CONF-920316 4--3

BNL-48604

Contribution to the
Workshop on the Physics and Techniques of Secondary Nuclear Beams
Dourdan, France
March 23-25, 1992

THE ADRIA PROJECT FOR HIGH INTENSITY RADIOACTIVE BEAMS PRODUCTION

G. Bisoffi, M. Cavenago, A. Dainelli,
A. Facco, G. Fortuna, A. Lombardi,
M. F. Moisio, A. Pisent, P. Spolaore, B. Tiveron
Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
A. G. Ruggiero*
Brookhaven National Laboratory, Upton, USA
L. Tecchio
Dipartimento di Fisica Sperimentale and INFN, Torino, Italy

Abstract

A proposal of an accelerator complex (ADRIA) for the Laboratori Nazionali di Legnaro (LNL) is described in this report. The main components of the complex are a Heavy Ion Injection system and two rings, a Booster and a Decelerator, both with a maximum rigidity of 22.25 Tm, connected by a Transfer Line where exotic isotopes are produced and selected. The proposal has two main goals consisting in the acceleration of stable ion species up to kinetic energies of the order of few GeV/u, at a repetition rate of 10 Hz with intensities of about 10^{12} ions per second, for fixed target experiments in nuclear physics and for the production of fully stripped radioactive beams, using particle fragmentation method, for nuclear spectroscopy experiments. Fragments are accumulated in the Decelerator, with intensities $10^8 \div 10^9$ ions/s, cooled and delivered at the production energies or decelerated down to energies of few MeV/u, in proximity of the Coulomb barrier.

Contribution to the Workshop on the Physics and Techniques of Secondary Nuclear Beams, Dourdan, France, Mar 23-25, 1992.

---

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

1 - Introduction

With the completion of the construction and the start of the operation of the ALPI post-accelerator, beams of heavy ions will be available with a broad range of energies, intensities and charge states from Deuterium to Uranium[1)]. As a natural upgrading of the facility, a proposal has been presented to the INFN for the construction of two circular accelerators with the circumference of 267 m and a magnetic rigidity of 22.25 Tm [2)]. The first accelerator can deliver beams of heavy ions with specific kinetic energies up to a few GeV/u, e.g. 1 GeV/u for Gold ions and 2.5 GeV/u for lighter ones. The repetition rate of the magnetic cycle has been fixed to 10 Hz and the achievable beam intensities are about 10^{12} ions per second.

In addition to the normal mode of operation, where the primary beam is sent toward a fixed target for studies of nuclear and subnuclear physics, the proposal foresees the production of well collimated beams of unstable exotic fragments, by impinging the primary beam on a target located in the transfer line connecting the two rings. Prior acceleration of the primary beam to energies of few GeV/u is required for the production of the exotic elements with significantly large rates. The secondary beam intensities are estimated in the range of $10^8 \div 10^9$ ions/s.

The second ring is used for the accumulation and deceleration of the unstable isotopes. To increase the phase space density of the circulating ion beam, electron and stochastic cooling are applied after injection. When the desired beam intensity has been reached, the whole beam can be decelerated down to energies of about 5 MeV/u corresponding to the Coulomb barrier of heavy ion systems, extracted and used for experiments dealing with nuclear structure studies.

It is also possible to produce beams of electrons, muons and π mesons for experiments and detector developments. The availability of heavy ions with specific energies in the range of hundreds of MeV/u enables also many other applications such as study of cancer therapy with range-controlled probes, material science and solid state physics. Furthermore, the ADRIA complex can be also a useful tool for preliminary studies of the physics and the engineering for inertial confinement thermo-nuclear fusion driven by heavy-ion beams. In the following sections the main features of the ADRIA complex will be presented.

2 - The ADRIA Complex

The schematics of the ADRIA complex[2)] is given in Figure 2.1 and its location on the LNL site is shown in Figure 2.2. The individual components are the following:

- a Heavy Ion Injector (XTU tandem and the ALPI post-accelerator);
- a Fast Cycling Synchrotron (Booster);
- a Slow Cycling Synchrotron (Decelerator);
- a Transfer Line (connecting the two rings);
- an Experimental Area;

The two accelerators have the same size and similar lattices. They can hold beams of particles with magnetic rigidity of 22.25 Tm, and are arranged in a vertical layout with the Decelerator exactly on top of the Booster and 2.5 metres above it.

Both rings are housed in the same underground enclosure with the Booster beam axis 1.5 m below the ALPI line. The lattices of the two rings have been designed to allow enough drift space for rf cavities, components for injection and extraction, and other devices. A four-fold superperiodicity has been found convenient, with each superperiod made of a 90° arc and a 22 m long straight section. The arcs consists of FODO cells 11 metres long. The betatron tunes are 5.8 (horizontal) and 3.8 (vertical), away from any low-order systematic resonance. The transition γ of 4.6 is high enough to be avoided by all acceleration cycles.

The Decelerator has basically the same lattice of the Booster, the same circumference and geometry, except for the long straight sections; a different quadrupole configuration allows a magnet-free 11.5 m long drift space, to accommodate electron cooling of the ion fragments.

Dipole magnets have a gap of 10 cm, are 3.5 metres long and have a maximum field of 1.26 T. The excitation of the dipole field has a 38 T/s rate. The physical aperture of the quadrupoles is circular with a 7 cm radius. The number of power supply buses is minimized for easy tracking and tuning.The general magnetic layout is reported in Figure 2.3 and a summary of lattice parameters is given in Table 2.1.

Table 2.1: General Lattice Parameters of the Two Rings.

Max. Magnetic Rigidity		22.25	Tm
Circumference		266.6667	m
Bending Radius		17.62	m
Maximum Dipole Field		1.26	T
Dipole vertical gap		10	cm
Max. Quadrupole grad.		9.0	T/m
Quadrupole bore radius		7	cm
Superperiodicity		4	
Transition Energy (γ_t)		4.6	
Betatron tunes:			
Horizontal plane	ν_h	5.8	
Vertical plane	ν_v	3.8	
Natural Chromaticity:			
Horizontal plane	ξ_h	-5.5	
Vertical plane	ξ_v	-4.9	

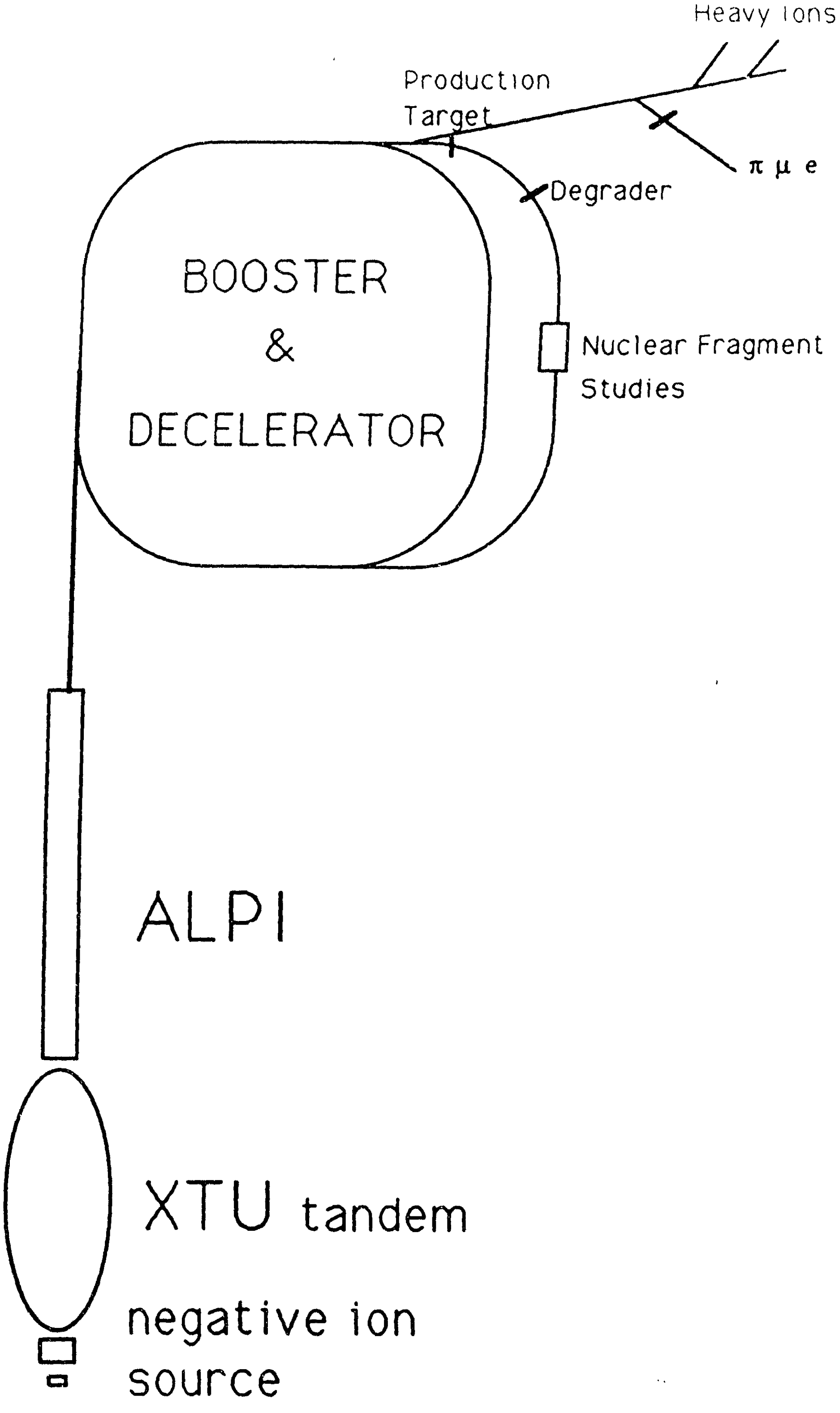

Figure 2.1: Schematics of the ADRIA Complex

Figure 2.2: The ADRIA Complex on the LNL Site

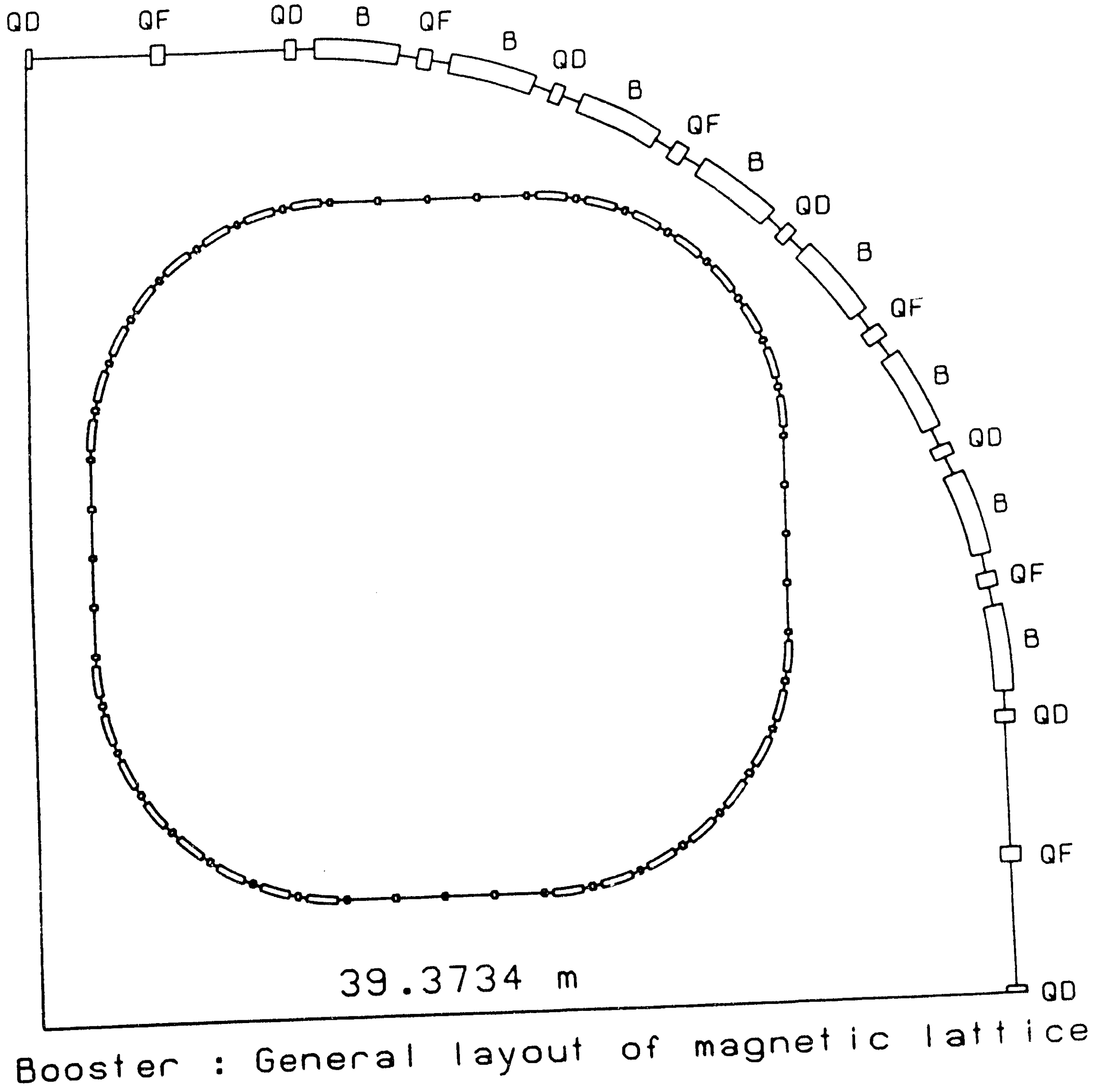

Figure 2.3: General Magnetic Layout

3 - Heavy Ion Injector

The Laboratori Nazionali di Legnaro own and operate a Tandem Van de Graaff with a terminal voltage of 16 MV, used to accelerate continuous heavy ion beams [3]. Essentially all ion species up to lead can be accelerated at large intensities; acceleration of Uranium requires source development. We propose a pulsed mode of operation of the Tandem, as already demonstrated successful with a similar machine at Brookhaven National Laboratory. This mode of operation makes the Tandem the ideal injector for a heavy ion facility which employs a fast cycling synchrotron. A negative ion source is pulsed with a pulse duration of 360 μs at the repetition rate of 10 Hz. The following analysis is based on the example of Gold. In the scheme proposed here, the ions are accelerated towards the high voltage terminal (+16 MV), where they hit a target and are partially stripped. In the case of Gold an intermediate charge state of +13 is obtained, and ions are further accelerated from the positive terminal toward ground where they exit the Tandem. The Tandem is well known to deliver intense beams without spoiling the small betatron emittance and momentum spread. The specific kinetic energy of Au^{+13} at the exit of the Tandem is about 1 MeV/u.

At the Laboratori Nazionali di Legnaro the construction of a linear accelerator (ALPI) is in a completion phase; the project is made of superconducting cavities at 80 and 160 MHz with the equivalent of a 40 MV total accelerating voltage[1]. The project will allow acceleration of heavy ions to an energy of 5-30 MeV/u depending on the species and charge state. For the proposal described here, ions of Gold with charge state +13 are accelerated through a section corresponding to a total voltage of 36 MV; at the end of this section, where $\beta > 0.08$, they hit a second stripping target where a new charge state (+51) is produced. After acceleration through the final 4 MV section of the linear post-accelerator the final beam energy is 4.6 MeV/u, corresponding to $\beta \sim 0.1$.

The time structure of the ALPI beam is generated by a 5 MHz pre-buncher located at the Tandem entrance, with a compression system (buncher) made of 80 and 160 MHz superconducting cavities located at the entrance of the post-accelerator. With this bunching system only one bucket out of 32 will carry beam at the exit of ALPI. In the near future an alternate injection system to ALPI will be available; this consists of an ECR source coupled to an RFQ device. This new injector can be used to complement the performance of the Tandem with a different range of charge states, energies and intensities. Which of the two pre-injectors can be best used for filling the ADRIA complex will depend on the mass of the ions and of the experience gained by that time. In the following we shall limit our study to the case of the Tandem-ALPI combination as injector to ADRIA.

4 - Injection and Acceleration in the Booster

The circumference of the Booster has been chosen to correspond to the injection of 45 bunches of Gold ions per turn; the number of turns that can be injected is about 40. The rf harmonic at injection is also 45, corresponding to an injection frequency of 5 MHz, equal to the pre-buncher frequency. With this choice, all the rf buckets are occupied by beam bunches, except for the gap required for beam extraction.

Each injected bunch is very short, about 1/50 of the length of the rf bucket. Thus a "painting" procedure can be applied to the multi-turn injection of the heavy ions to fill the rf buckets uniformly. At the end of the process about 5×10^{10} ions of Gold have been injected. The resulting tune depression due to space charge is estimated to be 0.5, assuming that the beam fills essentially all the available aperture; this yields a normalized betatron emittance of 12 π mm-mrad. The beam is then accelerated to 1 GeV/u at a rate of 10 Hz, yielding 5×10^{11} ions of Gold per second. Even higher intensities and energies can be obtained with lighter ions. The maximum dipole field required for this mode is less than 1.3 T, and the maximum rate of change is 38 T/s.

A peak voltage of 220 kV is required during the acceleration cycle; the beam velocity varies between $\beta = 0.1$ and $\beta = 0.9$ requiring a large frequency swing from 5 to 45 MHz. This is accomplished with two rf cavity systems: the first operates from 5 to 32 MHz, the second from 30 to 45 MHz. A summary of beam parameters at the end of the acceleration cycle in the Booster is given in Table 4.1

Table 4.1: General Parameters of Heavy Ion Acceleration.

	S	Cu	I	Au	U	
Atomic Number Z	16	29	53	79	92	
Mass Number A	32	63	127	197	238	
Charge State Q	16	27	40	51	54	
Inj. Kin. Energy	16.4	10.4	6.1	4.6	3.9	MeV/u
Extr. Kin. Energy	2.53	2.08	1.4	1.03	0.85	GeV/u
Harmonic number	24	30	39	45	49	
Beam Intensity	2.0	1.3	0.7	0.5	0.5	10^{12} ions/s
Norm. Emittance	23	18	14	12	11	π mm-mrad
Bunch Area	0.017	0.011	0.007	0.005	0.005	eV/u - s

Several operation modes are possible with heavy ions: the beam can be extracted at the end of the acceleration cycle and sent toward external target stations; it can be also transferred to the Decelerator which can be used as a Stretcher, for energies up to few GeV/u, with slow-spill extraction for 100% duty cycle.

5 - Fragment Production and Accumulation

A transfer line takes the beam from the Booster to the Decelerator. Along the transport the beam first encounters a target where fragments are produced, with about the same kinetic energy of the incoming stable nuclei, with medium-to-large mass numbers, and completely stripped. Selection of the required fragment species is then obtained with a second target, called the *degrader*, placed in a region of large dispersion, and a system of collimators. The combination of the targeting and the focusing along the transport will allow the capture of a total momentum spread of 0.7% and a betatron emittance of 20 π mm-mrad in both planes. The expected yield can be as high as 1×10^{-3} fragments per incident ion. The secondary beam is then injected into the Decelerator. Here the bunches of fragments are captured by a 45 MHz rf system, rotated in the longitudinal phase space to give a smaller momentum spread (0.1%) and displaced by an additional rf system to an off-momentum trajectory, with a slight (1.2%) different momentum, where they are allowed to debunch. The required voltage for the bunch operation is 1.4 MV, which can be obtained with two cavities. Electron cooling is applied to the beam on the stacking orbit. A new pulse is injected every 100 ms, and the injection rate has to be matched with the electron cooling rate. Both transverse and momentum cooling take place: the more important requirement is to reduce the beam momentum spread by an order of magnitude. This process repeats until 12 pulses have been stacked (Figure 5.1); electron cooling then continues for further 0.5 seconds, in conjunction with stochastic cooling.

Table 5.1: General Parameters of Fragment Production.

Target Length	1	g/cm^2
β^* @ target	1	m
Angular Acceptance (full)	7.5	mrad
Momentum Acceptance (full)	0.7	%
No. of Booster pulses/cycle	12	
Minimum Cycle Period	2	s
Bunch Length (rms)	0.5	ns

	S	Cu	I	Au	U	
Mass Number, A	32	63	127	197	238	
Atomic Number, Z	16	29	53	79	92	
No. of Fragments/s	$4.0 \cdot 10^9$	$1.6 \cdot 10^9$	$5.0 \cdot 10^8$	$1.5 \cdot 10^8$	$1.5 \cdot 10^8$	
Mom. Spread (rms)	0.09	0.11	0.20	0.28	0.38	%
Angular Spread (rms)	3.2	3.7	5.0	5.8	7.3	mrad
Harmonic Number	24	30	39	45	44	

Initial Emittance	20	π mm-mrad
Final Emittance	1	π mm-mrad
Final Momentum Spread	0.01	%

Finally the beam can be decelerated from the energy of the fragments at production, down to about 5 MeV/u. The deceleration lasts 0.3 s, and is followed by an interval of 0.1 s during which the field is reset to its initial value. At the end of the 2 second long cycle, the beam is extracted and directed to the experimental area.

The beam momentum spread at this stage is 0.1%. A second step of electron cooling lasting about 100 ms can be applied just before extraction, for a further reduction of the beam momentum spread, for instance to 0.01%. The Decelerator can also be operated with an internal gas-jet target producing a high luminosity for precision experiments. Table 5.1 lists the main parameters of fragment production and accumulation. The cycle described above is only one example of the possible operation modes of the Decelerator. The duration of the cycle as well as the extraction energy can be varied according to the user requirements. It is also possible to adjust the rate and the length of the extraction spill which may result in a compromise between intensities and duty cycle. The primary beam pulses of the Booster cycle not involved in the fragment production may be directly used at the Booster energy range for different purposes (nuclear physics, applied research, cancer therapy, ...).

6 - Conclusions

The project can be developed in three phases: (1) construction of the first accelerator and targetry for the study of secondary beams; (2) construction of the second accelerator and completion of the transfer line for accumulation and deceleration of exotic fragments; (3) addition of electron cooling. The scale of the project is such that the first phase can be built over a four-year period starting the construction phase in January 1995 and the commissioning phase in January 1998. The second and third phases are to be completed in the following years.

There is considerable interest in the acceleration of beams of protons in the ADRIA facility. This is indeed possible with modifications and additions that do not alter the main features of the complex which accelerates and accumulates heavy ions. A study was also performed to demostrate feasibility and compatibility of proton acceleration in ADRIA[4]. Polarized protons can also be accelerated in the Booster.

References

1) G. Fortuna et al., Nucl. Instr. and Meth. A287 (1990) 253-256.
2) R. A. Ricci and C. Signorini, Nucl. Instr. and Meth. 184 (1981) 35.
3) "The ADRIA Proposal", LNL-INFN(REP) 58/92 (1992).
4) "Feasibility Study of a Hadron Facility", Conceptual Design Report, LNL-INFN(REP) 57/92 (1992).

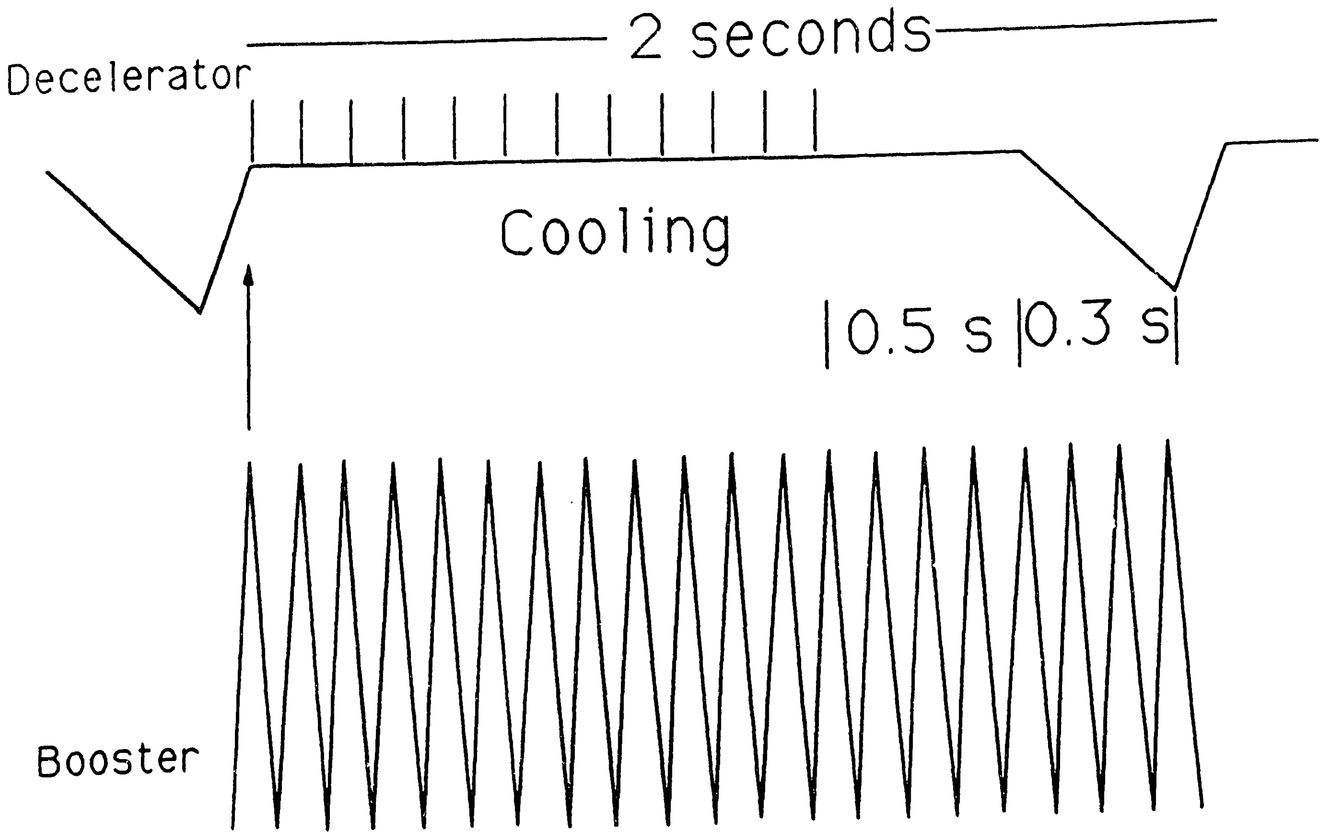

Figure 5.1: Magnetic cycle of the ADRIA Complex.

END

DATE
FILMED
6/23/93