THE DIAMOND LIGHT SOURCE BOOSTER RF SYSTEM

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Abstract

The Diamond Light Source (DLS) accelerator complex can be divided into three major components; a 3 GeV 561 m circumference storage ring, a 158.4 m circumference full-energy booster synchrotron and a 100 MeV pre-injector linac. This paper describes the design and presents commissioning results of the RF system for the booster synchrotron. Booster RF commissioning took place in late 2005 and early 2006 and involved the setting-into-operation of a 60 kW IOT amplifier, supplied by Thales Broadcast and Multimedia, a 5-cell copper cavity, manufactured by Accel Instruments, and a low-level RF system designed and built by Sincrotrone Trieste.

THE BOOSTER CAVITY

The accelerating cavity chosen for the booster of the Diamond Light Source is a copper structure of the PETRA type, manufactured by Accel Instruments [1]. Figure 1 is a photograph of the cavity installed in the booster.

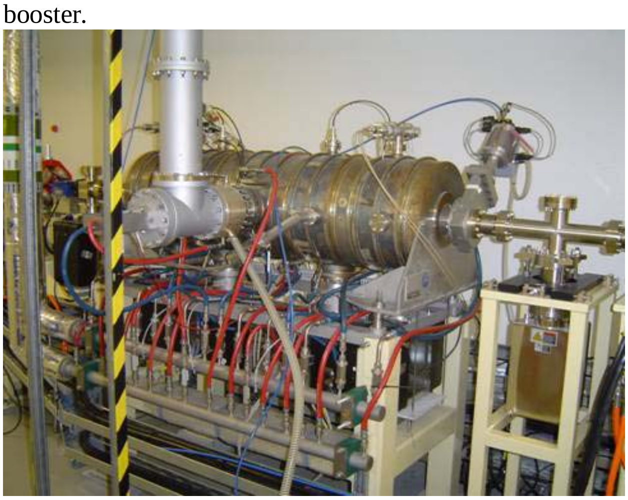

Figure 1: Booster cavity.

The cavity is a 5-cell structure with frequency tuning plungers mounted on cells 2 and 4. A water and air-cooled high-power coupler is mounted on cell 3 and the cavity is pumped by two 300 l/s ion pumps on cells 1 and 5. The coaxial transmission line and coupler are in the foreground of figure 1 and the tuning plungers are behind the cooling manifold under the cavity.

There are four pick-up loops in the cavity with a nominal sensitivity of 44.8 dB, and two full-range Pirani/IMG pressure gauge pairs.

The basic parameters of the cavity were measured during fabrication, and are given in table 1.

Table 1: RF cavity parameters

Parameter	Value	Unit
Operating frequency	499.654	MHz
Tuning range	499.315 – 500.365	MHz in atmosphere under ambient conditions
Q_0	29750	
RF power	60	kW

The field flatness of the assembled cavity without tuning plungers was determined prior to delivery to DLS with a bead pull measurement. The field flatness, defined to be the cell-to-cell difference in maximum amplitude – minimum amplitude, was 4.7 %. The accelerating voltage at 60 kW operation is 1.3 MV.

The cavity was evacuated and baked out before delivery. With all ports blind flanged, the leak rate was less than 2×10^{-10} mBar l/s. The bake-out lasted 60 hours at a maximum temperature of 160°C and the pressure in the cavity was 1×10^{-7} mBar before bake-out and 1×10^{-9} mBar after bake-out.

THE BOOSTER AMPLIFIER

The DLS booster amplifier is a 60 kW unit, manufactured by Thales Broadcast and Multimedia. It consists of a Thales DCX Millennium high power amplifier (HPA), together with a circulator, RF load and control and interlock system. The HPA uses a TH793 inductive output tube (IOT) for high power amplification. This is the same IOT as that used in the DLS storage ring amplifier [2]. The amplifier is connected to the cavity by a length of 6 1/8” coaxial transmission line.

The amplifier is designed to operate at power levels up to 60 kW, in both CW mode and in pulsed mode. When operating in pulsed mode, the amplifier output follows an arbitrary waveform at repetition frequencies up to 5 Hz. Basic amplifier parameters were measured at several different output power levels; a summary of 1 kW and at 60 kW CW operating parameters is given in table 2.

Table 2: Amplifier parameters

Parameter	1 kW	60 kW
Beam voltage [kV]	34.2	33
Beam current [A]	0.36	2.64
IOT drive power [W]	25	276
IOT gain [dB]	16.0	23.4
Beam efficiency [%]	8	69

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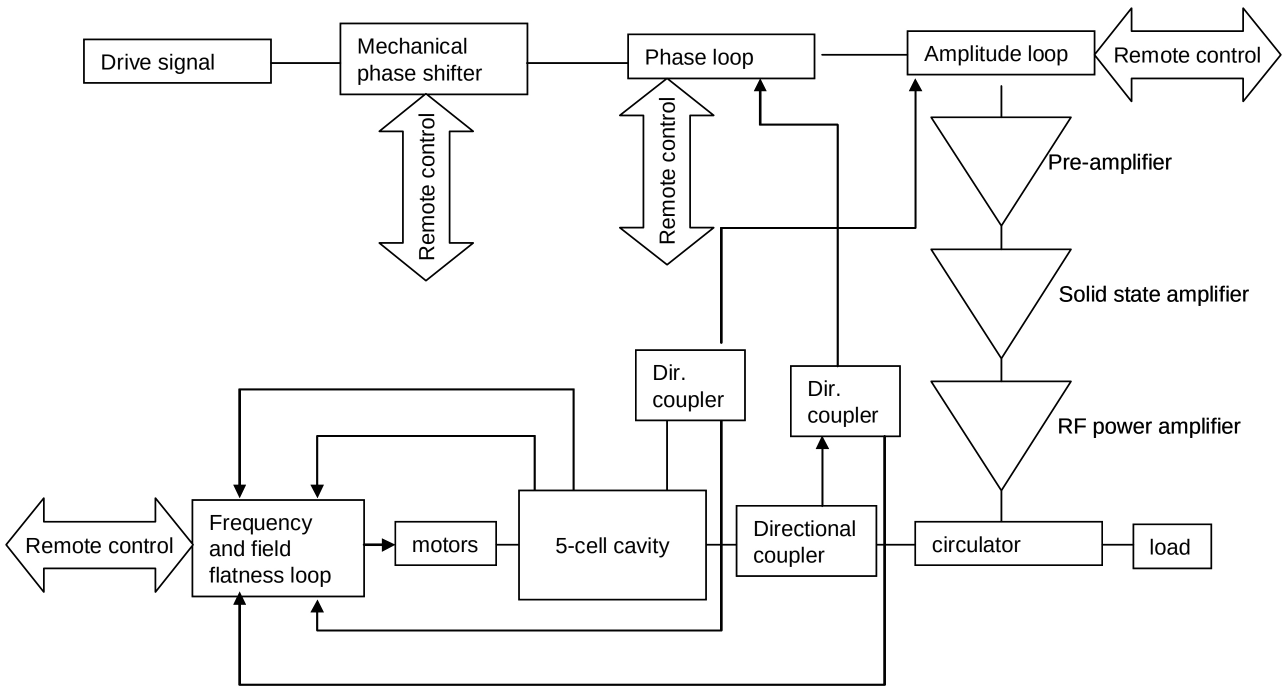

Figure 2: Interfaces between components in the booster RF system.

Harmonic content of the generated output power was investigated at multiples of the central operating frequency of 499.654 MHz at 6 kW operation and at 60kW operation. Harmonic suppression was found to be better than the specified value of 35 dB in both cases. Noise level within a ± 1 MHz band around the operating frequency was measured to be greater than 40 dB down on the peak power at operating levels of 10 kW and 60 kW. Both harmonic content and noise level measurements were around the noise floor level of the detecting apparatus.

Two extended time tests were carried out with the amplifier running into a water-cooled dummy load: an 8 hour full power run at 60 kW CW, and a 24 hour ramped run. During the ramped run the amplifier was driven by a triangular wave signal causing the amplifier output to rise linearly from 6 kW to 60 kW and then fall back linearly to 6 kW with a 5 Hz repetition frequency. The amplifier completed both endurance tests without interruption, and cooling water temperatures were measured to remain within specification for the entire duration of both tests.

LOW-LEVEL RF SYSTEM

The interface between the booster cavity, amplifier and DLS control system is handled by a low-level RF system (LLRF) manufactured by Sincrotrone Trieste (ST), based on similar systems developed by ST for ELETTRA, ANKA and the SLS. The LLRF keeps the cavity tuned, and controls the amplitude and phase of the cavity gap voltage. The LLRF is composed of an amplitude loop, a phase loop, frequency and field flatness loops together with a preamplifier and supporting hardware. Figure 2 is a schematic diagram illustrating the interfaces between the LLRF, cavity and amplifier.

The LLRF amplitude loop regulates the cavity gap voltage; it can operate in open loop mode, where the cavity voltage is set manually, or closed loop mode in which the amplifier drive signal level is regulated against a sample of the cavity field picked up in the central cell of the cavity. In both modes, the field is held to within ±1% of the target value. Recovery time for the amplitude loop from a 40% amplitude modulation is less than 10 ms.

A sample of the forward power into the cavity is taken at the directional coupler in the transmission line and is used together with the drive signal in the phase loop to maintain phase stability within ±0.5° over a phase range of ±30°. A mechanical phase shifter within the phase loop is used to provide a phase offset for the zeroing of the loop, and provides a phase shift of 290°/GHz. There is a further independent mechanical phase shifter identified in Fig. 2 with a phase range of over 400°.

Frequency and field flatness loops are built into one unit and act on the cavity tuning plungers. The frequency loop drives the two plungers simultaneously to compensate for changes in the cavity temperature and reactive beam loading, whereas the field flatness loop drives the two plungers independently to maintain an equal field in the different cells of the cavity. The pick-ups in cells 2 and 4 are used to provide the inputs to the field flatness loop, and the fields in the two cells can be maintained to within ±5% of each other. The response speed of the tuners has been established to be in excess of 1 kHz/s.

The first amplifier in the drive chain is part of the LLRF, and the signal from this unit is used to drive a 500 W solid state amplifier, which in turn drives the IOT. All control loops can be operated in local or remote mode.

SYSTEM PERFORMANCE

Cavity Conditioning

Cavity conditioning was carried out in two phases: first, in December 2005 to 20 kW and then, in early 2006 to the maximum cavity operational power of 60 kW. The first phase of conditioning was carried out without the LLRF system, with manual control of input power level and with tuner plunger positions set manually to minimise reflected power measured on the directional coupler in the transmission line. This was followed by initial LLRF commissioning at 20 kW, allowing the second phase of conditioning to use the LLRF amplitude loop and frequency and field flatness loops. A final test of LLRF was carried out in April 2006 at power levels up to 60 kW. Two regions of enhanced vacuum activity were found during conditioning: firstly between 5 kW and 9 kW, and then between 35 kW and 45 kW. These regions were conditioned out with careful control of input power level and conditioning pulse length.

Following the initial beam commissioning of the DLS booster to an intermediate extracted energy of 700 MeV, in which the RF plant was operated at a very low power level, it was found that the cavity required re-conditioning to reach 60 kW. This was a relatively short procedure lasting several hours, in which the CW power level into the cavity was increased from zero to the maximum. This ramp was controlled by a Matlab script which monitored the vacuum pressure within the cavity and regulated the input power level accordingly. A summary of the parameters recorded during a 30 minute sweep to close to full power following reconditioning is shown in Fig. 3.

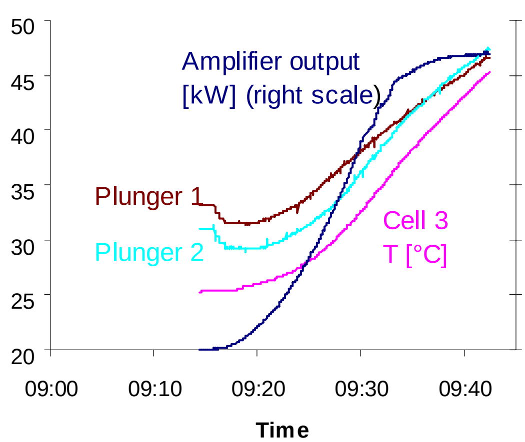

Figure 3: Slow ramp of power in booster cavity.

Figure 3 shows the rise in temperature of the central cell of the cavity, measured with a thermocouple, as the input power increases. As the temperature rises, the plungers move in to compensate for the change in resonant frequency of the cavity. The plunger position, in percentage of total travel, is on the left side of the figure, with 0% corresponding to the plungers fully out and 100% fully in.

CW and Ramped Operation

The first stage of booster commissioning with beam required RF capture. This involved application of a low level of power to the booster cavity with a 100 MeV circulating beam. The mechanical phase shifter was scanned through 360° and RF capture was apparent as an increase in beam lifetime at one phase setting.

Initial booster ramps were to 700 MeV, and in this mode the RF plant was operated in CW mode at power levels of 1 kW or less. Operation of the booster to the full energy of 3 GeV requires the booster voltage to be ramped. The booster operates with a linear ramp in power during the magnet ramp and then a linear recovery to the lower level when the magnet falls. An oscilloscope trace of the signal from the pick-up in the central cell of the cavity is for a full power ramp is shown in Fig. 4, illustrating the linear ramp. In normal 3 GeV operation the ramp is from 1 kW to 25 kW, corresponding to approximately 20 kV to 850 kV across the cavity.

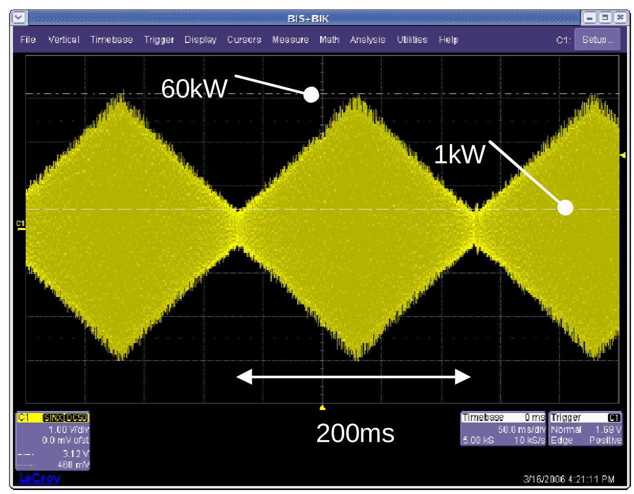

Figure 4: Oscilloscope trace of 5Hz fast ramping of power in booster cavity.

SUMMARY

The entire DLS booster RF plant, comprising cavity, amplifier, low-level RF and supporting infrastructure, cabling and controls has been commissioned and integrated. Ramping of the beam from 100 MeV to 3 GeV has been successfully carried out, using a 5 Hz linear RF ramp.

REFERENCES

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