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A PRACTICAL DEMONSTRATION OF THE CRFQ STORAGE RING*

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Abstract

A collaboration between Brookhaven National Laboratory, the University of Naples, the University of Sannio, and the INFN-Section of Naples (Italy) was created for the purpose of developing a proof of principle of the Circular Radiofrequency Quadrupole (CRFQ). This is a new concept of particle storage and accelerator ring, basically a Linear Radio-Frequency Quadrupole completely bent on a circle. The advantages are expected to be equivalent to those of a Linear RFQ, namely higher beam intensity and smaller beam dimensions. Initially the main goal is the demonstration of the curvature effect of the quadrupolar RFQ field. At that purpose, the project is actually made of three phases: (i) develop an adequate 30 keV proton source, (ii) design, manufacture and test a linear RFQ section, and (iii) design, manufacture and test a curved RFQ section, both operating at 200 MHz. The final goal of the collaboration is eventually to build enough curved sections to complete the storage ring where to demonstrate storage of 30 - 100 keV protons over long periods of time. The demonstration is taking place at the *Laboratorio dell'Acceleratore* of the *Dipartimento di Scienze Fisiche* of the University of Naples where an adequate ion source is already available.

INTRODUCTION

The CRFQ is a new concept of Storage and Accelerator Ring for intense beams of light and heavy ions, protons and electrons. It is basically a Linear RFQ completely bent on a circle. The advantages [1], similar to those of a Linear RFQ, are: (1) Any location around the ring has a time-varying focusing field that eliminates any geometrical periodicity. Though the device is mechanically and geometrically closed on itself, it is nonetheless electrically open, equivalent to an indefinitely long transport beam line. Concern with the presence of intrinsic resonances is thus removed. (2) As a consequence, high beam intensities are expected, since the limitation, as in a Linear RFQ, is set by the depression caused by space charge of the phase advance per period, for instance from 90° down to 45°. This is expected to be superior to the limit typically encountered in conventional magnetic storage rings, where only a very small depression of the phase advance per period can be tolerated. (3) Small beam dimensions are also expected since they are related to the focusing period that is now of only few centimeters, compared to the several meters in conventional magnetic storage rings. The ratio of beam intensity to transverse dimension (brilliance) is thus expected to be very high. (4) At sufficiently low energy and large radius of curvature, the device will be able to bend the beam trajectory without the help of external bending magnets. Nevertheless a radial offset is expected that can be easily calculated. (5) Such a storage ring, that combines simultaneously bending and strong focusing, results in an overall more compact device. (6) It is also possible to provide acceleration. At this purpose the rods, that otherwise are smooth, are longitudinally modulated with the same focusing period $L = \beta\lambda$. This will create an accelerating longitudinal field for acceleration. As the beam velocity β varies one will have to readjust the RF wavelength λ so that L remains constant.

POSSIBLE APPLICATIONS

Several applications are possible with a compact low-energy CRFQ: (1) γ - Radiography with a 1.8-MeV proton beam impinging on a Carbon Foil; (2) Neutron Production with protons of few MeV on Beryllium or Lithium targets; (3) Radioisotopes Production with an intense 60-MeV proton beam; (4) X-Rays by back-Compton Scattering using 15-MeV electrons; (5) Next generation of X-ray Source (emittance ~ 1μm); (6) Medical Applications. Also high energy applications are possible. For instance, for ultra-relativistic beams with $\beta \sim 1$ a RF of 200 MHz would still yield a focusing period of about 1.5 m, considerably shorter that what can be achieved with magnetic focusing. In the high energy case the focusing circular RF structure should be located within the gap of a dipole magnet to ease the bending of the main trajectory. There is thus need to build a Prototype for the proof of principle. This is the scope of the Collaboration.

PARAMETERS AND LAYOUT

To minimize cost and the impact of the RF requirements of the first demonstration, we have agreed on a set of parameters that suits well the availability both in space and equipment of the *Laboratorio dell'Acceleratore* in Naples. The parameters are listed in Table 1 and the final configuration of the prototype is sketched in Figure 1. The cross-section of one sector of the CRFQ is essentially made of four cylindrical copper rods each with 10 mm diameter, coupled together by convenient RF cells described in another paper also given to this Conference [2]. We have opted for a parallel square rod configuration to easily allow injection of the beam.

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Table1: Parameter List of the CRFQ Prototype

Kinetic Energy	30 keV (100 keV)
RF frequency	202.56 MHz
Peak Voltage	36 kV
Dissipated RF Power (peak)	20 kW
Focusing Period	2.2 cm
Max Radial Displacement	< 1 mm
Rod Diameter	10 mm
Internal Diameter	10 mm
Curvature Radius	90 cm
No. of Sectors	8
Sector Length	70.7 cm
Drift Length	10 mm

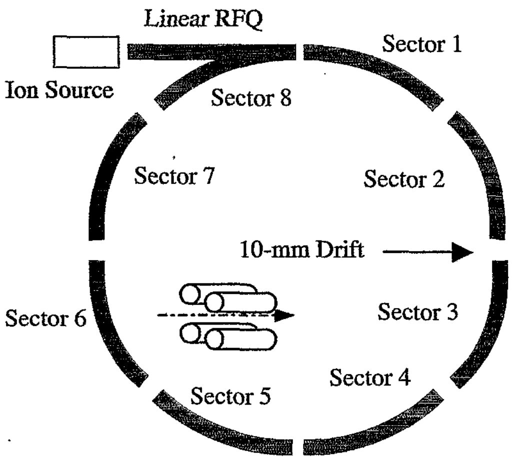

Figure 1. Layout of the CRFQ Prototype in the final stage.

A computer simulation of the motion of protons for one complete revolution has shown that the beam cross-section is preserved also in the presence of the 10-mm drifts between the sectors, and that the structure does not need to be exactly continuous either electrically or mechanically. Indeed the motion is as if the beam enters a Linear or Curved RFQ, exits it, travels for a short distance, and enters the next RFQ sector. Since the beam pulse is longer than the periodicity $L = \beta\lambda$, particles enter a sector with any RF phase. Thus the actual RF phase between one sector and the next is not relevant, and sectors can be excited independently. The short drift between the sectors cause a dilution of the beam cross-section that nevertheless remains confined to a small amount, as long the drift does not exceed the period length L. It was also determined that in order to match the beam size within the transverse aperture of the CRFQ the ion source ought to deliver a beam with an emittance not exceeding 5 π mm-mrad in both focusing planes.

GOALS OF THE PROTOTYPE PROJECT

Ultimately, the main goal of the collaboration is to demonstrate storage of a 30 to 100 keV proton beam, circulating in the CRFQ Ring for a reasonable long period of time. A storage for a one-second period is considered sufficient. A possible mode of operation is to store about one beam pulse per minute. This diluted mode of operation will remove the need for water-cooling and radiation shielding. Also, at the end of the storage, the beam can be dispersed in the surrounding by simply turning off the RF. The low duty cycle will minimize the RF and AC power requirements. The next step is to demonstrate storage of intense beams at level exceeding the space-charge limit of conventional storage rings made of magnets. This last step will require a further development of the present ion source. The execution of our collaborative initiative is planned to take place in three phases.

Short-Term Phase

This is shown in Figure 2. There are four components: (A) One Radio-Frequency Source at 30 kVolt and 1 mA of Proton continuous current. (B) One matching section also operating at 30 kVolt. We chose it to be a Linear RFQ to provide the same focusing conditions at the exit and at the entrance of the following curved RFQ sector. (C) One curved RFQ sector without acceleration also operating at 30 kVolt, main item of the explorative study. (D) Collection of the diagnostic data of the emergent beam. The ion source (A) is already available at the *Laboratorio dell'Acceleratore* in Naples. Some minor modifications have been made for full time and consistent operation. It will be necessary to determine the following characteristics of the beam in exit: the peak intensity, the time structure, emittance, that is transverse dimensions and angular divergences, and the energy spread. The source is equipped with proper electrostatic lens to match the focusing conditions at the entrance of the Linear RFQ (B), with a pair of deflectors, and proper Beam Position Monitors.

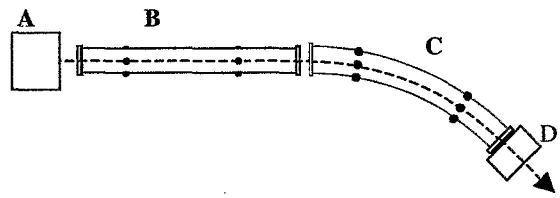

Figure 2. Components for the Short-Term Phase

The Linear matching Section is also 70.7 cm long, as the curved sector, and is otherwise identical to it, except that it is straight. The structure will be studied also to demonstrate the RF excitation in a mode [2] that is not commonly used, for which further research is desirable. The Curved Sector (C) follows the matching section (B). Its parameters are also given in Table 1. It is identical to the linear Section, with the exception to be bent at an angle of 45°. The two sections will be separated by a 10-mm long drift. The RF excitation of the curved sector is identical to the straight one. The beam in exit of the curved sector (C) is detected by a Diagnostic Box (D), under vacuum and rigidly connected to the rest of the apparatus. The box contains a beam wire profile monitor, two beam position monitors, one for each of the two transverse directions, and a beam current monitor. The beam stops at an absorbing concrete block, at the end of the transport. The main goals of the experiment are: (i) the measurement of the beam transmission, possibly also at large intensities, thus of the beam current in entrance and exit, (ii) of the transverse beam dimensions, and (iii) of the deflection of the beam trajectory.

Medium-Term Phase

This phase uses the same components already installed with the following variations:

a. The four smooth rods of the Linear Matching Section will be replaced with others having longitudinal modulation to create a longitudinal electric field for beam acceleration to 100 keV. The demonstration of acceleration, combined to the special RF excitation, is one of the two main goals of this phase. The other is the observation of the beam properties at the exit of the curved sector at the higher energy, in particular of the deflection of its trajectory.
b. A second curved sector identical to (C) will be built and placed following (C) itself. The beam trajectory is now bent by 90°. The same observations and measurements are then repeated. Furthermore, this configuration with two curved sectors in sequence allows to study the interface between the exit form the first sector and the entrance to the next. A drift, also 10-mm long, separates the two curved sectors.
c. Five more identical curved sectors will be built and installed one after the other following the initial two sectors, as shown in Figure 3. Each time a new sector is installed the beam will be transported and observed in exit with the same modalities. One will have then demonstrated the capability to transport the beam from one sector to the following until 7/8 of a complete revolution. As usual a 10-mm long drift is placed between two consecutive sectors.

Long-Term Phase

The main goal now is the demonstration of the circulation of the beam in the CRFQ over many revolutions and storage for a long period of time. For this purpose one more curved sector is built and installed. Mechanically now, the ring is closed, and it is crucial to study methods for beam injection without interfering with the mechanical structure.

Single-Turn Injection

In the low intensity mode, it may be sufficient to inject only a single turn with a beam pulse chopped to a length of only a fraction of the revolution period. The last of the eight curved sectors will act as an RF kicker. It is off during the injection of the beam pulse to be immediately turned on as soon the head of the pulse is approaching its location. The main concern is the transport of the beam in a drift between the exit of the Linear RFQ and the injection into the first curved sector.

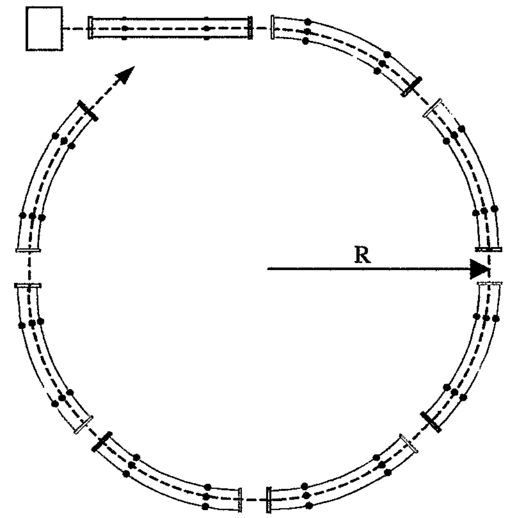

Figure 3. Layout with 7 out of 8 Curved Sections.

Multi-Turn Injection

For high intensity demonstrations it is necessary to device methods of multi-turn injection. At this purpose we should rely primarily on the charge exchange method and make use of negative hydrogen ions (H^-). A bump will be created around the main closed orbit with the help of two steering elements placed at 180° phase advance from each other. A carbon foil in the middle of the bump will strip the incoming beam and allow merging of the two beams moving in the same direction

CONCLUSION

We have given a status report of the Collaborative Initiative between Brookhaven National Laboratory and Italian Research Institutions in Naples and Benevento for the Demonstration of Principle of the Circular Radio-Frequency Quadrupole Storage Ring.

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