STUDY OF A 10-MW CONTINUOUS SPALLATION NEUTRON SOURCE*

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Abstract

This paper reports on the feasibility study of a proton Super-Conducting Linac as the driver for an Accelerator-based Continuous Neutron Source (ACNS) [1] to be located at Brookhaven National Laboratory (BNL). The Linac is to be operated in the Continuous Wave (CW) mode to produce an average 10 MW of beam power. The Linac beam energy is taken to be 1.25 GeV. The required average proton beam intensity in exit is then 8 mA.

INTRODUCTION

It is commonly agreed that a Super-Conducting Linac (SCL) is the most effective choice for a continuous high-power proton beam in the GeV range. Other devices, like Cyclotrons or Fixed-Field Alternating-Gradient accelerators, should also be considered, but they are less efficient and are more prone to uncontrolled beam losses.

A SCL is also most suitable for a <u>continuous mode of operation</u> (CW), where <u>average</u> and <u>peak</u> performance are equal, as opposed to a <u>pulsed mode</u> where the peak performance determines the design and requirements. The design of SCL is simplified with the CW mode of operation, since it avoids large excursion between average and peak values, and related fatigue effects. In the CW mode the concern with cavity *Filling Time* and *Lorentz Force*s are removed.

Though the feasibility of SCL is within present mechanical, cryogenic, and RF technology, it has nonetheless not been proven entirely yet. One SCL is presently being build for the Spallation Neutron Source (SNS) [2] project; and another has been proposed and conceptually designed for the AGS Upgrade at Brookhaven [3]. The Accelerator-based Continuous Neutron Source (ACNS) can also make use of a similar SCL. Despite the larger average beam power required, it compares favorably with the other two projects, as it can be seen from the comparison in Table 1.

The proposed SCL driver for the ACNS accelerates protons to 1.25 GeV, operates in the CW mode, and generates an average beam power of 10 MWatt. The average beam current is 8 mA, and the total length of the superconducting section about 160 m. The Linac is made of three parts: a Front-End, that is a 10 mA ion source followed by a 2-MeV RFQ, a room temperature 200-MeV Drift-Tube Linac (DTL), and the Super-Conducting Linac (SCL) proper. This in turn is made of three sections: the low-energy (LE) section that accelerates protons to 400 MeV, the medium-energy (ME) section for further acceleration to 800 MeV, and the high-energy (HE) section that accelerates to the final energy of 1.25 GeV.

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The selected operating frequency of the room temperature components, RFQ and DTL, is 350 MHz; the LE section of the SCL captures and accelerates the beam at 700 MHz, whereas the last two sections can either operate also at 700 MHz or at 1,400 MHz. In the first case we rely on available industrial RF power sources, in the latter case the RF power sources, at twice the frequency, need to be demonstrated and developed, but could allow a shorter length of the accelerator and be more economical. In any case, the study has shown that the accelerator is feasible, can be built in a relatively short period of few years, and has an estimated total cost for the superconducting sections of about 100 M$.

REQUIREMENTS OF THE PROTON DRIVER

The accelerator driver of the ACSN facility is schematically shown in Figure 1. The proton beam aims directly to the core, and can be placed either underneath or above the target, with Figure 1 showing the former case. The actual location of the accelerator with respect to the target and the interface with final transport, bend and the target itself remain to be investigated.

Acceleration of positive-ions (protons) is assumed, since there is no requirement for the injection in a subsequent circular storage device as in the SNS project. For the same reason, the beam in exit of the RFQ does not need to be pre-chopped.

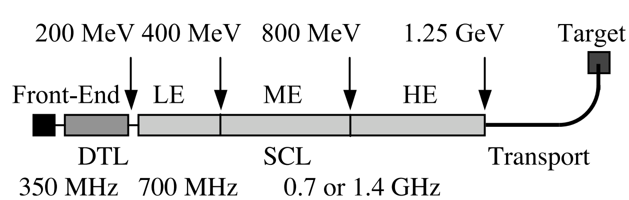

Figure 1. Layout of the 1.25-GeV, 10-MW SCL

The Front-End is made of an Ion Source placed on a platform at 35-50 kVolt. It has a continuous beam output of 10 mA. It is followed by a 350-MHZ RFQ which focus, bunch and accelerate the beam to about 2 MeV. At the exit, the beam bunches are compressed sufficiently to be squeezed within the rf buckets of the Drift-Tube Linac (DTL) which operates also at 350 MHz. Because of the relatively low beam current, and the absence of stringent requirements on the beam emittance and momentum spread, space-charge effects are not expected to play a relevant role. As a consequence, no major beam losses are expected in the RFQ. A transmission of 80% is conservatively assumed, and the beam intensity at the exit of the RFQ is 8 mA. We assume that there are no further losses during the transfer of the beam through the rest of the accelerator, all the way down to the Target. At the exit of the SCL, and on the Target, the beam intensity is then 8 mA.

Table 1. Comparison of three SCL Projects

	SNS	AGS	ACNS
Kinetic Energy, GeV	1.0	1.2	1.25
Ave. Power, MW	1.0	0.045	10
Duty Factor, %	6.0	0.18	**100**
Repetition Rate, Hz	60	2.5	--
Pulse Length, ms	1.0	0.72	--
Peak Power, MW	16.7	25	10
Ion Source Current, mA	35	35	**10**
Ave. Beam Current, mA	1.0	0.035	**8**
Peak Beam Current, mA	26	21	**8**
Protons / Bunch, x 10^8	4.3	8.7	**1.43**
RF, GHz	0.805	0.805-1,61	0.7 - 1,4
Coupler RF Power, MW	170-350	260 - 400	**80 - 155**
Length, m	158	120	163
Inj. Energy, MeV	185.6	200	200
Cryo. Power (2.1°K), kW	0.5	0.15	**5.3**
Ave. AC Power, MW	3.1	0.28	**23**
Ave. Gradient, MV/m	3.1 - 6.5	5.3-10.0	3.3 - 8.7
Efficiency, %	26 -30	9 - 16	**35 - 40**
Capital Cost, M$	110	97	**85**
Operation Cost, M$ / yr	2.0	0.18	**15.2**

Blue – Positive Features
Red – Negative Features

LINAC DESIGN

In a proton linac there is a large variation of beam velocity, in our case from β = 0.08 at 2 MeV to β = 0.90 at 1.25 GeV. The first accelerating section cannot be made of half-wavelength super-conducting RF cavities, though quarter-wavelength super-conducting linear accelerators do exist and are successfully operational. We prefer to assume here a room-temperature conventional Drift-Tube Linac (DTL) operating in a continuous mode. We shall also assume an energy of 200 MeV for this section to ease the design and manufacturing of the RF cavities in the early part of the SCL proper. Also, the RFQ, if desired, can be made super-conducting to ease the concern with the thermal load. Other solutions are of course possible, and they should be examined with a more careful and detailed design.

Thus, the SCL proper starts at 200 MeV and ends at 1.25 GeV. The corresponding variation of velocity is from β = 0.5662 to β = 0.9034. Since the length of the rf cavity cells is $L = \beta\lambda/2$, it should in principle vary between 12.2 and 19.4 cm, with λ = 42.83 cm, the RF wavelength at 700 MHz, the chosen operating RF frequency of the SCL. To optimize the accelerating gradient it would be desirable to manufacture cavities with cells varying in length as the beam accelerates. This may not be economical, and we prefer to manufacture RF cavities all with the same cell length. This simplifies the design, and reduces the cost, at the expense of a modest reduction of the transit time factor. Here we assume that the SCL is divided in three sections each operating at three intermediate values of velocity. The super-conducting LE section, from 200 to 400 MeV, has the cavity cell length adjusted to the intermediate value β = 0.616, the ME section, from 400 to 800 MeV, to β = 0.755, and the HE section, from 800 MeV to 1.25 GeV, is designed with the intermediate value β = 0.852.

The layout of the Super-Conducting Linac is described in [4]. For more details see also the contribution to this Conference [3], where a SCL in pulsed mode is described. It is made of a sequence of identical periods each consisting of a Warm-Insertion for the location of focussing quadrupoles, steering magnets, vacuum pumps, and instrumentation, and of a Cryo-Module including a number of cavities all with the same number of individual cells. Each cavity is powered by a single RF coupler connected directly to one Klystron, the RF power source.

The parameters of the SCL are given in Tables 2 to 4. Table 3 shows the RF for the ME and HE sections to be 1.4 GHz, this gives a compact super-conducting structure with a total length of 160 m that may cost about 100 M$ to be build. When the RF of 700 MHz is chosen also for the last two sections, we found that the length and the expected cost have increased by about 20%.

Table 2. SCL Parameters for 10-MW ACNS

Increm. Linac Ave. Power	8.4 MW
Type of Particles	Protons (H^+)
Kinetic Energy in entrance	200 MeV
Kinetic Energy in exit	1.25 GeV
β	0.9034
Momentum, GeV/c	1.9769
Magnetic Rigidity, T-m	6.594
Repetition Rate	CW
Linac Duty Cycle, %	100
Ion Source Current	10 mA
RFQ Transmission, %	80
Chopping Ratio, %	100
Linac Average Current, mA	8.0

CONCLUSION

When compared to a pulsed mode of operation, a CW SCL requires considerably much more cryogenic power and, despite a higher efficiency, more electrical AC power. In our case the AC power requirement needed just for the operation of the SCL exceeds 20 MW that cannot be easily acquired on the BNL site. An energy recovery is thus desirable, as it can be obtained for example from the spallation target itself when this is operated in a hybrid configuration [5]. But on the other end, the performance of the accelerator in CW mode is expected to be more stable than that in pulsed mode when the peak performance values are even larger and pose a significant operational concern. Moreover, a non small feature is the lower intensity per bunch, as seen in Table 1, that removes some of the concern with beam halo formation and consequent latent, uncontrolled beam loss.

It should be reminded that the first proposal for a high-power proton SCL in the GeV energy range was the Accelerator-based Production of Tritium (APT) [6]. This also was to be operated in the CW mode, and the beam power required had an ambitious figure of hundreds of MW. Yet the design of the project was found to be entirely feasible, and removed several concerns for the application of superconductivity to a proton linear accelerator. We have all learned considerably from this earlier project of which the same design criteria still apply.

Table 3. General Parameters of the SCL

Linac Section	LE	ME	HE
Ave. increm. Power, MW	1.60	3.20	3.60
Average Beam Current, mA	8.0	8.0	8.0
Initial Kinetic Energy, MeV	200	400	800
Final Kinetic Energy, MeV	400	800	1250
Frequency, MHz	700	1400	1400
Protons / Bunch $\times 10^8$	1.43	1.43	1.43
Temperature, ^{o}K	2.1	2.1	2.1
Cells / Cavity	8	8	8
Cavities / Cryo-Module	4	4	4
Cavity Separation, cm	60.0	30.0	30.0
Cold-Warm Transition, cm	70	30	30
Cavity Internal Diameter, cm	12	6	6
Length of Warm Insertion, m	1.30	1.30	1.30
Acceler. Gradient, MeV/m	8.21	22.3	22.7
Average Gradient, MeV/m	**3.28**	**8.08**	**8.63**
Cavities / Klystron	1	1	1
RF Couplers / Cavity	1	1	1
Rf Phase Angle	30^o	30^o	30^o
Transverse Focussing	FODO	FODO	FODO
Phase Advance / FODO cell	90^o	90^o	90^o
Norm. rms Emitt., π mm-mrad	**0.3**	**0.3**	**0.3**
Rms Bunch Area, π ^{o}MeV	0.5	0.5	0.5

REFERENCES

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Table 4. Summary of the SCL Design

Linac Section	LE	ME	HE
Velocity, β: In	0.5662	0.7131	0.8418
Out	0.7131	0.8418	0.9034
Cell Reference β_0	**0.616**	**0.755**	**0.852**
Cell Length, cm	13.19	8.08	9.12
Total No. of Periods	7	8	8
Length of a period, m	8.721	6.187	6.519
FODO-Cell ampl. func., β_Q, m	29.78	21.12	22.26
Total Length, m	*61.05*	*49.49*	*52.15*
Coupler rf Power, kW (*)	81	135	155
Energy Gain/Period, MeV	30.00	50.00	57.50
Total No. of Klystrons	28	32	32
Klystron Power, kW (*)	81	135	155
$Z_0T_0^2$, ohm/m	379.5	570.0	725.9
Q_0 $\times 10^{10}$	1.07	0.68	0.77
Transit Time Factor, T_0	0.785	0.785	0.785
Ave. Axial Field, E_a, MV/m	10.4	28.4	29.0
Filling Time, ms	0.778	0.802	0.714
Ave. Dissipated Power, kW	0.385	2.369	2.149
Ave. HOM-Power, W	17.2	39.3	39.3
Ave. Cryogenic Power, kW	0.506	2.486	2.272
Ave. Beam Power, MW	1.60	3.20	3.60
Total Ave. rf Power, MW (*)	2.16	4.32	4.86
Ave. AC Power for rf, MW (*)	3.69	7.39	8.31
Ave. AC Power for Cryo., MW	0.359	1.763	1.612
Total Ave. AC Power, MW (*)	4.052	9.152	9.923
Efficiency, % (*)	39.49	34.96	36.28

(*) Including 35% rf power contingency.