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THE PRORAD BEAM LINE DESIGN FOR PRAE

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Abstract

The Platform for Research and Applications with Electrons (PRAE) is a multidisciplinary R&D facility around a high-performance electron accelerator with beam energies up to 70 MeV. One important application of the PRAE is the proton radius (ProRad) measurement, which requires an extremely low energy spread (5×10^{-4}) and low divergence with beam energies 30, 50 and 70 MeV. In this paper, the beam line design and simulation for the ProRad are presented. Then the tolerance for quadrupoles misalignment is studied and the beam-based alignment technique is used to improve this tolerance.

INTRODUCTION

Proton is one of the most fundamental particles that had been discovered in the universe, the exact knowledge of its radius is very important. The proton radius measured using the Lamb shift of muonic hydrogen is 0.84184±0.00067 fm [1]. However, the electron scattering experiments gives result 0.879±0.008 fm [2]. The discrepancy between these two methods is larger than 5 standard deviations, which is known as proton charge radius puzzle. A large number of possible explanations ranging from inaccurate extraction of the proton radius up to genuine physics effects and Physics Beyond the Standard Model have been proposed to explain this striking discrepancy. However, the existing world data set is not enough in order to provide a consensus.

The Platform for Research and Applications with Electrons (PRAE) is a multidisciplinary R&D facility around a high-performance electron accelerator with beam energies up to 70 MeV [3,4]. This facility can be used to measure the proton radius at very high accuracy, providing high quality electron beam with energy 30–70 MeV.

In the following, the requirement for the The Proton Radius (ProRad) is first presented. The principle for the energy compressor is explained following. Then the facility of the electron accelerator is illustrated, including the RF gun and the linac, the beam line dedicated to ProRad. The beam simulation and the tolerance for the quadrupoles are then presented. Finally, a summary for these work is given.

THE REQUIREMENTS OF THE PRORAD

ProRad experiment at PRAE aims at collecting high accuracy data (1%) about the proton electric form factor $G_E(Q^2)$ in the unexplored four-momentum Q^2 range 10^{-5}–10^{-4} (GeV/c^2)^2. This will give requirements for the electron beam like: beam energies are 30, 50 and 70 MeV; bunch charge is between 10–100 pC; energy spread is less than 5×10^{-4}; beam size is 20 – 30 µm in one direction and 100–200 µm in another direction; the divergence is smaller than 50 µrad.

In the following, we will mainly focus the energy spread requirement.

THE ENERGY COMPRESSOR SYSTEM

In order to provide the low energy spread, an energy compressor system (ECS) is needed. Fig. 1 shows the principle of the ideal ECS. The magnetic chicane will rotate the longitudinal phase space of the incoming electron bunch such that the head of the bunch will have energy higher than the tail. Then a rf cavity can be used to reduce the energy spread. The cost is the bunch length will be longer.

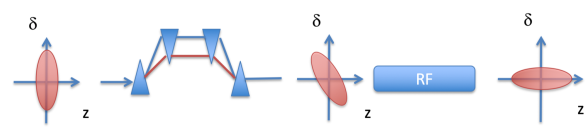

Figure 1: The principle of the ideal ECS.

The final energy spread for such a ECS can be expressed as:

$$\sigma_{\delta_f}^2 = R_{65}^2\sigma_{z_i}^2 + (1 + R_{56}R_{65})^2\sigma_{\delta_i}^2.$$

Here the R_{56} and R_{65} are the element of the response matrix for the ECS, σ_{δ_i} and σ_{z_i} are the initial energy spread and bunch length. Using the fully compression condition $1 + R_{56}R_{65} = 0$, the final energy spread depends only on initial bunch length. The bunch length is 1 mm in our case, the R_{65} will be 0.5 m^{-1} in order to get the energy spread 5×10^{-4}. Then the R_{56} will be -2 m. Given the magnets length 0.4 m, the magnet space 2 m, the angle of the chicane will be 38°. This is a really large magnetic chicane. For a 3 GHz rf cavity with length 0.2 m, the R_{65} will give the gradient 2.8 MV/m.

Usually the ECS use the RF system to reduce the energy spread, however there are also other methods to do this.

One method is using a passive wakefield structure (dielectric or corrugated). When the electron bunch pass through the structure, the generated wakefield reduces the energy spread. The requirement for this method is that the electron bunch should have a positive energy chirp (the bunch tail has more energy). In order to use the passive structure, we must design a chicane with small R_{56}. And the electron should have a positive energy chirp at the end of the linac. The problem for this method will the large nonlinear effect.

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Another method is using a collimator to remove the electrons whose energies are far away from the average energy. The PRAE can delivery electron bunches with charge up to 1 nC, while the ProRad requires bunch charge of only 10-100 pC. So the particle losses due to the collimation is not a problem. The collimator is put between the second and the third magnet of the chicane. The angle of the chicane is chosen as 30 degree which is the same as deviated angle of the dogleg for radiobiology beam line.

THE RF GUN AND LINAC

The experiment requires the beam with extremely small emittance, so the photo-injector is chosen as electron source. The properties of the RF gun have been shown in the reference [5]. The magnesium is used as cathode, which can deliver electron bunch with charge more than 1 nC. The S-band rf gun with frequency 3 GHz is made of 2.5 copper cells , providing an accelerating gradient of 80 MV/m given the input power of 5 MW. The energy gain at the exit of the gun is about 5 MeV. Two solenoids separated longitudinally by 23 cm are used to compensate the space charge effect in the rf gun, providing maximum magnetic field 0.257 T.

After the RF gun, there are several instrumentation elements to measure and control the beam, including ICT, BPM and dipole corrector. The distance between the RF gun and the linac is optimized as 1.67 m to provide the minimum emittance.

The linac is a 3.47 m long S-band (3 GHz) traveling wave structure, working on the mode $2\pi/3$. Such structure will provide an energy gain of 65 MeV for an input peak power of 30 MW.

Astra [6] is used to simulate the rf gun. The particle distribution from the Astra is then used as input for the RF-Track [7] to simulate the acceleration in the linac.

THE BEAM LINE DESIGN

The layout of the PRAE accelerator is shown in Fig. 2.

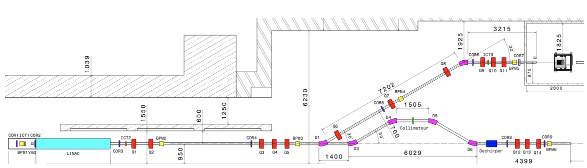

Figure 2: The layout the PRAE beam line.

There are two beam lines for the PRAE. The deviated line with a dogleg is used for the radiobiology experiment. The direct line with a magnetic chicane is used for the ProRad experiment.

The RF gun is shown in the left of this figure, followed by the first HG linac. A quadrupole doublet and triplet are then used to focus the beam after the linac. Between these quadrupoles, a drift space around 4 meters is reserved for the future upgrade (for the radiobiology experiment).

After the triplet, a 30 degree dipole magnet is used to provide beam for the radiobiology experiment. This magnet will be switched off during the ProRad experiment. The instrumentation elements YAG/OTR are put after the dipole magnet to measure the beam profile. Then a D-shape magnetic shape is used to form the energy compression system. A collimator is put in the middle of the chicane. Finally, another quadrupole triplet is used to provide the beam with specified beam size.

In order to perform the beam measurement and correction, the standard instrumentation elements ICT, YAG/OTR screen, BPMs and dipole correctors are inserted in the beam line.

The transverse beam size at the end of the beam line is required to be 200 µm and the beam should reach the beam waist to give less divergence. And the β function along the beam line is required to be smaller than 100 m in order to adapt the beam pipe with radius of 2 cm. Those requirements are matched with the software MADX [8]. The matched optics for the ProRad beam line can be seen in Fig. 3. The R_{56} is -1.4 m for this kind of design. The horizontal beam size at the middle of chicane will be about 4 mm due to dispersion.

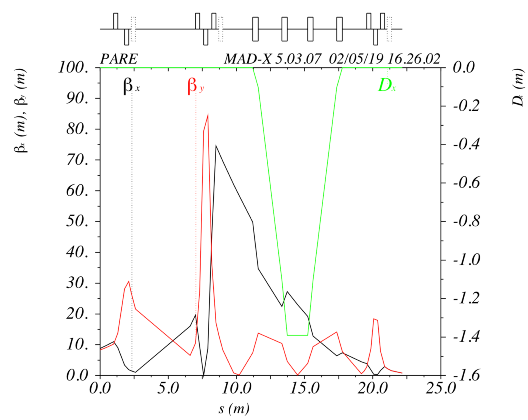

Figure 3: The optics for the beam line.

The beam from the rf gun and the linac (working on crest) is used for this designed beam line. PLACET [9] is used to track the beam until the end of beam line (without collimator). The phase spaces of the beam at the end are shown in Fig. 4.

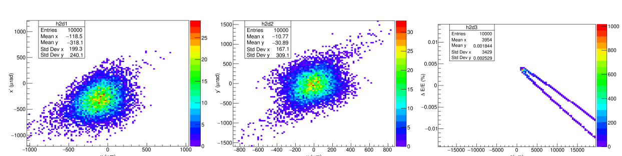

Figure 4: The phase space at the end of beam line.

THE EFFECT OF THE COLLIMATOR

A 1 meter long collimator with half aperture of 2 mm in the horizontal plane is put in the middle of the chicane to reduce the energy spread. The comparisons between the with and without collimator are shown in Fig. 5. It can be seen the particles with relative low energies are removed by the collimator. There is about 48% of particles can pass through the

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collimator and the energy spread for those survived particles is 4.2×10^{-4}.

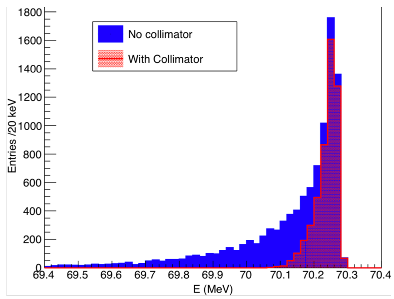

Figure 5: The comparison of energy between with and without collimator.

The transverse position distributions are shown in Fig. 6. It can be seen that after the collimation, the transverse position distributions still keep symmetric. The central positions are about 200 and 70 μm for x and y plane, respectively. These offsets are coming from the initial beam and can be corrected with some dipole correctors.

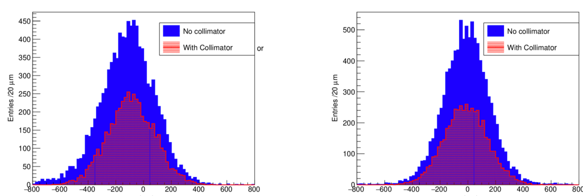

Figure 6: The comparison of transverse distribution between with and without collimator. The left side plot show the distribution of x and the right side plot shows the distribution of y.

MISALIGNMENT TOLERANCE STUDY

The above simulations are based on ideal machines. In the real machine, there will many kinds of imperfection. Here we consider the misalignment tolerance for all the elements in the lattice: the dipole magnets, the quadrupoles and the collimator. The misalignments include the position offset, the angle offset and the rotation errors. In the following simulation, we will simulate 100 machines with random misalignment errors of gaussian distribution.

The mechanical alignment can align the element error to the level of 100 μm and 100 μrad. In such a imperfection level, if we require that the percentage of survived particle large than 20%, there are only 45% machines have energy spread smaller than 5×10^{-4}. This means that we must use the beam base alignment technique to correct the beam line during operation. The distributions of the number of survived particles and the energy spreads are shown in Fig. 7.

The tolerance about the misalignments is got by reducing the imperfection level, it is found that the imperfection of 20 μm and 20 μrad will give 93% of the machines with energy spread less than 5×10^{-4} and particles percentage large than 20%.

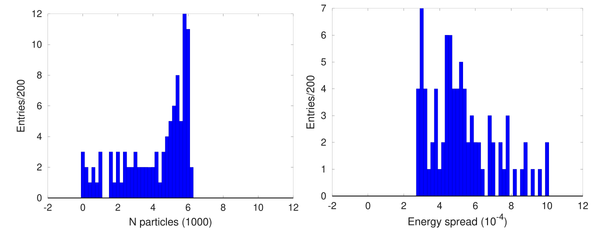

Figure 7: The machine distributions for the imperfection of 100 μm and 100 μrad. The left side plot shows the number of survived particles distribution and the right side plot show the energy spread distribution for machines with survived particles percentage more than 20%.

THE BEAM BASED ALIGNMENT

In order to improve the tolerance level, four BPMs and three dipole correctors are put along the ProRad beam line in order to correct the errors due to the magnets. The algorithm one-to-one correction (1:1) is used to improve the orbit. This a simple and faster algorithm which is often used first to correct the misalignment errors. We use the Eq. (1) to get strength of the dipole correctors for the 1:1 correction.

$$\theta = \min||\mathbf{\Delta u} - \mathbf{R}\theta||_2^2 + \alpha^2||\theta||_2^2; \quad (1)$$

Here, θ is the strength of the dipole correctors. $\Delta\mathbf{u} = \mathbf{u} - \mathbf{u}_0$ represent the beam position difference recorded by BPMs between misalignment machine and perfect machine. $\mathbf{R}$ is the response matrix between the dipole correctors and the BPMs. α is damping factor which is used to avoid the large fluctuation of corrector strength.

With the help of the BBA, the tolerance for the quadrupoles errors can be increased to 500 μm and 500 μrad, which are easy be reached using the state-to-art alignment techniques. The distributions of the number of survived particles and the energy spreads are shown in Fig. 8.

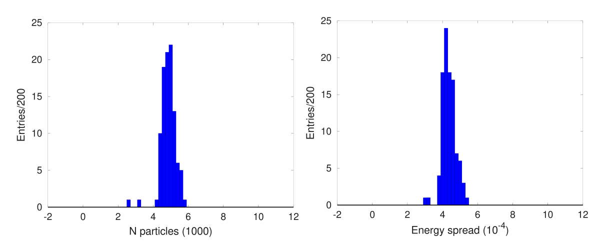

Figure 8: The machine distributions for the imperfection of 500 μm and 500 μrad after beam based alignment.

SUMMARY

In this paper, the electron beam line design for the proton radius experiment is presented. This lattice include a energy compressor system composed by a D-type magnetic chicane with a collimator in the middle. For this lattice, the tolerance of the quadrupoles misalignment is determined as 20 μm and 20 μrad. With the help of BBA, the tolerance can be increased to 500 μm and 500 μrad. The energy spread requirement 5×10^{-4} can be reached using such a lattice.

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