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Superconducting Electron Linac Concepts for Molybdenum-99 Production

Chemical Sciences and Engineering Division

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CONTENTS

1 INTRODUCTION 1

2 CHOICE OF SC CAVITIES AND OPERATING PARAMETERS 4

2.1 Introduction 4
2.2 Recent SC Cavity Performance 5
2.3 Cavity Operating Parameters 5

3 ACCELERATOR 8

3.1 Electron Source 8
3.2 Low Energy Electron Beam Line 8
3.3 Superconducting CW Linac 8
3.3.1 Superconducting Cavities 9
3.3.2 Superconducting Cavity Cryomodules 9
3.3.3 Superconducting Cavity Power Couplers 10
3.3.4 Low-Level RF Control Systems 11
3.3.5 High-Power RF Systems 12
3.3.6 Helium Cryogenic Plant 13
3.3.7 Miscellaneous Cost Estimate Items 13

4 PROJECT COST AND RISK 14

5 CONCLUSIONS 17

6 REFERENCES 18

FIGURES

1 Recent Superconducting Niobium Cavity Performance 6

2 A Picture of the Argonne ATLAS 72 MHz Quarter-Wave Cavity Cryomodule 10

3 RF Power Required to Operate Several of the Cavities at the Proposed Operating Level 12

TABLES

1 A General Comparison of 250 kW Normal Conducting and Superconducting Accelerators for the Production of Mo-99 2

2 Summary of the Seven Options Considered in this Cost Estimate 3

3 Overview of the Cost and Operating Parameters for the 5-mA, 50-MeV Electron Linac 15

SUPERCONDUCTING ELECTRON LINAC CONCEPTS FOR MOLYBDENUM-99 PRODUCTION

1 INTRODUCTION

The purpose of this effort is to evaluate the appropriateness and maturity of superconducting linac technology for use in Mo-99 production. Historically, electron accelerators have been made of copper and operated with water cooling to remove the heat generated in the accelerator. In the past 35 years, designers of a growing number of accelerators have chosen superconducting technology over normal conducting copper. For Mo-99 production, the motivation for using superconducting cavities is to avoid the excessive radio-frequency (RF) heating of the copper cavities (which is not practical for a 50-MeV, 250-kW electron beam) and the very large RF amplifiers required to operate the cavities. There are no copper cavities capable of operating in the continuous wave (CW) mode. Superconducting accelerators avoid most of these issues because most of the RF power is coupled to the beam and does not go into the cavity. This arrangement is in contrast to copper cavities where the RF power going into the cavities is comparable to the beam power requirements. Table 1 lists several of the main differences and similarities between a normal conducting copper and a superconducting niobium accelerator, which are useful in choosing the technology to be used.

Based upon these high level considerations, a superconducting linac appears to be preferable for the application of Mo-99 production. A superconducting linac interacts with the electron beam in a manner identical to that found in a normal conducting linac and will not change the physics of Mo-99 production. The only differences are in the material used to form the cavity resonators, the added cryogenic helium refrigerator and its maintenance, and the extra thermal insulation used around superconducting cavities (referred to as “cryomodules”). The superconducting accelerator cavities are made from niobium and must be cooled with a liquid helium bath. Niobium has RF resistances of a few nano-ohms at temperatures ranging from 2 to 4.5 K while copper has an RF resistance 0.8 milli-ohms at room temperature. This corresponds to the niobium cavities dissipating a few watts of power into the helium cryogenic bath, requiring a low temperature refrigerator. However, superconducting cavities allow for the excitation to high field levels (> 5-10 MV/m) with duty cycles up to continuous wave in regimes where the copper cavity’s RF losses could melt the copper even with highly engineered water cooling systems.

The evaluation of superconducting linac technology is based upon a pre-conceptual analysis of several design options for a CW superconducting linear accelerator capable of delivering 250-kW beams of 50-MeV, 5-mA electrons—accelerator parameters appropriate for this application. Seven options were analyzed to compare the required manpower and maintenance and services (M&S) costs, and the options are summarized in Table 2. The options differ in technology and approach, but there is no difference in the Mo-99 production physics.

The seven options share many common components, which include a low-energy electron source on a high voltage deck, a copper buncher cavity, normal conducting quadrupole focusing and steering magnets, beam diagnostics, liquid nitrogen distribution systems, and low-level RF control systems. These items are considered identical in this estimate across the

TABLE 1 A General Comparison of 250 kW Normal Conducting and Superconducting Accelerators for the Production of Mo-99

Parameter	Normal Conducting RF	Superconducting RF (SRF)
RF Power	Roughly double SRF	~Beam power
RF Power Consumption	~1.5 MW	~0.63 MW
Wall Plug Power (includes everything)	~2.0 MW	~1.6 MW
Technology Demonstrated	No	Yes
Maintenance	Straightforward	Helium cryogenics maintenance added.
Capital Costs	$15 million for ~100 kW linac	$20-$30 million
Operating Costs	~$8 million per year, with no helium cryogenics maintenance but increased RF power and water cooling requirements.	Saves on RF power and wall plug power. ~$7 million per year for manpower, capital equipment, and M&S.
Minimum Total Footprint	140 m^2	120 m^2
Radiation Shielding	Due to small aperture, beam losses can generate neutrons.	Large aperture, negligible beam losses.
Upgrade Potential	Difficult	Straightforward for 500 kW
Operation	Short pulse	Long duty cycle or continuous wave
Reliability	Questionable at the required beam power level.	>90%

options. The differences are the type of superconducting (SC) cavity used, the operating temperature of the accelerator, the material used to form the SC cavities, and the operating power of each cavity.

This report starts with the description of how we chose the SC linac parameters based on extensive Physics Division experience (Section 2). These parameters were used to develop the baseline designs of the seven SC linac options. Section 3 briefly describes each part of the cost estimate. Finally, comments on the cost, risk, relative maturity, and relative merits of each of the seven options for Mo-99 production are given in Section 4.

TABLE 2 Summary of the Seven Options Considered in this Cost Estimate. ECR = elliptical cell resonator, TSR = triple spoke resonator. All options are for a 5-mA, 50-MeV electron beam.

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
Cavity Type	ECR	ECR	ECR	ECR	TSR	TSR	TSR
Cavity Voltage (MV)	6	10	6	6	6	10	6
# of Cavities	8	5	8	8	9	5	9
Frequency (MHz)	1300	1300	650	1300	325	325	325
SC Material	Niobium	Niobium	Niobium	Nb_3Sn	Niobium	Niobium	Niobium
Operating Temperature (K)	2.0	2.0	2.0	4.5	2.0	2.0	4.5

2 CHOICE OF SC CAVITIES AND OPERATING PARAMETERS

2.1 INTRODUCTION

The Physics Division approach to the choice of SC operating parameters for a new 50-MeV, 5-mA electron accelerator begins with the following high-level considerations:

- What are the anticipated operating conditions (beam types, current, availability, and reliability)?
- What SC cavity options are available to satisfy the high-level considerations?
- What is the overall linac voltage requirement and what are appropriate voltages for individual cavities?
- How much margin is reasonable for each cavity in the SC linac?

Each of these questions, of course, entails consideration of a host of related issues. For example, operation at the full beam energy must be possible under both nominal design conditions and in the case where individual components (e.g., SC cavity) are unavailable or operating below design values. For this cost estimate, a brief overview was conducted, and the details are included here.

First, the expected operating conditions are that a 5 mA electron beam be transported and accelerated to 50 MeV with a 90% or greater reliability, operating at least 6000 hr per year. The Argonne choice of SC cavity parameters relies on past experience to estimate these goals. For a new 5-mA, 50-MeV electron accelerator, this means that we make use of (1) a quantitative analysis of recent cavity field and sub-system performance, together with (2) an assessment of present Argonne personnel and vendor skills and hardware capabilities that are relevant to the requirements for this accelerator. Using these considerations, we determined that using a commercially available 650 and 1300 MHz ECR or 325 MHz TSR produced by a Department of Energy (DOE) laboratory are the only viable options. We considered two ECRs that have been produced by American industry:

1. The 1300 MHz niobium ECR that has been produced in America for the past 15 years.
2. The 650 MHz niobium ECR that has been produced in America for the past 2 years.

The TSRs have been produced previously within the DOE national laboratory complex and are available for production. A single vendor, Niowave, has built a TSR for Old Dominion University. All of these cavities are able to perform at operating levels appropriate for this project.

The rest of this section discusses the choice of SC cavity parameters. First, recent cavity performance and processing are discussed. Then, the choice of cavity operating voltage is discussed in the context of recent cavity performance, the reliability of existing RF power couplers, and the availability of commercially available RF power supplies.

2.2 RECENT SC CAVITY PERFORMANCE

Figure 1 shows recent results from Fermi National Accelerator Laboratory (FNAL) on 1300 MHz ECR performance [1], from the Jefferson Lab (JLAB) on single-cell 650 MHz ECR performance [2], and from Argonne on 345 MHz triple-spoke cavity performance [3]. Superimposed on these graphs are red dashed lines corresponding to the proposed operation levels of the cavities. Notice that the proposed operating levels do not push the operating limits of the cavities. Rather, the limitation is due to the level of RF power coupled to the beam in each SC cavity. Continuous-wave power couplers at the frequencies of interest have been developed, but not at power levels sufficient for the proposed higher operating levels. More details are provided in the coupler sub-section of Section 3. The operating performance of the ECR cavities allows for low-cryogenic loads with accelerating gradients extending up to 30 MV/m with peak surface fields of 60 MV/m electric and 124.5 mT magnetic, as well as a large margin for future upgrades.

Recently, encouraging results were obtained in the development of Nb_3Sn-coated superconducting cavities at Cornell University. Single-cell 1.3 GHz cavities have operated at 4.5 K, instead of 1.8 K, with low RF losses up to accelerating gradients of ~12 MV/m. Assuming that these cavities are successful, we include an estimate in the analysis, but it carries a much higher risk and does not include the development cost.

2.3 CAVITY OPERATING PARAMETERS

The limit on the cavity accelerating voltage is the power couplers. The remaining substantive choice of cavity operating parameters requires a reasonable estimate of anticipated cavity RF losses. The cryoplant size scales directly with the RF losses, and, therefore, the choice should be made carefully so as to not risk insufficient cooling capacity or, conversely, drive up cost needlessly. The intrinsic cavity BCS (Bardeen, Cooper, and Schrieffer) RF losses and the effect of the cavity geometry on losses are mostly fixed once the cavity type is chosen (e.g., 1.3 GHz or 650 MHz ECRs) and, here, favors the 1.3 GHz option. The problem is then reduced to choosing a reasonable value for the residual surface resistance at the operating field level.

A similar quantitative comparison in terms of residual resistance (R_{RES}) taken from measured the resonator quality factor (Q) as a function of accelerating field (E) for the considered cavities gives:

- R_{RES} (1300 MHz, Nb, 2 K) ~ 5 nΩ at peak magnetic field (B_{PEAK}) = 24-40 mT
- R_{RES} (650 MHz, Nb, 2 K) ~ 5 nΩ at B_{PEAK} = 22 mT

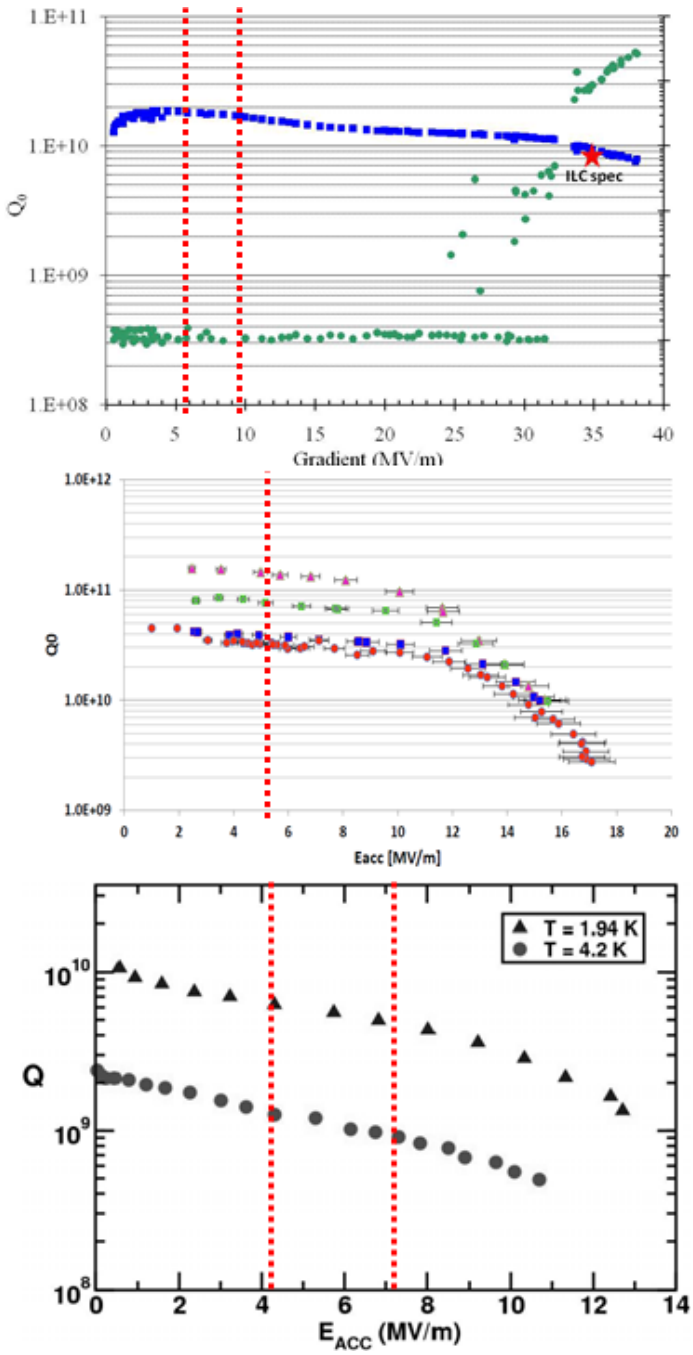

FIGURE 1 Recent Superconducting Niobium Cavity Performance. Top, recent 9-cell 1300 MHz ECR cavity performance measured at FNAL, with all of these cavities processed and cleaned at Argonne prior to testing. Middle, recent 650 MHz single-cell ECR test results from JLAB. This is not a 5-cell cavity, which is used in this report and development work is required. Bottom, test results from a 345 MHz beta = 0.62 TSR build and processed at Argonne as part of the Rare Isotope Accelerator (RIA) project. Red dashed lines correspond to proposed operating levels.

- R_{RES} (1300 MHz, Nb_3Sn, 4.5 K) ~ 12 nΩ at B_{PEAK} = 22 mT
- R_{RES} (325 MHz, Nb, 2 K) ~ 12 nΩ at B_{PEAK} = 36 mT
- R_{RES} (325 MHz, Nb, 2 K) ~ 17 nΩ at B_{PEAK} = 57 mT
- R_{RES} (325 MHz, Nb, 4.5 K) ~ 20 nΩ at B_{PEAK} = 36 mT

The surface resistance is written in terms of different proposed operating values for B_{PEAK}, since the surface magnetic field is most closely associated with R_{RES} and Q-slope. There is no *a-priori* reason to use different values, except that we consider operation at different field levels as part of our cost analysis. The above values are used to calculate the cryogenic thermal load for each of the seven options, and the cryoplant is discussed in Section 3.

3 ACCELERATOR

3.1 ELECTRON SOURCE

To maintain a high level of operational reliability, we recommend the use of an electron source on a high voltage deck followed by normal conducting quadrupole magnet focusing and a buncher cavity. This hardware is commercially available and poses a low technical risk. The output beam energy from the electron source is boosted by placing it on a 300 kV high-voltage deck. This minimizes the cost and complexity of the low-energy acceleration of the electron beam. We propose to purchase an electron gun and high-voltage deck similar to those proposed for the TRIUMF electron linac [4]. The TRIUMF-type electron gun produces up to 16 mA of bunched CW beam with a repetition rate of 650 MHz. The beam is bunched by superimposing an RF modulation to overcome a DC suppression voltage on the grid. The main components of the source are a gridded dispenser cathode and an in-air high-voltage power supply. The RF modulation to the grid is transmitted through a ceramic waveguide located inside an SF_6-filled vessel.

3.2 LOW ENERGY ELECTRON BEAM LINE

The accelerator needs a beam line between the output of the electron-gun/high-voltage deck and the input of the superconducting accelerator. This beam line allows for:

- The installation of focusing magnets to transversely confine the electron beam
- The installation of beam diagnostics
- The installation of beam-line vacuum systems

For the purposes of this estimate, the focusing magnets are all assumed to be room-temperature quadrupole triplets. There will be two triplets in the low-energy beam line: one immediately after the high-voltage deck, and the second after the last normal-conducting cavity. The beam diagnostics are commercially available and include a parametric current transformer for real-time monitoring of the beam current, beam position monitors, and intercepting faraday cups for the beam-energy measurement. None of the hardware estimated here requires new development, and costs are based upon those estimated at TRIUMF [5].

3.3 SUPERCONDUCTING CW LINAC

The superconducting linac for the 5-mA, 50-MeV electron accelerator comprises two cryomodules with 5-9 superconducting cavities. There are no superconducting magnets interspersed throughout the SC cavity lattice, but provisions have been made for several steering coils. A detailed lattice design study needs to be done to finalize the numbers discussed as part of this estimate. Here, the cavity count was determined by matching the voltage gain and velocity

acceptance of successive cavities to determine the cavity types and numbers required for operation. As a result, each option has a single-cell or a single-spoke cavity added to the front end to efficiently match the beam from the electron source into the longitudinal acceptance of the beta = 1 SC cavity linac.

The SC linac estimates are based on existing ATLAS and International Linear Collider (ILC) technology [6] with slight modifications; e.g., the cryomodules are shorter in this cost estimate. This builds upon the considerable development work performed for this technology over the past 30 years. The SC linac estimates include the cavities, cryomodules, cryomodule sub-systems (tuners, alignment, and vacuum pumping), couplers, and RF control/power systems. In the following sub-sections the main cost drivers of the SC linac are described.

Only two cryoplants were estimated. Each was the largest required for the given operating temperature of either 2 K or 4.5 K.

3.3.1 Superconducting Cavities

The SC cavities estimated here are mostly well understood and commercially available. They are designed and fabricated based on techniques established both in-house at Argonne and in industry over the past four decades. The exception here is the development of the Nb_3Sn coating for the 1300-MHz, 4.5-K ECR option. This cost was not estimated, and due to the high risk of this option and the small time-scale available for this work, it may be significantly reduced if Nb_3Sn becomes an option in the next ten years.

The 650 and 1300 MHz ECR cavities are commercially available from Advanced Energy Systems (AES, Upton, NY) [7]. The cost estimates presented here are based upon estimates supplied by AES for the niobium cavities. The titanium helium jacketing estimates are based upon AES developing an outside company (Ti Fab in NJ) for the welding of the titanium helium jackets. In addition, PAVAC (Vancouver, BC), Research Instruments (RI, located in Germany), and Zanon (Italy) can supply the 1300 MHz ECR cavities. Costs estimated by RI exceeded the AES price by almost a factor of two and were not incorporated into this work. The high cost of ordering the cavities from RI is, in no small part, due to its facility being oversubscribed for the production of the European X-ray Free Electron Laser (XFEL) SC cavities.

Close analogues of the 325 MHz TSRs required for this project have been successfully developed by Argonne [3, 8]. These cavities are built in collaboration with AES and pose no significant technical risk.

3.3.2 Superconducting Cavity Cryomodules

The SC cryomodule designs used for estimating the costs are based upon existing Argonne box-cryomodule technology and existing ILC/XFEL technology [6, 9]. See Figure 2 for an example of an Argonne box-cryomodule. A cryomodule similar to this would be used for the TSR accelerator options. The cryomodules have been shortened due to the small number of

FIGURE 2 A Picture of the Argonne ATLAS 72 MHz Quarter-Wave Cavity Cryomodule. A similar vessel would be used for the TSR cavity cryomodules. This cryomodule was successfully installed in the ATLAS linac in February 2014 and has been in operation ever since.

required cavities, and the costs presented here are slightly lower than what would be expected for a full ILC/XFEL cryomodule. All cryomodules are estimated by assuming that:

1. Liquid nitrogen is used for all 80 K thermal intercepting.

2. Liquid helium coolant is supplied for the 4.5 K operating options.

3. Pressurized (3 bar) gaseous helium is supplied to expansion valves located outside of the cryomodules to be operated at 2 K. The liquid derived from the expansion of the helium gas is then supplied to the cryomodule via specialized helium transfer lines.

3.3.3 Superconducting Cavity Power Couplers

Two classes of RF power couplers for superconducting cavities, one based on a co-axial transmission line and the other on a waveguide, are capable of delivering high average power (>100 kW) at the frequencies (~400 MHz-1.5 GHz) of interest here. Overview articles including high-level performance requirements and major design considerations are available [10, 11].

Both coaxial and waveguide types would be suitable for the 1.3 GHz cavities considered here. Physical size constraints preclude the use of a waveguide attached directly to a 325 MHz spoke cavity.

The RF losses in a coaxial line scale with the square root of the frequency so that, all else being equal, the coaxial line power handling capability is roughly double at 325 MHz compared to that at 1.3 GHz. In practice, development effort has been focused at the higher frequency. Cornell University operates a 1.3 GHz cavity/power coupler system meeting the high-level requirements, that is, a CW transfer of close to 50 kW of RF power per coupler to the beam [12]. The technical design uses a pair of couplers, vertically opposed on the cavity beam tube, which provide a total beam power of ~100 kW per cavity. This system is, however, operating close to its practical power limit, and the initially planned operation of a 75 kW/coupler has not been demonstrated to date. A similar 1.3 GHz dual-coupler system, rated for 50 kW per coupler, is planned for the e-linac project at TRIUMF [4]. Operation at full power has not so far been announced.

Power couplers for 325 MHz and ~100 kW do not yet exist; however, several have been developed and operated at nearby frequencies. The KEKB 508 MHz coaxial power coupler [14] operates in CW mode with RF power of 380 kW. A 700 MHz coaxial coupler was demonstrated at power levels close to 1 MW [15]. Low-frequency (175-325 MHz), high-power couplers are under development at Fermi National Accelerator Laboratory (Fermilab), Saclay, and elsewhere.

Power couplers considered in this report are all of a coaxial type. In each case, it is assumed the power couplers will require engineering development with existing vendors such as Communications and Power Industries (CPI), Mitsubishi, or MPF Products and a prototyping and testing phase conducted at Argonne or elsewhere. Further, to compare options with similar technical risk, it is assumed that a dual-coupler system would be used for 1.3 GHz cavities, while a single coupler would be developed for 325 MHz spoke cavities.

3.3.4 Low-Level RF Control Systems

The electromagnetic field in the SC cavities has to be matched to the electron-beam phase. The electronics that monitor the phase relationship between the electron beam and the synchronous RF phases are referred to as the low-level RF (LLRF) system. LLRF hardware is available from several commercial suppliers, where two stand out:

1. Dimtel, Inc., San Jose, CA

2. Research Instruments (RI), Gmbh., Germany

Both of these companies have supplied accelerator LLRF control system to projects that have been in operation for many years. Given this proven track record, only these two companies were considered. RI did not respond to a request for a budgetary quote. Dimtel declined to give a budgetary quote but did provide rough costs for an LLRF system (part number LLRF9 [16]). Exact costing of the LLRF hardware requires a detailed specification, and more accelerator

information is required before this can be generated. Questions that need to be answered include: What is the required phase stability of the cavity RF fields? What loop delay times will there be in the feedback circuit? The costs given here represent an educated guess and should not vary by more than 25% in the actual accelerator.

3.3.5 High-Power RF Systems

The LLRF system includes all of the electronics for phase stabilizing of the SC cavity RF field for the beam acceleration, and the high-power RF (HPRF) system encompasses all of the amplifiers, transmission lines, circulators, and loads. Each cavity requires between 35 and 55 kW of RF power in operation. These values are only a rough estimate and do not include enough overhead to accommodate long transmission line losses or excessively noisy RF field stabilization. Figure 3 shows the required cavity power for three cases: (1) a 1.3 GHz ECR operating at 6 MV, (2) a 1.3 GHz ECR operating at 10 MV, and (3) a 325 MHz TSR operating at 6 MV.

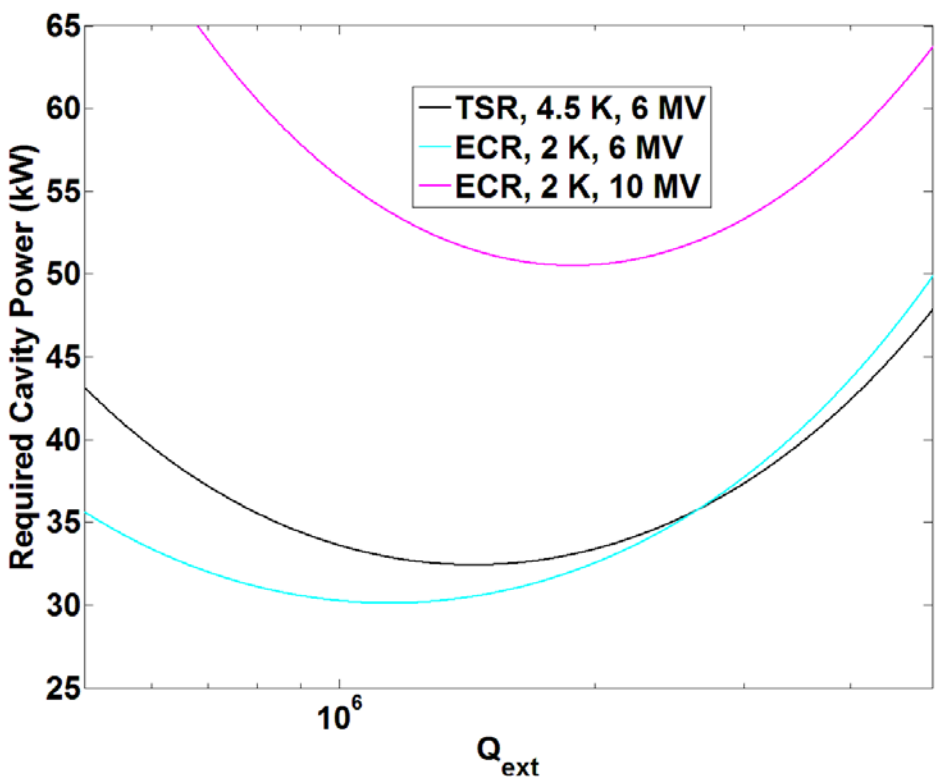

FIGURE 3 RF Power Required to Operate Several of the Cavities at the Proposed Operating Level. The minima in each curve represent the minimum required power and are used in the estimates. Notice that the TSR requires slightly more power than the ECR cavity option. This is due to its lower shunt impedance.

High power systems capable of delivering the required power are highly specialized. For 1.3 GHz, there are two options: klystrons and inductive output tubes (IOTs). A quote for a 30 kW IOT system, including the amplifier, circulator, and dummy load, was requested from CPI, and its cost estimate was $650,000. TRIUMF shared their klystron cost estimates, and these were significantly cheaper than those of the IOT option. The klystron cost estimates for a 500-kW electron beam from TRIUMF are used here. The costs will be slightly less (35%) for a 250-kW electron beam, as is the case for this accelerator. Using a klystron power system adds an additional complication to the accelerator: each klystron has to excite multiple cavities. However, techniques for doing this have been demonstrated [15].

3.3.6 Helium Cryogenic Plant

Two distinct helium cryogenic plants were estimated as part of this work: one for the supply of 4.5 K helium liquid to the cryomodules and the other for the supply of 2 K helium liquid. The estimated cryogenic plants are sufficient for the highest thermal loads estimated and do not account for options with lower loads; e.g., the 4.5 K helium plant was estimated to be 280 W for the 325 MHz TSR option. The TSR cavities operating at 6 MV dissipate 18 W per cavity into the 4.5 K coolant stream. This dissipation is much larger than that of the Nb_3Sn option, with only 2.2 W of losses per cavity. The cryoplant cost and size could be reduced for this option, but this possibility was beyond the scope of this work.

All cryogenic plant costs are based upon estimates supplied by Linde, and the ancillary equipment (water chillers, storage tanks, distribution lines, etc.) costs are based upon recent experience at Argonne and Fermilab for the fabrication of similar hardware. All of these estimates used preliminary numbers for the cryogenic loads, and a more detailed study of these loads must be done for the final accelerator configuration.

3.3.7 Miscellaneous Cost Estimate Items

The estimates include line items for the design of the facility, the cost of a liquid-nitrogen distribution system, and the cost of assembling the facility (for installation of one accelerator). These costs are based upon recent Argonne experience accrued during the ATLAS intensity upgrade. Several other major costs not included in the scope of this document should be considered:

1. Electrical utilities installation

2. Building facilities preparation/refurbishment

3. Safety documentation

4. Argonne Facilities Management and Services charges

4 PROJECT COST AND RISK

The analysis results for all seven options are summarized in Table 3. Each option has the costs broken down among the major sub-portions of the project with both M&S and manpower separated. This separation was done because the manpower estimates are for the effort of Argonne National Laboratory Physics Division personnel, and private companies will have cheaper and possibly more efficient labor. The options have costs that range from $21 to $27 million, and none is risk free. For example, all options require the implementation of high power couplers, with which there is little experience. In the remainder of this section, we list a few of the major risk considerations of the various options.

1. Option 1 Risk Considerations:
   a. Cavity power couplers have little operating experience at the required power levels.
   b. ECR cavity designs are not intended for 35 kW or more CW power. This must be evaluated with multiphysics analyses and prototyped to demonstrate the feasibility of this approach.
   c. The remainder of the technology is, for the most part, commercially available.

2. Option 2 Risk Considerations:
   a. Cavity power couplers have no operating experience at the required power levels and require new development.
   b. The ECR cavity designs are not intended for 55 kW or more continuous wave power. This must be evaluated with multiphysics analyses and prototyped to demonstrate the feasibility of this approach.
   c. This option is attractive because it reduces the component count and simplifies the accelerator.
   d. The remainder of the technology is, for the most part, commercially available.

3. Option 3 is discarded due to its high cost and the lack of operating data for the proposed 650 MHz ECRs. This option would require new couplers, new cavity helium jackets, new cryomodules, new cryomodule sub-systems, and many other items. This is in contrast to the other options where many of these components have been developed.

4. Option 4 requires everything in option 1 with the addition of the Nb_3Sn coating of the cavities. This has never been done before and has a high risk of taking > 5 years and being too expensive.

5. Option 5 Risk Considerations:
   a. A TSR for beta = 1 has never been built, but similar cavities have been built and tested at Argonne in the past 10 years.

TABLE 3 Overview of the Cost and Operating Parameters for the 5-mA, 50-MeV Electron Linac

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
Cavity Type	ECR	ECR	ECR	ECR	TSR	TSR	TSR
Linac Energy (MeV)	50	50	50	50	50	50	50
Average Beam Current (mA)	5	5	5	5	5	5	5
Cavity Frqeuency (MHz)	1300	1300	650	1300	325	325	325
Operating Temperature (K)	2.0	2.0	2.0	4.5	2.0	2.0	4.5
Typicaly Cavity β	1	1	1	1	1	1	1
Cells Per Cavity	9	9	5	9	3	3	3
Cavity Effective Length ($\beta\lambda/2$, m)	1.04	1.04	1.15	1.04	1.38	1.38	1.38
Accelerating Gradient (MV/m, n*$\beta\lambda/2$)	5.8	9.6	5.2	5.8	4.3	7.2	4.3
Voltage Per Cavity (MV)	6.0	10.0	6.0	6.0	6.0	10.0	6.0
R/Q (Ω)	1036.0	1036.0	638.0	1036.0	715.0	715.0	715.0
G (Ω)	270.0	270.0	255.0	270.0	175.0	175.0	175.0
BCS Surface Resistance (nΩ)	10.9	10.9	2.7	4.8	0.7	0.7	41.1
Residual Resistance (nΩ)	5.0	5.0	5.0	12.0	12.0	17.0	20.0
Total Surface Resistance (nΩ)	15.9	15.9	7.7	16.8	12.7	17.7	61.1
Number of High Beta Cavities	8	5	8	8	9	5	9
Q_0	1.7E+10	1.7E+10	3.3E+10	1.6E+10	1.4E+10	9.9E+09	2.9E+09
Dynamic Cryo Load Per Cavity (W)	2.1	5.7	1.7	2.2	3.6	14.1	17.6
Design Drafting Engineering	$1,381,360	$1,381,360	$1,381,360	$1,381,360	$1,461,520	$1,461,520	$1,461,520
Helium Cryogenics	$5,454,720	$5,454,720	$5,454,720	$2,960,600	$5,454,720	$5,454,720	$2,960,600
Liquid Nitrogen	$482,840	$482,840	$482,840	$482,840	$482,840	$482,840	$482,840
Electron Source	$459,000	$459,000	$459,000	$459,000	$459,000	$459,000	$459,000
Superconducting Cavities	$2,234,120	$1,686,840	$5,340,240	$3,284,528	$4,018,000	$3,669,222	$4,018,000
Power Couplers	$557,280	$644,320	$557,280	$557,280	$675,330	$635,330	$675,330
Magnets	$715,200	$715,200	$715,200	$715,200	$715,200	$715,200	$715,200
Cryomodules	$3,220,000	$2,476,923	$3,220,000	$2,598,416	$3,220,000	$2,476,923	$2,598,416
Low-Level RF Sytem	$788,040	$788,040	$788,040	$788,040	$788,040	$788,040	$788,040
High Power RF System	$6,571,213	$6,571,213	$6,571,213	$6,571,213	$5,412,413	$5,412,413	$5,412,413
Beam Diagnostics	$363,760	$363,760	$363,760	$363,760	$363,760	$363,760	$363,760
Facility Assembly	$1,480,400	$1,480,400	$1,480,400	$1,223,120	$1,480,400	$1,480,400	$1,223,120
Total Cost	**$23,707,933**	**$22,504,616**	**$26,814,053**	**$21,385,357**	**$24,531,223**	**$23,399,368**	**$21,158,239**
Risk (1 = Lowest, 7 = Highest)	**4**	**5**	**6**	**7**	**2**	**3**	**1**
Manpower (FTE Years)	**25**	**27**	**24**	**26**	**26**	**25**	**23**
Manpower	**$5,677,031**	**$6,014,531**	**$5,365,781**	**$5,814,844**	**$5,739,844**	**$5,721,094**	**$5,072,344**
M&S	**$18,030,902**	**$16,490,085**	**$21,448,272**	**$15,570,513**	**$18,791,379**	**$17,678,275**	**$16,085,895**

b. The power couplers are based upon existing technology demonstrated at room temperature, which gives a proof of principle for their operation at lower temperatures.
c. The cryomodules for these cavities have never been built but could be developed by modifying existing designs.

6. Option 6 Risk Considerations:
   a. There is a high power per cavity required in operation relative to option 5.
   b. A TSR for beta = 1 has never been built, but similar cavities have been built and tested at Argonne in the past 10 years.
   c. The power couplers are based upon existing technology demonstrated at room temperature, which gives a proof of principle for their operation at lower temperatures.
   d. The cryomodules for these cavities have never been built but could be developed by modifying existing designs.
   e. The lower component count is attractive.

7. Option 7 Risk Considerations.
   a. A TSR for beta = 1 has never been built, but similar cavities have been built and tested at Argonne in the past 10 years.
   b. The power couplers are based upon existing technology demonstrated at room temperature, which gives a proof of principle for their operation at lower temperatures.
   c. The cryomodules for these cavities have never been built but could be developed by modifying existing designs.
   d. This option is proposed to operate at 4.5 K, which is simpler than the 2 K options and much more resilient to operational accidents.

5 CONCLUSIONS

Molybdenum-99 production requires an accelerator with a high reliability and a high availability. The above risk considerations and the relative accelerator cost eliminate the 650 MHz ECR and the Nb_3Sn ECR accelerator options immediately. The maturity considerations and risk of the remaining options are dominated by the power handling of the cavities, both the cavity design and the power couplers exciting the cavities. The ECRs have been commercially available for several years, but the TSRs have better intrinsic beam power handling and lower frequency couplers. The appropriateness of both options is roughly equivalent, and both are mature enough for the linac fabrication. A recommendation of pursuing the 325 TSR option operating at 4.5 K is made based upon the relative cost. This option will take 6 years to build and commission if using experienced superconducting linac personnel. Please note that adding vendor development will extend the project time frame and increase cost.

6 REFERENCES

[1] Fermilab, "ILC-SRF R&D," http://ilc.fnal.gov, accessed October 2014.

[2] F. Marhauser, F. Marhauser, P. Kneisel, A. Burrill, P. Kushnick, and R. A. Rimmer, "Preliminary Test Results from 650 MHz Single Cell Medium Beta Cavities for Project X," Proceedings of SRF2011, Chicago, IL, p. 271 (2011).

[3] K.W. Shepard, M.P. Kelly, J.D. Fuerst, M. Kedzie, and Z.A. Conway, "Prototype Superconducting Triple-Spoke Cavity for Beta = 0.63," Proceedings of PAC2005, Knoxville, TN, p. 4338 (2005).

[4] R.E. Laxdal et al., "Status of Superconducting Electron Linac Driver for Rare Ion Beam Production at TRIUMF," to be published in the Proceedings of IPAC2014, Geneva, Switzerland.

[5 Private communication from R.E. Laxdal (TRIUMF) to P.N. Ostroumov (Argonne National Laboratory).

[6] Fermilab, "International Linear Collider: Cryomodule Documentation," http://ilc-dms.fnal.gov/Workgroups/CryomoduleDocumentation, accessed October 2014.

[7] Advanced Energy Systems, Inc., http://www.aesys.net, accessed October 2014.

[8] K.W. Shepard, M.P. Kelly, J.D. Fuerst, M. Kedzie, and Z.A. Conway, "Superconducting Triple-Spoke Cavity for Beta = 0.5 Ions," Proceedings of PAC2005, Knoxville, TN, p. 4344 (2005).

[9] Z.A. Conway, A. Barcikowski, G. L. Cherry, R. L. Fischer, J. D. Fuerst, W. G. Jansma, S. M. Gerbick, M. J. Kedzie, M. P. Kelly, S. H. Kim, S. W. T. MacDonald, R. C. Murphy, P. N. Ostroumov, T. C. Reid, and K. W. Shepard, "Assembly and Commissioning of a New SRF Cryomodule for the ATLAS Intensity Upgrade," Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference **1573**, 1829-1836 (2014).

[10] S. Belomestnykh, M. Liepe, H. Padamsee, V. Shemelin, and V. Veshcherevich, "High Average Power Fundamental Input Couplers for the Cornell University ERL: Requirements, Design Challenges and First Ideas," Cornell LEPP Report ERL 02-8 (2002).

[11] E. Kako, "High Power Input Couplers and HOM Couplers for Superconducting Cavities", Tutorials at the 16th International Conference on RF Superconductivity, https://indico.in2p3.fr/event/9782/session/0/contribution/5/material/slides/0.pdf (2013).

[12] V. Veshcherevich, S. Belomestnykh, M. Liepe, V. Medjidzade, H. Padamsee, V. Shemelin, N. Sobenin, and A. Zavadtsev, “Design of High Power Input Coupler for Cornell ERL Injector Cavities,” Proceedings of SRF’05, Ithaca, NY (2005).

[13] Y. Kijima, S. Mitsunobu, T. Furuya, and T. Tajima, “Input Coupler of Superconducting Cavity for KEKB,” Proceedings of PAC’99, Vienna, Austria, p. 2040 (1999).

[14] R.A. Rimmer, G. Koehler, T. Saleh, R.Weidenbach , K.A. Cummings, P.A. Torrez, E.R. Partridge, J.S. Harrison, J. De Baca, and M. B. Rodriguez, “A High-Power L-Band RF Window,” Proceedings of PAC’01, Chicago, Illinois, p. 921 (2001).

[15] A. Gamp, S. Goloborodko, A. Kholodnyi, M. Liepe, T. Plawski, K. Rehlich, T. Schilcher, S.N. Simrock, Y. Tchernoousko, and M. Hüning, “Experience with the Control of the Vector Sum at the TESLA Test Facility,” Proceedings of EPAC98, Stockholm, Sweden, p. 173 (1998).

[16] Dimtel, Inc., “Introducing Low-Level RF Control Solution,” http://www.dimtel.com, accessed October 2014.

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