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Abstract:

This report presents an overview of the Advanced Optics Control (AOC) workshop, which was co-supported by EuCARD2 Task 5.2 "Extreme Colliders," and organized at CERN in February 2015. The AOC workshop reviewed recent advancements in optics measurement, correction, and understanding from colliders and synchrotrons around the world. One obvious focus was the preparation for the Run-2 of the LHC. Other highlights included novel modelling approaches at light sources, the challenges posed by the High-Luminosity LHC, by Future Circular Colliders, and by storage rings dedicated to measuring the electric dipole moment of the stored particles. AOC followed two earlier events with related subject matters, namely the 2011 EuCARD-AccNet workshop on Optics Measurements, Corrections and Modeling for High-Performance Storage Rings (OMCM), and the 2013 LHC Optics Measurement and Corrections Review, co-supported by EuCARD-AccNet.

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1. INTRODUCTION

This EuCARD-2 XBEAM-XCOLL/XRING workshop on Advanced Optics Control (AOC) was the third workshop devoted to optics measurements, corrections, and control, following two earlier workshops which had been organized in the frame of EuCARD-AccNet, namely the 2011 EuCARD-AccNet workshop on Optics Measurements, Corrections and Modeling for for High-Performance Storage Rings (http://indico.cern.ch/event/132526) and the 2013 LHC Optics Measurement and Corrections review (http://indico.cern.ch/event/246159).

One key topic of AOC2015 was the lessons from LHC Run-1 and the preparation for the LHC Run-2. Interesting new diagnostics and modelling approaches were reported from various state-of-the-art light sources. Optics challenges for future machines were also reviewed, including the High-Luminosity LHC, the Future Circular Colliders for hadron and leptons, new light sources like the ESRF upgrade, special storage rings dedicated to measuring the electric dipole moment of protons or deuterons.

The AOC2015 workshop was organised by CERN, together with GSI and FZ Jülich in Germany, and it took place on the CERN Meyrin site, Switzerland, from 5 to 6 February 2015. The scientific program of the workshop had been set up following suggestions by an Organizing Committee composed of:

M. Bai (FZ Jülich), G. Franchetti (GSI), M. Giovannozzi (CERN), M. Lamont (CERN), R. Tomas CERN), F. Zimmermann (CERN).

The following scientific secretaries helped with the organization and documentation of the sessions:

A. Huschauer (TU Vienna & CERN), R. Martin (Humboldt U. Berlin & CERN), E. H. Maclean (Manchester U. & CERN), T. Persson (CERN).

D. Rivoiron (CERN), serving as workshop secretary, diligently took care of all organizational and administrative matters.

The workshop was sponsored and supported by EuCARD-2 XBEAM, EuCARD-2 XRING, CERN, HIC for FAIR, ICFA, CERN PS MTE, HiLumi LHC and LIU.

The program was composed of 24 oral contributions (for 49 participants) and addressed the following topics, corresponding to the four sessions:

- Current and future colliders (RHIC, LHC, HiLumi LHC, FCC)
- Advanced techniques (resonance driving terms, automatic tuning, resonance mapping, advanced diagnostics)
- Lepton machines (SLS, SPEAR, ESRF upgrade, DIAMOND upgrade, SuperKEKB, FCC-ee, MICE)
- Exotics (FNAL IOTA, EDM ring, PS islands, septum-less injection, fixed lines, nonlinear alpha buckets)

2. PRESENTATION SUMMARIES

The details of the program as well as a collection of all talks are available on the indico web site http://indico.cern.ch/event/349643.

2.1. Opening

Paul Collier commented on the impressive start-up of the Large Hadron Collider (LHC), during which both understanding and control of the essential beam optics had been obtained quickly. He contrasted this with the experience of the Large Electron Positron Collider (LEP) in which he light-heartedly described the betatron squeeze as an adventure. Paul Collier highlighted that such **improvements in the LHC performance** relative to its historical predecessors had come about as the **result of advances in both the understanding of beam optics, and through improvements in the tools and methodologies available for measurement and control**. He then emphasised that the **LHC project, like other potential future machines, would not succeed without a good control of the beam optics**. Within the context of advances in optics measurement and control taking place in a wide variety of different institutes, he therefore highlighted the **significance of workshops such as this one for bringing together tools and expertise from around the world in order to enable the accelerator community to meet the challenges posed by current and future machines.**

2.2. Session 1: Current and future colliders. Chaired by Mike Lamont (CERN)

2.2.1. Optics needs for the LHC, Rogelio Tomas Garcia (CERN)

At present KEKB (operating with Q_x~Q_y~0.5) leads the global accelerator community in regard to instantaneous luminosity, with $L=2.1\times10^{34}$ cm^{-2}s^{-1}. There is a narrow window of opportunity over the next two years (until SuperKEKB begins to produce high luminosity) however, in which the instantaneous luminosity of the LHC may be able to exceed that of KEK. It is relevant, therefore, to consider the limiting factors on LHC luminosity production.

Ultimately limitations on the LHC luminosity may come from the particle physics detectors, which are at present only capable of handling 50 events within a given bunch crossing (a "pile-up" of 50). Limitations also arise from the maximum heat load in the triplet quadrupoles: combining the many sources of heating (quoted were debris from the IP, synchrotron radiation heating, and the effect of electron-cloud) would limit the luminosity to $L\leq1.75\times10^{34}$ cm^{-2}s^{-1}. This luminosity corresponds neatly to a pile-up of 50 events, and may represent a difficult barrier for the LHC to overcome. However, the role of electron cloud with respect to the heat load and beam instability or emittance growth poses a serious threat to even such a luminosity target. In case of limitation due to electron cloud a fall-back solution for LHC operation would be to reduce the number of LHC bunches by ≥ 30%, implying a corresponding increase in the bunch charge. Such a machine configuration will require the **implementation of β* levelling** to limit pile-up in the detectors, together with the **largest possible decrease of β*** in order to allow the maximum integrated luminosity to be obtained. While the LHC will begin in 2015 with a relatively relaxed optics configuration, therefore, to achieve a strong luminosity performance during Run 2 it will be necessary to move to a more pushed optics. This represents **significant challenges with regard to optics control**.

An overview of the planned schedule for LHC commissioning and its operation during Run 2 was presented next. Then a historical overview of the evolution of optics correction in the LHC was given. Prior to correction the β-beating in the LHC had been up to 100% at β*=0.6 m. **In order to optimize the accelerator performance, and to minimize luminosity imbalances between the particle physics detectors, it is necessary to perform careful corrections after every manipulation of the LHC optics.** It was highlighted that in 2012 the LHC optics control made history, achieving a **record quality of the β-beating for colliders** [R. Tomas *et al.*, "Record low β-beating in the LHC, Phys. Rev. ST Accel. Beams, **15** (091001), 2012]. In spite of the good control of LHC optics in Run 1 however, to meet the challenges for the future operation, improvements in accuracy, resolution and speed of the optics measurements will be required. Several avenues are being explored in this regard: new methods such as the N-BPM method (for details see another talk in these proceedings: 2.3.3); better LHC models; the implementation of a coupling feed-back [T. Persson and R. Tomas, Improved Control of the Betatron coupling in the Large Hadron Collider, Phys. Rev. ST Accel. Beams, **17** (051004), 2014]; the use of higher resolution BPMs (for details see 2.3.6); and longer AC-dipole acquisition were all discussed.

With regard to improving the LHC luminosity a number of possibilities were raised. The use of β* levelling was discussed in the context of moving to high-current/low−β* operation or to electron-cloud limited operation. However it was emphasised that while this has been done successfully at RHIC (talk 2.2.2.) there is no experience in the LHC of the sort of **dynamic linear optics correction necessary to facilitate β*-levelling**. The possibility of performing a combined ramp and squeeze to save time in the LHC cycle was raised. It was highlighted that this has been implemented at RHIC. A reduction in the LHC beam lifetime in 2012, as compared with 2011, was shown, and the possible role of nonlinear dynamics in reducing the LHC lifetime was underlined. It was stressed that correction of the nonlinear dynamics is expected to become much more important in Run 2. Pertinent strategies are being developed (2.3.2.). Finally, the **possibility of moving to alternative LHC working points** was discussed - particularly with regard to the working point Q_x~Q_y~0.5 so successfully used at KEKB. It was pointed out that studies in Run 1 had shown a decent β-beating at this working point, but also demonstrated sensitivity to chromatic effects. Further studies will be required. The high luminosity LHC upgrade (HL-LHC) was introduced.

Improvements to software tools for optics measurement and correction were discussed. The benefits of having physicists collaborating with computer scientists were strongly emphasized in this regard.

In summary it became clear that the LHC was getting close to its limits, while setting an unprecedented demand on optics control for its safe exploitation, but that the OMC team at CERN were eagerly awaiting the start of Run 2.

In the discussion after the talk, it was pointed out that while the LHC had set records for collider β-beating, light-sources typically operate with Δβ/β=1%. What were the reasons for the differences between colliders and light sources? R. Tomas responded that the LHC should aim for light source quality. However, colliders did have some particular challenges (low-β insertions and long arcs for example). It was suggested that **once a small β-beat of ~3% will have been obtained it may be possible to really understand the differences with respect to light sources.**

It was also discussed whether it was believed that the high quality of local optics correction in the LHC reflected the knowledge of where exactly the errors were originating from. R. Tomas responded that yes, it was believed that the main errors were understood. However, in addition there were many small errors around the ring, the origins of which were individually invisible at this point.

2.2.2. Beta* leverage during RHIC AuAu run, Guillaume Robert-Demolaize (BNL)

In RHIC, emittance reduction due to stochastic cooling, which has been implemented since 2011, provides enough additional transverse aperture in the IR triplets that it is possible to squeeze the β* in the STAR and PHENIX experimental insertions to provide integrated luminosity levelling. Since previously used lattices for heavy-ion operation in RHIC had little spare capacity in the IR shunt supplies to provide a significant squeeze of the β*, in this context also the feasibility of CERN's Achromatic Telescopic Scheme (ATS) has been studied for RHIC.

In an ATS scheme, originally developed for the LHC, insertions around the targeted IRs are used to launch and cancel a β-beating wave in both planes, traversing the arcs, which would have its waist at the IP, and requires a betatron phase advance (Δμ) per cell close to 90^{o} for increased chromatic correction efficiency. In RHIC, however, there are a number of additional complications which had to be overcome in the implementation of ATS optics - in particular the fact that the location of STAR and PHENIX in neighbouring insertions adds an additional constraint on the phase advance in order for the ATS scheme to be simultaneously effective in both IRs, and additional constraints on the optics matching enforced by the nested quadrupole wiring scheme employed at RHIC.

The Run 12 Uranium-Uranium RHIC lattice was used as the baseline upon which the ATS scheme was built, as it offered the best performance in terms of dynamic aperture and integrated lifetime. The matched ATS optics was shown for the Blue lattice, with Yellow being the same. As the quadrupole powering for the RHIC ATS scheme was calculated assuming perfect unperturbed optics, the practical implementation of the ATS required optics corrections. A technique based on the response matrix was developed to reproduce the β-beating from turn-by-turn BPM data. A comparison between the predicted and measured data revealed a good agreement. Optics corrections were calculated, applied, and shown by measurements to significantly reduce the β-beating.

The **RHIC ATS optics was successfully implemented in the machine, and obtained β*s very close to the targeted values of 50 cm**. The Telescopic Hi-Lumi Optics for RHIC (THOR) was declared operational on 6/12/2014. An example of the luminosity gain due to the dynamic β* squeeze was shown, with predicted and measured luminosity gains in close agreement.

In conclusion, the **concept of ATS optics has been successfully implemented at RHIC, allowing for dynamic β* squeezing and leading to an increased luminosity.** For the future the aim will be to level the luminosity throughout the entire length of the store. A new lattice has also been developed for the next run, which satisfies all the theoretical requirements for a "full"-ATS implementation in RHIC.

In the discussion following the talk, it was commented that the THOR lattice shows an irregular pattern in the arcs, so that the phase advance is different from the ATS scheme at the LHC. In reply, while the THOR lattice is based on the LHC ATS scheme, indeed it is not exactly the same. The issue of how machine protection concerns had been addressed was also raised: The RHIC experts had been very cautious during the implementation, and that there had been a lot of work done on collimation during end-of-fill studies to ensure these activities were safe and profitable for the experiments. It was also questioned whether one should worry about the orbit shifts during the dynamic β* squeeze. The answer was that at RHIC the orbit, tune, and coupling feed-backs are active during the squeeze, but that with protons this will be more challenging due to the poorer response of the BBQ.

2.2.3. Optics challenges for future hadron colliders, Daniel Schulte (CERN)

The European strategy for high-energy physics is focused primarily upon full exploitation of the LHC. However, it includes as a second priority a request that Europe should be able to propose an ambitious project at CERN for the post-LHC era: either CLIC or the FCC. The FCC study is working towards a conceptual design report in 2018, and there are many interesting and important optics challenges to be overcome.

Target beam parameters and the preliminary layout of the FCC were reviewed, before discussing the main optics challenges related to its design. It is noted in regard to the energy of the collider that both the site length and dipole field are limited: this will require the minimization of space used for insertions, and the maximization of the dipole filling factor in the arcs. With respect to maximizing the luminosity it is noted that **it will be necessary to minimize the β* while maximizing the beam current, both of which may lead to additional challenges**. In a more general sense it is also noted that cost and power will put pressure on many systems.

Design of the FCC dipoles will be a main cost and parameter driver. In particular the field level will be a challenge. However, there are many related issues with regard to the optics: for example smaller physical apertures will allow cheaper magnet construction, but require better optics control; the field quality of the dipoles will also impact upon the optics and tolerances.

Synchrotron radiation in the arcs is a concern, as at FCC energies even protons will radiate significantly. Radiation damping of the emittance may be advantageous fir the collider. However, the radiation may also lead to additional difficulties in maintaining cooling of the magnets. An alternative beam-screen design was shown, which may aid in this regard, but which would require excellent control of the optics.

Many issues remain to be addressed in the **design of FCC interaction regions** (IRs). Notable, however, is collision debris and radiation coming from the particle physics experiments themselves. Improvements may be required in the shielding or radiation hardness of the final focus magnets. A new alternative, namely **optimizing the IR optics with the aim of minimizing losses from pions, is also being examined.**

Implications of the FCC energy (>8 GJ per beam) for machine protection were discussed. It was noted that beams of this energy to could melt 12 tons of copper or drill a 300 m hole. However, small losses from the beam (due to the nonlinear dynamics or beam-gas scattering for example) could also be significant, as they may lead to magnet quenches or additional background in the particle physics experiments. This implies that **collimation in the FCC will be a significant concern.**

Injection into the FCC may also pose a particular challenge in view of possible kicker misfire. The total energy which can be injected into the HL-LHC is 5 MJ. If the same limit is assumed for the FCC, a very fast, and therefore long, kicker magnet will be required. Such a magnet may cause other issues, e.g. with regard to the impedance. It was questioned whether it is possible to design an optics with a more safely distributed loss pattern. Many other further issues also remain to be addressed.

The proposed FCC site and time line were presented. The presentation concluded with a reminder that help is welcome from those not already involved in the project, and details of how to get involved were provided. It is noted that the LHC experience will be important for finalizing the design of the FCC, which, however, also poses many challenges beyond those of existing colliders.

In the subsequent discussion, it was questioned whether any **consideration of materials** has been made **in preliminary studies of the collimation**. D. Schulte responded that this is one of the technical challenges which will have to be addressed, but that detailed studies of collimator materials had not yet been performed, the baseline effort being to establish a safe and reasonable collimation system. Consideration of materials may help refine the collimation system design in future studies. It was also questioned **which new tools / instrumentation will be of most interest to the FCC**. It was responded that **crab-cavities and beam-beam wire compensation** are interesting, but both concepts have been around for a while.

2.2.4. Modelling needs for future colliders, Ghislain Roy (CERN)

The concept of a model in the sciences was discussed in very general, high level terms. It was emphasised that a **model is inevitably limited by the assumptions and hypotheses** upon which it is built, with necessary implication for model development in regard to the simplicity/complexity of the model, and its range of applicability. It was emphasised, however, that the **aim of a model is in general either to facilitate calculation of relevant parameters, or to make predictions as to the behaviour of a system**, and that this objective should never be lost out of sight during the model construction. In this regard it was also debated whether it is better to utilize multiple specialized models, as opposed to a single overarching (but possibly shaky) construct.

It was stressed that one must always be clear (especially when sharing models / tools) as to the **correct range of applicability**. The example of simulation codes with the assumption β_{rel}~1 buried within the code was given as an example. There are a broad range of different types of future accelerator being considered by the community at present, and it was emphasised that these machines will have differing considerations with respect to model construction, for example in regard to steady-state vs variable energies, or single- vs multi-pass systems.

The generic "model" may be regarded as being composed of **three components: (1) data**, for example the accelerator lattice and magnet strengths; **(2) engines,** for example the physics equations and mathematical algorithms which will take the data and preform relevant calculations or generate predictions as to the system behaviour; and **(3) the user interface**. It was emphasised, however, that each of these elements of the model is liable to evolve. The importance of keeping data up to date was stressed, as was the importance of code benchmarking to check for regression and undesired side effects of updates.

Next an overview of simulation needs for accelerator design and operation was given. Particularly noted was the **distinction in time scales** required for these applications - for example the distinction between an online model being used by operators for “what-if?” scenarios, compared to codes for offline analysis and simulation of machine development studies. It was also noted that consideration of the appropriate time scale had to be made early on in the model development: for example an “online” model so complex that it cannot run online is of little use. However, with good design it should be possible to aim for a smooth transition between on- and off-line simulations. It was emphasised that **where models/codes are to be integrated with accelerator control structures this should be done as early as possible** in the development. “Cultural issues”, for example different groups within the accelerator community using different units, should also not be underestimated.

Finally the **possibilities of data mining and the use of a “Model Agent**” (a system which is aware in real time of the machine state and can rapidly calculate appropriate responses, in order to support the human operators) were raised.

In the following discussion, it was questioned whether accelerator physicists were generally good at obeying some of the good practice principles outlined in the talk. G. Roy responded that in general this was not the case, and emphasised the benefits which can be gained by collaboration between physicists and computer scientists. The earlier talk by R. Tomas (Section 2.2.1) was cited as giving an example where such collaboration had been shown to result in significantly improved software in the control room.

2.2.5. Diamond upgrade, Riccardo Bartolini (Diamond / JAI University of Oxford)

Diamond began operation in 2007 at the top of the international light source league. Since then, however, other light sources have progressed quickly and Diamond has moved down the rankings. Many activities are ongoing with the aim of improving the Diamond performance. However, the most significant development would be the Diamond upgrade.

Several possible designs for the upgrade were reviewed. It was not possible to press the optics too far due to limitations from the dynamic aperture. The most pushed optics considered was a 7BA lattice. However, IBS means much of the gains from moving to this lattice are wiped out. A 5BA lattice offers a 20-fold reduction in emittance (less than the 7BA, but with a smaller impact from IBS and a lower impact on the DA). However, the **strongest candidate for the upgrade appears to be a 4BA (with a factor 10 reduction in emittance),** as this configuration would also double the number of insertions available in the ring.

Many challenges had to be overcome in the lattice design: notable are the desire to increase the length of the straight sections to provide additional space for insertions, constraints in the lattice design due to the existing geometry, and the existence of broken symmetry in the lattice to provide customized optics in two of the Diamond insertions.

A suite of tools for optimization of the accelerator optics were summarized. In Diamond optimization is mostly done through **RDT minimization or MOGA**. Riccardo Bartolini commented that while he has moved back and forth between the methods over the years, he now feels he is coming down on the side of the **advanced automatic computational methods (MOGA).**

Given the additional space for an insertion in the 4BA lattice, a modified 4BA cell has been included in the existing Diamond lattice (this is now known as a DDBA cell) in order to increase the number of available insertions. This has provided the opportunity to prototype components and to perform some R&D for the 4BA lattice. The main engineering issues were summarized.

In conclusion it was noted that Diamond is moving in the same direction as the industry in general, through the development of a 4BA lattice. Riccardo Bartolini highlighted a series of workshops serving the low emittance ring community, and advertised the EUCARD 2 – WP6 workshop on beam dynamics for low emittance ring, which will be held at ALBA, Barcelona, on 23-24 April 2015.

In the subsequent discussion, it was questioned whether Riccardo Bartolini was happy with **MOGA.** He responded that experience at Diamond and other accelerators showed it was **superior to conventional methods**. However, for a physicist it was not the most satisfying technique, therefore he was reluctantly happy. It was also questioned how long it took to run MOGA. Riccardo Bartolini responded that it could take as long as you wanted and were prepared to wait - and that 3 weeks on a cluster of 500 processors was not uncommon. If time were a problem then a larger cluster might be needed, though it was also commented that the industry was in general moving towards hiring computer scientists to improve the efficiency of the codes.

2.3. Session 3: Current and future colliders. Chaired by Mei Bai (FZ Jülich)

2.3.1. Experience with resonance driving (and chromatic) terms at ESRF storage ring, Andrea Franchi (ESRF)

The **Resonance Driving Terms (RDTs)** are normally inferred from the Fourier transform of the complex Courant-Snyder variables. At ESRF they have instead used the real Turn-by-Turn data to get the RDTs from the measurements [A. Franchi *et al.*, "First Simultaneous Measurement of Sextupolar and Octupolar Resonance Driving Terms in a Circular Accelerator from Turn-by-Turn Beam Position Monitor Data", Phys. Rev. ST Accel. Beams, **17** (074001), 2014]. The data was normalized using the β-functions from the lattice model. The measured sextupole RDTs were used to calculate the magnetic sextupole fields which were compared to what was expected from the model. A relatively big discrepancy was discovered. However, more than 50% of the discrepancy was deriving from errors in focusing (β-beat). A fit of the errors of the sextupoles was done to see which errors were needed to reproduce the measurements. In most cases the errors were within the 1% specification of the magnets. Only a special type of sextupole had larger errors.

12 sextupole correctors were used to correct the RDT in ESRF SR. The hypothesis was that matching the RDT to the model would give a larger Dynamic Aperture (DA) and a better lifetime. The correction improved the lifetime compared to when the corrector were switched off for the low current and low chromaticity beam. **In case of a high current and high chromaticity the life time was degraded, however**. This was partly explained by the fact that the high current beam was dominated by Tousche scattering. In such a case the chromatic terms are expected to play a large role. This was confirmed for the case of the proposed new storage ring at ESRF. The simulations for that machine showed that only matching the RDT resulted in a decrease of the DA and lifetime. However, considering also the chromatic terms in the correction improved the situation drastically.

In the subsequent discussion, Rogelio Tomas asked whether there would be any skew sextupoles in the new ESRF storage ring. Andrea Franchi replied that the idea was to use skew quadrupoles and regular sextupoles to correct the chromatic terms but that their setting would have to be a trade-off with regard to normal coupling correction. Mei Bai raised the question if MOGA had been tested. In response, MOGA had been used and showed an improvement in simulation for the new ESRF but it had never been used for the running machine. Andrea Franchi also answered a question about the size of the kicks. He said that the average kick was roughly 5mm and higher kicks would create second order effects

2.3.2. Nonlinear puzzles of the LHC, Ewen Hamish Maclean (University of Manchester)

A summary of the non-linear studies during run 1 was presented. At injection the non-linear chromaticity was measured. A large discrepancy to the model was measured but the difference was constant form July 2011 to November 2012. A beam based correction of the *Q*'' and *Q*''' was demonstrated in July 2012 using global trims of octupolar and decapolar correctors in the arcs. The shifts in *Q*'' and *Q*''' upon correction agree well with the model.

For large kicks in the vertical planes the ΔQ_{min} appears to be much larger than what is expected from the measured linear coupling. This was also qualitatively reproduced in the model.

Measurements demonstrated that the correction of the *Q*'' and *Q*''' terms improved the DA of the LHC at injection [E. Maclean, *et al.*, "Measurement of Nonlinear Observables in the Large Hadron Collider using Kicked Beams, Phys. Rev. ST Accel. Beams, **17** (081002), 2014].

The chromatic coupling was derived from the measured energy dependencies of the f_{1001}. The results were consistent with what the model predictions. Based on the measurements a correction was calculated which significantly decreased the chromatic coupling. These corrections will be included in the commissioning for LHC Run 2 [T.H.B. Persson, *et al.*, "Chromatic Coupling Correction in the Large Hadron Collider. Phys. Rev. ST Accel. Beams, **16** (081003), 2013].

Also the measured chromatic β-function, the Montague functions are in good agreement with the model [R. Tomas *et al.*, "Record Low Beta-Beating in the LHC," Phys. Rev. ST Accel. Beams, **15** (091001), 2012].

A new method to measure the amplitude detuning using an AC-dipole was demonstrated. It was compared with the normal kicks at injection [S. White, *et al.*, "Direct Amplitude Detuning Measurement with AC Dipole," Phys. Rev. ST Accel. Beams, **16** (071002), 2013].

The non-linear errors at the IPs were investigated through adjusting crossing angles as well as orbits bumps and by looking at relevant feed down parameters.

The following discussion focused on the **differences between model predictions and measurements of first order chromaticity for different machines**. In the LHC this difference normally is between 5-10 units, in RHIC it is 3-4 units for the blue line and 10-15 for the counter clock line.

Mei Bai asked whether the octupolar line observed was real or an artefact. Rogelio Tomas answered that its origin is still unclear, but that this line moves with the tune.

2.3.3. Advanced Algorithms for the LHC Optics, Andy Langner (U. Hamburg)

Instead of using only 3 BPMs to reconstruct the β-function, **a new method was presented, which uses a set of BPMs with suitable phase advances to reconstruct the β-function**. The method also combines different sets to calculate the β-function at a given location. However, this also introduces the effect that the different sets are not independent since several of them are based on the same BPMs. A co-variance matrix description takes this effect into account. The systematic errors were calculated from known uncertainties using Monte-Carlo simulations. Two co-variance matrices were calculated for large ranges of BPMs. Simulated measurements were used to identify the optimal number of BPM combinations for minimizing the relative accuracy and precision. The systematic errors were overestimated for the 2012 run and will be significantly reduced with the new method [R. Tomas A. Langner, "Improvements in the Optics Measurement Resolution for the LHC," Proc. IPAC'14, Dresden, Germany, 2014].

Next a new method to calculate the ΔQ_{min} from the RDTs was presented. It gives a significantly more accurate estimate, in particular further away from the resonance.

Pairing BPMs with phase advances close to 90 degrees increases the resolution by more than a factor 2 in the LHC case [T. Persson and R. Tomas, "Improved Control of the Betatron Coupling in the Large Hadron Collider," Phys. Rev. ST Accel. Beams, **17** (051004), 2014].

In the discussion, it was asked if the co-variance matrix was calculated only once. Andy Lagner explained that it has to be calculated several times depending on the relative uncertainty of the measurements from the different BPMs.

2.3.4. Resonance Mapping in the PS, Raymond Wasef (CERN)

A measurement to localize octupolar errors was performed through varying the amplitude of a localized bump and measuring the tune shift. This experiment was done for different settings of an artificially introduced octupolar error. The method was successful in identifying and localizing the intentional error.

Attempts to measure the RDT were reported. This measurement was problematic owing to the fact that the signal was already damped after 80 turns. The transfer feedback will be prepared to be used as AC-dipole after the winter shutdown.

The loss maps in the PS showed a strong skew sextupolar resonance ($2Q_x + Q_y$ and $3Q_y$). A proof of principle demonstration for correcting the skew sextupolar resonances had been achieved in 2013. In the PTC model random errors were distributed on the magnets to then compute the driving terms. The simulated tests were successful in compensating the resonances, but a better understanding of the real error sources is needed.

In the subsequent discussion, the question was asked **if the RDTs are affected by the use of the AC-dipole**. Rogelio Tomas replied that the AC-dipole introduces systematic errors but that these can in general be controlled. This had for example been done analytically for coupling by Ryoichi Miyamoto. Higher-order effects might or might not be described by analytical formulas, but these could always be addressed through numerical simulations.

2.3.5. Automatic tuning for machine control, Xiaobiao Huang (SSRL/SLAC)

Machine tuning is often a non-linear multi-variable optimization problem. Manual tuning is hard and in general only works for a small number of knobs. The requirements for an automatic tuning algorithm are that it has to be fast and robust against, noise, outliers and machine failures.

Robust Conjugate Direction Search (RCDS) is a Powell's conjugate method plus a robust line optimizer. In order to be efficient it is important to provide a good initial conjugate direction set, which may be calculated from a model. The algorithm was used to correct the coupling both in simulation and in the real machine. The method outperformed LOCO in this case [X. Huang, *et al.*, “An Algorithm for Online Optimization of Accelerators” Nucl. Instrum. & Methods A **726** (0): 77 – 83, 2013].

A comparison between different methods to correct the coupling while observing the losses was shown. The genetic algorithm needed 20 000 evaluation, the Particle Swarm optimization needed 3000 and the RCDS around 300 to reach the same level. It was stated that **stochastic methods are better in finding global minima of solutions** and **when stochastic methods** [X. Huang and J. Safranek, “Nonlinear Dynamics Optimization with Particle Swarm and Genetic Algorithms for SPEAR3 Emittance Upgrade,” Nucl. Instrum. & Methods A **757**(0): 48 – 53, 2014].

In the discussion, Rogelio Tomas asked **what kind of input** was needed for the method. Xiaobiao Huang answered that a **directional coupling set** was needed which might be provided by the model.

2.3.6. Advances in Beam Instrumentation, Rhodri Jones (CERN)

The new **Diode Orbit and Oscillation system (DOROS)** was presented. It is based on diode detectors. In the past the diode systems were not precise enough for orbit measurements mainly due to the voltage temperature dependence. However, the DOROS system has a special compensation for this dependence, which enables it to be used both for oscillations and orbit measurements. The accuracy over 15 minutes is in the μm range. The oscillation part of the system will be used to measure β-beat and coupling. The system will require excitation levels on the order of 10 μm to be able to provide good measurements [M. Gasior and J Olexa, “Synchronisation of the LHC Betatron Coupling and Phase Advance Measurement System,” CERN-BE-2014-001, CERN, Geneva, 2014].

A **Beam Gas Vertex Detector** has been developed to measure the beam profile in the LHC. The first tests are foreseen for the end of 2015 and the detector will hopefully be able to provide bunch-by-bunch measurements with a resolution of 5% within 5 minutes.

The discussion raised the question for the **main systematic error of the BPMs**. Rhodri Jones replied that most of the systematics was removed through switching the polarity while observing a stable beam. However, the part before the switching is taking place is still causing systematic errors.

Another question was if it is possible to use the synchrotron light for turn-by-turn measurements. Rhodri Jones replied that this was in principle possible and a camera had been bought for this purpose, but in view of the high radiation at the LHC it is now being used at ALBA instead.

2.4. Session 3: Lepton Machines. Chaired by F. Zimmermann (CERN)

2.4.1. Recent Optics Measurements at SLS, Masamitsu Aiba (PSI)

At the SLS, the LOCO optics correction did not fully converge for vertical β beating <2%. Investigations have shown particular problems in the vertical plane. Probing the ring optics locally might provide better understanding of the problems. For this, a local response matrix was established: The orbit response as in LOCO was measured for the correctors in the local section while keeping the orbit feedback running in the rest of the machine. The statistical error is ~0.02 m/rad in the vertical plane. Larger errors in the horizontal plane are not yet fully understood. First results indicate the problems located at Sect. 4-5 with straight section 5 accommodating the Femto beam line including wiggler, chicane, additional quads, additional π phase advance and irregular optics.

The vertical emittance monitor at SLS measures the vertically polarized synchrotron radiation to determine the vertical beam size from which the vertical emittance is derived. Monitor #1 was used for achieving a vertical emittance of ε_y = 0.9 pm corresponding to a beam size of σ_y ~3.6 µm. Here the method reached its resolution limit given by diffraction.

To improve the resolution, a second emittance monitor is being developed, featuring a longer arm, interferometric method and toroidal mirror optics for wavelength independence. However, toroidal misalignments cause difficulties with small image aberrations. For the normal lens optics, another tuning campaign of the vertical emittance is foreseen.

An energy-spread measurement using TBT data has been attempted: TBT data from all BPMs is merged and fitted locally with a sine function to find the envelope of the betatron oscillation. The envelope is then fitted with a theoretical formula including the energy spread as a fitting parameter. The first order chromaticity is a fixed parameter and measured separately. The fitting parameters are amplitude dependent tune shift, second order chromaticity, synchrotron tune and kick amplitude.

2.4.2. Improving Fitting Technique for Global Optics Correction, Xioabiao Huang (SSRL/SLAC)

By fitting the orbit response matrix to the lattice model, the optics of a machine can be recovered. The least-squares problem occurring here is solved by an iterative method. Fitting TBT data against a model can be used for optics correction. An experiment with a section of SPEAR3 with errors added to 5 quadrupoles showed that the 3 upstream quadrupoles were well determined while the 2 downstream ones were not well constraint. In a simulation with the full ring, all parameters were successfully recovered. Major weaknesses of the fitting method are correlations between fitting parameters (e.g. quadrupole strength) and parameters that had impacts on the χ^2 at the noise level. Solutions to these problems are adding constraints to or removing fitting parameters and cutting off singular values in the matrix inversion. Constraints do not change the global minimum of χ^2, but the convergence path has smaller relative gradients which make unrealistic results less likely.

From the practical perspective, fitting only the parameters that can be adjusted is advisable. Fitting iterations should be stopped when changes χ^2 become small to avoid unreasonable results due to e.g. counteracting quadrupoles.

A new method using independent component analysis of TBT data has been developed to correct optics and coupling simultaneously.

2.4.3. ESRF upgrade: Needs and challenges for optics control, Simone M. Liuzzo (ESRF)

A new lattice design is planned for the ESRF in order to achieve a strong gain in brilliance, especially at high photon energies. The upgrade will change the lattice type from double bend achromat to hybrid multi-bend achromats, including combined gradient dipoles and longitudinal gradient dipoles for emittance optimization. The new lattice cells are symmetrical with a -I transformation between the dispersion bump of the sextupoles, cancelling their resonance drifting terms.

The new cell design allows a large dynamic aperture. However, it is not sufficient for off-axis injection. A dedicated injection cell with high β is adopted and the shape and emittance of the injected beam are being optimized to solve this problem. The result is an injection efficiency of 98±1% as compared to less than 50% with injection in a standard straight section and normal booster beam.

Studies revealed that errors in the strong quadrupoles in the centre of the cells have the biggest impact on the Touschek lifetime.

For optics correction, 9 correctors are needed per cell, one at every sextupole and 3 separate ones. All magnets are individually powered. This will be exploited for linear and nonlinear optics correction and off energy beam dynamics.

The correction iteration starts with finding a closed orbit by correcting open trajectories. The orbit is then corrected by creating an error model in accordance with the measured response matrix. The resonance driving terms are calculated and corrected before fixing the tune and chromaticity. This method allows correction to residual resonance strength similar to, or better than the current lattice.

2.4.4. SuperKEKB, Hiroshi Sugimoto (KEK)

SuperKEKB has a luminosity goal of 8×10^{35} $cm^{-2}s^{-1}$. This will be achieved by a high beam current and the Nano-Beam scheme including a low emittance and an extremely small β_y*.

The project is currently in an early stage of commissioning with the main ring completing construction, the LINAC being upgraded and software in development. Four quadrupole magnets of the final focus system were assembled with corrector magnets and cold tested. They reached nominal current without a quench and showed acceptable field quality. 43 corrector magnets for the IR have been assembled at BNL and will be delivered to KEK.

The injector complex receives substantial upgrades including a photo cathode RF gun, a new positron source, a damping ring, new timing system and development in the low level RF system, and it is being commissioned in parallel.

For optics measurements, every quadrupole will be accompanied by a BPM, totalling ca. 450 BPMs per ring of which 135 can be used in TBT mode. The measurements are based on orbit response analysis. X-Y coupling is measured by associating vertical leakage orbits to horizontal kicks, dispersion by the response with RF frequency changes and β functions by the orbit response to steering kicks. Simulations of the low emittance tuning have reached values of the vertical emittance satisfying the luminosity requirements. The on-momentum dynamic aperture has been recovered. However, chromaticity correction and its feedback on on-momentum optics are still an open issue.

2.4.5. Status and Challenges of Crab Waist Interaction Region for FCC-ee, Anton Bogomyagkov (BINP)

The high luminosity requirements of FCC-ee demand a **low β*.** This in turn leads to high β functions in the final quadrupoles, inducing high nonlinear chromaticity and limiting the energy acceptance. Strong counteracting sextupoles are needed but those limit the dynamic aperture. An interaction region has been developed to cope with these challenges. It contains a **local chromaticity correction and crab sextupoles for luminosity optimization**. In its current status, the geometry has been changed to move the synchrotron radiation fans further away from the detector area and to recombine both beams with a separation of 0.72 m at the end of the matching section (in an earlier version this separation was ~3 m).

The Montague functions of the arc have been matched to acceptable levels resulting in an energy acceptance of [-3.1%, +1.9%]. **By controlling the first and second order Montague functions, a knob has been created to control the third order chromaticity in the vertical plane**.

2.4.6. Towards Muon Colliders: Single Particle Emittance Measurement in MICE Cooling Experiment at RAL, Jaroslaw Pasternak (Imperial College London)

Muons used in colliding beams experiments offer great advantages over e^+e^- and *pp* colliders. Due to low synchrotron radiation collider facilities can be relatively compact while at the same time offering the physics advantages of elementary leptons.

However, muons are produced as tertiary particles with a lifetime of only ~2.2 μs, requiring a fast beam cooling, e.g. ionization cooling.

6D cooling channel concepts have been designed and simulated with encouraging results. However, the parameters are challenging and ionization cooling has not yet been demonstrated. MICE (Muon Ionization Cooling Experiment) is a proof of principle experiment with the goal of designing, building commissioning a realistic section of the cooling channel and measuring its performance. The unusual emittance measurement of MICE will be based on recording and analyzing many individual muon tracks. The measurement of emittance reduction aims for a precision level of 0.1%. In step IV of MICE, studies of material properties affecting the cooling will be conducted. The final stage will include measurements of the longitudinal emittance.

2.5. Session 4: Exotic. Chaired by M. Giovannozzi (CERN)

2.5.1. The Fermilab Integrable Optics Test Accelerator (IOTA), Giulio Stancari (Fermilab)}

The Advanced Superconducting Test Accelerator (ASTA) [P. Piot, et al., "The Advanced Superconducting Test Accelerator (ASTA) at Fermilab: A User-Driven Facility Dedicated to Accelerator Science & Technology," FERMILAB-CONF-13-086-AD-APC, 2013], a new research facility currently under construction at Fermilab, was presented. Its purpose is to study fundamental limitations to high-intensity beams, which cause beam loss, space-charge effects and transverse and longitudinal instabilities. The facility will eventually consist of two injectors providing 50-300 MeV electrons and 2.5 MeV protons, several high-energy beam lines and the Integrable Optics Test Accelerator (IOTA).

The aim of the IOTA project is to demonstrate the **feasibility of an intrinsically non-linear stable lattice with large dynamic aperture**, which provides a large natural tune spread to suppress instabilities via increased Landau damping as well as to mitigate effects of space charge and magnetic field errors. This novel concept could be used to create high-intensity beams in, e.g., a rapid cycling synchrotron for neutrino production.

To achieve stability using non-linear optics the existence of invariants of motion is required. This can be realized by a linear lattice with phase advance of $n\pi$, a so-called T-insert, and a specific thin kick, which can be either generated by an electron lens or by using special multipole magnets with longitudinally dependent strength and geometry [E. M. McMillan, "Some Thoughts on Stability in Non-Linear Periodic Focusing Systems," 1967. V. Danilov and S. Nagaitsev, "Nonlinear Accelerator Lattices with One and Two Analytic Invariants. Phys. Rev. ST Accel. Beams, **13** (084002), 2010].

The proposed IOTA lattice contains several short straight sections for up to two non-linear magnets and one electron lens. The transverse particles distribution will follow an hourglass shape, completely different from the case of standard accelerator rings. This feature should be the distinctive point of the integrable beam dynamics. The numerical simulations performed predict a value of the dynamic aperture of this accelerator comparable with the pole aperture of the non-linear elements. The reported value of 0.3% lost particles corresponds to the effect of resonance overlap, causing diffusion, which eventually leads to amplitude growth beyond the mechanical aperture. It is worth mentioning that the longitudinal beam dynamics has not shown any effect on the integrability of the system in the numerical simulations performed so far.

The experimental program is planned with a two-stage approach. Firstly, the closed orbit and the lattice parameters will be precisely measured and controlled using electron beams. The non-linear magnets and the electron lens will then be implemented and a tune shift of 0.25 without loss of the dynamic aperture should be achieved. Secondly, protons will be injected to study space charge dynamics and to reach a tune shift of 0.6.

It has been discussed that the proposed studies for IOTA could, in principle, also be conducted in a hadron machine in which an electron lens is installed. The crucial point is that the lattice should be flexible enough to ensure the required tuning and the electron beam should generate the required McMillan-type kick.

2.5.2. Challenges in Optics Requirement and Control of Storage Rings for Precision Measurements of EDM, A. Lehrach (RWTH Aachen University & FZ Jülich)

In order to disentangle various sources of CP violation it is important to measure the electric dipole moment (EDM) not only of neutrons, but also of protons and deuterons. For charged hadrons no EDM measurements exist so far, as dedicated storage rings have to be used for this purpose. Apart from Jülich, the 100 members of the JEDI collaboration are looking into the principles of how to measure the EDM of charged particles in a storage ring. Jülich is strongly connected to Aachen. At Brookhaven, the Storage Ring (SR) EDM collaboration investigates options to be possibly implemented in the AGS tunnel.

The applied technique looks for the development of a spin component in the vertical direction: initially, the spin is only processing in the horizontal plane and the existence of an EDM would lead to a measurable vertical polarization. In such a storage ring the major contribution to systematic errors would be due to radial magnetic and vertical electric fields, which will be accounted for by using two beams rotating in opposite directions.

Research at the Cooler Synchrotron (COSY) has already provided important outcome. Vertically polarized deuterons are injected and their spin is flipped into the horizontal plane by means of RF fields. The beam is then slowly extracted and the polarization is determined by elastic scattering.

Furthermore, a method to determine the spin tune with a precision of 10^{-10} was presented.

Another challenging effect is the de-coherence of the spin, which is caused by the momentum spread of the beam. To prolong the spin coherence time correction of chromaticity with sextupoles has proven to be a very successful tool and time constants in the order of 400 s could be achieved.

The high precision required for EDM measurements poses stringent requirements on the control of an accelerator. Algorithms for precise beam control and knowledge of the systematics are important, as the global orbit has to be controlled down to the nm-level, but statistically it is possible to achieve a resolution of 10 nm of the beam position. It has been stressed that the active feedback, which is currently available, is not able to detect movements of the accelerator components.

It was also mentioned that SQUID BPMs are currently under development and will be tested at COSY. Squids have been used in Watanabe, Japan, and at GSI. In principle it is possible to achieve 1 fm/Hz^2. However, this has not yet been reached in an accelerator environment. Furthermore, an extensive amount of infrastructure is required for cooling the device and the overall feasibility has yet to be proved.

Simulations with spin tracking codes are also absolutely required to study the feasibility of EDM measurements. Therefore, several codes were developed, which are used for tracking of particle distributions over billions of turns.

2.5.3. Optics measurements in the PS islands, Antoine Lachaize (CEA)

In the framework of the Multi-Turn Extraction (MTE) [M. Giovannozzi (ed.), *et al.*, “The CERN PS Multi-Turn Extraction Based on Beam Splitting in Stable Islands of Transverse Phase Space,” CERN-2006-011, 2006] different measurements of the optical parameters of the PS were conducted in order to improve the accelerator model. Due to the complexity of the combined function magnets, which include also a series of coils used to control the PS working point (linear and non-linear), the standard approach is to introduce multipolar kicks in the lattice model. The actual values are determined by fitting the results of tune measurements while varying the momentum offset.

In the absence of non-linear elements, which are used for the transverse trapping process, β-beating measurements showed a peak value of about 3% in the horizontal plane, with statistical error bars being much larger than this value, thus showing that the obtained value is compatible with zero. Repeating the same measurement with a pencil beam kicked into the islands revealed an increased β–beating in the horizontal plane. Furthermore, it was shown that the β -beating significantly increased by increasing the islands' amplitude. This is clearly due to the fact that the linear optics around the stable fixed points is generated by the global feed down effects, which are amplitude dependent.

Additional discrepancies between the model and the experimental data were observed when kicking the beam to large amplitude and extracting linear chromaticity and detuning with amplitude. This is not surprising, as the standard approach used to reconstruct the effective model does not take into account chromo-geometric effects. In any case, it was possible to restore a good agreement with the model prediction by inserting additional octupoles at the centre of each main unit.

Measurements of resonance driving terms were also presented and very good agreement with simulations was observed for sextupolar terms.

In the discussion following the presentation, it was emphasized that the optical functions differ significantly between the islands and the core and that a lattice composed of four times the one of the PS has to be considered to obtain a periodic solution for the islands.

2.5.4. Can we inject or extract a beam without septum devices?, Andrea Franchi (ESRF)

During the MTE gymnastics performed in the PS, one slow and two fast orbit bumps, as well as a magnetic septum, are used to extract the five beamlets. It was shown that the extraction could actually also take place using a different approach, which does neither require the bumps nor the septum. Indeed, local insertion optics with quadrupole magnets could be used to extract the islands and a dipole kicker may be used for the core.

In a slightly different manner this concept could also be applied to replace the conventional fast extraction. The actual implementation requires the creation of unpopulated islands in the vicinity of a, e.g., fourth-order resonance. Using the insertion optics as mentioned above, the trajectory of one of the islands is directed towards the extraction line. A fast dipole kicker is then needed to put the beam from the central orbit into the island. In order to reduce the kicker strength the horizontal β-function should be maximized at the kicker location.

This approach could also be used to inject beams without a septum, as the extraction process could be applied in reversed order.

In principle the order of the resonance can be arbitrarily chosen; however, the choice should allow both removing the septum and reducing the kicker strength. Moreover, it should be kept in mind that the islands’ surfaces is decreasing for increasing resonance order, which could make it difficult to accommodate the transverse beam size of the extracted or injected beams.

In addition, it has been stressed that, while all the examples given in the presentation have been based on the PS lattice, the proposed method is completely general and could even be better adapted to machines featuring insertions.

2.5.5. Fixed Lines, Giuliano Franchetti (GSI)

An introduction to the dynamics close to a coupled third-order resonance was presented in this talk. So far, the known analytical concepts only allowed to determine the border of stability close to a one-dimensional resonance, such as $3Q_x=N$.

Experimentally it was recently observed that the interplay between space charge and a coupled resonance of the type $Q_x+2Q_y=N$ leads to strong halo formation for bunched beams. To describe this phenomenon an understanding of the four-dimensional dynamics close to such a resonance is fundamental.

The mathematical framework of the presented work is based on the same formalism as developed in [G. Guignard, “A General Treatment of Resonances in Accelerators,” CERN78-11, 1978]. The key point is that it is possible to **generalise the concept of fixed points to 1D sets**, which are invariants under the dynamics generated in the neighbourhood of the coupled resonance.

It was, furthermore, shown that there exist an infinite number of fixed lines, which can be either stable or unstable. Turn after turn a particle moves along a fixed line and only the projections of this motion can be observed. The shape of the fixed line is determined by the order of the resonance, while its amplitude by the single particle emittances.

The mathematical treatment leads to two invariants of motion and the stability domain can be described using scaling factors, which allow generalization to resonances of arbitrary orders. However, it is not clear whether the surface described by the two invariants is compact or not.

Comparison with the results of numerical simulations aimed at computing the dynamic aperture of the system under consideration, i.e., with only sextupolar errors, revealed a very good agreement.

2.5.6. Effect of Nonlinear Errors on the Alpha Bucket, Stefan Sorge (GSI)

When accelerating protons in the SIS-100, transition crossing will be avoided by creating a strongly oscillating horizontal dispersion function to reduce the linear momentum compaction factor. Using this special lattice configuration **alpha-buckets can be exploited to decrease the length of the single bunch prior to extraction** as the linear phase slip factor becomes very small.

A chromaticity correction scheme also needs to be implemented to reduce the chromatic tune spread, but also to enlarge the bucket area to accommodate the required longitudinal emittance. However, this implies independent power supplies for all sextupoles.

3. A FEW HIGHLIGHTS

The talks and discussions at this workshop and the subsequent discussions have drawn attention to several critical issues. A few of the key highlights of the meeting are as follows:

- Excellent optics performance of the LHC is the result of advances in the understanding of beam optics, and improvements in the tools and methodologies available for measurement and control.
- LHC achieved a record low β beating for colliders, but the latter is still not as good as for light sources.
- β^* levelling has been successfully implemented at RHIC.
- Future machines like HL-LHC, upgrades of existing light sources, FCC etc. will require even better optics and orbit control; this is especially true for a proposed EDM storage ring.
- MOGA has become a preferred technique for optics control at many light sources.
- Chromatic and nonlinear corrections become ever more important.
- Nonlinear optics is being specifically designed and exploited, e.g. for multi-turn extraction (CERN PS), more stable dynamics (IOTA), septum-less extraction/injection, or bunch shortening.
- Close collaboration of accelerator physicists and computer scientists is essential for advancing the optics control of cutting-edge accelerators, as is illustrated by the remarkable progress at the LHC, compared with earlier colliders.
- AOC workshop brought together tools and expertise from around the world and has helped enabling the accelerator community to meet the challenges posed by current and future machines.

4. BASIC WORKSHOP STATISTICS AND ILLUSTRATIONS

Type of activity	Topical Workshop
Title	Advanced Optics Control (AOC 2015)
Date	5-6 February 2015
Place	CERN
Type of audience	Scientific community
Size of audience	49 participants (CERN: 27, other Switzerland: 1, France: 2, Germany: 7, Japan: 1, Russia: 1, Spain: 2, UK: 5, USA: 3)
Countries Addressed[1]	**FRANCE**: ESRF 2, **GERMANY**: FZ Jülich 2, GSI 2, IAP Frankfurt 1, U. Hamburg 1 **JAPAN**: KEK 1 **SPAIN**: CELLS-ALBA 2 **SWITZERLAND**: CERN 27, PSI 1 **UK**: Imperial College 1, JAI Oxford 1, U. Liverpool 1, U Manchester 1, Royal Holloway 1 **USA**: BNL 1, FNAL 1, SLAC 1
Link	http://indico.cern.ch/event/349643
Partners involved	HIC for FAIR, High Luminosity LHC, LIU, ICFA, CERN PS MTE

[1] Country distribution of the attendees

Figure 1: Workshop poster. The background shows a detail of the AD ring at CERN combined with a drawing of Newton's "Optics". On the right, the logos of the workshop partners and sponsors are displayed, including EuCARD-2, XBEAM XCOLL and XBEAM XRING.

Figure 2: Photos of AOC2015 participants during a dinner on 5 February.