# A SUPERCONDUCTING LINAC FOR THE ENERGY AMPLIFIER

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*Abstract**

Because of the safer and more reliable mode of operation, a Superconducting Linac has been proposed as the proton beam accelerator which drives a nuclear plant based on the concept of the Energy Amplifier. An example based on the net generation of 400 MW (electric) is described. This requires a proton beam energy of 1 GeV with a continuous beam current of 10 mA, corresponding to a beam power of 10 MW. Two frequencies cases, 360 and 805 MHz, have been considered for the Linac design. Performance and cost comparison for the two cases are given.

## 1 THE CONCEPT OF THE ENERGY AMPLIFIER

It was proposed by Bowman [1] and Rubbia [2] that it is possible to sustain a nuclear fission chain reaction under subcritical conditions by providing the required balance of neutrons with a steady flow of neutrons from the spallation of an intense beam of protons on a solid target. This is a granular mixture of inertial material, like Tungsten or Lead, and fissionable material, for instance $Th^{232}$. This method has the advantage of a safer operation since the chain reaction, if needed, can be easily controlled by acting on the proton accelerator.

An example of Energy Amplifier based on these concepts was also given [3]. The power plant assumed as the driver a continuous proton beam of 1 GeV with an average intensity of 10 mA, that is an average power of 10 MW. With realistic assumptions, it was demonstrated that the device could be capable to deliver 400 MW on an external load, with an extra 25 MW for the operation of the proton accelerator and another 5 MW for the facility surrounding the complex.

The original concept of the Energy Amplifier assumed one or two cyclotrons as the proton accelerator [4]. But there are several serious technical concerns with the operation of cyclotrons at very large beam power, which deal with space charge effects at injection, components activation due to slow beam losses caused by the narrow gap of the accelerator magnet, and the complexity of the beam extraction. Thus, as an alternative it was proposed [3] to use a Superconducting Linac (SCL) as the proton accelerator. The Linac would remove several of the technical concerns of the cyclotrons. For instance, at the intensity level of 10 mA, space charge effects are small, understood and easily controlled. The ratio of the physical aperture to the beam size is also very large, which essentially eliminates the problem of activating the Linac itself by the slow beam losses. The RF architecture and the operation is simple. Lastly, very important, a large electric to beam energy conversion efficiency is expected, close indeed to the 40% level used in the cited example.

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## 2 THE SUPERCONDUCTING LINAC

The Linac is made of three sections: the Front-End, the Normal Conducting Linac, and the Superconducting Linac proper. The Front-End is made of a 12-mA positive-ion source followed by an RFQ. The Normal Conducting Linac accelerates the 10-mA proton beam to 100 MeV. It is actually made of two parts. The first part accelerates the beam to 20 MeV and is a typical Drift Tube Linac with permanent magnets inserted in the drift tube themselves. The second part is made of a Cavity-Coupled Drift Tube Linac which optimizes acceleration of protons in the velocity range $\beta$ = 0.1 to 0.4.

The last section is the Superconducting Linac proper which accelerates the beam from 100 MeV to 1.0 GeV. The analysis and the design concepts of a Superconducting Linac are discussed in [5]. A Superconducting Linac is made of an alternating sequence of Warm Insertions and Cryo-Modules. The Warm Insertions are needed to accommodate beam steering and focussing magnets, beam position monitors and vacuum pumps. The Cryo-Modules house the RF Cavities. A Cryo-Module is made of a number of Cavities, and each Cavity is made of a number of Cells.

The Linac design is based on a constant energy gain per Cryo-Module. The optimum Transit Time Factor (TTF) is obtained by adjusting the Cell length $d$ so that, denoting with $\lambda$ the RF wavelength, $d = \beta\lambda / 2$. As the beam is accelerated, $\beta$ varies, and the Cell length $d$ has to be adjusted accordingly. This would not be practical since all Cryo-Modules would look different in shape and size. A more practical solution is obtained by dividing the Superconducting Linac in two sections. Each section is made of Cavities with Cells of the same length, shape and size, corresponding to a geometrical $\beta = \beta_0$ in proximity of the middle of the accelerating range. There is a penalty of lowering the TTF which can be compensated with an increase of the axial electric field. This way all the Cryo-Modules in the same section are identical in shape and size.

We shall assume in the following that each Cavity is individually driven by a single RF Coupler. To resolve phase adjustment to a sufficiently high degree, one should not allow more than two cavities under the same Klystron. The preferred mode of operation is to provide the same amount of power to all the RF Couplers in the same Linac section. Because the Cavity-Cell-Coupler configuration is

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the same for all Cryo-Modules in one section, the energy gain per Cryo-Module is also the same.

The original proposal of the Superconducting Linac [3] made use of an RF system operating at 805 MHz in line with similar assumptions made at Los Alamos National Laboratory. Later other studies and designs of the Superconducting Linac [6] considered the frequency of 360 MHz. The purpose of our work, which is summarized here is to compare the performance and the cost for these two frequency choices.

## 3 DESIGN OF THE 10-MW SUPERCONDUCTING LINAC

A list of the general parameters of the 1.0 GeV Superconducting Linac is given in Table 1. To reduce the wall-dissipated losses we have taken a temperature of $2^o$ Kelvin for the cavities. There are 4 Cells per Cavity and 4 Cavities per Cryo-Module. The synchronous RF phase angle for acceleration is $-30^o$. Transverse focussing is provided by arranging quadrupoles in the Warm Insertions in a typical FODO arrangement with a betatron phase advance of $90^o$ per FODO cell in both planes. Bunch area and beam emittances are also shown in Table 1.

Table 1. The 1.0-GeV Superconducting Linac

| | |
|---|---|
| Total Beam Power (CW) | 10 MW |
| Beam Current | 10 mA |
| Ion Source Current | 12 mA |
| Initial Kinetic Energy | 100 MeV |
| Final Kinetic Energy | 1.0 GeV |
| Temperature | 2.0 $^o$K |
| Cells / Cavity | 4 |
| Cavities / CryoModule | 4 |
| Cavities / Klystron | 2 |
| No. of RF Couplers / Cavity | 1 |
| RF Phase Angle | $-30^o$ |
| Method for Transverse Focussing | FODO |
| Betatron Phase Advance / FODO cell | $90^o$ |
| Normalized rms Emittance | 0.30 $\pi$ mm mrad |
| rms Bunch Area | 1.725 $\pi$ $\mu$eV-s |

A more detailed list of parameters for the two sections of the Superconducting Linac is given in Table 2, where the two frequency cases are also compared to each other. For both cases the first section accelerates protons from 100 to 300 MeV, the second section from 0.3 to 1.0 GeV. We define as a period the combination of a Warm Section and the following Cryo-Module. As noted and expected, because of the relatively low number of particles per bunch, the losses to the Higher-Order Modes (HOM) of the Cavities are negligible. The required cryogenic power is estimated assuming a conservative static loss in the cryostats of 5 W/m. The AC-to-RF efficiency for Klystrons is taken to be 58.5%. The cryogenic efficiency is 0.4%.

Table 2. Comparison of SCL at two different Frequencies

| Frequ. (MHz) | 360 | | 805 | |
|---|---|---|---|---|
| | L-E | H-E | L-E | H-E |
| Velocity, $\beta$: in<br>out | 0.428<br>0.653 | 0.653<br>0.875 | 0.428<br>0.653 | 0.653<br>0.875 |
| Cell Refer. $\beta_0$ | 0.48 | 0.69 | 0.48 | 0.69 |
| Cell Length, cm | 19.99 | 28.73 | 8.94 | 12.85 |
| No. of Periods | 16 | 22 | 36 | 51 |
| Total Length, m | 141.6 | 225.5 | 143.6 | 235.4 |
| Period Length, m | 8.85 | 10.25 | 3.99 | 4.62 |
| Cryo. Length, m | 6.650 | 8.049 | 2.990 | 3.616 |
| Warm Insert., m | 2.2 | 2.2 | 1.0 | 1.0 |
| Quad. Length cm | 67 | 67 | 30 | 30 |
| Bore Radius, cm | 11 | 11 | 5 | 5 |
| Transitions, cm | 67 | 67 | 30 | 30 |
| Pwr/Coupl., kW | 32.5 | 80.0 | 14.0 | 35.0 |
| Gain/Per., MeV | 13.0 | 32.0 | 5.6 | 14.0 |
| Surf. Imped., n$\Omega$ | 20.80 | 20.80 | 24.00 | 24.00 |
| $Q_0$, in $10^9$ | 5.70 | 8.20 | 4.94 | 7.10 |
| $ZT^2$, ohm/m | 490 | 1,013 | 223 | 461 |
| Diss. Power, kW | 3.73 | 2.98 | 9.05 | 7.63 |
| HOM - Power, W | 16 | 22 | 79 | 113 |
| Cryog. Pwr, kW | 4.28 | 3.89 | 9.67 | 8.67 |
| RF Power, MW | 2.70 | 9.45 | 2.71 | 9.46 |
| AC Power, MW | 5.69 | 17.13 | 7.05 | 18.34 |
| Efficiency, % | 35.14 | 40.86 | 28.37 | 38.18 |

We have assumed CW mode of operation. Moreover, we have allowed an extra 35% of RF power as contingency to allow phase and amplitude tuning of the Cavities.

As one can see the overall efficiency is indeed close to 40% as originally projected. In particular, the amount of power in the RF Coupler, which has been chosen so that the surface field never exceeds the limit of 17 MV/m, is within the technical demonstrated capabilities.

## 4 COST

The capital cost of the Superconducting Linac is estimated assuming 100 k$ / m for the Warm Insertions and 300 k$ / m for the Cryo-Modules. The tunnel cost is taken to be 70 k$ / m. All the required parameters are shown in Table 3. The cost of Klystrons, including waveguides, windows, etc..., depends on their number, RF architecture, and total RF power required. An extra 35% of RF power has also been added for the tune-up operation of the Linac. The cost of the refrigeration plant is estimated assuming 2 k$ per Watt at 2 $^{o}$Kelvin. The distribution of the AC power has also a cost, taken at 0.14 $ per Watt. The summary given in Table 4 shows a total of 160 - 185 M$ for the Superconducting Linac, to which one should add the cost of the front-end and of the normal-conducting section, which could be another 30-35 M$. The accelerator cost is expected to be only a small fraction of the total cost of the facility, which includes the target station, the energy recovery and electrical transformation systems, the processing plant, etc... etc... Once in full operation, it is of course expected that the cost of the operation of the facility will not include the AC electric power, since this will be provided by the plant itself. Nevertheless, during the early commissioning stages, the AC electric power may be provided only externally and at full cost. A total of 20 - 25 MW of AC power is then required, that somewhere in USA may contribute to an operational cost of 7-8 M$ a year, assuming that the Linac is to be available at least 75% of the yearly time.

## 5 COMPARISON AND CONCLUSIONS

The comparison of the performance of the two frequency cases is given in Table 2, and that of the cost in Table 4. No major differences are noticed between the two cases. The number of Modules (and of periods) is lower, by about half, in the 360 MHz case than in the 805 MHz case, but the periods are about twice as long and the cryostats are larger.

Table 3. Cost and Other Parameters

| | |
|---|---|
| AC-to-RF Efficiency | 0.585 for CW mode |
| Cryogenic Efficiency | 0.004 @t 2.0 $^{o}$K |
| Electricity Cost | 0.05 $/kWh (in USA) |
| Availability | 75% of yearly time |
| Normal Conducting Structure Cost | 100 k$/m |
| Superconducting Structure Cost | 300 k$/m |
| Tunnel Cost | 70 k$/m |
| Cost of Klystron (*) | 1.68 $/W of RF Power |
| Cost of Refrigeration Plant | 2k$/W @ 2.0 $^{o}$K |
| Cost of Electrical Distribution | 0.14 $/W of AC Power |

(*) Assuming a single step of RF power splitting

The overall length is about the same, 270 m in both cases. Because the focusing period is longer, the quadrupole gradient is weaker in the low frequency case, and the beam size is larger. Yet, the ratio of cavity aperture to beam size is larger at 360 MHz. The most important difference is the wall-dissipated power: a total of 6.7 kW at 360 MHz, and 16.7 kW at 805 MHz. This gives a negligible impact to the total RF requirement, which is essentially given by the beam power, but a substantial contribution to the required Cryogenic power which from 8 kW at 360 MHz increases to 18 kW at 805 MHz, with a corresponding increase of the AC power for the Cryogenic plant from 2 to 4.5 MW respectively. As a result, the overall efficiency is somewhat lower at the high frequency case. There is about a 20 M$ difference in the capital cost, with the low frequency case being less expensive. This difference is the consequence of the larger dissipated power in the 805 MHz frequency case. Though the difference in absolute values are not large, the 360 MHz frequency would actually represent a better choice. For instance, the lower number of modules required, could lead to an easier construction and maintenance of the facility.

Table 4. Cost Comparison

| Frequ. (MHz) | 360 | | 805 | |
|---|---|---|---|---|
| | L-E | H-E | L-E | H-E |
| Operat. Cost, M$/y | 1.87 | 5.628 | 2.316 | 6.023 |
| Capit. Cost: (M$) | | | | |
| RF Klystrons | 4.54 | 15.88 | 4.55 | 15.89 |
| Electr. Distrib. | 0.797 | 2.398 | 0.987 | 2.567 |
| Refrig. Plant | 8.55 | 7.78 | 19.34 | 17.34 |
| Warm Struct. | 3.52 | 4.84 | 3.60 | 5.10 |
| Cold Struct. | 31.92 | 53.12 | 32.29 | 55.32 |
| Tunnel | 9.91 | 15.78 | 10.06 | 16.48 |
| Total Cost (M$) | 59.24 | 99.81 | 70.83 | 112.7 |

## 6 REFERENCES

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