HIGH-BRIGHTNESS H^- ACCELERATORS*

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Abstract

Neutral particle beam (NPB) devices based on high-brightness H^- accelerators are an important component of proposed strategic defense systems. The basic rationale and R&D program are outlined and examples given of the underlying technology thrusts toward advanced systems. Much of the research accomplished in the past year is applicable to accelerator systems in general; some of these activities are discussed.

Introduction

Neutral particle-beam devices as part of a strategic defense system continue to be a robust concept, enhanced by the ability of NPB to perform a variety of mission functions for both the near- and far-term strategies. These functions include target detection, sensing the difference between actual missiles and decoys, and the capability to disable or destroy exoatmospheric targets, ranging from low-level electronic upset to physical destruction. System architecture studies place NPB devices in a variety of roles. This is not surprising on fundamental grounds considering the three basic types of destructive projectiles—kinetic, particle, and photon. Kinetic projectiles pack a lot of energy but are difficult to deliver quickly over long distances. Photons travel at light speed but can only deposit their energy on a surface, depending on surface erosion or subsequent thermal effects. Particle beams can travel at substantial fractions of light speed and penetrate deep into a target, releasing their energy with great force and causing secondary nuclear reactions that are useful in the sensing function.

Light-ion beams, accelerated by radio-frequency (rf) powered linear accelerators, are optimum for the Strategic Defense Initiative (SDI) particle-beam requirements; research into the possibility of their use for strategic defense is not new, but has been expanded in recent years. The program now involves many sponsor, laboratory, and industrial organizations and ranges from near-term projects and demonstrations to far-term R&D for full-capability weapons. There are several interlocking program elements.

An Integrated Space Experiment (ISE) is proposed to investigate the operability and basic performance of an NPB device in the space environment. Fielding of this shuttle-launched experiment has been delayed by the Challenger Shuttle disaster and the present budget scenario. Two large aerospace teams are now completing a Phase I study program that has produced preliminary designs; one team will be chosen to proceed with the ISE.

A complementary major part of the NPB program is the construction of the Ground Test Accelerator (GTA), at Los Alamos, to provide a fully integrated, highly diagnosed experimental NPB ground device that tests and demonstrates all the physics features and most of the engineering features of advanced flight devices. The GTA is a necessary link between technology development elements and ISE flight devices; the GTA must be a flexible vehicle for incorporating technological advances made during its life. In its original definition, GTA had two sequenced stages. The GTA-1 was defined at the same basic parameters as the first ISE and would feed essential data to the ISE. The higher-energy GTA-2 would be built in parallel, anticipating the use of many GTA-1 parts, and would develop the required advanced accelerator, low-divergence beam optics, precision beam sensing, and retargeting technology necessary, along with the ISE results, to make a decision to proceed with a full-scale NPB engineering model.[1] Much of the preliminary design and long-lead procurement and construction work for GTA-1 has been completed this year. However, the shuttle and funding delays have led to a major restudy of the precise goals of the GTA and its integration with the revised schedule for the ISE flight, future program decision points, and available funding. Present program planning directs the GTA toward ambitious longer-term research that would produce major advances in system brightness. (In the next section, we will examine the driving technology terms further.)

A third major program component is termed the "Tech Base" element, covering the near- and medium-term R&D that produces components, subsystems, and system development feeding into the GTA and ISE integrated experiments. The Tech Base program is concentrated around the Accelerator Test Stand (ATS) at Los Alamos and the Beam Experiments Aboard Aboard Rockets (BEAR) project. The ATS is an operational, 425-MHz, low-duty-factor linac system comprising an ion source, low-energy beam transport (LEBT), a 100-keV to 2-MeV radio-frequency-quadrupole (RFQ) preaccelerator, a 2-to 5-MeV drift-tube linac (DTL), and diagnostic area. The ATS lab is supplemented by several separate ion-source test setups at Los Alamos, LBL, Culham, ORNL, at areospace contractor facilities, and by capabilities for doing accelerator structure development, rf power tests of components, and so on. As part of the shift in program definition, the ATS will continually evolve as the primary test facility until the GTA is completed; our present proposal involves extending the ATS to enable full current tests of prototype beam optics, neutralizer, and sensing elements.

The BEAR project will use an Aries rocket to take a 1000-kg payload, including a 1-MeV, 10-mA NPB device, to altitudes greater than 200 km for about 300 s. This will be the first time that real test results will be obtained on the operation of an integrated NPB experiment in space and on the effects of beam emission on the space vehicle and local space environment and vice versa. The ATS and BEAR projects are very active now, and aspects of each project will be discussed further below.

Other program elements cover international collaborations and advanced R&D. The former primarily involves ion-source and continuous-wave (cw) accelerator development at the Culham Laboratory in England.

We next discuss how development in key technology areas could lower the mass of an NPB platform and, therefore, lower its cost, increasing its feasibility as a defensive counter against the cost of an increase in a strategic offense.

Reducing NPB Platform Mass

Cost is a primary factor in determining whether a major project will be undertaken, and strategic defense is no exception. Certainly the cost of the defense must be advantageous in the main and also at the margin compared to what would be required to counter the defense with a larger offense. The cost of large systems can be estimated with some accuracy from the overall mass times a specific cost factor (around \$30 000/kg is the figure used by system architects for NPB platforms). In estimating the eventual cost of an NPB space platform, it should be noted that the planned heavy lift capability would result in the launch cost being a low fraction of the total life-cycle cost of the platform. Therefore, the importance of mass reduction is in terms of direct cost saving rather than in the costs of putting the mass into orbit. In this rough framework, the evolution of less massive NPB platforms via a progression of technology development* might occur as indicated in Fig. 1. The mass

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*J. W. McKee and T. J. Trapp, internal communication, Los Alamos National Laboratory, December 1986.

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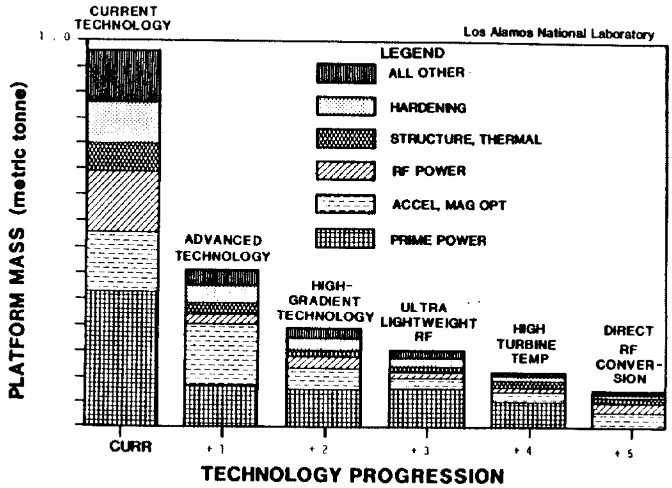
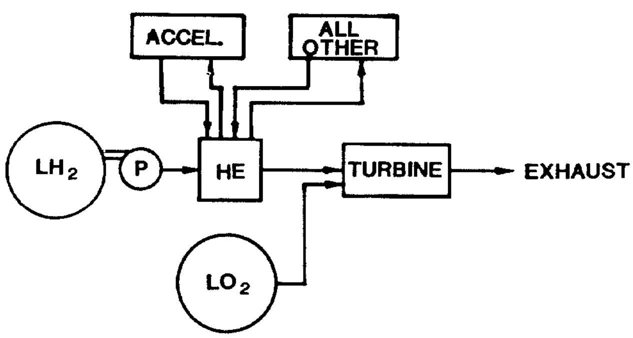


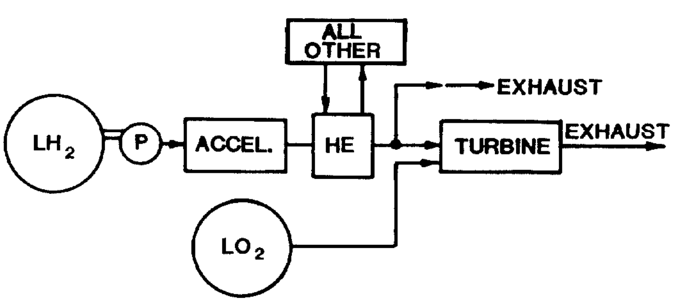
Fig. 1. Evolution of NPB mass properties.

axis can be normalized to one for the "Current Technology" bar because the arguments follow without much dependence on the particular mission.

The "current technology" is represented by a chemical-combustion turboalternator prime-power system, magnetic optics using today's permanent-magnet materials or electromagnets in a mass-optimized mix, rf power at 0.3 g/W, and a room-temperature linac structure with a 4.4-MeV/m accelerating gradient. The basic thermal management layout is shown in Fig. 2(a). From 1-10 metric tonnes (depending on the mission) of liquid hydrogen are required for prime power. The heat exchanger would use supercritical hydrogen and would require development. The system is clearly dominated by the prime power and rf power. Reducing the mass of these components would produce a direct saving, but also would result in lightening of other components such as the attitude control system and self-defense shielding.



(a)



(b)

Fig. 2. Comparison of thermal management basics: (a) accelerator structure is room temperature (LH_2 = liquid hydrogen, LO_2 = liquid oxygen, HE = heat exchanger), (b) accelerator structure is cryogenic at 20K.

The power requirements of a pure copper rf linac drop significantly if the structure temperature is lowered to the cryogenic range; after development, a factor of 2 or more power reduction could be expected at liquid hydrogen to liquid helium temperature. Linac efficiency is expressed as beam power divided by the sum of beam power and structure waste power, so an efficiency improvement of 50% or more is readily calculated for beam loadings of 50-60% at room temperature and 80-90% at cryogenic temperatures. The thermal management arrangement would be as shown in Fig. 2(b). The basic prime-power components are the same; therefore, the specific prime-power cost is about the same. Some missions would require about three times as much additional liquid hydrogen to cool the accelerator as is required for the prime power; this would not be an excessive mass or cost impact. The cryogenic accelerator structure now requires development, while the heat exchanger design is more straightforward. Thus, the cost optimization is different than would result from changing a ground-based system from room temperature to cryogenic, because here the same cryogenic prime-power system is used in both cases; only the accelerator structure is changed. The more than factor of 2 mass saving shown by the "Advanced Technology" bar is achieved with such a cryogenic accelerator system, with the added assumption that the linac would use a 6-MeV/m accelerating gradient and that a three-fold improvement in the weight ratio of the rf-power system, to 0.1 g/W, is achieved. The main impact on the system cost is derived from the reduced rf requirement of the cryoaccelerator.

Subsequent improvements are smaller in absolute terms but still important because of the high specific cost. "High-Gradient Technology" (Fig. 1) proposes the use of a fully superconducting accelerator structure with 20-MeV/m accelerating gradient. This gradient has already been demonstrated for single cells in laboratory tests but requires development for multiple cells; it also requires exquisite beam performance because any stray beam could cause the structure to return abruptly to normal conductivity. The merits of proceeding directly from room temperature to superconducting structures, without the intermediate step of cryogenic structures, is being debated. The rf weight/power ratio in this case is still 0.1 g/W, and the magnetic-optics mass reduction derives from the use of advanced magnetic materials. The remaining bars speculate on the possible long-term development of 0.05-g/W rf power, use of very high temperatures in the turbine, and direct conversion of turbine-shaft horsepower to rf power at high efficiency.

Increasingly intricate studies of this type are being conducted in conjunction with overall SDI system-architecture modeling. The steps through the third bar (High-Gradient Technology) appear quite feasible given a thorough development program; the resulting masses project the favorable efficiency of the defensive mechanism compared to the costs of more offensive missiles. Another paper[2] reports the demonstration of approximately the expected Q improvement in a DTL-type structure at liquid nitrogen and helium temperatures and at the required rf voltage and power levels. A two-cell cryogenic DTL structure will be installed on the ATS and tested during this year.

Research Accomplishments

Many new things have recently been achieved in rf accelerator technology for directed-energy applications. In total, this work has already begun to change radically the way linac systems will be built from now on. A few areas of broad interest to the accelerator community are now outlined.

Ion Sources and Low-Energy Beam Transport (LEBT)

The Dudnikov-type "surface-plasma source" continues to be the only H^- source capable of meeting the brightness requirements for the ISE and GTA; in the past year, performance increases in this source have been dramatic. Researchers found from sophisticated optical spectrometry, emissive probe beam potential measurements, and comparison with volume sources, that the Dudnikov source also operates on a volume basis and, hence, should be renamed. Reliable performance has been achieved on the Los Alamos 4X source at 250 mA with approximately 0.02 π·cm·mrad rms, normalized emittance in each plane and with a very quiet beam-current pulse. The source was also operated at extended duty factors with pulse lengths up to 4 ms; cw tests at 25% output current are scheduled. Although this source has the disadvantage of using cesium, which adds operational complexity, it still provides the standard that other potential sources must match.

Other sources of the volume type are being developed at several laboratories.[3–5] In September 1986, the Culham Laboratory source produced 140 mA continuously for 30 s with good beam quality; emittance measurements are in progress. Recently, LBL has been making good progress in their volume source research. The possibility of using LaB_6 cathodes continues to be investigated; this material can achieve the required current density and can avoid the operational problems of cesium, but the LaB_6 sources are quite noisy. The volume sources without cesium may eventually be the preferred sources; they are intrinsically quiet, capable of quick turn-on, and simple to operate.

Negative deuteron production was also demonstrated in the Los Alamos Dudnikov and volume ion sources; scaling relations were verified. Physics modeling of the LEBT continues between the ion source and RFQ entrance, but a consistent model including space-charge neutralization effects is not available. However, work with the ATS column and a longitudinally adjustable permanent-magnet-quadrupole matching system (Fig. 3) have resolved the operational matching problem; the new system is now always capable of producing a matched beam to the RFQ.

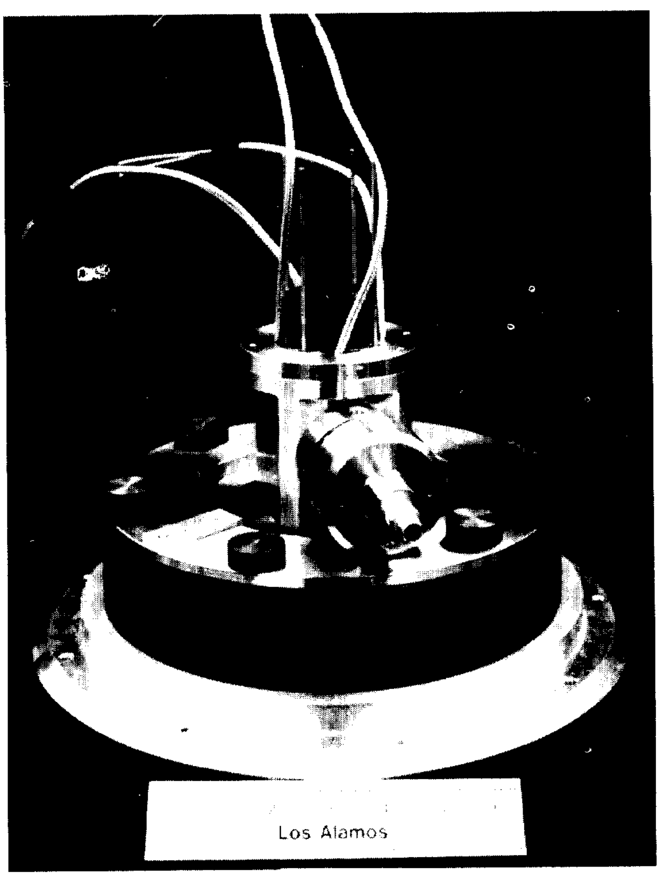


Fig. 3. BEAR ion source.

RFQ and DTL

Using new interior parts in the RFQ (constant radius of curvature vanes) and the first complete test of a DTL with permanent-magnet quadrupoles, the ATS has successfully accelerated a 100-mA beam to 5 MeV. The performance of the RFQ/DTL system agrees with predictions, and there is no loss of either beam current or beam quality in the transition between structures or in the DTL. This accomplishment verifies the performance required for the ISE and sets the stage for the design of an advanced GTA.

An important technology baseline was established with final operation of the FMIT 75-keV to 2-MeV, 80-MHz cw RFQ at 50 mA before funding support was terminated. Many important engineering lessons were learned during operation of this facility, and the beam performance qualitatively agreed with predictions. Unfortunately, it was not possible to perform the detailed beam-dynamics experiments on brightness behavior, beam halos, and beam losses that were the reason (apart from the engineering) for building the prototype.

Technology Transfer

Many new ideas and prototypes have resulted from an agressive technology transfer program with industry over the past year, spearheaded by the BEAR and ISE/GTA programs. The BEAR ion source (Dudnikov type) and RFQ have completely new engineering configurations, as shown in Figs. 4 and 5. A major goal for the RFQ and DTL is to use nonadjustable vanes and drift-tube mounts. This is accomplished in the RFQ by machining quarter segments put together with electroformed

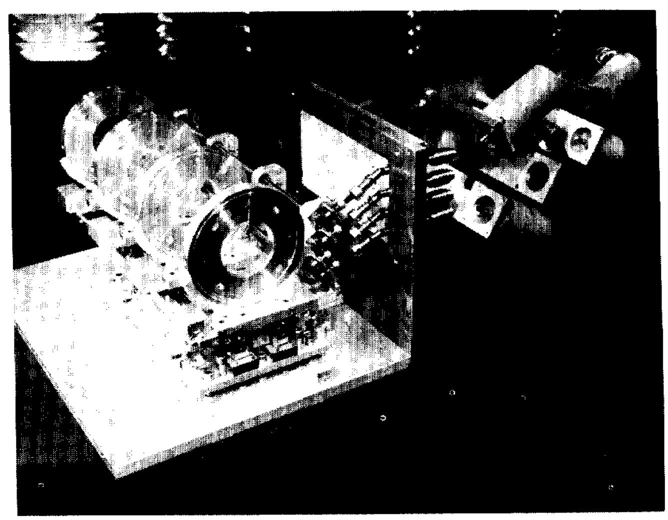


Fig. 4. Permanent-magnet, low-energy beam transport with longitudinally movable quadrupoles.

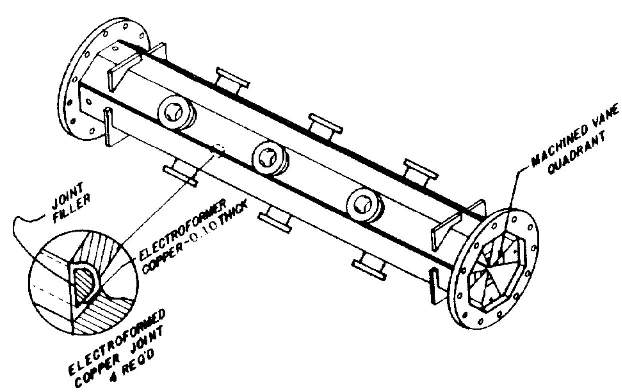


Fig. 5. The BEAR RFQ assembly flight model.

joints and in the DTL by some form of hard-socketing, precision-aligned drift-tube mounts. The tanks are being made of aluminum with copper-plated inner surfaces. The basic tests of electroforming and copper plating on aluminum were successful; extensive development is now being done to work out the detailed procedures necessary to achieve high-integrity joints and surfaces in the complicated geometries of the actual tanks. These new structures will be much lighter, and the successful ones will be scalable to cryogenic and cw operation.

Beam Dynamics and Accelerator Design Code Development

The more stringent requirements of advanced high-brightness rf linacs require continued development of the design tools. Many codes exist for designing beam-transport systems without acceleration, but none of them include high-order aberration treatment, nonlinear space charge, and design optimization, simultaneously. The codes MARYLIE, GIOS, and TRANSPORT, all third-order codes with analytical representation of discrete beamline elements, have been benchmarked for a collinear system of several quadrupoles; the three codes (after translating to common units) agreed to a few parts in ten thousand in all aberration coefficients.[6] The codes GENMAP (a member of the MARYLIE family), MOTER, and SYMOPT (an embryonic symplectic-integrator code), all ray-tracing codes and all equipped with the Halbach field representation of permanent-magnet quadrupoles, have been benchmarked against each other and against direct numerical integration for a quadrupole triplet and drift-length system with point-to-parallel imaging in both planes, simultaneously.[7] The GENMAP and MOTER codes now agree within about half a microradian in the divergence; SYMOPT agrees to about two microradians and is being checked further.

An optimizer was written* for MARYLIE, and work has begun on GENMAP/MARYLIE to produce a new optimizing third-order ray-tracing code that will replace MOTER and GIOS. The MARYLIE code also appears to be the one most readily extended to higher (5th) order; this work and also the inclusion of space charge is in progress.

DESY, KFA Jülich, and Los Alamos continue to collaborate in the development of the three-dimensional MAFIA (MAxwell's Equation solved by the Finite Integration Algorithm) codes, a system intended for computer-aided design of magnets, rf structures, and structures in which wake fields are important. Figure 6 shows the present relationship between the sections of the MAFIA codes—M3, R3, E31, P3, and T3 are now available to friendly users; they have been put on the MFE CRAY network and can also be obtained directly from DESY.

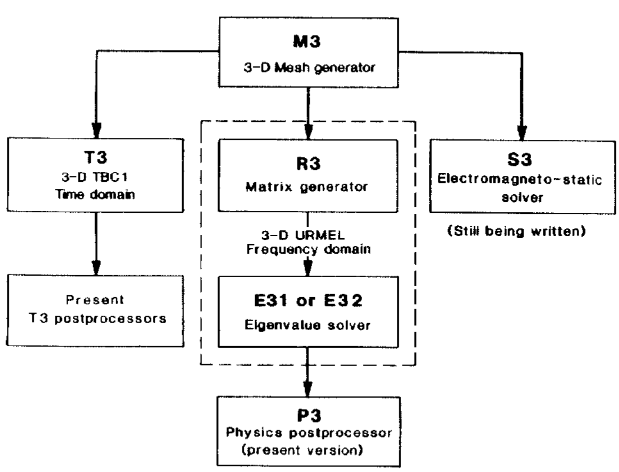


Fig. 6. Major parts of the 3-D MAFIA code.

*C. T. Mottershead, internal communication, Los Alamos National Laboratory, December 1986.

Work is continuing on S3, the generalization of P3, and revision of the direct-access file structure. The rf cavity codes have been tested on several realistic structures (e.g., Fig. 7) and appear to be working well. The lowest three frequencies of this cavity without the ferrite rings compared within 7.5% of the laboratory measurements, in spite of the complicated shape and a coarse 15 000-point mesh (Fig. 8). The model of Fig. 9 was used to study the cavity fundamental frequency variation as a function of the ferrite permeability; good agreement with experimental data was again achieved.

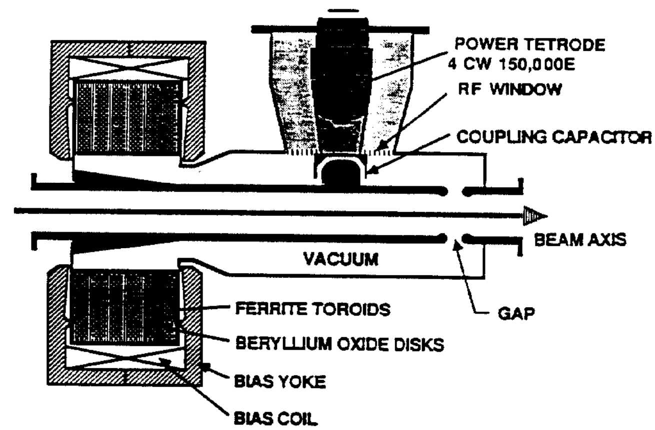


Fig. 7. Cross section of a ferrite-tuned rf cavity for circular accelerator.

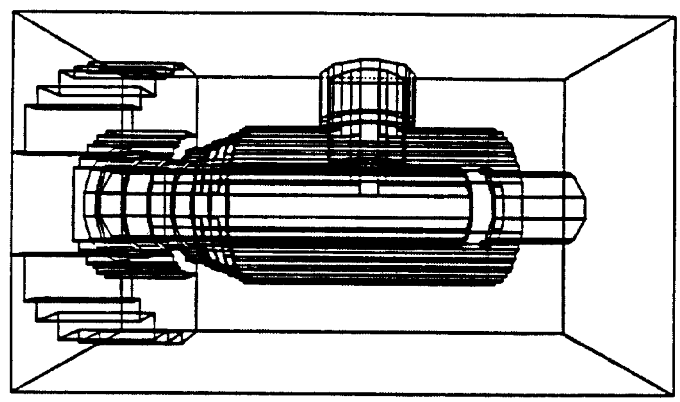


Fig. 8. MAFIA code model of the ferrite-tuned rf cavity used to compute resonant frequencies.

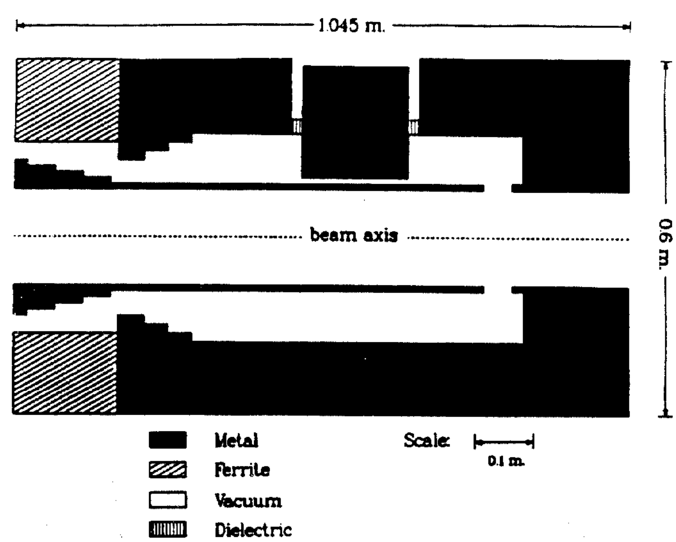


Fig. 9. MAFIA code model of the ferrite-tuned rf cavity, used to compute fundamental frequency as function of ferrite permeability.

Emittance Growth Physics

Separate investigations into the basic physics mechanisms underlying emittance growth in accelerator and beam-transport systems have taken years to bear fruit, but in the past year, breakthroughs have occurred.[8] For the first time, it is now possible to predict analytically the final emittance to be expected for bunched, space-charge-dominated beams in terms of a charge redistribution and a kinetic-energy exchange between the coordinate projection planes. A basic equation, derived by T. P. Wangler,[8] is

$$\epsilon_f^2 = \left[\frac{2+P_i}{2+P_f}\right]\epsilon_i^2 + \frac{16G_x(Z_{rms}/X_{rms})}{(2+P_f)}\left(\frac{K_3^2\beta\lambda}{\sigma_0}\right)^{2/3}\beta_\gamma(U_{ni}-U_{nf}) , \quad (1)$$

where i = initial, f = final, U_n = nonlinear field energy of the distribution, P = partition parameter = $\overline{Z'^2}/\overline{X'^2}$, G_x = bunching factor, K_3 = bunched-beam perveance, σ_0 = zero-current tune, and λ = rf wavelength. At the space-charge limit, the beam-charge distribution tends to uniformity within a plasma length. The uniform distribution has zero nonlinear field energy, hence a uniform initial beam would stay uniform, and the second term would be zero. If the energy balance between planes is unequal, an equilibration, or equipartitioning, will occur in the space-charge-dominated situation, also causing emittance growth.

Wangler has now practically applied this basic result to the RFQ:

$$\epsilon_f^2 = a_1\epsilon_i^2 + a_2\frac{\lambda^2}{\sigma_0^{2/3}}\left(\frac{q\hat{I}}{A}\right)^{4/3} , \quad (2)$$

where a_1 and a_2 are empirical constants dependent on the RFQ design procedure and functions of the adiabatic bunching process and particle losses. Although this result is semiempirical, it agrees remarkably well with detailed simulations, as shown in Fig. 10, where the final emittance of a collection of neon and uranium accelerators operating over a wide frequency range is compared (for matched beams) as found by Eq. (2) and as computed by the simulation code PARMTEQ. This result will eliminate many tedious computer runs previously needed in scoping studies. Eventually, we hope to extend these results to DTLs and general beam-transport problems and to obtain new design prescriptions leading to higher performance.

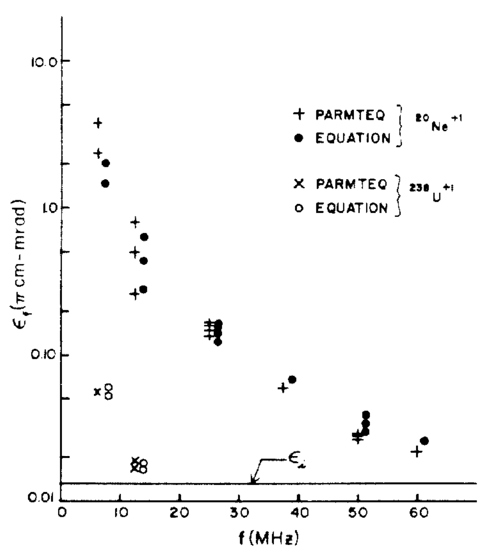


Fig. 10. Comparison of new analytic formulas and PARMTEQ for emittance growth in RFQs.

Conclusion

Other important developments are under way: developments such as advanced beam-funneling schemes,[9,10] studies of the intricacies of multiple rf drives to an rf cavity, application of permanent magnets, increasing insight into the physics of beam-halo generation, techniques for preserving beam brightness in the high-energy beam transport and steering elements, and detailed engineering of all components and ancillary equipment. Overall, the thrust toward lower-mass accelerator systems is driving development of more efficient rf power generators with lower weight and volume per watt and the development of cryogenic and superconducting accelerator structures capable of operating at gradients higher than achievable with cw room-temperature devices. Complementary beam-dynamics development is directed at ensuring low beam loss so the superconducting structures can accelerate high-brightness beams. Most of these activities will be of interest to other accelerator applications. The few items that it has been my privilege to briefly outline here are the work of many others, whose efforts I gladly acknowledge, applaud, and encourage.

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