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THE STATUS OF NORMAL CONDUCTING RF (NCRF) GUNS,

A SUMMARY OF THE ERL2005 WORKSHOP

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ABSTRACT

The 32nd Advanced ICFA Beam Dynamics Workshop on Energy Recovering Linacs (ERL2005) was held at Jefferson Laboratory, March 20 to 23, 2005. A wide range of ERL-related topics were presented and discussed in several working groups with Working Group 1 concentrated upon the physics and technology issues for DC, superconducting RF (SRF) and normal conducting RF (NCRF) guns. This paper summarizes the NCRF gun talks and reviews the status of NCRF gun technology. It begins with the presentations made on the subject of low-frequency, high-duty factor guns most appropriate for ERLs. One such gun at 433MHz was demonstrated at 25%DF in 1992, while the CW and much improved version is currently being constructed at 700MHz for LANL. In addition, the idea of combining the NCRF gun with a SRF linac booster was presented and is described in this paper. There was also a talk on high-field guns typically used for SASE free electron lasers. In particular, the DESY coaxial RF feed design provides rotationally symmetric RF fields and greater flexibility in the placement of the focusing magnetic field. While in the LCLS approach, the symmetric fields are obtained with a dual RF feed and racetrack cell shape. Although these guns cannot be operated at high-duty factor, they do produce the best quality beams. With these limitations in mind, a section with material not presented at the workshop has been included in the paper. This work describes a re-entrant approach which may allow NCRF guns to operate with simultaneously increased RF fields and duty factors. And finally, a novel proposal describing a high-duty factor, two-frequency RF gun using a field emission source instead of a laser driven photocathode was also presented.

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Keywords: RF guns, normal conducting, superconducting, radio frequency fields

1. INTRODUCTION (D. H. DOWELL, SLAC)

This report summarizes the normal conducting RF (NCRF) gun presentations given in the Working Group I session at the Jefferson Lab ERL2005 Workshop. Although the re-entrant gun material of Section III was not presented in the workshop, we consider it to be very relevant to this topic and include it in this summary.

The report is organized into the following sections: Section II reviews the best demonstrated performance for a NCRF gun at high duty factor. Next Dinh Nguyen describes a next generation NCRF gun LANL and AES have designed for CW operation. This 700MHz gun is scheduled for completion in 2005 and should surpass many of the performance parameters of any previous NCRF system. Dinh also proposes combining the NCRF gun with a SRF booster linac for a hybrid injector design. In Section IV Robert Rimmer applies experience gained in building the PEP-II cavities for the B-Factory at SLAC to propose a more efficient NCRF design. In his approach the cells are made with very re-entrant nose cones to increase the on-axis RF field, improve the shunt impedance and reduce the thermal stresses. Although this work was not presented in the working group, it’s been included because of its relevance to the discussion of NCRF guns. Coaxial fed guns are described in Section V. The principle advantages of this type of gun are the elimination of all RF field asymmetries and complete freedom in the placement of the emittance compensation solenoid. This gun has produced excellent quality beams for the VUV-FEL at DESY in Hamburg, Germany. Another approach to generating symmetric fields is given in Section VI. In this gun design for the

SLAC/LCLS X-ray FEL, a rotationally symmetric field is achieved with dual RF feeds and an elliptical cavity shape. In Section VII, John Lewellen proposes a two-frequency gun to limit the time for field emission from a cathode stalk to a small portion of an RF cycle. In this way he eliminates the need for a drive laser. Section VIII is the summary.

2. STATE-OF-THE-ART (D. H. DOWELL, SLAC)

In terms of duty factor and average power operation, the Boeing/LANL 433 MHz gun remains the state-of-the-art. This gun was fabricated in 1988-1989 [1] and tested at high-average power from 1990-1992 up to 5 MeV beam energy [2]. In 1994-1996 it was incorporated into a higher energy accelerator (20MeV) and was used as the electron source in bunch compression experiments demonstrating third-harmonic linearization of the longitudinal phase space [3]. Figure 1 shows a photograph taken from the photocathode end of the gun. The cathode deposition chamber is in the foreground with the large RF waveguide feeds (black) connected at 45 degrees (relative to vertical) to independently power the two gun cells.

Table I lists the parameters for the 433MHz gun which were demonstrated during the 1992 high-duty test. Unfortunately, the gun's performance was severely limited by poor vacuum which reduced the cathode lifetime to only 2 – 3 hours [2]. This short lifetime was due to a vacuum leak from the water cooling channels into the gun as evidenced by the large partial pressure of water.

The general configuration of this gun is given in Figure 2. In this design, the emittance compensation coil is embedded (brazed) into the copper structure. This brazing distorted the embedded coil producing a large dipole kick. This dipole magnetic field was corrected using an array of permanent magnets clocked at 90degrees around the coil [4]. After correcting for the distortion, the rms emittance was measured to be fairly good at [4.4+1.1*Q(nC)] microns. The general shape of the gun cells can also be seen in Figure 2. The re-entrant design allowed the relatively high rf field of 25MV/m (peak) to be reached at high-duty factor. This same re-entrant shape for the nose cones is further optimized to reduce thermal stress as described in Section III.

3. THE LOS ALAMOS/AES CW NCRF GUN (D. NGUYEN, LANL)

A key component of an energy recovery linac is a low-emittance, high-average-current electron gun. The electron beam’s average current (~1A) determines the electron bunch charge (~1nC) and bunch repetition rate (~1GHz). The most straightforward approach to achieve low emittance (~2mm-mrad) at 1nC bunch charge is through the use of the room-temperature RF photocathode gun. These qualities have been achieved with RF guns operating at low duty factors. To date, a high-average-current RF photocathode gun, operating continuously at 100% duty factor, is yet to be demonstrated. The principal challenges of a high-duty-factor normal-conducting RF gun are caused by the large RF ohmic losses in the cavity walls and the relatively poor vacuum environment of the RF injectors under continuous operation. What is needed is a demonstration of thermal and vacuum management of a room-temperature RF gun operating continuously (100% duty).

Funded by NAVSEA and the JTO, Los Alamos and Advanced Energy System (AES) have designed a water-cooled 700 MHz copper photocathode gun with a dense array of cooling channels for thermal management and sufficient vacuum pumping to provide a good vacuum in the photocathode cell [5]. The design of a normal-conducting, 700 MHz gun operating at 7, 7 and 5 MV/m is shown in Figure 3. The photocathode gun is designed to produce 2.5 MeV electron beams. It consists of a π-mode, 2½-cell, RF cavity with on-axis electric coupling and emittance compensation, and a non-resonant vacuum plenum. The non-resonant vacuum plenum can accommodate up to 8 ion pumps to ensure adequate vacuum pumping of the RF injector. Large-diameter apertures between the resonant cells and the non-resonant vacuum plenum are used to maintain high-conductance passages for pumping the photocathode cell. Heat removal in the resonant cells is achieved via dense arrays of internal cooling passages capable of handling high-velocity water flows. The septum walls are almost flat to keep the cooling channels as close to the RF surface as possible. Megawatt RF power is coupled into the gun through two tapered ridge-loaded waveguides [6]. PARMELA simulations show that the room-temperature RF photocathode gun can produce a 6mm-mrad emittance at 3nC bunch charge.

The 2½-cell, RF gun is being fabricated at AES with an expected delivery of November 2005. Concurrent efforts are being carried out to prepare the Low Energy Accelerator Facility (LEDA) for the installation, commissioning and testing the room-temperature RF gun. As soon as the NCRF gun is delivered to Los Alamos, we plan to perform the thermal test with a 1MW 700 MHz klystron in the LEDA facility. This thermal test will answer the question whether sufficient gradient can be applied continuously to the normal-conducting RF gun to pull up to 3nC of electron charge per bunch and still maintain thermo-mechanical integrity in the RF gun. The thermal test is expected to complete by May 2006. Subsequent beam tests using either the bi-alkali (K_2CsSb) or tri-alkali ($Cs:Na_2KSb$) as the photocathode are being planned and, if funding permits, scheduled for late 2006. This 2½-cell, RF photocathode gun can also be easily redesigned to suit the ERL applications.

A shorten version of this NCRF gun can be incorporated into a hybrid (normal-conducting + superconducting) RF photoinjector as shown in Figure 4. This design consists of a normal-conducting, 1½-cell, RF gun followed by three independently driven RF superconducting cavities as energy boosters for the RF gun. Emittance compensation is accomplished through an external magnetic field near the photocathode. This magnetic field must be shielded from the superconducting cavities as it is incompatible with superconductivity. High quantum-efficiency semiconductor photocathodes can be used at elevated temperatures in the first half-cell via a quarter-wave choke joint serving as thermal insulation. The cryogenically cooled interior provides an excellent vacuum that could significantly improve the photocathode lifetime. Release of debris from the photocathode into subsequent superconducting cavities, which could lead to quenching, can be minimized with a drift tube. The electron bunches generated in the normal-conducting 1½-cell RF gun are matched into independently-powered superconducting RF cavities for acceleration to higher beam energy. RF power is coupled into the photoinjector cells from both sides via the APT-type RF power couplers that have been tested up to a few hundred kilowatts. In many high current applications with significant beam loading, the loss of RF efficiency with use of normal conducting 1½-cell gun is negligible compared to the total system RF power consumption. The simplicity of a room-temperature RF gun outweighs any loss in RF efficiency when properly compared to the complexity of a fully superconducting gun.

4. THE LUX RE-ENTRANT GUN (R. RIMMER, JLAB)

The goal of the Linac/Laser-Based Ultrafast X-ray Facility (LUX) normal-conducting photocathode gun proposed by Lawrence Berkeley National Laboratory is to combine the best of warm re-entrant cavity technology with the good properties of conventional laser photocathode sources. It is known from the long history of warm RF development that re-entrant cavities offer a significant advantage in efficiency over the traditional "pillbox" shape. For high duty factor or CW sources this is very important, as these guns are most often limited by wall power dissipation rather than peak surface electric field. For a given stress level or surface power density a re-entrant shape allows a higher electric field on the cathode. The re-entrant LUX design (see Figure 5) shows that peak electric fields on the cathode of the order of 15 MV/m should be achievable in CW mode with a safety factor of 2 in stress, without resorting to exotic materials, cryogenic operation or other complications. The reasons for this are efficient RF design, a simple but effective cooling channel layout and a mechanical design that avoids stress-concentrating features like sharp corners and edges. The beam dynamics performance of the re-entrant gun is very similar to any other RF gun with comparable fields close to the axis.

The target cathode field for LUX was 64 MV/m for 5% duty factor at 1300 MHz, with an average power of 31 kW and a maximum wall-power density of about 100 W/sq-cm [7]. This equates to about 15.5 MV/m CW with a peak surface temperature rise of

67°C and a maximum stress of 65 MPa (~9400 psi). While this level of stress is not insignificant it is well below the endurance limit of copper of 124 MPa (~18,000 psi) at 10,000 cycles [6] (equivalent to three full temperature cycles a day for 10 years). In fact, pushing the cavity to 20 MV/m only raises the stress to 108 MPa. For comparison, the PEP-II copper RF cavities were designed for 75 MPa at 150 kW [8, 9] and operate routinely at ~100 kW, and about 50 MPa (~7300 psi), with multi-ampere beam currents and hundreds of kW of RF power per cavity delivered to the beam. With careful design and careful stress management (such as varying the cooling channel density and routing the water to minimize thermal gradients) these stresses could be lowered further, allowing even higher cathode gradients.

Going to lower frequency also helps [10]. RF sources, couplers and windows operating at MW power levels are commonplace in L-band and should not be a limiting factor in gun design. Mechanical assembly does not have to be difficult or expensive if well though out, especially if the RF design is efficient to start with. Conventional cavity construction techniques within the accelerator and tube industries are more than adequate. Cutting openings into the cavity for pumping or RF power coupling can lead to local stress concentrations, but the LUX design shows that these can be held to levels at or below the peak stresses elsewhere in the body. Provided apertures are located symmetrically about the beam axis dipole kicks can be avoided. On-axis coupling would be another way to avoid the problem. While the LUX study focused on high duty factor operation, the same shape optimization is valid for low repetition rate high peak power guns, which are often limited by surface pulse heating. The efficient design minimizes surface magnetic fields, allowing higher peak electric fields before the (magnetic) surface damage threshold is reached. This would be particularly useful for extreme guns such as those proposed for LCLS or the Tesla X-FEL.

5. COAXIAL FEED NCRF GUNS (D.H. DOWELL, SLAC)

Implementing a coaxial rf power feed produces a rotationally symmetric rf field. By moving the axial coupler to either the beam exit or through cathode stalk, the region along the cells is now available for placing the solenoid field anywhere along the length of the gun. The design for the Tesla Test Facility (TTF) is shown in Figure 6. In addition to the beam exit coupler approach as shown in Figure 6, there is also a design for a high-duty factor NCRF gun with the rf coupling into the cavity through the cathode stick [10].

The complete freedom of unrestricted axial field shape along the gun allows for more ideal compensation matching of the bunch into the booster linac. Compensation for the various types of slice misalignment is done by matching the bunch transverse dynamics to the booster fields and acceleration.

6. SYMMETRIC DUAL-FEED, RACE-TRACK GUN (D. H. DOWELL, SLAC)

The RF fields can also be made symmetric by using a dual feed and a race track cell shape. The dual feeds cancel the dipole fields, and the elliptical cell shape corrects for the quadrupole field. The shape and integrated quadrupole kick, uncorrected and corrected, are shown in Figure 7 for the LCLS gun [11].

7. FIELD-EMISSION CATHODE GATING (J. W. LEWELLEN, ANL)

A common feature of most high-brightness electron guns is the use of a photocathode drive laser to generate the electron beam. RF injectors, however, have been made using thermionic (hot) cathodes, which emit electrons simply due to their elevated temperature. Thermionic-cathode rf (TCRF) guns have proven to be very successful sources of moderate quality (normalized emittances of 10 – 20 μm), moderate charge (100 – 350 pC / bunch), high average macropulse current (0.3 – 1 A) beams.

The primary limiting aspect of TCRF gun performance is the continuous nature of the electron emission from the cathode. In fact, the main purpose of a photocathode drive laser is to gate the electron emission to a small fraction of the rf period. The disadvantage of the photocathode gun is also embodied within the drive laser: high-average-current guns require high-power drive lasers as well as high-quantum-efficiency photocathodes. The final result is that photocathode rf guns, as a rule, are far more complicated and expensive than thermionic-cathode rf guns.

There has recently been proposed [12] a method for gating electron emission from a field-emission (FE) cathode within an rf gun. By adding a third-harmonic component to the field within a gun cavity, the phase of peak gradient on the cathode is shifted from 90 deg. to approximately 50 deg. By carefully tuning the gun geometry (so as to control the ratio between the 1st and 3rd harmonics spatially as well as temporally), and by selecting the gradient and cathode parameters, the FE cathode emission window can be gated to approximately 10 deg. The method therefore combines the simplicity and potentially high average currents of TCRF guns, with the narrow emission gating of photocathode guns.

The initial design was intended as a driver for high-voltage electron microscopes, and so is optimized for low average currents (0.1 – 10 mA). In principle, however, the process can easily be extended to higher average beam currents; in such cases, the existing "bag of tricks" for dealing with large space-charge forces – such as solenoidal focusing, cathode-region focusing, etc. – can be brought to bear. Although much additional study and experimental verification remain, the method appears to be a promising approach towards development of high-current, high-brightness beam sources.

In principle this technique could be applied to either NCRF or cryogenic rf guns; however, there is considerable appeal in terms of simplicity of design, making the FE-cathode gating scheme a natural complement to a high-duty-factor NCRF gun.

8. SUMMARY AND CONCLUSIONS (D.H. DOWELL, SLAC)

Working group presentations and discussions on the topic of NCRF guns fall into two general categories: those capable of operating at high-duty factor and those at low-duty factor. The high-duty factor guns have lower peak field on the cathode because of RF heating issues while the low-duty guns can have very high peak fields (~100MV/m) and thereby produce very bright beams. Many ERL applications require both high-duty factor and high beam brightness, necessitating significant efforts in thermal and vacuum engineering of the NCRF gun design for efficient heat removal and long cathode lifetime.

The high-power operation of a NCRF gun at 25% duty factor was first demonstrated in 1992. This 433MHz gun was a collaboration of Boeing and LANL. This gun is now ‘retired’. A new 700MHz gun, currently under construction by AES for LANL, has been designed for true CW operation and is scheduled for completion in 2005. The high power RF testing will be at LANL and will take advantage of the existing LEDA RF power and cooling infrastructure.

Low-duty factor NCRF guns represent the state-of-the-art sources for high quality electron beams. The guns developed for SLAC’s LCLS and the DESY XFEL are examples of these types of high frequency (2.856GHz and 1.3GHz, respectively) guns. In these guns the RF fields are rotationally symmetric and the cathode electric field is high (~60 to 120 MV/m). However they are not capable of operating CW as needed for most ERL’s.

Also presented in this working group was a reasonably high-average current CW gun which requires no drive laser. This two-frequency gun would use the field shaped by two RF frequencies to switch on and off a field-emission cathode.

The re-entrant gun described in this report suggests the possibility of NCRF guns with both high cathode electric fields (~20MV/m) and efficient CW operation. While not as efficient as the SRF gun, this approach when combined with a SRF booster linac could provide a technology bridge between the NCRF gun and the full SRF gun.

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TABLE I.

PARAMETERS DEMONSTRATED DURING THE 1992 HIGH-DUTY TEST OF THE 433MHZ NCRF GUN

Photocathode Performance:		
	Photosensitive Material:	K_2CsSb Multialkali
	Quantum Efficiency:	5% to 12%
	Peak Current:	45 to 132 amperes
	Cathode Lifetime:	1 to 10 hours
	Angle of Incidence:	near normal incidence
Gun Parameters:		
	Cathode Gradient:	26 MV/meter
	Cavity Type:	Water-cooled copper
	Number of cells:	4
	RF Frequency:	433 $x10^6$ Hertz
	Final Energy:	5 MeV(4-cells)
	RF Power:	600 $x10^3$ Watts
	Duty Factor:	25%, 30 Hertz and 8.3 ms
Laser Parameters:		
	Micropulse Length:	53 ps, FWHM
	Micropulse Frequency:	27 $x10^6$ Hertz
	Macropulse Length:	10 ms
	Macropulse frequency:	30 Hertz
	Wavelength:	527 nm
	Cathode Spot Size:	3-5 mm FWHM
	Temporal and Transverse Distribution:	gaussian, gaussian
	Micropulse Energy:	0.47 microjoule
	Energy Stability:	1% to 5%
	Pulse-to-pulse separation:	37 ns
	Micropulse Frequency:	27 $x10^6$ Hertz
Gun Performance:		
	Emittance (microns, RMS):	5 to 10 for 1 to 7 nCoulomb
	Charge:	1 to 7 nCoulomb
	Energy:	5 MeV
	Energy Spread:	100 to 150 keV

FIGURE CAPTIONS

Figure 1. Photograph of the Boeing/LANL 433MHz NCRF gun in the test vault.

Figure 2. Drawing of the 433MHz gun showing the re-entrant design and the locations of the emittance compensation coil and cathode field bucking coil. Cells 3 and 4 indicated in Table I are not shown. The cathode was fabricated in an attached deposition chamber and inserted into the gun under vacuum via a long cathode stick. See Figure 1 and References [2, 3].

Figure 3. Exploded view of the 2 ½ - cell NCRF gun being fabricated by AES for LANL.gun being developed by LANL and AES. The non-resonant cell provides additional vacuum pumping for the 1.5-cell gun.

Figure 4. A proposed hybrid NCRF gun + SRF booster injector based upon the NCRF.

Figure 5. Re-entrant cavity shape, RF field lines and placement of the solenoid coils of the LUX gun.

Figure 6. Drawing of the Tesla Test Facility (TTF) NCRF gun with a coaxial rf feed.

Figure 7. The race track shape and corrected and uncorrected quadrupole distortion for the LCLS gun design.

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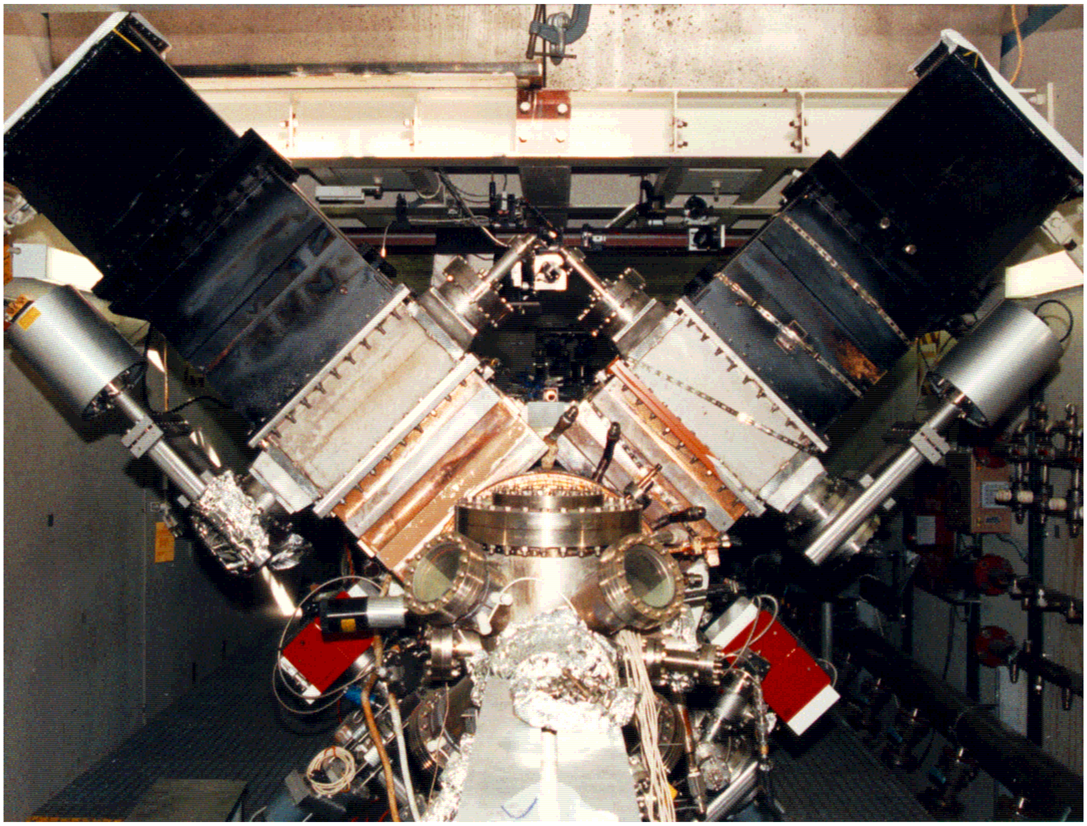

FIGURE 1.

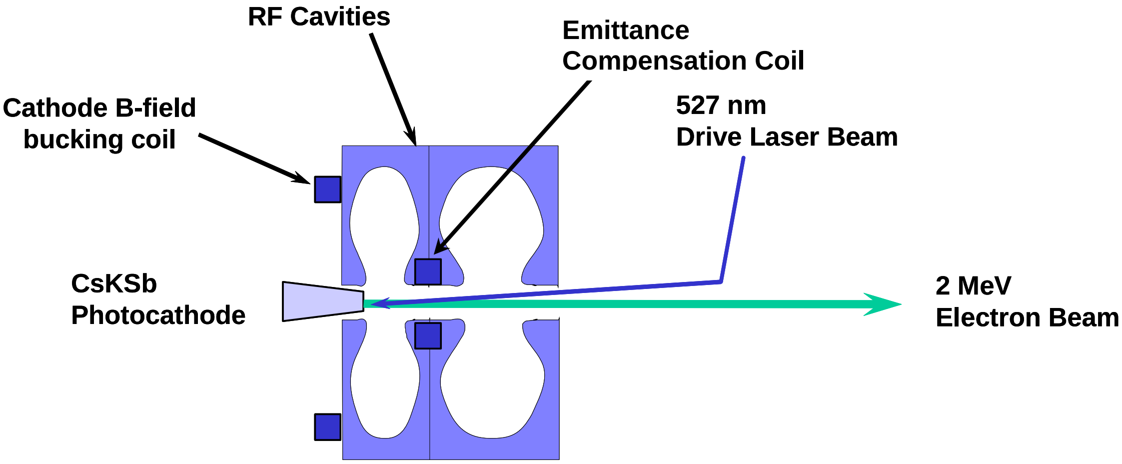
RF Cavities
Emittance Compensation Coil
Cathode B-field bucking coil
527 nm Drive Laser Beam
CsKSb Photocathode
2 MeV Electron Beam

FIGURE 2.

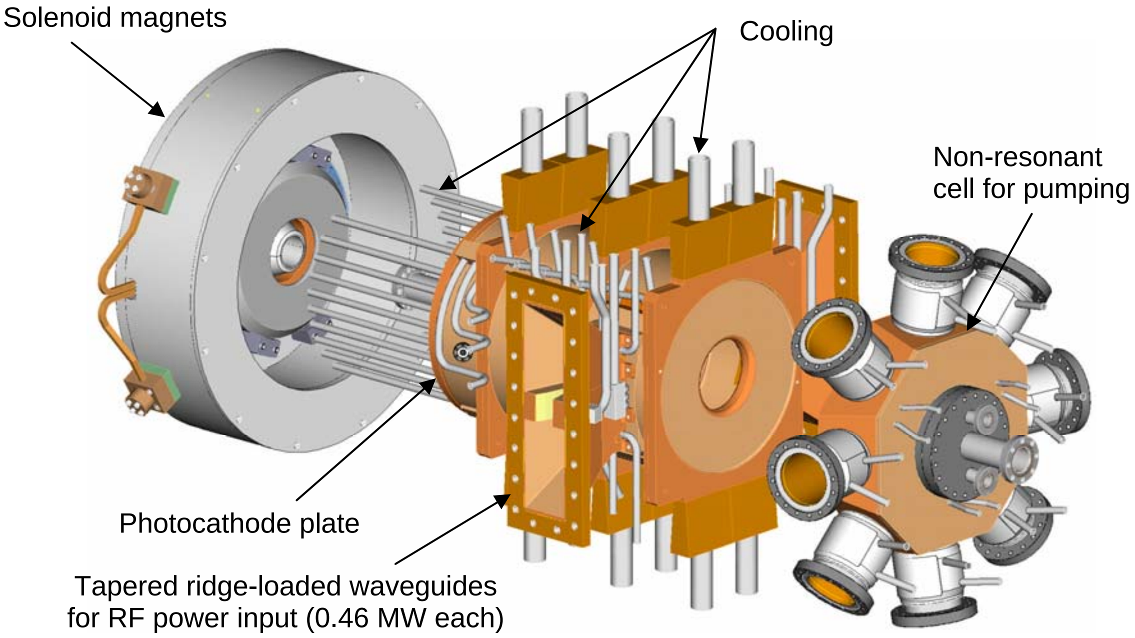
Solenoid magnets
Cooling
Non-resonant cell for pumping
Photocathode plate
Tapered ridge-loaded waveguides for RF power input (0.46 MW each)

FIGURE 3.

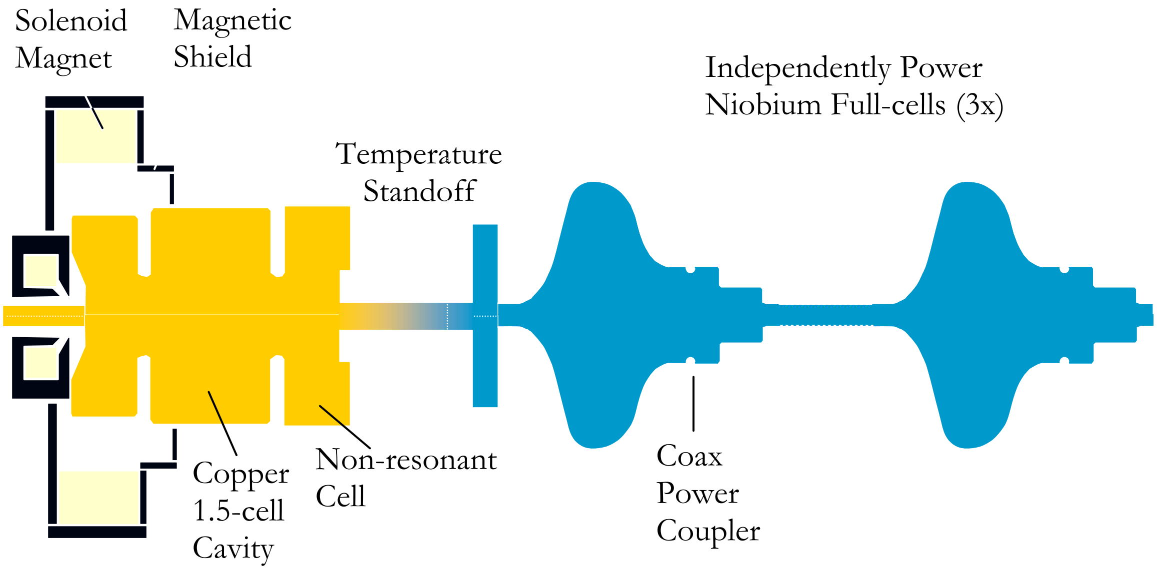
Solenoid Magnet
Magnetic Shield
Independently Power Niobium Full-cells (3x)
Temperature Standoff
Copper 1.5-cell Cavity
Non-resonant Cell
Coax Power Coupler

FIGURE 4.

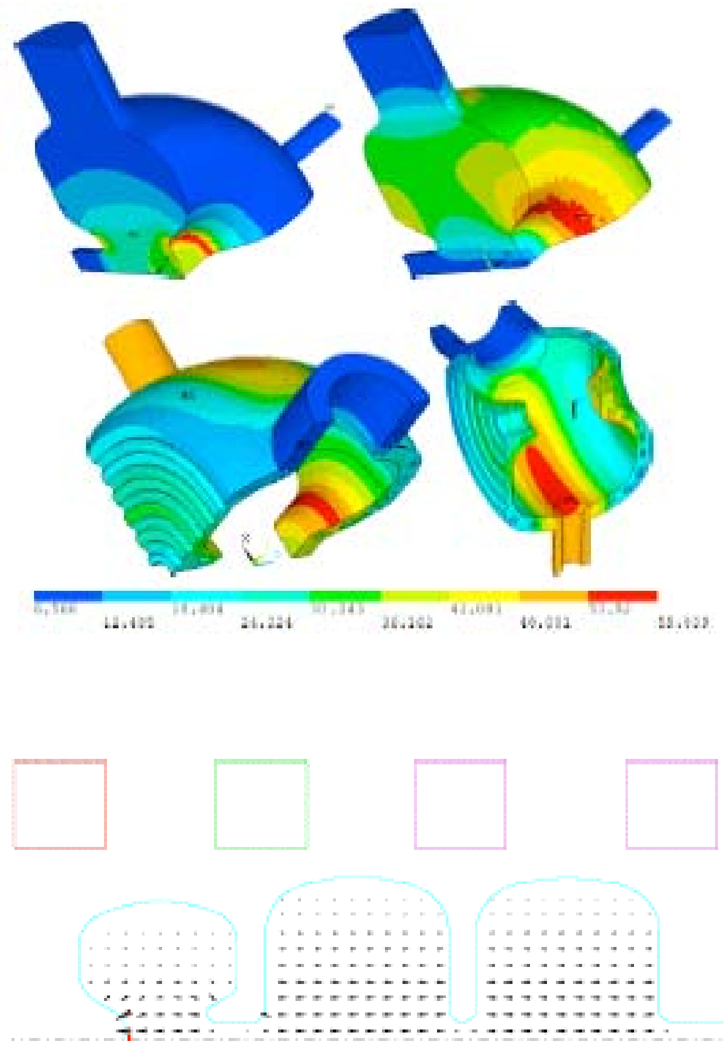

FIGURE 5.

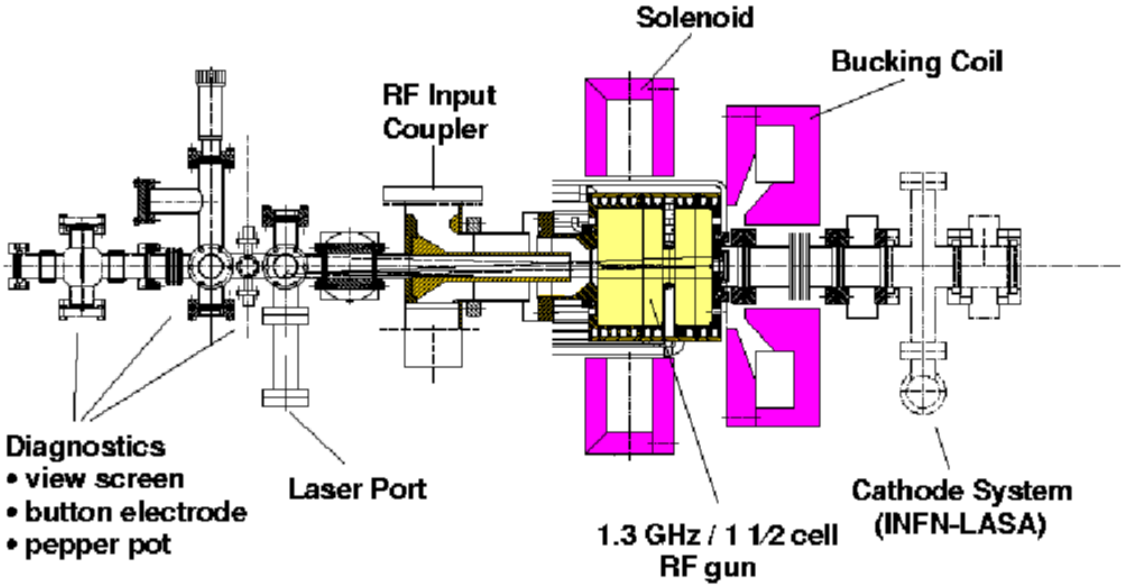
Solenoid
Bucking Coil
RF Input Coupler
Diagnostics
• view screen
• button electrode
• pepper pot
Laser Port
1.3 GHz / 1 1⁄2 cell RF gun
Cathode System (INFN-LASA)

FIGURE 6.

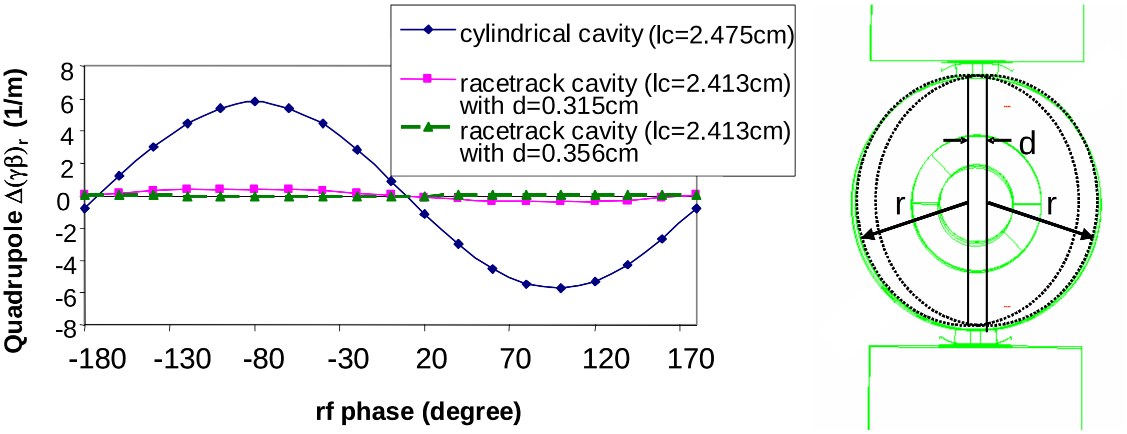
cylindrical cavity (lc=2.475cm)
racetrack cavity (lc=2.413cm) with d=0.315cm
racetrack cavity (lc=2.413cm) with d=0.356cm
Quadrupole Δ(γβ)r (1/m)
8
6
4
2
0
-2
-4
-6
-8
-180
-130
-80
-30
20
70
120
170
rf phase (degree)
d
r
r

FIGURE 7.