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3D Modeling of the Debuncher and Achromat

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PSI is involved in the development of a suite of powerful state-of-the-art modeling tools which enables us to gain quantitative understanding of space charge dominated beam transport. We use these tools mainly to perform beam dynamics studies on our CW cyclotron, delivering now up to 1.2 MW beam power on target with a proton final energy of 590 MeV. The general nature of one of the tools MAD9P (Methodological Accelerator Design Version 9 Parallel) - a full 3d parallel tracking code with space charge allows us to perform beam dynamic studies beyond the usual tasks at PSI. In the frame of the CERN studies for a Neutrino Factory we performed calculations of the Debuncher and the 2.2 GeV Achromat. We show results and discuss the possibilities for a full accumulator ring simulation.

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The simulation of the beam transfer line from SPL to the accumulator and compressor ring validates the particle tracker part of MAD9P by comparison with MAD9 envelope tracking on a line which is non-trivial in terms of its length and optics. Equally it proves the universal usefulness of MAD9P. The presented calculations of rms beam sizes will show no greater difficulties in the present design of the line.

This work was done in collaboration with members of the PS-AE group at CERN and presented at a "Neutrino Factory Working Group" meeting [3].

I. MOTIVATION AND CHALLENGES FOR A ν-FACTORY

A neutrino source based on a muon storage ring, nicknamed "Neutrino Factory", requires a much lower density of particles and should thus be easier to build than a muon collider. At the present time the ν-factory is seen as a project in its own right as well as a feasibility study on the more challenging parts of a muon collider. The key requirement is a very intense proton accelerator (SPL super-conducting proton linac), shown in Figure 1, delivering several megawatts of beam power. These protons will be used to create pions, which will be magnetically collected. Designing a target to withstand such a high power is beyond what has been achieved so far, and will require either a liquid jet target or a very large rotating wheel to dissipate the heat. Pion collection is optimized for rather low momentum - about 300 MeV/c. These pions rapidly decay into muons of similar momentum. At this point the "beam" is about 1 m across and has a large momentum spread. The design challenge is to shrink the momentum spread to 5% and the beam size to a few centimetre within a few microseconds to shape the muons into an acceptable beam. This requires two crucial elements. The first, "phase rotation" (monochromatization), uses variable longitudinal electric fields of a few million volts per metre to slow down the faster particles and accelerate the slower ones. This needs either high-gradient, low-frequency RF-cavities or an induction linac, with considerably improved performance over what has been achieved so far. The second crucial element is beam cooling. This is a key feature in every antiproton machine, collecting the largest possible number of rare particles produced from a target into a beam. While antiprotons for example are stable and can be stored almost indefinitely, muons need quick action. However, as muons choose not to interact strongly with nuclear matter, one can use cooling via ionization energy loss. The three-dimensional momentum reduction, followed by reacceleration in the beam direction via a longitudinal electric field, will decrease the transverse momentum. Simulations are promising, but the technique has yet to be demonstrated in practice.

This initial conditioning is followed by a series of fast accelerators to take the muon beam to high energy. If well designed, the system retains enough muons after decay or acceptance losses that, from the original 10^{16} protons per second, 10^{14} high-energy muons per second can be injected into a storage ring, where during a few hundred turns positively charged muons (for example) will decay into electrons, accompanied by electron neutrinos and muon antineutrinos.

In order to set up a powerful proton source for a future Neutrino Factory, at the same time increasing the flux of protons available for new and existing facilities, CERN is studying a 2.2 GeV super-conducting H^- linac for 4 MW beam power, called the SPL. The super-conducting part of this linac covers the energy range from 120 MeV to 2.2 GeV. Three sections with 352 MHz cavities with nominal β values of 0.52, 0.7 and 0.8 bring the beam energy up to 1 GeV. From this energy, super-conducting cavities from LEP, or other (new) cavities, can be used to reach the final energy of 2.2 GeV.

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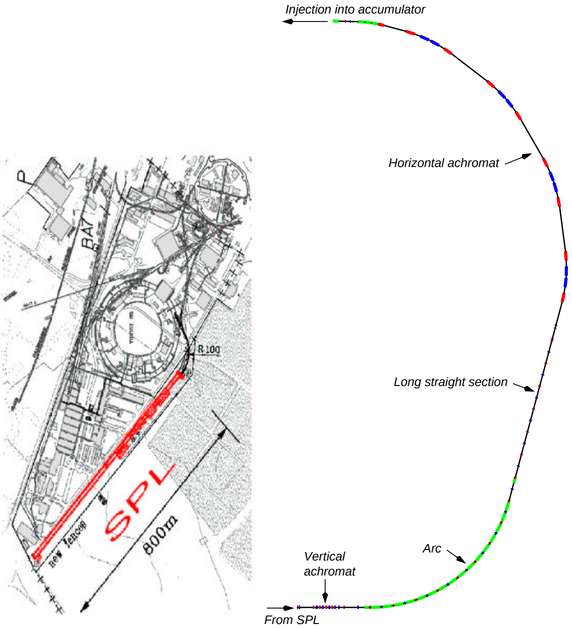

FIG. 1: (color) Left: Super-conducting Proton Linac (SPL). Right: the 560 meter long beam line connecting the SPL with the accumulator

II. MAD9P A SHORT INTRODUCTION

MAD9P (**m**ethodical **a**ccelerator **d**esign version **9** - **p**arallel) is a general purpose parallel particle tracking program including 3D space charge calculation. It is based on MAD9, and two frameworks CLASSIC (class library for accelerator system simulation and control) and POOMA (parallel object oriented methods and applications) [4]. A detailed description of MAD9P and more design studies can be found in [2]. The canonical MAD web page is located at: *www.cern.ch/mad/mad9.html.*

A. Problem Frame

PSI's current situation and the planned update will be best summarized in [1, 5, 7]. In order to achieve the challenging goals of reliability and high power operation we need a better qualitative understanding of the beam behavior in the transport lines and the cyclotrons.

III. PHYSICAL AND MATHEMATICAL MODEL

MAD9P is based on the Vlasov-Maxwell equations. In this model, particle motion is governed by external fields and a mean-field approach for the space-charge fields. Particle collisions and radiation are neglected. All physical elements are assumed to be perfectly aligned. The total Hamiltonian for a beam line element can be written as a sum of two parts, $\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2$, which correspond to the external and space charge contributions. A second-order integration algorithm (split operator) for a single step is then given by

$$\mathcal{M}(\tau) = \mathcal{M}_1(\tau/2)\ \mathcal{M}_2(\tau)\ \mathcal{M}_1(\tau/2) + \mathcal{O}(\tau^3) \qquad (1)$$

where τ denotes the step size, $\mathcal{M}_1$ is the map corresponding to $\mathcal{H}_1$ obtained by differential algebra (DA) methods from a general relativistic Hamiltonian and $\mathcal{M}_2$ is the map corresponding to $\mathcal{H}_2$. $\mathcal{M}_2$ is obtained by discretizing the resulting Poisson problem on a rectangular mesh using Fourier techniques to solve the time consuming cyclic convolution in $\mathcal{O}(M \log M)$, where M is the number of grid points. Open and periodic boundary conditions are available.

A. mad9p a general 3D Particle Tracker with Space Charge

In order to ease the task of writing efficient parallel applications, we employ the POOMA framework. POOMA provides abstraction for mathematical/physical quantities (particles, fields, meshes, differential operators etc.) in an n-dimensional parallel fashion. For an architectural overview of MAD9P see Figure 2. The object-oriented approach manages the complexity of explicit parallel programming; it encapsulates the data distribution and communication between real or virtual processors. POOMA and all the other components are implemented as a set of templated C++ classes. When used in a parallel environment, MAD9P partitions the particles in a particle container among the separate processors. The particle spatial layout will keep a particle on the node

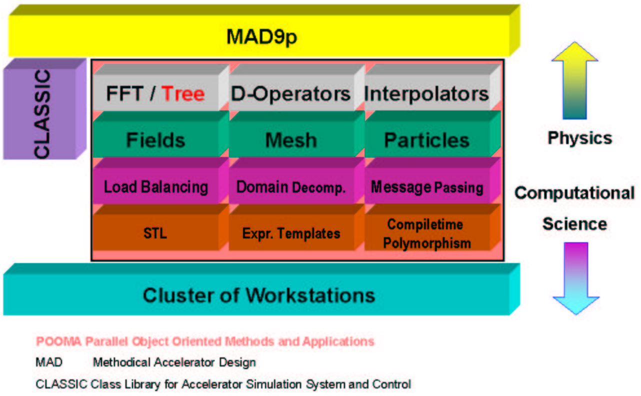

FIG. 2: (color) Architectural overview of MAD9P.

which contains the section of the field in which the particle is located. If the particle moves to a new position, this layout will reassign it to a new node when necessary. This will maintain locality between the particles and any distributed field and it will help keep particles which are spatially close to each other local to the same processor as well. With this concept (inherited in the particle and field class) we do not need an explicit and complicated particle manager class. A 3D parallel particle-mesh solver is implemented on top of the POOMA framework and makes use of their efficient parallel Fourier transformation routines. Using up to 32 processors on a Beowulf cluster at PSI with flat communication structure, we obtain 87.5% of the optimal speedup. Using 128 processors, again on a Beowulf cluster, but with a non flat communication structure, we get still 37.5% of the optimal speedup (using ten million particles and a mesh with 128^3 points). On the other hand, it is well known that the numerical noise only decreases with $1/\sqrt{N}$ when the number of particles N is increased. The parallel approach allows us to use routinely configurations of $N = 10^7 \cdots 10^8$ and mesh sizes from 128^3 to $128^2 \times 2048$. MAD9P runs on a variety of UNIX platforms such as the SGI-ORIGIN 2000, IBM-SP2 and Linux clusters. Validation of the code is done by comparison with (semi) analytic models.

B. First Simulation Results with mad9p

In the context of a feasibility study on how to accelerate a 3 mA proton beam with the PSI cyclotron facility, necessary upgrade steps for the different system components are under consideration. In particular, the qualitative **and** quantitative knowledge of phase space transformations of the proton beam at injection into the PSI Injector 2 cyclotron are essential for the successful production of high intensity beams with low losses. To obtain proper initial conditions for the Injector 2 cyclotron, we start with modeling the 870 keV injection line (B870) from Cockroft-Walton pre-injector to the Injector 2.

IV. SPL TO ACCUMULATOR TRANSFER LINE

A. Initial Conditions

The initial conditions, shown in Table I, for the transfer line from SPL to the accumulator compressor ring were obtained by an IMPACT [8] simulation of the SPL [6].

α_x	0.2125
$\beta_x[m/rad]$	11.91
α_y	-0.3411
$\beta_y[m/rad]$	11.91
α_t	-0.1171
$\beta_t[deg/MeV]$	1.811
$\epsilon_x[mrad]$	0.410
$\epsilon_y[mrad]$	0.206
$\epsilon_t[degMeV]$	0.297

TABLE I: (color) Twiss parameters at the end of the SPL

Additional simulation parameters are: 1 million particles; simulation current: 40mA; design current: 22mA; energy 2235 MeV; RF: 352.2 MHz.

B. Zero-Current Tracking

Figure 3 shows good agreement between the MAD9 envelope tracking and MAD9P particle tracking without space-charge. The same agreement is obtained for all other parameters such as the vertical and longitudinal β-functions.

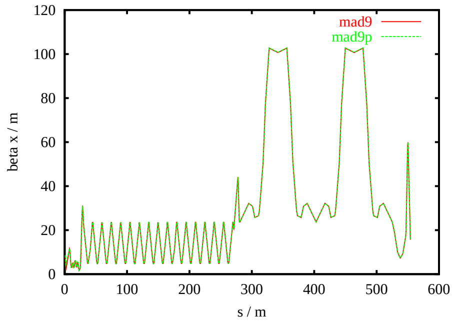

FIG. 3: (color) Horizontal β-function $I = 0$

C. Tracking with Space-Charge

In Figures 4, 5 and 6 the transverse β-functions and the longitudinal rms beam sizes are shown. For the nominal current of 22 mA negligible space-charge effects are observed. As expected, the longitudinal changes are also small and can be easily compensated by small design changes to the optics of the lattice. A case with $220mA$ is also shown in Figure 6 where we can observe the expected non-negligible bunch lengthening.

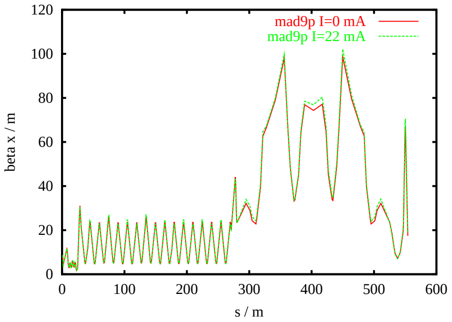

FIG. 4: (color) Horizontal β-function

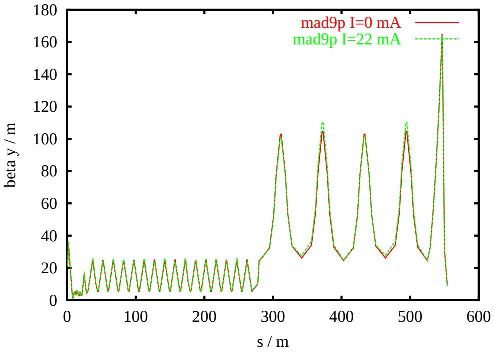

FIG. 5: (color) Vertical β-function

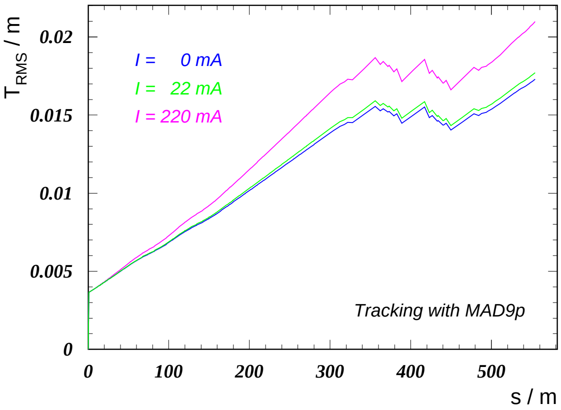

FIG. 6: (color) Longitudinal rms beam sizes at different currents

D. Future Work

Future work includes the full 3D simulation of the accumulator including effects like: space charge and electron cloud.

Acknowledgments

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