GENERATING HIGH-BRIGHTNESS ELECTRON BEAMS*

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Abstract

We have designed a compact **LIN**ear **AC**celerator injected pulsed **R**ace **T**rack **M**icrotron to produce ~150 pC/bunch, 5π mm × mrad normalized transverse emittance, 5 ps bunch electron beams with energy selectable between 5 and 35 MeV in 2.5 MeV increments.

1 INTRODUCTION

Our proposed compact inexpensive electron source has advantages over a conventional LINAC but could be bunch charge limited [1]. Here we detail our design study of this system in which we investigated the injector, the RTM, and the injection/extraction line beam dynamics and obtained the **C**oherent **S**ynchrotron **R**adiation and transverse **B**eam **B**low **U**p bunch charge limits.

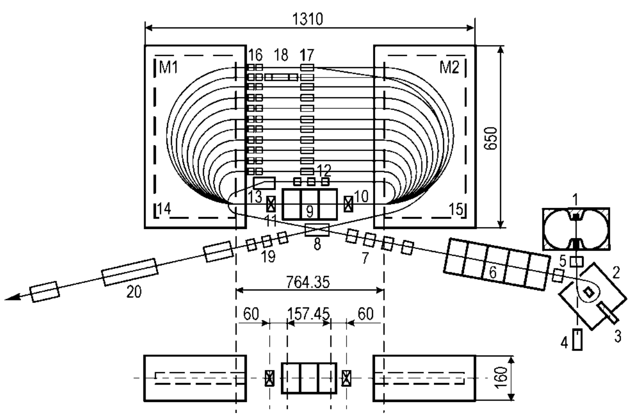

Figure 1: Electron source schematic

Our system, seen in Fig. 1 whose principal parameters are listed in Table 1, consists of (1) a **R**adio **F**requency gun, (2) an α-magnet, (3) a slit, (4) a laser, (5) lenses, (6) the injector **A**ccelerating **S**tructure, (7,12,19) quadrupole triplets, (8,13) dipole magnets, (9) the RTM AS, (10,11) quadrupole singlets, (14,15) end dipole magnets, (16) correcting magnets, (17) extraction magnets, (18) a phase adjusting chicane, and (20) a bunch compressor. Our electron source has three important features: (a) High-energy (5 MeV) injection provided by a thermionic RF gun, an α-magnet, and the injector AS; (b) Simple RTM optics and permanent magnet end dipoles; and (c) Beam compression by simultaneously using the RTM AS, the end magnets, and an external chicane.

Table 1: RTM parameters

Injection Energy	5 MeV
Output Beam Energies	5 - 35 MeV
Peak Beam Current	~30 - 100 A
Pulsed Beam Current	115 mA
Norm. Beam Emittance	5 π mm × mrad
Longitudinal Emittance	50 keV × deg
Beam Micro-pulse Length	5 - 1 ps
Beam Macro-pulse Length	5 μs
Pulse Repetition Rate	1 to 300 Hz
RF Frequency	2,856 MHz
RTM Dimensions	$130 \times 65 \times 16$ cm^3
Pulsed RF Power	6 MW
End Magnet Field	0.5 T
End Magnet Weight	2 × 160 kg

2 INJECTOR

By separating the injector from the RTM, we can generate bunches using a variety of techniques and then optimize the RTM without concern for bunch formation. Our injection energy is high enough to suppress ordinary space charge effects and to simply solve the "first orbit" problem but sufficiently low so as to be economical. Injecting at 5 MeV is a reasonable compromise.

A conventional electron gun will not give us our injector bunch parameters, while a photocathode RF gun is too expensive. Thus, we will form bunches with a thermionic RF gun. To decrease/regulate the RTM beam loading, we can either operate the RF gun at the 4th subharmonic or alternatively at the 4th subharmonic or fundamental frequency using a preheated LaB_6 cathode gated by long pulses from an inexpensive laser [2]. The beam dynamics are unaffected for laser pulses whose length is comparable or greater than the RF period.

We study the beam dynamics in a single cavity 714 MHz RF gun (1) whose cavity length and RF field amplitude gives a 1.8 MeV maximum energy beam with a unique energy-phase correlated longitudinal phase space distribution. We then longitudinally prepare the 5 MeV injector bunches to match the RTM acceptance by a phase space transformation using an α-magnet (2) with an adjustable collimating slit (3) and a five cell standing

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wave AS (6). We transversely focus the injector beam with quadrupole triplets (5) placed at the α-magnet entrance and exit.

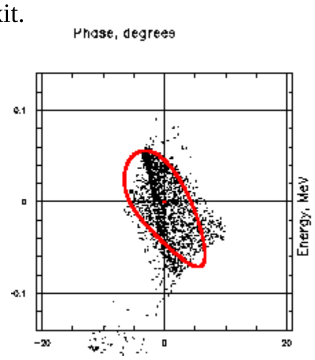

Figure 2: Longitudinal injector exit phase space

Figure 2 shows the longitudinal phase space at the injector exit matched to the RTM acceptance while Table 2 gives the bunch parameters at the injector exit [3,4].

Table 2: Injector exit bunch parameters

Q_{beam}	280 pC
Normalized $\langle\varepsilon_x\rangle$	18.4 mm × mrad
Normalized $\langle\varepsilon_y\rangle$	20.3 mm × mrad
$\langle W_{beam}\rangle$	5.0 MeV
ΔW_{beam}	± 56 keV
$\Delta\varphi_{beam}$	± 3.6°
$\langle\varepsilon_L\rangle$	200 keV × deg

3 RTM

Our RTM has a 2.5 MeV synchronous energy gain per orbit and attains the 35 MeV maximum energy beam in 12 orbits. To maximize the longitudinal acceptance we chose the incremental number, ν, to be 1 and so 0.5 T is the end magnet main field.

High-energy injection simplifies the RTM beam dynamics where we achieve focusing by quadrupole singlets installed at each end of the RTM AS as in **C**ontinuous **W**ave machines [5]. We optimize the quadrupole gradients and find matched transverse and longitudinal phase space ellipses parameters.

Our calculated bunch parameters at the RTM exit neglecting space charge effects, listed in Table 3, have transverse and longitudinal emittances slightly greater than our desired values. However, we have some excess bunch charge that we reduce by decreasing the α-magnet collimating slit width and thereby decrease the beam emittance.

Table 3: Bunch parameters at the RTM exit

Q_{beam}	230 pC
Normalized $\langle\varepsilon_x\rangle$	12.97 mm × mrad
Normalized $\langle\varepsilon_y\rangle$	16.20 mm × mrad
$\langle W_{beam}\rangle$	35.1 MeV
$\langle\Delta W_{beam}\rangle$	± 30 keV
$\Delta\varphi_{beam}$	± 5°
$\langle\varepsilon_L\rangle$	102.8 keV × deg

As in our 70 MeV RTM design [6], we use permanent magnet box-type end magnets [7] which in contrast to electromagnets require no power supply, cooling, or complicated control system and are more compact and weighs less. To compensate for beam defocusing, we form a reverse field at the magnet entrance with a second, opposite polarity, pole.

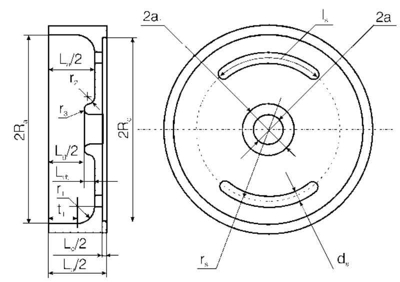

Figure 3: RTM accelerating structure

We use a standing wave on-axis coupled AS in both the injector and RTM. The three accelerating cell RTM AS, seen in Fig. 3, have $f_{\pi/2}$ = 2,856.04 MHz, r_{sh} = 72.7 MΩ/m, k_c = 7.0 %, and Q = 14,530.

4 INJECTION AND EXTRACTION

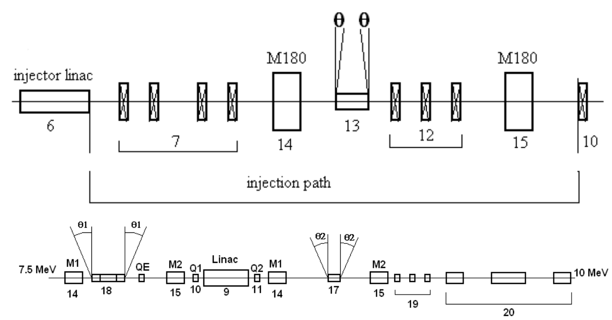

Figure 4 Injection (top) and extraction (bottom) paths

The injection path, shown in Fig. 4, provides a dispersion free beam which is transversely matched to the RTM acceptance.

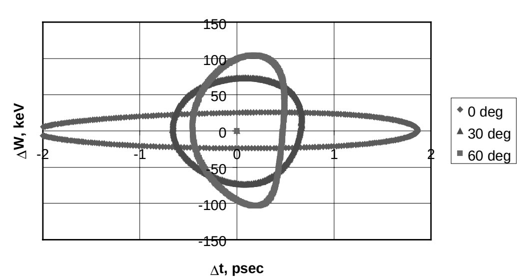

Figure 5: Extracted bunch longitudinal phase space

The extraction path provides a dispersion free extracted beam from any orbit after the 2nd whose bunches are simultaneously compressed. A three-magnet chicane installed at return path (18) shifts the extracted bunch phase by 15-60° on the penultimate orbit. On the final AS pass, the bunch gets an additional energy spread and then, between the end magnets, it is deflected by ~5°

horizontally by an extraction magnet (17), so that it enters end magnet M2 at nearly the same place as on its previous orbit. The bunch emerges at ~5° to the structure axis and is displaced by ~33 mm. After quadrupole focusing the bunch is compressed in a second three-magnet chicane (20). Fig. 5 shows the exiting longitudinal bunch phase space for three phase offsets.

5 PARASITIC PHENOMENA

Our high charge, short bunches and high pulsed current have never been obtained in a classical microtron or a RTM. Thus we must investigate CSR and regenerative transverse BBU, which can limit our accelerated bunch charge and pulsed current. CSR forces, which can increase the longitudinal and bending plane emittance from 3 to 5 times depending on the bunch length, δ_z [1,8], can be suppressed by decreasing the vacuum chamber height. A bunch circulating with radius R between two infinitely conducting plates separated by a distance of $2h$ radiates CSR power depending on the parameter $\Sigma=\delta_z/(2R\Delta^{3/2})$, where $\Delta=h/R$ [9]. Reducing h causes $\Sigma\approx0.7$ to reduce the radiated CSR power by a factor of ten. Since CSR induced emittance growth is greatest in the 12th orbit, the emittance growth will also be reduced by an order of magnitude for $\delta_z\approx0.5$ mm, $R\approx25$ cm, and $h\approx3$ mm. We will construct our vacuum chamber using the full 3 cm end magnet gap height into which we will place vertically movable plates so that we can experimentally investigate the CSR effects. In this way we hope to find a compromise between the beam losses and emittance growth.

Table 4: Main AS TM_{11}-like parasitic modes

N	f (MHz)	Q	$r_\perp$ (MΩ)	Pol.	Cell #
1	4862.16	22,657	1.25	X	1,3
2	4883.74	13,602	0.432	Y	1,3
3	4892.09	10,861	0.707	Y	2
4	4923.41	19,667	1.10	X	2

Regenerative transverse BBU has only been investigated in superconducting CW recirculating machines [10]. With our high pulsed current, we can reach the BBU threshold. The most dangerous RTM AS parasitic modes are TM_{11}-like and listed in Table 4.

The worst case steady state threshold BBU current is

$$I_t \bullet r'_\perp = 4E_z\lambda_r/[\pi\,\beta N\ln(W_e/Wi)],$$

where $r'_\perp$ is transverse shunt impedance per unit length, E_z is the accelerating field, the β-function is taken at the structure center, and Wi and W_e are injection and extraction energies [11]. For $E_z\approx1.6\times10^7$ V/m, $\lambda_r\approx0.061$ m, $N = 12$, $\langle\beta\rangle$ ~3 m, and injection and extraction energies of 5 and 35 MeV, respectively, $I_t \bullet r'_\perp \approx 0.018$ A×MΩ/m. For our RTM AS the maximum $r'_\perp$ is ~15 MΩ/m and so I_t ~1 mA. However, our design calls for 115 mA so transverse BBU is important. Our computer simulations with both steady state and time dependent codes predict an I_t larger by an order of magnitude in the horizontal plane and by two orders in the vertical plane. To increase our threshold BBU current above our desired 115 mA, we will damp the parasitic mode Qs by coupling them to external loads.

6 CONCLUSION

With our detailed design study and extensive computer simulations of a high charge/bunch low emittance 35 MeV electron source now complete, we are preparing to construct a prototype.

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