THE 16 MV TANDEM OF THE LABORATORI NAZIONALI DI LEGNARO

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Résumé. — Un accélérateur Van de Graaff Tandem de 16 MV est en construction au Laboratoire National de Legnaro près de Padoue. La machine équipée de deux Laddertrons horizontaux, sera utilisée pour un programme de recherche en physique nucléaire. Des courants élevés d'ions lourds sont prévus, jusqu'à 0,25 μA en chlore et 0,10 μA en iode à 16 MV.

Un injecteur avec une résolution en masse élevée (mieux que 1 pour 100) sera également installé. Cette installation est prévue pour fonctionner en 1980.

Abstract. — A 16 MV Tandem Van de Graaff accelerator is under construction at the Laboratori Nazionali di Legnaro near Padova.

The machine, equipped with two horizontal Laddertron charging systems, will be used for a nuclear physics research program.

High currents of heavy ion beams are planned : up to 0.25 μA of chlorine and 0.10 μA of iodine at 16 MV.

An injector with high mass resolution (better than 1 over 100) will also be installed.

This facility is expected to be in full operation early 1980.

1. Introduction. — The idea of an electrostatic Tandem Van de Graaff accelerator at the Laboratori Nazionali di Legnaro (LNL), near Padova (Italy) was born few years after the installation, in the early 60's, of the single ended CN 5.5 MeV Van de Graaff accelerator.

This idea concretized in 1966 with the proposal [1] for a 10 MV-MP Tandem. After several problems and strong fluctuations of the hope of the real feasibility of the project in 1974 a new proposal [2] for a 14 to 20 MV Tandem was submitted and in the late autumn 1975 the INFN (Istituto Nazionale di Fisica Nucleare) placed the order of the 16 MV XTU Tandem at High Voltage Engineering Co. (HVEC - Burlington, Mass. USA) and decided to install it at his national laboratory placed in Legnaro.

The chief responsible of the project is Prof. R.A. Ricci (also director of LNL) who is leading a team of INFN researchers and technicians, and of researchers of several Universities (Padova, Milano, etc.), associated to the scientific programs of the INFN.

Once in full operation the new Tandem laboratory will be a facility open to all Italian physicists working in the field of pure and applied nuclear physics as well as in nuclear physics interdisciplinary fields.

The laboratory is expected to start in full operation around end 1979 beginning 1980.

This talk wants to be a presentation of the project with some comments on its most critical points. The present status of the project with the first results on

the tests on some parts of the equipment will also be given.

2. The accelerator facility. — 2.1. GENERAL CONSIDERATIONS. — The whole accelerator system, including injector, tank and 90° magnet analyzer, will be manufactured under responsibility of HVEC. In particular the injector will be constructed by General Ionex Co. (Ipswich, Mass. USA) and the accelerator tank by Belleli Industrie Meccaniche S.p.A. (Mantova, Italy).

A broad range of particles from $A = 1$ (Hydrogen) up to $A > 127$ (iodine) is supposed to be accelerated with currents above 100 nA (particle) up to 16 MV terminal voltage for the researches programs connected with the Tandem accelerator itself as well as with the Tandem + superconductive Cyclotron postaccelerator planned for the future (see the last part of the report).

2.2. THE XTU TANDEM MACHINE. — The most important parameters and specifications of the XTU-Tandem are given in Table I.

The structure of the machine is very similar to that one of the upgraded - MP Tandem (always from HVEC, with 13 MV guaranteed specifications).

The column will be that one of the XTU Tandem originally constructed at Burlington and tested without tubes up to 21 MV (rated voltage 20 MV).

The tank length will be the same of the MP machine (81 ft = 24.2 m) plus two feet (total length 82 ft = 25.00 m); but the tank diameter will be consi-

TABLE I

Parameters of the XTU - Tandem

Terminal voltage range without tubes	0-20 MV
Terminal voltage range with tubes	0-16 MV
Analyzed protons	5 μ A at 3 MV 10 μ A at 7.5 MV 5 μ A at 16 MV
Analyzed iodine	0.1 μ A at 16 MV (most probable charge state)
Analyzed chlorine	0.25 μ A at 16 MV (most probable charge state) 50 % transmission with 0.25 μ A injected
Terminal voltage stability	± 1.5 kV
Totale charging current with laddertron	800 μ A

derably bigger 25 ft (= 7.6 m) instead of 18 ft (= 5.5 m).

The insulating gas will be pure SF_6 at a pressure of 91 psi (6.4 atm) for a total weight of ~ 37 t to be stored in liquid phase during all the tank opening for servicing or repairing of the machine. The SF_6 gas storing system, of conventional type, delivered also by HVEC has as main components two 150 HP non lube compressors. A Kiney pump is supplied to evacuate the tank up to ~ 100 torr. The total turn around time tank opening + closing is estimated around 24 h.

The basis vacuum will be guaranteed by two large 10" oil (polyphenil aether) diffusion pumps at the low and high-energy end of the machine. The pumps have a freon refrigerator: cold cap plus a liquid nitrogen trap.

The vacuum seals inside the machine will be metallic. Following the positive experience in the last MP installations (i.e. Strasbourg) aluminium coated Helicoflex gaskets will be adopted. Outside the tank ordinary viton o-rings will be used.

The structure of the high voltage terminal housing is represented in figure 1. The terminal spinning is

FIG. 1. — Lay out of the XTU Tandem high voltage terminal.

made by a structure which completely encloses the terminal region instead of the longitudinal bars adopted in the standard MP installations. The terminal is 10 feet long (3.0 m) and 81 inches (206 cm) in diameter. Power is provided by an insulating rotating shaft and terminal generator developing 6 kW.

Two ion getter pumps (250 l/s - by Aerovac) will

be placed at the two extremities in order to improve the vacuum conditions in the accelerating tubes.

The stripping system includes a 43.3" long (1.10 m) 34" (~ 9 mm) diameter gas tube plus a 120 position foil chain mounted in such a way that the foils are positionable in the middle of the stripping channel.

The flow of the stripping gas is handled by a Titanium sublimation pump (4 Ti-ballTM sublimators by Varian inside a container below the stripping channel) and small aperture at both ends of the stripping channel.

The terminal houses also a 4-pole electrostatic triplet powered in such a way to have also some vertical steering features.

The acceleration tubes are 8 (4 each side), 14" diameter, with stainless steel inclined field electrodes and small apertures 11/8" (2.85 cm) vertical times 5" (12.70 cm) horizontal.

Each tube has 72 glass insulator 1" thick and 73 electrodes; the 1st and the 73rd electrodes are against terminations. The tube gradient is 56 kV/in (= column gradient).

The XTU Tandem will have practically the same tubes installed in the upgraded MP (were the guaranteed performances of 13 MV are well reached). The only difference is that the MP installations two pairs of electrodes for each tube section are short circuited because of the MP column structure while in the XTU this does not appear. The extrapolation of the voltage holding capability of these tubes up to 16 MV is based on the test at Burlington in spring 1973 (discussed in detail in reference [3]). Were the following beam species were analyzed: protons 0.5 μ A, 50 % transmission, at 16 MV, oxygen 0.23 μ A, 30-40 % transmission (6⁺ state analyzed, most probable charge state with solid stripper) at 14 MV and iodine 0.13 μ A, 10-20 % transmission (6⁺ state analyzed, gas stripper) at 13 MV.

The voltage divider system will be of mixed type.

The tube sections 1, 2, 3 and 6, 7, 8 will have a unique voltage divider located on the column: the

equipotential planes of the column and the tubes (1" distance) are connected.

The tube sections 4 and 5, the most critical because next to the high voltage terminal will have two separate dividers along the column and along the tubes connected only on the dead sections.

In this way column and tubes are somehow decoupled independently behaving so that small discharges along one will not effect the others. The advantages of this system, which has in itself the disadvantage of a bigger cost and complexity are extensively discussed in reference [4] and are summarized in the following:

- a) reduction in the energy available for individual conditioning processes (microdischarges),
- b) the gradient control along the tubes is not upset by local corona currents or discharges within the column,
- c) reduction in tubes over voltages by column to tank breakdown in a region close to the terminal,
- d) tube discharges (induced by the beam) are less likely to trigger column local discharges and (possible) column to tank big discharges.

In practice beam quality and tube lifetime should increase. These solutions are now operating at Yale, Rochester and BNL and will be adopted at Munich and Daresbury.

HVEC experiences ⁽¹⁾ during several test programs have shown that:

- a) anyhow a strong connection between tubes and column is very bad (damages on the glass insulators),
- b) violence of sparking during the high voltage test, (Heta program) was somehow reduced by the adoption of a second voltage divider.

The resistors will be the so called *blue resistors* impregnated in blue epoxy with 600 m Ω per set (20 elements each set, spark gap every two elements) for the single divider and 1 200 M Ω for the double one.

The charging current to the high voltage terminal will be delivered by two laddertrons running horizontally in the place originally foreseen in the XTU for the belt. A current of 400 μ A (up charge + down charge) is expected for each laddertron for a total current transported of 800 μ A. The advantages of a Laddertron charging system over a traditional belt are extensively discussed in reference [5].

The version developed at HVEC derives from the researches developed at Daresbury after the agreement of collaboration between HVEC and the Science Research Council (GB).

The basic difference is that the HVEC version has to run horizontally instead of vertically as at Daresbury.

The HVEC version derives from the first Daresbury prototype (so called Reading version) with basi-

cally the same dimensions finally adopted for the NSF: each rung has a length of 190.5 mm, a height of 33.75 mm and a distance from the next one of 6 mm.

Each rung consists of 2 end sleeves of stainless steel casted (cylindrical shape), a cross tube of aluminium (rectangular shape) and four screws to tighten the different pieces together, the insulating links are done from monocast nylon.

The cross tubes are smaller in height (< 33.75 mm) to avoid that sparking takes places across aluminium easily corroded in SF₆ atmosphere.

The final version will be supported in the 3 dead sections by idler pulleys.

A half length section of the Laddertron ($\sim$ 5.7 m on the centers) has been operated successfully in mechanical test in atmosphere for more than 2 000 h. A full length section ($\approx$ double length) has been operated for extra 500 hours. The results indicate that the mechanical concepts of this system—drive pulleys, idler pulleys and chain itself are basically sound. The chain was run at 12 m s⁻¹ for most of the time somewhat in excess of expected operating speed of 10 m s⁻¹. The installation of this system in MPO is in process. Testing is expected to start around june 1977.

The figure 2 shows a photo of the half length Laddertron assembled at HVEC.

FIG. 2. — Half length horizontal laddertron assembled at HVEC during mechanical tests in air.

The analyzing system consists of 90° analyzing magnet double focusing with a mass energy product ME/Z² = 500. The main characteristics of the magnet are a radius of 80" (203 cm) a gap of 1.63" (4.14 cm) with a maximum field of 1.6 T. This magnet is rotatable of a 90° angle around a vertical axis in the horizontal plane by means of an air cushion. By such a rotation the entrance and exit ports can be interchar-

⁽¹⁾ Private communication.

ged so that practically both $+90^\circ$ and -90° deflection angles are available. This feature is requested by the planned installation of a superconductive cyclotron as post accelerator.

3. The 150 kV injector. — The injector of the XTU Tandem will be the IONEX 141 OA system built by GIC (Ipswich, Mass. USA) as subcontractor of HVEC. This system is intended to increase the performances and the versatility of the Tandem accelerator by improved matching of the emittance of the injected beam to the admittance of the accelerator ion optical system and by good mass resolution over a large range of ion species.

The schematics of the system (including the configuration adopted for the tests later presented) is shown in figure 3. The whole system can be fully controlled remotely or locally.

FIG. 3. — Schematic of the 150 kV negative ion injector system adopted also for the tests at GIC plants.

The main feature are the following:

a) *optics*: The following elements are found in sequence the negative ion beams are *extracted* by the ion source with ~ 20 kV voltage. Two power supplies are delivered: 30 kV - 4 mA (basically for the duoplasmatron source) and 20 kV - 10 mA (for the sputtering source which needs higher current drain because of the Cs vapours).

An *electrostatic Einzel lens* with variable astigmatization is installed to make small corrections to the focal properties of the inflection magnet. The powering of the lens provides also vertical steering of the beam.

The beam is *analyzed* in a 90° double focusing deflection magnet with a radius of 14" (356 mm) and a gap of 41 mm. The mass energy product is $ME/Z^2 = 9.6$ so that 40 keV ion with $A = 240$ can be bent.

The beam is accelerated to ground potential by an *injection voltage* up to 150 kV (3 $\emptyset$ insulation transformer 150 kV and 150 kV power supply).

A *gridded lens* located after the acceleration tube produce a waist at the entrance of the Tandem. Steering in X and Y directions is provided before an after the gridded lens.

b) *Vacuum and cooling*: The vacuum $< 10^{-5}$ torr (according to the ion source used) is provided by two oil diffusion pumps with a freon refrigerated baffle. A

4" pumps is located before the acceleration tube and a larger one 6" near the ion source the handle the gas load coming from the ion source.

The two pumps operating in parallel provide pumping speeds, after the baffles of ~ 300 and 700 l/s respectively. One closed circuit with freon and one with demineralized water are supplied.

A photo of the injector is shown in figure 4.

FIG. 4. — Photo of the injector.

3.1. TEST. — The injector includes also three negative ion sources:

- a) — off axis duoplasmatron,
- b) — duoplasmatron with exchange channel,
- c) — sputter.

The whole system, including the 3 ion sources, was successfully tested during 1 week period at GIC plants by INFN and GIC people together.

The operation of the whole system turned out to be very reliable, except for some small minor troubles. In particular with 6 mm $\emptyset$ exit slits the mass resolution turned out to be $M/\Delta M > 100$ (well above the specification guaranteed $M/\Delta M > 60$).

A typical spectrum taken with a mixed Ni + Cu come on the sputtering source is shown in figure 5.

The test data on the three ion sources are shown in table II.

Figure 6 shows the data about Ca beam obtained with a spray of NH_3 according to the results of Middleton [6] and Korschinek *et al* [7].

In this case the vacuum reading was $\sim 2 \times 10^{-5}$ Torr.

FIG. 5. — Negative ions extracted by the sputtering source with a mixed Cu-Ni cone. The mass resolution is better than 1 : 100.

TABLE II
Negative ion source tests

Source	Beam	Current	
		measured	guaranteed
Duoplasmatron off-axis	H ⁻	50 μA	—
Sputtering	¹² C ⁻	45 μA	—
	²⁸ Si ⁻	7 μA	—
	⁶³ Cu ⁻	1.6 μA	2.0 μA, Cu ⁻
	⁶⁵ Cu ⁻	0.6 μA	
	⁵⁸ Ni ⁻	2.3 μA	3.0 μA, Ni ⁻
	⁶⁰ Ni ⁻	0.8 μA	
	⁵⁶ Fe ⁻	220 nA	200 nA, Fe ⁻
	⁵⁴ Fe ⁻	13 nA	
	⁴⁰ CaH ⁻	440 nA	200 nA, Ca ⁻
	⁴⁸ TiH ⁻	230 nA	200 nA, Ti ⁻
	⁵¹ V ⁻	220 nA	200 nA
Duoplasmatron + lithium channel	⁷ Li ⁻	3 μA	2 μA
	⁶ Li ⁻	0.3 μA	—
	⁴ He ⁻	7.3 μA	4 μA

FIG. 6. — Test data of Ca beam with the sputtering source.

4. Building and auxiliary equipments. — The new accelerator building will be located near the already existing CN Van de Graaff laboratory as indicated in figure 7.

FIG. 7. — Planimetry of the LNL laboratory.

The present consideration is to have beyond the accelerator vault a large target area and a large experimental area, this last one devoted also to the Tandem control and to the computing facility. The building will house also some offices and laboratory only for the basic operation and servicing of the machine and preparation of the experiments, since a comprehensive workshop organization already exists within the laboratory.

The general layout of the building is seen in figure 8.

FIG. 8. — Gound floor plan to the XTU — Tandem building.

The main characteristics are the following:

— The accelerator room has dimensions 13 m × 59.2 × 10.5 m (height), the floor is foreseen for a specific weight of 2t/m², the walls thickness is 1.5 m and the ceiling 0.9 m of reinforced concrete.

— The room is equipped with an overhead crane with a 10t hoist.

— On the side of the accelerator there are the rooms for the SF_6 recovery system and for the main power transformers located all at ground level.

The target area fulfil the following purposes:

a) Two rooms completely screened from each other so that they can work in a ping-pong basis; i.e. in one room experiments can be prepared while the other one is used for the measurements. Both rooms have an overhead crane with a ~ 10 t hoist which can service practically each point of the floor.

b) One room (dimension $16 \text{ m} \times 30.5 \text{ m} \times 7 \text{ m}$) is heavily shielded (some wall and ceiling thickness as the Tandem vault) for *hot* beams, mainly protons, deuterons, where high dosis of radiations can be expected.

c) One room (dimensions $19 \text{ m} \times 32 \text{ m} \times 11.6 \text{ m}$) has no permanent heavy shielding and will be used for heavy ion beams and for time of flight measurements.

The floors are foreseen for a specific weight of 10 t/m^2 except the part of the non shielded room next to the Tandem were a specific weight of 20 t/m^2 is foreseen for the possible installation of a magnetic spectrograph.

The control room, is $12.6 \text{ m} \times 32.4 \text{ m} \times 3.60 \text{ m}$ (height) has a floating floor and will be divided in three sections, one for the control of the machine, one for the control of the experiments and one for the on-line computer facility.

A cellar will run under the accelerator, target and control rooms.

4.1. BEAM TRANSPORT. — The beam transport from the exit of the 90° magnet to the targets is quite conventional and consists in a large switching plus quadrupoles as schematically indicated in figure 9.

The whole system will be constructed by Danfysik (Jyllinge Denmark).

FIG. 9. — Lay out of the beam transport system.

The characteristics of the system are the followings:

a) *Switching magnet*: of semicircular type pole gap 50 mm, maximum field 1.6 T.

The following deflection angles are possible: $\pm 70^\circ, \pm 60^\circ, \pm 50^\circ, \pm 40^\circ, \pm 30^\circ, \pm 20^\circ, \pm 10^\circ$ with a mass energy product of 120, 155, 335, 585, 1 310, 5 190 respectively. The power supply of 37 kW can be controlled analogically and digitally.

b) *Quadrupole doublets*: are all identical, inclusive the one placed before the switching magnet. They have an aperture of 100 mm diameter, max gradient of $1.2 \text{ kGauss cm}^{-1}$, effective length of 300 mm and a separation of 150 mm.

The optical characteristics are such that they can produce a stigmatic image at 5 m from the exit for an object at 5 m from the entrance for a maximum magnetic rigidity $B\rho = 3.3 \text{ T.m}$. With these quadrupoles one can have, as schematized in figure 9, *short channels* $\sim 12\text{-}14 \text{ m}$ long with one lens and *long channels* $20\text{-}24 \text{ m}$ long with two lenses.

Practically the whole system from $\pm 10^\circ$ up to $\pm 30^\circ$ can handle beams with $B\rho = 3.3$ which is the rigidity of the beam produced also by the superconductive cyclotron.

5. The superconductive cyclotron booster. — In connection with this XTU-Tandem project the Milano group of INFN leader by F. Resmini has studied and proposed the construction of a superconductive cyclotron to be used essentially as booster of the Tandem.

The ions from the Tandem are injected along a

TABLE III

Parameters of the superconductive cyclotron

max. energy	55 MeV/Nucl. $\rightarrow$ 10 MeV/Nucl.
min. energy	1/4 of max. energy
$K = ME/Z^2 = 500$	
$0.1\% < \Delta E/E < 0.2\%$	
Emittance (A): 4 mm.mrad. $< A < 6 \text{ mm.mrad.}$	
if $A_{\text{Tandem}} < 15 \text{ mm.mrad.}$	
Current: $10^{11} - 10^{12} \text{ particles s}^{-1}$	
if the Tandem delivers $10^{12} - 10^{13} \text{ particles s}^{-1}$	

Construction data

POLE DIA: 1.8 m	
$22 \text{ kG} < B < 41 \text{ kG}$ (3 sectors - spiral shape).	
Acceleration Dees: 3 with 100 kV peak voltage.	
Deflection: electrostatic $120 \text{ or } 140 \text{ kV cm}^{-1}$.	
Bunching of the beam injected into the cyclotron before.	
Tandem at 400-500 kV level with two cavities.	
Frequency 21 or 63 MHz	
$\Delta\phi \pm 1.5^\circ \text{ or } \pm 3^\circ$	
Efficiency 35 % or 60 %	
after Tandem electrostatic chopper operating on a frequency locked to cyclotron frequency.	

circular path around the middle of the cyclotron, stripped (in this way their magnetic rigidity is strongly reduced so that they are placed in a much smaller circular orbit) and then accelerated as usual by the radiofrequency.

The superconductive field reduces strongly the dimensions of the Cyclotron and consequently also the cost (even if a liquid helium cryostat has to be installed).

In this way the *Tandem* of the two machines would constitute one of the largest nuclear physics facility.

The project has for the moment got funds for a model (model cyclotron 1 : 6; model RF cavity 1 : 1).

The measurements on the model, in particular the mapping of the superconductive magnetic field, will help also to fix the definitive parameters of the machine.

The location of the cyclotron with respect to the Tandem is indicated in figure 10. The beam is bent by the rotatable 90° magnet in the direction apposite to that of the switching magnet, injected in the cyclotron, extracted at an angle of $\sim 180^\circ$ to the injection direction, and then brought back into the beam transport system between the 90° and the switching magnet. In this way all the experimental facilities will be used also for the combination of the two machines.

6. Time schedule. — Time schedule is always a very crucial and delicate points because very often it happens that delays appear even when everything is carefully planned.

For the moment we are considering the following schedule.

The physical construction of the building will start

FIG. 10. — Proposed position of the superconductive cyclotron with respect to the XTU — Tandem.

in June 1977 and after one year the tank will be *in situ* so that the mounting of the machine (to be shipped early in 1978 by HVEC) will start.

After one year it is expected that the acceptance tests will start so that sometimes between end 1979 and beginning of 1980 the experiments should start.

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