Communications in Physics, Vol. 29, No. 3SI (2019), pp. 385-392
DOI:10.15625/0868-3166/29/3SI/14327

PARAMETER ASSESSMENT OF BEAM TRANSPORT LINE FOR NUCLEAR PHYSICS RESEARCH

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Received 22 August 2019
Accepted for publication 28 September 2019
Published 18 October 2019

Abstract. *The IBA CP30 cyclotron was installed at the 108 Central Hospital in Hanoi, Vietnam. A proton beam with energy range from 15 to 30 MeV can be delivered by this facility. Currently, facility is mainly used for medical radioactive isotope production. There is an idea to use this accelerator for scientific research as well. For this purpose, a new beam line should be designed. A high energy resolution with minimum momentum spread is a key point for designing. A preliminary design of the beam line using matrix codes, modeling 3D optical elements, magnetic field calculations, and beam dynamics analysis is presented in this paper.*

Keywords: cyclotron; beam proton; accelerator.

Classification numbers: 29.20.-c; 29.20.dg; 29.27.-a; 29.27.Eg.

I. INTRODUCTION

The IBA CP30 cyclotron was installed at the 108 Central hospital in Hanoi and it is being operated since 2009 for producing radioactive isotopes (^{18}F-FDG, ^{201}Tl, ^{11}C, ^{67}Ga) for medical use including positron emission tomography (PET), single proton computed tomography (SPECT). Output energy of the proton beam can be changed from 15 to 30 MeV by variation of radial position of stripping foil that is used for the beam extraction. The beam intensity reaches to 500 μA. Accelerating frequency is 65 MHz. The beam parameters at the exit of cyclotron, which are used as initial values for designing the transport line including the horizontal and vertical geometric emittances are presented in Table 1. The input Twiss parameters used for the simulation namely α_x, β_x, α_y, β_y were provided by IBA company which were measured using a similar CP30 cyclotron.

Table 1. Parameters of beam extracted from the cyclotron.

Parameters	Value
ε_x	23.69 π.mm.mrad
ε_y	16.87 π.mm.mrad
α_x	-2.029
β_x	2.2978 m
α_y	0.00
β_y	0.432 m

The requirements listed in Table 2 for designing the final beam are: beam transverse ellipses upright has the horizontal (x) and vertical (y) beam size should be 2.5 mm and 10 mm, respectively. Furthermore, the energy spread should be below than 2%.

Table 2. The requirements of the transport beam line.

Parameters	Value
$X_{\max}$	2.5 mm
$Y_{\max}$	10 mm
α_x	0
α_y	0
Energy spread	$\leq 2\%$

II. TRANSPORT LINE DESIGN

A problem of development and optimization of a transport line, intended for providing good beam quality of the final beam, can be presented as two separate tasks. The first task is to control of the beam envelopes. The second one is modeling of energy spread reducing system (ESRS). To solve the first task it is necessary to use the computer codes for beam dynamics analysis. At the first stage, the matrix codes such as Transport [1] or Trace3D [2], which allow fast definition of the line parameters, can be used.

For the second task, we need to allocate free space for ESRS that can be achieved by using a set of collimators. An analyzing magnet should be used downstream ESRS. The next step after having information of beam envelopes and line parameters is to design the optical elements (such as quadrupole and dipole magnets) and calculate 3D fields. When finishing design of the optical elements and fields are in agreement with the requirements, full 3D analysis of the beam dynamics can be obtained with tracing code.

Initial design of our beam line consists of eight quadrupole magnets for control of the beam envelopes (Fig. 1). There is a single 20-degree dipole, which can be used as an analyzing device. Free space after the dipole, where collimating system can be located, is 1.3 m. The line has achromatic properties with dispersion about zero at the final point. Total length of the line is 10.6 m. The beam envelopes do not exceed 30 mm and the final beam spot size is about 15 × 15 mm^2 (Fig. 2). The final beam has the energy spread about ±1.1%, which is not more than 2% as requested above.

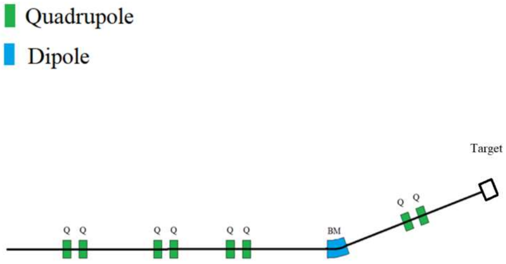
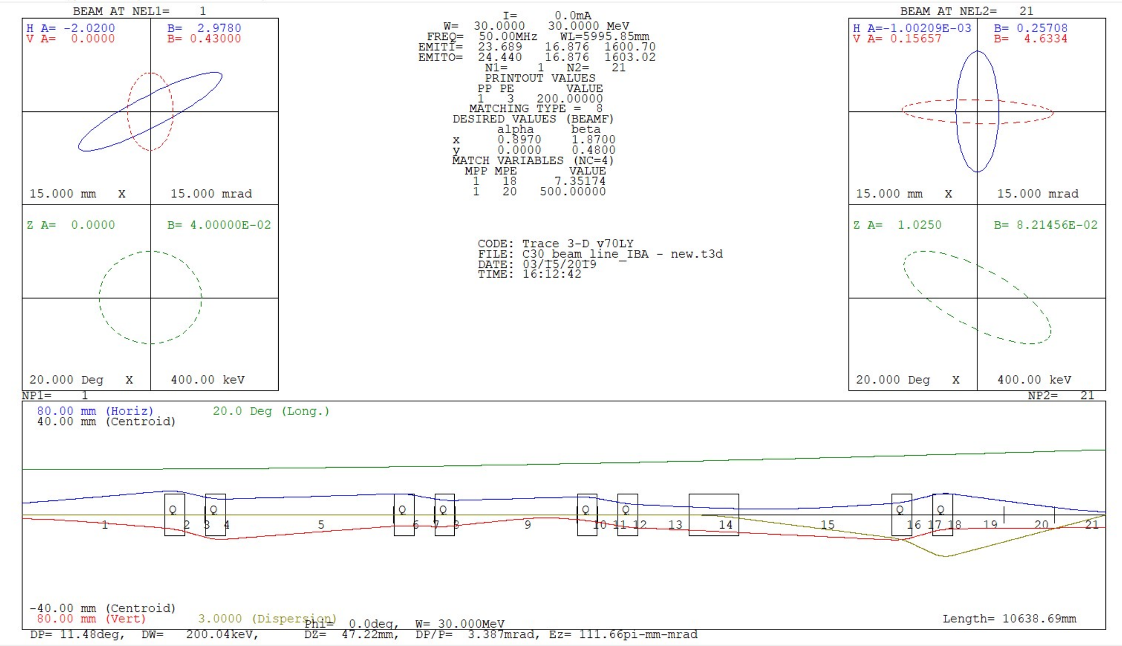


Fig. 1. Post-cyclotron transport line preliminary design: Q – quadrupole, BM – bending magnet.



```
BEAM AT NEL1=    1
H A= -2.0200       B=  2.9780
V A=  0.0000       B= 0.43000
15.000 mm    X     15.000 mrad
Z A=   0.0000      B= 4.00000E-02
20.000 Deg   X     400.00 keV
NP1=     1

            I=      0.0mA
     W=  30.0000   30.0000 MeV
  FREQ=  50.00MHz   WL=5995.85mm
 EMITI=  23.689   16.876  1600.70
 EMITO=  24.440   16.876  1603.02
         N1=    1   N2=   21
         PRINTOUT VALUES
        PP PE        VALUE
        1   3   200.00000
       MATCHING TYPE =  8
     DESIRED VALUES (BEAMF)
          alpha      beta
     x     0.8970    1.8700
     y     0.0000    0.4800
     MATCH VARIABLES (NC=4)
       MPP MPE        VALUE
        1   18      7.35174
        1   20    500.00000

        CODE: Trace 3-D v70LY
        FILE: C30 beam line_IBA - new.t3d
        DATE: 03/15/2019
        TIME: 16:12:42

BEAM AT NEL2=    21
H A=-1.00209E-03   B= 0.25708
V A= 0.15657       B=  4.6334
15.000 mm    X     15.000 mrad
Z A=   1.0250      B= 8.21456E-02
20.000 Deg   X     400.00 keV
                                   NP2=    21

80.00 mm (Horiz)        20.0 Deg (Long.)
40.00 mm (Centroid)

-40.00 mm (Centroid)
80.00 mm (Vert)        3.0000 (Dispersion)  Phi=   0.0deg,   W= 30.000MeV         Length= 10638.69mm
DP= 11.48deg,   DW=    200.04keV,        DZ=  47.22mm,   DP/P=  3.387mrad, Ez= 111.66pi-mm-mrad
```

Fig. 2. Beam transportation calculated with Trace3D code.

In order to investigate the beam spot size at the target position, the phase spaces contour plot of beam distributions obtained by TRANSPORT code and TRACE-3D code has been compared, which are shown in Fig. 9. As listed in Table 1, the transverse ellipse upright at final point need to be satisfied the condition of $X_{\max} = 2.5$ mm and $Y_{\max} = 10$ mm, that are the maximum horizontal and vertical beam size.

Another design, which is more powerful and more complicated transport line was also designed. In this design, the line has a length of 15 m and it consists of 12 quadrupoles and two 45-degree bending magnets as presented in Fig. 3.

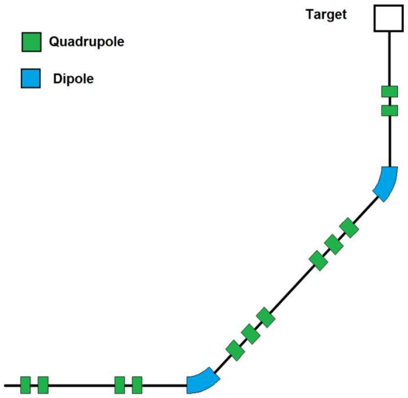


Fig. 3. Transport line consists achromatic optics.

The line consists of three parts including a preparation part of the beam, an achromatic part and a final beam preparation. The achromatic part is a double-achromatic-bending system [3], which contains two quadrupole triplets, and also two of 45-degree dipole magnets with mirror symmetry. A distance between two quadrupole triplets in the achromatic part is 1.5 m that is enough for installing a collimation system for limiting energy spread. Energy dispersion is maximal at the middle point of achromatic part. An optimal conditions for installation of the collimation system can be obtained since the horizontal size of the beam should be maximal. The horizontal position of the proton beam depends on its energy, and selection of energy spread can be done by variation of horizontal size of the collimator slits. The dispersion value will be suppressed to zero at the final point of the beam line in order to provide minimal size of the beam spot (see Fig. 4).

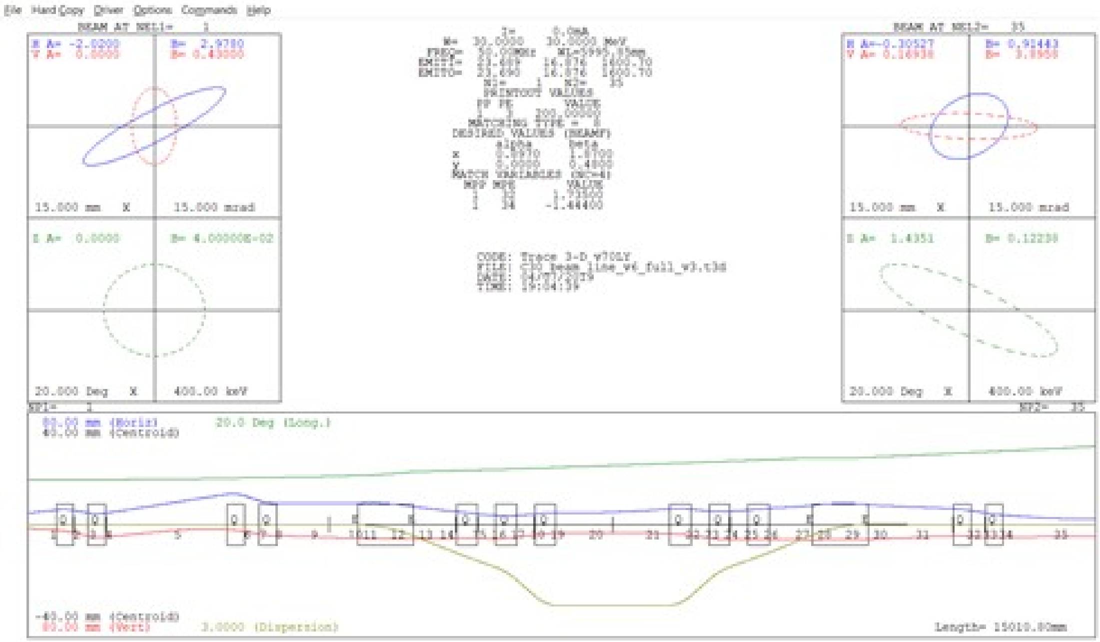


Fig. 4. Beam envelopes and dispersion obtained with Trace3D.

III. 3D DESIGN OF OPTICAL ELEMENTS

For the first transport beam line presented in Fig. 1, we need to carry out a realistic 3D design of elements. This task has been done by simulation with the help of TOSCA/OPERA3D program. The main magnet parameters namely aperture radius, effective length, field gradient and the good field region have been obtained by simulation using Trace3D. The beam transport line is designed in such a way that the beam intensity loss should be minimal. A good field region (GFR) of each element is two times larger than the maximum beam size.

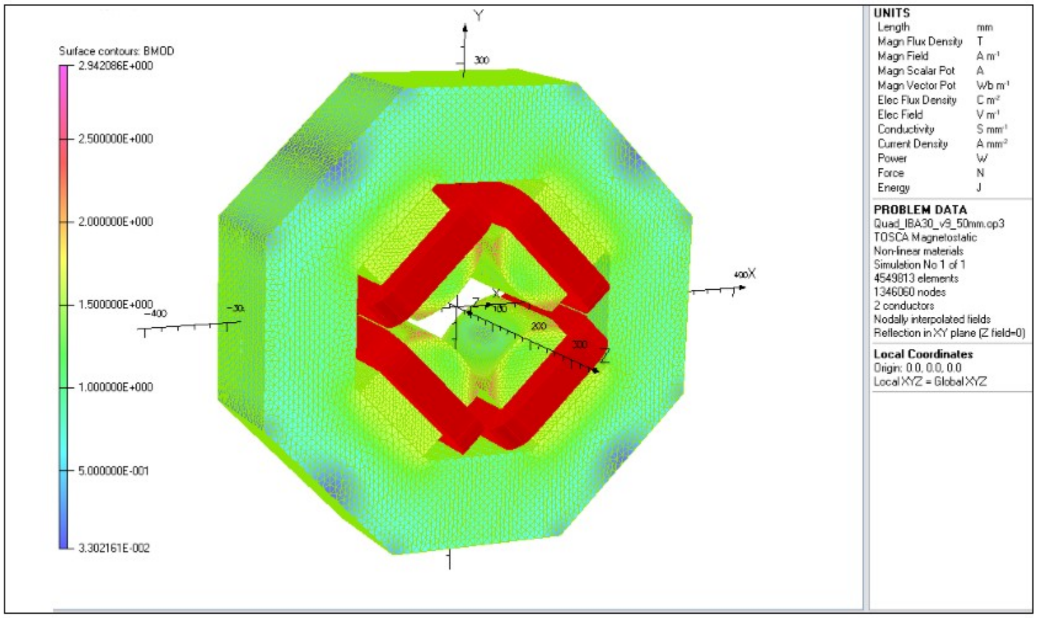
III.1. Design concept of quadrupole magnet

The design of quadrupole is in symmetric case, and 45 degree skew to the upright geometry. The quadrupole has 50 mm of aperture radius and the overall dimensions are 560 mm (height) ×560 mm (width) × 160 mm (length). In order to achieve the required nominal field gradient, each coil should provide 7560 Ampere-turns. The main parameters of quadrupole magnet designed by us are listed in Table 3.

Table 3. The parameters of quadrupole magnet.

Magnet name	**Value**
Nominal field gradient	7.5 T/m
Effective length	215 mm
Gradient spread	1.4 %
Aperture radius	50 mm
Amperes turns per pole	7560 A.turns
Current density	7 $\mathrm{A.mm^{-2}}$
Coil cross section	13.5 $\mathrm{cm^2}$
Good field region (GFR)	± 30mm
Yoke height × width × length	560mm × 560mm × 160mm

Figure 5 shows the field distribution on the magnet surface obtained with OPERA3D. The field gradient distribution along radius of the quadrupole is shown in Fig. 6. In addition, to achieve the nominal field gradient $\sim$ 7.5 T/m, the realistic field gradient should be 10% higher than the field gradient written in Table 3. The result of simulation presents the field $\sim$ 8.2 T/m in the good field region which was shown in Fig. 7. It can be seen from this figure that the field gradient slightly decreases at the end of the good field region because of the fringed field of the magnet.



UNITS

Length	mm
Magn Flux Density	T
Magn Field	A m⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m⁻¹
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S mm⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J

PROBLEM DATA
Quad_IBA30_v9_50mm.op3
TOSCA Magnetostatic
Non-linear materials
Simulation No 1 of 1
4549813 elements
1346060 nodes
2 conductors
Nodally interpolated fields
Reflection in XY plane (Z field=0)

Local Coordinates
Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ

Fig. 5. TOSCA/OPERA-3D model of the quadrupole magnet.

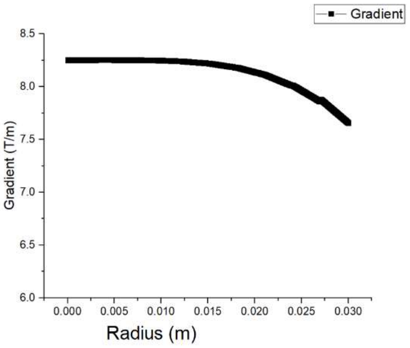


Fig. 6. Field gradient distribution along Z-axis.

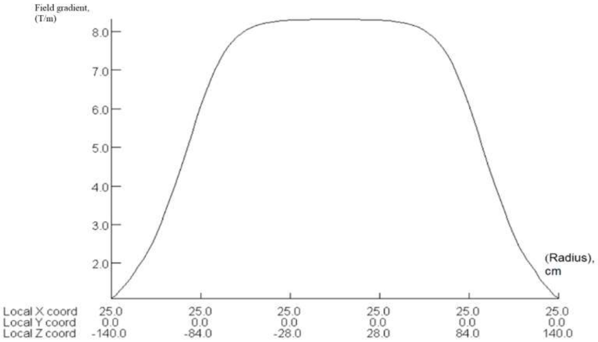


Fig. 7. Field gradient along the radius of quadrupole magnet.

III.2. Design concept of the dipole magnet

The dipole magnet has been designed by using TOSCA/OPERA-3D and the beam optic has been designed with a requirement of minimal beam intensity loss. Thus, the GFR radius obtained by TRACE-3D at the target position is double than beam size. The dipole is H-type curved iron yoke with 539 mm of length and 20 degree of bending angle. Iron yoke is divided into upper core and lower core as show in Fig. 8. The nominal magnetic field is 0.63 T, and the gap height is 46 mm.

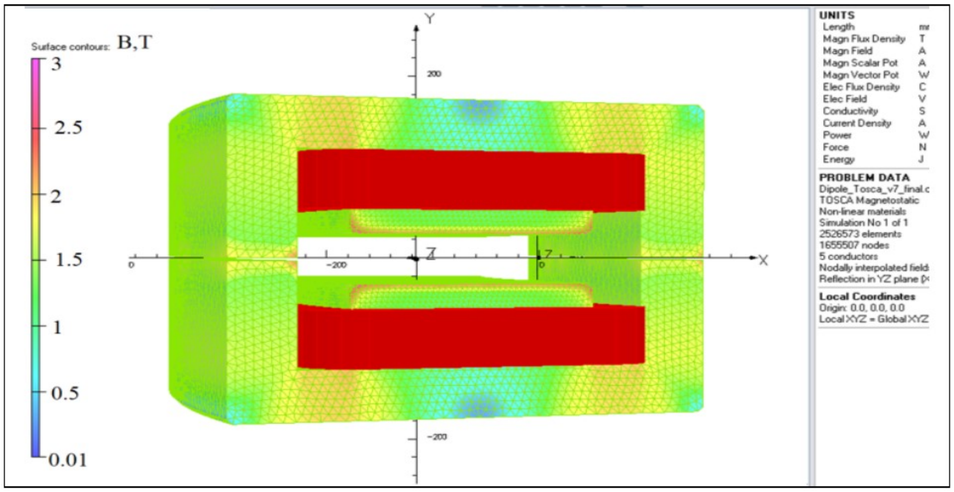


Fig. 8. TOSCA/OPERA-3D model of the H-type dipole magnet.

Table 4. The parameters of dipole magnet.

Magnet name	**Value**
Nominal field level	0.63 T
Good field region (GFR) radius	± 30mm
Maximum current density	7 A.mm^{-2}
Bending angle	20^o
Bending radius	1400m
Effective length	539 mm
Yoke length	488 mm
Weight	239 kg
Coil cross section	22 cm^2
Pole gap height	46 mm

IV. BEAM TRACKING

To carry out a cross-check of calculations obtained with matrix codes, the beam dynamics analysis has been performed using the tracing code. The 3D fields of elements were used in the calculations. The field distribution of quadrupoles and dipoles cover their fringe fields. The 3D bunch consisting of several thousand of macro-particles was generated at the entrance of the line. An optimization of the system parameters was conducted under criterion similar for the beam envelopes. The small corrections of the field levels of the elements were done. Calculations show that the difference between beam envelopes obtained with Trace3D and tracing code SNOP [4] is very small and can be ignored (Fig. 9). The transversal emittances at the interface point are close to the requirements.

We are planning to perform more careful analysis of the beam dynamics with using tracing code in the future and the space charge will be taken into account. It is noted that the SNOP code

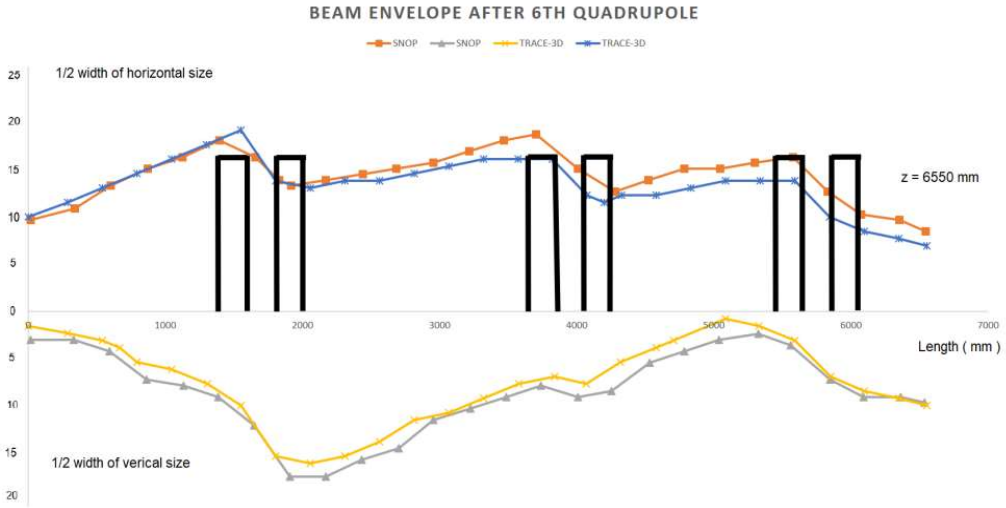


Fig. 9. Beam envelope comparison between using 3D field maps tracking code and matrix code.

allows to estimate the particle losses at the surfaces of the structure elements, therefore the system intended for control of energy spread can be also taken into account.

V. CONCLUSION

The conceptual design of two beam transport lines for scientific research has been presented. The design of the optical elements was carried out by using the computer-aided design software. The 3D magnetic fields have been calculated by using TOSCA/OPERA-3D and the beam dynamics analysis was done with 3D tracing code. Development of technical parameters of magnets including the structure of the coil wires, cooling system, power supply, and other should be done at the next stage to get following productions. In near further, the investigation of feasibility the transport line, and the tracking of particles should be considered.

ACKNOWLEDGMENT

This work partly supported by Vietnam Academy of Science and Technology under the Grant NVCC 05.03/19-19.

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