BARC/1992/E/008

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GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

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BIBLIOGRAPHIC DESCRIPTION SHEET FOR TECHNICAL REPORT

(as per IS : 9400 - 1980)

01	Security classification :	Unclassified
02	Distribution :	External
03	Report status :	New
04	Series :	BARC External
05	Report type :	Technical Report
06	Report No. :	BARC/1992/E/008
07	Part No. or Volume No. :	
08	Contract No. :	
10	Title and subtitle :	An experimental program for collective acceleration of ions using intense relativistic electron beams
11	Collation :	65 p., figs., tabs.
13	Project No. :	
20	Personal author(s) :	T. Vijayan, P. Roychowdhury, S.K. Iyyengar
21	Affiliation of author(s) :	Neutron Physics Division, Bhabha Atomic Research Centre, Bombay
22	Corporate author(s) :	Bhabha Atomic Research Centre, Bombay - 400 085
23	Originating unit :	Neutron Physics Division, BARC, Bombay
24	Sponsor(s) Name :	Department of Atomic Energy
	Type :	Government
30	Date of submission .	April 1992
31	Publication/Issue date :	May 1992

Contd... (ii)

40	Publisher/Distributor :	Head, Library and Information Division, Bhabha Atomic Research Centre, Bombay
42	Form of distribution :	Hard Copy
50	Language of text :	English
51	Language of summary :	English
52	No. of references :	35 refs.
53	Gives data on :	

60 Abstract : A program of collective ion acceleration using intense relativistic electron beam (IREB) of 0.25-1MeV, 6-80kA, 60ns on the Kilo Ampere Linear Injector (KALI) systems to accelerate light and heavy ions to high energies approaching GeV with currents over tens of amperes, is envisaged in this report. The accelerator will make use of the intense space-charge field of electron beam in vacuum for accelerating ions which are injected into it. For ion injection, various alternatives, such as, localized gas puff, dielectric insert, laser plasma, etc. have been considered as present and long-term objectives. Among the variety of diagnostic methods chosen for characterizing the accelerated ions include range-energy in foil, CR-39 track detector, nuclear activation technique and time-of-flight for energy and species determination; ion Faraday cup for current measurement; and Thomson parabola analyzer for determining the post-acceleration charge-state. In the proposed MAHAKALI collective accelerator, protons of energy over 10MeV and higher charge state metal ions around a GeV are predicted using a REB of 1MeV, 30kA, 60ns from KALI-5000. In present experiments using KALI-200 with REB parameters of 250keV, 60kA, 80ns, protons over a MeV and carbon and fluorine ions respectively for 12MeV and 16MeV in significant currents have been accelerated.

70 Keywords/Descriptors : RELATIVISTIC BEAM INJECTION; ION BEAMS; ACCELERATION; ELECTRON BEAM INJECTION; COLLECTIVE ACCELERATORS; CARBON IONS; FLUORINE IONS; SPACE CHARGE; TIME-OF-FLIGHT METHOD; MEV RANGE 01-10; GEV RANGE; PROTONS

71	Class No. :	INIS Subject Category : E1632
99	Supplementary elements :	

CONTENTS

1. Introduction.

Generation and propagation of intense ion beams have potential applications in advanced areas, such as accelerators and new accelerator concepts,[1,2] directed energy systems, controlled thermonuclear fusion research, and so on. The method of collective ion acceleration (CIA) is seen as one of the ways of generating such intense beams. In collective ion acceleration,[3-7] an intense (tens to hundreds of kA) relativistic electron beam (IREB) when injected into vacuum, forms a deep potential well due to the collective space charge field of REB electrons. The electric field in well in this case is as high as 10^6-10^7 volts/cm. Ions injected in to this well are accelerated in the REB direction giving rise to collective ion acceleration. The high field in this case is made possible due to the high intensity of REB and has no breakdown limitation in vacuum since no electrode gaps are involved for creating the field. Typical schematic of a collective ion accelerator is shown in Fig.1. Accelerated proton energies over twenty times the REB electron energy have been reported by several groups[3,4] and ion currents reach many kA in some of the experiments.[8,9] Heavy ions of higher charge states have been accelerated to energies very close to GeV and in excess of 10MeV/amu[5-7] in the University of Maryland experiments.

Table 1 gives a equivalence of ion flux from a collective accelerator to that in a continuous beam accelerator. Table 1

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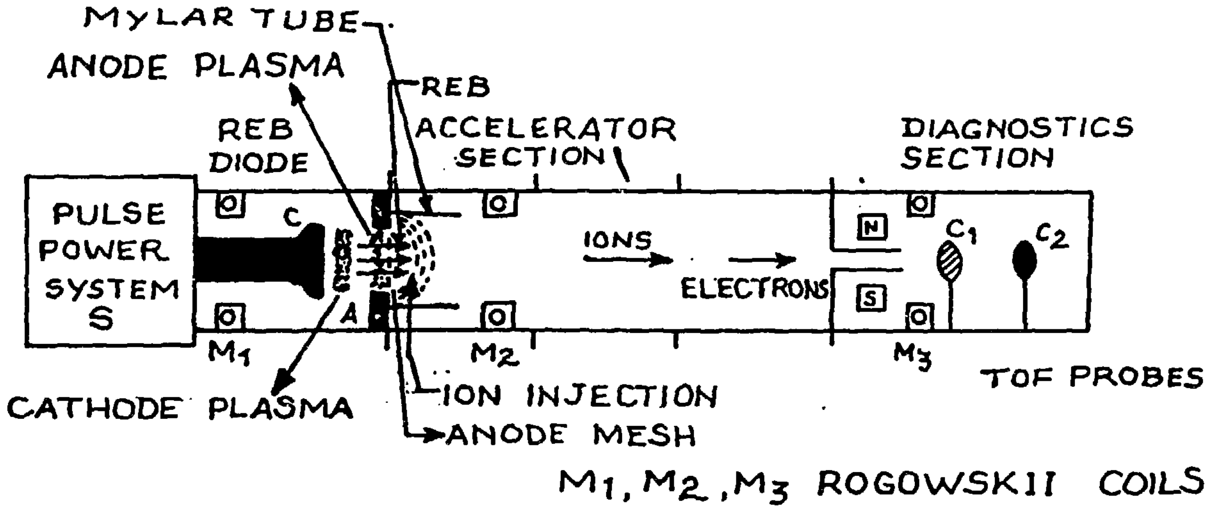


FIG. 1. SCHEMATIC OF A COLLECTIVE ION ACCELERATOR

also shows that with a moderate repetition rate of 20Hz a collective ion accelerator is equivalent to a continuous accelerator of 2-200μA ion current.

Hence, realizing the usefulness of intense ion beams in the frontline areas and the efficacy of collective acceleration method to accelerate high energy light and heavy ion beams, a program to develop a linear collective ion accelerator and to investigate the phenomena of generation and transport of ions so accelerated has been conceived. Towards this goal, development of a collective ion accelerator employing the Kilo Ampere Linear Injector (KALI) facilities which are presently in various stages of development, has been proposed as part of the VIII plan program of this division, viz, 'High power particle beams and

Table 1. Collective ion currents in repetitive mode

Ion current (kA)	Pulse duration (nsec)	Repetition rate (Hz)	Equivalent cw beam (μA)
		0.01	0.001-0.1
		1	0.1-10
0.01-1	1-10	20	2-200
		100	10-1000

intense radiation sources'. This accelerator will enable extensive studies on the phenomena, generation and transport of pulsed but intense light and heavy ions through the collective acceleration process using relativistic electron beam, finally culminating in a GeV heavy ion accelerator.

This report describes the details of the accelerator and the various experiments planned on it. Accordingly, section 2 reviews the present scenario of collective ion acceleration experiments, whereas section 3 describes the scheme of linear collective ion acceleration, various ion injection options and numerous diagnostic methods useful for characterizing the ions. Section 4 discusses the present experiments of collective ion acceleration conducted on the KALI-200 accelerator in this laboratory. The significant results obtained from these experiments are highlighted in this. Section 4 also details the proposed and more extensive studies planned on the KALI-1000 and KALI-5000 systems using significantly higher REB intensities. The important results expected from the program are summarized and finaliy concluded in section 5.

2. Scenario of collective ion acceleration experiments.

Table 2 gives results of important experiments on collective ion acceleration conducted in various laboratories around the world by injecting intense relativistic electron beams into vacuum, and Table 3 shows the important results of acceleration by injecting IREB into a neutral gas (hydrogen) channel.

Table 2. Collective ion acceleration experiments in vacuum

Laboratory	REB parameters	Characteristics of ions generated		
Boeing Aerospace Co. USA[8]	3MeV, 90kA, 40ns	H	30MeV	I_i ~ 10-20kA, 5-10ns
Univ. Maryland USA[3,7,9]	1-2MeV, 40kA, 30ns	H	16MeV	I_i ~ 12kA, 5ns
	1.2MeV, 30kA, 30ns	Xe	961	N_i ~ 10^7-10^{12} 1-10ns
		Fe	600	
		Al	280	
		C	122	
		Kr	390	
		A	186	
		Ne	77	
		N	65	
		H	5	
Sandia Nat Lab.[10] USA	5MeV, 40kA, 125ns	H	16.5	N_i ~ 10^9-10^{14}
	8MeV, 230kA, 200ns	He	40	
Ion Phys.[10] USA	1.7MeV, 30kA, 50ns	H, D	5	I_i ~ 10-100A 3-10ns
		He	9	
		N	20	
Inst. Nucl. Phys.[11] Tomsk	1MeV, 1.6kJ	H	15	N_i ~ 2×10^{11}
		He	45	N_i ~ 10^{10}
	0.3MeV, 0.3kJ	H	12	N_i ~ 5×10^{12}
Moscow Eng. Phys. Inst.[12]	0.2MeV, 7kA, 10ns	D	0.7	N_i ~ 10^{13}, 10ns
Kanzawa Univ.[6]	0.6MeV, 16kA, 10ns	Ba	270	

Table 3. Collective ion acceleration experiments in neutral gas[a]

Laboratory	REB used[b]				Pressure	Ions generated[c]		
	ϵ_e (MeV)	I_e (kA)	τ_r (ns)	τ_b (ns)	(Torr)	ϵ_i (MeV)	I_i (A)	τ_i (ns)
Phys. Internat. USA[13]	0.2	200	15	80	0.2	0.8	200-3300	5-8
Lebedev Inst. Moscow[14]	0.65	15 -20	15	50	0.005 -0.4	1-3.8	16-32	5-10
Ion Phys. USA[15]	1.3	35	10	40	0.05-0.3	4.8	100	3
Univ. California Irvine[16]	1.3	50	35	50	0.3	4.5	320	5

[a] hydrogen

[b] REB rise time (τ_r) and pulse width (τ_b)

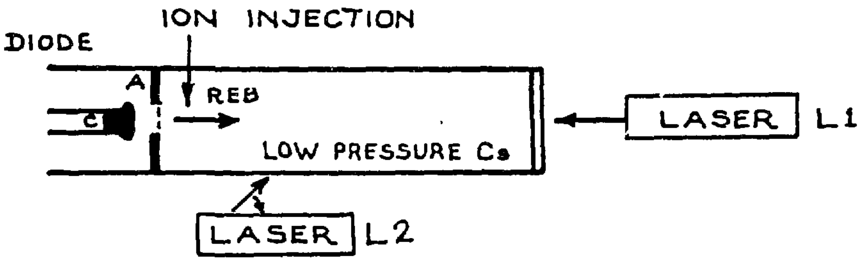
[c] ion pulse width (τ_i)

Comparing the proton energies accelerated by the two methods in these tables, it can be seen that significantly large ion energies and currents are attained by adopting the vacuum acceleration method as compared to the gas channel method. Moreover, the vacuum method can be adapted to accelerate ions from metals and fluids as well. As can be seen from Table 2, xenon ions of energy close to GeV have been accelerated by the Maryland group by the vacuum injection route. Hence, of late significant interest is shown, in general, to the vacuum route of collective ion acceleration.

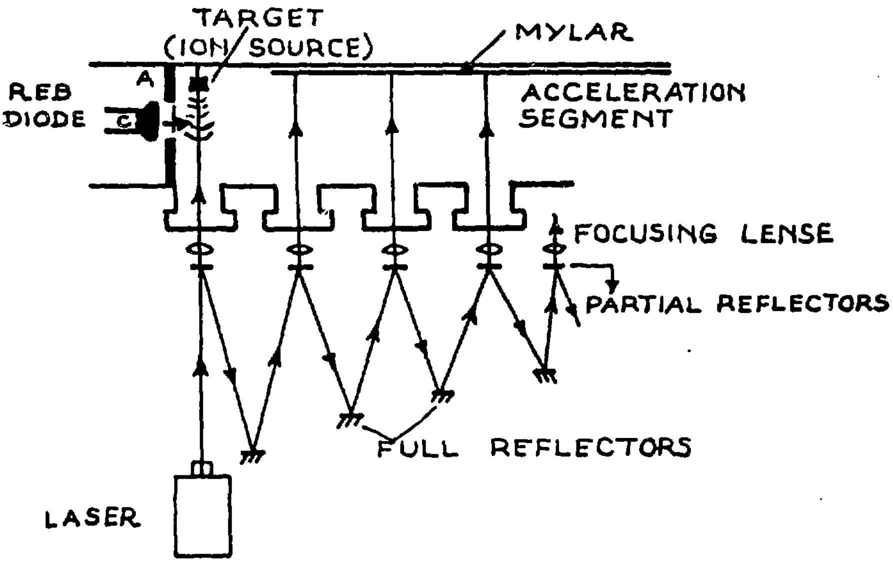
Also, there are advanced collective accelerator schemes currently pursued which are intended to accelerate protons of energy over GeV and currents of tens of kA. One such scheme is the ionization front accelerator[2] (IFA) of Sandia laboratories, USA and is schematically shown in Fig.2a. In this, maximum ion acceleration is obtained by carefully controlling the REB well front movement. This is done with the help of two laser beams L_1 and L_2 which form a low pressure cesium plasma background around the beam head and move it along with the beam in a precisely controlled manner. For this, cesium vapor at low pressure is filled inside the acceleration column and the laser L_1 is used to take the cesium vapor close to the threshold of ionization. Laser L_2 at this stage is swiftly deflected in synchronization with the well front movement for effecting the actual ionization and plasma formation. In the Maryland scheme[1] shown in Fig.2b, the

FIG. 2.

IONIZATION FRONT ACCELERATOR SCHEMES



(a) SANDIA SCHEME



(b) MARYLAND SCHEME

control of the well front is attained through a single laser beam but laser in this case is directed on a long length of mylar sheet (positioned along the acceleration length) with help of a series of partially and totally reflecting mirrors. Here, the ions produced from mylar surface on laser irradiation, provide the field neutralization needed for well movement, while path lengths between mirrors are adjusted for control of the movement. Similar schemes,[17] such as, a large injunction method as in Fig.2c and a multiple injection scheme as in Fig.2d, have also been proposed. In the large injection scheme, the electrons get accumulated in well due to the ion injection rendered over a length. The number of electrons accumulated N_e in this scheme can be approximated as

$$N_e = e^{-1} \sum_{0}^{\tau_e} I_e dt$$

where, I_e is the instantaneous REB current and τ_e beam duration. The large injection scheme is best suited for an exploding wire plasma as ion source. In this case, the exploding wire is located at a suitable angle (as shown in Fig.2c) for controlling the well movement. Whereas, in a multiple injection scheme, several separate exploding wires which are exploded in a time sequenced manner, provide the multiple ion sources in Fig.2d for control of well movement. Alternatively, several wires located at increasing

FIG. 2c. LARGE INJECTION METHOD

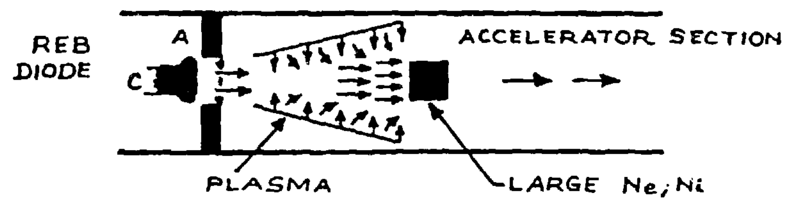
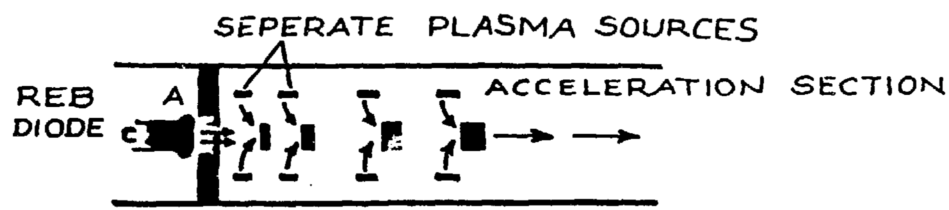


FIG. 2d. SEVERAL INJECTIONS



distances downstream of REB when exploded simultaneously can give the same effect. In a multiple injection scheme with n number of ion injections, the number of electrons accumulated will be

$$N_e = \sum_{0}^{n} N_i Z_i \Gamma^2$$

where, N_i is the number of ions per injection, Z_i is ion charge state, $\Gamma = (1-\beta_f^2)^{1/2}$ is the relativistic factor, $\beta_f c$ is the self consistent velocity and c is speed of light.

There are also other concepts of collective ion acceleration using REB, such as, the electron ring accelerator[18] (ERA), the cusp field accelerator[19] (CFA), the autoresonant accelerator[20] (ARA), the converging guide accelerator[21] (CGA) and the wake-field accelerator[22] (WFA). In the electron ring accelerator schematically shown in Fig.3a, an electron ring is formed by injecting REB transverse to a high magnetic field (usually of a few tesla) and then is compressed by increasing the magnetic field as a function of time. The compressed ring now moves in the direction of applied magnetic field due to the force acting on it by a small component (a few Gauss) of radial magnetic field. Ions are trapped into the potential well of electron ring and accelerated in same direction. Historically, the electron ring accelerator has been the first major attempt to demonstrate the collective ion acceleration mechanism using space-charge field of

FIG. 3a. RING COMPRESSION USING LINEAR REB

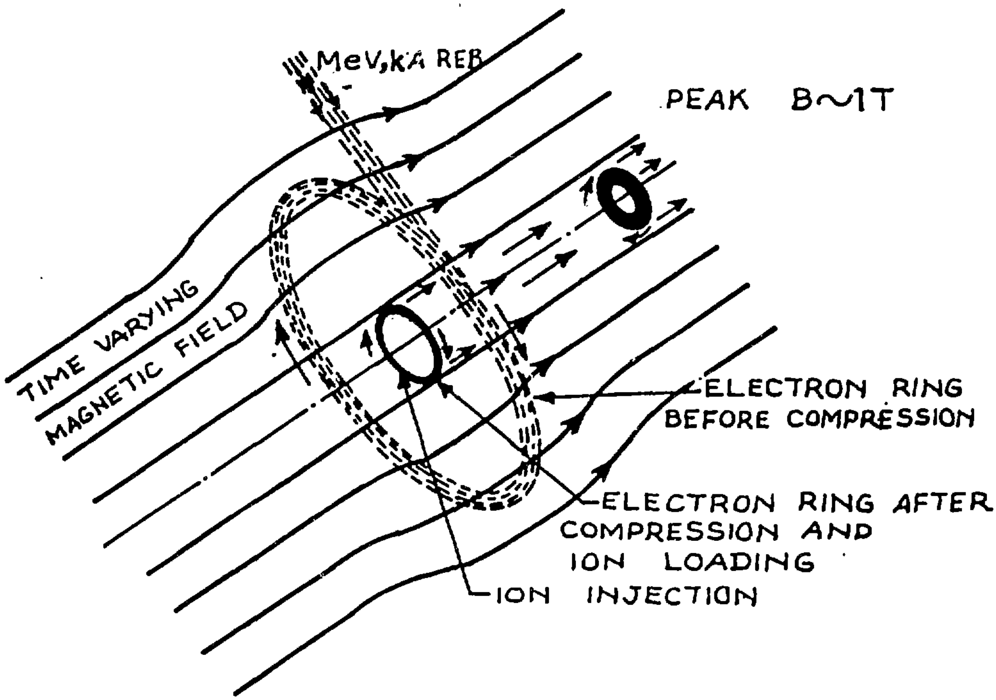
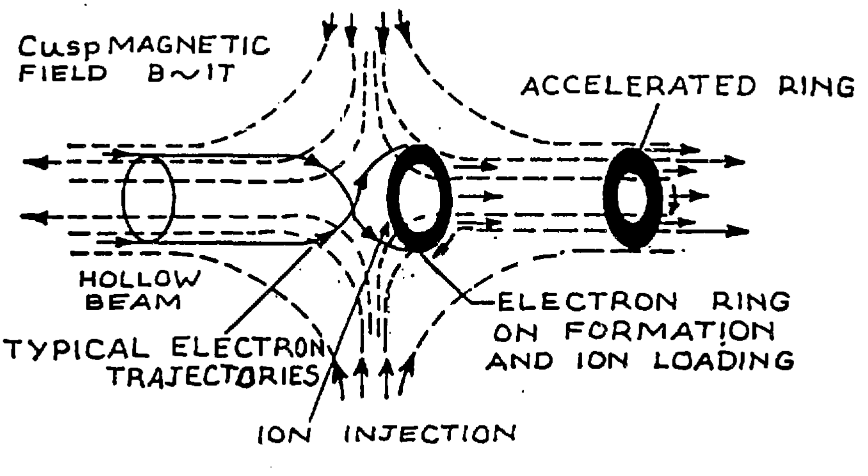


FIG. 3b. RING COMPRESSION USING HOLLOW REB



electron beam. In early experiments[23] however, limitations in the holding power of ring has been experienced due to large loading impedence caused by the modest confining magnetic fields of 1-2T. Even so, compression of ring from 15cm to 2.3cm in major radius has been attained giving proton energies around 200keV. For better compression of ring, a higher field about 6-10T has been suggested. In the cusp field accelerator scheme shown in Fig.3b, the electron ring is formed by injecting a hollow REB into a cusp field geometry and then ions are injected in and accelerated.

In the autoresonant accelerator scheme in Fig.3c, the IREB is confined by an axial high magnetic field and a negative energy of s ⁄ cyclotron wave which is excited and grown on the REB is made use of for ion acceleration. In this, a spatially decreasing magnetic field in the acceleration section gives rise to an increase in the wave phase velocity (v_p) required for the purpose. E_z field about 7.5MV/m has been estimated[24] for REB parameters of 3MeV, 30kA, 200ns and B_z=2.4T, the required acceleration length being a few meters for attaining significant acceleration.

In the converging guide scheme in Fig.3d, the negative energy of a longitudinal space charge wave is made use for ion acceleration. The required increase in phase velocity of wave in acceleration section in this scheme is obtained through a converging shape of the guide tube, with beam radius being kept

FIG. 3c.

AUTORESONANT ACCELERATOR (ARA)

CYCLOTRON WAVE GROWTH AND
ION LOADING

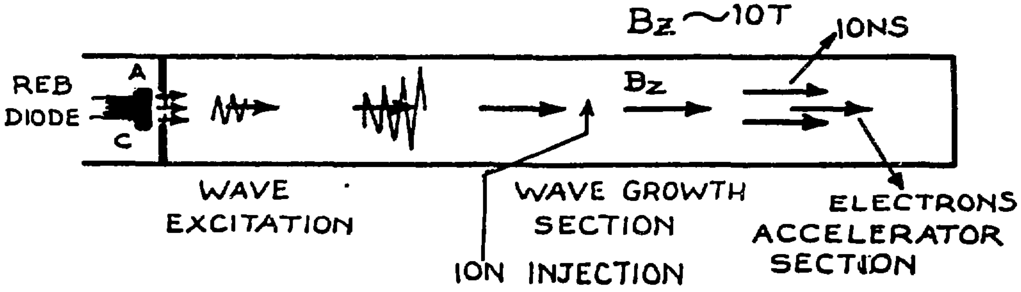
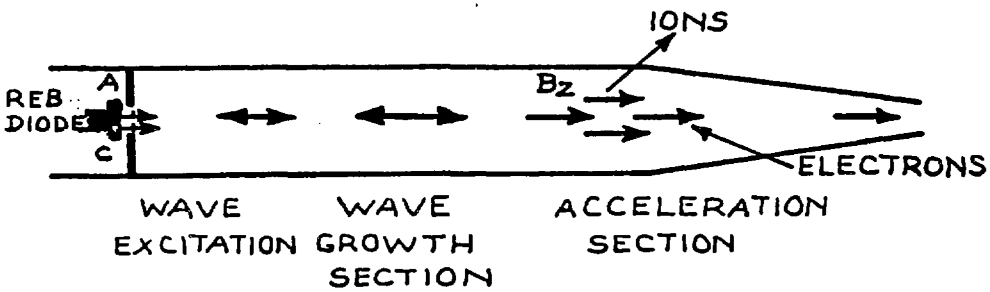


FIG. 3d.

CONVERGING GUIDE ACCELERATOR (CGA)

SPACE CHARGE WAVE GROWTH AND
ION LOADING



constant. Wave fields in the range of 20-30kV/cm has been obtained in the feasibility experiments by the Cornell group.[25]

In the wake-field accelerator shown schematically in Fig.3e, the REB is injected into a plasma channel where it excites large amplitude plasma waves through the two-stream instability. The large electric field inside these waves is made use in this case to accelerate the electrons themselves. Here, the latter part of REB electrons that arrive when the wave amplitude is positive and peaked, gets accelerated to still higher energies. Wave field about 10kV/cm has been measured in experiments of Argonne Laboratory[26] employing one beam for exciting the wave which accelerates a second beam.

Apart from interest in the development of a new breed of accelerators, various applications of current interest also justify their development. In general, ion beams find applications in advanced material research,[27] material processing, medical radiography and cancer therapy. Energetic but intense heavy ions are used for implosion and compression of an inertially confined pellet in thermonuclear fusion research. In the defence area, directed high energy particle beams have applications for supplying high energy on specified targets. High energy intense ion beams are immensely useful for generation of neutrons, production of isotopes, and spallation breeding of nuclear fuels. The authors in reference 15 have used 0.7MeV

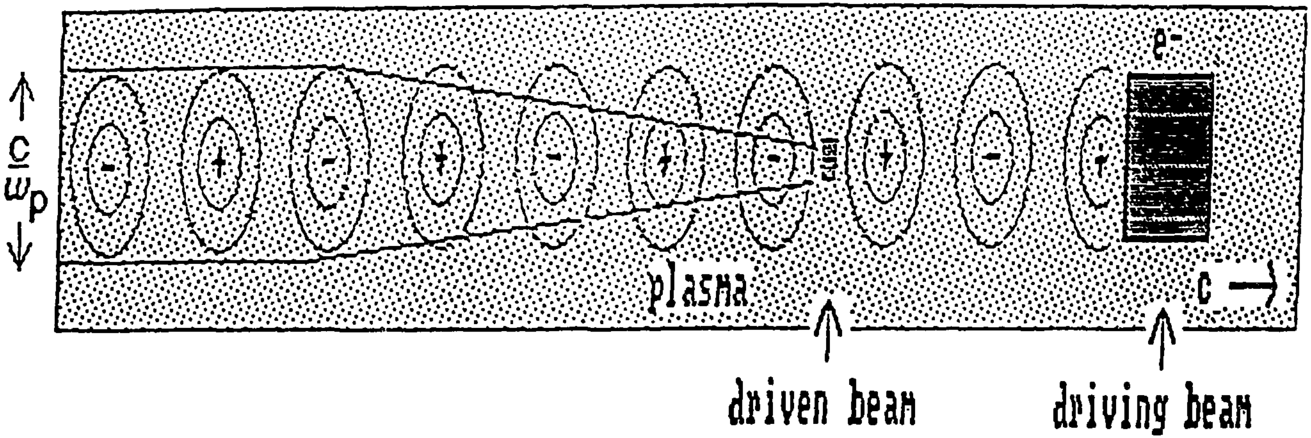


Fig 3e. Mechanism of wake-field excitation.

deuteron ions which are collectively accelerated by a 0.2MeV, 7kA, 10ns REB for generating neutron bursts of about 10^7-10^8 per pulse. Table 4 cites the various nuclear reactions[28] useful for enhanced emission of neutrons and for production of isotopes. Lithium production and transmutation of nuclear wastes are some of the important applications using nuclear reactions.

3. Scheme of Acceleration.

The collective ion accelerator shown in Fig,1, mainly consists of a REB diode, an ion injector, an accelerator column and many diagnostic devices.

3.1. REB and space-charge mechanism

3.1.1. REB generation.

In Fig.1, the REB diode has a field emission cathode C, a foil (or mesh) anode A, and a hard vacuum in the space between cathode and anode. A high voltage from a pulse power system S is impressed between the electrodes and this initiates the generation of an intense REB in the following manner. The applied voltage in diode creates a large electric field at the micro tips present all over the cathode surface and gives rise to significant field emissions from these whiskers. This in turn causes excessive Joule heating at the whiskers and makes them burst to form a cathode plasma. The electrons from this cathode plasma are drawn and accelerated by the anode voltage and they emerge through the anode foil/mesh as an intense REB. For very

Table 4. Some useful nuclear reactions due to high energy ions[28]

Ion specie	Ion energy[a] (MeV)	Reaction	Cross section σ (barn)
Protons	2.0	$^{7}Li(p,n)^{7}Be$	0.24
	2.5	$^{9}Be(p,n)^{9}B$	0.1
	(8.0)	$^{11}B(p,n)^{11}C$	0.35
	(10.0)	$^{66,67}Zn(p,n)^{66,67}Ga$	0.5
	(10.0)	$^{127}I(p,n)^{127}Xe$	0.5
	(11-18)	$^{63}Cu(p,n)^{63}Zn$	0.6
	(20.0)	$^{68}Zn(p,2n)^{67}Ga$	0.7
	(25.0)	$^{205}Tl(p,3n)^{203}Pb$	1.0
	(25,32)	$^{63}Cu(p,2n)^{62}Zn$	0.2
	(30.0)	$^{68}Zn(p,3n)^{66}Ga$	0.2
	(40.0)	$^{127}I(p,3n)^{125}Xe$	0.4
	(50.0)	$^{127}I(p,5n)^{123}Xe$	0.4
Deuterons	0.7	$d(d,n)^{3}He$	0.06
	1.0		0.08
	(4.0)		0.1
	0.1, 10.0		0.02
	0.6	$^{9}Be(d,n)^{10}B$	0.11
	(2.0)	$^{10}B(d,n)^{11}C$	0.25
	(2.25)	$^{12}C(d,n)^{13}N$	0.2
Helium-3	(4.0)	$^{9}Be(^{3}He,n)^{11}C$	0.11
Helium-4	(11-18)	$^{60}Ni(^{4}He,n)^{63}Zn$	0.6
Helium-4	(25-32)	$^{60}Ni(^{4}He,2n)^{62}Zn$	0.2
Nitrogen	(25.0)	$^{9}Be(^{14}N,\alpha n)^{18}F$	0.3

[a] ion energy in ( ) for maximum cross section.

high power beams, the diode is designed in such a way that the intense beam under influence of its self-magnetic field, is confined in a para-potential flow and emerges through the anode to the downstream.

In general, the REB current I_D in diode is deduced from the Child-Langmuir law

$$I_D = 2.34\times10^{-6} A_c V_D^{3/2}/D^2 \qquad (1)$$

where, A_c is the cathode area, V_D is the diode voltage and D is the anode-cathode gap. However, the magnitude of the current and its duration will be decided by the impedence of both the pulse power system as well as that of the diode. Usually, impedence matching between the diode and the pulse power system is followed to obtain proper pulse characteristics across the diode. The parameters of various KALI pulse power systems for this program including their impedences are as noted in Table 5. The diode impedence Z_D in general is evaluated from Eq.(1) as

$$Z_D = 0.136 V_D^{-1/2} D^2/R_c^2 \qquad (2)$$

where R_c is the cathode radius. The parameters D and R_c are chosen such that Z_D is nearly equal to the impedence of the given pulse power system. However, the dynamic impedence of diode during REB generation changes continuously with time due to the following reasons. Just as the cathode plasma is formed (as discussed above), an anode plasma is also formed over the anode surface due to electron impact. The explosive nature of formation of the two plasmas, viz., cathode and anode plasmas, makes them move towards each other. As the two plasmas move closer to each other, they give rise to an effective gap distance D_{eff} = (D-vt) between the cathode and anode, where v is the relative velocity between the two plasmas and t is time. This effective distance actually takes the place of D in the Child-Langmuir relation (1) and the diode impedence relation (2). A reduction in diode impedence in this manner gives rise to a reduced voltage across the diode and a lower electron energy. And when the two plasmas merge, this results in an abrupt termination of REB, i.e. even before complete energy from power system is drawn by beam. In order to avoid this situation, the cathode-anode gap has to be made sufficiently large so that the plasma closure of gap does

Table 5. **Parameters of KALI systems**

System	Voltage (kV)	Current (kA)	Pulse width (ns)	Impedence (Ω)
KALI-75[a]	250	2.0	40	200
KALI-200[a]	250	15.0	50	20
KALI-1000[b]	300	50.0	60	10[a]
KALI-5000[b]	1000	80.0	60	12

[a] measured values

[b] design values

not cause premature termination of REB. However, too large a value of D affects the magnitude of REB current itself due to the resulting low electric field.

3.1.2. Potential well and propagation.

The collective space-charge field of beam electrons gives rise to a limit in the electron current that can be propagated through a field-free region in vacuum. This limit I_L is given by the Olson-Poukey expression[10] as

$$I_L = 17\beta(\Gamma-1)/[1+2\ln(r_d/r_b)] \quad (kA) \quad (3)$$

where, $\Gamma=(1-\beta^2)^{-1/2}$ and r_d, r_b are the radii of the vacuum drift tube and beam respectively. This means that an electron current I greater than I_L will be stopped in vacuum due its own electric field. Hence, when a REB of large current is injected from a diode in to vacuum, it forms a deep potential well (or a virtual cathode) at the point of beam injection. The self electric field created in the well will be of large magnitude and this increases in the downstream beam direction towards its head. Ions injected into this well are trapped by the field and accelerated in the field direction. The average electric field E_a in the virtual cathode can be written from the beam values as

$$E_a = 6\times10^3\alpha I_e/\beta r_b \quad (V/m) \quad (4)$$

where, REB current I_e is in kA, β is the electron velocity component in field direction, and α is a factor[24] related to the width of well. α lies between 0.1 and 1 depending on whether the width of the well is large or small. As ions move into the virtual cathode, they tend to neutralize the electron space charge and allow electrons to move ahead and form the well downstream. The well movement in this case is described either by a charge neutralized model or the force neutralized model. In the charge neutralized model, electrons move ahead and form well downstream only when the stagnant total electronic charge is fully balanced by the charges of trapped ions, i.e. for $N_e = Z_i N_i$ and when neutralization factor $f_e = 1$, where N_e, N_i are the number of electrons and ions in well respectively and Z_i is ion charge state. α in Eq.(4) in this model will be about 0.5 for a well width equal to the electron beam diameter. The ions moving in the same direction as the electrons, continue to be accelerated by the well and follow the electrons. In this manner, the two charge groups move in tandem and a continuously moving well front is established which accelerate the ions to high energies in the process.

In the force neutralized model, for a neutralization factor $f_e = (1/\Gamma^2)$ the electrons continue to move downstream but with a slowed down speed and accelerating the ions. α in Eq.(4) for this case has to be replaced by $(1-f_e)$. In this model, the initial time needed for trapping the ions is not taken into account. This time will be around 10ns and during this time a stationary well is usually formed. The charge neutralized model has the drawback that ion acceleration is described only during the REB pulse duration. But experiments indicate ion acceleration even beyond

REB duration. In view of the above, a combined model appears to be more appropriate wherein the initial part of REB forms a stationary well in which the ions are trapped and accelerated. Thereafter for a force neutralized condition, electrons from later part of REB pass through the charge neutralized well and are slowed down to the ion velocity and propagated downstream and so on. In this process, electrons and the ions give rise to a moving beam front and accelerate the ions to even higher energies. The ion energy ϕ_i after accelerating over a distance z in this manner is obtained using Eq.(4) as

$$\phi_i = Z_i e \sum_{0}^{z} E_z \Delta z \qquad (eV) \qquad (5)$$

This in general is the mechanism of collective ion acceleration. As denoted by Eqs.(4) and (5), a higher value of (ν/Γ), will give higher acceleration, where, ν $(=\pi r_b^2 n_b r_e)$ is the Budker parameter giving the number of REB electrons contained in an axial distance equal to the classical electron radius r_e, and n_b is the electron number density. A more detailed description of collective acceleration is given in reference 29. The ion injection for collective acceleration is usually performed in one of the various ways, such as, REB generated ions from dielectric anode as in a Luce diode, REB ionization of localized gas clouds introduced in its path, pre-formed plasma from a plasma gun, laser-produced or exploding-wire plasma.

3.1.3. REB current limits.

As pointed out in section 3.1.2, a potential well does not form if the REB current is lower than the space-charge limiting current I_L. Hence, I_L is the threshold and a REB current very much higher than I_L is necessary to produce the intense electric field needed for significant collective ion acceleration. However, with larger currents, its self-magnetic field become considerably high and tends to turn back the electrons, thereby stopping their forward propagation. This in turn, imposes an upper limit to the current that can be transported in a device. That is, for currents higher than the Alfven limit[18] I_A, the beam will be turned back by its own self magnetic field and hence beam propagation in vacuum for ion acceleration will not be possible. I_A is given as

$$I_A = 17\beta\Gamma \qquad (kA) \qquad (6)$$

As can be seen from the above discussion, REB current between I_L and I_A is the useful range[30] for collective ion acceleration by injecting REB into vacuum. The current that can be generated in a given diode is however I_e as given in section 3.1.1. Also, the plasma closing of diode may happen even before the beam current rises to its peak value which is decided by the impedence of the complete circuit. Hence, the actual REB current (I_e) that is realized in practice, may be less than I_e. Table 6 gives the various current limits for different operating voltages of 0.15 to 1.5MeV in a REB diode. As seen from here, the actual current

Table 6. Comparison of different current limits for REB and predicted proton energies.

REB energy (MeV)	Space charge limited current I_L (kA)	Alfven current I_A (kA)	Current generated I_e (kA)	Proton peak energy with I_e (MeV)	
				r_b=1cm	r_b=2.5cm
1.5	8.58	65.1	35[a]	23.93	9.57
1.0[f]	5.15	47.6	27[b]	18.97	7.58
0.6	2.64	33.0	16[c]	16.42	6.57
0.3[g]	1.02	21.1	8[d]	8.76	3.5
0.25[e]	0.79	18.9	6[e]	6.88	2.75
0.15	0.38	14.0	2[d]	2.68	1.07

r_b REB radius, drift tube radius r_d=7.5cm.

[a] refer to 5, [b] refer to 7, [c] refer to 6.

[d] assessed from the value recorded at 0.25MeV in KALI-200.

[e] generated in KALI-200.

[f] same as in KALI-5000, [g] same as in KALI-1000.

value I_e is closer to the Alfven limit as the electron energy is increased. On this count, it can be said that a high energy beam facilitates a higher beam current as well. Hence, even though the well field decreases with a higher electron energy as given by Eq.(4), the enhanced beam current associated with higher energy, in reality, gives a higher field in well than the lower energy case. A higher energy REB in this manner gives an advantage for collective acceleration[31].

3.1.4. Influence of REB pulse profile.

From the above discussion, it is clear that a sufficiently large voltage is beneficial for collective ion acceleration using REB. However, too high a voltage in this case will make this method non attractive as compared to the conventional methods. Keeping this in mind, a voltage around a few MV in general is considered to be suitable for collective ion acceleration. This will keep the system size small at comparatively low costs. In our present program, the voltage source being developed for KALI-5000 is in this useful range with an operating voltage of 1MV and the capability for drawing current as high as 80kA. As shown in Table 6, this system is expected to provide proton beam energies as high as 19MeV using moderate REB current of 27kA concentrated in a beam radius of 1cm. As stated earlier, for ions of higher charge state, the ion energy will be correspondingly as many times higher. For example, Fe ions with post-acceleration charge state ~16 have been accelerated to about 600MeV in the University of Maryland[7] experiments. Since the REB parameters in KALI-5000 will be nearly same as in the Maryland accelerator, ion energies same or higher can be easily obtained by using suitable ion injection methods.

As is evident from Eq.(4), the higher the current density of REB, the higher will be the field in well, and this can be achieved in two ways, viz., either by increasing the current in a given beam radius or by reducing the beam radius with a constant current. These options however involve suitable design optimisations of the diode geometry. Here, reducing the REB radius, in effect reduces the number of ions trapped in well for acceleration and hence is not generally followed. Keeping this in view, a beam radius of a few cms is usually allowed and the attempt in general is to increase the beam current[30].

In a linear beam collective accelerator, a beam which is uniformly filling the entire beam radius (i.e., a solid beam) is generally preferred over an annular beam (or hollow beam). In the solid beam case, the field in well is high in a large volume and helps in inducting a sufficiently large ion current, while in the hollow beam case, the field is weak especially towards its axis.

As far as the REB pulse shape is concerned, the most ideal pulse for an instantaneous formation of well would be a square pulse. However, such a pulse shape is not attainable in practice due to the finite impedence of given system. The total system impedence in this case tends to give rise to the rising and falling parts of the REB current. Hence, at best a trapezoidal pulse is attained in practice, but will be a triangular pulse if the impedence is too high. In either case, when REB current I_e is less than I_L in the rising part, the potential well does not form. That is, the potential well is formed only at a time $t>(t_r I_L/I_p)$ for instance in the case of REB injected into vacuum, where t_r is the rise time and I_p is peak REB current. The well can develop to a deep potential well only thereafter. A fast rising REB gives an advantage here for formation of potential well and the acceleration of ions early in the REB pulse, thereby giving rise to relatively higher ion energies. However, a fast rising REB is a necessary condition for collective acceleration through REB injection in a low pressure gas channel. In the latter case, t_r has to be smaller than the charge neutralization time t_n during which the gas column is converted to a plasma channel by the REB electrons. For $t_r \geq t_n$, the REB will be charge neutralized $(f_e=1)$in the plasma so formed, enabling its uninterrupted propagation and hence a potential well does not form. That is, $t_r<t_n$ is a necessary condition for the formation of REB well in a low pressure gas channel.

3.2. Ion Injection Methods[10].

A source of ions giving a large number of particles in a short pulse is useful for injection in a collective accelerator. In particular, a pre-formed plasma is a suitable source of ions and is easily adapted for this purpose. Here, a source plasma density of 10^{14} to $10^{18}cm^{-3}$ is the useful range for collective ion acceleration. Initial high charge states are also attained in a pre-formed plasma. The other simple methods employed to inject ions are by locating dielectric material or gas cloud in the path of REB which then creates the required ions from the medium.

The ions on trapping and acceleration by potential well, occupy roughly about half the width of well. This approximately gives the ion pulse width $\tau_i = (r_b/\beta_i c)$ for given ion energy, where $\beta_i c$ is the ion velocity. Using this, the corresponding ion current I_i is obtained as

$$I_i = \pi r_b^2 n_e / \tau_i \qquad (7)$$

In the following, the various ion injection methods are described in more detail.

3.2.1. Luce diode configuration.

Some of the earliest experiments conducted on collective ion acceleration used a dielectric insert on anode (see Fig.4a) where the REB while passing through the dielectric, ionizes the atoms on it and forms protons, carbon ions, etc. In this Luce diode, the ions being free are trapped into potential well and accelerated. Proton energies over 20MeV have been attained in a number of experiments[3,4] using Luce diode. However, the ion specie in this method is limited to the constituent elements of dielectric materials. As seen in references 8 and 9, this configuration gives high ion currents over 10kA.

FIG. 4a. LUCE DIODE

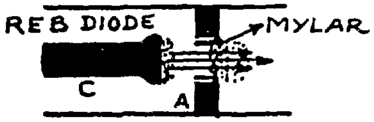


FIG. 4b. GAS PUFF METHOD

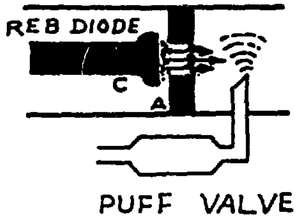


FIG. 4c. CO-AXIAL PLASMA

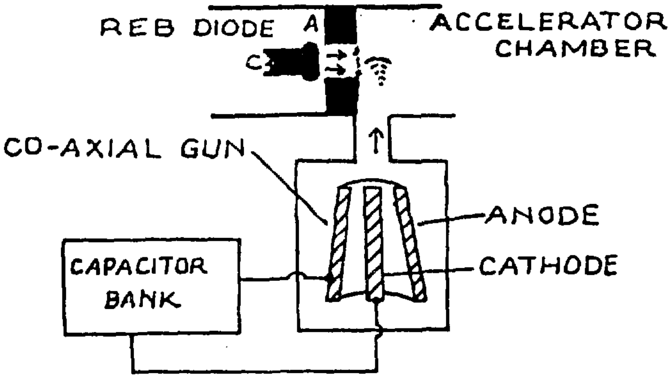
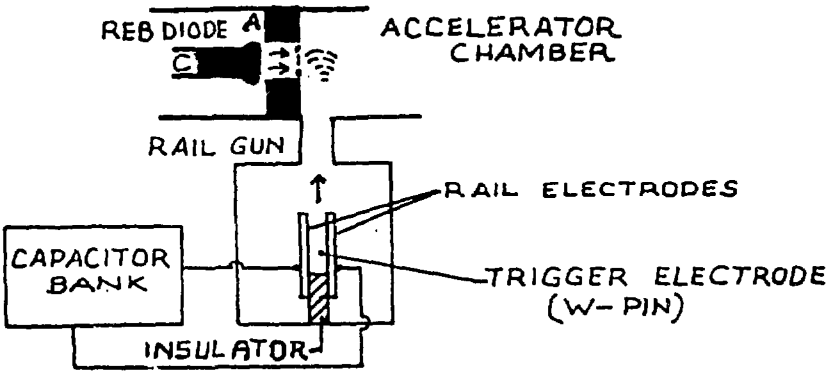


FIG. 4d. RAIL GUN PLASMA



3.2.2. Dielectric guide-tube geometry.

In this geometry, a short length of dielectric tube is attached coaxially to the anode electrode and located inside the downstream metallic vacuum drift chamber. A part of REB electrons strikes this tube and releases ions in to the potential well. Also, some of the electrons charge the dielectric tube and enhance the depth of potential well. As a result, this method is efficient both in terms of ion injection as well as in terms of enhancement of well field. An optimum length of dielectric tube in this case would give best results. A long tube length could result in surface flash-over and break-down towards anode, leading to the degradation of well. On the other hand, a very short length of tube would not allow sufficient ion trapping in well and in turn limits the electrons transported and the well depth.

3.2.3. Gas puff method.

In this method, a well localized gas cloud is introduced in the immediate downstream of anode by using a fast puff valve as shown in Fig.4b. The delay between firing of the gas puff and the REB pulse is carefully controlled so that when the electron beam arrives, the localized gas cloud is within a few centimeters from anode. This delay is expected to be in the 500μsec region. REB electrons ionize the gas through collisions and field ionization and form a plasma of density about 10^{14}-10^{16} cm^{-3}. Ions from this plasma are trapped and accelerated by the REB well. The advantage of this method is that it is possible to accelerate ions of all natural gases. Also, gas pressure in this case can be precisely monitored by a fast response ionization gauge, and controlled to give optimum acceleration conditions. The useful pressure for this is in the range 1-100 mTorr. Ion energies over 5MeV/nucleon and yields of about 10^{12} ions per pulse have been reported[8] using this method. Xenon ions have been accelerated close to GeV energy[5].

3.2.4. Pre-formed plasma sources.

3.2.4.1. Plasma guns.

A. Co-axial gun plasma.

In a co-axial plasma gun shown in Fig.4c, a high voltage (-5kV) from a capacitor bank is applied between two co-axial tubes and a breakdown is initiated by a gas puff in between them. A dense plasma is formed in this process and a high current flows through the plasma between the electrodes. This sets up a strong $\vec{j}\times\vec{B}$ force on the plasma accelerating it axially and propelling it out of the gun. This plasma is injected into the potential well [i.e. in place of gas puff in Fig.1] and the ions from it are accelerated. In view of the pre-formed ions in this method, their interactions with REB and well field thereafter are expected to enhance their charge state and hence their energy on acceleration as compared to a simple gas puff method. A suitable comparison of the two methods on these lines could be a good contribution.

B. **Rail-gun plasma.**

This method is useful for generating mainly metal ions. In the rail gun geometry shown in Fig.4d, a discharge is struck between two parallel plates of given metal by connecting them to a capacitor bank. The $\vec{j}\times\vec{B}$ force propels the metallic plasma so formed, out of the gun and is used for injection. Here, the two electrodes are made of the material whose ions are needed for acceleration. Barium ions of 270MeV has been generated[6] using the rail-gun ion injection.

3.2.4.2. **Laser-target source.**

The advantage of this method is that plasma of any given target material can be formed and used as ion injector into the REB potential well. For this, the given target material of about 1-2mm diameter is located (see Fig.4e) in the immediate downstream of anode and illuminated by an intense laser beam. A highly collimated but Q-switched ruby laser of 1-10J energy in a short duration of about 10ns is needed to give the energy density required for creating a dense and explosive plasma from the target material. Ions from this plasma on expansion, are trapped in well for acceleration. The advantage of this method is that, because of high energy density and resulting explosive nature of plasma generation, it gives rise to highly multiple-charge state ions[7]. The initial high charge state helps in an enhanced ion energy on acceleration. Acceleration of C, Al and Fe ions to hundreds of MeV energy have been reported[7] in this method which

FIG. 4e. LASER PLASMA

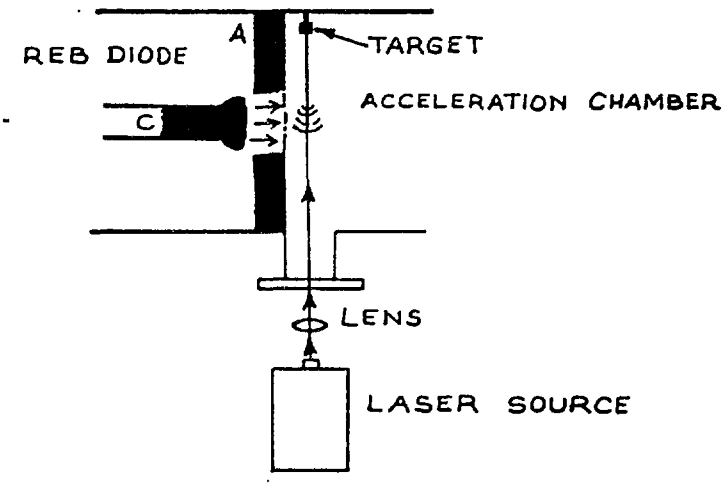
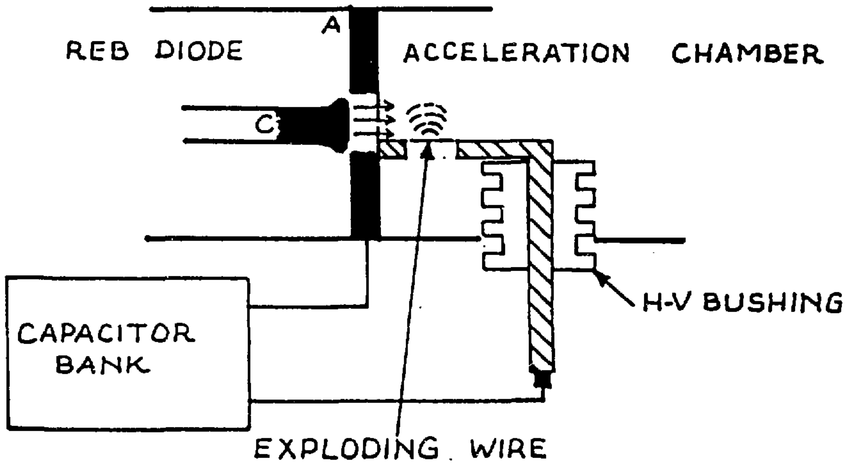


FIG. 4f. EXPLODING-WIRE PLASMA



shows promise for accelerating heavier ions to a few GeV energy. Typical delay time required between the firing of the laser and REB is around 0.5μsec.

3.2.4.3. Exploding-wire plasma.

In this method, the given material in a wire form is exploded using an intense energy pulse from a pulse forming line. Ions from resulting plasma on expansion are injected in to the potential well. This method also has the advantage of providing ions of multiple-charge states. Typical delay between the triggering of exploding-wire and firing of REB is in the μsec region. A schematic of accelerator section employing exploding wire plasma is shown in Fig.4f.

3.3. Diagnostics and ion characterization.

Referring to Fig.1, the Rogowski coil M1, placed inside the diode wall, measures the REB current generated inside diode and M2, placed immediately after the anode, measures the REB current injected downstream of anode. In the ion acceleration region, there is a net current flowing which is the sum of the REB and ion currents. This net current I_n is measured by another Rogowski coil M3 stationed at a place where the current measurement is desired.

At the end of the acceleration channel, a permanent magnet NS provides a sweeping field of about 1-2kG which is applied transverse to the propagation direction and filters the electron beam from the propagating ion beam. The ion beam thereafter is characterized by various diagnostic techniques employed in the downstream section (ion beam drift tube) of the accelerator. The details of these set-ups are illustrated schematically in figures 1 and 5a-5c. In the following, a brief description of various diagnostics of interest to ion beams is given.

3.3.1. Measurement of ion current.

The ion current is measured downstream of the sweeping magnet, by a low impedence current collector. A graphite stop in the form of a conical cup, is used as the current collector in order to minimize the back scattering, secondary and sputtered emissions. Here, the graphite in effect acts as a sponge for the penetrating ions. The graphite collector may be biased to a small positive voltage of a few hundred volts for reducing the effects of any small secondary emissions from graphite in case of large ion currents. The ion current collected by the Faraday cup is then recorded and analyzed on a 50Ω, 400MHz oscilloscope.

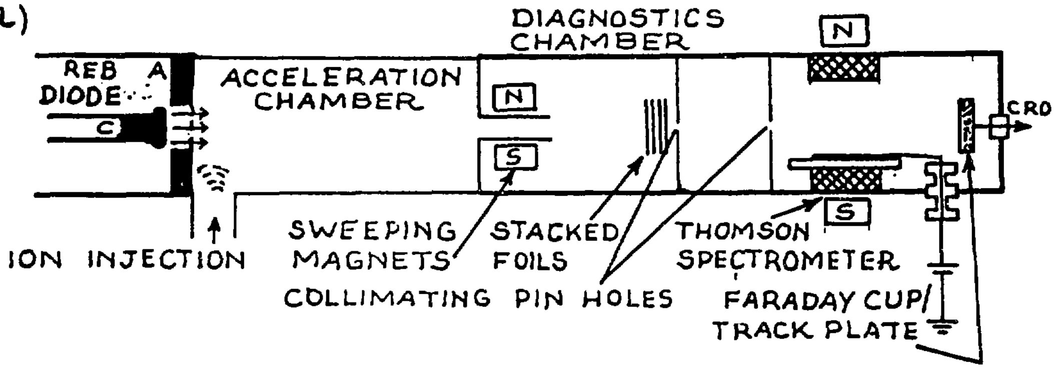
3.3.2. Ion energy measurements.

3.3.2.1. Time-of-flight analyzer.

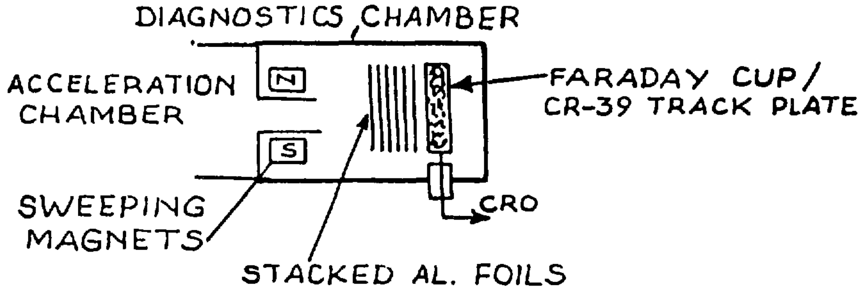
In Fig.1, C1 and C2 are two time-of-flight (TOF) probes about 7.5cm in diameters interspaced about 0.5m apart. The probe C1 is a stainless steel mesh with about 50 per cent transparency and the second probe C2 is a Faraday cup collecting the rest of ion current. Both these probes are connected by equal lengths of 50Ω co-axial cable to two 50Ω, 400MHz oscilloscopes through

FIG.5. POST-ACCELERATION DIAGNOSTICS

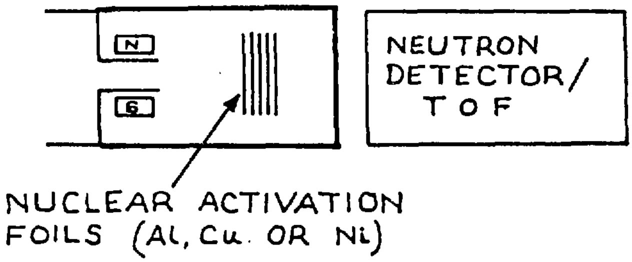
(a)



(b)



(c)



suitable terminators. The current signal from probe C1 is used to trigger the oscilloscopes simultaneously and the current signals from the probes are recorded on the oscilloscope screens. The delay between the rising parts (or any other identical parts) of the two current traces is used then to deduce the time of flight of the ions. Once the ion specie is known, its energy is then determined.

3.3.2.2. **Range-energy measurements.**

A. **Staggered-foil technique.**

In order to establish the ion energy, a range-energy measurement coupled with a TOF analysis, is found to be suitable. For this, the ions are allowed to penetrate a number of foils of known stopping power which are stacked together as shown in Fig.5b. The number of foils (for example, Al foils) in this case are chosen such that a measurable current is registered by the current probe stationed downstream of the foils. The stopping power tables[32-34] are then used along with the TOF data to obtain the ion specie and its maximum energy. Also, by varying the number of foils in the ion path, an energy distribution of ions also can be determined. This will however need a series of experiments with other conditions kept constant.

B. **CR-39 track method[35].**

A transparent material such as the modified polycarbonate (CR-39) is highly sensitive to energetic ions and hence is used as track detector to make a range-energy measurement (see in Fig.5b). The CR-39 track plate when exposed to ions, leaves behind burned tracks having pore size proportional to ion diameter inside the track plate medium. The track plate is then etched in a NaOH bath and the tracks are counted under a microscope. Then, energy and specie of the ions are concluded using range-energy data obtained from range-energy measurements. This is usually done by stacking aluminum foils over the track plate and then the complete assembly is exposed to the ion stream. In this process, the energy of the maximum energy ion component is in effect brought down and the low energy components are effectively suppressed by the foils. Hence, this facilitates counting of the high energy ions, while the foil range-energy data gives their energy. Here, an energy measurement is applied only when a sufficiently large number of tracks are registered on the CR-39 plate, i.e. large number of high energy ions penetrate the staggered foils and manage to reach the track plate for the count. In this method also, the energy distribution of ions can be determined by varying the number of aluminum foils over the track detector.

3.3.2.3. Calorimetry

A thermistor (or thermocouple) embedded inside the graphite collector of the Faraday cup (described in section 3.3.1) will measure the average temperature rise in graphite due to the ion energy dissipation. This in turn, gives the total ion energy absorbed by the collector. From this, the average ion energy is deduced once the ion specie and its number are known.

3.3.2.4. Nuclear reaction in foils[39].

It has been observed that, by exposing appropriate foil material to given ion specie, copious amount of neutrons or other particles are generated through nuclear reactions taking place between the ions and the foil material. The emitted particles are analyzed using suitable techniques. For example, a neutron TOF (see Fig.5c) coupled to a pair of silver activation neutron counters is used in case of neutrons. The ion specie, energy and their number are then known from the emitted particles and the activating foil material. The useful nuclear reactions for light ions of low energy, in general are

A. Employing positron activity

$$^{10}B(p,\gamma)^{11}C(\beta^{+})^{11}B$$

$$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C$$

$$^{27}Al(p,\gamma)^{28}Si(\beta^{+})^{28}Al.$$

The boron reaction product has a half life of about 20.4 minutes, while the aluminum reaction has over 100 resonance peaks in the proton energy range of 0.2-4MeV. However, the measurable counts per beam shot will be very much smaller than the noise level. This needs extra precautions to detect them by a photo-multiplier tube.

B. Employing neutron activity

$$(p,Li) \quad \text{-->} \quad {}^{7}Li(p,n)^{7}Be$$

(d,d)	-->	$d(d,n)^{3}He$
(d,C)	-->	$^{12}C(d,n)^{13}N$
(α,Be)	-->	$^{9}Be(\alpha,n)^{12}C$

The reaction (p,Li) has a threshold of 1.86MeV. For the reaction (d,C), a mylar foil is generally used and is also applied to monitor the high energy part of deuterons.

In order to detect the high energy part of other ions, the following reactions are useful.

(p,Li)	-->	$^{7}Li(p,2\alpha)$
(p,Cu)	-->	$^{63}Cu(p,n)^{63}Zn$
(α,Ni)	-->	$^{60}Ni(\alpha,n)^{63}Zn$
(N,Al)	-->	$^{27}Al(^{14}N,\alpha,n)^{34m}Cl$

The threshold energy for the above reactions depends mainly on the ion and foil combination. For the (p,Cu) combination, the threshold energy is about 4.2MeV, while for (N,Al) case it is about 40MeV. In addition, at higher ion energies the higher order reactions, such as (p,2n), (p,pn), etc. are also useful. Some of these reactions have been listed in Table 4.

The methods employed for the detection and counting of neutrons and determining their energies are fairly conventional in nature. They include direct measurement by means of scintillation or boron trifluride proportional counters. For moderate rates of neutron emission, a scintillator counter connected to PMT is satisfactory, and if the rate of neutron emission is not too high, the total yield can be determined by a boron trifluride proportional counter in conjunction with a solid hydrogeneous material such as polyethylene or paraffin to slow down the fast neutrons. If the total number of neutrons is sufficiently large, it is often convenient to use an activation counter to determine the total yield. The device consists of a standard instrument, such as a proportional counter or Geiger tube for counting beta particles, surrounded by a foil for e.g. silver or indium which becomes radioactive as a result of the capture of neutrons. The benefit of the delayed emission of beta in this case, keeps out any unwanted electrical pickups during the generation and transport of electron and ion beams.

The limitation of the nuclear diagnostics method is that its resolution for heavy ions is poor since the nuclear activation cross sections for heavy ions are small and the corresponding threshold activation energies are very high due to the large Coulomb energy barrier.

3.3.3. Charge measurement.

3.3.3.1. Post acceleration charge.

A Thomson spectrometer is used for determination of the post acceleration charge state as the ion energies will be very high. In this E,B analyzer (see Fig.5a), the two fields are applied in the same transverse direction to the ion propagation. Hence, ions of same charge state to mass ratio but having different energies, trace out a parabola on a track plate kept downstream of the analyzer. The magnetic field ~2kG of the analyzer is provided by the pole pieces (with separation about two cms and located inside a vacuum drift chamber) of a permanent magnet. A conductor plate located on (but insulated from) one pole piece, is connected to high voltage ~20kV to give the required E field. A CR-39 track plate is used to obtain the ion tracks and the traces of parabolas which indicate the charge and specie of the ions are analyzed.

The resolution of Thomson spectrometer is not good for high energy ions and hence is applied only upto ~1MeV/amu. Higher energy ions are however brought down to a suitable energy level by using staggered aluminum foil assembly, and then analyzed by the spectrometer as illustrated in the schematic of Fig.5a.

3.3.3.2. Pre-acceleration charge.

The final ion energy through the collective acceleration process significantly depends on the charge state of the ions. Enhancement of the charge state takes place also during the acceleration process. This, in general, is attained due to collisions and intense field conditions existing in the potential well both at the time of ion injection and during acceleration. Apart from this, if the injected ions have higher initial charge state as in the case of some of the pre-formed plasma sources described in section 3.2.4, this helps to enhance the final charge state and energy of accelerated ions. In this context, a measurement of initial charge state is important. Here, since the ion energies are small (less than keV) an electrostatic analyzer is preferred for the purpose. In this analyzer, ions from the pre-formed plasma are extracted using an extractor plate and then introduced between a pair of electrostatic deflector plates. As schematically shown in Fig.6, the deflection plates are suitably curved and spaced about a cm apart each other with a few hundred volts potential applied between them. The deflection of an ion with higher charge state will be more, and the curved geometry of the analyzer plates ensures a high energy resolution. A current collector with multiple probes located appropriately in the deflection direction will record the different charge states.

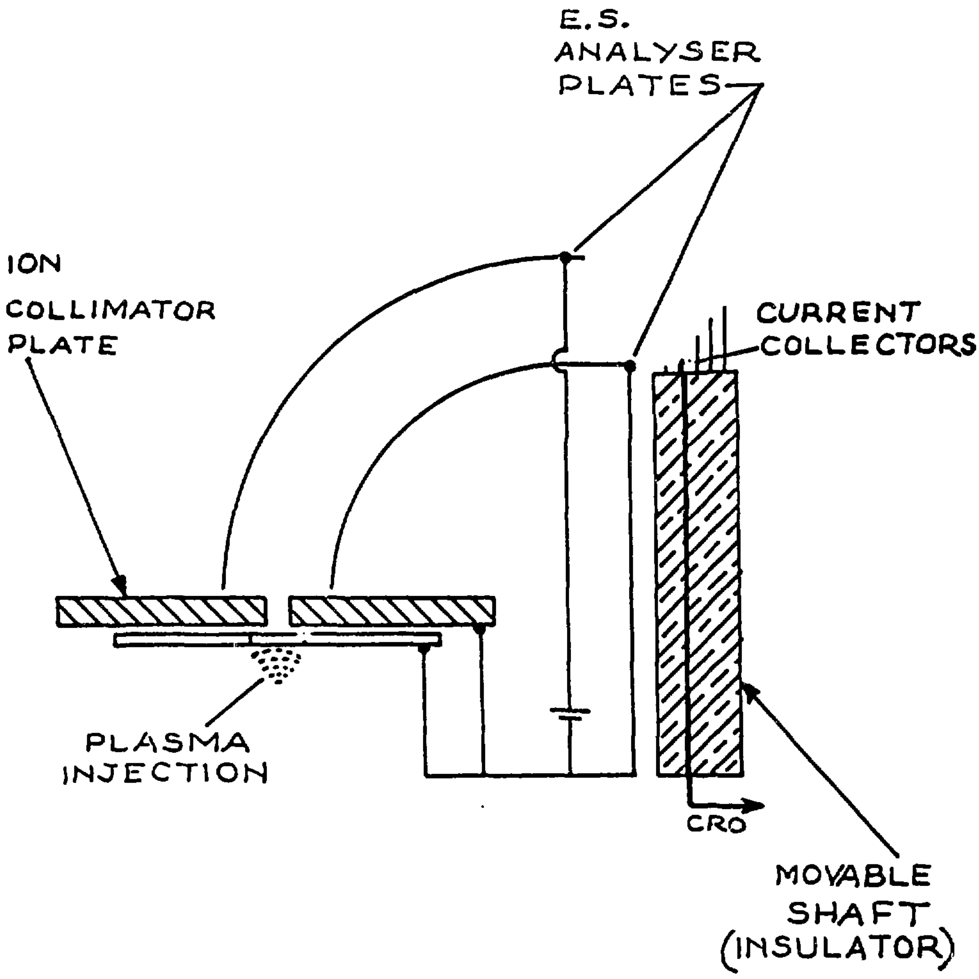
3.3.4. Other measurements.

The formation and propagation of the acceleration front can be photographed using a streak-camera system. Alternatively, open-shutter photography along with photodiode measurements can be employed for this purpose. The open-shutter photography makes use of the light emitted during radiative recombinations and will give a time integrated picture of electron and ion densities inside the front. Whereas, by comparing this to the time evolution of light output from a photo diode measurement, would ensure that the light responsible for the open-shutter photograph is really during the beam transports and not due to the decaying plasma left behind by the beam front.

4. Status of the Program.

The details of current experiments and status of proposed systems and experiments are as follows.

FIG. 6. PRE-ACCELERATION CHARGE ANALYSIS



Presently, experiments to investigate the collective ion acceleration are underway on the currently operational KALI-200 facility with REB parameters of 250keV, 8kA and 40ns. These experiments are presently directed towards a demonstration of the acceleration mechanism in our laboratory and to show that REB at above parameters can accelerate large number of ions to significant energies. The results obtained from these experiments will also be applied for scaling at the higher REB parameters in future experiments using KALI-1000 and -5000 systems.

4.1. On-going experiments

A collective ion accelerator has been built on the KALI-200 system by incorporating a dielectric guide-tube for ion injection (see details in section 3.2.2) in the accelerator scheme of Fig.1. This accelerator consists of a REB diode, a mylar guide-tube insert of length ~5cm which is placed coaxially as an extension of anode, and an acceleration channel of length ~1m. The intense REB when injected inside the mylar tube, forms a deep potential well and electrons striking the mylar tube liberate ions into well. These ions are accelerated by the well along the acceleration channel length. The acceleration column is followed by a sweeping magnet NS of transverse field ~0.6kG which removes the electrons from the ion stream. An ion diagnostics channel is connected after this for detecting and characterizing the ions. The ion diagnostics methods being employed are Faraday current collector, CR-39 track detector, silicon surface barrier detector, scintillation detector, range energy in stacked aluminum foils, and time of flight. Apart from this, the REB has been characterized by Rogowski coils, Faraday cup and a $CuSO_4$ voltage divider.

4.1.1. REB propagation in vacuum

In initial experiments, propagation of REB in vacuum aided by ions liberated from the mylar tube has been investigated as a function of axial distance. For this purpose, the sweeping magnet NS in Fig.1 is removed from position and the propagated net current is recorded at various axial distances by using a movable Faraday collector which uses a 1Ω shunt resistor. It is found that nearly the full electron current injected from the REB diode propagated beyond the mylar tube and a significant part of this propagated to a distance about a meter in vacuum. The current transported over long distances was smaller because of the radial electron losses during vacuum propagation due to inadequate charge neutralization present. Propagation experiments using different lengths (s) of mylar tube show (see Fig.7) that s=2.5cm gives a maximum propagated current~5kA at a distance X=3.5cm from anode and thereafter the measured current falls with distance. The propagated current is relatively smaller using a higher s and with increasing X. Typically for s=5cm, the current propagated is ~4.6kA at X=6cm and ~0.8kA at X=40cm.

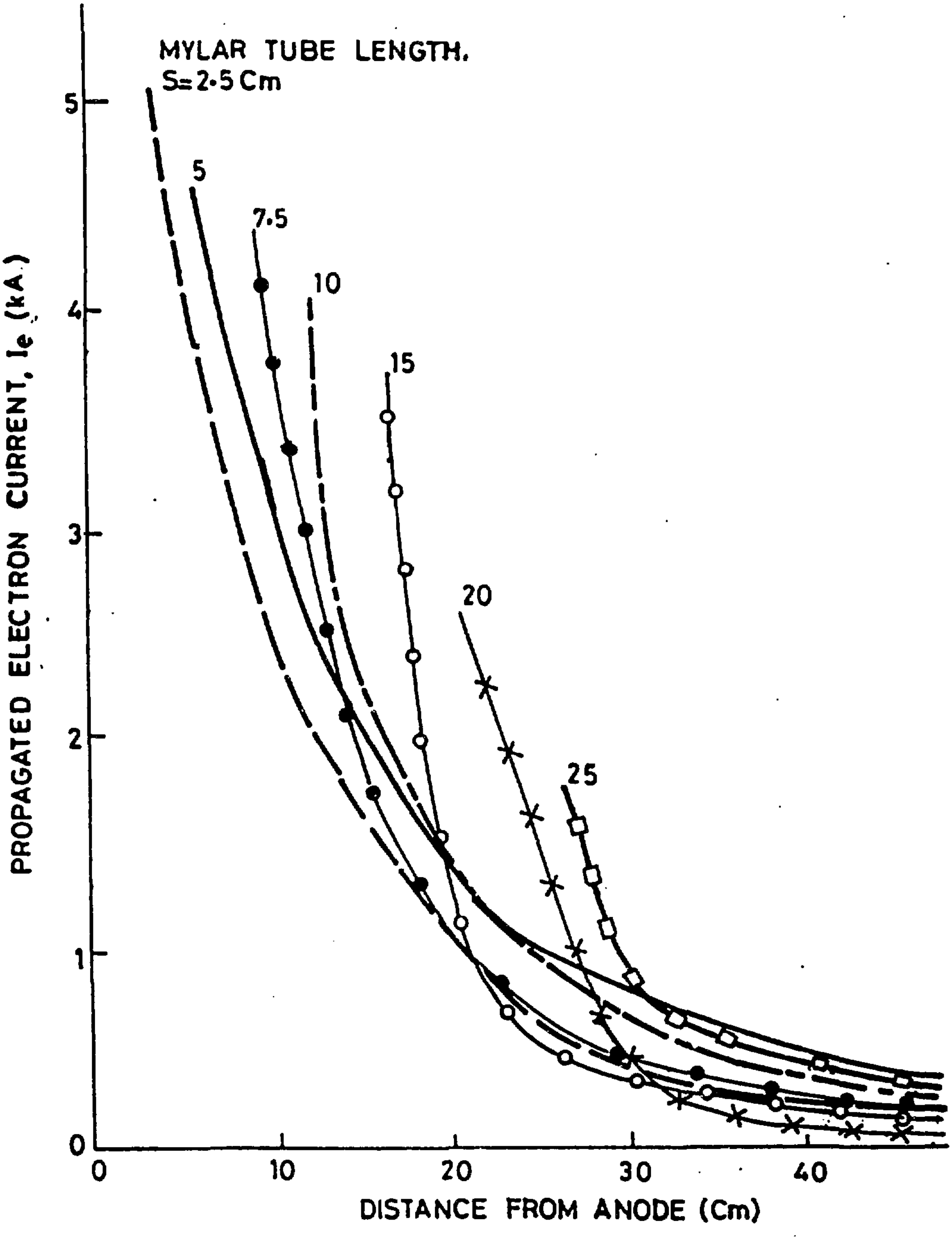


FIG.7. PROPAGATED CURRENT AS A FUNCTION OF DISTANCE FOR VARIOUS MYLAR TUBE LENGTHS.

4.1.2. Observation of ion acceleration

The sweeping magnet NS is now located in position as in Fig.1 in further experiments for isolating the ions by diverting the electrons to the side wall. The emerging ion pulse is filtered from stray electrons by using co-axial aperture diaphragms positioned across the beam. The ion current is then measured by using an ion Faraday collector with 50Ω shunt resistor. This ion current has been measured in various conditions, such as, different s, X, and acceleration lengths L. Acceleration length L is the distance between the anode and magnet (NS). Typically for s=5cm and L=21cm (see Fig.8), the ion current registered at X=30cm, is over 4.4A which falls to about 0.3A at X=50cm; while for L=71cm, an ion current of 0.3A is available at a longer distance of X=100cm. Corresponding to the above, the peak energy of protons as determined by range energy measurement in aluminum for L=21cm is around 0.5MeV and for L=71cm is about 1MeV. Typically, an energy analysis for L=71cm shows that the ion current penetrating a 12μm Al foil (i.e. proton energy above 1MeV) is 0.05A, 20ns (or $\sim 10^{-9}$C); that passing through 8μm (i.e. proton energy above 0.7MeV) is 0.2A, 40ns (or $\sim 8\times10^{-9}$C); and that of the full energy spectrum is 0.6A, 250ns (or 6×10^{-8}C). The ion signatures have been obtained also on CR-39 track detectors placed after the Al foils in the above examples. These ion currents include some amounts of carbon and

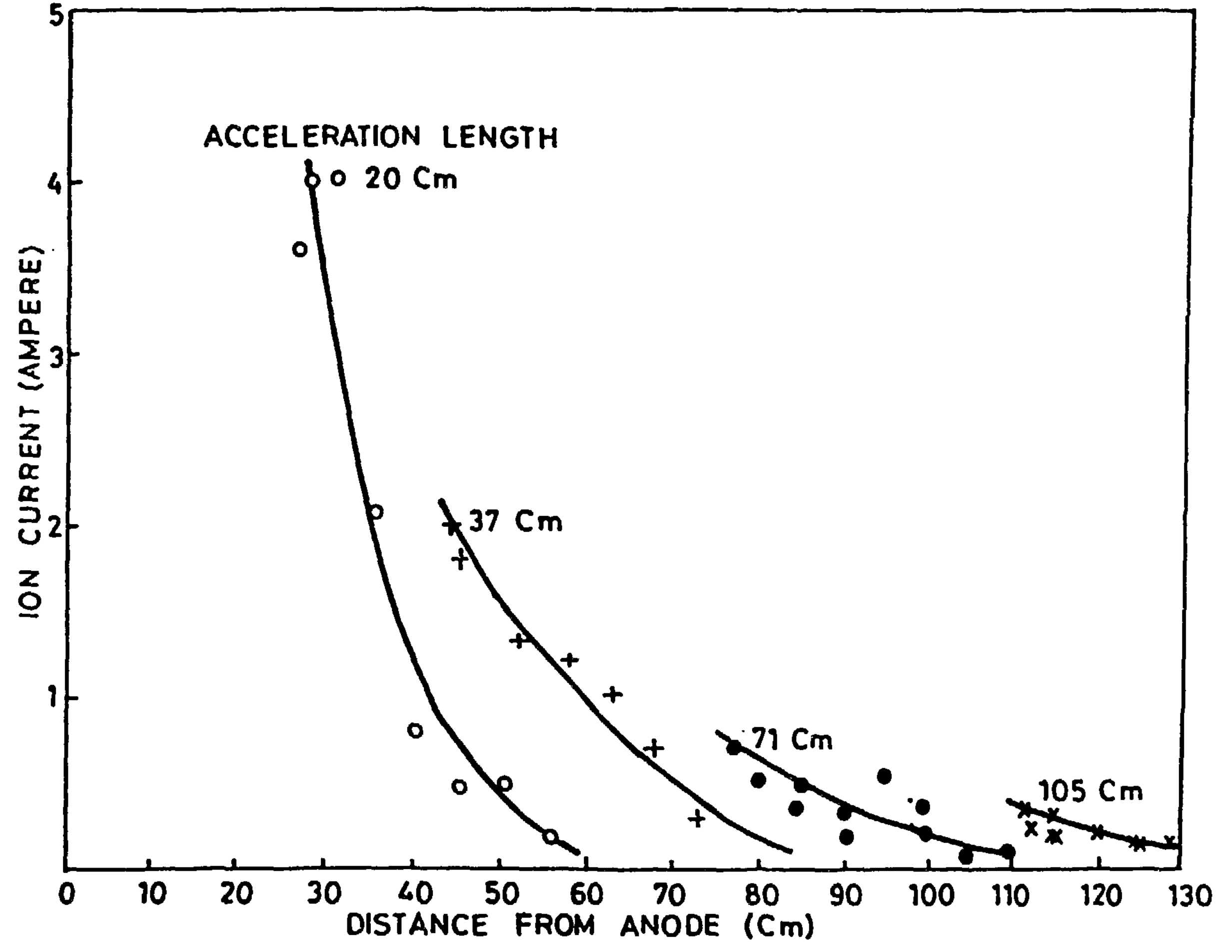


FIG.8 ION CURRENT VARIATION WITH AXIAL DISTANCE FOR VARIOUS ACCELERATION LENGTHS

oxygen ions as well since mylar is made of CH_2 chains with bonds of O. The corresponding energies of carbon ions would be 10 and 15MeV respectively after 8 and 12μm foils as compared to 0.7MeV and 1MeV of protons. In the case of oxygen, the energies are still higher around 15 and 21MeV respectively. These high energies are most likely due to a higher charge state of the ions. Had it been only single charge-state ions, the field in potential well would have accelerated the various ion species to similar energies.

Experiments on similar lines using teflon (C_2F_4) as dielectric tube shows that fluorine ions have been accelerated to about 16MeV and carbon to about 10MeV.

4.2. Proposed long-term experiments.

The various possible ways of generating intense ion beams through the collective acceleration process, have been detailed in section 3.2, while section 3.3 describes the different methods of ion and other diagnostics. In the following, the details of a program to develop a collective accelerator including as many of the above methods and to study acceleration of light and heavy ions in experiments, are envisaged. While doing so, the scheme for development of an advanced GeV collective ion accelerator is highlighted.

Referring to the Luce diode and the dielectric guide-tube configurations in sections 3.2.1 and 3.2.2, these methods are being presently studied in the KALI-200 accelerator.

For ion injection through gas-puff, since the delay needed between REB and gas puff is about 500μsec, puff valves with an open time about 100μsec are desired. A magnetic puff valve operated by a capacitor energy bank is suited for this, and is being developed.

The gas puff valve will be used for the co-axial gun plasma injection as well. A conical plasma gun geometry has been considered for this to suit the ion injection requirements, and is being developed.

In the case of laser-plasma source, a ruby laser of 10J, 10ns is being procured, while in the exploding-wire plasma case, an energy bank of 30kV, 100J, 100ns rating will be built. In the latter case, suitable high-voltage insulator-bushings will be developed for introducing the wire close to the REB well.

The wide range of studies discussed above, are planned for a period of five years and the time schedule for the development of systems and conducting different experiments in the program is shown in the pert chart in Fig.9.

4.2.1. Accelerator on KALI-1000.

The pulse power system of KALI-1000 is presently operating at a positive polarity of voltage 150kV. Whereas, a negative polarity with an operating voltage of 300kV is required for collective ion acceleration. For boosting the voltage to 300kV, design of the radial transformer has been modified and the same

Fig.9. Schedule for collective ion acceleration experiments.

0–1	1–2	2–3	3–4	4–5
Development of (1) Diode (2) Acceleration channel (3) Diagnostics chamber (4) Ion TOF channel (5) Dielectric tube (6) Luce diode (7) Neutron TOF channel	Development of (1) Puff valve (2) Synchronization Acceleration experiments (1) Gas puff (2) Co-axial plasma (3) Energy distribution (4) Current distribution (5) Nuclear diagnostics	Development of (1) E,B spectrometer (2) Electrostatic analyzer (3) Rail gun plasma (4) Exploding wire plasma Experiments (1) Charge state measurement (2) Radial ion distribution (3) Neutron generation	Development of Laser target plasma Experiments (1) Metal target (2) GeV acceleration study (3) Charge state pre & post acceleration	Investigations of (1) Electric field in well using ion probe (2) Well front control by laser plasma sweeping Detailed studies (1) Charge enhancement (2) Energy distribution (3) Rep-rate of acceleration (4) Multiple injections

0 1 2 3 4 5yr.

| --> KALI-1000 (from year 0)

| --> KALI-5000 (from year 3)

is presently under fabrication.

As REB current will be as high as 20kA, the REB diode of this accelerator is being re-designed for this. Also, an acceleration channel of modular construction has been designed for enabling convenient assembly and change of acceleration length in experiments.

In the KALI-1000 accelerator, the first ion injection method will be through gas puffing. For this as pointed out earlier, a fast puff valve of 100μs open time is under development. The other ion injections to follow will be the conical gun plasma and the exploding-wire plasma.

4.2.2. Status of KALI-5000.

All the sub systems needed for KALI-5000 pulse power generator are presently in advanced stages of fabrication and procurement.

As pointed out already, KALI-5000 can give a higher REB current than the other systems mentioned. That is, this system is superior for collective acceleration. Proton energy attainable in the various systems considered here for ion acceleration, are listed in Table 6. From this, it is seen that though the REB voltage is higher in KALI-5000, its capability for significantly large current gives an advantage for higher ion energy.

In this accelerator, the control of acceleration by incorporating multiple ion injections will be tried. For precise control of the field neutralization inside the moving well front, a low density proton plasma channel will be formed along the acceleration channel. Towards this, the laser radiation described in section 3.2.4.2 will be partly directed towards a mylar foil positioned along the accelerator wall by using an array of partially reflecting mirrors as schematically illustrated in Fig.2b. The path lengths between the mirrors in this are so adjusted that the arrival of the low density plasma cloud is synchronized with the arrival of the well front. Here, the laser power will be controlled to give the necessary plasma density.

In addition, when protons from different plasma channels get trapped into the potential well, these will act as multiple ion injection sources. In case of proton acceleration, these multiple injections would enhance the proton yield. For increasing the yield of heavy ions accelerated by the multiple injection scheme, several heavy ion sources will be suitably located along the accelerator length. Ions accelerated through multiple injections, however result in considerable energy spread of beam. As compared to this, for obtaining a fairly monoenergetic ion beam, a single injection mode is useful. The above concepts give tremendous scope for more extensive future studies.

4.2.3. A GeV Heavy Ion Collective Accelerator.

Making use of the high REB currents in KALI-5000, a GeV heavy ion collective accelerator is proposed to be built for accelerating heavy ions of lead, uranium, gold, etc. This will give rise to a multiple-charge aided heavy-ion accelerator on

KALI to be abbreviated as MAHAKALI. Towards the development of this, the ion injection method which uses a laser-target plasma in section 3.2.4.2. is ideally suited. An intense laser source of about 10J, 10ns is being procured for this.

5. Conclusions.

A detailed report on the program of collective ion acceleration using REB is presented here. The report lists the various different methods of ion injections useful for collective acceleration of ions from protons to heavy nuclei, ions from gases to metals and dielectrics, and using different plasma methods. These methods and the ion diagnostics useful for various range of ions, have been identified for the near-term and long-term experiments on the basis of their availability and the time required for development. A collective ion acceleration with repetitive rate of 20Hz is the aim of the program.

In current experiments conducted on the KALI-200 accelerator using REB of 250keV, 8kA, 40ns, ion currents of a few Amperes have been obtained with hydrogen, carbon and fluorine ions accelerated to energies over a MeV, 10MeV and 16MeV respectively.

The experiments and studies in this program in addition to to generating high energy light and heavy ions in significant numbers, will also generate new results in the following areas.

(a) The effect of gas-cloud density or injected plasma density on field neutralization process and propagation of well front will be determined.

(b) The electric field in potential well will be measured by using an ion probe beam.

(c) Energy distribution of ions will be conducted through range-energy measurements described in section 3.3.2.2.

(d) Radial distribution of ions will be measured by using variable aperture windows in the path of beam.

(e) As mentioned in section 3.2.4, investigations of the effect of initial charge state on the final ion energy, is an important study. This in turn will enable confirmation of the enhancement of ion charge during the acceleration.

(f) Exploding-wire plasma will be a new method of ion injection for collective ion acceleration of multiple-charged ions.

(g) Synchronization of events will be carried out in the microseconds time scale.

(h) Apart from the ion acceleration experiments, the generation and characterization of the 1MeV intense REB will also provide up-to-date and important results which will be useful for other applications like intense microwave generation.

The program envisaged herein, is large enough to be considered for experiments on a given machine for a continuous period of five years. In KALI-5000 accelerator, protons of energy over 10MeV and higher charge-state heavy ions of over GeV with ion currents in the range of tens of Amperes can be accelerated. Accordingly, a GeV heavy ion collective accelerator named MAHAKALI which makes use of the KALI-5000 REB generator and an intense laser source of 10J, 10ns is proposed for development.

Acknowledgments

We are extremely grateful to Dr. S. S. Kapoor, Director, Physics Group, for his keen interest in this program and constant encouragement, Dr. M. Srinivasan, Head, Neutron Physics Division and Dr. P. H. Ron, Head, Pulse Power Systems and Energetics Section, for useful discussions. We are also thankful to G. Venugopala Rao and S. N. Acharya for the ion energy characterization by time-of-flight and CR-39 techniques and to A. R. Chindarkar and J.A. Gokhale for assistance in experiments..

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