THE DESIGN OF A 12.5-MHZ WIDERÖE LINAC FOR ION BEAM FUSION

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Summary

Argonne National Laboratory (ANL) is currently developing a heavy ion beam driver for the inertial confinement fusion (ICF) program. The R&D program has as its goal to store a Xe^{+8} beam at 220 MeV by October, 1982. The preaccelerator is on station and near to meeting its design of 50 mA of Xe^{+1} at 1.5 MV. The first section of the low beta linac, which is to accelerate 20 mA of Xe^{+1} to 2.32 MeV, consists of four independently - phased short resonators. Two of the four short resonators have been tested beyond the rf linac power requirements without breakdown, or any major difficulties. The remaining two are currently being fabricated. The next section of the linac consists of three double-stub 12.5-MHz Wideröe linacs to accelerate the beam to 22.48 MeV. The first and third tank of the Wideröe array uses non-conventional FOFODODO quadrupole focusing, while the second tank uses FODO focusing. A pulsed quadrupole design has been selected for the Wideröe tanks because of the high power requirement of conventional DC quadrupoles. At 22.48 MeV, the beam is to be stripped to charge state +8, and accelerated in an array of 25 MHz triple-stub Wideröe linacs to 220 MeV, and then injected into a storage ring.

Introduction

Argonne National Laboratory is building a low beta linac and storage ring in conjunction with an on-going preaccelerator and ion source development program to demonstrate the adequacy of conventional accelerator technology as an ICF driver for a power plant. The initial phase of the program will accelerate 20 mA Xe^{+1} in an array of 12.5-MHz independently-phased linac resonators and Wideröe linacs to 22.48 MeV; strip to charge state +8, accelerate in a 25-MHz Wideröe an additional 7.7 MV to an energy of 84 MeV; inject and accumulate beam in a storage ring (using the Princeton-Penn accelerator magnets) housed in the ZGS tunnel. A later phase of this program will add: additional 25-MHz Wideröe linacs to make the final energy 220 MeV of Xe^{+8}; a storage ring and stacking ring. The extracted beam then will be transported, compressed, split into four beams and focused onto target foils. The program as planned allows upgrading of the facilities to reach a beam energy of 200-500 kJ which may be adequate to demonstrate a significant pellet burn.

Preaccelerator

The high voltage power supply is a modified Radiation Dynamics, Inc. (RDI) 4-MV Dynamitron[1] which had been obtained from Goddard Space Flight Center. It is a parallel-fed, capacitively-coupled multiplier, driven by a 110 kW oscillator at 105 kHz. Extensive modifications have been made to increase the current capability and allow pulsed operation.[2] As modified, the oscillator could ramp the terminal voltage from 0.5 MV to 1.5 MV in 7 ms with a peak stack current of 70 mA. At 1.5 MV, the voltage droop is less than 0.25% for 42 mA of associated beam current.

The low-emittance heavy-ion source for the preaccelerator was developed under contract by Hughes Research Laboratories.[3] It is a scaled-up version of their 2 mA single aperture source.[4] These utilize a Penning discharge for low plasma temperatures, and a Pierce geometry for minimal emittance dilution during acceleration. The source is capable of 100 mA Xe^{+1} at a current density of 15 mA/cm^2.

Conditioning of the accelerating column with beam had proceeded rapidly to 1.3 MV and 50 mA of Xe^{+1}. Before proceeding further with the conditioning to 1.5 MV, it was decided to examine the column. Damage of the ceramic and T-shaped rings along the outer shell was noted. The column and T-rings are being modified to reduce the electrical stress on the ceramic-metal interface and in the T-ring gaps.

12.5-MHz Wideröe Linacs

The first section of the linac is shown schematically in Fig. 1. It consists of the capacitively-loaded, single drift tube resonator, two "drum" loaded resonators with four gaps, and a π-3π double-stub Wideröe with 30 gaps. Not shown in the figure is the buncher, which is separated from the first accelerating resonator by a drift space of 4 m, containing a quadrupole triplet and beam diagnostics.

The capacitively-loaded resonator and the lumped-inductor resonator used as the buncher are described in Ref. 5. The capacitively-loaded resonator, which requires about 10 kW to reach its design value of 100 kV peak per gap, has been tested up to 25 kW without breakdown or multipactoring. Likewise, the lumped-inductor resonator, which requires 2 kW to reach its design value of 23 kV peak per gap, has been tested to 25 kW without breakdown or multipactoring. They both are installed in the beam line in preparation for acceleration measurements upon completion of the preaccelerator modifications. The "drum" resonators are currently being fabricated and should be on-line soon.

*Work supported by U. S. Department of Energy.
**Physical Dynamics, Inc; sub-contracted to ANL.

The π-3π double-stub Wideröe linac shown in Fig. 1 is followed by two more 12.5 MHz double-stub Wideröe linacs, shown schematically in Figs. 2 and 3. These in turn will be followed by a gas stripper to charge state +8, and 4 more triple-stub Wideröe linacs at 25 MHz, similar to the GSI[6] and Berkeley[7] designs, to reach 220 MeV.

The outside shell, stub lines, and inside structure of the Wideröe tanks in our design will be made of mild steel and electroplated with 0.254 mm copper, as was successfully accomplished by GSI. The drift tube, which does not contain quadrupoles ("short" drift tubes), are planned to be made of solid aluminum and electroplated with copper. It is not planned to provide direct cooling of the stems. This will greatly simplify the construction and cooling of the inner line. Since there is no outside penetration for cooling tubes, the inner line will be cooled by flooding the inside with water. At the same time, this will provide cooling of the inner stub lines. The alignment of the drift tubes containing quadrupoles ("long" drift tubes) is to be accomplished with bellows. The original plan called for using a fixed shim. This approach was abandoned in favor of a simple holding and adjusting fixture. By using this adjusting fixture and bellows, there was no cost savings in using the fixed-shim approach. The "short" drift tubes are to be aligned by attaching the stems to the inner line by silver-plated C-rings. This will allow up to 0.76 mm of adjustment, while maintaining good electrical contacts to the inner line; another advantage of using the solid stem without cooling. It is planned to align the axes of the drift tubes to $\pm$ 0.1 mm.

The Wideröe tanks were designed using a Wideröe linac code developed at the Lawrence Berkeley Laboratory[8] in collaboration with GSI.[9] The program is interactive and iterative. By varying the position and length of the stubs, input/output energy, and line loading, a consistent solution is found for frequency, drift tube table, energy gain per cell and gap voltages. In order to minimize phase space dilution, the tanks were designed to achieve a constant energy gain of 1.0 MV/m throughout the whole linac.

Table I lists the design parameters of the three 12.5 MHz Wideröe linac tanks. Tank 1 takes the beam energy from 2.32 MeV to 8.84 MeV. It operates in a π-3π mode with FOFODODO focusing, and has 30 accelerating gaps with a bore of 4 cm. Tank 2 takes the energy from 8.84 MeV to 15.24 MeV, operates in the π-3π mode with FODO focusing and has 20 gaps with a bore of 4 cm. Tank 3 takes the beam from 15.24 MeV to 22.48 MeV, operates in π-π mode with FOFODODO focusing. and has 34 gaps with a bore of 4 cm.

Rf System

Each independently-phased cavity of the linac is to be driven by a 25 kW pulsed rf amplifier, which uses push-pull 4CX5000A tetrodes as the final stage. The amplifiers are being built to ANL specifications by the firm: Instruments for Industry, Inc. Two of five units ordered have been delivered thus far. The amplifier is coupled to the cavity by an adjustable loop. A standard 3-1/8" rigid 50 Ω coaxial cable gas-barrier is used to separate cavity vacuum from the air-dielectric feed line. The feed line is 1-5/8" air-dielectric Heliax® cable and is 1/2 wavelength long.

Each 12.5-MHz Wideröe linac tank will be driven by a 450-kW pulsed rf amplifier. It is planned to use feed-forward as well as fast feedback loops to control tank field amplitude to 1% and phase to 1 degree. A specification has been written for the amplifier and proposals are currently being evaluated. It is planned to couple the amplifier to the tank through an adjustable loop, and separate the feed line (5" Heliax®) from tank high vacuum by a standard 6-1/8" rigid 50 Ω line gas-barrier. The feed line will be one wavelength long.

Quadrupole Magnet Design

In addition to the quadrupole gradients shown in Table I, other parameters are as follows:

Radius of the bore	2.5 cm	
Effective length (range)	11 - 43 cm	
Field gradient uniformity	$\pm$ 1.0%	for $r \leq 2.0$
Field harmonic uniformity	$\pm$ 0.5%	for $r \leq 2.0$

The large bore and high gradient eliminate the possibility of using rare earth cobalt permanent magnets. A conventional water-cooled conductor design was chosen because of the large ampere-turns required. The number of turns per pole was determined by matching the magnets to available pulsed power supplies.

A conformal transformation was made on a hyperbolic pole magnet with a two-layer coil. This resulted in a dipole magnet as shown in Fig. 4, with the dashed line as the pole tip. The computer program MIRT[10] was used to shim this magnet. One possible set of shims is also shown in Fig. 4. Transforming these shims back to the quadrupole results in the 1/8 magnet of Fig. 5.

The design philosophy is to use one pole contour for all laminated magnets. All magnets in a given tank are of the same length as the smallest one in that tank. The magnet ends will be chamfered to reduce the n = 6 duodecapole harmonic due to the ends. Many magnets will be pulsed in series from one power supply, using current shunts for each magnet to adjust the current. These shunts will have the same time-constant as the magnets.

Actual mechanical design of the magnets has recently started. Present plans call for stacking the cores in halves from stamped, deburred and oxide-insulated laminations. Individual laminations will be bonded together as core halves with "B" stage epoxy resin.

The coils will be insulated and wound on a separate fixture. Two coils will be assembled onto a core half, then two halves assembled using a steel ring to clamp them together. After testing the magnet electrically and checking it dimensionally, the entire unit will be vacuum impregnated to insure adequate electrical insulation and mechanical stability.

Simulation Studies

A detailed study of beam evolution and emittance growth was carried out for the first tank with a three-dimensional simulation code developed at Physical Dynamics, Inc.

The linac geometry was FOFODODO operating in a $\pi-3\pi$ mode. Input parameters for the Xe^+ beam were: average beam current 25 mA, input energy 2.27 MeV, gap voltage gradient 5 MV/m, synchronous phase -32^o, normalized transverse emittance $\beta_s\varepsilon_T$ = 0.3 mm mrad, longitudinal emittance 10^{-4} cm. The quadrupole length was taken as $\beta_s\lambda$ and the gap length as 0.2 $\beta_s\lambda$. The stability limits set by magnetic, gap and electrostatic defocusing forces govern the optimum choice of the magnetic field gradient, g , and limit the phase spread. For the present parameters, g = 5.1 kG/cm and the phase spread is $\pm$ 18°. The bunch length is thus limited to 0.7 cm, which is well within the 'bucket' size.

The matched beam input parameters for a K-V distribution at the injection point midway between x- focusing magnets were x_o = 2.2 cm, x' = 2.4 x 10^{-3}, y_o = 0.78 cm, y_o' = 6.7 x 10^{-3}. The beam envelope radius for 100%, 80%, 70%, and 50% of the total particle number is shown in Fig. 5. A bore radius of 4 cm would thus be required to transmit the full 25 mA. For a lower current of about 20 mA the radius can be limited to 2 cm.

Emittance calculations indicate (Fig. 7) that most of the growth in the transverse emittance occurs in the first 10 $\beta_s\lambda$, with little increase thereafter, for at least 80% of the particles. The total growth after about 7 m is a factor of about 8 for the full beam, and a factor of about 5 for 80% of the beam. This growth results from the nonlinear coupling between longitudinal and transverse motion and the nonlinear space charge forces. Studies are underway to determine whether lowering the gap voltages, and hence reducing the defocusing forces, will provide a better match to the input emittance. Also, the sensitivity of emittance growth to the input distribution will be studied.

Table I

12.5-MHz Wideröe Linac Parameters

Parameter	Wideröe Tank #1	Wideröe Tank #2	Wideröe Tank #3
Mode	$\pi-3\pi$	$\pi-3\pi$	$\pi-\pi$
Focusing	FOFODODO	FODO	FOFODODO
Number of Gaps	30	20	34
Length (m)	6.49	6.63	7.09
Peak Voltage on First Gap (kV)	242.1	372.8	245.3
Peak Voltage on Last Gap (kV)	378.3	458.9	297.2
First Gap Width (cm)	3.33	6.47	4.91
Last Gap Width (cm)	6.42	8.44	5.93
First Cell Length (cm)	30.31	58.20	37.88
Last Cell Length (cm)	56.89	74.40	45.47
First Quadrupole Gradient (T/m)	48.03	29.88	56.38
Last Quadrupole Gradient (T/m)	21.16	23.36	44.26
Excitation Power on Beam Current (KW)	192	278	151
Rf Power with Beam Current (KW)	355	438	332
Shunt Impedance (MΩ/m)	43.81	28.74	61.92

References

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3. R. P. Vahrenkamp and R. L. Seliger, "A 100-mA Low Emittance Ion Source for Ion Beam Fusion," IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, Part 1, p. 3101 (June 1979).

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7. J. Staples, et al., "A Wideröe Preaccelerator for the Super Hilac," Proc. of 1976 Proton Linear Accelerator Conference, p. 81, 1976.

8. J. Staples, Private communication on Berkeley's Wideröe Program.

9. K. Kaspar, "Studies for Dimensioning a Heavy Ion Linear Accelerator of the Wideröe Type," GSI Report 73-10 and UCRL-Trans-1522 (1973).

10. "MIRT" was developed by K. Halbach, LBL, and R. Holsinger, NEN, and was kindly supplied by them.

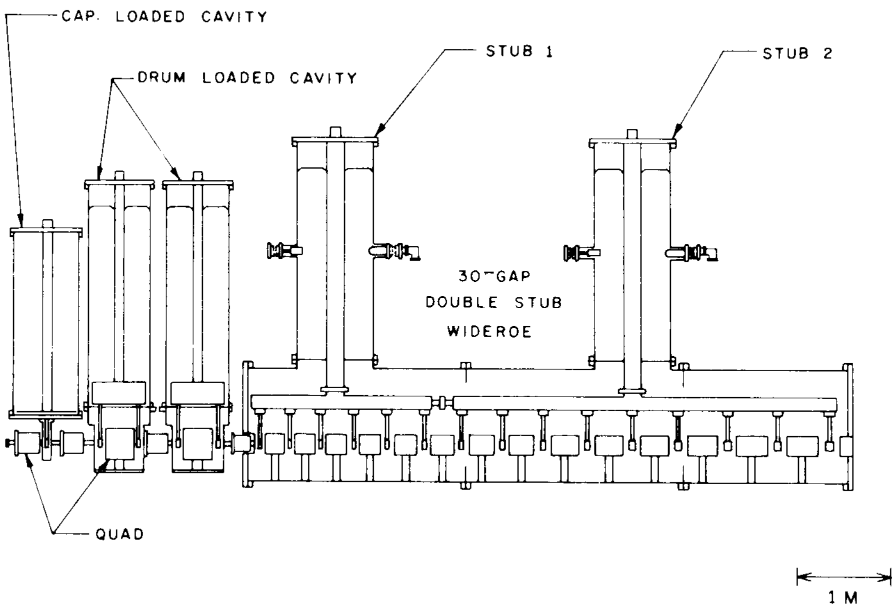


Figure 1. 30-Gap π-3π Double Stub Wideröe (Tank No. 1) and Independently-Phased Cavity Linac: 1.5 MeV to 8.84 MeV

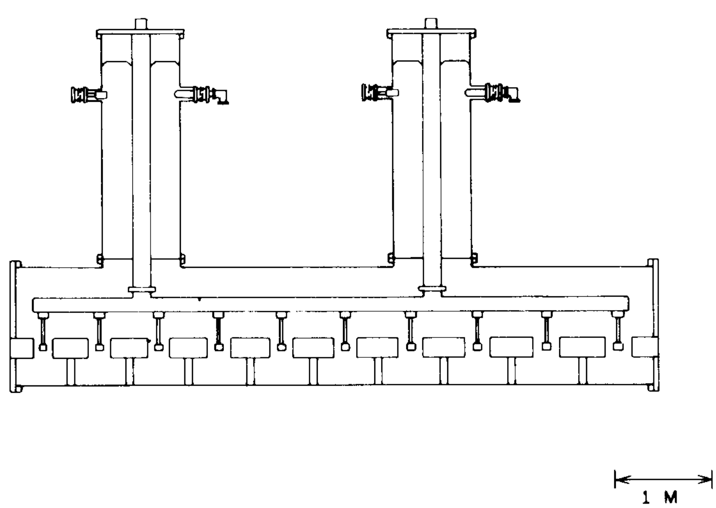


Figure 2. 20-Gap π-3π Double Stub Wideröe Linac (Tank No. 2): 8.84 MeV to 15.24 MeV

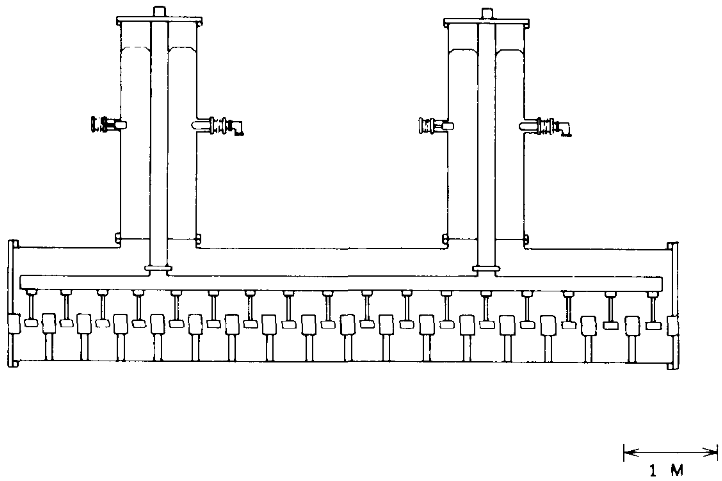


Figure 3. 34-Gap π-π Double Stub Wideröe Linac (Tank No. 3): 15.24 MeV to 22.48 MeV

Figure 4. Transformed Quadrupole Magnet

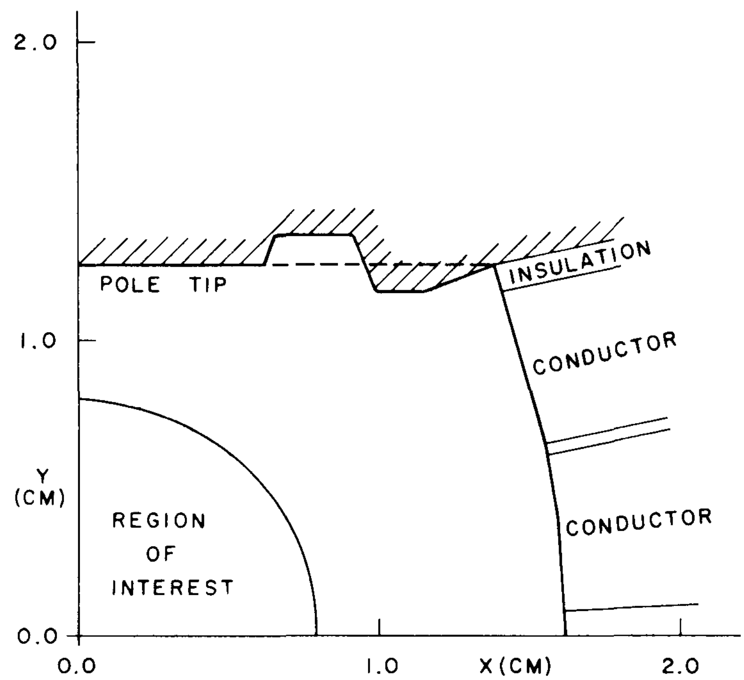
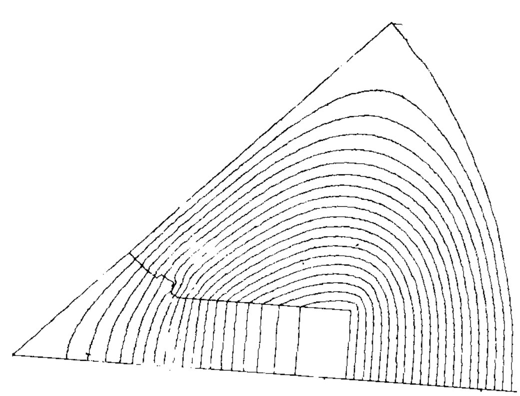


Figure 5. 1/8 Shimmed Quadrupole Magnet



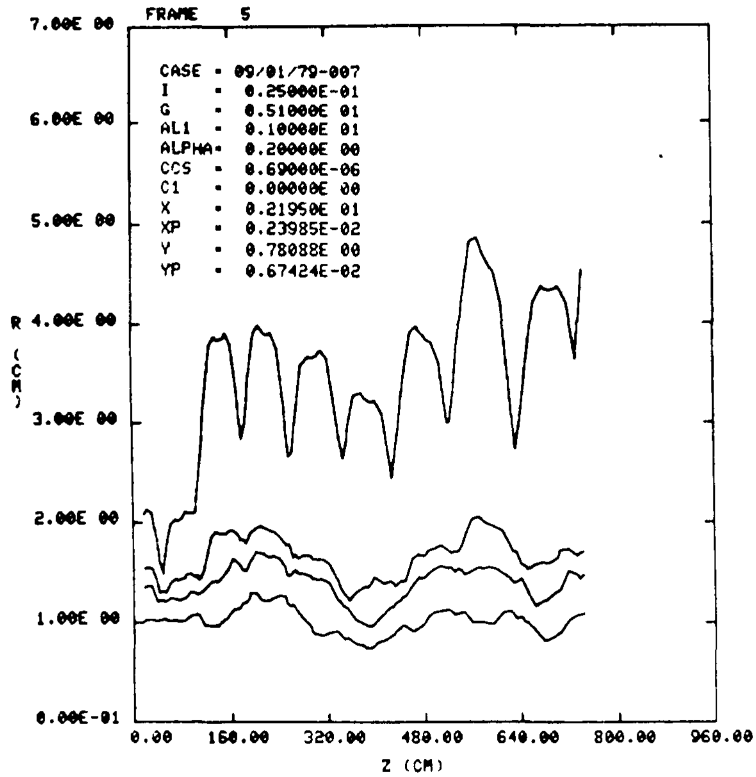


Figure 6. Beam Radial Envelope

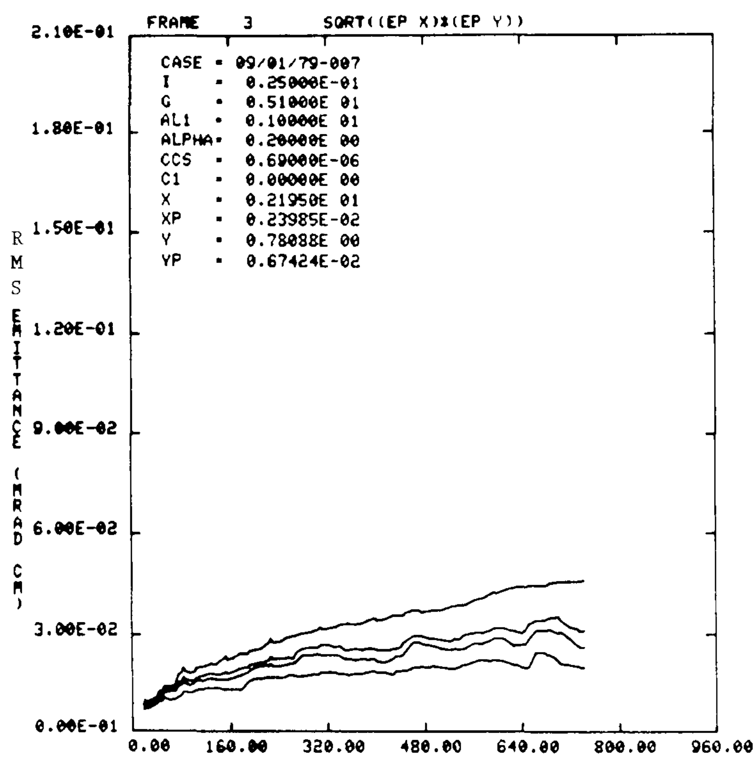


Figure 7. Transverse Emittance

Discussion

Mobley, BNL: With a 100 mA X_e^{+1} source, what did you start off with for the bore size? How many mA per square-centimeter?

Moretti: I think the diameter is about 3 cm and 15 mA/sq. cm.

Mobley: And at the first tank after one stage of rf acceleration are you getting 25 mA?

Moretti: Well, the space charge limit is 20 mA. We have not run the experiment yet.

Mobley: I see. What current are you shooting for at 22 MeV?

Moretti: 20 milliamps.

Mobley: On your quadrupoles in the rf system, what are the pole tip fields that you need?

Moretti: The gradients are 46 Tesla/m, or about 12 KG at the pole tip. That is the highest, then it goes somewhat lower, as beta increases.

Penner, NBS: Is the emittance growth at the beginning a non-linear space charge effect? If so, how was it calculated?

Moretti: Well,it is a non-linear effort due to the space charge. It was a numerical space charge simulation.

Penner: How many particles did he use? In a matched beam, the emittance should not start to grow immediately, if you carry enough particles to get the proper simulation.

Moretti: Well, I think S. Jorna has found that 160 is sort of the minimum required to get a fairly accurate distribution. He has gone to a thousand and noticed only 10-25% changes. The majority of calculations have been in the area of 160-200 particles.

Penner: I might make a comment for people who are trying to predict nonlinear space charge effects with particle simulations. We have two rather thorough independent studies by I. Haber and by A. Galejs and myself. You really don't see the effect you are looking for until you get to over one-thousand beamlets in a two-dimensional case. The problem is that when you simulate a beam with a small number of beamlets, matching isn't well defined. As a result, the entire beam is not matched and you get growth associated with that mismatch. You really must match the beam into the system properly,which requires a large number of particles and then you find that the moments of the beam will begin to grow at first, but the (rms) emittance will not start to grow for awhile. I think this is very well verified by the results, which in my case, went to 2,000 particles; in Haber's case to 16,000.

Moretti: Well, this is a three-dimensional code. Jorna has studied 1,000 particles and says it reflects accurately the beam dynamics to within 25%.