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PRESENT DESIGN OF THE LINAC OF THE SNQ PROJECT

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The present concept of the linear accelerator for the spallation neutron source project is described. The need for two 100 MHz RFQ's and for a funneling section in front of a 200 MHz Alvarez structure and the usefulness of single cells with separate RF power supplies following the alvarez accelerator is discussed. The single cell concept asks for a sophisticated control of the amplitude, phase and timing of the RF power. Because of the large number of components a special handling of failures is required. The consequences of beam loading are considered.

Introduction

The linear accelerator concept of the SNQ project was further developed since 1982 in the KFA Jülich after the joint KfK/KFA study was completed in 1981[1]. The user community of the SNQ, which was steadily growing during the study of the SNQ project, was asking for more flexibility in particular for a variable end energy of the accelerated proton beam and for shorter pulses with higher currents. According to this development the new design of the linear accelerator was governed by the changed pulse structure with an average pulse current $\overline{I}_P$ = 200 mA, a pulse length of 250 μsec, and a repetition rate of 100 Hz, as well as by the variable end energy $E \geq 350$ MeV, and by a stage concept as described by G. Bauer in the SNQ status report at this conference.

It is the purpose of this paper to describe the new linear accelerator concept. This has to be done at a time when the basic design values have been frozen in while however many essential parameters are still negotiable.

Basic design

Alvarez

The middle part of the new linear accelerator of the SNQ project consists of a 200 MHz Alvarez structure as is indicated in Fig. 1. In the Alvarez a proton beam at an injection energy of 2 MeV is accelerated to an energy of about 100 MeV. A 200 MHz Alvarez is a well known, reliable accelerator due to the experience of many years of operation at BNL, CERN and FNAL. In table 1 a few parameters of the SNQ Alvarez are compared with parameters of three existing Alvarez accelerators. The table indicates that the energy and the pulse current values of the SNQ Alvarez are comparable with those of the existing machines. However, the average current of the SNQ project exceeds the other average currents by at least an order of magnitude. This means that one has to emphasize the minimization of beam losses in the SNQ Alvarez which is for the existing machine not an important feature. At present, beam dynamic studies are performed to demonstrate that beam losses can be

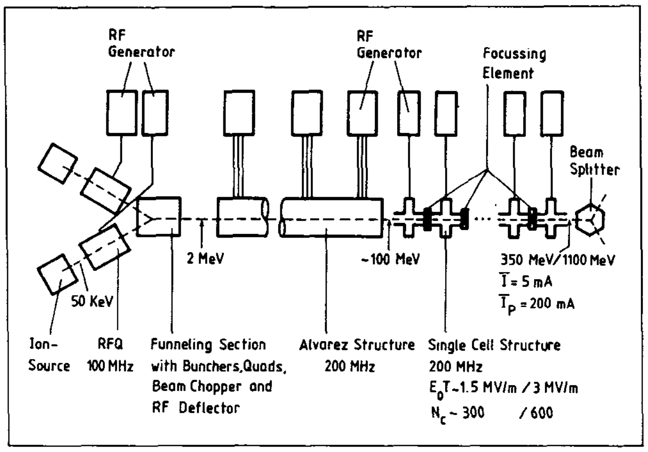

Fig. 1 Schematic view of the SNQ linear accelerator

	SNQ	BNL	CERN	FNAL
U_i[MeV]	2	0.75	0.75	0.75
U_f[MeV]	100	200.03	50	200.03
$\hat{I}$ [mA]	200	220	150	300
$\bar{I}$ [mA]	5	0.44	0.016	0.04
f_p[Hz]	100	10	1	15
f [MHz]	201.25	201.25	202.56	201.25

Table 1 Parameter of operating 200 MHz Alvarez accelerators and of the SNQ Alvarez. U_i injection energy, U_f Alvarez end energy, $\bar{I}_p$ averaged pulse current, $\bar{I}$ average current, f_p repetition rate and f rf frequency.

sufficiently suppressed by avoiding any possible effect, which leads to emittance growth, such as resonances, beam instabilities and mismatch[2].

RFQ

The fairly high injection energy of 2 MeV which ultimately allowed to choose a 200 MHz rf frequency for the Alvarez accelerator can only be achieved by a RFQ injector. At present there is no RFQ accelerator in permanent operation. However, a few successful beam tests with RFQ's have been reported. In table 2 parameters of projects with four vane RFQ structures are listed for which beam tests

Four Vane RFQ projects under beam test

Laboratory	$\bar{I}_{design}$ [mA]	f [MHz]	U_i [KeV/amu]	U_f [MeV/amu]	$\Delta\tau/\tau$	Part q/A	Status
IHEP (USSR)	150	148.5	100	0.620	$2.5 \cdot 10^{-5}$	p	200 mA (1974)
IHEP (USSR)	>200	148.5	100	1.98	$1 \cdot 10^{-5}$	p	130 mA (1979)
ITEP (USSR)	240	148.5	89	3.00	$3 \cdot 10^{-5}$	p	100 mA (1982)
Los Alamos (USA)	60	425	100	0.64	$< 1 \cdot 10^{-3}$	p	30 mA (1980)
Los Alamos (USA)	167	425	100	2.072	$1 \cdot 10^{-3}$	H^-	18 mA (1983)
CERN (Switz.)	-	202.56	50	0.52	-	p	70 mA (1983)
INS (Japan)	4	100	5	0.138	cw	≥1/7	H^+, H_2^+, H_3^+ beam test (1983)
LBL (USA)	0.9·A/q	199.3	7.1	0.2	$2 \cdot 10^{-3}$	≥1/7	beam test (1983)

Table 2 Parameters of four vane RFQ structure under beam tests, $\bar{I}$ = design current as designed, f - rf freguancy, U_i, U_f initial and final RFQ energy $\Delta\tau/\tau$ duty cycle, q and A charge and atomic number, respectively.

have been performed[3]. According to these beam tests it has been demonstrated that proton currents of about 100 mA can be accelerated in four vane RFQ's at a frequency of about 100 MHz starting from an energy as low as 50 KeV to a few MeV. Because of these promising results it seems to be justified that the injector of the SNQ linac is based on this recent development in accelerator technology.

The current limited by space charge, which can be accelerated in an RFQ structure, depends on the initial particle energy and on the frequency. In a linearized model a current limit can be estimated, which is represented by the solid line in Fig. 2. The validity of this current limit has been demonstrated by multi particle calculations since

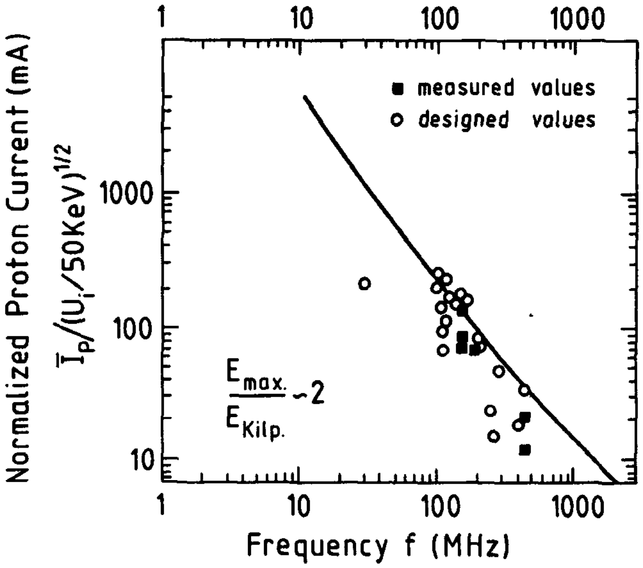

Fig. 2 Maximum RFQ proton current as a function of frequency and injection energy U_i

■ - measured currents from table 2

0 - results from many particle calculation

▬ - current limit estimate by a linearized model.

the calculated currents of designed RFQ accelerators lie at or below the solid line (see Fig. 2). A promissing result is that the measured currents of the six known RFQ's under beam test are close to the current limit. One reads from Fig. 2 that a current of 200 mA can probably not be accelerated in a 200 MHz RFQ from 50 KeV to 2 MeV as is required. However, by using two 100 MHz RFQ and by funneling the beam in order to feed the Alvarez accelerator with 200 MHz bunches, the situation is fourfold relaxed since each of the RFQ operates at the lower frequency of 100 MHz with higher current limit and has to accelerate only half of the current.

Funneling section

The funneling section consists of beam transport components as bunchers and quadrupoles, the fast choppers for cutting gaps in the current pulse and a rf deflector for merging the two 100 MHz bunches on a common beam axis. A detailed treatment of the beam dynamics with the linear model by regarding space charge and constraints due to the beam properties at the end of the RFQ and in front of the Alvarez has shown that sufficient space can be provided for the rf deflector and for the fast choppers if the latter are placed in the 100 MHz lines[4]. Multi particle simulations of the 11 m long funneling section are in progress.

Because of the beam funneling two identical ion sources are needed, each of it yielding a pulsed current of 100 mA. At present, a prototype of a magnetic multipole source and of the 50 KeV extraction system is under development.

High energy part

The high energy part of the SNQ linac consists of single cells with negligible rf coupling between the cells. Each single cell should be supplied with rf power by its own generator. The amplitude, phase, and timing of the rf power is electronically controlled and can be changed considerably during operation if required. The operation frequency is 200 MHz, the same as in the Alvarez accelerator, i.e., there is no frequency jump between the two accelerator parts. With an average accelerating voltage gradient E_0T of about 1.5 MV/m about 300 single cells are needed to accelerate the proton beam from 100 MeV to the end energy of 350 MeV (stage I). By installing another 300 single cells and by upgrading the rf power supply for stage II the voltage gradient can be increased to about 3 MV/m in order to reach the ultimate end energy of 1.1 GeV. It is this flexibility besides many other options and a large variety of advantages to be discussed in the next paragraph which has led to the concept of uncoupled accelerator structure.

Transverse focussing elements are placed between single cells. The number of elements will be optimized with respect to beam optics and beam losses. A large number of small magnetic quadrupole lenses has the additional advantage of reducing the electric power losses in the quads due to smaller aperture radii.

In Fig. 3 the estimated power consumption of the SNQ linac in stage II is compiled. The

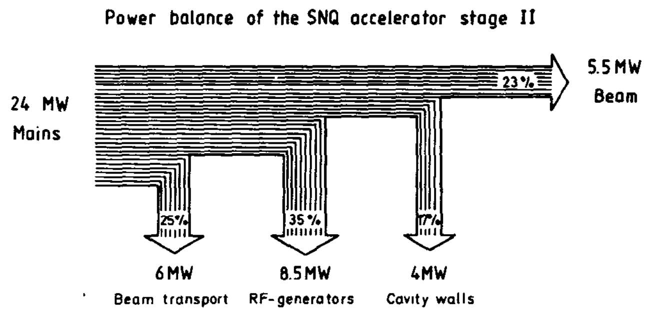

Fig. 3 Preliminary energy flow diagramme of the SNQ accelerator stage II

fraction of power going into the beam is relatively large because of the large effective shunt impedance of single cells (see Fig. 4) because of the large beam loading of 75 % and 62,5 % in stage I and II during the pulse, and because of the focussing via many small lenses.

Single cell concept

The alternative to the single cell concept, where each cell has its own relatively small rf power generator and its own control system, is an accelerator with coupled structures, e.g. side-coupled structure or Disk and Washer (D+W) structure with the rf power supply from large generators.

The single cell concept has a variety of advantages which will be discussed in the following by comparing it with a coupled structure concept.

Shunt impedance

It is generally accepted that a single cell has a higher shunt impedance ZT^2 than any coupled structure, provided the resonator wave mode and the ß value are the same. While in a coupled structure the length of the cell is a fixed parameter set for instance $\beta \cdot \lambda/2$, it is an additional adjustable parameter for uncoupled single cells. Knapp et al. estimated that ZT^2 values of coupled structures are 20 % less of that of single cells[5]. For a further comparison of shunt impedances of coupled and uncoupled structures, Disk and Washer values from literature were scaled according to $ZT^2 \sim f^{1/2}$ to the frequency of f = 200 MHz and corrected to a beam hole radius R_H = 3.5 cm with data from Manca and Knapp[6]. The scaling works quite well since the D+W values calculated originally for frequencies of 1.32 GHz by Schriber and of 324 MHz in the KFA/KfK study agree within 5 % as can be seen in Fig. 4[7,1]. These scaled ß-dependent values may be compared with calculated ZT^2 values for single cells at 200 MHz with bore radii of 3.5 cm diameter calculated by Lehmann[8]. Fig. 4 shows that the calculated shunt impedance of single cells in the E_{01} resonator mode is for $\beta \leq 0.7$ larger than the shunt impedance of the D+W structures at the E_{02} resonator mode. However, taking into account the relatively high losses due to the supporting structure in the D+W, the shunt impedance of single cells becomes even for the highest energy larger than the shunt impedance of D+W.

Variable end energy

Since the stable phase angle φ_s is an adjustable parameter in the single cell concept, particles at any velocity can be accelerated. This property can be utilized to operate the

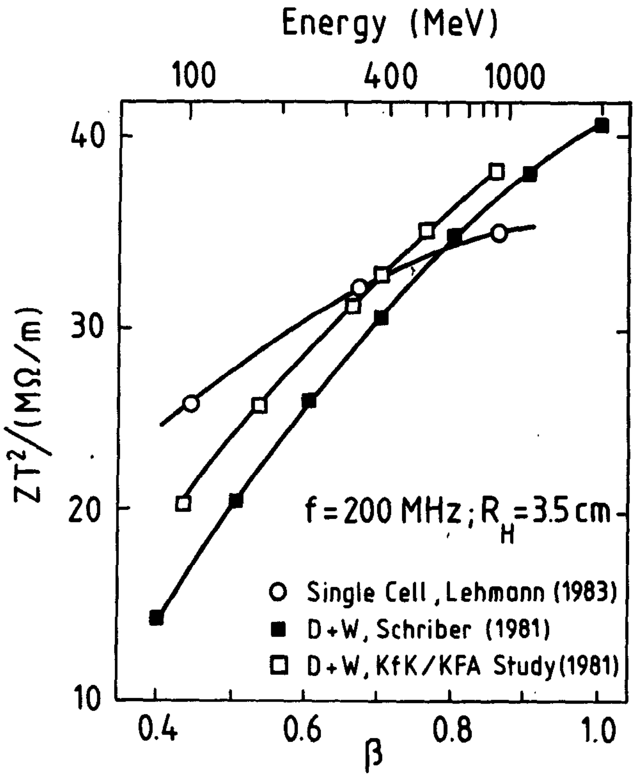

Fig. 4 Corrected, scaled and calibrated effective shunt impedances ZT^2 vers. ß for D+W structures and for single cells at 200 MHz and bore radius of 3.5 cm.

SNQ linac in other modes at higher end energies with smaller beam currents. In the single cell concept it is possible to use the extra rf power which is gained by reducing the beam current to increase the accelerator voltage gradient and hence the end energy. In a coupled structure the voltage gradient can not be changed without additional phase slip and therefore the extra RF power can not be used otherwise. In Fig. 5 the relation between end energy and current is shown for the SNQ linac of stage I. In addition it is shown how the neutron yield decreases if the end energy is increased at the expenses of a current reduction.

By decreasing the average current to 2 mA the end energy increases to 450 MeV. In this case the neutron intensity is reduced to 50 %, however, an important energy window for nuclear physic experiments can be scanned in this way.

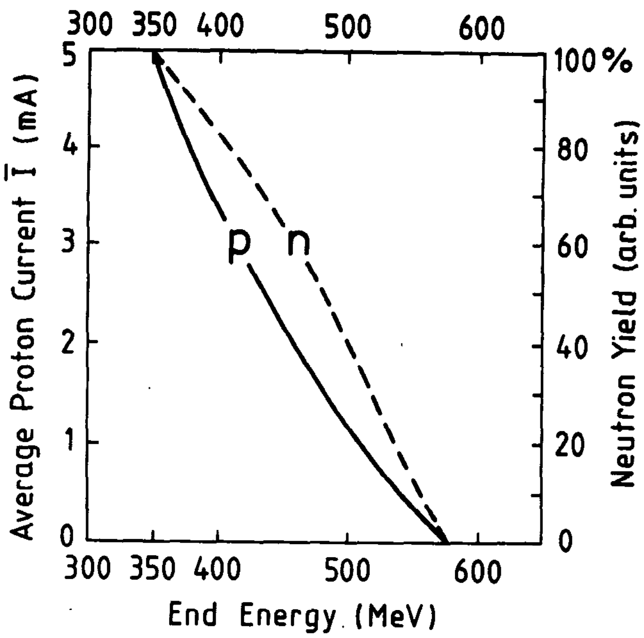

Fig. 5 Average proton current of the SNQ linac in stage I and the neutron yield in the target versus the end energy for constant rf power.

Beam losses

A limit of the beam losses in the order of 10^{-6} or less is required along the high energy part of the SNQ linac because otherwise it will not be possible to enter the accelerator tunnel 24 h after a shut-down of the accelerator. It is certainly a delicate task to predict beam losses at this low level and it is a big effort to estimate them with multi particle calculations. Nevertheless there are qualitative arguments which favorize the single cell concept in this respect:

1. The transverse focussing of the beam can be performed with many narrow spaced magnetic lenses, ultimately with a lens between consecutive cells. This way of transverse focussing assures a minimum of beam breathing implying less beam losses than the alternative solution of widely spaced lenses in the case of coupled structures.

2. An attempt can be made to reduce longitudinal beam losses in the single cell concept by changing to a more negative stable phase angle with the consequence of a decreased end energy. This flexibility of the single cell concept, which will widely be used when operation begins and during the test phase, does not exist with coupled structures except when stable angle and rf power are changed simultaneously.

3. In coupled structures the rf power is transported along the accelerating cells with the group velocity V which is of the order of 10 % (D+W: 50 %) of light velocity and thus smaller than the beam velocity. This situation leads to a ringing of the rf amplitude at the head of the current pulse, responsible for beam losses. For single cells the rf power is not transported along the cells and the term group velocity is meaningless in this concept. Consequently this source of beam losses does not exist. Similarly, the problem of rf amplitude gradient along the coupled structure is absent in the single cell concept.

4. Since each single cell has its own tuner a shift of the resonance frequency due to temperature or stress changes can be compensated by retuning. However for a coupled structure local temperature and stress changes lead to field distortions which cannot be compensated by the one tuner per tank. As a consequence additional phase slip occurs which may also lead to beam losses.

Mass production

The large number (300 and 600 for stage I and II, respectively) of identical components as cavity, control system, rf power generator and focussing device lowers the price per item because of mass production. On the other hand considerable effort can be spent to cost-optimize all items which are purchased in such large quantities. This leads to another reduction of cost. In addition, smaller items will atract more firms for tender.

Flexible stage concept

There are different ways to realize stage I of the SNQ linac and to reach the ultimate design values depending on the cash flow.

One has to assume that already in stage I the tunnel will have its final length of about 400 m for the high energy part of the linac as is required for stage II. One way of realisation of stage I and II is to keep the E_0T voltage gradients at the maximum value of 3 MV/m and to install in stage I the minimum number of single cells with the full rf power installation per cell. In this case only 1/4 of the tunnel would be used. A better way is according to Fig. 6 to fill about half the

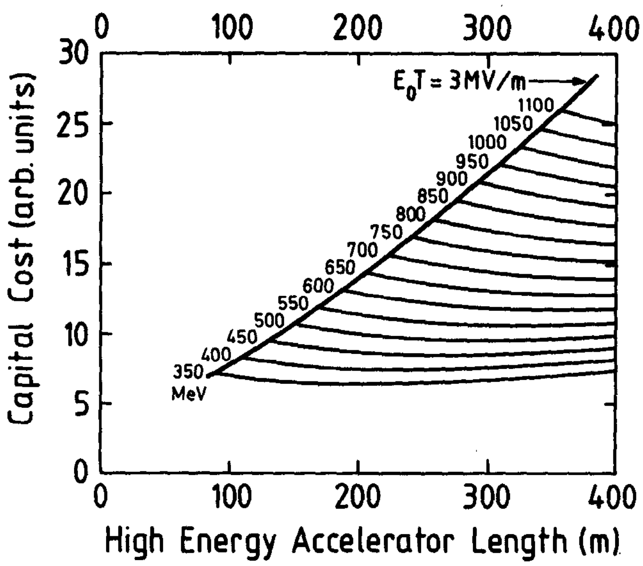

Fig. 6 Capital cost versus accelerator length of the high energy part of the SNQ linac in the range of $E_0T \leq 3$ MV/m. The results are based on a shunt impedance of 30 MΩ/m, a rf filling factor of 82 %, a stable phase angle of -20°, a current of 200 mA and an injection energy of 100 MeV and last not least on the costs per meter of rf structure, beam optics and tunnel, and on the cost per Watt of rf power.

tunnel with single cells. In this case the voltage gradient is only 1.5 MV/m and hence less rf power has to be provided. According to the cost estimates of rf structure, beam optics, tunnel and rf power, Fig. 6 indicates that the stage I linac with the smaller voltage gradient, which means more reliability, is less expensive. Due to the merits of the single cell concept one then can change over to an intermediate stage I' by simply upgrading the rf power and increasing the E_0T value to its maximum of 3 MV/m. In this case the end energy is 600 MeV at the same current $\bar{I}_p$ = 200 mA which means for instance a neutron intensity gain of about 2. The major advantage however is that one can gain experience about the operation of stage II before its installation (characterized by E_0T = 3 MV/m and energies up to 600 MeV) already in stage I'.

For the final upgrading to the end energy of 1.1 GeV all components used so far remain still in use.

In summary the single cell concept has the advantage that the rf power losses of the structure are smallest, that the mode of operation can be varied, that beam losses should be smaller in comparison to coupled structures and that the investment cost can be considerably reduced by mass production.

Failure compensation

Because of the large number of components a failure will frequently occur in the high energy part of the linac. The by far weakest component is certainly the amplifier chain. Assuming Poisson statistics and a life time of 8000 h of operation for the rf generator, one has to expect on average one failure per day with the 300 units of stage I. This large failure rate cannot be treated in the conventional way by switching off the linac, diagnosing the error, replacing the faulty component and then turning back to normal. This would cause too long shut-down periods. The situation is even more severe with the 600 components in stage II.

Fortunately, the single cell concept allows to continue operation if the rf power generator of one or even more single cells failed. A consequence of a single cell which does not accelerate any more is a change of the phase advance in the following cells. The phase mismatch is 1.30 and 0.20 for all following cells if the failure occurs at a cell operating at 100 MeV and 350 MeV, respectively, provided the single cell is detuned in order not to be charged up with rf power by the beam. Otherwise the phase change increases to values of 4.6° and 0.7° while the batch is passing. The presence of a non-accelerating single cell is signaled to the control system and the phase of the rf power in the following cells is changed to compensate for the resulting beam delay. As a result the beam is accelerated to an end energy which is by about 1 MeV smaller than the normal value. If necessary the correct end energy can be obtained by slightly decreasing the absolute value of the stable phase angle. This correction is performed by the end energy control circuit. It should be emphasized that the described means to compensate for a faulty rf generator of a single cell are performed within msec, i.e. between two pulses and that the operation of the accelerator continues without any interruption. Then, during operation the error can be further diagnosed and the faulty component may be replaced. Thereafter the operation turns back to normal.

The single cavity control system which is one part of the three level linac control system is shown in Fig. 7. The inner three control loops to the left of the cavity are conventional. By mechanical tuning the resonance

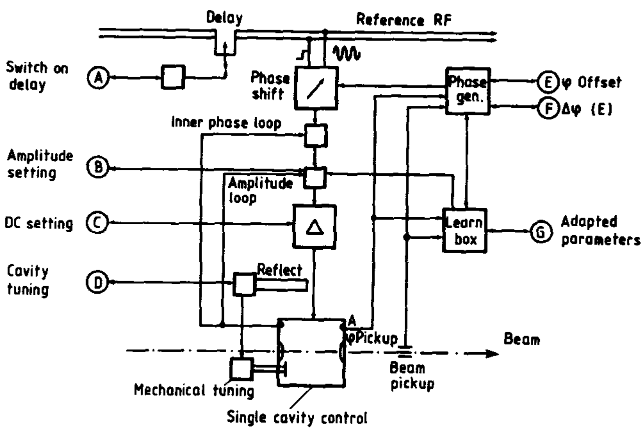

Fig. 7 Block diagramme of the single cavity control[9].

frequency is kept constant. In the other two loops the rf amplitude and phase are held at the same value. Because of the options to operate the high energy part of the SNQ accelerator at different stable phase angles, with small and large rf amplitudes and for different pulse currents the control loop needs input settings (E) for the phase generator, (D) for the amplitude loop, (C) for the amplifier chain, and (B) for the tuner. The phases are set with respect to a 200 MHz reference rf signal which is delayed for each single cell according to the arrival of the bunches in the center of the accelerator gap of a single cell. In a similar way the "switch on" signal is delayed in order to assure the precise charge-up with rf power when the first bunch of a batch enters the single cell.

The more advanced control loops are on the right hand side of Fig. 7. Pick-up signals for the rf phase and beam are fed into the phase generator for determining the actual phase advance φ_s which is compared with the setting value (E) in order to activate properly the phase shifter device. The offset value is corrected by the feed back value $\Delta\varphi(E)$ which originates from the end energy measuring device at the end of the accelerator.

An still more sophisticated part in the cavity control system is the learn box which observes the error signals during many batches in order to learn how to improve the control. For this purpose the learn box is provided with the actual phase advance value and setting value and with the phase generator response. Based on an analysis of this information collected from many batches the learn box may change directly the setting value for rf phase and amplitude or create with the support of a computer from a higher level a complete new set of parameter values (G) which are better adapted to the actual situation than the original settings.

An example should illustrate the way how the learn box works. For this purpose it is assumed that the current has suddenly changed to a lower value. Consequently, from then on at the beginning of each batch the rf amplitude becomes too large because of the reduced beam loading. Then the amplitude will be lowered by the inner amplitude loop and simultaneously the phase control becomes active. After some damped oscillations the control system will be quiet again. This procedure at the beginning of each batch would take place for ever if the learn box would not interfere. After having observed and analysed the actions of the control system for many batches the only reaction of the learn box should be to decrease the rf amplitude setting adapted to the changed beam loading.

RF power generation

In the single cell concept it would be possible to feed the cells with rf power from the largest rf generators of 4 MW power by distributing the rf power to a set of eight cells via power splitters and phase shifters. The advantages of the single cell concept quoted above exist however only if small rf generators, one for each cell, are used. Otherwise the discussed options of operation cannot be fully utilized. This restriction of small generators is in contrast to coupled structures where small and/or large generators can be used. A rather comprehensive study on the rf power generation at 200 MHz has been performed[10]. A few results of this study are compiled in table 3. With the listed life times of the driver chains the costs of the rf installation and of the replacements per watt are not very different between the three cases of small tetrodes, large triodes and klystrons. Table 3 indicates also that the solution with tetrodes which could be used as rf generators for the single cells is at medium cost compared to the other two. This relation holds for stage I and II. The major difference between the tetrode and klystron cases lies in the device failure rate as listed in table 3.

200 MHz RF Systems			
RF Amplifier	Small Tetrode 250 kŴ	Large Triode 1.5 MŴ	Large Klystron 3.0 MŴ
Single cell	Yes	No	No
Coupled cells	Yes	Yes	Yes
Number of power modules	I: 300 II: 1200	60 240	30 120
Device life time	8000 h	8000 h	40,000 h
Cost of installation [DM/W]	I: 0.6 II: 0.4	0.5 0.3	0.8 0.6
Replacement cost [DM/W]	0.05	0.025	0.08
Device failure rate	I: 1/d II: 4/d	1/5d 1/d	1/2m 2/m

Table 3 200 MHz RF systems with the pulsed power KW and MW, I, II refers to the stages.

Beam loading

With respect to the cavity accelerating voltage there are an rf cavity current I_{cav} and a beam current I_{beam} flowing into and out of the cavity. Their ratio I_{beam} / I_{cav} is the beam loading which is 75 % and 62.5 % in stage I and II, respectively. The fairly large beam-loading has consequences which will be discussed in the following:

1. In stage I about 1/4 of the cavity current is needed to maintain the voltage gradient E_oT while 3/4 are required for acceleration. Thus, for charging-up the cavity with rf power before each batch the total current, which is four times larger than the current needed to maintain the E_oT value, can be used. Therefore, the charge-up time is considerably shortened. By charging at resonance frequency the voltage change is given by (1)

$$\frac{dv}{dt} = I_{cav} \cdot (R/Q) \cdot \frac{\omega}{2} \exp\left(-\frac{\omega \cdot t}{2Q}\right) \qquad (1)$$

One calculates with a typical R/Q value of 330 Ω/m (Ohmic, not including transit time factor) for single cells that the voltage of 1/4 $I_{cav} \cdot R$ is reached after 20 µsec. If the design voltage would be reached assymptotically by charging with the needed current $I_{cav} - I_{beam}$ the charge-up time would be much larger since the characteristic time constant is already 100 µsec (= $2Q/\omega$). The rapid charge-up with full power within 20 µsec requires a precise timing for the onset of rf filling into the cavities with respect to the arrival of the first bunch of a batch.

2. In the case of a break down of a generator unit the beam will recharge the cavity. Assymptotically, a voltage gradient is

reached which is about four times as large as the value of normal operation in stage I. The voltage gradient becomes twice as large in stage II. Its polarity is such that the beam is decelerated. The characteristic time constant is again 100 μsec. The heavy loading of a cavity by the beam must be suppressed in order to avoid sparking in the cavity and energy modulation of the beam during the batch. Possible remedies are a fast short-circuiting of the cell or a strong mechanical detuning which unfortunately is slow. Both methods are expensive. It seems also possible to damp the cavity via the amplifier line even if the amplifier is out of service.

3. During a gap, i.e. a missing string of bunches as is deliberately produced by the fast choppers in the funneling section, the cavity voltage rises. The relative increase per missing bunch is $\Delta V/V = 2.10^{-4}$ with the parameters of stage I. For a typical switch gap in the batch of 20 missing bunches corresponding to 100 nsec the relative voltage rise is 0.4 % followed by a ringing of about the same magnitude. The voltage rise during the gap can be reduced by decreasing appropiately the cavity current I_{cav}. Such a measure requires however an amplifier with a band width of infinity. With a large band width of e.g. 20 MHz which might be achieved with small power generators the voltage rise is reduced to the tolerable value of 0.1 %.

4. The stable phase angle $\varphi_s \neq 0$ causes a reactive component of the beam current which is passed on to the generator. The reactive component can be compensated for the duration of a batch by working with an appropiately detuned cavity. For linacs the resonance frequency ω_{cav} must be larger than the generator frequency ω_g. During the charge-up with $\omega_g < \omega_{cav}$ the phase angle between the cavity current I_{cav} and the accelerating voltage $E_oT \cdot L$ increases from 0° to a value of about 20° as can be calculated from the data of stage I. A phase jump by just this value is then required to turn the cavity current I_{cav} in phase with the accelerating voltage, when the first bunch of a batch arrives and the design E_oT value has been reached. Because of the finite bandwidth of the driver chain the phase jump will result in some ringing effects of small amplitude even if the bandwidth is of the order of 20 MHz.

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