Science and Technology of Accelerators

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Abstract. The Mexican Particle Accelerator Community (CMAP) was created in 2015 and currently its members participate in different experiments around the world. Using their expertise, they are working in develop the particle accelerators area in Mexico. This paper provides a resume of the research done by its members and presents the preliminary design of an electron linear particle accelerator (eLINAC). This proposal will be the first accelerator designed and created in Mexico.

1. Introduction

Since 2007, the Division of Particles and Fields of the Mexican Physical Society (DPyC-SMF) sent a group of students to different laboratories to learn about particle accelerators [1], from this endeavor the CMAP was created. The good performance of their students allowed to consolidated the collaborations of this field between Mexican Universities and international Labs such as European Organization for Nuclear Research (CERN), Jefferson Lab, Berkeley Lab and ALBA. Additionally, the two Mexican Particle Accelerators Schools (MEPAS) were a key factor to support the growth of the accelerator community. The MEPAS represents a relevant resource for the training of the students. Indeed, thanks to that experience learned they continue its research in the area, moreover, CMAP members start as students in these schools.

Nowadays, several laboratories uses particles accelerators for their research around the world, in addition, the industry and government are also users of these machines. In Mexico, the user community of accelerator is large, however, the numbers of facilities and experts are insufficient to cover the demand. The CMAP is developing the project of eLINAC , which will be the first accelerator designed and created by Mexicans. The main goals of this proposal is to cover part of the necessities of the users and the consolidation of the particle accelerator area in Mexico, [3].
2. CMAP members Research

This section we explain some of the research made by the CMAP members. The beam propagation through the accelerator requires a deep understanding of the interaction of electromagnetic fields with charged particles in order to estimate the behavior of the charged particles. Moreover, the collective effects created by the interaction of the particle beam itself, such as the space charge, when the density is high needs to be taken in to account as well as the relativistic effects when the particles travel close to the speed of light or they lose energy due the synchrotron radiation. 

These studies in the machine required to run some complex simulations using several variables, codes as Methodical accelerator Design (MADX) [4] can estimate the propagation of the beam for long circumference like the LHC ring.

On the other hand, some quantum effects are needed to understand the beam formation in the plasma at the beam sources and the generation of secondary particles due electromagnetic fields or particle collisions.

Finally, another relevant subject is the beam losses. The particles lost in the ring are unavoidable, therefore, it is important to understand the mechanism that produced the losses and mitigate its effect in the acceleration chain in order to protect the workers safety and the integrity of the machine components. In the next subsection we resume the research expertise of some members of CMAP group:

2.1 Gerardo Guillermo Canton

Synchrotron Radiation (SR) Studies using numeric method tools (montecarlo) are important for the good performance of the LHC. SR photons are simulated inside an accelerator's beam pipe, they are tracked from generation until final absorption, though all reflections in the vacuum chamber. The tool used is Synrad3D developed at Cornell University by D. Sagan which uses a mathematical model by G. Dugan.

![Figure 1: Effect of the sawtooth in the chamber of LHC and the effect of ATS optics in HLLHC](image)

We have studied the difference between sudden (step function) changes of shape in the vacuum chamber and smooth changes regarding synchrotron absorption distribution.

Finally, the behavior of SR in a novel beam pipe (Figure 2) designed by R. Kersevan for FCC-hh which presents two slits in its equator.
2.2 Luis Medina Medrano

The dynamic aperture (DA) is a key parameter of an accelerator for the evaluation of its performance, since it is related to the stability of the trajectories of the particles in the beam. Estimations of the DA of the two current lattices of the Future Circular Collider - ee (FCC-ee) at the top pair energy have been obtained. Both lattices, for which significant progress has been made, have asymmetric interaction regions (IRs) with $\beta_x/\beta_y = 50 \text{ cm/mm.mrad}$ and $\varepsilon_x/\varepsilon_y = 2 \text{nm/2pm}$, and fulfil the geometric constrains arising from the compatibility with the FCC-hh machine.[5] The DA at the interaction point (IP) has been computed in the four-dimensional phase space for different energy deviations with MAD-X and PTC, and the results exhibit --in the on-momentum case a peak of $20\sigma-28\sigma$, for the different proposals. The review[6] of the DA with synchrotron motion, calculated using SAD and including different effects such as RF, tapering and radiation damping, shows that the requirement of $15\sigma$ for particles on-momentum, and $5\sigma$ for particles with up to $2\%$ energy deviation, is almost satisfied. A statistical approach implementing the random effect of radiation, and the inclusion of errors and misalignments in the magnets are being explored for more realistic estimations of the DA.

2.2.1 Performance of HL-LHC scenarios. The baseline of the HL-LHC, an approved upgrade of the LHC aiming at the increase of the integrated luminosity, [7] has been studied --with the latest set of parameters--, along with its main alternative scenarios: the 8b+4e filling scheme, the 200 MHz RF system, and two scenarios fore-seeing the inability to use crab cavities, [8] and their performance compared in terms of the respective integrated luminosities. The model for the simulation of a typical fill assumes a $\beta^*$ levelling technique (demonstrated at low intensity) for a constant pile-up of 140 in the two main IPs, the reduction of the beam intensity due to burn-off, and the evolution of emittances including radiation damping and intrabeam scattering. New criteria, such as the inclusion of penalty steps to consider, for example, the lost time during the change between optics, and the adoption of a step-based luminosity levelling, have been included as well.

Results for the baseline in its first stage, that is, with only partial compensation of the crossing angle by crab cavities, demonstrates that flat optics restores the nominal performance ($260 \text{fb}^{-1}$) that is lost with the use of round optics. The 200MHz option provides a similar performance to the nominal, while adding the advantage of electron cloud suppression. For the scenarios without crab cavities, regarded as a backup for operation, a drop of $8\%$ in performance is found provided that, an increase of $20\%$ or $60\%$, for the cases with and without wire compensation, respectively, of pile-up density is accepted. [9] It has been realized that adopting a levelling technique will require a large number of optics for the HL-LHC for the case of small luminosity steps; therefore a $5\%$ step seems to be reasonable, and with a negligible reduction of integrated luminosity. The different scenarios at a pile-up of 200 events/mm deliver a similar but more pronounced behaviour, as expected.
2.2.2 Beta-beating due to beam-beam effects. Studies on the β-beating due to beam-beam (BB) interactions were conducted for the LHC, and will be extended for the HL-LHC to aid in the optimization of its lattice design and, ultimately, its performance. Peak amplitudes of 8% and 6% in the horizontal and vertical planes, respectively, taking into account both head-on (HO) and long-range (LR) effects, have been found. [10]

To correct the β-beating due to BB-LR, a rematch of the IR with the closest quadrupole magnets to the IP (excluding the inner triplet) was implemented: scanning the strengths of Q4 and Q5 at the left and right of the IP (so that the identity map between them is preserved) around their nominal values, a reduction of the 2% peak β-beating along the machine by a factor of ten was found. Rematching the optics at the start and end of the IR, as well at the IP, involving different configurations of the quadrupole strengths of Q4 to Q7, was the strategy adopted to correct the effect induced by HO-BB. The correction achieved by the adjustment of a single quadrupole, such as Q4 or Q5, proved to be the most efficient option: the peak and rms β-beating are reduced by a factor of 4 in both planes, and the beating at exactly the IP is decreased at least by a factor of 2.5. In both cases, beams 1 and 2 were studied separately, with similar results. Future work for the HL-LHC contemplates the study of the BB effects in the different optics (and its corresponding parameters) from the levelling process, and the corresponding means of correction; experimental verification to validate the correction proposal for the LHC is foreseen as well.

2.3 Bruce Yee Rendon

2.3.1 Electron cloud at j-parc main ring. The Japan Proton Accelerator Research Complex (J-PARC) is a set of high power proton accelerators: Linac, Rapid Cycling Synchrotron (RCS) and Main Ring. The presence of Electron Cloud (EC) instability at Main ring during Slow extraction (SX) mode, represents a threat for the good performance of the high intensity beam. Several surveys are under developed to detect EC signal, study its properties, dependencies and find a way to mitigate it (See Figure 3)[11].

2.3.2 SIMULATIONS OF THE BEAM LOSS DISTRIBUTION AT J-PARC MAIN RING. At Main Ring of J-PARC, for some detectors the recorded signal is less than the one measured by hand dosimeters. Thus, using the software SAD and Geant 4, a model is created to explain the differences. The Figure 4
shows the results comparison between the simulations and values registered for the Beam Loss Monitors (BLM) [12].

Figure 4: The comparison between the loss count for the P-BLMs (top) and the lost particles obtained by using the programs SAD and Geant 4 (bottom) at the INS A of the MR. The statistical errors are included.

2.4 Juan Reyes Herrera

Development of Particle Induced X-ray Emission (PIXE)(Figure 5) and X-ray optics, beamlines designing and plasma treatment of optical surfaces in the ALBA light source.

Planning of the first Mexican synchrotron and research in synchrotron light industrial applications.

Figure 5: Characteristic X-ray emission spectra from a same sample, using XRF, PIXE and both simultaneously.
2.5 Cristhian Alfonso Valerio Lizarraga.

2.5.1 The space charge compensation (SCC) is one of the beam instabilities sources in the Low energy beam region. Studies at CERN explain how these instabilities can be predicted and propose a solution to set limits depending of the beam pressure [13].

2.5.2 Extraction systems design consists in the design of ion sources with its extraction system to enhance the emittance of the beam at the time of its creation, this work was applied in the linear accelerator LINAC4 at CERN where one of the designs is used to deliver beam in the actual accelerator.

2.6 Humberto Maury Cuna

2.6.1 Electron Cloud (EC) Effects in the Large Hadron Collider.

It is a group of electrons produced inside the vacuum chamber of an accelerator and is capable of interfering with the proper operation of the machine and/or degrade the quality of the particle beam. There are two main triggering process of an electron cloud: residual gas ionization and photoemission due to the beam-induced synchrotron radiation. This phenomenon has been a big concern for the LHC performance because the EC has prevented to reach the LHC nominal bunch spacing from its operation in 2010. An EC is able to produce beam instabilities, pressure rise and become an additional heat-load source to the LHC cryogenic systems. In order to improve the understanding of these effects simulations were performed, a review can be found in references [14, 15]. As part of my PhD thesis work, it was important to know the heat load due to the EC, in Figure 1 we can observe the average heat load for a 25 ns bunch spacing as a function of secondary emission yield.
2.6.2 Mapping of the beam-induced synchrotron radiation at the LHC. The synchrotron radiation (SR) due to the beam in the LHC is a key ingredient to electron cloud build-up codes. Employing codes as SYNRAD3D can help to map the distribution of the SR photons along the LHC. In Figure 8, we are reporting the distribution of absorption sites of the photons coming from beam-induced SR around the LHC arc beam pipe [16].

He is currently coordinating the particle accelerator group at Universidad de Guanajuato. Physics and engineer students integrate the group. They are working on the design of mechanical pieces for accelerator.

2.7 Karim Gibran Hernandez Chahin

Based on a combination of simulation and measurement results from different cavities with transverse deflecting for the high Luminosity LHC (3 different designs): the 400 MHz (CRAB) niobium cavity, 704 MHz 5-cell elliptical niobium accelerating cavity for the High Gradient project and two 1.3 GHz Monocell elliptical niobium cavities.

The goal is to define and validate the preparation and operational techniques that permit high gradient or high performance operation of bulk Niobium SRF cavities of both elliptical and non-elliptical geometry.

As part of the goal, quantitatively assesses the performance factors in bulk niobium superconducting RF cavities operating in superfluid helium baths. Focus is given to a detailed consideration of
cavity surface preparation and operational techniques that can affect the overall cavity performance.

To understand the cavity preparation, optimization in the electro-polish was done using different cathodes. The high-pressure rinse (HPR) is under study evaluating the performance as function of nozzles designs and operational pressures. Also studies to understand the different sources of contamination during the procedure of cavity manipulation and assembly in the cleanroom (based on the analysis of particulates by energy dispersive X-ray spectroscopy).

Diagnostic measurement and analysis techniques are under development to characterize the thermal loading and quench behavior of bare cavities, with an aim to separate and optimize the RF performance, material defect and geometrical factor effects in the cavity performance. This characterization leads to detailed list of induced cavity failure modes and quench types.

3. The eLinac project

A preliminary proposal for the Mexican eLINAC consists in a sequence of three 3-m in length FODO cells. Tree RF cavities are interspersed among the three cells. In order to minimize the beam size along the line, a 60° phase advance per cell is selected, thereby minimizing the maximum value of the beta functions; the emittances are assumed to be constants. Magnetic gradients for the three pairs of quadrupoles (from the source to end of the beamline) are 0.09 T/m, 0.5 T/m and 0.9 T/m, respectively. The maximum size of the beam is around 2 mm, therefore, that a transport tube with an inner radius an order of magnitude bigger, requires a 10-σ admittance. The last improvements on the design involves adding a solenoid magnet at the beginning of the Linac and incorporating a dipole magnet at the end of the beam line in order to bend the beam. The dipole will be employed to produce the synchrotron radiation and steering the beam to the target. In Table 1, the main machine and beam parameters are listed.

![Figure 9: Beam parameters evolution in the Linac fodo lattice](image-url)
Table 1. Basic parameters of the electron Linac

| Beam Parameter    | Value       |
|-------------------|-------------|
| Beam Energy       | 100 MeV     |
| Transversal       | 1mm.mrad    |
| Emittance         |             |
| Current           | 15 mA       |
| Fodo cells        | 3           |
| Number of         | 3           |
| Cavities          |             |

4. Final remarks
Mexican society has begun to have a critical mass of accelerator physicists and engineers capable of designing, building and operating an eLINAC able to provide two operation modes of beam: electron and Gamma radiation beams. With these two modes it can cover a wide range of applications from industrial, medical and basic research applications. This would improve technology development of the country and also boost the area along with the training of highly qualified scientists and engineers. In addition, the machine can serve as the first accelerating chain of a more complex machine.

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