The Nuclear Structure Laboratory at Notre Dame

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Nuclear Physics has a long history at the University of Notre Dame. It started in the early 1930's with the construction of the first accelerator located on campus. That accelerator was designed and built by Dr. Jose Caparo from Electrical Engineering and Dr. Collins from Physics as an open air machine with the ability to reach a terminal voltage of 1 million volts. The location was in a special room in what is today Cushing Hall. The university supported a request for $ 900 for building the instrument. However, at completion in 1935 the actual costs for the university added up to $3000.

Figure 1 shows the accelerator as it looked early in 1937. A double row of windows in Cushing Hall, allowed passerby's to be able to make out an incredibly huge copper sphere sitting up on its spindly legs. Remember that corona was a normal way of life for this machine, and it is said that the corona glow would at times fill the entire room. What a sight it must have been on a winter evening to see this monstrous machine bathed in a purple glow.

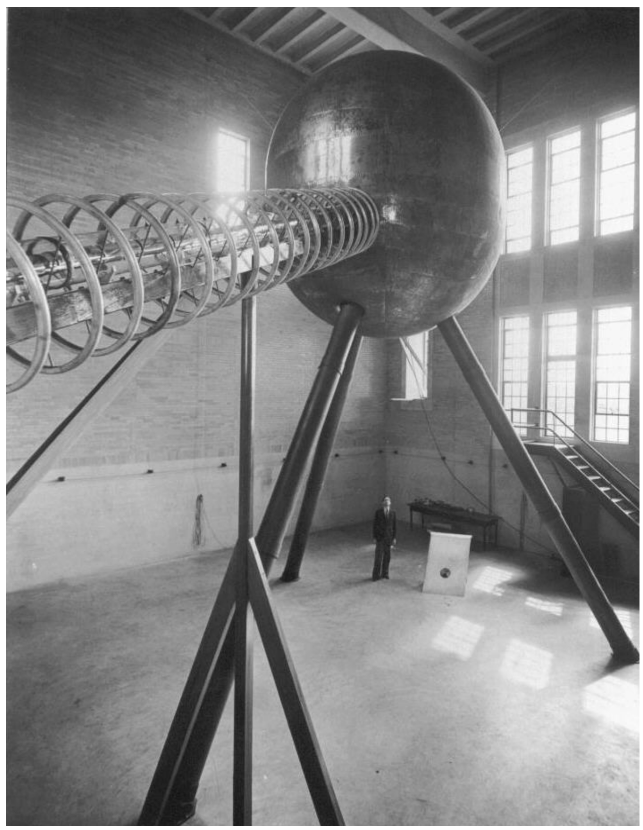

Figure 1. A 1937 photograph of the first Notre Dame accelerator, facing SE. Standing in the background is George Collins. At the time there was one belt, running to the lower left in the picture, The accelerator tube with one corona ring to each drift tube runs towards the upper left.

The terminal, by its sheer size, dominated the scene. It had two hand made copper sheet covered hemispherical sections. Each copper panel was hammered into shape with an air hammer, and then cut to fit the spaces in the frame, and nailed in place. The long legs were pieced together with insulating tubing to raise the terminal high above ground. The terminal was brought up to voltage by a 70 feet long paper made charging belt. Because the terminal was in open air, discharge along the tubes occurred regularly at times of high humidity as shown in Figure 2. The construction of this first accelerator started a tradition of accelerator based nuclear physics that has lasted now for nearly 70 years at Notre Dame. While the accelerator based research was initially concentrated on the use of electron beams over time and many generations of Notre Dame nuclear physicists the focus has changed to accelerating heavier positively charged particles for a broad range of scientific applications from nuclear structure to nuclear astrophysics.

Experimentation began upon the return of dry weather in the fall of 1937, and continued thereafter except for periods of high humidity during the summer months, which were devoted mostly to machine development. Routine operations continued until 1942. By that time most of the personnel had left for war-related work, and the second accelerator was already in operation, itself engaged in wartime research.

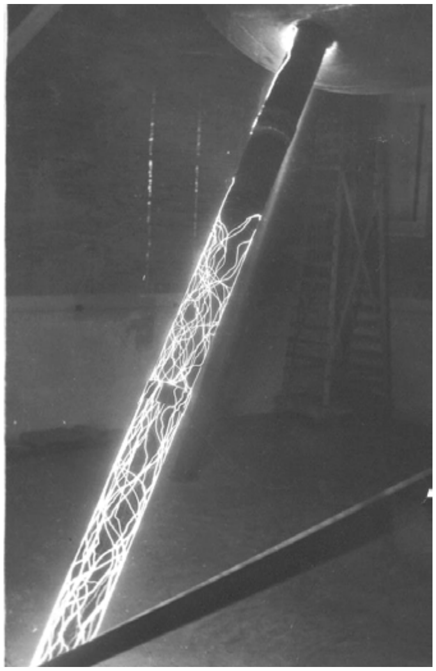

Figure 2. High voltage (~1.2 MV) spark running along one of the 20ft long insulating accelerator legs.

Some solid research was done with the first accelerator, including the first experimental confirmation of Cerenkov radiation, the first electro-disintegration of a nucleus, the first pair production by electrons, the experimental investigation of Mott scattering, and an investigation of the tip of the Bremsstrahlung spectrum.

Thanks to the success of the first accelerator, in the early forties the University funded the construction of the second one. This time it was decided to build a horizontal pressurized machine of the Van de Graaff type to overcome the discharge problems at times of high humidity. This machine was located in the basement of the old Science Building, today's La Fortune Center. This second Notre Dame accelerator was completed in early 1942. With a total length of 40 feet it was at the time one of the largest accelerators in the world. It was expected to generate 8 million volts, but there is no evidence that it ever topped 4 million volts. At that time a considerable staff was needed to maintain and operate the facility as shown in Figure 3.

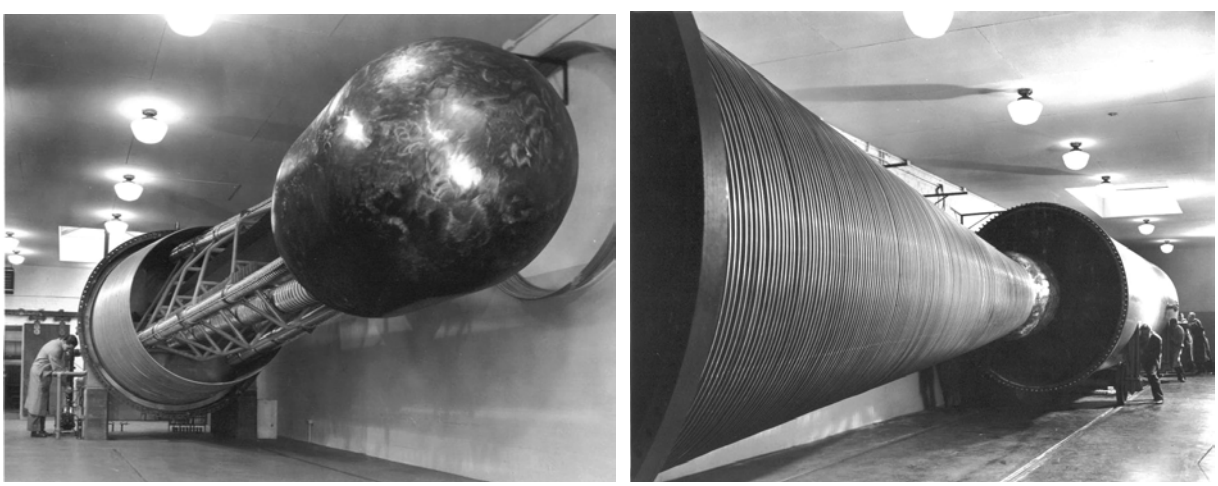

Figure 3. The picture on the left shows the open accelerator column, with the dome still mounted at the terminal while the hubs have been partly removed to allow free access to the column. The picture on the right shows the closing of the rail-guided tank by the technical staff.

Shortly after the pressurized accelerator was completed, in 1942 the Manhattan Project took over operations, putting fundamental research on hold. The Manhattan Project co-opted a number of laboratories with state of the art equipment around the United States in order to guide experimentation that would aid the development of a nuclear bomb. This was done in utmost secrecy, illustrated by the fact that the logbooks during this time were not made "public" until well after WWII and contained no figures or technical drawings in from 1942 to 1945. Even after the war, Notre Dame's involvement with the development of the bomb was not immediately made public. Among others, Walt Miller and H. Bolger were involved in running these experiments during the war.

After the war in 1946 the accelerator returned to peace time research on fundamental nuclear structure and was mainly used to study the interaction processes of up to 4MeV electrons with matter. The old Science building soon proved to be too small for the rapidly growing Departments of Physics and Chemistry. A new building, Nieuwland Science Hall was completed in 1953. While the old accelerator was not moved into the new building members of the Physics Department, Dr. Bernard Waldman and Dr. Walter Miller designed and constructed a new 4MV

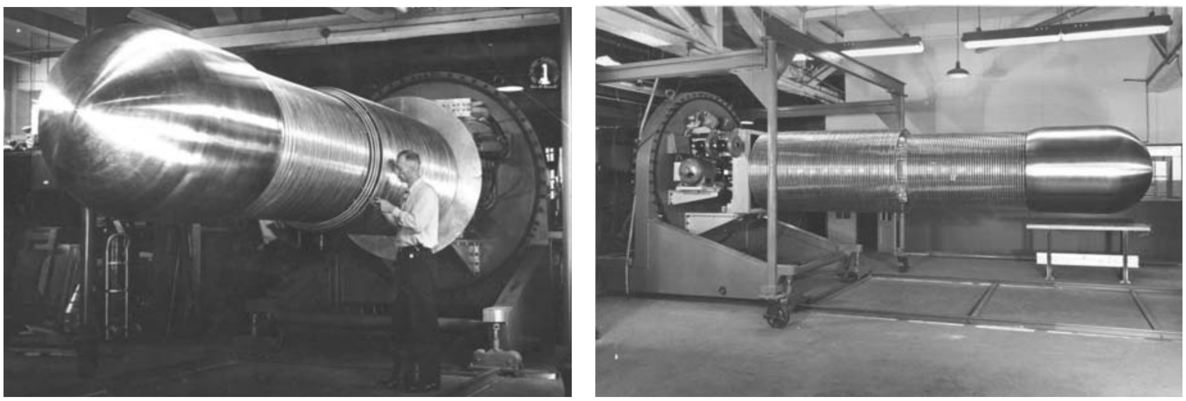

Figure 4. The next generation 4 MV Van De Graaff accelerator built in 1955. The machine was used both with negative charged terminal for the electron beam and with positive charged terminal for charged particle beams for low energy transfer reaction measurements.

32 feet long accelerator for continuing the electron beam based research program at the new location. This was supported through a grant of $ 35,000 from the AEC. The design followed the plans of the Brookhaven Cosmotron injector and was similar to the 4MV machine at Duke University. This third accelerator was the first to be used for a rapidly evolving training and research program for the rapidly growing PhD program at the Department of Physics that had 15 graduate students in nuclear physics in 1955. At that time also John Mihelich and Cornelius Browne from MIT joined the faculty and started building an active nuclear physics research program with light ion beams at Notre Dame. Since the original machine was designed with a negative terminal for electron beam use only, the belt charging system was made reversible so that positively charged ion beams could also be accelerated. To get this program going Corny Browne started building the first spectrograph of the Browne Buechner type for $12,000.

This accelerator was the core of an active nuclear physics research program at Notre Dame for more than 10 years which was mainly supported through funds from the Office of Naval Research ONR. In the early 1960^{ies} a proposal was made first to ONR and subsequently to the National Science Foundation (NSF) for the construction of a new Tandem accelerator. This kind of accelerator was a truly new development - called by some "Swindletron" (two accelerators for the price of one) – which was based on the invention of the negative ion source. With the design of accelerating a negative beam towards a positively charged terminal, and then stripping the ions to some positive charge distribution allowed to gain much higher energies than possible hitherto. The proposal was funded with about $2.5 million in December 1965, the largest research grant Notre

Dame had ever received. The accelerator itself, a so-called FN tandem machine was purchased for ~$1.4 million from High Voltage Engineering. The rest of the funds went into providing the necessary infrastructure. The new accelerator and the target halls for the planned research program needed a new building which was simply added to the back of Nieuwland Science Hall. The construction started in 1966 and the building was complete in 1967 with the accelerator being moved in by railroad in 1968. The new wing contained the accelerator hall, the control room

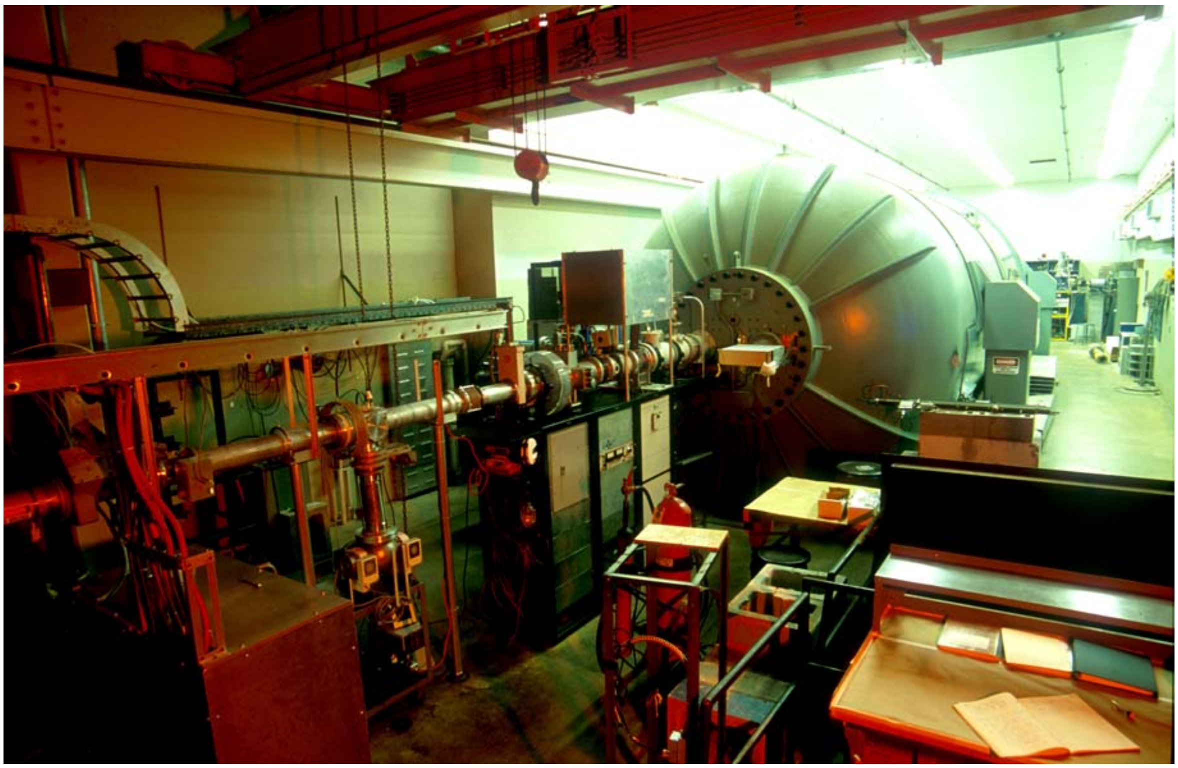

Figure 5. The FN tandem accelerator at the Notre Dame Nuclear Structure Laboratory seen from the low energy side (injector beam line). The tandem is presently operated with a terminal voltage of up to 11 MV. There are two ion sources, a duoplasmatron source which is mainly used for helium beams and a SNICS sputter source for the production of heavy ion beams.

facilities, a small shop, and two target rooms for the light and heavy ion experimental research program. Initially the accelerator was also equipped with an electron source at the terminal and an independent electron acceleration tube. A third target room was made available for electron beam experiments but with Walt Miller's retiring from research this program never really started. While this transition marked the end of electron beam related research at the physics department, it did not disappear from campus but was continued as a major research direction at the Notre Dame Radiation Laboratory. Instrumental in the planning and installation for the FN tandem was Ed Berners who was hired as research faculty member to the group mainly to take charge for the operation and maintenance of the new machine. Why traditionally the previous generations of accelerators were built, maintained and operated by faculty and students, with the growing focus on research this was not longer possible. New times had started.

At that time the nuclear physics group had six faculty members. After Walt Miller had become chairman and quit research, Cornelius Browne became the principle investigator for the NSF grant, other faculty members were Paul Chagnon, Sperry (Bud) Darden, Emerson Funk, and John Mihelich. They built an active and broad research program in nuclear structure physics. The research of Browne and Chagnon focused on the study of nuclear reactions to explore details of nuclear structure and reaction mechanisms. Their main tool was the newly developed second generation 100 cm Broad Range Spectrograph. This spectrograph was instrumental for active research in nuclear structure and nuclear astrophysics for more than 30 years. It is presently being refurbished for a third career as gas-filled spectrometer. Parallel to that a polarized beam program was developed centered around the newly purchased polarized ion source from the University of Wisconsin – this program ended with the retirement of Bud Darden as the last man who could operate the complexities of that source. A gamma spectroscopy program, at times one of the leading in the country, emerged from the close collaboration between Mihelich and Funk who built an in-beam spectroscopy program at the new machine.

After the retirement of Walt Miller two new faculty, Jim Kolata and Umesh Garg joined the nuclear group, with Kolata planning to develop a strong heavy ion beam research program and Garg joining the nuclear spectroscopy group. In particular Kolata coupled the old 4MV machine, which was hardly used anymore in these days, as negative beam injector to the FN tandem accelerator. This way considerably higher energies could be achieved which allowed a broader range of heavy ion beam experiments. This strengthening of the nuclear physics faculty proved to be just in time since in the early 1980^{ies} the NSF considered seriously to close the laboratory to because of the overall reduction of research funding for nuclear physics. The addition of two new faculty members which brought innovative research programs to Notre Dame had NSF reconsider and the Nuclear Structure Laboratory (NSL) remained fully funded. The NSF continued to support the NSL facilities and the research on the basis of three year funding periods, albeit on a basically flat budget which made it difficult to meet the ever growing demands on new technology and electronics necessary for the successful operation of a modern accelerator laboratory.

In 1986 Michael Wiescher joined the faculty and developed a new branch of nuclear physics at the laboratory, nuclear astrophysics. Joachim Görres came in late 1986 as postdoc and was later in 1989 appointed as research faculty member at the laboratory. In 1989 with John Mihelich retired Ani Aprahamian took his place to expand the program in nuclear structure physics. The old 4MV accelerator was hardly used anymore. With the purchase of a new heavy ion sputter source it was also not anymore used as injector for the FN tandem. It also did not provide sufficient intensities for developing a low energy nuclear astrophysics program. It therefore was decided to dismantle the machine after nearly forty years of service. It was replaced by a low energy 3.5MV KN Van de Graaff (VdG) from Queens University as fifth in the long succession of Notre Dame accelerators. This machine did not generate NSF funding at first so it was put together and operated entirely by undergraduate and graduate students. After two years of operation independent funding was eventually provided by the NSF to develop a low energy program in nuclear astrophysics to complement the continuing activities at the FN tandem.

In 1994 Cornelius Browne retired after nearly 30 years as Principle Investigator and Director of the Nuclear Structure Laboratory to be replaced by Jim Kolata. He had steered the laboratory through one of its most successful but also most difficult periods of its history. His last challenge came with the beginning of the last decade of the century. In 1990 the NSF had decided to phase out most of the country's small university operated tandem laboratories since lack of funding and government support had made it impossible to maintain and operate these labs any longer. From fourteen NSF supported accelerator laboratories, including facilities at CalTech, Princeton, and Wisconsin, only four were to continue. The decision was to be made on the basis of faculty use of the facility, its research program and its future development plans. The faculty with research programs at all these laboratories were asked to come to Washington and present their programs and plans at a two day NSF workshop. On the basis of this review the Notre Dame Nuclear Structure Laboratory was selected as one of the four midsize research accelerator laboratories in the country to be continued. That decision was mainly based on the success of the new directions the laboratory had chosen, radioactive beam physics and nuclear astrophysics.

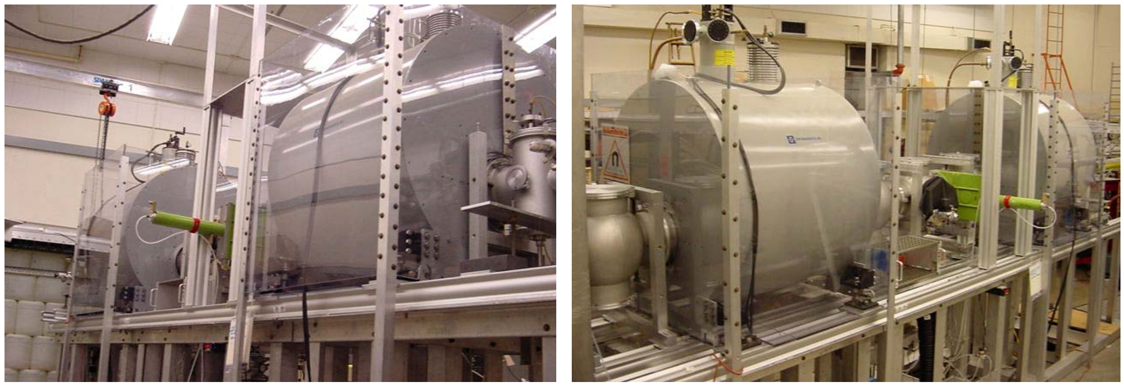

Figure 6. TwinSol, the first US radioactive beam facility for the study of nuclear reaction processes with radioactive beams. TwinSol was developed as a joint University of Michigan – Notre Dame project and was funded by the NSF.

Kolata's research program at that time had focused on the development of a radioactive ion beam facility in close collaboration with Fred Becchetti from the University of Michigan. They succeeded to design and build the first successful radioactive ion beam facility TwinSol in the country and developed a strong program with light radioactive beams in nuclear reaction physics, nuclear structure physics, and nuclear astrophysics. Nearly for a full decade this program was leading the newly emerging field of radioactive beam physics. Only in the first years of the twenty-first century radioactive beam programs at Oak Ridge National Laboratory, Argonne National Laboratory, and TRIUMF, Canada became competitive. TwinSol is centered around two superconducting solenoid magnets which were used to separate the radioactive ions produced by a nuclear reaction from the primary beam. The approach was simple and successful. After a pilot project showed that the idea worked NSF funded the design and construction of TwinSol with $350,000. To provide more stable and higher energies for the primary beams the Tandem was upgraded to 11 MV terminal voltage through funding by the Notre Dame Graduate School. In addition the traditional belt charging system was replaced by a Pelletron chain system in the middle nineties. This improved operation and reliability of the machine enormously. At that time also Ed Berners retired who for thirty years had maintained the successful operation of both the 4MV and the FN tandem accelerators at Notre Dame. He was replaced by Larry Lamm who had graduated from the Notre Dame PhD program in 1989.

Meanwhile the nuclear astrophysics program at Notre Dame became one of the most successful programs in the country. The experiments at the low energy accelerators were geared towards the simulation of nuclear processes driving stellar evolution. Parallel to that tandem experiments were performed which aimed to study nuclear structure effects which could provide signatures for the understanding of stellar explosions such as in supernovae or cataclysmic binary systems as novae and X-ray bursts. It was operated as part of the general NSF group grant but generated also independent funding for the program at the KN accelerator.

A new faculty member Alejandro Garcia had joined the group in 1994 to build a program in accelerator based weak interaction physics. This program run mainly at the FN tandem and added substantially to the visibility and to the broad spectrum of nuclear physics activities at the laboratory. Unfortunately he decided to follow an offer to join the faculty at the University of Washington in 2002.

With the end of the very successful funding period of 1988-2001 Jim Kolata decided to resign as principal investigator. He continued his research program in collaboration with Fred Becchetti through independent funding through the University of Michigan. He was replaced by Ani Aprahamian as the new Director of the NSL. In view of these new developments the NSF suggested to merge the two independent nuclear physics grants into one. The new grant brought a significant increase in funding which allowed the faculty to purchase new detector equipment and electronics to bring the laboratory up to the technological level necessary for a modern research laboratory. Besides that the university agreed to a major renovation of the laboratory – for the first time in nearly forty years. Significant funds were provided to provide new meeting and shop facilities besides a general facelift of one of the oldest and most successful research facilities of the university.

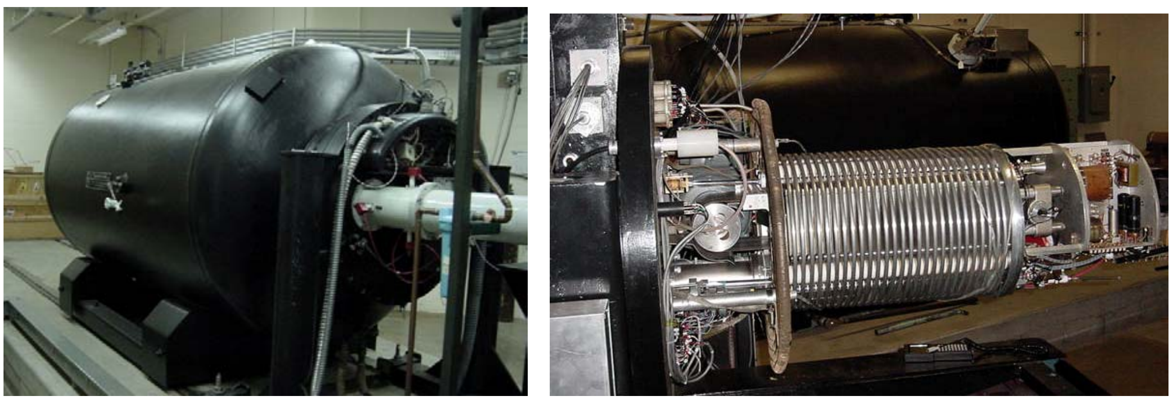

Figure 7. The 3.5 MV KN VdG accelerator is shown at the left hand side, the right hand side shows the short completely rebuilt accelerator column of the 1MV JN VdG, in the background is the tank of the KN machine.

TwinSol remained at Notre Dame. It was still one of the key research instruments of the laboratory. Jim Kolata and Fred Becchetti continued their program in low energy radioactive beam physics; Ani Aprahamian developed a new program in gamma spectroscopy with radioactive ^{6}He beams, and Michael Wiescher and Joachim Görres used TwinSol not as radioactive beam facility but as large acceptance momentum separator for astrophysics related experiments. The purchase of two new Ge-clover detectors provided new experimental opportunities in gamma spectroscopy but also in low energy astrophysics at the KN VdG accelerator. The development of a windowless gas-target system was also an important step to broaden the experimental instrumentation for the KN machine. The 100cm broad range spectrograph had been sitting idle since 1998, a new faculty member Philippe Collon has started complete renovation to convert it to a gas-filled spectrometer for his program in accelerator mass spectroscopy.

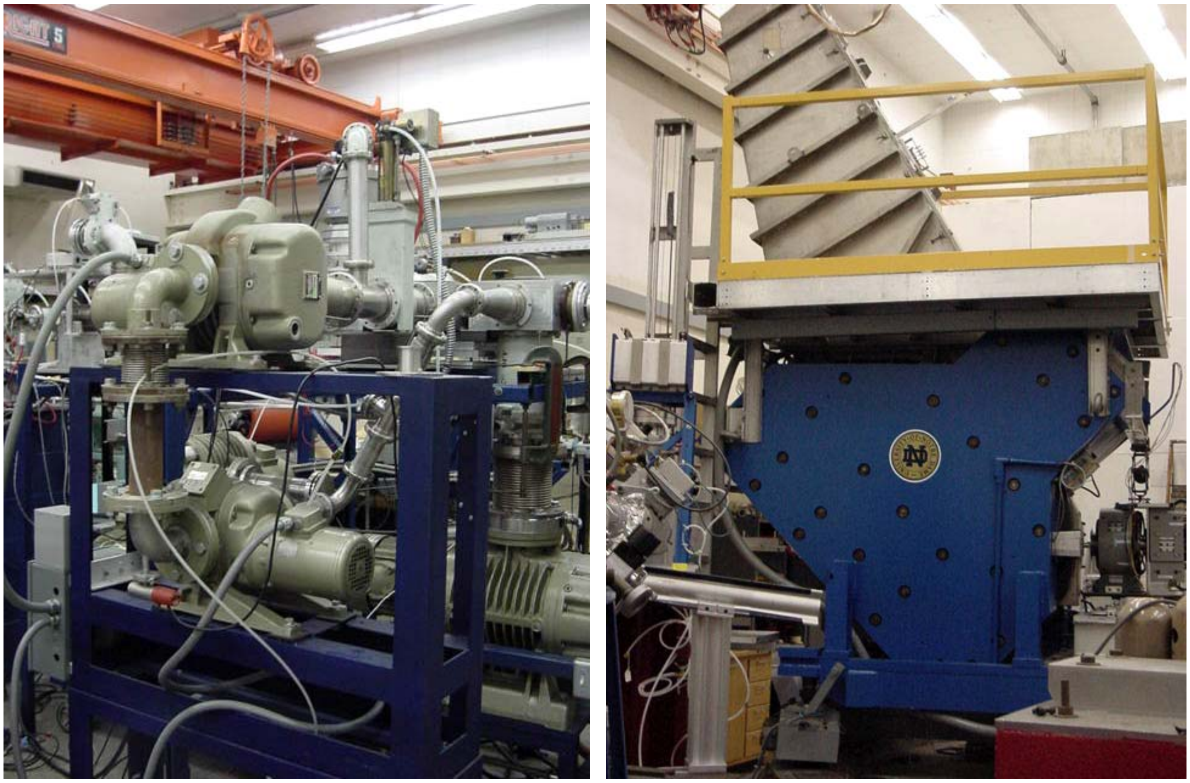

Figure 8. Experimental equipment at the NSL; the left hand side picture shows the windowless gas target systems built from components provided by Ohio State University; the right hand side picture shows the newly painted 100 cm broad range spectrograph which is presently being rebuilt.

A third accelerator, a JN VdG with a terminal voltage of 1MV from the University of Toronto was brought to campus in 2000 to strengthen the astrophysics program further. This accelerator had a long history on its own, originally used as He-beam injector for the Chalk River tandem in Canada, it was converted to a stand-alone low energy nuclear astrophysics machine at the University of Toronto where it had been used heavily by the Notre Dame group. Like the KN VdG from Queens this machine was brought on University funding from Canada to Notre Dame and was completely rebuilt by graduate students and postdocs and was by 2004 converted to a modern, entirely computer controlled, and high intensity accelerator.

In 2000 the nuclear astrophysics program at Notre Dame joined forces with astrophysics groups at Michigan State University and the University of Chicago to form the Joint Institute for Nuclear Astrophysics, JINA. While this institute was initially only supported with small funds from the NSF to develop a conference and visitor program in 2003 JINA was awarded a $10 Million NSF Grant for five years as a Physics Frontier Center in nuclear astrophysics. Again, that was the highest NSF award Notre Dame ever received at that time. While the main purpose of JINA is the development of a strong inter-institutional research program in nuclear astrophysics, a substantial fraction is also allocated for improving the experimental conditions and for developing novel experimental techniques in this field. Part of this program is the development of a next generation recoil separator for low energy nuclear astrophysics experiments in inverse kinematics.

The Physics Department at Notre Dame has operated for nearly seventy years a successful research program in nuclear physics. This program has been supported first by the Office of Naval Research and later by the National Science Foundation through most of these years. During the last forty years the laboratory generated a total funding of approximately $30 million for the university, not counting the JINA funds. For the National Science Foundation however, the Nuclear Structure Laboratory traditionally remained one of the lowest funded accelerator laboratories in the US. Despite the hardships that the limited funding presented for growth and expansion, the nuclear physics group today is one of the most productive groups in the country. With presently it five teaching and research faculty members, four research faculty, four postdoctoral fellows, three staff members, and twenty one graduate students the group provides today an active research environment. With the next funding period coming up in 2005, the nuclear structure laboratory looks forward to continue into the future its long and active research program.