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BREAKDOWN EXPERIMENTS AT 34 GHZ

1. Introduction.

An experimental program is proposed to study rf breakdown in NLC-type accelerating structures. Available facilities may allow experimental parameters to be reached that may go beyond those available at SLAC. This could be possible because measurements will be made on accelerating structures at 34.3 GHz, using the newly-installed 40 MW magnicon and associated components at Yale Beam Physics Laboratory. These measurements are to complement these made at SLAC and CERN, so as to establish with improved accuracy the scaling laws for maximum achievable accelerating gradient in NLC-type structures. The experiments could also strengthen the technology base that might make possible an upgrade to NLC that would operate at a multiple of 11.4 GHz.

2. Background.

Two phenomena limit the practical utility of accelerating structures for a linear collider, namely (*i*) surface fatigue due to pulsed heating that limits the structure lifetime, and (*ii*) rf breakdown that limits the accelerating gradient.

2.1 Surface fatigue.

A theory has been developed [1] that predicts accelerator structure lifetimes as a function of pulsed temperature rise. The theory indicates that for safe operation of an accelerating structure the temperature rise should not exceed about 110 °C. Pulsed heating experiments using 11.424 GHz cavities have been carried out at SLAC [2]. The experiments demonstrate that pulsed heating with a temperature rise of 120°C shows modification and damage of the copper surface after 5.5×10^7 pulses. However, even after such large number of pulses, the authors couldn't draw conclusions about the structure longevity. In order to make reliable measurements within a reasonable time for different materials and surface preparations, one should have a temperature rise up to 500-600 °C, which is not possible at 11.4 GHz. Thus, tests at higher frequencies are necessary. We proposed to develop a special test device driven with power from 40 MW, 34.272 GHz magnicon that is under installation at Yale Beam Physics Laboratory, to determine the maximum achievable accelerating gradient limit due to pulsed heating and metal fatigue. Utilization of a few MW of power in a 1 μsec pulse width should allow one to obtain pulsed heating excursions exceeding 500 °C and consequently to define the pulsed heating limit. Support for this work over the next two years has been recently obtained from DoE.

2.2 Rf breakdown.

Rf breakdown limits the accelerating gradient and thus indirectly determines the collider length. One of the most important questions in collider design is the frequency dependence of the maximum achievable accelerating gradient. Present breakdown experimental data in some cases are contradictory, incomplete, and inconclusive; as the following indicates. (*A*) Experiments by Loew and Wang [3-5] demonstrated a square root dependence of maximum surface gradient on frequency in the microsecond pulse length range; independent experiments on single cavities under similar conditions show maximum surface fields of 190 MV/m for S-band and 350-400 MV/m for X-band, in conformity with the square root dependence [9,14]. (*B*) For X-band accelerating structures such as those under extensive study in several research groups at SLAC, maximum surface field is always lower than in a single cavity, and spread of maximum surface gradient depends on the structure type and parameters. Some recent theoretical investigations at SLAC also indicate that one may expect an increase of the gradient with frequency [6-8]. (*C*) CERN experiments [10,11,12] contradict the SLAC results, as follows. (*i*) For 20, 30 and 40 GHz the maximum surface gradient for a single cavity excited by the beam doesn't depend on frequency, and equals about 380 MV/m for very short pulse width [13] (at SLAC the same surface gradient was achieved in a single X-band cavity for pulse width 100 times longer). These differences are not understood (even—it seems—by SLAC researchers), but it is suggested that the CERN experiments were done under different conditions using different methods, as compared to other experiments performed at SLAC, KEK, and Budker INP. (*ii*) No significant difference was found at CERN between the maximum surface field for single cavities and various accelerating structures; in further contradiction to the SLAC results.

3. Proposal.

It is not possible to develop the next generation of linear colliders without careful investigations of the maximum achievable accelerating gradient for higher frequencies; this point has been enunciated repeatedly within the accelerator community (e.g., Snowmass2001). This knowledge is important for NLC, because exact information as to what maximum accelerating gradient can be available and what the optimal operating frequency should be may allow design of a collider upgrade to a center-of-mass energy which enhanced X-band technology will not allow. This is true whether the up-grade scenario involves discrete rf sources, or is based a two-beam (CLIC-like) architecture. In addition, at SLAC the breakdown investigations under way include development of models of this phenomena, and validation of these models will require experiments over a range frequencies including frequencies higher than X-band, but carried out under similar conditions. Because at present there is no evidence that the maximum achievable gradient grows with the frequency faster than the square root, one should operate at frequencies significantly higher than X-band to observe a clear effect of frequency. Assuming square root dependence, the maximum gradient for 34 GHz is expected to be 1.7 times higher. Besides, because this frequency is very close to CLIC's 30 GHz, it would be possible to compare the results to be obtained with CERN results. To be able to compare measurement results for S, X and Ka bands and to exclude extraneous effects, these measurements must be done using the same method as at SLAC: high-power RF amplifier, waveguide system, pulse compressor, variable pulse width, flexibility of conditioning process, etc. The Yale Beam Physics Laboratory's 34-GHz program to establish a Ka-band accelerator test facility satisfies these requirements. Experiments can begin in the coming months, right after the magnicon is put into operation. Design and fabrication of test accelerator structures can proceed in parallel with development of power enhancement devices such as pulse compressors, and components such as oversized waveguides, mode converters, etc. Support for development of high-power Ka-band transmission line components has recently been approved by DoE.

In order to achieve the maximum gradient one should make correct choices for details of the accelerating structure. We propose a test structure with both strong defenses against rf electrical breakdown and low peak surface magnetic field (in order to prevent pulse heating leading to metal fatigue). The improvements are based on the following innovations: (*a*) elliptical irises which reduce the maximum surface electric field: elliptical irises were suggested by the authors [15,16] and now are used in SLAC structures; (*b*) the first cell of the structure [17] that will operate in the TE_{020} mode, so as to eliminate an additional overvoltage caused by the input coupler; there is also no magnetic field enhancement near the coupling slot. The structure has a group velocity $v_{gr} = 0.05c$. This turns out to be a reasonable choice in light of experiments with various X-band accelerating structures at SLAC. These SLAC tests show upstream iris damage and phase advance changes as high power is applied. One explanation is that the higher group velocity at the upstream end of the structure leads to more energy being absorbed in a breakdown arc. It may also explain why early prototype structures at low group velocities performed well at high gradients (for example, a 75-cm long NLC structure with $v_{gr}/c = 0.05$ was processed to 90 MeV/m without any apparent phase change. A series of low group velocity ($v_{gr}/c \approx 0.05$) X-band structures are being built at SLAC to verify the model and as a first step to develop a high gradient version for NLC/JLC. Thus, the choice of $v_{gr}/c = 0.05$ described here appears altogether logical since it will allow comparison of maximum achievable gradients at Ka-band and X-band under similar conditions. Details of the structure design are given in [17].

Successful operation of the Omega-P Ka-band magnicon (anticipated to occur in late Summer 2002) will allow development to proceed for the 34.272 GHz accelerating structure even before the availability of a full set of high-power Ka-band components, such as pulse compressors, mode convertors, etc. This is possible since it is proposed to apply the technique commonly used in evaluation of accelerating structures, namely to operate the structure first in a standing-wave mode. In the standing-wave mode it is expected that surface fields and accelerating gradients of 690 MV/m and 180 MeV/m can be realized, using 30 MW of rf drive power fed directly to the structure from the magnicon. At a surface gradient of 690 MV/m in the traveling-wave mode, the accelerating gradient would be more than 340 MeV/m.

4. Personnel

Senior research staff that will conduct the proposed research include Dr. Oleg A. Nezhevenko and Dr. Vyachislav P. Yakovlev. Engineering design work for the accelerator structure(s) will be carried out by identified employees of the vendors. From the second year onwards, support for a postdoctoral researcher is requested; he/she would join the effort to participate in the extensive testing experiments that will commence after the first accelerator structure is fabricated and installed at the 34-GHz test facility. Assistance from other scientific and technical personnel will be available, as needed. Principal Investigator for the project will be J. L. Hirshfield, Professor Adjunct of Physics. Resumés for key personnel are available.

5. Budget estimate.

	year #1	year #2	year #3
1. design/engineering services	40,000	30,000	20,000
2. fabrication	60,000	70,000	80,000
3. post-doc salary	-	43,000	45,000
4. fringe benefits	-	15,050	15,750
5. travel, materials, supplies	5,000	5,000	5,000
6. overhead on items 3, 4, 5	3,175	40,037	41,751
7. totals	108,175	203,087	207,501

6. References.

Pulse heating:

[1] O.A. Nezhevenko, “On the Limitation of Accelerating Gradient in Linear Colliders Due to the Pulse Heating,” PAC97, Vancouver, 1997, p. 3013.

[2] D.P. Pritzkau and R.H. Seiman, “Results on an RF Pulse Heating Experiments at SLAC,” SLAC-PUB-8554, August 2000.

SLAC:

[3] G.A. Loew and J.W. Wang, SLAC-PUB-4647 (1988).

[4] G.A. Loew and J.W. Wang, XIVth Int. Symp. on Disch. and Elec. Ins. in Vacuum, Santa Fe, New Mexico, September 16-20, 1990.

[5] J.W. Wang, *et al*, “High Gradient Tests of SLAC Linear Collider Accelerating Structures,” SLAC-PUB-6617 (1994).

[6] C. Adolphsen, *et al*, “RF Processing of X-Band Accelerator Structures at the NLCTA,” LINAC2000, August, 2000, Monterey, Ca.

[7] C. Adolphsen, *et al*, Paper ROAA003, PAC2001.

[8] R. Miller, *et al*, Paper FPAH062, PAC2001.

[9] L. Laurent, “Windowtron” RF Breakdown Studies at SLAC and Snowmass Summary, RF2001, Snowbird, Utah, October 1-5, 2001.

CERN:

[10] C. Achard, *et al*, “ A 30 GHz Beam Driven High Gradient Single Cell Cavity Test,” CLIC Note 498, PS/AE Note 2001-010

[11] H.H. Braun, *et al*, “High-Power Testing of 30 GHz Accelerating Structures at the CLIC Test Facility,” CERN/PS 2001-009 (AE)

[12] D. Yu, *et al*, “High Power Test of 30 GHz Planar Accelerator,” CLIC Note 491

[13] W. Wuensch, private communications.

Budker INP:

[14] V.E. Balakin, *et al*, “Investigation of Ultimate Accelerating Gradient in Linear Accelerator VLEPP,” Proc. of the XIII Int. Conf. On High Enrgy Acc., Novosibirsk, 1987, v. 1, p. 144.

34 GHz structure:

[15] M.M. Karliner, O.A. Nezhevenko, B.M. Fomel, V.P. Yakovlev, "On Comparison of Accelerating Structures, Operating in the Stored Energy Mode", Preprint INP 86-146 (Novosibirsk, 1986, in Russian)

[16] O. Nezhevenko, D. Myakishev, V. Tarnetsky, V. Yakovlev, “TW accelerating structures with minimal electric field”, PAC95, Dallas, p. 1076

[17] O.A. Nezhevenko, V.P. Yakovlev, “Traveling-Wave Accelerating Structure at 34.4 GHz,” PAC99, New York