RADIOTECHNICAL INSTITUTE ACTIVITY IN THE LINAC FIELD

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For many years, the Radiotechnical Institute has been involved in a number of projects aimed at constructing linear accerators for protons or electrons. This report summarizes the experience gained and covers 1) some problems of developing linacs to serve as meson or neutron generators, 2) results of study of a linac with asymmetric alternating phase focusing, and 3) electron linac projects.

1. Meson-Factory Linac

A number of unusual problems arise when developing and designing a linac to produce a few-hundred-MeV, 1-mA average current. These problems are quite different from what one encounters in designing a linac to be a proton synchrotron injector, and these were the problems faced by our Institute as it was engaged in a linac project for a meson factory sponsored by the USSR Academy of Sciences. Specifications of this linac, its basic design solutions, and the various project stages were reported at several conferences[1-3] and were also described in a separate publication.[4,5]

The design works have been completed and some working blue-prints have been passed to the industry. Full-scale prototypes of both a 100-MeV module and a higher-energy module have been tested at designed power levels. Each module comprises a resonator, an RF power amplifier channel, and vacuum hardware. The accelerator control, RF field control and beam-measuring systems have been tested.

1.1. Beam dynamics

Basic problems of beam dynamics were discussed in Ref.6 and 7. In this works, formalism has been derived to represent error effects in a focusing channel, and the transverse positioning of proton and H^- beams being accelerated simultaneously has been studied. Therefore, only more recent results are discussed here, i.e., effects of space charge and of nonlinear alternating-gradient fields.

The following problems have been considered in terms of space-charge effects:

1) single-component beam bunching,

2) simultaneous bunching of H^+ and H^- ions in a common beam-transport channel.

These problems were solved on a computer. The real bunch was divided into a number of macroparticles and the Vlasov equation was integrated along a macroparticle path. B.I.Bondarev and V.S.Kabanov used this technique to solve the above problems in a 6-dimensional phase space with the space charge taken into account[8]. A computational theory has been developed that enables the most efficient flow-diagram to be chosen for specific problem. Theoretical studies led to complex algorithms that 1) provide for a conservative model implying that the net energy or the net momentum are conserved on a Lagrangian or Eulerian mesh, 2)give the highest possible accuracy for the Coulomb forces (i.e. the lowest rms deviations), and 3) make kynetic parameters (scattering cross section, etc.) of a set of macroparticles match that of the real bunch.

The following results were obtained for H^+ and H^- ions being simultaneously accelerated at a current between 10 and 200 mA:

1) Nonlinear interaction between bunches and intense energy exchange lead to any longitudinal momentum modulation ceasing to exist during bunching for phase angles $|\varphi-\varphi_s| > \pi/2$ and to ions being trapped into the center of an unlike bunch.

2) The effective emittance increases in a buncher by as much as 90 per cent at 200 mA due to nonlinear space-charge forces as well as due to coupling between longitudinal and transverse motions. Another increase by about 15% occurs due to the effects produced by unlike bunches.

3) Effects 1 and 2 are significant for currents above 100 mA and do not essentially affect the beam quality at peak currents to be accelerated in the meson factory linac.

An analytic approach to the space-charge problem has been developed. This involves the distribution function parametrized and the Vlasov equation approximately solved by minimizing a functional[9]

$$\Phi(f) = \int (\partial f/\partial t + \{f, H_f\})^2 dx \ .$$

With a "model function" having elliptic symmetry in the phase space it appears possible to find conditions for a beam with space-charge to be matched to a periodic focusing system.

Effects of nonlinear focusing fields (pole pieces deviations from a hyperbolic shape) have been studied by B.I.Bondarev, A.P.Durkin, and L.Yu.Soloviev. They have derived closed-form relationships between the beam size and the nonlinear-field harmonic amplitude, its number, the focusing-channel parameters. Analysis of these relationships with different kinds of nonlinearity shows that, in addition to nonlinearities, the lens refractive strength and the transverse oscillation frequency contribute to the beam radius increase. Resonances may build up if transverse oscillation period is a multiple of focusing-period length. These results will be discussed in detail elsewhere.

Nonlinear components adopted in the meson factory linac (1% in the 100-MeV section and 0.25% in the higher-energy section) were estimated to result in a fractional beam size increase of less than 5%.

1.2. Accelerating structures for Energies above 100 MeV

Two accelerating $\pi/2$ -structures have been developed at the Radiotechnical Institute: one with discs and washers[10] and the other with ring coupling cells[11] like the structure developed at Los Alamos(Fig.1,2).

In order to study their relative characteristics full-scale prototype tanks were manufactured and tested at nominal and higher power levels. Both structures showed good experimental results in accordance with design parameters. As for multipactor effects they are approximately equal. After 15-20 hours of RF training the nominal power level was achieved and there were no multipactor discharges and break-downs in resonators after that. Their shunt impedances are also approximately equal (24 MOhm/m for disc-and-washer structure and 25.5 MOhm/m for ring-coupled structure at β = 0.43).

At the same time the disc-and-washer structure has two very important advantages over the ring-coupled structure: high value of the coupling coefficient K_c and high vacuum (pumping) conductivity. At energies of 100-600 MeV K_c is 35-47% accordingly. For ring-coupled structure it equals 6-7%. With increase of K_c the sensitivity of RF field distribution to perturbations decreases essentially, which makes it much more easy to adjust resonators and encreases reliability. Fig.3 shows a measured dispersion curve for $\beta \simeq 0.8$ (600 MeV) of a model resonator with disc-and-washer structure. This curve is linear through the operating range and the nearest modes are placed symmetrically relative to the operating mode.

High vacuum conductivity of this structure made it possible to simplify the pumping system and on the other hand to get in future higher vacuum which is very essential for acceleration of intense H^- beams.

These advantages of the disc-and-washer structure were determinative while choosing it for the meson factory linac. From our point of view this structure is very perspective for acceleration of high intensity beams.

1.3. RF Power Supply and Field Control Systems

In recent years, much efforts have been devoted to constructing experimental modules to search for better design of amplifier channels and RF coupling units.

The amplifier channel characteristics achieved on full-scale models are better than designed values (see Table 1, designed values are shown in brackets),(Fig.4).

Table 1

Parameters	Units	Accelerator 1-st part	Accelerator 2-nd part
Operating Frequency	MHz	198.2	991
Repetition Rate	Hz	100	100
Pulse Duration	μs	up to 700 (300)	up to 170 (120)
Peak Power	Mw	5 (4)	4.75 (3.8)
Awerage Power	Kw	200	50

Several control systems are envisaged in the project. These are systems to control the RF amplitude and phase in each of the cavities, to control the phase relationship between any two adjacent cavities, to eliminate coherent phase (longitudinal) oscillations and to thermocontrol resonator frequency[12-15]. Recent experimental studies have led us to revize some decisions made earlier and to make the control hardware for the 100-MeV part somewhat more sophisticated. First, RF output power control by varying the driving RF power has not been achieved. While this type of control is readily obtained in the first three amplifier stages, an output power reduction by some 10 or 15% off the designed level results in spurious VHF oscillations in the output 5-MW stage (GI - 54A triode) accompanied by breakdowns in the tube. Therefore, field amplitude in the 100-MeV part will be controlled by varying the plate voltage of the GI-54 A triode similar to how it is done at Batavia, Brookhaven or Los Alamos.

Also, model experiments have shown significant coupling to exist between two systems that provide fast amplitude and phase control through controlled parameter (accelerating field), regulator (fast phase-shifter and plate modulator of the output stage) and load (beam current). In order to avoid this coupling special balancing cross-couplings had to be introduced in the controllers to decouple the two systems.

1.4. Beam Measuring System

It was reported earlier[3] that non-intercepting beam-measuring techniques were optioned. These make use of the appropriate field modes excited in a measuring cavity by the beam in question[16].

The hardware available at present enables the following quantities to be measured:

a) the currents of protons and negative ions being accelerated simultaneously, with a threshold sensitivity better than 1 μA ,

b) the beam transverse position, with a threshold sensitivity about 0.1 mm at a peak current of 50 mA,

c) the average particle velocity, with an accuracy of 0.05% at relative measurements and of 1% at absolute measurements,

d) the transit time through a resonator (with an accuracy of 2^o-3^o relative to phase angle).

Prototype systems to measure the bunch average velocity have been tested straight on the I-100 injector (100 MeV output energy) to the Serpukhov PS. The operation of the latter has shown the non-intercepting system to justify the expectations.

In conclusion it is worth noting that experience gained at RTI during meson factory linac development may be successfully used in neutron generator linac projects.

II. Studies of Ion Linacs Using Asymmetric Alternating-Phase Focusing

The asymmetric alternating-phase focusing (AAPF) implies a general class of techniques to provide for simultaneous longitudinal and transverse beam stability due to the accelerating field itself. These techniques are based on the alternating-phase focusing of Good and Fainberg[17,18]. They suggested that the sign of synchronous phase alternate periodically along the linac. Early versions of this type of focusing were limited due to a low trapping factor. What made it possible to increase the trapping factor was a suggestion by V.V.Kushin to introduce an asymmetry in the structure of accelerating/focusing period.[19] This asymmetry is attained by periodically modulating the modulus of synchronous phase[20] and the field amplitude[21] along the linac. These modulations may follow different schemes [22-24]. The studies at the Institute showed that a trapping phase region 60 or 70 degrees wide is possible with the AAPF and this conclusion has been verified on an experimental linac[25].

During last 2-3 years AAPF studies continued in two directions. The first one relates to the computation of, designing and experimenting with the beginning part of an AAPF proton linac having a relatively low injection energy. This low-energy region is characterized by a strong dependence of stability on the gap field structure and on the space-charge effects. Computations showed that with aperture radius R greater $0.2\beta\lambda$ stability can be lost.

The aperture limitation leads to an upper limit of accelerated current available with a given injection energy. This limit is approximately given by

$$I = 22 \times (E_m R^2/\lambda) \times \chi \quad (mA)$$

with longitudinal space-charge repulsion taken into account. Here, E_m is field amplitude (2.5 to 5 MV/m or more in an AAPF linac), λ is wavelength (usually 1.5 or 2 m), R is aperture radius (4 or 5 mm with an injection energy of 100 keV), and χ is a function representing the parameters of structure period. With the most advantageous FODO period having χ = 0.04 to 0.06, the limiting current is 20 or 25 mA.

These estimates have been verified by computing the bunch motion in the beginning part. A macroparticle model was used to account for space-charge effects. The upper limit of accelerated current is shown in Fig.5 as a function of the injected current in an optimal mode of operation. Trapping factor is equal 16% (phase trapping region of 60^o). From this dependence one can estimate the upper proton current limit to be 12-15 mA instead of 20-25 mA, calculated by the above approximate equation.

An experimental linac was constructed (Fig.6) to study the AAPF behaviour in the beginning part with the following parameters: the accelerating field frequency is 150 MHz, the injection energy is 100 keV, the output proton energy is 1.8 MeV, the number of gaps is 10, the gap field is 150 kV/cm, the acceleration rate is 5 MeV/m, the total linac length is 40 cm, the diameter is 40 cm, the aperture diameter is 8 mm. An H-type (interdigital) structure is used. In the first six gaps, a FODO structure is adopted with the synchronous phase being alternately -65 or 55 degrees. This structure provides for optimum trapping conditions. In the remaining gaps, the synchronous phase varies to become 27.5, 0, -27.5 degrees, respectively. A rather low output energy was chosen so that no neutrons could be produced in the target.

Experimenting on this linac has begun. An output current of 4 mA at the designed energy has been obtained with 30 mA injected. The 13% trapping factor is lower than the calculated 16% value.

The second direction in the AAPF studies at the RTI involves a linac project to accelerate U^{7+} ions from 0.012 MeV/u up to 3.0 MeV/u. Application of AAPF for heavy ion acceleration is attractive because at low β it permits to use H-resonators which provide high energy gain at high value of shunt impedance. And besides the resonators themselves become more simple due to absence of special focusing elements.

The heavy ion linac is designed to consist of two parts in order to optimize shunt impedance, particle trapping and resonator geometry. In the first part with operating frequency 25 MHz the U^{7+} ions will be accelerated from the injection energy up to 0.3 MeV/u. After that they will be reinjected into the second part with operating frequency 75 MHz and accelerated up to the final energy. Resonator diameter is approximately 0.9-1,2 m. The full accelerator length will be 40 m approximately. Study at the RTI showed that heavy ion linac with AAPF can successfully compete with other types of heavy ion accelerators.

III. Electron Linacs

A 60-MeV electron linac with a peak pulsed current of 1 A has been developed and commissioned for the Kurchatov Atomic Energy Institute[26]. This linac is to be used in a series of studies in the field of solid-state physics and time-of-flight neutron spectroscopy.

The main difficulty to be solved was the beam blow-up. The underlying effects in a relatively long pulse as well as possible countermeasures were considered elsewhere (e.g., Re.27 and 28). The following countermeasures were adopted in this project: the structure chosen was of a $2\pi/3$ type with varying dimensions and radial slits also provided in the loading disks. The linac consists of six sections, the first one providing for bunching at a 16.5 cm wavelength. The a/λ parameter varies from 0.12 at the input up to 0.1 at the output (a is disc aperture radius and λ is wavelength) in each of the five $2\pi/3$ accelerating sections. Each disc has two orthogonal slits.

The tests showed that these countermeasures are sufficient to provide for the designed output current with no blow-up effects observed at different modes of operation.

With pulses of 0.25, 0.05 or 0.01 μs duration the linac operates in a stored-energy mode. In principle, this mode presents an opportunity of increasing the beam current above its quasi-steady-state level. However, such an encrease is accompained by a wider energy spread. Table 2 shows beam parameters for several modes of operation.

Table 2

60-MeV ACCELERATOR BEAM PARAMETERS

Pulse length, μs	Peak current, A	FWHM energy spread, %
5.5	1.1	5.3
.25	.75	69
.05	3.2	33
.01	3.3	10.2

Fig.7 shows a photograph of the linac.

Another electron linac has been developed to produce a peak current of 10 A, 10 ns duration at an energy of 30 MeV for the time-of-flight spectroscopy[29]. An actual energy 1.5 times the designed value is provided. This higher energy anticipates an option of converting an electron beam into a beam of positrons. The linac uses the energy stored in a disc-loaded waveguide, to accelerate electrons.

The accelerating structure has two identical sections with a/λ varying from 0.1154 at the input up to 0.1 at the output. An essentially flat 100-kV/cm field is produced in this way. A single-cavity accelerator with a low-energy diode gun serves as an injector. Table 3 presents linac main parameters.

Table 3

MAIN PARAMETERS OF 30-MeV LINAC

Energy	30 MeV
FWHM energy spread	25%
Peak current	10 A

(to be followed)

Beam pulse length	10 ns
Pulse repetition rate	400 or 3000 s^{-1}
RF pulse length	1.4 μs
Peak RF power	30 MW (2 x 15 MW)
Average RF power	100 kW (2 x 50 kW)
Operating frequency	1818 MHz
Number of sections	2
Section length	3795 mm
Mode	$2\pi/3$
Build-up time	0.97 μs

This linac has been manufactured and its first section has been tested in conjunction with the injection system.

Efforts are also being made that are oriented at future projects such as superconducting linacs for which accelerating structures are being studied, superconducting solenoids and quadrupoles with permanent magnets for beam focusing[30,31].

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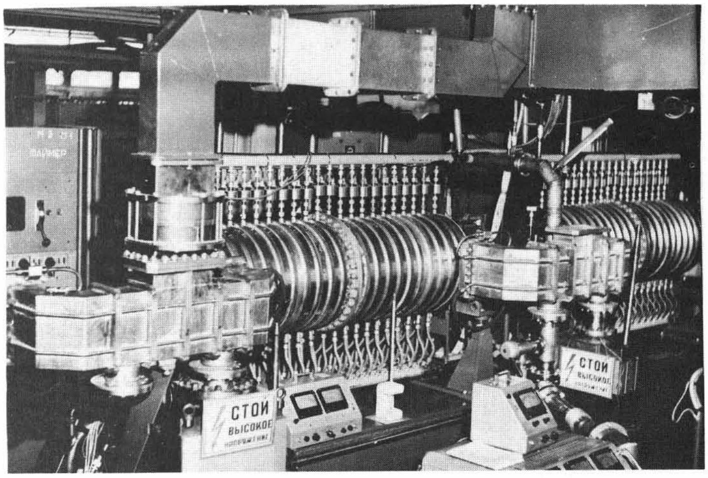

Fig. 1 Prototype resonator for high energy linac section. Structure loaded with washers and discs.

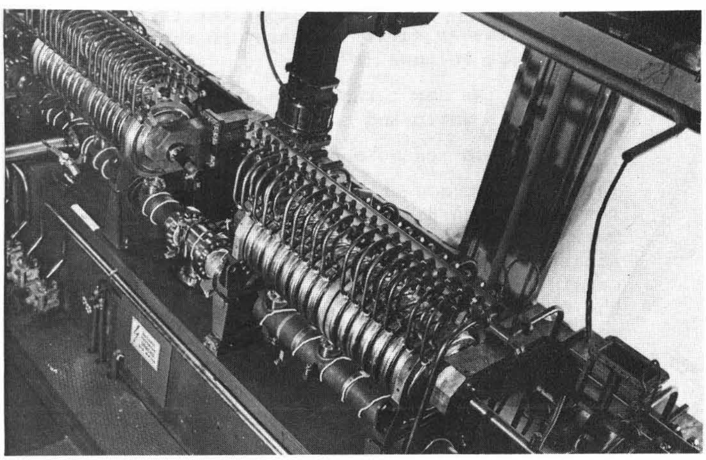

Fig. 2 Prototype resonator for high energy linac section. Ring coupled cells structure.

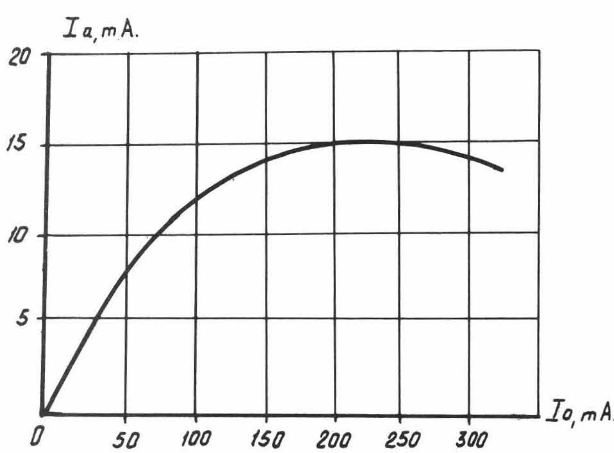

Fig. 5 Limiting current as a function of injected beam current in linac with AAPF.

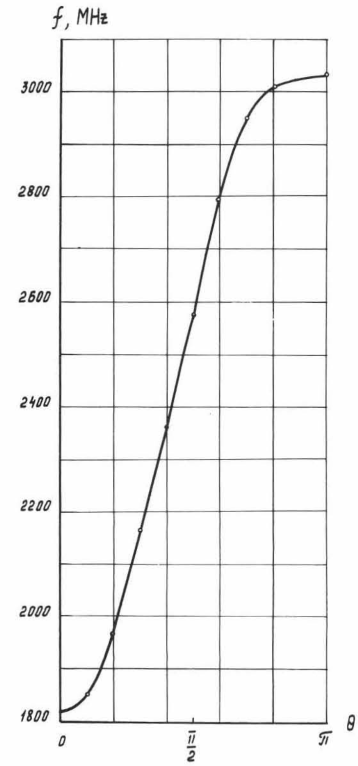

Fig. 3 Dispersion curve of a cavity loaded with washers and discs; β = 0.8, K_c = 47%.

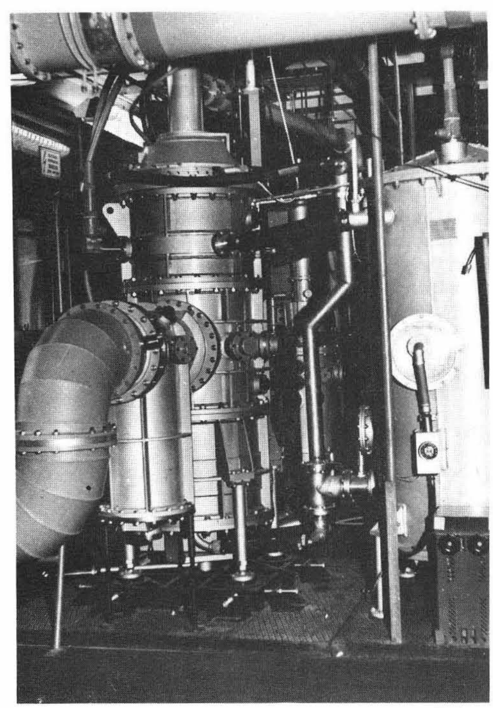

Fig. 4 Output stage of amplifier channel for low energy linac section.

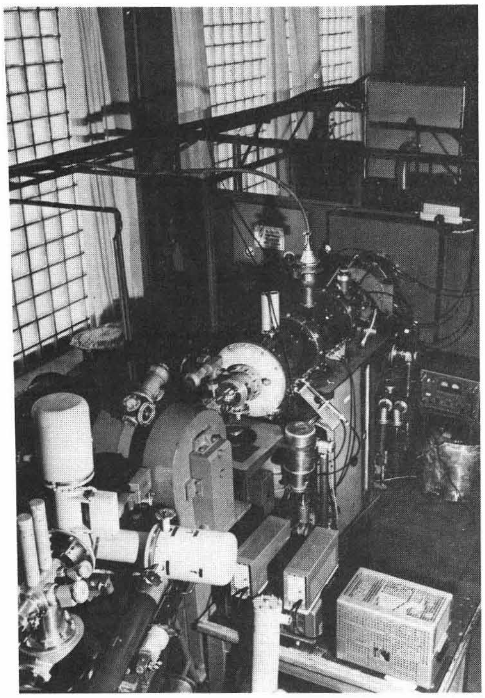

Fig. 6 Experimental linac using the asymmetric alternating phase focusing.

DISCUSSION

H. Klein, Frankfurt: Concerning your heavy ion linac project what is the shunt impedance of the structure? What is the average accelerating field and what is the acceptance of this accelerator with alternating phase focussing?

G.I. Batskikh, RTI, Moscow: Shunt impedance for this structure varies. We have two parts. First one, impedance falls from 100 MΩ/m down to 40 MΩ/m. For the second part, shunt impedance falls from 100 MΩ/m down to 35 MΩ/m. Average accelerating field is approximately 5 MeV/m. Acceptance is very like UNILAC.

E.A. Knapp, LASL: You quoted the shunt impedance for the disc and iris loaded structure as 25 MΩ/m at $\beta = 0.4$. What frequency is this? 1000 MHz?

Batskikh: 991 MHz.

Knapp: Could you quote the shunt impedance at a higher beta, like 0.8?

Batskikh: It rises approximately to 40 MΩ/m.

D. Böhne, GSI: The rf amplifiers you have shown on the slides, the 4-stage amplifiers, for what frequency are they designed and for what output power, either pulse or cw ratings?

Batskikh: For the first part of the accelerator the operating frequencies = 198.2 MHz, average power ∿ 200 kW, peak power ∿ 5 MW.

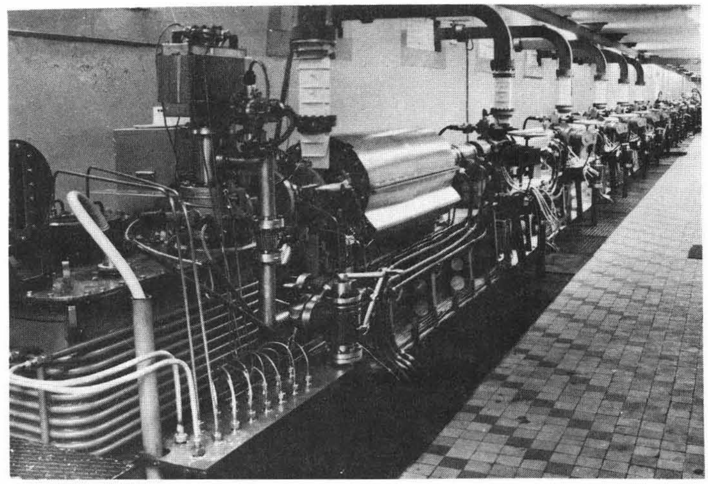

Fig. 7 60 MeV electron linac.

W.E. Jule, LASL: You said that the tightly coupled disc and washer cavity was easy to tune. How do you propose to tune it?

Batskikh: We don't tune each cell. We tune the cavity as a whole and then braze the structure.

Jule: How do you go about the tuning?

Batskikh: We assemble the cavity, measure the resonant frequency, then disassemble, if necessary, making the same correction to all cells. After the final correction and check, we braze it. Since the cavity is compensated, when the frequency is correct the field distribution is correct. This has been measured and found flat to within 1%.