Optimization of the Fixed Target Beamline for the Neutron Therapy Facility

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Founded 1861

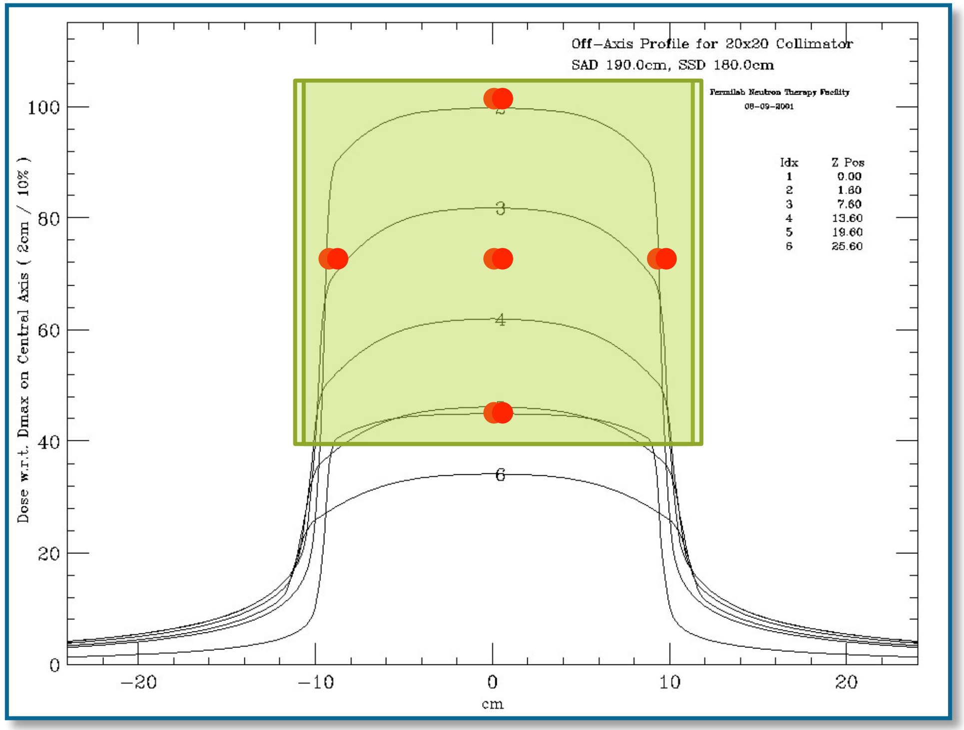
Fermilab

Overview

- Introduction:
  - Objective
  - Background
- The NTF Beamline
- Accelerator Programs
  - OptiM
  - MAD8
- Finding the Bend Center
- Results
- Conclusions & Future Work

Introduction: Purpose

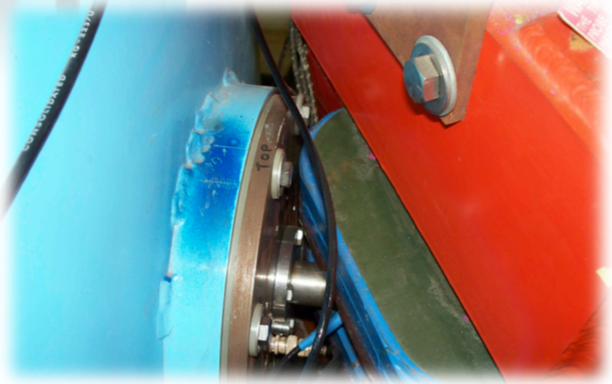
- Existing fully operational, fixed-target beamline
  - Served as the source of neutrons for irradiation in the Neutron Therapy Facility (NTF) that ceased its treatment of cancer patients in 2011
  - Due to data previously collected and analyzed we proposed that the beam may be entering off-axis
- The purpose of our project was:
  - Reduce the Quadrupole magnet currents in the beamline
  - Verify misalignment in the existing fixed-target beamline
  - If misaligned, optimize the beamline such that it enters the NTF line on-axis



Introduction: Background

- Leader in the area of particle physics, Fermi National Accelerator Laboratory uses a series of accelerators to create powerful beams of particles
- Fermi's linear particle accelerator (Linac) creates the proton beams needed for various experiments
  - 750keV H- ion source in the Linac's pre-accelerator
  - Approximately 500 feet long
  - Accelerates the proton beam up to 400 million electron volts(MeV)

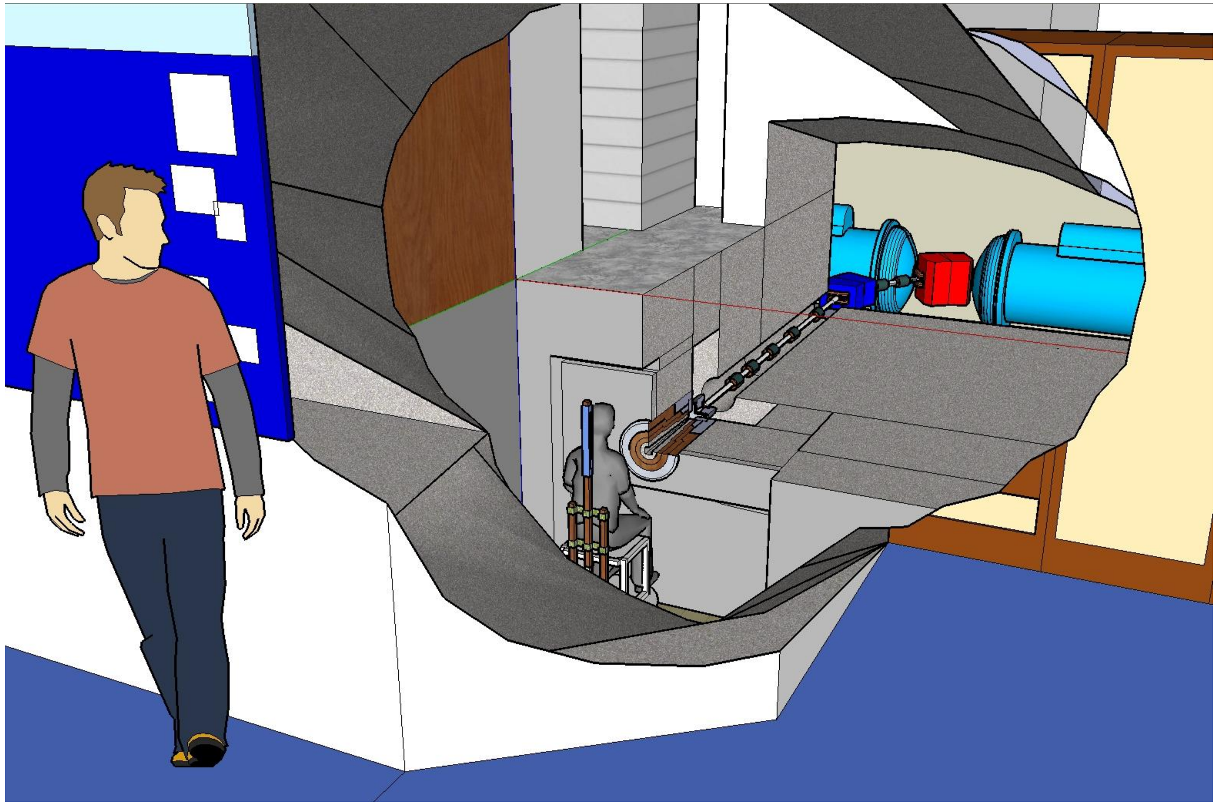
- Linear accelerators have significant applications to medicine
  - Dr. Robert Stone began experimenting with neutron therapy for cancer patients in 1938.
  - In the 1970s, Dr. Robert Wilson of Fermilab created the Neutron Therapy Facility(NTF)
    - September 7, 1976 NTF treated their first patient.



The Entrance to the NTF Beamline

The NTF Beamline

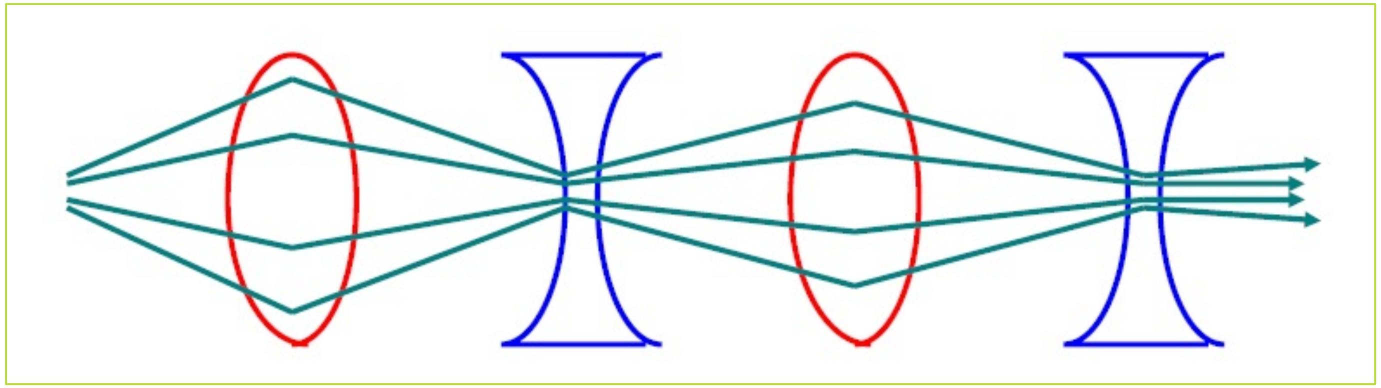
- 58° rectangular dipole bending magnet marks the entrance of the beamline
- 2 quadrupole magnets placed in an optically focus-defocus pattern
- To complete 90°, the beam reaches another rectangular bending dipole magnet of 32°
- Sequence of 5 additional focusing quadrupoles completes the beamline



Accelerator Programming Background

- Elements of the Beamline
  - Dipoles
    - "Bending Magnets"
    - A dipole magnet has 2 poles. This magnet is used to realize bends in the design trajectory of the particle beam.
  - Quadrupoles
    - "Focusing Magnets"
    - A quadrupole magnet has 4 poles. This magnet is horizontally defocusing. A quadrupole which defocuses in one plane focuses in the other.

- Optical Lens Analogy
  - Need for FODO
    - Concave/Convex



Accelerator Programming Background

- Applications of Linear Algebra
  - Matrices for focusing and defocusing quadrupoles
  - Apply Thin Lens Approximation
- TWISS Parameters
  - Useful in measuring beam emittance
    - $\beta_{x,y}$ components
    - $\alpha_{x,y}$ components

$$\mathbf{M}_{\mathrm{F}} = \begin{bmatrix} \cos(\kappa_0 l) & \frac{1}{\kappa_0}\sin(\kappa_0 l) \\ -\kappa_0 \sin(\kappa_0 l) & \cos(\kappa_0 l) \end{bmatrix}.$$

$$\mathbf{M}_{\mathrm{D}} = \begin{bmatrix} \cosh(|\kappa_0| l) & \frac{1}{|\kappa_0|}\sinh(|\kappa_0| l) \\ |\kappa_0| \sinh(|\kappa_0| l) & \cosh(|\kappa_0| l) \end{bmatrix}$$

$$\mathbf{M}_{\mathrm{F(D)}} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

OptiMX

- Developed and maintained by Fermi physicists
- Aimed at assisting with the linear optics design of particle accelerators
- Allows the user to compute dispersion and beam sizes
- Linear optics calculations done based on a 6 dimensional transfer matrix
- Able to output and plot betatron functions (Twiss Parameters)

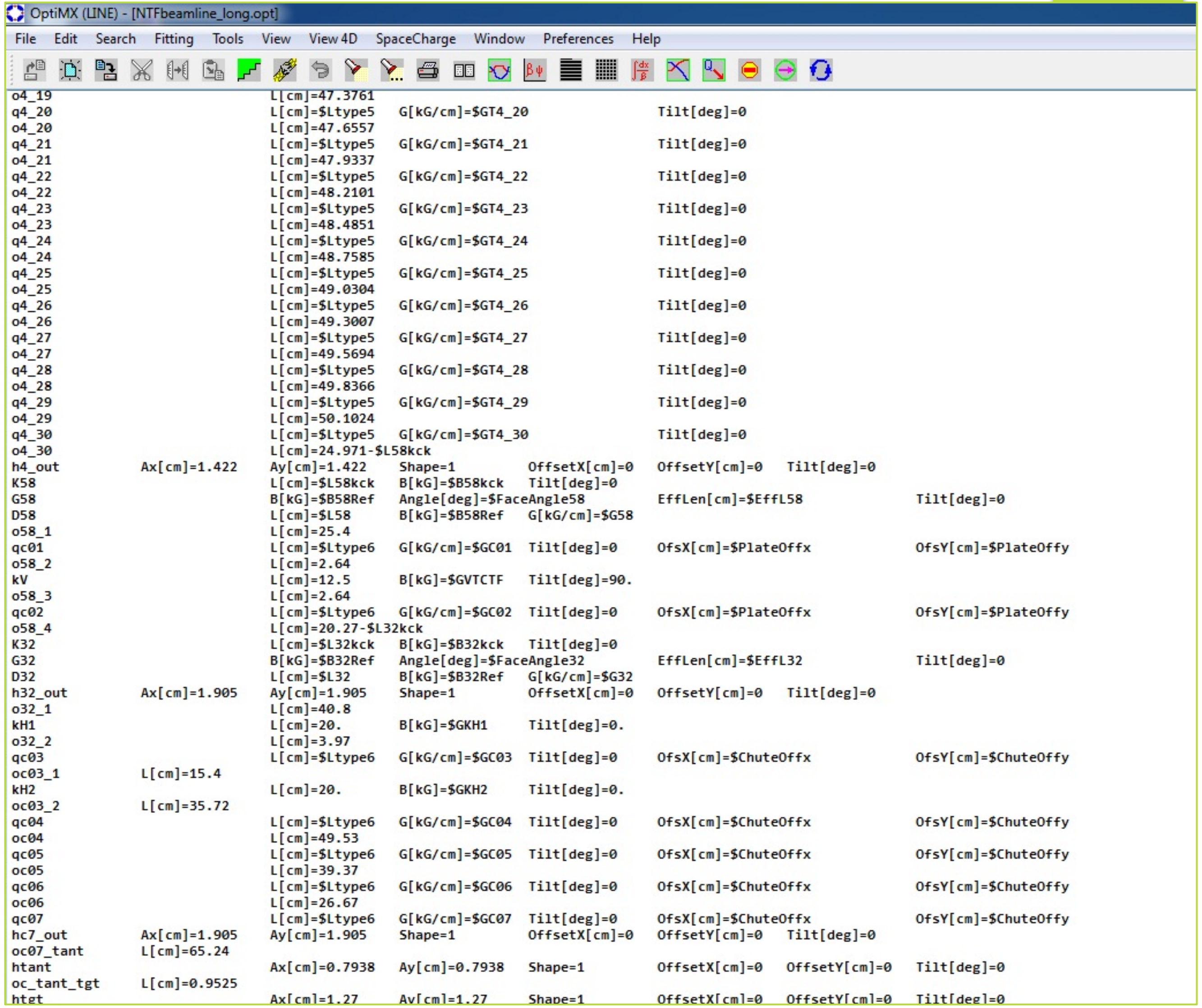
OptiMX: Input Files

- Input initial values for momentum & energy of 66 Mev Proton

$E = m_0 c^2 + K$ $E^2 = p^2 c^2 + m_0 c^2$

$p = \sqrt{(E^2 - m_0 c^2)} / c^2$

- Verified that the existing OptiMX files matched the survey lengths for each of the elements along the beamline


OptiMX (LINE) - [NTFbeamline_long.opt]
File Edit Search Fitting Tools View View 4D SpaceCharge Window Preferences Help

```
o4_19                            L[cm]=47.3761
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o4_20                            L[cm]=47.6557
q4_21                            L[cm]=$Ltype5    G[kG/cm]=$GT4_21                 Tilt[deg]=0
o4_21                            L[cm]=47.9337
q4_22                            L[cm]=$Ltype5    G[kG/cm]=$GT4_22                 Tilt[deg]=0
o4_22                            L[cm]=48.2101
q4_23                            L[cm]=$Ltype5    G[kG/cm]=$GT4_23                 Tilt[deg]=0
o4_23                            L[cm]=48.4851
q4_24                            L[cm]=$Ltype5    G[kG/cm]=$GT4_24                 Tilt[deg]=0
o4_24                            L[cm]=48.7585
q4_25                            L[cm]=$Ltype5    G[kG/cm]=$GT4_25                 Tilt[deg]=0
o4_25                            L[cm]=49.0304
q4_26                            L[cm]=$Ltype5    G[kG/cm]=$GT4_26                 Tilt[deg]=0
o4_26                            L[cm]=49.3007
q4_27                            L[cm]=$Ltype5    G[kG/cm]=$GT4_27                 Tilt[deg]=0
o4_27                            L[cm]=49.5694
q4_28                            L[cm]=$Ltype5    G[kG/cm]=$GT4_28                 Tilt[deg]=0
o4_28                            L[cm]=49.8366
q4_29                            L[cm]=$Ltype5    G[kG/cm]=$GT4_29                 Tilt[deg]=0
o4_29                            L[cm]=50.1024
q4_30                            L[cm]=$Ltype5    G[kG/cm]=$GT4_30                 Tilt[deg]=0
o4_30                            L[cm]=24.971-$L58kck
h4_out          Ax[cm]=1.422     Ay[cm]=1.422     Shape=1          OffsetX[cm]=0   OffsetY[cm]=0   Tilt[deg]=0
K58                              L[cm]=$L58kck    B[kG]=$B58kck    Tilt[deg]=0
G58                              B[kG]=$B58Ref    Angle[deg]=$FaceAngle58          EffLen[cm]=$EffL58              Tilt[deg]=0
D58                              L[cm]=$L58       B[kG]=$B58Ref    G[kG/cm]=$G58
o58_1                            L[cm]=25.4
qc01                             L[cm]=$Ltype6    G[kG/cm]=$GC01   Tilt[deg]=0     OfsX[cm]=$PlateOffx             OfsY[cm]=$PlateOffy
o58_2                            L[cm]=2.64
kV                               L[cm]=12.5       B[kG]=$GVTCTF    Tilt[deg]=90.
o58_3                            L[cm]=2.64
qc02                             L[cm]=$Ltype6    G[kG/cm]=$GC02   Tilt[deg]=0     OfsX[cm]=$PlateOffx             OfsY[cm]=$PlateOffy
o58_4                            L[cm]=20.27-$L32kck
K32                              L[cm]=$L32kck    B[kG]=$B32kck    Tilt[deg]=0
G32                              B[kG]=$B32Ref    Angle[deg]=$FaceAngle32          EffLen[cm]=$EffL32              Tilt[deg]=0
D32                              L[cm]=$L32       B[kG]=$B32Ref    G[kG/cm]=$G32
h32_out         Ax[cm]=1.905     Ay[cm]=1.905     Shape=1          OffsetX[cm]=0   OffsetY[cm]=0   Tilt[deg]=0
o32_1                            L[cm]=40.8
kH1                              L[cm]=20.        B[kG]=$GKH1      Tilt[deg]=0.
o32_2                            L[cm]=3.97
qc03                             L[cm]=$Ltype6    G[kG/cm]=$GC03   Tilt[deg]=0     OfsX[cm]=$ChuteOffx             OfsY[cm]=$ChuteOffy
oc03_1          L[cm]=15.4
kH2                              L[cm]=20.        B[kG]=$GKH2      Tilt[deg]=0.
oc03_2          L[cm]=35.72
qc04                             L[cm]=$Ltype6    G[kG/cm]=$GC04   Tilt[deg]=0     OfsX[cm]=$ChuteOffx             OfsY[cm]=$ChuteOffy
oc04                             L[cm]=49.53
qc05                             L[cm]=$Ltype6    G[kG/cm]=$GC05   Tilt[deg]=0     OfsX[cm]=$ChuteOffx             OfsY[cm]=$ChuteOffy
oc05                             L[cm]=39.37
qc06                             L[cm]=$Ltype6    G[kG/cm]=$GC06   Tilt[deg]=0     OfsX[cm]=$ChuteOffx             OfsY[cm]=$ChuteOffy
oc06                             L[cm]=26.67
qc07                             L[cm]=$Ltype6    G[kG/cm]=$GC07   Tilt[deg]=0     OfsX[cm]=$ChuteOffx             OfsY[cm]=$ChuteOffy
hc7_out         Ax[cm]=1.905     Ay[cm]=1.905     Shape=1          OffsetX[cm]=0   OffsetY[cm]=0   Tilt[deg]=0
oc07_tant       L[cm]=65.24
htant                            Ax[cm]=0.7938    Ay[cm]=0.7938    Shape=1         OffsetX[cm]=0   OffsetY[cm]=0   Tilt[deg]=0
oc_tant_tgt     L[cm]=0.9525
htgt                             Ax[cm]=1.27      Ay[cm]=1.27      Shape=1         OffsetX[cm]=0   OffsetY[cm]=0   Tilt[deg]=0
```
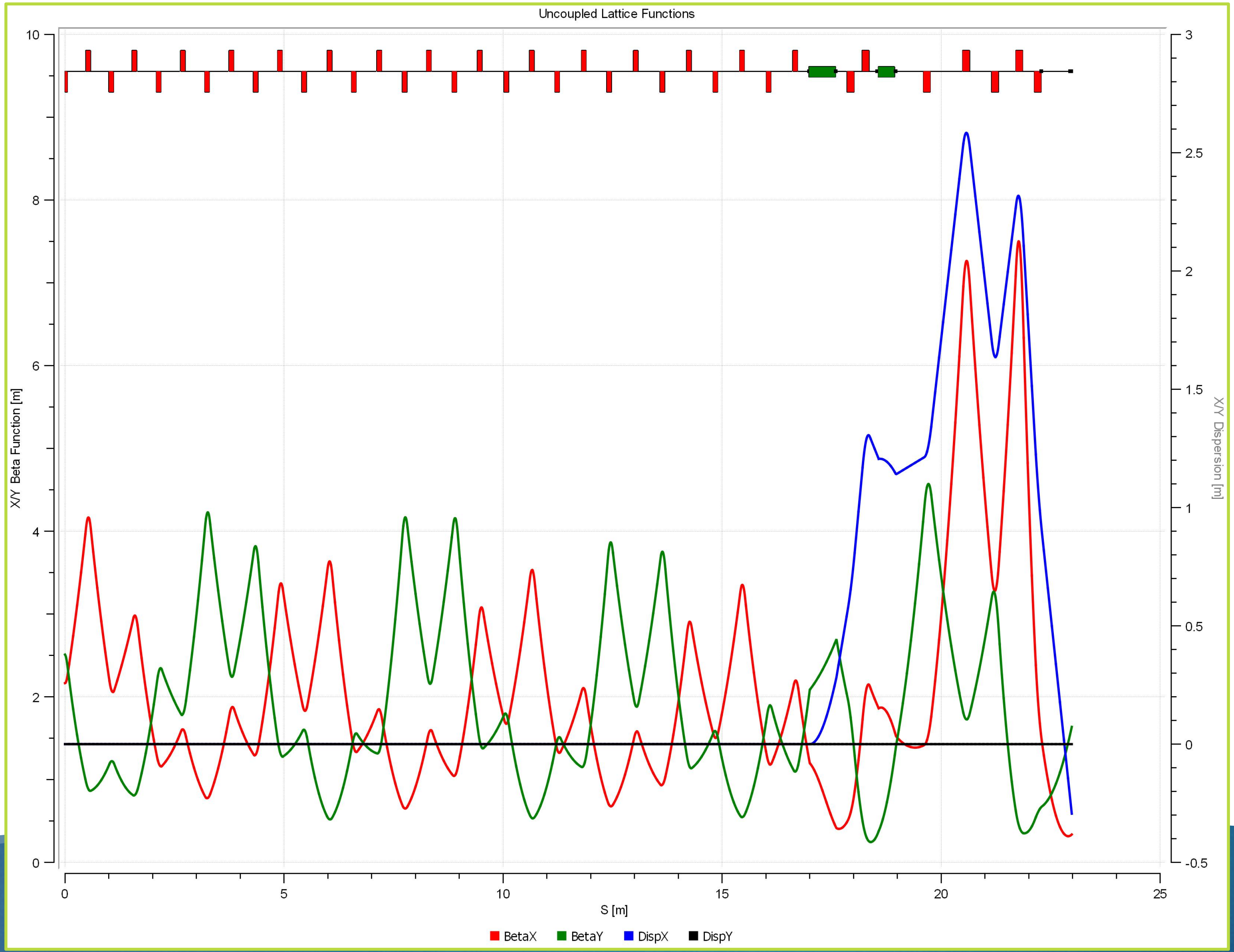



OptiMX: Twiss Parameters

MAD8

- Methodical Accelerator Design, v. 8.0
- Performs many functions that OptiM simply cannot
- MAD-X currently maintained and operated by CERN
- Forefront of particle accelerator design and simulation
- One of the standard scripting languages for accelerators

MAD8: Input Files

C:\Users\kvazquez\Desktop\mad8test\NTF_beamline_long_clean.txt - Notepad++

File Edit Search View Encoding Language Settings Macro Run Plugins Window ?

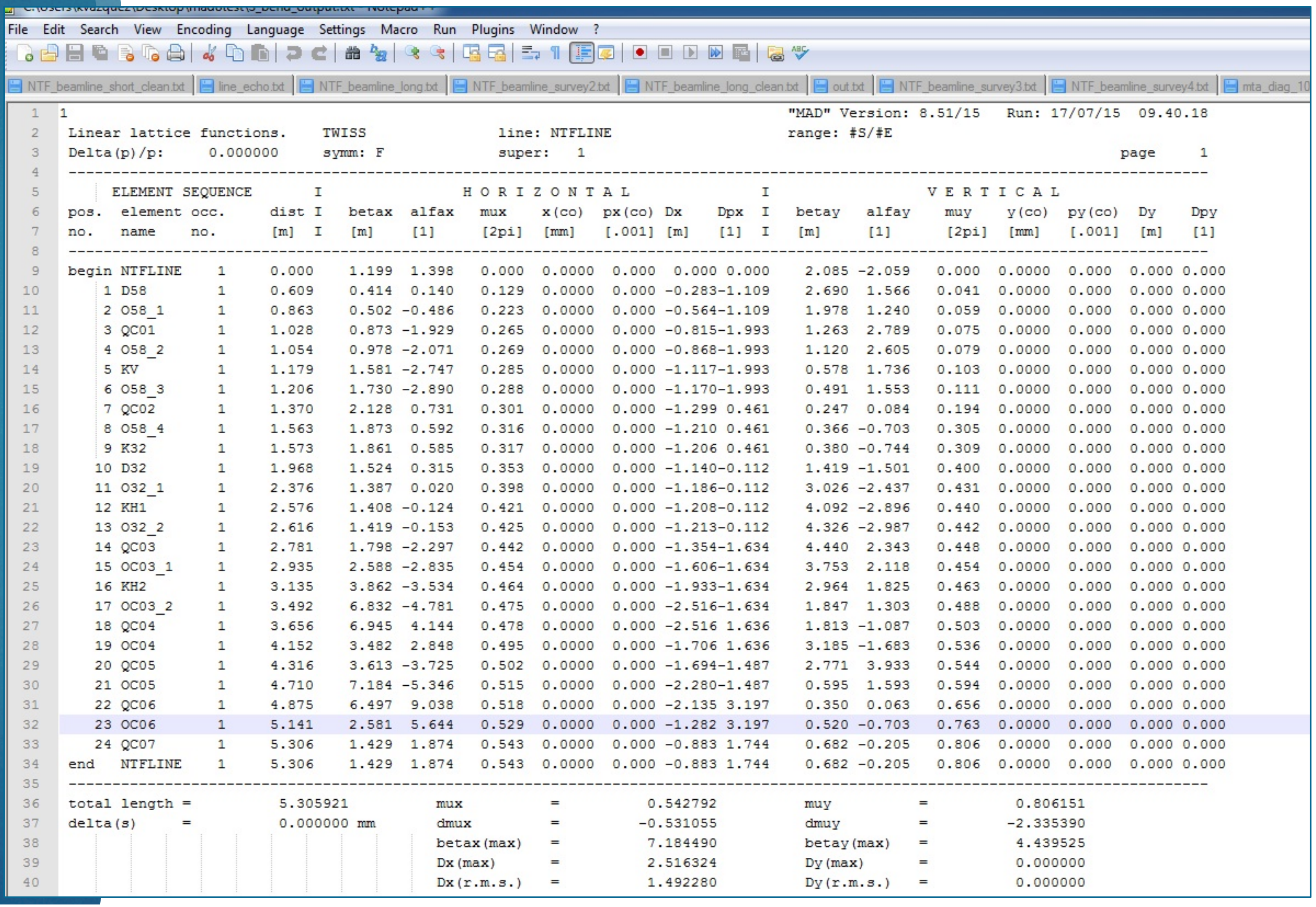
NTF_beamline_short_clean.txt | line_echo.txt | NTF_beamline_long.txt | NTF_beamline_survey2.txt | NTF_beamline_long_clean.txt

```
!*******NTF Line Quads*******

q4_30: QUADRUPOLE, L=    0.1138,  K1=13.64609376
qc01: QUADRUPOLE,  L=    0.1646,  K1= -7.92782537
qc02: QUADRUPOLE,  L=    0.1646,  K1= 11.75706379
qc03: QUADRUPOLE,  L=    0.1646,  K1= -7.321122559
qc04: QUADRUPOLE,  L=    0.1646,  K1=  7.755709743
qc05: QUADRUPOLE,  L=    0.1646,  K1=-11.44731296
qc06: QUADRUPOLE,  L=    0.1646,  K1= 12.5266174
qc07: QUADRUPOLE,  L=    0.1646,  K1= -8.304913327

!*******NTF Line Drifts*******

o4_30: DRIFT, L=0.23971
o58_1: DRIFT, L=0.254
o58_2: DRIFT, L=0.0264
o58_3: DRIFT, L=0.0264
o58_4: DRIFT, L=0.1927
o32_1: DRIFT, L=0.408
o32_2: DRIFT, L=0.0397
oc03_1:DRIFT, L=0.154
oc03_2:DRIFT, L=0.3572
oc04:  DRIFT, L=0.4953
oc05:  DRIFT, L=0.3937
oc06:  DRIFT, L=0.2667
oc07_tant: DRIFT, L= 0.6524
oc_tant_tgt: DRIFT, L=0.009525
oc_tgt:DRIFT, L=0.0127

!*******NTF Line Bends*******

D58: SBEND,  L= 0.6091987,  ANGLE=1.012294284&
    ,  E1=0.5061454831 ,  HGAP=0.01891964739, FINT=0.5 &
    ,  E2=0.5061454831 ,  HGAP=0.01891964739, FINTX=0.5
D32: SBEND,  L= 0.3954221,  ANGLE=0.558505791&
    ,  E1=0.2792526803 ,  HGAP=0.01572596577, FINT=0.5 &
    ,  E2=0.2792526803 ,  HGAP=0.01572596577, FINTX=0.5
```

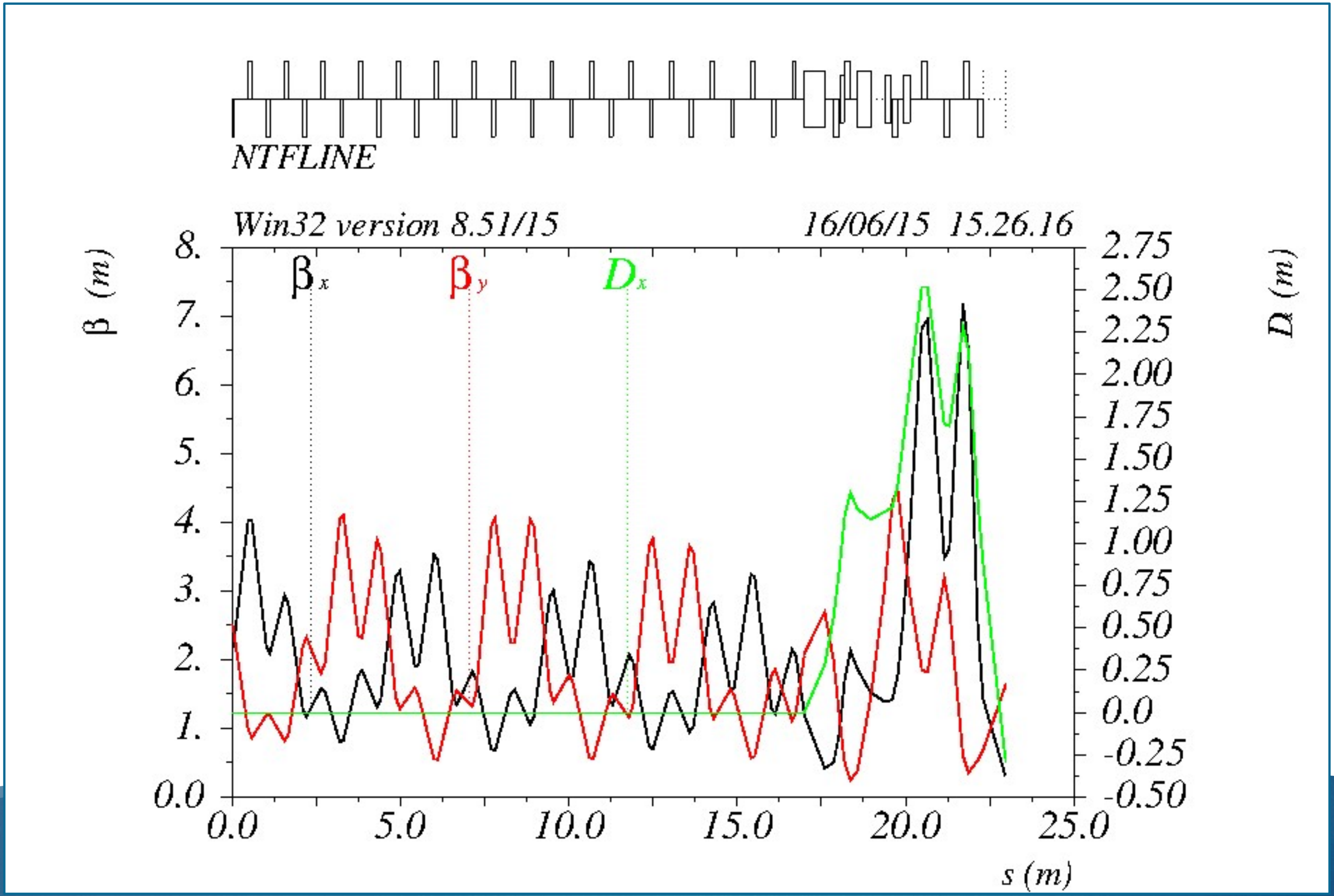
```
!****************************Beamline from Linac tank 4 to NTF line**************************

NTFLINE: LINE=(q4_1, o4_1, q4_2, o4_2, q4_3, o4_3, q4_4, o4_4, q4_5, o4_5,  &
q4_6, o4_6, q4_7, o4_7, q4_8, o4_8, q4_9, o4_9, q4_10, o4_10, q4_11, o4_11,  &
q4_12, o4_12, q4_13, o4_13, q4_14, o4_14, q4_15, o4_15, q4_16, o4_16,  &
q4_17, o4_17, q4_18, o4_18, q4_19, o4_19, q4_20, o4_20, q4_21, o4_21,  &
q4_22, o4_22, q4_23, o4_23, q4_24, o4_24, q4_25, o4_25, q4_26, o4_26,  &
q4_27, o4_27, q4_28, o4_28, q4_29, o4_29, q4_30, o4_30, h4_out, K58, D58,  &
o58_1, qc01, o58_2, kV, o58_3, qc02, o58_4, K32, D32, h32_out, o32_1, kH1,  &
o32_2, qc03, oc03_1, kH2, oc03_2, qc04, oc04, qc05, oc05, qc06, oc06, qc07,  &
hc7_out, oc07_tant, htant, oc_tant_tgt, htgt, oc_tgt)

use,ntfline

twiss, save, couple, betx= 2.1649,  alfx= 0.04022,  &
     bety=  2.5102,  alfy= 0.29886, &
     dx=        0,dpx=       0, &
     dy=        0,dpy=       0, TAPE=line.twiss

survey,save, z0=0,x0=0,TAPE=line.survey
plot,table=twiss,colour=100,haxis=s,vaxis1=betx,bety,&
vaxis2=dx
plot,table=twiss,colour=100,haxis=s,vaxis1=betx,bety,&
```

MAD8: Output Files

- Verified that all of the TWISS parameters matched those calculated in OptiM
- Generated plots of the β x,y functions
- Using the SURVEY command, we were able to output a geometrical survey of the elements

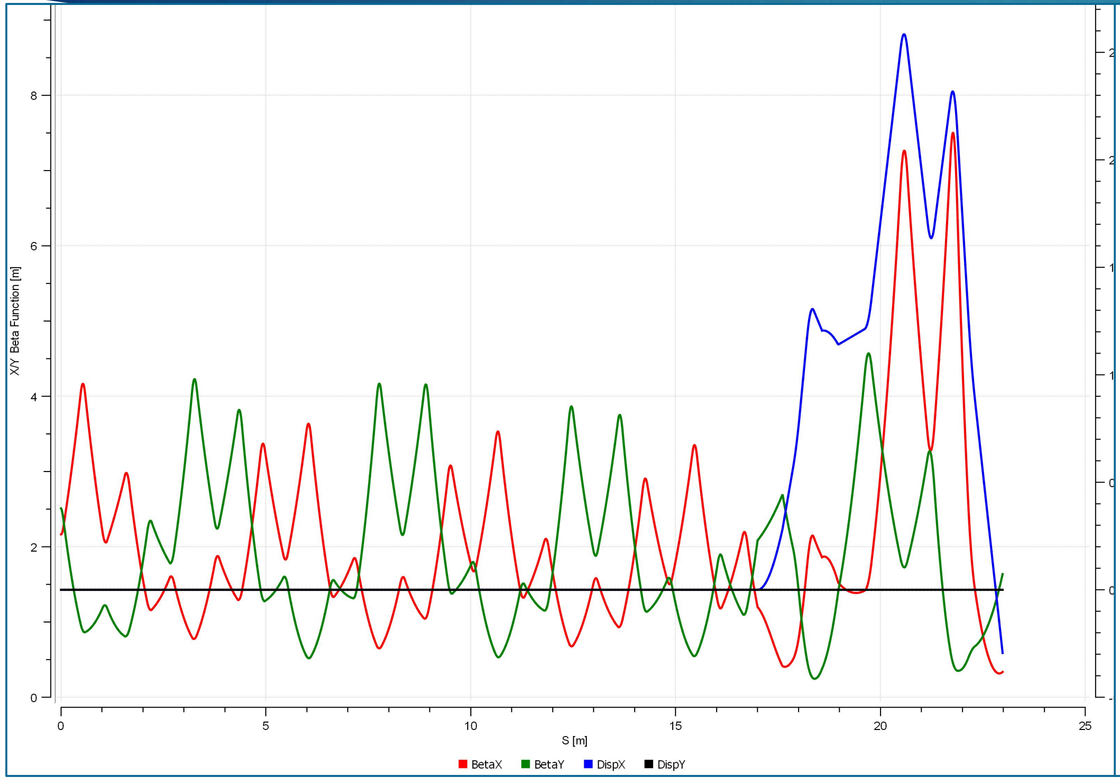


```
1                                                                                        "MAD" Version: 8.51/15   Run: 17/07/15   09.40.18
 Linear lattice functions.    TWISS               line: NTFLINE                          range: #S/#E
 Delta(p)/p:      0.000000    symm: F             super:    1                                                                  page     1
 ---------------------------------------------------------------------------------------------------------------------------------------
     ELEMENT SEQUENCE       I              H O R I Z O N T A L              I              V E R T I C A L
 pos.  element occ.     dist I   betax  alfax   mux    x(co)  px(co) Dx     Dpx  I   betay   alfay    muy    y(co)  py(co)  Dy     Dpy
 no.   name     no.     [m]  I   [m]    [1]    [2pi]   [mm]   [.001] [m]    [1]  I   [m]     [1]     [2pi]   [mm]   [.001]  [m]    [1]
 ---------------------------------------------------------------------------------------------------------------------------------------
 begin NTFLINE    1     0.000     1.199  1.398    0.000  0.0000   0.000   0.000 0.000    2.085 -2.059    0.000  0.0000  0.000  0.000 0.000
     1 D58        1     0.609     0.414  0.140    0.129  0.0000   0.000 -0.283-1.109     2.690  1.566    0.041  0.0000  0.000  0.000 0.000
     2 O58_1      1     0.863     0.502 -0.486    0.223  0.0000   0.000 -0.564-1.109     1.978  1.240    0.059  0.0000  0.000  0.000 0.000
     3 QC01       1     1.028     0.873 -1.929    0.265  0.0000   0.000 -0.815-1.993     1.263  2.789    0.075  0.0000  0.000  0.000 0.000
     4 O58_2      1     1.054     0.978 -2.071    0.269  0.0000   0.000 -0.868-1.993     1.120  2.605    0.079  0.0000  0.000  0.000 0.000
     5 KV         1     1.179     1.581 -2.747    0.285  0.0000   0.000 -1.117-1.993     0.578  1.736    0.103  0.0000  0.000  0.000 0.000
     6 O58_3      1     1.206     1.730 -2.890    0.288  0.0000   0.000 -1.170-1.993     0.491  1.553    0.111  0.0000  0.000  0.000 0.000
     7 QC02       1     1.370     2.128  0.731    0.301  0.0000   0.000 -1.299 0.461     0.247  0.084    0.194  0.0000  0.000  0.000 0.000
     8 O58_4      1     1.563     1.873  0.592    0.316  0.0000   0.000 -1.210 0.461     0.366 -0.703    0.305  0.0000  0.000  0.000 0.000
     9 K32        1     1.573     1.861  0.585    0.317  0.0000   0.000 -1.206 0.461     0.380 -0.744    0.309  0.0000  0.000  0.000 0.000
    10 D32        1     1.968     1.524  0.315    0.353  0.0000   0.000 -1.140-0.112     1.419 -1.501    0.400  0.0000  0.000  0.000 0.000
    11 O32_1      1     2.376     1.387  0.020    0.398  0.0000   0.000 -1.186-0.112     3.026 -2.437    0.431  0.0000  0.000  0.000 0.000
    12 KH1        1     2.576     1.408 -0.124    0.421  0.0000   0.000 -1.208-0.112     4.092 -2.896    0.440  0.0000  0.000  0.000 0.000
    13 O32_2      1     2.616     1.419 -0.153    0.425  0.0000   0.000 -1.213-0.112     4.326 -2.987    0.442  0.0000  0.000  0.000 0.000
    14 QC03       1     2.781     1.798 -2.297    0.442  0.0000   0.000 -1.354-1.634     4.440  2.343    0.448  0.0000  0.000  0.000 0.000
    15 OC03_1     1     2.935     2.588 -2.835    0.454  0.0000   0.000 -1.606-1.634     3.753  2.118    0.454  0.0000  0.000  0.000 0.000
    16 KH2        1     3.135     3.862 -3.534    0.464  0.0000   0.000 -1.933-1.634     2.964  1.825    0.463  0.0000  0.000  0.000 0.000
    17 OC03_2     1     3.492     6.832 -4.781    0.475  0.0000   0.000 -2.516-1.634     1.847  1.303    0.488  0.0000  0.000  0.000 0.000
    18 QC04       1     3.656     6.945  4.144    0.478  0.0000   0.000 -2.516 1.636     1.813 -1.087    0.503  0.0000  0.000  0.000 0.000
    19 OC04       1     4.152     3.482  2.848    0.495  0.0000   0.000 -1.706 1.636     3.185 -1.683    0.536  0.0000  0.000  0.000 0.000
    20 QC05       1     4.316     3.613 -3.725    0.502  0.0000   0.000 -1.694-1.487     2.771  3.933    0.544  0.0000  0.000  0.000 0.000
    21 OC05       1     4.710     7.184 -5.346    0.515  0.0000   0.000 -2.280-1.487     0.595  1.593    0.594  0.0000  0.000  0.000 0.000
    22 QC06       1     4.875     6.497  9.038    0.518  0.0000   0.000 -2.135 3.197     0.350  0.063    0.656  0.0000  0.000  0.000 0.000
    23 OC06       1     5.141     2.581  5.644    0.529  0.0000   0.000 -1.282 3.197     0.520 -0.703    0.763  0.0000  0.000  0.000 0.000
    24 QC07       1     5.306     1.429  1.874    0.543  0.0000   0.000 -0.883 1.744     0.682 -0.205    0.806  0.0000  0.000  0.000 0.000
 end   NTFLINE    1     5.306     1.429  1.874    0.543  0.0000   0.000 -0.883 1.744     0.682 -0.205    0.806  0.0000  0.000  0.000 0.000
 ---------------------------------------------------------------------------------------------------------------------------------------
 total length =          5.305921         mux          =        0.542792        muy          =        0.806151
 delta(s)     =          0.000000 mm      dmux         =       -0.531055        dmuy         =       -2.335390
                                          betax(max)   =        7.184490        betay(max)   =        4.439525
                                          Dx(max)      =        2.516324        Dy(max)      =        0.000000
                                          Dx(r.m.s.)   =        1.492280        Dy(r.m.s.)   =        0.000000
```

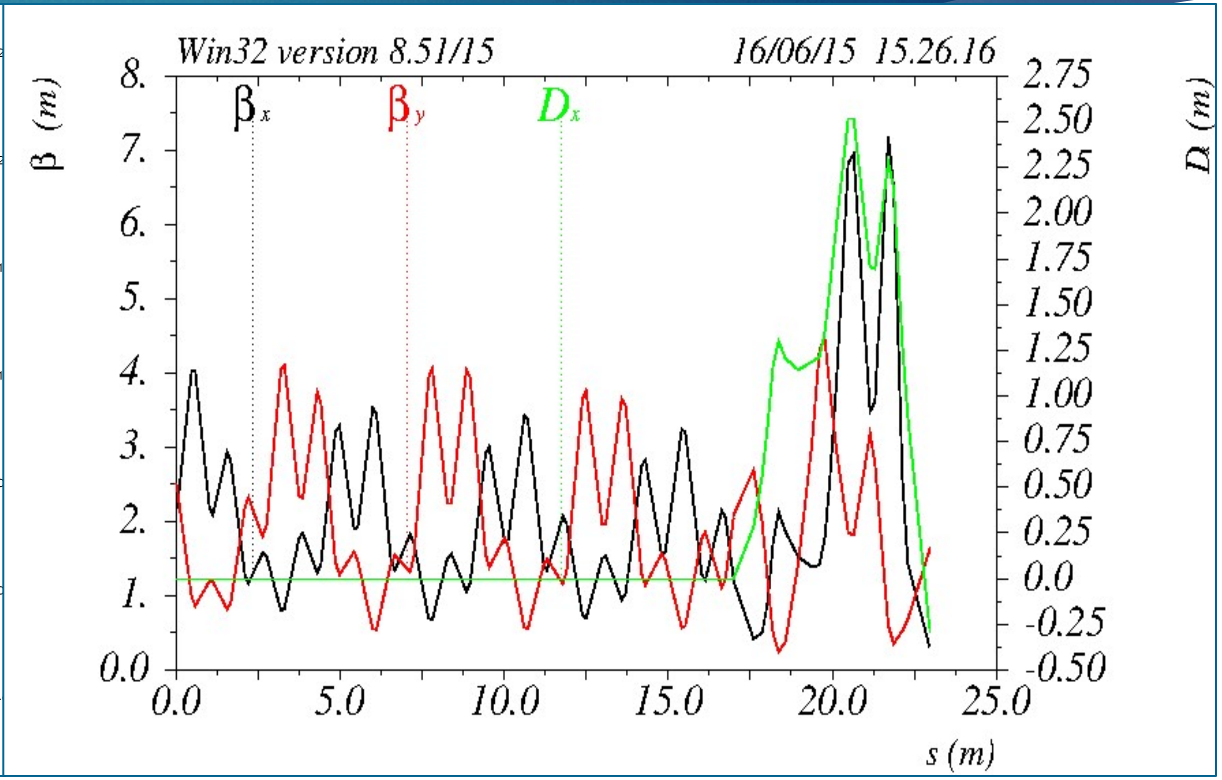


MAD8: TWISS Parameters

Matching



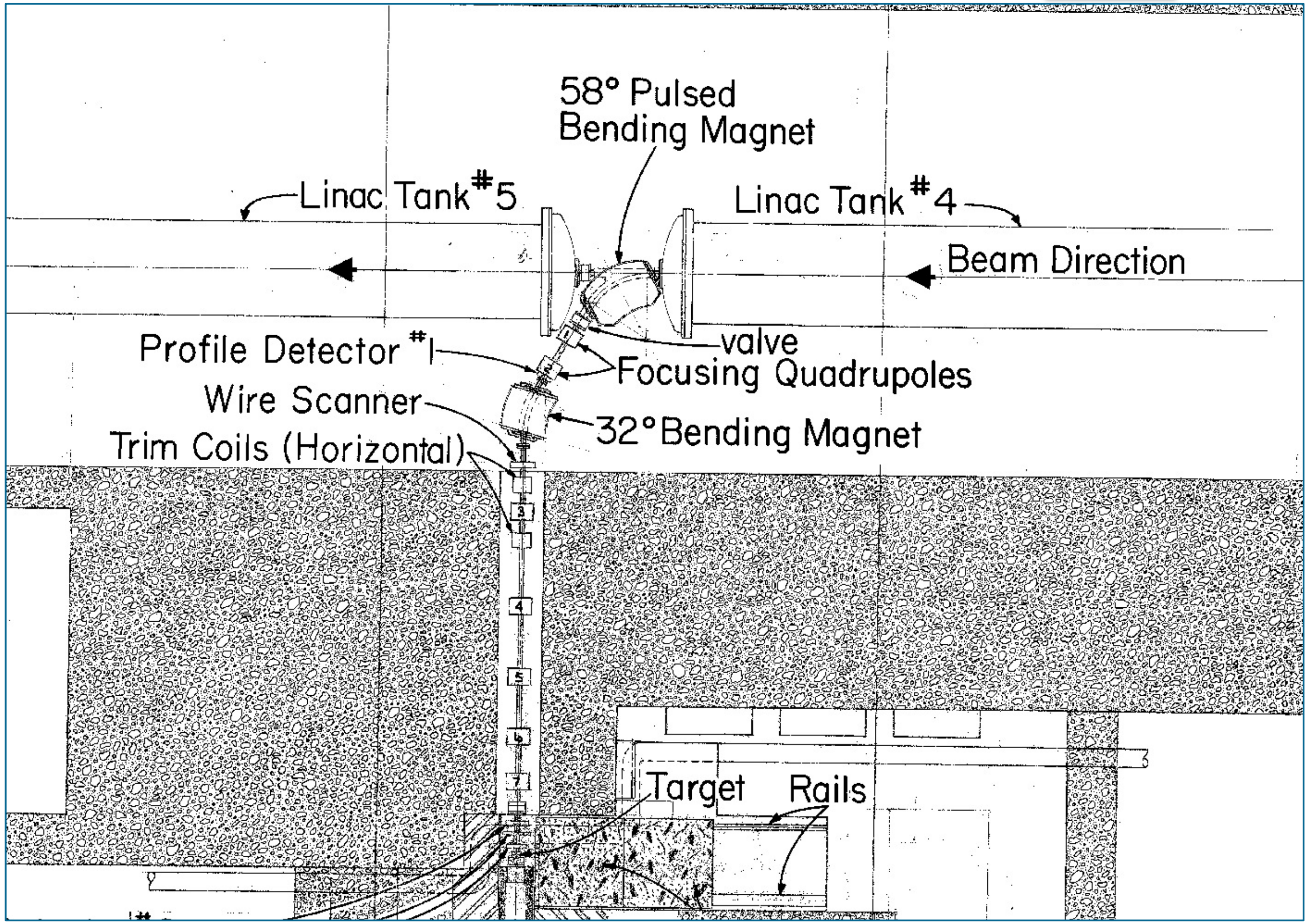
OptiMX



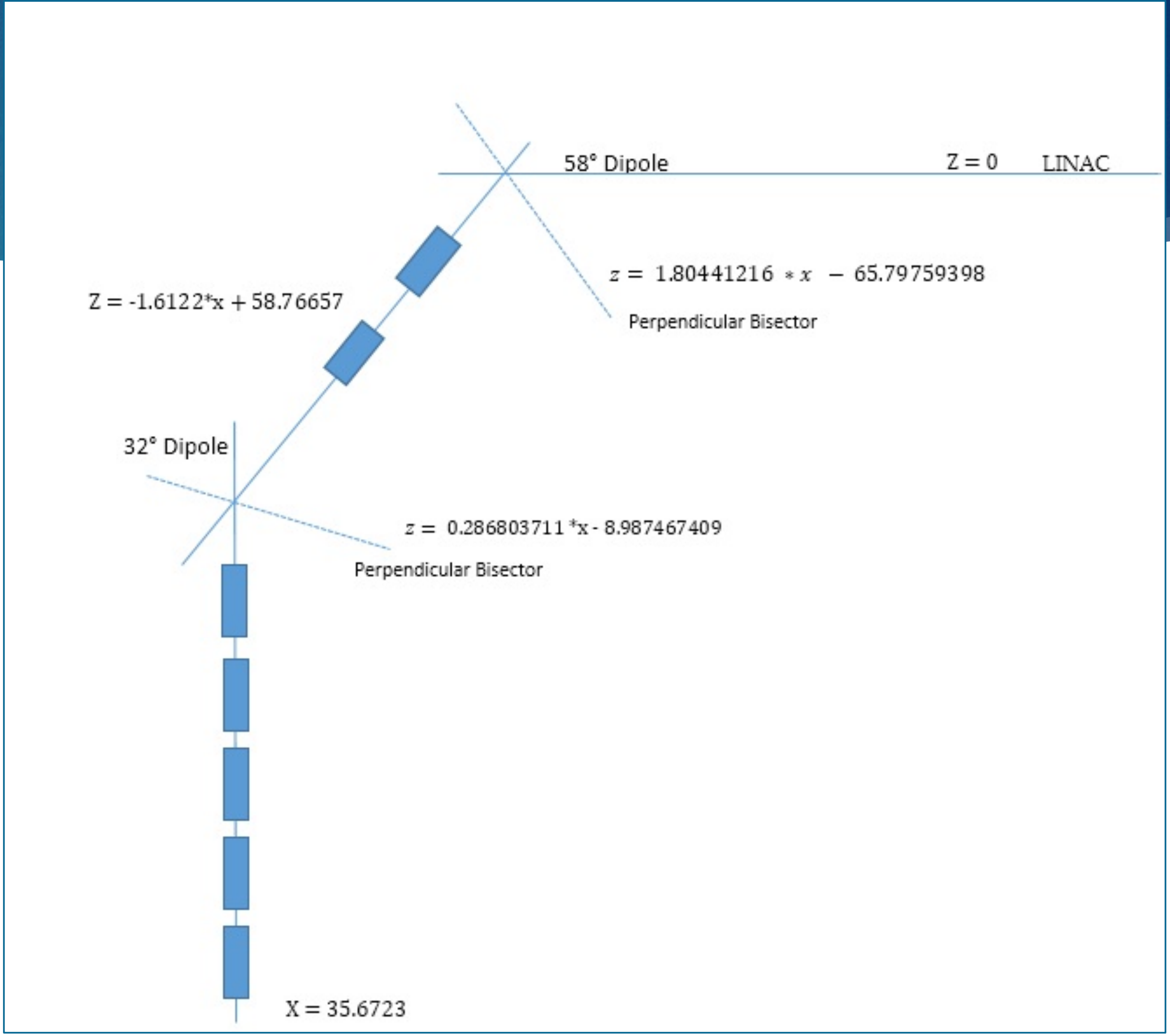
MAD8

Finding the Bend Center of the Magnets

- Survey alignment data was used to develop equations that fit the coordinates
  - If correctly aligned on-axis the beam should strike through the bend center of each of the bending dipole magnets
- Survey command in MAD gave the $\theta_{Bearing}$
  - Using these equations the physical intersection points of the lines were calculated
- The equation for the perpendicular bisector of each of the dipoles was found
  - Coordinates of the intersection point of the line bisecting the dipole and the line through the physical elements was determined



Schematic Layout



MAD8: Survey and Error Analysis

- SURVEY command
  - Outputs a geometrical survey of the elements that allowed us to compare physical lengths to effective
- ERROR command
  - Assigns calculated misalignments to specific elements

```

use,ntfline
print,range=ntfline


!SELECT, flag=error, D58
!EALIGN,DS=0.01393


SELECT, flag=error, D32
EALIGN,DS=0.01170
EPRINT, RANGE=NTFLINE
```

```
 -----------------------------------------------------------------------------------------------------------------------------
1                                                                                       "MAD" Version: 8.51/15   Run: 21/07/15  09.36.55
 Survey.                     SURVEY             line: NTFLINE                           range: #S/#E
                             symm: F            super:   1                                                                page     1
 -----------------------------------------------------------------------------------------------------------------------------
       E L E M E N T   S E Q U E N C E      I            P O S I T I O N S            I              A N G L E S
 pos.  element occ.     sum(L)       arc     I   x              y              z         I   theta          phi            psi
 no.   name    no.      [m]          [m]     I   [m]            [m]            [m]       I   [rad]          [rad]          [rad]
 -----------------------------------------------------------------------------------------------------------------------------
 begin NTFLINE    1     0.000000     0.000000      36.792000      0.000000      -0.012000      4.712477       0.000000       0.000000
     1 D58        1     0.583519     0.609199      36.281668      0.000000       0.270941      5.724771       0.000000       0.000000
     2 O58_1      1     0.837519     0.863199      36.147088      0.000000       0.486358      5.724771       0.000000       0.000000
     3 QC01       1     1.002119     1.027799      36.059876      0.000000       0.625955      5.724771       0.000000       0.000000
     4 O58_2      1     1.028519     1.054199      36.045889      0.000000       0.648344      5.724771       0.000000       0.000000
     5 KV         1     1.153519     1.179199      35.979658      0.000000       0.754356      5.724771       0.000000       0.000000
     6 O58_3      1     1.179919     1.205599      35.965670      0.000000       0.776746      5.724771       0.000000       0.000000
     7 QC02       1     1.344519     1.370199      35.878458      0.000000       0.916343      5.724771       0.000000       0.000000
     8 O58_4      1     1.537219     1.562899      35.776358      0.000000       1.079771      5.724771       0.000000       0.000000
     9 K32        1     1.547219     1.572899      35.771060      0.000000       1.088252      5.724771       0.000000       0.000000
    10 D32        1     1.937535     1.968335      35.663508      0.000000       1.463458      6.283277       0.000000       0.000000
    11 O32_1      1     2.345535     2.376335      35.663546      0.000000       1.871458      6.283277       0.000000       0.000000
    12 KH1        1     2.545535     2.576335      35.663564      0.000000       2.071458      6.283277       0.000000       0.000000
    13 O32_2      1     2.585235     2.616035      35.663568      0.000000       2.111158      6.283277       0.000000       0.000000
    14 QC03       1     2.749835     2.780635      35.663583      0.000000       2.275758      6.283277       0.000000       0.000000
    15 OC03_1     1     2.903835     2.934635      35.663597      0.000000       2.429758      6.283277       0.000000       0.000000
    16 KH2        1     3.103835     3.134635      35.663615      0.000000       2.629758      6.283277       0.000000       0.000000
    17 OC03_2     1     3.461035     3.491835      35.663648      0.000000       2.986958      6.283277       0.000000       0.000000
    18 QC04       1     3.625635     3.656435      35.663663      0.000000       3.151558      6.283277       0.000000       0.000000
    19 OC04       1     4.120935     4.151735      35.663708      0.000000       3.646858      6.283277       0.000000       0.000000
    20 QC05       1     4.285535     4.316335      35.663723      0.000000       3.811458      6.283277       0.000000       0.000000
    21 OC05       1     4.679235     4.710035      35.663760      0.000000       4.205158      6.283277       0.000000       0.000000
    22 QC06       1     4.843835     4.874635      35.663775      0.000000       4.369758      6.283277       0.000000       0.000000
    23 OC06       1     5.110535     5.141335      35.663799      0.000000       4.636458      6.283277       0.000000       0.000000
    24 QC07       1     5.275135     5.305935      35.663814      0.000000       4.801058      6.283277       0.000000       0.000000
 end   NTFLINE    1     5.275135     5.305935      35.663814      0.000000       4.801058      6.283277       0.000000       0.000000
 -----------------------------------------------------------------------------------------------------------------------------
 total length =          5.275135        arc length    =        5.305935
 error(x)     =        -0.112819E+01     error(y)      =        0.000000E+00      error(z)     =        0.481306E+01
 error(theta) =         0.157080E+01     error(phi)    =        0.000000E+00      error(psi)   =        0.000000E+00
 -----------------------------------------------------------------------------------------------------------------------------
```

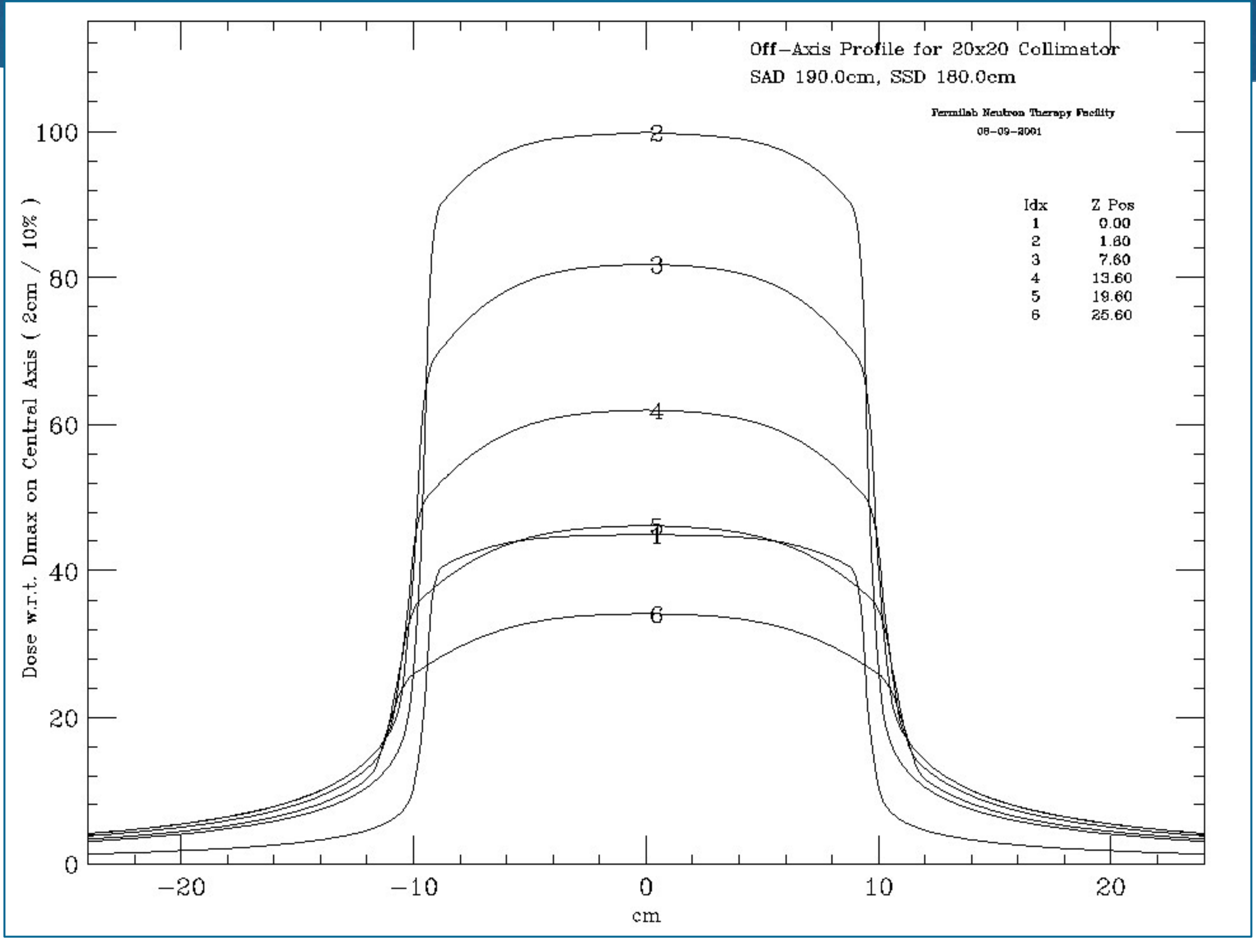
Results

- Successful conversion from OptiM to MAD8
- Compared output to that of the alignment survey
- Calculated intersection points and found misalignment error

	Distance(cm)**
Misalignment in 32°	1.17022
Misalignment in 58°	1.39255
Total Misalignment	1.34487

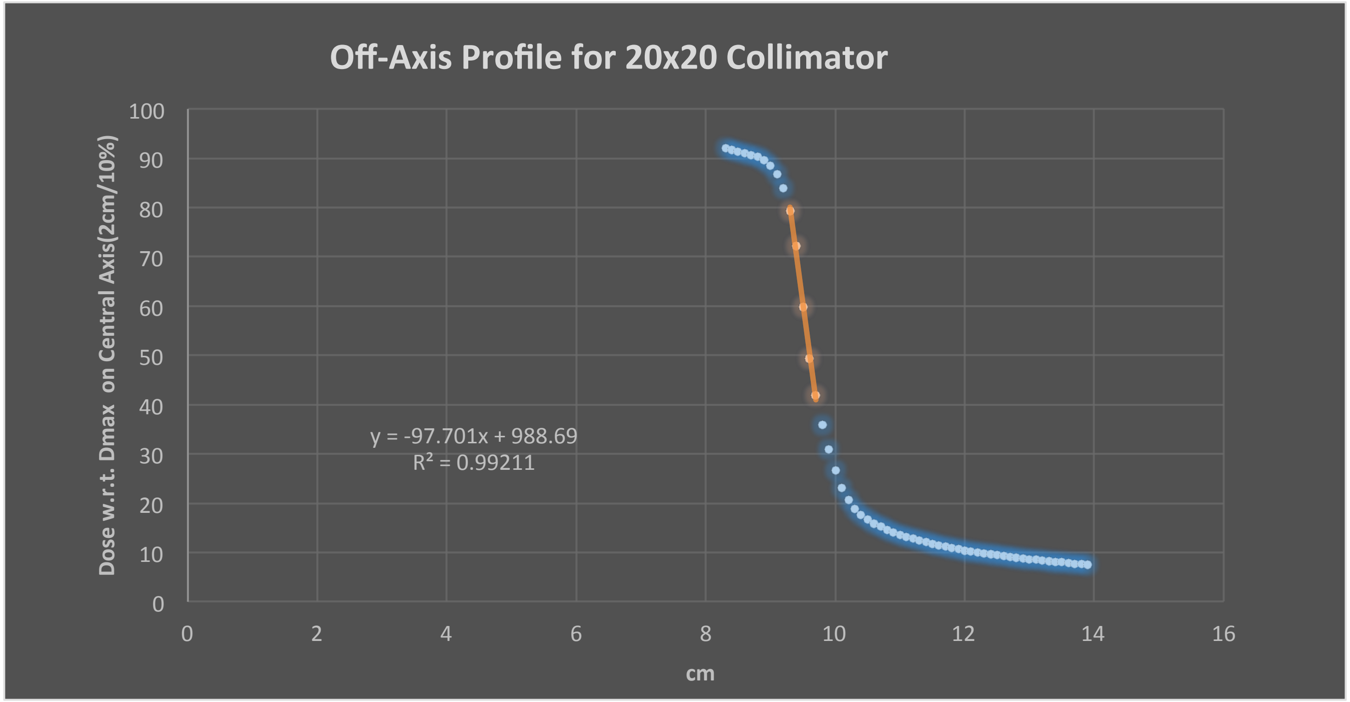
**Denotes misalignment upstream

Conclusions & Future Work



Conclusions & Future Work

- Restatement of Purpose:
  - Reduce the Quadrupole magnet currents in the beamline
  - Verify misalignment in the existing fixed-target beamline
  - If misaligned, optimize the beamline such that it enters the NTF line on-axis
- Bringing it all together
  - We must verify the MAD error alignment output of 0.0134487 meters upstream
  - Use the values collected at the target showing the off-axis beam distribution and work back upstream

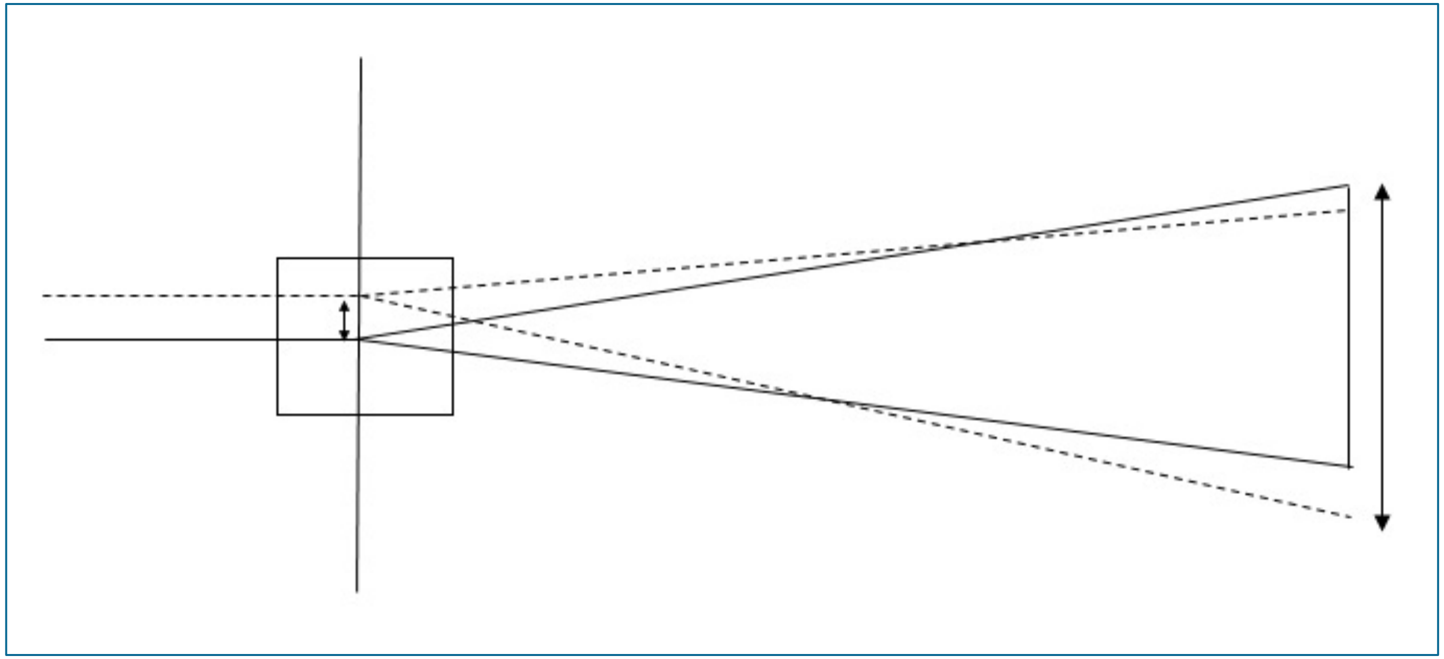


$$y = -97.701x + 988.69$$

$$x = (y - 988.69)/-97.701$$

Conclusions & Future Work

- Using the x-coordinates calculated we can find the relationship between change in current and horizontal motion
- We can find the corresponding distance upstream using geometrical ratios
- This distance allows us to compare to the MAD misalignment



$$B' = 8\pi \cdot 10^{-4} N \frac{I}{r^2} \quad kG/cm$$

$$x\text{-}coordinate/190cm = y/109cm$$

References

- [1] Hans Grote and F. Christoph Iselin. *The MAD Program User's Reference Manual*. Geneva, Switzerland, 2013.
- [2] Valeri Lebedev and J.F. Ostiguy .*The OptiMX User Guide.* Fermilab. 2014.
- [3] Fermilab. *Accelerator Report No. 4-5*. 2004.
- [4] All pictures of the Neutron Therapy Facility used with permission of Fermilab.

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Questions?