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Prospects for generating polarized electron beams for a linear collider using an RF gun*

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Abstract

The next generation of linear colliders--represented by the Japanese Linear Collider (JLC) and the Next Linear Collider (NLC)--will probably utilize polarized electrons generated by a photocathode gun. A photocathode gun with high polarization (P_e) photocathodes (up to Pe~80% achieved to date) is currently providing polarized electrons for the SLC. The SLC source requires subharmonic bunching at low energy to reduce the bunch length prior to S-band bunching and a damping ring at high energy to reduce the transverse emittance. The use of an RF gun can eliminate the former and possibly simplify the latter. However, RF guns as presently developed have serious problems with vacuum contamination, which would quickly lower the quantum efficiency (QE) of a semiconductor photocathode. In addition, the "charge limit" previously reported for high peak current pulses puts a limit on the laser power usable for photoexciting a low QE cathode near the bandgap threshold. These problems have so far precluded any serious attempt to design an RF gun for polarized electrons. Several technical advances that now improve the prospects for a practical polarized electron RF gun are described. Finally, new ideas for high polarization photocathodes that permit operation in a relatively poor vacuum and techniques being explored to mitigate the low QE "charge limit" are discussed.

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Introduction

Polarized electrons for high energy physics increase the effective luminosity for some measurements and improve the systematic uncertainties associated with those measurements [1]. Polarized electron beams are particularly inviting for linear colliders, since there is no significant depolarizing mechanism in the acceleration process itself. Polarized electrons for linear colliders must be generated by an external source. Such sources exist today, most notably for the SLC. All presently operating polarized electron sources for high energy accelerators are designed as low brightness sources matched to injectors which originally or alternatively use thermionic electron sources.

The design of future colliders must take advantage of technological advances that reduce costs or increase simplicity. Since their inception, RF guns have held out the promise of being able to produce high brightness beams for direct injection into an accelerator without relying on complex and expensive emittance reducing systems. Although RF guns for unpolarized beams have not yet proven reliable enough for dedicated use in a major high energy particle accelerator, this technology is likely to exist soon. Consequently, it is reasonable to begin now to consider how such RF guns could be designed so as to produce polarized electrons.

Linear Collider Requirements

The SLC and all linear colliders being planned are inherently low duty factor accelerators. In the following discussion of pulse structure for colliders, the terminology of Fig. 1 is used. A macrobunch of electrons is accelerated to high energy in one linac, a positron macrobunch in another. At high energy there is a single intense electron-positron collision after which the severely disrupted particles are dumped. The repetition rate for accelerating macrobunches is limited by the RF power sources that are economically feasible to ~1 kHz. The microstructure of the bunches is constrained by the total RF power stored in the accelerating structure for each RF pulse. Generally individual microbunches are limited to about 10^{11} particles if there are only a few bunches in the pulse train. By dropping the particles per bunch to about 10^{10}, the number of microbunches can be increased to the order of several hundred. Depending on the RF frequency chosen for high energy acceleration, the next generation of colliders will require 0.7 to 1.7 x 10^{10} e^- per microbunch and 90 to 46 microbunches per macrobunch for X-band to S-band respectively. The microbunch spacing varies from 1.4 ns for X-band to 5.6 ns for S-band [2,3].

The transverse normalized RMS emittance, $\gamma\varepsilon$, of the NLC/JLC for flat beams is required to be on the order of 5 x 10^{-8} m in the vertical plane but only ~5 x 10^{-6} m in the horizontal. Low emittances will be achieved in damping rings after initial acceleration to a few GeV. In principle this initial acceleration can be done at any convenient RF frequency, including S-band.

SLC Polarized Gun Performance

The SLC began operating on a continuous basis with a polarized electron source in the spring of 1992. The gun operates with a DC cathode bias of -120 kV. The active area of the cathode has a diameter of 14 mm. For initial operation, a bulk GaAs cathode was used. A flashlamp-pumped dye laser and associated optical pulse chopping system generated the two required 2-ns laser pulses separated by 60 ns at a repetition rate of 120 Hz. The laser was limited by the choice of long life dyes to 715 nm which in turn limited the polarization at the source to about 28% (cathode at 0°C). A total charge limitation required a QE > 4% (measured at 120 kV with a low power 750 nm diode laser) in order to maintain the required 6 x 10^{10} e^- per bunch out of the source [4,5].

In 1993, the SLC has been operating with a 0.3 μm strained (active) layer GaAs cathode grown on a GaAsP sublayer. (Similar cathodes operating at room temperature had been shown [6] to have a polarization of ~80% at ~860 nm, but a QE of only ~0.1%.) A pulsed Ti:sapphire laser tunable from 750 to 870 nm, combined with an optical chopping system produces the required 2 ns pulses [7]. The source operates at a laser wavelength of 865 nm with an electron polarization of ~80%.[8] The crucial question of photoelectron yield for these very thin cathodes proved to have an acceptable answer for the SLC. The initial QE following activation was ~1% (measured at 120 kV with an 830 nm diode laser). The higher QE is attributed to the beneficial effects of introducing the cathode under vacuum into the gun after the latter is baked. The rate of decrease of QE is unaffected by the presence of the photoelectron beam, but is possibly influenced by dark currents. With HV off, the CO partial pressure is 10^{-12} Torr. In one test, dark currents on the order of 350 nA (which resulted in an increase of about 10^{-13} Torr in the CO partial pressure) shortened the cathode lifetime by a factor of three. The charge limit at 850 nm for a 2 ns pulse was found to be ~10^{11} e^- at QE = 1%, slightly less than the space charge limit of the gun (1.2×10^{11} e^- at 120 kV), decreasing more or less in proportion to the decrease in QE. With the SLC source operating at 120 kV producing 5×10^{10} e^- per bunch at 120 Hz, the QE decreases from 0.5% at a rate of about 0.05% (absolute) per day despite a total vacuum of 10^{-11} Torr (dominated by H_2) and a dark current <50 nA. The QE is easily restored by a small charge of Cs to the surface of the cathode, a process that was be repeated >25 times over an 8 week period before the first reactivation [8].

The rms normalized emittance of the bunched SLC beam after acceleration to 40 MeV is ~10^{-4} m. It is possible this emittance could be improved with a different buncher design.

The SLC performance is compared to the NLC/JLC design parameters in Table I. For a given cathode area, the strength of the space charge forces at non-relativistic energies is proportional to the peak current (I_{peak}). The potential magnitude of beam-induced molecular desorption at the source is indicated by the total charge per second (N_{total}).

RF Gun Performance

RF guns are being vigorously developed as high brightness sources for FELs. As discussed earlier, a successful RF gun may be able to significantly simplify a linac injector and damping system. The problem of heavy beam-loading in bunching systems due to multibunch operation is possibly less severe if an RF gun is used. Likewise, even if a DR cannot be avoided, any lowering of the transverse emittance of the input beam will make the DR design easier [9]. L-Band (1.3 GHz) RF guns with multi-alkali cathodes have been under study at LANL since 1987 [10]. These guns typically provide a surface gradient at the cathode of 20-30 MeV/m, an order of magnitude higher than the SLC gun, and rapidly accelerate the particles to relativistic energies, thus minimizing the emittance debilitating effects of space charge fields at low electron energies. Since the emission delay from the cathode is on the order of a picosecond or less, short pulse lasers can be used to directly generate an electron pulse train suitable for direct acceleration by L-band and probably also by S-band RF (3 GHz) without the necessity of intervening sub-harmonic bunching systems. Macrobunches a microsecond or so in length with microbunches of several nanocoulomb each (peak currents of several hundred amperes per microbunch) at a spacing on the order of 10 ns (100 MHz) have been accelerated by L-band RF guns to several MeV with normalized RMS emittances on the order of 10^{-5} m [11,12]. The peak currents and total charge per second were similar to those shown in Table I for the NLC/JLC. An S-band RF gun has already been constructed at KEK as a possible electron source (unpolarized) for the JLC [13].

Multi-alkali cathodes, which can have a shelf life on the order of months [14], were chosen over GaAs for unpolarized sources in part because in a poor vacuum they retain a higher QE for visible light. Although the total pressure in an RF gun cavity as low as 10^{-10} Torr with no RF has been reported, the pressure rose to at least 10^{-9} Torr when the RF was operating [11]. Dark currents in one experiment were on the order of 2 nC per μs of RF power (26 MV/m at the cathode) [15]. For an NLC RF gun, an RF pulsewidth of 1 μs would generate a dark current of 360 nA, which is an order of magnitude higher than the upper limit suggested by the SLC polarized source experience. To date, lifetimes of multi-alkali cathodes in RF guns have been no better than 10-30 hours when the RF is operating [11,16]. Because of this lifetime problem, some RF guns are being designed with metal cathodes despite their inherently lower QE and significantly higher threshold for photoemission.

Polarized RF Gun Design Considerations

The high dark currents generated in RF guns are the major obstacle to a stable QE for a photocathode. It is fairly well established that the dark current is due to field emission from point sites. Latham has pointed out that these sites have the properties of micron-sized particulate structures whose electron emission characteristics indicate the involvement of a semiconducting or insulating medium [17]. It is known that the peak field needed to generate a given level of dark current increases as the pulse width decreases. It is reasonable to expect that it will be possible to increase the RF fields an order of magnitude higher than DC fields without increasing the dark currents.

One of the advantages of superconducting (SC) RF Nb cavities over normal conducting (NC) Cu cavities is less dark current. The successful reduction of dark currents in SC RF cavities over the past 10 years has led to a significant increase in practical accelerating gradients. The techniques employed in this endeavor [18]--heat treatment (HT), high power RF processing (HPP), and selection of materials--can be applied in some degree to NC RF gun cavities. 1) HT in the range of 1400-1500°C is successfully employed for Nb cavities. Unfortunately Cu cavities cannot be heated this high. 2) HPP with millisecond pulses of up to 50 kW peak power have shown promise. See Fig. 2. 3) It is already common practice for the design of high gradient NC Cu cavities to select the very highest purity oxygen-free Cu. Some additional purity in the Cu might be gained by employing the HIP (hot isostatic pressing) process as described in Ref. [19] However, for high gradient Cu RF cavities, the most consistent improvement, as shown in Fig. 3, has come by avoiding surface contamination in the manufacturing process [20].

Electron stimulated desorption of molecules from the vacuum walls is another factor affecting the cathode lifetime. Cavity designs that take advantage of careful particle trajectory simulations can help for desorption related to the electron beam, but not for dark current. For the SLC polarized source beam transport design, wall interception of the beam current in the first meter was restricted to $<10^{-3}$. [21]. However, field emitted electrons (dark current) and backward accelerated photoemitted electrons are more difficult to control. The latter might be reduced by producing an ultra-fast rise and fall time for the laser pulse. For NC cavities, operation at cryogenic temperatures should reduce the desorption coefficient.

The most effective pumping for polarized electron sources has been a combination of ion pumps and NEG pumps. Total pressures $<10^{-11}$ Torr (dominated by H_2) have been achieved, with the CO partial pressure being $\sim10^{-12}$ Torr. While such pressures are probably crucial for cathode activation, properly activated cathodes may tolerate a poorer vacuum. There is evidence that continuous deposition of Cs will protect the cathode [22], but excess Cs may cause an increase in dark currents in an RF cavity. Other more compatible means that might possibly extend the cathode lifetime in a poor environment include careful preparation of the surface to create additional oxide bonding to GaAs as well as to Cs [23], and use of larger bandgap materials [24]. More research is needed to determine the limits of the vacuum system for the operating cathode.

The laser wavelength for a polarized RF gun must be near the bandgap edge. To utilize all the possible high-polarization cathodes, the laser should be tunable over the range 750-870 nm. At present this limits one to a Ti:sapphire laser. With mode-locking, there is no problem producing 10 ps pulses at 714 MHz phase locked to S-band RF to within 1 ps. This is certainly an advantage over Nd:YAG lasers presently used to photoexcite multi-alkali cathodes. For high peak intensities, Ti:sapphire lasers are usually Nd:YAG pumped, although at present there are no suitable commercial YAGs that operate above 60 Hz. However, 2 or more YAGs can be combined to pump a single Ti:sapphire cavity as is done for the SLC. A more serious problem is related to the 714 MHz structure of the microbunches. Mode-locked lasers can certainly generate such a pulse train cw at low amplitude. The problem comes with power amplification: a single micropulse is too short while the macropulse is too long to use regenerative amplification. For the alternative amplification method, since the gain of a single Ti:sapphire amplifier stage is quite low, many such stages are required, making stability a problem.

The optimal pulse width of the electron beam at the cathode is on the order of 10 ps. The temporal emission response of a negative electron affinity (NEA) GaAs cathode has not been measured to this level. However, the time, t, for an electron minority carrier to diffuse through an active layer of thickness x varies as x^2/D, where D is the electron diffusion constant. At room temperature D ~ 300 cm^2s^{-1}, so t is expected to be on the order of 3 ps or less for strained layer photocathodes.

A serious question arises as to whether the charge limitation reported for the SLC polarized source [5] will prohibit the fast extraction of the charge required for the NLC or JLC. Assuming equal cathode areas the charge density per microbunch required for the NLC is five times lower than a typical operating value for the SLC. The question concerns the allowed peak current density, J_{peak}. For a 10 ps laser pulse and an S-band RF gun having a cathode diameter of 14 mm, Jpeak ~ 100 A cm^{-2} for the NLC. Although this is well below the space charge current limit (estimated to be ~300 A cm^{-2} at 30 MeV/m), it is more than an order of magnitude higher than for the SLC source. Charge densities as high as 180 A cm^{-2} have been reported for GaAs cathodes using shorter wavelength excitation [25]. The charge limit is much more restrictive for excitation near the bandgap. It is clear that the maximum current density that can be extracted from GaAs in the picosecond regime at bandgap wavelengths needs more investigation. The intrabunch effects of the charge limit also need more study [26].

The initial RF and beam processing of the RF cavity may prove crucial to achieving good vacuum. A load-lock design for the cathode permits RF processing with a dummy cathode. A load-lock also makes beam processing possible using a metal cathode in combination with a powerful short wavelength laser. In addition, introducing the cathode into the vacuum system after the latter is baked for good vacuum has been shown at SLAC to produce consistently higher initial QEs [27].

A schematic for a possible load-lock design suitable for generating polarized electrons is shown in Fig. 4. It follows closely the SLC design described in ref. [28]. A magnetic manipulator [29] is used to insert or withdraw the cathode stalk. The GaAs cathode is attached to a puck that is itself clamped to the cathode stalk by spring-loaded rollers. For in situ cesiations, the cathode is withdrawn past valve V1 to an intermediate position where channel cesiators and an oxide source are located. Valve V1 can be closed to protect the gun vacuum system during cesiations or when transferring cathodes. By using channel cesiators and a stepping motor for the cathode retraction, the cesiation can be done remotely and should take no more than ~30 minutes. The cathode is activated in a separate vacuum chamber equipped with a similar load-lock. This allows the cathode to be fully tested for QE, P_e, lifetime, and maximum charge before committing it to use in the gun. When needed, a newly activated cathode is transferred under vacuum to the gun. The transfer mechanism consists of a second magnetic manipulator plus valve V3. A puck is held in the transfer mechanism by a fork whose motion is orthogonal to that of the cathode stalk. Clearly the activation chamber should have a very good vacuum. The transfer vacuum need not be as good. Once attached, the intermediate volume between V2 and V3 need only be baked under vacuum for a couple of hours before transfering the puck between the transfer mechanism and the cathode stalk. Cathode changes, which should be relatively rare, are performed manually.

The cathode puck as well as the cathode stalk can be hollow, allowing the possibility of operating the cathode in transmission mode. The latter mode greatly simplifies the transport of the laser beam to the cathode, but appropriate cathodes have not yet been developed. Strained GaAs on GaAsP can be placed on a transparent (index matched to the laser wavelength to eliminate reflection) amorphous substrate. However, a thin layer of GaAs placed directly on the amorphous substrate at a growth temperature that will assure the desired strain of the GaAs lattice when returned to the normal cathode operating temperature is another intriguing possibility [30].

Since the charge limit experienced with the SLC polarized source scales linearly with voltage [31], the high fields of the RF source present a distinct advantage when operating at lower QEs as long as there is sufficient laser power. Nonetheless, this charge limit may yet be a significant factor at the lowest QEs. There is reason to believe this effect can be reduced if not eliminated by providing the proper means to discharge the surface during the high intensity laser pulse. Assuming the electron polarization is not significantly reduced, use of such techniques would allow longer operating periods between cesiations.

Conclusion

Given the advances that have been made with the SLC in the operation of a high peak current, pulsed polarized electron source using DC voltage, the prospect for generating polarized electron beams with an RF gun now appear to be quite good. The technological advances already proven, or which hold promise for the near future, can be applied to present RF gun designs to produce a low-emittance highly-polarized beam suitable for the JLC/NLC injector.

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Figure Captions

1. Schematic representation of JLC pulse train for an RF gun, showing spacing of (a) macrobunches, and (b) microbunches. The range of values is determined by the final choice of linac accelerating frequency: macro- and microbunch separations of 6.67 ms (150 Hz) and 1.4 ns or 2.8 ns for X- or C-band acceleration respectively, and 20 ms (50 Hz) and 5.6 ns for S-band.

2. HPP results on a 2-cell cavity [18].

3. Modified Fowler-Nordheim plots for three Cu structures designed for high RF acceleration: (a) conventional, (b) electroplated, and (c) clean [20]. The maximum accelerating gradient before breakdown is indicated.

4. Schematic of an S-band RF gun showing especially the load lock scheme proposed. The notation is as follows: P=vacuum pump, MM= magnetic manipulator, and V=vacuum valve.

Table I. Polarized electron source parameters

Parameter	SLC performance at gun	at 40 MeV	after DR	NLC design [2] X-band	JLC design [3] X-band	C-band	S-band
Macrobunch rate (Hz)	120	120	120	180	150	150	150
Microbunches per macrobunch	2	2	3	90	90	72	46/55
Spacing (ns)	60	60	60	1.4	1.4	2.8	5.6
Microbunch width (ps)	2000	35	10	10 [a]	10 [a]	10 [a]	10 [a]
$N_{microbunch}$ (10^{10} e^-) [b]	5	4	3	1	1	1.5	2.0/2.4
N_{total} (10^{10} e^-/s)	1200	1000	1100	16200	13500	10800	6900/9900
I_{peak} (A)	4	180	480	160	160	240	320/384
$\gamma\varepsilon_x$ (10^{-8} m)	1000	10000	5000	500[c]	300[c]	300[c]	300[c]
$\gamma\varepsilon_y$ (10^{-8} m)	1000	10000	500	5 [c]	3 [c]	3 [c]	3 [c]

[a] The pulse width assumed here is for the laser system described in the text.

[b] The number of particles produced at the source is shown here as 40% higher than needed by the linac to make up for unavoidable losses.

[c] The emittance for NLC/JLC is the requirement for the high energy linac.

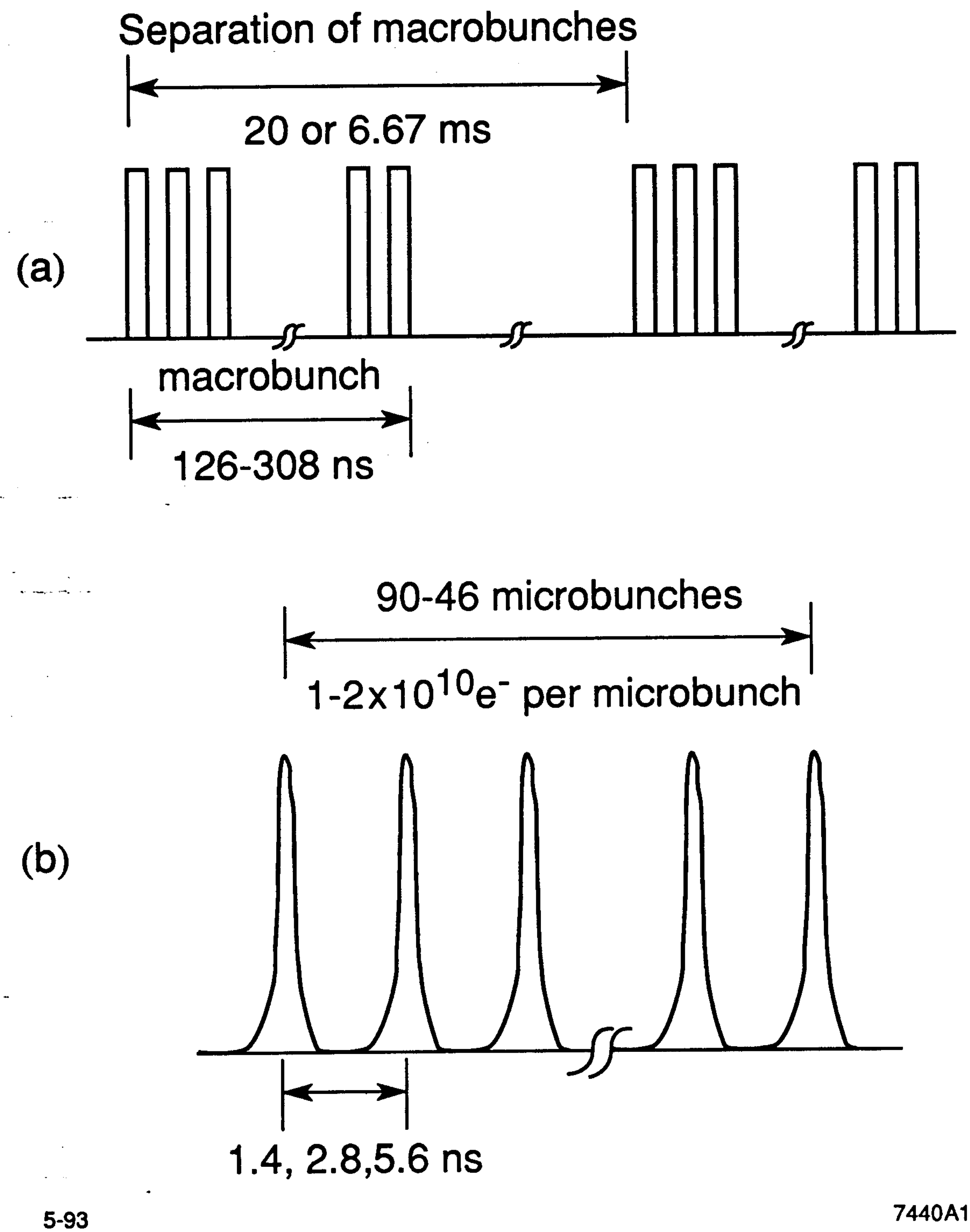

Separation of macrobunches
20 or 6.67 ms
(a)
macrobunch
126-308 ns
90-46 microbunches
1-2x10¹⁰e⁻ per microbunch
(b)
1.4, 2.8,5.6 ns
5-93
7440A1

Figure 1

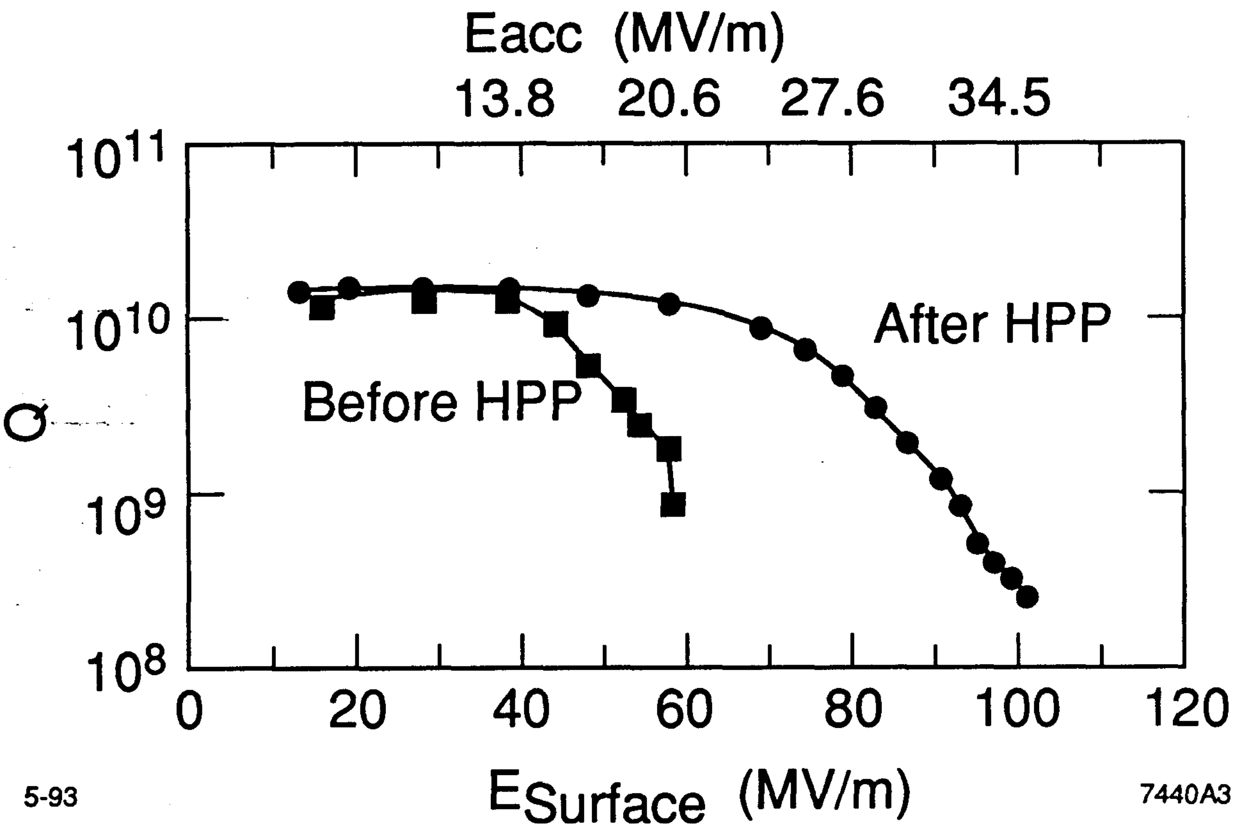
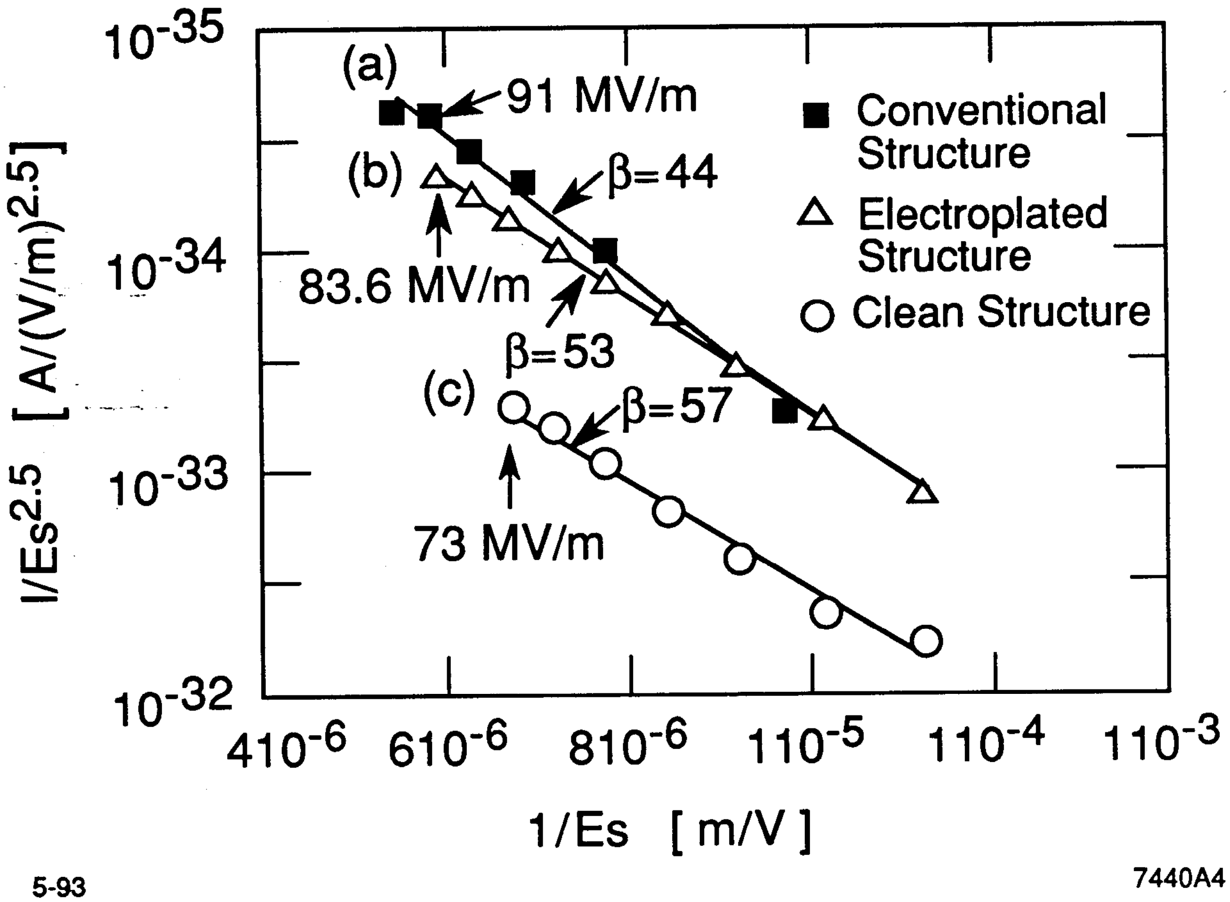

Eacc (MV/m)
13.8
20.6
27.6
34.5
10^{11}
10^{10}
10^{9}
10^{8}
Q
After HPP
Before HPP
0
20
40
60
80
100
120
$E_{Surface}$ (MV/m)
5-93
7440A3

Figure 2



10-35
10-34
10-33
10-32
I/Es2.5 [A/(V/m)2.5]
(a)
91 MV/m
β=44
(b)
83.6 MV/m
β=53
(c)
β=57
73 MV/m
Conventional Structure
Electroplated Structure
Clean Structure
410-6
610-6
810-6
110-5
110-4
110-3
1/Es [m/V]
5-93
7440A4

Figure 3

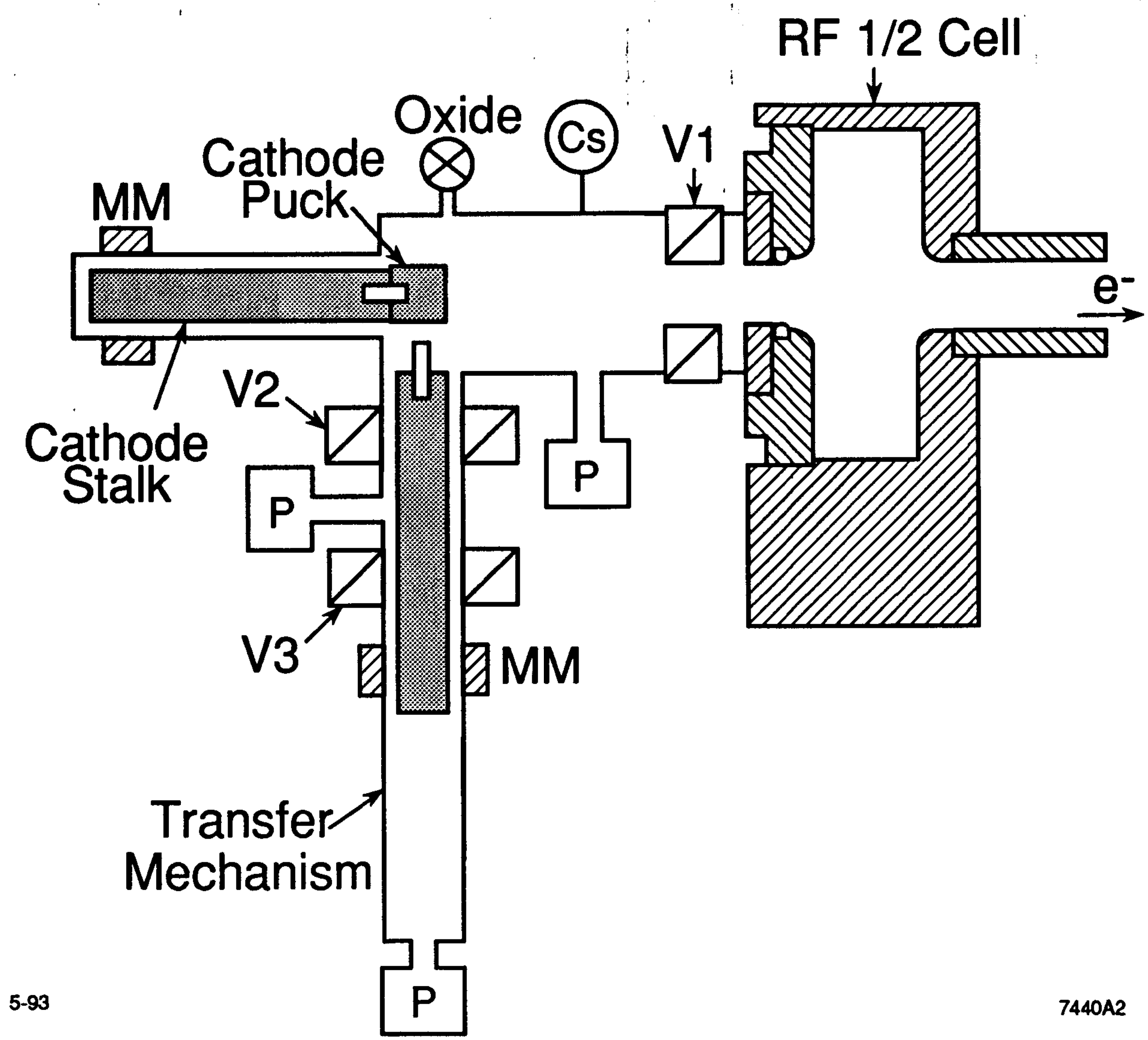

RF 1/2 Cell
Oxide
Cs
V1
Cathode
Puck
MM
e-
V2
Cathode
Stalk
P
P
V3
MM
Transfer
Mechanism
P
5-93
7440A2

Figure 4