NEW AND PROPOSED LINACS AT CERN : THE LEP (e^+/e^-) INJECTOR AND THE SPS HEAVY ION (Pb) INJECTOR

D. J. Warner
PS Division, CERN, 1211 Geneva 23, Switzerland

The LEP Preinjector Linac (LIL) has been operating at 500 MeV since July 1986 to supply electrons and then positrons (April 1987) for the commissioning of the machines in the LEP injection chain i.e. for EPA, CPS, SPS and finally in July 1988, an octant of LEP.

There has been renewed interest in a purpose-built linac for heavy ions (e.g. lead) with q/A < 1/8 and its use as an injector for the PSB, CPS and SPS chain,[4] following the successful operation of Linac 1 with O^{6+} and then in 1987 with S^{12+} ions.

This paper has two sections, the first treating LIL after two years commissioning and operation, and the second summarising a proposal for the "Lead Linac".

THE LEP (e+/e-) INJECTOR LINAC (LIL)

Characteristics

The design of LIL and its evolution from the first LEP proposals until the design was essentially frozen (1984) are given in detail in several papers[1,2] mostly written in collaboration with LAL/Orsay, CERN's partner for the design and construction. A comprehensive parameter list of LIL and its ancilliary systems has been published.[3] The essential characteristics of LIL are recalled here (see Fig 1).

There are two S-Band Linacs in tandem, the first, LIL V, nominal output energy 200 MeV, delivers an e- (electron) beam of 2.5 A for 10 to 25 nsec, to a tungsten target, the e- to e+ (positron) converter. The second, LIL W, nominal output energy 600 MeV, accelerates positrons (12 mA) from the target or electrons (60 mA) either from an off-axis gun (until mid 1987) or more recently from LIL V gun. Present operating energies are 215 MeV and 500 MeV respectively for LIL V and LIL W.

There are 16 accelerating sections of $2\pi/3$ travelling wave type each with nine constant impedance parts forming a quasi-constant-gradient section 4.6 m long. The six klystron stations have a maximum peak output of 35 MW with a 4.5 μs pulse at 100 Hz. Two feed LIL V, the SW 25 MeV buncher and four TW sections respectively. For LIL W the four klystron stations feed two, four, four and two TW sections respectively. With 500 MeV the operating power outputs are about 20 MW and where four sections are fed, the RF pulse compression system, LIPS, is used.[4] Proceeding along the Linacs, the focusing arrangements are solenoids (0.2 T) between the 90 keV gun and end of the buncher (V), then quadrupole triplets between the TW sections and a quadruplet to produce the 2 mm diameter beam on the e-/e+ converter.

Immediately after there is a short pulsed solenoid (1.6 T) matching the e+ beam (nominally 6.5 to 8.5 MeV) into LIL W. The focusing on the first two sections is by a continuous solenoid (0.3 T). There are 35 quadrupoles around the other 10 sections of LIL W, and four between. The first five magnets match the beam at about 100 MeV into a FODO system with element spacing increasing from 0.6 m to 2.3 m as the beam momentum increases. LIL is well provided with correction dipoles to cope with the earth's magnetic field (at low energy), with dipole errors in the long solenoid and with the effects of quadrupole misalignments. In addition there is a comprehensive array of beam diagnostics instrumentation for beam current, position, transverse profile, energy, energy spread and phase.[5]

Performance

During the successive stages of commissioning and operation with the accelerators in the LEP injection chain, the foreseen operational modes have been implemented. LIL injects either positrons or electrons into the Electron Positron Accumulator (EPA) which matches the beam quality and repetition rate of LIL (100 Hz) to that required by the Proton Synchrotron (PS) operating as an e+/e- synchrotron from 0.5 GeV to 3.5 Gev with a cycle period of 1.2 s. Similarly the SPS operates as an e+/e- synchrotron between 3.5 GeV and 20 GeV, the nominal LEP injection energy. Table I shows the development in performance with time.

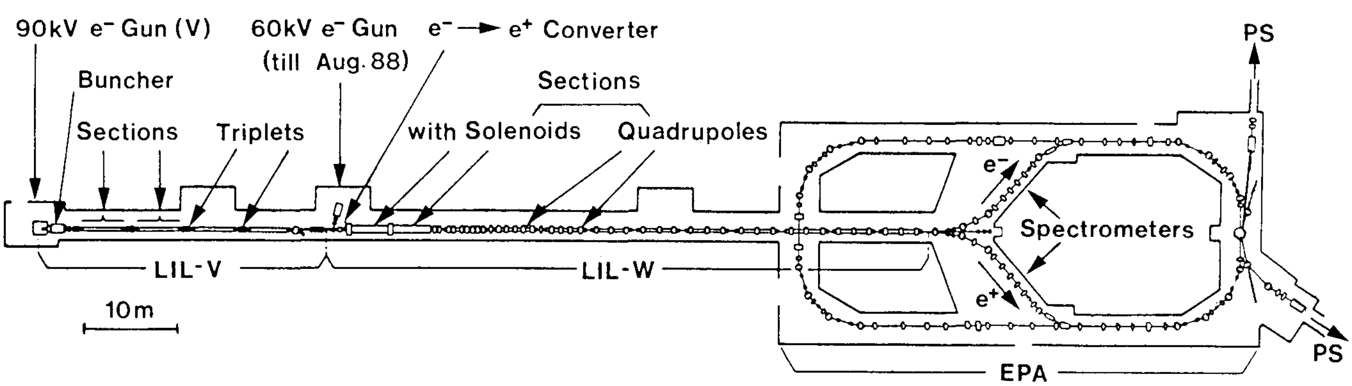

Fig.1 Layout of LIL/EPA

TABLE I

Date	Performance Milestones	Notes
Nov. 81	25 MeV e- beam (Buncher V)	At LAL till Dec.84
Dec. 85	4 Mev e- beam (Buncher W)	4 MeV test area
June 86	500 MeV e- beam (LIL W)	Injection into EPA
Sept.86	500 MeV e- for EPA + PS	
Dec. 86	200 Mev e- beam (LILV)	At spectrometer
March87	500 MeV e+ beam (LIL V+LIL W)	
April87	500 MeV e+ for EPA	
June 87	500 MeV e+ for EPA+PS	
July 87	500 MeV e+ for EPA+PS+SPS	
Oct. 87	500 MeV e+/e- for EPA+PS+SPS	11.4s e+/2.4s e-
July 88	500 MeV e+ for EPA+PS+SPS+FIRST OCTANT OF LEP	

Some of these stages have been reported at Linac conferences[6,7], at the 1987 PAC[8] and at the 1988 EPAC[9] with some performance data. The latest stage, injection into one octant of LEP at 18 GeV, was made with the injection chain supplying four e+ bunches of nominal intensity to LEP every SPS cycle. This paper gives a systematic account of the beam performance including the operating procedures now used to suit the present requiments (see Table II).

Comments on the Beam Parameters

Beam Current

The nominal beam currents are based on equal filling rates of LEP for e+ and e- beams given the capture/transfer efficiencies and the beam instability thresholds in the EPA, PS and SPS.[1] The output energies and repetition rates of LIL V and LIL W and number of beam bunches in EPA are further constraints. Thus the Gun V current and pulse length must be consistent with an acceptable transient energy spread after acceleration in LIL V so as to ensure maximum charge within a 2 mm spot on the converter and hence to achieve the nominal 12mA of positron current into EPA. As 11.2 s of the super-cycle is for e+ accumulation in EPA, and 2.4s for e- accumulation, about 60 mA e- current is required. This is comparatively easy and for I < 100 mA, tp <20ns the energy transient in LIL W is < 2.5 MeV. Currents can be measured with adequate band-width at 22 places between Gun V and the input to EPA but the variable mixture of e+ and e- during e+ operation prevents proper observation of the current along LIL W.[5]

TABLE II Nominal and Operating Beam Parameters

Beam Parameter	Nominal[1]	Operational	
High-Current Linac (LIL V)			
Current (from Gun V)	6	6*	A
Input Energy (Gun V)	90	70	keV
Pulse Length	12	10-25	ns
Output Current	2.5	2.0-3.0	A
Output Energy (Mean)	200	215	MeV
Energy Spread (for q=30nc)		±7.5	%
Positron Operation (LIL W)			
Input Energy (mean)	8	6	MeV
Output Energy	600	500	MeV
Output Current in dE/E=2%	12	8	mA
Conversion at 200 MeV	0.0048	0.0040	e+/e-
Emittance 80% of I at 500MeV	4.8	6	π.mm.mr
Electron Operation (LIL W)			
Energy at LIL W Input	4	220(4)	MeV
Current at LIL W Input	-	160(40)	mA
Output Energy	600	500	MeV
Output Current	60	80(30)	mA
Emittance (80% of I)	<1	0.3	π.mm.mr
Energy Spread (80% of I)	<1	(1.0)	%

* Maximum Gun V current = 12 A,
Values in brackets are for the previous mode of operation using the off-axis Gun W (until August 1987).

Beam Energy and Energy Spread

The nominal values for LIL V and LIL W respectively match the e+ production and the EPA and PS requirements. The beam energy is proportional to [RF Power supplied]$^{0.5}$. The minimum energy spread and maximum energy correspond to the acceleration and beam vectors being aligned i.e. to the correct relative phases between the six RF stations and the beam. Experience has shown that for stable beams, the klystron output powers should be set for about 510 Mev with optimised phases, the fine energy adjustment made with LIPS[4] phase-inversion timing, and the energy spread optimised with one phase setting e.g. that of Buncher V. So

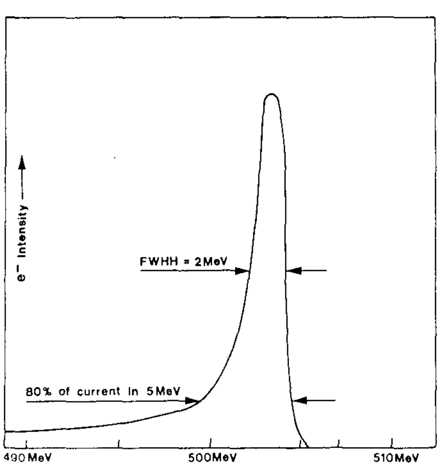

Fig.2 Energy Spectrum of e- Beam at 500 MeV

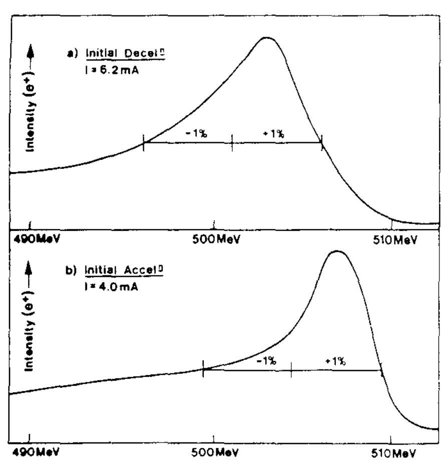

Fig.3 Energy Spectra of e+ for
a) Initial Deceleration
b) Initial Acceleration

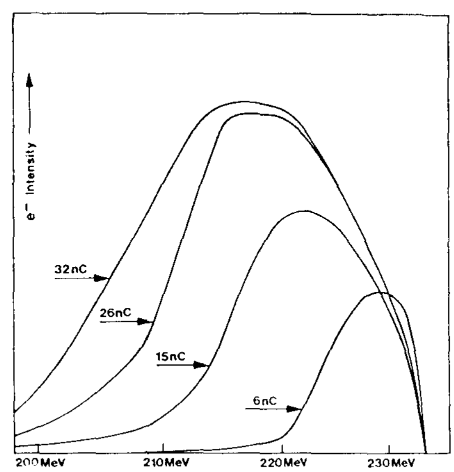

Fig.4 Energy Spectra of e- Beam at 215 MeV versus Charge Accelerated

far operation of LIL W as an e+/e- injector has been at 500 MeV, due mainly to an unreliable high-voltage capacitor in the modulators. This has been acceptable due to the EPA trapping being >50% (nominal 30%) in spite of the damping rate at 500 MeV being 58% of that at 600 MeV. When the operational energy of LIL W is raised to 600 MeV, the 500 MeV will be a safe back-up energy in the event of certain RF or section faults.

The energy spectra from LIL V at high current, LIL W with e- and LIL W with e+, demonstrate three distinct phenomena. For the low current e- beam where the transient energy spread is negligible, the obtainable dE/E < 1% for 80% of I, is determined largely by the beam phase spread after the buncher, ($\Delta\varphi$ <16° inferred from dE/E), see Fig.2. The e+ beam after the converter has a large energy spread and angular dispersion, and $\Delta\varphi$ depending both on the incident e- beam and on the drift, deceleration and acceleration conditions at LIL W input. Thus the beam at 500 MeV has a larger energy spread and less explicable form (see Fig.3 and details of e+/e- conversion below). High current e^- operation of LIL V is dominated by the transient energy spread arising from the reduction of stored energy in the accelerating sections during the passage of the nominal 30 nC pulse. This is about 0.8 MeV/nC of beam and the effect is evident on the spectra (see Fig.4).

Studies of energy and energy spread as functions of operating parameters have determined optimum settings. Often sufficient precision is obtained using the scintillator screen/TV ensembles that are in the transport lines near the SEM-grid detectors of the spectrometers and these screens were essential when setting up LIL. The video output of the TV scan is ideal when quick relative measurements are required e.g. the recent measurements at 230 MeV with a 0.1 A electron beam, studying the variation of energy gain versus LIPS timing settings. The optimum settings agreed well with the predictions after[10] normalising to the maximum measured energy (Fig.5).

Transverse Beam Properties

For LIL V with high current, the solenoid after the buncher, the triplets between the sections and the final quadruplet were initially set empirically for smallest beam size , as deduced from transverse profiles measured with a wire beam scanner (WBS) just before the converter. Recent computations have shown some advantages for weaker focusing (i.e. less envelope modulation and generally larger[11] diameter beams) and this solution is now used. Current losses are minimised and the beam centred on the target using eight dipoles installed within the triplets supplemented by four "saddle" coils on the sections.

In principle the emittance at 200 Mev for low pulse charge can be determined from the beam profile versus the focusing quadruplet setting. With correct bias on the WBS, clean profiles could be obtained for currents up to 2.5 A, (Fig.6). At high pulse charge, the energy spread prevents a sensible interpretation for the emittance.

In LIL W the critical settings are for the larger emittance, e+ beam. After the solenoid focused sections, five matching quadrupoles are set empirically for maximum e+ current in the injection line to EPA, with the FODO system quadrupoles set to their computed values. This rather laborious procedure results from the e+/e- mixture which prevents use of current monitors or the profile monitor at the 130 MeV point. The setting of the 20 steering dipoles (installed within the quadrupoles of LIL W) is also empirical. By adjusting each dipole with all others set to zero the subset, which maximises the beam current going to EPA, can be found. Thus only about four dipoles before the 250 MeV point need to be adjusted. The e-/e+ mixture at 500 MeV vitiates any emittance measurements on the straight measuring line; however it has been possible to deduce the emittance at the end of LIL W from profile measurements in EPA.

For electrons, unambiguous current, position and profile measurements are possible. The focusing settings for the much smaller e- emittance stay as for the e+ beam, but the dipoles which can be varied between e+ and e- cycles, are readjusted either empirically or with a computer algorithm minimising the measured beam deviations. Measurements of emittance made on the "straight line" confirmed that the e- beam emittance is small.

Positron Production and Conversion Efficiency

The LIL design was optimised around its positron performance i.e. the number of e+/pulse which are delivered within the EPA transverse and longitudinal acceptance. All accelerator and measuring systems are involved when operating with positrons and several examples of measurements are described above. Basing the

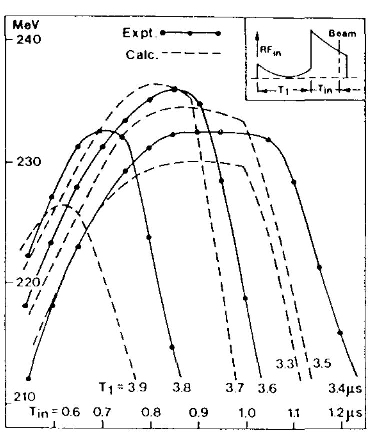

Fig.5 Mean Energy LIL-V versus LIPS Timing (Experimental and Calculated)

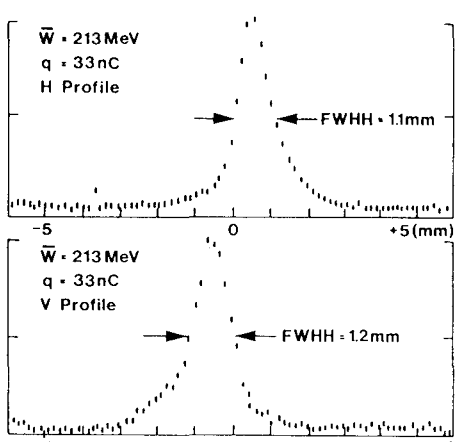

Fig.6 Beam Profiles at Converter

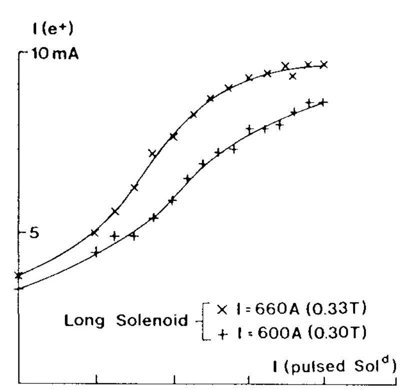

Fig.7 Positron Current versus Currents in Solenoids after Converter

nominal e+ current on the experimental values from SLAC, DESY, LAL and Frascati, the corresponding conversion efficiency is one e+/42 GeV e-. The e+ production depends on delivering the maximum electron beam energy within a 2 mm diameter spot and within 20° (at 3 GHz) to the target , then collecting the e+'s efficiently for acceleration in LIL W. This process has been described generally and as applied to LIL.[12]

In the LIL converter the pulsed solenoid following the target optimally focuses 8 MeV positrons. This reduces phase debunching before acceleration in LIL W, preserving the small beam phase spread from LIL V and hence gives a good energy spread after acceleration in LIL W. This mode implies an optimised phase spread in the LIL V beam, maximum field (1.8 T) in the λ/4 solenoid and phase of LIL W set for immediate acceleration. In fact much of the operation in 1987 was made with the pulsed solenoid at < 1 T, focusing positrons around 4 MeV and operating with an initially decelerating phase in LIL so that there is rebunching of the e+ beam before acceleration.[13] This mode gave about 50% more useful e+ current with typically 65% of beam at the 500 MeV spectrometer within ± 1% energy spread c.f 80% nominal. Spectra at 500 MeV for both modes are shown in Fig 3. Present operation is at 1.2 T in the deceleration mode.

An optimisation of LIL for maximum e+ beam is lengthy but can be done in two stages. Firstly, by referring to the 200 MeV e- beam current, energy, energy spread and transverse profiles before the target, and then by an optimisation of converter and LIL W parameters via the resolved e+ current in the EPA injection line. The 500 MeV e+ current versus pulsed solenoid and long solenoid currents are shown in Fig.7. During the initial PS and SPS running-in 40% of the maximum e+ current was still available without the pulsed solenoid. The overall e+ production and EPA injection efficiency seem weakly dependant on the gun V pulse shape; a triangular pulse (FWHH = 14ns) was used successfully during the SPS runs in 1987. This confirmed that modulation of gun V current via the grid bias was a practical option in spite of the poor e- pulse shapes for the triode gun biased nearly to cut-off. Recent measurements with a good gun pulse form gave an optimum EPA filling rate for 2A x 20 ns at the converter, cf. 2.5 x 12 ns nominal. Concerning the phase spread of the 200 MeV beam, the few measurements at CERN using a deflector cavity at 25 MeV confirm the typical phase spreads, FWHH < 20°, obtained at LAL.[6]

The continuing programme to improve the e+ intensity and beam quality aims to increase the RF power to the four TW sections of LIL V and hence the beam power at the converter in the same ratio, and then to upgrade the pulsed λ/4 solenoid so that the accelerating mode at LIL W input can be tested at the nominal e+ energy (8 MeV). Operation at 600 MeV should allow better beam transport through LIL W to EPA.

Two Recent Applications of LIL

i) For calibrating detectors of the LEP L3 experiment a mode of operation providing one e-/1.2 s at a precise energy between 100 and 300 MeV has been developed. By using the converter, a beam of 10^8 e-/pulse can be set up with the normal beam monitors and screens then by reducing the intensity and energy of the LIL V beam the "single" e- is obtained at a photomultiplier detector in a special line branching from the e- extraction of EPA.[14]

ii) Preliminary measurements have been made of the modes excited by the high current 215 MeV beam in a 3 GHz model of the 30 GHz transfer structure proposed for CLIC.[15]

Operation as an Injector to EPA, PS and SPS

An injector Linac for a long chain of accelerators needs to be ready, with requested beams set-up for long periods, which conditions the type of machine study which can be scheduled. In fact, of the 3800 hours of LIL's scheduled operation during 1987 and 1988, 2500 hours (66%) were as an injector to EPA, including 1650 hours with acceleration in the PS and 750 hours for the PS/SPS.

PPM Operation:

The requirement to fill LEP evenly with e+ and e- implied pulse-to-pulse modulation[1] (PPM) with 11.4 sec injection of e+ into EPA followed by 2.4 sec of e-. To limit the number of machine conditions varied by PPM the original scheme used the off-axis gun before the input of LIL W during the e- cycles. However after the separate e+ and e-operation it was realised that gun V could be used for both cycles, by biasing near cut-off for the low current. Before the converter both high and low current beams are at about 215 MeV with similar transverse profiles; During e- cycles the target swings away leaving a 5 mm aperture. The e- beam has the wrong energy and matching to pass without loss through the beginning of LIL W, but there is sufficient margin in current. The final energy must be set to 500 MeV for EPA within 150 ms, so LIL W energy gain has to be reduced to 290 MeV, by delaying the trigger of the first modulator with LIPS by 5 ms (170 MeV less gain) and changing the π phase-switch timing on the other LIPS modulator. Large phase changes (180 deg) are unnecessary with e+ operation in the initially decelerating mode. The beam steering in LIL W is optimised for e- and e+ operation using (some of) the 20 dipoles which can be varied in PPM.

LIL Consolidation Programme

Although, in combination with EPA, PS and SPS, LIL can already satisfy the LEP injection requirements, there will be continuing machine studies aimed at understanding and improving the e+ production (see above) and raising the operating energy to 600 MeV. The latter "milestone" depends on completion of the modulator upgrade, particularly the high voltage feedthrough capacitors. With the off-axis gun W now removed, the gun V is the unique source of electrons on LIL so improvements to accessibility and reliability are urgent. This year several of the accelerator section vacuum envelopes have sprung leaks probably due to corrosion from a flux used during manufacture. As this could occur on all sections, a systematic replacement of the input faces will be made over the next nine months.

The first injection into the complete LEP ring is scheduled during the next major operating period, Summer 1989.

THE SPS HEAVY ION (Pb) INJECTOR

A comprehensive report[16] presenting a "Concept for a Lead Ion Accelerating Facility at CERN" covered the changes required in the existing CERN accelerators i.e. the 1 GeV Booster Synchrotron (PSB), the 28 GeV Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS) as well as a proposal for the new Linac which would be necessary to accelerate ions with q/A =1/9. In this paper the essential features of this Linac are treated while another paper at this conference[17] concentrates on a proposed focusing arrangement.

Ion acceleration at CERN

In 1964 deuterons were accelerated in the CERN 50 MeV Proton Linac (Linac 1) in the 2βλ mode by making modest adjustments to the normal electric field distribution. This gave an energy of 11.7 MeV/u. After successfully providing deuterons[18] and alpha particles[19] for ISR physics it was clear that Linac 1, PSB and PS could accelerate fully stripped ions with q/A=1/2. The next stage was a proposal with GSI and LBL to accelerate O^{8+} ions to maximum SPS energy. The Linac part had an electron cyclotron resonance source (ECR made by R. Geller, Grenoble) producing 100 μA (electrical) of O^{6+} ions at 90 keV (5.6 keV/u), followed by an RFQ accelerating to 130 keV/u, then Linac 1 to 11.7 MeV/u and finally after the foil stripper, a 30 μA O^{8+} beam was delivered to the PSB. One major problem was to condition tank 1 to hold the 33% higher electric field necessary for O^{6+} (q/A=0.375). Successful physics runs were made with O^{8+} ions[20] in 1986 and with S^{16+} ions[21] in 1987 after an ECR source for S^{12+} had been installed. There has been a clear demand from the physics community for heavier ions e.g. Lead at SPS output energy.[22] Further development of Linac 1, which is limited to q/A = 0.375, is impossible for lead ions especially as ion sources giving reasonable currents have q/A ≅ 0.1. Thus a new "custom built" Linac has been proposed with characteristics e.g. energy, current and beam quality matched to the following accelerators and physics requirements.

Beam Quality Considerations

The users want 5×10^7 ions corresponding to about 4×10^9 charges/pulse of Pb^{82+} from the SPS. The losses along the chain of accelerators are mainly due to stripping from Pb^{25+} to Pb^{53+}, charge exchange in the residual gas in PSB and PS, and rebunching on new harmonics or other RF manipulations in PSB and SPS. It is estimated that 0.9% of the ions from the source arrive at the experiment so with four pulses of 30 μAe Pb^{25+} ions for 400 μs, the final intensity for one pulse from the SPS will be 11×10^7 ions, safely above the requested value. The Linac energy was determined by two main constraints, the most probable charge state after stripping at the Linac output coupled with the need to have a magnetic rigidity in the PSB injection line and pulsed distributor no more than 15% above that for 50 MeV protons. For lead ions between 2 and 8 MeV/u, the most probable charge state Q produced after a carbon foil is given by :

$$Q = 82\ (1 - \exp(-0.51\sqrt{W})) \quad \text{with W in MeV/u.}^{23}$$

The non-relativistic approximation:

$$B\rho = 30\ (\sqrt{W})/Q \quad \text{assumes A=208 for Pb, } B\rho \text{ in Tm.}$$

Solving the above for Bρ = 1.16 Tm (13 % greater than that for 50 MeV protons) gives a Linac energy of 4.2 MeV/u and stripping to Pb^{53+}, which is also consistent with allowable harmonic changes, and avoidance of transfers near transition in the synchrotrons. Experience with O^{6+} and S^{12+} ions confirmed that the attainable emittances are less than for protons. In fact assuming an increase in normalised emittance in the Linac from 1 to 2 π mm mrad, at 4.2 MeV/u the geometric emittance will be 21 π mm mrad so there should be no aperture problems in the transport line to the PSB. With phase stable acceleration in the Linac the longitudinal emittance, assumed to be twice that obtained from the RFQ (240 keV/u*) can be shaped by the existing debunchers to give the desired 0.1 % energy spread at the PSB.

Options

Some firm design choices had to be made for the main Linac to develop this proposal. These choices were aimed at meeting the specifications with technical solutions which could be costed. However other options considered could be preferred after further study, when their technical and/or cost advantages have been demonstrated.

Ion Source

The preferred solution is an ECR source which is an extrapolation from the O^{6+} and S^{12+} sources used on Linac 1. Other sources considered were the EBIS source which could potentially approach the required performance and laser excited sources which are mechanically simple in concept but have yet to be applied to heavy ions.

Low Energy Acceleration

The preferred modern solution for an accelerator between 2.8 keV/u and 250 keV/u is the Radio Frequency Quadrupole (RFQ) and the choice here is of operating frequency and mechanical construction e.g. 202.5 MHz or 101.3 MHz and 4 vanes or 4 rods. There is an advantage in retaining 202.5 MHz as there would be spares and tried solutions from Linacs 1 and 2. However, the lower frequency must be preferred for more efficient focusing at the lower energies especially if we require some margin on the transverse acceptance.

High Energy Acceleration

A βλ drift-tube structure at 202.5 MHz for ions with q/A = 1/9 at low energy (0.25 MeV/u) and with focusing quadrupoles in a FODO arrangement, requires pole tip fields >1.3 T. This limitation can be avoided if the 2βλ acceleration mode is used as there is more space in the drift-tubes for quadrupoles.[24] An extension of this principle is to increase the distance between centres of drift tubes containing quadrupoles to 4βλ for example, and to insert two smaller drift tubes with βλ periodicity but without quadrupoles.[17] This allows a drastic reduction in the number of quadrupoles for acceptable focusing, and a significant increase in both the accelerating rate and shunt impedance.

The Interdigital-H (IH) structure[25] has a much higher shunt impedance than the Alvarez drift-tube structure due to the field mode, (H instead of E), the acceleration mode (βλ/2 instead of βλ), and the low capacitive loading between small diameter drift-tubes (without quadrupoles). However there are still problems concerning 3-dimensional cavity calculations, practical tuning and electric field law adjustments in a discontinuous structure, and complicated quasi-stable acceleration schemes. These uncertainties in the IH structure outweigh, at present the advantage of the high shunt impedance.

Proposed Design

ECR Source[26]

The aim is to produce 30μAe of Pb ions with q above 25+. The ionisation process is multi-step with the ionising electrons having typically four times the binding energy of the last electron removed e.g 4x1 keV. In the ECR, the electrons come from a plasma heated by microwaves in a multi-mode cavity which is immersed in a magnetic field satisfying the electron cyclotron resonance condition of 28 GHz/T. Longitudinal and transverse confinement are provided by the magnetic field distribution, while the ion extraction is by an accelerating gap at the edge of the plasma. An ECR source for Pb ions could have the following parameters: RF power 3 to 6 kW at 20 to 30 GHz, with magnetic field 0.84 to 1.25 T giving plasma densities 4 to $9\times10^{12}/cm^3$ and ion formation in 25 to 50 ms.

Radio Frequency Quadrupole

Matching of the rotationally symmetric beam at 2.8 keV/u from the source into the RFQ can be made with an einzel lens in the pre-accelerator followed by two iron-clad solenoids (1 T peak field) which give more flexibility than the strict minimum of two variable elements. With low q/A ions, high electric fields are required in the RFQ to contain the particles transversely and longitudinally. The phase advance, σ_T over a structure period is given by

$$(\sigma_T)^2 = Q^2 -0.5(\sigma_L)^2$$

where Q^2 corresponds to the mean focusing in a period, $0.5(\sigma_L)^2$ is the RF defocusing term and σ_L is given by the longitudinal phase advance over a structure period.[24] At low energies, the defocusing term, which scales as W^{-1}, essentially reduces the σ_T below the acceptable minimum at 202.5 MHz, if one stays below the electric field limit, $E_s < 2E_k$, where E_k is the Kilpatrick field limit.[16]
This limitation was confirmed by the computer exploration in parameter space where with choices of

$$\sigma_T = 23^\circ \quad \text{and } s_L = 21^\circ\text{, at } 101.3\text{MHz},$$

a satisfactory design with respect to transmission (94%), no emittance growth and with surface electric field (<20MV/m), was obtained. The length is 5.3 m for 0.25 MeV/u output energy and the aperture radius 3 mm. The computed beam dynamics is the same for four vane or four rod designs but the latter has smaller transverse dimensions at 101.3 MHz.

Drift-Tube Linac

The input beam conditions are given in Table 3. There is a change of frequency between the RFQ and the drift-tube Linac but the longitudinal emittance from the RFQ, 1.6×10^{-6} eV s (114 kev/u° at 202.5 MHz) can be matched into the following acceptance by an ensemble of drift space (0.33m), buncher (11 keV/u peak modulation) and drift space (0.28 m). Four quadrupoles will also be required here to ensure transverse matching.

Two input constraints in the DT Linac design were the quadrupole pole tip field < 1.3 T and Es < $1.5E_k$ < 21 MV/m). As mentioned above, the solution to the focusing problem is to have drift-tubes with longer quadrupoles (3βλ/2) in 2βλ cells separated in the structure by two or more "empty" drift-tubes in βλ cells. Thus if the length of the FODO focusing period is Nβλ it comprises two long drift-tubes and N-4 "empty" ones.[11] The optimisation using a matrix multiplication method and including RF defocusing, leads to the N=8 configuration in the most difficult region at 0.25 MeV/u; this is retained up to 2 MeV/u where N=10 can be used. Another limitation at 0.25 MeV/u is the minimum tolerable Transit Time Factor (TTF) of 0.65 which implies a drift-tube aperture radius of 6 mm. For $\sigma_T = 80^\circ$, $\sigma_L = 100^\circ$ both measured over 8 βλ, the required gradient at 0.25 MeV/u is 178 T/m which gives a beam envelope maximum of 5.1 mm (cf. 6mm aperture) and minimum of 2mm, for a normalised emittance of 1 π mm mrad. The require gradient diminishes approximately as $\beta^{-1.2}$.

In this proposal,there are two types of drift-tube, the larger of diameter 150 mm, length about βλ contains a quadrupole and the smaller of diameter 80 mm, length about 0.75 βλ is "empty".

The program SUPERFISH was used to establish the dimensions, e.g. the cavity diameter and the gaps for resonance at 202.5 MHz, for two cavities with energies 0.25 MeV to 2 MeV, and 2 MeV to 4.2 MeV respectively. In addition the program gives shunt impedances ZT^2 and transit time factors. The latter are required to generate the linac dimensions for a "safe" design (as in Table 3) or for an "economic" design which reduces the number of drift-tubes (and quadrupoles) at the cost of higher surface electric fields and RF power dissipations.[16]

Other Features

The building for Linac 1 will become available for the lead Linac so that there will be enough space for the linac, the RF system and comprehensive beam measuring facilities in the tunnel (Fig 8). For the proposed design there will be four RF amplifier chains, one at 102.3 MHz (500 kW) for the RFQ, a 50 kW chain for the buncher and two 1.5 MW chains for the two linac tanks, the last three being at 202.5 MHz and based on the designs used for Linac 2.

The quadrupoles can be scaled from Linac 2 with some simplifications in the pulsers due to much less stored energy. For the control system it is feasible to recuperate much of the equipment used for Linac 1 though the more comprehensive set of application programs available on Linac 2 should also be installed. It is estimated that 2000 control channels (e.g. four channels/power supply) will be needed.

The beam monitoring equipment will have to cope with low intensity beams of different charge states. At present comprehensive measuring systems are proposed between the source and RFQ and in the beam transport line directly after the Linac with a minimum of measuring equipment between the RFQ and DT linac.

With metal seals and clean metal surfaces, triode ion pumps will suffice for 10^{-7} Torr vacuum. The linac tanks can be made in five cylindrical sections from copper-clad steel with the drift-tubes hung from the inside but having outside reference surfaces.

TABLE 3 Provisional Parameters of the Lead Linac[16]

ECR Source

Species:	Pb 208	q > 25
Output Current	30 µAe	(single charge state)

RFQ f = 102.28 MHz

Energy (keV/u)	2.8	to	250
Length (m)	5.3		
Aperture Rad. (mm)	3		

DT Linac f = 202.56 MHz

	Tank 1	Tank 2
Energy MeV/u)	0.25 to 2.0	2.0 to 4.2
Tank Length (m)	9.3	9.4
Tank Diameter (m)	1.05	1.02
DT's (with Quads)	36 + 2x1/2	15 + 2x1/2
DT's (empty)	74	48
Aperture Rad.(mm)	6 to 8	9 to 10
RF Power (MW)	1.2	1.2

Realisation of the Project

There is sufficient information on the possible technical solutions, the estimated cost (17 MSF for the Linac part) and the time scale (3 years overall) for the project to be launched. As for the oxygen ion project, CERN will rely on active collaboration with outside laboratories for the detailed design and construction of a significant fraction of the Linac systems.

Acknowledgements

I would like to thank my colleagues in the LP and HI Groups of the PS Division for providing information and useful comments on this Invited Paper. In particular, the help of K. Hubner and J. Madsen on the LIL part and H. Haseroth on the Lead Linac part is gratefully acknowledged.

References

1. The LEP Injector Study Group, "The LEP Injector Chain", CERN/PS/DL/83-31.
2. F. Dupont, CERN-LAL Collaboration, "Status of the LEP e+/e- Injector Linacs", Proc.1984 Linear Acc. Conf., p.288.
3. D. Blechschmidt and D. J. Warner, "Parameters of the LEP Injector Linacs", CERN/PS/88-7 (LPI).
4. A.Fiebig et al., Proc.1987 IEEE Part. Acc. Conf., p.1931.
5. S. Battisti et al., Proc. 1987 IEEE Part. Acc. Conf.,p.570.
6. P. Brunet, R. Chaput, Proc. 1984 Linear Acc. Conf.,p.189.
7. D.J. Warner, CERN-LAL, "First Electron Beams from the LEP Injector Linacs", Proc. 1986 Linear Acc. Conf.,p.465.
8. J.H.B. Madsen et al., Proc. 1987 IEEE Part. Acc. Conf.,p.298.
9. J.H.B. Madsen et al., Status Report on the LEP Pre-Injector (LPI) and the Proton Synchrotron (PS) as an e^+/e^- Accelerator, Proc. EPAC, Rome, 1988
10. G. Bienvenue, LAL PI 86-17/T, 1986.
11. A. Riche and L.Rinolfi, "Optics of Linac V", Note PS/LP/88-22.
12. K. Hubner, CERN/PS/88-19(LP),1988.
13. K. Hubner, "Positron Production at LIL", To be published.
14. L. Rinolfi, "Single Electron Project", Note PS/LP/88-66.
15. T. Garvey et al., "New Developments in Particle Acceleration Techniques",CERN 87-11, p.188(1987).
16. H. Haseroth (ed.), "Concept for a Lead Ion Accelerating Facility at CERN", Future CERN Report.
17. D.J. Warner, "Heavy Ion Acceleration Using Drift-Tube Structures with Optimised Focusing", This Conference.
18. P. Asboe-Hansen et al.,IEEE Trans. NS-24, p.1557, (1977).
19. M. Boutheon et al., IEEE Trans. NS-28, p.2049, (1981).
20. H. Haseroth et al., 1986 Linear Acc. Conf. Proc., p. 355.
21. N. Angert et al., EPAC Rome, (1988).
22. G. W. London et al., CERN/SPSC 87-52 (1987).
23. U. Tallgren (ed.), PS/DI/DS Min. 88-2.
24. H. Haseroth, A. Lombardi and M. Weiss, Proc. 1987 IEEE Part. Acc. Conf., p.295.
25. U. Ratzinger, "A Low Beta RF Structure of the IH-Type with Improved Radial Acceptance, This Conf.
26. R. Geller, " ECR Sources, Status and Recent Developments, Invited Paper at this Conference.

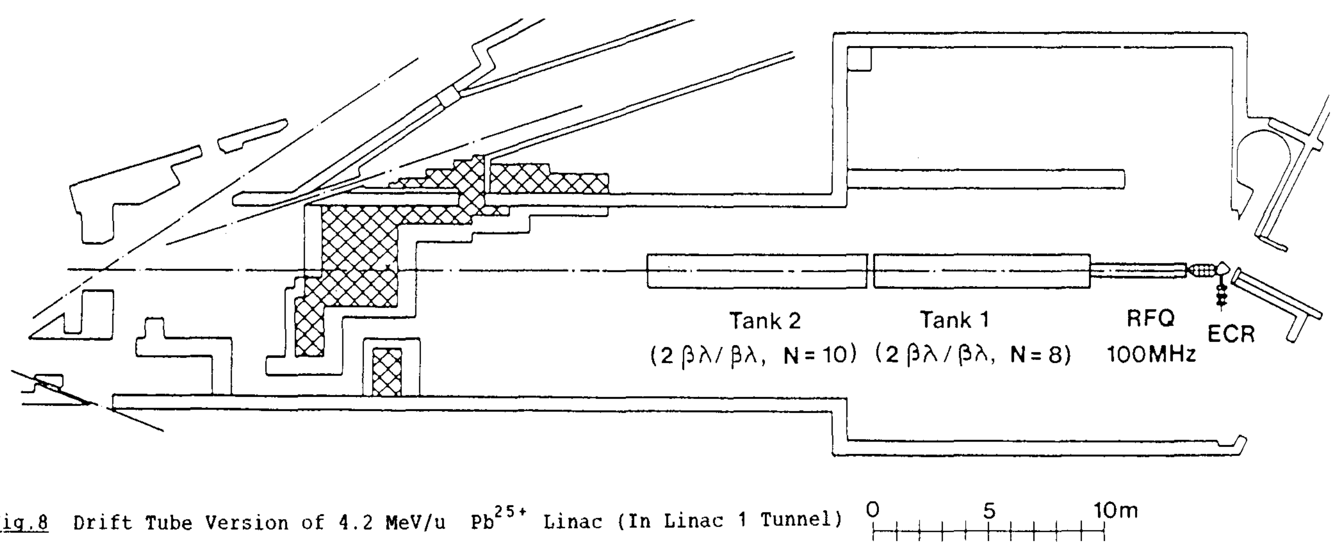

Fig.8 Drift Tube Version of 4.2 MeV/u Pb^{25+} Linac (In Linac 1 Tunnel)