Two major excavation / construction projects have taken place around the main ring at Fermilab during a four week August-September shutdown. The use of precast construction techniques permitted them to be completed comfortably within the scheduled time.

1. To the southeast of the Central Laboratory building, the transfer hall has been lengthened to help in maintenance and to reduce personnel exposure to residual activity (particularly important at the higher intensities at which the accelerator is now running). It will also make extraction at 1 TeV feasible. The main ring lies exposed on the left and a precast tunnel section is being lowered into position in the transfer hall.

geometry should they be needed.

Typical targets will be 3.5 cm of copper or molybdenum. The expected pion intensities which can be directed into the patient are typically $2 \times 10^9$ per s, giving a dose rate of 50 rads/min in a cylindrical volume of 1 litre. A therapy fraction may thus be delivered in a few minutes.

Work is now proceeding on the constructional details, on the very demanding therapy planning schemes necessary to realize the required doses in all cases, and on the numerous administrative activities with international and Swiss medical personnel, concerned with the coordination and realization of therapy in the course of 1979.

FERMILAB

Preparing for colliding beams

A three week Study on colliding beams was held in Aspen, Colorado, from June 27 to July 15 concentrating on proton-proton and antiproton-proton collisions using the Fermilab Main Ring and Energy Doubler / Saver. A year ago, the decision was taken to exploit the possibility of colliding the proton beams in the two accelerators and a new Department, the Colliding Beams Department headed by Jim Cronin, was established in the Research Division. The study was organized by this Department to aid its work in the coming months. It involved about fifty physicists from 15 institutions and laboratories in the USA (including ERDA and NSF) and guests from CERN and Saclay.

The two principal objectives are to achieve proton-proton collisions at energies up to 1 TeV against 250 GeV with a luminosity of $10^{28}$ per cm per s or more and antiproton-proton collisions in the Doubler / Saver providing up to 2 TeV in the centre-of-mass with a luminosity of $10^{29}$ or more.

As a step towards the first objective, experiments on beam storage have been under way in the Main Ring to investigate its suitability as a storage ring. The results of these experiments (reported below) were one of the major topics of discussion, led by Alvin Tollesstrup, at the Study. As a step towards the second objective, the Accelerator Division under Russ Huson has started construction of a small ring beside the Booster to test electron cooling of a proton beam; work on this topic at the study was led by Peter McIntyre of Harvard/Fermilab.

The test ring for the electron-cooling was given considerable attention and some aspects of the interaction of the solenoidal magnetic field at the cooling region with the beam were clarified together with corresponding necessary modifications of the lattice. Other subjects were a detailed comparison of the electron beam design with that planned in the equivalent cooling project at CERN, a review of antiproton production cross-sections, target system, beam transport and acceptance by the Booster. Two solutions were obtained to the problem of correct phasing of the r.f. system for simultaneous acceleration of both antiprotons and protons in the one ring. Utilization of the intense antiproton beams available at up to 1 TeV for fixed target physics was also considered and preliminary discussions were held on a more ambitious antiproton cooling project that would yield higher luminosity.

There were three other headings for the discussions — beam manipulation at intersection regions (led by Bob Diebold of Argonne), detectors (led by Dave Hitlin of SLAC) and other topics (led by David Ayres of Argonne).

Two basic arrangements for bringing about Main Ring / Doubler collisions were studied — a transposed geometry in which the beams cross and a 'kissing' geometry in which the two beams are brought to touch while moving in opposite directions.

In general, the transposed geometry has more flexibility and was found to be better suited to experiments. For example, a full 50 m can be left free for experiments with a fixed interaction point at the centre and the luminosity can be increased by adding special magnets to make the beams cross at a small angle and still leave approximately 10 m for a detector. The special magnets are considerably more straightforward in the transposed scheme. The principal drawback is that at least one sixth of the Main Ring must be lowered and the Energy Doubler built as a non planar machine.

The detector group considered detection systems emphasizing the physics of particle production at large angles and studied optimum systems for the two cases of asymmetric proton-proton collisions of 1000 and...
250 GeV and symmetric 1000 and 1000 GeV antiproton-proton collisions.

Four magnetic detectors received attention — solenoid, dipole, toroid, and magnetized iron configurations. The solenoid design was chosen as the best for the central detector. A thin superconducting coil with a radius of about 1.25 m and a length of 6 m producing 1 to 1.5 T served as the basis and various track chamber packages for inside the coil were examined. Liquid argon with lead plates located just outside the coil was regarded as a suitable photon and electron detector. Iron for the return flux was integrated into a hadron calorimeter utilizing proportional tubes and located behind the argon detector. Finally, 0.5 m or so of iron constituted an outer shell and acted as an external muon identifier. End-cap detectors were envisaged to increase the angular coverage.

The major item for the General Topics group was the design of colliding beam areas. Various designs that could accommodate a variety of experiments were examined and recommendations were made to perform some radiation measurements to help the design. These measurements and final area design will be a major activity in the next year.

Consideration was given to the future development of a bypass to the Main Ring providing up to a 300 m long straight section for studying colliding beam interactions under optimum conditions at up to 2 TeV. Finally, the possibility of a 15 GeV electron beam in the Main Ring colliding with 1 TeV protons in the Energy Doubler was considered; a luminosity of $10^{32}$ per cm$^2$ per s appeared feasible.

The storage ring tests

The characteristics of the Main Ring at Fermilab as a storage ring have been explored in several recent accelerator study periods, in preparation for its use as part of the colliding beam facility. The time dependence of the beam intensity along with transverse and longitudinal beam distributions were measured as functions of vacuum pressure, horizontal and vertical machine tune, beam energy and other operating conditions.

Most stores were initiated at intensities from $1.5 \times 10^{13}$ protons and the energy varied from 75 GeV to 200 GeV. The pressure averaged around the ring was $10^{-7}$ torr or less. Backgrounds at a long straight section were measured and significant effort went into the control techniques so as to simplify the storage procedure and to record the data of interest.

Scattering from residual gas is one cause of deterioration of beam quality and reduction of intensity, setting a limit to how long a useful beam can be stored. There are two ways that a proton can interact with a nucleus of the residual gas — the catastrophic nuclear interaction and the gentler, but much more frequent, Coulomb scattering. A proton undergoing a nuclear interaction is immediately lost and this mechanism alone should lead to an exponential decline in intensity without altering beam size. With a pressure of $10^{-2}$ torr the predicted lifetime is 12,000 s roughly independent of energy. Lifetimes, measured from the initial rate of change of intensity during a store, have been as long as 25,000 s (about 7 hours), corresponding to an average pressure of about $5 \times 10^{-8}$ torr.

Coulomb scattering, on the other hand is a diffusion process leading to gradual growth in beam size. Initially, when the size is well within limiting apertures, very little beam is lost but as the size grows protons can pass beyond the boundary. After a long time, the beam asymptotically approaches a size determined by the limiting aperture and the intensity then decays exponentially with a lifetime that depends quadratically on the energy. At $10^{-2}$ torr, the expected lifetime for this process is 2800 s at 100 GeV and 11,200 s at 200 GeV.

As in normal acceleration, the horizontal and vertical tunes of the machine (number of betatron oscillations per revolution) are extremely important variables when storing a beam. For example, setting the tune at the fifth-order resonances at 19.4 causes rapid beam growth and intensity loss, and, conversely, at the empirically-determined best tunes, the intensity dependence approaches the gas scattering limits.

As understanding of the intensity dependence grew, more attention turned to the transverse and longitudinal beam distributions. The luminosity for head-on collisions is directly proportional to the product of the two beam intensities and inversely proportional to the beam size. The
longitudinal distribution of a bunch affects the length of the interaction region and hence the size of the detectors.

Transversely, the beam growth rate settles down to the predicted gas scattering value after an initial period of about a minute of somewhat faster growth which can be prevented by starting with longer bunches. The bunch length grows from about 2 to 5 ns in a similar period and then stabilizes. The early evolution of these beam distributions is receiving much experimental and theoretical attention.

The backgrounds in the straight section were large and the variations with angle and distance from the beam pipe were measured under various conditions. Integrating the early measurements gave an estimated total flux of 230 MHz through a hypothetical detector of 1 m radius for 10^{13} protons in the ring; later measurements, with somewhat better average pressure, correspond to a flux of 84 MHz.

There are indications that the backgrounds are due to high multiplicity events affecting a small fraction of the bunches. The background rate is approximately proportional to intensity (rather than to proton loss rate) and to local vacuum pressure, suggesting an origin in local beam-gas interactions. A bakable vacuum pipe has been installed in the straight section to reduce local pressure and further background reduction will be accomplished by means of vacuum improvements throughout the ring, by shielding, and by beam scrapers.

### Building particles from new quarks

The observation at Fermilab of high mass enhancements in muon pairs is evidence, though not yet conclusive, for the existence of a new heavy quark (see August issue, page 223).

The study of the spectroscopy of the now abundant charmed mesons has enabled physicists to parameterise the interaction between heavy quark-antiquark pairs and months before the sighting of the Upsilon enhancements by the Columbia / Fermilab / Stony Brook collaboration, E. Eichten and K. Gottfried from Cornell had pointed out that heavier quarks, if they existed, would have an even richer spectroscopy. The structure which already seems to be seen in the Upsilon enhancements could bear this out.

By analogy with the well known positronium bound states of an electron and a positron, these quark-antiquark bound states are often referred to by an 'onium' suffix, so that the bound states of a charmed quark and a charmed antiquark (the J/psi family) are examples of 'charmonium'.

For the lightest quarks (u and d — the constituents of the nucleons), the quark-antiquark binding is not powerful enough to form proper 'onium' states but only resonances which decay strongly. For the strange quark (s), the situation is marginal. The phi meson, for example, is only just above the threshold energy for strong decay into KK. If the ss binding were a little more powerful, then a 'strangeonium' bound state would be seen.

For charmed quarks (c), the masses and binding energies are such that the lowest lying cc bound states cannot decay into a channel which displays 'naked' charm. The lightest of the naked charm mesons, the D, has a mass of 1864 MeV, and a charmonium state has to be heavier than 3728 MeV (2 x 1864 MeV) before strong decays into D mesons become possible. Lighter charmonium states, like the J/psi at 3095 MeV, therefore have very high stability (narrow widths) compared with their heavier counterparts and this was the feature which made the J/psi discovery so dramatic.

Since the discovery in 1974 of the first charmonium states, at 3095 and 3684 MeV respectively, the spectroscopy of charmonium has been unfolded by an impressive series of experiments at SPEAR and DORIS.

The new states correspond to higher excitations of the qq interaction, to states where the qq has rotational angular momentum as well as intrinsic spin, and to states where the qq spins line up antiparallel. Quarks with spin 1/2 can bind together as qq states either with their spins parallel (total spin 1), or antiparallel (total spin 0). These latter charmonium states are particularly difficult to observe as their symmetry properties preclude them from coupling directly to a photon and they are therefore seen only indirectly in the decays of the spin 1 states formed in colliding beam experiments.

The interaction between a quark and an antiquark can be simulated by a static attractive potential that is independent of quark mass. Neglecting spin effects, the expected spectrum of bound states can then be calculated using the Schrödinger equation, where the quark mass comes in through a kinetic energy term. The calculated

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**The predicted variation in the pattern of quark-antiquark 'onium' bound states, neglecting spin. The shaded area shows where strong decays into mesons having 'naked' flavours are possible.**

On the left, one sees the spectrum of charmonium with 1s (the psi), 2s (psi prime) and 1p (chi) states all below this threshold. The higher the quark mass, the greater the number of stable (narrow width) states.