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ISAC spherical benders and 9° deflector error

R. Baartman

TRIUMF

Abstract: Working tunes show a systematic difference compared with the theoretical setting of the electrode potentials. This is likely due to a slight 3 to 4% errors in the effective length.

4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3 Tel: 604 222-1047 Fax: 604 222-1074
www.triumf.ca

1 45° Benders

Note that this section includes the 36° benders as well. These work on the exact same principal and are the same shape as the 45° benders, but simply shortened by 9°. The shorter ones have separate 9° deflectors that allow the benders to switch quickly. The deflectors are in the next section.

1.1 Theory

The 45° electrostatic benders have spherical electrodes. The trajectory is intended to be midway between the two electrodes and has a radius of $R = 10$ inches. The potentials must provide the electric field to keep a particle along this radius, and thus

$$qE_r = mv^2/R = 2K/R \tag{1}$$

where K is the kinetic energy. For a beam that has kinetic energy per charge of 60 kV we thus have that at intended radius R, $E_r = 12\,\mathrm{kV/in}$.

As the electrodes are spherical, the electric field is everywhere except at entrance and exit, the same as that due to a Coulomb potential, i.e., proportional to $1/r$:

$$V(r) = C_1 - C_2/r \tag{2}$$

To avoid the beam changing energy upon entry and exit, the central trajectory is to be at ground, and thus $C_1 = C_2/R$ and $V(r) = C_1(1-R/r)$, and to achieve the central electric field, we need $-\,\mathrm{d}V/\,\mathrm{d}r|_{r=R} = 12\,\mathrm{kV/in}$ so $C_1 = 120\,\mathrm{kV}$.

The gap between electrodes is 1.5 inches, so the radii of the electrodes are 9.25 and 10.75 inches. With $V(r) = 120\,\mathrm{kV}(1 - 10\,\mathrm{in}/r)$, The inner electrode has potential $-9.73\,\mathrm{kV}$, and the outer has $8.37\,\mathrm{kV}$.

These are the original “theoretical” settings of the bender electrode voltages. In particular, the average of the negative of the inner electrode and the outer electrode is

$$V_{\mathrm{avg}} = (-V(9.25\mathrm{in}) + V(10.75\mathrm{in}))/2 = 9.05\,\mathrm{kV}. \tag{3}$$

1.2 Data

All the ISAC tunes from years 2005, 2021, 2022, 2023 were downloaded and analyzed. The ‘snap’ files were searched for the bias voltage and the appropriate bender voltages. All results were normalized by dividing the latter by the former and multiplying by 60 kV. In other words, all results were normalized to an energy per charge of 60 kV.

Histograms of $V_{\rm avg}$ are shown in the figures. These support a conclusion that $V_{\rm avg} = 9.3$ kV; 2.7% higher than theory. Note that the earlier year, 2005, still

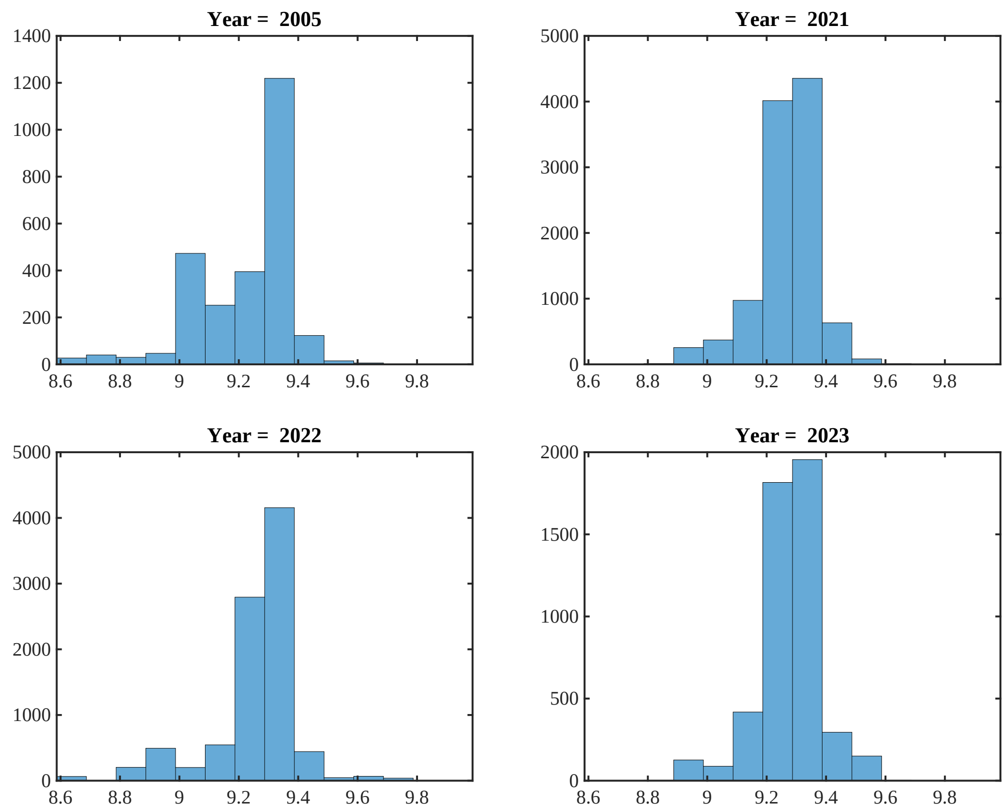

Figure 1: Histograms of $V_{\rm avg}$.

showed some vestiges of the original "theory" value of 9.05 kV that had been recommended by me, but the 3 most recent years show a solid preferred value near 9.3 kV.

There remains a question of whether individual benders prefer their own individual values, perhaps due to local errors.

In the following tables, 13 of the 18 entries list two benders. These are the combinations where one bend section module bends the beam 90°. In these cases, the inner electrodes have a common (negative) power supply, while the outers have separate positive power supplies. The three voltages are combined by first taking the average of the two independent electrodes and then taking the average of this quantity and the strength (absolute value) of the positive power supply setting. In the single bender cases, $V_{\rm avg}$ is calculated as in eqn. 3.

The third column is the average of $V_{\rm avg}$ across all the saved 'snap' tunes and the fourth column is the standard deviation. The fifth column is the difference of third column from 9.287 kV, divided by the fourth column.

Table 1: Year 2021: total samples = 10710, average of all = 9.267 kV.

Bender	No. of samples	Avg. of $V_{\rm avg}$ (kV)	Std. Dev. (kV)	Rel. Error
`IOS:B1A`	950	9.171	0.158	−0.7
`IMS:B18`	1462	9.345	0.043	1.3
`IMS:B30,B33`	1302	9.292	0.049	0.1
`ILT:VB3,VB6`	1302	9.242	0.095	−0.5
`ILZ:VB1,VB4`	4	9.285	0.021	−0.1
`ILT:VB21,VB24`	830	9.292	0.052	0.1
`ILE:B1,B4`	585	9.292	0.032	0.2
`ILT:B43,B46`	1355	9.267	0.053	−0.4
`IOS:B10,B13`	1195	9.236	0.054	−1.0
`ILE2:B21`	454	9.163	0.201	−0.6
`CSB:B1,B4`	116	9.353	0.084	0.8
`CSB:B15,B16`	119	9.193	0.097	−1.0
`CSB:VB17,VB20`	119	9.202	0.215	−0.4
`ILE1:B1,B4`	170	9.358	0.019	3.7
`ILE1B:B1,B4`	170	9.324	0.056	0.7
`ILE2A:B7`	39	9.301	0.000	∞
`ILE2:B1,B10`	454	9.287	0.112	0.0
`ILE2T:B1`	84	9.209	0.143	−0.5

Under normal ('normal' in the gaussian sense) conditions, one expects two standard deviations away from the mean to contain $\sim 95\%$ of the cases. So these statistics show that except for one case, these data appear to be quite random, with none of the benders needing their own particular value. Thus, on this basis, the recommended setting for benders is $V_{\rm avg} = 9.3\,{\rm kV}$. Or adhering to the desired split in the voltages needed to keep the central trajectory at ground, we have:

$$V_{\rm inner} = -10.00\,{\rm kV,\ and\ } V_{\rm outer} = +8.60\,{\rm kV}. \tag{4}$$

The cause of this change from 9.05 kV to 9.3 kV may be simply due to the effective length of the bender. There was no detailed calculation; the location of the skimmers (field clamps) were set according to a chart provided in one of H. Wollnik's papers. As the length of each is $\pi/4 \times 254$ mm it would correspond to the effective field boundary to be displaced by 2.7 mm at each end.

Table 2: Year 2022: total samples = 9059, average of all = 9.260 kV

Bender	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
`IOS:B1A`	604	9.163	0.234	−0.5
`IMS:B18`	1112	9.309	0.036	0.6
`IMS:B30,B33`	1052	9.301	0.049	0.3
`ILT:VB3,VB6`	1046	9.173	0.149	−0.8
`ILZ:VB1,VB4`	2	9.317	0.000	∞
`ILT:VB21,VB24`	693	9.295	0.060	0.1
`ILE:B1,B4`	465	9.312	0.023	1.1
`ILT:B43,B46`	1538	9.273	0.106	−0.1
`IOS:B10,B13`	1325	9.245	0.124	−0.3
`ILE2:B21`	440	9.072	0.134	−1.6
`CSB:B1,B4`	30	9.243	0.123	−0.4
`CSB:B15,B16`	30	9.352	0.002	29.7
`CSB:VB17,VB20`	26	9.394	0.019	5.7
`ILE1:B1,B4`	89	9.370	0.018	4.5
`ILE1B:B1,B4`	89	9.331	0.061	0.7
`ILE2A:B7`	19	9.635	0.000	∞
`ILE2:B1,B10`	443	9.378	0.150	0.6
`ILE2T:B1`	56	9.323	0.056	0.6

The exceptional case is `ILE1:B1, ILE1:B4`. It appeared normal in 2005 but I speculate that sometime between then and 2021, the `ILE1:B1` bender was opened and then not shut completely closed. The average is 9.366 kV, 79 V higher. The gap is 39 mm, pivots on one side, so this would require the open side to be 0.66 mm from being completely closed.

2 9° Deflectors

Originally, it was 'guessed' that the effective length is 2.2 inches, but as will be seen, the data suggest it should be 2.3 inches.

2.1 Theory

This is the same as for benders, but since the deflector plates are flat, the electric field is constant rather than having a $1/r$ dependence. Thus the potentials used are equal and opposite in sign. The gap g is also the same as for

Table 3: Year 2023: total samples = 4855, average of all = 9.283 kV

Bender	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
IOS:B1A	165	9.205	0.103	−0.8
IMS:B18	720	9.319	0.031	1.0
IMS:B30,B33	624	9.278	0.044	−0.2
ILT:VB3,VB6	622	9.211	0.075	−1.0
ILZ:VB1,VB4	3	9.152	0.143	−0.9
ILT:VB21,VB24	478	9.321	0.057	0.6
ILE:B1,B4	261	9.312	0.019	1.3
ILT:B43,B46	690	9.266	0.049	−0.4
IOS:B10,B13	480	9.247	0.030	−1.3
ILE2:B21	204	9.063	0.206	−1.1
CSB:B1,B4	89	9.485	0.089	2.2
CSB:B15,B16	91	9.378	0.046	2.0
CSB:VB17,VB20	80	9.354	0.041	1.7
ILE1:B1,B4	34	9.397	0.019	5.8
ILE1B:B1,B4	34	9.282	0.119	−0.0
ILE2A:B7	39	9.402	0.069	1.7
ILE2:B1,B10	204	9.486	0.088	2.3
ILE2T:B1	37	9.342	0.055	1.0

Table 4: Year 2005: total samples = 2675, average of all = 9.222 kV

Bender	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
IOS:B1A	381	9.057	0.212	−1.1
IMS:B18	332	9.319	0.035	0.9
IMS:B30,B33	330	9.282	0.081	−0.1
ILT:VB3,VB6	331	9.222	0.125	−0.5
ILZ:VB1,VB4	8	9.284	0.008	−0.4
ILT:VB21,VB24	209	9.297	0.104	0.1
ILE:B1,B4	165	9.279	0.035	−0.2
ILT:B43,B46	415	9.210	0.143	−0.5
IOS:B10,B13	344	9.211	0.148	−0.5
ILE1:B1,B4	47	9.282	0.037	−0.1
ILE2:B21	113	9.149	0.061	−2.3

the benders: 1.5 inches.

We have

$$qE_x = m\frac{\mathrm{d}v_x}{\mathrm{d}t} \approx mv^2\frac{\mathrm{d}}{\mathrm{d}s}\frac{\mathrm{d}x}{\mathrm{d}s} = 2K\frac{\mathrm{d}}{\mathrm{d}s}\frac{\mathrm{d}x}{\mathrm{d}s}. \tag{5}$$

Integrating once, we get the change in the beam's angle:

$$9^\circ = \Delta\frac{\mathrm{d}x}{\mathrm{d}s} = \frac{q}{2K}\int E_x\,\mathrm{d}s \approx \frac{q}{2K}\frac{\Delta V L_{\mathrm{eff}}}{g} \tag{6}$$

where ΔV is the voltage across the plates, and as we want the centre to be at ground potential, the two plates have equal and opposite voltages; $V_p = \Delta V/2$ and $-\Delta V/2$. We thus have

$$9^\circ = \frac{V_p}{K/q}\frac{L_{\mathrm{eff}}}{g} \tag{7}$$

We normalize all following results again to $K/q = 60\,\mathrm{kV}$ and solve for V_p:

$$V_p = \frac{g}{L_{\mathrm{eff}}} \times 9.425\,\mathrm{kV} \tag{8}$$

which is 6.42 kV for the originally guessed effective length of 2.2 in. The finding below is that $V_p = 6.14\,\mathrm{kV}$ and thus the effective length is 2.3 in.

2.2 Data

Histograms of V_{avg} are shown in the figures. The data were again normalized to an energy per charge of 60 kV and summarized by using both the positive and the negative plates, subtracting them and dividing by 2. In other words, the quoted figures represent the average of the absolute values of the potentials on the two plates.

Note that the earlier year, 2005, still showed some vestiges of the original "theory" value of 6.4 kV that had been recommended by me, but the 3 most recent years show a preferred value somewhere between 6.1 and 6.2 kV.

The data again are consistent with a normal random distribution of values, with the exception of the OLIS triple bender `IOS:XCB1A`. This one is so consistently low, that there must be other issues with it. It was thus excluded from the calculation of the average.

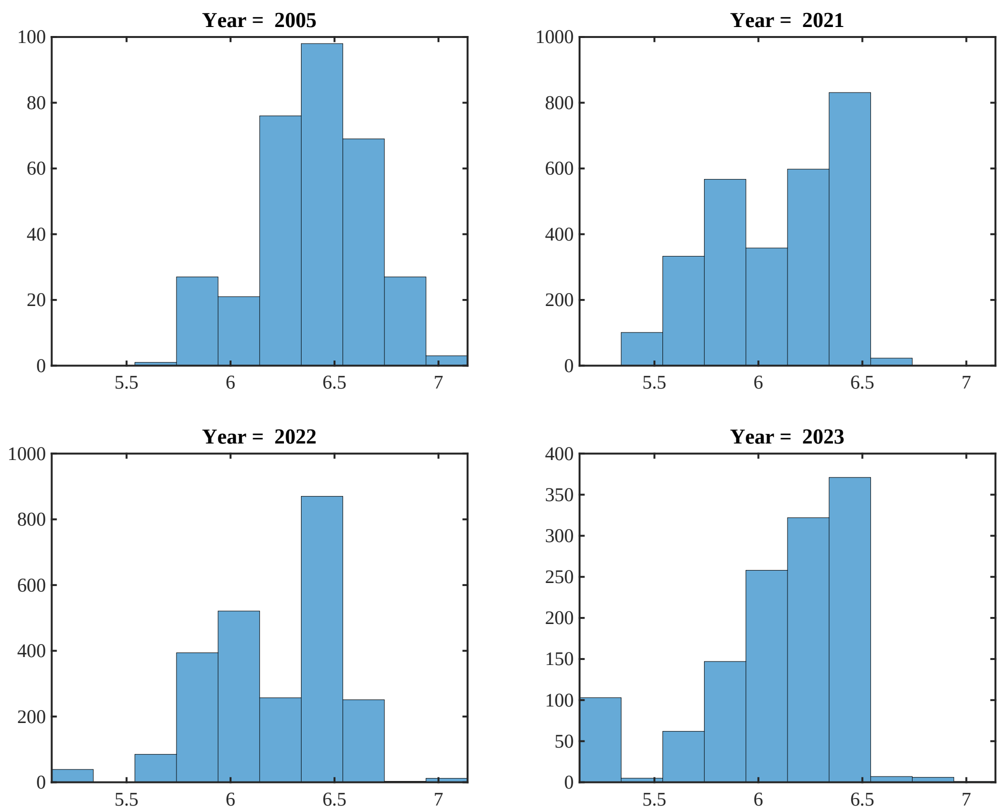

Figure 2: Histograms of V_{avg} for the 9° deflectors.

Table 5: Year 2023: total samples = 1282, average of all = 6.100, relative to 6.140

Deflector	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
`IOS:XCB1A`	57	5.461	0.312	-2.2
`ILE2:XCB11`	204	5.523	0.316	-2.0
`ILE2:XCB21`	204	6.345	0.102	2.0
`ILE2A:XCB2`	134	6.224	0.070	1.2
`ILT:XCB7`	714	6.165	0.240	0.1
`ILE2T:YCB3`	26	6.270	0.081	1.6

Table 6: Year 2022: total samples = 2433, average of all = 6.176, relative to 6.140

Deflector	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
IOS:XCB1A	96	5.521	0.316	-2.0
ILE2:XCB11	441	5.973	0.294	-0.6
ILE2:XCB21	441	6.388	0.067	3.7
ILE2A:XCB2	420	6.452	0.234	1.3
ILT:XCB7	1075	6.057	0.285	-0.3
ILE2T:YCB3	56	6.330	0.092	2.1

Table 7: Year 2021: total samples = 2812, average of all = 6.089, relative to 6.140

Deflector	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
IOS:XCB1A	287	5.967	0.454	-0.4
ILE2:XCB11	454	5.935	0.216	-0.9
ILE2:XCB21	454	6.067	0.450	-0.2
ILE2A:XCB2	414	5.996	0.318	-0.5
ILT:XCB7	1411	6.160	0.221	0.1
ILE2T:YCB3	79	6.329	0.119	1.6

Table 8: Year 2005: total samples = 322, average of all = 6.384, relative to 6.140

Deflector	No. of samples	Avg. of V_{avg} (kV)	Std. Dev. (kV)	Rel. Error
IOS:XCB1A	273	5.867	0.462	-0.6
ILE2:XCB11	116	6.248	0.336	0.3
ILE2:XCB21	116	6.336	0.128	1.5
ILE2A:XCB2	90	6.621	0.234	2.1

3 Acknowledgement

Paul Jung provided the script to filter the log files. Working within the directory of the log files, one runs the script with argument being a regex of the bender name. If for example the bender combination is `ILE:B1,B4`, the argument would be `ILE:B[14]`, and this generates a table whose first column is the bias, and the second and third are the two voltages, `B1` and `B4`. If the bender is a single, the string is the bender name, and there will be only two columns.

```
#!/bin/bash

# Pass in the Element Name you want to search for as the first argument
STATICMATCH=":BIAS:VOL"
MATCHES=$(grep -il "$1" $(grep -iRl $STATICMATCH $(pwd)))
#echo "$MATCHES"
for i in $MATCHES; do
  echo $(grep -i "$STATICMATCH" $i | awk '{print $NF}') $(grep -i "$1" $i | awk '{print $NF}')
done
```