CHAPTER 3: SUPERCONDUCTING RF PHOTOINJECTORS

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Keywords

Superconducting RF Injector, Superconducting RF Gun, High Average Current Gun, High Average Current Injector, High Duty Factor Injector, Single Cell Gun, Multi-cell Gun, Elliptical Resonator, Quarter-wave Resonator, ELBE SCRF Injector, 1.3-GHz Gun, 1.5-GHz Gun, 703-MHz Injector, 500-MHz Gun, 112-MHz Gun, BNL Gun, NPS Gun, BERLinPro, Field Emission, Multipacting, Emittance Compensation, Power Coupling

Abstract

High average current RF injectors typically operate at a higher duty factor, while maintaining as high an accelerating gradient as possible. This combination gives rise to increased wall current and RF loss leading to thermal management issues. One way is to address it is to operate it in superconducting RF (SCRF) mode. The development of SCRF injectors are still in its infancy. In this chapter, we establish the need for SCRF injectors and describe a number of systems that are currently in various stages of development. For those interested in building a SCRF injector, we list a number of questions to be answered prior to starting the design process and key issues that would impact the design, which is followed by the evolution of the design process and validation.

3.1 INTRODUCTION AND ASSUMPTIONS

This chapter centers on the beam physics design concerns for superconducting RF (SCRF) photoinjectors. An SCRF photoinjector is a specialized superconducting accelerator, and there are wealths of knowledge regarding various aspects of SCRF accelerator design and operation. Repeating that work in this chapter would not be fruitful in no small part because the author is a beam dynamicist and not an SCRF accelerator expert. Thus, many topics of high importance (such as multipacting and the resulting restrictions on cavity shape) to SCRF accelerator design and operation are only lightly touched upon here, simply to highlight issues of which the SCRF injector designer must be aware.

SCRF photoinjector design is still in its infancy. At least three different design paradigms are currently being developed; there are certainly other possibilities, as well. While the state of affairs results in an exciting area of research, unfortunately, it also limits the number of "guaranteed-to-work" suggestions one can offer. We do not know enough about how these devices will operate; it will be interesting finding out.

I start with some nomenclature and assumptions. A "cavity" refers to a single RF structure, and may consist of one or more "cells," or regions in which the beam is accelerated. For instance, a standard 1.3 GHz TESLA structure is a 9-cell cavity. Generally, the phrase "cathode cell" refers to the first cell in a multi-cell photoinjector, within which the cathode is located. A "full cell" is taken to be a cavity of length ~$\lambda/2$, where λ is the free-space RF wavelength corresponding to the injector's operating frequency. The term "injector" refers here to SCRF photoinjectors unless stated otherwise. The "gun" is the portion of the injector containing the cathode cell. References to beam energy are to the beam's kinetic energy, unless stated otherwise. For temperatures, "2K" refers to a 2.1 K superfluid liquid helium system. The term "4K" refers to either a 4.2 K system in which the liquid helium boils at standard atmospheric pressure, or to a 4.5 K system employing a supercritical refrigerator.

3.2 WHY SHOULD WE USE AN SCRF PHOTOINJECTOR?

A quick perusal of the preceding chapters illustrates that there is a large, thorough body of work, both theoretical and experimental, on developing and using normal conducting RF (NCRF) photoinjectors. Much of the initial theory rested upon analytical models of on- and near-axis RF fields with simple sinusoidal longitudinal components; aperture-coupled pillbox cavities present a convenient way to generate such fields. Typically, however, such cavity profiles are unsuitable for SCRF applications due to their susceptibility to multipacting. SCRF cell geometry in general, and cathode support structures in gun cells, in particular, can lead to electromagnetic field profiles considerably different from those assumed in classic emittance compensation theory. As a result, SCRF injector design places more emphasis on computer simulation rather than on theoretical modeling. There are fewer points of direct comparison with basic theory and correspondingly less guidance when moving into new operational regimes.

Peak electric and magnetic field strengths on the surface of the cavity are often of more immediate concern in an SCRF- than in an NCRF-cavity design. Too high of a peak magnetic field in an SCRF cavity can “quench” the cavity, or cause it to locally become non-superconducting. Multipacting can occur at modest surface electric fields, while high surface fields can lead to field emission. While field emission and multipacting can be problematic in any high gradient accelerator cavity, these effects can be especially pernicious within an SCRF accelerator for two reasons. First, even modest levels of field emission or multipacting can greatly increase the amount of RF power the cavity requires to attain a given gradient; second, the resulting heating from these phenomena increases the load on the cryogenics system and can quench the cavity. High multipacting currents can also pull the cavity resonant frequency off the design value.

Solenoidal magnetic fields are used in the immediate vicinity of essentially all NCRF photoinjectors as part of the emittance compensation process, as described in Chapter 1. Generally, these fields are applied as close to the cathode as possible. Typical installations also include employing a “bucking” solenoid sited on or near the back wall of the cathode cell to zero out the on-axis magnetic field at the cathode. In contrast, in designing SCRF accelerators, great efforts are made to keep magnetic fields away from the cavities, such as incorporating magnetic shielding into the accelerator’s support structures to reduce the earth’s magnetic field. This introduces challenges in designing both the accelerator structures and beam dynamics, as compromise is required.

Finally, an SCRF photoinjector must be operated at cryogenic temperatures; depending on the cavity resonant frequency and facility, this temperature might be 2K or 4K. However, in both cases, the injector cavity is surrounded successively by a liquid helium bath, a vacuum, a magnetic shield, a liquid nitrogen-cooled heat shield and another vacuum. The cryostat containing the gun will also incorporate layers of superinsulation, cavity tuning mechanisms and so forth. Both the design effort (for items such as cavity field probes, RF power couplers and laser injection ports) and routine maintenance (such as replacing the cathode) will be more complicated than for an NCRF injector.

None of these issues are insurmountable, but overall pose the question of whether it is worthwhile to choose an SCRF photoinjector since NCRF photoinjectors operate well. I believe the answer can be an emphatic “yes,” depending on the tasks the photoinjector is to perform. I consider several regimes in which an SCRF photoinjector is an eminently, or the only, practical choice.

3.2.1 High Average Current or High Duty Factor Operation

The amount of power required to generate a given beam current from an RF photoinjector is the sum of the RF power needed to generate the accelerating fields (which scales with the shunt impedance), the RF power delivered to the beam (beam loading) and the power required to extract waste heat from the cavity. For a superconducting accelerator, there is also a power cost associated with keeping the cavity cold, even when it is not operating.

Regardless of the required beam current, NCRF photoinjectors (and NCRF accelerating structures in general) typically require large amounts of RF power to maintain their accelerating fields at operating levels. For instance, a typical SLAC/BNL/UCLA "Gen-IV" S-band photoinjector has a shunt impedance of around 3 MΩ [3.1].[2] Therefore, to obtain a 5 MeV beam energy, approximately 8 MW of RF power must be delivered. This is not a problem if the photoinjector operates only for a few microseconds at a time. Most S-band NCRF linac installations use klystrons rated at 40-50 MW pulsed output, but with *average* power outputs on the order of several tens of kilowatts at most. 8 MW, continuous wave (CW) klystrons at any frequency are rare, which is one obstacle towards running such a photoinjector CW. Even assuming a 1 MeV beam energy, for example, was satisfactory, 350 kW would be required. This still is high power for a CW klystron.

Even positing the availability of a CW klystron (or other RF source) at the required frequency and power, the RF power lost into the walls of the photoinjector must be removed. At high duty factors, dissipating such heat is a non-trivial task; the Los Alamos CW NCRF photoinjector, operating at 700 MHz, requires more than 500 kW RF power simply to generate the desired accelerating fields of 5-7 MV m^{-1} needed to obtain the design beam energy of 2.7 MeV [3.2]. The gun's structure arguably consists of more water passages than copper. At gradients and frequencies much above these levels, heat cannot be removed quickly enough from the cavity's inner surface to sustain CW operation.

In comparison, the ELBE SCRF photoinjector has a shunt impedance of around 3.4 TΩ when at its operating temperature of 2.1 K. Therefore, obtaining its nominal accelerating voltage of 9.6 MV requires a mere 26 W of RF power [3.3]. Since each watt removed from a 2K operating bath requires approximately 1 kW at room temperature [3.4], only ~26 kW of input power is required to dissipate the heat generated from running the photoinjector CW at high gradients.[3] While this is a non-trivial refrigeration system, it must be compared to the multi-megawatt CW RF system and water-cooling plant a conventional copper linac would need to operate CW at ~10 MeV.

The outcome is that for pulsed beams, up to 0.1-1 kHz, an NCRF photoinjector is an excellent choice. As the RF duty factor increases (either due to a demand for higher average beam currents, or for higher bunch repetition rates), the challenges associated with cooling an NCRF injector and providing the required RF power outweigh those associated with operating a superconducting injector. The crossover point in this decision will vary, depending upon particular requirements and system parameters[4] (and the opinions of those discussing the choices), but generally will lie between 1 μA and 1 mA average beam current. At 10 μA, a 10 MeV CW injector requires 100 W for the beam, in addition to that required to sustain the

[2] For shunt impedance, I use the definition $r_s = V_{acc}^2 P_c^{-1}$, where V_{acc} is the accelerating voltage and P_c is the RF power. A common alternate definition has an additional factor of two in the denominator.

[3] This assumes no problems with – or additional power consumption by – field emission or multipacting.

[4] Among other factors, the crossover point will depend upon the RF frequency, Q of the cavity, the required electron beam bunch pattern, and average current.

accelerating fields. For an SCRF photoinjector that value most likely already would exceed the cavity's RF power requirements, whereas for an NCRF photoinjector, it barely would be a noticeable additional load on the RF system.

Typical envisioned applications for high average current machines include Energy Recovery Linacs (ERLs) for light source applications and accelerators for producing radioisotopes.

3.2.2 Small Stand-Alone Installations

The potential applications discussed below are highly speculative and have not been explored with the thoroughness of light source-related applications. However, it is the author's belief that, there is great potential for small, stand-alone applications of superconducting injectors.

Electron microscopy is a very interesting "non-traditional" application for high-brightness photoinjectors. Intrinsically pulsed and intended to deliver high quality beams at megaelectron volt range energies, RF photoinjectors increasingly are viewed as candidates for next generation time-resolved electron microscope sources [3.5]. Initial experiments using S-band NCRF photoinjectors proved promising [3.6], [3.7]. SCRF injector-based electron beam sources are natural candidates for electron microscopy applications because they can operate in CW operation and offer a range of options for adjusting the beam's repetition rate, average current and bunch charge.

A related application would be a modest energy SCRF injector as an electron beam welder. Electron beam powers of 100-1 000 W (0.1-1 mA beam currents at 1 MeV), combined with very low emittance, would allow the precise application of extremely high power densities; the megavolt range beam energy would allow deeper penetration of the electron beam into the joint being welded. The net result could be more efficient, faster and produce cleaner welding. Since electron beam welding is a primary fabrication technique for superconducting cavities, there is a certain bootstrapping appeal to this application.

In any such application, the injector likely would be operated as a stand-alone apparatus in a small facility (relative to most accelerators). A suitable selection of operating frequency will allow an SCRF photoinjector to operate at 4K, simplifying the needed cryogenic system. CW operation would require only modest RF power to achieve high average beam power, as discussed above. The size of the overall installation needed would be comparable to that of a stand-alone pulsed NCRF photoinjector; the advantage of the SCRF photoinjector is that, in principle, it could be operated CW with relatively minor expense, while the NCRF photoinjector likely could not be. Whilst SCRF injectors, and particularly these types of applications, are in the very early stages of development, the ability to generate low emittance beams at useful currents and powers in small installations might lead to many applications beyond those discussed here.

3.3 PRESENT STATE-OF-THE-ART

Seemingly a greater variety of SCRF photoinjector types is under development than there are NCRF photoinjector variants under investigation. While refinements continue to be developed and implemented for the latter, their designs generally have converged toward a pillbox geometry, with a cathode cell typically slightly longer than $\lambda/4$ integrated with one to two full ($\lambda/2$) cells. (There are exceptions, such as the LBNL's VHF gun [3.8].) The NCRF gun typically is followed by a drift space and linac structures to freeze the emittance *via* additional acceleration. This basic design works very well in practice. In contrast, SCRF photoinjector development is comparable to the state of NCRF photoinjectors two decades ago; there is much to learn, and what works "best" has not been determined.

The two major SCRF injector design paradigms are single-cell and multi-cell guns, often, but not always, followed by booster linac sections before the beam's entry into the main linac (*via*, *e.g.*, an ERL merger). The designs of multi-cell SCRF guns are often similar in concept to those of multi-cell NCRF guns. There are also variations in the design of the individual SCRF cathode cells; the two main variants currently being developed are elliptical cells and quarter-wave cells.

This section exhaustively lists the current projects worldwide developing SCRF guns. Many laboratories, universities and companies are engaged in such research, and every conference seemingly brings new ideas and participants. Rather, this section surveys the current major design paradigms for SCRF injectors, in particular guns, illustrating them with existing projects.

3.3.1 Multi-Cell Gun Designs

ELBE Injector

The ELBE SCRF photoinjector (also termed the Rossendorf or Drossel SCRF injector) was the first SCRF photoinjector in the world to operate as an injector. It produced first beam in November 2007 [3.9] and in 2010, the ELBE accelerator started operating with this source [3.10]. A cross section view is shown in Figure **3.1(a)**. The ELBE injector is powered through an ELBE 10 kW RF power coupler [3.11] that is visible entering the beam pipe at the downstream (right) end of the injector. The three full cells are TESLA-type elliptical cells. The cathode cell is a foreshortened elliptical cavity.

The ELBE injector operating frequency is 1.3 GHz, the same as the ELBE linac. The design energy is 9.5 MeV.

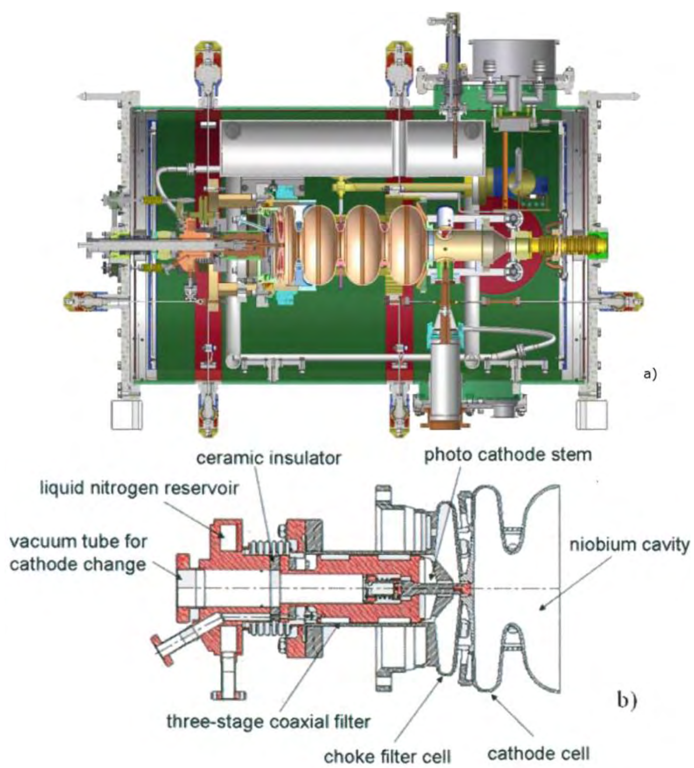

Figure 3.1. (a) A cutaway view of the ELBE SCRF injector. The ELBE RF power coupler can be seen entering the beam pipe, to the right of the third full cell. (b) Design of the EBLE injector cathode choke joint and cathode insertion mechanism. [[3.12]; Available under Creative Common Attribution 3.0 License (www.creativecommons.org/licenses/by/3.0/us/) at www.JACoW.org.] [Courtesy of A. Arnold]

The cathode in the ELBE injector does not touch the walls of the SCRF cavity; rather, an RF choke cavity (located to the left of the cathode cell in Figure **3.1**) provides RF isolation. The injector has operated with both Cu and Cs_2Te cathodes; the latter is the cathode of choice for operation due to its higher quantum efficiency (QE). No degradation was observed in the cavity's performance due to contamination from the cathode after 500 hr of operation. An external liquid N_2 reservoir cools the cathode. The design of the choke joint and the cathode's insertion mechanism is shown in Figure **3.1(b)**.

Several early variations of this injector's design incorporated RF-based focusing schemes near the cathode [3.13]. In the ELBE injector as built, a solenoid is located in the beamline after the 3.5-cell gun. An interesting method of performing emittance compensation was proposed, using this injector as the design platform. Rather than employing an electromagnet to generate a solenoidal field, a TE (magnetic) mode is excited in one of the cells in the gun. As the beam traverses this cell, as well as being accelerated, it receives a focusing kick suitable for emittance compensation [3.14].

The beam from the 3.5-cell ELBE photoinjector is directed into the ELBE linac without further acceleration.

BERLinPro Injector Test Gun

The HZB BERLinPro injector is envisioned as operating with a 1.6-cell SCRF gun, followed by a higher energy booster linac. The injector for BERLinPro must deliver 100 mA average current, with 1 μm emittance and 77 pC bunch charge. To support high average beam currents, the BERLinPro injector's baseline cathode is Cs_2KSb on a normal conducting insert. A staged approach towards attaining these parameters was adopted. In the first stage, the BERLinPro prototype gun is to be installed in the HoBiCaT cryovessel. The first prototype gun will have a portion of the back wall of the cathode cell coated with a Pb film to act as the cathode. RF power is provided *via* a coaxial coupler into the beam pipe.

The design frequency of the BERLinPro injector is 1.3 GHz for compatibility with the remainder of the linac. Its nominal beam energy is 1.5 MeV; the beam will be followed by a booster linac to raise the beam energy to 5-10 MeV [3.15]. The basic concept for the beam dynamics is similar to that of a typical 1.6-cell S-band NCRF injector.

As Figure **3.2** shows, a superconducting solenoid will be placed immediately downstream of the RF power coupler, providing the ability to perform emittance compensation. The solenoid is designed such that its fringe fields do not interfere when the cavity is transitioning to its superconducting state.

The next stage of the planned program of incremental improvements and upgrades includes implementing a gun with a K_2CsB cathode to support operations at high average currents.

3.3.2 Single-Cell Gun Designs

Single-cell guns arguably are preferable when high average current beams are required because this minimizes the amount of power that a single RF coupler must supply. They also are often used when a project's goal is to test aspects of SCRF injector technology related to developing cathodes or addressing electron beam formation, as fabrication generally is simpler than for multi-cell structures.

The primary disadvantage to single-cell gun designs compared with multi-cell designs is the relatively low beam energy that is produced, due to limitations on achievable gradients. For high bunch charges (~1 nC) especially, this can lead to difficulties in transporting the beam from the gun to the remainder of the injector.

Currently (at least) two types of single-cell gun designs are in development: Cells based upon elliptical geometries and cells based upon quarter-wave resonator geometries.

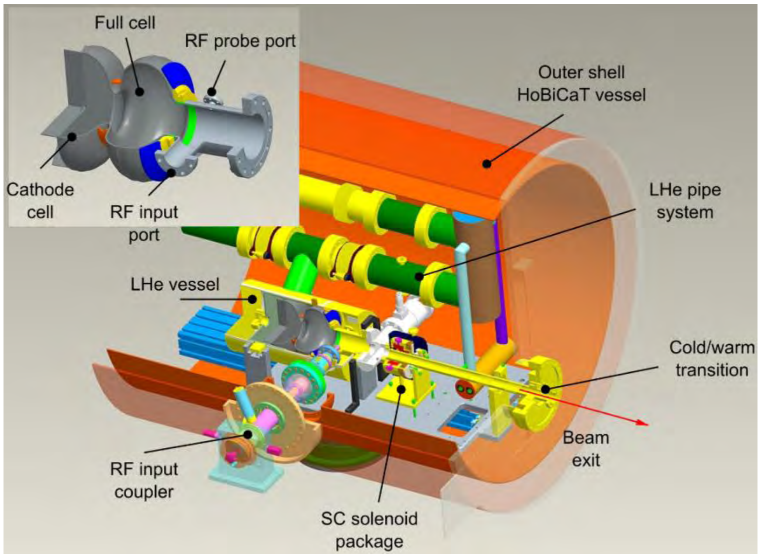

Figure 3.2. Conceptual design of the HoBiCaT SCRF injector test installation. [3.16]Courtesy T. Kamps]

3.3.2.1 Elliptical Guns

Elliptical guns, as the name implies, use elliptical-section cathode cells. The upstream and downstream ends of the cathode cell may or may not be identical in profile (*e.g.*, the wall angle may differ). As the beam starts out at rest from the cathode, the cavities typically have lengths of ~λ/4.

BNL/AES and DESY 1.3 GHz Single-Cell Guns; JLab 1.5 GHz Single-Cell Guns

The Brookhaven National Laboratory/Advanced Energy Systems (BNL/AES) single-cell 1.3 GHz SCRF guns, shown in Figure **3.3**, were not intended for use as part of stand-alone beam sources, or as parts of higher energy injectors. Rather, they were designed for research and development of SCRF gun technology. They have played, and are playing important roles in evolving the SCRF injector, with first beam being produced in 2005 [3.17].

Typical applications for these guns include testing cathode materials, such as gallium arsenide, in SCRF cavity environments [3.18], and cathode mounting techniques, such as quarter-wave chokes [3.19].

Similar guns were constructed at Thomas Jefferson National Accelerator Laboratory (JLab) and DESY [3.20], [3.21] as part of the path towards higher energy, multi-cell SCRF injectors.

A gun of this type, using a lead (Pb) cathode, will be installed in the HoBiCaT cryostat as the first stage of the BERLinPro Project.

BNL/AES 703.75-MHz High Current Injector

Unlike the 1.3-GHz test cells, the BNL/AES 703.75-MHz SCRF gun is intended to serve as a true stand-alone injector. The nominal application for this gun is to provide beam to a high current ERL (up to 500 mA). Hence, high bunch charges and high average currents are required. As envisioned, the gun sends its beam directly to an ERL merge and then into the main linac, at an energy of 2 MeV [3.22]. Figure **3.4** is a cross sectional view of the gun's cavity and its cryostat. The cavity fields and cathode choke joint are shown in Figure **3.5**, along with photographs of the two prototype cavities. One of the prototype cavities was fabricated from large grain niobium.

The 703.75 MHz injector employs two high power RF couplers, located in the beam pipe immediately after the gun cavity. With a nominal beam current of 0.5 A, each power coupler is required to deliver 500 kW.

The flared beam pipe shown in Figure **3.5** is intended to improve extraction of higher order mode RF power from the gun cavity.

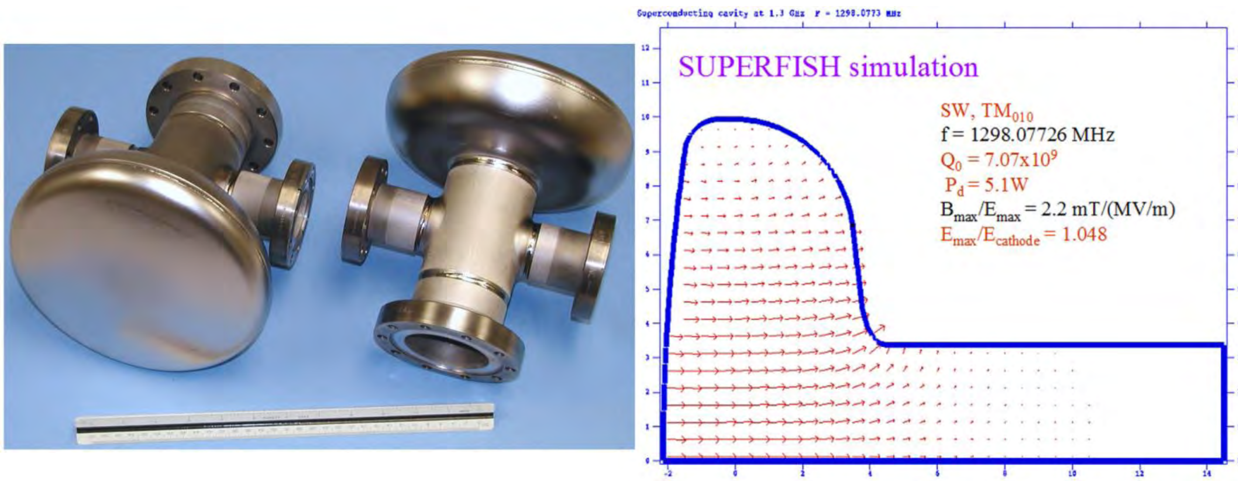

Figure 3.3. Pictures of the BNL/AES 1.3-GHz SCRF guns (left) and as-designed field profile (right). The field profile plot, generated by SUPERFISH, shows the electric field *E*(*z*,*r*) vectors within the cavity. SUPERFISH assumes cylindrical symmetry about the *z* (horizontal) axis, so effects of the coupling ports are not included in the model. [Reprinted from [3.17], with permission from Elsevier.]

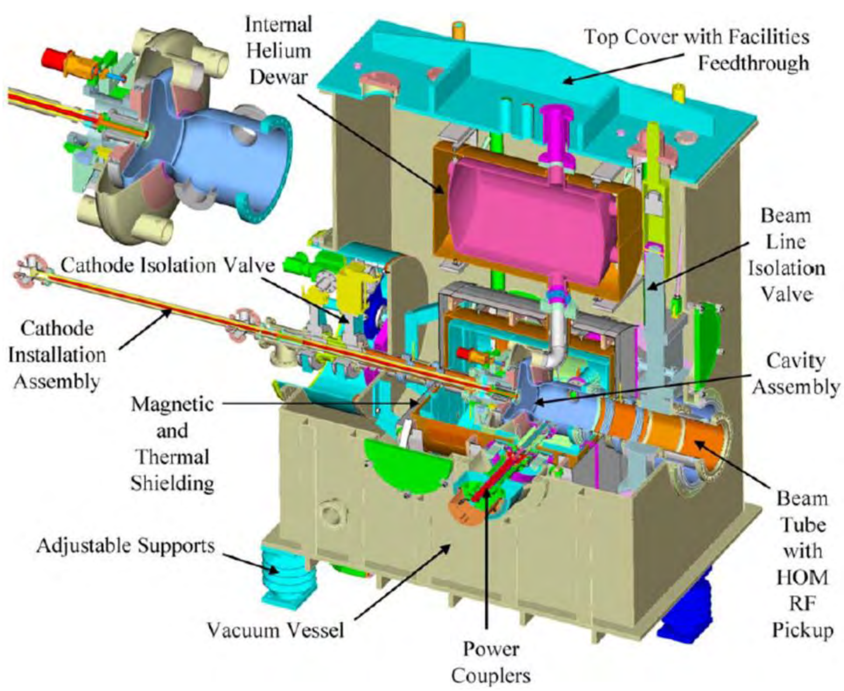

Figure 3.4. BNL/AES 703.75 MHz SCRF gun design. The inset figure shows the gun cavity itself. The cryostat includes a built-in load-lock to facilitate cathode exchange. [Reprinted from [3.23], with permission from Elsevier]

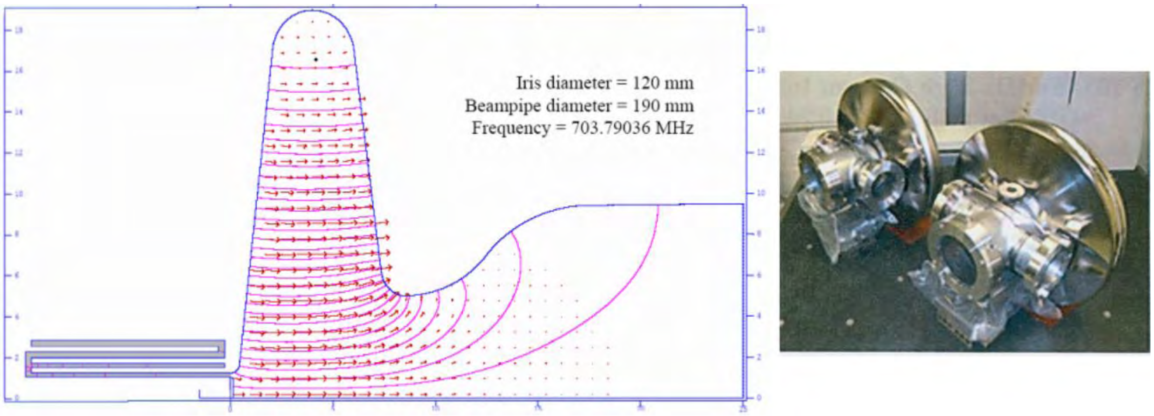

Figure 3.5. SUPERFISH plot of cavity fields and quarter-wave choke joint of the BNL/AES 705.75 MHz gun (left), where the solid lines indicate constant H_z and the red arrows indicate electric field strength and direction; photographs of the two prototype cavities (right); the rightmost prototype was fabricated from large grain Nb. [Adapted from [3.23], with permission from Elsevier] [Courtesy I Ben-Zvi]

A novel cathode concept, the diamond amplifier cathode, was developed to be the beam source for this with this gun [3.24]–[3.26]; details are given in later chapters. As opposed to a choke cavity, as is used in the ELBE injector design, the 703.75 MHz gun uses a folded quarter-wave choke joint that offers a more compact installation, but does not as directly permit adjustment of the cathode's longitudinal position. This gun cavity has successfully completed its vertical dewar tests and first beam is anticipated in 2011 [3.27].

The ultra-high vacuum (UHV) load-lock system is an important part of any gun system employing high quantum efficiency cathodes; load-lock systems for superconducting gun present additional challenges due to the extreme sensitivity of the SCRF cavity to contamination. A load-lock system was developed for the BNL/AES 703.75 MHz SCRF gun that encompasses both a preparation chamber and a cathode transporter.

3.3.2.2 Quarter-Wave Cavities

Quarter-wave (QW) SCRF gun cavities are based upon designs originating in the heavy-ion accelerator community, wherein quarter-wavelength structures are used for low-β acceleration of ions. However, in an SCRF injector application, the direction of beam propagation is parallel to the axis of the QW cavity, rather than perpendicular to it.[5] Two such guns were fabricated, one of which has generated beam; at least two others are under development.

Compared to a cell with elliptical geometry of the same diameter, a QW cell can be designed to have a considerably lower operating frequency, permitting the use of a more compact cryomodule. Another potential advantage of the QW structure is the ability to easily fabricate cavities with small accelerating gaps, leading to high transit-time factors. (In contrast, for elliptical cells, the cell's length effectively is the gap length, so that attempting to reduce the accelerating gap tends to result in a "pancake" cavity shape.) This arrangement may allow beams to be launched from the cathode at larger RF phases (measured from the zero-crossing) and may be beneficial for alternate cathode types, such as field emitters.

NPS / Niowave / Boeing (NNB) Mark I

The Naval Postgraduate School Mark I SCRF injector, built by Niowave, Inc. and operated in collaboration with The Boeing Company, produced its first beam in June 2010. The Mark I was intended primarily as a

[5] For researchers familiar with electron linac design, as employed as SCRF gun cavities, quarter-wave structures can be thought of as asymmetric highly reentrant cavities.

research and development tool to explore issues in designing and operating SCRF guns in general, and QW SCRF guns in particular, although it can serve as an injector for the NPS Beam Physics Laboratory's linac. It uses an on-axis coaxial RF power coupler and has a resonant frequency of 500 MHz. This low frequency allows operation at 4K, thereby greatly simplifying the requirements of the cryogenic support system. Nominal beam energy is 1 MeV, with a maximum attained energy of 0.5 MeV to date. A cross sectional view and photograph of the NNB Mark I are shown, respectively, in Figure **3.6(a)** and Figure **3.6(b)**; the geometry of the cathode and power coupler geometry is depicted in Figure **3.7** [3.27].

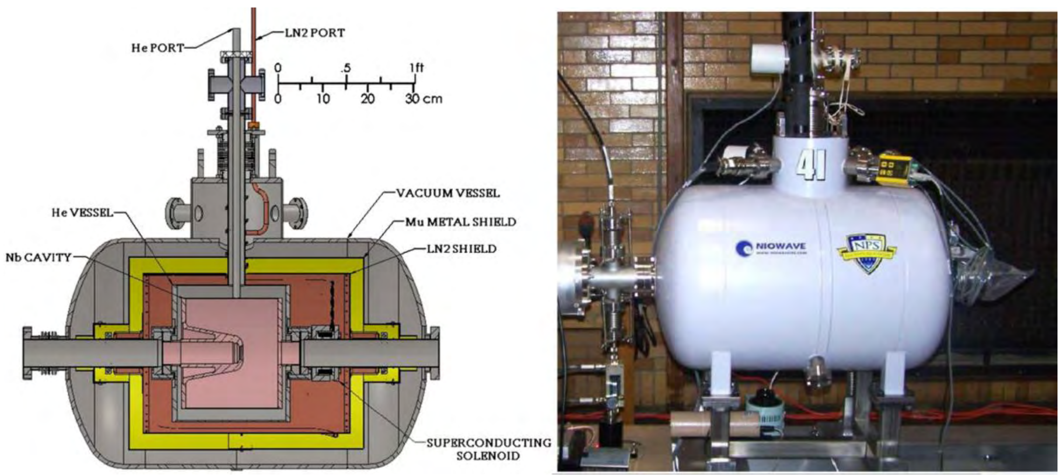

Figure 3.6. NNB Mark I quarter-wave gun: (a) cross section of cryomodule and (b) assembled injector. [Reprinted figures with permission from [3.27]. Copyright 2011 by American Physical Society.]

The accelerating gap in the Mark I is very short compared the wavelength; at ~$\lambda/7$, it is approximately half the length of a "normal" 500-MHz cathode cell, thereby resulting in a very high transit time factor compared to $\lambda/4$ cathode cells.

A significant advantage of the on-axis RF power coupler is that it allows placement of a superconducting solenoid close to the cavity, thereby aiding the emittance compensation process. The impact of the solenoid upon the cavity's performance was tested by repeatedly allowing the cavity to quench with the solenoid energized and measuring the cavity's *Q* between quenches. A moderate decrease in cavity performance was noted, however, the original cavity *Q* was recovered simply by degaussing the solenoid with the cavity quenched [3.29].

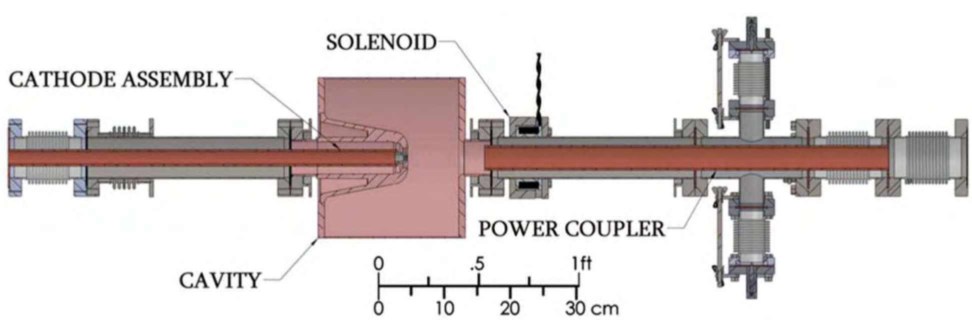

Figure 3.7. NPS Mark I cathode and on-axis power coupler geometry. The cathode assembly can also serve as a cavity field probe, as it forms a coaxial transmission line. [Reprinted figure with permission from [3.27]. Copyright 2011 by American Physical Society.]

The NPS Mark I does not use a sophisticated cathode joint arrangement. Rather, the cathode simply extends on a stalk of length λ. Since this configuration forms a coaxial transmission line, RF fields will be present all along the cathode stalk, resulting in up to several hundred watts of RF power dissipation on the normal-conducting cathode at the design cavity gradient. To reduce this RF power loss, the cathode's surface area was reduced and the radius of the cathode's stalk was stepped at several locations (not shown in Figure **3.7**).

First beam was produced with an Nb cathode; future plans include testing higher-QE metals, as well as semiconductor and field emission cathodes. Initial operation was limited to 0.5 MeV beam energy due to the available RF power, field emission and local radiation shielding, with detailed measurements performed at 0.3-0.5 MeV [3.27]. Continued testing is planned at higher energies.

Other Quarter-Wave Guns Under Development

Brookhaven National Laboratory and Niowave Inc. constructed a 112 MHz SCRF gun using a QW geometry, also intended as a candidate injector for an electron-cooling ERL. The nominal beam energy is 2.7 MeV. This gun is essentially completed and awaiting its initial cool-down tests. Its cross section is shown in Figure **3.8(a)**.

Figure **3.8(b)** shows the cross-section of the University of Wisconsin's (UW) SCRF gun, intended to serve as the beam source for the proposed WiFEL linac-based light source. The UW gun operates at 200 MHz and has a nominal beam energy of 4 MeV.

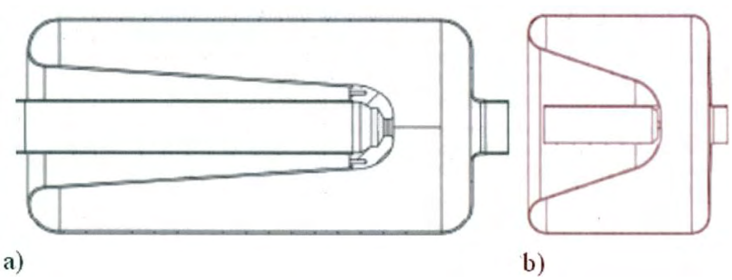

Figure 3.8. Profiles of (a) the Brookhaven 112-MHz and (b) University of Wisconsin 200-MHz quarter-wave injectors. The shaded region in the center is represents the cathode. For scale, the accelerating gap in the 112-MHz Brookhaven cavity is approximately 16 cm. [Courtesy of Niowave Inc.]

Finally, based on the rapid development cycle and initial success with the Mark I, NPS and Niowave have begun working on the design of a Mark II QW SCRF injector, to operate at 700 MHz. The Mark II resolves many of the issues encountered during the fabrication and initial operation of the Mark I version. The design retains the small accelerating gap at ~λ/6.

3.3.3 Hybrids

The hybrid DC/SCRF is an interesting concept that has seen substantial development. In this design, the cathode is replaced *in toto* by a miniature DC gun for the initial acceleration of the beam. The Peking University group reported developing such designs, most recently with a 3.5-cell SCRF cavity based on the design of the ELBE SCRF photoinjector [3.30].

3.4 INITIAL QUESTIONS TO CONSIDER

This section presents some questions that should be considered before the SCRF photoinjector design process begins. The answers are subject to change both because the project goals may change, and because as the design process evolves, better or alternate approaches may be found.

3.4.1 What are the Performance Goals for the Injector?

These are some of the most fundamental questions to ask at the start of the design process. Typical parameters include bunch charge, length and energy spread; transverse emittance; and, the required Twiss parameter values and tolerances at the entrance to the main accelerator.

Two parameters of particular note are the required average beam current and kinetic energy. Together, they establish the total RF power required to accelerate the beam. They also strongly influence the choice of whether to design the injector as a single multi-cell cavity (as in the ELBE design), as a series of single cells, each with its own RF power feed, or as a combined approach with (for instance) a single-cell "gun" containing the cathode followed by multi-cell structures.

There is insufficient experience as yet to suggest which approach might be "best," (furthermore, the answer most likely depends upon the application), but considering the state-of-the-art of RF power coupling suggests that requiring no more than 100 kW per power coupler should provide a good margin of safety.[6] Thus, having a requirement for 100 mA beam current at 10 MeV would suggest using a series of individual cells, while a 10 mA beam current at 10 MeV would suggest the feasibility of an integrated design. (A design based around individual cells might still be preferable for other reasons, depending upon the application.)

3.4.2 What System Characteristics are Already Fixed? What Might be Changed Later?

It is important to know which parameters have been previously fixed, and which are subject to change during the course of the injector design process. This does not refer to the injector's performance goals (which are also subject to change), but rather, to the physical conditions under which it will operate.

While it is quite likely that key parameters, such as frequency and operating temperatures, are already set, it is worth asking whether there are good reasons why the photoinjector could, or should, be different from those used by the rest of the accelerator.

3.4.2.1 Is the Linac Frequency the Best Choice for the Injector's Frequency?

The injector's operating frequency is seemingly a simple and obvious selection; make it the frequency of the remainder of the linac. However, using an integer subharmonic frequency to the main linac frequency might be considered if there are advantages in doing so for beam dynamics or other parameters.

For instance, the accelerator modules intended for use in the Naval Postgraduate School linac are Stanford/Rossendorf style cryomodules, with an operating frequency of 1.3 GHz. The NPS/Niowave Mark I SCRF QW injector, in contrast, was designed to operate at 500 MHz. The common frequency with the linac is 100 MHz, a suitable repetition rate for the intended experimental program.

The lower frequency of the Mark I photoinjector allows its operation at 4.2K (*e.g.*, at standard atmospheric pressure over the helium reservoir), so it can be tested and characterized well in advance of constructing the linac's cryoplant.

[6] This is another area of lively debate and anticipated experimental demonstration. Megawatt class couplers were built and tested on test stands, but to date no SCRF injector has been operated at even the level of 100 kW beam power.

3.4.2.2 What is the Injector's Operating Temperature?

Generally, lower frequency cavities can be operated at 4K, while higher frequency cavities must be operated at 2K to generate useful accelerating gradients. While there is no single cutoff point – and the answer will depend upon the frequency, gradient and duty factor needed – the general consensus is that below 500 MHz, 4K will suffice; above 1 GHz, 2K is required. The answer to temperatures in between depends on the system's particulars.

There are significant advantages to operating at 2K. Superfluid helium allows for excellent heat removal, and RF losses are lower at lower temperatures; a lower temperature allows higher operating gradients and peak surface magnetic fields. However, operating at 2K also has several disadvantages in terms of the required complexity, and corresponding cost, of the refrigeration system. A 4.2 K injector can be operated simply by supplying liquid He at room pressure into the injector's cryostat from a nearby dewar. At a minimum, an injector requiring 2K to operate requires a vacuum pump system to lower the gas pressure on the liquid helium bath.

If the photoinjector is to be part of a larger SCRF installation, then whatever temperature the remainder of the system uses probably is the best choice for the injector.

3.4.3 What Degree of Operational Flexibility is Desired?

Many injectors, if not most, are eventually operated under conditions different from their nominal design. Certainly this will be the case during initial commissioning of the injector, and is expected. However, in-service operation may be considerably different than originally envisioned because the application that the injector supports operates better under different conditions. A recent example is the Linac Coherent Light Source at the SLAC; by operating the injector at a reduced bunch charge from the nominal 1 nC case, wakefield effects in the main linac are reduced and a higher quality beam can be transported to the undulator.

Fortunately, most injectors tend to be flexible in terms of their operational regimes; SCRF photoinjectors may pose several extra challenges due to the constraints under which they are fabricated and operated. From the standpoint of beam dynamics, changes to the bunch charge density and average beam power are of particular concern.

Some SCRF photoinjector designs incorporate cathode-region focusing, *via* the RF field, to either augment or replace solenoid-based emittance compensation. As with the classic Pierce DC electrode geometry, the method attempts to balance the radial RF electric field against the radial space charge force within the electron bunch. If the electron beam's charge density is changed from its design value, the RF focusing strength will be incorrect. The ratio between longitudinal (accelerating) and radial (focusing) field strengths can be adjusted by moving the cathode longitudinally, but this action also impacts the cavity's tuning and, potentially, RF power dissipation on the cathode.

Similarly, operating the cathode cell at a different gradient from its design point will impact any RF-based emittance compensation scheme.

To first order, RF power coupling should not require modification so long as the average electron beam power (the product of the average beam current and voltage) remains constant. However, altering the bunch charge and repetition rate can change the generation and impact of wakefields, particularly for high average current injectors, even if the average current remains constant.

3.4.4 What Cathode(s) will be Used?

Photocathode selection is largely a function of the required average beam current. Traditional photoinjector cathodes include metals (usually copper or magnesium in NCRF injectors, but niobium and lead have also been used in SCRF photoinjectors); thin-film semiconductors (Cs_2Te, CsKBr); and crystalline structures (*e.g.*, Cs:GaAs). More complex cathodes are under development, such as the Brookhaven diamond amplifier, but have not been demonstrated in SCRF injectors. Cathodes are well treated in Chapters 5 through Chapter 8, so relative performance characteristics will not be reviewed in detail here.

However, there are two points to consider regarding the use of any type of cathode in an SCRF photoinjector.

First, the cathode will be operating within a cryogenic environment. If high average currents are required, high power photocathode drive lasers may also be required to obtain that current. At milliampere currents, several Watts of laser power may be required; at hundreds of milliamperes, a 100 W drive laser might be required. This laser power, deposited on the cathode, represents an additional heat load that must be removed from the cavity. A contact cathode joint will dump that heat, *via* conduction, into the cavity's liquid helium bath. A non-contact cathode may require external cooling, perhaps through a liquid nitrogen cooling circuit, to avoid overheating the cathode within the cavity. Most SCRF injectors intended to use removable cathodes have used non-contact cathode designs.

Second, SCRF cavities are sensitive to contamination from dust and from deposition of materials liable to increase field emission, such as cesium. Inserting and replacing cathodes introduces the possibility of generating dust. Concern has also been expressed regarding the use of cesiated cathodes, which includes essentially all non-metal cathodes, in SCRF cavities. The worry is that Cs emitted from the cathode will redeposit in high field regions. Results from the ELBE SCRF photoinjector indicates that operation with Cs_2Te cathodes appears to viable; but again, experience with other cathodes in SCRF photoinjectors is very limited.

3.4.5 What is the Cathode's Position? Should it be Adjustable?

In most conventional NCRF photoinjectors, the cathode is usually flush, or nearly so, with the back wall of the cathode cell, providing an RF field commensurate with the basic emittance compensation theory. In particular, as shown in Figure **1.6** in Chapter 1, the radial RF fields near the cathode are very small.

By recessing a cathode somewhat behind the back wall of the gun cell, radial RF fields can provide initial focusing to the electron beam as it leaves the cathode, much in the way Pierce geometry functions in a DC electron gun. Early designs of the ELBE photoinjector considered implementing this scheme [3.13], and the initial simulations were promising. While some of these simulations assumed a curved cathode, the technique can operate well even with planar cathodes, as focusing is provided by the change in longitudinal gradient along the axis.

Moving the cathode longitudinally to adjust the RF focusing has two consequences. First, the cathode will act as a tuner, changing the cavity's resonant frequency; in a multi-cell photoinjector, compensating for this could be difficult as the RF field balance between the cells could also be affected. Second, moving the cathode changes the longitudinal field gradient on the cathode's surface. In addition to affecting initial acceleration, this can also strongly influence the RF power dissipated on the cathode in some designs and will change the space charge limited emission current density. Finally, altering the cathode's position can vary the strength of nonlinear radial components of the RF field.

If positioning the cathode at a particular location to obtain a given RF field configuration is an integral part of the beam physics design, early studies should include alternate charge scenarios to determine whether the cathode can remain in place under those conditions.

3.4.6 How will the Cathode be Mounted?

In several SCRF guns the cathodes are deposited directly upon the back wall of the cathode cell, as in the BNL/AES 1 300 MHz gun tests with Pb cathodes; however, this method does not lend itself to readily changing cathodes. The general assumption for high average current operation is that the cathode must be intermittently replaced or rejuvenated. In such cases, for instance in a user facility, a removable cathode is almost essential.

To date, three basic cathode mounting and isolation schemes have been used in SCRF injectors: Rossendorf-style choke cavities (as exemplified by the ELBE injector); quarter-wave folded chokes (as in the BNL/AES 703.75 MHz injector); and, cathode-on-a-stick (as in the NPS/Niowave/Boeing Mark I). None of these designs are contact cathodes, in the sense that there is no direct electrically conductive path between the cathode's outer rim and the body of the cathode cell. In all three schemes, the termination is far from the cathode's surface and the cathode forms a coaxial transmission line into and out of the cavity, along which RF induced currents will flow: the three schemes differ in the approach they take to dealing with, and terminating, that flow. All three schemes will impact the RF field near the cathode, to a greater or lesser extent, compared to a cathode flush with and in direct contact with the back wall of the gun cavity. At least an approximation of the selected cathode mounting scheme should therefore be included from the start of the design process.

A significant advantage of a non-contact cathode is that the cathode's temperature need not be the same as the cavity temperature. Indeed, the Mark I cathode is not cooled; the ELBE and BNL/AES injectors both incorporate provisions for liquid N_2 cooling. Particularly for operation at high average beam currents, when significant drive laser power may be directed onto the cathode, thermal isolation between the cathode and gun may be advantageous. A second, non-trivial advantage is that the cathode's contact point is far from the cavity. Barring a misalignment that scrapes the edge of the cathode during its insertion or removal, the non-contact cathodes minimize the potential for introducing dust or other contaminants into the cathode cell.

In principle, the cathode-on-a-stick approach allows ready change of the cathode's position along the axis of the cavity. This can aid in implementing RF focusing schemes, but the lack of a hard stop may make repeatable transverse and longitudinal positioning challenging. Further, in addition to changing the cavity's frequency, moving the cathode longitudinally changes the amount of RF power dissipated along the cathode stalk. Multipacting is also a serious concern with this design, although to date it has not been observed in the Mark I injector.

The choke cavity and folded choke designs both address the issue of RF power loss along the cathode stalk, and should provide improved repeatability and transverse alignment, but they are mechanically more complex. In operation, the Rossendorf-style choke cavity has proved successful; the folded choke design suffered from multipacting during initial testing, but the issue is being addressed.

3.4.7 Is a Single-Cell or Multi-Cell Gun Design Preferred?

The theoretical maximum accelerating gradient in a given SCRF cavity design depends upon the frequency, temperature, geometry and, in particular, the ratios between the peak on-axis and surface fields. The achievable beam energy gain will depend upon the gradient achieved in practice, the acceleration gap and the launch (or injection) phase of the electron beam.

Generally, the cathode cell in an SCRF photoinjector is expected to provide initial beam energies of 1-2 MeV, and each full cell ($\lambda/2$) is expected to deliver at most between 2-3 MeV additional energy gain. More conservative designs, multi-cell designs, or those which are expected to be heavily beam-loaded (such as the BERLinPro injector) often have lower energy gain design goals. Single-cell gun designs typically try to push the output energy as high as possible to help ameliorate space charge effects in the drift space to the first booster cavity.

In a multi-cell gun design, such as the ELBE 3.5-cell injector, RF power is supplied to the gun as a whole and cell-to-cell coupling provides RF power to each of the individual cells. This arrangement has the advantages of providing the highest possible real-estate gradient, and therefore the fastest acceleration to the injector's output energy. Minimizing the distance the beam spends at low energy helps to preserve beam quality, particularly for bunch charges in the nanocoulomb range. The gun may be followed by an energy booster (as in the BERLinPro design), or may serve as the entire injector (as in the ELBE design).

In many injector designs based on single-cell guns, such as the AES designs for high power ERLs, the injector consists of a cathode cell followed by a drift space and an energy booster. The booster consists of independently powered cavities, often (but not mandatorily) single cells; an example of such a booster is shown in Figure **3.9**.

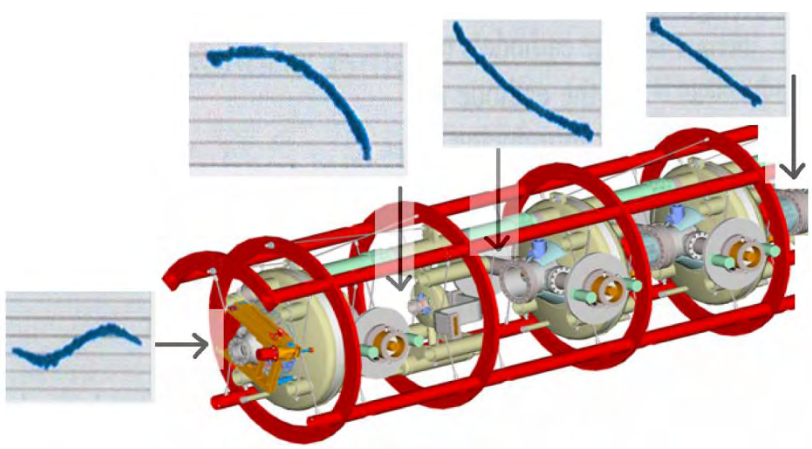

Figure 3.9. An example of an energy booster, as designed by Advanced Energy Systems. In this particular design, the gun would sit in a separate cryomodule located to the left of the booster. This design incorporates three energy booster cavities at the frequency of the injector and a third-harmonic cavity used to assist with longitudinal phase-space control. [Adapted from [3.23], with permission from Elsevier]

Independent control of RF power and phase to each cavity in the booster offers additional tuning "knobs" that can be used to exercise a high degree of control over the beam's energy spread and, to an extent, the bunch length at the exit of the injector. In Figure **3.9**, for instance, the booster cell gradients and phases have been selected so as to linearize the longitudinal phase space for the beam. There is also (theoretically) space between the booster cavities for additional diagnostics as well as RF power couplers, solenoids, *etc.* Thus, this approach may be very attractive for injectors for ERLs, as it permits greater control over the beam parameters at the end of the injector. However, greater control comes at the price of significantly increased complexity of the cryomodules and RF systems. Further, the increased distance between cells lowers the real-estate gradient, thus production of high charge, low emittance beams may be more difficult due to the increased drift distances at low energy.

3.5 CAVITY GEOMETRY CONSIDERATIONS

This section discusses several effects of particular concern to the design of the cavity itself, and is primarily written for the NCRF injector (and, in particular, gun) designer making forays into the realm of SCRF injector design.

As mentioned above, lack of space precludes a comprehensive discussion; the SCRF injector designer is strongly encouraged to obtain a copy of *RF Superconductivity for Accelerators***,** by Padamsee, Knoblock and Hays.

3.5.1 Field Emission and Multipacting

All RF cavities can experience field emission and multipacting, and are subject to performance limits based upon peak surface fields. However, there are significant differences in practice between SCRF- and NCRF-cavities.

For field emission, the electron current depends upon the gradient of the electric field applied to the surface. Field emission (FE) current generally follows the Fowler-Nordheim law, so small increases in gradients can lead to exponentially larger currents. FE current in an SCRF injector may exit the cavity into the beam pipe following the injector (in which case, it is also called dark current), or may impact on the wall of the cavity. FE current is therefore problematic for three reasons: First, it consumes RF power *via* beam loading; second, it deposits additional heat inside the SCRF cavity, potentially quenching it and definitely leading to higher liquid He consumption and cooling requirements; third, the impact of the field emission current inside the cavity can generate significant amounts of radiation, in turn driving radiation shielding requirements. The magnitude of field emission depends upon both the smoothness (in the sense of surface field enhancement) and cleanliness of the SCRF cavity's interior, as well as the operating gradient.

Multipacting, in contrast, is a resonance phenomenon, representing a buildup of electrons being emitted into the cavity and eventually returning to their starting point, with impact of each electron resulting, statistically, in the emission of more than one electron. It is encountered more often at low accelerating gradients, although any RF cavity will have low field regions, even when operating at its design gradient.

The probability of electron emission, and thus the buildup of multipacting current, depends on surface conditions and impact energy. As the multipacting current builds, RF power is absorbed and the cavity eventually will quench or move off resonance. The general solution is to design the cavity such that no simple resonant paths are available. This means, among other things, avoiding parallel walls and right angles. TESLA cavities, for instance, were designed with a primary goal of avoiding a multipacting-supporting geometry.

Both field emission and multipacting can sometimes be conditioned away by RF processing techniques, but this is not guaranteed. Multipacting can be addressed partly by choosing a cavity geometry that lowers the likelihood of a supporting a viable multipacting path. Field emission can be addressed, in part, by choosing a cavity geometry that is easy to clean and by using good cavity processing techniques.

3.5.2 Power Dissipation

Unlike NCRF cavities, typical power consumption by SCRF cavities is usually on the order of tens of Watts (barring field emission and multipacting). However, that heat must be removed if the inner cavity surface is to stay superconducting. This means choosing designs that minimize the distance between the interior surface of the cavity and the liquid He bath. In the NPS Mark I injector, for instance, the inner third of the nose cone is a concern as it is fabricated from relatively thick, solid niobium. While surface currents are relatively low there, the nose cone will still experience some heating, perhaps augmented by field emission as this is a high electric field region.

3.5.3 Emittance Compensation

Classic emittance compensation relies upon employing an externally applied radial focusing magnetic field, combined with evolution of the beam through a subsequent drift space, to "re-align" longitudinal slices of the electron beam's transverse phase space. Ideally, this focusing is applied as soon as possible after the beam is generated and given its initial acceleration.

Unfortunately, this is problematic in SCRF injectors. Besides the potential for reducing the cavity's Q due to stray magnetic fields from the solenoid, the use of transverse coaxial power couplers further extends the distance between the cathode and the first available beamline location for a solenoid. Nevertheless, good beam dynamics solutions were found with the solenoid relatively far from the cathode, as in the Brookhaven 703.75 MHz design, while alternate power coupler geometries, such as the NPS Mark I on-axis coupler, allow closer placement of the solenoid.

One trick for modeling solenoids in the proximity of SCRF cavities may prove useful. Putting the SCRF cavity's geometry (perhaps simplified) into the magnetostatic model of the solenoid with an infinitesimal magnetic permeability (μ) will exclude the flux from the cavity walls. By re-running the model with the permeability set to unity, an easy analysis can be made of the potential for "flux leakage" inside the SCRF cavity if it were to quench with the solenoid turned on. This also determines perturbations to the solenoid field caused by the presence of a superconducting cavity, potentially important when the goal is to generate very low emittance beams.

Figure **3.10** shows a simple example, using the POISSON model of the NPS Mark I solenoid. The image on the left shows the field of the solenoid, distorted by a superconducting disk placed within the solenoid's bore. The image on the right is the same model, but with the permeability of the disk set to unity.

The recent studies of emittance compensation using TE-mode magnetic fields are intriguing. To date, there is no published study of this technique applied to a single-cell SCRF gun, but, in principle, there is no reason why it could not work there as well as in the multi-cell ELBE SCRF injector cavity. Further study of this method is needed as it both avoids the issue of requiring DC magnetic fields near the cavity and could allow the application of magnetic focusing much closer to the cathode.

3.5.4 Power Coupler Options

Chapter 10 covers RF power coupling thoroughly: here, I briefly overview the advantages and disadvantages of two prevalent designs.

The TESLA-style transverse coaxial coupling scheme for SCRF cavities has been a popular choice for SCRF injector design. In the transverse coax coupling scheme, a coaxial line perpendicular to the axis of the cavity transfers power into the beam pipe immediately downstream from the gun cavity. (For an energy booster, couplers could be placed either upstream or downstream of the cavity.) It is well understood and successful in practice. Due to their location in the beam pipe, TESLA-style couplers also provide a relatively obvious location for RF field probes. The drawback of this scheme is that the couplers perturb the RF fields, breaking radial symmetry and potentially generating increased emittance. Their location generally restricts siting other components, such as solenoids, to locations further downstream from the cavity.

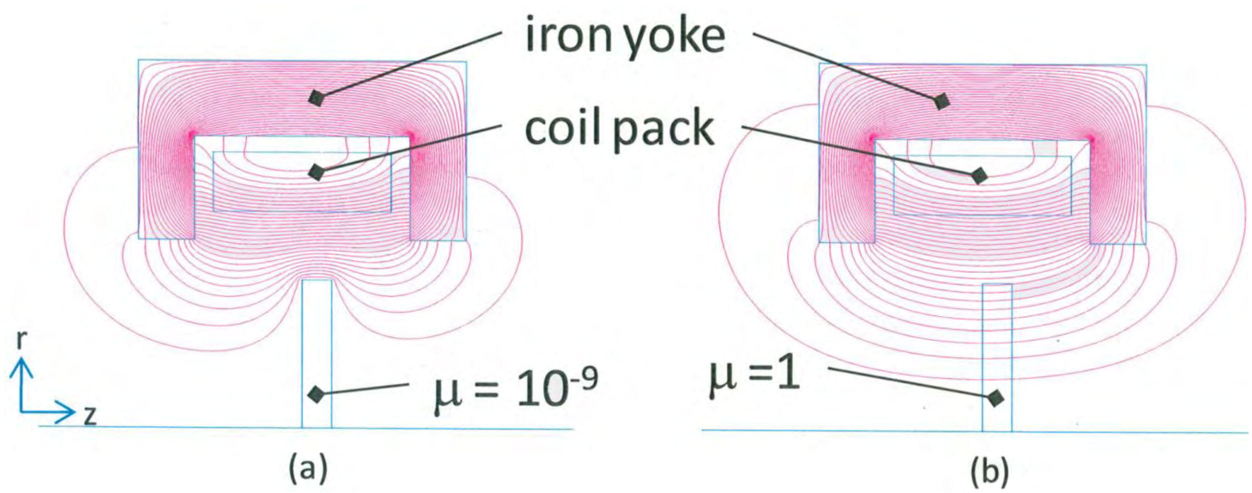

Figure 3.10. POISSON model of the NPS Mark I solenoid, with a disk placed off-center along the axis. The disk is (a) superconducting and (b) non-superconducting and non-magnetic. Blue lines indicate geometry; pink lines are contours of constant rA_ϕ (radius times the azimuthal component of the magnetic vector potential).

The on-axis coaxial coupler design (also used highly successfully in the TESLA Test Facility NCRF photoinjectors) uses a hollow coaxial line parallel to the beam axis to deliver RF power to the injector. RF power flows to the cavity between the outer wall and the center conductor; the beam travels through the center of the hollow center conductor. Under ideal conditions, this scheme maintains radial symmetry. Further, solenoids can be placed closer to the cavity if desired. Disadvantages include a smaller diameter passage through which the beam can travel, and the possibility of breaking radial symmetry anyway if the central conductor is misaligned.

Jefferson Lab-style (JLab) waveguide couplers have been conspicuous by their absence in SCRF photoinjector designs; the reason for their exclusion is not clear. Many SCRF photoinjector designs were undertaken at institutions that typically employ transverse coax power couplers for their other SCRF cavities rather than waveguide couplers, suggesting unfamiliarity with the latter might be a partial explanation.

3.5.5 Injector Cryomodule Diagnostics

Throughout the remainder of this chapter, “diagnostics” refers primarily to devices used to characterize the electron beam produced by the injector. Chapter 11 discusses such devices.

The cryomodule(s) containing the injector cavities will also require diagnostics to determine how well the injector is performing in terms of its cryogenics and RF characteristics. Cryogenic and RF diagnostics are important components of the SCRF photoinjector and should be incorporated into the design of the cryomodule(s) housing the photoinjector cavities from the start of the design process.

Typical cryogenic diagnostics include temperature sensors and helium level sensors. Temperature sensors should be placed not only on the injector cavities themselves, but also on critical components in close proximity to the injector cavities, such as superconducting solenoids, cathode support structures and electron beam diagnostics. Data from temperature sensors can be used to monitor conditions when the SCRF injector is operating normally, or to help resolve problems. For example, temperature sensors placed along the beam pipe could help diagnose problems with excessive FE current, or in a high current injector, problems with trapped modes or wakefields.

RF probes are very weakly coupled ports into the cavity radio frequency envelope. They can be placed in the beam pipe or directly embedded into the cavity wall to measure the evanescent field from the cavity. RF probes are potential sources of problems, in particular vacuum leaks, as they represent extra openings into the superconducting cavity's RF environment. However, RF probes, properly designed and placed, can provide important information about the electromagnetic fields within the SCRF injector cavities. As such, they are often of great use when attempting to diagnose why a cavity is not performing as anticipated.

3.6 DESIGN PROCESS

The notes and suggestions below are primarily from the perspective of a beam dynamicist, *i.e.* one whose area of expertise lies in the generation and transport of the electron beam itself, as opposed to the fabrication and operation of the structures generating the various required fields. In practice, the development effort must be a collaboration between beam dynamicists, SCRF scientists and the designers of the mechanical systems because a change in any part of the system can dramatically affect every part of the injector. Figure **3.1**, Figure **3.4**, Figure **3.6** and Figure **3.9** illustrate this point. Each injector development project will differ; this is not intended to be a prescription to follow as much as a highlight of some of the major stages involved.

3.6.1 Initial Modeling

Initial modeling encompasses the RF cavities used to generate the accelerating fields, as well as the initial layouts of the components within the injector's cryomodule(s).

Once the basic parameters for the injector are defined, initial cavity modeling is perhaps best undertaken with a fast 2-D code, such as SUPERFISH [3.31]. There are more advanced 3-D capable codes available, but SUPERFISH has three significant advantages: It runs quickly; it can be operated *via* command line (by other codes); and, its field maps can be easily imported into most of the commonly used particle-pusher beam simulation codes. SUPERFISH can also provide good initial guidance on the expected power dissipation within the cavity, which is important for beginning the cryogenic system's design. As shown on Figure **3.3** above, however, SUPERFISH does not incorporate features which break azimuthal symmetry. If maintaining a very low beam emittance is a primary goal, early incorporation of 3-D RF modeling codes into the design process is recommended. Experience with the LCLS S-band NCRF photoinjector, for instance, demonstrates the importance of fully understanding and controlling the fields experienced by the electron beam.

The initial mechanical design should focus on identifying and reserving beamline space for major items that are critical to operation, such as power couplers, but which are not yet included into the beam dynamics. This will avoid, for instance, finding out later that the optimized location for a superconducting solenoid is inside a power coupler.

In short, the goal for the initial cavity modeling should be to obtain a good, balanced design upon which to build further refinements. The cavity geometry should be reasonable from a fabrication and cleaning standpoint, incorporating known elements of good SCRF design. The required cavity field gradients should provide for a margin of safety relative to their theoretical maximum values; the electron beam parameters should approximate the targets established for the injector. Finally, there should be sufficient information to provide mechanical designers with an approximate component layout along the beamline.

3.6.2 Initial Beam Dynamics

Once the initial cavity model is defined from a "field map" perspective and constraints on component placement identified, beam dynamics calculations can begin. If the RF modeling and beam dynamics codes both allow command line operation, then both can be incorporated into a single optimization loop. This allows researchers to readily determine the effects of, say, cathode cell length or cathode-region focusing on the beam dynamics in a way that maintains consistency with the cavity model.

Some of the "knobs," or design parameters, can easily be adjusted during a photoinjector's operation, as well as in simulation; examples include RF power delivered to the cavity[7], or size of the laser spot on the cathode. Some knobs, such as the physical geometry of the cathode cell, can easily be adjusted in simulation, but are fixed in an operating photoinjector. Depending on details of the physical design, some knobs, such as the radius of the cathode, may be easy, difficult or impossible to adjust after the photoinjector is built, and over what range the adjustment may be made.

A major goal for the initial beam dynamics studies is to determine how meeting the design goals will affect the injector's physical design; this includes, ideally, how (or whether) new changes to the desired operating parameters can be accommodated once the injector is actually built.

For two examples, consider cathode-region focusing schemes and solenoid placement. If cathode-region focusing is to be used, this is the appropriate stage of the modeling process to set both a baseline position and nominal range of cathode locations, as this information is essential to designing the injector cavity tuner(s). The position of the cathode is an example of a knob that could be easy or difficult to adjust after the photoinjector is built. Simulating the injector's performance with the cathode at various locations provides important guidance to the engineering team as to how much effort to spend on making it easy. Arguably such studies are, or should be, made as a matter of course. While this is true, such studies are often aimed at meeting the initial design goals. Here, the emphasis is on thinking about what else the injector may be required to do.

If optimization includes altering the location of an emittance compensation solenoid, this will impact the placement of other components in the injector beamline (which is usually too short by about a factor of two for everything that needs to be placed in the beamline, but too long by about a factor of two for ideal beam size and emittance control). This is an example of a "knob" which is likely to be all but impossible to change once the photoinjector is built, so additional care should be taken to ensure that the solenoid placement doesn't unduly restrict the operation of the photoinjector. For instance, if it is very far from the gun, there may be a limit on achievable bunch charge due to space-charge-driven expansion of the beam. If it is very close to the gun, there may be a limit on the focusing field strength that can be applied due to quenching concerns.

[7] Whether the RF power is well-matched into the cavity, however, will depend on whether the RF engineers were told that variable power coupling would be required.

3.6.3 Refinement

Refinement should begin with examination of the preliminary beam dynamics in light of the original requirements, as well as the lay-out of the cryomodule and injector line.

Assuming the initial results are acceptable, refinement consists of successively improving the fidelity of modeling of the cavity fields and electron beam dynamics. Electromagnetic field simulations should be transitioned to 3-D and used to improve the fidelity of the beam dynamics simulations. Locations of RF power couplers, diagnostics ports and similar hardware should be finalized. More physical effects are incorporated at this stage, such as non-uniform current emission from the cathode. Particle-in-cell (PIC) codes are increasingly utilized, perhaps for wakefield analysis and multipacting studies, as well as for basic beam dynamics. The process is iterated, as needed, until a final design is obtained. If significant changes to the injector design are proposed, they should be evaluated quickly using the tools and techniques developed for the initial modeling process.

As the injector line will include diagnostics, it is well worth considering simulating the performance of the diagnostics. Beam dynamics codes usually can provide the full 6-D phase space of the beam at arbitrary locations along the beamline. However, simulating the particular technique to be used for, say, the emittance measurement (*e.g.* slits, quadrupole-, or solenoid-scan) helps to ensure the proposed diagnostics will properly measure the quantities in question at the desired resolution.

There is a phrase, “In a high power injector, any diagnostic can become non-intercepting.” This means that diagnostic devices which physically block the beam (such as viewscreens or emittance measurement slits) will have some physical limit to how much power they can absorb. Beyond that limit, they will be damaged. The damage can be done not only by the desired beam from the injector, but also from field emission current. Thus, this is also a good time to begin thinking about the interlocks that will need to be applied to the injector diagnostics, and how those interlocks will obtain the information they need to operate properly. Diagnostics which are able to characterize field emission current, at least to a basic level (for instance, position and average current), should be strongly considered for incorporation into the final design.

3.6.4 Validation

This is the stage at which the actual performance of the SCRF photoinjector is compared the models and simulation used to design it. (Construction is well beyond the scope of this chapter.) It encompasses both setting the physical parameters to match the assumptions in the simulation as closely as possible and repeating the simulations based on measured physical parameters of the as-built, as-operated system.

The validation process consists of many stages, and will range from testing of an individual superconducting cavity to measuring the output beam parameters of the injector as a whole. Details of the validation process will necessarily be different for every injector, but there are some common themes worth mentioning.

Thorough RF characterization of the SCRF cavities used in the injector is critical. Cavity performance has a critical impact upon the performance of the injector as a whole. The characterization should include how the cavity’s properties (quality factor, power dissipation, central frequency, *etc.*) change as parameters relevant to beam dynamics, such as cathode position, are adjusted, even if they are not initially envisioned to be altered significantly during normal operation. Particularly in user facilities, obtaining such information after normal operation commences can prove to be difficult due to time and scheduling constraints.

It is worthwhile to develop a comprehensive, but flexible, validation and commissioning plan for the SCRF photoinjector. Generating the plan helps to ensure that all of the desired measurements will in fact be made, in part because it provides a reasonable basis for estimating the required time to thoroughly commission the injector. The injector commissioning time requirements can then be incorporated directly into the overall project schedule.

3.7 CONCLUDING THOUGHTS

I have attempted to present an overview of issues specific to SCRF photoinjector design, along with a very brief review of designs presently in development or operation.

As high power accelerators enter into more widespread use and become more specialized in their designs, so too will their injectors. SCRF photoinjectors have crucial roles to play in the future of accelerator technology.

The SCRF photoinjector field is evolving very rapidly. Many of the current designs mentioned above borrow heavily from the experience and good results obtained *via* normal conducting photoinjector design. Given how well the NCRF injectors operate, this is an eminently reasonable starting point. However, there are fundamental differences – in terms of RF power consumption and interactions with external fields – between NCRF and SCRF accelerator technology. It is exciting to see how some of the new designs are beginning to explore and exploit those differences. An example is the use of a TE cavity mode to provide solenoid-like focusing, as proposed for the Rossendorf gun. (Of course, I am biased – I have enjoyed working with multi-frequency and multi-mode cavities in simulation and would like to see more of them implemented in practice.)

While this chapter focuses on beam dynamics, successful development of an SCRF photoinjector requires a collaborative effort. The ultimate goal of any injector design process is the same: provide a beam which meets the requirements of its associated accelerator. SCRF photoinjectors offer some unique capabilities that allow us to meet those needs, and it is my hope that this chapter provides some insights into the challenges that must be met to accomplish that goal.

3.8 CONFLICT OF INTEREST AND ACKNOWLEDGEMENT

The author confirms that this article content has no conflicts of interest and would like to acknowledge the support of the Office of Naval Research, the High-Energy Laser Joint Technology Office and the Naval Postgraduate School.

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