BNL-101982-2014-TECH

AD/RHIC/70;BNL-101982-2013-IR

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June 1990

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U.S. Department of Energy

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(Submitted to Nuclear Instruments and Methods)

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ABSTRACT

The increased particle current demands on both ion source and injection facility by a heavy ion synchrotron collider are analyzed. Also, the existing injector arrangement and performance for most of the world's fixed target heavy ion synchrotrons are compared. At the present time, the Brookhaven relativistic heavy ion collider (RHIC) requirements for the heaviest ions can be met by an injector with a front end consisting of a negative ion source and electrostatic tandem Van de Graaff accelerator. For the heaviest ions, considerable research and development is necessary on both ECR and EBIS high charge state ion sources before required particle currents can be met.

I. Introduction

There has been a tremendous growth in the last few years in the experimental study of heavy ion collisions at ultra-relativistic energies. At the Brookhaven National Laboratory (BNL) these studies have centered on the Alternating Gradient Synchrotron (AGS) facility,[1] where beams of fully stripped $^{16}O^{8+}$ and $^{28}Si^{14+}$ ions have been accelerated to energies of 14.6 GeV/amu, and targeted on various atomic masses. In addition, the completion of the AGS-Booster synchrotron[2] in 1991 will enable heavier nuclei to be accelerated in the AGS (i.e. $^{197}Au^{79+}$ to 10.4 GeV/amu). At the European Organization for Nuclear Research (CERN), the Super Proton Synchrotron (SPS) facility[3] has accelerated heavy ion beams of fully stripped $^{16}O^{8+}$ and $^{32}S^{16+}$ ions to energies of 200 GeV/amu. The CERN heavy ion program also plans for heavier particle beams in the mid-1990's (i.e. $^{208}Pb^{82+}$ at 200 GeV/amu) with the expected completion of a new ^{208}Pb ion source, Radio Frequency Quadrupole (RFQ), and linac.[4] At BNL, a Relativistic Heavy Ion Collider (RHIC)[5] for ions up to gold will soon begin construction.

Unlike traditional low energy heavy ion accelerators such as cyclotrons, linacs, and tandem machines that provide continuous or continuous wave (CW) beam currents, synchrotrons require the injection of a pulse of high intensity, high charge state heavy ion beams for a few hundred microseconds. In synchrotrons these ion beams are then bunched, accelerated, and extracted either bunch by bunch in one revolution or in the form of a DC particle beam with up to 50% duty cycle. Although many heavy ion source injection systems can provide the relatively low current requirements for the CW low energy machines, it is considerably more difficult to provide the high intensity pulses for the injection of synchrotrons, even when they support fixed target experiments.

The beam requirements for a synchrotron collider place even greater demands on source technology. In beam collider physics, the target is only a beam of particles and is ~1000 or more times thinner than the customary 1-3% interaction thickness used for fixed target research. This means that for optimum collider performance, the synchrotron injector must provide up to 100 or even more times the beam current required for the present fixed target synchrotron research programs. In this paper we critically analyze the available injector options for heavy ion synchrotrons, with the emphasis on future heavy ion colliders.

Most of the fixed target heavy ion experimental studies at both BNL and CERN synchrotrons have focussed on the exotic matter that may be formed in a central nuclear collision at ultrarelativistic energies. It is expected that above a certain energy the nuclear collision will produce sufficient energy density and temperatures that a phase transition will take place from the high density-temperature baryon or hadronic matter to a so-called quark-gluon plasma.[6] From the point of view of Quantum Chromodynamics (QCD), ultrarelativistic heavy ion collisions offer the means of studying the fundamental theory of strong interactions in the limit of high energy densities. It should also be possible to study the physical properties of the QCD vacuum state and the mechanism of quark confinement,[5] both of which reflect long-range scales that cannot be realized in collisions of elementary particles.

For the energy ranges that are currently available at heavy ion synchrotron facilities operating with fixed targets, there is no unambiguous evidence that a phase transition to quark matter has taken place. Higher beam energies are required to produce higher energy densities and temperatures. With the completion of RHIC at BNL in 1996, it will be possible to cause ^{197}Au ion beams up to energies of 100 GeV/amu to collide, corresponding to an equivalent single beam fixed target energy of 22,000 GeV/amu. At these energies, there is considerable promise that central collisions will produce the thermodynamic conditions that are favorable for a phase transition to quark matter.

While a collider offers obvious advantages as to the energy available in the collision, the very nature of a collider places increased demands on both the particle source and injection facility. This is seen most clearly through the design luminosity, L, of the collider. For instance, at the crossing points of a collider the number of desired central collisions per second is given by $L\sigma_c$, where σ_c is the cross section for the central collision, and L is given for head-on collisions of circular beams by,

$$L = \frac{3}{2} f_{REV} \frac{B(\beta\gamma) N_B^2}{\varepsilon_N \beta^*}$$

Here f_{REV} is the revolution frequency of the beam, B is the number of bunches per beam, N_B is the number of particles per bunch, β^* is the lattice function at the crossing point, and ε_N is the normalized transverse emittance of the beam. In both Fig. 1 and Table I, the luminosity L is given for a range of heavy ion species at RHIC. In Fig. 1, RHIC and fixed target AGS performances are compared, including the number of central collisions per second. The luminosity in Table I corresponds to the top energy value at the beginning of the storage period. For instance, this table shows that in order to achieve an initial luminosity value of $L=2\text{x}10^{26}$ cm^{-2} sec^{-1} for $^{197}Au^{79+}$ beams at full energy, the number of ions per bunch in the collider must be $N_B=10^9$.

It is important that only heavy ions fully stripped of their atomic electrons be accelerated and stored in a collider. If atomic electrons are present, charge stripping reactions will occur both at beam crossings and during collisions with residual gas molecules in the beam chamber. This will lead to serious depletion of the beam in a short period of time.

It is the requirement of only using fully stripped heavy ions in a collider, plus the high number of required particles per bunch, that put increased demands on available particle sources and injector facilities.

For the more important heavier particles in the mass range around ^{197}Au, no ion source to date can produce fully stripped ions. The atomic electrons that remain attached to the nucleus after source extraction and pre-acceleration are further stripped by passing through one or more stripping foils as the ion energy is increased through the injector accelerator complex.

For a beam of partially stripped ions, passage through an equilibrium thickness stripping foil produces an approximately Gaussian distribution of charge states. For low

Table I

Initial Luminosity at Maximum Energy for RHIC

	N_B	E/A (GeV/u)	$\epsilon_N \pi$ (mm·mrad)	Luminosity ($cm^{-2}sec^{-1}$)
	$x10^9$			
Proton	100	250.7	20	$1.4x10^{31}$
Oxygen	8.3	124.9	10	$9.8x10^{28}$
Silicon	5.6	124.9	10	$4.4x10^{28}$
Copper	2.7	114.9	10	$9.5x10^{27}$
Iodine	1.5	104.1	10	$2.7x10^{27}$
Gold	1.0	100	60	$2x10^{26}$
Gold	1.0	100	10	$1.1x10^{27}$

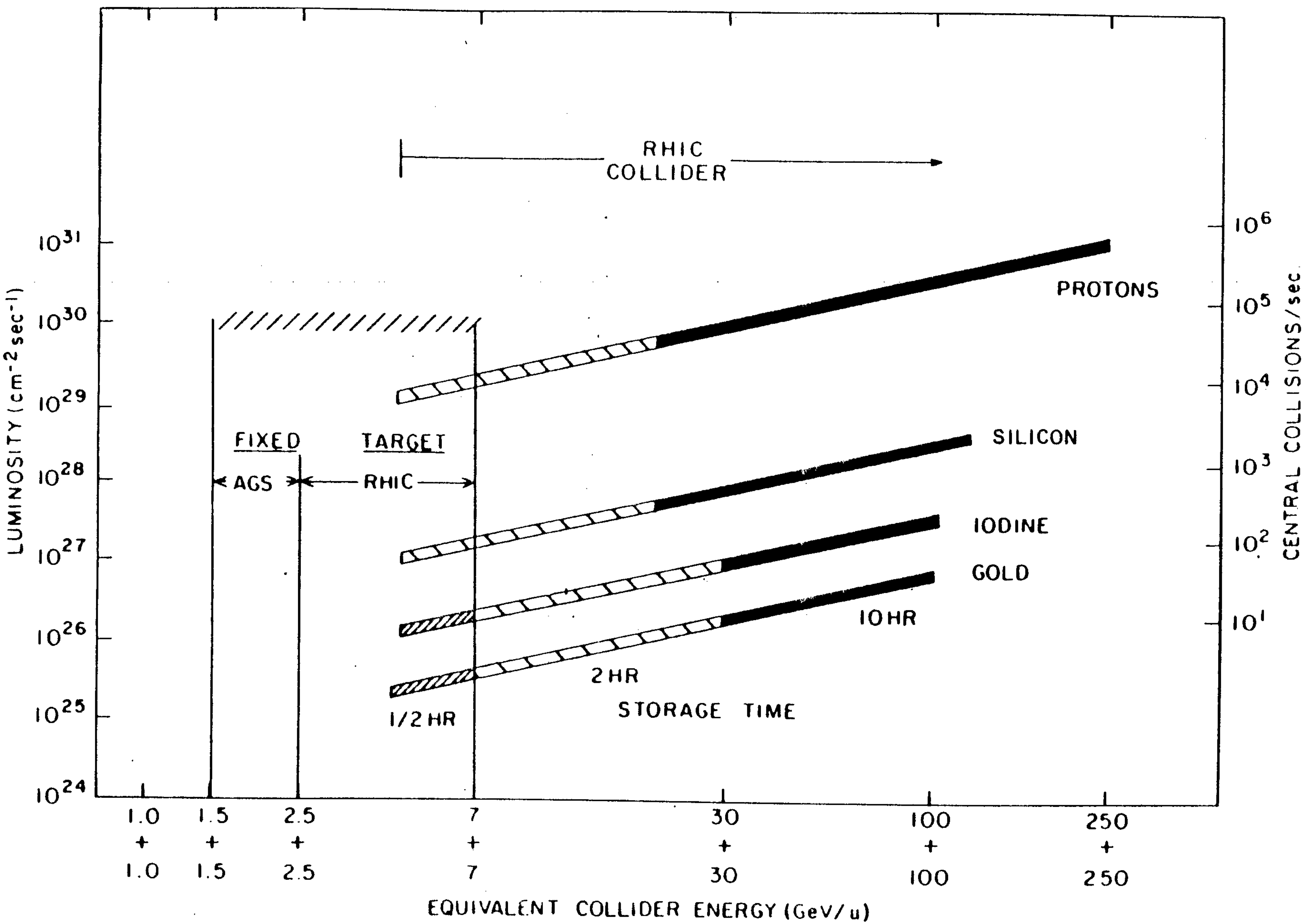

Fig. 1: The design luminosity, for various ion masses, as a function of collisions energy over the full range accessible with AGS and RHIC. On the right-hand scale, central collisions correspond to impact parameter less than 1 Fermi.

energy beams ($E_{BEAM} \leq 5$ MeV/amu) the average charge state $\bar{q}$ of the Gaussian distribution has been parameterized from experimental data as

$$\bar{q} = Z\left(1 - e^{-3.86\sqrt{E_{BEAM}}/Z^{0.447}}\right)$$

where Z is the atomic number of the ion. Empirically determined corrections to this formula are being used at Brookhaven to obtain better agreement with experimental values. At the lower energies approximately 20% of the ion beam is in the average charge state after passage through a foil. At relativistic energies ($E_{BEAM} > 200$ MeV/amu) measurements have been made[7,8] on the probability of producing fully stripped very heavy ions, or ions with filled K-shell electrons. At these energies, the charge distribution is skewed so that as much as 50% or more of the ion beam may be in the charge state of interest.

The required number of fully stripped heavy ions in a collider, multiplied by a compensation factor for the overall dilution of the heavy ion beam by multiple passage through stripping foils, combine to impose severe new demands on heavy ion sources. These demands may be further amplified if there are non-negligible transmission losses within the synchrotron injection complex. For partially stripped heavy ions, these transmission losses are most likely caused by collisions with residual gases in various accelerator vacuum systems.

In Section II of this paper the injector arrangements and their performance for most of the world's fixed target heavy ion synchrotrons are compared. This comparison highlights the overall inadequacy of these schemes to meet the new demands imposed by the luminosity requirements of heavy ion colliders. The solutions planned at BNL[9] for meeting the demands of RHIC are discussed in detail in Section III, and shown to be more than adequate to meet the present intensity requirements for RHIC. In Section IV, the future possible role of Electron Beam Ion Sources (EBIS) and Electron Cyclotron Resonance (ECR) sources for heavy ion colliders is discussed. These sources have the advantage that they can produce much higher charge states than most of the present operating sources at the world's heavy ion synchrotrons. This advantage should be useful in reducing the size and complexity of the injector and the number of times that the ion beam has to pass through stripping foils to achieve a fully stripped status. However, the achieved particle currents from these sources are at present too low to satisfy RHIC injector requirements.

II. Comparison of Heavy Ion Synchrotron Performance

There are only a few synchrotrons in the world that accelerate heavy ions and most of them were first designed and built to accelerate protons and then later suitably modified to accelerate heavy ions. At Lawrence Berkeley Laboratory (LBL) and BNL, existing low energy heavy ion facilities were connected by transfer lines to the proton synchrotrons for direct injection. The SATURNE machine at Saclay, France and the Synchrophasotron at the Joint Institute for Nuclear Research (JINR), Moscow, Dubna, USSR were built originally as proton facilities and later converted to heavy ion acceleration; the new synchrotron SIS at the Gesellschaft für Schwerionenforschung, Darmstadt, West Germany (GSI) was designed for heavy ions to be injected by the UNILAC linac. The CERN proton synchrotrons were injected with heavy ions by adding a new ion source and an RFQ to the existing linac injection system. In all cases except BNL the injection systems for the different synchrotons consist of RF accelerating structures, RFQ's and linacs, which follow a positive heavy ion source. It is a common feature of all these injectors that their size and complexity depend on the initial charge state of ions as they are extracted from the source; the higher the charge state, the more compact the injector. In distinct contrast to these systems the BNL heavy ion injection system is comprised of two large (MP-class) Van de Graaff tandem accelerators injected by pulsed negative heavy ion sources. Here the high ionization states desirable for synchrotron injection are achieved after acceleration by the tandem and one or more strippings.

An interesting comparison of different heavy ion injection systems for different synchrotron accelerator facilities can be made utilizing schematic block diagrams that show the performance characteristics for light and heavy ions beginning with the ion source, and through all individual acceleration stages and strippers, to the final output yield of accelerated heavy ions from the synchrotron. In all cases the pulsed beam currents at different stages of acceleration are quoted in particle current units (e.g. pμA) (electrical current/ion charge state) unless otherwise indicated. Block diagrams corresponding to the

Bevatron at LBL, SIS at GSI; SATURNE at Saclay; the Synchrophasotron at JINR; SPS at CERN; and the AGS at BNL are shown in Figures 2-7. In general, all these facilities have been designed around existing machines, which was a decisive factor in the choice of the type of ion source and first acceleration stages that would best suit the purpose. The only machine in routine operation with Au and U beams is the Bevatron. Although SIS has accelerated U beams to full energy it is still in the tune and adjustment phase of operation. Both BNL and CERN plan to accelerate Au and Pb ion beams, respectively, in the future after necessary new construction is completed: a booster synchrotron at BNL and a special ECR source for Pb^{20-25+} ions, RFQ, and linac at CERN.

A block diagram of the Bevalac facility[10] at LBL is shown in Fig. 2. The system has been created by linking two existing accelerators, a large linear accelerator (HILAC) and a synchrotron (Bevatron); later on a second injector was added for neon beams. The system produces many ion species up to uranium and supports the main heavy ion research program at LBL. The injector into the linear accelerator is a Cockcroft-Walton stage with an intense low charge state PIG source in the terminal. The parameters of particle beams between the stages of acceleration are typical of this approach: a high initial intensity decreases steeply as the acceleration progresses mostly due to losses in stripping foils. Still, the final intensity of 10^7 to 10^8 pps is adequate for most fixed target experiments. The neon line uses a new RFQ that bunches and accelerates the beam from the source.

The recently completed heavy ion synchrotron, SIS at GSI,[11] is shown in Fig. 3. The heavy ions are again produced in a PIG source and the large UNILAC heavy ion linac facility is used as the injector. All of the heavy ions listed (Ar^{18+}, Xe^{48+} and U^{72+}) have been accelerated to full energy; however, the ion beam extraction systems are currently under test and tuning. It is characteristic for this approach again that the ion source delivers a very intense beam of very low charge state ions; this is followed by several stages of acceleration and a reduction in the intensity by up to three orders of magnitude. However, it was the existence of the UNILAC that dictated such an injector for the synchrotron. A

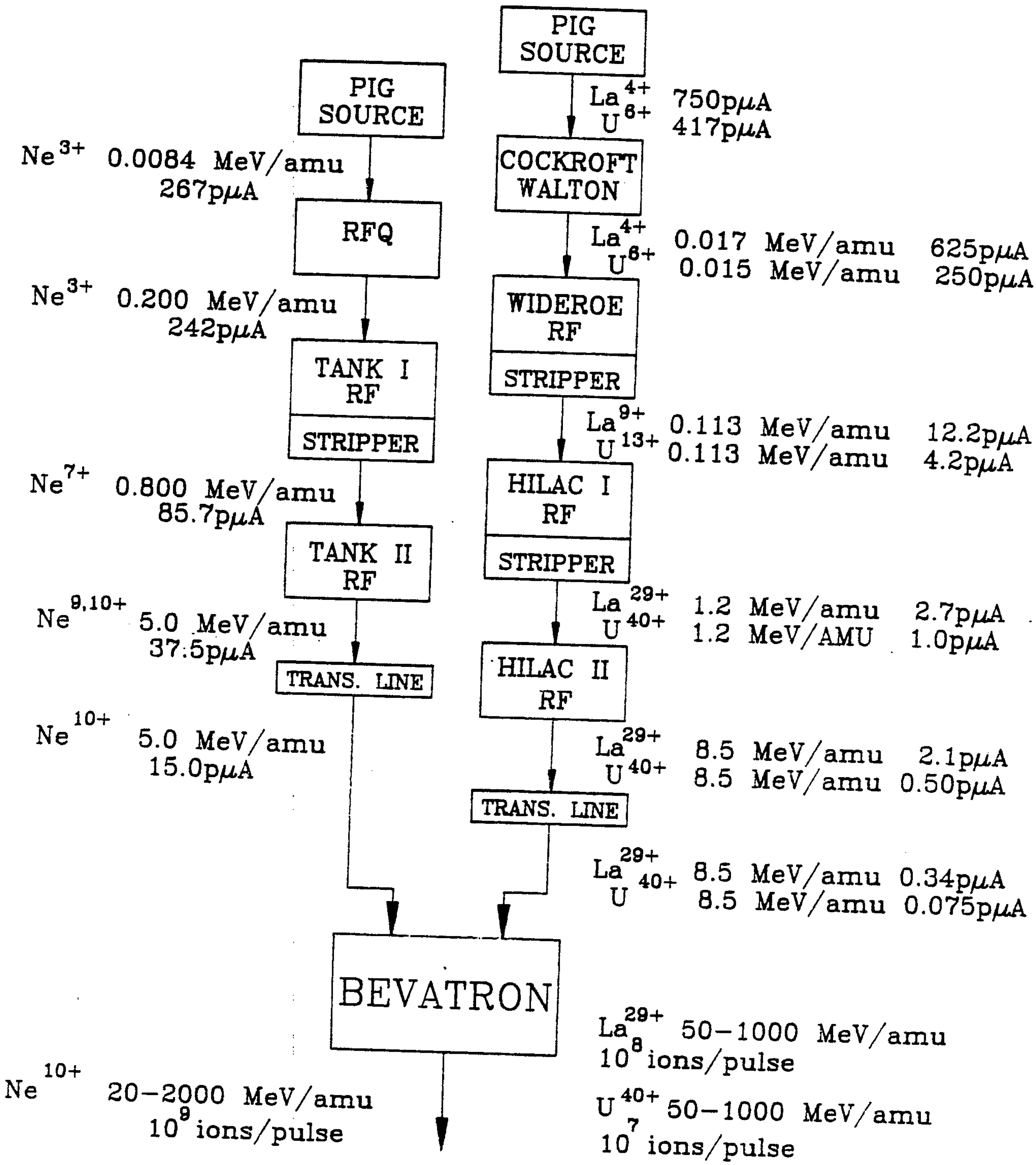

Fig. 2: Block diagram of the Bevalac facility at LBL. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

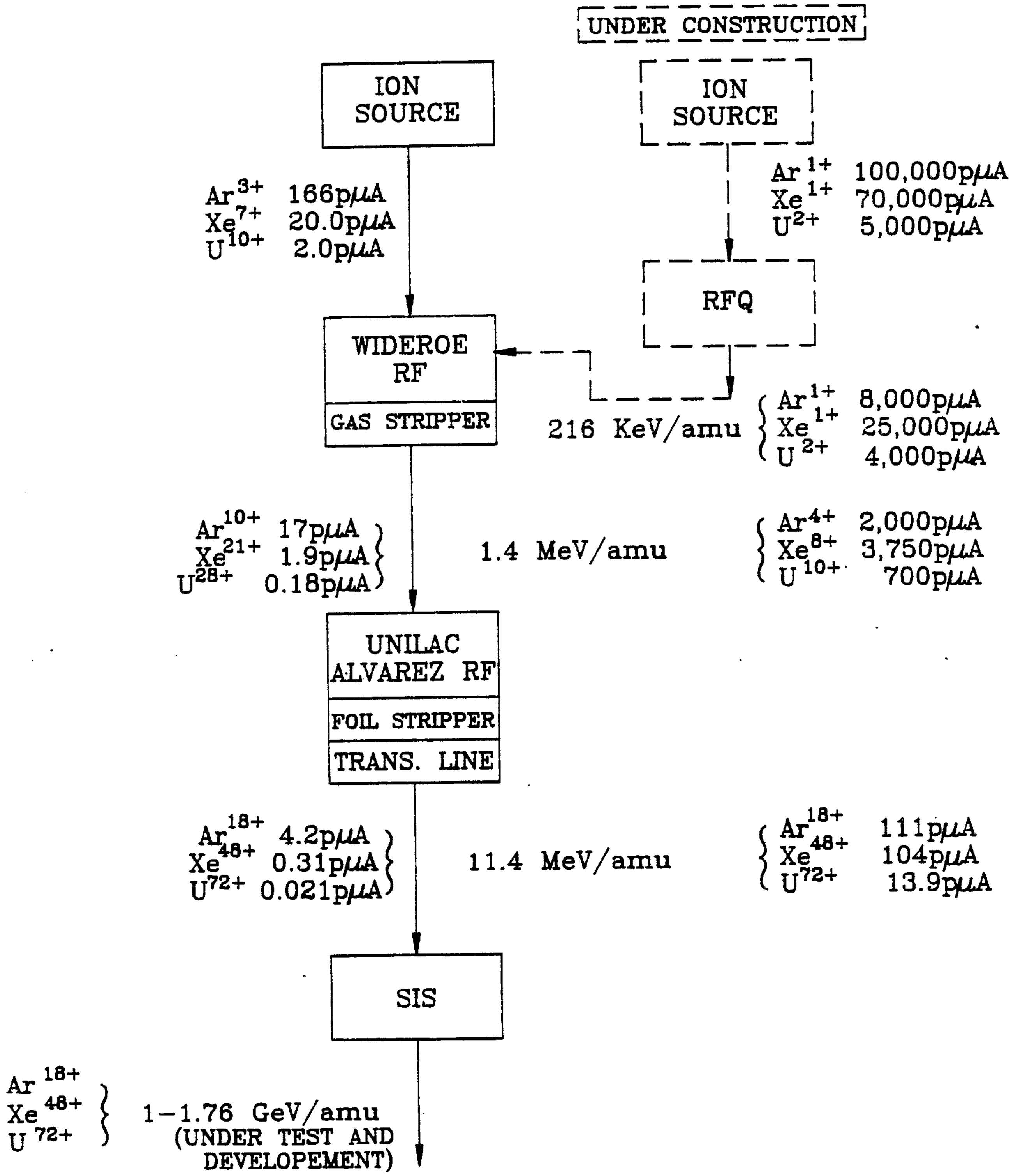

Fig. 3: Block diagram of the heavy ion SIS facility at GSI. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

completely new ion source system is now under construction and will produce very high (up to 100 mA) currents of singly charged positive heavy ions which will be preaccelerated by an RFQ accelerator and then injected into the Wideroe linac. These heavy ion particle currents at synchrotron injection will be 10-100 times higher than what is currently being used.

The block diagram for the SATURNE synchrotron at Saclay[12] is shown in Fig. 4. Its injection system uses an electron beam ion source (EBIS-DIONE) that produces low intensity, high charge state pulsed ion beams of many ion species up to $^{84}Kr^{30+}$. These are then accelerated by an RFQ, and injected into the MIMAS booster synchrotron, which in turn injects the SATURNE synchrotron. In order to increase the final beam intensity, up to four pulses from the source are injected and accumulated in MIMAS. For krypton ions the RFQ stage following the source requires charge states of at least 30+. The operation is made possible by first tuning the entire machine complex on $^{14}N^{5+}$, which is a much more intense beam but with almost the same charge to mass ratio q/m as $^{84}Kr^{30+}$, and then switching to krypton for experiments. There are no stripping foils in the system and the final charge state of ions from SATURNE is the same as delivered by the source. Consequently, the losses are relatively small. A new EBIS source with much higher intensity is presently under consideration.

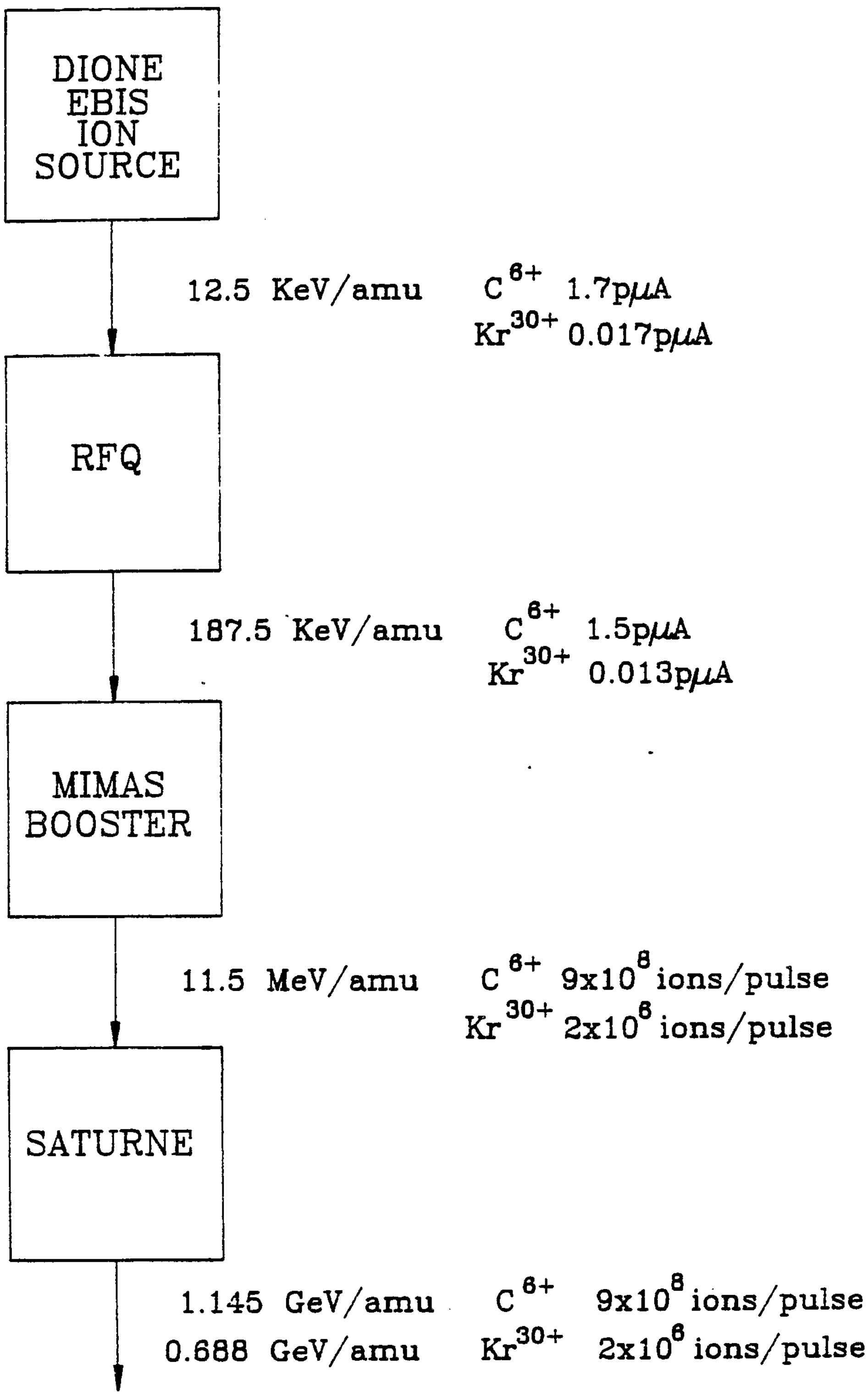

Fig. 4: Block diagram of the heavy ion Saturne facility at Saclay. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

The Synchrophasotron at JINR[13] is diagrammed in Fig. 5. This weak focussing synchrotron is used extensively for light ion (p,d,α) research; however, only the heavy ion performance is indicated. A new laser driven ion source provides C^{4+} and Mg^{6+} ions at very high intensities that ultimately provide synchrotron energy research beams at intensities comparable to the other facilities discussed in this paper. Unfortunately the most recent performance information on this facility is limited.

The large super proton synchrotron (SPS) at CERN[14] is diagrammed in Fig. 6. This facility uses a commercially available electron cyclotron resonance (ECR) source "MAFIOSA" that produces high charge state ions in a continuous wave mode of operation. Production and acceleration of oxygen ions is straightforward, but for sulphur ions a tracer beam (oxygen) is used because the $^{32}S^{12+}$ source intensity is only about 5% of the $^{16}O^{6+}$ intensity. The produced oxygen and sulphur ions are almost identical in charge to mass ratio and remain so after full stripping, so that they program through all the different accelerating structures identically. The two species are not separated until the proton synchrotron (PS) goes through "transition" which is a portion of the acceleration cycle in large machines that acts like a precision mass separator. The slight q/m difference between the two ions allows them to be completely separated and selected for further acceleration through the rest of the acceleration cycle and then injected into the SPS. Most of the elements of this system were originally designed for proton operation and the selection of the two ion species (O and S) was determined by the operating limits of the linear accelerator and by the availability of ECR sources. In spite of just one stripping foil in the system the losses are substantial due in large part to an insufficient vacuum in the booster synchrotron. A lead beam, $^{208}Pb^{82+}$, is planned in the 90's; however, a new ECR source, RFQ and Linac will have to be constructed in order to accelerate the much lower velocity Pb ions. The planned performance for the Pb ion beam acceleration is indicated.

Figure 7 shows the role of the two Tandem Van de Graaff machines at BNL as injectors, either directly into the AGS (present mode of operation) or into the booster

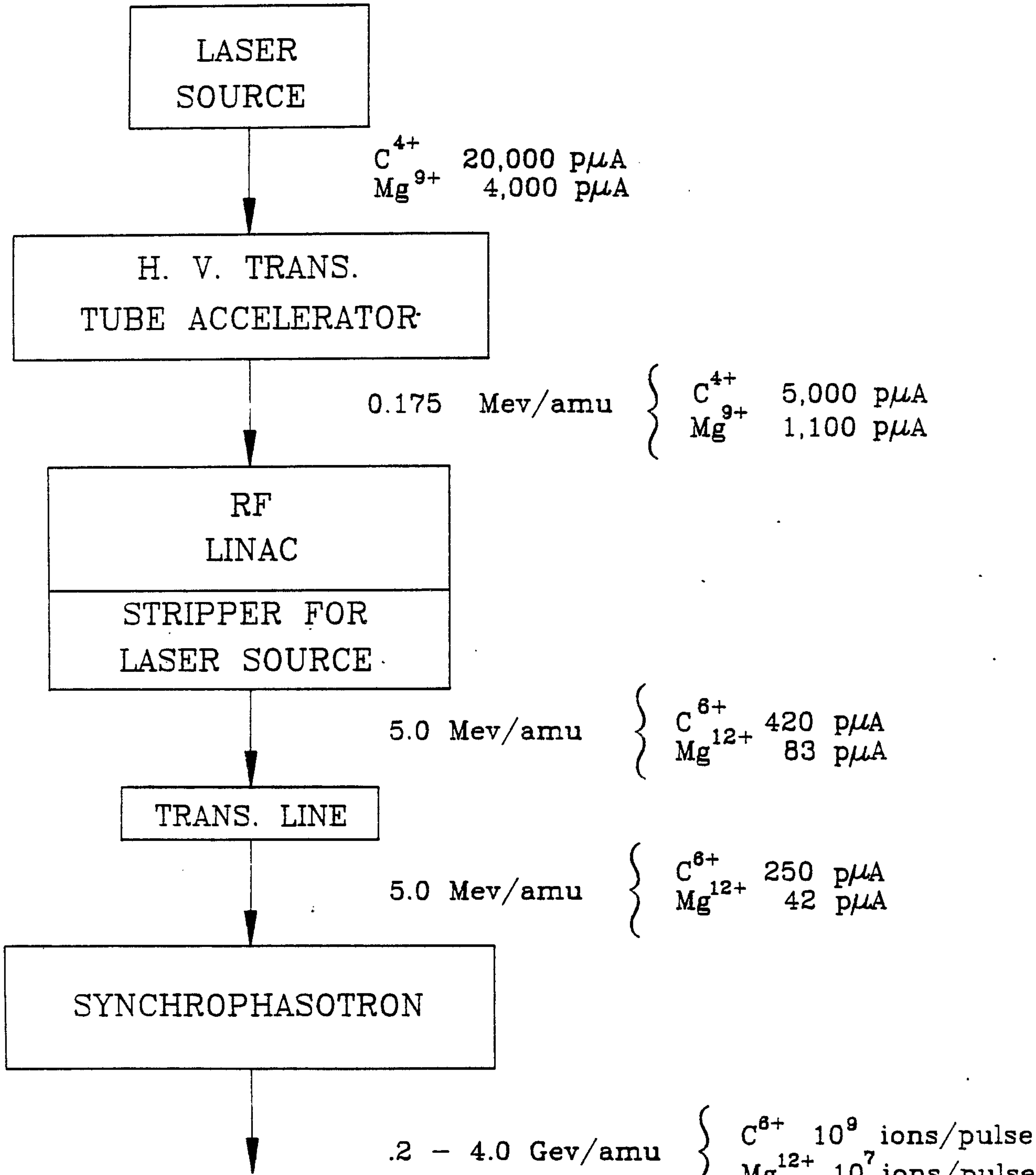

Fig. 5: Block diagram of the heavy ion synchrophasotronn facility at Dubna. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

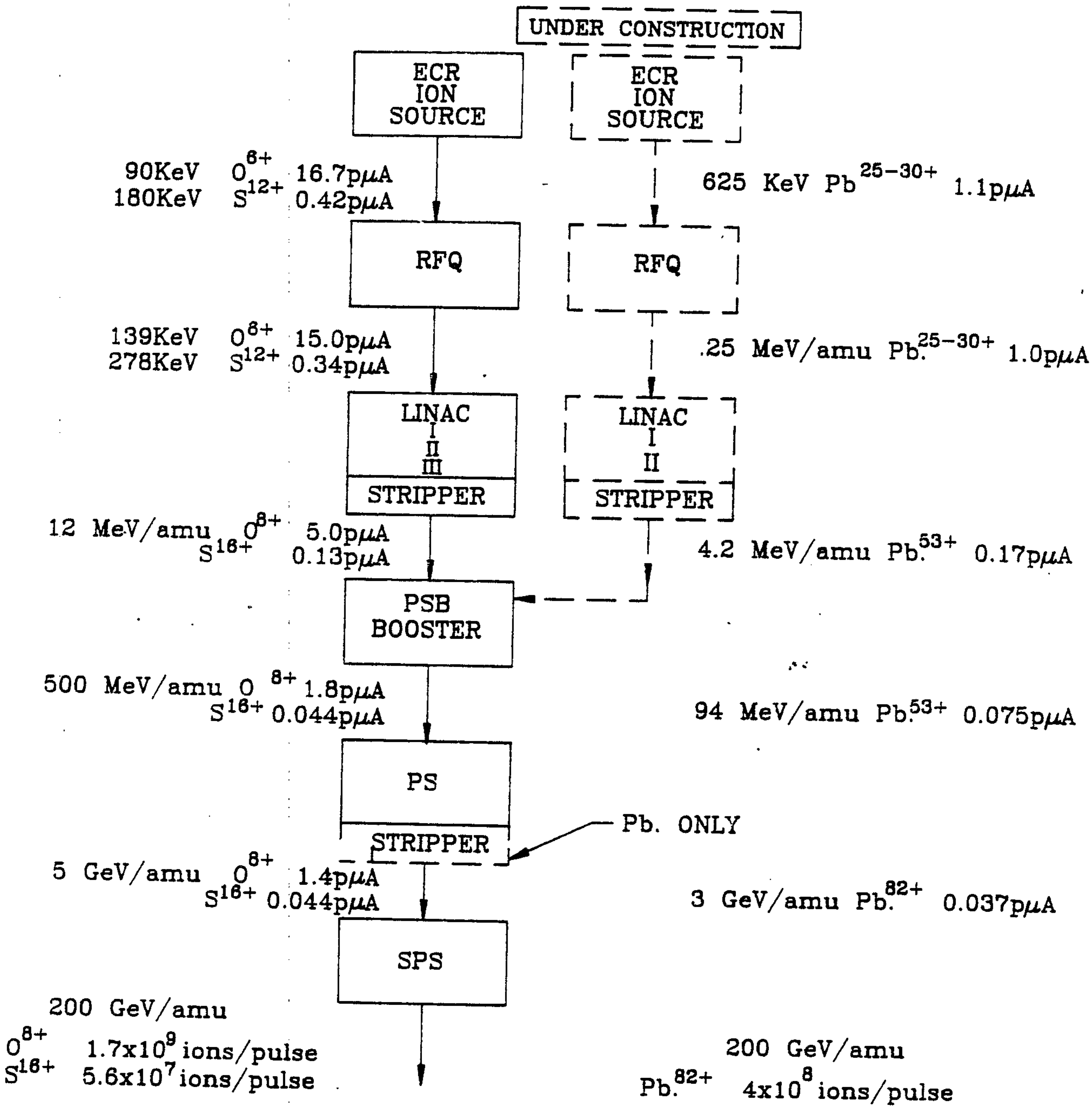

Fig. 6: Block diagram of the heavy ion SPS facility at CERN. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

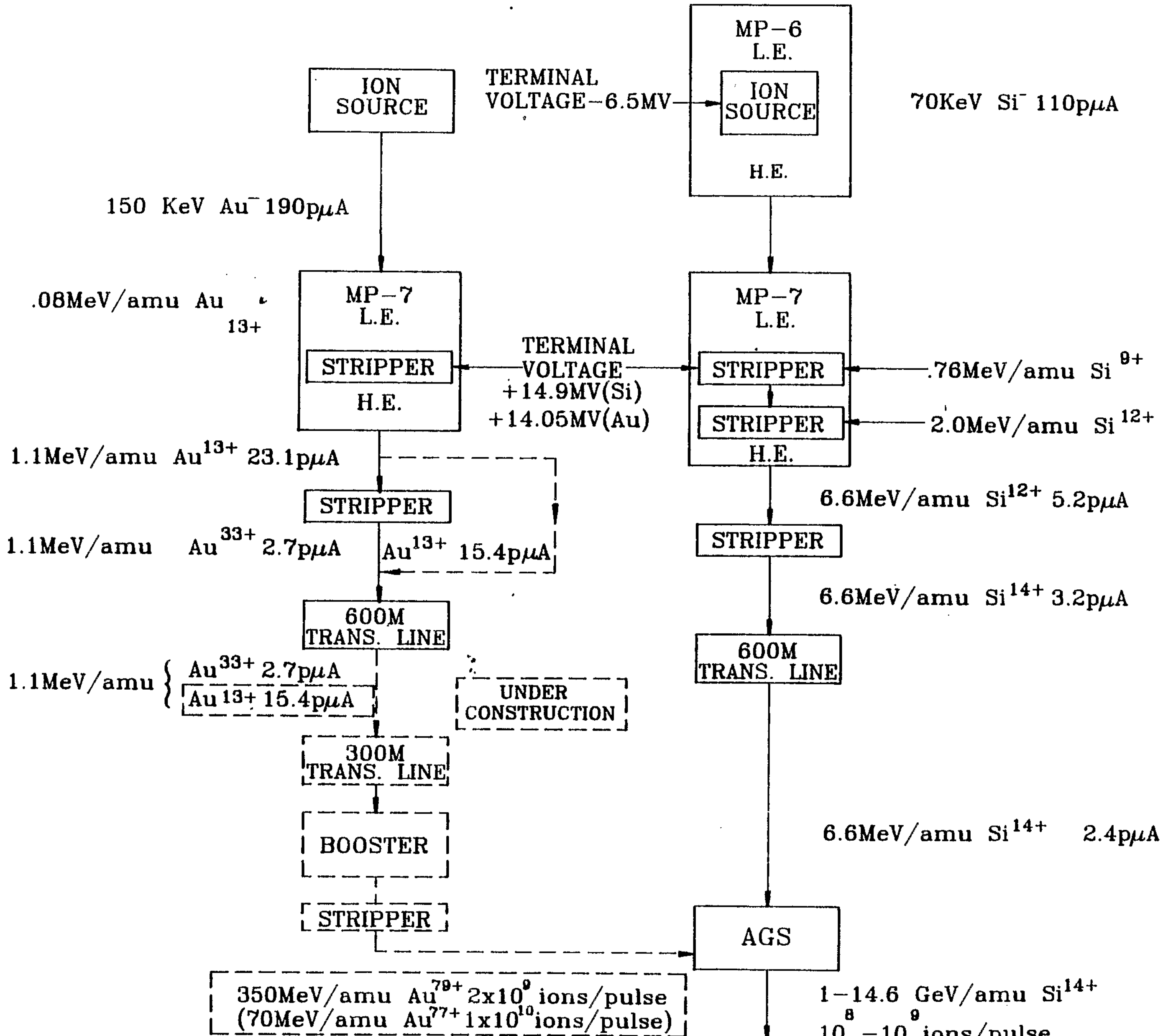

Fig. 7: Block diagram of the heavy ion AGS facility at BNL. The currents indicated are in particle microamperes in order to clearly indicate the particle losses through the various accelerator components. See text for details.

synchrotron (future mode of operation). Lighter fully stripped ions like $^{16}O^{8+}$ can be easily provided with conventional single tandem operation, with 15-20 pμA routinely available for injection into the AGS. For operation with silicon, it is necessary to use one tandem (MP6) as a negative ion injector into the other, MP-7 (so-called "three-stage" mode) in order to achieve the sufficient energy for a full stripping of silicon ions. The planned operation with the new booster synchrotron will only require one tandem for any mass ion up to $^{197}Au^{79}$, because of the ultra high vacuum in the booster ($\sim 10^{-11}$ Torr) that will allow the acceleration of partially stripped ions as produced by the tandem.

III. The Brookhaven Perspective: Electrostatic Tandem Accelerators as Injectors for the Booster and AGS Synchrotrons

Fortunately, the BNL electrostatic tandem accelerators satisfy the requirements of both the fixed target mode of operation and the much more severe requirements of the proposed collider. The existing accelerator complex at BNL, as shown in Fig. 8, consisting of the tandem, the heavy ion transfer line, the booster and the AGS will provide beams of many ion species up to gold (^{197}Au) for the fixed target program, and serve as well as an injector of heavy ions for RHIC. In order to achieve the design luminosity value for RHIC, several limiting characteristics of the injection components must be respected. These include the vacuum of the AGS (10^{-7} Torr at present, 10^{-8} Torr after upgrade program), which prohibits the acceleration of heavy ions with many atomic electrons, the lowest achievable frequency of the Booster cavities, the stripping foil efficiencies, and the current technological limitations of heavy ion sources at the Tandem.

Following the first tests in 1983 of high intensity pulsed beam operation of a tandem accelerator[15], ample experience has been gathered regarding the acceleration of pulsed beams.[16,17] Operation of the AGS for fixed target heavy ion experiments started in 1986 with the delivery of O^{8+} beams. For oxygen acceleration, only one tandem and two stripping foils are required. The maximum intensity achieved for this beam is 2.7×10^{10} particles in a 250 μs long AGS injection pulse corresponding to a particle current of 18 pμA. So far there have been four AGS operations with oxygen ions totaling 1500 hours.

At present only fully stripped ions can be accelerated in the AGS. This was the reason that a more complex scheme had to be devised for the production of silicon ions, the next step in the AGS fixed target heavy ion research program. The negative ion source is located inside the high voltage terminal of the first tandem, MP6, operating at a voltage of $\sim$ -6.5 MV. Negative ions are accelerated to ground potential, injected into the second tandem, MP7, and accelerated to the +15 MV terminal, where Si^- ions with a total energy of 21.5 MeV are stripped to an average charge of 9+. Positive ions in a charge state 9+

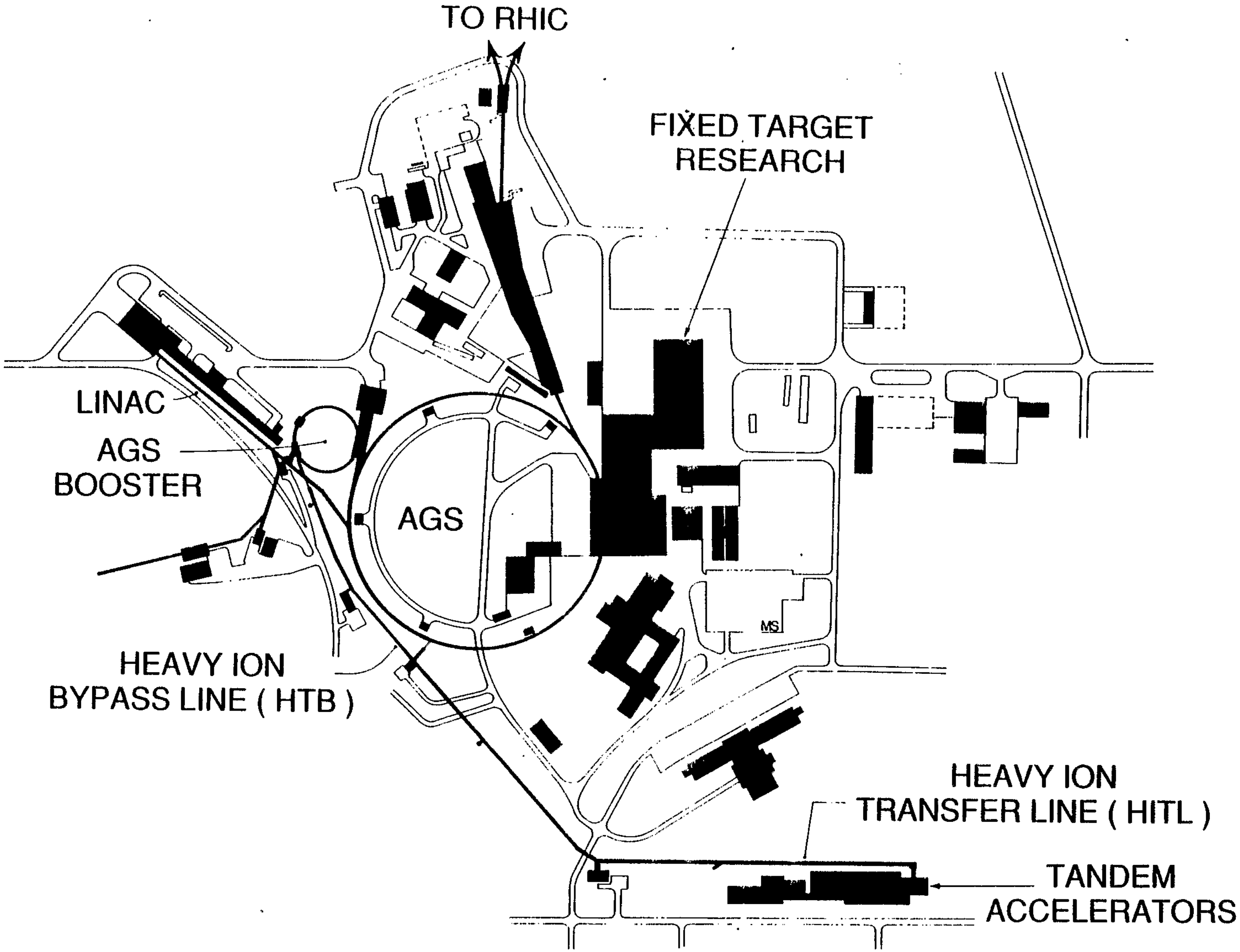

Fig. 8: The Brookhaven Relativistic Heavy Ion Collider (RHIC) injector complex. The tandem accelerators provide heavy ions up to mass ^{28}Si for direct injection into the AGS through the heavy ion transfer line (HITL). A new extension of this line beyond the direct injection point called the heavy ion bypass line (HTB), now under construction, will transport the heavy ions for injection into the AGS booster (also under construction). The AGS booster will then be able to supply fully stripped ions from $^{16}O^{8+}$ to $^{197}Au^{79+}$ for injection into the AGS for research in the fixed target experimental area or for transport to the two superconducting synchrotron collider rings of RHIC.

are then accelerated toward ground potential to the next stripper, located at a potential of +11.2 MV, where the average charge state is raised to 12+.[18] Final acceleration to the ground potential raises the energy to 6.6 MeV/amu which is sufficient for a full stripping to 14+ with 60% efficiency. After the final magnetic analysis the beam of fully stripped silicon ions is sent to the AGS through the heavy ion transfer line. The maximum intensity achieved for this beam corresponds to a current of 2.5 pμA, or 3.9 x 10^9 particles during the 250 μs injection interval of AGS. So far there have been four AGS operations with silicon ions totaling 2100 hours. The complexity of this system, the fact that two tandem accelerators are involved, and the relatively inaccessible location of the ion source inside the high voltage terminal of MP6 make this operation much more difficult; nevertheless, consistently reliable operation has been achieved. With the booster in operation, only one tandem accelerator will be required and the second, when suitably upgraded and appropriate beam transfer lines installed, will serve as a complete spare injector that will be available for backup operation in an hour's time or less. It will also provide dual injector operation when the RHIC rings are filled for special asymmetric collision studies (i.e., Au + Fe).

Gold beam tests were performed at an energy of 1.1 MeV/amu for two different final charge states.[19] First, a beam intensity of 3.0 pμA of Au^{33+} ions was measured at the AGS end of the present 700 m long heavy ion transfer line. This charge state corresponds to the average charge state of the 1.1 MeV/amu gold beam after passing through a stripping foil at the exit of the tandem. Once the booster is on line, Au^{33+} ions would be injected and accelerated to 350 MeV/amu, which is sufficient to achieve 50% of fully stripped gold ions for injection into the AGS.[15] An alternative scheme consists of injecting into the booster gold ions in a charge state* 13^{+}, avoiding in this way the stripping foil between the tandem and the booster. The resulting exit energy from the booster would be much lower,

* The optimal charge state selected for further acceleration in the injector complex may vary by ~1 unit.

70 MeV/amu, but still sufficient to achieve 60% of helium-like Au^{77+} ions[20] after stripping for injection into the AGS. The intensity of Au^{13+} ions was determined to be 16 pμA at the same location as for Au^{33+} ions. Although Au^{77+} is not fully stripped, calculations indicate that the two K-electrons are so tightly bound to the high Z Au nucleus that their stripping cross section in the improved AGS vacuum should result in a loss of only a few percent. After acceleration to ~10 GeV/amu, the Au^{77+} ions will be foil stripped to Au^{79+} with ~100% efficiency and transferred to RHIC for further acceleration and storage. The pulsed beam performance of the BNL tandems and the heavy ion transfer line are summarized in Table II. The intensities of various beams are given in pμA units during the pulse; the number of particles injected into a synchrotron (booster, AGS) will depend on the injection interval.

Besides the modest intensity of high charge state heavy ions produced by the tandem accelerator injectors, these heavy ion beams have an extremely small invariant emittance of ~12π mm mrad $MeV^{1/2}$. For $^{197}Au^{13+}$ beams out of the Tandem, for example, this corresponds to a $\beta\gamma$ normalized emittance ϵ_N= .041π mm mrad. Such small emittance is only possible because singly charged negative ions, are accelerated to 15 MeV energy before stripping to the high charge state, thus minimizing any space charge degradation of emittance. A small emittance is important for filling a synchrotron with beam because it allows many turns of the beam to be injected into the available phase space or admittance of the synchrotron.

In summary, long term reliable operation of the tandem accelerators at beam intensities sufficient for both fixed target AGS operation and future RHIC operation, has been demonstrated. The main drawback of the tandems, namely the relatively long turnaround time when the high pressure vessel must be opened for maintenance, will be eliminated after the upgrade of the MP6 machine as discussed previously. Naturally, the selection of ion species is not limited to those in Table II, because the tandem negative ion source is capable of producing sufficient intensities of many ion species. Even higher intensities

Table II

Pulsed Beam Performance of the BNL Tandems
and the Heavy Ion Transfer Line

Beam Species	Charge State	Acceleration Mode	Energy (MeV/amu)	Maximum Intensity (pμA)	No. of Runs	Total Time (hours)	Reliability
^{16}O	8+	two-stage	6.6	18	4	1500	90%
^{28}Si	14+	three-stage	6.6	2.2	4	2100	90%
^{197}Au	33+	two-stage	1.1	2.7	1	—	—
^{197}Au	13+	two-stage	1.1	15.4	1	—	—

than quoted in Table II may become possible with the development of new, more intense negative ion sources now under development and test.[21]

IV. INJECTORS BASED ON HIGH CHARGE STATE ION SOURCES

Characteristics of any future injector, contemplated to improve the performance of any heavy ion collider, must match or surpass the characteristics of the existing injectors. Requests for heavy ion beams having parameters (ion species, intensity) suitable for injection into the rings of a heavy ion collider have appeared rather recently, at a stage when the high charge state ion sources, which in principle are capable of producing many ion species, have not yet reached such a level of performance. Therefore, consideration of such sources and their associated RF accelerator systems as a future replacement for say, tandem accelerators will have to rely on the extrapolation of results from existing source models, developed for a different purpose. At the same time, future collider requirements for more intense heavy ion beams should serve as a stimulus for the development of adequate high charge state ion sources, potentially a better alternative than the tandem injector. In any cascade of accelerator stages, the acceleration can be achieved in a shorter length, with a better power efficiency and less expense if the charge to mass ratio of particles is higher. This is the main reason that high charge state ion sources are considered and developed.

A. ELECTRON BEAM ION SOURCES

In an Electron Beam Ion Source (EBIS),[22] multiply charged ions are produced by electron impact on ions by a magnetically confined electron beam of proper energy. The ions are confined radially by the space charge of the electron beam; the axial confinement depends on the desired mode of operation, i.e., whether the source operates d.c. or in pulses. For injection into a synchrotron, only the pulsed mode is of interest and the source can use the interval between two pulses to build up and store a higher charge state distribution than in the d.c. mode. A cycle of operation consists of a short injection pulse (either atoms or singly charged ions may be injected), followed by the confinement period to build up the desired charge state distribution and ending with the expulsion of ions from the source. The shape of the axial distribution of potential varies during the cycle to assure the proper operation of the source.

EBIS sources have a number of important design and operating parameters that all must be properly selected and controlled in order to optimize the yield of the desired charge state. The maximum number of positive charges, Q^+_{max}, that the trap can store equals the number of electrons in the trap. The latter is proportional to the length of the trap, electron beam voltage and to the perveance of the electron gun. However, the actually available number of positive ions in the desired charge state q will be substantially smaller than Q^+_{max}/q because of an incomplete neutralization of the electron space charge and the fact that only a fraction of the extracted ions is in the charge state q. The other important EBIS parameter is the product of the electron beam current density and the confinement time; it determines the evolution of the charge state distribution.

The only EBIS now operating with an injector is DIONE,[22] which has been in use with the SATURNE[11] machine since 1987.[23] The source produces beams of light and medium heavy ions (up to Kr^{30+}), but the selection of the charge state to be accelerated is limited by the next stage, an RFQ. For example, the best source yield of krypton ions is in the charge state 26+, which corresponds to the K and L shells filled, but the RFQ can accept only krypton ions in the charge states 30+ and higher. Still, the output intensity of SATURNE ranges from 10^8 to 10^9 particles per pulse except for krypton, where it is only 10^6 ppp. The operation of the source is stable and reliable and the beam was delivered for fixed target experiments over several thousand hours. Most of the other dozen or so EBIS devices in operation have been designed with the purpose to serve as sources of low intensity but very high charge state ion beams; fully stripped ions of elements up to xenon have already been produced.

In principle an EBIS could be capable of delivering beams for RHIC; it does produce high charge state ions with a narrow charge state distribution, and the beams have a very low emittance, typically around ϵ_N=0.2π mm mrad (norm). It is a pulsed device, well suited for injection into synchrotrons. However, most of the development efforts so far have concentrated on devices for atomic physics, and it is necessary to extrapolate these known characteristics when considering an EBIS as a source for RHIC. By combining the state-of-the-art values for the important EBIS parameters, the performance of such a hypothetical device may be considered. A list of selected parameters includes an electron beam current of 1A, beam perveance of $2 \cdot 10^{-6}$ $AV^{-3/2}$ and the product of the beam current density and confinement time equal to $6 \cdot 10^{19}$ cm^{-2}. In contrast to other sources, where the particle current values adequately describe their performance, the number of particles available per pulse is more relevant for EBIS sources; the pulse length then can be matched to the injection interval of the synchrotron. Table III shows what an EBIS source based on the above parameters should be capable of providing for a few selected ion species. It should be noted that a higher intensity could be reached by injecting a sequence of several EBIS pulses into the Booster during an accumulation mode. This would be similar to the MIMAS scheme.

An EBIS source would have to be followed by an RFQ and a linac. Relatively high values of the ratio q/m >0.2 result in a compact RFQ design. As the next stage, a 10-15 MV linac would be adequate to inject Au^{43+} into the Booster with sufficient kinetic energy to operate the rf cavities with the desired harmonic number of h=3.

Table III shows that an EBIS source based on state-of-the-art parameters could not surpass the proposed Tandem mode for the medium mass or heaviest ions. However, Table III shows an EBIS would be satisfactory for fixed target operation, injection of lighter ions, and for timing studies with intensities below the full RHIC intensity. Using existing technologies (electron guns, superconducting magnets, ultra-high vacuum) such a source could be developed within five years and it would serve to gain experience and knowledge required for a possible future upgrade in the next stage of development.

For the next source stage, the most critical element requiring a substantial development effort is the electron beam current because it should reach the 5-10 A range, at a

Table III
Idealized EBIS Source Charge State Production

Element	Charge state	q/m	No. of particles per pulse, (x 10^9)
Ne	8+	0.4	6
S	14+	0.44	3.5
Kr	24+	0.29	1
Xe	26+	0.20	1
Au	43+	0.21	0.35

beam perveance of about $2 \cdot 10^{-6}$ $AV^{-3/2}$. New developments in the field of CW gyrotron electron guns as well as the recently discovered phenomenon of ion cooling by means of adding some lighter ions into the trap[23] may lead ultimately to a device providing the full range of ion species and currents for heavy ion synchrotrons and colliders. This source, linked again to an RFQ and a short linac, could become a compact, efficient injector for RHIC for all ions up to uranium.

B. <u>ELECTRON CYCLOTRON RESONANCE ION SOURCES (ECR-IS)</u>

In an electron cyclotron resonance ion source, multiply charged ions are produced by impact of energetic electrons in a plasma. Electrons are selectively heated by electromagnetic waves in regions of the source where the electron cyclotron frequency equals the wave frequency. The magnetic field in modern sources of this type is of the B-minimum configuration, consisting of an axial mirror field with a superimposed multipole field (usually hexapole or octopole). In such a field, there is a closed surface where the resonance condition for the waves is satisfied. ECR ion sources are steady state devices, in principle, with equilibrium electron energy and ion charge state distributions.

There are a certain number of basic relationships valid for ECR sources. In addition to the resonance condition, the wave frequency f_w has to be higher than the plasma frequency f_p. Geller[24] has proposed several scaling laws for ECR sources, which are in a reasonable agreement with experimental data and can be used to scale up the parameters of existing devices. In distinction from EBIS sources, where a simple relationship exists between electron beam parameters and the maximum number of positive (ion) charges that can be accumulated in the device, the ECR scaling laws involve plasma parameters and are much more empirical in nature. For example, the rf power used in the source determines the electron energy; at lower levels, the electron energy is proportional to the rf power P, at higher levels it becomes proportional to $P^{1/2}$ and this will most often be the case. The optimum charge state scales with frequency, but only logarithmically.

There are several dozen ECR sources in operation, but only one is being used to inject heavy ions (O, S) into a synchrotron (CERN, operation with a fixed target). Its performance, while satisfactory for fixed target heavy ion synchrotron research, is far below what a heavy ion collider would require. Proceeding in a similar way as with projecting EBIS performance, one can compile best results from several sources and consider this to be an optimal device. For light and medium heavy ions (up to krypton), the two "state-of-the-art" devices (EBIS and ECRIS) are comparable, although the latter may require more powerful r.f. acceleration due to a lower exit charge state. The emittance of ECRIS beams tends to be substantially higher than for EBIS or tandem beams, and the extrapolation to a device that would serve in a RHIC injector is more difficult for ECR sources. Scaling of source parameters, such as the r.f. frequency and power, will require new and expensive technologies (gyrotrons) in order to increase the yield of high charge state heavy ions by more than an order of magnitude beyond the values presently available.

V. Discussion

A comparison of the particle currents available at the world's existing fixed target heavy ion synchrotrons shows that with the possible exception of the new SIS machine, all currently used injection scenarios would not be adequate to meet the needs of a heavy ion collider. At BNL, the challenge of satisfying the demands of a collider have been met by the combination of a negative ion sputter source and an electrostatic Tandem accelerator. Measurements to date of the particle currents at the injection to the AGS strongly suggest that the initial luminosity requirements of RHIC can be achieved. In addition, newly developed negative ion sources[21] hold considerable promise for improvements in the near future.

The fact that only fully stripped heavy ions may be accelerated in a collider, together with the unavoidable beam loss on stripping atomic electrons from low charge state ions, suggests particle sources that produce high charge state ions will have immediate advantages over PIG sources or negative ion sources. To date, the high charge state EBIS and ECR ion sources have provided very heavy highly stripped ions at low intensities mainly for atomic physics research (EBIS) and low energy CW machines like cyclotrons and superconducting linacs (ECR). In the future, a new ECR source is expected to provide high charge state Pb ions suitable for the fixed target program at the CERN synchrotrons. However, the current from this ECR source would still be much lower than what is currently available from the BNL electrostatic tandem injector. The analysis in Section IV shows that considerable R&D work on EBIS or ECR devices would be necessary to achieve the particle intensities required by colliders. It is also important to note that for the more important heaviest ions such as ^{197}Au, the required intensities are well beyond the present day performance of these devices.

While it is difficult to project or forecast future developments in positive or negative heavy ion source technologies, there would appear to be a growing urgency to focus on the most promising new methods for generating more intense heavy ion particle currents for colliders. These demands come from the ultimate luminosity performance of RHIC, the likely promise of accelerating heavy ions in the Large Hadron Collider (LHC) at CERN, and even the future possibility of accelerating heavy ions in the Superconducting Super Collider (SSC). For the immediate future negative ion sources and a Tandem electrostatic machine are the most promising.

Acknowledgements

Special thanks are due to F.H.G. Lothrop, N. Augert, P.A. Chamouard, A. Kurepin, and H. Haseroth for providing the latest detailed heavy ion performance of the different synchrotrons compared in this paper.

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