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# Summary of the AccNet-EuCARD Workshop on Optics Measurements, Corrections and Modelling for High-Performance Storage Rings "OMCM," CERN, Geneva, 20-22 June 2011

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**Summary of the AccNet-EuCARD Workshop on Optics Measurements,  
Corrections and Modelling for High-Performance Storage Rings “OMCM”,  
CERN, Geneva, 20-22 June 2011**

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**Abstract**

The LHC, its luminosity upgrade HL-LHC, its injectors upgrade LIU and other high performance storage rings around the world are facing challenging requirements for optics measurements, correction and modelling. This workshop aims to do a review of the existing techniques to measure and control linear and non-linear optics parameters. The precise optics determination has proven to be a key ingredient to improve the performance of the past and present accelerators. From 20 to 22 June 2011 an international workshop, “OMCM,” was held at CERN with the goal of assessing the limits of the present techniques and evaluating new paths for improvement.

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## **1. Session 1: Motivation for HE machines, colliders, HI machines, light sources and damping rings**

The accurate modelling, measurement and correction of the magnetic optics of accelerator is a prerequisite and a key to high and reproducible performance. This session introduces the topic by reviewing the challenges of different types of machines, to better appreciate the requirements on optics modelling, measurement and correction. Three talks covered: collider challenges [1]; light source challenges [2]; high intensity challenges [3].

The present and future colliders require ever increasing luminosities [1]. For proton colliders, this requirement is in relation with the increased beam energy necessary to extend the discovery range and of the scarcity of new processes. For electron colliders, precision physics is based on ever increasing luminosities. In all cases, the very high design performance necessitates pushing the existing concepts (strongly focusing low-beta insertions, maximum use of mechanical aperture) and incorporating a variety of new devices, very demanding in terms of precision of the beam trajectories, beam extent and tunes (crab cavities and crab waist sextupoles,...). In a number of cases, the impact of non-linearities is prone to require better modelling, measurement and correction capabilities. New goals for linear optics precision would be a beta-beating of 1% and betatron phase errors less than  $1^\circ$ , i.e. an improvement by an order of magnitude beyond above usual performance.

### Highlights from the discussion

- Radiation: Hadron colliders have the additional challenge of radiation issues that can limit the performance.
- Linear beam-beam effect: “Dynamic” beta-beating should be considered when pushing the performance.
- Strategy for specifications: Very tight constraints (such as that of TOTEM in LHC) should first be investigated to ensure they are fully justified.
- K-modulation in the LHC: the long time it takes (20 min) is not related to the measuring device but to the time needed to ramp the magnets.
- Finding the beta waist in a low-beta insertion: the location can be determined by performing left/right measurements with K-modulation. The waist position is correct to some 10 cm.
- Identification of optics: does LOCO fit the non-regular optics of colliders?

As a tentative conclusion, the progress in performance requires tighter tolerance on the beam optics. Gaining an order of magnitude in optics precision by tighter magnetic field requirements

may be very difficult and/or expensive. Improving instrumentation and correction methods is probably the practical yet challenging approach, as shown by achievements in SOLEIL and DIAMOND.

The brightness of SR sources has increased by as much as 12 orders of magnitude in the last 30 years [2]. This has been achieved by optimal lattice design (minimum emittance lattices), and by using insertion devices (wigglers, undulators). However, these provisions drive the beam dynamics into a non-linear regime, for both the transverse and longitudinal motion. Appropriate corrections are needed to reach a long beam lifetime. This non-linear optimization relies on iterations between analytic and numerical studies and requires excellent optical modelling. Optical modelling is however not sufficient, e.g., intra-beam scattering must be included. In control rooms, optical imperfections driven by field errors, such as coupling and dispersion, are better and better corrected, with a residual dispersion reaching 0.1 mm. The high resolution required from the beam size monitors is made possible when using X-rays or polarized visible light. The top-up operations is favourable for high precision measurements, as the beam instrumentation operates in a much smaller dynamic range.

#### Highlights from the discussion

- Dynamic aperture in LHC: it is a non-issue thanks to optics design and specification, follow-up of production and swift reaction, sorting and a significantly lower operational beam emittance.

To approach the quantum limit for the vertical emittance, even better measurements and stability must be achieved. Collective effects need to be included in the models.

The accelerators under consideration are the neutron spallation sources [3]. The present beam power is typically 1 MW, e.g. SNS and J-PARC, about an order of magnitude above former sources. The next generation is planned up to 10 MW. The overwhelming issue is a very low level of beam loss, typically below 1 W/m, equivalent to a fractional loss below  $10^{-6}/m$ . The machine design, modelling, the beam measurements and correction systems must cope with these goals at the design stage. The charge exchange injection is evolving from foil stripper to laser stripping, coming up as a possible alternative technology with reduced losses. It is however in a very initial R&D phase. The requested high accuracy simulations require talking into account features such as fringe fields, overlapping magnetic fields and need high accuracy 6D phase space distribution. Collective effects are reasonably understood except the e-p instability. Yet the model prediction of low-loss tunes can be far away from observations. A pragmatic approach is thus to design a flexible optics.

#### Highlights from the discussion

- Laser stripping: The laser power presently limits the laser stripping to only 10 ns long pulses.
- Simulation accuracy:  $10^{-6}$  loss rates are a real challenge from the numerical simulation point of view. Is the goal realistic?

- Model accuracy: due to the peculiarities of the actual magnetic fields, the actual SNS optics is rather different from the nominal one. The empirical minimization of losses contributes as well to these differences.

As a tentative conclusion, beam losses at the level of the  $< 10^{-6}$  level are extremely sensitive to fine details of the machine, of the injection process and of the beam 6D distribution and its evolution. Pushing further the beam intensity will depend on the progress in accuracy of the modelling and of the instrumentation, especially the beam distribution including its low intensity tails. The new injection concept of laser stripping is promising to decrease losses by design. The e-p beam instability characteristics need to be better understood.

Finally, the case for a significant improvement of the accuracy of optics modelling, beam instrumentation and correction methods is very clear for all three kinds of machines. It will largely contribute to setting their maximum potential in performance. Besides, new concepts, such as laser stripping for charge exchange injection, or a better understanding of e-p instabilities are needed to realize this improved potential.

## **2. Session 2: Experience from colliders, high energy and intensity machines - I**

The first of the two sessions on the operational experience from collider storage rings was devoted to a summary of the operational experience in RHIC [4], TEVATRON [5], LHC [6], KEKB [7] and PEP-II [8]. It featured in total five 20 minute long presentations, one for each machine.

The Optics model for RHIC [4] is being built via MAD8 and MADX as the main optics modelling tools. The two programs are used for building the linear optics model and automatic tools are in place for generating the powering currents for each setting and for providing an online model of the RHIC machine (OptiCal). The main unknown in this setup are the actual magnet transfer functions that determine for a required magnetic field setting the required magnet current. A suite of optics measurement techniques is in place for verifying and correcting the actual optics in the RHIC machine. The main measurement techniques comprise: AC dipole measurements, modulation of the triplet quadrupole magnet currents, orbit response matrix measurements and precise tune measurements. The LHC ‘Segment By Segment Tool’ (SBST) technique was introduced for Run 2011 but is not yet fully operational.

Overall, the optics modelling in RHIC reaches an accuracy of ca. 20%. The main limitations are the limited number of knobs and the unknown magnet current transfer functions (nested powering circuits in RHIC).

The Optics model for the TEVATRON is based on OptiM as the main optics modelling tool [5]. It includes all known transfer functions for the magnets and all optics related instrumentation and aperture limitations. However such a “design” model poorly represents the optics of the real machine. The actual machine optics is build via measurements. In addition to the “design” model it includes pseudo-elements (quadrupoles and skew-quadrupoles) located near each quadrupole and at each dipole (skew-quadrupole component). The main tool for this ‘empirical’ optics reconstruction is the Linear Optics from Closed Orbit (LOCO) response matrix measurements. While the first data analysis was essentially done manually, the TEVATRON features by now a

fully automated procedure for the data analysis (based on the SVD analysis) of the LOCO measurements. Typically each differential orbit is an averaged difference of ca. 20 orbit acquisitions for each polarity of the orbit excitation (by change of corrector settings). With ca. 2 seconds per acquisition and ca. 50 orbit corrector magnets one full measurement of the TEVATRON optics requires a total of ca. 2000 acquisitions and takes between one and two hours. The measurement accuracy has been greatly improved by a new BPM system with better acquisition accuracy reducing the residual fit errors from about 50 to 15 $\mu$ m. Typical BPM gain errors are 1-2% with maximum errors of up to 5%. In addition to computing focusing errors, the LOCO software also computes these BPM gain errors, BPM roll errors and errors of corrector excitation. There is a systematic roll angle for all BPMs of ~5 deg. (related to the asymmetric location of the feedthroughs) with an rms spread of the roll errors of 1-2 deg. and a maximum roll angle of up to 6 deg. Although the calibration errors for the corrector magnets are on average indistinguishable from the BPM calibration errors the calibration errors do not affect an accuracy of the optics model built with LOCO. In addition, the dispersion measurements greatly improve the LOCO convergence. Strong coupling in the Tevatron is excited by the displacement of superconducting coils in the dipoles relative to their iron cores. The model analysis is based on the extended Mais-Ripken representation and represents well the x-y coupled motion of the machine. The suppression of the vertical dispersion at the IPs was an important part of the optics correction (redesign). The overall accuracy of the optics functions is estimated to be better than 5-10%.

An efficient Graphical User Interface (GUI) is a key ingredient for a successful application of the optics measurements in the TEVATRON. The optics modelling is further complicated in the TEVATRON by the Helical orbit separation which separates the two counter rotating beams in the common vacuum beam pipe. The Helical orbit changes the beta-functions in the TEVATRON by approximately 15%.

For the transfer lines the LOCO method provides an optics accuracy of the 20% to 30%, which is satisfactory for the TEVATRON operation.

Other tools than LOCO have been tried for the optics measurements in the TEVATRON:

- A Turn-by-Turn BPM measurement has been highly desirable (faster measurement time) but its implementation has been difficult due to several technical problems. They are: strong coupling in the machine; operation near the coupling resonance; presence of longitudinal modes which result in an overlap of betatron modes spectra, and an absence of direct dispersion measurements. Actually the dispersion modes have been visible in the turn-by-turn data but they had a poor accuracy due to their small amplitudes. An additional problem was that the oscillation decay times depend on the beam emittance and therefore vary significantly from measurement to measurement.
- AC-Dipole measurements are non-trivial in the TEVATRON due to coupling and synchro-betatron oscillations and cannot be deployed in the Booster due to its fast cycling time. Therefore they were not seriously pursued as an alternative optics measurement to be used in the Tevatron complex.

The Optics model for the LHC is based on MADX as the main optics modelling tool [6]. The AC dipole technique was used extensively for segment-by-segment measurements of the

optics function propagation along the machine (treatment of each segment like a transfer line with given initial conditions; mainly used for a local correction of the optics in the LHC) and orbit response matrix measurements (mainly used for global correction of the optics in the machine). The local correction via SBST provides optics accuracy of the order of 15% to 20%. Combining the SBST method with a global correction based on response matrix measurements reduces the measured optics error in the machine further to ca. 10% which is approximately twice the value of the optics stability between fills and the start to end of fill variation of the optics in the machine. It still needs to be demonstrated if similar good optics correction can still be achieved for a fully squeezed optics ( $\beta^* = 0.55$  m) and additional measurement techniques (e.g. local magnet current modulations and precise tune measurements) might be required for addressing this challenge.

Improving the optics accuracy of the squeezed optics ( $\beta^* = 3.5$ m) with the help of a global correction raises the question to what extent these global corrections should also be incorporated in the correction of the un-squeezed optics (the current LHC injection optics has an accuracy of ca. 30% but could be further optimized if required). Further studies are underway in order to address this question.

KEKB operated very close to the half-integer resonance requiring a very good control of the optics model in the machine [7]. The optics model for the KEBK is mainly built via orbit response matrix measurements using the signals of approximately 450 Beam Position Monitors and transverse orbit corrector magnets as well as RF frequency trims for dispersion measurements. The KEBK operation mainly focuses on the correction of coupling (including chromatic coupling), beta-functions (orbit response matrix) and dispersion (RF trims). The coupling correction was based on single pass BPM data that provides a measurement that is independent of phase and beta-functions. The corrections are based on iterative procedures of measurements and corrections and finishing a full iteration loop takes approximately 30 to 60 minutes and achieves accuracies of ca. 10mm to 15mm for the spurious dispersion (horizontal and vertical), 7% to 5% beta-beat (horizontal and vertical) and an RMS phase error of the approximately 4 degrees.

KEKB featured a ‘maintenance day’ every two weeks that was followed by a global correction campaign before resuming physics operation using low beam currents. This correction strategy was sufficient for providing good conditions for physics operation (e.g. up to 20% luminosity gain due to the correction of chromatic coupling). With the correction in place, the machine could be operated close to the half integer tune.

The PEP-II optics measurements are mainly built on resonant excitation of orbit excursions in the machine and the PEP-II optics modelling was centred on the MIA (Model Independent Analysis) program [8]. Resonance excitation at the horizontal betatron (eigen) tune and then at the vertical tune and the synchrotron tune, each lasting for ca. 1000 turns, were used for getting a complete set of linear optics data. The validity of the BPM readings was consecutively validated by symplecticity and noise checks of the measured data sets. The MIA program allows a direct measurement of the BPM gain and cross coupling errors. This continued interplay between measurements and BPM validation has resulted over the years in a continuous improvement of the PEP-II BPM data. The measurements of four independent orbit sets determine the complete linear optics values.

The MIA measurements are first used for establishing a ‘virtual’ PEP-II machine that is used for identifying wrong or bad BMPs. This ‘virtual’ machine is then used as a reference for implementing further improvements of the optics into the real machine via dedicated ‘knobs’. This procedure could provide optics correction such as beta beat correction, which allowed bringing the machine operation close to the half integer resonance, provided a linear coupling reduction, IP optics improvements. Symmetric and anti-symmetric orbit corrector bumps were furthermore very helpful in improving the PEP-II optics online. There is no need to have a separate cover page for these reports and the text may start directly below the summary on the first page.

### **3. Session 3: Experience from colliders, high energy & intensity machines - II**

The second of the two sessions on the operational experience from collider storage rings was devoted to a summary of the operational experience in DAΦNE [9], linear optics measurements using TBT analysis at the FNAL Booster [10], the experience with a new low emittance tuning tool for SuperB, Diamond, SLS, and DAΦNE [11], and the HERA experience [12]. It featured in total four 20 minute long presentations, one for each machine.

DAΦNE, in Frascati, is a lepton collider working at the c.m. energy of the  $\Phi$  meson resonance and consisting of two independent rings. Each ring has a circumference of 97 m with many magnetic elements and no periodicity, and is strongly affected by the detector solenoidal field ( $\int B ds = 2.4 \text{ Tm}$ , to be compared with a magnetic rigidity  $B\rho = 1.7 \text{ Tm}$ ). As a consequence the model parameters are far from being independent of each other. The DAΦNE optics model is based on beam measurements, which have been essential in identifying the factor limiting the collider performance as well as in defining the strategy for the upgrades that have been implemented over the last years.

The two DAΦNE rings feature BPM systems from Bergoz and (more recently) also from Libera. The resolution depends on the beam current. For the Bergoz system it is  $10 \mu\text{m}$  with beam current above 2-3 mA. Orbit steering is implemented with the help of response matrices. Optics measurements are based both on the tune response to quadrupole strength changes as well as on measured orbit response matrices. For the 2002 DEAR run the final triplet had been changed to a doublet and 100 contiguous bunches, with 2.7 ns spacing, were collided for the first time. In the original DAΦNE IRs there were 24 parasitic collisions, interplaying with the machine nonlinearity. Wire compensators and octupole magnet were used to compensate part of the parasitic-collision effect. At DAΦNE longitudinal and transverse instability thresholds were studied for different values of momentum compaction, which can be varied over a large range, including large negative values. A strong correlation is observed between the longitudinal microwave instability and the vertical size blow-up. The threshold for the latter is higher with larger momentum compaction. Closed orbit and vertical dispersion correction are done together using steering magnets and skew quadrupoles. As a by-product sextupole misalignments are uncovered and corrected. A large detuning with horizontal position had revealed the presence of a significant nonlinear wiggler field. Betatron coupling correction had been accomplished by rotating quadrupoles in the IR region, complemented by a response matrix calculation and global correction using skew quadrupoles. The residual coupling had been of order 0.3%. More recently, for the upgraded KLOE IR with anti-solenoids, betatron coupling has been corrected using a normal mode analysis, reaching a coupling of 0.14%. In conclusion the DAΦNE model has been essential for setting up collisions in several configurations, with two low beta regions (one always



detuned), including crab waist collision scheme, changing beam emittance, crossing angle and beta\*, as well as high & negative momentum compaction.

Subsequent discussion clarified that the rotation of quadrupoles had been needed since the anti-solenoids only cancelled the integrated field from the solenoid. The rotating quadrupoles are powerful elements and can correct the local source of the coupling. Remotely controlled quadrupole rotations were possible until 2006, at which time there was a detector upgrade and since then magnet rotation are no longer possible. The correlation of threshold increase and transverse blow up is attributed to interference between transverse and longitudinal plane, e.g. the effect of an increase in momentum spread. A similar transverse-longitudinal interference was also seen in experiments at high positive momentum compaction; with large negative momentum compaction collision with low sextupole strength had been possible.

The Fermilab Booster accelerates protons from 0.4 to 8 GeV kinetic energy within 33 ms. The analysis of turn-by-turn BPM data gives a relatively straightforward mean of measuring linear optics and coupling. Linear coupling had been measured through TBT Fourier analysis at both the Tevatron and the Booster. The Booster optics had been obtained from TBT FT. The TBT FT results can be compared with an ICA analysis. At least two techniques can be used to measure the optics, namely the closed orbit response and the analysis of beam oscillations. The linear coupling can also be computed through the TBT analysis. Distributed coupling sources define the periodic coupling functions  $c_{\pm}$ . The FFT of an excitation excited at the tune for the nominally orthogonal plane is proportional to the coupling functions. A discontinuity in the  $w_{\pm}$  values computed from 3 consecutive BPMs reveals the presence of coupling source. The method was successfully applied to 2005 data at the Tevatron. For the Booster the method was improved by introducing a phased sum for determining beam tunes and by a two-peak analysis for identifying peaks. The phased-sum analysis is better than a normal FT in terms of signal-to-noise ratio. For the booster the method provided the coupling functions versus position as well as the beta functions. A spatial Fourier analysis showed that the beta beating in the booster is of the order of 10%. There is no AC dipole in either the Tevatron or the booster. Fourier analysis and ICA have been compared. For the optics measurement they give identical results. Fourier analysis of TBT data has become a reliable on-line tool to measure the machine tune, the optics and coupling in the Booster. The Fourier analysis was improved by phased sum (if phase advance between BPMs is known) and by the 2-peaks algorithm. Next steps would be the beam-based calibration of skew quadrupole circuits and a systematic correction of linear coupling.

Subsequent discussion clarified that the BPM calibration for the coupling analysis relied on the LOCO minimization, which included this calibration. It is not necessary to correct for the tilt of the kickers, since a tilted kicker excites both modes, and there is no problem. The two peak analysis allows finding other contributions to the coupling. ICA and the FT provide the same information on the optics, but ICA proved extremely useful for getting the tunes from a few turns.

HERA was designed as electron (or positron) - proton collider with maximum beam energies of 30 GeV for the leptons and 920 GeV for the proton beam. The machine was built as two independent storage rings with common interaction regions (IRs) around the collision points. As a special feature of the machine, the different characteristics of the lepton and proton beams had to be considered: The flat electron beam had to be well matched to the "round" proton beam at the two interaction points. In addition, the dynamic influence of the electron mini beta magnets in

the interaction region on the proton optics and orbit, as well as the effect of the stray fields of the proton magnets on the electron beam dynamics had to be compensated carefully to establish well defined beam optics during the complete machine cycle and to guarantee the matched beam sizes of the electron and proton beam in collision. Another challenge was establishing high polarization for the electron beam. Starting from very basic measurements of the beta function in the beginning of the HERA run period, modern tools were being developed over the years and applied to measure and optimise the optical parameters like beta function, dispersion and effective beam size at the IP.

The proton ring was almost completely superconducting, but there were no superconducting magnets inside the IR except for the e- focusing magnets at the centre. Measurements of the beta function were done for a long time by changing the gradient of individual quadrupole magnets, and later by orbit response matrix measurements (Joachim Keil) with ORM difference orbits of order 1 mm in the arcs. The mini beta quadrupoles inserted in detector resulted in the influence of the calorimeter position on orbit (5mm) and in the optics (20% beta beat). The dispersion correction in the HERA e- ring was important for polarization. A problem for the beam-based alignment in the IR was the control of the synchrotron radiation. For the protons the chromaticity drift at injection, and the non-reproducibility after different pre-cycles been a concern and were partly addressed with the help reference magnets. There was about 245-275 unit of Q' contribution from the dipole  $b_3$  component. A lot of simulation effort and measurements had been devoted to the dynamic aperture at injection. A dynamic aperture of  $4.5 \sigma$  was found in tracking, to be compared with  $4.1 \sigma$  measured in 1994. A new dynamic aperture campaign was launched in 2000 after reducing the detuning with amplitude. No effect of the decapole corrector coils was ever observed. The effective beam cross section at the IP was measured with van der Meer scans taking special care of the dynamic beta beating. The electron emittance was reduced through a change in the RF frequency of 350 Hz.

Subsequent discussion pointed out that the LHC Q' prediction within 0 and 2 units supersedes everything what has been done before, including HERA. Electron polarization with beam-beam was an issue at HERA. The beam-beam tune shift in HERA amounted 0.08 for electrons (quoting the total tune shift from two IPs).

For the SuperB project a Low Emittance Tuning (LET) algorithm was developed. It allows obtaining a low emittance, by correcting simultaneously orbit, dispersion, coupling and beta-beating using correctors and skew quadrupoles. The LET technique is based on determining an orbit that takes advantage of passing off axis through sextupoles and quadrupoles, and can lower the vertical emittance by almost a factor of ten (in simulations for SuperB) with respect to the conventional Dispersion Free Steering. BPM tilts are also estimated from the measurements and selected for correction. The technique has been tested at Diamond and at SLS, and is currently under test at Daphne. Preliminary results have been presented at the OMCM workshop. LET & SVD tuning were compared with regard to the effect on emittance. The LET coupling-free steering works better than SVD. The LET tool is used to determine the magnet alignment and BPM resolution tolerances for SuperB. In a test at Diamond, the expected gain factor was not observed however. For SLS only one shift was available for LET test, with promising preliminary results. There is a plan to test LET at DAΦNE.

Discussion clarified the following aspects. The tilting of BPMs was quoted as a limitation, but there was no idea about the value desired for these tilts. A 20  $\mu\text{rad}$  tilt tolerance was quoted for the quadrupoles. How to achieve this tolerance still was work in progress. A much better performance had been expected for LET than for LOCO, but this had not been observed in DIAMOND tests. Indeed the LET result was even slightly worse. But LET was much faster. Neither missing BPMs nor BPM scaling or calibration errors were included in the simulations.

#### **4. Session 4: Experience from light sources and damping rings**

The LOCO (Linear Optics from Closed Orbits) algorithm is used to find and correct errors in the linear optics of storage rings [13]. This technique has been used to correct the optics of many storage rings. The method LOCO minimizes chi-square, the deviation between the model and measured response matrix. In his presentation the LOCO method was described, with an error analysis and adding constraints in the fittings. Examples of using LOCO to correct beta functions and dispersion, correct coupling, measured impedance from the NSLS VUV Ring, NSLS XRAY Ring, SOLEIL, Australian Light Source, and APS were given. Overall, a good agreement between the measurements and the theoretical model was found. LOCO is a powerful algorithm for: i) finding and correcting BPM and steering magnet errors; ii) finding and correcting normal and skew gradient errors; iii) correcting  $\beta$  and  $\eta$  functions; iv) correcting for ID focusing; v) minimizing coupling; vi) calibrating transverse impedance and chromatic errors.

The second presentation [14] reviewed the modelling based on beam orbit measurements with the “Resonance Driving Terms” (RDT). An overview of the RDT-method was given. Beta beating, coupling and vertical dispersion are corrected from this model. The minimization of the coupling resonance driving terms (RDT) allowed to reduce the vertical emittance down to 3 – 4 pm, a record low values for the ESRF. This was only possible with the low noise BPM’s. Vertical dispersion becomes a key parameter for further reduction of vertical emittance. The relationship between the closed orbit errors and chromaticity has been explained and possible cures explored. For ultra low vertical emittance, vertical dispersion is of importance.

The linear optics of SLS has been measured with the response of the tune to small variation of quadrupole strength and corrected based on SVD [15]. The corrected optics allows employing the model response matrix for the orbit correction / feedback and the linear coupling correction. The nonlinear optics has been corrected using pre-defined theoretical knobs to suppress relevant resonances. One of the highlights of SLS performance is the small vertical emittance  $\sim 2$  pm thanks to the well corrected betatron coupling and vertical dispersion with dispersive and non-dispersive skew quadrupoles. SLS is relying very much on LOCO and turn-by-turn BPM-measurements. The idea is to compare the results from independent measurements. Girder re-alignment is also underway to challenge even smaller vertical emittance for future accelerators.

The SOLEIL 2.75 GeV third generation synchrotron light source has been delivering photon beam to users since January 2007 [16]. For the linear optics modelling a modified version of FCO with constraints on the gradient variation has been applied and the  $\beta$  – beating could be reduced to 0.3%. To achieve such performance carefully modelling and optimization of the linear and non-linear optics are required. For the chromaticity measurements the variation of the bending magnet and switching off the sextupoles has been used. Some deviations in the chromaticity between the model and the measurements (at Soleil as well at LNL) have been found, but without an

explanation. By using a so called “Dead Band” at SOLEIL so slow as well the fast orbit feedback are working in harmony together. The stability in the vertical direction could be reduced to 200 nm. For the determination of the energy spread the Frequency Map Analysis (FMA) is used.

LOCO has solved the problems of the correct implementation of the linear optics at DIAMOND [17]. The beta beating at the diamond storage ring has been reduced to 0.4 % peak-to-peak and the linear coupling to 0.08% at the source point, providing a vertical emittance of about 2.2 pm. With skew quadrupoles and LOCO correction the vertical dispersion could be reduced to 700  $\mu\text{m}$ . The comparison between the real lattice and the model for the linear and nonlinear optics will be done with: i) closed orbit response matrix (LOCO); ii) frequency map analysis (FMA); iii) frequency analysis of betatron motion (RDT-method).

## **5. Session 5: Techniques review - I**

K. Fuchsberger’s presentation started with a review of the LOCO algorithm, and then discussed some of the challenges of applying this method at the LHC [18]. The challenges include: memory requirements for Jacobian matrix, computation time, and measurement time. The Jacobian matrix requires ~10 to tens of GBytes, depending on the parameters included in the fit and the number of steering magnets included in the orbit response matrix (ORM). The computation time is dominated by calculating the many ORMs required for building the Jacobian matrix. For example, if only 8 of the 530 steering magnets are used in the ORM and 500 parameters are varied in the LOCO fit, then the Jacobian requires about 2.5 hours to calculate on a 3.17 GHz PC.

In his presentation later in the workshop, Glenn Decker pointed out that the LOCO algorithm is regularly used in a code by Vadim Sajaev to correct the optics at APS. Though APS is physically much smaller than LHC, it has a similar number of BPMs, steering magnets and quadrupoles, so the LOCO problem is comparable. Vadim gets around the computational challenges by parallel processing with 80 cores. He also does not re-calculate the Jacobian at each iteration. Rather, he pre-calculates the Jacobian and loads it for each iteration in the fit.

The LOCO method has already been used at CERN to calibrate BPM gains, diagnose betatron phase advance and chromatic error in the TI 8 transport line, fix dispersion mis-match between TI 8 and LHC, and diagnose systematic quadrupole and sextupole errors in LHC.

The ALOHA (Another Linear Optics Helper Application) GUI was presented. ALOHA debugs optics errors using turn-by-turn and dispersion BPM data. It is well integrated into CERN’s MADX and Java environment.

J. Cardona proposed action-phase analysis as a tool for finding and correcting normal and skew quadrupole errors in the triplet quadrupoles at LHC’s interaction points [19]. Action-phase analysis has been applied previously for skew quadrupole correction at RHIC and for estimating nonlinear components at SPS.

The algorithm consists of fitting action and phase to measured difference trajectories for upstream BPMs. The model action-phase is then propagated to compare to measurements at downstream BPMs. A jump in measured action or in the difference between the model and measured phase indicates some magnetic field error. A jump in off-plane action indicates a skew

field. For example, for a difference trajectory in  $x$ , the start of nonzero  $y$  indicates the location of a skew field.

The very large beta functions at the IP triplet make the storage ring optics very sensitive to errors in these quadrupoles. Action-phase analysis can only identify two normal and one skew quadrupole errors associated with each triplet. These values do not correspond to the actual error values of any of the three quadrupoles. The skew quadrupole value corresponds to what should be used in the skew quadrupole corrector of the triplet to cancel out the coupling produced by all skew quadrupole errors that might be present in the triplets' quadrupoles. Similarly, the two normal quadrupole values are corrections that, when they are applied to the corresponding pair of quadrupoles, cancel out the beta beating produced by the triplet. In summary, the action and phase method shows that it is not necessary to know all six possible errors (skew and normal) in the triplet but only three related quantities are enough to do a proper linear correction.

An analysis of simulated data for 24 turns resolved gradient errors to within  $10^{-6} \text{ m}^{-2}$  for the collision lattice of the LHC.

A. Petrenko presented model independent analysis (MIA) of simulated and measured Tevatron and LHC turn-by-turn BPM data [20]. In MIA, a matrix is built of the measured trajectories of the beam on different turns in the storage ring. Each matrix column is associated with a BPM, and each row is associated with a turn. For the Tevatron, the matrix included about 8000 turns, while for LHC about 1900 turns were used. Singular value decomposition (SVD) of this matrix yields a set of eigenvectors in position (BPMs) and time (turns). The pairs of (position, time) eigenvectors with large singular values tend to be associated with different modes of real beam motion, while those with small singular values are associated with BPM noise.

In order to use the MIA modes for some practical purpose like the calculation of beta-functions it is necessary to solve the MIA mode mixing problem. Typically a MIA mode corresponding to some physical process has also small residual contributions from other physical modes. The standard MIA principle component analysis (PCA) described above can be extended by an additional linear transformation (usually rotation) of the obtained basis of MIA modes. This approach is sometimes referred to as Independent Component Analysis (ICA). For example, in order to untangle the physical modes corresponding to coupled betatron motion in the Tevatron the following method is used: each BPM is treated as two BPMs separated in a ring by exactly one turn. This leads to a simple criterion of MIA mode separation: the betatron phase advance between any BPM and its counterpart shifted by one turn should be equal to betatron tune and therefore should not depend on BPM position in the ring.

The four eigen-modes associated with coupled betatron motion in two planes can be used to calculate elements of the transport matrix between BPMs, namely  $R_{12}$ ,  $R_{32}$ ,  $R_{14}$ ,  $R_{34}$ . Differences between these measured ( $R_{ij}$ )s and those of the model identify locations of optics or BPM errors.

These MIA analyses also successfully identified modes associated with vibrational motion of the Tevatron final focus quadrupoles. Analysis of LHC data identified multiple noisy BPMs as well as several large deviations from the design model. The beta-functions were

obtained not only in BPMs but also everywhere in several long sections of LHC which are free of large focusing errors.

## 6. Session 6: Techniques review - II

Direct Fourier Transform and its limit in terms of amplitude, phase and frequency resolution are discussed [21]. Several other methods allow overcoming the DFT limits, such as FFTc, ApFFT, Sussix and NAFF. The previous methods are compared by means of simulation aimed at determining amplitude, phase and frequency. Cases without noise as well as with 1% and 10% additive Gaussian noise are taken into account. The results presented show that:

- Without noise the most accurate result is returned by the NAFF algorithm, followed by FFTc and Sussix. The relative error scales in the three cases as  $1/N^3$ ,  $1/N^2$  and  $1/N$  respectively (N is the number of turns).
- With noise FFTc, Sussix and NAFF do not show considerable differences.
- With noise the relative error for NAFF and FFTc is similar and scales as  $1/N$ .
- With noise all the algorithms achieve the same resolution on the phase analysis which scales as  $1/N$ .

A possible FFTc application for the localization of coupling impedance source relying on the improved resolution in determining the phase advance between BPMs is prospected.

During the discussion it emerges that some of the results presented should be checked as the error dependence on the number of turns N does not seem to be correct. In principle, damping and decoherence should be included in the numerical simulations.

Optics measurements at Tevatron have been presented with special emphasis on  $\beta^*$  measurement and adjustment [22]. Differential orbit from all corrector magnets plus off-energy orbit are acquired in both planes and used for LOCO linear optics analysis. The measurement takes 1-2 hours according the accuracy required. Data from orbit measurement show how the new BPMs system provides an improved accuracy (from 50  $\mu\text{m}$  to 15  $\mu\text{m}$ ), this achieving its best performance after 20 years of operation! Unaccounted gain factors in the BPMs introduce up to 10% error in the beta beat. The turn-by-turn data is certainly a promising approach but it is not in an operational state.

Super conductive quadrupole and dipole strength show a systematic difference with respect to magnetic measurements (30 years old) their strength is  $\sim 0.15\%$  and  $0.18\%$  higher at the injection and top energy respectively.

Tevatron collision optics (full coupling) at the central orbit is presented,  $\beta^* = 28$  cm and  $\eta_{x,y} = 0$  at the IP. Two beams collision optics requires beam separation implemented by electrostatic separators. The resulting helix like orbit determines a 15% change in  $\beta$  values. Waist position in the IPs is strongly affected by BPMs relative sensitivity. A  $\Delta\text{err} = 0.01\%$  moves the waist by 3.7 cm.

Measured chromatic beta-functions are in good agreement with the model around the CDF IP, but they need to be corrected. Grouping chromatic quadrupoles into families almost cancelled chromatic beta-beating and, in turn, second-order chromaticity.

During run II, betatron coupling, originally high with a tune split  $\sim 0.4$ , has been corrected by shimming those dipoles which had no skew quadrupoles nearby achieving a tune split of less than  $5 \times 10^{-3}$ .

A method to measure non-linear components in circular accelerator is presented, the so-called nonlinear tune response matrix (NTRM) [23], based on the measurement of the tune variation induced by closed orbit distortions. This approach has been successfully benchmarked on the SIS18 machine by introducing six controlled sextupolar errors in chromatic sextupole magnets and using six horizontal dipole correctors as probes. The effectiveness of the method depends on which correctors are used and the average relative error affecting the reconstructed nonlinearity grows with the number of condition of the orbit response matrix. In particular, the dipole correctors nearest to the source of non-linear errors are the most effective ones for reconstructing the non-linear components.

The matrix used in the NTRM is square due to that the number of steering magnets is equal to the number of the considered nonlinear errors, for this reason it is not necessary to use the SVD technique. Of course, in case an increased number of dipoles is used, the NTRM matrix becomes rectangular and the SVD solver should be used, iterating till it converges to the solution. SVD-NTRM is under development.

The accuracy in retrieving probing errors is in all cases except one well below 15%. It is emphasised that, even if dipole correctors are used, the method is independent on dispersive effects.

The same technique has been used to reconstruct second order terms in the magnetic field of the dipoles. The procedure has been repeated for three different working points. The computed components are not, however, in full agreement with the dipole magnetic measurements. A further check could be made, by comparing the measured components with those obtained by means of closed bumps over the dipoles.

Further developments aimed at making this method independent from magnet current, working point, beam quality, etc. are under way. It is clear, however, that as the method is in any case perturbative, octupolar effects can be hardly included in this approach (unless it is used with  $Q'$  instead of  $Q$ ).

A review of chromatic measurements in RHIC and LHC was given [24]. Measurements taken on LHC for both beams are compared with the machine model. Chromatic functions fit the model reasonably well at 3.5 TeV and with  $\beta^* = 3.5$  m, with the exception of two IRs for Beam 1. Chromatic beta-beating is not in good agreement with the model in the horizontal plane both at injection and top energy. When lowering  $\beta^*$  to 1.5 m if a local correction is applied, then the beta-beating can be contained within 20%. As a comment, LHC natural chromaticity cannot be measured via changing  $\Delta p/p$  due to large sextupole contributions, rather one should vary the B field with the beam going through the centre of the sextupoles.

Chromatic measurements taken at RHIC after reducing  $\beta^*$  ( $\beta^*=0.7$  m now, it was  $\beta^*=0.8$  m in 2007) are presented. Beam losses have been observed during positive off-momentum scans, mainly in the Yellow ring (p run 2009). The beta-beating was originally large, especially in the Yellow ring (2009 run with energy of 250 GeV), but it has been reduced during Au runs in 2011. Chromatic beta-beating at injection energy (Blue ring only) are in the range  $\pm 5\%$  (p run 2009). Chromatic beta-beating (p run 2009 with energy 250 GeV) is in the range  $\pm 40\%$  and shows a poor agreement with the model in the case of the Blue ring in the horizontal plane and of the Yellow one in the vertical one. The latest value of the chromatic beta beat (2011 Au run with energy 100 GeV) is  $\pm 50\%$ . Phase advance tuning between the two IPs is proposed to overcome the observed beating.

Non linear chromaticity measured at RHIC with  $\beta^*=0.8$  m fits quite well the model prediction, but large discrepancies have been observed with  $\beta^*=0.7$  m [25]. Since  $\beta^*$  is going to be moved to 0.5 m, a non-linear chromaticity correction strategy is necessary in order to avoid large off-momentum tune shift beta beat and to keep momentum aperture as large as possible. In principle non linear chromaticity can be easily corrected if the optics model reproduces the real machine, that was certainly the case for the lattice with  $\beta^*=0.8$  m. The 144 sextupoles installed in the six arcs are arranged in 24 sub-families.

The second order chromaticity has been successfully corrected grouping chromatic sextupoles in four pairs of chromatic sextupoles families according their contribution to the half-integer resonance driving terms. The procedure does not affect the linear chromaticity. The main contributions to non-linear chromaticity come from the magnet in IR6 and IR8, for this reason the phase advance between the two IRs has been optimized compatibly with the fact that not all the quadrupoles are independently powered.

Non-linear errors in the IRs magnets have been corrected by means of high-order multipole correctors whose strength has been optimized experimentally using a scanner program.

The  $3Q_x$  resonance driving term has been measured, but not yet corrected.

## 7. Session 7: Modelling

The Session included five talks ranging from modelling of magnetic imperfections to beam dynamics.

E. Todesco discussed the present status of the modelling of the magnetic errors in the LHC magnets [26]. Five types of errors are considered, caused by geometry, saturation, magnetization, decay and snapback respectively. These are made available for the beam dynamics simulations via the WISE code. Despite the issues reported in the exact assignment of the current set points, in the time decay of the chromaticity and tunes, it is believed that the magnetic model is solid and it underpinned the successful commissioning of new LHC optics in few hours.

D. Einfeld reported the progress with the comparison between the main accelerator design codes [27]. The comparison encompassed linear and nonlinear dynamics both on-energy and off-energy. The codes generally agreed for the linear optics. Some discrepancies were found in the off-energy momentum aperture. The discussion following the talk queried the relevance of



this alleged black-box approach. It was explained that there are plans to extend and strengthen this work with a careful explanation of the assumption beyond each code and with a comparison with measurements at various machines. The exemplar case of the vertical natural chromaticity was quoted, where some disagreement seems to exist between codes and between measurements at different machines.

G. Robert-Demolaize talked about the online modelling and optics feedback at RHIC [28]. The orbit, tunes, optics and the chromaticity can be controlled during the ramp. A set of GUI were created and the online model is used for orbit, tune and chromaticity feedback, to monitor and understand beam losses and to rematch the IP optics. Shorter ramp period and better control of the beam properties were reported.

J. G. Müller presented the work on LHC online modelling [29]. The high level software shown uses the MAD-X code to control the LHC orbit and optics. These tools have been used successfully during the last two years to commission the LHC. Accurate information on the machine performance can be controlled and corrected via the model in terms of seconds. The emphasis of most of the application is on the safe operation of the machine.

F. Schmidt gave an overview of the work on the on-line modelling of the nonlinear beam dynamics at the LHC [30]. The MAD-X code has been further extended to include the PTC modules. Links with the WISE database are provided and the full thick lens description of the machine is available. The comparison with the first data on the nonlinear chromaticity seems very encouraging.

The session highlighted the high standard reached in the modelling of the machine imperfections and there was wide agreement on the usefulness of complementing the machine operation with an online model, provided all the possible information on the magnet errors, machine misalignments and apertures are carefully included. In terms of codes MAD-X with the addition of the PTC model was the most widely used in the collider community while, Tracy (AT) and elegant were most popular with the light source community. Both are used as reference for online modelling at various facilities.

## **8. Session 8: Beam Diagnostic**

LHC BPMs perform very well (high availability), the main problem for the reproducibility is a dependence of the measured beam position on crate temperature and on the filling pattern [31]. Temperature stabilized crates will be installed in the future to reduce this effect that can be as large as 0.2 mm even after correction of the temperature drifts.

Tune and chromaticity diagnostics is based on BBQ (Base Band Q) systems. Those systems are very sensitive and accurate ( $10^{-4}$  to  $10^{-6}$ ) but suffer from the presence/use of transverse dampers. The chromaticity is obtained from tune tracking in the presence of RF frequency modulation.

In the future a continuous phase advance measurement system (based on BBQ hardware) could be installed in critical locations (for example collimation sections, IRs). This system could be tracking beta-beat changes at the level of 1% or less across the LHC cycle.

An injection matching monitor based on an OTR system with turn by turn capabilities is also in the pipeline. A complex 2D system is not feasible, but it seems possible to provide turn-by-turn 1D projections.

Orbit response methods (LOCO-like) are used by all light sources where the method profits from sub-microns orbit accuracy (over the time scale of the measurement) [32]. Spectacular correction quality is achieved for lattice functions, BPM gains, impedance measurements, chromaticity correction etc.

Turn by turn analysis of the BPM data is used further to diagnose the lattices, resonances and dynamic aperture.

X-band cavity BPMs are appearing in linear machines (FELs) now feature sub-micron shot-by-shot resolution, opening the field of high accuracy optics modelling in such devices.

The TOTEM experiment at the LHC aims to measure the total pp cross section. For this determination TOTEM relies on a precise knowledge of the local optics (in fact the transfer matrix) from the IR to the location of its detectors [33]. The TOTEM detectors are installed in Roman pot devices that can be moved close to the beams.

TOTEM can take advantage of the correlation of the 2 protons in elastic collisions to constrain the optics between IR and detectors. TOTEM is also capable of measuring the angle of the protons with their detectors, adding additional information.

TOTEM used the data recorded during special runs to perform a constrained fit (that also included the magnet errors) and reconstruct the transport matrix from the IR to the detectors. This proved to be a powerful analysis tool of the local optics in LHC IR5. Further developments are expected in 2011 from runs with a 90 m  $\beta^*$  optics.

## **9. Session 9: LHC complex present and future plans**

The Optics Measurements, Corrections and Modelling workshop for high performance storage rings featured one session on the current status of the LHC and its upgrade plans. Four presentations covered this topic.

A comprehensive review of the current status of LHC operation was given [34]. Since the end of the 2010 run it was clear that the performance of the LHC and its injectors was better than expected (see, e.g., available aperture, beta-beating, beam-beam effects, collimation system performance, beam brightness). Careful tests and debugging of the key systems, to be noted that the first injection tests started in 2004, have been the reason for the excellent performance achieved in a very short period since the machine start up. The high quality of the models developed for LHC operations (optical model, magnetic model) made the rest by providing the required machine reproducibility and the optics quality before and after correction. The feedback systems have added the last bit to the reproducibility during the critical stages such as ramp and squeeze. A review of the performance reach till the end of 2011 was also made, emphasizing the potential brought by the increase of the bunch number, intensity, and emittance reduction thanks to the double batch injection from the PS Booster. In 2012 a slight energy increase should be possible with an option to move to 25 ns operations. According to the official CERN master plan a long shut down should take place in 2013-14, after which the LHC energy should be ramped

towards the nominal value of 7 TeV and the optics squeezed down to 55 cm, with bunch spacing of 25 ns, provided that no impedance issue is found due to the tight settings of the collimators. At the horizon of 2022 another long shut down will bring to life the upgraded LHC.

The successful and fast LHC beam commissioning already opened the possibility of performing beam dynamics studies during the current year [35]. The precursor of these studies was the attempt to perform luminosity levelling for the LHCb experiment, which was successfully tested and then put in operation since at least May this year. A working group was set up to collect, prioritise requests for the beam dynamics studies and then discuss the results. In the schedule for the year 2011, five blocks preceding the regular technical stops have been scheduled for a total of twenty plus two floating days. In terms of beam time requested, beam-beam studies are at the top of the list, followed by RF and optics (where the term optics stands for any single-particle beam dynamics study, ranging from machine optics studies to non-linear single-particle beam dynamics). Studies of e-cloud effects, collimation system, injection, and impedance are also an important part of the requests for beam time. It is worth emphasising that the priority of these studies is either based on their relevance for the performance ramp up (e.g., beam-beam studies aimed at determining the actual limits of the LHC machine), or for the upgrade studies (e.g., the proposed ATS optics, see later). In few cases the studies can be considered as a continuation of the commissioning (e.g., the tests with the 90 m  $\beta^*$  optics for TOTEM and ATLAS). The reports of the beam experiments can be found from the following web site <https://espace.cern.ch/lhc-md/default.aspx>.

At the Chamonix workshop 2010 key decisions were taken about the upgrade of the CERN machines, the low-power SPL and PS2 being replaced by a simpler energy upgrade of the PS Booster and the so-called Phase 1 upgrade of the LHC reviewed by a dedicated task force. The outcome of this analysis led to the proposal of a new upgrade project for the LHC, where the former Phase 1 and Phase 2 upgrades have been merged into one single upgrade at the horizon of 2022. The scope of the High-Luminosity LHC upgrade is to implement a new layout in view of reaching a peak luminosity of  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  with levelling, allowing an integrated luminosity of about  $250 \text{ fb}^{-1}$  per year [36]. This, in turn, should provide a total of  $3000 \text{ fb}^{-1}$  over the twelve years following the completion of the upgrade. The changes in layout will be concentrated in the insertion regions, even if other key systems (e.g., collimation, dump, power converters, etc.) will be reviewed in details. Not only low-beta triplets will be replaced with new magnets, but also separation dipoles and matching quadrupoles will be replaced with improved devices. The new triplets will call for R&D as the current ideas focus on large aperture and high-field magnets, for which  $\text{Nb}_3\text{Sn}$  is an interesting option. To be noted that the path to the upgrade will not consider only the reduction of  $\beta^*$  or the increase in intensity as means to achieve the goals, but also non-conventional paths such as the use of crab cavities to restore the bunch overlap reduced by the unavoidable crossing angle. It is worth emphasizing that, in parallel, the Hilumi Design Study, which contains a subset of the work packages of the HL-LHC projects, has been launched and approved in the framework of the Seventh European Framework programme.

The first step in any upgrade scheme is to provide a new layout capable of reducing  $\beta^*$  further down with respect to the nominal performance, i.e. 55 cm. A first analysis focused on the pros and cons of the standard round vs. flat beam optics (i.e., in which  $\beta^*$  is equal in both planes or different, respectively – the emittances being always the same). Indeed, both options will be retained in the proposed layout, the former being adapted to use in combination with crab

cavities. The limits and boundary conditions to any upgrade path can be listed as: the minimum distance from the triplets to the interaction point; the total length of the matching section; the strength of the quadrupoles in the matching section; the aperture of the magnetic elements in the matching section; the chromatic effects that stems from the triplets. The solution proposed within the Phase 1 project was addressing these points with a very complicated solution that did not leave any optical flexibility. The novel optical scheme recently proposed, called Achromatic Telescoping Squeeze (ATS), is based on the generation of a beta-beating wave in the arcs next to the high-luminosity insertions combined with a strict  $90^\circ$  phase advance in the FODO cell [37]. This enables enhancing the strength of the arc sextupoles used to correct the chromatic effects. Then, the squeeze strategy consists in reducing  $\beta^*$  down to a specified value, below which the beta-functions in the neighbouring arcs will be increased. This will passively reduce  $\beta^*$  while keeping the chromatic properties constant. This scheme is being tested not only on paper, but also in dedicated machine experiments.

## **10. Session 10: Prospects and future developments**

The objectives of the session were twofold: i) introduce the planned upgrades and future projects with emphasis on new goals and requirement for optics modelling and beam instrumentation; ii) assess whether these goals are challenging enough.

R. Garoby discussed the LHC Injectors Upgrade project [38]. The LHC Injectors Upgrade (LIU) project is in charge of making the CERN accelerator complex capable of reliably providing the beams required by the high luminosity LHC until at least 2030. Except for Linac4, which is already in construction, the baseline solution is to upgrade the existing accelerators, PS Booster (PSB), PS and SPS. The project is presently in a study phase, the objective being to finalise the implementation of the upgrades during the second long LHC shutdown, probably in 2018. The current limitations of the different accelerators have been reviewed, as well as the improvements under consideration.

Two main principles of action are considered: Performance increase and reliability and lifetime improvement (until to 2030, tightly linked with consolidation). Linac4 should replace Linac2, providing a higher-energy, namely 160 MeV, H<sup>-</sup> beam to the PSB for higher brightness. The injection energy both of the PSB and PS should be increased. Some upgrades are foreseen in the PSB, PS and SPS to be able to cope with the higher brightness beams (feedbacks, impedance reduction, electron cloud mitigation, etc.). By April 2014 Linac4 should deliver 160 MeV beams. A Rapid Cycling Synchrotron is considered as a cost-competitive alternative to replace the PSB and a feasibility report was expected for end of July 2011 in order to take a final decision. A new challenging bunch compression scheme in the PS is considered, with potential brightness increase. Machines Developments sessions were conducted in May 2011 which demonstrated the feasibility of the RF gymnastics at 2 GeV. Significant effort is required to reach 26 GeV and provide beam to the SPS. Tune scans in the PS and the SPS are being addressed to identify dangerous resonances.

Some expected beam behaviour are: 5% and 10% beam loss in the PS and the SPS, respectively; 5% and 5% transverse blow-up in the PS and SPS respectively; 10% fluctuations of all bunch parameters within a given PS bunch train. Estimated limits of bunch population from

the injectors are  $2.7 \times 10^{11}$  and  $2.1 \times 10^{11}$  for 50 ns and 25 ns, respectively. The overall planning concludes with beam characteristics for HL-LHC in 2021:

- MDs during 2011-2012 are essential to refine the knowledge and understanding of the injectors and to check the potential of upgrades.
- Preliminary requirement and first goal is getting confidence in beam instrumentation, which requires extensive debugging. The progress is steady, but time-consuming.
- Recent observations in 2011 tend to demonstrate that the accelerators perform better than in the previous years.
- Need to interact with HL-LHC for selecting reachable beam parameters which are sufficient for HL-LHC to reach its goals.
- Irrelevant to the decision to connect Linac4 to the PSB during LS1 and to the choice between PSB/RCS, the beam characteristics specified for LIU will be met some time after the end of LS2 (~2020).

Y. Papaphilippou discussed the Low gamma-t optics in the SPS [39]. In order to increase the bunch current instability thresholds that limit the LHC bunch intensities in the SPS, several optics were proposed targeting at the reduction of the transition energy. In particular, a simple solution by decreasing the integer tunes of the actual working point by 6 units was developed and applied to the real machine, enabling the injection and acceleration up to the flat top of single bunches with threefold increase in the intensity, within the nominal LHC-type beam sizes.

Several intensity thresholds scale with the slippage factor in the SPS. Therefore a higher slippage factor would increase these instability thresholds thanks to the faster synchrotron motion and the damping of instabilities. The increase in the slippage factor is achieved by reducing the integer part of the tune to 20. Similar attempts were done in the past but to different integer tunes resulting in not so optimum operation.

Several machine studies were conducted in the SPS with the new Q20 optics. In particular optics measurements at injection confirmed just a 20% beta-beating and a remarkable good agreement between model and measured normalized dispersion. The synchrotron frequency is used to estimate the relative increase of the slippage factor by 2.65 (MAD-X predicts 2.86). Non-linear chromaticity measurements and a corresponding fit of the machine multipolar content was presented. The fitted sextupolar and decapolar multipoles in the main dipoles shows consistency between the Q20 and Q26 lattices. However the octupolar component in the quadrupoles changes sign. Beam losses of up to 4% for  $3 \times 10^{11}$  protons were observed at injection energy for Q20. This is to be compared with 10% losses for  $2.5 \times 10^{11}$  for Q26. In summary:

- New low transition energy optics was proposed and implemented in SPS for machine studies during 2010-2011, showing promising results.
- Single bunches injected and accelerated successfully with intensities up to  $3.3 \times 10^{11}$  p/b.

- No clear triggering of TMCI instability even for low chromaticity settings with only small emittance blow-up.
- Transverse emittances below 2.5  $\mu\text{m}$  at the end of a long cycle for single bunches with intensities of  $3 \times 10^{11}$  p/b with moderate losses.
- Multi-bunch injection (12 bunches) and acceleration for nominal LHC beam parameters.
- Yet another attempt to build a non-linear machine model for SPS and working point optimization for high intensity.
- Emittance blow-up for high intensity single bunches in both optics.
- Remaining to setup the extraction for new optics to LHC.
- Large simulation effort for qualifying the impact on instabilities, e-cloud, space charge.
- It remains to be seen the impact of the RF voltage limitations and the multi-bunch operation.

G. Franchetti presented the FAIR project and optics challenges [40]. Beam loss control is an important issue in all superconducting accelerators. In the FAIR project the requirement of beam loss control becomes demanding by the complications created by the high intensity. The response of the beam to the linear and nonlinear machine optics is magnified by the space charge. Issues of optics and resonance control (compensation) during storage and acceleration become essential for machine performance.

The SIS18 optics changes from injection to extraction to optimise the injection and extraction processes. This poses the challenge to apply optics dependent corrections of closed orbit and tune. For the SIS-100 ring a maximum beam loss of 5-10% is tolerable. One important mechanism for particle loss is the multiple resonance crossing induced by space charge. Computer simulations were performed to address the energy loss and identify dangerous resonances. The first finding is that there is a strong dependence between beam intensity and beam survival and that the third resonance is the responsible for the energy loss. By compensated the identified sextupolar resonance the losses were considerably reduced to below the 5% level. SIS300 is a fast ramping machine with superconducting magnets. Slow extraction using the third order resonance is foreseen. This will be the first time superconducting sextupoles are used for slow extraction.

In order to be ready to monitor and control of the non-linear phenomena in the FAIR project various beam-based techniques are being studied at GSI. In particular the NTRM approach based to controlled orbit excursions for the reconstruction of sextupolar errors has been tested in the SIS18. A new method to measure acceptance and dynamic aperture based on intensity evolution versus time with controlled excitation has also been tested. In summary:

- Beam dynamics affected by space charge makes the sensitivity to beam optics more important.

- Beam optics control and resonance compensation is essential for the high intensity scenarios.
- It is crucial to be prepared for the challenge to measure and model the machine properties: Measured magnetic components inventory, development of beam-based methods for optics and non-linear corrections, resonance compensation, control of beam optics during acceleration.

M. Biagini presented an overview of the SuperB project [41]. The SuperB project for an asymmetric  $e^+e^-$  collider at the Y(4S) energy has been recently approved by the Italian Government. The Collider will be built in Italy, but will profit from the work of a large international collaboration. The design is based on the large Piwinski angle (LPA) and crab waist collision scheme already successfully tested at the DAΦNE Phi-Factory at Frascati National Laboratories in 2008-9. The LPA and the crab waist scheme provided luminosity increase by a factor 2.5, almost reaching the design goal of DAΦNE. The scheme requires state-of-the-art technology for emittance and coupling minimization, optics control and modelling, vibrations and misalignment control, e-cloud suppression. SuperB shares many similarities with the Damping rings of ILC and CLIC and with the latest generation of SR sources and profits from the collaboration among these communities. The choice of beam parameters is driven by the following considerations:

- Maintain wall plug power, beam currents, bunch lengths, and RF requirements comparable to past B-Factories.
- Plan for the reuse as much as possible of the PEP-II hardware.
- Require ring parameters as close as possible to those already achieved in the B-Factories, or under study for the ILC Damping Ring or achieved at the ATF ILC-DR test facility.
- Simplify IR design as much as possible. In particular, reduce the synchrotron radiation in the IR, reduce the HOM power and increase the beam stay-clear.
- Eliminate the effects of the parasitic beam crossing.
- Design the Final Focus system to follow as closely as possible already tested systems, and integrating the system as much as possible into the ring design.

The SuperB Final Focus contains dedicated sections for the correction of horizontal and vertical chromaticity plus an extra section with the sextupole for the crab waist. The designed coupling correction system compensates each half-IR independently and contains the following elements on each side of IP:

- Rotated permanent quads.
- Skew winding on superconducting quads to simulate rotation.
- Superconducting anti-solenoid of strength 1.5 T and 0.55 m long aligned with the beam axis.

- 2 vertical and 2 horizontal dipole correctors for orbit correction.
- 4 skew quads at non-dispersive locations for coupling correction.
- 2 skew quads at dispersive locations for correction of vertical dispersion and slope
- The nominal FF quads are used to rematch the Twiss functions and horizontal dispersion.

In summary SuperB is a great challenge in terms of optics control, modelling and beam instrumentation.

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- [6] G. Vanbavinckhove – CERN & Technische Universiteit Delft, “LHC Experience”.
- [7] Y. Ohnishi - KEK, “KEKB Experience”.
- [8] Y. Yan - SLAC, “PEP-II Experience”.
- [9] C. Milardi - INFN – LNF, “DAFNE Experience”.
- [10] E. Gianfelice – FNAL, “Linear Optics Measurements by TBT Analysis at Fermilab Booster”.
- [11] S. Liuzzo – INFN, “Experience with low emittance tuning tool for SuperB, Diamond, SLS, and Dafne”.
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- [14] T. Perron – ESRF, “Linear lattice errors at the ESRF, measurement and correction”.
- [15] M. Aiba – SLS, “SLS Experience”.
- [16] L. Nadolski – SOLEIL, “SOLEIL Experience”.
- [17] R. Bartolini - Diamond Light Source and John Adams Institute, “DIAMOND Experience”.
- [18] K. Fuchsberger – CERN, “LOCO for LHC”.
- [19] J. F. Cardona - Departamento de Fisica-Universidad Nacional de Colombia, “Action-Phase analysis”.
- [20] A. Petrenko – FNAL, “Model-Independent Analysis of Turn-by-Turn BPM Measurements in Storage Rings”.
- [21] N. Biancacci - Università di Roma I 'La Sapienza' and INFN, Roma I, “Refined techniques for phase measurements”.
- [22] V. Lebedev – FNAL, “Beta\* measurement and adjustment”.
- [23] A. Parfenova – GSI, “Probing non-linear fields with orbit bumps”.
- [24] R. Calaga – BNL, “Chromatic measurements in RHIC and LHC”.
- [25] Y. Luo – BNL, “RHIC non-linear chromaticity and IR corrections”.
- [26] E. Todesco – CERN, “LHC magnet modelling”.
- [27] D. Einfeld – CELLS, “Optics codes”.
- [28] G. Robert-Demolaize – BNL, “RHIC online modelling and experience with feedbacks”.
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- [30] F. Schmidt – CERN, “Non-linear modelling of accelerators”.
- [31] R. Jones – CERN, “LHC Instrumentation & future developments”.
- [32] G. Decker – ANL, “Light Source Instrumentation.
- [33] H. Niewiadomski - Brunel University, “Roman pots for beam diagnostics”.
- [34] M. Lamont – CERN, “LHC Operations”.
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- [37] S. Fartoukh – CERN, “The optics challenges of the LHC Upgrade and a novel concept to reach low beta\*”.
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