SEARCHING FOR THE OPTIMAL WORKING POINT OF THE MEIC AT JLAB USING AN EVOLUTIONARY ALGORITHM*

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Abstract

The Medium-energy Electron Ion Collider (MEIC) is a proposed medium-energy, ring-ring, electron-ion collider based on CEBAF at Jefferson Lab. The collider luminosity and stability are sensitive to the choice of a working point – the betatron and synchrotron tunes of the two colliding beams. Therefore, a careful selection of the working point is essential for stable operation of the collider, as well as for achieving high luminosity. Here we describe a novel approach for locating an optimal working point based on evolutionary algorithm techniques.

THE MEIC

Over the last decade, Jefferson Lab has been developing a preliminary design of an electron-ion collider for future nuclear physics research articulated in the most recent Long Range Plan of the DOE/NSF Nuclear Science Advisory Committee [1]. Our primary focus is on the MEIC, with the energy range of up to 100 GeV ion and 11 GeV electron beams, as the best compromise between science, technology and project cost. We also maintain a clear path toward the future high-energy upgrade. The MEIC, based on CEBAF recirculating SRF linac, would provide collisions between polarized electrons and polarized protons/light ions or unpolarized heavy ions over a wide CM energy range at multiple interaction points (IP). The design is geared toward realizing high luminosity, nearing 10^{34} cm^{-2}s^{-1} per detector, attainable using concepts of high bunch repetition rate, crab crossing, small transverse emittance and bunch length of both electron and ion beams, and strong final focusing at IPs (Table 1).

SIMULATION CODES

We developed a suite of programs for optimization of a working point in particle colliders. It combines the parallelized beam-beam simulations and an evolutionary (genetic) algorithm techniques to locate high-luminosity working points. While it was originally designed for the MEIC project at Jefferson Lab, it is sufficiently modular and can be modified to address other optimization problems in collider design.

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Table 1: Design parameters for the MEIC.

Quantity	Unit	e^- beam	p beam
Energy	GeV	5	60
Collision frequency	MHz	1497	
Particles per bunch	10^{10}	1.25	0.416
Beam current	A	3	1
Energy spread	10^{-3}	0.71	0.3
rms bunch length	mm	7.5	10
Horiz. bunch size at IP	μm	23.4	
Vertical bunch size at IP	μm	4.7	
Horiz. emit. (norm.)	μm	53.5	0.35
Vertical emit. (norm.)	μm	10.7	0.07
Horizontal β^*	cm	10	10
Vertical β^*	cm	2	2
Vertical beam tuneshift		0.03	0.007
Damping time	turns	1516	$\sim$2.4e6
	ms	5	$\sim$ 8000
Synchrotron tune		0.045	0.045
Ring length	m	995	995
Peak luminosity	cm^{-2}s^{-1}	0.564×10^{34}	
Reduction (hourglass)		0.957	
Peak luminosity with hourglass effect	cm^{-2}s^{-1}	0.54×10^{34}	

Beam-Beam Simulations

For numerical simulation of beam transport in the rings and collisions at the IP, we use *BeamBeam3D* [2] simulation code, developed at LBNL. *BeamBeam3D* is a 3D, self-consistent, particle-in-cell beam-beam code which uses shifted integrated Green's function method to solve the Poisson equation for electromagnetic fields on a 3D mesh of a beam bunch, which then provide the beam-beam kicks to the colliding beams. *BeamBeam3D* code has been successfully compared to experimental data and other beam-beam codes [3], and has been used for simulating beam-beam effects in several machines, including RHIC and LHC. It is parallelized and scalable to up to tens of thousands of processors. The simulations in the present study have been carried out on Jefferson Lab's cluster, consisting of over 1500 cores, using a parallel MPI paradigm.

In the present beam-beam simulations, collisions take place at one IP, while the transport of beams through the collider rings is modeled by one-turn linear maps. The beam transport model includes synchrotron radiation damping and associated quantum fluctuations for electron beam, and damping of the proton/ion beam due to electron cooling. A more sophisticated model that replaces linear maps with the higher-order symplectic maps of a complete ring lattice will be employed in the future MEIC beam-beam simulations.

Evolutionary Algorithm

The evolutionary algorithm suite consists of two separate programs: *var* and *spea2* [4]. They are based on code developed at ETH Zürich [5]. Together with *BeamBeam3D*, the three programs coordinate with each other to search the betatron tune space.

The functions of *var* (which stands for variator) are to generate the initial population, to recombine and mutate parents in order to form the offspring, and to call *BeamBeam3D* which computes the luminosity for each working point. *var* is complemented by *spea2* (for Strength Pareto Evolutionary Algorithm 2). *spea2* is the selector: given a set of working points (and their luminosities) provided by *var*, it selects first the working points that are combined to form offspring, and later the working points that are retained as the next generation. *spea2* is a sophisticated multiobjective selector; it uses a special algorithm (strength pareto) to make selection decisions when there are multiple independent objectives.

In this study, there is only one objective – luminosity (averaged over last 100 turns), so much of *spea2*'s power goes unused. However, we are currently implementing a multi-objective simulation to optimize both the luminosity and the size of the well-performing region around the working point in tune space.

The details of the earlier evolutionary algorithm implementations are given in [4, 5, 6] and the details of ours in [7].

NUMERICAL SIMULATIONS

In this study we keep the synchrotron tunes fixed, and search the betatron tune space (x- and y-tunes for each beam, thus yielding a 4D problem). Our present implementation presents a proof-of-concept that an evolutionary algorithm can efficiently find the optimal working point in a multidimensional tune space. We expect that this formalism can be extended to include also the synchrotron tunes, as well as possibly the particle spin.

Restricting the Betatron Tune Space

Systematically scanning the multidimensional tune space in search of an optimal working point is computationally prohibitively expensive. For instance, if one was to cover each of the N tunes with a modest resolution of 0.01, the required number of function evaluations to cover the entire space would be 10^{2N}, which, for the problem at hand where we search over 4 betatron tunes only, would result in 10^8 multi-hour function evaluations. The evolutionary algorithm which we implement here would also require much larger populations and many more generations to provide a reasonable working point, due to the vastness of the parameter search space.

We restrict the search space by imposing that it contains no destabilizing resonances. Figure 1 contains both unstable (sum resonances; denoted by black lines) and stable (difference resonances; denoted by green lines) resonances in the betatron tune space of up to order 7. In sum resonances the difference of the two beams emittances is constant (thus allowing them to blow up together), while for the difference resonances the sum of the beams emittances is constant. Resonant lines are defined by $m\nu_x + k\nu_y = n$ where m, k and n are integers and n is the order of the resonance. The shaded regions are entirely devoid of destabilizing resonances (black lines). The reason we do not include the regions close to the integer tunes (near (0,0) and (1,1)) is that the colliders with betatron tunes close to the integer is in general considered a bad idea. The 16 regions (symmetric with respect to (0.5, 0.5) point) cover only about 3.6% of the entire 2D tune space, which reduces the search space and computational load by a factor of nearly 1000. With this realization, the search of the multidimensional parameter space becomes again computationally tractable.

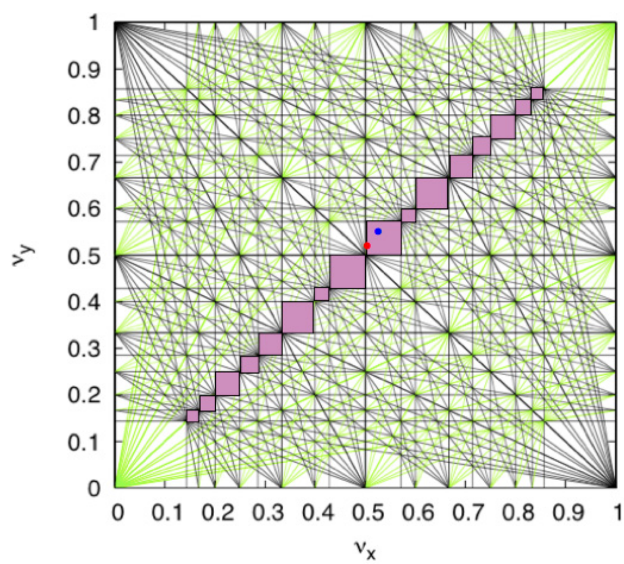

Figure 1: Tune space with unstable (sum) resonances (black lines), and stable (difference) resonances (green lines). Shaded regions mark restricted search space for the evolutionary algorithm, which is completely devoid of black resonance lines. The dots denote the optimal working point: red represents the betatron tunes for the proton beam, and blue for the electron beam.

Results

Given that each function evaluation may require hours of computing time, it is imperative that the new algorithm locates a good working point within as few steps as possible. Each beams tune can be located in any of the 16 regions of the tune space, which means that there is a total of $16^2 = 256$ areas of the tune space available for search. Randomly populating all of the 256 areas leads to solutions which slowly converge toward the near-optimal solution, in the sense that the most consequent generations were concentrated in the region in betatron tune space just beyond the half-integer resonance: $[0.5, 0.55]^2$, for each of the two colliding beams. The working point obtained in this comprehensive search exceeds design luminosity, but, as we later realized, it is not optimal. To that end, we further restrict our search space to the single high-performing region [0.5, 0.55] in each of the four tunes. This choice was also corroborated by the fact that PEP-II and KEK-B empirically converged to working points just beyond the half-integer resonance.

Figure 2 shows the luminosity for 5 generations, each consisting of 64 individuals, which initially randomly sample $[0.5, 0.55]^4$ space. Within only 320 function evaluations, the algorithm located a working point at $\nu_x = 0.53$, $\nu_y = 0.548456$ for the electron beam and $\nu_x = 0.501184$, $\nu_y = 0.526639$ for the proton beam with luminosity of $7.05 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which exceeds design luminosity corrected for the hourglass effect of $5.42 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by 30%.

Figure 3 illustrates that even better working points can be found with a more massive search, which includes more generations and individuals (20 generations, 128 individuals each). However, in most cases, additional work (here about 6 times) does not justify the modest improvement in the luminosity of the working point (here about 9%).

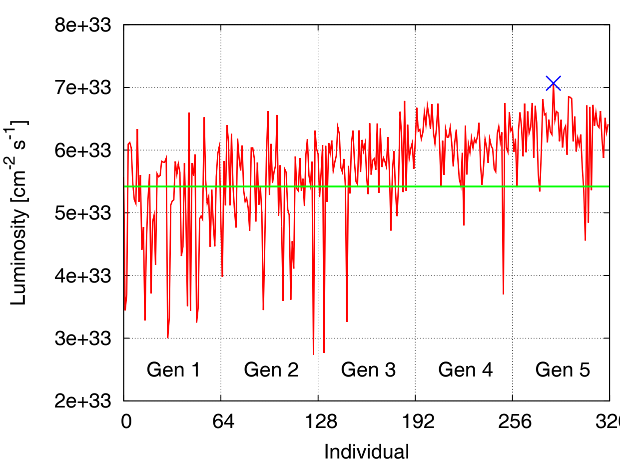

Figure 2: Evolutionary algorithm at work: beam-beam simulation with 5 generations of 64 individuals each, sampling the 4D tune space. Green line represents the design luminosity. The simulation locates a (near-)optimal working point within only 320 simulations (blue x).

SUMMARY

We implemented a search for an optimal working point in the betatron tune space based on an evolutionary algorithm. After incorporating the constraint that the optimal

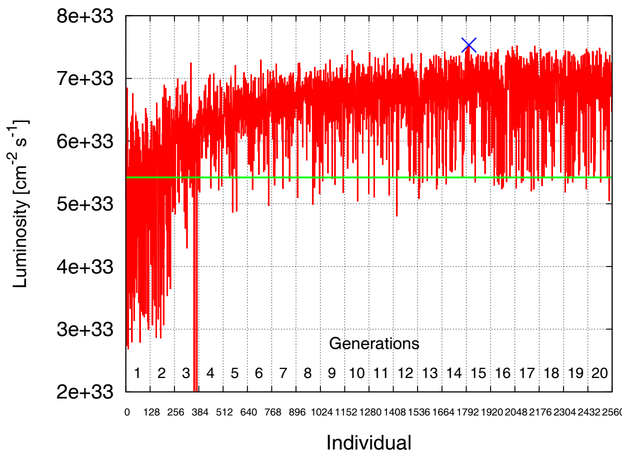

Figure 3: Same as Figure 2, but for 20 generations of 128 individuals each. The improved working point (blue x) is about 9% better than the one in Figure 2.

working point must lie in one of the small regions along the diagonal of the tune space devoid of unstable resonances, the search space is reduced by about three orders of magnitude, which, in turn, makes the problem computationally tractable. The first results are quite encouraging: we were able to find a number of working points that yielded luminosities which were substantially higher than the design luminosity of the MEIC.

This study serves as a proof-of-concept that the powerful evolutionary algorithm can be successfully used in a variety of optimization problems in collider design and beyond.

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