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Neutral Particle Beam Popup Applications

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Neutral Particle Beam Popup Applications

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NEUTRAL PARTICLE BEAM POPUP APPLICATIONS

by

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ABSTRACT

Popup neutral particle beams (NPBs) could have high leverage in discriminating decoyed threats. There is considerable leeway in the choice of platform parameters. For deuterium beams the number of platforms is modest for all energies. Hydrogen beams might use higher energies to reduce the number of platforms. Low energies minimize platform cost for both.

I. INTRODUCTION

This paper discusses applications for NPBs that are small enough to be popped up or launched on warning of attack. The calculations indicate that there is considerable flexibility in choosing platform parameters. If low energy beams can be used, it could be possible to develop useful popup discrimination platforms in the near term.

The equations that govern NPB propagation and interaction have been derived elsewhere[1] and used to discuss the beam parameters required for applications ranging from satellite protection to missile, bus, and reentry vehicle kill.[2] Of these defensive applications, discrimination appears to be both feasible and of high priority for strategic defense. It is used below to illustrate the scaling of popup platforms; other applications scale similarly. NPBs discriminate much more efficiently than other directed energy weapons. Modest constellations could discriminate heavily decoyed threats.[3]

Predeployed constellations do, however, involve tens of platforms, each of which could be large and expensive. Moreover, for predeployed constellations, typically $\leq 10\%$ of the platforms are within range of threat trajectories.[4,5] Popup deployments place platforms only where needed, which should largely eliminate absenteeism. Thus, popup deployments are intrinsically a factor of ≈ 10 smaller and less costly than predeployed constellations. Moreover, popup platforms would operate in convergent geometries in which attacking objects would have to approach the neutral particle beams in order to attack their targets, which should significantly reduce the number of platforms and their energy, current, size, and cost.

II. FLUENCES

This section derives the equations needed for estimates of discrimination effectiveness, which are essentially those derived earlier, modified for convergent popup geometries.[6] Foil neutralizers produce a beam full angle divergence of[7,8]

$$\theta = \theta_p/\sqrt{E} = 30\ \mu\text{rad-}\sqrt{\text{MeV}}/\sqrt{(E \cdot A_p)}\ \alpha\ 1/\sqrt{(E \cdot A_p)}, \qquad (1)$$

where E is the beam energy and A_p is the atomic mass of the particles in it. That divergence produces a far field beam diameter of $\approx \theta r$ at range r. Thus, a neutral particle beam of current I would produce an energy flux of $\approx IE/(\theta r)^2 \equiv B/r^2$ at r, where $B \equiv IE/\theta^2$ is the beam brightness. Because $\theta^{-2}\ \alpha\ EA_p$,

$$B = IE/\theta^2\ \alpha\ IE^2 A_p, \qquad (2)$$

which scales quadratically on E and bilinearly on I and A_p, which are the three primary parameters that must be traded off to most effectively meet the brightness needed for discrimination.

Discrimination requires that an adequate fluence be delivered, that enough of the return be collected, and that the resulting signal be sufficiently greater than the background.

Neutral particle beams of brightness B produces an energy flux B/r^2 at r, so in time t they deliver a fluence

$$J = Bt/r^2. \tag{3}$$

If the beam is composed of particles of charge q, the particle fluence is $It/q(\theta r)^2$. Thus, an object of area $A < (\theta r)^2$ that produced ϵ isotropic neutrons per incident particle, would deliver a neutron fluence

$$J_n = [It/q(\theta r)^2][\epsilon A/4\pi r_D{}^2] \tag{4}$$

on a detector at range r_D from the object irradiated. The conversion efficiency ϵ scales as E^3 for hydrogen and E^2 for deuterium on thick targets. For decoys, ϵ is reduced by roughly the ratio of their areal density to the beam's range, but that is not of interest here. The adequacy of weapon-to-decoy signal ratios is discussed elsewhere.[9] If the detector had area A_D and unit detection efficiency, its signal would be J_nA_D. Equating that to the $S_D \approx 1{,}000$ counts needed for detection gives

$$It = 4\pi q S_D(r_D r\theta)^2/\epsilon A A_D, \tag{5}$$

which shows quadratic scaling on detector range, object range, and beam divergence and a weaker scaling on other parameters.

The time needed to discriminate an object at long range, that is, $r > \sqrt{A}/\theta$, is thus

$$t_L = (4\pi q S_D r_D{}^2 E/\epsilon A A_D)\cdot r^2/B \equiv J_L r^2/B, \tag{6}$$

where $J_L \equiv 4\pi q S_D r_D{}^2 E/\epsilon A A_D$ is the fluence required, which scales strongly on r_D, ϵ, and E. Typical parameters, for example $S_D \approx 1{,}000$, E = 250 Mev, $r_D = 500$ km, $\epsilon \approx 1$, and $A = A_D = 1\ m^2$, give $J_D \approx 10\ kJ/m^2$, which is a factor of $\approx 10^4$ less than the $\approx 10^8\ kJ/m^2$ fluence required to melt, detonate, and destroy weapons.[10] This comparatively modest fluence for interrogation is the basis for particle beams' effectiveness in discrimination.

The derivation leading to Eq. (15) is restricted to long ranges, that is, $r > \sqrt{A}/\theta$. For short ranges the beam irradiates only a portion of the object. Thus, an adequate signal must be produced by the part that is irradiated. If the total beam current is deposited in the object and converted into signal with efficiency ϵ, the signal on the detector is

$$S_D = A_D\epsilon It/4\pi q r_D{}^2. \tag{7}$$

The time required to discriminate objects at short range is

$$t_S = 4\pi q S_D r_D^2/\epsilon I A_D, \tag{8}$$

which scales strongly on r_D, ϵ, and I, and is independent of E, A, and r.

Note that t_S can be written as $t_S = t_L A/(\theta r)^2$, so that the effective fluence required to discriminate at short ranges is J_S $t_S B/r^2 = J_L A/(\theta r)^2$. That is typically larger than the fluence required for long ranges, but the total energy required is just $J_S(\theta r)^2 = J_L A$. The difference between long and short range interrogation is that at short range all of the beam energy is deposited in the object, while at long range only a fraction, $A/(\theta r)^2$, is deposited.

For the estimates below, it is sufficiently accurate to add t_L and t_S to provide an average discrimination time of

$$t_D = t_S + t_L = [J_L r^2/B][1+A/(\theta r)^2], \tag{9}$$

from which the combined discrimination fluence is

$$J_D = J_L[1+A/(\theta r)^2] = [S_D q E 4\pi r_D^2/\epsilon A A_D][1+A/(\theta r)^2]. \tag{10}$$

For long ranges, J_D reduces to J_L; for short ranges,

$$J_D \approx (S_D q 4\pi r_D^2/I\epsilon A_D)(B/r^2). \tag{11}$$

Because the time to interrogate a target is $\approx J_D r^2/B$, it is independent of r at short ranges.

III. BACKGROUND

For appropriate beam parameters the return from a 1% decoy should be about 1% of that from a weapon. That choice should also dominate natural backgrounds. The dominant background is expected to be that from precursor nuclear bursts, which scale on the number of weapons and the rate at which they are detonated. Prompt signals can be gated in time; delayed neutrons from fission debris cannot. Up to ≈ 10 s after a burst, they could unacceptably degrade the signal-to-noise ratio of neutrons with energies $E_n < 5$ MeV; at 60 s they could still degrade those below ≈ 3 MeV. The delayed neutron spectrum falls as $E_n^{-3/2}$ for 1 MeV $\leq E_n \leq E/2$; filtering out the neutrons below E_o would reduce their signal by a factor of $\approx 1/\sqrt{E_o} \approx 0.5$.

This reduction cannot be compensated for by increasing A_D by $\sqrt{E_o}$; precursor and albedo signals would increase proportionally. Improving the signal-to-noise ratio requires some collimation of the detector. A detector with an acceptance angle of 6^o that was 500 km from the threat would see an area $\approx$ (100 km)^2. Masking a midcourse threat distributed over $\approx$ (2000 km)^2 would thus take $\approx$ (2000 km/100 km)^2 $\approx$ 400 bursts. Covering the threat throughout its 2,000 s trajectory would require detonating that number of bursts every $\approx$ 2000 km ÷ 8 km/s $\approx$ 250 s, or a total of $\approx$ 400·(2000 s ÷ 250 s) $\approx$ 3200 weapons. As the sensor collimation increased, the penalty to the attacker would increase roughly as the inverse of the solid angle subtended by each detector. Such detectors are standard; their mass would have to be reduced to use them as popups.

IV. THREAT

If N_W weapons penetrated the boost phase defenses and each was accompanied by D decoys, the number of objects in the midcourse threat would be $N_W(D+1)$. If 500 missiles penetrated, each had 10 RVs, and each RV had D $\approx$ 50 credible decoys, that would give $N_W(D+1) = 500\cdot10(50+1) \approx 250{,}000$ objects, which could be possible 1-2 decades after the deployment of partial boost phase defenses. Without them the threat could consist of $\approx$ 1000 missiles, 10 weapons per missile, and 100 decoys per weapon, for a total of $\approx 10^6$ objects.

Thus, 10^5-10^6 objects roughly bound all out attacks; limited defenses could address attacks down to 1 missile, 10 weapons per missile, and 10 decoys per weapon, or $\approx$ 100 objects. Even for that number good discrimination could be preferable to hundreds of interceptors.

For simultaneous launch the objects would approach each platform as essentially a shell in which the object density would be $D'' = N_W(D+1)/A$, where A(r) is the cross sectional area of the threat tube at radius r. Simultaneous launch represents a worst case threat. Platforms would have only the tens of seconds of the objects' passage to discriminate them, and most platforms would be elsewhere in their orbits. The latter is an order of magnitude penalty for predeployed space platforms, but it does not apply to popup basing. If the objects passed by over a period of hundreds of seconds rather than the tens of seconds of simultaneous launches, defensive requirements would fall roughly as the inverse of the launch duration.

For current distributions of launchers in longitude, the midcourse threat would extend over ≈ 4000 km horizontally above the pole. It could also be dispersed ≈ 1,000 km vertically without degrading the timing of attacks. That would give A ≈ 4 Mm^2, D" ≈ $10^6 \div 4\ Mm^2 \approx 0.25\ km^{-2}$, and an average separation between objects of ≈ $1/\sqrt{D"}$ ≈ 2 km. Thus, retarget angles would be small, although each platform would have to retarget many times to engage a significant fraction of the threat.

Attacks on bombers, command, or value would cover much of the ≈ 5 Mm^2 of the continental United States, which would anchor the size of the arrival end of the threat tube and its rough size throughout. The defensive requirements have been studied.[11] If the weapons attacked missiles, they would concentrate on an area of ≈ $(1,000\ km)^2$, and the threat tube would have a ≈ four-fold compression after midcourse. Near term defense of missiles is geometrically more difficult than the defense of value.[12]

If, in time, it was possible for the attacker to concentrate the launchers before an attack on military targets, the threat could be approximated by a single, joint trajectory from the launch to the attack point. That is the most stressing scenario for systems that are predeployed in space, but it is actually less stressing than current geometries for popup systems. The analysis that follows below treats near term attacks on concentrated military target sets from widely distributed missiles.

V. ANALYSIS

Particle beams must address a significant portion of the threat to be effective, which means they must interrogate each object in milliseconds and switch between them in a comparable period of time. Neutral particle beams can deliver enough energy to discriminate objects at range r in a time $J_D r^2/B$, where J_D is the discrimination fluence of Eq. (10) and B is the beam brightness of Eq. (2). Adding to it T_S, the time the beam takes to move between objects, gives the total time required to discriminate an object, whose reciprocal is the beam's discrimination rate

$$dn/dt = (J_D r^2/B + T_S)^{-1}, \qquad (12)$$

where n is the number of objects discriminated up to time t. For small target areas, the objects fly approximately radially in toward the target area and the particle beams over it. Then, time derivatives can be replaced by spatial derivatives, for example , $d/dt \rightarrow -Vd/dr$, where V is the objects' orbital velocity. Equation (12) can then be solved formally as

$$n(r) = \Sigma_0^Z \, dr/V(J_D r^2/B + T_S), \qquad (13)$$

where the maximum range $Z \approx (2R_e h)^{1/2}$ is set by the Earth's radius $R_e \approx 6{,}400$ km and is $Z \approx 3{,}000$ km for platforms at altitudes of $h \approx 1{,}000$ km. For a threat of $N_W \cdot (D+1)$ objects, the number of platforms required is

$$N \approx N_W \cdot (D+1)/n(r=0), \qquad (14)$$

assuming they are uniformly distributed and that the platforms' fields of fire do not overlap. J_D varies strongly with r, so it is generally necessary to solve for n(r) numerically.

VI. RESULTS

Figure 1 shows the constellation sizes required for popup hydrogen and deuterium platforms for beam energies of E = 50-200 MeV. In this figure the threat is taken to be $N_W \cdot (D+1) = 10^6$ objects; the results scale linearly to other threats. At E = 200 MeV, hydrogen beams require ≈ 20 platforms; deuterium ≈ 12. By 100 MeV they increase to ≈ 55 and 20 platforms, respectively. At 50 MeV the number of hydrogen platforms is several hundred, but for deuterium it is ≈ 45. The difference is the larger neutron production efficiency for deuterium at low energies. Signal-to-noise ratios should be relatively constant, but the weapon-to-decoy signal ratio decreases from ≈ 10:1 at 100 MeV to 3-4 at lower beam energies.[13]

Figure 2 shows the discrimination rate versus range for hydrogen beams, which are strongly peaked at $r = 500$ km, the range at which the detector was placed. Their peaks rise strongly for small E and then saturate for $E \geq 150$ MeV. From Eq. (10), at a given E, $J_D \propto r_D^2$. The appendix shows that for convergent geometries, $r_D \approx |r-R_D|$, where r is the range from the beam to the object and R_D that from the beam to the detectors. Thus, the dominant scaling is $J_D \propto (r-R_D)^2$. For $r \approx R_D$, J_D is small and the discrimination rate in Eq. (12) saturates at T_S^{-1}.

For other ranges, $J_D \propto r_D^2[1+A/(\theta r)^2]$, as shown in Fig. 3. For objects at long range, that is $r \gg R_D$ and $\sqrt{A}/\theta$, $J_D \propto r^2$, which truncates Eq. (12) as r^{-4}. For $r \ll R_D$, $J_D \propto |R_D-r|$, and discrimination varies as $1/r^2(R_D-r)^2$. Those sharp truncations are seen on the shoulders of the curves on Fig. 2, which makes discrimination quite local around R_D.

Figure 4 shows the variation of hydrogen beam constellation sizes with retarget time. The variation is steepest at small T_S, where increasing T_S from 1 ms to 2.5 ms almost doubles the constellation size. The scaling weakens for larger T_S, but a ten-fold increase from the nominal 1 ms still quadruples the number of beam platforms.

Figure 5 shows the number of 100-MeV hydrogen beams needed as a function of the range from the beam platform to the detector array. The left-hand ordinate gives the number of predeployed platforms needed; the right-hand ordinate gives the number of popup platforms needed, which is about a factor of 10 lower at a typical absentee ratio of ≈ 10. The middle points at 500 km straddle the corresponding 55-platform result at 100 MeV on the top curve of Fig. 1. At lower r the number is ≈ 20% lower; at larger ≈ 50% higher. Both are due to the R_D^{-2} falloff of the beam; neither is particularly significant.

Figure 6 shows the discrimination rates as functions of r. The peaks fall off slightly with R_D in accord with the increase in Fig. 5, but the curves are basically translated to the range of the detector. That could be exploited. If the beam had not one but five detectors at the ranges shown in Fig. 6, the wings of the detector curves would not overlap greatly, and the result would be a total number of discriminations about five times greater than that from any one of them, which by Eq. (14) would reduce the constellation size by a factor of 5 to about 55/5 ≈ 11 platforms--at the expense of five rather than one detector. Whether that is useful depends on the relative costs of the beam and the detector. Given the size and complexity of even the low-energy beams, however, adding detectors would probably cost relatively little.

The five detectors used as an example are not a limit. A particle beam at h ≈ 1000 km can see about 3000 km, into which 15 of the detectors of Fig. 6 could be fitted with little overlap and possibly some benefit in cross-correlating signals. Their spacing varies slightly with energy. From Fig. 2 the width of a 50-MeV beam is about 100 km; 100 MeV is about 150 km. By 200 MeV, where the discrimination rate at the center saturates, the width increases to about 350 km. For the latter, a 3000 km useful range would again support about 10 detectors. For bulk discriminations it would appear that low energy beams were adequate. Higher-energy beams would, however, experience less falloff at long ranges. Long ranges are important if the beams are used to discriminate for interceptors with modest flyout speeds. Even a 3000 km range would only support an intercept at ≈ 1500 km with current interceptors. Closer discriminations would support continual commitment and shoot-look-shoot doctrines.

Popping the particle beams upward at ≈ 3 km/s rather than back along the threat trajectory minimizes the relative velocity in Eq. (13), to which the constellation size of Eq. (14) is directly proportional. Popping up also saves platform fuel, mass, and expense. Even allowing for warning and release, popping the platforms up could permit them to access roughly half the threat objects' trajectories. An equal number of beams predeployed in space could only access 10-20% as much over the whole trajectory.

The hydrogen beam curve on Fig. 1 scales as E^{-1}; deuterium roughly scales as $1/\sqrt{E}$. If the cost per platform scaled as the beam energy, the cost for a hydrogen beam constellation would be roughly independent of E. For deuterium beams it would scale roughly as $\sqrt{E}$; hence, it would be lower by about a factor of 2 at 50 MeV than at 200 MeV. There is also much to be said for more and smaller platforms' reliability, flexibility, and survivability.

VII. SUMMARY AND CONCLUSIONS

There appears to be considerable leeway in the choice of parameters for popup particle beam platforms. For deuterium the number of platforms is modest for all energies, particularly if many detectors are used with each platform. If weapon-to-decoy signal ratios are adequate at low energies, low-energy platforms would minimize cost. Hydrogen beams might use higher energies to reduce the number of platforms. Greatly reduced constellations would, however, depend critically on cheap, efficient, survivable detectors.

The parameters that emerge from simple analyses could be demonstrated using facilities now in development. Current accelerators explore both hydrogen and deuterium and scale to ≈ 25 MeV; a direct extension could reach the ≈ 50 MeV entry level for deuterium. All that would be lacking is a demonstration of lightweighting and integration with pointing and tracking, which could be simplified at lower energies. It would seem possible to extend the current 25-MeV accelerator demonstrator to ≈ 50 MeV with space hardware above 25 MeV, build a space-qualified proton or deuterium front end in parallel, test them separately, connect them, and call it a prototype.

Overall, the possible leverage of popup platforms could be quite high. Platforms and detectors appear achievable, and their constellations appear quite modest compared to those of space-based particle beams. They could support a defense whose sensors and defenders were insensitive to all of the fundamental countermeasures available to the attacker in the boost and midcourse phases.

APPENDIX: DETECTOR PLACEMENT

Detectors need not be collocated with the platforms; for point targets that is not the optimal placement. This section gives an approximate treatment of their placement and the resulting object-to-detector ranges.

A. Platform Angles

Let the total solid angle subtended by the threat at the target point be Ω, which is approximately the launch area A_L divided by the square of the length of the objects' trajectories, $R_L \approx 10{,}000$ km. That is

$$\Omega \approx A_L/R_L^2 \approx 10\ \mathrm{Mm}^2 \div (10\ \mathrm{Mm})^2 \approx 0.01\ \mathrm{sr} \qquad (1)$$

for current parameters. Over time, Ω could approach zero if launches were compacted. If N_D detectors were deployed, in the absence of overlap, the part of Ω for which each should be responsible is

$$\sigma \approx \Omega/N_D \approx 0.01/N_D \approx 0.001\ \mathrm{sr}, \qquad (2)$$

for $N_D \approx 10$. Ω is small; σ is typically smaller.

More detectors than beams reduces the object-to-detector ranges at the price of more detectors; fewer detectors than beams reduces the number of detectors. Which is preferred depends on the costs of the detectors and the reduction they make. If a beam has a detector at range R_D in the center of its field of view, an object at range r, which the beam sees off boresight by an angle θ, is a distance from the detector

$$\mu = [(r-R_D)^2 + r^2\sin^2\theta]^{1/2}. \qquad (3)$$

The quantity needed for the analysis is the average of μ over the angle $\theta \le \theta_m = (\sigma/\pi)^{1/2}$, for which the detector is responsible, which is

$$\langle\mu^2\rangle \approx (r-R_D)^2 + r^2\theta_m^4/8, \qquad (4)$$

where the smallness of $\theta_m \approx (10^{-3}\ \mathrm{sr}/\pi)^{1/2} \approx 0.02$ rad has been used. For that value $\theta_m^4/8 \approx 10^{-8}$, so except at $r \approx R_D$ the second term is negligible and $\sqrt{\langle\mu^2\rangle} \approx |r-R_D|$.

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13. G. Canavan, "Target Returns for Neutral Particle Beam Discrimination," op. cit. Fig. 4.

Fig.1. Constellation size

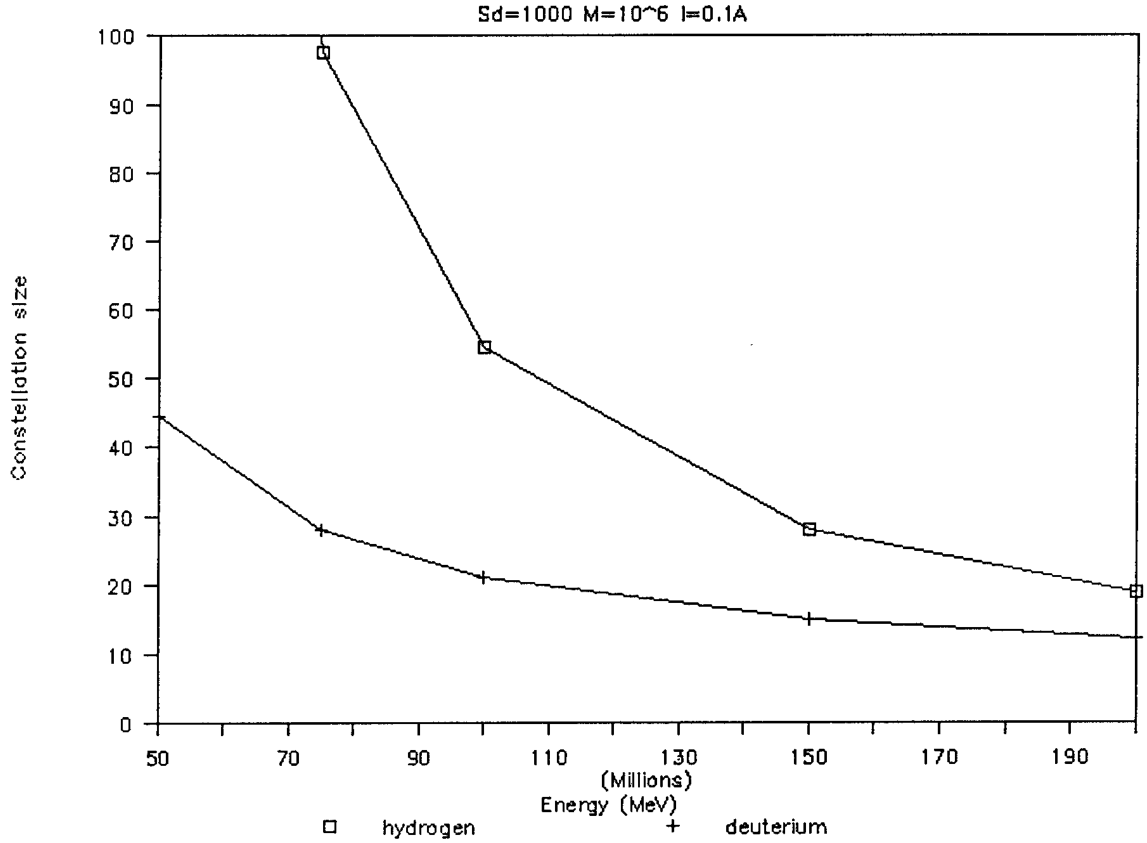

Fig.2. Discrimination rate vs range

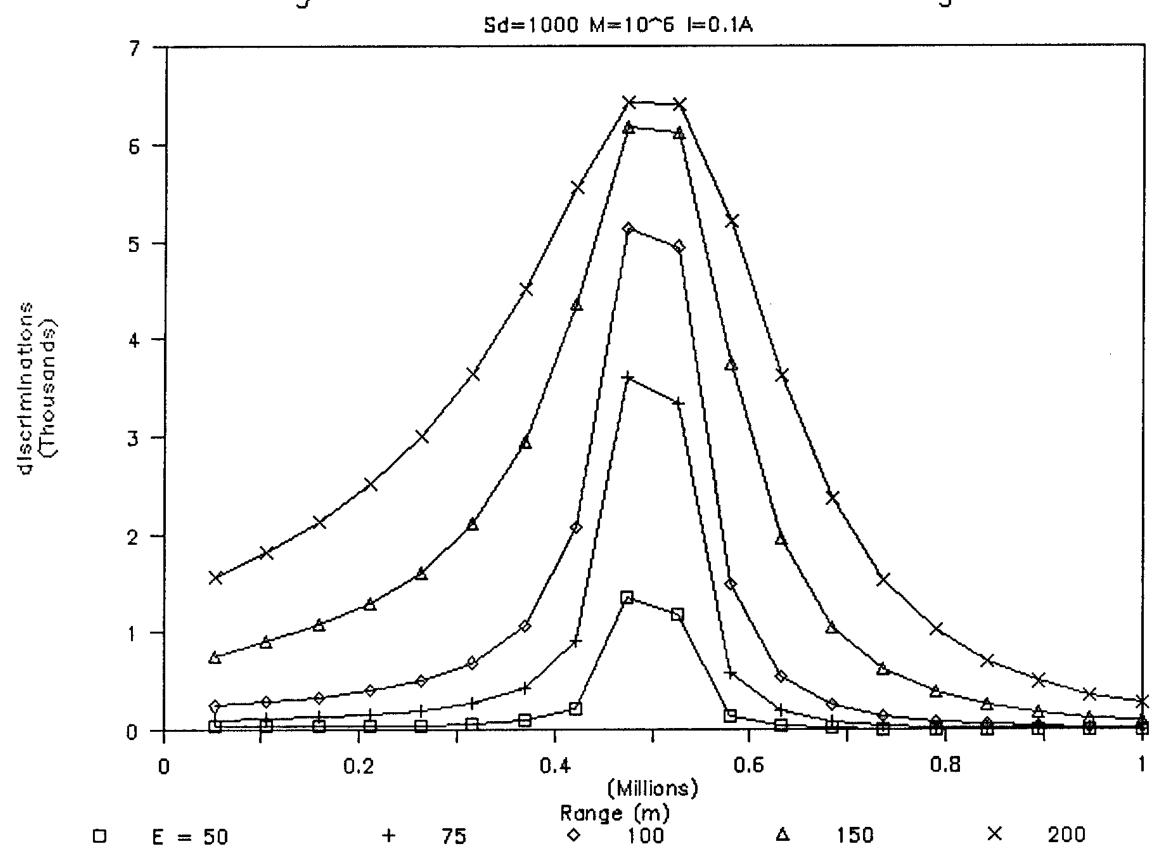

Fig.3. Discrimination fluence

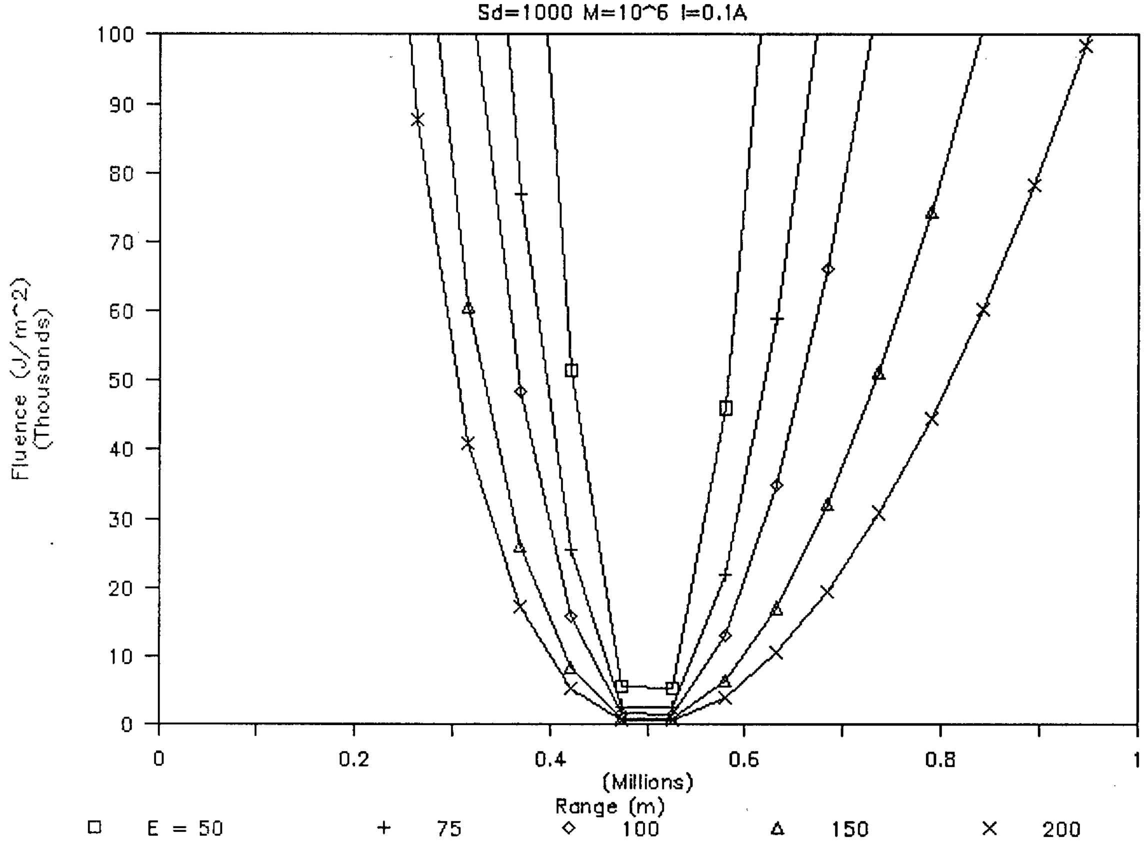

Fig.4. Constellation size vs retarget t

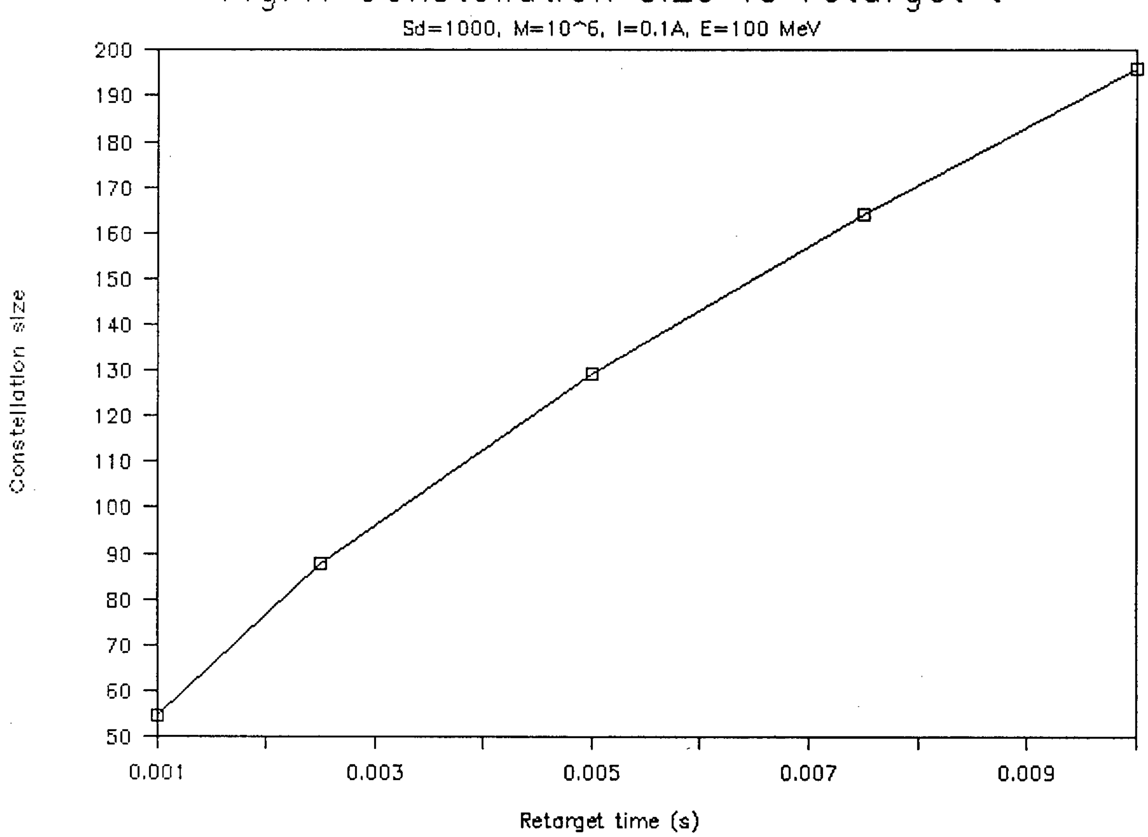

Fig.5. Platforms vs detector range

Sd=1000 M=10^6 I=0.1A, E=100 MeV

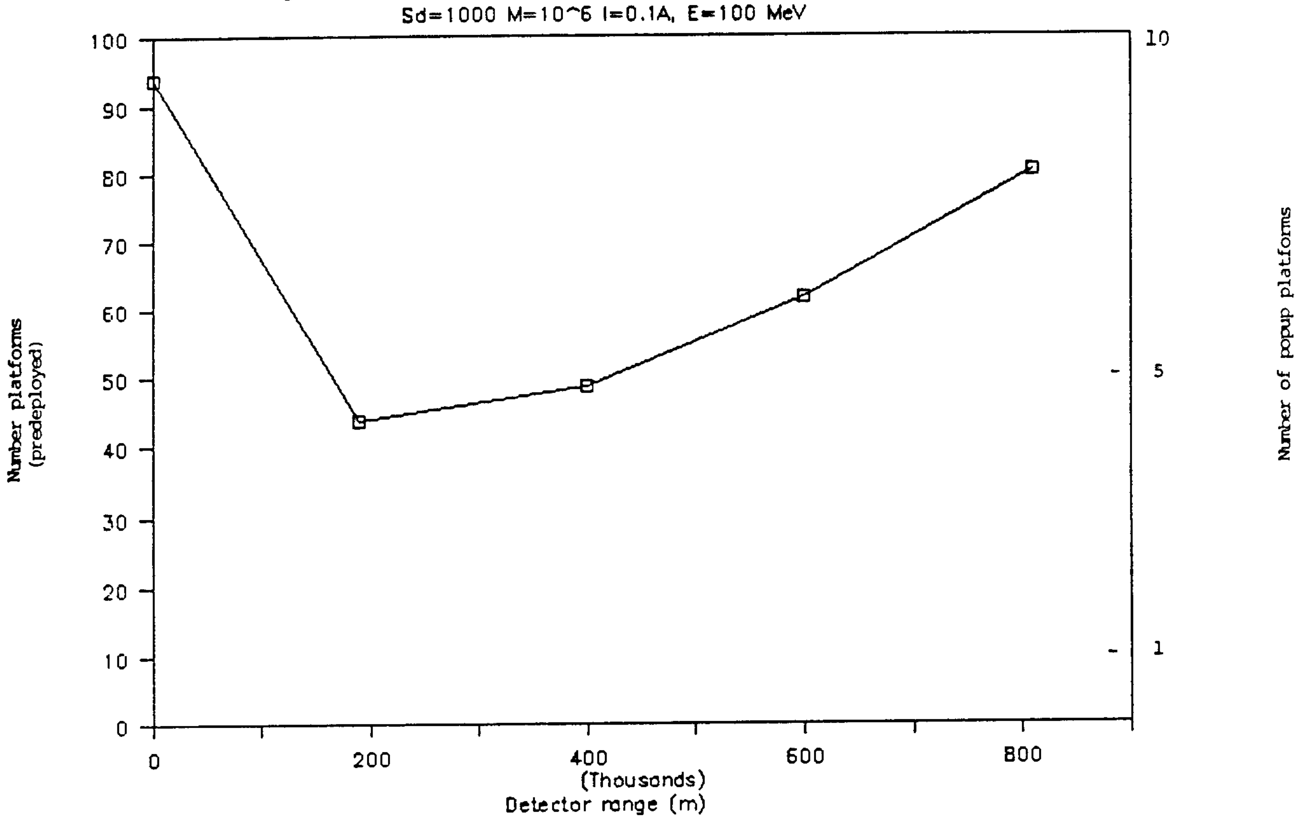

Fig.6. Discrimination vs detector range

Sd=1000 M=10^6 I=0.1A, E=100 MeV