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Subject Specification of quadrupoles for the SEBT, SEBT3, and SEBT3A/B beam lines of ISAC–II		

1. Introduction

R. Baartman[1)] recently specified the maximum apertures and gradients that are required for the two quadrupoles in the SEBT beam line downstream of the F5 location, and for those in the SEBT3 and SEBT3A/B beam lines of the ISAC–II experimental area. This report examines which of the available quadrupoles could be used at each location and attempts to make a reasonable choice of power supply in each instance.

Finally, a proposal for quadrupole and power supply assignment is made for these beam lines.

2. Specifications for the quadrupoles

Table 1 below lists the maximum gradients and minimum apertures required as specified in ref[1)] for the last two quadrupoles in the accelerator vault and in the SEBT and SEBT3 and SEBT3A/B beam lines.

Table 1 – SEBT quadrupole specifications of R. Baartman as of 2006/11/28

Name	Length (cm)	Gradient (T/m)	Maximum beam size (cm)
SEBT:Q21	32.5	12.7	3.6
SEBT:Q22	32.5	13.4	5.7
SEBT3:Q1,4	32.5	14.9	4.8
SEBT3:Q2,3	32.5	8.7	3.9
SEBT3A:Q1	32.5	11.5	5.4
SEBT3A:Q2	20.0	22.5	4.2
SEBT3A:Q3	32.5	20.3	6.0
SEBT3A:Q4	18.0	29.4	3.3
SEBT3B:Q1	32.5	16.6	5.7
SEBT3B:Q2	32.5	14.0	5.4
SEBT3B:Q3	40.6	11.5	9.6
SEBT3B:Q4	17.5	25.5	5.4

The gradients listed are for particles with a magnetic rigidity of 3 T–m, the maximum rigidity expected from the accelerators. In ref[1)] maximum beam half-sizes were calculated for an emittance of 4π mm–mr. These were then multiplied by a factor of three—a factor of two to obtain the maximum beam size for an emittance of 4π mm–mr and plus a factor of $2{\times}0.5$ to allow for larger emittance halo, misalignments, etc.—to determine the minimum quadrupole apertures. These numbers are listed in the rightmost column of table 1 and define the minimum values for the apertures of the quadrupoles at each location.

In table 2 we list the magnetic and electrical characteristics of the quadrupoles that are available at TRIUMF. The leftmost column lists the quadrupole type and, beside it in parentheses, the number of that type available. Magnetic characteristics of the Lx-type quadrupoles are taken from AECL specifications;

their electrical parameters are taken from their DANFYSIK nameplates. Magnetic and electrical parameters for the 4Q14/8 quadrupoles are taken from the TRIUMF Magnet Index.

Table 2 – Properties of quadrupoles available for ISAC–II

Type	Bore[a] (cm)	Gradient[b] (T/m)	L_{eff} [b] (cm)	Voltage[a] (V)	Current[a] (A)	Power[c] (kW)
L1 (1)	5.2	27(30)	17.5	27.0	93	2.51
L2 (6)	5.2	27(30)	32.5	37.0	88	3.26
L3 (2)	3.0	47	15.0	12.5	84	1.05
L4 (2)	3.0	47	20.0	15.0	84	1.26
L5 (5)	7.2	25	20.0	30.0	195	5.85
L6 (2)	7.2	25	32.5	40.0	195	7.80
L7 (5)	4.25	37(41)	32.5	28.0	86	2.41
L8 (8)	4.25	33(36)	17.5	22.0	80	1.76
4Q14/8[d] (5)	10.31	16.5	40.5	13.0	500	6.50

[a] – From DANFYSIK nameplate.
[b] – From AECL specifications; unparenthesized (parenthesized) numbers are nominal (maximum) values.
[c] – Nameplate power × nameplate current.
[d] – From TRIUMF Magnet Index data; Their B–I curve become non-linear above a current of $\sim$375 A.

We define V_2, I_2 and G_2 as the, voltage, current and gradient, respectively, that are listed on the nameplate of the quadrupole and that are reproduced in table 2. Then the power listed in table 2 is then simply

$$P_2 = V_2 \times I_2 \ .$$

It is now *assumed* that at a voltage V_2, a current I_2, and a power P_2 the *nominal* gradient G_2 is produced and that the *maximum* gradient listed in table 2 is produced by increasing the current delivered to a quadrupole. This is an overestimate because the nominal gradient is probably produced at a lower current. Consequently, the estimates of voltage, current, and power given below should provide a safety factor.

In the AECL specifications for the Lx-type quadrupoles some types are specified with both a nominal operating gradient and a maximum gradient. The former are listed in table 2 unparenthesized whereas the latter values, where available, are listed in parentheses. In this report it is further *assumed* that the values given for the gradient on the nameplate refer to the *nominal* operating gradient.

3. General comments on quadrupoles

In the following section the type of quadrupole required to meet the given specifications is discussed in detail. However, before making these calculations it is thought best to make some general comments in regarding the types available.

1. Given that the minimum aperture required is 3.3 cm and that their effective lengths are short, quadrupole types L3 and L4 will not in general be considered because of probable beam losses.

2. Quadrupole types L5 and L6 have the largest apertures—7.2 cm—and would be useful. However, the L5 type, of which there are 5 on hand, are short and only 2 of the L6 type with an effective length of 32.5 cm are available. Their "oddball" aperture will require a special beam tube and adapting flanges. Further, their power supply specifications are different. Both require (relatively) high-power supplies but Xantrex only lists a 30V, 200A supply as a standard component. Such a supply might work for the L5 quadrupoles but there would be no allowance for lead loss if full power were required.

3. The L7 and L8 series could be useful but their 4.25 cm aperture would again require special beam tube and adapter flanges. There are several places where these could be used but beam would fill over 90% of their apertures in a worst-case scenario.

4. The 4Q14/8 quadrupole is a standard 4-inch quadrupole of the primary beam lines at TRIUMF. Although listed above as requiring 13V, 500A supplies their standard supply at TRIUMF is a 22V, 500A, 11 kW unit from CTS. This, again, is not a type of supply listed by Xantrex—in fact no (DC) 500A supplies are listed by them. These quadrupoles are limited by a maximum gradient of approximately 16 T/m but would be useful where (relatively) long, large-bore quadrupoles are required. Power supplies could be obtained from the proton experimental hall.

5. It will be assumed that quadrupoles in the SEBT3A and SEBT3B lines will be fed from power supplies that are switched between one line and the other as required. Consequently, quadrupoles should be chosen such that this is possible. Ideally this would require quadrupole pairs SEBT3A:Q1 and SEBT3B:Q1, SEBT3A:Q2 and SEBT3B:Q2, SEBT3A:Q3 and SEBT3B:Q3, and SEBT3A:Q4 and SEBT3B:Q4 to be identical, although the individual pairs may be of different quadrupole types.
One could always use a supply that suits the largest aperture as a supply for the smaller quadrupole—assuming that the supply parameters are adequate. Another option could be to cross-couple quadrupoles other than noted above. Thus, for example, SEBT3A:Q1 and SEBT3B:Q2, etc. This, however, would complicate the control problem.

4. Comments on individual quadrupoles

Here we consider which quadrupole type(s) of quadrupole(s) could be used at each quadrupole location. Given that the requirements for each quadrupole listed in table 1 are different, this is done in a four-step process.

1. If the effective length of the quadrupole type under consideration L_{eff} differs from that of the type listed in table 1 $L_{eff,1}$, the required gradient G is obtained by scaling that required in table 1, G_1, by the ratio of these lengths:

$$G = \frac{L_{eff}}{L_{eff,1}} \times G_1 \ .$$

2. The required current I is obtained from G by scaling from the gradient and current, G_2 and I_2 respectively, listed in table 2 for the quadrupole type being considered:

$$I = \frac{G}{G_2} \times I_2 \ .$$

3. The required power P is found by scaling the power P_2 listed in table 2 by the ratio of the squares of I and I_2:

$$P = \left[\frac{I}{I_2}\right]^2 \times P_2 \ .$$

This assumes that the resistance of the quadrupole does not change as a function of excitation. Because the resistance increases because of I^2R heating this assumption also provides a (small) safety factor.

4. The required voltage V is then calculated by the ratio of the calculated power P and the calculated current I:

$$V = \frac{P}{I} \; .$$

Using the calculated current, voltage and power consideration is given to an 'optimum' power supply for that specific type of quadrupole. Optimum is put in single quotes because only Xantrex supplies are being considered (Klaus prefers to use them [2)]). As will be seen, in a number of cases it is necessary to pick a power supply of higher power than necessary because a lower-power supply is not an off-the-shelf Xantrex product.

Note: All existing power supplies for the ISAC beam-line quadrupoles are from Xantrex and are rated at 35 V, 85 A, 2.8 kW.

Consideration of individuals quadrupoles is now undertaken.

SEBT:Q21 The maximum beam size is 3.6 cm and the maximum gradient is 12.7 T/m. A **type L2** quadrupole is now installed at this location. As an example, an detailed treatment of steps 1 through 4 is given for this quadrupole. Calculations are abbreviated for the other quadrupoles.

1. (This step is normally omitted in a case like this when $L_{eff} = L_{eff,1}$.)

$$G = \frac{L_{eff}}{L_{eff,1}} \times G_1 = \frac{0.325\,\mathrm{m}}{0.325\,\mathrm{m}} \times 12.7\,\mathrm{T/m} = 12.7\,\mathrm{T/m} \; .$$

2. $$I = \frac{G}{G_2} \times I_2 = \frac{12.7\,\mathrm{T/m}}{27\,\mathrm{T/m}} \times 88\,\mathrm{A} = 41.4\,\mathrm{A} \; .$$

3. $$P = \left[\frac{I}{I_2}\right]^2 \times P_2 = \left[\frac{41.4\,\mathrm{A}}{88\,\mathrm{A}}\right]^2 \times 3.26\,\mathrm{kW} = 0.722\,\mathrm{kW} \; .$$

4. $$V = \frac{P}{I} = \frac{722\,\mathrm{W}}{41.4\,\mathrm{A}} = 17.5\,V \; .$$

These ratings are within the specifications of the Xantrex 35 V, 85 A, 2.8 kW supplies that are now used. Consequently, if such supplies are available one could be used for this quadrupole.

SEBT:Q22 The maximum beam size is 5.7 cm and the maximum gradient is 13.4 T/m. A **type L2** quadrupole with a 5.2 cm bore is installed. Either one accepts lower transmission or one uses a type L6 or L5 quadrupole.

For a **type L2** quadrupole a current of $88\,\mathrm{A} \times 13.4/25 = 47.2\,\mathrm{A}$ is required. This implies a power of $3.26\,\mathrm{kW} \times (47.2/88)^2 = 0.938\,\mathrm{kW}$ and a minimum voltage of $938\,\mathrm{W}/47.2\,\mathrm{A} = 19.9\,\mathrm{V}$. If lower transmission is accepted, an Xantrex 35 V, 85 A, 2.8 kW supply is suitable.

To meet the requirements specified, a **type L6** quadrupole requires a current of $195\,\mathrm{A} \times 13.4/25 = 105\,\mathrm{A}$ and a power of $7.8\,\mathrm{kW} \times (105/195)^2 = 2.26\,\mathrm{kW}$. The minimum voltage required would be $2,260\,\mathrm{W}/105\,\mathrm{A} = 21.5\,\mathrm{V}$. Xantrex makes a 40 V, 150 A supply that would be suitable. They also make a 30 V, 200 A supply that would also meet these specifications.

Because of its shorter effective length the **type L5** quadrupole requires a gradient of (13.4 T/m×32.5/20 = 21.8 T/m, implying a current of 195 A×21.8/25 = 170 A and a power of 5.85 kW×$(170/195)^2$ = 4.45 kW. The required minimum voltage would be 4,450 W/170 A = 26.2 V. An Xantrex 30 V, 200 A, 6 kW supply that would meet these specifications.

SEBT3:Q1/4 The maximum beam sizes and maximum gradients of these quadrupoles are 4.8 cm and 14.9 T/m respectively. Suitable quadrupole types would be L2s, L5s, or L6s.

Type L2 quadrupoles would meet these specifications although 4.8/5.2 = 0.923 or 92% of their apertures would be filled. Current requirements would be 88 A×14.9/27 = 48.6 A. Power requirements would be 3.3 kW×$(48.6/88)^2$ = 1.0 kW in which case the required voltages are 1,000 W/48.6 A = 20.6 V. An Xantrex 33 V, 85 A, 2.8 kW supply would be suitable.

Type L6 quadrupoles would require currents of 195 A×14.9/25 = 116 A and a power of 7.8 kW×$(116/195)^2$ = 2.76 kW, in which case the required minimum voltage would be 2,760 W/116 A = 23.8 V. An Xantrex 30 V, 200 A, 6 kW supply would meet these specifications.

Again, because of their shorter effective lengths, **type L5** quadrupoles would require currents of gradients of 14.9 T/m×(32.5/20) = 24.2 T/m, implying a current of 195 A×24.2/25 = 189 A and a power of 5.58 kW×$(189/195)^2$ = 5.50 kW. The required minimum voltage would be 5,500 W/189 A = 29.1 V. An Xantrex 30 V, 200 A supply would *just* meet these specifications, leaving no room for lead loss at maximum power level. Better choices would be one of an Xantrex 40 V, 300 A or their 60 V, 200 A 12 kW supplies.

SEBT3:Q2/3 Maximum beam sizes and maximum gradients of these quadrupoles are 3.9 cm and 8.7 T/m respectively. Suitable quadrupole types would be L2s, L5s, L6s, L7s, or L8s.

To produce the required gradients **type L2** quadrupoles would require a current of 88 A×8.7/25 = 32 A and a power of 3.3 kW×$(32/88)^2$ = 0.44 kW, in which case the required minimum voltage would be 440 W/32 A = 13.8 V. An Xantrex 20 V, 60 A, 1.2 kW or 35 V, 35 A, 1.2 kW supply is suitable.

Type L6 quadrupoles would require currents of 195 A×8.7/25 = 68 A, implying a power of 7.8 kW×$(68/195)^2$ = 0.95 kW. The required minimum voltage would be 950 W/68 A = 14.0 V. The conventional Xantrex 33 V, 85 A, 2.8 kW supplies should suffice.

Type L5 quadrupoles would require gradients of 8.7 T/m×32.5/20 = 14.1 T/m. This requires a current of 195 A×14.1/25 = 110 A and a power of 5.85 kW×$(110/195)^2$ = 1.86 kW, in which case the required minimum voltage would be 1,860 W/110 A = 16.9 V. An Xantrex 20 V, 150 A, 3 kW supply will suffice.

Because of their smaller aperture, **type L7** quadrupoles would be (3.9/4.25) = 0.918 or 92% filled with beam. Their required currents would be 86 A×8.7/37 = 20.2 A. The required powers would be 2.41 kW×$(20.2/86)^2$ = 0.133 kW. The required minimum voltage would be 133 W/20.2 A = 6.6 V. An Xantrex 20 V, 50 A, 1 kW supply will suffice.

Type L8 quadrupoles also would be 92% filled with beam because of their smaller apertures. They are shorter so their required gradients are 8.7 T/m×32.5/17.5 = 16.2 T/m, implying a current of 80 A×16.2/33 = 39.3 A and a power of 1.76 kW×$(39.3/80)^2$ = 0.425 kW. The required minimum voltage would be 425 W/39.3 A = 10.8 V. An Xantrex 20 V, 50 A, 1 kW supply will suffice.

SEBT3A/B:Q1 SEBT3A:Q1 has a maximum beam size of 5.4 cm and gradient of 11.5 T/m; those parameters of SEBT3B:Q1 are 5.7 cm and 16.6 T/m respectively. We treat these as a pair with maximum beam sizes and gradients corresponding to those the of SEBT3B:Q1 quadrupole. However, if type

L2 quadrupoles were installed there would be a beam loss of ∼5% in SEBT3A:Q1 and ∼10% in SEBT3B:Q1; other possibilities are types L5, L6 or 4Q14/8.

At the maximum gradient of SEBT3B:Q1, **Type L2** quadrupoles require currents of $88\,A \times (16.6\,\mathrm{T/m}/27\,\mathrm{T/m}) = 54.1\,\mathrm{A}$ and a power of $3.26\,\mathrm{kW} \times (54.1/88)^2 = 1.24\,\mathrm{kW}$. The minimum voltage require is $1,240\,\mathrm{W}/54.1\,\mathrm{A} = 23\,\mathrm{V}$. An Xantrex 33 V, 85 A, 2.8 kW supply would be adequate if some beam loss is accepted.

Type L5 quadrupoles require gradients of $16.6\,\mathrm{T/m} \times 32.5/20 = 27.0\,\mathrm{T/m}$, which is approximately 8% higher than their specifications. However, because the AECL specifications for most of their quadrupoles specify a "maximum" gradient that is approximately 10% higher than a "nominal" gradient, the values listed on the previous page. That being true for the L5s—something that can be checked at TRIUMF—it seem reasonable to at least explore the possibility of using type L5 quadrupoles.

Thus the current necessary to produce a gradient of 27.0 T/m is $195\,\mathrm{A} \times 27/25 = 211\,\mathrm{A}$. This corresponds to a power of $5.85\,\mathrm{kW} \times (211/195)^2 = 6.85\,\mathrm{kW}$ at a voltage of $6,850\,W/211\,A = 32.5\,\mathrm{V}$. An Xantrex 40 V, 300 A, 12 kW supply would be adequate.

Type L6 quadrupoles require currents of $195\,\mathrm{A} \times 16.6/25 = 130\,\mathrm{A}$ corresponding to a power of $7.8\,\mathrm{kW} \times (130/195)^2 = 3.5\,\mathrm{kW}$. The required voltage is then $3,500\,W/130\,A = 26.7\,\mathrm{V}$. Thus either a 40 V, 150 A, 6 kW unit or a 30 V, 200 A, 6 kW unit from Xantrex would suffice.

Because of a longer effective length, a **type 4Q14/8** quadrupole requires a gradient of $16.6\,\mathrm{T/m} \times (0.325\,\mathrm{m}/0.405\,\mathrm{m} = 13.4\,\mathrm{T/m}$. This implies a current of $500\,\mathrm{A} \times (13.4/16.5) = 406\,\mathrm{A}$ and a power of $6.5\,\mathrm{kW} \times (406/500)^2 = 4.29\,\mathrm{kW}$. The required minimum voltage is then $4,290\,W/406\,A = 10.6\,\mathrm{V}$. Xantrex lists a 20 V, 600 A, 12 kW supply that would be suitable, but a CTS 22 V, 500 A, 11 kW supply could be used because such is available from the Proton Hall.

SEBT3A/B:Q2 Based on an effective length of 20 cm SEBT3A:Q2 has a maximum beam size of 4.2 cm and a maximum gradient of 22.5 T/m; for an effective length of 32.5 cm similar parameters for SEBT3B:Q2 are 5.4 cm and 14.0 T/m respectively. These specifications are so dissimilar that one's first reaction is that these quadrupoles should be of different types.

Quadrupole **SEBT3A:Q2** could be any quadrupole type except L3 and L4. If type L7 or L8 were used beam would completely fill the quadrupole aperture. Consequently, the L7 or L8 option will be ignored.

A **type L1** quadrupole requires a gradient of $22.5\,\mathrm{T/m} \times 20/17.5 = 25.7\,\mathrm{T/m}$ because of its shorter effective length. This implies a current of $93\,\mathrm{A} \times 25.7/27 = 88.6\,\mathrm{A}$ and corresponds to a power of $2.51\,\mathrm{kW} \times (88.6/93)^2 = 2.28\,\mathrm{kW}$. The required voltage is then $2,280\,W/88.6\,A = 25.7\,\mathrm{V}$. A 35 V, 85 A, 2.8 kW unit from Xantrex has the voltage capability but it is ∼5% low in current capacity. One of their higher power 30 V–200 A, 40 V–150 A, or 60 V–100 A 6 kW units would be more suitable.

A **type L2** quadrupole requires a gradient of $22.5\,\mathrm{T/m} \times 20/32.5 = 13.9\,\mathrm{T/m}$ because of its longer effective length. This implies a current of $88\,\mathrm{A} \times 13.9/27 = 45.3\,\mathrm{A}$ corresponding to a power of $3.26\,\mathrm{kW} \times (45.3/88)^2 = 0.864\,\mathrm{kW}$. The required voltage is then $864\,W/45.3\,A = 19.1\,\mathrm{V}$. An Xantrex 20 V, 60 A, 1.2 kW supply is sufficient but there would be no allowance at maximum power for lead loss. One of their 33 V, 85 A, 2.8 kW or 40 V, 70 A, 2.8 kW supplies would be suitable for this quadrupole.

A **type L5** quadrupole requires a current of $195\,\mathrm{A} \times 22.5/25 = 175.5\,\mathrm{A}$ corresponding to a power of $5.85\,\mathrm{kW} \times (175.5/195)^2 = 4.74\,\mathrm{kW}$. The required voltage is then $4,740\,W/175.5\,A = 27.0\,\mathrm{V}$. A 30 V, 200 A, 6 kW supply is required in this instance.

Because types L2 and L6 quadrupoles have the identical effective lengths, a **type L6** quadrupole also requires a gradient 13.9 T/m. This implies a current of 195 A×13.9/25 = 108.5 A corresponding to a power of 7.80 kW×$(108.5/195)^2$ = 2.42 kW. The required voltage is then $2,420\,W/108.4\,A = 22.3$ V. A 30 V, 200 A, 6 kW supply is required for a type L6 quadrupole.

Quadrupole **SEBT3B:Q2** could be any quadrupole of type L1, L2, L4, L5, or L6. If type L1 or L2 were used there would be beam spilled in the quadrupoles when operated under the maximum conditions specified. However, such operation will be considered.

A **type L1** quadrupole requires a gradient of 14.0 T/m×32.5/17.5 = 26.0 T/m because of its shorter effective length. This implies a current of 93 A×26/27 = 89.6 A corresponding to a power of 2.51 kW×$(89.6/93)^2$ = 2.33 kW. The required voltage is then $2,330\,W/89.6\,A = 26.0$ V. A 'standard' 33 V, 85 A, 2.8 kW supply meets the voltage requirement but falls ∼6% short on the current. One could be used if a lower value for the maximum gradient is accepted but a more robust supply would be better. The smallest available from Xantrex would be their 30 V, 200 A, 6 kW unit.

A **type L2** quadrupole requires a current of 88 A×14/27 = 45.7 A corresponding to a power of 3.26 kW×$(45.7/88)^2$ = 0.88 kW. The required voltage is then $880\,W/45.7\,A = 19.3$ V. An Xantrex 35 V, 85 , 2.8 kW supply is suitable in this case.

A **type L5** quadrupole requires a gradient of 14.0 T/m×32.5/20 = 22.8 T/m because of its shorter effective length. This implies a current of 195 A×22.8/25 = 178 A corresponding to a power of 5.85 kW×$(178/195)^2$ = 4.88 kW. The required voltage is then $4,880\,W/178\,A = 27.5$ V. Thus a 30 V, 200 A, 6 kW supply is applicable for this quadrupole.

A **type L6** quadrupole requires a current of 195 A×14/25 = 109.2 A corresponding to a power of 7.80 kW×$(109.2/195)^2$ = 2.45 kW. The required voltage is $2,450\,W/109.2\,A = 22.5$ V. A 30 V, 200 A, 6 kW or 40 V, 150 A, 6 kW supply from Xantrex is suitable in this case.

From the above it is seen that if quadrupoles SEBT3A:Q2 and SEBT3B:Q2 each are of the type L5 a single 30 V, 200 A, 6 kW Xantrex supply could be switched between them. From that point of view this would be an appropriate solution.

SEBT3A/B:Q3 Quadrupole SEBT3A:Q3 requires a maximum beam size of 6.0 cm and a maximum gradient of 20.3 T/m; similar parameters for SEBT3B:Q3 are ≥10 cm and 11.5 T/m respectively. Of the quadrupoles available only types L6 and 4Q14/8 satisfy the requirements for SEBT3A:Q3 and only type 4Q14/8 satisfies those for SEBT3B:Q3. Because it is preferable to be able to switch a supply between the two beam lines, use of a type 4Q14/8 for each quadrupole is desirable.

For SEBT3A:Q3 a **type L6** quadrupole requires a current of 195 A×20.3/25 = 158.4 A corresponding to a power of 7.80 kW×$(158.4/195)^2$ = 5.15 kW. The required voltage is $5,150\,W/158.4\,A = 32.5$ V. The choice of power supply for this case is a toss-up. The voltage is 8% too low if a 30 V, 200 A, 6 kW supply were used; there would also be no provision for lead loss. The current is 6% too low if a 40 V, 150 A, 6 kW supply were used. To reach the required voltage and current an Xantrex 40 V, 300 A, 12 kW supply or a 60 V, 200 A, 12 kW supply is necessary.

A **type 4Q14/8** quadrupole at this location requires a gradient of 20.3 T/m×32.5/40.5 = 16.3 T/m because of its longer effective length. This implies a current of 500 A×16.3/16.5 = 494 A corresponding to a power of 6.50 kW×$(494/500)^2$ = 6.35 kW. The required voltage is then $6,350\,W/494\,A =$ 12.9 V. No supply listed by Xantrex meets these requirements. Consequently, it would be best to use one of the 22 V, 560 A, 22 kW supplies from beam lines 4A/B.

For SEBT3B:Q3 a **type 4Q14/8** quadrupole requires a current of 500 A×11.5/16.5 = 349 A corresponding to a power of 6.50 kW×$(349/500)^2$ = 3.17 kW. The required voltage is then

$3,170\,W/349\,A = 9.10\,\mathrm{V}$.

The only supply listed by Xantrex meeting these requirements is their 30 V, 400 A, 12 kW supply. Again, it would be best to use one of the 22 kW supplies from beam lines 4A/B. $3,170\,W/349\,A = 9.10\,\mathrm{V}$. The only supply listed by Xantrex meeting these requirements is their 30 V, 400 A, 12 kW supply. Again, it would be best to use one of the 22 kW supplies from beam lines 4A/B.

SEBT3A/B:Q4 Optics requires that these quadrupoles be short. SEBT3A:Q4 with an effective length of 18.0 cm produces a maximum beam size of 3.3 cm at a maximum gradient of 29.4 T/m; similar parameters for SEBT3B:Q4 with an effective length of 17.5 cm are 5.4 cm and 25.5 T/m respectively. Given that the quadrupoles must be short, only types L1, L3, L4, L5, and L8 can be used. Of the apertures of types L3 and L4 are too small and these will be ignored. If types L1 and L5 are used it would be necessary to operate them at power levels 10%–20% above their *nominal* ratings. A type L8 can only be used for quadrupole SEBT3A:Q4.

For SEBT3A:Q4 a **type L1** quadrupole requires a gradient of $29.4\,\mathrm{T/m}\times18/17.5 = 30.24\,\mathrm{T/m}$, which is slightly above the maximum gradient specified. However, assuming that this gradient can be reached the current required would be $93\,\mathrm{A}\times30.24/27 = 104.2\,\mathrm{A}$, implying a power of $2.51\,\mathrm{kW}\times(104.2/93)^2 = 3.15\,\mathrm{kW}$. The required voltage is $3,040\,\mathrm{W}/104.2\,A = 30.3\,\mathrm{V}$. This calls for a 40 V, 150 , 6 kW power supply.

A **type L5** quadrupole requires a gradient of $29.4\,\mathrm{T/m}\times18/20 = 26.5\,\mathrm{T/m}$. This requires a current of $195\,\mathrm{A}\times26.5/25 = 206.7\,\mathrm{A}$ and a power of $5.85\,\mathrm{kW}\times(206.7/195)^2 = 6.57\,\mathrm{kW}$. The voltage required is $6,570\,\mathrm{W}/206.7\,A = 31.8\,\mathrm{V}$. This calls for a 40 V, 300 A, 12 kW power supply.

A **type L8** quadrupole requires a gradient of $29.4\,\mathrm{T/m}\times18/17.5 = 30.24\,\mathrm{T/m}$. This requires a current of $88\,\mathrm{A}\times30.24/33 = 80.7\,\mathrm{A}$ and a power of $1.76\,\mathrm{kW}\times(80.7/88)^2 = 1.48\,\mathrm{kW}$. The voltage required is $1,480\,\mathrm{W}/80.7\,A = 18.4\,\mathrm{V}$. A Xantrex model XMP2600–2.4Kw unit *almost* meets these requirements with its 0–8 V to 0–160 V, 1.25 A to 80 A output. What is really needed is a 30 V, 100 A, 3 kW supply. The closest Xantrex supply listed appears to be either a 40 V, 150 A, 6 kW power supply or a 60 V, 100 A, 6 kW unit.

For SEBT3B:Q4 a **type L1** quadrupole requires a current of $93\,\mathrm{A}\times25.5/27 = 87.8\,\mathrm{A}$ implying a power of $2.51\,\mathrm{kW}\times(87.8/93)^2 = 2.24\,\mathrm{kW}$. The required voltage is $2,240\,\mathrm{W}/87.8\,A = 25.5\,\mathrm{V}$. At a minimum this calls for a 30 V, 200 A, 6 kW power supply; a 40 V, 150 A, 6 kW power supply would be better.

A **type L5** quadrupole requires a current of $195\,\mathrm{A}\times25.5/25 = 199\,\mathrm{A}$ and a power of $5.85\,\mathrm{kW}\times(199/195)^2 = 6.09\,\mathrm{kW}$. The voltage required is $6,090\,\mathrm{W}/199\,\mathrm{A} = 30.6\,\mathrm{V}$. A 30 V, 200 A, 6 kW power supply is marginal and does not allow for any lead loss. A 40 V, 250 A, 10 kW power supply would be ideal but, restricting ourselves to Xantrex supplies a 40 V, 300 A, 12 kW power supply is called for.

4.1 Summary of the results of this section

Table 3 summarizes the results of this section. For each of the quadrupoles of the beam lines most (but not all) possibilities are listed. In each case, a (albeit brief) comment is made as to the appropriateness of the given type of quadrupole.

At this point, however, no choice is ruled out except for the use of the L3 and L4 types and that is done because of the smaller apertures. Further, except for the type 4Q14/8 quadrupoles for which a CTS 22 kW supply is necessary, no attempt has been made to optimize the quadrupole choices as to their power supplies. An attempt to do so will be made in the following section.

Table 3 – Summary of calculations for individual quadrupoles

Quadrupole location	Type	Power Supply (Xantrex)	Comments
SEBT:Q21	L2	35 V, 85 A, 2.8 kW	Already installed, good choice
SEBT:Q22	L2	33 V, 85 A, 2.8 kW	Already installed, 10% beam loss at largest emittance
	L5	30 V, 200 A, 6 kW	Good but requires replacement of existing L2 quadrupole
	L6	40 V, 150 A, 6 kW	Good but requires replacement of existing L2 quadrupole
SEBT3:Q1/4	L2	33 V, 85 A, 2.8 kW	Good but 92% of aperture filled
	L5	60 V, 200 A, 12 kW	Good
	L6	30 V, 200 A, 6 kW	Good
SEBT3:Q2/3	L2	20 V, 60 A, 1.2 kW	Good
	L5	20 V, 150 A, 3 kW	Good
	L6	33 V, 85 A, 2.8 kW	Good; 75% of aperture filled
	L7	20 V, 50 A, 1 kW	Good but 92% of aperture filled
	L8	20 V, 50 A, 1 kW	Good but 92% of aperture filled
SEBT3A/B:Q1	L2	33 V, 85 A, 2.8 kW	Good but has 5% loss in SEBT3A:Q1 and 10% loss in SEBT3B:Q1
	L5	40 V, 300 A, 12 kW	Good but requires ∼10% higher gradient than nominal
	L6	40 V, 150 A, 6 kW	Good
	4Q14/8	20 V, 600 A, 12 kW	Good; Xantrex supply
		22 V, 500 A, 11 kW	Good; CTS supply
SEBT3A/B:Q2	L1	30 V, 200 A, 6 kW	Good, no loss in SEBT3A:Q2 and 10% loss in SEBT3B:Q2
	L2	33 V, 85 A, 2.8 kW	Good, no loss in SEBT3A:Q2 and 5% loss in SEBT3B:Q2
	L5	30 V, 200 A, 6 kW	Good
	L6	30 V, 200 A, 6 kW	Good
SEBT3A/B:Q3	4Q14/8	22 V, 500 A, 11 kW (CTS supply)	Only possible quadrupole and supply if supply is switched between SEBT3A and SEBT3B
SEBT3A/B:Q4	L1	40 V, 150 A, 6 kW	Only one available, suitable for SEBT3B:Q4
	L5	40 V, 300 A, 12 kW	Good but requires ∼6% higher gradient than nominal for SEBT3A:Q4
	L8	40 V, 150 A, 6 kW	Suitable for SEBT3A:Q4 only

5. Suggested assignment of quadrupoles

Given that there are a limited number of some types of quadrupoles it is important that quadrupoles be assigned to specific locations in such a manner as to not compromise (unknown) future tunes for beam delivery to the experimental area. Consequently, types of quadrupoles of which there are a limited quantity should be assigned first and these should be assigned to the most critical areas.

Further, selection and assignment of quadrupoles will depend on how strongly one adheres to the requirements given in table 1. In the following it is assumed that these are followed as closely as possible. Thus quadrupoles and their types are selected for *maximum* transmission.

In the opinion of the author the most critical area is the selection of the quadrupoles located between the two dipoles—SEBT3:Q1/4 and SEBT3:Q2/3. There are a minimum of three tunes for these quadrupoles—a 'low' resolution tune for SEBT3A and 'high' and 'low' resolution tunes for SEBT3B. These quadrupoles should have large apertures, be capable of reaching high gradients, and be (relatively) long.

From table 3 it is seen that type L6 quadrupoles meet these criteria for the SEBT3:Q1/4 and SEBT3:Q2/3 pairs. However, only two of this type of quadrupole are available and another type of quadrupole must be used for one of the pairs. Again it is seen from table 3 that either of type L2 or L5 would be suitable. It is suggested that **type L6** quadrupoles be installed for quadrupoles **SEBT3:Q1/4** because the maximum beam size in them is greater than 5 cm.

The choice between types L2 and L5 for quadrupoles SEBT3:Q2/3 is difficult. At maximum emittance beam fills ∼75% of the aperture of a type L2 quadrupole but only 54% of that of a type L5 quadrupole. For the requirements of table 1 a type L2 quadrupole reaches 32% of its maximum gradient whereas a type L5 quadrupole is required to reach 56% of its maximum gradient. Were L2 quadrupoles used operation with their 35 V, 35 A, 1.2 kW supply would be less expensive than operation of type L5 quadrupoles with their 20 V, 150 A, 3 kW supply.

It is unlikely that the gradients of these two quadrupoles would double in another tune. *For maximum transmission* quadrupoles SEBT3:Q2/3 should be of type L5. However, type L2 quadrupoles are an excellent alternative if the possibility of future beam loss can be tolerated. Consequently, it is recommended that the risk be taken and that **type L2** quadrupoles be initially installed for quadrupoles **SEBT3:Q2/3**

The quadrupole pair SEBT3A/B:Q4 is also important because these quadrupoles must be short for optical reasons. It appears that these quadrupoles should be of different types. It is recommended that quadrupole **SEBT3A:Q4** be of **type L8** and quadrupole **SEBT3B:Q4** be of **type L5**.

Turning now to the remaining quadrupoles we now first consider SEBT3:Q22. Given that the two type L6 quadrupoles have been assigned to quadrupoles SEBT3:Q1/4, the remaining choice is between a type L2 and a type L5. The former type is already in position; however, a 10% beam loss will occur at large emittances. Installation of the latter type would be better because no beam is lost, but this requires that the existing quadrupole be replaced. Because beam loss is predicted it is recommended that the existing quadrupole **SEBT3:Q22** be removed and replaced with a quadrupole of **type L5**.

Use of type L2 quadrupoles for the quadrupole pair SEBT3A/B:Q1 would result in beam loss at large emittances and the the gradient required of type L5 quadrupoles exceeds that of their specification by ∼10%. Further, only five quadrupoles of this type are available and one has been assigned to quadrupole SEBT3B:Q4. Consequently, the only suitable quadrupole type remaining that will satisfy both aperture and gradient requirements is type 4Q14/8. Therefore it is suggested that the each of the quadrupole pair **SEBT3A/B:Q1** be of **type 4Q14/8**.

To avoid beam loss in the quadrupole pair SEBT3A/B:Q2 table 3 indicates that these quadrupoles should be type L5s. Therefore it is recommended that **type L5** quadrupoles be installed for the **SEBT3A/B:Q2** quadrupole pair.

The only suitable quadrupole for SEBT3B:Q3 is a type 4Q14/8. Because this type will also satisfy the requirements of quadrupole SEBT3A:Q3, it is recommended that quadrupoles **SEBT3A/B:Q3** each be of **type 4Q14/8**.

A summary of quadrupole disposition for *maximum* transmission is given in table 4 below. In some cases suggestions for other than Xantrex power supplies are given. Data for Power*Ten* power supplies was provided by Klaus Reiniger[2)].

Table 4 – Summary of quadrupole disposition for *maximum* transmission.

Quadrupole location	Type	Power Supply	Comments
SEBT:Q21	L2	35 V, 85 A, 2.8 kW	Already installed
SEBT:Q22	L5	30 V, 200 A, 6 kW	Requires replacement of existing L2 quadrupole
SEBT3:Q1/4	L6	30 V, 200 A, 6 kW 25 V, 132 A, 3.3 kW	Xantrex supply Power*Ten* supply; only 4% allowance for voltage line loss
SEBT3:Q2/3	L2	20 V, 60 A, 1.2 kW 30 V, 66 A, 2 kW	Xantrex supply Power*Ten* supply
SEBT3A/B:Q1	4Q14/8	22 V, 500 A, 11 kW 15 V, 440 A, 6.6 kW	CTS supply Power*Ten* supply
SEBT3A/B:Q2	L5	30 V, 200 A, 6 kW	Xantrex supply
SEBT3A/B:Q3	4Q14/8	22 V, 500 A, 11 kW 20 V, 500 A, 10 kW	CTS supply Power*Ten* supply
SEBT3A:Q4	L8	40 V, 150 A, 6 kW 30 V, 100 A, 3 kW	Xantrex supply Power*Ten* supply
SEBT3B:Q4	L5	40 V, 300 A, 12 kW 40 V, 250 A, 10 kW	Xantrex supply Power*Ten* supply

5.1 Discussion of the disposition given above

It is important to reiterate again that the choices of quadrupoles given above were made to meet the requirements set out in table 1. Clearly if those restrictions are not taken as cast in stone, other distributions are possible. However, given the choices that have been made here, there are (at least) two of them that could be questioned.

First, the choice of a type L5 quadrupole for SEBT:Q22 requires the removal of the existing type L2 quadrupole and its power supply. While it is true that a type L2 quadrupole will satisfy most of the requirements, there would be beam loss in it when dealing with emittances larger than 4π mm-mr. With a type L5 quadrupole this would not happen.

Second, the choice of type 4Q14/8 quadrupoles for the SEBT3A/B:Q1 quadrupole pair is arguable. However, given the limited number of available quadrupole types this seems to be a reasonable choice.

Overall, it is felt that these choices would provide systems that would meet the stringent requirements given in table 1 and, should they be relaxed, will provide a suitable starting point for discussion of a different distribution of quadrupoles.

6. Discussion

This note has presented a suggestion for the distribution of quadrupoles in the beam lines of the ISAC–II experimental hall. The distribution has been based on the requirements given in table 1 and on the various types of quadrupoles that are available at TRIUMF. Should the requirements of table 1 be relaxed, this note should serve as a basis from which an alternate distribution of quadrupoles may be found.

References

1. R. Baartman, *E-mail to G. Stinson*, TRIUMF, 28 November, 2006.
2. K. Reiniger,*Private communication*, TRIUMF, December, 2006.