INTENSE ION BEAM APPLICATIONS TO MAGNETIC CONFINEMENT FUSION

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A handwritten signature in cursive script, reading "Daniel Hammer", with a long horizontal flourish extending to the right.

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I. Introduction

This is a request for renewal of Contract No. DE-AS02-77ET53005 for the period October 15, 1980 to October 14, 1981.

The objective of the Ion Ring project funded by this contract is to trap a ring of high energy, axis-encircling ions in a magnetic mirror. The number of ring ions should be such as to produce $\delta B/B$ on the ring axis of order 10%.

During the past year excellent progress has been made towards this objective on the IREX. A 3% diamagnetic ring of 430 keV protons is formed in an 8 kG solenoid using a magnetically insulated annular ring shaped diode which injects a hollow annular beam through a magnetic cusp. This ring couples its axial energy to azimuthal currents induced in the background plasma when injected into 15-400 mT air. Over 50% of the ring is reflected from a downstream mirror. Azimuthal currents are not induced if the background is a hydrogen plasma. This is explained in terms of the fact that the pulse time is greater than the hydrogen cyclotron period which shorts the radial electric field required for driving azimuthal currents.

Most noteworthy of the experimental results is the fact of the dispersionless propagation of the 3% diamagnetic ring for 2 m to the downstream mirror. This means that the self-field is in equilibrium with the axial beam energy spread of <10 keV (in the beam reference frame). Thus, the care expended in the careful design of the diode in which the injected ions are born on a flux surface to reduce their spread in canonical angular momentum has been vindicated by the small energy spread downstream of the cusp. A maximum diamagnetic signal of 875 G

($\delta B/B \approx 8\%$) from a diode power of only 0.05 TW has been achieved by bunching the beam against a 33% upstream mirror (peak field 10.5 kG).

The second experiment, LONGSHOT, is directed to producing a long pulse ion beam source so that the total number of protons required for an ion ring can be provided at lower diode power and, hence, at much less cost than that of 100 nsec pulsed power generators like the NRL GAMBLE II.

LONGSHOT now routinely produces 600-700 nsec 100 keV, 10 kA peak ion beams and 3×10^{16} protons are injected through a cusp into a spatially increasing solenoidal field. Spatial bunching has been observed.

A detailed report of the progress during last year on both IREX and LONGSHOT is given in Sec. II.

In any practical fusion reactor based on a compact torus geometry created by charged particle beam injection, the confined high β plasma also contributes a significant fraction of the toroidal current. Field reversed ion ring equilibria with axis encircling orbits and a confined plasma with a pressure profile $p(\psi)$, where ψ is the flux function, have been computed by means of a modified form¹ of RINGA code.² Figure 1 shows an ion ring without plasma and Fig. 2 shows the same ion ring with a confined plasma of $\langle\beta\rangle \sim 0.51$, where β is computed with respect to the external field. Note that the plasma current $I_p = 0.34 I_b$, the fast ion beam current. Figure 3 shows a field reversed equilibrium composed entirely of plasma currents with no fast ions encircling the

JTHETA

TIME= 500.

MAX= 1.88E-01 DELTA= 1.88E-02

EQL14
FRAME 35

FLDLINES

TIME= 500.

MAX= 6.75E+00 DELTA= 3.38E-01

EQL14
FRAME 34

FIG. 1. Azimuthal current density contours and magnetic field lines for an Ion Ring Equilibrium without plasma using RINGA.

$$\langle \beta \rangle \approx 0.51$$

$$-4- \quad I_p/I_b \approx 0.34$$

JTHETA

TIME= 1000.

MAX= 1.73E-01 DELTA= 1.73E-02

ASM04
FRAME 43

FLDLINES

TIME= 1000.

MAX= 6.75E+00 DELTA= 3.38E-01

ASM04
FRAME 42

FIG. 2. Azimuthal current density contours and magnetic field lines for an Ion Ring Equilibrium with plasma using RINGA.

FIG. 3. The flux surfaces of a field reversed equilibrium produced entirely by plasma currents. (from RINGA)

axis. This example would correspond to say a field reversed θ -pinch geometry. Although these equilibria seem equivalent in so far as the shape of flux surfaces are concerned, they will have considerable differences in their stability properties. It is known experimentally from work with E-rings that no tilting instability is observed for equilibria of Fig. 1 while it is quite likely to occur for those of Fig. 3. The important question is whether mixed equilibria of Fig. 2 are stable to tilting.

A recent theoretical investigation³ based on the energy principle of Sudan and Rosenbluth⁴ shows that thin bicycle tire equilibria are stable to tilting for $\zeta \equiv \delta B/B \sim a/R$, where R/a is the aspect ratio of the ring. Clearly the situation will improve for low aspect ratio compact tori but numerical methods will be required to complete the calculation for this case. To test the proposition that stability can result if the toroidal

current is shared between energetic ions and plasma drifts, a model calculation³ is performed as follows. A spheromak equilibrium is perturbed by the inclusion of a small component of toroidal current to be carried by a rigid rotor distribution $f_R \sim \exp - (H + \Omega P_\theta)/T$, where H is the particle energy, P_θ is the canonical angular momentum, and T is the temperature. The perturbed equilibrium is found to be an oblate spheroid as opposed to a sphere in the absence of fast particle current. This in itself has a stabilizing influence. Further stabilizing effects come from the gyroscopic action of the fast particles but the calculation is not complete as of the time of submitting this proposal.

In any case, it is worth realizing that the ultimate configuration is that of Fig. 2, which could be approached in either of two ways:

- (1) by creating a field reversed ring and then trapping a hot plasma; this approach is being followed by Fleischmann in electron rings; and
- (2) inject an ion ring which is not fully field reversed into a field reversed configuration made up of plasma currents, e.g., the LASL reversed field θ -pinch.

Addressing ourselves to the second approach we find that several questions have to be examined theoretically and experimentally viz.:

- (i) will the rate of field line reconnection be fast enough to allow the ring to enter the θ -pinch configuration, (ii) will the ring lose enough axial energy not to exit from the θ -pinch. Recent calculations⁵ show that the reconnection rate in cases where the current is carried by fast particles is much higher than the corresponding plasma case so that the answer to the first question is probably in the affirmative. The second question will be tackled numerically on the RINGA code. If the second approach is feasible the possibility of a steady state reactor in which the field reversed compact torus is maintained by charged particle injection becomes very attractive.

We expect to look more deeply into the above considerations of a hybrid ion ring/compact torus during the coming year and the possibility of directing the IREX and LONGSHOT programs towards this end.

The proposed program for FY 1981 is furnished in Sec. III. The goals of this program are the production of stronger proton rings than the present 3-8% levels and better understanding of their dynamics.

The work statement and budget for FY 1981 are provided in Sec. IV. For the complete performance of all the tasks requires a budget of \$216,000. If some of the tasks are shifted to FY 1982 as indicated in Sec. IV, a reduced budget of \$175,000 is presented.

II. Progress, October 1979 - August 1980

Since our last proposal was written in September of 1979, major advances have been made on both of our Ion Ring Program experiments, IREX and LONGSHOT. IREX has now demonstrated all of the physics issues needed for the trapping of an ion ring produced by a ≤ 100 nsec generator in a magnetic mirror field. LONGSHOT now routinely produces 600-700 nsec, ~ 100 keV, 10 kA peak current ion beams, and 3×10^{16} protons are injected into a solenoidal magnetic field and spatially bunched. Details of these results are described in this section together with a discussion of some of their implications to the formation of ion rings. Our proposed experimental program, to continue these experiments and exploit the results described in this section, is contained in Sec. III.

A. IREX

In this section we report experimental results on the formation and dynamics of a rotating proton ring using a short pulse (≤ 100 nsec) pulsed power generator. This experiment, called IREX (Ion Ring Experiment), has been described in detail in earlier proposals. Therefore, our description of the apparatus is brief here, and we shall concentrate on results.

1. The IREX Apparatus and Operation

A schematic diagram of IREX is shown in Fig. 4. The proton source is an annular magnetically insulated diode powered by a 90 nsec, 550 kV (typical peak voltage), 90 kA peak current pulse from the Neptune 800 generator. The diode is contained within a 2.5 m long, 3 second

Figure 4. Schematic of IREX showing: A - Neptune generator output terminal; B - anode support structure and coil; C - DC solenoidal field coils; D - cathode support structure with 2 μm mylar foil; E - typical proton orbit; F - upstream mirror coil; G - wall resistor wires; H - diagnostic cantilever; I - aluminum vacuum vessel; J - acrylic ring; X - magnetic pickup loop. Also shown is the magnetic field profile on axis with (dashed line), and without (solid line), the upstream mirror coil energized.

pulse solenoid driven by a Transrex SCR power supply and operated at 8 kG in most of the experiments discussed here. The pulsed coils within the anode of the diode (Fig. 5) provide both closed magnetic flux surfaces around the anode which insulate against electron flow, and a cusp-like transition to the solenoidal field. The radial component of the cusp field converts beam energy to rotation as the beam drifts to the uniform section. This field shape has two special properties: 1) protons are all born on approximately the same flux surface, as indicated by Fig. 5, so there is little spread in their canonical angular momenta; 2) unlike a standard cusp, the radial component of the Lorentz force is radially inward, rather than outward, on the upstream side of the separatrix. The first property tends to minimize the axial velocity spread of particles which traverse the cusp, assuming the diode voltage is reasonably constant. The second property is found experimentally to allow the cusp to be operated near the critical field for cusp transmission without serious beam defocusing. Let us now briefly consider single particle dynamics in an axisymmetric cusp analytically to provide a basis for the first property.

The field produced by the "D.C." coil and the anode coils can be characterized by the vector potential $\tilde{A} = A_{\theta}(r,z)\hat{e}_{\theta}$, in which case the canonical angular momentum P_{θ} of an ion of charge q and mass m can be written

$$P_{\theta} = mr^2\dot{\theta} + qrA_{\theta}/c. \quad 2.1$$

Figure 5. Ring3 diode cross section. The magnetic flux surfaces are dashed, the coils are crosshatched, and the aluminum vacuum vessel is shaded. A - Vacuum vessel; B - Cathode flashover switch; C - Coils; D - "Active" anode; E - Cathode foil holder; F - $2\mu\text{m}$ mylar cathode foil; G - Edge for virtual cathode formation.

In the uniform region of the solenoid, $A_\theta = rB_0/2$, where B_0 is the magnetic field in that region. For an axis-centered orbit, we have $\dot{\theta} = -\omega_c$ and $P_\theta = -qr_g^2 B_0/2c$, where $r_g = mc v_\perp / q B_0 \equiv v_\perp / \omega_c$ is the gyroradius and ω_c is the gyrofrequency of the ion. Since the total particle kinetic energy W_T is $\frac{m}{2}(v_\perp^2 + v_z^2)$, we may write

$$\frac{1}{2} m v_z^2 = W_T + \omega_c P_\theta. \quad 2.2$$

For a particle which is not axis-centered this relationship becomes

$$\frac{1}{2} m v_z^2 + \frac{m}{2} \omega_c^2 r_{gc}^2 = W_T + \omega_c P_\theta. \quad 2.3$$

In this form, we can see two implications: 1) launching all particles axially ($\dot{\theta} \approx 0$) from the same flux surface, i.e., a surface of constant rA_θ , and with the same kinetic energy, minimizes the downstream axial velocity spread and radial extent of the resulting rotating ion beam; and 2) there is a maximum value of the field B_0 for which a particle can traverse the cusp, namely when r_{gc} and v_z are both zero,

$$B_{MAX} = \frac{\sqrt{2mW_T}c}{qr_g}. \quad 2.4$$

Returning now to the operation of IREX, upon traversing the cusp, the ring propagates 2 m to the 1.23 mirror ratio downstream mirror, M_2 , where it is partially reflected if B_0 is sufficiently close to

B_{MAX} . Variable mirror M_1 , necessary for ring trapping if sufficient axial energy can be removed from the ring, is produced by a pulsed coil within the 40 cm diameter aluminum vacuum vessel. The ring may lose axial energy by inductive coupling to an array of resistor wires located between 70 and 190 cm from the diode, or to plasma currents if a neutral gas is present in the chamber. For most of the experiments described here, the beam is injected into the cusp region through a 2 μ m thick mylar foil, with about 130 keV energy loss, into 15-400 mT of neutral gas. The resulting beam-produced plasma enables the beam to be charge neutralized as it propagates through the cusp region, as we shall discuss shortly.

Diagnostics used to evaluate diode operation and proton ring formation and dynamics include the following: 1) ten fast magnetic pickup loops to measure magnetic field changes on the axis at 20 cm intervals from 32 to 212 cm from the diode; 2) magnetically insulated Faraday cups oriented to measure the rotating proton flux; 3) four small Rogowski belts to measure the current induced in four of the wall resistor wires; 4) magnetic probes outside the ring oriented to measure axial and azimuthal magnetic fields of the ring; and 5) thermofax paper witness targets to measure the radial extent of the ring.

Figure 6 illustrates typical traces in an IREX pulse showing the three time scales and the relative timing of the different parts of the apparatus, the "D.C." solenoidal coil, the pulsed field coils, and the pulsed power generator. Of particular interest here is the

Figure 6. IREX timing sequence. The DC field coil is energized by the Transrex power supply. After 2.5 sec the 130 kJ bank is fired into the anode coil, followed a few hundred μsec later by the 10 kJ bank firing into the upstream mirror coil. When the anode coil current has reached the proper value, the comparison circuit fires Neptune. Inductively corrected diode voltage and diode current waveforms are shown.

shape of the diode voltage waveform. Because the cusp acts as an energy filter, and because the magnetic fields are set near B_{MAX} the useful portion of the pulse is seen to be only about 60 nsec.

2. Results

It was found early on that if an ion beam was injected into an evacuated experiment chamber (pressure ≤ 0.5 mT), even with "flashboards" surrounding the beam in the cusp region as were used on our earlier experiment ANNEX,⁶ beam propagation was unacceptably poor. This was "cured" by separating the diode region from the drift chamber with the 2 μ m mylar foil referred to previously, and back-filling the chamber with 15-400 mT of air, H_2 , D_2 , or He. This is shown in Fig. 7 in which the beam dispersion and loss is obviously worse in the 0.1 mT data from diamagnetic probes as compared to the 30 mT data. Evidently the presence of the neutral gas allowed space charge neutralization of the beam in the cusp region to take place. Further experiments showed that gas fills of at least 15 mT air, 60 m H_2 and 100 mT He gave good beam propagation. Thermofax paper witness targets were used to determine the radial extent of the beam at various axial locations in the chamber with 30 mT air; sharply defined annular rings were obtained up to 220 cm from the diode with inner and outer radii of 6 cm and 13 cm, respectively. (Note that the mirror M_2 is located at 200 cm.)

Proton beam dynamics in the magnetic mirror region are a strong function of the gas species and a weak function of pressure. A lower bound on the beam generated plasma density is obtained by

Figure 7. Beam propagation in 30 mT vs. 0.1 mT air for three consecutive and otherwise identical shots.

considering only impact ionization by the fast protons. Using tabulated cross sections,⁷ plasma densities of about 4×10^{12} and $1.5 \times 10^{13} \text{ cm}^{-3}$ are produced by the 25 A/cm^2 ($1.7 \times 10^{11} \text{ cm}^{-3}$) beam in 100 mT of hydrogen and air, respectively. Ionization by secondaries and avalanching in the induced electric fields of the beam will surely cause these densities to be substantially higher. Null measurements of azimuthal magnetic fields with magnetic probes show that the ring is 90-100% axially current neutralized by induced plasma currents. Azimuthal plasma currents, on the other hand, are observed only in the heavier gases - air, nitrogen, and helium, but not in hydrogen or deuterium. Three plasma current "signatures" are seen: the magnetic signals (1) persist after passage of the high energy protons, (2) are often flat-topped, evidently due to the plasma current starting to flow as some critical plasma condition is reached, and (3) are pressure dependent. The rotating proton flux is measured using small Faraday cups (magnetically insulated by the solenoidal field) at various axial positions, and at 10 cm radius, with their axes oriented in the azimuthal direction. The cups' apertures were covered with 2 μm thick mylar foil to discriminate against low energy particles, and the pressure inside the cups was maintained at 0.1 mT. Faraday cup and axis diamagnetic signals at the same axial positions are compared in Fig. 8 for shots into 240 mT hydrogen and 230 mT air. There is good correspondence between the two for a hydrogen fill. Moreover, the magnetic signal amplitudes and widths are independent of pressure in hydrogen. However, in air the magnetic signals

Figure 8. Beam diamagnetism and Faraday cup measurements of the rotating proton flux for (a) in 240 mT H_2 and (b) in 230 mT air. The time sweep is 200 nsec/div and the Faraday cup signal is in A/cm^2 .

are much longer than the particle flux signals and they tend to be flat topped at pressures >100 mT. The duration of their tails increases with the square root of the fill pressure, and they oscillate at low pressures, ≤ 30 mT. This plasma current behavior as a function of ion mass is as predicted theoretically for the similar problem of return currents induced by a rotating electron beam in a plasma in an axial magnetic field by Lee and Sudan⁸ and by Chu and Rostoker.⁹ To summarize the implications of these theoretical works, the hydrogen ions can undergo drift motion in response to the ring electric fields on the time scale of beam transit, but the heavier ions cannot. Therefore, net currents can flow only in the heavier ion plasmas.

A set of diamagnetic loop signals is shown in Fig. 9 for a shot in which the diode voltage was 590 kV peak, the total diode current was 100 kA peak and the beam was injected into 320 mT. This shot was typical for beams injected into 60 mT to 400 mT hydrogen. Also shown are the currents flowing in two of the wall resistor wires. The average injected energy is 430 keV, due to the energy loss in the $2\text{ }\mu\text{m}$ mylar foil, giving a total proton velocity of 9.1×10^8 cm/sec. The diamagnetism is strongest at 52 cm, ~ 350 G, just before the beam reaches the uniform field. Evidently, some fraction of the beam is reflected by the ramp between the cusp and the uniform field beginning at about 60 cm. Between 72 cm and 172 cm the peak diamagnetism and its full width at half maximum are typically 200 G and 100 nsec, respectively, with random variations of $\leq 10\%$ from shot-to-shot and

Figure 9. Ring diamagnetic signals and wall resistor currents for a 590 kV peak diode voltage pulse into 320 mT Hydrogen. Note the relatively distortion-free propagation of the main pulse, and the reflection of a low axial velocity tail.

position-to-position. Note also that the signals have long, weak tails with a complicated structure. Time-of-flight measurements of the diamagnetic peak give an average axial velocity of $(3.8 \pm 0.3) \times 10^8$ cm/sec, corresponding to an average axial energy of 75 keV. Thus, >80% of the kinetic energy of the protons is converted to rotation by the cusp. The ratio of axial to rotational energy, $W_z/W_\perp$ is 0.21 ± 0.07 , so that partial reflection of the ring from the 23% mirror, M_2 , is expected. Comparison of the diamagnetic signals at 172, 192, and 212 cm shows only partial transmission, and, indeed, some of the features of the signal tails are seen to be propagating back towards the diode from 152 cm to 32 cm, as indicated by the dashed lines in Fig. 9.

The total number of protons in the ring and its total and axial energy content can be estimated from the diamagnetic signals by taking a long solenoid model for the ring. The axial energy coupled from the ring to the wall resistor is then estimated from the two measured wire currents also shown in Fig. 9. The results are the following: The ring contains $(5.5 \pm 2) \times 10^{15}$ protons as it propagates downstream and $(2 \pm 1) \times 10^{15}$ protons both pass through and reflect from M_2 . Taking 5.5×10^{15} protons at 430 keV each gives a ring energy of 390 J. The ring's axial energy is, therefore, about 65 J. Of the later energy, $0.5 \text{ J} \pm 0.2 \text{ J}$ is dissipated in the wall resistor. Note that 5.5×10^{15} protons requires an injected proton current of 16 kA for 60 nsec.

A very significant result shown in Fig. 9 is implied by the minimal dispersion of the first peak of the diamagnetic signals in the uniform region of the solenoid, namely from 72 cm to 172 cm. Evidently this is due to a large fraction of the ring protons being held together within their own diamagnetic well. If the self-fields of the ring are neglected, the signal dispersion implies an axial velocity spread $\delta v_z \lesssim 0.14 \times 10^8$ cm/sec. However, the 2.5% diamagnetic well of the ring confines protons with relative axial velocities of up to about 1.3×10^8 cm/sec, or about 10 keV in the ring frame of reference. The signal tails are evidently due to protons which are not held in the ring by self-fields. Indeed, the 172 cm diamagnetic signal shows that slower protons pile up at the foot of M_2 and are reflected from it, giving the reflected structure noted above.

Diamagnetic signals from a much less typical shot are shown in Fig. 10. The diode voltage history was virtually indistinguishable from the shot just discussed, and the hydrogen pressure was 390 mT. The unusual feature here is the separation of a second peak from the main peak at 92 cm. This weaker ring which this represents, propagates with an axial velocity of $(2.5 \pm 0.2) \times 10^8$ cm/sec. Evidently, these protons are moving just a bit too slowly to be contained by the well of the main ring, consistent with the discussion above. Unlike the particles which were not contained on the previous shot, these are able to collect themselves into a second ring. Since its average axial energy is only about 32 keV, we have $W_z/W_\perp = 0.09 \pm 0.02$. Therefore, this ring is expected to reflect from M_2 , as it clearly does. This

Figure 10. Ring diamagnetic signals and wall resistor currents for an unusual shot involving a 590 kV peak diode voltage beam injected into 390 mT hydrogen. Note the slow speed packet which separates out from the main part of the diamagnetic signal, reflecting coherently from the downstream mirror. The decay of the reflected packet's diamagnetism is consistent with particle loss due to classical slowing down.

ring is also able to hold itself together during the reflection. Evidently, this is because all of the protons are reflected over a length of about 10 cm near the foot of the mirror. If the ring velocity spread were larger, protons would be reflected over a longer length of the mirror and they would be dispersed in the process.

The injection of virtually identical proton beams into 120-140 mT air yielded qualitatively and quantitatively different diamagnetic signals from the hydrogen cases because of the return currents induced behind the beam in the beam-formed plasma. Oscillographs of the axis diamagnetism for a shot into 120 mT are shown in Fig. 11. Both tails and 'flat-topping' are evident as the signals are both smaller and of longer duration than those from the hydrogen shots. The reflected ring, especially at 152 cm is much larger and transmission through M_2 is noticeably reduced. Mean values of the ring diamagnetism for both the hydrogen and air shots are plotted versus position in Fig. 12. The peak diamagnetism in air tends to be about 25% smaller than in hydrogen as the ring propagates to M_2 . However, the diamagnetism of the reflected rings is about 50% stronger than in hydrogen. The larger reflections in air are attributed to coupling of axial energy from the ring to the magnetic energy of the return current configuration. This is 5 to 10 J out of the approximately 65 J of axial energy.

In one series of shots in air, the fill pressure was varied from 15 mT to 300 mT. While propagation to M_2 is pressure independent, both ring reflection and propagation of the reflected ring improve with increasing pressure in the range between 15 and 150 mT. A graph of

Figure 11. Diamagnetism for a 590 kV peak diode voltage beam into 120 mT air with a 500 G upstream mirror. Note the flat tops, long tails, and sign changes of the magnetic signals. The reflected beam on this shot is larger than that seen for any shot in hydrogen, despite the presence of the upstream mirror. Two wall resistor currents are also shown.

Figure 12. Mean values of beam diamagnetism as a function of position for six 566 kV shots into an air fill of 120 mT to 150 mT. Error bars shown are one standard deviation. Average values for hydrogen fill shots are shown by open circles. Note that the diamagnetic signals are larger in hydrogen.

the ratio of the reflected beam diamagnetism at 72 cm to 152 cm is shown in Fig. 13. The decay of the diamagnetism with time could be due to either proton loss, or to progressive current neutralization. A similar decay of the rotating proton flux is observed with Faraday cups, so the decay is attributed to proton loss. At the highest pressures, this loss is consistent with classical collisional expectations. At lower pressures it is not yet understood.

It is desirable to verify that the dynamics of the beam in the applied magnetic field are in agreement with expectations based on space charge neutrality of the beam. Its self-magnetic fields are weak, so its propagation and interaction with the mirrors should be described by single particle orbits. As the diode voltage is increased, the axial energy of the ring and the fraction of the protons passing through M_2 should both increase. With other parameters constant, increasing the value of M_1 should increase the fraction of the ring which is transmitted through M_2 by preselecting "fast" protons (see Eq. 2.4). As M_1 is increased, reflection and axial bunching of the beam just upstream of M_1 should occur, while transmission into the uniform region should decrease. The axial energy corresponding to the propagation of the leading half-maximum point of the diamagnetic signal for shots into 120 mT air is plotted versus diode voltage in Fig. 14. The inferred axial energy dependence is consistent with the prediction (see Eq. 2.3). The ratios of the ring diamagnetism transmitted through M_2 to 212 cm, and of the ring reflected back to 152 cm are plotted in Fig. 15 versus M_1 as a function of diode voltage. The

Figure 13. The ratio of the peak diamagnetism of the reflected beam at 72 cm to 152 cm versus air fill pressure.

Figure 14. Axial energy vs. injection voltage for shots into a 120 mT air fill. The axial energy is inferred from the propagation speed of the leading half maximum of the beam diamagnetism, with an uncertainty of about 25%. The uncertainty in the diode voltage is about 25 kV. The line shown has a slope of unity.

Figure 15. Ratios of the diamagnetism of the beam transmitted through the downstream mirror to 212 cm, and of the beam reflected back to 152 cm, to the diamagnetism of the injected beam at 152 cm versus upstream mirror strength, as a function of diode voltage.

expected trends as a function of M_1 are seen for each value of the diode voltage. For constant values of M_1 , transmission increases, and reflection decreases, as the diode voltage is increased..

A number of shots were taken into 100 mT hydrogen with comparatively high diode voltage, up to 610 kV, and large M_1 , up to 33%, 3 kG on axis. Recall that M_1 is 56 cm downstream from the diode. Magnetic signals at 32, 52, and 92 cm for three shots with increasing values of M_1 are shown in Fig. 16. Three changes are evident as the mirror is increased from zero to 12% to 33%. First, at 32 cm, a second peak develops 160 nsec after the first. Second, the diamagnetism at 52 cm steadily increases. Third, the tail of the 92 cm signal is cut off. The first and third features are attributed to reflection of low axial energy particles by the mirror. The second is attributed to axial bunching of the beam as protons slow down approaching the mirror.

The beam bunching produced the largest value of the beam diamagnetism observed so far in IREX, 875 G out of a total applied field of 11 kG, 8 kG from the DC coil and 3 kG from M_1 at the ring radius. This result is rather remarkable in that the operating diode power is only 0.05 TW. The total number of protons in this ring at 52 cm is estimated to be $\sim 1 \times 10^{16}$.

The implications of these results are discussed in some detail in our proposed program section. At this juncture, two points are significant. First, inductive coupling of beam axial energy to a wall resistor is proportional to K_θ^2 , where K_θ is the ring current

Figure 16. Reflection, bunching and transmission at the upstream mirror. As the upstream mirror (at 56 cm) strength is increased, note the (i) appearance of a reflected beam at 32 cm, (ii) increased diamagnetism at 52 cm due to bunching, and (iii) cutoff of the diamagnetic signal tails at 92 cm. These were 600-610 kV peak diode voltage shots.

per unit length. Second, the wall resistor was not optimized for the experiment described above. We estimate that with recent generator improvements and diode optimization that the proton current injected into IREX can be increased by a factor of 3. Therefore, by increasing the wall resistivity by a factor of 4 and by varying the shape of the magnetic mirrors, based upon the results described above we believe an ion ring can be trapped on IREX using the wall resistor for damping the axial energy.

B. LONGSHOT

In this section we describe the LONGSHOT experimental device as it presently is operating, discuss the evolution of the injector, and then present results of preliminary beam propagation experiments obtained with it.

1. The LONGSHOT Apparatus

The heart of the LONGSHOT generator is an annular magnetically insulated diode which has been developed specifically to allow long pulse ($\leq 1 \mu\text{sec}$) operation. The configuration is similar to that developed by Dreike for IREX, both having radial insulating magnetic fields. However, the details are substantially different as is evident by comparing the LONGSHOT schematic, shown in Fig. 17, with the IREX diode in Fig. 2. The version of LONGSHOT which we presently operate evolved from a device designed by Humphries¹⁰ which is used as the first stage in a multi-stage accelerator. It includes a number of new features which enhance its performance and demonstrate several phenomena important to the operation of magnetically insulated ion diodes.

LONGSHOT SYSTEM

AXIAL MAGNETIC FIELD

FIG. 17 LONGSHOT system diagram, magnetic field and diode detail.

The LONGSHOT diode is driven by a low inductance ($0.6 \mu\text{h}$) Marx generator with four $1.8 \mu\text{f}$, 60 kV capacitors. The inductance of the entire Marx-ion injector system is $0.9 \mu\text{h}$ including the cables delivering the power to the diode and the diode itself. The generator stores 8 kJ at the typical charging voltage of 45 kV, much more than is released during the useful pulse duration, and it has about 1Ω characteristic impedance. Thus, the driving circuit is essentially a constant voltage source, typically 180 kV, with a $0.9 \mu\text{h}$ series inductance and a 1Ω series (damping) resistor, and the pulse duration and current are determined predominantly by the behavior of the magnetically insulated injector gap.

An ion beam produced in the diode gap propagates 15 cm in an annular drift space and then is injected into a 30 cm diameter glass pipe evacuated to 10^{-4} T and surrounded by a solenoidal magnetic field coil. The coil produces a half-cusp configuration which is sharpened up by the flux excluding end flange of the injector. The coil is driven by a capacitor bank operated at up to 12 kV which produces a field of up to 9 kG in the drift chamber. The field configuration is in the form of a ramp, as illustrated in the lower portion of Fig. 17, which is specifically designed to reflect ions in such a way as to spatially bunch the beam produced by the LONGSHOT injector, as discussed in the next subsection.

2. LONGSHOT Diode Operation

The factors associated with the gap configuration which have been found to affect diode impedance behavior are the radial shape of the insulating field, connection to cathode (ground) potential surfaces of magnetic field lines which intersect or come close to the anode, and the geometry of the virtual cathode - determining electrodes. In addition, of course, the Marx charging voltage and the magnitude of the insulating field are important.

The insulating field is produced by two pulsed coils on the cathode side of the diode together with shaped aluminum flux excluding surfaces on the anode side, as shown in Fig. 17. The shaping of the field lines by the flux excluders is intended to serve two functions. First, the field lines at the surface of the pinned plastic "flashborard" anode are concave, and the amount of curvature is used to control beam optics to give maximum extracted current. Second, the radial mirror serves to confine electrons in the gap, enhancing the ion current density and allowing a longer pulse. The importance of the latter effect, suggested by Humphries, has now been clearly shown with LONGSHOT. Figure 18a shows diode voltage (measured with a resistive monitor) and current (measured with a Rogowski coil) for concave and flat flux excluders. The diode current is increased by about 50% with the curved excluders with no degradation in the (~600 nsec) pulse duration.

The connection to cathode surfaces of field lines which intersect, or come close to, the active anode surface cannot be entirely avoided. However, the

FIG. 18

a.) LONGSHOT diode voltage (5kV/division) and current (17kA/division for shots with (1) flat anode flux excluder, and (2) curved flux excluder.

b.) LONGSHOT pulses (1) without, and (2) with outer hoop intercepting field lines passing close to anode surface.

flux penetrable metal hoop radially outside the gap, shown in Fig. 17 intercepts magnetic field lines which pass through the gap near the anode surface. This blocks a direct path for plasma from the anode surface to the grounded drift tube along field lines. The insertion of this hoop increases the pulse duration, as shown in Fig. 18b apparently by eliminating external breakdown paths since it also eliminates arc damage to the drift tube. Without the hoop, increasing the gap voltage decreases the pulse duration even if the insulating magnetic field, B_g , is increased, whereas with it the pulse duration can be maintained as gap voltage is increased by increasing B_g . An additional effect of the hoop on gap behavior is also evident in Fig. 18b namely that significant diode current flows much earlier in the pulse with it in place. The transition from slow to fast current "turn on" occurs when the leading edge of the hoop is moved far enough forward to intercept field lines which pass along the active anode surface. The effect is maximized when the hoop is 2-3 mm further out for the 8 mm gap typically used. Evidently the hoop enhances the emission of electrons early in the pulse which can then cross from the cathode region into the gap, aiding in the suppression of ion space charge and enhancing extracted ion current density, which is also measured during these tests.

The final aspect of diode behavior to be discussed here concerns the method of supplying electrons to form the virtual cathode. The ion current and the electron leakage current in the gap region produce an azimuthal magnetic field. Therefore, whereas in the absence of this

field the electrons $\vec{E} \times \vec{B}$ drift in the azimuthal direction, with the self-field, there is a radial component to the drift as well. This tends to degrade electron confinement and to change the shape of the virtual cathode. In order to compensate for this, the physical cathode has been varied. Specifically, when the inner cathode portion shown dashed in Fig. 17 is removed, the pulse length is increased from 600 nsec to 700 nsec, and a higher quality beam (i.e, more parallel across the extraction annulus) is obtained.

3. Beam Propagation and Bunching Experiments

The LONGSHOT injector output of $\geq 3 \times 10^{16}$ protons per pulse at low peak power ($< 5 \times 10^9$ W) makes this source an attractive candidate for ion ring formation. In order to effectively use this output, the annular beam must be given diamagnetic rotation, it must be bunched axially to make a compact ring and it must be trapped in a mirror field. Present LONGSHOT experiments and supporting numerical simulations are addressing the first two of these issues. Figure 17 shows the magnetic field used in the experiments.

Results to date may be summarized as follows. The beam has been transported across a half-cusp to form a rotating diamagnetic layer, with >50% transmission efficiency and no significant space-charge disruption. The latter conclusion is reached because the proton dynamics are consistent with single particle orbits assuming complete charge neutralization. This layer has then propagated the length of the 1 m ramped axial field, and evidence of bunching and reflection has been seen. Diamagnetism of >3% is observed, as shown in Fig. 19 at the position in the ramp of maximum δB . No gas fill is used in these experiments; the pressure is 10^{-4} T.

FIG. 19 Diamagnetic signals measured with B loops at conducting wall, at four axial positions, with two different ramp field strengths (B_0 given at 60cm position). Vertical scale mark corresponds to 1% B at 60cm for the $B_0 = 4.8\text{kG}$ shot, 1% at 30cm for $B_0 = 6.9\text{kG}$ shot. With the lower field, the beam bunches at 45-60cm; with higher field, maximum bunching occurs at 30cm.

These experiments have shown the importance of several basic issues which will be addressed by future work. First, beam propagation through the cusp has been greatly enhanced by the improvements in injected beam optics we have described. For example, an increase of a factor of two in $\delta B/B$ was observed when the injector inner cathode piece was removed. Further injector optimization should give further improvement.

Second, beam propagation was improved greatly by the provision of a secondary electron emitting surface just outside the beam radius in the cusp region. Before this surface was added, the clear evidence of beam bunching of Fig. 19 was not seen. This suggests that space charge effects in the cusp were not negligible without this electron source. Consequently, a plasma gun will be used to provide a plasma fill in the cusp to investigate the value of still better suppression of space charge.

Third, the mean injection radius of 10 cm results in a rotating beam at the downstream end of the ramp of ≤ 6 cm radius, due to radial compression of ion orbits in traversing the cusp and the adiabatic ramp. Because of this small radius, a large ramp field strength (~ 10 kg) is necessary for complete beam reflection. An increase in the injection radius by building a larger annular injector gap will serve the dual purpose of decreasing the ramp field strength requirement and providing more particles from a larger injector area.

Fourth, the ramp and voltage pulse shape are not yet optimized for beam bunching and reflection. Changing the ramp shape is a simple

matter of changing coil positions, but injector pulse shape is more difficult to control. Two means of achieving this control will be described in some detail in Sec. III B. To summarize briefly, a pulse forming network can be interposed between Marx generator and injector, and/or the injector impedance history can be controlled by replacing the passive "flashboard" anode with a separately activated, controlled source of anode plasma.

III. Proposed Research, FY 1981

The ultimate goal of this research program is the achievement of a field reversed magnetic confinement configuration produced by a ring of energetic ions, or by a combination of plasma currents and energetic ions such that the ion contribution is sufficient to stabilize the system. At the present time, the stability criterion concerning the fraction of the current which must be carried by energetic ions is not precisely known. Therefore, the goals of our program during FY' 81 are: 1.) the production of stronger proton rings than our present 3 - 8% levels, and 2.) the improvement of our understanding of the dynamics of these rings, in order to be sure the technology and physics will be ready for stable compact toroid production when the needs are known. These goals require the continuation of the development of both short and long pulse ion beam sources, and of the trapping experiments which have been performed on IREX and LONGSHOT during FY '80 and which were described in Section II.

In the following subsections, we describe first our proposed research on the short pulse experiment, IREX, and then the long pulse experiment LONGSHOT.

A. IREX

The IREX experiment has now demonstrated all of the physics issues required for the trapping of a proton ring in a magnetic mirror: 1.) A magnetically insulated diode in a cusp-like magnetic field has produced an annular proton beam with little particle loss and $\geq 80\%$ of the proton energy in the transverse direction

in an 8kG magnetic field. It is estimated that $> 20\text{kA}$ of the 90kA peak diode current was protons. 2.) With a neutral gas fill of 0.1T air or 0.1 - 0.4T hydrogen, charge neutralization and axial current neutralization were obtained; azimuthal plasma currents were observed in the heavier gases tested, air, helium and nitrogen, but not in hydrogen or deuterium, in reasonable agreement predictions of return current models. 3.) The proton energy and canonical angular momentum spread were sufficiently small that the rotating beam coalesced into a ring contained axially by its own 3% diamagnetic well as it propagated in the uniform portion of the magnetic mirror in hydrogen gas. The beam was also well defined in the radial direction, with an inner radius of 7cm and an outer radius of 13cm. 4.) Axial energy dissipated by the wall resistor with hydrogen gas in the chamber was in agreement with expectations based upon theoretical models, amounting to about 1% of the beam axial energy for the beam and wall resistor parameters used. With air in the chamber, up to 15% of the beam axial energy was extracted by dissipation of the induced azimuthal plasma currents. 5.) Up to 50% of the rotating beam was reflected from a 23% mirror located 2 m from the injector in an air fill by properly matching the injector voltage and the magnetic field strength. Smaller fractions were typically reflected with hydrogen fill, evidently a result of the additional axial energy lost by the ring in air to the azimuthal plasma currents. 6.) With the exception of the return current effects, the beam dynamics are in good agreement with expectations based upon single particle orbits in the applied magnetic

fields.

With these results in mind, we believe that an ion ring can be trapped on IREX, if it is properly "tuned". The following activities are planned during the coming year to bring about a trapped ring twelve to eighteen months from now, depending upon our support level.

1. During the course of the experimental work which provided the results summarized above, emphasis was placed upon investigating the characteristics of the propagating beam. There was no effort to optimize the annular diode proton source. Such an optimization includes a.) variation of the shape of the insulating magnetic field in the diode gap, which as been shown to be so important on LONGSHOT, b.) testing different virtual cathode producing geometries, and gap spacings, and c.) varying the anode material and area. The overall goal of this work will be to lower the operating impedance of the ion diode, while maintaining the ratio of ion current to total diode current at least at the 1/4 to 1/3 level we have achieved so far on IREX.

2. The plasma source being prepared for use on LONGSHOT (to be described below), will be tested on IREX to determine if a low density plasma ($\sim 10^{12}/\text{cm}^3$) in the cusp region can be used to a.) enable us to eliminate the need for $\sim 100\text{mT}$ gas in the chamber; b.) eliminate the need for the cathode foil (which is presently necessary to separate the $\sim 100\text{mT}$ drift chamber from the 0.1mT diode), which requires that the plasma not cause a diode short circuit; and c.) if b. works, to lower the diode operating impedance.

3. Once the diode operating impedance has been dropped to 3 - 4 Ω from the present $\geq 6 \Omega$, we will be in position to utilize the substantially higher energy presently available from the upgraded Neptune 800 Marx Generator. This merely involves charging the 7 Ω Neptune line to its full 800kV rating and utilizing the under-matching of the diode (3 - 4 Ω vs 7 Ω) to reduce the diode gap voltage to the 500 - 600kV level that we want. The resultant 150 - 175kA current, an extracted fraction of 1/3 and a useful pulse of 60nsec combine to imply about 2×10^{16} protons in the propagating ring, the number previously predicted to be capable of being trapped using resistive walls.¹¹ If the proton efficiency of the diode is improved, the number of injected protons is, of course, proportionally increased.

4. As soon as we are confident that we have increased the number of extracted protons from the annular diode by a factor of at least two, trapping experiments will be attempted again. Based upon present projections of Neptune scheduling, these experiments will take place during the summer of 1981 following two 6 to 8 week runs on the generator devoted to the diode operation experiments. For the trapping run, the IREX apparatus will be modified as follows. a.) The resistivity of the wall resistor network will be increased by a factor of 4 in order to have a more optimum ring axial energy extraction efficiency. This, together with the increase of a factor of at least two in the number of protons in the ring, will increase the drag force on the ring by an order of magnitude as it propagates through the system. b.) The plasma fill in the cusp region will eliminate the need for a 100mT gas fill for

successful injection, increasing the classical ring lifetime to many microseconds. Such a time scale will be long enough for trapped protons to make several transits in the mirror. If, in addition, the plasma source allows us to eliminate the cathode foil, our shot rate will increase by a factor of 2 or 3, allowing many more trapping tests to be made. c.) If our FY '81 support level is sufficient, we will also modify the shape of the IREX magnetic field structure in the vicinity of the mirrors in order to maximize the number of particles which are able to pass through M_1 but be reflected from M_2 . This will be done based upon computer simulations of the ring dynamics near the mirrors for the experimentally expected number of protons. Our goal here is an 8 - 10%, self confining ring in the uniform region of the solenoid. Mirror M_2 will be sharpened to allow a more coherent reflection of the ring from M_2 , enabling the ring to be self confining on its upstream transit through the uniform region also. Since this will allow the ring to interact strongly with the resistive wall twice rather than once, we will gain an additional factor of two in axial energy extraction and, therefore, an improved chance to trap the ring. This task will require the funding given in parenthesis at the end of IREX task 4. The costs are for a small additional capacitor bank to drive additional pulsed coils within the IREX system, and the manpower to build them.

If the above steps are successful, the next step, in FY '82, is to modify the Neptune generator pulse forming line to $\lesssim 3\Omega$ and up to 150 nsec pulse duration if diode impedance can be held sufficiently constant that long. This combination will increase the available output power using the same Marx generator by 30% and double the useful pulse duration. The number of trappable protons would then be sufficient to produce a 25 % diamagnetic proton layer.

B. LONGSHOT

The LONGSHOT device is now routinely injecting $(2 - 3) \times 10^{16}$ 60 - 100keV protons in the form of an annular beam of 600 - 700ns duration into a solenoidal magnetic field of 5kG. By reflecting the higher energy protons injected early in the pulse (see Fig. 18) from a ramp shaped magnetic field, spatial bunching of the beam is achieved where the slower and faster ions have their confluence. A 3% diamagnetic proton beam has been obtained. However, it is expected that such a beam would be difficult to trap because of its axial energy spread of ± 20 keV. Such a spread would require the beam's diamagnetic field to be $\geq 30\%$ of the applied field, a task which is beyond the capability of LONGSHOT in its present state. Therefore, as in the case of IREX, the proposed work on LONGSHOT for FY '81 involves improvement of the present proton beam source together with continuing beam propagation experiments. By the tasks described below, we hope to inject as many as 5×10^{16} protons into the magnetic solenoid, and, by producing a more optimal voltage pulse shape than we presently have, we expect that the resulting beam will be more suitable for producing a

strongly diamagnetic proton ring, and for trapping that ring in a magnetic mirror.

The tasks to be undertaken to upgrade the LONGSHOT proton beam source are as follows:

1. A larger radius (15cm mean radius instead of the present value of 10 cm) and area (300cm^2 instead of 140cm^2) annular injector will be built. This will require a new outer injector vessel and flanges, insulating field coils and supporting structures. The design will be compatible with later inclusion of an active source of anode plasma to be located behind the physical electrode. There is plenty of reserve in the LONGSHOT Marx Generator to handle the higher current operation expected from the larger diode area.

2. Pulse shaping techniques will be used in order to keep the voltage pulse more flat (see Fig. 18) in the face of the falling diode impedance as a function of time. It may even be advantageous to have the voltage ramp up slightly. Ideally we would like the anode plasma source to "turn on" faster giving a more constant (high) current during the pulse. This would serve to provide more protons as well as a more constant voltage. However, it is likely that this will require an active anode plasma source, to be discussed in the next paragraph. Even with such a source, however, some shaping via lumped circuit elements will be necessary to have a flat (or slightly increasing) voltage waveform, since the diode impedance is bound to fall to some extent over

the 600 - 700 nsec pulse duration. The best way to perform this pulse shaping is being considered at the present time.

3. If funding allows, plasma guns will be designed and built for operation behind the anode in order to provide an active anode plasma source. The principal reason was discussed in item 2, above. Successful development of such a source would also favorably impact the repetitive pulse capabilities of LONGSHOT, a significant plus in the long run.

The work related to beam propagation experiments to be undertaken in FY '81 includes the following:

1.) The drift chamber and solenoidal field coil will be modified to be able to handle the increased radius injected beam. This will require a new vacuum vessel section, some larger diameter field coils and additional capacitors for the coil capacitor bank.

2.) A single plasma gun will be installed in the LONGSHOT drift chamber to provide a $\sim 10^{12}/\text{cm}^3$ plasma in the cusp region. We noted in Section II B that the LONGSHOT beam appears to behave as if the protons follow single particle orbits, and we concluded that the beam must, therefore, be highly charge neutralized even though the drift chamber pressure is low ($\sim 10^{-4}\text{T}$). This task is designed to determine if a preionized plasma improves beam dynamics or if the beam can, in fact, provide charge neutralizing electrons as fast as it needs them from the passive flashboard presently in the system.

3.) As improvements are made in diode operation, beam propagation and bunching experiments will be performed. The coil

configuration will be modified to best take advantage of the beam pulse voltage and current characteristics. This task has as its goal the formation of a ring which is strong enough and compact enough to hold itself together, as we have achieved on IREX.

IV. Work Statement and Budget, FY '81

We propose to perform the research tasks concerning the formation and trapping of ion rings which are briefly outlined below for the budget which follows. Details of the work involved and the motivation for the listed tasks were contained in Section III. Note that the performance of the full set of tasks will require the full budget of \$216,000. For the last task listed under each of IREX and LONGSHOT, the portion of the budget which would be shifted into FY '82 by putting them off until then is indicated.

A. IREX Tasks

1. Optimize the present IREX diode. The goal here is to lower the operating impedance of the ion diode while maintaining the ratio of ion current to total diode current at at least the $1/4$ to $1/3$ we presently obtain. This will allow operation of the Neptune Generator at higher peak power.
2. Test the effect of an active plasma source in the region of the cusp on beam propagation in the absense of a gas fill. Also, determine if the plasma source allows the elimination of the cathode foil without causing diode short-circuiting.
3. Perform injection and trapping experiments on the full IREX system using the optimized diode and the plasma source in the drift chamber. These experiments will include a more optimized resistive wall for ring axial energy extraction than we previously used.
4. Modify the shape of the IREX mirrors to enhance the number of protons injected into the trapping region and to allow a more coherent reflection from the downstream mirror. The goal here is

to maximize our capability to trap a ring, as described at the end of Section II A. (The portion of the budget allotted to this task is approximately \$20,000, of which \$6,000, included under Capital equipment, is for capacitors and an ignitron.)

B. LONGSHOT Tasks

1. Test the effect of an active plasma source in the LONGSHOT cusp region on beam propagation.

2. Use pulse shaping techniques to produce a LONGSHOT voltage pulse which is more optimum for trapping the resulting proton beam in a magnetic mirror.

3. Enlarge the LONGSHOT diode. The goal here is to achieve a doubling of the anode area without degrading the quality of the resulting ion beam or the beam pulse duration.

4. Modify the LONGSHOT drift chamber and magnetic field coil system to accept the beam from the enlarged LONGSHOT diode.

5. Perform beam propagation and bunching experiments using the upgraded LONGSHOT beam.

6. Design, construct and test active plasma gun sources for the LONGSHOT anode plasma. The goal here is improved diode impedance control and more efficient utilization of the available energy in the LONGSHOT Marx Generator to produce protons. (The portion of the budget allocated to this task is approximately \$21,000, of which \$4,000, included in the Capital equipment budget, is for capacitors and power supplies.)

BUDGET - Capital Equipment Justification

Most of the oscilloscopes used for our experiments were obtained as surplus from various government agencies. As a result, we suffer regular failures from them with typically 1/3 being repaired at any one time. Replacement Cathode Ray Tubes now cost between \$500 and \$850 for the three model dual beam 'scopes we use. Therefore, we request funds for the acquisition of a new Dual Beam Oscilloscope system (Tektronix 7844 and associated components). We not only expect much more reliable operation from such a unit, but also it consumes much less electricity than the unit it will replace (~250W vs ~1kW), and its lower heat load within our screened room can be expected to decrease the failure rate of the remaining older oscilloscopes.

It may be possible for us to assemble an oscilloscope trace digitization and data handling system based upon a Hamamatsu Vidicon tube scanner and a LSI-11 minicomputer by cost-sharing the system among the National Science Foundation Research Equipment Program, Cornell's College of Engineering, and our research contracts. If this should be the case, a portion of the capital equipment budget will be allocated to help pay for that system.

Capacitors, Power Supplies, ignitrons, and so forth, are the major components of capacitor banks. Of the \$17,000 allocated for these items, \$10,000 is associated with new banks required by IREX task 4 and LONGSHOT task 6. The remainder is partially for replacement of components which fail, and partially for increasing

the capability of existing banks to better be able to handle the ongoing IREX and LONGSHOT experiments.

The remainder of capital is to replace diagnostic equipment which has failed.

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V. PERSONNEL

Professor R. N. Sudan will be the Principal Investigator of this project. Professor David Hammer will be the Co-Investigator and supervise the experimental operations.