Electron Model of a

THREE-DIMENSIONAL RELATIVISTIC CYCLOTRON

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Institution:	Brookhaven National Laboratory
Street Address/City/State/Zip:	PO Box 5000 Upton, NY 11973-5000
Principal Investigator (PI):	Stephen Brooks
Position Title of PI:	Accelerator Physicist
Business Mailing Address of PI:	Room 201, Building 911B, Brookhaven National Laboratory, Upton, NY 11973
Telephone Number of PI:	(631) 344-8844
Email of PI:	sbrooks@bnl.gov
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BROOKHAVEN NATIONAL LABORATORY

1.0 PROJECT NARRATIVE

1.1 Research Plan Introduction

This research intends to overcome a limitation in the energy range of isochronous cyclotrons by extending them into the third dimension, forming a bowl-shaped accelerator (**Figure 1**), capable of significantly more relativistic (γ>2) energies [1]. When applied to protons, such a device would provide the high average currents of cyclotrons but at ≥1GeV energies, in a footprint much smaller than a 1GeV linac. This 3D cyclotron would be suitable for the drive beam of an accelerator-driven subcritical reactor (ADSR) to transmute nuclear waste into shorter-lived nuclides [2], as well as extending existing applications of cyclotrons. Since the proton version of this design would be a large device (radius * maximum field ≥ 15T.m), this proposal is to build a scaled-down demonstrator using electrons (radius * maximum field ~ 0.03T.m), which would be the first accelerator of its kind.

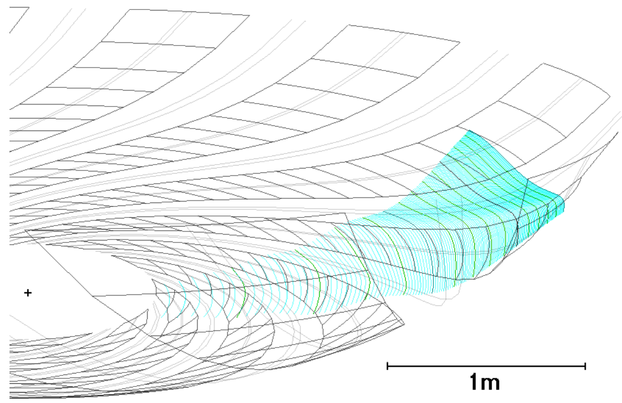

Figure 1. Closed orbits (blue) for protons in the range 40MeV to 1.5GeV through one sector of the 3D cyclotron detailed in [1], in perspective view.

Relevance to the Mission of HEP

This proposal is suggested for category V(e), "Accelerator Science and Technology R&D in High Energy Physics" since it is R&D for a novel accelerator concept. It produces beams of intermediate energy but high average current, so should be considered an intensity frontier technology (rather than strictly "high energy"). It will use BNL's leadership in advanced accelerator research and development to achieve its mission focus in the physical and energy sciences in multiple ways:

- In **nuclear energy** the 3D cyclotron is the only accelerator smaller than a linac that can perform half-life reduction of nuclear waste, which requires beams of ≥ 1GeV energy ([2], p.462), which is more than the highest energy of any existing cyclotron (590MeV at PSI [3]).
- In **high energy physics** the 3D cyclotron would enhance rare process experiments such as DAEδALUS [4], an intense neutrino source currently proposed to be driven by a proton cyclotron. Here, as in many of these applications, high integrated flux is the main goal but energy above a certain threshold is required to produce the desired particle species efficiently. The promise of the 3D cyclotron is to combine continuous-wave acceleration, which gives high integrated flux using manageable peak beam currents, with energies higher than in a conventional cyclotron.
- In **nuclear physics** it would enhance many cyclotron-driven experiments such as exotic nuclei production for theoretical studies or nuclear astrophysics [5].
- Finally, in **accelerator physics** it is an unexplored advancement in the field of circular accelerators that promises to combine constant ('isochronous') revolution frequencies with fixed magnetic fields and fixed machine tunes (the number of oscillations particles undergo in X and Y about the beam centroid per turn). Isochronism enables the use of fixed-frequency RF systems that can obtain higher efficiencies than variable frequency systems as used in synchrotrons. Making the machine tunes fixed allows the beam dynamics to avoid crossing resonance regimes triggered by the beam self-repulsion ('space charge') in high intensity operation. The combination of these three properties has been a goal of accelerator physicists for some time, for instance Teichmann [6] referred to it as "complete isochronism" in 1962.

1.1.1 Relevant Literature

Fixed-field accelerators other than cyclotrons, known as 'FFAGs', were developed as early as the 1950s, in particular by the MURA collaboration [7]. After initial exploration and building of some prototypes, research stayed dormant until the advent of computer tracking codes good enough to verify the design of FFAG magnets. At this point FFAGs spawned applications too numerous to summarise here, but a fairly recent survey of the field is [8]. The ongoing annual "FFAG" workshops provide the most up-to-date information and the proceedings of FFAG'09 were published [9].

The 3D cyclotron incorporates elements from vertical orbit-excursion FFAGs (VFFAGs) in the high-energy range. VFFAGs were conceived independently by Stephen Brooks in 2009, with subsequent publications [10,11,12]. However, further literature searches found the earliest record of the VFFAG idea was due to Ohkawa in 1955 [13], who suggested a VFFAG for electrons with fixed-frequency RF, calling it an "FFAG cyclotron". Leleux *et al.* in 1959 again found the vertical field configuration and analysed its linear dynamics and stability in their report [14]. They call it a "helicoidal FFAG" after the helical progression of the orbit upwards in the ring as it is accelerated. Teichmann continued developing Ohkawa's idea in order to achieve "complete isochronism" [6] and presents an interesting figure showing that an inward deviation from exact vertical orbit excursion can make the orbits of even sub-relativistic particles exactly isochronous, which is the beginnings of the 3D cyclotron principle.

The 3D cyclotron itself was first introduced explicitly in [1] with computer tracking studies, although the possibility was also discussed at the end of [12].

References to applications of these accelerators are all cited in the previous section "Relevance to the Mission of HEP".

1.2 Objectives/Aims

The objective is to build a 3D cyclotron [1] using electrons and accelerate the beam to relativistic velocities well beyond that achieved by cyclotrons to date, which would correspond to an electron energy of 600keV or more. This would serve as a scaled-down model of a ≥1GeV 3D cyclotron for protons, with applications in high energy physics, nuclear physics and nuclear waste transmutation. The implementation as an "accelerator in a box" would have spinoff benefits for testing other novel machine configurations.

A model is required to reduce the financial risk in basing a full-sized >$100M facility on an untested accelerator principle. It will also serve to mature the tools and methods needed to design the complex 3D magnet shapes and to verify nothing has been missed in simulations.

The cost advantages of cyclotrons over linacs observed in existing machines are shown in **Figure 2**. Here, cyclotrons cost $80–90M per GeV and linacs are in the $230–400M per GeV range. Not many high-energy CW linacs have been built, possibly because cyclotrons already fill that niche at a lower cost, so all relevant comparisons are pulsed. This comparison does not include the larger site required for a linac.

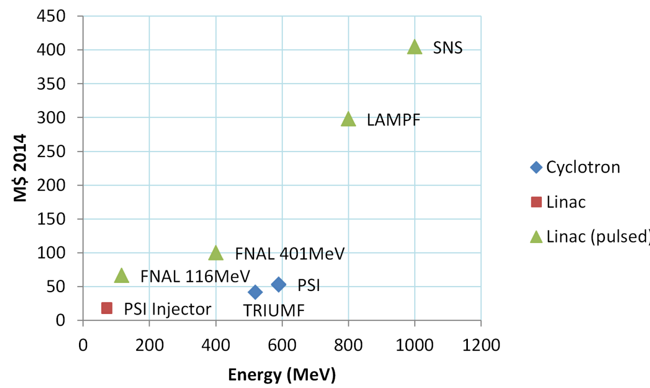

Figure 2. Comparison of the hardware-only costs of some existing linacs and cyclotrons [15], converted to year 2014 dollars.

Scientific and/or Technical Merit of the Project

The theoretical basis of the design comes from the observation that in an isochronous cyclotron, the orbit circumference must be proportional to the beam velocity to maintain a fixed revolution period, yet in the relativistic regime this is limited by the speed of light. Thus the highly relativistic orbits "pile up" near a limiting radius $c/(2\pi f)$, while the magnetic fields required at these positions continue to increase with the rigidity (proportional to momentum) of the beam. This leads to a large magnetic gradient that eventually prevents the focussing optics of each sector of the machine from being stable. The advantage of letting the orbits move vertically is that the different energies no longer have to be spatially so close together, limiting the normalised strength of the gradient. The ultra-relativistic limit of this is the VFFAG (Vertical orbit excursion Fixed-Field Alternating Gradient) machine described in [12] and previous references therein. In a VFFAG, the closed orbits have a fixed circumference and move vertically with energy into regions of larger magnetic field. The fixed circumference of the orbits means that VFFAGs tend towards isochronism as $v \rightarrow c$. The increase of vertical field component B_y with y means that the magnetic gradients in these machines resemble skew quadrupoles but this still permits alternating gradient optics rotated by 45 degrees; stable optics using magnet edge angle focussing in a VFFAG is also tracked in [12]. If the magnetic field depends exponentially on height, the machine obeys a symmetry law ($y \rightarrow y + y$, $\mathbf{B} \rightarrow \mathbf{B}e^{k\,y}$) and the closed orbit tunes are constant up to arbitrary energies.

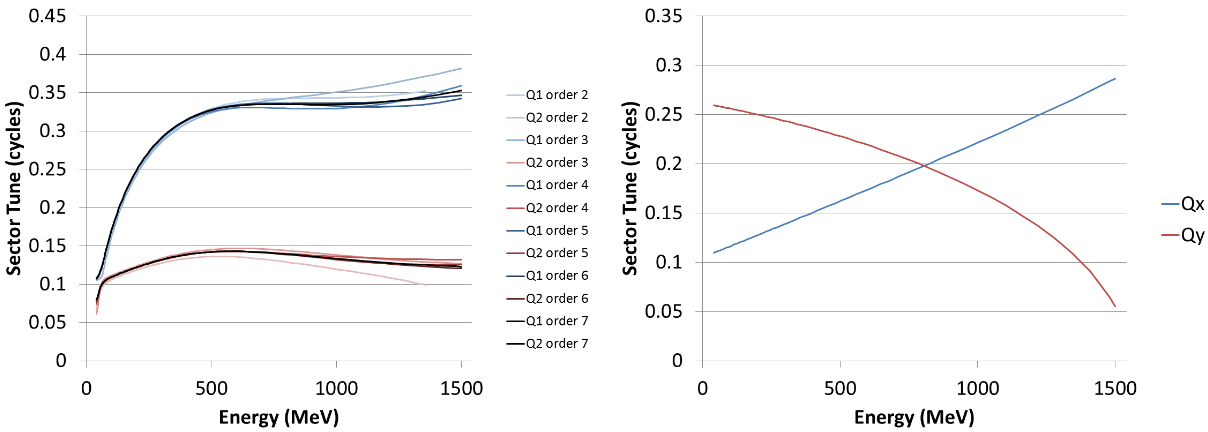

Figure 3. (left) Eigentunes in one sector of the 3D cyclotron as a function of energy, showing convergence with increasing order of the magnetic field series used. (right) Tunes in one sector of a comparable planar cyclotron, specified in [1], which tend towards instability (Q_y=0) at high energy.

The 3D cyclotron, then, is an attempt to merge a conventional isochronous planar cyclotron at weakly relativistic (γ<2) energies with a VFFAG in the limit $\gamma \rightarrow \infty$. The orbit excursion direction gradually changes from horizontal to vertical and the orientation of the quadrupole focussing changes by half this angle, from normal orientation to 45 degrees (skew). **Figure 3** shows the advantage of approaching a VFFAG configuration at high energies: the tunes of the 3D cyclotron do not vary dramatically at high energies while the planar cyclotron has a clear limitation. Here, it should be noted that the design in [1] is proof-of-concept tracking that still has two unused tuning variables as functions of energy: the spiral angle was kept constant as a function of energy, whereas in real spiral cyclotrons such as TRIUMF it changes; also the field strength variation with radius was set to the ideal analytic formula rather than incorporating corrections to reduce the variation in orbit revolution times. Even without these two free parameters, the design achieved comparatively flat tunes in the trans-relativistic region of interest (from 0.5-1.5GeV) and only ±0.6% time of flight variation.

It is anticipated that the beam current limit for the 3D cyclotron will be similar to that of conventional cyclotrons as space charge is strongest at lower energies and the transverse focussing strength remains similar. It will be possible to have separated turns at the extraction energy (in the full-sized proton machine) although this will require more RF for very relativistic energies (2GeV+) since the orbit height in a VFFAG only increases with log momentum.

Different approaches have been investigated by others for the sorts of applications the 3D cyclotron would address. Some applications such as ADSR only require a slightly higher energy (~1GeV) than the highest energy existing cyclotron (the 590MeV PSI machine [3]) so there have been studies to extend a conventional cyclotron to higher energies, for instance 800MeV [4]. In fact the author's paper [1] found a 1.5GeV planar cyclotron but both of these examples have machine tunes that will cross ring integer tune resonances (**Figure 3** (right) and **Figure 6(b)** of [4]) and as explained above, this is a generic behaviour of planar cyclotrons at high energy. Ring tune resonances are excited by space charge, so a machine that avoids crossing them such as the 3D cyclotron should have better behaviour at high beam currents.

Another approach to the 1GeV energy range is to use a ring based on a non-scaling FFAG [16], where there are two different types of magnet that control the tunes and time of flight. The example cited achieves time of flight behaviour almost as good as the 3D cyclotron in [1] and tune variations more controlled than a conventional cyclotron. However, a characteristic of non-scaling FFAGs is their limited momentum range, with the largest proposed being the 5x range in eRHIC [17]. This means the non-scaling 1GeV accelerator needs at least a 250MeV accelerator as injector, whereas the 3D cyclotron is just a normal cyclotron at low energy, with the example in [1] injecting at 40MeV.

It should be noted that the 3D cyclotron's energy is not limited to 1 or 1.5GeV as there is no theoretical upper limit on the energy in the vertical orbit excursion regime; the practical limit will be the magnetic fields and the machine size required. Higher energies are useful for sources of other particles, for example the European Spallation Source will use a 350m long linac to produce protons at 2GeV for spallation neutron production but scaling the machine in [1] to this energy and halving the field (to the more reasonable value of <3.4T) would result in a diameter of 16m.

Using a 3D cyclotron to accelerate electrons from the non-relativistic into the relativistic regime (γ=2, 3 or more) would be a strong demonstration of the feasibility of this machine type and would pave the way for larger versions accelerating protons to make sources of nuclides, neutrinos or neutrons. Since these production sources depend on high beam current, measuring the variation of machine tune with energy (as detailed in section 1.3.5) to be flat would be compelling evidence that resonances can be avoided and the beam behaves well at high currents.

1.3 Description and Justification of the Project

As described in section 1.4, the first 18 months of the project are actually devoted to finding and testing the correct engineering methods for building the 3D cyclotron electron model. The description in this proposal, therefore, is a "educated guess" containing methods the author believes to be feasible as well as fall-back scenarios.

The expected parameters of the model accelerator are shown in **Table 1**. These are derived from the proton machine tracked in [1], which was scaled to a 1 metre diameter machine for electrons. The change from protons to electrons decreases the magnetic rigidity (bend radius*field) required by the mass ratio m_p/m_e=1836.153. This can be split between decreasing the field and decreasing the radius; here, the field has been reduced the most (about 300x) and the radius decreased by about 6x to give table-top dimensions. The magnetic field needed to be reduced a lot because the full-size proton machine example used superconducting magnets.

It is expected with the further computer optics optimisation scheduled in year 1 of the project, the maximum energy of the machine can be made even more relativistic. ~3MeV is considered an energy that may have industrial uses, so an extrapolation of the height of the machine to this energy, which is 4x the original, is estimated. This determines the size of chamber required for the machine under similar designs, as well as the expected maximum magnetic field required, which is scaled up by particle momentum.

Table 1. Outline parameters of the 3D cyclotron and its electron model.

Parameters	Proton machine from IPAC'14 [1]	Directly scaled to R=0.5m electron model	Electron model extrapolated to 4x energy (~3MeV)
Energy range	40 – 1500 MeV	21.7 – 817 keV	21.7 keV – 3.27 MeV
Maximum |B| field	6.747 T	0.0230 T	~ 0.0703 T
Asymptotic radius R = r(v=c)	3.1297 m	0.5000 m	0.5000 m
Height (total vertical orbit excursion)	0.9040 m	0.1444 m	~ 0.272 m, dependent on final optics
Relativistic β range	0.2830 – 0.9230	0.2830 – 0.9230	0.2830 – 0.9908
Orbit radius range	0.8858 – 2.8887 m	0.1415 – 0.4615 m	0.1415 – 0.4954 m
Revolution frequency	15.245 MHz	95.427 MHz	95.427 MHz

Being a first-of-its-kind test accelerator, the equipment will be optimised for ease of beam diagnosis, rather than criteria such as high beam current or low cost normally used for full-size accelerators. It is crucial that problems with the alignment of the beam can be made visible in all stages of acceleration all the way back to injection. This leads to the "unconventional" choices of a vacuum chamber with at least one very large window (or even a bell jar) and putting the magnet structures inside the vacuum so that the gaps between magnet sectors can be used for inserting a selection of movable screens and beam blockers. The electron gun should also be movable to facilitate injection, with a screen nearby to probe the beam position before injection. Additionally, it may be possible to inject gas that fluoresces (e.g. neon) under impact from the electron beam to show its position in three dimensions directly. This is the same principle used in the Crookes tube often used as an educational demonstration of cathode rays. Even if the gas eventually produces unwanted levels of scattering, it should be sufficient to diagnose local problems over the few centimetres of beam transport from the gun through injection.

Technical Risk Mitigation

By design, the project can be built up starting from something of the complexity of an educational demonstration (just an electron beam and screen), inserting successively more complex magnet and accelerating structures to see at what point difficulties arise. Being able to take small steps reduces the risk of complete failure or a non-diagnosable fault.

The computer simulation required for beam dynamics and magnet design before the first complete magnet support structure is built is significant. This can take place in Year 1 of the project but development will also continue in the period between writing this proposal (Nov 2014) and the start of the first budget year (Aug 2015). If even more extra time is required for simulation work, the vacuum chamber and electron gun are only loosely coupled to the optical design and can be purchased before it finishes. The two years (4 and 5) allowed for machine exploitation could also be compressed in case of severe schedule slippage.

The magnetic field required obeys Maxwell's equations and is not of impractically large magnitude; an outline scheme of how to achieve any desired field components on a 2-dimensional surface by placing different coil winding sheets above and below is also known in concept and mentioned briefly in [1]. However, the unexpected situation where the desired winding scheme is unbuildable for some reason must be considered, as well as unexpected beam dynamics problems from simulation using coil-generated fields rather than analytic field forms. In this case the equipment can be used to test other machine configurations of relevance, for instance planar cyclotron designs that extend the velocity range above the current state of the art, or a non-isochronous VFFAG design with pure vertical orbit excursion (which would also be a first of its kind machine). Other situations such as introducing only a small amount of vertical orbit excursion into an otherwise-conventional cyclotron could be studied for the beam dynamics insights.

The acceleration system is intended to use an RF voltage gap, but if forced to build a non-isochronous machine, inductive acceleration can be used (Radiabeam Technologies has built such a system for a ~1m diameter machine with 3kV per turn).

A benefit of this flexible approach is that even in the case where the 3D cyclotron is successful, the electron gun and vacuum equipment could be re-used to test different novel electron machine configurations in the future.

<u>**Details of the Methods to be Utilized**</u>

1.3.1 Magnet and Support Structure

Scaling the 3D cyclotron to use electrons allows the use of relatively small magnetic fields, no more than ~0.07 T. Magnetic field in the vertical direction is required to produce the roughly circular beam orbit in the horizontal plane at each energy, but this vertical magnetic field exists in an aperture that ranges from horizontal (as in a planar cyclotron) at low energies to vertical at high energies (as in VFFAGs). The former configuration can be favourably achieved using iron, with the magnetic field lines emerging perpendicularly to the surfaces of iron slabs placed above and below the machine. However, in the VFFAG domain, the field must be parallel to the vertical direction of beam excursion with energy. This is fairly difficult to achieve with iron and is more optimised ([12], section II) for the bare conductor windings found in superconducting magnets. As the highest fields in the model machine will be in the high-energy VFFAG region, it is proposed that the magnets are entirely made using bare copper coils. These are a close analogy to the superconducting windings in the full-size machine and it also becomes easier to handle magnetic field calculations and optimisation, which can be done entirely with various numerical integrations of the Biot-Savart law. A fall-back position would be to use permanent magnets, although these may not have reliable enough field quality compared to known numbers of wire turns.

An infinite slab of copper conductor of thickness X and current density J parallel to the slab plane will produce a change in B field of $_{0}JX$ from one side to the other. For a rough estimate the VFFAG magnet can be approximated as two of these slabs with opposing currents and non-zero B field between the two.

Assuming the maximum allowable winding thickness is 1cm, as the further the windings get from the beam plane, the larger fringes they will produce in the on-plane field, this gives a current density of 5.59A/mm^2. This is possible but definitely needs active cooling, especially if the magnet is in a vacuum. For example, each 10x10x1cm volume of conductor slab would produce 52.5W of heat.

A related issue is that the coils must be wound around some sort of frame or support structure to determine their position accurately. The current plan is that this structure can also serve as the container for the cooling fluid: deionised water or mineral oil that gets in and out of the vacuum chamber via feedthroughs and hoses to the magnets. The structure for each side of the magnet would be made of two pieces that bolt together tightly (possibly including O-rings), with the internal faces having ridges or pillars in certain positions designed to hold various numbers of windings each. The flow of cooling fluid would ensure good heat transfer both conductively and advectively. An alternative method that is commonly used in accelerator magnets is a thick copper conductor that is hollow and contains its own cooling water. This was not preferred here because of the comparatively small size of the magnets and the fact that many quite thin windings may be required to get the right field profile by finely varying the number of turns in each location.

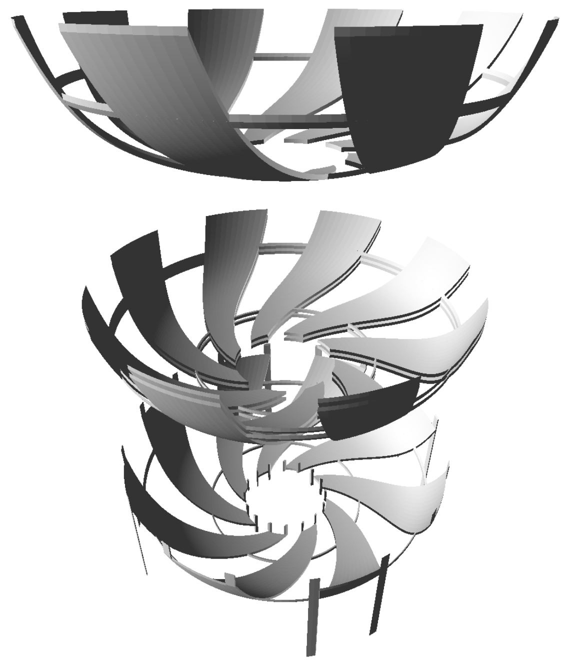

Figure 4. Exploded view of the three layers of the magnet support structure.

The support structure would have quite a complex shape since the 3D cyclotron both bends upwards like a bowl as well as having sectors that (in the current design) spiral as radius increases. This is an opportunity to use emerging technologies such as 3D printing with laser sintering of metal powder to produce a rigid shape. Alternative methods to consider would be conventional computer-controlled subtractive machining (CNC) of a metal block, or using non-metallic materials. The larger printers or CNC machines could produce an entire sector of the ring in one print, including fittings that are supposed to attach to adjacent sectors. This is a nice way of avoiding having to manually align the magnet sectors independently: they would be rigidly joined together, leveraging the positional accuracy of the original CNC machine or 3D printer. A possible assembly would have a total of three stacked pieces: the central one having the beam-facing sides of both the upper and lower magnet sectors, with spacing columns at the inner and outer radii of the machine; the upper piece bolting on from above and the lower piece bolting on from below and also including fixtures to the vacuum chamber base plate. This geometry is conceptually shown in **Figure 4**.

1.3.2 Vacuum

The small size of the 3D cyclotron electron model means it is possible to consider putting the entire machine inside one large vacuum chamber (**Figure 5**). The alternative of fitting the chamber to excursion of the beam trajectory would require a wide, custom-shaped curved chamber with a narrow gap between top and bottom. As well as being costly to manufacture, this would restrict the space available for diagnostic devices and increase the distance between the beam and the magnet, thus making the magnet require more windings and power. It would also have to be re-manufactured if a late change to the machine design required a different vertical orbit excursion slope. Perhaps the most important reason not to use such a chamber in this model machine is that it would be a strange shape to fit windows onto and would obscure the view of the beam, making diagnosis of problems, such as localising beam loss, more difficult.

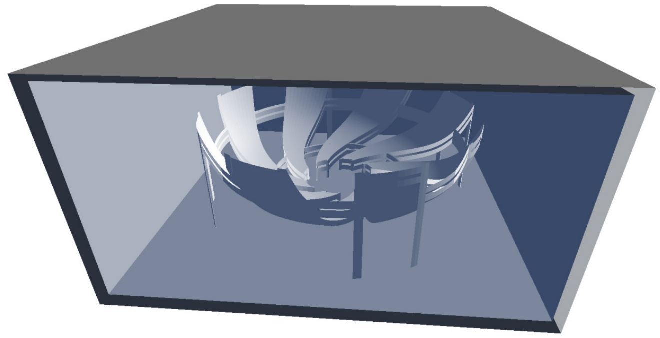

Figure 5. The 3D cyclotron model fits inside a 4x4x2ft vacuum chamber with one clear side.

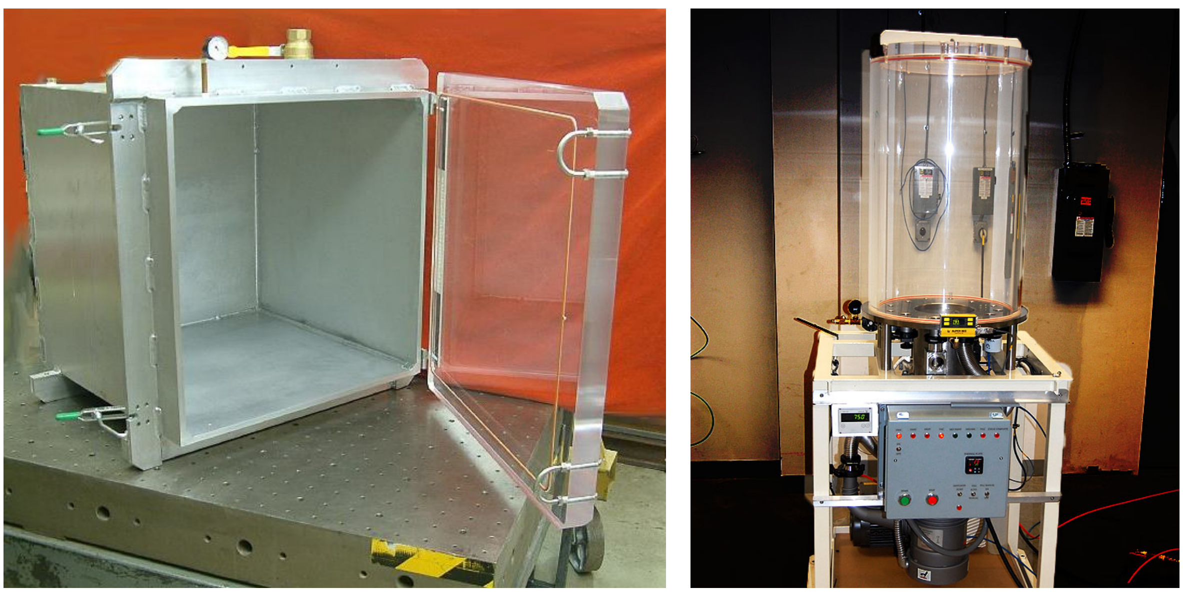

Figure 6. Examples of vacuum chambers with partially (left) or fully (right) transparent walls, from Abbess Instruments. The chamber on the left is 2x2x2ft inner dimension but I have received a custom quote for a 4x4x2ft inner dimension high-vacuum chamber plus feedthroughs, turbomolecular pumps and bakeout heaters for $147k.

Instead, this proposal envisages using a large volume chamber with at least one clear side, similar to the examples shown in **Figure 6**. The model machine will be approximately 1 metre in diameter and 50cm in height, which sets the size of the vacuum chamber. This is slightly larger than off-the-shelf models but at least one company has confirmed they can build such a chamber with a clear side. A fully-clear “bell jar” analogue would probably have to be a hemisphere of acrylic or similar material in order to distribute the atmospheric pressure load well (similar domes are used at higher pressures for the windows of submersibles). Alternatively, due to the large size it may be more practical to use a part-metal, part-clear chamber for additional strength, this choice being one of the things to be investigated during the first two years of the project.

The quality of the vacuum should allow the beam to travel for the full acceleration cycle without being excessively lost or scattered. Approximately, if the accelerating voltage is 3kV per turn, there will be at most ~1000 turns with a total length of ~3km. If the mean free path of electrons at atmospheric pressure is 0.5 m, achieving a value of 5km would require pressures of 10^{-10} atm = 10^{-7} mbar = 10^{-5} Pa, in the high vacuum regime and comparable to that used in electron tubes. A turbomolecular pump will be necessary in addition to a roughing pump to achieve vacuum in this range.

1.3.3 Electron Gun and Injection

To effectively demonstrate the energy range capabilities of the 3D cyclotron, the particles must be injected as a non-relativistic beam and be accelerated into the relativistic regime. Scaling the design in [1] with 40MeV proton injection gives 21.7keV electron injection. Although the choice of 40MeV was somewhat arbitrary, it corresponds to β=0.283, which is the sort of low value for velocity that is needed. Injection energy is constrained below by the hole in the centre of the model (of radius 0.5m×β) becoming too small to inject through and the kick from the RF acceleration becoming too large a fraction of the beam energy to give roughly adiabatic motion in the first few turns. It is constrained above by the difficulty of obtaining a very high voltage electron gun and also the fact that beyond β=0.5, which corresponds to 79.1keV, it could be questioned whether it was truly testing the non-relativistic regime.

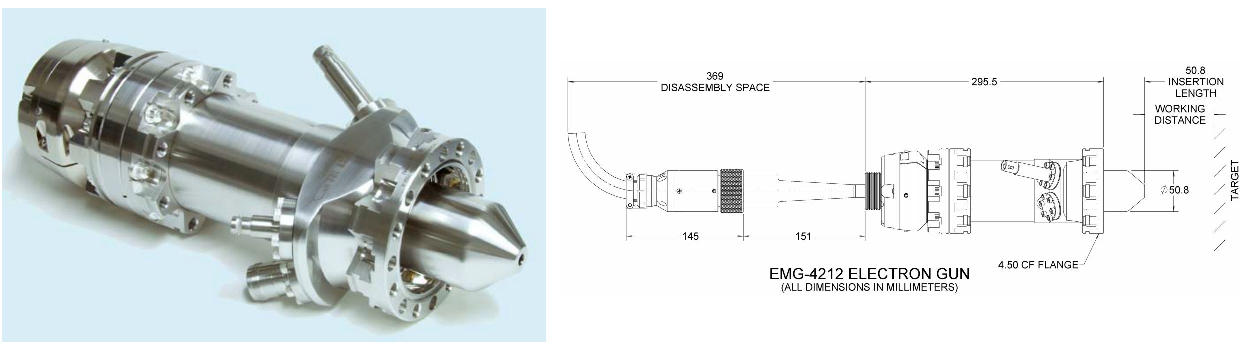

Figure 7. Example of an electron gun from Kimball Physics Inc., capable of adjustable beam energy from 1keV to 30keV, beam spot down to 0.5mm diameter and current up to 100 A. This was quoted for $46k including power supplies and cables.

Fortunately, electron guns are readily available in this energy range, since a typical CRT television has an electron gun with a voltage of about 25kV. These demonstrably produce a pencil beam with enough beam current to illuminate a phosphor screen, which will be one of the diagnostics used in this project. An off-the-shelf adjustable energy gun for experimental use is shown in **Figure 7**.

Injection is typically difficult because, as can be seen by considering the determinism of particle trajectories under time reversal, the same beam with the same energy in a static magnetic field cannot have come from two different places. In other words, without an accelerating component in the ring (or a change in electrical charge, which is possible for ions but not electrons), the beam will collide with the injection structure after one turn. Acceleration is considered in the next section, but for now it will suffice to assume that the first turn after injection will only miss the injection apparatus by a very small distance. Quantitatively, if the energy increases from 21.7 to 24.7keV on the first turn, β increases from 0.283 to 0.300, an increase of 0.017 that corresponds to an increase in radius of 8.5mm in this R=0.5m machine.

The injected particles must experience a different field to the circulating ones until they have reached their desired position in the machine. As injection takes place on the inside edge of the machine, the field must be increased to give a tighter radius of curvature so that the beam can join the circulating beams from the inside. This needs a self-contained septum magnet capable of producing (say) a 5cm radius of curvature in a 21.7keV electron beam, which is no wider than 8.5mm. The field required for this is

0.01T, so this seems practical. Both the electron gun and the injection septum should be movable in some way. It is possible to have some mechanical feedthroughs into the vacuum chamber so that the lengths of supports for these components can be changed to adjust their orientation. Alternatively, the septum could be attached to the magnet support structure in the expected place with alignment adjustments only being done when vacuum is off. If the current in the septum is adjustable, this would add back one tuning parameter for beam injection while the machine is running.

1.3.4 RF Acceleration

As discussed in the previous section, each turn needs an acceleration of a few kilovolts in order to separate the turns near injection sufficiently. The revolution frequency of 95.4MHz falls in the FM radio band, meaning RF sources and amplifiers at this frequency are readily available.

The earliest cyclotrons used "dees" to fully enclose the two halves of the machine and opposing RF voltages were applied to each side. These had to be the innermost component to the beam to impose the correct electrical potential, which was not so difficult in the case of a uniform dipole magnet. However, in this proposal, the fields are much more complex than a uniform dipole and coils have the best control over field distribution when they are the closest components to the beam, so using dees is not preferred, although it could be a fall-back option.

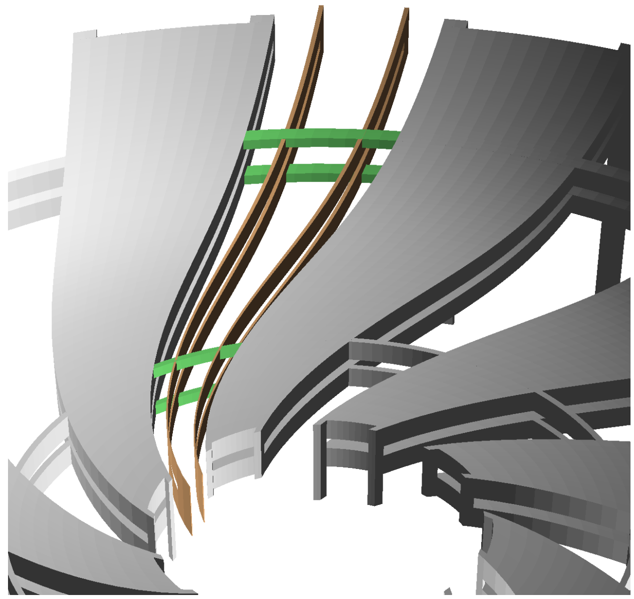

Figure 8. Conceptual layout of a pair of slotted electrodes (copper) held between two magnet sectors by ceramic supports (green). The electrodes follow the spiral and vertical shape of the sectors, while the transit time remains constant since their separation is proportional to particle velocity.

Instead, an approach analogous to that used in high-energy sector cyclotrons is proposed, where an accelerating gap is inserted between two of the sectors of the 3D cyclotron model, or possibly in more than one inter-sector space if the voltage from one system is insufficient. As vacuum is already provided, this could simply be two electrodes spanning the radial extent of the machine as shown in **Figure 8**, with a slot along the middle for the beam turns to go through, joined to the magnet support structure by ceramic standoffs sufficient to insulate the peak voltage. The two electrodes would be connected via coaxial cables (and high-voltage vacuum feedthroughs) to the RF power amplifier outside. As the acceleration in such a system relies on the *change* in voltage during the beam transit time between electrodes and not the electrode voltages themselves, the actual peak voltage on the electrodes would be an order of magnitude higher than the beam energy gain, roughly 30kV for a 3kV energy gain.

1.3.5 Diagnostic Devices and Beam Dynamics Studies

While commissioning the machine, the most important diagnostic is to test for beam presence and position at various radii. This can be done with radially movable phosphor screens between some of the sectors, the movement being achieved via wires attached to a rotary mechanical vacuum feedthrough controlled by a slow motor. For these areas, the bracing between sectors would be rerouted above and below with an additional metal track following the sector shape for the phosphor screen to sit in.

This diagnostic would allow the turns of the beam to be examined one at a time (they are separated by ~8.5mm initially, before becoming closer together) while other parameters such as electron gun voltage, RF gap voltage and injection septum field are varied. Once a configuration has been found where the beam follows the design orbit without oscillations, a small permanent magnet can be attached to a modified phosphor screen to apply a kick to particular turns of the beam. The phase advance of the oscillating response with each turn is the fractional part of the machine ring tune, which is the sector tune multiplied by the number of sectors. If two screens are installed in consecutive sector gaps, the phase difference on either side of the sector (of the same turn) is the sector tune. These two measurements can be cross-checked and measured in all energies of the machine. Being able to obtain a constant machine tune is important for keeping high-intensity beams stable and away from resonance conditions in a full-sized 3D cyclotron.

An additional diagnostic that might be particularly informative around the injection area is to add fluorescent gas so that the electron beam glows temporarily to show its position in three dimensions. As this is at the low-energy end of the machine, X-rays are not produced and this can be done with the experimenter looking at the device and adjusting the injection alignment. Injection is emphasised because over many turns, the gas may scatter the electron beam until it is lost. However, it could also be possible to locally apply gas in higher-energy problem areas using a tube and take photographs or video from various angles to show the positions of the turns.

The beam energy will be inferred from its orbit radius (unless a better energy diagnostic is thought of during the project). This is because the orbit circumference must be proportional to velocity in order for the beam to return to the RF gap at equally-spaced times and be accelerated coherently. The orbit radius is also proportional to beam momentum divided by magnetic field, so if the magnetic field is well known, this is a second way to determine the energy.

Finally, more ambitious beam dynamics studies could increase the current from the electron gun to investigate space charge phenomena, with the beam screens probing the beam distribution as well as the location of the turns. A screen with a hole could serve as a halo monitor as the gun current is varied. Transmitted current could be measured using a Faraday cup that is also the beam dump, as described in the next section.

1.3.6 Beam Dump and Safety

The beam dump could take the form of a metal plate that slides to various radii in the same manner as the phosphor screens. As significant X-ray production starts to occur at the higher energies of the machine, the dump plate should be left towards the inside of the machine when experimenters are working directly on the machine, for instance when establishing injection where no energies beyond 50keV are needed. The machine should be enclosed in an X-ray shielded room (lead plating) with as much of the electronic equipment as possible placed outside the room to prevent interference from the ionising X-rays.

A conductive dump plate would prevent static charge from building up and could also have an ammeter put in series with its connection to ground as a diagnostic of transmitted current. If this differs significantly from the electron gun extracted current, it is a sign that large beam loss is occurring somewhere in the machine, potentially damaging the magnet assembly or vacuum chamber. Although high beam powers are not a requirement for the initial configuration of the machine, if such powers are used later in advanced beam dynamics studies (space charge, etc.) the high beam loss condition should trigger a warning and/or shut off the electron gun. Additionally, the dump plate (which is in vacuum) may have to be upgraded with liquid cooling and joined to the magnet coolant circuit for high power operation.

The liquid-cooled magnet carries the usual hazards of overheating due to short circuit or insufficient coolant flow. The RF is a high voltage device, although the only exposed high voltage surfaces will be inside the vacuum chamber itself. The only really unusual hazard compared to most accelerators is the large evacuated volume, which could release a lot of potential energy if it implodes. Glassy bell jars must be used behind shields for this reason. However, acrylic is not so brittle and its use in submarine windows is both to a higher pressure and human rated. If high beam powers are used, the possibility of the electron beam heating and drilling a hole through the vacuum chamber is one reason among many why the experimenters should not be inside the shielded room in this situation.

Overall, the safety case is not unusual for the Collider-Accelerator Department, who operate much larger accelerators. It will be advanced through the official channels.

1.4 Project Timeline

As the project will design, construct and operate a self-contained particle accelerator (using an operating principle that has not been tried before), the schedule must take into account the high difficulty and technical risk in several ways. Firstly, it must not rush into building the final machine to prevent early engineering choice errors from becoming embedded in the design in a way that cannot be undone. A long period (1-1.5 years) of design, prototyping and evaluation of components will occur before the machine is constructed. Secondly, it must not be assumed that the machine will work first time, or that the scientific results can be obtained in a short period right at the end of the project. This would lead to the risk that schedule slips could lose this exploitation time entirely. Thus, the machine construction and commissioning should be neither near the beginning nor near the end of the project, leading to its place in year 3 below.

The PI will spend 60% of his time on this project in all years below. In years 2 and 3, an RF scientist (grade SCI3) will spend 25% of their time to design and build the RF accelerating gap system. Although the accelerating gap is simple in principle, the PI is not an RF expert so will require assistance. In years 1 and 3, an experienced mechanical engineer (grade PROF4) will be available at 25% to advise on the structural elements of the accelerator, the overall concept in year 1 and detailed systems such as diagnostic movers in year 3. In years 4 and 5 a post-doc will assist the PI with experiments using the machine and publication of results.

1.4.1 Year 1

- Computer optimisation of beam dynamics and machine shape
- Computer modelling of 3D magnet winding configuration and support structure design
- Prototype small pieces of proposed magnet and support structure technology
- Make initial quantitative investigations of the hardware required for all subsystems, discuss with relevant hardware experts at BNL
- Find appropriate lab space for equipment, taking into account safety requirements for ~MeV electron beams
- Engineering drawing of vacuum chamber flange with feedthroughs
- Large component: vacuum chamber and pump, should be bought this year
- **Deliverable:** initial machine beam optics configuration

1.4.2 Year 2

- Baseline parameters for all components required
- Begin RF design of accelerating gap electrodes
- Vacuum chamber and pump testing
- Most hardware purchases will happen this year, including the main magnet support structure and an initial set of diagnostics
- Test assembly of magnet outside of vacuum including liquid cooling loop
- Electron gun should be bought for a basic test in the vacuum chamber against the various diagnostic screens and devices, though this will continue into Year 3
- **Deliverable:** initial machine hardware configuration

1.4.3 Year 3

- Purchase RF power supplies, build accelerating gap electrodes
- Finish procurement and build of other components
- Machine assembly (initially could be without RF acceleration)
- Machine commissioning
- **Deliverable:** first beam

1.4.4 Year 4

- Machine tuning, aiming for acceleration of electrons to high (relativistic) energies
- **Project success would be acceleration to 600keV (equivalent to >1GeV for protons)**
- Hardware budget for machine modifications is available in years 4-5, as is a post-doc

1.4.5 Year 5

- Continued machine operation responsively to results; other research topics include:
- Orbit bump to measure machine tunes
- Investigating current limitation and space charge effects
- **Deliverable:** at least one journal paper (e.g. PRSTAB), probably more if project successful

1.5 Competency of Personnel and Adequacy of Proposed Resources

The idea of the 3D cyclotron was proposed by Stephen Brooks, who performed the first particle tracking, design studies and published results on it [1]. This means he has the mathematical framework [18], computer codes [19] and tools ready to start with the design; others would be at a disadvantage trying to pick up this work.

The work will be performed in the Collider-Accelerator Department at BNL. This department is responsible for running the 3.8km-circumference RHIC heavy ion collider. The department therefore has staff who are world class in terms of designing, building and operating all subsystems of a particle accelerator. Finding the RF scientist and mechanical engineer for this project will not be a problem.

The $2.5M budget of the Early Career Award appears correct for an accelerator of this size, given the most costly hardware subsystem (vacuum chamber and pumps) is in the $150k range. The budget attached to this proposal also keeps $20-40k spare for miscellaneous small purchases in each year. The 5-year time frame is generous enough to consider a project as ambitious as building an entire accelerator (3 years would not have been enough).

The Collider-Accelerator Department has large warehouses already used in parts for test accelerators such as the Brookhaven ERL (Energy Recovery Linac) and Accelerator Test Facility (ATF). The Department's facilities are therefore ideal for building a new test accelerator such as the 3D cyclotron electron model. Investigations for a possible site will start as early in the project as possible.

1.5.1 Principal Investigator Leadership Capabilities

As well as originating the concept of the 3D cyclotron, Stephen Brooks has re-established a research programme in vertical orbit-excursion FFAGs (VFFAGs) [10,11,12], a field that had been dormant since the 1960s [6]. This is now being recognised internationally with plans to use such a machine for intense muon production at the KURRI institute in Japan [20]. He is also involved in defining the baseline lattices for the eRHIC future FFAG project at BNL [17], which will build two stacked FFAGs in the existing RHIC tunnel. This year, he gave an invited talk at the main annual accelerator conference IPAC'14 [1, 21] about VFFAGs and 3D cyclotrons and was also a consultant at the machine design review of the Radiatron, a small industrial electron FFAG, being built by RadiaBeam Technologies.

APPENDIX 1: BIOGRAPHICAL SKETCH

Education and Training:

D.Phil. Particle Physics, 2010
University of Oxford, Oxford, United Kingdom
Research Advisors: Dr Christopher R. Prior, Dr John H. Cobb
Thesis Title: "Muon Capture Schemes for the Neutrino Factory"

M.Math. Mathematics, 2003
University of Oxford, Oxford, United Kingdom

B.Sc. Mostly Applied Mathematics, 2001
The Open University, Buckinghamshire, United Kingdom

Research and Professional Experience:

Assistant Physicist 10/2013 - present
Collider-Accelerator Department
Brookhaven National Laboratory

Lattice design for the eRHIC accelerator, using FFAGs.

Accelerator Physicist 09/2003 – 10/2013
Rutherford Appleton Laboratory

Research topics currently include: beam dynamics and magnetic field simulations in FFAG (fixed-field) particle accelerators; heat deposition and yield of particle beam targets. Previously worked on the Neutrino Factory "muon front end" design, including setting up a public distributed computing project to run the simulations and optimise the design automatically.

Associate Lecturer in Physics 2007 - 2003
The Open University

Tutored the course "S357: Space Time and Cosmology" for two years at distance learning university, with ~20 students in the class. Syllabus included classical mechanics, special and general relativity and cosmology.

Vacation Studentships Summer 2000 – Easter 2003
Rutherford Appleton Laboratory

Developed graphics for interactive particle beam transport simulations.

Publications:

Vertical Orbit-excursion Fixed Field Alternating Gradient Accelerators (V-FFAGs) and 3D Cyclotrons, S.J. Brooks, Proc. IPAC'14.

Vertical Orbit Excursion Fixed Field Alternating Gradient Accelerators, S.J. Brooks, Phys. Rev. ST Accel. Beams **16**, 084001 (2013).

Acceleration in Vertical Orbit Excursion FFAGs with Edge Focussing, S.J. Brooks, Proc. HB2012.

Vertical Orbit Excursion FFAGs, S.J. Brooks, Proc. HB2010.

Extending the Energy Range of 50Hz Proton FFAGs, S.J. Brooks, Proc. PAC'09.

The Muon1 particle tracking code, detailed in Chapter 2 of my thesis:

> *Muon capture schemes for the neutrino factory*. DPhil. University of Oxford. Stephen Brooks, (2010). http://ora.ox.ac.uk/objects/uuid:7b724028-e4ef-4248-9d42-505e571c9e19

Extrapolation of Magnetic Fields from a Curved Surface, S.J. Brooks technical note (2014) available from http://stephenbrooks.org/ap/report/2014-2/offsurface.pdf

eRHIC Design Study: An Electron-Ion Collider at BNL, E.C. Aschenauer *et al.*, pre-print (2014) available from http://arxiv.org/abs/1409.1633

The above are selected publications from a total of 12 conference papers and 4 journal papers including those where I am an author as part of a collaboration. I also have 16 technical notes available on the web.

Synergistic Activities:

I am involved in the design team of the eRHIC accelerator at BNL, which is also an FFAG. My code (Muon1 [19]) has been used extensively in producing new baseline designs, as well as being benchmarked against other widely-used codes to verify correctness. The eRHIC project [17] also required evaluation of different magnet and vacuum vessel technologies and co-optimisation of those with the beam optics, something I have been very involved with and is relevant to the 3D cyclotron model.

I gave an invited talk at IPAC'14 (the main international accelerator conference) about VFFAGs and 3D cyclotrons [1, 21], suggesting the idea of an electron model at the end.

I was an invited consultant at the Radiatron machine design review held at RadiaBeam Technologies in July 2014. The Radiatron is a small electron FFAG with a few-MeV beam energy for industrial X-ray production.

Collaborators and Co-editors:

Nikolai Avreline, RadiaBeam Technologies

Salime Boucher, RadiaBeam Technologies

Christopher Mayes, Cornell University

Alex Murokh, RadiaBeam Technologies

Stephen Webb, RadiaSoft LLC

Graduate and Postdoctoral Advisors and Advisees:

John Cobb, University of Oxford

Christopher Prior, STFC Rutherford Appleton Laboratory

APPENDIX 2: CURRENT AND PENDING SUPPORT

The Principal Investigator, Stephen Brooks, is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics (KB020201-1), in his role supporting accelerator R&D and facility upgrade projects at BNL's RHIC complex. This is currently at 12 person-months per year.

The PI currently has no other research grant requests pending or ongoing.

APPENDIX 3: BIBLIOGRAPHY & REFERENCES CITED

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[10] *Vertical Orbit Excursion FFAGs*, S.J. Brooks, Proc. HB2010.

[11] *Acceleration in Vertical Orbit Excursion FFAGs with Edge Focussing*, S.J. Brooks, Proc. HB2012.

[12] *Vertical Orbit Excursion Fixed Field Alternating Gradient Accelerators*, S.J. Brooks, Phys. Rev. ST Accel. Beams **16**, 084001 (2013).

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[17] *eRHIC Design Study: An Electron-Ion Collider at BNL*, E.C. Aschenauer *et al.*, pre-print (2014) available from http://arxiv.org/abs/1409.1633

[18] *Extrapolation of Magnetic Fields from a Curved Surface*, S.J. Brooks techncial note available from http://stephenbrooks.org/ap/report/2014-2/offsurface.pdf (2014).

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[20] https://indico.bnl.gov/getFile.py/access?contribId=7&sessionId=4&resId=0&materialId=slides&confId=686 slides 71-83, presented at FFAG'14.

[21] Invited talk at IPAC'14, see http://www.ipac14.org/?node=71 for agenda and http://accelconf.web.cern.ch/AccelConf/IPAC2014/html/auth0480.htm for slides.

APPENDIX 4: FACILITIES & OTHER RESOURCES

The work will be performed in the Collider-Accelerator Department at BNL. This department is responsible for running the 3.8km-circumference RHIC heavy ion collider. The Collider-Accelerator Department has at least $12000m^2$ of warehouses already used in parts for test accelerators such as the Brookhaven ERL (Energy Recovery Linac), the BNL ATF (Accelerator Test Facility) as well as a superconducting RF test stand. The lab has several machine shops and electronics labs on site. Their facilities are therefore ideal for building a new test accelerator such as the 3D cyclotron electron model.

This project will require a relatively small experimental space a few metres on a side, with the area containing the accelerator to be shielded against the X-rays produced from 3MeV electrons and some of the electronic equipment outside. This is lower energy than most of the other accelerator test areas already existing at BNL. Office space and a computer are already provided by the lab.

Possibly the most valuable resource is the expertise already available in the Collider-Accelerator Department, which covers all aspects of designing, building and running a particle accelerator.

APPENDIX 5: EQUIPMENT

Most of the items used in this proposal will be new equipment, not re-used. However, it may be possible to borrow or re-use some standard items (turbomolecular pumps, DC power supplies) from other projects at BNL.

APPENDIX 6: OTHER ATTACHMENTS

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Office of the Director

Building 460
P.O. Box 5000
Upton, NY 11973-5000
Phone 631 344-4608
Fax 631 344-5803
gibbs@bnl.gov

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November 17, 2014

Dr. Lek K. Len
Accelerator Science and Technology Research & Development
Office of High Energy Physics
SC-25.1/Germantown Building
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Dr. Len,

As Director of Brookhaven National Laboratory (BNL), I wish to express my strong support for the proposal submitted to the DOE-sponsored Office of Science Early Career Research Program (LAB 14-1170) by principal investigator Dr. Stephen J. Brooks, Assistant Scientist in the Collider-Accelerator Department, entitled "Electron model of a three-dimensional relativistic cyclotron."

I confirm that the proposed research expressed in his submission falls within the scope of the Office of High Energy Physics-funded programs at BNL. As stated by Dr. Brooks, three-dimensional cyclotrons could provide the high average beam currents of traditional proton cyclotrons but at higher energies, in a footprint much smaller than a comparable linear accelerator. These beams have multiple uses relevant to BNL's mission, such as driving a reactor to transmute nuclear waste and more intense sources of neutrinos and rare nuclei. To have confidence that these full-scale facilities will work, a smaller version of this first-of-its-kind accelerator (an "electron model") can be built to verify the behavior of the beam and magnet configurations. His proposal will exploit the unique resources of the Collider-Accelerator Department, here at BNL, to develop a fully-operational prototype accelerator including the diagnostics required to optimize the stability of beam acceleration.

Sincerely,

Doon Gibbs
Lab Director