

# CONSTRUCTION, COMMISSIONING AND OPERATIONAL EXPERIENCE OF THE ADVANCED PHOTON SOURCE (APS) LINEAR ACCELERATOR

M. White, N. Arnold, W. Berg, A. Cours, R. Fuja, A. E. Grelick, K. Ko\*, Y. L. Qian\*\*, T. Russell\*\*\*, N. Sereno, and W. Wesolowski

Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439-4800 USA

\*ASIC Designs, Inc., Naperville, IL, \*\*IIT, Chicago, IL, \*\*\*Ehrhorn Tech. Ops., Colorado Springs, CO

## Abstract

The Advanced Photon Source [1] linear accelerator system consists of a 200-MeV, 2856-MHz S-band electron linac and a 2-radiation-thick tungsten target followed by a 450-MeV positron linac. The linac system has operated 24 hours per day for the past year to support accelerator commissioning and beam studies and to provide beam for the user experimental program. It achieves the design goal for positron current of 8 mA and produces electron energies up to 650 MeV without the target in place. The linac is described and its operation and performance are discussed.

## Introduction

The Advanced Photon Source [1] linear accelerator system consists of a 200-MeV, 2856-MHz S-band electron linac and a 2-radiation-thick tungsten target followed by a 450-MeV positron linac. The linac is designed to accelerate 30-nsec-long pulses containing 50 nC of electrons to an energy of 200 MeV at 48 pulses per second. The 480-W beam is focused to a 3- to 5-mm diameter spot on a 7-mm-thick water-cooled tungsten target that serves as a positron converter. A 1.5-T pulsed coil immediately downstream of the target refocuses the bremsstrahlung-pair-produced (BPP) positrons and electrons and directs them into the positron linac. Electrons and positrons can be accelerated to about 450 MeV. Final optimization is achieved by rf phasing combined with focusing corrections to optimize matching into the Positron Accumulator Ring (PAR). Electrons transported directly from the gun to the end of the positron linac can reach an energy of 650 MeV.

Initial commissioning of the APS injector and storage ring was performed using primary electrons from the linac. Commissioning then proceeded for several months using BPP electrons in order to ensure that the linac reliability would be adequate for positron production. Linac reliability was good, and magnet polarities in the PAR, synchrotron, and storage ring were reversed in July of 1996. The APS facility has operated with positrons since that time, serving the scientific user community and accelerator physicists and engineers. Use of positrons avoids ion-trapping problems.

## Equipment - rf

Figure 1 shows the basic features of the linac. For clarity, the electron and positron linacs are drawn parallel to each other in the figure. Electrons are produced by an

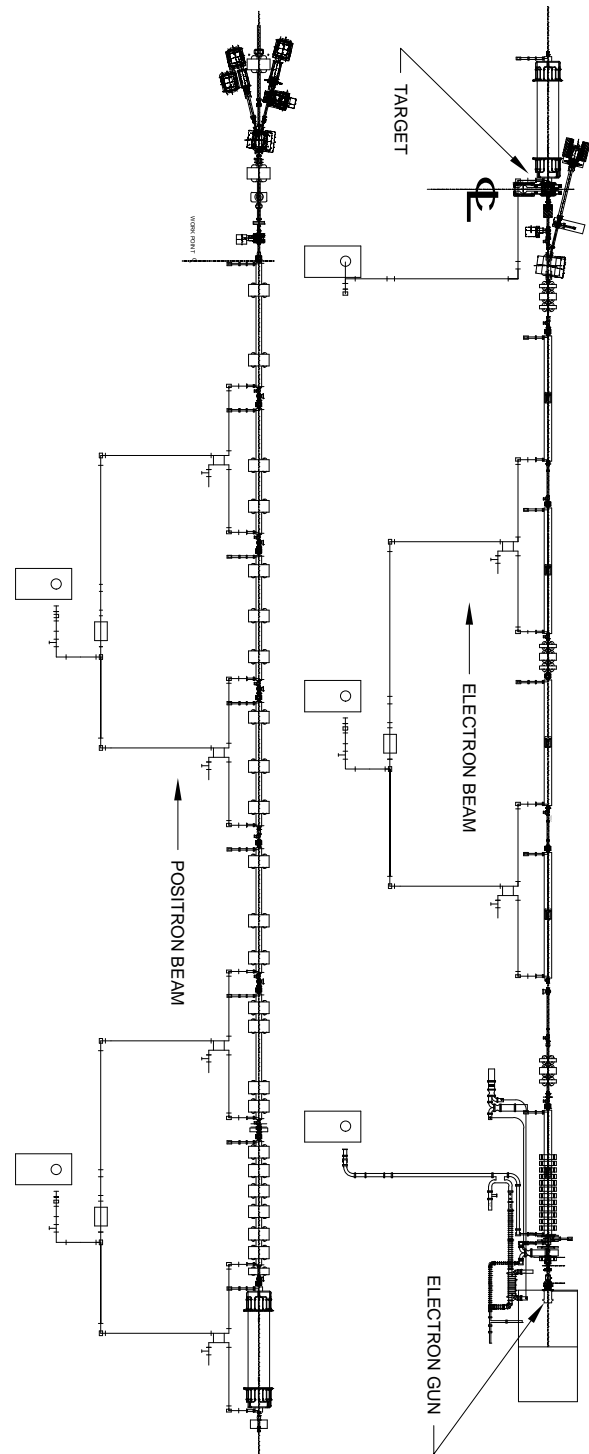


Fig. 1. Schematic view of the linac. The electron and positron linacs are shown parallel to each other for clarity, and the two scales are slightly different.

electron gun with a thermionic cathode. They are transported with the aid of focusing lenses to a single-gap prebuncher and a constant impedance ( $v_p = 0.75c$ ) buncher, both of which operate at 2856 MHz.

The beam then enters a 3-m-long, SLAC-type accelerating structure surrounded by Helmholtz magnets and is accelerated to 50 MeV. Further acceleration to 220 MeV is accomplished by four additional accelerating structures in the electron linac. The five accelerating structures in the electron linac and nine in the positron linac are powered by five 35-MW TH2128 pulsed klystrons. The upstream accelerating structure in each linac is directly powered by a klystron, while the remaining 12 structures are powered in groups of four by a klystron and SLED cavity assembly as indicated in Figure 1. Coupling cells at the output ends of the structures direct rf power into water-loads to be dissipated as heat. Power to the klystrons is provided by 100-MW line-type pulse modulators [2].

Accelerating structures, SLED cavities, and waveguide components are kept at constant temperature ( $\pm 0.1^\circ\text{F}$ ) to maintain cavity dimensions and energy stability. To find the operating temperature, the SLED cavity assembly is detuned, and beam energy is measured while the temperature of the accelerating structures and other rf components in that sector is varied. The operating temperature is reached when maximum beam energy is achieved. The SLED is tuned to achieve maximum beam energy at that temperature. Optimum temperatures are different for each sector and also must be re-established when changes are made to building temperature setpoints or air-flow patterns.

The modulator and SLED trigger timing in each sector are individually adjusted to achieve maximum energy gain.

A basic operation in setting up the linac is to establish the correct phase between rf components. Phase is initially set using diagnostic lines at the end of each of the two linacs (see Figure 1). A dipole magnet bends beam out of the linac and into a separate beamline equipped with a beam position monitor (BPM) [3], fluorescent screen [4], and a Faraday cup.

Phase is optimized by maximizing beam energy and minimizing energy spread, while viewing changes in the beam image. Some effort has been devoted toward automation of the phase optimization process. The image width on the fluorescent screen varies with the energy spread and its position varies with energy. Proper phase is maintained by automatic phase-control software [5]. The auto-phase control screen is shown in Figure 2. Phase and amplitude of the buncher and prebuncher are adjusted to maximize transport efficiency in the electron linac and minimize energy spread in the positron beam.

Additional information about the rf instrumentation is provided in a separate paper in these proceedings [6].

## Beam Diagnostics

Linac beam current is measured by a toroidal coil and three wall-current monitors. Beam position is measured by eleven 4-button stripline BPMs that also measure the beam current [3]. Diagnostic instrumentation performance is discussed elsewhere in these proceedings [6].

Electrons and positrons are simultaneously accelerated in the positron linac. If phasing is chosen to optimize positrons, the electrons then fall into the next available bucket and are accelerated, but have lower energy and larger energy spread than the positrons. Unfortunately, readouts from the wall-current monitor and BPMs in the positron linac are unreliable during positron runs, due to the mixed nature of the beam. A harmonic BPM [6,7,8] currently under development will enable us to differentiate between the two species.

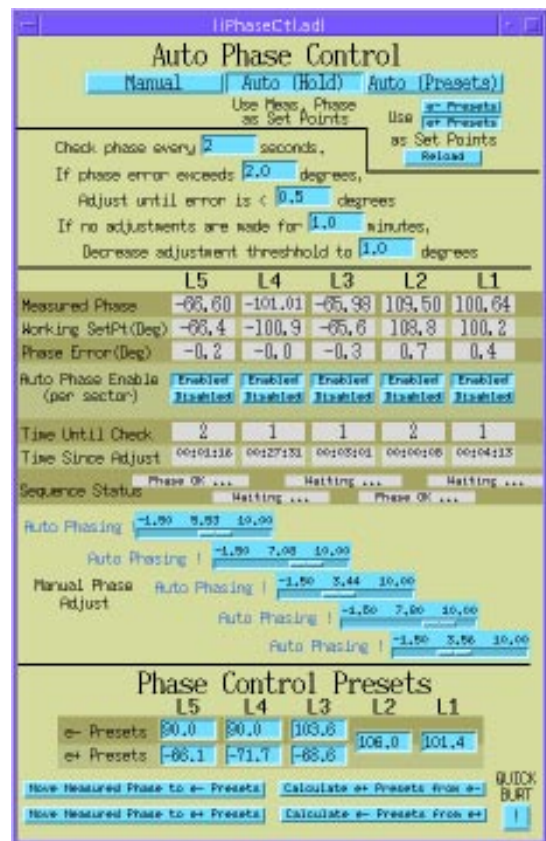


Fig. 2. The automatic phase control screen allows storage of all measured phase values in memory, individual phase adjustment, calculation of positron phase from electron phase and vice versa, and fast loading of pre-recorded phase values.

The positron linac diagnostic line, shown in Figure 3a, was used to simultaneously measure beam energy and energy spread of the positrons and electrons in our mixed-species beam after it had been optimized for positrons. Data in Figure 3b were obtained by using sddsexperiment

[9] to sweep the mixed beam across the Faraday cups at the end of the positron linac. Other sdds [9] routines were used to process and present the data.

Beam profile information is obtained by inserting fluorescent screens [4] that are viewed by cameras into the beam. Real-time beam images are visible in the control room, and digitized information can be collected and analyzed via the controls system. Experience with CID cameras has been fairly good thus far, even in the high radiation area near the target. CCD cameras have not fared as well, and some have degraded noticeably within days.

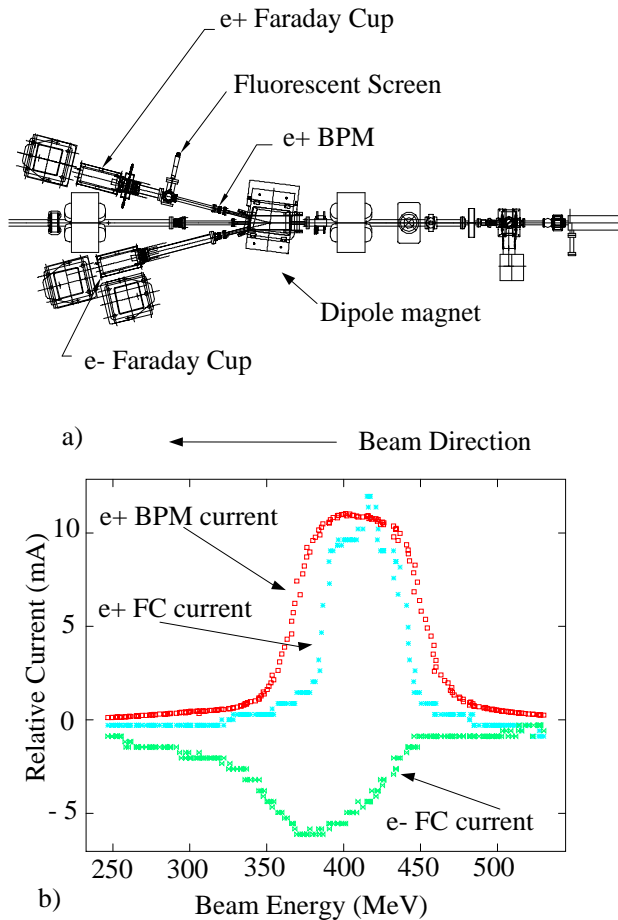


Fig. 3. Diagnostic line at the end of the linac (a), showing Faraday cups (FC), dipole magnet, and a BPM. Electron and positron energy and energy spread with beam optimized for positrons (b). Data were collected by sddsexperiment [9].

Fourteen gas-filled particle detectors run the length of the linac and allow areas of high beam loss to be localized.

Real-time beam current, position, and profile information are used to optimize settings for the 42 focusing and 38 steering magnets throughout the linac. Magnets can be controlled singly or in groups by simple scripts. For example, transport efficiency from the gun to the target was improved from 60% to greater than 85% after a systematic algorithm to optimize focusing and

steering in the first sector was developed and applied.

Beam position information, rf power measurements, and corrector magnet response matrices are used as input to any of several automatic trajectory control programs for beam within the linac and to energy control programs for beam injected from the linac into the PAR [10].

Trajectory control is also extremely useful during beam tuning and optimization of new linac configurations.

## Radiation Measurements

The linac shielded enclosure is constructed of 2-m-thick concrete along the entire length between the linac and the klystron gallery. The shield is modified in the vicinity of the positron target, where 0.4-m-thick steel plates are embedded within 1.6-m-thick concrete to further reduce photon radiation levels in the klystron gallery. Calculated unshielded x-ray dose rates inside the linac tunnel 1 m downstream of the positron target are as high as  $7 \times 10^9$  mrem/h. Unshielded neutron dose rates are on the order of  $10^6$  mrem/h at that position.

Measurements of radiation from the target were made in normally occupied areas of the klystron gallery using gamma and neutron instruments. The measured data are compared to computations of the estimated radiation leakage [11] at the nominal operating power, as shown in Figure 4. The linac safety envelope is set at 1 kW of beam power. It can be defined in terms of beam power since production yields of secondary radiation, including positrons, neutrons, and gamma rays, are proportional to beam power within the linac's energy range. Measured radiation fields were due only to gammas, and no detectable neutron radiation has ever been found.

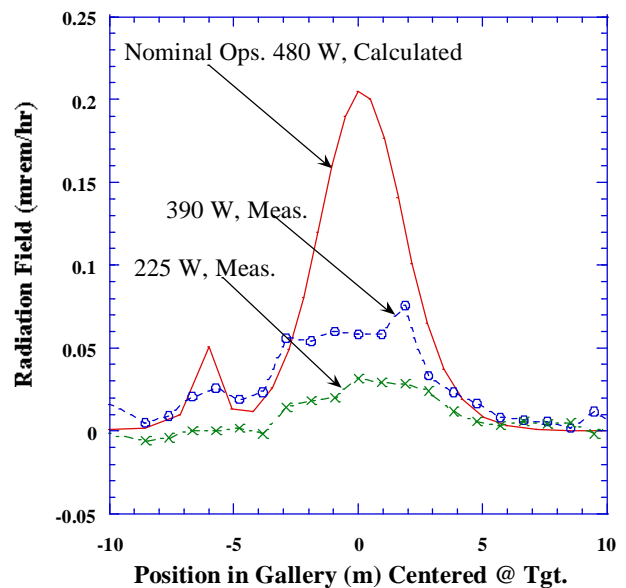


Fig. 4. Calculated radiation field in the klystron gallery at the nominal 480 W operating power, and measured gamma radiation at 225 and 390 W.

Penetrations in the shield wall that permit passage of transmission waveguides, cables, water, and other utilities are individually shielded and are frequently monitored to ensure that there is no abnormal radiation leakage.

Since radiation levels near the linac are extremely high during operation, all linac systems capable of producing or accelerating beam are interlocked to the personnel safety system. These systems are deactivated by two independent chains by doubly redundant methods whenever the tunnel is open for access or when beam permissive is removed for any reason.

Radiation levels in all potentially occupied areas near the linac are within DOE guidelines.

### Performance

Table 1 summarizes the achieved linac performance to date.

Table 1. Linac Performance Summary		
<b>Electron Linac</b>	Design Goal	Achieved
<b>e<sup>-</sup></b>		
Energy on Target	200 MeV	240 MeV
Pulse Length	30 ns	30 ns
Target Spot Size	$\phi \leq 3$ mm	$\phi \leq 5$ mm
Power on Target	480 W	390 W
Current on Target	1.7 A	> 2.0 A
Repetition Rate	48 pps at a 60-Hz rate	Beam: 30 Hz rf: 60 Hz
Maximum Energy	650 MeV	> 655 MeV
Energy Spread	$\pm 8$ %	$\leq \pm 8$ %
Emittance (mm mrad)	$\leq 1.2$	$\leq 1.2$
<b>Positron Linac</b>	Design Goal	Achieved
<b>e<sup>+</sup></b>		
Energy	450 MeV	454 MeV
Current	8 mA	14 mA
Energy Spread	$\pm 1$ %	$\leq \pm 1.6$ %
<b>BPP e<sup>-</sup></b>		
Energy	Unplanned	> 400 MeV
Current	Unplanned	> 17 mA

### Control and Monitoring

The linac is controlled by the Experimental Physics and Industrial Control System (EPICS) [12]. EPICS is extremely flexible and, when combined with the sdds toolkit [9], provides a powerful environment for monitoring as well as active and passive control of the accelerator and its various subsystems.

A powerful save, compare, and restore (SCR) tool allows a detailed record of any given accelerator configuration to be created and stored. Previously recorded configurations can be restored, in part or totally, and an

existing accelerator configuration can be compared to any previously recorded files to within predetermined tolerance levels.

Extensive data are recorded by the Archiver and are readily available for further analysis, a feature that is extremely useful for long-term problem debugging. Records are kept of all standard process variables (PVs) as well as PVs that are calculated relationships between other PVs, such as the klystron perveance. An alarm logger maintains a comprehensive record of all alarms, and those data are also available for processing.

### Planned Improvements

The APS facility plans a 95% or better availability; thus the equipment reliability is critical. Several improvements are underway to increase the overall reliability of the linac.

Transmission waveguide vacuum has been less reliable than desired due to fragile braze joints. Most waveguide sectors have temporary patches and indium-coated gaskets. New waveguide has been procured and will be installed in the next few months.

Accelerating structure removal and cleaning procedures are well known as a result of an accident at the beginning of linac commissioning; however, we wish not to repeat the exercise. Additional rf windows will be installed along with the new waveguide in order to isolate all water loads. This will prevent flooding should a water load fail for any reason in the future.

Efficient positron production and acceleration requires all modulators and klystrons to be functional, thus a sixth klystron and modulator that will act as a switchable spare is being constructed. This system will enable normal linac operation to continue after a short switching delay.

The use of constant current power supplies [13] to replace some modulator components is being actively pursued as a means to improve modulator reliability. One of these supplies is now being installed in the sixth modulator for testing.

### Future Plans

#### LEUTL

Plans are underway to add a separate electron source in the linac capable of significantly lower normalized emittance and higher peak current than the present DC gun. To implement this, we initially plan to install a thermionic rf gun source and alpha magnet pulse compressor combination, but ultimately we plan to upgrade to a photocathode-based rf gun. This new, high quality source forms the heart of the Low-Energy Undulator Test Line (LEUTL) [14].

The LEUTL has a number of different purposes. One is to allow for the testing of specialized undulators before

their possible installation into a storage ring. Yet another example is to explore such beam/undulator operating modes as that expected during self-amplified stimulated emission (SASE) below 100 nm.

### Slow Positrons

The linac can be used for various purposes between injection cycles, including slow positron production [15]. The nominal beam power of 480 W can be greatly increased for slow positron production by detuning the SLEDs and increasing the beam pulse length. Target design simulation studies are underway at this time. Safe operation of the facility must be assured and radiation issues must be addressed in detail. A possible layout of the slow positron area and the LEUTL beamline is shown in Figure 5.

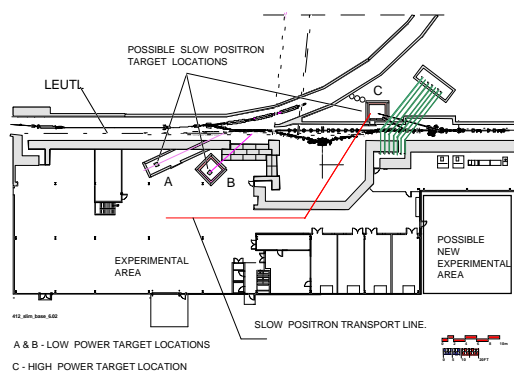


Fig. 5. A possible layout of the slow positron target area, beam transport, and experimental area. The upstream end of the LEUTL is also shown.

### Conclusions

The linac has met its design goals and reliably produces positrons for injection into the PAR. Injection efficiency for positron operation is still being improved, but has been as high as 65%. Improvements to the linac are planned, and future plans include a low energy undulator test line and SASE FEL, and a slow positron source.

For information about the Advanced Photon Source, and about Argonne National Laboratory, please check our Web Page at <http://www.aps.anl.gov/welcome.html> and the links therein.

### Acknowledgments

Work supported by the U. S. Department of Energy, Office of Basic Energy Sciences under the Contract W-31-109-ENG-38. We would particularly like to acknowledge M. Douell, D. Fallin, C. Gold, J. Goral, J. Hoyt, D. Jefferson, T. Jonasson, M. Lagessie, D. Meyer, S. Pasky, L. Peterson, V. Svirtun, and D. Yuen for their efforts in

constructing the linac; J. Haumann for overseeing design and construction of the modulator controls; and Mr. F. Onesto for expediting. We thank G. Mavrogenes for his valuable insight and experience. Slow positron target simulations are carried out by E. Lessner. We also acknowledge the efforts of the entire APS staff who constructed, commissioned, and now operate the facility. Lastly, we greatly appreciate the expertise of D. Haid in graphics manipulations for this document.

### References

- [1] 7-GeV Advanced Photon Source Conceptual Design Report, ANL-87-15, April 1987.
- [2] T. Russell and A. Cours, "Klystron Modulator Operation and Upgrades for the APS Linac," Proc. of the 1995 Particle Accelerator Conf., 1-5 May 1995, Dallas, TX, pp. 1559-1561 (1996).
- [3] R. E. Fuja and M. White, "Performance of the Advanced Photon Source (APS) Linac Beam Position Monitors (BPMs) with Logarithmic Amplifier Electronics," Proc. of the 1995 Particle Accelerator Conf., 1-5 May 1995, Dallas, TX, pp. 2595-2597 (1996).
- [4] W. Berg and K. Ko, "Status of the Fluorescent Screens and Image Processing for the APS Linac," Beam Instrumentation Workshop Proc., Santa Fe, NM, Oct. 1993.
- [5] A. Grelick et al., "Phase Control and Intra-Pulse Phase Compensation of the Advanced Photon Source (APS) Linear Accelerator," Proc. of the 1995 Particle Accelerator Conf., 1-5 May 1995, Dallas, TX, pp. 1082-1084 (1996).
- [6] A. E. Grelick, R. Fuja, N. Arnold, and M. White, "Rf and Beam Diagnostic Instrumentation at the Advanced Photon Source Linear Accelerator (Linac)," these proceedings.
- [7] W. Sellyey, private communication.
- [8] N. Sereno, R. Fuja, "Positron Beam Positron Measurement for a Beam Containing Both Positrons and Electrons," Beam Instr. Wkshp., Argonne Nat'l. Lab. May 1996, to be published.
- [9] M. Borland, "A Self-Describing File Protocol for Simulation Integration and Shared Postprocessors," Proc. of the 1995 Particle Accelerator Conf., 1-5 May 1995, Dallas, TX, pp. 2184-2186 (1996).
- [10] L. Emery, N. Sereno, private communication.
- [11] H. J. Moe et al., "Radiation Measurements at the Advanced Photon Source (APS) Linear Accelerator," Proc. of the 1995 Particle Accelerator Conf., 1-5 May 1995, Dallas, TX, pp. 1064-1066 (1996).
- [12] L. Dalesio et al., "The experimental physics and industrial control system architecture: Past, present and future," *Nucl. Instrum. and Methods A* **352**, 179 (1994).
- [13] Electronic Measurements Inc. Neptune, NJ Models 202,203.
- [14] S. Milton, private communication.
- [15] M. White and E. S. Lessner, "The Advanced Photon Source (APS) Linear Accelerator as a Source of Slow Positrons," Proceedings of SLOPOS-7, Unteragregi, Switzerland, 2-7 June 1996, to be published.