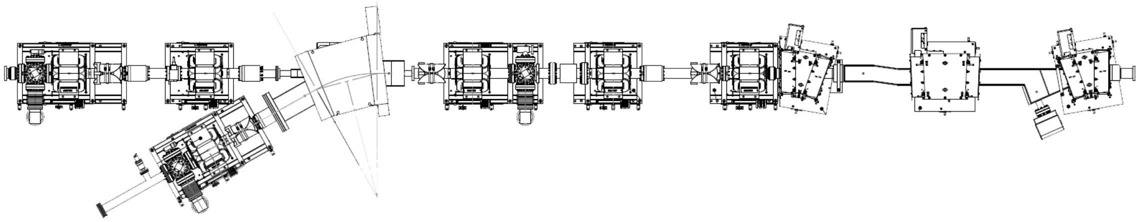

Figure 2: Close up view of the extraction chicane, the first three quadrupoles in the 2F region, the dipole that directs beam to the isotope beamline (beam direction is from right to left). The isotope line consists of a single quadrupole with a BPM/correct pair upstream and a beam viewer downstream.

Lattice Performance

The required beta functions at the Be window (4 m and 8 m) are moderate and easily obtained with minimal tuning of the 1F lattice. The result is an easily tunable, low-risk beamline. The beta functions and dispersion for the isotope setup – from the entrance of the linac cryomodule to the entrance of the Be window – are shown in Figs. 3 and 4 for 18.5 and 40.0 MeV, respectively. In both instances, the beam remains round and, if need be, the spot size can be increased by a factor of ~2 by varying a single quadrupole (QX2F03) with some trim adjustment using the dump quadrupole (QX1X01). The associated rms beam sizes for both energies are plotted in Fig. 5.

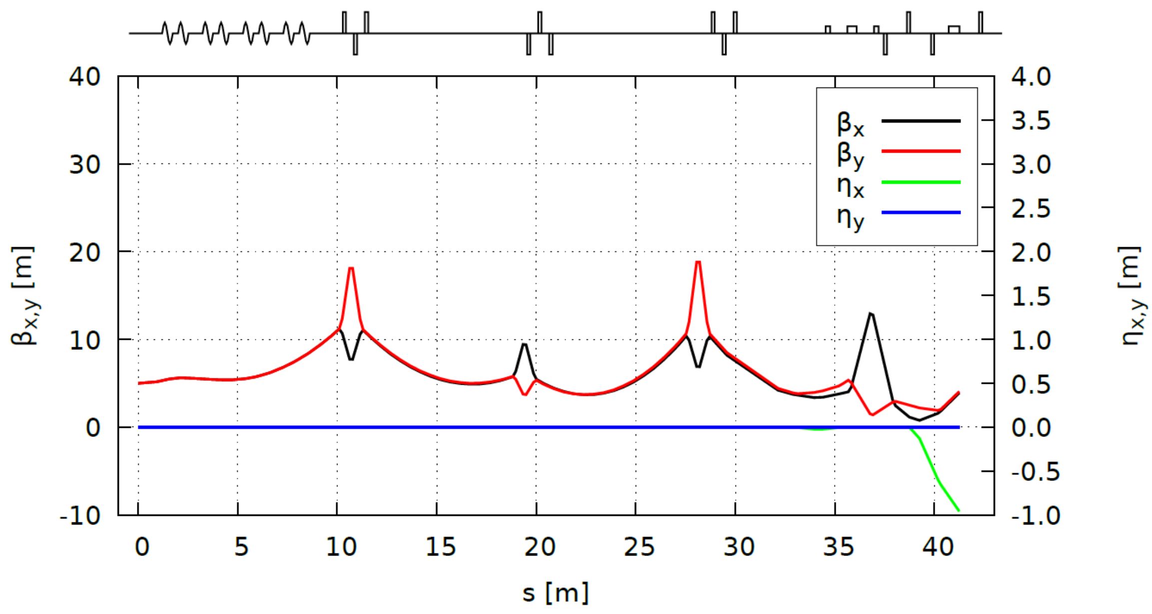

Figure 3: Twiss parameters for the optics solution at E_{final} = 18.5 MeV/c. Beam starts at the entrance to the cryomodule in zone 2 (s = 0 m) and extends 0.925 m downstream of the QX1X01 quadrupole in the isotope beamline (s = 41 m).

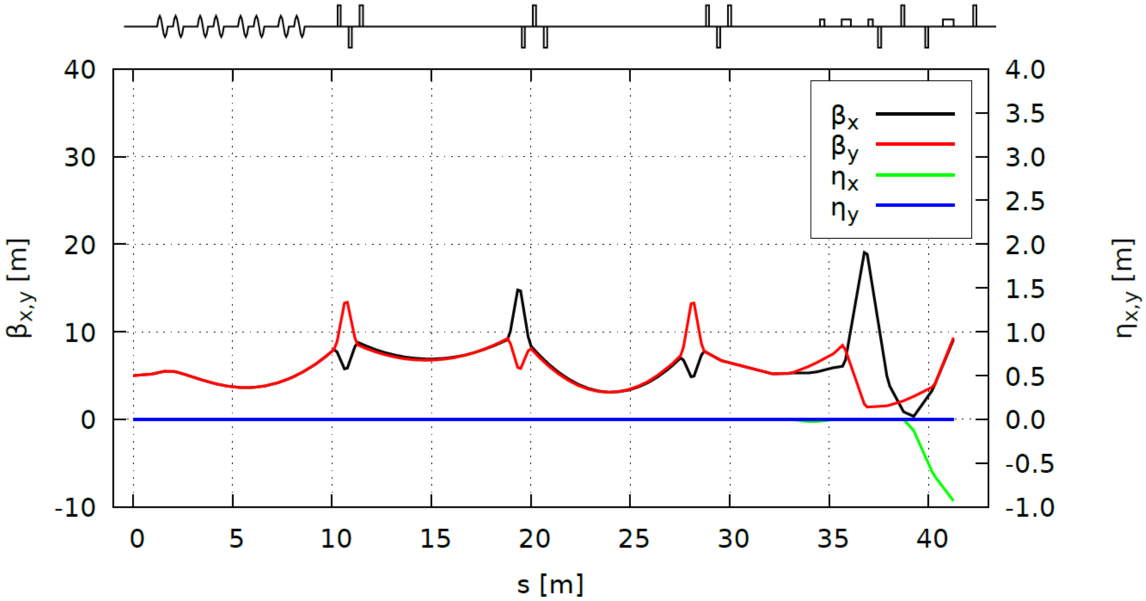

Figure 4: Twiss parameters for the optics solution at E_{final} = 40.0 MeV/c. Beam starts at the entrance to the cryomodule in zone 2 (s = 0 m) and extends 0.925 m downstream of the QX1X01 quadrupole in the isotope beamline (s = 41 m).

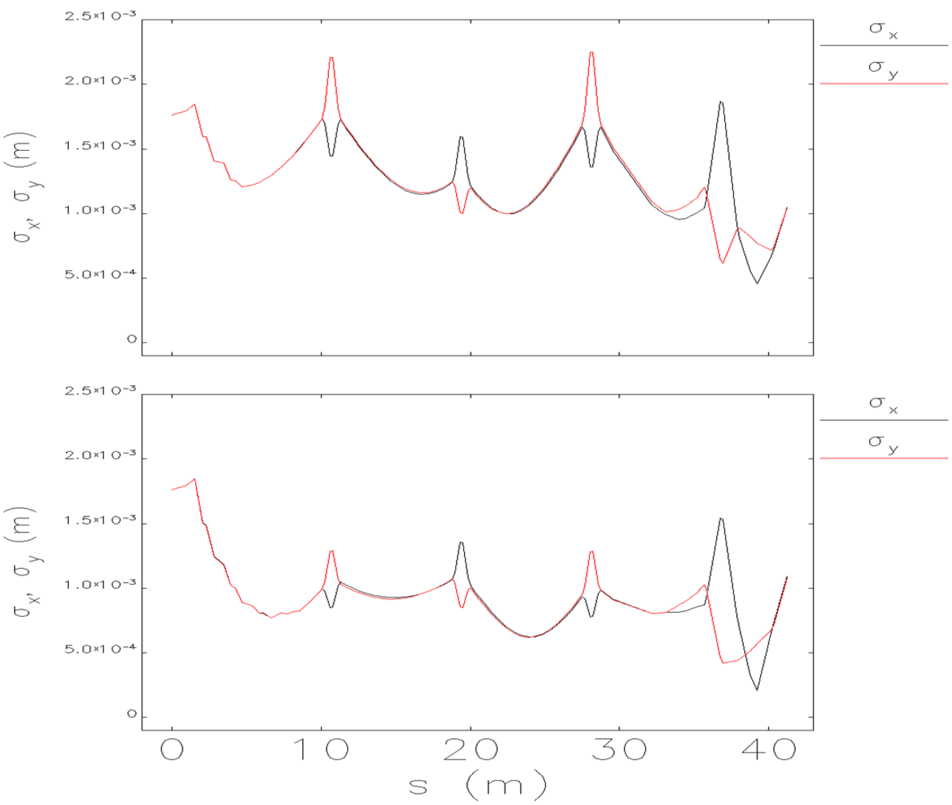

Figure 5: Transverse rms spot sizes for 18.5 MeV (top) and 40.0 MeV (bottom) showing round 1.1 mm spots incident on the Be window. The simulation results assume a beam with 10 mm-mrad (normalized) transverse emittances.

Table 1 lists the quadrupole fields required for machine setup at both 18.5 MeV and 40.0 MeV. (The quadrupole strengths in the 2F region have changed from the values listed in Table 2 of Ref [2] which described only the tuning up to, but not including, the isotope beamline).

Table 1: Quadrupole strengths for the quadrupoles in the 1F and beginning of the 2F region for two different energy setpoints. The quadrupoles are listed in the order that they are seen by the beam.

Quadrupole	**Integrated Field (G)**	
	18.5 MeV	*40.0 MeV*
QX1F03	300.83	650.45
QX1F03A	-571.12	-1234.85
QX1F03B	300.83	650.45
QX1F04	-324.90	-702.49
QX1F04A	610.92	1320.91
QX1F04B	-324.90	-702.49
QX1F05	350.82	758.52
QX1F05A	-654.43	-1414.98
QX1F05B	350.82	758.52
QX2F01	-402.65	-930.64
QX2F02	585.00	1224.85
QX2F03	-347.12	-350.24
QX1X01	175.87	440.30

Summary

We have described the design of a dedicated isotope target beamline that meets the beam size requirements at the Be window. The design has enough flexibility to generate spot sizes a factor of 2 larger if required (i.e. either to reduce the power density on the Be window or because the larger spots produce a better yield). Generating spot sizes larger than this requires prohibitively large beta functions which creates challenges in lossless CW beam transport. (We note in passing that if large beams are necessary, we could leverage an existing raster system which has been characterized with beam [4]).

References

[1] A. Hutton, D. Wells and J. Zweit, "Isotope Production R&D at Jefferson Lab's High-Power Electron Accelerators", Proposal in Response to DOE National Lab Announcement LAB 16-1588.
[2] C. Tennant "Beam Optics in the 1F Region to Support Isotope Production at the LERF", Jefferson Laboratory Technical Note 18-050 (2018).
[3] J. Gubeli, *e-mail correspondence October 24, 2018*.
[4] J. Grames, *private communication*.

Appendix A: Hardware Layout

Table A1 gives the hardware coordinates starting from the last injection merger dipole to the entrance of the Beryllium window. Element names with a "-C" denote the coordinates of the center point of the element. (Drift lengths are split into multiple shorter sections to better resolve plots of the Twiss parameters).

Table A1: Hardware coordinates for the LERF 2F region.

Element	Element Type	X	Y	Z	Theta	Phi	Psi
		{m}	{m}	{m}	{rad}	{rad}	{rad}
BEG	MARK	0.04	0.00	0.0000	-0.35	0.00	0.00
GV0F06A-C	SBEN	0.02	0.00	0.1026	-0.17	0.00	0.00
GV0F06A	SBEN	0.00	0.00	0.2052	0.00	0.00	0.00
GV0F06A-VP	VERTEX-POINT	0.00	0.00	0.0994	-0.35	0.00	0.00
D1F01A	DRIF	0.00	0.00	0.6948	0.00	0.00	0.00
ORIGIN	WATCH	0.00	0.00	0.6948	0.00	0.00	0.00
D0	DRIF	0.00	0.00	1.6224	0.00	0.00	0.00
DA1	DRIF	0.00	0.00	2.2562	0.00	0.00	0.00
R428	RFCA	0.00	0.00	2.7569	0.00	0.00	0.00
DA2	DRIF	0.00	0.00	3.0062	0.00	0.00	0.00
R427	RFCA	0.00	0.00	3.5069	0.00	0.00	0.00
DA3	DRIF	0.00	0.00	4.1668	0.00	0.00	0.00
R426	RFCA	0.00	0.00	4.6675	0.00	0.00	0.00
DA2	DRIF	0.00	0.00	4.9168	0.00	0.00	0.00
R425	RFCA	0.00	0.00	5.4175	0.00	0.00	0.00
DA3	DRIF	0.00	0.00	6.0774	0.00	0.00	0.00
R424	RFCA	0.00	0.00	6.5781	0.00	0.00	0.00
DA2	DRIF	0.00	0.00	6.8274	0.00	0.00	0.00
R423	RFCA	0.00	0.00	7.3281	0.00	0.00	0.00
DA3	DRIF	0.00	0.00	7.9880	0.00	0.00	0.00
R422	RFCA	0.00	0.00	8.4887	0.00	0.00	0.00
DA2	DRIF	0.00	0.00	8.7380	0.00	0.00	0.00
R421	RFCA	0.00	0.00	9.2387	0.00	0.00	0.00
DA1	DRIF	0.00	0.00	9.8724	0.00	0.00	0.00
DGAP	DRIF	0.00	0.00	10.4172	0.00	0.00	0.00
DG1	DRIF	0.00	0.00	10.7958	0.00	0.00	0.00
QX1F03-C	QUAD	0.00	0.00	10.8708	0.00	0.00	0.00
QX1F03	QUAD	0.00	0.00	10.9458	0.00	0.00	0.00
DG2	DRIF	0.00	0.00	11.3198	0.00	0.00	0.00
QX1F03A-C	QUAD	0.00	0.00	11.3948	0.00	0.00	0.00
QX1F03A	QUAD	0.00	0.00	11.4698	0.00	0.00	0.00
DG2	DRIF	0.00	0.00	11.8438	0.00	0.00	0.00
QX1F03B-C	QUAD	0.00	0.00	11.9188	0.00	0.00	0.00

QX1F03B	QUAD	0.00	0.00	11.9938	0.00	0.00	0.00
DG3	DRIF	0.00	0.00	12.3724	0.00	0.00	0.00
FIT1	MARK	0.00	0.00	12.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	12.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	13.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	13.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	14.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	14.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	15.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	15.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	16.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	16.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	17.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	17.8724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	18.3724	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	18.8724	0.00	0.00	0.00
DAB	DRIF	0.00	0.00	19.1324	0.00	0.00	0.00
DG1	DRIF	0.00	0.00	19.5110	0.00	0.00	0.00
QX1F04-C	QUAD	0.00	0.00	19.5860	0.00	0.00	0.00
QX1F04	QUAD	0.00	0.00	19.6610	0.00	0.00	0.00
DG2	DRIF	0.00	0.00	20.0350	0.00	0.00	0.00
QX1F04A-C	QUAD	0.00	0.00	20.1100	0.00	0.00	0.00
QX1F04A	QUAD	0.00	0.00	20.1850	0.00	0.00	0.00
DG2	DRIF	0.00	0.00	20.5590	0.00	0.00	0.00
QX1F04B-C	QUAD	0.00	0.00	20.6340	0.00	0.00	0.00
QX1F04B	QUAD	0.00	0.00	20.7090	0.00	0.00	0.00
DG3	DRIF	0.00	0.00	21.0876	0.00	0.00	0.00
FIT2	MARK	0.00	0.00	21.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	21.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	22.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	22.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	23.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	23.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	24.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	24.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	25.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	25.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	26.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	26.5876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	27.0876	0.00	0.00	0.00
DAA	DRIF	0.00	0.00	27.5876	0.00	0.00	0.00
DAB	DRIF	0.00	0.00	27.8476	0.00	0.00	0.00
DG3	DRIF	0.00	0.00	28.2262	0.00	0.00	0.00

QX1F05-C	QUAD	0.00	0.00	28.3012	0.00	0.00	0.00
QX1F05	QUAD	0.00	0.00	28.3762	0.00	0.00	0.00
DF2	DRIF	0.00	0.00	28.7502	0.00	0.00	0.00
QX1F05A-C	QUAD	0.00	0.00	28.8252	0.00	0.00	0.00
QX1F05A	QUAD	0.00	0.00	28.9002	0.00	0.00	0.00
DF2	DRIF	0.00	0.00	29.2742	0.00	0.00	0.00
QX1F05B-C	QUAD	0.00	0.00	29.3492	0.00	0.00	0.00
QX1F05B	QUAD	0.00	0.00	29.4242	0.00	0.00	0.00
DF1	DRIF	0.00	0.00	30.2752	0.00	0.00	0.00
FIT3	MARK	0.00	0.00	30.2752	0.00	0.00	0.00
D2EXTRA	DRIF	0.00	0.00	32.8448	0.00	0.00	0.00
DBCM	DRIF	0.00	0.00	33.6204	0.00	0.00	0.00
GV2F00-C	SBEN	0.00	0.00	33.7291	0.01	0.00	0.00
GV2F00	SBEN	0.00	0.00	33.8378	0.02	0.00	0.00
GV2F00-VP	VERTEX-POINT	0.00	0.00	33.7291	0.00	0.00	0.00
DREINJ1	DRIF	0.02	0.00	34.6530	0.02	0.00	0.00
GU2F00-C	SBEN	0.02	0.00	34.8704	0.00	0.00	0.00
GU2F00	SBEN	0.02	0.00	35.0878	-0.02	0.00	0.00
GU2F00-VP	VERTEX-POINT	0.03	0.00	34.8704	0.02	0.00	0.00
DREINJ1	DRIF	0.00	0.00	35.9030	-0.02	0.00	0.00
GV2F00A-C	SBEN	0.00	0.00	36.0117	-0.01	0.00	0.00
GV2F00A	SBEN	0.00	0.00	36.1204	0.00	0.00	0.00
FIT4	MARK	0.00	0.00	36.1204	0.00	0.00	0.00
GV2F00A-VP	VERTEX-POINT	0.00	0.00	36.0117	-0.02	0.00	0.00
DM11ALT	DRIF	0.00	0.00	36.3704	0.00	0.00	0.00
QX2F01-C	QUAD	0.00	0.00	36.4454	0.00	0.00	0.00
QX2F01	QUAD	0.00	0.00	36.5204	0.00	0.00	0.00
DM13	DRIF	0.00	0.00	37.4654	0.00	0.00	0.00
QX2F02-C	QUAD	0.00	0.00	37.5404	0.00	0.00	0.00
QX2F02	QUAD	0.00	0.00	37.6154	0.00	0.00	0.00
DM13B	DRIF	0.00	0.00	38.5984	0.00	0.00	0.00
QX2F03-C	QUAD	0.00	0.00	38.6734	0.00	0.00	0.00
QX2F03	QUAD	0.00	0.00	38.7484	0.00	0.00	0.00
DM14	DRIF	0.00	0.00	39.4384	0.00	0.00	0.00
DQ-C	SBEN	0.06	0.00	39.6837	0.26	0.00	0.00
DQ	SBEN	0.13	0.00	39.9289	0.51	0.00	0.00
DQ-VP	VERTEX-POINT	0.00	0.00	39.7005	0.00	0.00	0.00
D0X	DRIF	0.58	0.00	40.7350	0.51	0.00	0.00
QX1X01-C	QUAD	0.62	0.00	40.8003	0.51	0.00	0.00
QX1X01	QUAD	0.66	0.00	40.8657	0.51	0.00	0.00
D0X	DRIF	1.11	0.00	41.6717	0.51	0.00	0.00