Sixth International Conf. on Ion Sources, Whistler, B.C., Canada, September 10-16, 1995.

BNL-61797

CONF-9509125--3

Development of an EBIS for a RHIC Preinjector *

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Abstract

At Brookhaven, an Electron Beam Ion Source (EBIS) is operational as a test bed for development of a high current EBIS for RHIC. Previously, the goal of most EBIS research has been to produce bare or nearly bare nuclei. At BNL, the EBIS is required to produce only medium charge states of heavy ions e.g., Au^{35+}, since there is further stripping at higher energies. The BNL effort is directed at reaching intensities of interest to RHIC, approximately $3\ x10^9$ particles/pulse, which will require an EBIS electron beam on the order of 10A. Initial tests using a 1mm LaB_6 cathode have produced electron beam currents up to the design value of 110mA. A 2mm LaB_6 cathode has been installed and in a first run has produced currents up to 350mA. This source has so far produced charge states up to Ar^{16+} using neutral gas injection, and up to Tl^{50+} using external ion injection. Results of these studies and ion injection trials are presented.

*Work performed under the auspices of the U.S. Department of Energy.

Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is scheduled to be commissioned in 1999. The Tandem Van de Graaff accelerator presently supplies ions for the fixed target heavy ion program at the Alternating Gradient Synchrotron (AGS), and will initially serve as the preinjector for RHIC as well. We are now considering an alternative approach, where high charge state heavy ions would be produced in a source, accelerated in an RFQ followed by a short linac, and then injected into the AGS Booster. In principle such a preinjector should be simpler than a Tandem, more flexible in that it will offer a full spectrum of ion species, and allow for future increases in RHIC luminosity. Unfortunately, a high charge state heavy ion source that would satisfy the RHIC requirements still does not exist, but may be developed by scaling up of a device now available. The rest of the preinjector, an RFQ and linac, is a technology already adopted by industry.

From the point of view of the RFQ and linac, it is preferable to get from the source ions in charge states as high as possible, to make the preinjector more compact and efficient. We have considered several possible approaches to develop such an ion source, and have concluded that scaling-up of an Electron Beam Ion Source (EBIS) should be the most straightforward. EBISs deliver highly charged ions of virtually any species which are injected into the ion trap either as neutral gas or as low-charged ions. An EBIS operates best as a pulsed device, and can be well matched to a synchrotron with respect to pulse length. (Since the total charge per pulse is essentially independent of the extracted pulse width, short pulses can be extracted for efficient single-turn injection into a synchrotron). The evolution of charge states depends on the electron beam energy E and the product of the electron beam density and the ion confinement time, so that the charge state is easily optimized by variation of these parameters. While existing EBIS yields are lower than that

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required for RHIC by at least an order of magnitude, this can at least in part be attributed to the fact that before the advent of large heavy ion colliders there was little need for high intensities of high charge state heavy ions.

Starting with an estimate of $3x10^9$ Au^{35+} ions per pulse of source output necessary to yield $1x10^9$ ions per bunch in the 57 RHIC bunches, Prelec et. al.**[ref1]** have worked out the main operating parameters of the source, based on the experience of existing EBISs. These parameters are summarized in **Table I**. The 10A electron beam current is much higher than existing EBISs produce (0.5A). However, the requirement on the ion charge state is modest, thus allowing a relaxation of other parameters, i.e. the electron beam energy and current density, which have made EBISs technically difficult.

BNL EBIS R&D Program

Many of the issues which need to be addressed prior to the design of an EBIS for the new AGS Booster injector require an operating Test EBIS. Fortunately, we have obtained on a long term loan the Sandia National Laboratory ``SuperEBIS" **[ref 2]**, and put it into operation in our ion source laboratory as the BNL "Test EBIS" . Over the next two years our plans for this Test EBIS are the following: Using a 3mm LaB_6 cathode we expect to reach 1 A electron beam current, exceeding the usual operating current of EBIS devices. If our experiments on an electron gun test stand show that other cathode types are promising, they too may be tried on the Test EBIS. We will continue external ion injection studies in order to provide a variety of ions (especially metallic) required for RHIC. Possible sources of instabilities will be investigated to see whether they might develop in an EBIS as the electron beam current is increased above the levels presently achieved in similar devices. In particular, a spectrum analyzer will be used to aid in the quiet, low loss electron beam propagation which has been shown to result in improved extracted ion intensities from EBIS. **[ref3]** Fast extraction of ions will be studied, because the single turn injection of ions into the AGS Booster ring would greatly simplify the process and lead to a high capture efficiency. In order to achieve this, ions must be extracted in a pulse of less than 10μs duration. Cooling of ions in the trap will be studied and applied to improve the performance of the test EBIS. Measurements of the output beam emittance will be performed in order to characterize beam parameters and design the matching section to the next element, the RFQ.

Source Description

A schematic of the EBIS source and associated devices is given in Figure 1. The Test EBIS consists of a vertical bore, nine coil, unshielded superconducting solenoid. The coils are powered by three independent power supplies to produce a solenoidal main field with fringe fields taylored by upper and lower bucking fields. In the present configuration, the electron gun cathode is immersed in the fringe field at 5-10% of the maximum field. At present, we use a maximum field strength less than 1.7 T, but we expect to be able to operate up to 3T. The 120 cm long cold bore is occupied by 6.25 mm I.D. drift electrodes. The effective trap length when operating with intermediate potential barriers in the neutral gas injection mode is about 80 cm. Axial "drift tube" electrodes are used to control the ion production processes. The potentials to these electrodes are supplied by custom built HV power supplies with a dynamic range of 1kV and 10μs risetimes **[ref4]**. A d.c. bias can be imposed which allows the application of potentials of up to 5 kV to the trap region with respect to laboratory ground.

The helium cryostat, the insulating vacuum volume of the cryostat, and the cold bore (source) volume are in principle separated; however, operation has been somewhat hampered by helium leaks at both interfaces. LHe consumption is rather high, averaging about 15L/hr, but running in a constant transfer mode with a high efficiency transfer line from 500L dewars has resulted in rather low maintenance operation. (The helium is liquified on site by the RHIC facility and is sent back via a recovery line).

The power supplies controlling the electron beam launch and collection are mounted on a high voltage platform which is expected to operate at up to 20kV with respect to laboratory ground potential. The electron beam is formed by making the first anode positive with respect to the cathode, but propagation through the source is possible only when an accelerator potential applied to the platform makes the cathode sufficiently negative compared to all source drift tubes. The electrons are decelerated just before collection, so that power dissipated on the electron collector is a fraction, e.g. 25%, of the maximum beam power. The advantage of this platform scheme is that only the collector supply must provide high power while the anode and accelerator supplies can be used to monitor electron beam losses and can be set to switch off the electron beam propagation when losses exceed preset limits, usually about 1mA. This prevents damage to the drift tubes and other electrodes in the event that an electron beam excursion occurs. An IBM compatible computer on the high voltage platform contains commercial DAC and ADC boards for controlling and monitoring the power suppies. A computer at laboratory potential provides a graphical user interface and performs the conversions and other necessary calculations. Data is transfered between the two computers over a serial fiber optic link. [ref5] Presently the system provides central control and readback of remote power supplies and will be upgraded to monitor the electron beam propagation efficiency to provide rapid shutdown when losses exceed preset values.

Operating Modes and Results

Initial tests were made with the electron gun geometry as designed at Sandia National Laboratories and constructed at BNL. A 1mm LaB_6 cathode was used to produce electron beam currents up to 110mA and current densities of 100-400A/cm^2. The cathode was immersed on axis in the solenoidal fringe field to a level of 400-800Gauss. The beam was then compressed by the increasing axial field, typically 1.2T. This geomety was used in the initial testing of the EBIS with neutral gas injection and resulted in the production of Argon charge states up to 16+. Subsequently, the electron gun anode apertures were increased from 2mm to 4mm diameter and a 2mm LaB_6 cathode capable of producing beams up to 0.5A was installed. Electron beam currents of up to 350mA have been propagated through the source, with some heating of the structure evident at this level. Further tests to increase of the electron beam current were suspended at this point to allow the introduction of loss monitor diagnostics and to allow concentration on the production of ions using external ion injection.

Neutral gas injection is the most commonly used method for introducing the species to be ionized into an EBIS. Low charged ions formed in the gas injection region are allowed to reach the main trap region during a specified injection period according to the value of potential applied to an intervening electrode. Transfer of ions using this method is called "electronic injection" following the early description of this process by Donets [**ref6**]. In **Figure 2**, a time of flight spectrum for neutral gas injection of argon is given. Contaminant peaks of H^+, He^{2+} and He^+ are present due to helium leak and residual hydrogen background. Argon charge states from Ar^{11+} through Ar^{16+} are observed after an injection period of 50ms and confinement period of 300ms. The total charge extracted in this case was 925pC during an extraction pulse of duration 75μs FWHM, corresponding to 77% neutralization of a 76mA electron beam.

Ion injection into EBIS has been well demonstrated at Saclay [ref7] and Stockholm. [ref8] It is somewhat more difficult to implement but is expected to provide better performance for our long term goal of producing milliampere currents of moderate charged metallic ions. Impregnated zeolite (thermionic emitter) ion sources [ref9] and microMEVVA [ref10] ion sources have been configured to be interchangeable modular units to serve as EBIS teststand injectors. They have been adapted to include a deceleration stage which provides high extraction energies for increased beam current, while accommodating the rather low injection energies necessary for ion trapping in the EBIS. The zeolite sources are useful for producing ions of Na, Cs, and Tl whereas the microMEVVA source can produce a broader range of metal ions, e.g, we have operated the source with Ti, Ta, and U.

External ion injection can be made in both fast and slow modes. In the fast mode, the potential of an EBIS trap barrier electrode is pulsed lower than the trap region potential for a preset duration, typically <1 ms. Those ions which have sufficiently low energy do not complete a round trip during this time and hence can be captured. Since only a single bunch is captured in this mode it imperative to retard the injector beam sufficiently (typically ~10eV) to increase the linear current density inside the source. Furthermore, low transverse energy is required, so that the resulting low angular momentum results in a high percentage ion beam electron beam overlap, essential for rapid ionization. This mode has the advantage of a well defined confinement period and shorter overall cycle times, since the injection period is negligible.

In contrast, the slow ion injection mode allows for some accumulation of ions during a relatively long injection period (10-100ms). Ions are injected with energy sufficient to traverse the barrier potential and propagate through the source with typically 100eV with respect to the trap electrodes. Ions which are further ionized before completing a roundtrip transit are captured. This mode is relatively easy to initiate with both lower current ion sources and unoptimized ion optics. Once this mode is achieved it is relatively easy to fine tune the ion optics and injector beam energy to proceed to the fast injection mode.

After initial testing of both sources, we decided to use a sodium impregnated zeolite source to accomplish the first external injection into the EBIS. The source produces ~10μA beams of Na^+ in a DC mode of operation, with emitter lifetimes ~100 hours. In order to extend the emitter lifetime we operate in a pulsed extraction mode, producing beams only during the EBIS injection period. To be able to quickly optimize both the EBIS injection and extraction efficiencies, it is convenient to operate with a repetition rate of 5 Hz or more. In the present configuration, the zeolite source provides a stable beam of 1+ ions in pulses ranging from 500μs to D.C.

Typically, extraction from the auxillary source is made at 5kV and the beam is retarded to 1-3kV, i.e, the potential of the EBIS trap region electrodes. Na^+ beams of about 5μA are obtained at a Faraday cup just outside the EBIS electron collector. Improvements to our control system which allow control of the ion optics, beam energies, and timing have facilitated the ion injection procedure. In figure 3, a TOF spectrum of highly charged sodium extracted from the EBIS is shown. The externally injected Na^+ ions were injected into a 7keV, 115mA EBIS electron beam during an injection time of 15ms. After a confinement time of 50ms the most probable charge state was Na^{7+}. Figure 4 shows a TOF spectrum of highly charged thallium ions peaked at Tl^{41+}, formed from externally injected Tl^+ ions. The confinement time was 500ms for electron beam energy and current 7keV and 125mA, respectively. Figure 5 displays the EGUN [ref11] electron beam trajectories for the beam producing the spectrum of figure 4, launched from a 2mm cathode. The calculation yields an electron beam current density of 66.5A/cm^2 in the main B-field of 1.45T.

The development of a control system has been an important part of our program. A simple

EBIS controller has been constructed around commercially available PC timing boards which can be used to specify events at the microsecond level. A timeline is generated which multiplexes preset analog reference potentials to control the EBIS trap electrode high voltage. In addition, pulses are generated to control the external ion source, ion optics, and diagnostics such as the time-of-flight spectrometer. The duration of a complete EBIS cycle is on the order of 100ms, with several distinct subperiods such as injection, confinement, and extraction. Eventually, the control system will facilitate setting and monitoring all potentials and intervals through a graphic oriented PC interface.

During external ion injection , accurate total current measurement of the extracted highly charged ions has been hampered by helium contamination and lack of a suitable Faraday cup. Improvements made recently to the vacuum interface between the insulating and ionization volumes are expected to alleviate the helium contamination. Modifications to the beamline are underway to allow introduction of a harp-type beam profile monitor and a compact retractable emittance head between the EBIS exit and the existing reflex time of flight (TOF) spectrometer used to analyze the EBIS highly charged ions. Both devices were designed and constructed at BNL and tested using the EBIS and beam profile electronics in Stockholm. Two harp designs have been implemented; the first provides a 16mm aperature with 0.5mm resolution and 90% transparency and the second provides a 28mm aperature with 1mm resolution and 97.5% transparency. The harps allow monitoring of the injector and EBIS beam profiles as well as the total current without interuption of the injection processes.

Modifications are also underway to improve the neutral gas injection. Previously, the gas has been injected perpendicular to the beam axis as a jet such that neutrals not ionized in a single pass through the electron beam were purged into the bore region outside the drift tubes. A more efficient method which has been implemented successfully in other sources is to use an extended drift electrode as a gas cell.[ref12] The cell can be heated to about 100K by a resistive heater. In addition, Lakeshore diode temperature sensors TP120G, which operate in the magnetic field are being installed to allow the detection of the onset of electron beam induced heating of the drift tube structure.

Acknowledgements

This work is performed under the auspicies of the U.S. Department of Energy. We would like to thank D. Boeje, L. DeSanto, B. Erickson, W. Hensel, R. Lockey, D. McCafferty, D. Raparia, P. Stein, K. Talukdar and W. Tramm for their help on this project. The contributions of L. Liljeby and A. Pikin to the HV platform control system and cryogenics, respectively are greatly appreciated. We would also like to thank M. Bjorkhage, A. Engstrom, S. Framling, A. Paal and U. Rosengard for their help during the testing of the BNL harp-type profile monitors and compact emittance head at the Stockholm EBIS. We thank P. Schoch and J. Schatz of the RPI Plasma Dynamics Group for providing us with the zeolite emitters and ion source which were used as the external ion injector to the EBIS during these studies.

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Table Captions

Table 1 Parameters for an EBIS meeting RHIC Requirements

Figure Captions

Figure 1 Schematic of BNL Test EBIS setup

Figure 2 Argon TOF spectrum from the EBIS

Figure 3 Sodium TOF spectrum from the EBIS

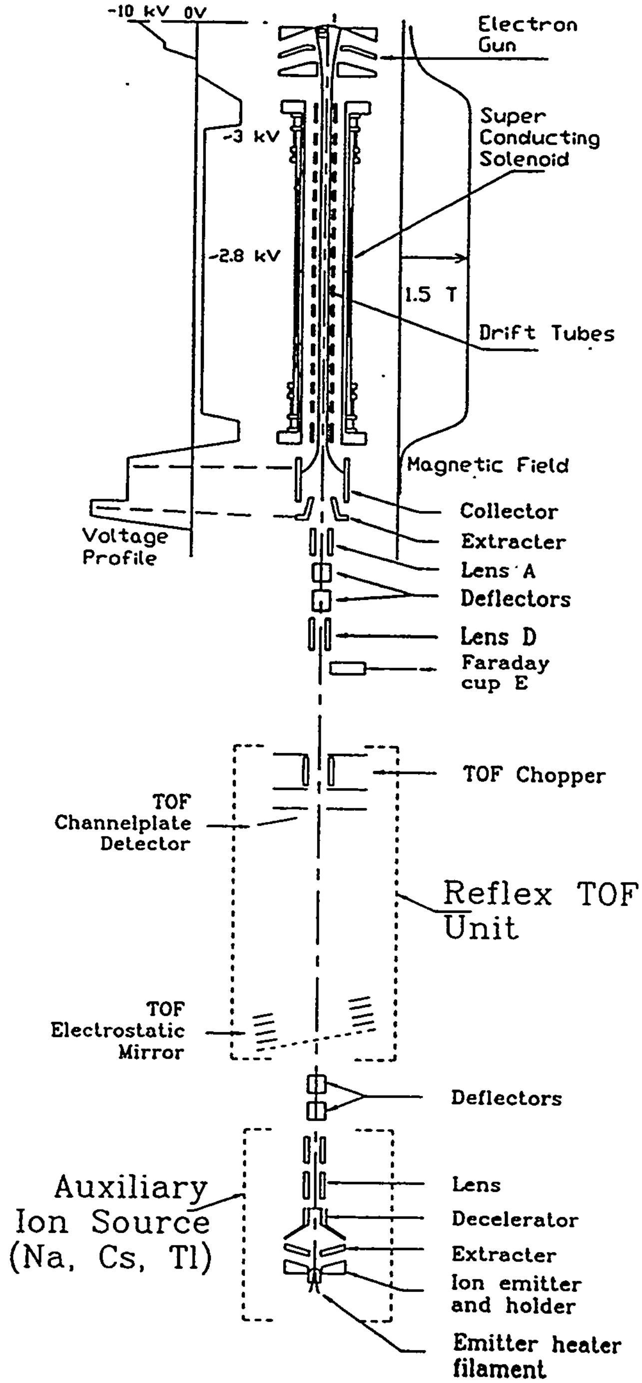
Figure 4 Thallium TOF spectrum from the EBIS

Figure 5 EGUN simulation of the electron beam trajectories corresponding to the Thallium spectrum of fig.4. (1grid unit=0.1mm)

Electron beam current	10A
Electron beam Voltage	20kV
Length	1.5m
Trap capacity	1.1×10^{12} charges
Yield, positive charges	5.25×10^{11}
Yield, Au^{35+}, design value	3×10^{9} ions/pulse
Yield, Pb^{53+}, design value	2×10^{9} ion/pulse

Table I
Parameters for an EBIS meeting RHIC requirements.

BNL EBIS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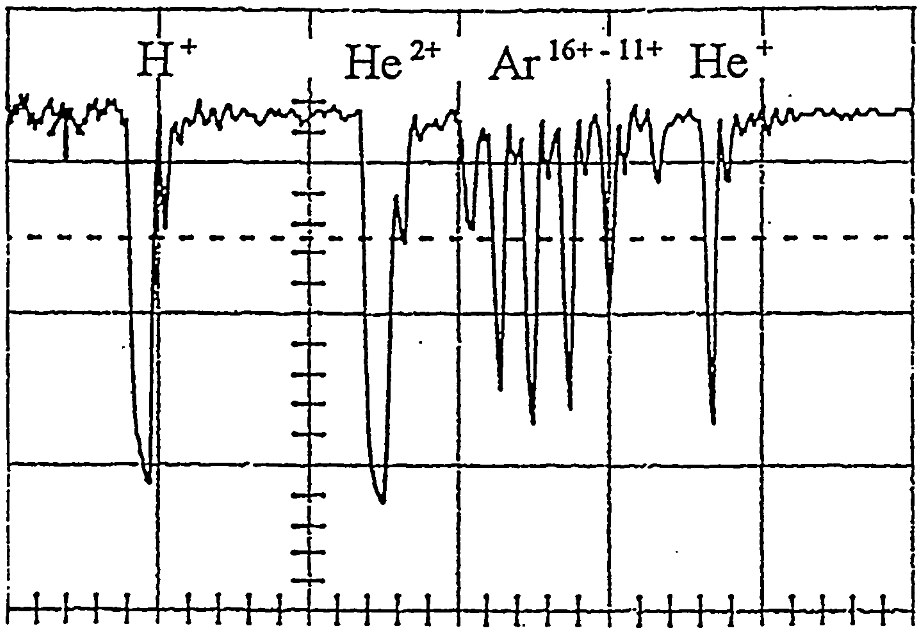
Voltage Profile
Lens A
Deflectors
Lens D
Faraday cup E
TOF Chopper
TOF Channelplate Detector
Reflex TOF Unit
TOF Electrostatic Mirror
Deflectors
Auxiliary Ion Source (Na, Cs, Tl)
Lens
Decelerator
Extracter
Ion emitter and holder
Emitter heater filament



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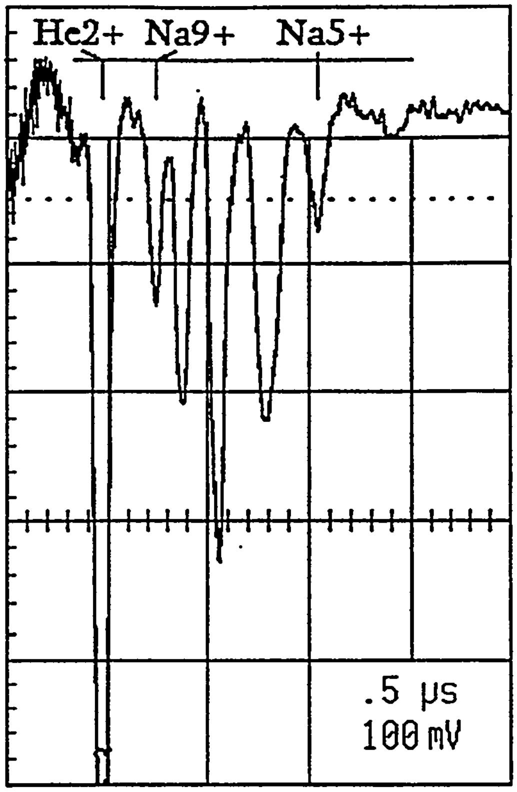

figure 3

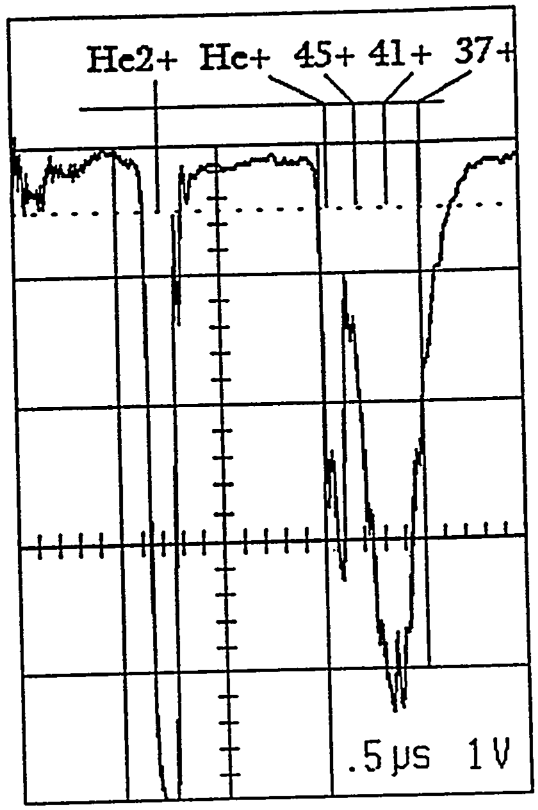

figure 4

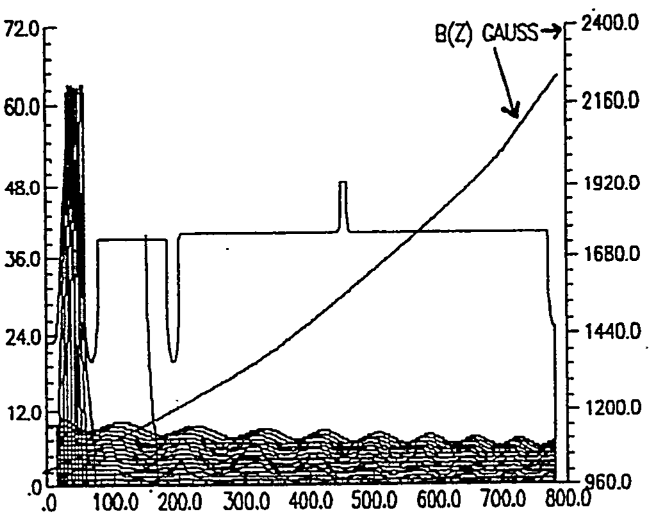

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figure 5