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COMPACT CYCLOTRON ENGINEERING FOR APPLICATION

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ABSTRACT

Some current uses of compact cyclotrons in
the fields of physics, nuclear medicine, and
neutron therapy are considered. The principle
cyclotron performance characteristics required
by each of these applications are discussed and
design innovations introduced to meet these re-
quirements presented.

INTRODUCTION

Dave Judd aptly pointed out in Gatlinburg that the cyclotron
is viewed differently by different groups. One viewpoint which
Dave did not touch on, however, was the "cyclotron as seen by the
cyclotron manufacturer." Today I will endeavor to fill that gap.

The principal problem faced by a manufacturer of compact
cyclotrons is to produce a simple economical machine which can be
used in a wide variety of applications. These applications which
range from physics and radioisotope production to neutron therapy
make widely varying demands on the cyclotron. Thus the radioisotope
producers usually want as much energy and external beam current as
possible while the physicists want variable energy negative ion
acceleration and extremely good emittance. The therapists, and
everyone else for that matter, want high reliability. To develop
a basic compact cyclotron which can be economically adapted to these
varying requirements has indeed been an interesting task.

Over the last seven years we have built thirteen compact
cyclotrons. Of these, seven are used for radioisotope production,
five for physics, and one for neutron therapy. My intention is to
review these applications with you and to share with you our
approach to some of the engineering problems they have presented.
Let us start by first looking at one of the current basic compact
cyclotron designs.

A BASIC COMPACT CYCLOTRON

The CS-30 is our most current basic compact cyclotron. To
date two of these machines have been built; one for radioisotope
production and the other for neutron therapy. The basic speci-
fications of this machine are given in Table I. A more detailed
description of the components which make up our compact cyclotrons
can be found in the literature.[1,2,3,4]

Table I Basic Specifications of CS-30 Cyclotron

Type of Cyclotron	Isochronous
Proton Energy	26.2 MeV
Deuteron Energy	15.0 MeV
Helium Three Energy	39.0 MeV
External Beam Power	2000 Watts
Pole Diameter	38 Inches
Number of Sectors	3
Weight	22 Metric Tons
Number of Dees	2
Acceleration Mode	Fundamental
Maximum Voltage Gain per Turn	10^5 Volts
Price	$390,000

The appellation CS-30 denotes a fixed energy cyclotron having an external beam with a maximum mass-energy product of 30.

The basic CS-30 has been modified by the addition of an external negative ion source, an axial injection system, and a negative ion extraction system to form a negative ion cyclotron which we call CNI-30. This negative ion machine was recently completed and is now serving as an injector to an EN Tandem Van de Graaff at the Australian National University.

The basic CS-30 has also been modified by the addition of profile coils and a remotely adjustable RF system to form a variable energy cyclotron which we designate as CV-28. The maximum mass energy product of the CV-28 is less than that of the CS-30 due to the necessity of removing pole iron in order to install the profile coils. Two CV-28 cyclotrons are currently under construction.

The concept of developing a basic cyclotron design and reusing components and concepts as often as possible has played a key role in the economical development of compact cyclotrons. Let us now look as some compact cyclotron applications and the design problems they presented.

RADIOISOTOPE PRODUCTION

Within the last few years we have installed five compact cyclotrons which are now routinely producing radioisotopes for use in medicine. Before the end of the year we will complete two additional medical cyclotron installations. The isotopes which can be produced by these cyclotrons are currently used in a wide range of clinical applications. Generally these clinical applications fall into four groups which Glass and Silvester[5] have summarized as follows.

Localization Studies. These studies include use of ^{18}F to detect metastasis in bone, ^{81}Rb to localize and detect enlargement of the spleen, ^{123}I to detect thyroid nodules in children, and ^{67}Ga for detection of soft tissue tumors.

Estimation of Body Spaces. These studies include use of ^{11}C to estimate red cell volume and ^{43}K to estimate the exchangeable potassium in multiple electrolyte studies.

Measurement of Blood Flow. These measurements include use of ^{84}Rb to determine myocardial blood flow and ^{15}O to determine cerebral blood flow and metabolism.

Study of Organ Function. These studies include use of ^{81}Rb to estimate rate of red cell destruction by the spleen, ^{123}I for the thyroid function in children and in pregnancy and for cardiopulmonary function, ^{15}O for lung function and organ blood flow and oxygen. ^{11}C for assessment of cardiac shunts and lung function, and ^{13}N for lung function studies.

The amounts of radioisotope administered depend on a number of factors including the half life of the isotope and the rate at which it is eliminated from the body. The amounts generally administered vary between a few hundred microcuries and 5 millicuries.

The reactions used to produce several commonly used radio-isotopes as well as the production rates achieved are summarized below. This data has been compiled in cooperation with several of the groups as indicated by the references.

Fluorine 18 - 110 min. Sloan-Kettering Institute[6] reports a yield rate of 6 mCi/μA-hour using 20 MeV He^3 ions on distilled water. Typical runs yield 70 mCi/30 min at 25μA in a 10 ml volume of water.

Argonne Cancer Research Hospital[7] reports a gross yield of 10 mCi/μA-hour using 8 MeV deuterons on a Ne^{20} gas target. About 85% can be washed out of the quartz-lined target chamber. ARCH has not attempted to operate at high currents or produce more than a few mCi due to personnel hazard problems. Hammersmith Hospital in London plans to switch to this technique, possibly using a continuous flow system. The yield would be limited by window heating. Presently 70μA to 80μA is a practical range.

Gallium 67 - 78 hours. ARCH reports[8] a yield of 100μCi/μA-hour using 8 MeV deuterons on Zn^{66}. No data is given on the gross yield, but an internal target should withstand 30 - 100μA to provide 1 to 3 mCi per hour. Sloan-Kettering reports a similar yield rate, and believes that 100μA is a practical internal target current.[9]

Indium 111 - 2.8 days. ORNL[10] reports a yield rate of 600μCi/μA hour. Gross yield should be 30 mCi/hour using a 50μA beam of 15 MeV protons on Cadmium 111 enriched to 95-98% abundance. The ORNL 86-inch cyclotron was used to deliver a 200μA beam of 22 MeV protons to an internal water cooled powder target. Net energy at the target was 15 MeV after passing through the water cooling tube, and target geometry was such that 50% of the measured current struck the target material.

Sloan Kettering Institute reports[9] a yield rate of 420μCi/μA hour, and believes an external target could be designed for 100μA operation to yield 42 mCi/hour.

Iodine 123 - 13.3 hours. Sloan-Kettering Institute[11] has studied various reactions, and concludes that for their CS-15 cyclotron the most efficient method is to use 15 MeV protons on 77% enriched Te^{123}. Their measured yield rate is 5 mCi/μA hour, with a gross rate of 50 mCi/hour to produce 100 to 200 mCi batches.

Brookhaven National Laboratory[12] reports a yield of 726μCi/μA hour using 30 MeV He-3 ions (CS-22 cyclotron energy) on 77% enriched Te^{123}, in a continuous flow target system. This reaction produces Xe^{123} which is purified to remove unwanted fractions of the iodine isotopes before decaying to I-123.

Carbon 11 - 20.4 min. Sloan-Kettering Institute[11] generates Carbon-11 with a variety of gas targets to produce $^{11}CO_2$ and ^{11}CO with yields ranging from 100μCi/liter to 3000μCi/liter, beam intensities up to 15μA. Flow rate is nominally one liter per minute at N.T.D.

Iron-52 - 8 hours. Sloan-Kettering Institute[11] reports a yield of 0.7μCi/μA hour using He-3 on chromium. Saturation yield is calculated to be 8.4μCi/μA hour. At 100μA on an internal target, a practical yield would be 70μCi/hour.

Rubidium 81 - 4.7 hours. Sloan-Kettering Institute[11] reports a yield rate of 35μCi/μA hour for He-3 on a Na Br target. At a current of 25μA on a covered external target, a practical yield would be 835μCi/hour.

Technetium 99m - 6.0 hours. Beaver and Hupt[13] project a yield rate of 32 mCi/μA hour of T^c 99m and 600μCi/μA hour of Mo-99 using 22 MeV protons from a CS-22 cyclotron, with internal targets. They believe that currents up to 500μA can be used, for a gross yield of 15 Ci/hour of Tc-99m.

For the CS-15, yield rate of Tc-99m would be 11 mCi/μA hour, and of Mo-99, 100μCi/μA hour.

ATTAINING HIGH BEAM POWER FOR RADIOISOTOPE PRODUCTION

The primary requirement for an isotope production cyclotron is a routinely available external beam of 50 to 100 microamperes. The New England Nuclear cyclotron for example routinely runs an external 22 MeV proton beam of more than 90 microamperes, and has run external proton currents as high as 160μA.

Our principle problem with the extraction of high beam currents is the high beam density at the extractor due to the strong vertical focussing in the fringe field where the extractor is located. To overcome this difficulty we first followed the customary procedure of making a long tapered notch in the septum in an effort to spread the beam out horizontally. As the notch became long enough to be effective we had serious degradation of the radial beam quality due to the dependence of deflection on beam height. Further, the tip of the notch always had a tendency to fail. With this type of septum we found ourselves limited to a reliable external beam of somewhat less than one kilowatt. In order to overcome this difficulty we developed what we call a "preseptum." This is

a curved sloped tungsten knife edge which shadows the septum from
the incoming beam. The preseptum has no electrostatic field behind
it so that we may use a very gradual slope without destroying the
radial beam quality. The main septum now requires no notch at all
which improves radial beam quality. The preseptum is a simple
assembly which is fastened by a single clamp and can be removed
and replaced with a manipulator. With the addition of the preseptum
we found we could reliably extract about 1700 watts of external
beam. Since the preseptum which is easy to replace fails rather
than the main septum, radiation doses received during extraction
system servicing are reduced.

To further increase the external beam which can be reliably
extracted and to reduce the power density on our internal target
we have developed another device which we call the vertical beam
expander. This is simply a pair of horizontal plates, one above
the beam and one below the beam. An RF potential having the same
frequency as the axial betatron oscillation near the extraction
radius is applied between them. Typically enough voltage is
applied to reduce the beam density by a factor of two. Use of this
device allows reliable external beam power well in excess of 2000
watts.

One of the consequences of the precessional extraction system
is that the beam density is a function of radius. Operationally
this causes a problem because a slight adjustment of the controls
may place a dense portion of the beam at the septum which results
in septum failure if the machine is operating at high power levels.
To overcome this difficulty we developed a light monitoring system
which monitors the light emitted by the cyclotron's tungsten pre-
septum. This device has proved a valuable tuning aid and may be
interlocked to prevent septum meltdown.

Using the preseptum, the vertical beam expander and the light
monitoring system we have achieved external beam powers as high
as 3600 watts with reliable routine operation of about 2500 watts.
The ability to reliably extract large external beam currents has
been a key economic factor in the three cyclotrons we have built
for commercial isotope producers.

PHYSICS APPLICATION

Five of the cyclotrons we have built are being used for
physics applications. Three of them are negative ion cyclotrons[4]
which are used as injectors to tandem electrostatic accelerators.
The remaining two are variable energy cyclotrons which are presently
under construction. The variable energy machines will be used for
neutron physics and nuclear structure work.

The negative ion cyclotrons[4] are high energy sources of
negative ions for tandem electrostatic accelerators. Due to the
relatively high gas flow required for the production of negative
ions and the high stripping cross-section of negative hydrogen ions
the cyclotron source is located outside the acceleration chamber
and the negative ions axially injected. In this way the pressure

in the cyclotron may be maintained below 10^{-5} Torr. Our experience
indicates that beam loss due to stripping becomes appreciable in
the region of 1 to 2 x 10^{-5} Torr. In addition to the vacuum consid-
erations the design of the positive extraction electrode required
for negative ion extraction is rather critical in that care must be
taken to prevent Penning discharges and other forms of electron
loading.

In May we completed installation and testing of our largest
negative ion cyclotron at the Australian National University. This
cyclotron has an H^- energy of 26.2 MeV and a D^- energy in excess of
14 MeV. Its energy resolution without phase limitation is less than
50 KeV FWHM and its emittance is less than 20 mm-mr in the horizon-
tal and vertical plane. Maximum external H^- current is of the
order of 20μ A external.

We are also building variable energy cyclotrons for physics
applications. The variable energy cyclotron we now have under
construction for Physikalisch-Technische Bundesanstalt, Braunschweig,
West Germany is designed to operate in the single turn extraction
mode with pulse selection in the cyclotron center. Due to the high
magnetic field and relatively low dee voltage, phase selection by
means of a slit system eliminates a great deal of the beam lying
within the correct phase interval. For this reason we are employing
a radio frequency phase selector which deflects the beam upward or
downward depending on whether it is leading or lagging the desired
phase. The phase is then limited by introducing horizontal colli-
mator slits. Since the aperture of these slits may be greater than
the inherent beam height the center of the phase interval is trans-
mitted unattenuated by the phase selection system. Degradation of
the axial beam quality is reduced by making the axial deflection
field include approximately $1/\nu_z$ turns.

It is noteworthy that this pulsed cyclotron will be mounted on
a carriage which moves on a tract concentric with a neutron pro-
ducing target. A long neutron time of flight spectrometer remains
stationary and the cyclotron moved in order to make differential
cross-section measurements. We hope to achieve as much as 3 x 10^{-12}
coulombs per pulse from the cyclotron to facilitate these measure-
ments.

GOOD GEOMETRICAL BEAM QUALITY

Good geometric beam quality which is desirable to reduce beam
transport system costs becomes essential when the beam is to be
directed through a tandem electrostatic accelerator. For this
reason we have worked hard to improve the geometric beam quality of
the external beam. As the cyclotron beam passes through the electro-
static deflector and subsequently through the cyclotron fringe
field it is radially defocussed as well as dispersed. Since cyclo-
tron fringe fields tend to be anything but linear, sextupole and
higher order field components operate on the beam. The wider the beam
becomes the more strongly these components are coupled. Unless one

corrects for these nonlinear effects outside the cyclotron the effective emittance of the beam is increased.

Our approach has been to minimize nonlinear effects by keeping the exiting beam narrow in the radial direction, thus reducing the coupling of nonlinear field components. This is accomplished by a series of magnetic channels[14] which locally reverse the gradient of the cyclotron fringe field and produce radial focussing. In the Australian National University cyclotron, for example, we use two magnetic channels; one located on the electrostatic deflector and one about halfway between the electrostatic deflector and the exit port. Careful design of these channels allows us to get 90% of the beam in a full area phase ellipse with an area less than 15 mm-mr.

We have also found it useful to make the linear field area of one of the magnetic channel sections substantially wider than the beam. We can remotely vary the radial position of this section which allows us to steer the beam at the cyclotron exit port.

NEUTRON THERAPY

One of our cyclotrons which is currently completing tests in Berkeley will be used primarily for neutron therapy. This machine which will be installed early next year at Tokyo University, will be used in a neutron therapy program similar to that which has been underway at Hammersmith Hospital in London for the last several years.[15]

The 15 MeV deuteron beam from this machine will produce fast neutrons via the $^9Be(d,n)^{10}B$ reaction. Even though the deuteron energy is about 1 MeV less than that used at Hammersmith we expect a depth for 50% dose of 8.5 cm for a 10 cm x 10 cm field with a source to skin distance (SSD) of 125 cm, using a thick beryllium target. Table II which was prepared by Dr. John Parnell[16] of Hammersmith summarizes dose rates and depths for 1/2 dose for various field sizes, target thicknesses, and source to skin distances.

Table II   Neutron Therapy Data for CS-30 Cyclotron

Reaction: $^9Be(d,n)B^{10}$
Deuteron Energy: 15.0 MeV

Thick Target

SSD	Dose Rate (Rad/min/100 μA)			Depth for 50% of Dose at 0.5 cm		
	5 x 5 field	10 x 10 field	20 x 20 field	5 x 5 field	10 x 10 field	20 x 20 field
125 cm	35 ± 3	37 ± 3	40 ± 3	7.4 ± 0.3	8.9 ± 0.3	10.9 ± 0.3
160 cm	22 ± 2	23 ± 2	24 ± 2	7.7 ± 0.3	9.2 ± 0.3	10.5 ± 0.3

Thin Target (70 mg/cm^2) Ta backing

SSD	Dose Rate (Rad/min/100μA)			Depth for 50% of Dose at 0.5 cm		
	5 x 5 field	10 x 10 field	20 x 20 field	5 x 5 field	10 x 10 field	20 x 20 field
125 cm	18 ± 3	19 ± 3	20 ± 3	8.3 ± 0.5	9.8 ± 0.5	11.1 ± 0.5
160 cm	11 ± 3	12 ± 3	12 ± 3	8.6 ± 0.5	10.1 ± 0.5	11.4 ± 0.5

The work of Goodman and Brennan,[17] and Bewley and Parnell[18] have been particularly helpful in estimating the value of compact cyclotrons to current neutron therapy programs.

It must be observed that while dose rates of 20 rads per minute are generally believed to be adequate for neutron therapy purposes depth for one half dose distances of less than 10 cm are not. D-T fusion generators which produce 14 MeV neutrons can provide depths for one half dose greater than 10 cm; they have not yet however produced steady state neutron source strengths of 8 x 10^{12}, n/sec 4¶ which is required to provide 20 rad per minute in 10 cm x 10 cm field 125 cm from the source.[17] Until such a generator is built neutron therapy programs must rely on cyclotrons to produce fast neutrons. Compact cyclotrons will have a role in neutron therapy programs where the tumor to be treated is not deeply seated.

In order to increase the usefulness of the cyclotron as a therapy tool we are developing an "isocentric" neutron therapy system. This device which is similar to isocentric devices used with electron linacs allows moving the collimated neutron beam concentric with a tumor without moving the patient. Development of this type of equipment as well as target systems and dosimetry systems is typical of the challenges facing the cyclotron manufacturer today.

CONCLUSION

We have seen that compact cyclotrons have proven useful for physics and radioisotope production and may have an application in neutron therapy programs. The design and performance of these compact machines has made significant advances in order to satisfy these applications. What the future may hold is hard to say. On the one hand the isotope producers and therapists are demanding machines with increased energy and beam power while the physicists are pressing for better energy resolution and emittance. If the short lived gasses ^{11}C, ^{13}N, ^{15}O come into general use there may be a demand for an ultra compact self shielded cyclotron for general use in hospitals.

Whatever the outcome of these trends it is the job of the cyclotron manufacturer to be ready with equipment which can economically meet these requirements.

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DISCUSSION

WEGNER: Could you comment just a little bit more on the outstanding problems of making a hospital cyclotron with an on/off switch?

HENDRY: I think I can answer that in almost one word--they are formidable! The first thing that we would do is limit the cyclotron to a single particle, single energy machine. At this time it looks like it would be deuterons, somewhere around 6 to 8 MeV. My feeling is that as far as the cyclotron is concerned that simplifies things a great deal. It would have an external beam. We all know deuterons are quite easy to extract. The major area that concerns me in the simple box with an on/off switch approach is actually what do the isotope-producing targets look like and how best do we interface the cyclotron with some rather complicated chemical systems.

WILLAX: Have you made a test of your pulsing device, and if so could you explain a little more about it?

HENDRY: I thoroughly expected that question. No, we have not yet made a test of the pulsing device. It is scheduled to be tested in January of next year. The components are currently being built. We have made some fairly detailed computer studies as well as analytical studies of how the beam behaves in the electric field set up by the pulse shortening RF field. The results of these studies indicate that it is practical to get a pulse with a width of about 0.5 nsec at the base line. This is substantially better than we need. This would occur for a potential of about 40 kV across a 1 cm plate spacing. It is also interesting to note that the deflection is related to the cube of the length of the plates.

FINLAN: Can you tell me if you considered building a four-sector, separated sector, cyclotron for large external beam currents?

HENDRY: I don't feel that the question of three or four sectors is an extremely important factor in the amount of external beam current we can get. We initially chose a three-sector design.

FINLAN: Sorry, I should have said 'separated' sector only.

HENDRY: No, we haven't really considered getting into that at this
point.   We are closely watching what is happening in Bloomington and
SIN.   Some of the problems are quite beyond the scope of the manufac-
turer.   We must wait for the academic community to solve most of the
major problems before we get involved, because I just don't think we
have the resources to build that class of machine from scratch.

MORRISON: Fluorine-18 delivered in Vancouver costs us about $60 a
patient for bone scanning, and I suspect that perhaps your choice of
fluorine might have been better in that technetium may now be used
as a phosphate, phosphonate or a polyphospate for bone scanning with
physical characteristics which are considerably better detection-wise
than is fluorine.   I wonder what your comments are regarding the use
of fluorine vs technetium polyphosphate for bone scanning, because
using technetium, bone scanning is now available to virtually every
hospital in the world that can afford a molybdenum-technetium
generator.

HENDRY: I think I have to answer the question on two levels. Wearing
the hat of a cyclotron manufacturer, of course, we would like to see
as many applications as possible for compact cyclotrons.   On the
other hand, as far as the art of nuclear medicine goes, I think we
all as human beings are interested in seeing it progress in the best
way that it can.