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THE DETERMINATION OF THE BEAM CHARACTERISTICS OF R&D BEAM TRANSPORT LINE OF TURKISH ATOMIC ENERGY AUTHORITY PROTON ACCELERATOR FACILITY BY USING QUADRUPOLE VARIATION METHOD

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TÜRKİYE ATOM ENERJİSİ KURUMU PROTON HIZLANDIRICI TESİSİ AR-GE DEMET İLETİM HATTI İÇİN KUADRUPOL VARYASYON YÖNTEMİ KULLANILARAK DEMET ÖZELLİKLERİNİN BELİRLENMESİ

Abstract:

Main policy of TAEA is to enhance the usage of nuclear technology products and applications for the utmost benefits of Turkey. As moving from this goal, TAEA PAF was established at Sarayköy Nuclear Research and Training Centre in 2012 in order to produce, quality control and patient dose distribution of currently imported radioisotopes and their radiopharmaceuticals which are used for diagnosis purpose for nuclear medicine in Turkey. By the commissioning of TAEA-PAF, an infrastructure for accelerator technology with an multi-purpose facility that is designed for radioisotope and radiopharmaceutical production, quality control and research and development studies established in Turkey for the first time. Thus, some studies based on charged particle applications on material science, nuclear physics, industry and also training regarding accelerators technologies are projected in TAEA-PAF also. In accordance with these objectives, the studies were started at TAEA-PAF to build required infrastructure in order to service for proton based application requests of universities and institutes in our country. In the first part of the study; it is reported that the arrangements on the existing Beamline 1.1 in the TAEA PAF R&D irradiation vault to make it possible to measure the proton beam parameters such as beam spot, emittance, current and energy. In the second part, the results on the determination of the emittance value of the proton beam in the existing R&D Beamline 1.1 by the quadrupole variation method are presented.

Özet:

TAEK'in ana politikası, nükleer teknoloji ürünlerinin ve uygulamalarının ülkemize en fazla yararı sağlamak üzere kullanımının arttırılmasıdır. Söz konusu hedeften hareketle, ülkemizde nükleer tıpta teşhis amacıyla kullanılan ve hâlihazırda ithal edilmekte olan radyoizotoplar ile bunların radyofarmasötiklerinin üretimi, kalite kontrolü ve hasta dozu olarak dağıtımını gerçekleştirmek amacıyla 2012 yılında Sarayköy Nükleer Araştırma ve Eğitim Merkezi'nde TAEK PHT kurulmuştur. TAEK-PHT'nin devreye alınmasıyla birlikte, radyoizotop ve radyofarmasötik üretimi, kalite kontrolü ve araştırma-geliştirme çalışmalarına yönelik olarak tasarlanan çok amaçlı bir tesis olan hızlandırıcı teknolojileri için önemli bir altyapı Türkiye'de ilk kez kurulmuştur. Bu sayede, yüklü parçacık aktivasyonuna dayanan malzeme araştırmaları, nükleer fizik, endüstriyel uygulamalar üzerine çalışmalar ile aynı zamanda hızlandırıcı teknolojileriyle alakalı eğitim çalışmalarının TAEK-PHT'de yapılması hedeflenmektedir. Söz konusu amaçlara uygun olarak, ülkemizdeki üniversite ve enstitülerin protona dayalı uygulama taleplerinin karşılanmasına yönelik olarak gerekli alt yapı oluşturma

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çalışmalarına TAEK-PHT'de başlanmıştır. Bu bağlamda çalışmanın ilk bölümünde TAEK-PHT Ar-Ge ışınlama odasındaki demet hattında, proton demetinin spot, emitans, akım ve enerji parametrelerinin ölçülebilmesi için yapılan düzenlemeler paylaşılmıştır. Çalışmanın ikinci bölümü olarak ise mevcut Ar-Ge demet hattındaki proton demetinin emitans değerinin, kuadrupol varyasyon metodu ile belirlenmesi üzerine elde edilen sonuçlar sunulmaktadır.

Keywords: Particle accelerators, cyclotron, proton beam, beam transport line, quadrupole magnet, quadrupole variation (scanning) method, beam spot, beam emittance, twiss parameters.

Anahtar kelimeler: Parçacık hızlandırıcıları, siklotron, proton demeti, demet iletim hattı, kuadrupol mıknatıs, kuadrupol varyasyon (tarama) yöntemi, demet spotu, demet emitansı, twiss parametreleri.

1. Introduction

The multipurpose accelerator facilities like TAEA-PAF having the cyclotrons from the family of mid-energy accelerators are preferred for the production of radioisotopes and radiopharmaceuticals used for diagnosis and treatment purposes in nuclear medicine. They have also widely been used in various studies related to nuclear physics and spectroscopy and some industrial applications in addition (Yuksel, 2008). The most important requirement for such multipurpose accelerator facilities, which can provide considerable infrastructure for R&D studies of various types for the above summarized applications, is the transportation of these charged particle beams gathered from the accelerator with the lowest beam loss to the experimental stations (Dehnel, 2005). For this purpose, the original beam transport line (BTL) solutions were designed and passed on. In order to be successful for these designs, the studies have been carried out to correctly determine the beam profile of the charged particle beam to be transported at first. TAEA's cyclotron has the energy and current values as, 15-30 MeV, 0,1 μA - 1,2 mA respectively. Since one of our aim is to run this commercial machine at low beam current levels especially for our R&D studies, it is of prime importance for us to characterize this existing low current proton beam in terms of its beam diagnostic properties. In accordance with this aim, the studies have already been focused heavily on beam dynamics such as; spot size, beam profile determination which is important in terms of transverse beam dynamics characterization. As it is well known, beam emittance is very important in transverse beam dynamics and, hence, emittance and twiss parameters (also called as Courant-Snyder functions) determination studies have been realized by using of quadrupole scanning method; especially for future planned low beam current R&D studies. Our next objective will be the design of a specific BTL and experimental station assembly which is possible to transport beam within the required parameters for the above mentioned studies and primarily for materials science related studies (Yuksel, 2011).

2. Material and Method

2.1. TAEA-PAF

The Cyclone 30 cyclotron designed by Ion Beam Application S.A. is the first kind of its family of production in terms of the ion source yielding maximum total proton current. This vault was surrounded by four target vaults. Three target vaults also included three main BTLs in connection with related targets systems such as liquid target, gas target and solid targets performing radioisotope production. The final vault was dedicated to research and training activities. For this purpose, "Beamline 1.1" transports proton beam from the cyclotron to the R&D vault (Figure 1).

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(a) **(b)**

Figure 1. TAEA-PAF R & D irradiation vault and Beamline 1.1 just after construction; (a) The layout plan (b) The photo of the regarding general view.

As in the TAEA PAF, the cyclotron type accelerators with 15-30 MeV energy of proton beam are especially preferred for the production of medical radioisotopes; also it is possible to achieve important scientific research studies by using extracted proton beam from these accelerators. This multi-functionality requires to do design and improvement studies related with the BTLs which could transfer extracted beam from accelerator to the different sections in the facility. For the multi-purpose accelerator facilities, the transportation of the extracted beam with desired quality and parameters (low beam spot size, emittance, envelope etc.) depending on the intended utilization purpose of the beam is quite important. Therefore the original BTLs solutions have been implemented together with the experimental stations and new BTL designs which would be equipped with various sub-systems are put forward.

2.2. Renovation Studies for Existing Beamline 1.1 at R&D vault of TAEA-PAF

TAEA PAF R&D Beamline 1.1 was left as untapped during installation phase of the facility by designer (Ion Beam Application S.A./Belgium) of the facility (Figure 2a.). So some renovation studies for Beamline 1.1 at R&D vault of TAEA-PAF were performed in order to achieve applications especially based on low beam current. As the first part of the study; required arrangements were performed on the existing Beamline 1.1 in order to measure the required beam parameters such as beam spot size, emittance, current, energy and also to provide service for basic irradiation requests from other institutions. For this purpose, a vacuum exit window with havar foil of which is 50 μm thickness and 29 mm diameter was mounted at the end of the Beamline 1.1 via a flange assembly. A havar foil for the exit window assembly was preferred because of its good thermal conductivity (13.0 W/mK), a high melting point (1480 ^{0}C), durability and flexibility (29.5 x 10^{6} PSI) and corrosion-resistance (Anonymous, 2012).

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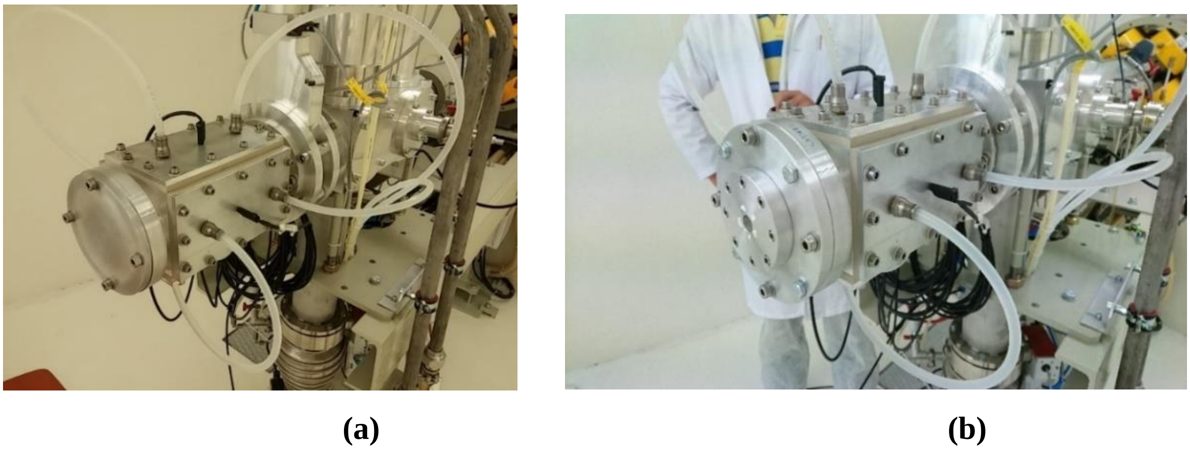
(a) (b)

Figure 2. TAEA-PAF R&D Beamline 1.1; (a) before (b) after renovation

Figure 3. Both images during the manufacturing of the flange assembly

The flange assembly was mounted to the end of the R&D Beamline 1.1 as seen in Figure 2b. This homemade flange was manufactured and machined at SNRTC mechanical workshop as seen in Figure 3. Thus, this Beamline 1.1 which was intentionally left as inoperable during the establishment of the cyclotron, was made operable for the first time. In addition, short time irradiation studies were performed for the first time, by sending the 15-30 MeV and 0,1-2 μA proton beam freely flying within the path length of a few centimetres, without needing any cooling (Figure 4.).

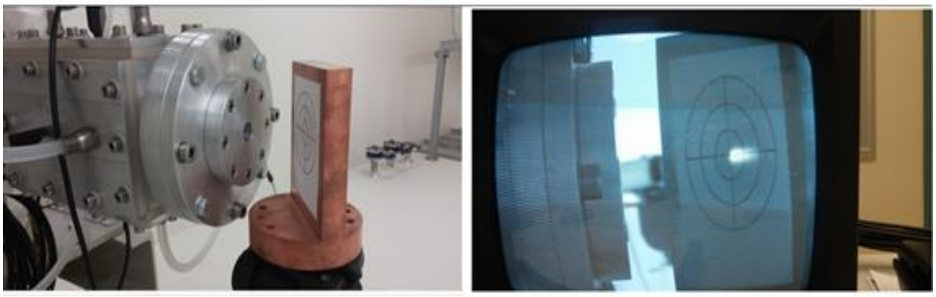

Figure 4. View of proton beam hitting on alumina screen passing through the flange assembly at end of Beamline 1.1 and then spreading ~5 cm distance in the air by depending on the beam energy.

2.3. Emittance Determination Studies for R&D Beamline 1.1 of TAEA PAF

2.3.1. Beam Emittance

The beam emittance and its measurement are essential to guide tune-up accelerator (Raich, 2009) and key parameter on an accelerator performance (Braun, 2008). Therefore, beam

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emittance plays quite an important role on the characterisation of the beam composed of many accelerated charged particles. Beam emittance is identified in transverse and longitudinal directions. Transverse emittance is defined as the area (ellipse) in phase space by particles. Each charged particle included by beam moves with a velocity at a specific position. In order to calculate the beam emittance, this area which is occupied by particles in x (position), x^1 (velocity) planes divided by π (Figure 5). Beam ellipse and its orientation are defined by 4 parameters ε, α, β, γ which are related to the Twiss or Courant-Snyder parameters. Along the BTL, the orientation and aspect ratio of beam ellipse in x, x^1 planes vary but the area remains constant.

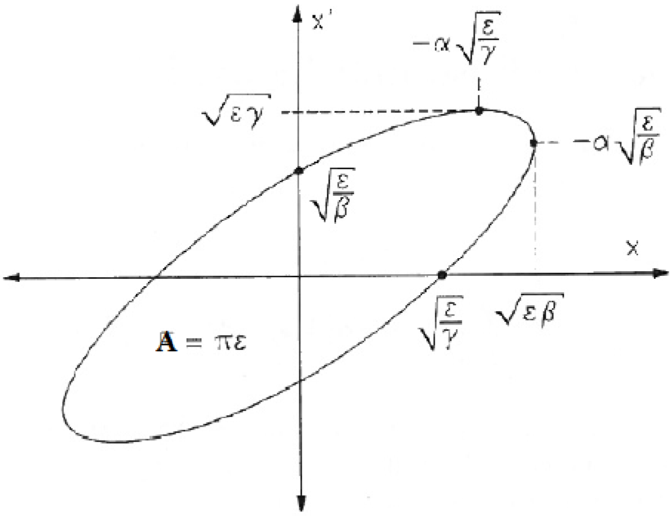

Figure 5. Distribution of a charged particle beam in phase space; The Emittance.

2.3.2. Quadrupole Variation (Scanning) Method

There are different types of techniques in the determination of the above mentioned emittance value. Those techniques can be briefly listed as; slit-wire/grid scan, three grid scan, Allison scanner, pepper-pot scan and quadrupole variation methods (Forck, 2011). In quadrupole variation method, the charged particle beam is send to a beam viewer having a scintillation screen made of scintillating materials, and this beam causes a creation of photon beam in the visible region and thus the spot size of the particle beam becomes visible. It can be easily monitored with the help of a CCD system, as seen Figure 6. (Forck, 2011).

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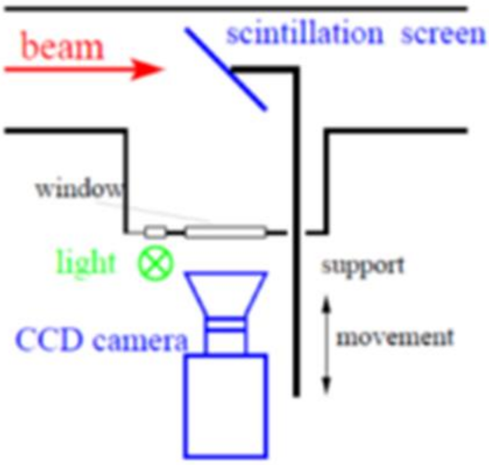

Figure 6. The schematic representation of the set-up to observe the beam spot and its distribution in a BTL.

In the quadrupole variation method; the change in spot size is followed by altering the magnetic focusing field (quadrupole strength, k) of the last quadrupole magnet placed at the end of the BTL as seen in Figure 7 (Forck, 2011). Then, the spot images corresponding to each magnetic field intensity values, are monitored and recorded by a digital video recorder (DVR). The spot images obtained, are processed by using a suitable image processing program and finally the transverse beam properties i.e. horizontal and vertical dimensions are obtained.

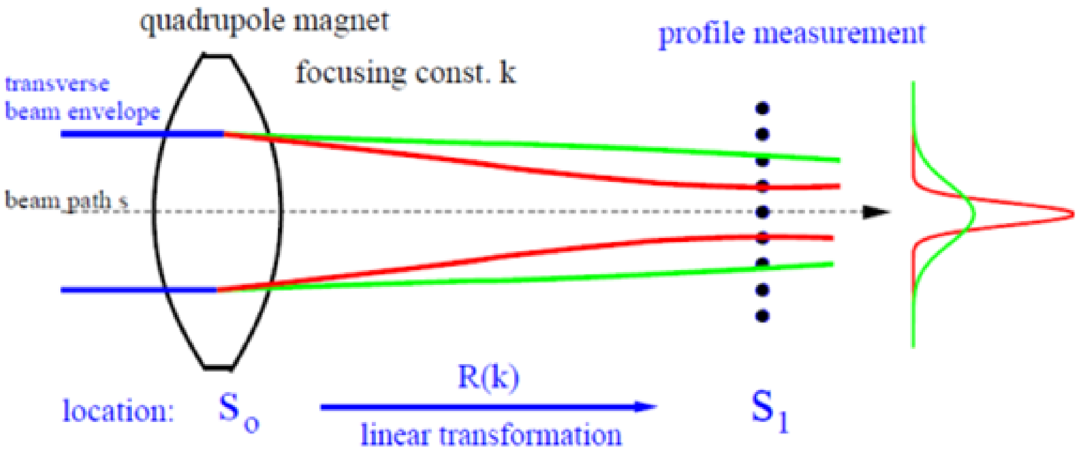

Figure 7. The change in the beam profile of the charged particle beam on the beam viewer at S_1 location in BTL by changing the magnetic field intensity of the quadrupole magnet at S_0 position in BTL.

2.3.3. Experimental Setup

In order to measure the emittance; 30 MeV and ~0,3 µA of proton beam was sent onto a 2 kW beam-viewer of which has scintillation screen made of alumina on the beam transportation line in R&D vault of the TAEA-PAF (Figure 8.).

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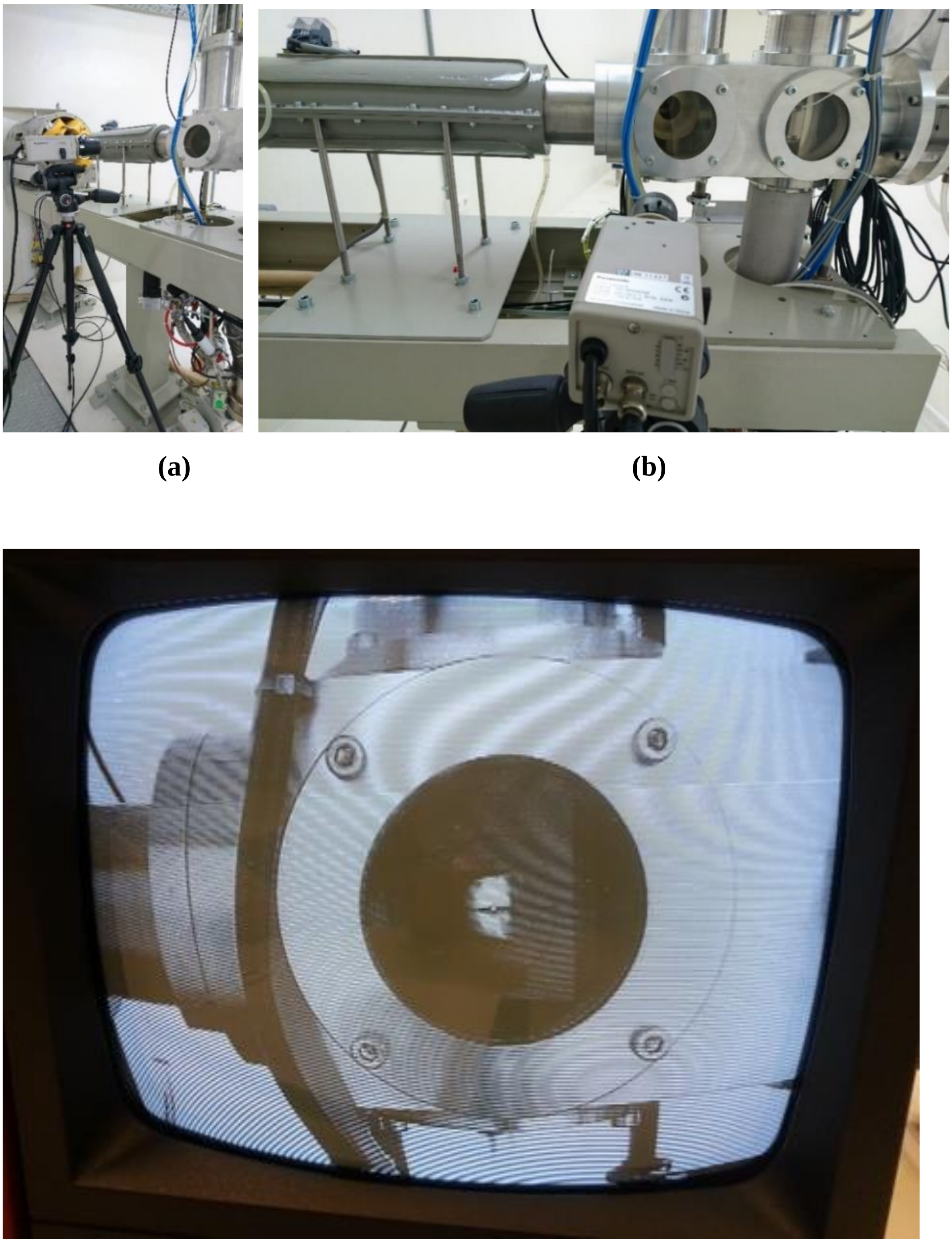


(a) **(b)**

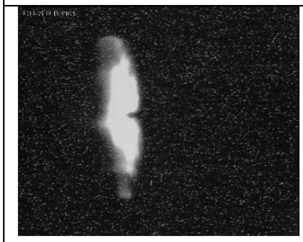
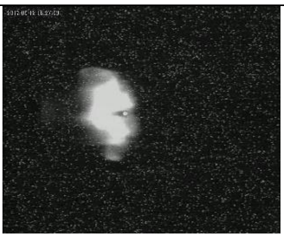
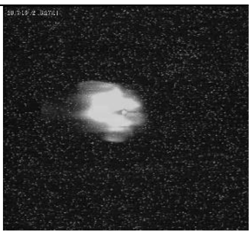
(c)

Figure 8. The experimental set-up at TAEA-PAF R&D Irradiation Vault Beamline 1.1; **(a)** a general view, **(b)** Panasonic camera and Tomron optical lens assembly, **(c)** a beam spot view on the 2 kW beam viewer for the proton beam with 30 MeV beam energy and 0,3 μA beam current.

3. Finding and Results

The images of the changes in the spot profile of the proton beam falling onto the scintillation screen (beam viewer) according to the changing magnetic field intensity (focussing strength, k) by varying the feed current applied to the quadrupole magnet placed at the end of the BTL are given in Table 1.

Table 1. The beam spot views on the beam viewer's scintillation screen in the R&D Beamline 1.1 by changing feed current value of the last quadrupole.

QM Current= 10 A	**QM Current = 20 A**	**QM Current = 30 A**	**QM Current = 40 A**
			
QM Current = 50 A	**QM Current = 60 A**	**QM Current = 70 A**	**QM Current = 80 A**
			

The images gathered were analyzed with the help of an image processing program (Anonymus, 2016) and the results regarding with horizontal and vertical distributions of beam spot in transverse plane corresponding to each feeding current value of last quadrupole were calculated as presented in Table 2.

Table 2. Horizontal and vertical distributions of beam spot in the transverse plane corresponding to each current value of last quadrupole magnet

Quadrupole Magnet Feed Current, I (A)	**Beam Spot Horizontal Width, σ_x (mm)**	**Beam Spot Vertical Width, σ_y (mm)**
10,00	8,60	35,88
20,00	10,78	27,22
30,00	12,38	21,40
40,00	16,05	13,73
50,00	19,15	8,04
60,00	24,19	3,59
70,00	23,73	6,68
80,00	22,93	9,40

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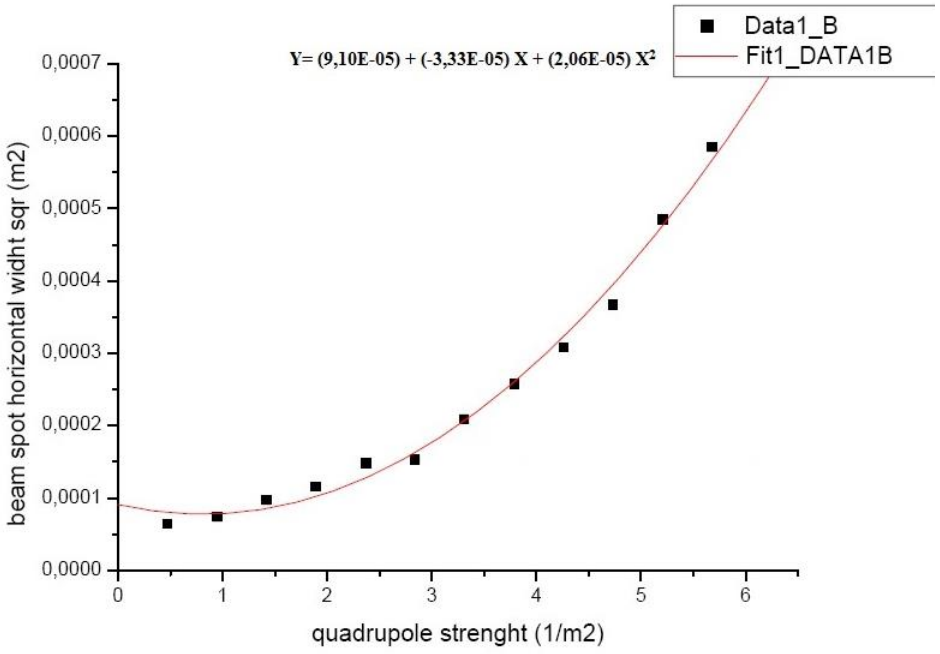
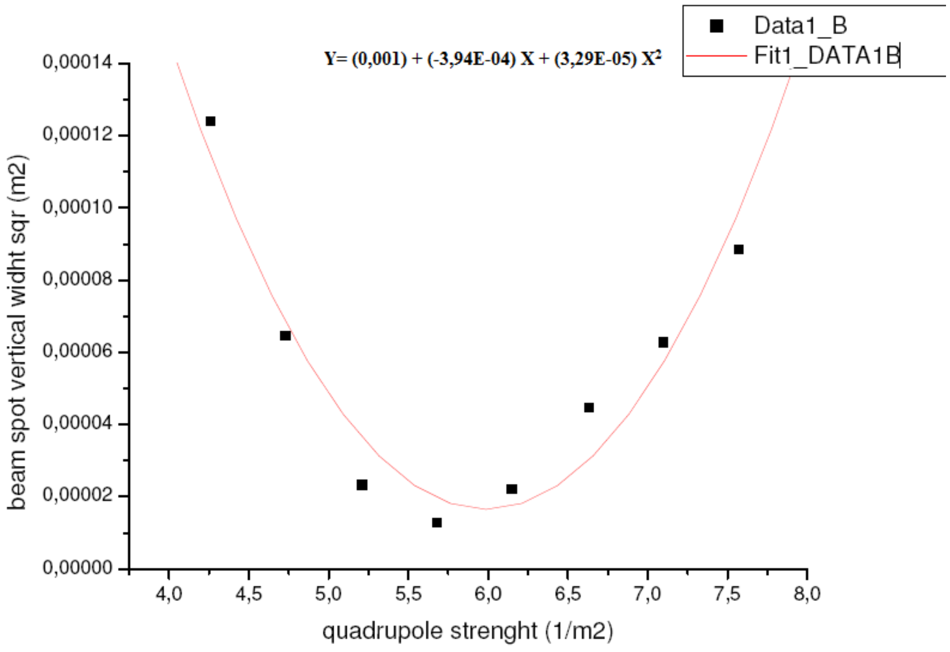
By using the feed current values of the last quadrupole magnet given in Table 2., the quadrupole strengths (k) corresponding to each current value were calculated. Then, the changes in the spot sizes (spot width's squares by unit of m^2) with respect to the changing quadrupole strength values of the last quadrupole magnet, both in horizontal and vertical dimensions were given in Figure 9 which were fitted well to parabolic functions.



(a)



(b)

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Figure 9. The variation of beam spot widths corresponding to quadrupole strength values of the last quadrupole magnet; **(a)** for horizontal plane (b) for vertical plane.(■: experimental; theoretical red line: calculated using polynomial function)

According to the protocol of the mathematical model used in quadrupole variation technique, the horizontal (ε_x rms) emittance, vertical emittance (ε_y rms) values and related twiss parameters (β, α, γ) were calculated by using the coefficients obtained from the above mentioned parabolic equations (Minty, 2004). So the results are shown in Table 3.

Table 3. Horizontal and vertical emittance values and related twiss parameters calculated for proton beam with 30 MeV energy and 0.3 µA current at the 2kW beam viewer position

Calculated values for horizontal emittance and related twiss parameters									
A	**B**	**C**	**S_{11}**	**S_{12} (m)**	**ε_x rms (π mm.mrad)**	**ε_x N (π mm.mrad)**	**β_x**	**α_x**	**γ_x**
2,06E-05	8,08E-01	7,76E-05	1	0,95	14,11	3,63	0,52	0,96	3,36
Calculated values for vertical emittance and related twiss parameters									
A	**B**	**C**	**S_{11}**	**S_{12} (m)**	**ε_y rms (π mm.mrad)**	**ε_y N (π mm.mrad)**	**β_y**	**α_y**	**γ_y**
3,29E-05	5,99E+00	2,09E-05	1	0,95	9,25	2,38	2,38	1,26	8,84

4. Conclusions

According to the technical specifications given by IBA’s Cyclone 30 model cyclotron regarding horizontal (ε_x rms) emittance, vertical emittance (ε_y rms) values for 30 MeV proton beam are as of ε_x rms < 15 π mm.mrad, ε_y rms < 10 π mm.mrad respectively (Anonymous, 2008). However, the emittance values were calculated as ε_x rms ~ 14 π mm.mrad and ε_y rms ~ 9,25 π mm.mrad respectively for the TAEA-PAF R&D Beamline 1.1 in this study. It was observed that the calculated emittance values and twiss parameters during the study vary depending on the parameters of the ion source subsystems and the status of the carbon foil in the extraction system (Nesteruk, 2015). By considering the above mentioned conditions, it was evaluated that the calculated emittances were in accordance with the values given in the technical specification document of Cyclone 30. It is estimated that the measurements can be more compatible by using a new stripper and precise adjustments to the ion source subsystems. As it is well known, the emittance describes the beam quality. In addition, it provides initial beam conditions for any BTL, allows to compute optimum operational settings of any BTL instruments with minimum beam loss and tells whether a beam fits in the vacuum chamber or not. Moreover, it verifies and improves the beam optics model of any BTL and related experimental station which will serve to the desired specific purpose or purposes. TAEA-PAF also aims to run this commercial machine especially at low beam current levels for R&D studies. Therefore, our next objective is going to be the design of specific BTLs and related experimental station branching at TAEA-PAF R&D vault which would make it possible to

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transport the beam within the required parameters for the purpose of specific applications for materials science researches. Consequently; thanks to this study, it was achieved that beam emittance value for TAEA-PAF R&D Beamline 1.1 was determined for the first time which is most important beam characteristic in order to proceed to the next step mentioned above.

5. Thanks

All the studies which are carried out in accordance with the needs of our country, industry and universities were fully performed at TAEK-PAF by using valuable resources of the TAEA. I present my gratitude to the Presidency of the TAEA, the Directorate of SNRTC and the Management of the PAF.

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