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Project Title “Development of a Tunable Dielectric Loaded Acceleration Structure”

1. Introduction.

Euclid Techlabs LLC, in collaboration with the Accelerator R&D group of the High Energy Physics Division of Argonne National Laboratory submits this Phase I report to present our Phase I results in the development of a new, crucial experimental device - the first tunable dielectric loaded accelerator (DLA). This report outlines Phase I of a three-phase program for the design, development and demonstration of a frequency tunable DLA.

The principal goal of this project was to develop a tunable DLA to allow one to adjust the phase velocity of the DLA after it has been assembled into its final form. The need for frequency tuning (or phase velocity adjustment) of any accelerating structure arises from the fact that the phase velocity of the assembled accelerating structure will, in general, differ from the design phase velocity due to various sources of error. In a DLA structure, these errors can be caused by machining tolerance of the dielectric dimensions, thermal expansion of the structure, dielectric constant heterogeneity, etc. In summary, the feasibility of making DLA structures practical is greatly advanced by the development of a frequency tuning method. This new frequency adjustment technique has straightforward applications to the design of externally powered DLA structures, multistaging dielectric based accelerators, wakefield bunch train generation and two-beam acceleration schemes.

The method used to vary the frequency of a DLA structure consists of a thin layer of a ferroelectric material backing a layer of conventional ceramic. A DC bias voltage is used to vary the permittivity of the ferroelectric layer and thus tune the overall frequency of the DLA structure. In this report, a model for this device is given and an experimental test is presented. We have identified a suitable material for this application: a BST-MgO (BSM) ferroelectric composite material with a dielectric constant of 300 - 500. A tuning range of (3 - 5) % could be achieved for X-band and Ka-band dielectric based accelerating structures.

Critical technologies relevant to the demonstration of the tunable DLA structure have been demonstrated in Phase I of the project:

- ❑ Development of a ferroelectric material with extremely high tunability of 25-30 % at 4.5 V/ μm bias field and dielectric loss factor as low as $(4-5)\times 10^{-3}$ at X-band;
- ❑ A new “transparent” dc contact design for the tunable DLA has been tested, and a high vacuum dc connector has been proposed;
- ❑ Development and experimental testing of a prototype planar tunable DLA structure. A frequency shift of 160 MHz has been demonstrated;
- ❑ The temperature dependence of the tunable BSM ferroelectric has been studied and the use of thermoconductive AlN layer has been proposed for structure temperature control;
- ❑ Cylindrical and planar tunable DLA structures have been simulated with optimized parameters.

In the framework of Phase I of this project the ferroelectric material to be used as an additional layer in the accelerating structures has been manufactured and the required tunability $\Delta\epsilon/\epsilon$ of 25- 30% at 4-5 4.5 V/ μm dc bias field and dielectric losses of $4-5\times 10^{-3}$ at X-band and $5-8\times 10^{-3}$ at Ka-band have been achieved. We have carried out a short dc pulse dielectric response experiment and demonstrated tunability of 8-9% at 2 V/ μm (corresponding to 20-23 % at 4.5 V/ μm) with a 10 μsec long dc pulse. We proposed and experimentally tested a new method of supplying a dc bias field into the dielectric loaded accelerating structure: the transparent dc contact design allows higher dc bias voltages and a correspondingly higher overall tuning frequency range of the structure. Note the rf transparency of the proposed dc contact design.

We fabricated and tested a tunable planar 11.424 GHz prototype DLA structure (ferroelectric permittivity of 450, loss factor of 5×10^{-3}) which, when excited by an electron beam, will allow an overall frequency tunability of 2.5-3.5 %. We have tested a prototype tunable DLA structure (a reflective rectangular resonator partially filled with the linear ceramic and ferroelectric layers) and a frequency shift of 120-160 MHz at 2 V/ μm has been demonstrated. Note that this corresponds to a 250-300 MHz frequency shift of a double-sided tunable DLA at 4-5 V/ μm bias voltages.

Temperature control is an important issue for the success of the tunable DLA concept. We have measured the dielectric permittivity at 70-310 $^{\circ}\text{K}$ at 1MHz and at 280-310 $^{\circ}\text{K}$ at Ka band frequencies. We gave particular emphasis to studies of the temperature rise of a typical dielectric loaded accelerating structure operating at X-band at 10-50 MW input power, 500 nsec pulse length and varying pulse repetition rates. We proposed a thermoconductive AlN ceramic design for the tunable DLA structure able to operate reliably at 100 pps replate.

Dielectric response parameters of the BSM ferroelectric layer have been estimated and measured. Numerical simulations of the cylindrical and planar tunable DLA structures have been completed and the accelerating gradient, shunt impedance, power attenuation, quality factor and field enhancement parameters have been optimized. Details of the tunable DLA experiment have been presented at the Particle Accelerator Conference in May 2005 [36].

2. Phase I Results

2.1 Phase I Technical Objectives

The overall objective for the proposed Phase I program is the design, development, and fabrication of a planar ferroelectric tunable DLA. Phase I culminated in a low power test of the 11.424 GHz planar, tunable, ferroelectric-ceramic DLA structure to demonstrate a frequency shift of 200 - 300 MHz.

The Work plan includes the following tasks:

- ❑ Manufacturing of the BST ferroelectric substrates of 11.424 GHz, dielectric constant of 300 - 600, loss tangent $\tan \delta = (3 - 5) \times 10^{-3}$, tunability factor of 1.15 - 1.20.
- ❑ Microstrip configuration design and development to supply bias DC field in the range of (2 - 8) V/ μm into the ferroelectric substrate for the tuning of the effective dielectric constant of the BST substrate. Insertion loss reduction. Biasing dc testing.
- ❑ Numerical simulations of the wakefields and frequency adjustment of the double layer tunable DLA structure excited by the beam train. Beam dynamics simulations of a drive beam bunch train passing through the tunable DLA structure.
- ❑ Design and development of a planar 11.424 GHz double layer ferroelectric-ceramic structure made of the ceramic substrate, dielectric constant of (9 - 16), loss factor of $(2 - 4) \times 10^{-4}$ and BST composition ferroelectric substrate (250 - 500) μm thickness dielectric constant of 250 - 600, loss tangent of $\tan \delta = (3 - 5) \times 10^{-3}$, leading to an overall frequency shift range of (250 - 300) MHz (2.5 - 3%).
- ❑ Final bench test of the tunable ferroelectric 11.424 GHz DLA structure and frequency adjustment measurements.
- ❑ Formulation of the proposal for the Phase II program. Final report preparation.

2.2. Introduction.

Dielectric Based Accelerators. In this section, we briefly describe the DLA structure. Dielectric loaded accelerator (DLA) structures excited by a high current electron beam or an external high frequency high power RF source have been under extensive study in recent years [1-7]. The basic RF structure is very simple - a cylindrical, dielectric loaded waveguide with an axial vacuum channel is inserted into a conductive sleeve. In wakefield acceleration, a high charge, (typically 20 - 40 nC), short, (1 - 4 mm) electron drive beam generates TM₀₁ mode electromagnetic Cherenkov radiation (wakefields) while propagating down the vacuum channel. Following at a delay adjusted to catch the accelerating phase of the wakefield is a second electron witness beam. The witness beam is accelerated to high energy by the wakefield produced by the drive beam. [1-3,6,7]. This DLA structure can be excited by an external RF power source as well [16]. A series of proof of principle experiments have been successfully performed at Argonne's Advanced Accelerator Test [1] and Argonne Wakefield Accelerator facilities [6-7,13-15,17-22]. Other important experimental work in this area has been done by the Columbia-BNL and Omega-P - Yale University groups [8-11]. SLAC has contributed in the area of dielectric acceleration as well [12]. A novel planar dielectric structure accelerator based on SiC material has been described [29].

Tunable Dielectric Loaded Accelerating Structure. A DLA structure, unlike a conventional metallic one, admits a unique possibility for implementing tunability by using a nonlinear material as part of the dielectric loading of the accelerating structure [1-6]. The frequency of a metallic accelerating structure is defined entirely by its geometry. DLA structures, on the other hand, have an additional parameter that determines the frequency spectrum --- the dielectric constant of the loading material. There are two classes of materials whose electromagnetic properties can be adjusted by external fields: **ferrites**, controlled by magnetic fields, and **ferroelectrics** [24-28], controlled by electric fields. Ferrite materials do not appear to be practical solutions for use in high frequency high gradient accelerators because of the extremely high loss factors and also because of possible interference of the high magnetic fields with the electron beam optics. We propose a new scheme that will allow control of the dielectric constant (and consequently the frequency spectrum) for dielectric waveguides by incorporating externally biased ferroelectric layers [23,30-33]. The use of ferroelectrics for tuning purposes would appear to be a natural solution, except for the fact that most ferroelectrics are very lossy in the > 10 GHz frequency range. The typical loss factor for commercially available $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ (BST) ferroelectric, commonly used at room temperature, is $(1-3)\times 10^{-2}$ around 10 GHz [24-28] (our recently developed material achieves 5×10^{-3} at 10 GHz), compared to $(1-5)\times 10^{-4}$ for a good linear microwave ceramic [34,35].

Tunable DLA structure design uses a combination of ferroelectric and ceramic layers to permit tuning of a composite ceramic-ferroelectric waveguide while keeping the overall material loss factor in the $(4-5)\times 10^{-4}$ range. One can show that the losses in our composite structure are comparable to the losses in conventional DLA structures that consist of a single dielectric cylinder inserted into a conductive copper jacket.

The most notable feature of the tunable DLA is the replacement of a single ceramic by a composite of 2 layers. The inner layer is ceramic, with permittivity ϵ_1 typically in the range of 4 - 36. The outer layer is a film made of BST ferroelectric, of permittivity ϵ_2 , placed between the ceramic layer and the copper sleeve. DLA structure tuning is achieved by varying the permittivity, ϵ_2 , of the ferroelectric film by applying an external DC electric field across the ferroelectric. This allows us to control the effective dielectric constant of the composite system and therefore, to control the structure frequency during operation.

The ferroelectric layer is actually 10 times thinner than the ceramic layer. For structures in the 10 GHz frequency range the typical thickness is (2-3) mm for the ceramic layer and (200-300) μm for the ferroelectric film. It should be mentioned that this geometric ratio of 10 plays an important role for this structure design. The relative permittivity of the BST ferroelectric is typically in the range of 1000-2000. One can reduce this to 300-500 by using a mixture of BST and oxides [34,35] to avoid any extra magnetic losses at the conducting walls. A DC field can vary the permittivity of the BST-oxide material over the range of (20-30) % or about 100 units. Adjustment of the permittivity of the ferroelectric outer layer permits adjustment of the phase velocity of the structure. The loss factor of this composite DLA structure will be about the same as the ceramic-only structure due to the geometric ratio, since the volume of high loss ferroelectric material is much smaller than the basic ceramic.

A (9-11) GHz tunable DLA structure has been tested in Phase I of the project with a permittivity 400-500 ferroelectric layer 500-1000 μm thick, tunability of 25-29%, loss factor of $(4-5)\times 10^{-3}$, and a peak applied DC bias field of 4.5 V/ μm . An overall structure tunability of **160 MHz** was demonstrated. This tuning effect is fast and programmable in real time during operation of the accelerator.

2.3 Summary of Phase I Results

The principal goal of this project is a proof of the nonlinear tunable ferroelectric material concept for linear accelerator applications and a tunable DLA structure experimental demonstration.

In Phase I we have fabricated and experimentally tested BST ferroelectric samples which, when a dc electric field is applied, allow varying of the effective dielectric constant of the rf resonator/waveguide loading material and, therefore, tuning and control of the operating frequency of the device. We have developed BST-MgO ferroelectric samples to be able to test the dielectric response at X-band and Ka-band as well as to define the tunability range of the newly developed nonlinear ceramic.

We designed and tested a prototype planar 11.424 GHz double layer ferroelectric-ceramic structure consisting of a linear ceramic substrate (dielectric constant of (20 - 100), loss factor of $(2 - 4) \times 10^{-4}$) and a BSM composition ferroelectric substrate of 0.5-1.0 mm thickness, dielectric constant of 400 - 500, loss tangent $\tan \delta = (4 - 5) \times 10^{-3}$ at X-band and tunability of 1.2-1.3 at 4-5 V/ μm bias field. The frequency shift of the one-sided tunable DLA of 120-160 MHz has been demonstrated leading to an overall DLA structure frequency tuning range of (250 - 300) MHz (2.5 - 3) % [36].

2.3.1. Ferroelectric Sample Fabrication. Material studies.

Figure 1. Ceramic waveguide layer made of BST-MgO (BSM) ferroelectric with wall thickness 600 μm , diameter 10 mm and length 4.5 cm. The sample has been fabricated for the 11.424 GHz tunable DLA structure.

We have studied the nonlinear dielectric properties of the newly developed bulk BST-MgO (BSM) composite ferroelectric material. We measured the dielectric constant ϵ , loss factor $\tan \delta$, tunability $\Delta\epsilon/\epsilon$ and the temperature dependence of the BSM composition at 1 MHz, 3-8 GHz, and at X-band and Ka-band as well. It was found that the dielectric permittivity of the BSM composition did not exceed 500, loss factor was of $(4-6) \times 10^{-3}$ at X-band and $(6-8) \times 10^{-3}$ at Ka-band and tunability range of 1.22-1.29 at 3.8- 4.5 V/ μm dc bias electric field.

Special attention has been paid the short dc voltage pulse measurements. The set of the BSM samples have been tested with a pulse rise time of 10 μsec with a front edge of a few ns. The BSM

samples demonstrated 5.8-7.5 % tunability at 2 V/ μ m bias field magnitude. This tunability level corresponds to 15-24 % tunability at 4.5 V/ μ m bias voltages for the short dc pulses applied.

Various BSM ferroelectric ceramic samples have been fabricated in Phase I of the project. We have manufactured disk ferroelectric samples for dielectric response measurements in the 1 MHz frequency range. BSM ferroelectric substrates of dimensions $22.8 \times 25.0 \times (0.5-1.0)$ mm³ have been developed for the X-band tunable reflective resonator design. We also fabricated and tested a thin 200 μ m substrate of 7.2×3.4 mm² surface area for Ka-band accelerator applications.

We have achieved a unique result in ferroelectric cylindrical waveguide manufacturing: the wall thickness of the 4.5 cm long BSM ferroelectric did not exceed 600 μ m, Fig. 1. We have attained 200-300 μ m wall thicknesses for short 1-1.5 cm tubes recently. The successful demonstration of this technology enables the development of new capabilities for tunable dielectric based accelerating structures.

2.3.2 Design and Development of the Planar Double-Layer Tunable Resonator.

(a)

(b)

(c)

Figure 2. The rectangular reflective resonator using transparent dc contacts to provide the bias field. (a) – top view. (b)- waveguide flange view showing the linear and ferroelectric ceramic substrates. (c) ferroelectric sample with the deposited Cr dc contact .

Adjusting the permittivity of the ferroelectric requires the use of a DC bias field. The electrode geometry used to produce the bias field must be compatible with the rf accelerating mode of the structure. The transparent electrode technology was developed to improve the overall tunability of the 11.424 GHz tunable dielectric loaded accelerating structure. It allowed us to overcome the high voltage biasing limitations of the inter-digital bias electrode topology that had been used previously for tunability measurements of ceramic substrates [35]. The transparent electrode technology presented here enables higher biasing voltage to be applied to the ferroelectric substrate as well as providing the required degree of dc field homogeneity inside the BSM substrate, Fig. 2.

We designed a Super High Vacuum dc adapter based on a commercial 20 kV dc connector for supplying the dc bias voltage to the operational dielectric based accelerating structure as well.

2.3.3 Tunable Dielectric Loaded Resonator (prototype DLA structure) demonstration.

The LSM mode spectra of the “transparent contact” tunable reflective resonator have been calculated. The 3D model of the resonator with a rectangular $10 \times 10 \text{ mm}^2$ coupling section and 0.5 mm slot for the ceramic shoulder (dc connector) have been simulated. We report here the loss factor measurements of the X-band reflective resonator partially filled with the BST-MgO (BSM) ceramic substrate and the experimental study of a 7.8 GHz bulk dielectric resonator. Both methods yielded loss factor values of $(4-6) \times 10^{-3}$ in the (8-12) GHz frequency range.

Figure 3. S11 parameters of the X band “transparent contact” resonator, BSM substrate of $23 \times 19 \times 1.0 \text{ mm}^3$, permittivity of the ceramic and ferroelectric of 20 and 481 respectively, frequency shift of 116 MHz (first resonance) and 162 MHz (second resonance) at $1.7 \text{ V}/\mu\text{m}$ bias field.

The overall frequency shift of the X-band prototype tunable accelerating structure has been demonstrated in the range of 100-160 MHz at (1.7-2.5) V/ μ m applied dc bias field, Fig.3. This frequency shift of the prototype reflective resonator corresponds to the 200-250 MHz tuning frequency range of a double-sided planar dielectric loaded accelerating structure.

2.3.4 Dielectric Response of the BSM ferroelectric ceramic at Ka-band.

The dielectric permittivity, quality factor and loss tangent have been measured for the newly developed BST-MgO (BSM) ferroelectric substrates in the 20-36 GHz frequency range. We developed the reflective resonator technology for measurements on the basis of the LSE eigenfunction solutions and 3D finite element simulations for the reflective rectangular resonator (planar prototype DLA structure). The substrate testing yielded the dielectric constants in the range of 310-515 with loss factors of $(5-8) \times 10^{-3}$ in the 20-36 GHz frequency range.

2.3.5 Temperature dependence of the BSM ferroelectric parameters.

The dielectric constant variation with temperature of the BST-MgO (BSM) ferroelectric substrates to be used for the tunable DLA designs has been studied. We measured the dielectric permittivity at 70-310 $^{\circ}$ K at 1MHz and at 280-310 $^{\circ}$ K at Ka band frequencies. The dielectric constant variation with temperature has been determined to be in the range $\Delta\epsilon/\Delta T = 3.12-3.30$ $^{\circ}$ K.

We especially studied the temperature rise of a typical dielectric loaded accelerating structure operating at X-band at 10-50 MW input power, 500 ns pulse duration and 1-10-100 pps replate. It was shown that at the power levels used and 1-10 pps replate there is no noticeable temperature rise that can affect the dielectric constant variation. We have designed planar and cylindrical structures that are able to operate reliably at 100 pps rep rate. The key issue of our new design is a thermoconductive AlN ceramic layer between the ferroelectric and the copper sleeve. This ceramic will provide both heat extraction and reduction in wall losses for the structure.

2.3.6 Numerical Simulations of the *Cylindrical* Tunable Dielectric Based Accelerating Structures.

Ka-band and X-band *cylindrical* DLA structures with a ferroelectric layer introduced for accelerating mode frequency control have been considered. The structure parameters have been optimized for the required level of overall frequency tunability, accelerating gradient, wall loss factor as well as the parasitic rf field magnitude inside the tuning layer. Optimized parameters of the tunable DLA structure required for wakefield and externally powered structure designs have been presented.

2.3.7 Numerical Simulations of the *Planar* Tunable Dielectric Based Accelerating Structures.

Ka-band and X-band *planar* tunable DLA structures with a ferroelectric tuning layer have been simulated. Optimized parameters of the prototype tunable DLA structure required for wakefield and externally powered structure designs are presented. We have observed higher power attenuation compared to the X-band cylindrical structure design. At the same time, the planar design facilitates matching section fabrication and high power testing. Our simulation showed an acceptable level of power attenuation (9 dB/m) and quality factor greater than 10^3 .

3. References.

1. W. Gai, P. Schoessow, B. Cole, R. Konecny, J. Norm, J. Rosenzweig and J. Simpson, Phys. Rev. Lett. 61, 2756 (1988).
2. A. Piwinski, DESY Report No. 72/72 (unpublished).
3. R. Keinigs, M. Jones and W. Gai, Part. Accel. 24, 223 (1989).
4. R. Ruth, A. Chao, P. Morton and P. Wilson, Part. Accel. 17, 171 (1985).
5. E. Chojnacki, W. Gai, P. Schoessow and J. Simpson, in Proceedings of Particle Accelerator Conference, San Francisco, May 6-9, pp.2557-2559 (1991).
6. W. Gai and J. Simpson ANL_HEP_WF_173 (1993).
7. W. Gai, A.D. Kanareykin, A.L. Kustov, J. Simpson, Phys. Rev. E, v. 55, N 3, pp. 3481-3488, (1997).
8. T-B. Zhang, J.L. Hirshfield, T.C. Marshall and B. Hafizi, Physical Review E56, 4647 (1997)
9. T.C. Marshall, J-M. Fang, J.L. Hirshfield, S.Y. Park. AIP Conference Proceedings #569 (AIP, New York) p.316-325 (2000)
10. T.C. Marshall, C. Wang, and J.L. Hirshfield, Physical Review ST-AB, v. 4, 121301 (2002)
11. T. C. Marshall, J.-M. Fang, J. L. Hirshfield, Changbiao Wang, V. P. Tarakanov, and S. Y. Park. AIP conference Proceedings v. 647 (AIP, New York), p. 361-370 (2002)
12. M. Hill, C. Adolphsen, R. Callin, X. Lin, M. Seidel, T. Slaton, D. Whittum. Phys. Rev. Letters, v.87, N9, p.094801 (2001)
13. Barsukov K.A., Kanareykin A.D., Kustov A.L. International J. of Modern Physics, (Proc. Suppl.) 2A p.531-533 (1993).
14. W. Gai, Kanareykin A.D., J.D. Simpson. 1995 Linear Collider Workshop, KEK Proceedings 95, Tsukuba, Japan, (1995).
15. W. Gai, Kanareykin A.D., A. Kustov and J. Simpson. AIP Conference Proceedings 335 (AIP, New York), p.463-473, (1995).
16. P. Zou, W. Gai, A. Kanareykin, R. Konecny, X. Sun and T. Wong. Review of Scientific Instruments, 71, 6, pp. 2301-2304, (2000).
17. Wei Gai, R. Konecny and J. Simpson, In Proceedings of the 1997 Particle Accelerator Conference, (1999).
18. Kanareykin A.D., Sheinman I.L., Nenasheva E.A., Kartenko N.F., Gai W., Simpson J., In book : Physics at the Turn of the 21st Century, St. Petersburg, Russia, pp 57-58, (1998).
19. J. Power, Wei Gai, and P. Schoessow, Phys. Rev. E60, p. 6061, (1999).
20. J.G. Power, M.E. Conde, W. Gai, A. Kanareykin, R. Konecny, and P. Schoessow, AIP Conference Proceedings 569, (AIP, New York), p.258-265. (2001)
21. J.G. Power, W. Gai, X. Sun, A. Kanareykin. Proceedings of the 2001 Particle Accelerator Conference, Chicago, IEEE 2001, p.114-116 (2001).
22. A. Kanareykin, W. Gai, J. Power, E. Sheinman and A. Altmark. AIP Conference Proceedings v. 647 (AIP, New York), p. 565-576 (2002)

23. A. Kanareykin, I. Sheinman, A. Altmark. Technical Physics Letters, v.28, pp. 916-919, (2002).
24. O. Vendik. Ferroelectrics at Microwave. Moscow, Radio, p.44, (1979).
25. B.A. Rotenberg. Ceramic capacitor dielectrics. RFFI. St.Petersburg, (2000).
26. M. DiDomenico Jr., D.D. Johnson, R.H. Pantell. J.of Appl. Phys. v.33, N.5, p.1697 (1962)
27. K.M. Johnson, J.of Appl. Phys. v.33, N.9, p.2826 (1962)
28. O.G. Vendik, E.K. Hollman, A.B. Kozirev, A.M. Prudan. J.of Superconductivity, v.12, N 2, p.325 (1999).
29. G. Shvets. AIP Conference Proceedings, v. 647, 371 (2002).
30. A.M. Altmark, A.D. Kanareykin, I.L. Sheinman. Technical Physics Letters, v.29, pp.862-865, (2003).
31. A. Kanareykin, W. Gai, J. G. Power, E. Nenasheva, S. Karmanenko, I. Sheinman. Proceedings PAC-2003, pp. 1888-1890 (2003).
32. A. Kanareykin, A. Altmark, I. Sheinman. Proceedings PAC-2003, pp. 1897-1899, (2003).
33. A. Kanareykin, A. Altmark, I. Sheinman. Proceedings PAC-2003, pp. 1891-1893, (2003).
34. E.A. Nenasheva, A.D. Kanareykin, N.F. Kartenko, S.F. Karmanenko. Proceedings of ICE2003, Journal of Electroceramics, v.13, 235-238 (2004).
35. S.F. Karmanenko, A.D. Kanareykin, E.A. Nenasheva, A.I. Dedyk, A.A. Semenov. Proceedings EMF2003, Integrated Ferroelectrics, v.61, 177-181 (2004).
36. Kanareykin et al. Experimental Investigation of A X-band Tunable Dielectric Accelerating Structure. Proceedings PAC 2005, to be published.