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On-Line Validation of DTL Autofocus

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Abstract: This report documents two successful development results of model coupled accelerator tuning at the variable energy ISAC-DTL. Using sequential tune optimization in `TRANSOPTR`, the machine optics were set to model computed values. Manual de-tuning of the MEBT optics, in particular the corner and injection matching quadrupoles (MEBT:Q6 to MEBT:Q13), while keeping DTL and HEBT at MCAT values, resulted in high transmission.

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Introduction

This report outlines the use of the `TRANSOPTR` model of the ISAC drift tube linac[1] during machine development in November 2022, to establish a model computed tune for the linac. Sequential optimization[2] of the ISAC-DTL quadrupoles has been used to compute the transverse tune, including the HEBT line, allowing for the successful application of the DTL Autofocus algorithm[3]. Two separate beams, ^{14}N and ^{23}Na were produced at the OLIS terminal, stripped using a thin carbon foil in the MEBT section, and successfully accelerated through the linac using the model optics, resulting in high transmission.

Previous development had succeeded in establishing a drifting tune through the structure[4], in which the RF was left unpowered, to test the model's representation of the quadrupole lenses[5]. Though previous work has explored quadrupole scans and tomographic reconstruction[6, 7], tunes computed with the extracted beam distribution have systematically suffered from low transmission through the DTL[8].

A key development has been the postulation of the **MEBT mismatch hypothesis**[9], which states that the MEBT optics systematically mismatches DTL injection. Consequently, in order to achieve nominal transport and acceleration through the drift tube structure, it is necessary to manually de-tune the medium energy section optics, with the model computed DTL and HEBT quadrupole settings left untouched. An important caveat to the result presented herein is that this tuning procedure does not attempt to extract the distribution. Rather, it seeks to establish a transport channel through the accelerator, where the manual detuning of the medium energy optics causes the injected distribution to be contained within the model's distribution.

Robust Autofocus Methodology

Unlike past development tests, a new **robust autofocus** method has been used to compute the DTL transverse tune. Generally speaking, the IH structures deviate from the conventional $V\cos\phi$-esque behaviour usually encountered in single or double gap bunchers. In fact, when the global rf phase parameter ϕ is configured for $\mathbf{M}_{65}+\mathbf{M}_{43}+\mathbf{M}_{21}\approx 0$, they produce a better than linear response of the beam energy to changes in on-axis field scaling[10]. For any of these (ϕ, V) pairs, the overall transfer matrix of the rf cavity of length L, in either transverse canonical dimension pair (x, Px) or (y, Py), takes the form:

$$\mathbf{M}=\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}. \tag{1}$$

In other words, the cavity is transversely equivalent to a drift in free space; the RF focal effects are minimized. Exploiting this for the DTL autofocus, it is possible to discretely (and unphysically) increase the beam energy at the cavity mid-point in `TRANSOPTR`. While this unfaithfully represents the longitudinal dynamics, it produces the correct transverse dynamics, suitable for the computation of the quadrupole triplet gradients necessary to maintain the transverse tune across the range of operating energies in the machine.

This has been used to simplify the sequential tuning optimization sequence. Previous implementations of the DTL autofocus had to optimize (ϕ, V) pairs for each cavity in the accelerator, in order to obtain the correct longitudinal beam energy. This represents up to 8 optimizations (5 IH tanks, 3 bunchers), necessary to then compute the 4 separate triplet optimizations. This significantly degraded algorithm performance, since most of the computing time was spent solving for the longitudinal tune. Exploiting (1), it is instead possible to call `TRANSOPTR` subroutine `rfgap` and directly set the energy. This in turn simplifies the optimization to only 4 groups of triplets, significantly increasing the reliability of the algorithm and reducing computing time.

```
2.114 0.0 0.0 13042.3 3.0 0.0 ! En[MeV], mom., brho, mass[MeV], charge, beam current or bunch charge
-1 5 0.0001 0.1 ! iprint (-1=slim output for envelope app, >0 for legacy optr outputs)
0 0.0 1.0 0.0 ! for external Bs field: nb. lines in data file (0=disable), s offset, unit of s (1=cm), unit of Bs (1=kG)
0.5 0.05 0.5 0.05 0.1345 0.025171 ! bunch dim: x,x’,y,y’,z(bun. len.),dp/p
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 ! 1 means x,y,z in cm, x’,y’,dp/p in rad (dimensionless)
3
1 2 -0.89 3 4 -0.9 5 6 -0.62
27
0.238      0.0        800.0      0 ! ISAC1:DTL1:EOVERA EAT1 V
89.29      15.0       250.0      0 ! DTL:Q1:CUR QM1 A
88.59      15.0       250.0      0 ! DTL:Q2:CUR QM2 A
89.29      15.0       250.0      0 ! DTL:Q3:CUR QM3 A
0.251      0.0        1140.0     0 ! ISAC1:BUNCH1:EOVERA EAB1 V
0.438      0.0        1220.0     0 ! ISAC1:DTL2:EOVERA EAT2 V
107.8      15.0       250.0      0 ! DTL:Q4:CUR QM4 A
111.8      15.0       250.0      0 ! DTL:Q5:CUR QM5 A
107.8      15.0       250.0      0 ! DTL:Q6:CUR QM6 A
0.461      0.0        1900.0     0 ! ISAC1:BUNCH2:EOVERA EAB2 V
0.781      0.0        1130.0     0 ! ISAC1:DTL3:EOVERA EAT3 V
108.9      15.0       250.0      0 ! DTL:Q7:CUR QM7 A
121.3      15.0       250.0      0 ! DTL:Q8:CUR QM8 A
108.9      15.0       250.0      0 ! DTL:Q9:CUR QM9 A
0.803      0.0        5000.0     0 ! ISAC1:BUNCH3:EOVERA EAB3 V
1.0        0.0        1300.0     0 ! ISAC1:DTL4:EOVERA EAT4 V
126.3      15.0       250.0      0 ! DTL:Q10:CUR QM10 A
140.3      15.0       250.0      0 ! DTL:Q11:CUR QM11 A
126.3      15.0       250.0      0 ! DTL:Q12:CUR QM12 A
1.0        0.0        1580.0     0 ! ISAC1:DTL5:EOVERA EAT5 V
19.67      0.0        60.0       0 ! HEBT:Q1:CUR QM13 A
21.75      0.0        60.0       0 ! HEBT:Q2:CUR QM14 A
11.05      0.0        60.0       0 ! HEBT:Q3:CUR QM15 A
2.509      0.0        60.0       0 ! HEBT:Q5:CUR QM16 A
13.02      0.0        60.0       0 ! HEBT:Q6:CUR QM17 A
15.92      0.0        60.0       0 ! HEBT:Q7:CUR QM18 A
15.58      0.0        60.0       0 ! HEBT:Q8:CUR QM19 A
1e-08 100
10 2.0 0.95 20
```

Figure 1: `data.dat` file produced by `robust-autofocus` procedure, for the ^{14}N^{3+} tune. Note the beam E/A is set directly at each cavity. Note: All triplets have outer quads tied together.

```
! RF cavity/linac: ISAC1:DTL1
call drift(32.6/2,’.’)
qdeltaET1=(qmass*EAT1-energki)/charge !effective voltage in MV
call rfgap(qdeltaET1,90.0,1.0608e+08,0)
call drift(32.6/2,’.’)
```

Figure 2: Snippet from `sy.f` used in `robust-autofocus`, showing use of `rfgap` for DTL Tank-1. Variable `qmass` is the reference particle mass in amu, `EAT1` is Tank-1 E/A (see Fig. 3).

```
3.473 0.0 0.0 21426.7 6.0 0.0 ! En[MeV], mom., brho, mass[MeV], charge, beam current or bunch charge
-1 5 0.0001 0.1 ! iprint (-1=slim output for envelope app, >0 for legacy optr outputs), IVOPT (4: 4-D space-charge, 5: 6-D space-charge), ini
0 0.0 1.0 0.0 ! for external Bs field: nb. lines in data file (0=disable), s offset, unit of s (1=cm), unit of Bs (1=kG)
0.5 0.05 0.5 0.05 0.1345 0.025171 ! bunch dim: x,x’,y,y’,z(bun. len.),dp/p
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 ! 1 means x,y,z in cm, x’,y’,dp/p in rad (dimensionless)
3
1 2 -0.89 3 4 -0.9 5 6 -0.62
27
0.238      0.0        800.0      0 ! ISAC1:DTL1:EOVERA EAT1 V
73.28      15.0       250.0      0 ! DTL:Q1:CUR QM1 A
72.72      15.0       250.0      0 ! DTL:Q2:CUR QM2 A
73.28      15.0       250.0      0 ! DTL:Q3:CUR QM3 A
0.251      0.0        1140.0     0 ! ISAC1:BUNCH1:EOVERA EAB1 V
0.438      0.0        1220.0     0 ! ISAC1:DTL2:EOVERA EAT2 V
88.37      15.0       250.0      0 ! DTL:Q4:CUR QM4 A
91.64      15.0       250.0      0 ! DTL:Q5:CUR QM5 A
88.37      15.0       250.0      0 ! DTL:Q6:CUR QM6 A
0.461      0.0        1900.0     0 ! ISAC1:BUNCH2:EOVERA EAB2 V
0.781      0.0        1130.0     0 ! ISAC1:DTL3:EOVERA EAT3 V
89.2       15.0       250.0      0 ! DTL:Q7:CUR QM7 A
99.22      15.0       250.0      0 ! DTL:Q8:CUR QM8 A
89.2       15.0       250.0      0 ! DTL:Q9:CUR QM9 A
0.803      0.0        5000.0     0 ! ISAC1:BUNCH3:EOVERA EAB3 V
1.149      0.0        1300.0     0 ! ISAC1:DTL4:EOVERA EAT4 V
109.5      15.0       250.0      0 ! DTL:Q10:CUR QM10 A
121.7      15.0       250.0      0 ! DTL:Q11:CUR QM11 A
109.5      15.0       250.0      0 ! DTL:Q12:CUR QM12 A
1.7        0.0        1580.0     0 ! ISAC1:DTL5:EOVERA EAT5 V
13.74      0.0        60.0       0 ! HEBT:Q1:CUR QM13 A
23.27      0.0        60.0       0 ! HEBT:Q2:CUR QM14 A
19.01      0.0        60.0       0 ! HEBT:Q3:CUR QM15 A
32.59      0.0        60.0       0 ! HEBT:Q5:CUR QM16 A
13.97      0.0        60.0       0 ! HEBT:Q6:CUR QM17 A
17.07      0.0        60.0       0 ! HEBT:Q7:CUR QM18 A
16.69      0.0        60.0       0 ! HEBT:Q8:CUR QM19 A
1e-08 100
10 2.0 0.95 20
```

Figure 3: `data.dat` file produced by `robust-autofocus` procedure, for the ^{23}N^{6+} tune. Note the beam E/A is set directly at each cavity. Note: All triplets have outer quads tied together.

Autofocus Tuning Sequence

```
mcat_procedure_dtl_autofocus2(1.0,70,2.0,globParams,optr_output_dir)
    [...]
def mcat_procedure_dtl_autofocus2(mult,steps,temperature,globParams,optr_output_dir):

    case=globParams[’beamparams’][’case’]
    ops_energies=[0.238,0.251,0.438,0.461,0.781,0.803,1.149,1.53]
    submit_eovera=[]
    eovera_final=float(globParams[’eovera_final’])
    #figure out which tanks are on
    #say we have E/A = 0.500MeV/u. How do we do this?
    #0.500 - 0.238 > 0 => tank-1 on. remainder: 0.262MeV/u
    #0.262 - (0.251-0.238) > 0 => buncher1 on. remainder 0.249
    #0.249 - (0.438 - 0.251) = 0.249 - 0.187... way too much work.
    for i in range(0,len(ops_energies)):
        if(float(ops_energies[i]) < eovera_final):
            submit_eovera.append(ops_energies[i])
        elif((float(ops_energies[i]) > eovera_final) and (eovera_final < ops_energies[0])):#decelerating case
                submit_eovera.append(eovera_final)
        else:
            submit_eovera.append(eovera_final)
    #for the above example of 0.500MeV/u, this would give i = 4, which is tank-3.
    #with this info, we have to set in redis the variables in the robust_autofocus file.
    r2 = redis.StrictRedis(host=’redis’, port=6379, db=2)
    r2.mset({
        ’ISAC1:DTL1:EOVERA’       :  submit_eovera[0],
        ’ISAC1:BUNCH1:EOVERA’     :  submit_eovera[1],
        ’ISAC1:DTL2:EOVERA’       :  submit_eovera[2],
        ’ISAC1:BUNCH2:EOVERA’     :  submit_eovera[3],
        ’ISAC1:DTL3:EOVERA’       :  submit_eovera[4],
        ’ISAC1:BUNCH3:EOVERA’     :  submit_eovera[5],
        ’ISAC1:DTL4:EOVERA’       :  submit_eovera[6],
        ’ISAC1:DTL5:EOVERA’       :  submit_eovera[7]}) #set these in database 2(model), let model fetch and set

    MCATPV={
    ’0’    :       [’dtl-triplet1-focus’,’DTL:Q1:CUR*’+str(mult),  ’DTL:Q2:CUR*’+str(mult), ’DTL:Q3:CUR*’+str(mult)],
    ’1’    :       [’dtl-triplet2-focus’,’DTL:Q4:CUR*’+str(mult),  ’DTL:Q5:CUR*’+str(mult), ’DTL:Q6:CUR*’+str(mult)],
    ’2’    :       [’dtl-triplet3-focus’,’DTL:Q7:CUR*’+str(mult),  ’DTL:Q8:CUR*’+str(mult), ’DTL:Q9:CUR*’+str(mult)],
    ’3’    :       [’dtl-triplet4-focus’,’DTL:Q10:CUR*’+str(mult),’DTL:Q11:CUR*’+str(mult),’DTL:Q12:CUR*’+str(mult)],
    ’4’    :       [’set-hebt-rpm5-focus’,’HEBT:Q1:CUR*0.1’,’HEBT:Q2:CUR*0.1’,’HEBT:Q3:CUR*0.1’,’HEBT:Q5:CUR*0.1’],
    ’5’    :       [’set-hebt-rpm5-focus’,’HEBT:Q1:CUR*-1’,’HEBT:Q2:CUR*-1’,’HEBT:Q3:CUR*-1’,’HEBT:Q5:CUR*-1’],
    ’6’    :       [’set-prague-focus’,’HEBT:Q6:CUR*0.1’,’HEBT:Q7:CUR*0.1’,’HEBT:Q8:CUR*0.1’],
    ’7’    :       [’skip’],
            }
    #zero unwanted signals in database-2
    r2.mset({#’HEBT:Q1:CUR’                :   0.0,
             ’HEBT:Q8:CUR’                :   0.0,
             ’ISAC1:HEBT11:AMP:SETPT’     :   0.0,
             ’ISAC1:HEBT11:PHASE:SETPT’   :   0.0,
             ’ISAC1:HEBT35:AMP:SETPT’     :   0.0,
             ’ISAC1:HEBT35:PHASE:SETPT’   :   0.0})


    MCATSequencer(MCATPV,20.0,100.,temperature,optr_output_dir)

    return 1
#end autofocus
```

^{14}N^{3+} Autofocus Output

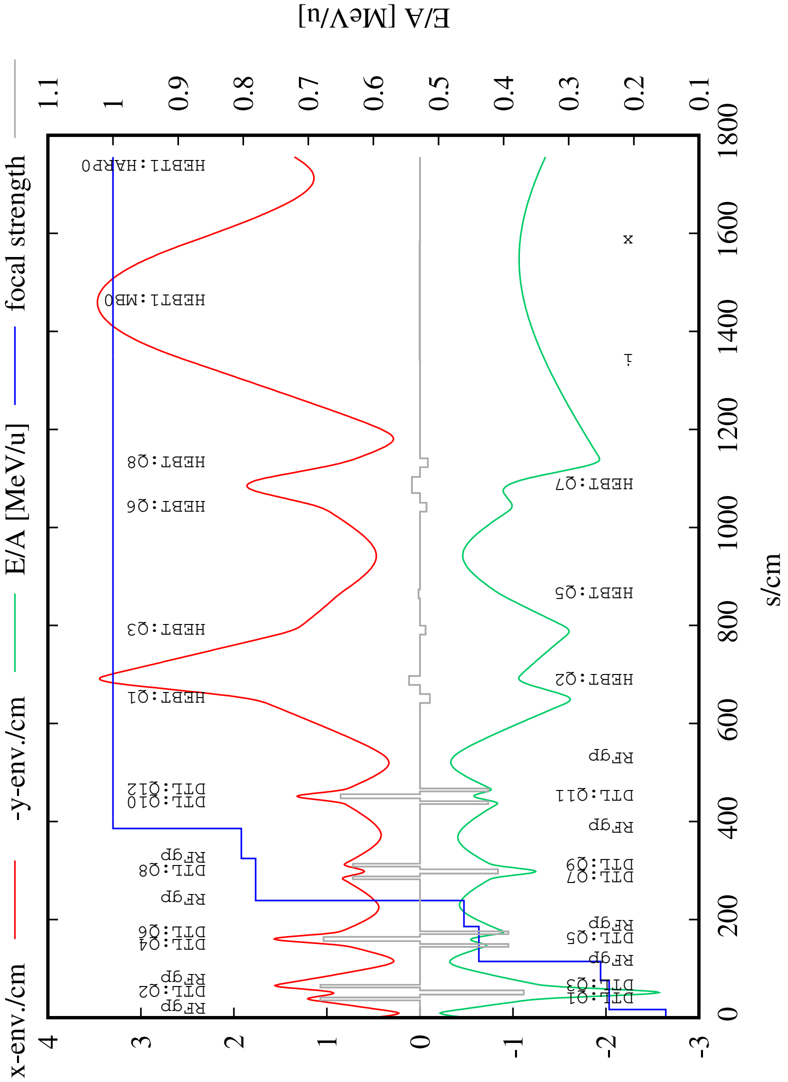

Figure 4: `TRANSOPTR` simulation of the computed DTL tune for ^{14}N^{3+}, using the file `data.dat` from Figure 3 at E/A = 1.0 MeV/u. During machine development, this tune achieved 88% transmission on 2022-11-25.

^{23}Na^{6+} Autofocus Output

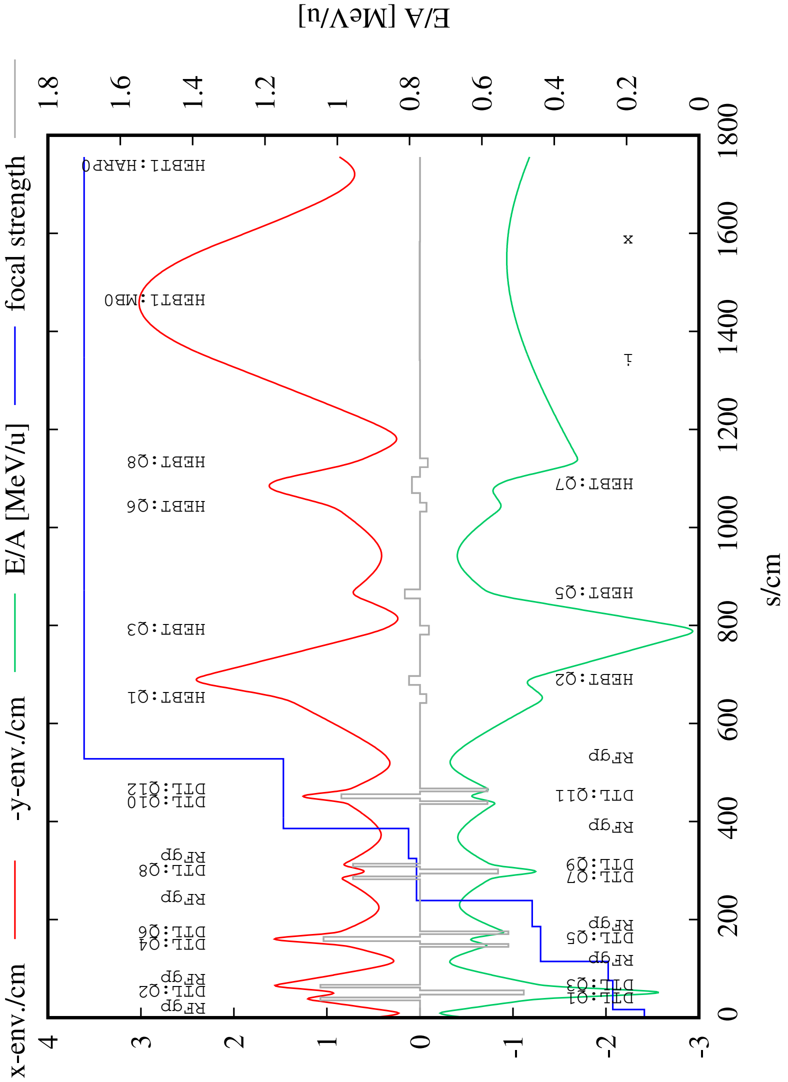

Figure 5: TRANSOPTR simulation of the computed DTL tune for ^{23}Na^{6+}, using the file `data.dat` from Figure 3 at E/A = 1.7 MeV/u. An RIB Operator achieved 90% transmission with this tune on 2022-11-26.

References

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