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DRIVER OF THE ENERGY AMPLIFIER**

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A Superconducting Linac as the Driver of the Energy Amplifier

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Abstract

Because of the safer and more reliable mode of operation, a Superconducting Linac is proposed here as the proton beam accelerator which drives a nuclear plant based on the concept of the Energy Amplifier. The accelerator has also high electric power efficiency. An example based on the net generation of 400 MW (electric) is described here. 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.

Introduction

A well established method to produce energy is obtained with the process of nuclear fission reactions as it is done in nuclear reactors. Very heavy elements, like Uranium 235 or 238, are made to split by scattering with relatively low velocity neutrons. During the process more neutrons are produced which will generate in turn other fission events. This cascade process, referred to as a chain reaction, produces ultimately a continuous flow of energy starting from the kinetic energy of the neutrons involved in the process and of the products of the fission events. Eventually, the kinetic energy is converted to thermal energy, and then to electric energy by means of thermally propelled turbines which operate electric generators.

In order to sustain the chain reaction, a sufficient large number of neutrons are to be involved continuously in the process. This is measured by the *criticality factor* k defined as the ratio of the total number of neutrons produced per fission event to the number of neutrons which are in average required to produce a single fission event. The criticality parameter k is to be sufficiently larger than unit in order to sustain continuously the chain reaction. If $k < 1$, eventually, not enough neutrons are produced and the chain reaction will subside.

The operation of a nuclear reactor is often perceived by the community at large as dangerous and undesirable for producing energy. If a run-away of the chain reaction is initiated and made unstable, the reactor core may melt-down with imaginable catastrophic consequences. Moreover, poisonous elements are generated as side-product which are to be disposed with a suitable "waste management" program. Finally, the stockpile of fissionable material, like U^{235} and P^{238} , can be tapped in for use as fuel of nuclear weapons.

It was initially proposed by Bowman [1] that it is still possible to sustain a nuclear fission chain reaction under subcritical conditions, with k slightly below unit, 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, for instance tungsten, stainless steel or lead. 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.

The same concept was re-proposed subsequently by Rubbia [2]. One of his major innovating ideas is the optimization of the target which has a mixture of fissionable and spallation material, similar to the high-energy detector calorimeters, which makes the device more efficient and capable to operate at even lower criticality parameter k . Rubbia also pointed out the advantage of this method, that he named "Energy Amplifier", which greatly reduces the amount of toxic fission products, like actinides, by using fissionable material from the Thorium family. This also eliminates or reduces significantly the presence of Uranium or Plutonium stockpiles, and thus one of the major worries of uncontrolled manufacturing of nuclear weapons. Rubbia's proposal is a compact, easily assembled facility for energy production which can be delivered to and used by third-world countries which are desperately in need of energy sources. The facility would be easy and safe to operate also by countries which are less technology developed, with a marginal nuclear waste that can eventually be incinerated by the same proton beam, and still would not be suitable for producing radioactive material for nuclear weapons.

The concept of the "Energy Amplifier"

A continuous proton beam of a kinetic energy of few GeV is impinging on a target as shown in Figure 1. The target is a granular mixture of inertial material, for instance Tungsten or Lead, and of fissionable material, for instance Th^{232} . Neutrons are initially produced by spallation of the protons with the nuclei of the inertial material. Let n_{sp} be the number of neutrons produced in average per proton. Each spallation neutron initiates a chain reaction with the nuclei of the fissionable material, so that more neutrons are produced, with ν the number of neutrons produced per fission event. A fraction of neutrons is also lost and not absorbed.

Figure 1. The concept of the Energy Amplifier

Define the criticality parameter

$$k = \frac{\text{total number of neutrons produced}}{\text{no. of absorbed neutrons} + \text{no. of lost neutrons}} \quad (1)$$

It can be derived that the total number of neutrons absorbed per fission events, in the total target volume, is

$$n_{\text{tot}} = a k / v (1 - k) \quad (2)$$

where a is a target geometrical factor.

Each fission event releases an amount of energy U , so that the total nuclear power involved is

$$P_{\text{nuclear}} = n_{\text{sp}} (dn_p / dt) a k U / v (1 - k) \quad (3)$$

where dn_p / dt is the number of protons on the target per unit of time. With typical values $n_{\text{sp}} = 33$, $a = 1$, $v = 2.5$ and $U = 200$ MeV, we obtain

$$P_{\text{nuclear}} = (2.64 \text{ MW}) k I_{\text{mA}} / (1 - k) \quad (4)$$

where I_{mA} is the average proton beam current in milliamperes.

As an example, with a criticality factor $k = 0.98$ and an average proton intensity $I_{\text{mA}} = 10$ mA, the total nuclear power $P_{\text{nuclear}} = 1.3$ GW. Assuming a thermal-to-electric power conversion efficiency of $1/3$, the expected generated electric power is $P_{\text{electric}} = 430$ MW.

On the other end, with a proton beam energy of 1 GeV, a proton beam current of 10 mA corresponds to an average beam power of 10 MW. If we also assume an accelerator efficiency, that is the ratio of beam power to the total AC power required, of 40%, the total power needed to operate the accelerator is $P_{\text{acceleration}} = 25$ MW. This yields a power amplification factor

$$A = P_{\text{electric}} / P_{\text{acceleration}} = 17.2 \quad (5)$$

This is an example used to demonstrate the practicability of the concept of the "Energy Amplifier". Of course other sets of parameter values can be chosen, depending on the assumption made for the target, the accelerator and the requirements for the overall power plant.

The Proton Accelerator

The original concept of the Energy Amplifier assumed one or two cyclotrons as the proton accelerator, operating either in Tandem or in parallel [3]. Presently, relative safe and reliable operation of cyclotrons with a beam power close to 1 MW at an energy of 0.6 GeV has been demonstrated at the Paul Scherrer Institut [4]. Yet a 5 to 10 MW proton cyclotron still remains a problematic

project. There are several serious technical concerns which deals with space charge effects at injection, components activation due to slow beam losses caused by the narrow gap of the accelerator magnet, and due to the complexity of the beam extraction.

The alternative that is proposed here is the use of a Superconducting Linac as the proton accelerator. In our opinion 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 conversion efficiency is expected, close indeed to the 40% level used in the example above.

We shall describe next a 1 GeV linac with a continuous beam of 10 mA for a total beam power of 10 MW. The configuration is shown in Figure 2 which explains the interface with the target and the conversion and handling of the generated nuclear power. It is based on the example given above, 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 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 positive-ion source followed by a 402.5 MHz RFQ. It is about 5 meter long and may cost around 5 M\$ (1996 value). The ion source generates a continuous proton beam of 12 - 15 mA which is well within the capability of presently demonstrated technology. A 20% beam loss is expected when the beam is focussed, accelerated and bunched by the RFQ, so that a 10 mA beam is obtained at the exit of the Front-End and at injection into the next stage: the Normal Conducting Linac.

The Normal Conducting Linac accelerates the proton beam to 100 MeV. Like the Front-End, the conceptual design and cost estimate of the Linac are already available from different sources, since it has been proposed for a variety of other applications [5]. We shall not discuss it in much details except noting that it is an RF structure at 805 MHz, twice the RFQ frequency, about 50 m long, and a cost of about 20-30 M\$. The RFQ will bunch the beam and compress each bunch to a length short enough to fit it in the 805-MHz accelerating RF buckets. Because of the frequency difference between the Front-End and the rest of the Linac, only one every other bucket has a beam bunch. The Normal-Conducting Linac is actually made of two parts. The first part accelerates the beam to 20 MeV and is a typical Drift Tube Linac where focussing is provided with permanent magnets inserted in the drift tube themselves. The second part, which accelerates the beam to 100 MeV, is made of Cavity-Coupled Drift Tube Linac, a novel accelerator layout concept [6] 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 [7]. We review below briefly the main concepts.

Figure 2. Layout of a Proton Superconducting Linac driving an Energy Amplifier

A Superconducting Linac is made of an alternating sequence of Warm Insertions and Cryo-Modules as shown in Figure 3. The Warm Insertions, about one meter long, are needed to accommodate beam steering and focussing magnets, beam position monitors and vacuum pumps. The Cryo-Modules house the RF Cavities as shown in Figure 4. A Cryo-Module, which may have a length of 5 to 10 meter, is made of a number N of Cavities, and each Cavity is made of M Cells.

Figure 3. A Superconducting Linac Structure

Ideally, a continuous matched solution of the Linac design is obtained with constant longitudinal focussing, that is by letting the accelerating gradient to increase with $(\beta\gamma)^3$. This is usually not practical, and as an alternative, the design is based on a constant energy gain per Cryo-Module. This may introduce some mismatch due to the non-adiabaticity of the motion, especially during the early stages of the acceleration.

Figure 4. Example of a Cryo-Module with $N = 4$ Cavities each with $M = 4$ Cells

The optimum Transit Time Factor (TTF) which yields the highest accelerating rate is obtained by adjusting the Cell length d so that, denoting with λ the RF wavelength,

$$d = \beta\lambda / 2 \quad (6)$$

As the beam is accelerated, β 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. The convenience of Superconducting Cavities for acceleration in a Linac is that they can be individually powered and have their phase and amplitude independently adjusted. A typical RF architecture is shown in Figure 5 where we have opted for Klystrons as the power amplifiers. To resolve phase adjustment to a sufficiently high degree, one should not allow more than two cavities under the same Klystron.

Figure 5. RF Architecture for Superconducting Cavities

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 the same for all Cryo-Modules the energy gain per Cryo-Module is also the same.

Design of a 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° Kelvin for the cavities. The RF frequency is also 805 MHz. There are 4 Cells per Cavity and 4 Cavities per Cryo-Module. The longitudinal axial electric field is about 13 MV/m. The synchronous rf phase angle for acceleration is -30° which gives a sufficiently large RF buckets to contain the beam bunches. Transverse

focussing is provided by arranging quadrupoles in the Warm Insertions in a typical FODO arrangement with a betatron phase advance of 90° per FODO cell in both planes. Bunch area and beam emittances are also shown in Table 1.

Table 1. General Parameters of 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
Frequency	805 MHz
No. of Protons / Bunch	1.6×10^8
Temperature	2.0 °K
Cells / Cavity, M	4
Cavities / CryoModule, N	4
Cavity Separation	32 cm
Cold-Warm Transition	30 cm
Cavity Internal Diameter	10 cm
Length of Insertion	1.00 m
Accelerating Gradient	12.919 MeV/m
Cavities / Klystron	2
No. of rf Couplers / Cavity	1
RF Phase Angle	-30°
Method for Transverse Focussing	FODO
Betatron Phase Advance / FODO cell	90°
Normalized rms Emittance	$0.30 \pi \text{ mm mrad}$
rms Bunch Area	$1.725 \pi \mu\text{eV-s}$
	$0.5 \pi^\circ \text{ MeV (805 MHz)}$

A more detailed list of parameters for the two sections of the Superconducting Linac is given in Table 3, which in particular gives the geometrical values β_0 used to assign the length d of the Cavity Cells. The first section accelerates protons from 100 to 300 MeV, the second section from 0.3 to 1.0 GeV. Defining a period as a combination of a Warm Section and the following Cryo-Module, the number of periods is 13 in the low-energy section and 31 in the high-energy section. 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 wall-dissipated power figures are derived assuming an environment cold temperature of 2° Kelvin. The AC-to-RF efficiency for Klystrons is taken to be 58.5%. The cryogenic efficiency is 0.4%. We have of course

assumed CW mode of operation, which indeed makes the use of the Superconducting Linac very attractive and advantageous. 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. All the parameters, which are also summarized in Table 2, are reasonable and attainable. In particular, the amount of power in the RF Coupler is within the technical demonstrated capabilities.

Table 2. Cost and Other Parameters

AC-to-RF Efficiency	0.585	for CW mode
Cryogenic Efficiency	0.004	at 2.0 °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	2	k\$/W of Power @ 2.0 °K
Cost of Electrical Distribution	0.14	\$/W of AC Power

(*) Assuming a single step of rf power splitting

The result of beam dynamics is displayed in Figures 6a to 6d for the low-energy section, and in Figures 7a to 7d for the high-energy section. The physical parameters plotted versus the number of cryostats (tanks) are: the kinetic energy, the beam velocity β , the ratio of the cavity internal radius to the rms beam size, the ratio of β_0 / β , the Transit Time Factor, the actual accelerating field, the quadrupole gradient, the rms bunch length and momentum spread, and the dissipated and cryogenic power per cryostat. The mismatch due to the non-adiabaticity of the motion is measured by α , the Twiss parameter which gives the rotation of the beam ellipse with respect to reference upright position, and the amplitude function which determines the width of the bunch ellipse. Finally, the longitudinal tune is the number of longitudinal oscillations per period. Especially at the beginning of the linac, this quantity can be large. To avoid unstable motion, the accelerating gradient is to be maintained sufficiently low.

Cost

The capital cost of the Superconducting Linac is estimated assuming a cost 100 k\$ per meter of the Warm Insertions and 300 k\$ per meter of the Cryo-Modules. The tunnel cost is taken to be 70 k\$ / m. All the required parameters are shown in Table 2. 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 °Kelvin. The distribution of the AC power has also a cost, taken at 0.14 \$ per Watt. The summary given in Table 3 shows a total of

Table 3. Summary of the 1.0-GeV 10-mA Superconducting Linac Design

	Low-Energy	High-Energy
Energy: in	100 MeV	300 MeV
out	300 MeV	1.0 GeV
Velocity, β : in	0.4282	0.6526
out	0.6526	0.8750
Cell Reference β_0	0.48	0.69
Cell Length, cm	8.94	12.85
Total No. of <i>Periods</i>	13	31
Length of a Period, m	3.990	4.616
FODO-Cell ampl. func., β_Q , m	13.6	15.76
Total Length, m	51.87	143.09
Coupler rf Power, kW (*)	54.0	77.6
Energy Gain/Period, MeV	16.00	23.00
Total No. of Klystrons	26	62
Klystron Power, kW (*)	108	155
$Z_0 T_0^2$, ohm/m	223	461
Q_0	4.94×10^9	7.10×10^9
Dissipated Power, kW	3.36	3.43
HOM-Power, kW	0.029	0.068
Cryogenic Power, kW	3.59	4.06
Beam Power, MW	2.00	7.00
Total rf Power, MW (*)	2.70	9.45
AC Power for rf, MW (*)	4.62	16.16
AC Power for Cryo., MW	0.90	1.01
Total AC Power, MW (*)	5.52	17.17
Efficiency, % (*)	36.3	40.8
Capital Cost: rf Klystrons (*)	4.542	15.882
Electr. Distr. (*)	0.772	2.404
Refrig. Plant	7.170	8.116
Warm Struct.	1.300	3.100
Cold Struct.	11.661	33.626
Tunnel	3.631	10.016
Total Cost, M\$ (*)	29.076	73.144
Operation Cost, M\$/y (*)	1.812	5.642

(*) Including 35% power contingency.

about a hundred million dollars 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 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.

More Compact Configurations

The total length of the linac, including front-end and the normal-conducting section, is about 250 meter, if the accelerator is to be laid-out linearly. Thus, the effective, real-estate accelerating gradient is an average 4 MeV/m. More compact configurations are certainly possible, by increasing the average accelerating gradient to 5 or 6 MeV/m, especially toward the high-energy end. Nevertheless, because of the considerably lower kinetic energy, it is not possible to accelerate protons at significantly higher gradients, like in the case of electrons, because the longitudinal motion would become unstable [7].

If required, a more compact configuration, which would reduce by about half the total length of the real estate, is obtained by bending the linac and folding the accelerator in three parallel sections, as shown in Figure 8. This configuration requires some modest bending and focussing at both ends; but the linac can also be divided in three sections, by splitting the high-energy part in two further sections, from 0.3 to 0.5 and from 0.5 to 1.0 GeV. This could also allow a more efficient and higher accelerating gradient.

An example of a very compact linac, which requires even a shorter real estate length (about 60 m), and a higher proton energy (2 GeV) is shown in Figure 9. It is based on the re-circulation principle, similar to the re-circulation of electrons in the CEBAF linac [8]. The major difference here is that the velocity of protons will vary during acceleration and that, especially during the early stages of acceleration, β is significantly less than unit. Thus, a section of the linac can be repeatedly used for acceleration of protons only when the velocity is sufficiently large. Because of the velocity jump, from one passage to the next, there is a penalty of lowering the overall accelerating gradient due to a loss of the Transit Time Factor. On the other end, proper phase adjustment between leaving a section and entering the subsequent one is not a problem, since it can be achieved, partially electronically, and partially by adjusting properly the path length of the arcs. The example shown in Figure 9 has actually been numerically designed, and demonstrated feasible.

Figure 6a. Dynamics of the Low-Energy Superconducting Linac Section

Figure 6b. Dynamics of the Low-Energy Superconducting Linac Section

Figure 6c. Dynamics of the Low-Energy Superconducting Linac Section

Figure 6d. Dynamics of the Low-Energy Superconducting Linac Section

Figure 7a. Dynamics of the High-Energy Superconducting Linac Section

Figure 7b. Dynamics of the High-Energy Superconducting Linac Section

Figure 7c. Dynamics of the High-Energy Superconducting Linac Section

Figure 7d. Dynamics of the High-Energy Superconducting Linac Section

Figure 8. A compact Driver for the Energy Amplifier

Figure 9. A very-compact Driver for the Energy Amplifier based on the Recirculation Principle

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