NUMERICAL OPTIMIZATION OF ACCELERATORS WITHIN oPAC

C.P. Welsch[#]

Cockcroft Institute, Daresbury, UK and The University of Liverpool, Liverpool, UK
on behalf of the oPAC Consortium

Abstract

Powerful simulation tools are required for every accelerator and light source to study the motion of charged particles through electromagnetic fields during the accelerator design process, to optimize the performance of machine diagnostics and to assess beam stability and non-linear effects. The Optimization of Particle Accelerators (oPAC) Project is funded by the EU within the 7th Framework Program and currently supports 23 Fellows that are based at institutions across Europe. This large network carries out R&D that closely links beam physics studies with the development of diagnostics and beyond state-of-the-art simulation tools. This contribution presents selected research outcomes from oPAC, including the numerical optimization of beam loss monitor locations along the European Spallation Source's 5 MW proton linac, results from tracking studies for the LHeC lattice that allow beam stability to be assessed, and multi-objective optimization of the linear and non-linear beam dynamics of the synchrotron SOLEIL. In addition, an overview of recent and future oPAC events is given.

INTRODUCTION

oPAC – Optimization of Particle Accelerators – is a Training Network funded by the European Union [1]. With a budget of almost €6M shared between 12 beneficiary partners over a 4-year period, it brings together 34 institutions across the industry and academia to provide formation on particle accelerators to a total of 23 early stage researchers. The main objective of the oPAC network is to train the next generation of accelerator scientists and engineers for the increasingly demanding community of accelerator facilities while strengthening the bonds within this community. oPAC is also strongly engaged in raising public awareness on the importance of particle accelerators for society, through their applications in health, industry, security, energy, and fundamental knowledge.

Each of the Fellows is developing a project set in one of the following topics: research of beam dynamics, development of beam diagnostics, numerical simulation tools, and accelerator control and data acquisition systems. In addition to the research in their home institution, the Fellows undertake secondments in any of the other partner institutions, complementing their formation and fostering collaborative research. Moreover, the Fellows receive regularly specific training on complementary skills and techniques through a series of topical workshops and schools that are held at different venues across the network. The Fellows together with the central management team are also carrying out an intensive program of outreach and dissemination, through the internet and social media, but also through the organization of events and participation in conferences, trade fairs, exhibitions, etc.

*This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289485.

#carsten.welsch@cockcroft.ac.uk

RESEARCH

As outlined before research within the network is carried out across four thematic work packages. The following subsections highlight progress made by three exemplar Fellows across these work packages.

Beam Loss Monitoring at ESS

The linear accelerator of ESS will produce a 5 MW proton beam. Beam of this power must be strictly monitored by a specialized Beam Loss Monitoring (BLM) system to detect any abnormal losses and to ensure that operational losses do not exceed a limit of 1 W/m. In order to optimize the detectors layout in terms of their numbers and locations a series of beam loss simulations was performed using the MARS Monte Carlo code. Different loss scenarios were considered and yielded an indication of the energy deposition along the ESS linac.

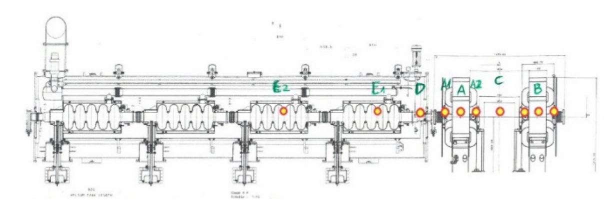

Figure 1: Loss point locations.

Different beam loss simulations were performed for four different energies in the ESS cold linac, ranging from 220-2,000 MeV [2]. For all of these energies 10 different possible locations along a cryomodule-quadrupole doublet were chosen, see Fig.1. At these locations three points on the beam pipe were considered as possible loss points. Losses were then simulated for 3 different angles: 1 mrad, 3 mrad and 1°. The power deposited in air around a loss was used as primary indicator for suitable BLM locations as it is proportional to the BLM signal within certain limits. For more accurate results, an approach using particle flux-to-generated charge converters shall be applied in the future. BLMs were placed around the cryomodule-quad assemblies in a way that optimizes three figures of merit: Distinguishability of individual losses, volume coverage and sensitivity. The aim is to avoid missing any loss (full volume coverage), ability to differentiate between individual losses, and detecting even smallest losses which are just above the noise level.

This was done by a custom-written MATLAB algorithm utilizing a matrix representation of the loss cases and detectors that are being considered. This algorithm was then compared to a brute force method which simply evaluates the root mean squares for pairs of detectors, see [2] for further details.

Tracking Studies in the LHeC Lattice

An interaction region design for the LHeC was proposed in the Conceptual Design Report [3]. The aim of this design was to achieve head-on electron-proton collisions in the interaction region 2 (IR2) at a luminosity of $L=10^{33}cm^{-2}s^{-1}$ which requires a low β*=10 cm. This was achieved by implementing a new set of quadrupoles closer to the interaction point, called the inner triplet (IT), at a distance L* from the IP. A first integration of the LHeC IR into the HL-LHC lattice was performed. This integration consisted in an extension of the ATS was done in the arc 23 to perform a telescopic squeeze to further reduce the value of β*in IP2 while leaving the HL-LHC insertions (IP1 and IP5) undisturbed. Achieving a value of β*=10 cm for IP2 and β* of 15 cm in IP1 and IP5.

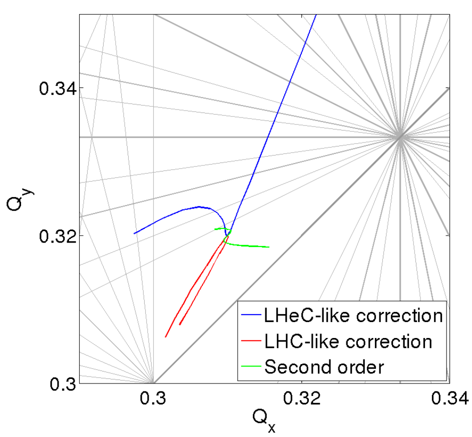

Figure 2: Calculated variation in horizontal and vertical tune for different corrections.

The flexibility of this design was studied in terms of minimizing β* to study the reach in luminosity, and in terms of increasing L* to reduce the synchrotron radiation. This work explores the different types of chromatic corrections for the nominal case with β*=10 cm and L*=10 m by studying its impact on the stability of the beam via the dynamic aperture and the effect of non linearities via frequency map analysis. Three different chromatic corrections were studied. The first one, named "LHC-like" performs the chromatic correction similar to the LHC by changing the focussing and defocussing families by the same amount. The second correction, named the "LHeC-like" adds a further constraint to control the Montague functions in the collimation insertions and allows each sextupole family to change by a different amount. And finally, the third one contemplates correcting the second order chromaticity.

DA studies were computed by E. Cruz from the Cockcroft Institute/University of Liverpool for three chromatic correction schemes in SixTrack using a polar grid of initial conditions with 30 particles for each 2σ interval and 5 different phase angle, over 10^5 turns [4]. The momentum offset was set to 2.7×10^{4}. Concerning the magnetic errors, 60 different realizations (seeds) were considered for the LHC magnets. Results show a similar behavior at small angles for all three cases. On the other hand it was observed that at bigger angles the second order correction gives a bigger dynamic aperture for angles ~75°, although not that different from the LHeC-like correction, while the LHC-like correction shows a negative impact for angles >50°. Frequency map analysis studies were then performed in SUSSIX and applied to calculate the variation in tunes over 5,000 and 10,000 turns for a sample of initial amplitudes via the diffusion factor. Similarities were again found for the LHeC-like and second order correction, except for the stable region observed at Qx ~Qy, where the latter case presents better results. Also, for bigger angles (Ix=0-5 σ and Iy ~20 σ) where the second order correction does not show the instability region observed in the LHeC-like case caused by resonance line (-1,4). The same regions are also different for the LHC-Like case. In this scenario the region for larger angles shows a higher instability, but the main difference is observed in the region with Qx ~Qy in which a stable region seen in the other corrections is no longer present, see Fig. 2.

Beam Dynamics Optimization at SOLEIL

The purpose of the project of X. Gavalda who is based at the Synchrotron SOLEIL, near Paris in France, is to optimize the linear and non-linear beam dynamics of the light source using Multi-Objective Genetic Algorithms (MOGA) [5] and the tracking code ELEGANT [6]. In general, the optimization of a storage ring lattice is a multi-objective problem that involves a high number of constraints and a multi-dimensional parameter space defined by the optimization variables. The introduction of the sextupole magnets to correct the strong focusing affects two important parameters of the beam dynamics: the dynamic and the momentum aperture. Both parameters are strongly related with the injection efficiency and the Touschek lifetime, respectively. In our case, the optimization objectives are the dynamic aperture and the Touschek lifetime, the variables are the settings of the quadrupole and sextupole magnets.

Genetic Algorithms [7] are a heuristic search that mimics the process of natural selection and generates solutions to optimization problems using techniques inspired by natural evolution, such as mutation, selection and evolution. Starting from an initial stable lattice called starting point (SP), MOGA searches the optimized lattices changing randomly the settings of variables: the focusing strength of the quadrupole and sextupole families. From this initial population, the algorithm chooses the best lattices that will become the parents of the next generation. With this process, the algorithm converges to the group of solutions with the best compromise between all objectives, the so called Pareto front. The process is iterative and stops when the maximum number of generations is achieved.

After the installation of MOGA at the SOLEIL cluster and the study of the preliminary optimized results, a complete comparison between ELEGANT and TRACY3 [8] has been done. The discrepancies observed between both codes in the calculation of the momentum acceptance and the vertical chromaticity were reduced introducing 6D tracking in the optimization process and changing the energy model of the dipole edge focusing, respectively. Thereafter, new lists of optimization solutions have been tested on the control room of SOLEIL using beam-based experiments to check their completeness. A complete study of the relation between the total beam, the Touschek and the gas lifetime was necessary to process these experimental data. The initial experimental results do not show an improvement of the Touschek lifetime provided by the simulations due to the proximity of the horizontal and vertical tunes to the integer resonance lines. A further study of the optimization process is necessary to improve the quality of MOGA and search the multi-dimensional space in a more complete way as defined by the quadrupole and sextupole families of the SOLEIL storage ring. These new solutions will then be tested experimentally in the near future.

TRAINING EVENTS

The League of European Research Universities, the UK-based Russel Group of research-led Universities and other similar networks recognize that best practice researcher training involves cohorts of candidates rather than individuals. The ITN structure is ideal for this and to achieve the aspirations of the EU Principles for Innovative Doctoral Training oPAC takes best advantage of industry participation and by providing regular network training to bring the Fellows together.

International Schools

All Fellows received a general introduction to the physics and technology of accelerators either through the CERN Accelerator School or the Joint Universities Accelerator School (JUAS) in 2013 or 2014. In addition, the network organized an Advanced School on Accelerator Optimization at Royal Holloway University of London in July 2014. It was attended by more than 70 delegates from within and outside of oPAC. The participation of external participants ensures knowledge exchange with a wider community and turned out to be an ideal opportunity for establishing links to other researchers working on similar topics. The school covered beam physics, instrumentation R&D and charged particle beam simulations at an advanced level [9].

Topical Workshops

oPAC has already organized a series of Topical Workshops across its work packages over the past 3 years. This includes a workshop on the Grand Challenges in Accelerator Optimization which took place at CERN, Geneva in June 2013 [10], a workshop on Beam Diagnostics hosted by CIVIDEC [11] and one on Libera Technology at Instrumentation Technologies. Most recently, a workshop on Computer-Aided Optimisation of Accelerators (CAoPAC) was held at the GSI Centre for Heavy Ion Research in Darmstadt, Germany from 10 – 13 March 2015. This was a special event for the network as it was organized by the Fellows of the network, providing them with the opportunity to take charge of a whole event from scratch, with a limited time-frame, limited resources, and the challenge of offering an interesting event to attract a good number of participants. The workshop brought together 51 participants from 18 institutions across Europe. It included talks about optics and beam dynamics modelling, control systems and data analysis, techniques for modelling accelerator components, such as diagnostics, as well as the generation and propagation of synchrotron light. A poster session and a visit of the GSI accelerator infrastructure complemented an exciting event. Two hands-on workshops have been provided by Bergoz on Beam Instrumentation and by CST their Particle Studio simulation suite. Finally, the University of Liverpool will host a workshop on Technology Transfer later in 2015 in conjunction with an outreach symposium.

Conference and Symposium

An international conference will be hosted by the national accelerator center (CNA) in Seville, Spain between 7-9 October 2015 [12]. It will promote all research outcomes from the network and enable the Fellows to engage with other university groups and private companies. The conference will also present an opportunity for follow-up activities between the oPAC partners and participating scientists from outside the network and thus serve as a career platform for all Fellows. An outreach Symposium on 26 June 2015 on Accelerators and Lasers for Science and Society will be organized at the Liverpool Convention Center as a finale to the outreach activities undertaken during the course of oPAC [13]. This will present the main project findings in an understandable way for the general public emphasizing the possible applications of the technologies concerned.

SUMMARY AND OUTLOOK

The Marie Curie network oPAC is currently in its final year and will conclude at the end of November 2015. The project has trained 23 early stage researchers in accelerator optimization and three examples of recent research results have been presented in this contribution.

In addition to a broad and interdisciplinary research program, oPAC also organizes a series of international events which have also been summarized in this paper. Despite the significant training effort provided through the network, it is clear from studies such as TIARA that many more training initiatives like oPAC will be needed to satisfy the high demand in skilled accelerator experts across Europe and around the world.

REFERENCES

[1] http://www.opac-project.eu

[2] M. Jarosz, et al., MOPTY047, Proc. IPAC, Richmond, USA (2015).

[3] LHeC Conceptual Design Report, J Physics G 39 (7) 075001 (2012).

[4] E. Cruz, et al., MOPJE079, Proc. IPAC, Richmond, USA (2015).

[5] C.M. Fonseca, P.J. Fleming, “Multi-objective genetic algorithm”, IEEE colloquium on ‘Genetic Algorithms for Control Systems Engineering’, Digest No 1993/130, (1993).

[6] M. Borland, “Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287 (2000)..

[7] Konak A. et al. “Multi-objective optimization using genetic algorithms: a tutorial”, Reliability Engineering and System Safety 91 (2006) 992-1007.

[8] L. Nadolski and J. Zhang, TRACY3 Manual – SOLEIL version.

[9] indico.cern.ch/conferenceDisplay.py?confId=297045

[10] indico.cern.ch/conferenceDisplay.py?confId=243336

[11] indico.cern.ch/conferenceDisplay.py?confId=293158

[12] indico.cern.ch/conferenceDisplay.py?confId=380975

[13] indico.cern.ch/conferenceDisplay.py?confId=368273