OVERVIEW OF THE STATUS OF THE DIAMOND PROJECT

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Abstract

An overview is presented of the major Diamond accelerator systems and the current status of commissioning.

INTRODUCTION

Construction and commissioning of Diamond, the UK's new medium-energy 3rd generation synchrotron light source [1,2], is progressing towards the original target of providing synchrotron radiation beams for users in January 2007. The main parameters are given in Table 1.

Table 1: Main parameters of the Diamond storage ring.

Energy	3 GeV
Circumference	561.6 m
RF frequency	500 MHz
Nominal current	300 mA
Nominal rms emittances (H,V)	2.7, 0.03 nm rad
Lattice	24-cell DBA
Straight sections	6 x 8 m, 18 x 5 m

The main building housing the synchrotron and experimental hall is now essentially complete (see Fig. 1). Provision of services, particularly process water cooling systems, has however been delayed for a variety of reasons. This has had a significant impact on machine commissioning, but has been mitigated as much as possible by installing temporary cooling systems initially for the linac, booster RF and storage ring RF, and subsequently also for the booster magnets. In addition, initial booster and storage ring commissioning has been carried out at 700 MeV rather than 3 GeV, at which level the magnets can be run safely without water cooling.

Figure 1: The Diamond site, October 2005.

LINAC

The 100 MeV linac was supplied as a turn-key system by ACCEL Instruments GmbH, with DLS providing beam diagnostics, beam analysis software, control system hardware and standard vacuum components. Installation was completed at the beginning of August 2005, and by the end of the month the first beam had been obtained from the gun. Shortly afterwards the first 100 MeV beam was obtained, and by mid October 2005 the acceptance tests had been completed, demonstrating that all parameters are well within specification in both single bunch and multi-bunch modes of operation [3]. The Linac has operated reliably since then, providing a 100 MeV multi-bunch beam, 200 ns long, for booster and storage ring commissioning, with a typical charge of about 1.7 nC.

BOOSTER

The 3 GeV, 5 Hz booster synchrotron is a conventional missing dipole 22-cell FODO lattice, providing zero-dispersion straight sections which are utilised for the injection, extraction and RF equipment. Table 2 lists the principal parameters. Components for the booster were purchased from industry, while installation and commissioning were carried out by DLS. Companion papers at this Conference give details of the characteristics of the booster magnets, power supplies, RF system and pulsed elements.

Table 2: Main booster parameters.

Energy (Injection, Extraction)	100 MeV, 3 GeV
Circumference	158.4 m
Repetition rate, max.	5 Hz
RF frequency	500 MHz
Nominal current	3 mA
Nominal emittance	141 nm rad

The commissioning strategy and timescales were largely dictated by hardware and services availability, the philosophy being to progress as far as possible at each stage in order to tackle any problems at the earliest opportunity. The principal restriction was the lack of cooling water for the magnets which initially only allowed a maximum energy of 700 MeV to be obtained. Further restrictions on working time were placed by the requirement to carry out the initial stages of commissioning at night, until radiation surveys could be carried out under reliable conditions to verify the integrity of the radiation shielding.

First injection attempts occurred on the 19th December 2005 with DC injection at 100 MeV, but were frustrated by the not uncommon problem of the septum polarity being reversed! Having resolved this, the beam was easily circulated through a complete turn, without correctors, on the night of Dec. 21st. The operation was greatly assisted by the turn-by-turn measurement capability of the BPM system which was available from the outset, giving readings with a reproducibility of around 0.1 mm. The first turn showed a maximum deviation of ± 5 mm in both planes. After only minor adjustment the beam circulated for over 1000 turns, with sextupoles and RF off.

The next stage was reached on Feb. 19th 2006 when beam survival for 200 ms was achieved with RF on. This then allowed a more accurate measurement of closed orbit to be made, using turn-by-turn data averaged over 1024 turns, which showed that it was within ± 6 mm horizontally and ± 4 mm vertically, without any correctors being applied. Closed orbit correction using the model response matrix and an SVD algorithm reduced the orbit distortion to less than 1 mm in both planes

By March power supplies were prepared for ramping, and on March 10th the first acceleration to 700 MeV was obtained. Given the low RF voltage demands at 700 MeV (1.7 keV energy loss/turn) acceleration was achieved with a constant RF power of 1 kW or less. Although possible, no correction of closed orbit during the ramp was necessary, DC correction being sufficient. Following commissioning of the extraction magnet pulsed power supplies, first extraction of the 700 MeV beam as far as the beam dump in the Booster-to-Storage ring transfer line (BTS) was achieved on April 4th.

Subsequent work concentrated on improving efficiency and reliability in readiness for storage ring commissioning. The tunes were corrected empirically to the nominal ones, and kept constant during the ramp to within $\Delta Q_x = 0.1$ and $\Delta Q_y = 0.05$ after making empirical corrections to the initial biased sinusoidal waveform. By the end of April, and throughout the Phase I storage ring commissioning in May, the booster was reliably accelerating typically 2 mA to 700 MeV, with a total efficiency between the end of the Linac-to-Booster transfer line (LTB) and the start of the BTS of typically 70 %. Only very small increases in vacuum pressure were observed due to the beam, and the pressure remained within a factor of two of the base level of $1\ 10^{-9}$ mbar.

Following initial storage ring commissioning, further temporary water cooling became available and 3 GeV testing started on June 5th. First acceleration to 3 GeV was obtained on the June 7th without difficulty after adjusting the synchronism between the power supplies. To reach 3 GeV a simple linear ramp was applied to the RF power, varying between 1 kW and 40 kW. As earlier at 700 MeV, no dynamic closed orbit correction was necessary, the orbit displacement remaining constant above 400 MeV and within a peak value of 3 mm in both planes. Whereas corrections were applied to the 700 MeV ramp to keep the tunes constant, a better adjustment of relative timing and amplitude has now resulted in the tunes being kept constant to 3 GeV within $\Delta Q_x = 0.07$ and $\Delta Q_y = 0.05$ using perfect sinusoidal waveforms.

As soon as significant current started to be obtained at 3 GeV pressure increases started to be observed, and even caused some initial vacuum trips. However this ceased to be a problem after a few days, and currently with 1.8 mA accelerated to 3 GeV the average pressure is around $2.3\ 10^{-8}$ mbar.

Extraction of the beam at 3 GeV was also readily achieved, and the beam sizes observed in the BTS transfer line were in good agreement with expectations. Further details of booster commissioning and optics measurements are given in [4,5].

STORAGE RING SYSTEMS

Control System

The Diamond accelerator and beamline control system [6] is based on the EPICS control system toolkit. The functionality needed at each stage of the machine commissioning has been available and the system has proved to be extremely stable in operation. Ongoing work includes development and commissioning of insertion device, front-end and beamline controls, together with secondary functionality such as the alarm handling, archiving and automatic sequencers for start-up and shutdown. Developments are also progressing in the design and implementation of a Fast Orbit Feedback system.

High-level, accelerator physics applications [7] have made extensive use of the MATLAB Accelerator Toolbox applications developed at the ALS and SPEAR3. These routines, adapted for use at Diamond and extended to cover operation of the booster and transfer lines, have so far proved to be very flexible and robust. Production of high-level software is continuing for the remainder of the commissioning period and for routine operation.

Diagnostics

The diagnostics available for initial storage ring commissioning were the electron Beam Position Monitors (BPMs), screens in the injection straight, a DCCT and the synchrotron light monitor. Remaining systems to be commissioned are the beam loss monitors, stripline excitation, pinhole cameras and collimators.

The same novel BPM electronics system has been selected for all BPMs in the booster, storage ring and transfer lines, based on direct AD conversion of the button signals and digital signal processing in a FPGA [8]. The system has proved extremely useful, providing since the beginning of commissioning data in various forms enabling first and subsequent turns to be optimised.

Front-Ends

Five beamline front-ends were installed before the start of storage ring commissioning, baked-out, and partly commissioned. Two further front-ends have subsequently been delivered and are now under installation. The final front-end for the initial batch of 8 beamlines is due to arrive mid-July. All 8 front-ends should be fully operational by the end of August [9].

Girders

The magnets and vacuum system in the arc regions were pre-assembled on 72 girders, 3 for each of the 24 cells, in a separate building close to the Diamond site. The girders were machined to an accuracy of 20 µm (peak-to-peak) in both flatness of vertical reference faces and straightness of the key-way. The measured deflection under load agreed with FEA simulations at 25 µm (peak-to-peak).

Each complete girder assembly, up to 6 m long and weighing up to 17 T, was surveyed in the assembly building to check the local alignment between magnets and to position two survey monuments above the girder central key-way. A water flow and pressure test was also carried out while in the assembly building.

A doubling of the initial capacity allowed 6 girders to be worked on at any time, in order to overcome delays in the supply of components, and a peak rate of installation of 3 girders per week was achieved. Fig. 2 shows one of the girders during installation. The last girder was installed on March 13th 2006.

The girders rest on four motorised cam assembly blocks (visible in Fig. 2), and can be aligned with five degrees of freedom using the five motorised cams [10]. The system has successfully been used in a local mode to initially align the girders to the survey network, but will eventually also permit beam-based girder alignment to be carried out.

Figure 2: Installation of a girder in the storage ring.

Preliminary vibration measurements of the storage ring and experimental hall concrete floor slab indicate significant damping of local sources has taken place by construction of the slab. A horizontal resonance has however been identified at 25 Hz which will be investigated further, as will any impact of water flow once cooling water is available [11].

Injection System

The 8.3 m injection straight accommodates the septum magnet and 4 kicker magnets, as well as horizontal and vertical collimators and two viewing screens. The septum magnet is of the ex-vacuum type, while the kickers are ex-vacuum with ceramic vacuum chambers [12] Some difficulties were experienced with the Ti coating of the ceramic chambers, which will require further chambers to be produced to substitute some of those currently installed, in order to achieve the desired uniformity which is required for future operation in top-up mode.

Insertion Devices

Seven Phase I insertion devices are currently at various stages of final assembly and installation [13]. Of these, five are in-vacuum undulators (INVU), with periods ranging from 21 to 27 mm, one is a 3.5 T superconducting multipole wiggler (SCW) and one an APPLE-II device for variable polarization (see Table 3). Other than the SCW (and one in-vacuum undulator whose magnetic assembly has been contracted out to overcome capacity limitations) all are being constructed in-house. Three in-vacuum devices have so far been shimmed at DLS. The first device achieved phase errors of 3.4-3.8^o between 5 mm and 7 mm gap, but this has been improved in the later two devices, 2.4-3.0^o, as a result of a better initial sorting.

Table 3: Main parameters of the Phase I insertion devices.

Beamline	ID type	Period (mm)	No. of Periods	Field (T)
I02, I04	INVU	23	85	1.06
I03	INVU	21	94	1.01
I06	APPLE-II	64	66	0.94
I15	SCW	60	24	3.5
I16, I18	INVU	27	72	1.14

The superconducting wiggler has a period of 60 mm and 45 full poles, and achieves a peak field of 3.7 T. The internal aperture for the beam is 80 mm (horizontal) x 10 mm (vertical). The vacuum chamber for the beam is part of the LHe vessel at 4.2 K, however a copper liner connected to the 20 K shield is employed to handle the head load from the beam more efficiently. Two 1 W 4.2K cryocoolers, and two 20K/40K cryocoolers are used to produce a near-zero Helium boil-off.

Magnets

The storage ring requires a total of 48 dipole magnets, 240 quadrupoles and 168 sextupoles; the latter have additional windings producing dipole and skew-quadrupole correction fields. The dipole magnets achieve the required 0.05% variation in the integrated field across ±15 mm. The magnet-to-magnet reproducibility of the integrated field was of the order of the measurement repeatability of 2 10^{-3}.

The quadrupoles were initially specified to meet defined mechanical tolerances, but the critical dimensions proved difficult to measure reliably, and so this was later changed in agreement with the manufacturer to a set of required multipole errors, which were based on the results of beam dynamics calculations. The required tolerances were achieved, after developing a procedure to determine the mechanical changes that were necessary to correct for sextupole and octupole errors. A great deal of attention was also devoted to alignment, and during magnetic measurement the positioning keys were shimmed so that the magnetic centres aligned with the reference axis to within 20 µm rms, and 80 µrad in roll angle [14].

The sextupole magnets also achieved the desired quality, with harmonic field errors typically < 4 10^{-4} at r=25mm, and magnet-to-magnet sextupole strength variations of 2 10^{-3}.

Power Supplies

The 1000 power supplies needed for the Diamond accelerators and transfer lines are all installed and operational [15,16]. Only the storage ring dipole supply has not yet been energised at full current due to the lack of water cooling. Significant attention was placed during the design on minimising the number of different types of power supply, and on redundancy, reliability, maintainability and EMC issues. All supplies, including the 10 pulsed units, are switched mode and make use of common digital controller and ADC cards. These provide a common interface to the EPICS control system, which greatly simplified the commissioning and operator training.

RF System

The RF system [17] will comprise initially two superconducting cavities each rated to 300 kW and an accelerating voltage of 2 MV. A third cavity has also been delivered but not installed, and is being kept as a spare. The two cavities conditioned quickly up to 2.2 and 2.3 MV, with Q_0 values in excess of specification (6-6.5 10^8 at 2 MV, 5 10^8 specified), although less than the figure of 10^9 achieved during the vertical tests, for unknown reasons. The static losses are 35 W/cavity, as specified, while dynamic losses (at 2 MV) are 105 and 113 W/cavity, less than the specified 125 W.

The 300 kW RF amplifiers, one per cavity, are of a novel design, consisting of four 80 kW IOTs with their outputs combined in a waveguide combiner [18].

The Low Level RF System, an analogue IQ system with a target performance of 0.5% rms amplitude and 0.2^o rms phase stability, is operational but not yet fully commissioned, since initial operation at 700 MeV was far outside its normal design parameters.

The cryogenic plant has achieved in excess of the specification, having demonstrated 488 W of refrigeration at maximum heater power (450 W specified), simultaneously with 20 l/h of liquefaction.

Survey and Alignment

The storage ring tunnel network consists of 48 survey monuments mounted on the inner wall, and 96 fixed targets mounted on the ratchet wall, requiring a total of 384 observations [19]. The initial girder alignment was provided by baseplates aligned with respect to the tunnel survey network and levelled to a local height datum. After completing the installation of the girders, a complete survey was carried out and the network readjusted. The resulting relative (absolute) radial positioning accuracy was in the range 25-70 (80-110) μm. The initial girder offsets determined by the survey were within 1.2 mm horizontally, 0.6 mm vertically, and 0.4 mrad in angle of their global design nominal position and orientation. In the time available before starting commissioning 20 girders were prioritised for final alignment. The alignment was completed in a single iteration using the girder mover system achieving the specified relative alignment tolerance and global position [10]. The remaining alignments will be completed prior to 3 GeV commissioning.

Vacuum

The vacuum system [20] is based on 316LN stainless-steel chambers with pumping provided mainly by ion pumps, augmented by Titanium sublimation pumps and NEG cartridge pumps. No in-situ bake-out is performed except for the in-vacuum and NEG-coated ID vessels, the “diagnostics straight” and front-ends. Straight section vessels and dipole/crotch vessels for the arc regions were supplied by industry clean, pre-baked and under-vacuum. These were then assembled by DLS into vacuum strings for each of the 3 girder types, up to 6 m in length, which were then baked in purpose built ovens at 200 ^oC, complete with ion-pumps and other attachments. The strings remained under vacuum with pressures of typically 1-2 10^{-10} mbar, until interconnections were made between them in the storage ring tunnel.

The 22 straight sections in which insertion devices can be installed have been completed initially with simple large aperture stainless steel vacuum chambers, with suitable tapered sections, supplied under vacuum and ready for installation. Although it was possible to perform an in-situ bakeout of these chambers, this was not carried out since the pressure levels after installation and pumping down were already sufficiently low.

After letting-up to dry Nitrogen, making the inter-connections of the vacuum vessels inside laminar flow tents, and pumping down, an average base pressure in the storage ring of 5 10^{-10} mbar was obtained.

STORAGE RING PHASE I COMMISSIONING

For radiation safety reasons, until the shielding can be verified, storage ring commissioning has been carried out outside normal working hours. As previously stated it has also been necessary to perform this at 700 MeV rather than 3 GeV because of the lack of cooling water. Rather than make the situation easier, this in fact added further complications, due to the lack of accurate magnet calibration data, the need to operate the RF at extremely low voltages resulting in poor signal/noise ratios and worse stability, and the need to operate the kicker magnets at a level where the pulse shapes had not been optimised. In addition, the long damping time (800 ms radially) affected the injection process.

Storage ring commissioning started on May 3rd when beam was successfully transported for the first time along the remaining part of the BTS and through the septum magnet. On the following night, the beam was circulated through a complete turn, without powering corrector magnets. On subsequent nights, 4 turns, and then 600 turns were achieved, without sextupoles or RF.

The next major achievement was obtaining 2000 turns on May 19th, with sextupoles on, and RF off, and on the following night survival for over 100,000 turns i.e. for 200 ms between injections from the booster, with RF on. The current surviving was initially extremely low, about 20 µA, however on the following night this was improved to 0.4 mA, representing 70% of the 2 mA circulating booster current (given the factor of 3.5 in circumference between booster and storage ring). Under those conditions switching injection off allowed the beam to be stored with a 1/e lifetime of 0.5 h.

Initially however there was no accumulation, the stored beam being lost each time the kicker magnets fired. This is believed to be due to a mis-match of the four kicker magnet pulse shapes [12] which had not been optimised for operation at 700 MeV. Following an optimisation of pulse amplitudes and timing it did however prove possible to accumulate more than 2 mA.

Tune values were generally within 0.4-0.5 of the model values, not unreasonable given the less precise magnet calibration data at 700 MeV. Measurements of the response matrix were carried out; these proved to be too noisy for detailed analysis, but were sufficient to show that there were no BPM or corrector polarity errors, and also to allow closed orbit correction to be carried out. Using the inverse response matrix the closed orbit was corrected to rms values of 1.3 mm horizontal, and 0.9 mm vertical, which is reasonable given the uncorrected position offsets of the girders and BPMs at that stage.

Only very small RF voltages were necessary to capture and store the beam, 100 kV or less, since the energy loss per turn was only 3 keV. At currents of 2 mA only a modest increase in vacuum pressure has been observed due to photo-stimulated desorption, approximately 5 10^{-10} mbar/mA in the arc regions. By comparison with simulations this is consistent with a desorption rate of approx. 10^{-3} molecules/photon, a typical value for an unconditioned, pre-baked stainless-steel vacuum system.

STATUS AND FUTURE PLANS

Phase I storage ring commissioning at 700 MeV has been a success, demonstrating that all major systems are working, and that beam can be accumulated and stored, albeit within the limitations imposed by operating at low energy and low beam current, due to the non-availability of water cooling. The booster is now operating at 3 GeV, and ready for injection into the storage ring at that energy.

Installation of insertion devices and remaining front-ends is currently underway. As soon as the cooling water issues are resolved, 3 GeV commissioning of the storage ring will then take place. Beamline commissioning will begin in October, with first external users and optimisation of the Phase I beamlines starting in January 2007.

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