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ACCELERATION AND STACKING OF DEUTERONS IN THE CERN PS AND ISR

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Introduction and Summary

Deuteron acceleration in the CERN 50 MeV Linac has been tried out already 13 years ago[1] followed by programmed acceleration in the CPS up to about 100 MeV[2].

The construction of a new proton Linac injector prompted studies to investigate the feasibility of using the old Linac to supply other particles to the CPS[3]. As part of this study programme, deuteron acceleration in the CPS was tried again. The tests were immediately successful in that deuterons could readily be accelerated, transferred and stacked in the ISR where several runs of pd and dd collisions were scheduled in 1976. On one occasion alpha particles were also successfully accelerated in the CPS to 40 GeV.

Acceleration in the Linac

Theory

Acceleration of protons in an Alvarez strcture must fulfil the condition that the particles take one cycle of the applied RF field to move from one gap to the next (2π mode). Acceleration of deuterons in the same mode would require field levels far above what is practicable in the CERN Linac, as their heavier mass requires correspondingly larger forces if they must reach the same velocity as protons. In addition, this would lead to particles with twice the proton momentum which could not be handled by the present PS injection line.

Consequently deuterons were accelerated with half the proton velocity, so that the time taken by a deuteron to move from one accelerating gap to the next is twice the RF cycle (4π mode). The corresponding cell length is then $2\beta\lambda$ instead of $\beta\lambda$ for protons. This mode has also the advantage of producing deuterons with almost the same momentum as protons. The mode has however a poor efficiency because of the reduced longitudinal acceptance.

The average energy gain per cell is given by

$$W = e\, E_Z\, L_n \cos \phi_s\, T$$

in which e is the electron charge, E_Z the longitudinal field component, L_n the cell length, ϕ_s the synchronous phase angle, T the transit time factor.

When evaluating the ratio R of effective accelerating voltage for deuterons compared to protons, one finds that in order to maintain a transit time factor $T_d = \frac{1}{2} T_p$, the electric field E_Z must be shaped (i.e. tilted) differently for deuterons than for protons.

The value of R along the Linac is given below[1].

Cavity I		Cavity II		Cavity III	
Gap 1	Gap 42	Gap 1	Gap 41	Gap 1	Gap 27
0.2625	0.5137	0.6345	0.3598	0.7613	0.4942

To keep R constant at about 0.5, the field at the entrance of tank I should be nearly doubled and then reduced at the entrance of tanks II and III. As one cannot achieve completely the desired field increase in tank I, one has to work with a much smaller longitudinal acceptance resulting from a less favourable stable phase angle.

Results

The following table compares the obtained results with those of 1964 .

	1964	1976
Source type	RF source	Duoplasmatron
Source current	100 mA	150 mA
Beam current after column	60 mA	100 mA
Linac input current	40 mA	70 mA
Energy	270 keV	264 keV
Current after cavity I	7 mA	13 mA
Current after cavity II	7 mA	12.5 mA
Current after cavity III	7 mA	12.5 mA
Current in injection line	-	12 mA
Beam emittance (90%)	30 π mm.mrad	12 π mm.mrad
Energy spread	-	< $\pm$100 keV
Pulse length	10 μs	100 μs

Discussion

Considering these figures it seems at first glance that a simple increase in the Linac input current produced a corresponding output, but a closer look shows that an increase of 75% of the input current was obtained while keeping the trapping efficiency at about 17.5%.

T. Sluyters[1] had already suggested several possible improvements : i) increased electrical field at the input end of the Linac (larger tilt), ii) smaller emittance of injected beam, iii) stronger focusing in the first cavity.

i) The range of the field tuners was indeed increased but the trapping increase was fairly modest, probably an indication that a large tilt should be accompanied by a corresponding readjustment of the field flatteners. As this would have required opening of the cavity followed by a lengthy reconditioning, it was not done for the present tests.

ii) A smaller beam emittance has been achieved after different modifications of the duoplasmatron source[4]. 150 mA is, by no means, the maximum current that one can get, it is a compromise to limit space charge effects which are stronger at higher currents and maintain a reasonably small emittance.

iii) A change in focusing gave the largest improvement. The CERN 50 MeV Linac has been built with a ++-- focusing system, partially because of the low proton injection energy (530 kV), partially because of the quadrupole technology of the late 1950's. This scheme was kept for deuterons except for the first 9 quadrupoles which were converted to +- focusing yielding a spectacular increase of beam current of about 50%.

Injection in the CPS

Multiturn injection

As the injected deuteron current was expected to be substantially lower than the normal proton current (10-12 mA against 80 mA), one has adopted a multiturn injection process which maximizes the PS circulating current. The 4π accelerating mode in the Linac gives deuterons with a momentum about 3.5% lower than the corresponding protons, which determines the injection field of 142 Gauss (against 147 G for 50 MeV protons). Taking an emittance of 10 π mm.mrad for the core of the beam ($\sim$ 75% of the particles) one finds that a maximum of 7 turns can be injected in the 100 π horizontal CPS acceptance. As one turn takes 13 μs with half the proton velocity, this figure is well matched with the Linac pulse length of 100 μs.

This injection mode required the modification of the time constant of the injection kickers, so that the closed orbit bump would collapse in $\sim$ 100 μs rather than the normal 20 μs (3 turns of 50 MeV protons corresponding to the CPS space charge limit with available Linac beam intensity).

It was also necessary to halve the voltage of the electrostatic inflector. The fields of the other injection line elements (bending magnets and quadrupoles) had to be reduced by 3.5% to compensate the momentum change. However it was found necessary to readjust the matching parameters as the deuteron beam has a different phase space aspect ratio compared to a proton beam because of the difference in Linac focusing.

Betatron tunes

The deuteron beam (3.10^{12} particles/pulse injected) is well into the space charge region and the vertical betatron tune Q_V had to be moved to 6.70 (while $Q_H = 6.30$) to accommodate the large space charge induced tune shift. However, the working point must be brought to $Q_H = 6.23$, $Q_V = 6.31$ for the flat top on which the harmonic number is changed (see next section). The working point is modified dynamically by programming the set of 40 low energy air core quadrupole . The stop bands $2Q_V = 13$, $2Q_H + Q_V = 19$, $2Q_V + Q_H = 19$ and $3Q_V = 19$ are compensated right at the start of the acceleration and programmed as well further on. Nevertheless, transverse losses do occur as the PS ring acceptance is fully filled.

RF Acceleration

A 100% increase of the RF system tuning range would be required on account of the reduction by a half of the particle speed if acceleration was to take place in the standard mode. However a frequency scaling scheme based on harmonic number switching can be used instead. The injected deuterons are trapped with the same RF frequency as the protons (2.998 MHz) but this frequency corresponds to the harmonic number h = 40 (instead of h = 20) as the deuterons rotate with half the proton velocity ($\beta_d = 0.16$). The beam is accelerated to $\beta_d = 0.5$ which corresponds to the upper frequency limit of the RF system (9.55 MHz) in the h = 40 mode. At this energy the beam is adiabatically debunched by reduction of the RF voltage and left coasting on an intermediate magnetic flat top at 515 G. After retuning to half frequency (4.77 MHz) of the RF system (corresponding to h = 20) the beam is adiabatically trapped and accelerated through transition (which occurs at 5360 Gauss (against 2680 G for protons), to the standard CPS momentum (26 GeV/c). Fig.1 shows oscillograms of the relevant machine parameters. The response time of the RF cavities tuning system determines the necessary intermediate flat top length of $\sim$ 100 ms (debunching and retrapping need only a few synchrotron periods, i.e. 1-2 ms).

As the beam will be further transferred to the ISR and stacked, it is desirable to preserve the longitudinal density. Some dilution is however unavoidable in the debunching-rebunching process.

The magnet and RF voltage programmes are adjusted to provide an acceptance of 8 mrad at injection and 16 mrad after the intermediate flat top.

Some changes have been introduced in the hardware.

i) The input parameters for the frequency programme generator which calculates on-line the frequency function

$$f = C \times h \frac{1}{\sqrt{1+(B_0/B)}} \quad \text{(where C and } B_0 \text{ are constants)}$$

from the bending field value B, had to be adapted.

ii) The compensation of the ferrite hysteresis had to be modified in the coarse tuning system of the RF cavities.

iii) For the second capture the master oscillator must be locked to a precise external frequency standard.

iv) The phase relationship between phase P.U. and RF cavities is different for h = 40 and h = 20 and must be changed at the frequency switch-back.

These changes were tried out and run in with protons during relatively short simulation test sessions to avoid the lengthy deuteron setting up procedure. For this, the proton trapping frequency was set up at 5.997 MHz corresponding to h = 40 and when the top RF frequency was reached at 255 Gauss, one proceeded to switch the harmonic number on an intermediate flat top. This ensured that deuterons could confidently be accelerated at the first trial.

Transfer and Stacking in the ISR

Problems due to deuterons

Acceleration of deuterons to the same standard momentum for ISR operation (26 GeV/c) as protons, their extraction by the PS fast ejection system and their transfer to the ISR could be achieved with the normal proton settings since all the elements are magnetic.

In the ISR, for a fixed momentum, the difference between protons and deuterons is manifest only in the relativistic parameters β and γ and the $\eta = \gamma_t^{-2} - \gamma^{-2}$ factor. Variation in these quantities will affect :

i) the revolution frequency $f_{RF} = \frac{h\beta c}{2\pi R}$ and its derivative

$$\frac{df}{dt} = \left\{ h \left(\frac{c}{2\pi R}\right)^2 \frac{\eta}{E_0} \right\} V \sin \phi_s \quad \text{(V is the RF voltage)}$$

ii) the stacking bucket area :

$$A = 6.383\ \alpha(\sin \phi_s)\sqrt{\frac{V\gamma}{h\eta E_0}} \quad (\alpha \text{ is the moving bucket area reduction factor})$$

must be matched to the area of the bunches to optimize the stacking efficiency;

iii) the relation between measured beam frequencies and average radial position and betatron tune spread derived by the Schottky scan technique.

The other parameters such as the beam trajectory, closed orbit, working lines, Q values in the stack, incoherent Q shift due to the stacked beam remain unchanged.

Stacking of protons and deuterons

In several of the scheduled runs with deuterons, the experiments requested protons to collide with deuterons. The stacking of protons with deuterons in the other ring is complicated by a process known as "overlap knockout"; the effect of the longitudinal frequencies of a bunched beam on the betatron frequencies of the stack[6]. For protons and deuterons, the dipolar overlap knock out resonances occur for

$$n = \frac{\bar{q}\, f_p}{f_p - f_d}$$

where n is the harmonic of the bunched beam revolution frequency, $\bar{q}$ is the non-integer part of the betatron tune (9-Q for the ISR) and f the particle revolution frequency.

This equation shows that for the fundamental harmonic of the RF system (h = 30), overlap knock out resonances will occur for $\bar{q} \leq 0.05$. The high intensity working lines for the ISR have $\bar{q}_H = 0.045$ and $\bar{q}_V = 0.065$ which are hence unsuitable for pd collisions. For this reason a working line with $\bar{q} \simeq .38$ was used. Even with these values, overlap resonances occur at the 5th harmonic of the bunch frequency and it was necessary to lengthen the bunches at injection to eliminate the higher order harmonics of the bunch frequency.

ISR Acceleration of Deuterons

The maximum PS momentum being 26 GeV/c, acceleration to 31.4 GeV/c takes place in the ISR, using the phase displacement technique. This involves sweeping empty RF buckets through the stack from high to low momentum[7]. Each sweep causes the whole stack to be accelerated by an amount proportional to the sum of the bucket areas. This area given by

$$A = 6.383\ \alpha(\sin\phi_s)\sqrt{\frac{V\gamma}{\eta\, E_o\, h}}$$

is different when accelerating deuterons. The required frequency range swept by the RF system must also be changed for deuteron acceleration. These parameters were introduced in the control computer which governs the acceleration process.

Operational Results

The Linac beam performance has already been discussed in section 2. Deuteron currents of 10-12 mA are obtained rather rapidly, setting-up from protons to deuterons being achieved within two hours.

With 7 turns 2.5 to 3.10^{12} deuterons/pulse are injected in the CPS but trapping losses being high it was found that to stay in a region with less resonance lines, optimum results were achieved with a lower injection intensity for 1.2 10^{12} d/p.. Some transverse losses do occur between injection and the intermediate flat top at 515 Gauss but debunching and rebunching can be done with a few percent losses. The last critical point is when one applies the full rate of rise after retrapping. Dilution of the remaining beam fraction is however small as the measured high energy longitudinal emittance is 9 mrad, so little or no loss is observed and one accelerates 4 to 6.10^{11} d/p. The best performance was 6.7 x 10^{11} d/p. Transverse emittances were comparable to proton values for similar intensities ($E_V = 0.95\ \pi$ mm.mrad at 20 GeV/c).

The peak current stacked in the ISR was 9.1 A in ring 1 against 8.5 A in ring 2 yielding at 26.6 GeV/c a luminosity of 1.6 10^{30} cm^{-2} sec^{-1}, 40% of the design ISR luminosity for protons. Beam intensities at 31.4 GeV/c were of course lower as a fraction of the beam is lost during phase displacement acceleration. Performance at 31.4 GeV/c were 7 x 4.7 A giving a luminosity of 0.56 10^{30} cm^{-2} sec^{-1}. Luminosities of 1.6 10^{30}cm^{-2}s^{-1} for protons/deuterons collisions were obtained at both 26 and 31.4 GeV/c. Fig.2 gives a typical density distribution in the ring 1 stack at 26.6 GeV/c (deuterons).

It is also worthwhile to mention that as a machine experiment, 5.5 A of protons and 3.3 A of deuterons were stacked in the same ring and in the same physical space by occupying different positions in the longitudinal phase plane. These beams were later separated by selectively accelerating by phase displacement only the deuterons.

Alpha Particle Acceleration

Alpha particles have been accelerated by first setting up and tuning the Linac for deuterons. The ion source is then fed with Helium. Normal settings of the source will produce a beam of He^+ which is not accepted by the first Linac cavity. By lowering the Helium pressure and increasing the source arc current by almost a factor two (up to 120 A) and by optimizing the other parameters, one achieves about 20% of He^{2+} at the expense of a reduced total beam. The Linac stays adjusted as for deuterons except for some changes in the quadrupoles current near the beginning of the first cavity because of the reduced total current and the presence of the He^+ beam. At the Linac output, the intensity of the alpha particle beam is 2 mA.

In the PS the main difficulty comes from the low intensity which is in the 10^{10} particle/pulse range. One is close to the sensitivity limit of the beam control system and adjustments are rather delicate. Intensities of about 2-3 x 10^{10} particles/pulse have been reached and accelerated on one occasion to a total energy of 40 GeV (10 GeV/nucleon).

Future Prospects

The results given above demonstrate clearly that particles with e/m = ½ the proton value can be rather easily accelerated and stacked in the CERN machines. For ions heavier than alpha, the problem is essentially one of having a suitable ion source. One is therefore developing an electron-beam ion source capable of giving fully stripped light ions[8]. Modifications to the first Linac tank to allow acceleration of partially stripped ions are also investigated[9].

As source intensity is a limitation for ions other than deuterium, the efficiency of the Linac is crucial. It is clear that a better tilt shape (by using the field flatteners) and stronger focusing in the first cavity would substantially improve the situation. Another improvement possibility is to modify the accelerating column for running at half the normal voltage. That means reducing the accelerating gap and increasing the voltage gradient in order to extract larger currents with a smaller emittance from the ion source. This requires giving up proton acceleration and could only be envisaged after successful commissioning of the new Linac if one abandons the back-up facility offered by the old Linac. A more interesting way however to a high intensity alpha particles beam would be to run the column at 530 keV with He^{+} ions and strip at that energy. The emerging beam then contains 30-40% of He^{2+} [10] and has obviously the desired energy (equivalent to He^{2+} accelerated to 265 keV).

The expected intensities for ions heavier than Helium [3] would lead to unacceptably low luminosities for ion/ion collisions in the ISR but light ions physics would be very attractive in the SPS [11] and the necessary acceleration procedure has already been investigated[12].

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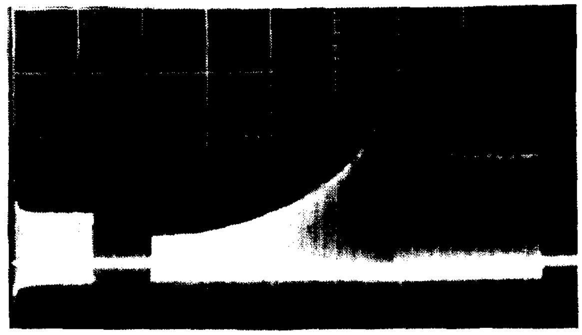
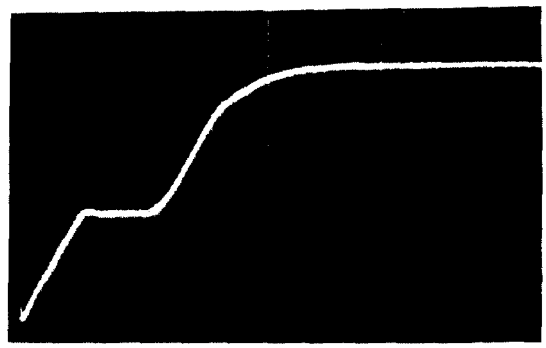


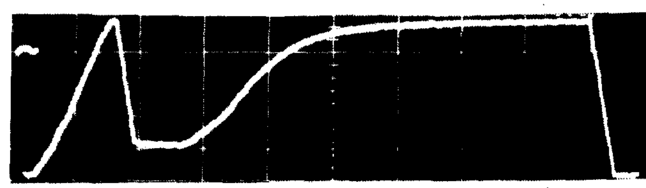
100 ms/div.

a) Wide-band pick-up station signal gap in signal waveform corresponds to coasting beam during harmonic number switching



100 ms/div.

b) Beam current transformer signal



100 ms/div.

c) Accelerating frequency programme

Fig. 1 : Deuteron Acceleration Signals

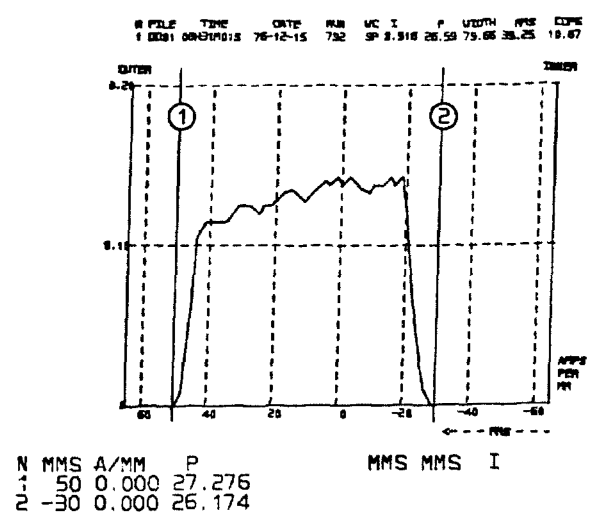


Fig. 2 : Profile of 26.6 GeV/c ISR deuteron stack