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CONF-870498-9

BNL 39976

TANDEM INJECTED RELATIVISTIC HEAVY ION FACILITY AT BROOKHAVEN,
PRESENT AND FUTURE

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BNL--39976

DE87 012872

Abstract

The Brookhaven Tandem Facility has been recently joined to the Alternating Gradient Synchrotron (AGS) by means of an ~680 meter long heavy ion transfer line. The design and construction of this line are described as well as the Tandem and AGS modifications which made it possible to initiate a relativistic heavy ion research program. Operational experience and performance during the first 14.6 GeV/amu ^{16}O and ^{28}Si runs are reviewed. At present the facility is capable of accelerating ions up to mass ~32. Future developments are described which will lead to the acceleration of heavier ions up to gold, and hopefully to the construction of a relativistic heavy ion collider for the entire mass range at center of mass energies up to 250 GeV per nucleon pair.

Introduction

The three-stage MP Van de Graaff facility at Brookhaven National Laboratory^{1,2} which has been operating since 1970 is now providing heavy ions for further acceleration to relativistic energies in a large synchrotron. In particular, the 30 GeV alternating gradient synchrotron (AGS) high energy accelerator has now been interconnected to the tandem facility with a ~680 meter long beam transfer line. The Tandem accelerators can directly inject the AGS with heavy ions up to a maximum mass of ^{32}S which are then accelerated up to energies of 14.6 GeV/nucleon.³ A new preinjection booster synchrotron for the AGS, which is now under construction⁴, will extend the mass range up to ^{198}Au . In

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addition, a large superconducting collider⁵ has been designed and proposed for construction that would boost the AGS energies to 100-125 GeV/nucleon in each of two counter-rotating beams. This relativistic heavy ion collider (RHIC) would then allow a new relativistic heavy ion physics program to explore the extreme regions of high nuclear density and temperature where the quark gluon plasma ("quark matter") may be formed and studied. The energy range as a function of heavy ion mass for these different accelerator facilities is shown in Fig. 1. A general description of these facilities and the physics envisaged appears in reference 6.

Operational Requirements

Most other tandem accelerator booster facilities utilize linacs or cyclotrons, which can operate in a continuous wave (CW) mode, thus only requiring the regular intensity direct current (DC) beams suitably chopped and bunched. In distinct contrast,⁷ injection into a synchrotron requires that the tandem ion source be pulsed at very high currents compared to normal operation, allowing a large amount of beam to be injected into the synchrotron in a short time. The beam is then rapidly accelerated in the synchrotron and slowly spilled out, producing the equivalent of a DC beam with a ~30% duty cycle and a 2-4 sec period.⁴ In order to achieve this tandem injected synchrotron operation it was necessary to modify the tandem accelerators so that high current beam pulses could be generated, accelerated and then fully stripped of all electrons for transport to the AGS. Fully stripped ions are necessary because the average vacuum of the AGS is $\sim 10^{-7}$ torr, which is quite suitable for proton acceleration, but unsuitable for partially stripped heavy ions because of high stripping probability.

The AGS also required modifications so that it could suitably accelerate the relatively low velocity ions supplied by the tandem accelerators. Under normal proton operation the AGS accelerates 200 MeV protons injected by a linac. In contrast, the heavy ions have an energy of only 7-8 MeV/nucleon and must be preaccelerated by a special rf cavity up to approximately 200 MeV/nucleon so that the main rf accelerator cavities can operate in their normal range.

The tunnel construction program was started in 1985 and all the construction of the tunnel, the beam transport line, and the accelerator modifications, were completed in approximately two years. The initial operation of the AGS with heavy ions began approximately a year ago. The first heavy ion operation of the facility was with ^{16}O and, more recently, with ^{28}Si .

Pulsed Ion Source Operation

The main development² required at the Tandem Accelerator Facility consisted in generating high intensity ($>100\mu\text{A}$) pulsed negative heavy ion beams and demonstrating reliable operation of the accelerators under these unusual conditions. For this purpose a high current negative ion source manufactured by the General Ionex Corporation, Model 860,^{7,8} was operated in a new pulsed configuration² as shown in the simplified schematic diagram in Fig. 2. In normal dc operation, positive cesium ions are accelerated through a potential difference of 3-5 kV and focussed onto a sputter target. Negative ions emerge from the sputter target after having picked up an additional electron from the cesium, and are then accelerated through an extraction potential of about 25 kV. In the pulsed mode of operation the cesium acceleration voltage is pulsed from a base level of up to 0.5 kV to a maximum of about 4.5 kV. The lower level is adjusted to provide a low

intensity DC tracer beam for accelerator stabilization and beam tuning. The maximum pulse amplitude is adjusted to optimize the instantaneous beam current and this adjustment varies depending on the ion species. The extractor voltage is held constant at all times.

Typical pulsed performance is 100 μA of $^{16}\text{O}^-$ ions and 70 μA of $^{28}\text{Si}^-$; with pulse lengths of 200-400 μsec . A voltage pulse rise time of less than 1 μsec provides a beam pulse rise time of 10 to 50 μsec . The duty cycle for this source for AGS operation is not required to exceed 10^{-4} , but it may be operated at much higher rates.

Acceleration in the Tandem Accelerator

The negative ion beams from the source are accelerated and converted to fully stripped ions in several stages. Brookhaven has two tandem accelerators, the MP6 injector machine, operating at about 10 MV, and the upgraded MP7 accelerator, which can operate as high as 16 MV, but normally runs at 14 to 15 MV. These facilities are used in two principal configurations illustrated in Fig. 3: a two-stage mode, using only MP7, and providing two stripping stages for the lighter ions such as oxygen, and a three-stage mode employing both machines with three stages of stripping for the most difficult cases of silicon or sulfur.

In the two-stage mode of operation the ion source is located near ground potential at the low energy end of MP7. Negative $^{16}\text{O}^-$ ions are accelerated to the high voltage terminal, reaching an energy of about 0.9 MeV/amu, sufficient to convert the beam to the $\text{O}(7+)$ ionization state with about 30% efficiency using a thin carbon stripping foil inside the high voltage terminal. Further acceleration toward ground potential yields an energy of 7-8 MeV/amu. After the energy analysis in the first 90° magnet and just beyond the energy regulation slits, the last electron can be

removed by a second final stripping foil with nearly 100% efficiency. The beam then is bent in the second 90° magnet and enters the first section of the transfer line.

For the more difficult case of $^{28}\text{Si}^-$, the ion source is inside the negative high voltage terminal of MP6. The negative $^{28}\text{Si}^-$ ions are accelerated to ground potential where they are transported and injected into MP7. The negative silicon beam arrives at the high voltage terminal of MP7 with an energy of approximately 0.78 MeV/amu, and is converted into $\text{Si}(9^+)$ with about 20% efficiency. A second stripping foil is inserted at the next field-free section, 25% of the way toward ground potential, where the beam is converted to $\text{Si}(12^+)$ with about 25% efficiency. The remaining three-quarters of the potential provides a final energy of ~ 6.6 MeV/amu. At this energy the last two electrons are stripped away by the final stripper with an efficiency of about 50%, yielding 2.5% of the original particle flux, about one order of magnitude lower than for oxygen. Even weaker phosphorous and sulfur beams will be used in tests to be conducted in the fall of 1987.

The Model 860 sources are pulsed using infrared light links either triggered locally or by the AGS master timing control. The ion source provides a longer pulse than necessary which is then chopped electrostatically after acceleration in MP7 in order to provide a shorter, more accurately timed and shaped pulse for injection into the AGS as indicated in Fig. 3.

The fractional energy spread of the heavy ion beams from the Tandem accelerators is about 2×10^{-4} with some additional contribution from the last stripping foil. The emittance of a pulsed oxygen (8^+) beam of 70 μA at 7 MeV/amu has been measured to be approximately $1.4 \text{ mm} \cdot \text{mrad}$. This

result is within 20% of that obtained with a 9 nA dc beam used for beam tuning and Tandem voltage control.

Beam Transfer to the AGS

The heavy ion transfer line (HITL), (see Fig. 9), about 680 m long, includes three major angle turns, a 180° turn near the Tandem, a 48° deflection near the midpoint, where the beam also acquires a slight downward pitch, and a third bend through 138° near the AGS injection point. Each bending section is comprised of two symmetric dipoles and quadrupole lenses and is achromatic in the horizontal plane. The image slits after the first of the two 90° bending magnets near the Tandem are used for energy stabilization of the accelerator. After the final stripping in a carbon foil located between the two 90° bending magnets, (Fig. 3), the second 90° magnet is used to select the fully stripped ions for transport through the line. The long straight portions of the transport line contain simple point-to-point focussing doublets, spaced approximately 75 m apart, and horizontal and vertical steering correction magnets at the quadrupoles, and halfway between near the beam waists. Multiwire beam profile monitors (harps) and Faraday cups can be inserted pneumatically at each of the beam waists. Special lens configurations near the Tandem and the AGS provide optimal matching into the transport channel and into the AGS lattice. All of the magnets and diagnostic equipment on HITL are controlled by the AGS distributed control system, with a local control station at the Tandem.

The Heavy Ion Transfer Line Vacuum System and Beam Instrumentation

One of the special features of HITL is the vacuum system which has maintained the vacuum in the line at $<1 \times 10^{-9}$ Torr for 1.5 years to date without any electric power use by the main part of the system. This low

pressure provides an ample margin for avoiding beam losses and allows the utilization of passive getter materials.

To achieve a vacuum of 10^{-9} Torr, low outgassing of the vacuum wall and high pumping speeds are required. Outgassing rates of $<10^{-11}$ Torr·l/s·cm² (or $<10^{-8}$ Torr·l/s·m for pipes of 9 cm diameter) for stainless steel can be achieved by in-situ bakeout at 150°C. A linear pumping speed of approximately 200 l/s·m is provided by linearly distributed non-evaporable getter (NEG) strips and small ion pumps. With this arrangement, the pumping speed is not conductance limited and an average pressure of 10^{-10} Torr can be obtained.

The vacuum system of the HITL uses the combination of 20 l/s diode ion pumps, every 37 meters and NEG strips⁹ lined along the length of the vacuum beam pipes in 10 m sections.¹⁰ The diode ion pumps remove the small amount of inert gases such as Ar and He, which are not pumped by the NEG. The NEG used here is called St 707 developed by SAES Getters, Inc.⁹ It is a Zr-V-Fe alloy deposited on a constantan support strip 0.2 mm thick and 3 cm wide. After activation at 400-500°C in vacuum, pumping speeds of 200 l/s·m and capacities of 1 Torr·l/m for active gases are available while operating at room temperature. Activation is done by resistive heating of the constantan support strip which also serves as the heat source during in-situ bakeout. The NEG strips mounted on insulators have a vertical dimension of 1 cm and comfortably fit inside a pipe of 9 cm diameter, allowing ample beam clearance. The NEG strip assembly is shown being inserted into a 10 m beam pipe section in Fig. 4.

The HITL is divided into 18 vacuum sectors of various lengths. A typical vacuum sector of 73 m in length consists of eight vacuum pipes with NEG strips installed, two 20 l/s diode ion pumps, several ion gauges and

one beam diagnostic box. The thermal expansion of the NEG strips during bakeout and activation is absorbed by two copper braids at each end of the pipe as shown in Fig. 4. Further details of this pumping system design, construction, and performances are available in ref. 10.

The beam transfer line was instrumented with 21 diagnostic stations. The AGS requires a 20-300 μsec beam pulse of 10-100 μA current at approximately 3 sec intervals, while, for setup, a dc beam of 1-20 nA is monitored at a 10 Hz rate. Beam profiles are measured with multiwire arrays (harps)¹¹ which have orthogonal grids of 100 μm tungsten-rhenium wires. All materials are metal or ceramic, as required for the in-situ bakeout of the vacuum system. Signal currents from the harps can vary from less than 100 pA to 10's of μA , which are accommodated through the use of microprocessor controlled, gated integrators. The beam intensity can be monitored destructively by Faraday cups located at 17 of the stations, while operational monitoring of the pulsed beam is provided by 5 beam current transformers of a design used elsewhere at the AGS. Three microprocessor based instrumentation controllers manage the data acquisition from this equipment as part of the new AGS distributed control system. Digital data can be acquired at workstation consoles at the Tandem and AGS control rooms, along with multiplexed analog signals suitable for oscilloscope display.

AGS Modifications and Performance

The AGS at Brookhaven is a 30 GeV proton accelerator, but it has been readily adapted for the acceleration of heavy ions. The maximum energy depends on the charge/mass ratio of the ions and it is about 15 GeV/amu for the lighter ion species and about 11 GeV/amu for gold. It would be quite inefficient to accelerate partially stripped ions, and moreover such ions

would quickly be lost from the equilibrium orbit of the accelerator because of electron stripping by the residual gas in the AGS vacuum chamber. It is necessary to inject fully stripped ions at an initial energy high enough to prevent charge pick-up from the residual gas during the first part of the acceleration cycle. Direct injection from the Tandem accelerators into AGS is possible only for lower mass heavy ions, a maximum of ^{32}S . The stripping efficiencies are too small for total ionization of heavier atoms at the maximum available Tandems energy, and an intermediate booster becomes necessary (see below).

Two modifications of the AGS are required to accommodate direct injection. First a new injection system is needed to permit multiturn stacking of the positively charged ions in the AGS aperture (protons are accumulated by stripping H^+ atoms). Second, there has to be some preacceleration in the AGS before the proton acceleration rf system can take over the task of accelerating the beam to full energy because the heavy ions are injected at a velocity much lower than that of the protons.

Stripped heavy ions from the Tandem Facility are stacked in horizontal phase space with a standard multiturn injection technique. An electrostatic injection septum provides a total deflection of about 9° to accommodate the steep angle of approach of the injected ions. During the injection process the AGS equilibrium orbit is distorted locally by means of a slowly collapsing half-wavelength magnetic bump. Initially the orbit is set up near the injection septum, and as the orbit bump collapses the early first ions fill the central region of the available phase space, and ions arriving on subsequent turns fill the outer regions. The orbit bump is excited by two ferrite magnets located about a quarter betatron wavelength 23 m upstream and downstream of the septum, providing deflection

of up to 4 cm at the septum location. Nominally, ten turn injection is envisaged as a standard, but the number of turns and the stacking efficiency can be optimized by varying the betatron tune of the synchrotron lattice and the rate of collapse of the equilibrium orbit bump. A nominal horizontal betatron tune of about 8.80 and a bump collapse rate of about 0.25 cm/turn are used for ten-turn injection.

The AGS magnetic field at injection is about 90 gauss. Beam is injected at a constant energy on a slowly rising field ramp, the rise rate being about 1.0 G/msec. The magnetic field profile as function of time for a complete acceleration cycle is shown in Fig. 5 and compared to the rf frequency and voltage profile as well as the beam current. The arrival time of the injected beam is locked to the injection field by a Gauss-clock, which integrates the time derivative of the magnetic field, and it is adjusted to optimize the survival of the first injected turn in the ring. The AGS magnetic field ripple at these low fields is equivalent to an equilibrium orbit uncertainty of about 1-2 mm, which is acceptable. During the injection of ten turns the equilibrium orbit is contracting, away from the septum, by about 6 mm per turn at the same time as the orbit bump collapses. A polaroid photo (Fig. 6a) of the oscilloscope display of an electrostatic pickup inside the AGS beam pipe shows a single short pulse of an $^{16}\text{O}^{+8}$ beam "coasting" around the ring for about 30 turns before colliding with the vacuum wall. For a long injected beam pulse Fig. 6b displays the initial buildup of the beam current in the AGS as about nine turns are accumulated in the accelerator.

The ion beam is captured and accelerated by the rf system on the 12th harmonic of the beam revolution frequency. The process is divided into two portions: the preacceleration of the ions with a new rf system^{12, 13} to

about 200 MeV/amu, the normal injection energy for protons, followed by "handoff" to the existing proton rf system for acceleration to the full energy (see Fig. 5). The frequency range of these two rf systems extends from 0.5 to 2.5 MHz, and from 2.5 to 4.5 MHz, respectively. After acceleration to full energy, which takes about 1.1 sec, the rf systems are turned off and the AGS magnet excitation is held on a nearly constant, slightly falling "flat-top", about 1 sec long, for slow resonant extraction or "spill" of the ions to the experimental areas.

The initial performance¹⁴ of the facility during commissioning provided adequate beam intensities for the experimental program. About 5×10^8 oxygen ions/spill and 10^8 silicon ions/spill were achieved. The experimental program requirements ranged from 10^9 ions/spill to 10^4 ions/spill with the majority of the experiments in the lower intensity range. The accelerator system is capable of yielding about an order of magnitude higher intensity once the AGS ion beam capture and acceleration efficiency are improved, and the ion source and tandem high voltage performance, as well as stripping efficiencies, are further optimized. Operational performance characteristics are listed in Table I.

The ion beams are delivered to the experimental floor using the same beam switchyard as for protons. The AGS external beam switchyard incorporates a series of electrostatic splitters and thin septum magnets enabling the delivery of beam to four primary beam lines simultaneously. This system was used to provide 2-100% of the beam to any particular line, as needed. When necessary, the beam was further attenuated by defocussing on a small aperture collimator, then refocussing onto a momentum defining collimator in order to eliminate off-momentum contaminants.

A miniature CCD camera¹⁵ used as a beam profile meter at the experimental target location by simply allowing the beam to pass through the entire camera, lens and all, showed the focus conditions at the target in great detail. A 1/30 second integration (one TV frame) of the 14.6 GeV/amu $^{16}\text{O}^{8+}$ ions passing through the CCD is shown in Fig. 7. The beam spot is $\sim 2 \times 3$ mm in size--somewhat comparable to that of a tandem accelerator. The beam purity was $>99\%$ at an intensity of about 10^4 ions per spill. The response of a 1 mm thick scintillation detector placed in the beam is shown in Fig. 8a. The large peak corresponds to the $^{16}\text{O}^{8+}$ beam ions and the few lower channel counts are the impurity fragments (perhaps made in the counter itself). Reaction products from a ^{198}Au target detected in a 1 mm quartz Cerenkov detector are shown in Fig. 8b compared with the superimposed ^{16}O peak.

Further Developments and Conclusions

For the acceleration of ions heavier than ^{32}S a booster synchrotron between the Tandem and the AGS is required. The Tandem accelerators are an adequate source of partially stripped heavy ions, which can be preaccelerated by a booster to an energy high enough to achieve efficient stripping of all electrons before injection into the AGS. The booster will be a synchrotron of 1/4 the circumference of the AGS, with a maximum $B\rho = 17.5$ Tm and will provide acceleration, for example, of $^{197}\text{Au}^{33+}$ ions from ~ 1 MeV/amu to 350 MeV/amu where fully stripped ions can be provided with about 50% efficiency. Construction has been authorized for the purpose of increasing the proton beam intensity of the AGS, as well as for extending the heavy ion capability to the heaviest masses. The completion of this second phase of the AGS heavy ion program is expected for 1991.

The third phase of the BNL heavy ion program entails the proposed construction of a Relativistic Heavy Ion Collider, or RHIC. This proposal is under review at the present time. The collider will provide two counter-rotating heavy ion beams, at an energy of 100-125 GeV/amu each, colliding in six experimental interaction regions. The two accelerator storage rings are to be installed in the existing tunnel constructed for the abandoned CBA Project, and they will employ superconducting magnets which will be cooled by the operational CBA refrigeration plant. Injected beams will be provided by the Tandem-Booster-AGS complex through a beam transfer line for which the tunnel and some magnet equipment already exist. A complete layout of all these facilities is shown in Fig. 9.

The RHIC facility will cover the energy range of 30-125 GeV/amu per beam in the colliding beam mode and will provide luminosities in the range of $10^{25} - 10^{29} \text{ (cm}^{-2} \text{ sec}^{-1}\text{)}$ for ions, and over an order of magnitude more for protons. Experimentation with internal gas jet targets at the lower energies allows the entire range between the AGS fixed target program and the maximum RHIC energy to be covered. With the completion of RHIC, Brookhaven will have a heavy ion research facility that spans more than 5 decades in energy.

ACKNOWLEDGEMENTS

The successful completion of Phase I of Brookhaven's relativistic heavy ion projects is due to the enthusiastic and expert efforts of many individuals. In particular, we would like to acknowledge the contributions made by C.W. Carlson, I.L. Feigenbaum, E. Jablonski, D. Larson, R. Lindgren, M.A. Manni, P. Mohn, R.T. Sanders, A. Soukas, A.J. Stevens, and R.L. Witkover.

FIGURE CAPTIONS

- Fig. 1 Energy vs Mass performance characteristics for various present and future accelerator facilities at Brookhaven National Laboratory.
- Fig. 2 Schematic of ion source arrangement for providing high current negative heavy ion pulses.
- Fig. 3 Schematic of the arrangement of MP Tandem accelerators, used as injectors. Both accelerators used in a three-stage configuration are required for ^{28}Si or ^{32}S beams while only the second one is used for the ^{16}O acceleration.
- Fig. 4 Getter pumping strip assembly being inserted into the stainless steel beam transfer vacuum pipe. The stainless steel wire frame supports the strip on grooved insulators through which the strip is free to move longitudinally under thermal expansion. The heavy braided copper connection (up to 70 A during strip activation) bends upwards as shown to accommodate the strip expansion. A 3 mm diameter quartz rod (observable under the copper braid) runs the length of the assembly and prevents any of the high current carrying components from touching the bottom of the pipe during differential expansion conditions.
- Fig. 5 A time profile for one cycle of the AGS showing the relation between the magnetic field, rf voltage and frequency and beam current.

- Fig. 6a An oscilloscope trace of the beam pickup electrode voltage showing ~30 complete revolutions of a short $^{16}\text{O}^{8+}$ beam pulse "coasting" around the machine before being lost on the walls of the vacuum chamber. Each turn takes ~22 μsec (100 μsec /division) and after an initial attenuation in the first two turns (subject to empirical optimization) holds up in intensity quite well until lost on the vacuum wall.
- Fig. 6b An oscilloscope trace (50 μs /division) of the AGS beam current showing the buildup of the beam during the multiturn injection process. About 9 turns are stacked in the AGS using part of the 300 μsec long beam pulse delivered by the Tandem.
- Fig. 7 A television monitor display (one frame, 1/30 sec integration time) of the focussed 14.6 GeV/amu $^{16}\text{O}^{8+}$ ion beam at one of the target positions. The 1/4 sec spill time provided ~40,000 ions, each of which illuminates one or more pixels of a miniature CCD television camera through which the beam is passing on the lens axis.
- Fig. 8 Initial beam purity studies at the E802 experimental station showing (a) the response of a 1 mm thick by 10 cm square plastic scintillator to the beam with ~1% particle contamination below the $^{16}\text{O}^{8+}$ ion beam distribution and (b) the reaction trigger response of a 1 mm Quartz Cerenkov counter exposed to reaction products from a gold target. The ^{16}O peak is superimposed for comparison.
- Fig. 9 The complete present and future relativistic heavy ion acceleration facilities at Brookhaven (see text).

TABLE I. Relativistic Heavy Ion Performance

	<u>^{16}O Acceleration, Oct-Nov '86</u>			<u>^{28}Si Acceleration, Apr '87</u>		
	<u>INTENSITY/PULSE</u>		<u>ION ENERGY</u>	<u>INTENSITY/PULSE</u>		<u>ION ENERGY</u>
	<u>(current x 300 μsec)</u>			<u>(current x 300 μsec)</u>		
LOCATION (Fig.3,9)	particles	charge		particles	charge	
ION SOURCE	2.3×10^{11} (125 pA)	2.3×10^{11} (125 μA)	140 keV	10^{11} (50 pA)	10^{11} (50 μA)	7 MeV
AT AGS INFLECTOR	2.3×10^{10} (12.5 pA)	1.9×10^{11} (100 μA)	106 MeV	2.0×10^9 (1 pA)	2.8×10^{10} (15 μA)	186 MeV
EXTRACTED	5.0×10^8	4.0×10^9	96-233 GeV (14.6 GeV/amu)	5.0×10^7	7.0×10^8	280-408 GeV (14.6 GeV/amu)

SOURCE: 20,000 - 25,000 pulses/day (900 hrs continuous operation, for silicon)

MP7 TANDEM: +14.8 MV

MP6 TANDEM: -8 MV

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Research carried out under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

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FIG 1

FIG 2

FIG 3

FIG 4

FIG 5

FIG 6b

FIG 7

FIG 8

SITE MAP

FIG 9