Light Source R&D

High-Brightness Sources

The performance of electron storage rings, thanks to the strong damping provided by synchrotron radiation, is not strongly dependent upon the performance of the electron-beam source. Over the course of many turns around the ring, the electron bunches are "damped down" into a configuration set by the ring itself, independently of the source parameters. Next-generation linac-based light sources, such as x-ray free-electron lasers and energy-recovery linacs, are essentially single-pass devices, and their performance depends almost entirely on the ability of the source to provide high-quality, high-peak-current electron beams, both at and beyond the present state of the art. The knowledge to be gained from designing these next-generation injectors also offers high promise for developing the ability to construct other devices, such as compact, high-powered THz radiation sources and multi-MV electron microscopes.

The APS has constructed a high-brightness injector test stand (ITS) at the gun end of the APS linac. Located in a separate accelerator enclosure and powered via the APS linac waveguide switching system, the ITS was first employed to characterize the new electron guns used for APS storage-ring injection several years ago. It has recently been upgraded to permit testing of new, high-brightness injector designs.

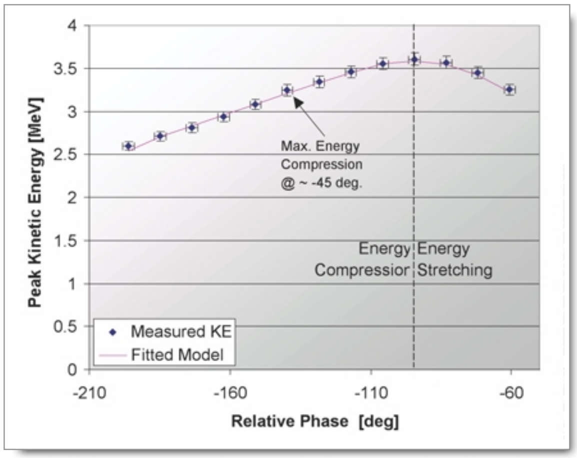

Fig. 4. Four-element CdTe detector, custom made by AMPTEK.

A ballistic-compression gun, intended to allow production of beams with very high peak currents and, more broadly, to explore longitudinal beam dynamics at low beam energies, is installed in the ITS. The initial benchmarking energy-compression experiments on the ballistic bunch compression gun have yielded results in very good agreement with theory (Fig. 4).

Provisions were also made for the installation in the injector test stand of a long-pulse drive, as well as a secondary beamline and rf shunt to allow two guns to be installed in the test area at the same time. This is being done partly to help expand the test stand's role in supporting ongoing APS operation (for instance, providing a gun specifically for operator training purposes), as well as to help prepare for the future requirements for the APS (for instance, testing ns-pulse lasers for direct booster injection applications).

Work has also continued on new injector designs, such as the higher-order mode rf gun, and novel focusing schemes to improve beam control and performance.

Operating Storage Ring Klystron rf Systems in Parallel

352-MHz rf System Topology

The APS storage ring rf systems operate at a nominal rf frequency of 351.93 MHz and supply the necessary rf power to store up to 300 mA of electrons at 7 GeV. There are four 1.1-MW klystron-based continuous-wave (CW) rf systems dedicated to supplying power to the 16 storage ring rf cavities. A waveguide switching/combining system (Fig. 5) is utilized to direct and combine the outputs of the four rf systems to provide

Fig. 5. Doug Horan (left) and Geoff Pile (both ASD-RF) walking under the rf waveguide switch #1.

12 discrete operating modes. These modes allow single-ended or parallel operation of the storage ring rf systems. Parallel-klystron operation will be required to store more than 150 mA in the APS storage ring because the total amount of rf power required will exceed 2 MW CW.

The 16 single-cell rf cavities in the storage ring are grouped in 4 sectors of 4 cavities each. These four sectors are combined in pairs, with each pair being driven by either a single rf station or two rf stations operating in parallel. In both cases, WR2300 3-dB hybrids, are used as splitters in single-ended modes or as a combiner/ splitters in parallel modes. Motor-driven WR2300 phase shifters located after the hybrid output ports compensate for output phase changes that depend on whether the hybrids are being driven in single-ended or parallel fashion. The phase of the rf power that drives the storage ring cavity sectors must be kept within approximately 5° of optimum for stable beam operation, and the rf power must be equally divided between the sector-pairs to avoid stressing cavity components. The use of 3-dB, 90° hybrids to combine and then equally split the output of two rf systems requires that the output amplitude and phase of the parallel rf systems be controlled to within 6% and 2°, respectively. Low-level rf and high-voltage power supply controls are utilized to maintain these amplitude and phase tolerances.

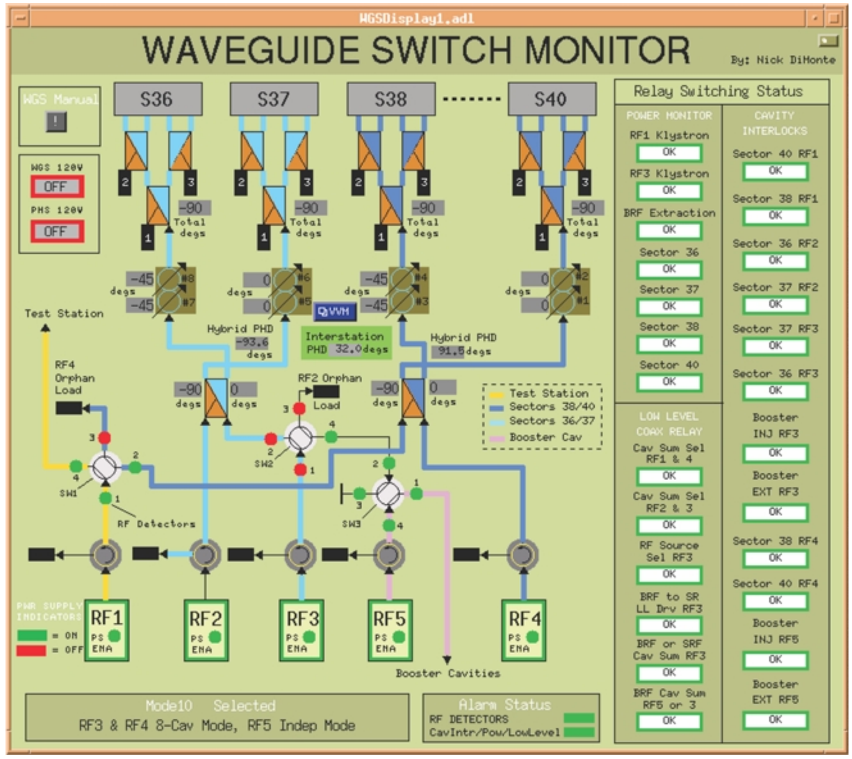

Fig. 6. APS rf waveguide switching and combining system.

PARALLEL-KLYSTRON PHASE AND AMPLITUDE CONTROL

In the APS parallel klystron configuration, the rf power output from two 352-MHz rf systems is combined and then split by a 3-dB 90° WR2300 waveguide hybrid. Each of the two outputs of the hybrid supplies one-half of the combined rf power to one sector of rf cavities. Directional couplers installed in the straight waveguide sections just prior to the hybrid ports sample the signals at each port of the hybrid. All of these directional couplers are positioned at precisely the same distance from each hybrid port waveguide flange to establish accurate phase references.

The two rf stations are operated in parallel configuration utilizing a "master-slave" relationship. As shown in Fig. 6, RF1 is the master station and RF4 is the slave station. The phase-control loop maintains a constant phase relationship between the two stations at the input of the hybrid. A vector voltmeter is used as a phase detector to minimize amplitude-to-phase cross modulation, with the reference input of the voltmeter driven by the output of the master station. The setpoint of the phase-control proportional-integral-differential (PID) card is manually adjusted to maintain the power balance between the hybrid output ports.

The amplitude-control loop maintains a constant amplitude relationship between the two stations at the input of the hybrid, utilizing two envelope detectors and a PID amplifier to generate a slave-station amplitude control voltage.

Fast rf interlocking is used to prevent overpowering of the rf cavities, should the outputs of the two parallel rf stations drift appreciatively out of phase from one another at the input ports of the combining/splitting hybrid.

SYSTEM PERFORMANCE WITH STORED BEAM

Initial no-beam tests of the parallel-klystron operating mode were performed in August 1999, with RF1 and RF4 configured in parallel mode. These tests demonstrated that the gap-voltage phase stability of the paralleled rf stations met the 1° peak-to-peak specification for the APS rf systems, with a static phase error of -3.5° between the output ports of the combining/splitting hybrid when the hybrid input powers were equal. In December 1999, 50 mA of beam was successfully stored using RF1 and RF4 operating in parallel mode and RF2 operating in single-ended mode. In the first high-current run that took place on September 30, 2001, 200 mA was stored using RF1 and RF4 operating in parallel mode and RF3 operating in single-ended mode.

SUMMARY OF THE 225-MA TEST RUN

After the successful 200-mA run, the RF Group completed installation and testing of all final-version hardware required for full parallel operation of the storage ring rf systems. This operating mode ("mode 1") configured RF1 and RF4 as one parallel pair, and RF2 and RF3 as a second parallel pair. This work was necessary to permit storage ring operation at currents higher than 200 mA.

On December 22, 2003, 225 mA was successfully stored with the rf systems operating in mode 1. This operating mode provided great flexibility in terms of uniform rf power require-

The new stand-alone EPICS IOC is shown here in the hands of Eric Norum (Controls Group), one of the developers of the device. This low-cost module, which is essentially a PC running Linux, can be used to implement an EPICS control system with much of the capability as the entire control rack seen above Eric's left shoulder.

ment and distribution from each klystron. A main concern during the current ramp to 225 mA was the reaction of two independent storage ring rf gap voltage, automatic gain-control feedback loops due to a beam loss, and how quickly the rf power to the cavities would be reduced to safe levels. There were only two trips attributed to rf cavity pressure spikes, and the recovery from both events was quick. There were some elevated temperatures in the rf cavities as the stored beam current was increased, but none of the cavity-component temperatures reached their upper allowed limits. After each beam dump, RF Group personnel were on hand to manually reset the rf system parallel control loops in preparation for injection. This function will be automated in preparation for the next high-current run.

It is clear more than ever that keeping the rf cavities under vacuum for a long time increases their power-handling capability. This was evident during the 225-mA high-current run.

In summary, full parallel-mode operation of the storage ring rf systems made it possible to reach 225 mA without stressing klystrons and while staying within comfortable operational parameters. Long-term conditioning of the rf cavities with and without beam made a huge difference in high-power handling of the cavities and their performance.

EPICS "iocCore"

The real-time accelerator and beamline control system at the APS is based on the Experimental Physics and Industrial Control System (EPICS) software toolkit, which was developed as a collaboration between Los Alamos National Laboratory and the APS Controls and Computing Group beginning in 1990 (see *APS Science 2002*). Since then, EPICS has grown in popularity among accelerator laboratories, telescope facilities, and even commercial applications and has become globally recognized as a capable, robust, and flexible platform upon which to build a control system. There are currently over 150 licensed users of the EPICS software, with many large Department of Energy facilities among them. Most beamlines at the APS and numerous beamlines at other light sources (14 at the National Synchrotron Light Source alone) use EPICS as the basis for beamline control. The APS continues to be a major contributor to the EPICS collaboration and is directly involved with EPICS development, documentation, distribution, and coordination.

Like all other accelerator technologies, EPICS must continually advance to stay current with emerging technology. A significant enhancement in the EPICS toolkit beginning with V.3.14.1 (December 2002) allows users of EPICS to take advantage of emerging computer platforms while significantly reducing the cost of EPICS implementation.

From its initial development, the real-time portion of EPICS (known as iocCore) was written to use a commercial real-time operating system (VxWorks® from Wind River Systems). Although VxWorks is extremely capable and robust, choosing it limited the selection of hardware that could be used for an input output controller (IOC). Almost all IOCs prior to V.3.14 consisted of a VME chassis, a VME single-board computer (for which VxWorks support was available), and a collection of VME modules for connections to the technical equipment. Many EPICS users found the "buy-in" cost to be as much as $10,000 to build their first IOC, an amount that was prohibitive for small projects.

However, thanks to EPICS V.3.14, EPICS iocCore can now be easily ported to different operating systems, greatly increasing the choices for implementing an IOC and reducing the buy-in cost. The standard distribution already supports numerous platforms, including Linux, Windows™, Solaris, Mac OS X, and RTEMS (an open source, real-time operating system). It is now possible to implement a stand-alone EPICS IOC for less than $500. This greatly increases the range of applications where EPICS is an attractive solution, suitable for even small projects.

Beamline Control Software

The Beamline Control and Data Acquisition (BCDA) Group has developed beamline software for APS-managed sectors 1 through 4, and has routinely made this software available to other facility sectors. With the expansion of the number of APS-managed sectors, BCDA interactions with sectors have increased even more. In particular, this accelerated activity has led to BCDA playing a key role in upgrading the beamline control system for IMMY/XOR.

Conversion of beamline-control software to work with the latest version of EPICS (V 3.14) allows beamline software to run on many more operating systems than possible under earlier versions of EPICS. The new operating systems include Linux and Windows. (We have noticed that Linux is becoming

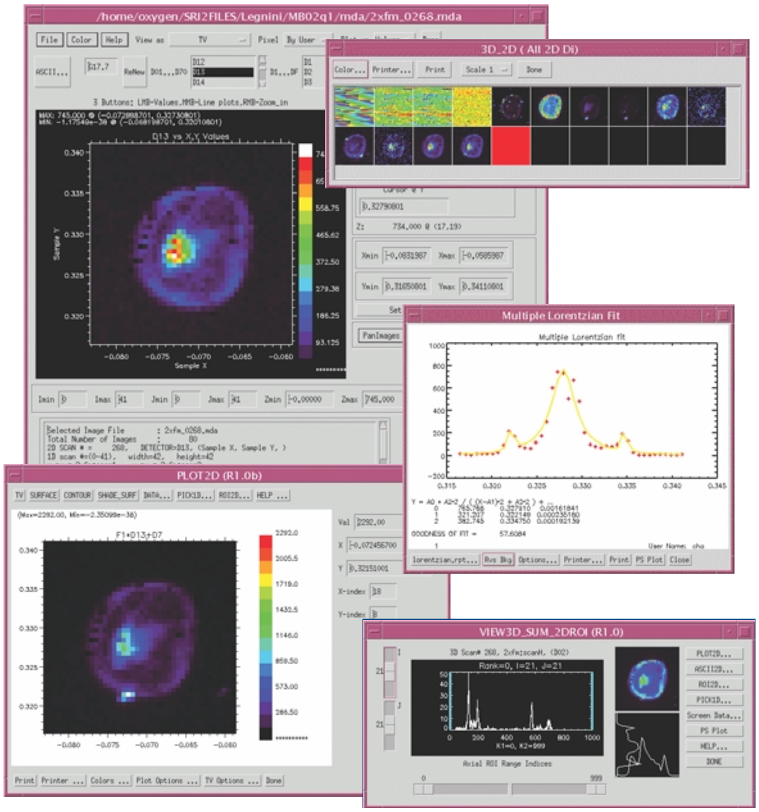

Fig. 7. Typical ScanSee display windows.

the most popular operating system among the APS user community.) Python, a powerful scripting language that has many advantages for use on beamlines, was used to write software to thoroughly test EPICS run-time calculation software. Python was also used for new modules to read and display scan data stored by beamline-control software.

EPICS plays a major role in another important BCDA initiative: data visualization. Using the RSI interactive display language (IDL), BCDA developed a flexible and easy-to-use visualization package. The EPICS/IDL visualization package includes a collection of general-purpose data visualization tools with simple analysis capabilities and several special-purpose scan-data visualization programs, such as catcher, viewer, and ScanSee (Fig. 7). They are written in the IDL programming language plus an interface layer of EPICS channel access function calls. All the visualization tools written in IDL are easily accessed by simple mouse clicks and are designed to be user friendly. The newly released IDL 6.0 also provides a new feature called the IDL virtual machine. This allows users to run previously compiled IDL programs without an IDL license. The BCDA took advantage of this fact by converting scan visualization tools to run on the IDL virtual machine. All visualization tools have been fully tested on both UNIX™ and Windows™ systems. They are available to users for free download from the BCDA web page (http://www.aps.anl.gov/aod/bcda/.

A new distribution system for beamline-control software has been introduced to make it easier for APS sectors to obtain BCDA software. By mirroring runable copies of most beamline software on APS-managed file servers, from which sector workstations and VME crates are permitted to read, the new distribution system enables sectors to use, and develop with, BCDA software without having to build or install it.

STREAMING VIDEO SYSTEM

A streaming video (SV) system has been installed at the APS for operational and diagnostics use in the accelerator facility. The system is composed of multiple Apple® Xserves running QuickTime Broadcaster to encode and multicast video data onto the APS computer network for viewing on client computers using the open-source Mpeg4ip SV software (Fig. 8). A key feature of this setup is the low latency in the video that is viewed on a client computer. The latency of the video (the amount of time needed for a packet of data to go from one designated point to another) is 1 s or less. Latency is a critical factor in the real-time environment of accelerator controls. Most SV systems are set up to buffer at least 3 s, or more, of video. This would impose a challenge to accelerator operators who must respond to events that occurred several seconds ago.

The APS SV system is integrated into the site-wide video distribution system. This allows computer systems within the APS to access any of the video sources on site (diagnostic cameras, instruments with video outputs, etc.). Switching and routing of the video signals to the SV system are done with the integration of the video system components via EPICS. The system is also set up to allow remote access; authorized persons away from the facility can view the video streams by logging in to the APS via the virtual private network. This is a valuable tool for remote troubleshooting during user runs. Remote users employ Apple's QuickTime Player application (Fig. 8) on a Macintosh or Windows PC to access a low-bandwidth stream. Plans to provide video archiving of streamed video for training and other uses are also under way.

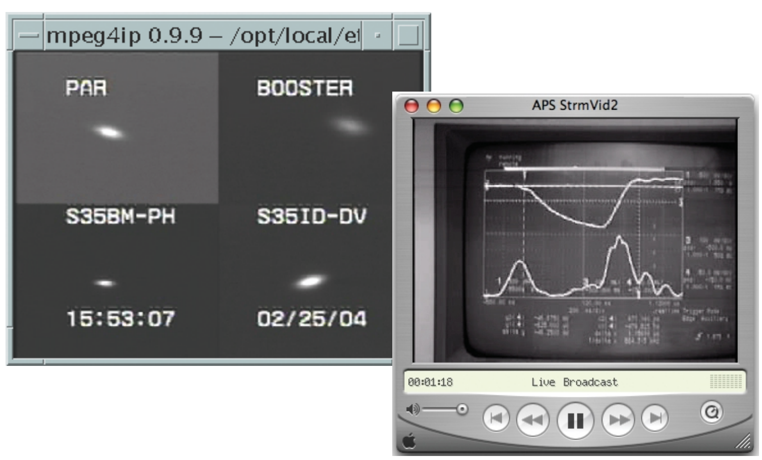

Fig. 8 (top). Mpeg4ip streaming video software shown running on a Solaris workstation. The software runs on Solaris, Linux, and Mac OS X. Bottom: QuickTime Player application showing a video stream from off site.