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NEW APPROACH TO DESIGN OF SC NLC

A.Mikhailichenko[1], Cornell U., LEPP, Ithaca, NY 14853

Abstract

We analyze here possibility for increase of repetition rate for the Next Linear Collider with SC structures up to 50 Hz simultaneously with decreasing the bunch train length. SC structure operating at SLAC frequency 2856 MHz and Tesla-type structures operating at 1300 MHz discussed here. We did not find any technical restrictions for realization of this transferring.

Advantages are in relaxed parameters of damping ring together with relaxed conditions for RF operation. All existing SLAC equipment can be appointed for operation of this new machine type.

INTRODUCTION

Now when the time for the Next Linear Collider decisions coming closer, the world concusses about its realization concentrated on two main types: TESLA type and NLC/JLC ones [1]. Seems that at the moment no one has evident advantages. Coming to comparison of these existing types of NLC, all speakers describing situation in many occasions, stopping here in admiration and leaving decision to somebody, hopefully present in audience. So far for direct question –which type is better –the answer was not given. This means that Physical Community is not ready for technical realization of NLC as some dissatisfaction present in the air. No doubt about, we must agree that significant work carried out by two (main) teams in developing technology for each of these two approaches has positive results. It looks like each is *almost* ready.

Right now the situation looks like SLAC stands for room temperature linac, and DESY for a superconducting one, where it was proposed.

It is interesting, however, that soon after 2 mile SLAC was build, the superconducting accelerator research program was established there in 1968 [1] (and references there). The goal was to convert of the SLAC accelerator to a two-mile 100 GeV SC machine. Designers did not associate this move with attempt to avoid synchrotron radiation (this link will appear six years later). This project developed up to detailed stage described in rather thick volume. One peculiarity of this scheme was a *traveling wave* structure with circled input/output flanges. This resonant loop required as group velocity is high, power passed through the structure practically without attenuation and that was the reason to redirect passed power to the input again. The power inserted into this loop with help of bridge with relatively small coupling. The coupling was defined by RF power, available from generator. Frequency of structure was the same as in SLAC –2856 MHz, naturally. Designers put in theirs project moderated unloaded quality factor $Q_0 \cong 10^9$ and found, that this is acceptable for cooling budget. Acceleration gradient supposed to be hence ~33 MeV/m. This program has created the Leapfrog project to test the 15-cavity, 52.5-cm long structure in Dewar. Further measurements were switched to X –band (10.5 GHz) cavity. Authors came to conclusion that Q's of the order 10^{11} and peak electric fields of the

[1] Phone: (607) 255-3785, Fax: (607) 255-8062, e-mail "mikhail@lns.cornell.edu

order 70MV/m *have been obtained* [3]. Present day technology of preparation of materials guarantees these parameters. This program did not receive further support, unfortunately.

If one not worries about power losses on some extend the simple traveling wave SC structure can be used for accelerator. As the attenuation length formally is very long, there is no formal limitation in the length of accelerating structure. Indeed in room temperature structures the length of accelerating structure is practically coincides with the attenuation length. Trade between the length of structure and attenuation length for travelling wave and standing wave described elsewhere.

Let's remind basic physical requirements however.

LUMINOSITY AND EMITTANCE

Physical parameters of the beam derived from the requirement, that SR on incoming bunch is limited by some value, few percent typically. For this the bunch must be flat, having significant aspect ratio (see [7] for references). In this case magnetic field reduced and defined by large (horizontal) size, so radiation on incoming bunch can be suppressed. As collisions are going in classic regime the losses by SR due to beamstrahlung can be described as

$$\left(\frac{\Delta E}{E}\right)_{max} \cong \frac{8\sqrt{\pi}}{3}\cdot\frac{r_0^3\gamma N^2}{\sigma_x^2\sigma_s}, \tag{1}$$

where σ_x and σ_s are horizontal and longitudinal dimensions respectively, then parameters included in this formula are *restrained* and radial size does not act as independent agent. Substitute this in formula for luminosity

$$L = \frac{N^2 f H}{4\pi\sigma_x\sigma_y} = \frac{N^2\gamma H f n}{4\pi\sqrt{\beta_x\beta_y\varepsilon_x\varepsilon_y}}, \tag{2}$$

where ε_x, ε_y stand for horizontal and vertical normalized emittances respectively, f stands for repetition rate, n –is the number of bunches in train, H is enhancement parameter, $\beta_{x,y}$ are envelope functions at IP, one can obtain for H=1, $\beta_y \equiv \sigma_s$ required value for vertical invariant emittance as

$$\varepsilon_y \cong \frac{N^2(f\cdot n)^2(\Delta E/E)_{max}}{L^2(4\pi)^2\frac{8}{3}\sqrt{\pi}r_0^3} = 3\cdot10^{-8}\frac{\left(\frac{N}{10^{11}}\right)^2\left(\frac{f\cdot n}{10^2}\right)^2\left(\frac{\Delta E/E}{0.8}\right)}{\left(\frac{L}{10^{34}}\right)^2}\ \text{[cm rad]}\,. \tag{3}$$

Substitute here for example $L = 10^{34}$ cm^{-2} s^{-1}, fn =100Hz, N=10^{11}, $\Delta E/E = 0.5$, one needs to get vertical emittance as low as $\varepsilon_y \cong 3\cdot10^{-8}$ cm rad. These parameters can be obtained in relatively simple damping ring, see lower.

So one can see that there is some trade between the numbers of particles, number of bunches in train and between repetition rate. Although these parameters participate in formula for emittance required as a product, the number of bunches in the train defines basically circumference of the damping ring. That is why is better to have this number as low as possible. Bunches cannot go every period, as the wakes will immediately destroy emittance. Some dead time required for cavity to restore accelerating field structure.

So general parameter list looks as the following:

Parameter	Units	e^+e^-	e^+e^-	$\gamma-\gamma$
Luminosity, L	$cm^{-2}\ s^{-1}$	10^{33}	10^{34}	10^{33}
Bunch population, N	$2\ 10^{11}$	1	1	1
Bunch length, σ_s	cm	0.1	0.1	0.1
Radial beta-function, β_x	cm	10.	10.	1.0
Vertical beta-function, β_y	cm	0.1	0.1	1.0
Vertical size at IP, σ_y	μm	0.004	0.0004	0.06
Horizontal size at IP, σ_x	μm	2.0	2.0	0.06
Vertical norm. emittance, ε_y	cm rad	3×10^{-6}	3×10^{-8}	8×10^{-5}
Horizontal norm. emittance, ε_y	cm rad	8×10^{-3}	8×10^{-3}	8×10^{-5}
Final lens vibration restrain	μm	0.02	0.002	0.1

One can easily renormalize these parameters for different number of particles per bunch, repetition rate and number of bunches per train. As the luminosity depends on repetition rate and on number of bunches in train, as a product of these values, there is a possibility to maneuver between these parameters.

RF STRUCTURE IN TESLA TYPE ACCELERATOR ([1], [4])

Right now the structures for TESLA have unloaded quality factor about $Q_0 \cong 10^{10}$. Frequency 1300 MHz corresponds period of $T_0 \cong 0.769$ ns. So the maximal filling time defined as a product of these values might be as high as $t = Q_0 T_0 \cong 10^{10}\cdot 0.769\cdot 10^{-9} \cong$ 7.7s. Filling time in reality is much shorter and defined only by the power available from RF source, however.

Let us remind the time structure of TESLA RF and beam. These are represented schematically in Fig. 1. What is important here is that filling of structure which lasts for ~400 μs, requires loaded quality factor about half of a million only. This is an attempt to reduce the power required from klystron, as it is

$$Power \cong \frac{Enery\ Stored}{Filling\ \ time} \cong \frac{E^2\lambda^2}{Filling\ \ time},$$

where E –is accelerating field, λ stands for the wavelength. The power of klystron is 5MW only. One 5 MW klystron, having two outputs, feeds three cryo-modules with 12 structures in each. Each structure has 9 cells. The question is why here 9 cells, and not, say, 90? The answer is in a fact, that this structure is the standing wave one, where energy flow rate between cells defined not only by geometrical coupling between the cells (diameter of irises), but by the *difference* in the fields in neighboring cells. Tangential component of the electrical field appeared due to the presence of halls. This component has input from two neighboring cell and is just a sum of electrical fields, but magnetic field has opposite values, so the Pointing vector amplitude is small. Formally the group velocity for this type of structure is zero. So one can use 90 cells, but the filling time will be long. During pumping, at the beginning, as the structure is not filled, mostly of power reflected from input. Although as we said the group velocity formally goes to zero for π –type mode, this restriction works only when structure is filled. But namely at this moment we do not need to fill the structure anymore. So filling of this structure becomes slower and slower, and the time constant not defined by coupling, while coming to equilibrium.

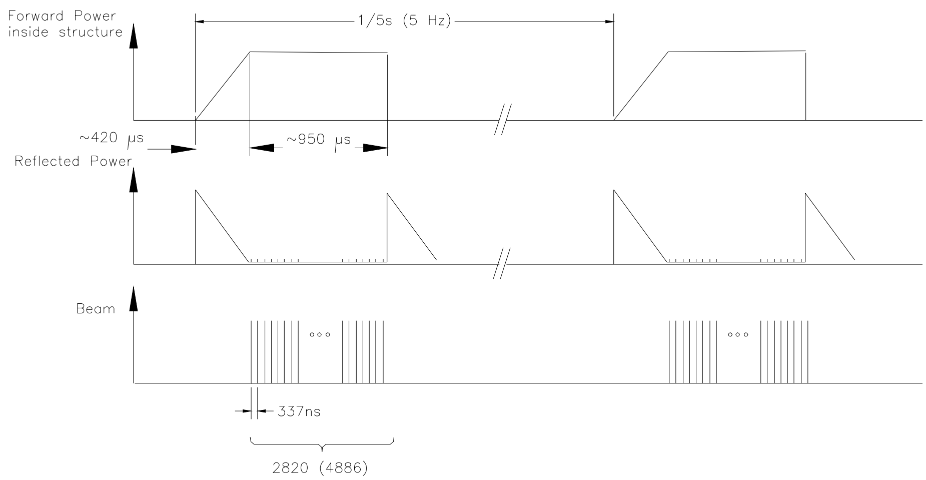

Figure 1: Time structure of RF and beam in TESLA type machine.

So one can see, that efficiency of utilizing power from klystron affected namely this finite filling time. By keeping operation time as ~950 µs, the efficiency of using power looks as

$$Eff. \cong \frac{Beam\ time}{Beam\ time + Filling\ time} \cong \frac{950}{950+420} \cong 69\%.$$

So if one reduces pumping time in half and simultaneously reduces beam time in half too, the efficiency does not change. Now one can cut the bunch train length in half and double repetition rate coming to the same wall plug power and the same power which heats the structure. So now as the bunch train is shorter, damping ring perimeter is twice shorter too. This process can be repeated one more time and so on. In this procedure one needs to check the filling time value and, maybe to change the coupling and/or number of cavities in the structure.

To cut in half pumping time one needs however double the power from klystron. Right now the Thompson TH2104 klystron is planned for usage. Some plans about usage of Magnicon not developed as well as not developed a klystron with grided cathode. The last type of klystron developed for VLEPP project. Stepping back from extreme parameters of the last device (1MV operational voltage, 400 A beam) one can expect that modification of HV part of this klystron can be successful.

Meanwhile parameters of TH2104 look as extremely modest ones. Newest codes used for optimization of X-band klystrons at SLAC and Protvino allow, definitely much higher parameters. For such low (compared with 11.4 or 14 GHz) frequency this is guaranteed.

So one can compare the following numbers, obtained just by scaling for the frequency 1300 MHz. These parameters give the same luminosity and the same heat deposition.

For high repetition rate the numbers one can treat as for power requirements, otherwise one needs to think about arrangement of necessary filling time either by changing the coupling or by cut of the structure length.

Parameter			
N of bunches	2820	564	282
Rep. Rate	5	25	50
Power of Klystron	5 MW	25MW	50 MW
Eff	69%	69%	69%

While switching to the higher frequency, namely from 1300 to 2856 MHz, the power required from klystron drops ~as square of wavelength as the accelerating field kept the same. We suggest ~the same shape of cavity. So for repetition rate 50 Hz and frequency 2856 MHz the power will require goes to ~10 MW only. Let us remind, that 150 MW klystron developed and tested at SLAC in framework of room temperature option for DESY collider. So the number of klystrons can be reduced significantly.

With reduction the number of bunches in train design of damping ring becomes an easy task.

DAMPING RING

Right now the energy of damping ring at TESLA is ~ 6GeV and even for so high energy, the wigglers required for arranging of necessary damping. Presence of wigglers makes beam dynamics problematic, however.

The ring circumference directly defined by the rise time in kicker. Although say SLAC version of NLC operates with 192 bunches spaced in structure with 1.4-ns, ($\cong 80.16$ meters total). TESLA has spacing 337 ns what defined by the rate of evacuation of HOM. Although the charge per bunch is ~three times higher for TESLA this looks as safety margins are much wider for TESLA. In the ring, the bunches spaced with ~20 ns, what defined by the rise time of kicker.

Pulsed kicks developed for synchrotron B-3M [5], [6] have rise time ~2ns and field integral ~40 kG·cm. Implementation of these in damping ring for NLC allow to have bunch spacing ~ 5ns. So having this spacing one can plan to have circumference ~ $C \cong 5\cdot 10^{-9}\cdot 200\cdot 3\cdot 10^{8} \cong 300$ m only. So taking relaxing conditions, a CESR scale machine with circumference ~628 m has the right size and scale. The ring even with twice bigger perimeter looks adequate. The ring structure and principles of its formation are the same as described in [7]. This ring has no wigglers and its energy is 6 GeV for the ring with perimeter 628 m.

The ring with circumference 628 m and bunch spacing 5 ns allows to have $\cong 420$ bunches.

GENERAL VIEW ON SC NLC

So the following general picture emerges form analyses. General line is to migrate to 2856 MHz. Disadvantage of this is in higher wake fields and higher losses. As the operational time and filing time is lowered this disadvantage can be tolerated. But in return one can expect increase of threshold electrical field strength. Good example of dealing with wakes is NLC developed by SLAC with even higher frequency, 11.4 GHz and DESY's room temperature option (SBLC).

Good engineering solutions associated with development of 1300 MHz structure can be used for 2856 MHz structure as well. Higher frequency and hence smaller waveguide diameter allow less heat losses and the coupling can be arranged in much easier way. This reduces the power from klystron too (less volume to fill with RF energy). Increased number of cavities per length can be tolerated, as they are easier to build. One possibility not investigated yet, is in stamping the *full length* of stricture with *longitudinal* cut (similar technology used for fabrication of muffing-tin structures at Cornell many years ago). Difference is that now the halves are *welded along* the longitudinal row (two side rows) accuracy in stamping is enough for these purposes.

Standing wave in structure allow in principle to accelerate particles in both directions, what may have some applications (fixed target experiments or *ep* interactions).

Schemes, using 1428 or 1300MHz (TEASLA type) are also acceptable for these purposes, but looks less elegant. To be implemented in the approach advocated some investments in klystron required. First this an optimization of geometry of klystron, maybe even utilization of second harmonics in it. Next is a possible utilization of Magnicon. For both of these devices, utilization of *grided gun* gives significant advantage as it excludes modulator.

For 2856 MHz despite slightly lowered quality factor losses remains acceptable. For this frequency 150 MW klystron developed solves all problems.

We do not exclude frequency 1300 MHz as lot of good quality jobs done there. However even for this frequency ride to higher repetition rate is desirable for many reasons. Shortening train of bunches cut circumference of damping ring and helps in evacuation of HOM.

CONCLUSION

So general idea of this proposal is in redistribution of the number of bunches in the train in favor of repetition rate. Other condition is that the power is not a limiting factor (<150 MW).

Superconducting accelerator with travelling (standing) wave, operating at 2856 MHz with repetition rate ~50 Hz is the best solution for the Next Linear Collider.

In this case RF power sources exist and *ready for use*. Significant part of equipment existing at SLAC such as klystrons, modulators and elements of RF control can be used in NLC fabrication. Although the direct cost reduction might be only ~15% the drawings are ready for remanufacturing.

Experience obtained while developing TESLA structures so cryomodules can be implemented directly into this new approach. For standing wave structure numerous input couplers can be joint inside the cryomodule, so the number of output waveguides remains the same. Original proposal for circling input/output flanges for travelling wave structure [1] also remains in power.

Within this approach there is no any difference in damping ring design for room temperature or SC collider –the ring is just the *same*. This ring operates at increased energy ~3-5 GeV to avoid wigglers and reduce IBS.

Increased coupling in structure and short duty time helps in evacuation of higher order modes from accelerating structure and lowering the dark current loading.

Short-term plan might be the following.

1). Fabricate and test full-scale structure with 2856 MHz operational frequency using newest technology of fabrication.

In support of traditional frequency,

2). Reconsider implementation of grided klystron for 1300 MHz.

3). Reconsider potential of Magnicon for 1300 MHz.

4). Concentrate on development of *universal* damping ring.

As practically all elements are in hands, this plan, carried in different Labs can be completed in short time.

Looks like schemes of linear collider can be converged to the one.

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