FIRST OPTICS DESIGN AND BEAM PERFORMANCE SIMULATION OF PRAE: PLATFORM FOR RESEARCH AND APPLICATIONS WITH ELECTRONS AT ORSAY

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Abstract

The PRAE project aims at creating a multidisciplinary R&D facility in the Orsay campus gathering various scientific communities involved in radiobiology, subatomic physics, instrumentation and particle accelerators around an electron accelerator delivering a high-performance beam with energy up to 70 MeV and later 140 MeV, in order to perform a series of unique measurements and future challenging R&D. In this paper, we report the first optics design and performance evaluations of such a multidisciplinary machine, including a first description of the experiments and the required beam instrumentation.

INTRODUCTION

From lowest to highest energies, electron beams represent exploration and measurement tools of high quality and unparalleled wealth. If the number and quality of research tools at both ends of the energy scale are encouraging, it should be noted the poverty of the accelerator park in the range of tens to hundreds of MeV [1-4]. The research laboratories IMNC, IPNO and LAL, gathered in the PRAE project for the creation of a multidisciplinary scientific R&D facility within the Orsay campus. The platform is based on an accelerator delivering a high-performance electron beam with an energy up to 70 MeV and then upgraded to 140 MeV, over the two successive time phases of the project. A layout is shown in Figure 1.
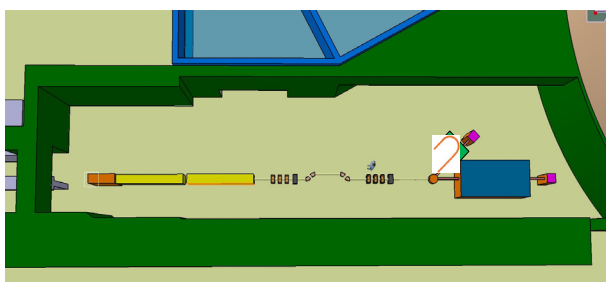

Figure 1: Schematic view of the PRAE accelerator (140 MeV) with the two experimental beam lines

In the energy range 30-70 MeV, PRAE will contribute to unravel the proton radius puzzle with the ProRad ex-

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periment. The 50-140 MeV electron energy range will allow developing radiobiology studies pursuing preclinical studies of new radiotherapy methods aiming for a better treatment of cancer. Over the full energy range, PRAE beams will provide the essential tools to characterize, optimize and validate instrumentation techniques for the next generation of detectors used in medical imaging, subatomic physics, particle physics, spatial technology and astrophysics.

THE EXPERIMENTAL PLATFORM

ProRad: Proton Radius Puzzle

The ProRad experiment 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} $(GeV/c^2)^2$ [5-7]. The essential components of ProRad are: a well-defined and established electron beam, a windowless thin hydrogen target, and an accurate knowledge of the scattering angles.
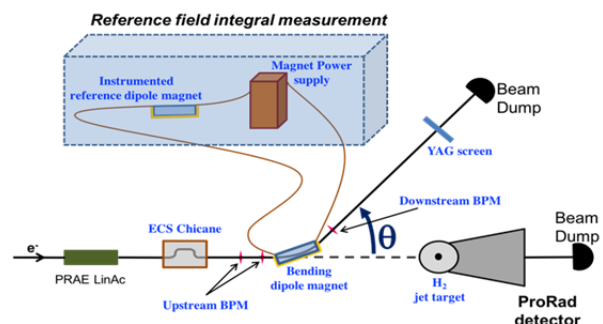

Figure 2: Conceptual view of the principle of operation of the ProRad experiment.

In order to get reproducibility and stability of the beam energy with a narrow beam energy spread necessary to get the required performances for the ProRad experiment, an Energy Compressor System (ECS) will be implemented to achieve a 5×10^{-4} beam energy dispersion. In addition, the measurement of the absolute value of the beam energy with a relative 5×10^{-4} uncertainty is required in order to meet the acceptable ProRad total uncertainty of

1×10^{-3}. Such a precise measurement is possible by using a dedicated additional deviated line located downstream of the ECS and relying on a pair of identical C-shaped dipole magnets serially powered together (Figure 2).

Radiobiology: eHGRT Technique

One of the main challenge in radiotherapy (RT) is to find novel approaches allowing the escalation of the dose delivered to the tumour, resulting in an improvement in the cure rate, while lowering the normal tissue complication probability. Electrons are currently used in conventional RT, with energies ranging from 5 to 20 MeV. However, they are not suitable for the treatment of deep-seated tumours due to their short range and substantial lateral scattering. This limitation can be overcome if the electron energy is increased above 70 MeV, whereby the penetration depth becomes longer and the transverse penumbra sharper. The objective of the radiobiology axis of the PRAE project is to explore such a dose delivery method in electron therapy, combining very high-energy electron beams and Spatially Fractionated Radiotherapy (SFR), and sub-millimetric beam sizes. Such SFR technique has been proven to be effective in delivering large cumulative doses of radiation with reduced healthy tissue complications. This novel approach will be called: electron High-energy Grid Radiation Therapy (eHGRT). It is based on the relative scanning of a micro-beam with respect to the irradiated sample, following a virtual grid (Figure 3). The theoretical proof of concept of this innovative technique has been recently published in [8]. At PRAE, feasibility studies, based on accurate dosimetry protocols and pre-clinical trials, will be performed to evaluate radiobiological effects of eHGRT.
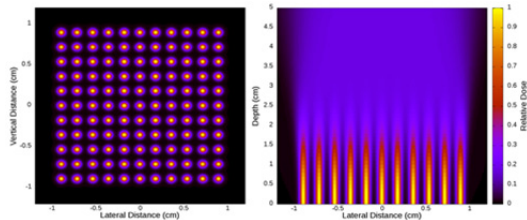

Figure 3: Illustration of the spatial fractionation of the dose with a grid pattern (left side) and the 2D depth-dose distribution in eHGRT (depth versus lateral distance) at 70 MeV.

Instrumentation for Detectors R&D

In the PRAE platform a fully equipped and instrumented platform will be made available to a user community from the academic and the industrial media willing to test and optimize detectors. The facility will provide an adjustable number of particles per pulse in a wide range of multiplicities (current/pulse: $1\text{-}10^{10}$ particles) and energies (50-140 MeV). Together with good spatial resolution (beam spot< 1 mm) and excellent timing properties (pulse width < 10 ps), this opens a wide range of applications for detector R&D. The test bench will be instrumented with a precise beam profile measurement device, a particle coun-

ter and a calorimeter as shown in figure 4. In order to operate remotely the beam diagnostic and detector positioning, we will design and produce a movable chamber at the beam exit, as in the PHIL/LEETECH facility [2, 9].
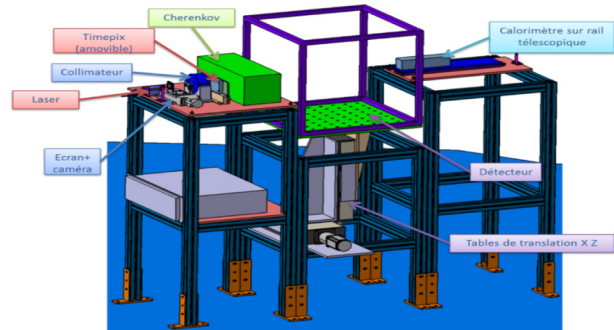

Figure 4: Schematic view of the instrumentation setup

THE PRAE ACCELERATOR

The PRAE accelerator consists of a photo-injector, an acceleration section and two beam lines with the corresponding experimental setups: the subatomic physics and radiobiology research axes share the direct line and the instrumentation platform is located the deviated line, as shown in figure 1. The performances of the PRAE accelerator are summarized in Table1.

Table1: PRAE accelerator performances

Parameters	Phase 1	Phase 2	Units
Energy	70	140	MeV
Charge (variable)	0.00005 – 2		nC
Normalized emittance	3-10		mm mrad
RF frequency	3.0		GHz
Repetition rate	50		Hz
Transverse size, rms	0.5		μm
Bunch length, rms	< 10		psec
Energy spread, rms	< 0.2		%
Bunches per pulse	1		

The RF Gun

Since a low emittance beam is required, a photo-injector has been chosen as electron source. Risks mini-mization guides towards the construction of a gun similar to the one constructed for the CTF3 at CERN [10] and running successfully since then. This technology is also used for the ThomX project now under construction [11]. To obtain high-charge per bunch, we will use a metallic magnesium photocathode, which can deliver more than 1 nC with a laser pulse energy of a few tens of a μJ at a wavelength of 260 nm. The gun is made of 2.5 copper cells, magnetically coupled to a waveguide. To get 1 nC with an emittance lower than 5 mm mrad, an accelerating field of 80 MV/m is required, which means a RF power of 5 MW in a 3 μs pulse. The electron beam energy at the exit of the gun will be of the order of 5 MeV.

An industrial laser will be used to extract electrons from the cathode by photoelectric effect. It will be synchronized with the RF frequency and triggered at 50 Hz.

The Linac Section

The PRAE acceleration section will be a 3.4 m long high-gradient (HG) S-band (3 GHz), in order to make the machine more compact. The section will be located after the RF gun. Collaboration between LAL and an industrial partner PMB-Alcen [12] on HG S-band structure research has been established in order to push the performance envelope of RF structures towards higher accelerating gradients. The HG accelerating structure will be a travelling wave (TW), quasi-constant gradient section and will operate at 3 GHz (30°C in vacuum) in the $2\pi/3$ mode. The choice of a single cell shape derives from an optimization aiming to maximize RF efficiency and minimize surface fields and modified Poynting vector at very high accelerating gradients. Such gradients can be achieved using shape optimized elliptical irises, quasi-symmetrical type coupler, and specialized fabrication procedures developed for HG structures [13]. Before the construction of the final HG structure, constant impedance (CI), prototypes with a reduced number of cells has been realized, in order to verify the validity of the manufacturing procedures and all technical choices. First prototypes are under construction and will be tested in fall 2017. The final HG structure will provide an energy gain of 65 MeV for an input peak power of 22 MW with a RF flat top pulse length of 3 μs and a repetition rate of 50 Hz.

These specifications lead us to choose a klystron producing 35 MW in a 4.5 μs pulse. To feed the klystron, a modulator is needed that provides high voltage pulses of typically 240 kV, through a high voltage transformer soaking in an oil tank. The two technologies, which can be used for this component, are commercially available. Between the RF gun and the acceleration section there is an instrumented beam line. Optimization of this beam line section is under progress in order to elucidate the eventual necessity of a focusing quadrupole doublet.

The Beam Lines Optics

A beam energy compressor section follows the accelerating structure before separating in the direct (ProRad/Radiobiology) and the deviated line (Instrumentation). Two quadrupole triplets provide flexible beam optics to cope the different beam characteristics and operation modes depending on the application. With respect to beam measurement and control, Beam Position Monitors (BPM), beam size (YAG) and intensity monitors are considered. A magnetic chicane coupled with a RF structure [14-16] or a passive corrugated structure [17-19] allows to control the beam momentum dispersion and a spectrometer provides the magnetic analysis of the beam energy in a deviated line. The choice of the final technology for the ECS will be made on the basis of the comparison of these two methods with respect to ProRad requirements. First optics design of the direct line with the ECS chicane and two quadrupole triplets is shown in

Figure 5. The last dipole is not active in this case, indicate the starting point of the deviated line for detector R&D platform. The optics design has been calculated with MADX [20].
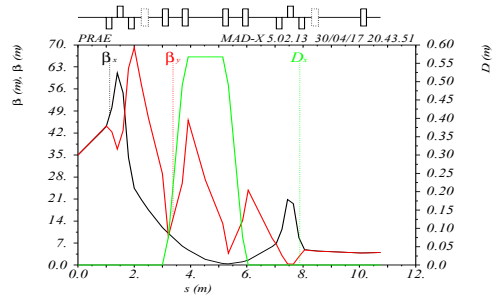

Figure 5: First optics design of the direct line with the ECS chicane and two quadrupole triplets.

Preliminary Beam Dynamics Studies

Preliminary start-to-end beam dynamics simulations have been performed using a concatenation of codes. The ASTRA (A Space Charge Tracking Algorithm) simulation code has been used in the design of RF photoinjector system [21]. The resulting particle distribution is performed using the new code RF-Track [22, 23] through the acceleration section from the exit of the RF gun to the end of the linac section. This new tracking code has been developed for the optimization of low-energy linacs in presence of space-charge effects. Furthermore, RF-Track gives possibility to transport bunched beams through conventional elements and field maps of oscillating electromagnetic fields. In the case of PRAE the 3D electromagnetic field profile of the accelerating section has been defined via HFSS [24]. One RF period of 3 cells has been considered, corresponding to a length of 100 mm. A total of 96 cells have been tracked in a simplified model without input and output couplers, substituted by drifts. The input power can change dynamically. To reach a final energy 70 MeV, RF power of about 22 MW is required. The total section length is about 3.47 m. The resulting particle distribution has been tracked along the beam line with the code PLACET [25, 26]. First preliminary results have been obtained and the optimization procedure of concatenation of codes is being established as well as a benchmarking of the results. Particular attention will be dedicated in future studies to the simulation of the ECS section, in order to elucidate the final technology choice, the effect of the coherent synchrotron radiation and the space charge effects given the relative low-energies in the first phase of the project.

ACKNOWLEDGEMENTS

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