INTENSITY LIMITS AND BEAM QUALITY IN THE LINATRON (RECYCLED ELECTRON LINAC)

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Abstract

The intensity limit of a recycled linac, set by the phase dynamics, can be raised with a beam-load compensation to the efficiency level of straightforward linacs, allowing full exploitation of its narrow spectrum and high voltage yield.

1. General considerations

The acceleration scheme that we call for short Linatron (Fig.1), long since proposed[1] and at present investigated for actual construction by a few groups[2-4], may be treated as a split-magnet microtron which happens to use a waveguide for acceleration, or as a linac recycled on a variable-harmonic-number pattern after external injection. The former standpoint has been usually adopted, with emphasis on geometry and spatial focusing, while no systematic attention has been paid to the latter point of view, i.e. the interplay between phase focusing and load characteristics of the linac, upon which the intensity and beam quality are predicated.

The linatron design is ruled by the following equations, where the geometry relates to the reference path, the injection parameters to the first entrance in the recycled waveguide, and times are computed from the front of its input RF pulse (of power P_o, length T_r, duty cycle D_r, wavelength $\lambda = c/f$):

- harmonic number: $N_n = N_o + nN$ (1)
- differential harmonic number: $N = 2\pi\Delta R/\lambda$ (2)
- basic harmonic number: $N_o = 2l_M/\lambda + Nr_i$ (3)
- synchronous gain: $\Delta E_s = N\lambda ecB/2\pi$ (4)
  (in MeV, T, GHz: $\Delta E_s/B = 14.3\ N/f$)
- injection ratio and transverse clearance:
  $r_i = E_{is}/\Delta E_s = 2\pi R_1/N\lambda - 1$ (5)
- orbit filling time: $T_n = (n/f)\left[N_o + \frac{1}{2}(n+1)N\right]$ (6)
- output energy: $E_b = (n'+r_i)\Delta E_s = ecBR_{n'}$ (7)
- nominal diameter: $d_M = 2R_{n'} = (n'+r_i)N\lambda/\pi$ (8)

where n = orbit number, n' = total number of orbits, R = orbit radius, $\Delta R = R_{n+1} - R_n$, l_M = distance of the recycle magnets, B = their constant uniform field, E_{is} = total injection energy for 'synchronism';

- load current: $I_c = n'I_i$ (9)
- load-pulse front: $I(t) = I_i \sum_1^{n'} U(t-t_i-T_{n-1})$ (10)
- pulse length: $T_b = T_r - T_d$ with $T_d = t_i + T_{n'-1}$ (11)

where I_i = injection current assumed accelerated without loss, t_i = injection time of the injection-pulse front, U(t) = step function; T_d = dead time.

- synchronous phase: $\sec\varphi_s = eV_p/\Delta E_s$ (12)
- $V_p(t,I_i) = V^o(t) - V^i(t,I_i)$ (13)

where V_p is the crest value of the accelerating voltage in the recycled waveguide, V^o its no-load value and V^i its beam-load drop;

- relative beam-load drop: $\xi = V_k^i/V_k^o = I_cR_b/V_k^o = I_c(rL/P_o)^{\frac{1}{2}} f_1(g)$ (14)
- output mean power: $P_{bm} = I_iE_bD_b/e = D_bI_cV_p(n'+r_i)/n'\sec\varphi_s \simeq D_bI_cV_{pk}$ (15)
- power transfer efficiency: $\eta = P_{bm}/D_rP_r \simeq (D_b/D_r)(P_o/P_r)(1-\xi)\xi f_2(g)$ (16)
- relative voltage yield: $\zeta = E_b/D_rP_r$ (17)

where V_k are the stationary values of the voltages; L, r, R_b the length, shunt impedance, 'beam resistance' of the guide, and g the fraction of P_o it dissipates at no load; $D_b = D_rT_b/T_r$ the beam duty cycle; P_r the output pulse power of the RF generator. In the following we assume to use traveling-wave, constant field guides, with filling time $T_f = f_3(g)$, and to inject with $t_i = T_f$ (Fig.2).

A recycled linac is just a transformer stepping up in voltage the power transferred to the load I_c.

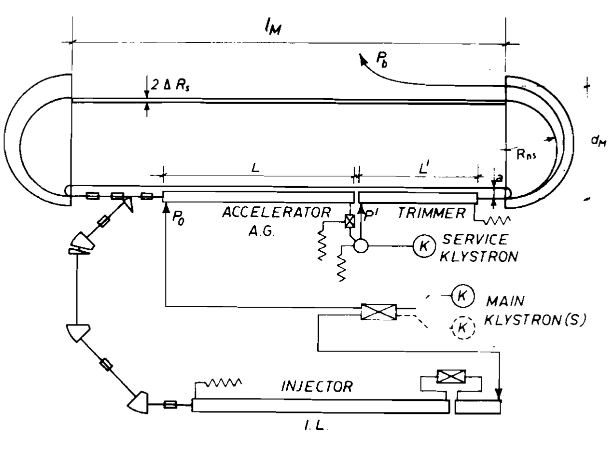

Fig.1 – Schematic Linatron layout (a = $2R_1$)

With respect to a straightforward linac, besides the obvious gain in terms of ξ, one may expect a much better performance in terms of power per unit spectrum width, owing to the narrow bin into which the output energy is compressed by the phase focusing, even at lower values of η. Of course the advantage can be actually reaped only if the machine is made able to accept a sufficient current.

2. Phase dynamics and longitudinal acceptance.

By longitudinal acceptance we mean the range of injection phase φ_i and injection total energy E_i which enable all the electrons entering the recycled linac at any time t_e between t_i and t_i+T_b to follow the n' orbits through the slits imposed by the spatial focusing system for any value of the acceleration parameters within their stability bin. It has been computed numerically, following in their course the electrons injected at the various points of the φ_i, E_i plane with full account taken of the time evolution of the linac fields (in phase and value, reckoning with the guide temperature) and of the deviations from norm in the coasting path (velocity lower than c at injection, radiation loss, alignment errors, spatial focusing and steering), and the conditions were sought which make it wide enough to accomodate the energy spread and phase jitter of the injection system.

The range of φ_i, E_i where the electrons are accepted when V_p and ΔE_s (hence φ_s) are fixed turns out to be an irregular region, here called "stable bucket for φ_s", that changes critically with φ_s in size, shape and position; the acceptance, obviously limited to the portion of the φ_i, E_i plane common to all the buckets relative to the φ_s range swept during T_b, is smaller than any of them and disappears

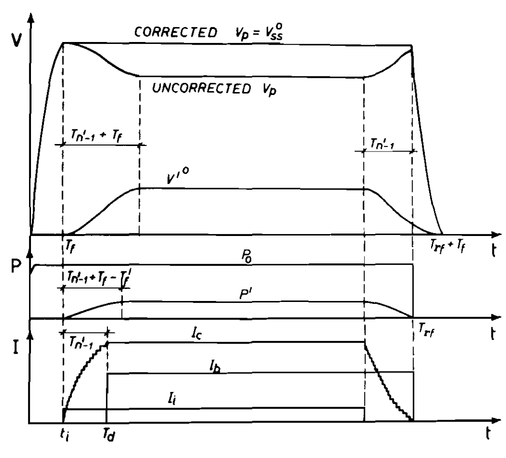

Fig.2 - Pulse shapes and time relationships (I_b= output current; vertical scales not correlated: indeed $P_o \gg P'$, $I_b = I_i = I_c/n'$)

as the φ_s range widens. For $r_i \simeq 1$ we found indeed that at N=1 admissible injection tolerances are consistent with sec φ_s variations of a few percent in the range $\sim 1.01 \leq \sec\varphi_s \leq \sim 1.10$, while at N=2 the buckets are much smaller and offer an acceptance only for too critical conditions of injection and acceleration.

This is a more severe restriction than the one suggested by the usual treatment of the microtron phase stability[1)], where the electrons are supposed to execute small fixed-amplitude phase oscillations about φ_s, following it adiabatically throughout the range which offers stable solutions to such dynamics (32 .5°at N=1). Actually, no reliable information on the linatron acceptance and tolerances can be gathered this way, because the situation is quite different: the electrons enter the recycle pattern with large initial deviations from 'synchronism', increasing or decreasing irregularly from orbit to orbit as they undergo $n \lessdot n'$ voltage-gain errors roughly alternate in sign, and lose themselves against the existing slits if their energy deviation gets too large. What happens can hardly be described in terms of regular 'phase oscillations' as the phase itself is defined only at a few discrete intervals of the order of half period and the parameters change noticeably within the few periods that exhaust the matter (often the point φ_s, E_{is} falls outside the bucket for φ_s, indicating a refusal of small initial deviations). The boundary of our buckets has nothing to do with phase-space trajectories at the limit of acceptability, but is just the border of a region defined in absolute terms in the φ_i, E_i plane correspondent to the range of initial deviations that the phase dynamics can handle.

As $\Delta E_s \propto B$ is stabler than V_p by two orders of magnitude, we may take sec $\varphi_s \propto V_p$ and deal only with the variation of V_p, which changes during T_b both for the jitter of P_o and the time evolution of V^1; this rises along a S-shaped curve to reach its stationary value at the time $t_i+T_{n'-1}+T_f$ (Fig.2), under the hypothesis that I_i keeps being accepted - the only case to consider as the acceptance to be found must be valid for the whole T_b. With P_o constant, for a given value of I_c, i.e. of ξ, the function $V_p(t)$ is given and a set of buckets may be computed for all the successive values of t_e, referred as a whole to sec φ_{so} = $= eV_{pk}/\Delta E_s$. The injection current is accepted only in the region where all these buckets overlap, here called "beam-loaded bucket for φ_{so} and ξ", which gets smaller as ξ increases and/or φ_{so} goes farther from its optimum. A set of beam-loaded buckets may now be computed for the same ξ and all the values taken by φ_{so} for the P_o jitter, i.e. throughout the stability bin of V_{pk}: the longitudinal acceptance is the region where all these last buckets overlap, and is of course smaller if the beam-loaded buckets are smaller and/or the V_{pk} bin wider.

For a given stability bin for injection and acceleration the intensity is thus limited to the range allowed for ξ by the size required of the beam-loaded buckets, a range small enough to call for a guide design rather inefficient in power transfer and voltage yield (at $\xi \sim 5\%$ the beam-loaded buckets are uncomfortably smaller than those of Fig.3); besides, the stabilization cannot be much pushed, as one needs a long T_r. A reasonable intensity however may be attained if the variation of V_p during the transitory is reduced by setting $t_i < T_f$.

3. Beam-load drop compensation

In order to exploit the full possibilities of the linatron scheme one must uncouple the design value of ξ from the φ_s fluctuation range by compensating the beam-load drop. This is made possible by the very fact which allows computing the beam-loaded buckets: the waveform $V^i(t)$ is strictly defined if the electrons keep being accepted and build up I_c according to (10), and may therefore be copied in a programmed voltage source.

To this end we shall add a Trimmer Guide long L', designed for $V_k'^o = (R_b+R_b')I_c$ and excited at the proper phase by a RF pulse with a leading edge programmed to yield $V'^o(t) = V^i(t)+V'^i(t)$ (Fig.2). The trimmer pulse will be shaped by adding in a magic tee a fraction $\frac{1}{2}P'$ of the output power from the main guide to the output $\frac{1}{2}P'$ of a service klystron small enough to be driven through a fast phase shifter coupled to an attenuator and controlled by a programmed logical circuit(°). The total accelerating voltage thus becomes equal to V_k^o for $t_i = T_f \leq t \leq T_r$ and the main guide may be designed for

$$\xi = V'_{pk}/V_k^o = (r'g'L'P'/rgLP_o)^{\frac{1}{2}} - R'_b I_c/V_k^o \qquad (18)$$

This value, being now limited mostly by the service klystron rating, can be brought up to the levels of quite efficient straightforward linacs without reducing in principle the bucket size. The set of buckets defined for constant P_o and all t_e now yields by complete overlapping a "load-compensated bucket" smaller than the stable buckets for $\sec\varphi_s = eV_k^o/\Delta E_s$ only by the extent due to the mismatch of the compensating device, thus leaving free to accommodate the fluctuation bin most of their overlapping capacity. We found indeed with our work data that operation centered on $\sec\varphi_s = 1.035$ at $r_i \sim 1$ accommodates a $\sim 2\%$ bin for both V_k^o and E_i, allowing for their uncorrelated phase jitter (Fig.3): the injection and acceleration power supplies may therefore be designed with equal and quite undemanding stabilization.

(°) This compensating device has been suggested by the staff of the Radiation Division, Vickers Ltd. (now Radiation Dynamics Ltd.).

Notice that T_f' need not be shorter than T_f, as the compensation is not fed back but programmed. One may therefore set $g = g'$, $r = r'$ and maximize I_c in the expression

$$\xi = I_c r L f_4(g)/V_k^o = (L'P'/LP_o)^{\frac{1}{2}} - I_c r L' f_4(g)/V_k^o \qquad (19)$$

by playing on g and the ratio L'/L within the limits allowed to $l_L = L+L'$ by the spatial focusing. With the other parameters constant, I_c is maximum for $L' = L$, and then is the higher the lower g; the optimum design sets L somewhat higher than $\frac{1}{2}l_L$. The attainable yield depends on the available klystron power, within the limits imposed by the BBU and the heat dissipation in the accelerator guide.

4. Injection

The main klystron power must split between the accelerator guide A.G. and an injector linac I.L., because with a reasonable transverse clearance at N=1 one must set $r_i \geq 0.85$. The injection bin must be stabilized at the origin within the longitudinal acceptance: indeed the longitudinal emittance cannot be adjusted with momentum-defining slits, which would translate energy fluctuations into current fluctuations, because the very size and position of the acceptance region is predicated on the regular build-up of I_c (with or without compensation). Therefore the transport system must be achromatic, and also isochronous to the extent of containing in due limits the phase spread associated with the energy bin.

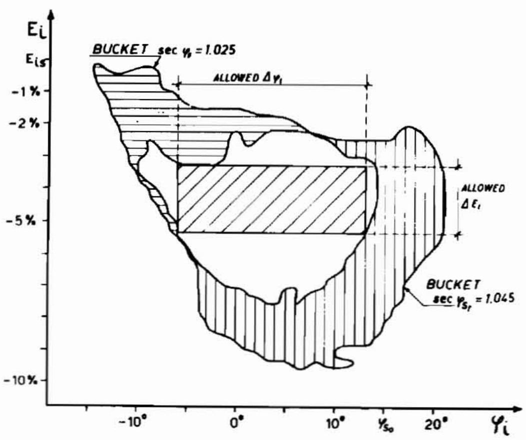

Fig.3 – Longitudinal acceptance in a beam-load compensated 1-GeV one-socket linatron scheme for $\sec\varphi_s = 1.035 \pm 0.01$, with N=1, N_o=85, $\Delta E_s = E_{is} = 13.5$ MeV, n'=75, I_c= 82 mA, L = 4.23 m, $t_i = T_f = 1.5\ \mu s$, 1°C temperature rise at constant gradient along the guide.

TABLE 1

Linatron Performance

accelerator	E_b GeV	P_{bm} kW	D_b %	spectrum %	efficiency η	η'	quality figures ε	ε'	ζ	ζ'	P_Q
Linatron:											
one-socket	0.5	25	2.25	0.07	0.20	0.12	2.90	0.11	4.05	2.37	805
	1	18	1.60	0.04	0.15	0.053	3.66	0.034	8.35	3.03	720
	1.36	12	1.07	0.04	0.098	0.027	2.44	0.013	11.05	3.10	320
two-sockets (alternate pulses)	0.5	50	4.49	0.07	0.20	0.15	2.90	0.22	2.03	1.50	3210
	1	36	3.20	0.04	0.15	0.078	3.66	0.067	4.16	2.22	2880
	1.36	24	2.14	0.04	0.098	0.043	2.44	0.025	5.53	2.42	1285
two-sockets (mixed pulses)	0.5	46	2.44	0.07	0.19	0.14	2.70	0.20	2.05	1.51	1605
	1	33	1.78	0.04	0.14	0.072	3.40	0.062	4.22	2.24	1470
	1.36	23	1.26	0.04	0.095	0.041	2.37	0.024	5.60	2.44	725
Advanced linacs:											
Saclay (15 sockets)	0.54	250	1.0	1.0	0.28	-	0.084	-	0.60	-	250
M.I.T. (10 sockets)	0.4	114	1.8	0.4	0.14	-	0.018	-	0.50	-	514
Classical machines:											
Orsay (16 sockets)	1	5	0.007	2	0.1	-	0.026	-	21	-	0.02
Frascati Synchrotron	1.1	0.35	5.0	0.5	0.054	0.001	0.11	0.0002	170	2.73	3.52

spectrum = long-term output energy bin for 50% beam power. ζ in MeV/kW, P_Q in kW. η', ε', ζ' computed adding the magnet power to P_r (both divided by their stability bin for ε'); assumptions for the linatron magnet power: 2n kW for focusing (2% stability), 15 kW for recycle at 0.5 GeV, scaled with d_M^2 (0.01% stab.).

An emittance adjustment is instead both possible and necessary in the transverse phase space, in order to fit the transverse acceptance ($\sim 10^{-5}$ rad.m per plane). A careful design of the injector buncher and the transport system allows to inject with a current loss of about a factor 10, carried out before entering the recycled guide in order to keep low the radiation background (another advantage for precision experiments). As $n' > 10$, the I.L. load is $I_{Li} < I_c$ and I.L. (which also requires a voltage somewhat lower than V_p) may be excited with only a fraction of the power devoted to A.G., as there is no limit on its design efficiency.

Notice that the I.L. power would not be spared by devices allowing injection at gun energy (e.g. by detouring the first orbits to avoid the clearance condition or operating at N=2), because the surplus current $I_{Li} - I_i$ spilling over the transverse acceptance would add anyhow to I_c, and the presence of a buncher in the recycle pattern would result in loss of efficiency.

5. Attainable performance

A first optimization of the several conflicting parameters led us to choose for the 0.5 GeV LIRF machine $\Delta E_s = 13.5$ MeV, i.e. B = 1.19 T at N=1, $\lambda =$ = 23.8 cm (the fringing-field correction called for to ease the spatial focusing[2,5]) is difficult at higher fields, while at lower ones d_M is too large and the I.L. emittance deteriorates), and $l_L = 7.1$ m as allowed by $l_M \simeq 10$ m (higher values would hamper the spatial focusing). While we plan for n'=36, the scheme obtains up to any reasonable magnet size, reaching 1 GeV for n'= 75 ($d_M = 5.75$ m).

With one commercial 4 MW - 3% klystron operated at $T_r = 20\,\mu s$ with 10% feed losses; 0.1 MW available from the service klystron; a 4 m, 40 MΩ/m accelerator guide with $T_f \simeq 1.6\,\mu s$ and heat load $\simeq 1.5$ W/cm^2; injection at $r_i = 0.85$ utilizing $\sim 0.3\ P_r$ in a guide with the same T_f; one may accelerate $I_c = 82$ mA and get the yields of the 'one-socket scheme' of Tab.1. The spectra are long-term ones, computed on the data of Fig.3 assuming a pessimistic uniform distribution in the injection bin ($12.71 \leqslant E_i \leqslant 13.00$ MeV, $-3° \leqslant \varphi_i \leqslant 12°$), taking an uncorrelated average on a uniform V_k^o bin ($\pm$ 1%), and adding the 10^{-4} stability bin of the recycle field. If two klystrons are used, one may feed the power-splitting device with their alternate pulses and double the repetition frequency, so that with the same design P_{bm} and D_b increase twofold (but also of course the heat load in the guide) and the quality figure P_Q fourfold. Were such feeding scheme not convenient, one may mix the two pulses and split the 8 MW output on a different design ($T_f \simeq 0.6\,\mu s$, heat load $\simeq 1.9$ W/cm^2, injection power $\sim 0.25\ P_r$), which allows to accelerate $I_c = 136$ mA and get the yields of the 'two-socket mixed pulses scheme'. These results are just an extrapolation from design parameters considered (not yet definitively) for building a 0.5 GeV machine within given budgetary and technological limits: better ones may be expected from optimization for other energies and conditions.

A comparison with the more advanced high-duty, high-energy linacs shows the jump in beam quality and efficiency offered by the scheme. With a power transfer efficiency of the same order, one or two orders of magnitude are gained in the "precision-transfer efficiency" defined as

$$\varepsilon = \frac{\text{beam mean power per unit spectrum width}}{\text{RF mean power per unit stability bin}} \qquad (20)$$

which gets higher than unity (an indicative cost index), and one order of magnitude in the voltage relative yield ζ, which allows to reach 1 GeV with just one klystron. In absolute terms, when precision and duty cycle are paramount, a convenient quality figure for the beam is

$$P_Q = \frac{(\text{beam mean power}) \times (\text{duty cycle})}{(\text{spectrum width})} \qquad (21)$$

and here too the gain may reach one order of magnitude. These advantages are accompanied by a substantial reduction in installation and operation costs: the d.c. short-gap magnetic system is much cheaper than the several highly stabilized RF generators required by multisection linacs. Of course the efficiency figures are lower if one accounts for the magnet power, but a comparison with the values of η', ε', ζ' in Tab.1 (which anyhow keep high) is much less meaningful, as d.c.-magnet power and waveguide power do not weigh the same. A retrospective glance at a couple of classical electron machines shows how in some respects the performance jump offered by the linatron with regard to the advanced linacs bears comparison with the one they represent with regard to the machines of the precedent generation.

These results are due to the unique, complete separation of functions offered by the load-compensated linatron scheme: besides the usual acceleration functions it indeed 'separates' also power output and voltage output, input stability and output stability, which last is trusted altogether on the easier parameter to control - a constant, uniform magnetic field.

6. Energy limits

A practical limit to the final energy is set by the magnet size and the reduction in duty cycle (eaten up by the dead time $T_d \propto E_b^2$) before the radiation losses rise up to jeopardize the phase dynamics. The scheme is certainly better suited to play the field of nuclear physics than the one of the elementary particles. The extrapolation of our work data to $n' = 100$ (1.36 GeV scheme in Tab.1) gives an idea on how fast the point of diminishing returns may be reached by increasing the magnet size. Of course cryogenic magnets would allow operation up to $\Delta E_s \sim$ ~ 100 MeV, but at a certain point (below 3 - 5 GeV) it becomes convenient to give up condition (4) and recycle a linac of higher energy with few orbits at different fields, making up for the increased RF hardware with the reduction in magnet area and dead time.

This geometry, where the orbits are defined by strings of sector magnets with separate fields, allows to correct for the radiation loss by decreasing the field along each orbit so as to keep at the proper value the length C_n of the curved portion of the reference path. The length S_n of the straight section replaces $2l_M$ in (3) and may be changed at will from orbit to orbit to adjust the layout as long as $N_o(n)$ is an integer. Indeed the phase dynamics is ruled only by the difference between the successive values of C_n, so that (2) obtains as $C_n = 2\pi R_n$ (with R_n averaged along the orbit if the case). We found the longitudinal acceptance indifferent to the value of N_o and little affected by n': except in useless fringes of the buckets an electron is either lost in the first 2 - 4 turns or accepted for them all. This suggests that even for few turns N must be low (≤ 2), which means that the required length of sector magnets is about the same for all orbits, i.e. the total magnetic length of the machine is

$$\sum C_n \approx (n'-1) C_{n'-1} \approx 2\pi (n'-1)^2 \Delta E_s / ecB_{n'-1} \qquad (22)$$

and the field increases roughly with n. Of course all the orbits must converge at the two ends of the linac in symmetric manifolds with equal field B_o. If, e.g., these are designed to bend all the orbits by the same angle α, then the fields of the sector magnets are given (save for the radiation loss correction) by the following rule, replacing (4):

$$\frac{\alpha}{B_o} + (2\pi - \alpha)\left(\frac{n + r_i + 1}{B_{n+1}} - \frac{n + r_i}{B_n}\right) = \frac{N\lambda ec}{\Delta E_s} \qquad (23)$$

As the layout is little affected by the choice of N, if kept so low, and (23) allows to set N=0, one may as well enjoy a synchrotron-like acceptance.

References

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DISCUSSION

F. NETTER: About the factor of quality for the Linatron, the comparison with the existing linacs is erroneous. For the Saclay high-duty-cycle linac, at 500 MeV, the total current is obtained in 0.3% energy dispersion and 50% of the current remains in 0.1% energy dispersion (i.e. 500 keV)

L. GONELLA: I quoted old figures and I am glad they have improved. Of course we are referring to long-term pessimistic spectra; when all the correlations are accounted for, we think the Linatron spectrum at 500 MeV will improve to 3×10^{-4}. We still have a good advantage, and at much lower cost.