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A High Intensity Proton Linear Accelerator for the German Spallation Neutron Source (SNQ)

The Linear Accelerator Working Group, Kernforschungszentrum Karlsruhe. Presented by

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Summary

A proton linac of 1100 MeV energy and 100 mA peak beam current and 5 to 10% duty cycle is proposed for the German Spallation Neutron Source (SNQ)[1]. Low beam loss, excellent stability of the accelerating fields and high rf-power conversion efficiency are the major design aspects. Basic parameters and layout are given.

Introduction

An accelerator-based neutron source is the subject of a study at the nuclear centres of Karlsruhe and Jülich with participation of industry and other accelerator centres such as SIN and CERN. The SNQ-project aims at time average fluxes of thermal neutrons equivalent to high flux reactors and at peak fluxes exceeding the capability of research reactors by at least one order of magnitude. As a dedicated source for neutron scattering research, the main parameters were optimized to the needs of these experiments. With the energy and intensity specified, the SNQ provides abundant fluxes of protons, high energy neutrons, mesons and neutrinos.

The basic machine consists of the 1100 MeV proton linac, experimental areas for nuclear physics and medicine and the spallation-target. This target consists of a rotating wheel containing water cooled lead as the reaction material. In a second step of construction, a compressor ring[2] shall be added to the linac to deliver proton pulses of <1 μs duration, 2.6×10^{14} ppp intensity and 100 Hz repetition rate. Pulses with this time structure are of particular interest for hot (>100 meV) neutron and for neutrino experiments.

Requirements

The desired thermal neutron flux of $7\times10^{14}cm^{-2}s^{-1}$, as produced by the proposed target-moderator system, required a time averaged beam power of 5.5 MW. A proton energy of 1100 MeV was chosen as a compromise between different arguments such as target heat density, neutron yield, linac cost, and the option to inject the full beam into a compressor ring. At this energy, a time averaged beam current of 5 mA yields the required neutron flux. An increase to 10 mA is considered as an option. While only some of the experiments will use the source in a stationary mode, most of the experiments will be optimized for peak fluxes. Neutron scattering instruments require a pulse length of <500 μs comparable to the time constant of thermal neutron moderators, and repetition rates around 100 Hz. From these requirements a peak current of 100 mA was indicated for the linac.

Table I: Main SNQ-linac parameters and options

	SNQ-design	Options
Particles	p	H^-
Final energy/MeV	350, 1100	
Av.beam current/mA	5	10
Beam pulse length/μs	500	1000
Repetition frequency/Hz	100	
Peak beam current/mA	100	

Linac Layout

A schematic layout for the accelerator is given in Fig.1. The linac consists of a magnetic multipole ion source, dc preacceleration to 450 keV, low energy beam transport including an ultrafast beam chopper, a 3-cavity-buncher system, and a two stage rf-accelerator. The Alvarez part accelerates the beam to 105 MeV followed by a matching section and a disk-and-washer (DAW-) accelerator. Fractions of the beam can be extracted at energies of 350 MeV and 1100 MeV, respectively, as demanded by the scientific programme. The peak rf-power of 21 MW, required to feed the Alvarez accelerator, is provided by 14 tetrode power amplifiers at a frequency of 108 MHz. The DAW-accelerator consists of 89 modules fed from 3.5 MW-klystrons at 324 MHz. Quadrupole doublets and beam diagnostics are placed between the DAW-tanks.

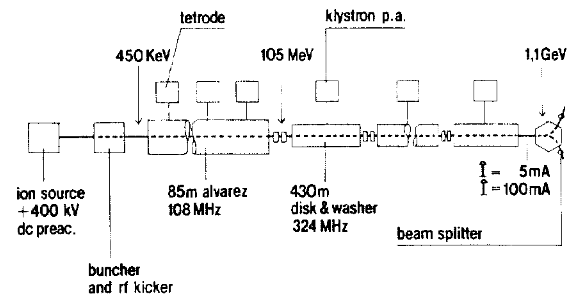

Fig.1: SNQ-linac, schematical arrangement

Design Philosophy

The linac design had to take into account the following additional requirements:

- Conceptual design and construction was expected to follow the project study immediately. Only modest development could therefore be allowed for the linac components and systems.
- The facility shall operate 6000 h per year. High component reliability and easy maintenance are therefore needed.
- High efficiency production of rf-power and optimum transfer to the beam. Development of high efficiency klystrons was initiated,[5] accelerating structures of high shunt-impedance (Alvarez, DAW) were chosen and the filling time of the cavities were optimized by the proposed rf-control systems.
- Beam loss and subsequent machine activation should be kept to a minimum.

The latter argument was considered the most important one and largely influenced the linac parameters. As examples, apertures were chosen large to accomodate beam halos developing between scrapers. Beam diagnostics and steering elements were provided in large numbers in the intertank drift spaces. High stability of the accelerating fields during the beam pulse were specified (see below).

It is therefore expected, that the accelerator can be kept clean except in a few defined regions and that hands-on-maintenance can be applied. All provisions have, however, been made to allow for higher beam spill. Choice of material, component design and layout of buildings started from loss assumptions 2 to 3 orders of magnitude higher than needed for unlimited access (e.g. 5×10^{-4} of the total beam current was assumed as a point source of loss at any location in the DAW-accelerator >600 MeV). SNQ-studies have shown, that the additional means to cope with higher dose levels will increase the construction cost of the facility by only a few percent.

Beam Dynamics

Beam dynamics in the Alvarez accelerator were studied analytically[3] to decide on the main injection and accelerator parameters. Detailed studies of beam behaviour in the Alvarez part were performed with multi-particle codes of CERN origin. The essential results are as follows:

- The injection energy should be as high as possible. However, limitations are given by the reliability of preaccelerators, 450 keV was therefore chosen.
- A low frequency (108 MHz) was favoured because of large transverse and longitudinal acceptances and more effective phase damping required for the jump in frequency by a factor of 3 at 105 MeV.
- Stable motion and tolerable emittance growth were found for normalized transverse emittances $\gtrsim 3\pi$ mm mrad at injection.
- About 10% of the particles bunched were found to be lost in the accelerator, but none of the 2000 macro-particles, simulating a beam current of 100 mA, were lost beyond the first tank (i.e. >15 MeV). (Fig.3).

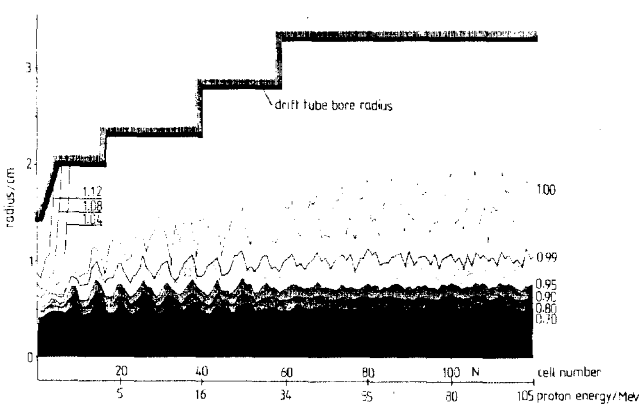

Fig. 2 Beam envelopes along the Alvarez accelerator. The beam contours contain the indicated fractions of the transmitted beam. About 12% of the injected beam is lost in the first gaps.

Matching sections between accelerator parts and beam dynamics in the DAW-accelerator were calculated in linear theory, which was felt adequate for defusing the focusing parameters and estimating the beam properties. Parameters chosen and beam quality are given in Table II.

Table II: Beam dynamics parameters and beam quality

	Alvarez-accelerator 108 MHz		DAW-accelerator 324 MHz	
Proton energy/MeV	0.45	105	105	1100
Acc.field strength/MVm^{-1}	2	2	3.4	4.2
Synchronous phase/°	-35	-35	-30	-25
Transverse tune/°	40	40	45	30
Long.tune, 100 mA/°	.28	2.5		
Phase width/° [1)]	150	18	44	20
Energy spread/MeV [1)]	0.12	1.4	1.7	3.7
Normalized transv. emittance/π mm mrad [2)]	3	6	6	15

1) FW, 100% of beam,

2) 100% of beam

Accelerator Components

In the magnetic multipole ion source under test at KfK, current densities of up to 500 mA/cm^2 were obtained and found homogeneous over several cm^2 of extraction area. Extracted currents showed noise levels of $<10^{-2}$ within 1 MHz bandwidth. On the 100 kV test stand, 70 mA of ion current were accelerated to 90 keV and transported over 1.5 m distance. A normalized transverse emittance of <1 π mm mrad was estimated from aperture sizes passed by the beam. Ion currents of 250 mA are expected from changes of the extraction electrode system.

The low energy beam transport (LEBT) was designed after the new CERN linac.[4] An ultrafast (<10 ns rise time) chopper is inserted in front of the 3 gap buncher system to allow for variable time structures of the particle beam as needed by the experiments. Principle and function correspond to the LAMPF-system.

In our concept for the Alvarez accelerator tanks. it was tried to combine the virtues of the GSI and the new CERN linac designs. Drifttubes are suspended from 4 m long girders (Fig.3) to facilitate access for repair and alignment. Mode stabilization is achieved by post couplers, adjustable to influence the field profile for optimum matching to the beam, which is of particular use in the first section of the Alvarez accelerator.

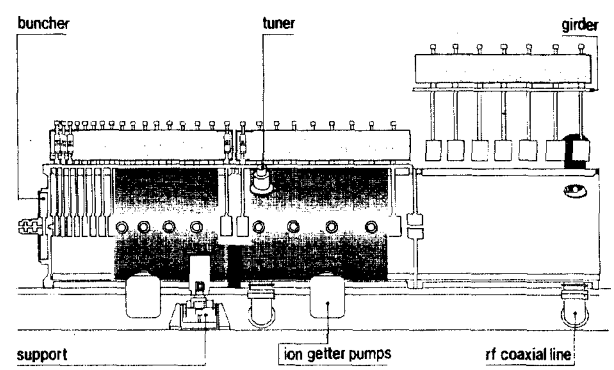

Fig.3: First Alvarez tank. Drift tubes are mounted on a girder to facilitate adjustment and repair.

The length of the DAW tanks is given by focusing demands. Separation of acceleration and focusing functions was preferred in spite of some trade-off in shuntimpedance because of better handling conditions. DAW-parameters were calculated with the SUPERFISH code, stem corrections were made by perturbation calculations. The outer radius was chosen constant along the accelerator with a value compromising shuntimpedance and unambiguous mode distribution in the dispersion diagram. Fig.4 shows a schematic of a DAW double tank consisting of electrically decoupled resonators, which are used at larger focusing distances above 350 MeV. The high energy beam transport (HEBT-) region consists of 3 channels, which guide the beam to the dump, to the nuclear physics area and to the main neutron target, respectively. A combination of a kicker and a Lambertson-type septum is used for fast beam switching. Gradients of bending magnets were chosen to allow for optional H$^-$ transport. Addition of a future compressor ring is considered in the HEBT design and will need only minor modifications.

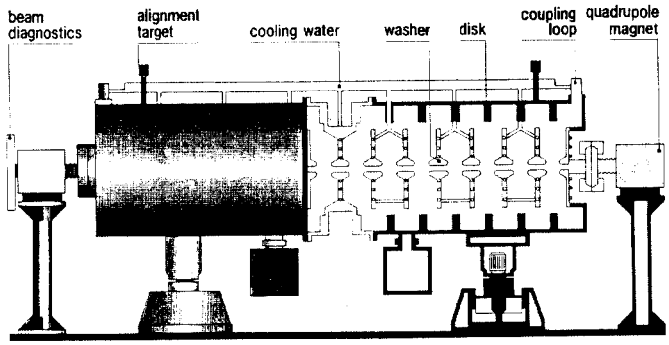

Fig.4: DAW-tank, consisting of two resonators individually fed with rf. DAW-tanks are between 3.3 and 8.5 m long and are designed for remote handling.

Rf-Amplifier and Control Systems

The rf amplifiers provide a total power of 300 MW peak, ~17 MW average. High efficiency, high power, grid modulated klystrons[5] were chosen to feed the DAW sections, which require more than 90% of the total rf power.

Design of the SNQ-control system for the accelerating field started from two main requirements:

- to optimize the cavity filling time, and
- to maintain a high stability of the field amplitude (±1‰) and phase (±0.2°) during the beam pulse.

The filling time of the cavity can be optimized by appropriate amplitude and phase steps of the generator. Transients of amplitude and phase of the unloaded cavity can thus be suppressed[6].

Field stability with beam loading can be significantly improved by a feed-forward-control system, supporting the operation of the amplitude and phase control loops. As shown in Fig.5, the amplitude error can be reduced by an order of magnitude during the transition of the beam pulse. Computer simulations of the control response have been performed, experiments are underway.

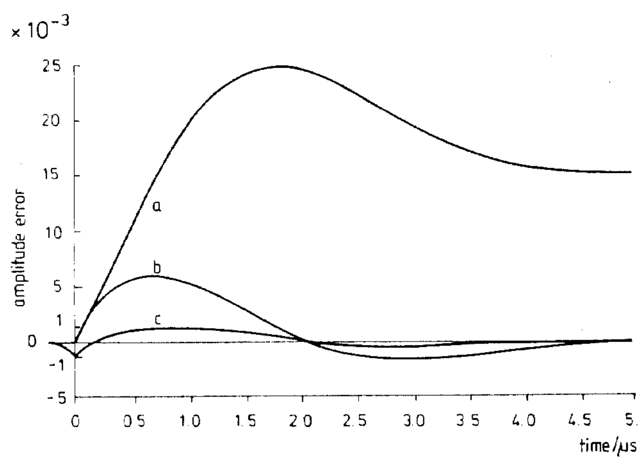

Fig.5: Amplitude error from beam loading is greatly reduced by the feed-forward-control system (FFC) as seen from (a) to (c): without FFC (a), FFC acting synchronous with the beam pulse (b), FFC action preceding the beam pulse at an optimized time (c).

Acknowledgements

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