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The Accelerator Research group consists of the following scientists.

- R.A. Baartman (head; theory, optics, collective effects)
- M.K. Cradddock (retired; accelerator design)
- J. Doornbos (secondary channel design)
- F.W. Jones (multi-particle simulations, parallel computing)
- S.R. Koscielniak (theory, novel accelerators, collective effects)
- Y.-N. Rao (cyclotron and beamline modelling)
- L.W. Root (cyclotron modelling, development, choppers)

The group as a component of the Organization Chart came into existence in October, 2004. The formation of the group did not change the members' activities; before that time, they were distributed among various divisions. At the formation, the following mandate was assigned:

- Operational support for the Cyclotrons and ISAC
- Beam physics developments for higher intensity in the cyclotron
- ISAC beam line optics and related developments
- Primary and secondary beam line optics
- Optics for spectrometers
- Beam studies for external projects such as CERN, BNL, J-PARC, Linear Collider
- New initiatives such as FFAGs, beta beams etc.

The priority of the group is to ensure that the beams required to satisfy the demands of the TRIUMF science program are met.

Another way to summarize the activity is to divide it into three broad classes; (1) support for operation and development of TRIUMF accelerators and beamlines, (2) support for approved collaborations with other accelerator laboratories, (3) research in theoretical aspects of accelerator physics.

The following summaries are organized in these 3 categories. The first 8 belong to category 1, sections 9 to 17 to category 2, and sections 18 to 25 to category 3.

An activity not captured in these summaries is the ongoing support for operation. This includes help with tuning accelerators, beamlines and the ISAC mass separator; development of software to facilitate tuning by operations, and training operators in understanding and operating beamline and accelerator components.

1 High Current Beam Development for TRIUMF

Introduction

TRIUMF is pursuing a high current beam development program aimed at increasing the extracted current from its pre-ISAC level of $\approx 200\ \mu$A to the 300 μA/400 μA which will be required to operate one/two ISAC beam lines at maximum intensity without having to lower the current to non-ISAC users.

Results and Progress

Since 2000 a large fraction of TRIUMF's one day per month beam development shifts has been devoted to using TRIUMF's low and high energy probes to measure beam quality and to developing high current/low spill tunes. In 2005 the experience gained, after some centre region re-alignment work and after the installation of a water cooled beam stopper on the first turn to prevent overheating of the centre region components, enabled TRIUMF to extract an average current of 298 μA without incident for 2.4 hours. This was followed by a week of beam production in 2006 during which 270 μA was extracted without incident. Although the existing beam lines only have a current capacity of 300 μA, in 2003 a peak current of 420 μA at 25 % duty cycle with good transmission was extracted, thus confirming that 400 μA is within TRIUMF's space charge limit.

Although TRIUMF's high current ion source I3, which has been defunct for many years, will resume operation in 2009, we won't be able to extract average currents greater than 300 μA until we have more beam dump capacity, improved centre region/ISIS cooling, and perhaps an ISIS vacuum upgrade.

In the mean time, 300 μA will be enough to satisfy all of the existing user's requirements, so TRIUMF will continue improving this tune and studying the 400 μA tune at reduced duty cycle.

2 Release of ^{7}Be from Stripping Foils

Introduction

Recent improvement in cyclotron beam quality has resulted in a denser beam on the Carbon foil used to strip the H^- to extract from the cyclotron. As a result, the foil runs hot enough at our highest extracted current that the ^{7}Be created by nuclear interactions is released rather than remaining and being conveniently contained in the foil. This release adds to cleanup time during shutdown.

We assigned the task of modeling the effect to a visitor from PSI. His results are clear, but need testing. This is ongoing; each shutdown the activation near the stripper is measured.

Results & Progress

Most of the foil heating is due to the stripped 270 keV electrons. These travel in spirals along the magnetic field lines, repeatedly traveling through the foil until either they are lost or completely lose their energy through straggling. A new result is that the multiple Coulomb scattering during each foil passage makes thinner foils preferred. The reason is that although scattering angle is smaller for thinner foils, it is a square root effect, not a linear effect. This means that for thinner foils the probability is higher that the electron scatters off the foil before it ranges out.

The standard foil has been 5 mg/cm^2. We are now testing foils down to 1 mg/cm^2, and looking for lower activation levels when the lid is raised during shutdown.

3 A New Spiral Inflector for TRIUMF

Introduction

TRIUMF's spiral inflector bends the 300 keV H^- axially injected beam coming from the ion source onto the median plane and centers it for injection into the dees. It consists of a pair of 12 inch high spiral shaped electrodes with a 1 inch gap operating with voltages of ± 28.7 kV. Although the existing inflector has performed well for over 30 years, the new one will allow TRIUMF to have the old one as a spare, be better engineered mechanically, and perform better since its design will be based on improved magnetic field measurements. As well, with modern CNC machining techniques, construction of additional spares is cost effective.

This work started in 2007; installation is planned for the beginning of 2009.

Results and progress

TRIUMF's inflector is a non-analytic version of Belmont and Pabot's original Grenoble design. It was designed using `AXORB`, a TRIUMF computer code which used a modified version of Belmont and Pabot's electric field and which took into account TRIUMF's magnetic field which varies between .5 kG and 3 kG along the inflector's central trajectory.

Due to time constraints, the calculations for the existing TRIUMF inflector were based on magnetic field measurements made on a 10:1 scale model of the magnet. After the inflector was constructed, more accurate axial magnetic field measurements were made on the main magnet. In early 2007 AXORB, which had been dormant for 30 years, was re-written so that it would run on TRIUMF's newer computers, and improved electrode shapes were calculated using the main magnet measurements. This should increase the spiral inflector's acceptance by 5 to 10%.

The inflector electrodes are routinely removed for maintenance. Mechanical engineering studies aimed at improving the electrode mounts so that the required mechanical tolerances can more easily be achieved when the electrodes are re-installed after maintenance, are being carried out.

4 Redesign of muon beam lines at TRIUMF

Introduction

The new M9A and M20 are both surface muon beam lines for μSR studies. Surface muons are so-called because the muons result from the decay at rest of pions that have stopped near the surface edge of the pion production target. Only positive muons can be obtained in this way. The maximum momentum is 29.8 MeV/c. The muon polarization is almost 100% longitudinally. They have a well defined source, unlike muons from the decay of pions in flight. This makes it possible to obtain at the end of the beam a small beam spot with high luminosity.

Complete new designs were made for the TRIUMF muon beam lines M9A and M20, and an extension was designed for beam line M13. Full funding was obtained for all three projects. The M13 extension will be installed in 2008, M9A in 2009 and M20 in 2010. These designs were made in 2006 and 2007.

Results & Progress

M9A and M20: The new beam lines will be equipped with spin rotators, basically crossed electric and magnetic fields, which can rotate the spin in a direction transverse to the direction of motion. In M9A the spin will be horizontally transverse. In M20 the spin will be vertically transverse. The spin rotator systems are achromatic, and this makes possible a high momentum acceptance. The achromaticity is achieved by using two spin rotators, each rotating the spin through 45°, and placing a quadrupole triplet between them. At present the TRIUMF beam line M15 is the only beam line in the world that has this feature.

An important aspect of both beam lines is the Muons On REquest (MORE) feature invented at TRIUMF. As soon as a muon enters the experimental target, the beam is switched away. This is done by using a fast electric kicker. In M9A the beam is discarded. In the case of M20, the beam is directed to an other leg. This means in effect that two experiments can run simultaneously on M20.

The optics has been designed to give a small beam spot and a high luminosity. This is important because the advanced modern experiments are done on small samples, of the order of 1.0 or 2.0 cm diameter. Several slit arrangements in both beams make it possible to limit the background effects.

M13: The extension of M13 was proposed by the accelerator research group in order to decrease the background of positrons in the PIENU experiment which intends to measure the decay of a positive pion into a positron and a neutrino to a high level of accuracy. The extension exists out of a 70° bending magnet and a quadrupole triplet.

5 TRIUMF cyclotron extraction and beamline optics

Introduction

Because extraction is by H^- stripping, the TRIUMF cyclotron is able to continuously supply multiple beams for multiple experiments. Typically about 50 kW is extracted into a beamline and this can be focused to a spot smaller than 2 mm diameter; sufficiently small to damage carefully prepared targets. It is therefore essential to accurately characterize the extracted beam.

Work on improving the agreement between calculated and measured beam sizes began by the end of 2004, as beam power on ISAC targets had reached 20 kW, and managing the size of the beam spot became essential. New tunes were developed and successfully used in 2005. At the present time, not all aspects of the various modes of operation are understood down to the 1 part in 10^5 level necessary for running without the spill monitors in beamline 2A tripping the beam off. Refinements continue: these are needed for the new mode of operation where the beam is swept across the ISAC target with AC steering magnets. A good understanding is also needed so that we can optimize the design of the new beamline 4.

Results and progress

In 2004, target damage as a result of over-dense beams caused us to re-investigate the coding of the equations of motion in the computer program used to track particles from the stripping foil to the beamline. We discovered an error that had existed for 30 years. As a result of this work, for the first time, we have an accurate description of these beamlines: we have obtained agreement of better than 15% everywhere between calculated and measured beam sizes in the beamlines, so we can confidently change the beam spot size to what is required by the target designers. (Design note TRI-DN-05-04.)

We are using GEANT4 to try to understand the beam distribution halo to the level of 1 part in 10^5 of the core.

6 TRIUMF injection line optics

Introduction

The space charge effect is important in the TRIUMF injection line because it strongly affects the fraction of beam that can be accepted by the cyclotron centre region as well as the amount of beam halos that can possibly spill out in the cyclotron and beamlines. Research in this area will be used to help design replacement optics needed for future upgrades to $> 400\,\mu$A extracted from the cyclotron.

A series of experiments was performed in 2003-2004 to measure the beam emittance and space charge neutralization level. Further experiments will be performed in 2008.

Results and progress

To achieve improved understanding and also to allow accurate modeling of the 300 keV injection line, we measured the important beam parameters such as space charge neutralization and emittance. This work prepared us for future development and exploration of the injection line for high current operation, aiming to reach an extracted current of $> 400\,\mu$A from the cyclotron.

Using software developed at TRIUMF, we performed transport calculations in 6-dimensional phase space with the linear space charge force included. Good agreement was achieved between the measured and calculated transverse sizes of the 300 keV beam in the injection line. The emittance is $\sim 0.13\,\mu$m (normalized) at a dc current of $575\,\mu$A. Matching to the periodic sections appears good in the horizontal section, bot not good in the vertical section where there are fewer diagnostics and beam size restraining collimators. With bunching, the local current reaches > 3 mA at cyclotron injection; the space charge effect becomes increasingly dominant as the beam travels along the injection line. For injection line currents above $500\,\mu$A, the fraction of beam that can be accepted by the cyclotron centre region begins to fall despite adjustments to the existing bunchers. This could be corrected by introducing an additional first harmonic buncher in the vertical section at ∼2.5 m upstream of the inflector. Or, this effect could be partially compensated by increasing the rf dee voltage, thereby increasing the longitudinal cyclotron phase acceptance. Alternatively, injection with dc beam current 5 mA is contemplated.

The choice of the final configuration for 450 μA extracted will be made based in this research and will largely depend on reliability, reproducibility and stability issues, including the ion source. (PAC03 conference paper)

7 Cyclotron computer code development

Introduction

Cyclotron (and FFAG) orbit dynamics are different in nature than that of most other accelerators. The reasons are that the model of separated elements (drifts, dipoles, focusing,...) is not a good one, and because there is no given reference orbit. Instead, particles must be tracked through varying fields and reference orbits found for each energy by an iterative technique.

From 2003 to 2005, updates were implemented in the orbit codes porting them from obsolete Operating Systems (OSs) to the Linux OS. In 2007, modifications were made to enable FFAG lattice studies.

Results and progress

Over years, TRIUMF developed a series of computer codes for cyclotron orbit dynamics research. This is one of the important contributions of TRIUMF in the cyclotron field, because these codes are essential for cyclotron design and research and maintaining optimal beam tune. From time to time TRIUMF receives requests from other laboratories, asking for help in using these codes for design of new machines. An ongoing activity is therefore maintaining these codes.

List of Institutes

CIAE (China), Thales (France), Nordion, D-Pace

TRIUMF role

TRIUMF played a leading role in the collaborations with CIAE and D-Pace/Thales in providing intellectual guidance to the cyclotron design and development: to the understanding and optimization of the magnetic field; to the approach of beam probe design; to the consideration and modeling of extraction optics.

8 Radioactive Ion Storage Ring

Introduction

We have studied the design of a storage ring to be fed by radioactive ions from ISAC-II. The low intensities of beams of unstable isotopes make it vital to use them efficiently. Their collection in a storage ring would open up a number of possibilities: 40,000-times-higher beam intensities, enabling better suppression of background and more accurate measurement of isotopic and ionic properties; higher luminosities, by the use of beam cooling and internal targets; acceleration to higher energies; quasi- simultaneous operation with fixed-target experiments; and colliding- or merging-beam experiments with protons, electrons, muons, etc.

This work was carried out in 2003, but discontinued when it became apparent that TRIUMF's highest priority for RI beam development was the provision of additional targets and beams. When these immediate aims are accomplished, however, a storage ring remains a potentially powerful tool for TRIUMF's further development.

Results

There were two main aspects to this study: estimating by what factor the ISAC beam intensity could be amplified by storage, and designing the magnet lattice for the ring itself. For injection of ions with short lifetimes it was clear that stripping is preferable to multi-turn stacking. Stripping also increases the ions' average charge state, lowering the magnet strengths required in the ring, and reduces the fractional width of the charge-state distribution, enabling a greater fraction of the beam to be contained. A stripping foil also presents an obstacle to the circulating ions, but it was found that "painting" the incoming beam could reduce the frequency of interceptions to an acceptable once in 400 turns. Moreover, it was found that the ion losses per foil traversal could be kept to 1% provided the charge/momentum acceptance of the ring was at least ±4%. With continuous injection, the stored beam intensity should be maintainable at 40,000 times that delivered by ISAC. Alternatively, pulsed operation could provide a 25,000 times improvement while allowing the beam to be shared with ISAC-I or ISAC-II.

To obtain a ring with large charge/momentum acceptance, low dispersion and low horizontal beta function, a double-bend achromat (DBA) lattice was chosen. The ring is four-sided, with a diameter of 15 m and the long straights assigned to injection, cooling, acceleration and experiment (or extraction). With a bending power of 2.6 T-m, light ions such as carbon can be accelerated to 80 MeV/u and heavier ones such as the rare earths to 35 MeV/u. Initial tracking studies showed good behaviour for charge or momentum excursions up to ±4%, as required.

- M.K. Craddock, D.I. Kaltchev, *Feasibility Studies for a Radioactive-Ion Storage Ring*, Proc. 2003 Particle Accelerator Conf., Portland OR, (IEEE, New York, 2003) pp. 1581-3.

9 Large scale simulations for the CERN LHC using distributed computing

Introduction

In the final design phase of the LHC it is required to verify the long term stability, in particular in the presence of the beam-beam forces which eventually limit the LHC performance. Due to the very non-linear nature of motion in the LHC only a detailed numerical simulation can reliably predict the long term behavior of the particles.

In 2004, the CERN IT Department developed the `LHC@home` system, based on the Berkeley Open Infrastructure for Network Computing (BOINC), providing access to more than 60,000 home computers, donated by more than 30,000 volunteers worldwide. The computing power provided by `LHC@home` allows to evaluate the parameter space with maximum accuracy and find possible problems which could be missed by a less detailed analysis.

TRIUMF participation in the work started in 2005; continuation beyond 2007 is not certain.

Results and progress

We have extended the CERN-based automatic procedures for launching tracking jobs with our own tools that automatically process large volumes of tracking data in order to extract information about long term stability: dynamic aperture and border of chaos.

In 2005-2006, tracking jobs launched from TRIUMF, totaling an estimated 6 million CPU hours, were used by CERN to make the final choice of the LHC crossing scheme, i.e. the plane in which the two beams collide, the LHC working point on the tune diagram and also to analyze the effect of multipole errors in the IP quadrupoles.

In 2007, a similar study was performed, but in conditions corresponding to LHC startup at injection energy.

There is a strong request from CERN for TRIUMF to continue the BOINC-tracking studies.

Some links:

- `http://athome.web.cern.ch/athome`
- `http://lhcathome.cern.ch/lhcathome`
- GridToday article;
- New Scientist article.

List of Institutes

CERN, Queen Mary University of London, Niels Bohr Institute and University of Copenhagen, Helsinki Institute of Physics via `GridPP`.

TRIUMF role

By following directions for machine studies coordinated with CERN, since late 2005 nearly all BOINC-tracking runs have been launched from TRIUMF. This is because of our knowledge of the LHC lattice optics, optical databases and tracking codes. During 2005-2006 this led to the present set of LHC parameters and enabled our CERN colleagues to test additional configurations and to define strategies for the start of the machine.

10 LHC collimation system

Introduction

Even a tiny release of the energy stored in the LHC beam would lead to a serious damage of equipment, hence the importance of the system of collimators whose function is to cut off the amplitudes of the circulating particles at 8 sigma at injection energy and 6 sigma at collision.

TRIUMF has played an important role in the design of lattice optics for the betatron- and momentum-collimation sections of the LHC and in the optimization of collimator parameters. Work on collimation continued in 2003; since then a new constraint was introduced – impedance.

At present the collimation system has been built. It will be first used during LHC commissioning in May 2008.

Results and progress

The main objectives were to maximize the beam size at the collimators (and so decrease their contribution to the ring impedance) and generate additional space for longer collimators.

By following the original design approach, by the end of 2003 a new arrangement of collimators was found and implemented in the LHC sequence. The final solution preserved the number of collimators, warm quadrupoles and maximum voltage of the power supplies. It provided a wider domain of betatron phases at intermediate locations, making it possible to position the collimators where the beam envelope is larger. A good cleaning efficiency was simultaneously maintained.

TRIUMF role

For a number of years, in an extensive collaboration with the LHC team, TRIUMF was responsible for the software that optimizes collimator parameters and for the design and maintenance of the optics (quadrupole parameters) of the betatron- and momentum-collimation insertions.

LHC Collimation Working Group – Collection of Publications: papers, talks.

List of Institutes

CERN

11 LHC Beam-Beam Effects and Parallel Codes

Introduction

As part of the Canadian contribution to the LHC, we have collaborated with CERN on studies of coherent beam-beam effects, which pose limitations to the performance of existing colliders and will play a role in the operation and performance of the LHC.

The first collaborations occurred prior to 2003, applying TRIUMF-developed space charge techniques to a prototype beam-beam code. The first 3D parallel code was developed in 2003–2004. The parallel multi-bunch multi-IP code was developed in 2006–2007, with further work on fast-multipole field computation to be done in 2008.

Results & Progress

Using routines developed at TRIUMF originally for space charge simulation, TRIUMF and CERN had co-developed the first application of fast multipole methods to beam-beam effects. The availability of parallel computing facilities at the University of Alberta, and later at the Westgrid facilities in Calgary and Vancouver, prompted us to extend this 2D code to 3D by implementing parallel algorithms to simultaneously treat the interactions of longitudinal bunch segments as they approach and leave the crossing point of the counter-rotating beams in the LHC. The resulting code `BEAMX` was among the first of its type to be able to exhibit and estimate longitudinal beam-beam effects such as the crossing angle and the frequency sidebands due to synchrotron motion.

- F.W. Jones and W. Herr, *Parallel Computation of Beam-Beam Interactions Including Longitudinal Motion*, Proc. 2003 Particle Accelerator Conference,
- BEAMX website.

More recently, further advances in the high-speed communications architecture of computing clusters have allowed us to pursue a more ambitious simulation. In the LHC the two beams consist of trains of thousands of distinct bunches of protons, and these bunches approach and collide with each other at four interaction points (IPs) where the four LHC experiments are sited, whereas existing beam-beam simulation codes were limited to a single pair of bunches and a single IP. For operational reasons the bunch trains have gaps in them and in general the two beams do not have exactly the same gap structure. In the LHC and other collider communities there is strong interest in being able to simulate the full complexity of collision patterns that arise from gaps and differences in the beam. We formulated plans for a new parallel simulation code which would track multiple bunches through multiple IPs. This project was approved for access to high-performance computing systems at EPFL Lausanne: a MYRINET based commodity cluster on which development, benchmarking and production were done and an IBM Blue Gene supercomputer where very large-scale performance tests could be done. The first production version of the code was completed and showed good parallel efficiency and excellent scaling properties. The code input and parallel communications scheme have been designed in a very general way, allowing arbitrary bunch patterns and extension to arbitrary numbers of bunches and IPs, limited only by the number of processors available in the computing cluster. Further enhancements of the simulation options and the field solution methods are planned.

- F.W. Jones (TRIUMF), W. Herr and T. Pieloni (CERN), *Parallel Beam-Beam Simulation Incorporating Multiple Bunches and Multiple Interaction Regions*, Proc. 2007 Particle Accelerator Conference.

List of Institutes

CERN. Computing resources and support provided by the High Performance Computing centre of École Polytechnique Fédérale de Lausanne.

TRIUMF Role

TRIUMF provides knowledge and experience in accelerator simulation, and undertakes the software conceptual design, application of numerical methods, parallel programming, testing and debugging, and collaborates on the production and analysis of results.

12 EURISOL Betabeam

Introduction

The EURISOL Design Study is funded by the Sixth Framework Programme of the European Union. Its mandate is to define a next-generation ISOL-based radioactive beam facility to be sited in Europe and to support a large and diverse research program. As a high-intensity source of radioactive ions, the EURISOL facility may act as the first stage of a neutrino factory based on the acceleration of these ions to high energies and their accumulation in a large racetrack-shaped storage ring where they emit neutrinos through the beta decay process.

Betabeam is a potential key to future long baseline neutrino experiments as it relies on known technology and is able to produce a neutrino beam of precise timing, low divergence, and low energy spread, as opposed to the technical challenges and high costs associated with the beam production and beam cooling in muon-based facilities. TRIUMF participates in the Betabeam task of the EURISOL study which will produce a conceptual design study incorporating all aspects of the Betabeam accelerator complex and its operation.

Results & Progress

Our beam dynamics group was invited to collaborate with Betabeam study members who had noted that the code `ACCSIM` was a good candidate for a platform on which to build a comprehensive simulation of the Decay Ring, incorporating ion injection, rf capture, tracking, decay, and detection and quantification of losses of the decay products.

At early Betabeam meetings TRIUMF presented a survey of the available computing tools and methods, and a plan for the software developments needed to meet the simulation requirements. Initially we worked with CEA Saclay personnel who were designing the optics and magnet lattice of the decay ring, to establish the parameters and operating conditions of the ring and how they would be imported into the simulation, and how simulation results could be folded back into their optimization process for the ring design. We also worked with CERN members to specify the simulation parameters for the injection, rf system, and stacking mechanisms that were envisaged for accumulation of radioactive ions in the decay ring.

This definition stage was followed by work on a 3-part upgrade package for `ACCSIM`, comprising (1) Generalization of tracking and acceleration for arbitrary ions, (2) Physics and tracking model for ion decay process, and (3) Accurate tracking and loss detection of secondary ions. In latter task some new tracking techniques were developed, involving transfer matrix scaling and direct computation of dipole trajectories.

With this package complete, the application to the decay ring was pursued as a joint TRIUMF-CERN project in which data sets of secondary ion losses were produced by `ACCSIM` runs and then were post-processed by the `FLUKA` code to account for ion interactions with the accelerator components, in particular the superconducting dipoles. The publication of these results represents a first look at Betabeam decay ring operation from the point of view of ion losses, radiation exposure of ring hardware, and especially the heat deposition in the dipoles which may result in magnet quenching. The latter result has led to a new design effort to specify an open-coil dipole which will be resistant to quenching via ion losses.

- F.W. Jones and E. Wildner, *Simulation of Decays and Secondary Ion Losses in a Betabeam Decay Ring*, Proc. 2007 Particle Accelerator Conference.

The new `ACCSIM` version has also been distributed to other Betabeam members who are using it to estimate losses and space-charge effects in the post-ISOL accelerators (CERN PS and SPS in the baseline scenario).

List of Institutes

CERN, CEA Saclay

TRIUMF Role

TRIUMF provides the design and programming of simulation tools needed for Betabeam studies, configuration for current lattice and operational parameters, and streamlining of simulation data flow to post-processing applications.

13 T2K experiment at J-PARC

Introduction

The T2K experiment needs a fast extracted proton beam from the 50 GeV J-PARC accelerator. TRIUMF was the main designer of the optics for the 200 m long transfer line between the accelerator and the target where the neutrinos are produced.

The design work was finished in 2005. The J-PARC 50 GeV ring is under construction.

Results & Progress

The beam line bends the beam through 90°. It consists of an arc of superconducting combined-function magnets, which combine quadrupole and dipole fields. The arc is preceded by a normal conducting preparation section, and followed by a normal conducting targeting section. Extreme care had to be taken to prevent the proton beam triggering the quenching of the magnets in the arc. The beam line is presently being built at J-PARC.

List of Institutes

KEK, JAERI.

14 Charged kaon beams at J-PARC

Introduction

In 2006 and 2007 the J-PARC PAC requested TRIUMF to perform an extensive external review of the designs for the proposed 1.8 GeV/c and 1.1 GeV/c kaon beams. These are clean kaon beams where the intensities of the various background particles, mainly pions and muons are reduced by a factor of several thousands by two stages of separation using DC separators. The very delicate and critical second and third order optics is corrected with sextupoles and octupoles. The beams will be used for the study of hyper-nuclear physics.

Results & Progress

The expertise developed at TRIUMF with respect to the design of clean kaon beams continues to be called upon. An example of that expertise can be found in the NIM paper NIM A444(2000)546-556, under the title *Optics design and performance of LESB3, a two-stage separated 800 MeV/c kaon beamline*. This beam line was built at Brookhaven.

After that a 800 MeV/c single stage separated beam (link1, link2) was designed by TRIUMF as a branch of the 1.1 GeV/c beam. Although it has only a single stage of separation the beam is clean due to the presence in the beginning of the beam line of an extra focus, where a beam defining slit can be placed. The beam is required by the TREK experiment at J-PARC that measures the polarization of the muon resulting from the Kμ3 decay. This is the only experiment in the world that directly measures T-violation, unlike experiments that deduce T-violation from CP-violation, assuming CPT invariance.

List of Institutes

KEK, JAERI

15 Pellet-Beam Interactions at HESR

Introduction

TRIUMF provided pellet target and beam interaction Monte Carlo simulations to the 14.5 GeV High Energy Storage Ring (HESR) at FAIR, GSI, Germany, for the the future PANDA experiment. A crucial question for the operation of HESR is the effect of target heating which will, in combination with the stochastic/electron cooling, define the equilibrium beam conditions. This equilibrium is strongly dependent on the mechanisms of cooling.

TRIUMF was invited to join the PANDA collaboration as part of the Uppsala group in Sweden in October 2004 to do the Monte Carlo studies. After the Technical Progress Report for PANDA was completed, work ceased.

Results

For the envisaged luminosity at PANDA the average target thickness will be a few times 10^{15} atoms/cm^2. The question whether the density distribution of the target may also affect the heating was raised. This is because in contrast to e.g. a cluster-jet target, the target density is not homogeneous but concentrated in pellets of a few tens of micron diameter; the local thickness reaches values of a few times 10^{19} atoms/cm^2. Though this effect was investigated for the CELSIUS ring and found to be small there, dedicated Monte Carlo simulations were made for the situations at the HESR.

For the first time the simulations were done using a beam of $T_{\bar{P}}$=800 MeV and $T_{\bar{P}}$=14.5 GeV; the lowest and highest energies respectively at which the HESR should operate. For the target, two different scenarios were used; discrete pellet and continuous distribution, of the same effective thickness of 2.8×10^{15} atoms/cm^2. The results of the Monte Carlo runs show that the growth in emittance does not deviate significantly for both cases. This supports the earlier findings of studies in CELSIUS and COSY rings that the effect of the strongly inhomogeneous distribution of a pellet target cannot be distinguished from a homogeneous distribution of the same effective thickness.

List of Institutes

TSL (Uppsala), GSI.

TRIUMF role

TRIUMF contributed Monte Carlo simulations dedicated for the HESR. This has been included in the PANDA Technical Progress Report (in Section 4.1.6, p. 60; link).

16 Microbunching for KOPIO

Introduction

TRIUMF performed beam-dynamics simulations of a new slow-extraction technique, called micro-bunching, for the CP-violation rare decay experiment KOPIO to be performed at the BNL AGS using 10^{14} protons per pulse.

From its inception in 1996 to cancellation in July 2005 for financial reasons, the KOPIO project spanned a decade. A series of micro-bunching demonstration experiments was performed at the AGS from 1997 to 2005. TRIUMF provided accelerator physics expertise on micro-bunched slow-extraction from 2000 to 2005.

Description

An experiment was designed to run at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS) that would make use of a microbunched slow extracted proton beam for studies of the rare decay $K_L^0 \to \pi_0 \nu \bar{\nu}$. This experiment, called KOPIO (E949), would use time-of-flight to measure the momentum of K_L that decay in flight inside the detector. 25 MHz rf cavities in the AGS ring would be used to confine the resonantly extracted proton beam into microbunches with RMS widths of about 150 ps every 40 ns. Elimination of backgrounds from other K_L decays generated outside of the microbunches translated into the requirement that the intra-bunch extinguishment be less than 10^{-3} of the bunch intensity. The beam dynamics challenge was two-fold: to produce very short bunches without excessive cavity voltage, and to achieve extremely low leakage of the extraction scheme.

Results & Progress

Micro-bunching relies on the interplay of a chromatic 1/3-integer extraction process and the longitudinal cusps of proton intensity that occur near the fixed-points when rf buckets perform phase-space displacement acceleration. TRIUMF developed software to perform a detailed 2-dimensional simulation of the extraction process, both as a tool to understanding experiments performed on the AGS, and as a means to develop and optimize the technique to a level suitable for KOPIO. TRIUMF proposed a combination of 25 MHz fundamental and anti-phased fourth harmonic rf acceleration to achieve the necessary bunch length with modest voltages; and TRIUMF constructed a prototype of the 25 MHz rf cavity, scaled from a 27 MHz design for the RHIC. The BNL slow-extraction team performed a variety of beam experiments first with 93 MHz cavities verifying the calculated bunch lengths and later using 4.5 MHz rf cavities to verify the intrabunch extinction of $\simeq 10^{-5}$. Both were in good agreement with the TRIUMF simulations. The last series of results was reported in NIM-A **560** (2006).

List of Institutes

Brookhaven National Laboratory; Institute for High Energy Physics, Protvino, Russia; Yale University; Stony Brook University; Virginia Polytechnic Institute & State University.

TRIUMF Role

TRIUMF was responsible for developing the microbunching technique originally conceived at BNL to a level where it could meet the demanding specification of the KOPIO experiment. TRIUMF wrote simulation software, calibrated it against known slow-extraction properties of the AGS, and based on extensive exploration of design parameters perfected the extraction scheme. Had the operation of the AGS for rare decay physics not been terminated in 2005, TRIUMF would have constructed the 25 MHz rf cavity.

17 Impedance and collective-effects at JPARC

Introduction

J-PARC pursues frontier science in particle physics, nuclear physics, materials science, life science and nuclear technology, using a new proton accelerator complex. J-PARC consists of a 180 MeV linac followed by 3 GeV and 50 GeV rapid cycling synchrotrons. TRIUMF was asked to consult on ring impedance estimates and advise on the potential for beam instability.

TRIUMF was invited to prepare estimates of collective effects in October 2002, and presented results and recommendations to the Accelerator Technical Advisory Committee (ATAC) in March 2003 and March 2004, at which time work ceased.

Results & Progress

A wide variety of impedance sources was considered, and in particular kicker magnets with reactive terminations – for which there were no previously existing formulae. Both bunched and coasting beam, longitudinal and transverse, instability thresholds and growth rates were estimated. This is complicated by the fact that there are vastly different parameter sets during injection, ramping and the fast and slow extractions. For the bunched beams, a key issue was to understand the stability of high-order head-tail modes at very large chromatic tune shift.

Recommendations made to the ATAC included (i) methods of beam-load compensation for the rf cavities; (ii) not to operate the ring with near zero chromaticity during slow extraction (iii) to be wary of introducing resonant transverse impedances into pumping-port enclosures and rf cavities by careless design; and (iv) to add small resistive loads or at least one matched termination to the TW-type kicker magnets to reduce troublesome reflections; etc. The head-tail modes were found to be stable throughout most of the Main Ring acceleration cycle, with the exception of a short period at injection.

List of Institutes

KEK, JAERI

TRIUMF Role

TRIUMF provided beam-impedance and collective-effects calculation expertise to the 3 GeV Booster and 50 GeV Main Ring of the Japan Proton Accelerator Research Complex (J-PARC).

18 GEANT4

Introduction

Motivated by our local expertise in medium energy hadronic reactions and in computing and simulation, TRIUMF was invited to join the GEANT4 collaboration during its formative stage. Since joining, TRIUMF has made major contributions to the design and implementation of GEANT4, has hosted two international GEANT4 workshops, and continues to provide new functionality and user support for this ongoing software collaboration. (See S. Agnostelli et al).

In recent years, we have seen significant efforts in the area of GEANT4 studies of beamlines, including detailed geometries of magnetic elements and other hardware. These have chiefly been in the areas of beam delivery systems for colliders (LHC and ILC), where experimental backgrounds need to be accurately predicted, and in muon cooling lines and experiments such as MICE. In works related to spectrometers and nanobeams, it has been demonstrated that (1) GEANT4 can accurately model magnetic elements and overlapping fringe fields, and (2) GEANT4 tracking is highly accurate, scalable, and can compete with dedicated ray-tracing codes.

GEANT4 is structured as a software toolkit and various beamline tools based on GEANT4 have emerged, such as Fermi `Beamtools`, `BDSIM`, `GMAD`, and `G4Beamline`. `G4Beamline` appears to be the most advanced of these and is applicable to a number of TRIUMF systems, but it has essentially been designed around muon cooling systems and there are a number of additional needs and avenues of further development to be considered for the future of this or similar codes.

Results & Progress

There are now prototype models of several TRIUMF beamlines in GEANT4 or `G4Beamline`. In 2008 a `G4Beamline` application for extraction line BL2A will be developed, with as high a level of optical accuracy as the knowledge of the hardware (particularly magnetic field data) will permit. This allows an opportunity to understand better the beamline behaviour and possibly to improve performance. `G4beamline` offers a number of features useful for this, but current indications are that further development of `G4beamline` would be needed to make it maximally useful for this and other TRIUMF beamlines. `G4beamline` is a product of the private company Muons Inc., but it is essentially written and supported by one person and is freely available with open source and GPL licensing. This means that in principle we can modify the source code to meet our needs, but it raises the question of whether these should be ad hoc modifications or should there be a more formal contribution to the evolution of the code or a product derivative of it. (G4Beamline link.)

List of Institutes

Many (see GEANT4 website).

TRIUMF Role

TRIUMF's membership in GEANT4 brings obligations but also privileges, including direct access and involvement in the evolution of the code (instead of just public release packages), as well as an inside track on issues of support, feature requests, and the opportunity to learn and discuss with experts about all aspects of the GEANT4 toolkit.

Because of this, and our local expertise in particle and nuclear physics, computing, and accelerators and beamlines, TRIUMF is well positioned to pursue advanced accelerator and beamline tools and applications built from GEANT4.

19 Development and Support Activities for ACCSIM

Introduction

The tracking and simulation code `ACCSIM` was developed at TRIUMF and has benefited from our local expertise in accelerators and beam lines as well as experience from previous well-known TRIUMF codes such as `COMA` and `REVMOC`. Like these codes, the emphasis in `ACCSIM` is on usability by those who may not have advanced computing skills, and on direct interaction and consultation with users to determine the needed functionality and the path of further development.

Results & Progress

With its free availability and comprehensive documentation, `ACCSIM` has been used in a variety of applications and this has led to collaborations between TRIUMF and other accelerator labs such as CERN, LANL, KEK, BNL, ORNL, and J-PARC. Specifically, `ACCSIM` played a role in the design effort for the J-PARC 3 GeV rapid-cycling synchrotron and for the ORNL SNS 1 GeV accumulator ring, both recently constructed and in commissioning or operation. It also was the vehicle or catalyst for two tasks in the Beam Dynamics component of the Canadian contribution to LHC, and has facilitated strong long-term relationships with a number of accelerator experts at CERN.

Other notable applications include several studies of the LANL PSR and its upgrades, simulation of the proposed LINAC IV H^- injection in the CERN PS Booster (part of the LHC upgrade program), the EURISOL Betabeam (described below) and tracking in the KEK 12 GeV PS under high-current operation for KEK-to-Kamiokande neutrino production. The latter study included one of the few direct comparisons that have been made between a space-charge tracking code and actual measured beam profiles in a ring (with good agreement being observed).

References for `ACCSIM` applications (2003 and later):

- Y. Shimosaki and K. Takayama, *Halo formation at early stage of injection in high-intensity hadron rings*, Phys. Rev. E **68**, 036503 (2003).
- S. Cousineau et al., *Space charge induced resonance excitation in high intensity rings*, Phys. Rev. ST Accel. Beams **6**, 034205 (2003).
- S. Cousineau et al., *Resonant beam behavior studies in the Proton Storage Ring*, Phys. Rev. ST Accel. Beams **6**, 074202 (2003).
- S. Igarashi et al., *Space charge effects during the injection period of the KEK PS main ring*, Proc. PAC 2003, 2610.
- M. Martini and C.R. Prior, *High-intensity and high-density charge-exchange injection studies into the CERN PS Booster at intermediate energies*, Proc. EPAC 2004, 1891.
- S. Igarashi et al., *Observation of emittance growth at the injection of the KEK PS main ring*, Proc. HB 2006, 250.
- M. Aiba et al., *Simulation of the CERN PS Booster performance with 160 MeV H^- injection from LINAC4*, Proc. PAC 2007, 1595.
- F.W. Jones and E. Wildner, *Simulation of decays and secondary ion losses in a Betabeam decay ring*, Proc. PAC 2007, 3232.

Other citations:

- S. Cousineau, *Simulation tools for high intensity rings*, Proc. PAC 2003, 259.
- N. Malitsky et al., *Towards the UAL open source project*, Proc. PAC 2003, 272.

- N. Malitsky and R. Talman, *UAL implementation of string space charge formalism*, Proc. EPAC 2004, 2200.
- S. Cousineau, *Benchmark of space charge simulations and comparison with experimental results for high intensity, low energy accelerators*, Proc. PAC 2005, 164.
- Y.-N. Rao and D. Reistad, *Monte Carlo simulations of thin internal target scattering in CELSIUS*, Proc. PAC 2005.

List of Institutes

CERN, LANL, KEK, JAERI, BNL, ORNL

TRIUMF Role

TRIUMF is the home base of `ACCSIM` where development, documentation and support is done, although the code has gained much by expert input and sharing of ideas from CERN and other laboratories. We have also engaged in direct collaborations with users towards new applications and enhancements to the code.

20 Space Charge Simulation Codes

Introduction

The simulation of intense proton beams in synchrotrons and storage rings has been of widespread interest in recent years, in studies and designs of hadron facilities, spallation neutron sources, and proton drivers for future neutrino and muon facilities. The space-charge simulation code `ACCSIM`, developed at TRIUMF with input from a number of experts, is one of a generation of innovative codes, created at various institutes, which are devoted to modeling these intense proton machines.

Results & Progress

After a seminal ICFA workshop in Oxford where much information on code development and progress were exchanged, the authors of several codes including `ACCSIM, SIMPSONS, ORBIT`, and others, undertook a long-term collaboration to compare, test, and validate these codes using common baseline configurations, with the CERN PS being the first reference lattice to be considered. Although these codes tend to run at the practical limits of current computing hardware, data sets were obtained and comparisons and analyses were published for a number of simulation cases and levels of accuracy. This led both to insights about the behaviour and applicability of the codes, and to new questions about differences between the codes. We expect that there will be further phases of this collaboration which will lead to refinements of our methodologies and better understanding of numerical issues and physics models.

- I. Hofmann et al., *Benchmarking of Simulation Codes Based on the Montague Resonance in the CERN Proton Synchrotron*, Proc. 2005 Particle Accelerator Conference (PAC 2005).

List of Institutes

CERN, ORNL, GSI, RAL, BNL, FNAL, LBNL, KEK

TRIUMF Role

This is a relatively small but active field of research in which the code authors have been able to establish long-term relationships and have collaborated with each other on various studies of actual and planned accelerators. In particular with CERN and ORNL, TRIUMF's development and support of `ACCSIM` is valued and our continued participation will be appreciated.

21 60 GeV/c rf separated kaon beam

Introduction

High energy rf separated kaon beams were built decades ago. They had very small intensities because of the large momentum related higher order optics aberrations, and the small electric gradients in the room temperature cavities. Nowadays, it is possible to make high gradient superconducting cavities that can be used in slow extracted beams.

Results & Progress

For the optics problem a solution was found at TRIUMF. The consequence of both developments is that now rf separated beams can be built at high energies with phase space acceptances more than an order of magnitude higher than in the past. Therefore, rf separated beams can now be built that approach the intensities of unseparated beams, but without large contamination by pions and protons.

Entirely new ways of making use of rf cavities for rf separation are described in: J. Doornbos, *Possibilities for a 15-25 GeV/c rf separated charged kaon beam* NIM A455(2000)253-270.

These techniques were applied at TRIUMF to design for a 22 GeV/c rf separated K^+ beam for the CKM experiment at FNAL. This experiment aimed to measure 100 events of the decay in flight of the kaon into a pion and two neutrinos. The E787 experiment at BNL had already measured 3 such events, but its continuation was canceled. Unfortunately the development of the CKM experiment was also terminated.

Due to new detection techniques developed by the CERN NA48 collaboration that can handle very high particle rates, an attempt is now being made at CERN to measure the decay in a 75 GeV/c unseparated beam. In this way they hope to measure 100 events. It was thought there that a separated beam would have too small a phase space acceptance. In order to demonstrate the feasibility of a separated beam at such high momenta in 2006 an optics design was made at TRIUMF for a 60 GeV/c rf separated kaon beam with very high acceptance, using superconducting X-band cavities. If the presently intended experiment with an unseparated beam succeeds, the thinking is that then a follow up experiment using an rf separated beam, with the same rate as the unseparated beam, but now mainly kaons, will make it possible to measure 1,000 events.

List of Institutes

FNAL, BNL, CERN

TRIUMF Role

Initial ideas originated at TRIUMF, so we are still consulted on new designs.

22 FFAG Studies

Introduction

TRIUMF is engaged in designs for a new and novel type of charged-particle accelerator, the non-scaling Fixed Field Alternating Gradient (FFAG) accelerator, that promises more cost effective acceleration of muons for HEP and of low-energy hadrons for cancer therapy. A demonstration model, EMMA, is under construction at Daresbury U.K.

The TRIUMF involvement with FFAGs began in October 2003, with US-led designs for a future Neutrino Factory and Muon Collider. Quickly it was perceived that FFAGs were a cost-effective alternative to recirculating linear accelerators (RLAs), such as CEBAF, because their enormous momentum acceptance meant that the costly multiple return arcs and much of the costly ionization cooling could be dispensed with. Later, the studies blossomed to include a demonstration model using low-energy electrons, and proton and carbon accelerators for cancer therapy. The work is ongoing through 2009 at least.

Results & Progress

U.S. and European scientists are developing FFAG research programs, and we have worked with them in achieving a breakthrough in understanding how FFAG designs may be simplified and the restrictions imposed by scaling avoided. In particular, we introduced "serpentine" acceleration (essential for muons), developed a theoretical model explaining the momentum dependence of orbit shape and period, and are helping to guide the design of the 10-20 MeV electron model, EMMA (Electron Model with Many Applications), which is under construction at the Daresbury Laboratory in the U.K. As with traditional isochronous cyclotrons, which are a type of non-scaling FFAG, this "first generation" machine has the demerit of resonance crossing due to the variation of the transverse betatron tune. Looking forward to the medical applications, and a much slower rate of acceleration than muons, we are actively working on designs involving wedge-shaped combined-function magnets in which the contributions of increased path length and edge focusing are used to stabilize the transverse tunes. If the design proves feasible, the UK consortium intends construction of a medical prototype, PAMELA.

- S.R. Koscielniak, M.K. Craddock: *Simple Analytic Formulae for the Properties*

of Nonscaling FFAG Lattices, Proc. 2004 European Particle Accelerator Conf., Lucerne, (EPS-AG, Geneva, 2004) pp. 1138-40.

- S. Koscielniak and C. Johnstone: *Mechanisms for nonlinear acceleration in FFAGs with fixed rf* NIM-A 523, pp. 25-49 (2004)
- C. Johnstone and S. Koscielniak: *FFAGs for rapid acceleration* NIM-A 503, pp. 445-457 (2003)

List of Institutes

TRIUMF is a member both of the US-led Neutrino Factory and Muon Collider Collaboration, and of the UK-led CONFORM consortium of laboratories and universities building the EMMA model and studying alternatives for a proton or carbon medical accelerator design.

TRIUMF Role

TRIUMF continues to play a key role in providing intellectual and creative leadership to the development of non-scaling FFAGs: to the understanding and optimization of the magnetic lattices, notably the extreme momentum compaction; to the cyclotron-like method of bucketless rf acceleration; to introducing the use of cyclotron orbit codes for FFAGs in place of synchrotron codes, which are awkward to use for spiral-orbit accelerators; to practical aspects of the EMMA design such as selection of the L-band cavity design; and to a high-gradient small-aperture version of the PAMELA concept.

23 Intensity Limitations in Cyclotrons

Introduction

The 500 MeV TRIUMF cyclotron's limitation on peak intensity is due to repulsive space charge forces overpowering the vertical focusing forces in the central region where beam energy is lowest. For upgrading to higher intensity, it is necessary to understand the limitation.

The vertical section of the injection line is to be re-built. The study will determine optimum matching conditions into the cyclotron, and so must be completed this year (2008), so that the new injection line can be completed within the current 5 year plan.

Results & Progress

The dynamics in an isochronous accelerator is non-intuitive as the space charge forces cannot relieve themselves by lengthening the bunches: the particles act in a sense as if they have infinite mass. One can model the dynamics using individual macro-particles, but the optimization is not transparent. There exists a much more efficient formalism which is statistical in nature; the 21 six-dimensional second moments of the particle bunch distributions are followed rather than the motion of millions of individual particles. This formalism has never been used to study the effects of space charge in the first few turns of a cyclotron. Besides transport in 6-dimensional phase space, acceleration must also be correctly handled. An error has been found in one standard code (TRACE-3D).

At sufficiently high intensity, the bunches become vortices; circular when observed from above the median plane. A new discovery is that this tendency alleviates the harmful influence of the "gap-crossing resonance" which causes a stretching of the beam in the median plane. This aspect is currently under study; it may result in higher charge per bunch than envisaged when the cyclotron was originally designed.

- Richard Baartman, Yi-Nong Rao (TRIUMF, Vancouver), Tianjue Zhang (CIAE, Beijing), Hongjuan Yao (CIAE, Beijing; TUB, Beijing), Yuzheng Lin (TUB, Beijing) *Gap-Crossing Resonance in CYCIAE-100 Cyclotron*, Proc. 2007 Conference on Cyclotrons and their Applications.

List of Institutes

There is a collaboration with the Chinese Institute of Atomic Energy (CIAE), as they are designing a 100 MeV cyclotron that would be affected by similar intensity limitations.

TRIUMF Role

This research is critical to our upgrade plans, so we play the key lead role.

24 Fringe Fields

Introduction

Understanding to a high accuracy the focusing effects of dipoles and quadrupoles pays dividends in tuning time saved. If the elements are quite long compared with aperture, accuracy is easily obtained. On the other hand, when the fringe field is relatively long, its effect must be well-understood. This applies both to linear effects and aberrations.

New beamlines are now designed knowing the effect of fringe fields, so they are relatively more easily commissioned than has been the case in the past. Older beamlines that have always been tuned empirically are, one-by-one becoming treated more scientifically.

Results & Progress

It is of course possible to use the element field map in a ray-tracing code. But this makes simple optics calculations very cumbersome. If only the linear and lowest order aberration are important, one can ask "How much of the detail of the field map is needed?". It turns out very little. For example, the linear effect of the quadrupole can be summarized exactly using only 3 parameters: effective length, effective strength, and a fringe field parameter. And the lowest order (cubic force) aberration depends not at all on the fringe field shape.

- R. Baartman, D. Kaltchev, *Short Quadrupole Parametrization*, Proc. 2007 Particle Accelerator Conference.

These results are used to distill the field maps into a simple and efficient form. For example, of the 100's of electrostatic quadrupoles used in both ISAC and ISIS (the cyclotron injection line), almost all are set to their theoretical values. This is in spite of the fact that many are short compared with their aperture. Magnetic quadrupoles are also being treated in this way. This has made the beam optics calculations sufficiently efficient that beam envelopes can be calculated continuously in a Graphical User Interface (GUI) as the operator tunes the elements.

25 Nonlinear transfer maps for charged particle beam transport

Introduction

Charged particle beam transport can be described with a Taylor map which, in the linear case, coincides with the familiar beam-transfer matrix. Traditional accelerator design codes, such as `TRANSPORT` of K. Brown and `MAD`, developed by CERN, utilize the next (second) order map while methods to construct maps of higher order and use them for nonlinear analysis were developed in the 80s by Dragt, Forest, Irwin, Berz and others. Such are the Lie-algebraic method, which fully accounts for the Hamiltonian (symplectic) nature of motion, or the Differential Algebra method, where the map is extracted directly from the equations of motion. In terms of mathematical apparatus, both these approaches, and especially the second one, require extensive numerical manipulations of polynomial functions. For this, the techniques of the truncated power series algebra (TPSA) are applied (also called automatic differentiation).

At present, increased power of analytic computational systems (such as `Mathematica`) provide the flexibility and speed needed to implement all the map-building methods described above. Nonlinear problems can then be studied with dedicated notebooks in a local environment. Work in this direction, pursued also by researches in many accelerator laboratories, has recently been initiated at TRIUMF. We have developed two packages – `LieMath` and `DARK` possessing many features and functions of two well established codes: `MARYLIE` of A. Dragt and `COSY` (of M. Berz).

Results and progress

Lie-algebra applications: `LieMath` (2004-2005) is a code we wrote which builds a symplectic 6 dimensional map in either Lie-factor, or Taylor form. The input to the code is a beam-line of optical elements written in the most popular MAD-input format. The code provides nonlinear optimization and normal form analysis to octupole order. As of 2006, a TPSA module is installed to speed up operations on polynomials.

In 2004, an early version of LieMath was used to produce 7-th order off-momentum map for the basic cell of the Fixed Field Alternating Gradient accelerator (FFAG); it is in full agreement with the corresponding map generated by `COSY-`∞.

In 2006, Lie-algebraic theory was applied (2005) to test and refine the existing CERN program for multipole correction of the LHC interaction-region quadrupoles (so called triplet correction).

In 2007, Lie-algebraic treatment of weak-strong beam-beam interaction produced the effective Hamiltonian in the case of an arbitrary number of collision (or interaction) points (IPs). This is related to the long-standing question whether the beam-beam resonances may be canceled by choosing some appropriate betatron phase advance between the two main IPs of the LHC – Atlas and CMS. Such resonances, manifesting themselves as dips in dynamic aperture positioned dangerously close to the LHC tune working point, were clearly seen in the tracking data. As a result we found that not all, but only some kinds of resonances would be canceled and the conditions for cancellation are rather stringent. The idea to tune the machine to a specific phase between the IPs has been, at least for now, abandoned.

Differential algebra applications: `DARK` (Differential Algebra + Runge-Kutta) is a Mathematica package that applies the TPSA method to compute the transfer map for arbitrary equations of motion describing an optical system. It has the same interface as LieMath, so the Taylor maps produced by these two codes can be compared directly, but it can also tackle the case when the focusing strength of an optical element is not constant along its axis, i.e. the case of fringe fields. The algorithm used is very similar to the one used in the code COSY-∞.

In mathematical terms, DARK is a differential algebra integrator – a numerical solver of the complete variational equations describing an optical system.

The code has been tested against numerical integration of individual trajectories and, for magnetic quadrupoles with fringe fields, against high-order maps generated with COSY-∞.

Possible applications are: nonlinear optimization of beam-lines, FFAG, a Linear Collider Interaction Region, existence of Third Order Achromats etc.

DARK was used recently to study fixed points and transition to chaos of the Duffing equation.

List of Institutes

There is incidental interaction with University of Maryland. CERN is involved only in the application of the codes.

TRIUMF role

In 2005, the LieMath package was added to the web-based dynamic accelerator physics software repository (CARE HHH European Network).

Currently DARK is being used to study fixed points and transition to chaos of the Duffing equation. This is intended for Section 18.11 (Taylor Approximations) in the book of Prof. Alex Dragt (link).