# STUDY OF MICROBUNCHING INSTABILITY IN MESA*

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## *Abstract*

The Institute for Nuclear Physics (KPH) at Mainz is building a multi-turn energy recovery linear accelerator, the Mainz Energy-recovering Superconducting Accelerator (MESA), to deliver a CW beam at 105 MeV with short pulses, high current and small emittance for physics experiments with an internal target. Space charge effects potentially cause beam quality degradation for medium energy beams in smaller machines like MESA. As beam quality preservation is a major concern in an ERL during recirculation. We present a study on Microbunching Instability (MBI) caused by Longitudinal Space Charge (LSC) in MESA. Our results demonstrate the impact of the MESA arc lattice design on the development of Microbunching Instability.

## INTRODUCTION

Energy recovery linacs (ERLs) provide electron beams of high current, high intensity with short pulses, facilitating their use as apparatus for various physics experiments and as free electron laser (FEL) drivers. ERLs were first proposed in 1965 and have gained tremendous interest since the 21st century [1]. At present, there are three operating ERLs: the JLab IR FEL Upgrade, the Japan Atomic Energy Agency (JAEA) FEL, and the Novosibirsk High Power THz FEL. While ERLs such as these three have been used largely for applications as FEL drivers, a large amount of research is focused on alternative applications such as dark photon detection and scattering experiments. Currently, upcoming ERL facilities include cERL at KEK, BerlinPro, and the Mainz Energy-recovering Superconducting Accelerator (MESA).

A detailed understanding of the physics of high current and high intensity beams in ERLs is of fundamental importance to preserve beam quality. While rapid advances have been made in the field of ERLs through investigations using particle tracking, the effect of space charge has received less attention. Space charge will be important in smaller machines and for medium energy and might, for example also affect the transport matrix in the arcs for recirculation [2]. It is important to develop an effective methodology to optimize the effect of space charge on lattice arcs. There is a need to explore measures to circumvent beam mismatch and corresponding emittance growth. Such studies rely on accurate predictions of the 3D beam envelope in the presence of space charge [3]. Longitudinal space charge (LSC) together dispersion can lead to the amplification of the initial shot noise, which is the well-known microbunching instability (MI). The linear microbunching gain process due to LSC can be depicted as follows [4]:

$$G \simeq 4\pi \frac{I_0}{I_A} L_s \frac{|Z(k)|}{Z_0} k |R_{56}| \tag{1}$$

where $Z(k)$ is longitudinal space charge impedance, $R_{56}$ is the longitudinal dispersion, the bunch peak current $I_0$ and the Alfven's current $I_A$.

We adopt the LSC impedance derived in Ref. [5]. The beam is assumed transversely uniform with a circular cross section of radius $r_b$ [5],

$$Z(k) = \frac{iZ_0}{\pi\gamma\, r_b}\left[1 - \frac{kr_b}{\gamma} K_1\left(\frac{kr_b}{\gamma}\right)\right] \tag{2}$$

where $r_b \approx 1.7(\sigma_x + \sigma_y)/2$.

The goal of our study is to predict the microbunching instability due to LSC, for the specific MESA lattice and beam parameters which we will describe below. Further, as a first step, we analyze the MESA lattice parameter in the presence of 3D space charge.

## BRIEF OVERVIEW OF MESA

MESA is a small-scale, multi-turn, double-sided recirculating linac with vertical stacking of the return arcs operating in cw mode. Currently there are two planned experiments in MESA [6]:

(I) Fixed target experiment for precise measurement of the Weinberg angle with the beam extracted to the experiment in the external beam (EB) mode at 155 MeV.

(II) Pseudo Internal Target (PIT) experiment in search for dark photons with high luminosity as compared to storage rings due to low emittance life time.

A 3D sketch of MESA is shown in Fig. 1. It consists of a 100 keV polarized photo-cathode electron gun [7] with a normal conducting injector linac with an extraction energy of 5 MeV. The photo-cathode electron gun produces very short electron bunches. There are two superconducting linac modules with an energy gain of 25 MeV for each pass with four spreader sections for separating and recombining the beam and two chicanes for injection and extraction of the 5 MeV beam [8]. For beam recirculation there are five arcs to support the beam corresponding to five different energy levels: 55 MeV, 80 MeV, 105 MeV,130 MeV and 155 MeV. The proposed beam parameters for MESA are in Table. 1. After the PIT experiment, the beam re-enters the main module with a $180^0$ phase shift and starts to decelerate. The decelerated beam is dumped at 5 MeV [8].

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* Work supported by DFG through GRK 2128
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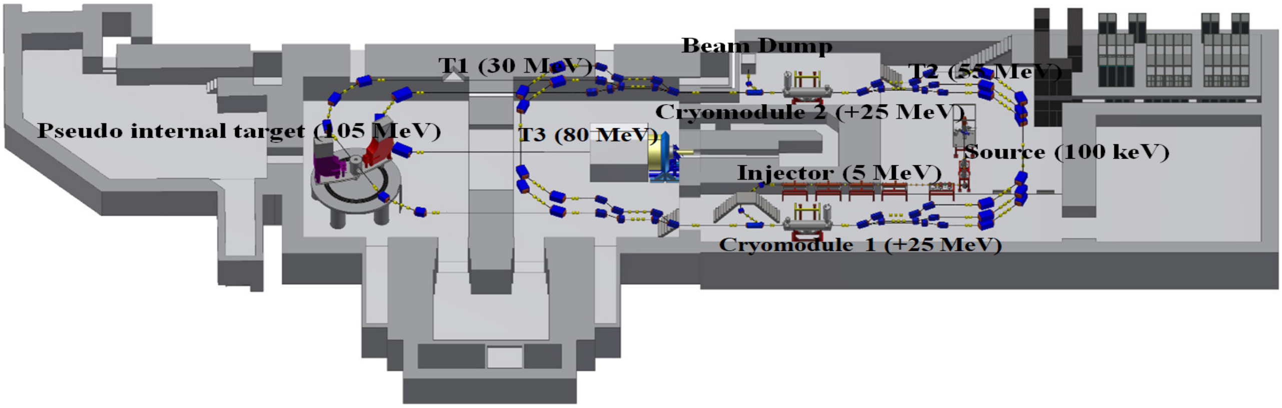

Figure 1: 3D sketch of MESA

Table 1: MESA Beam Parameters

| Beam Parameter | Value | Unit |
|---|---|---|
| Beam Energy | 105 | MeV |
| Beam Charge | 7.7 | pC |
| Beam Current | 10 | mA |
| Operation Frequency | 1300 | MHz |
| Bunch Length | 1.281 | mm |
| Normalized emittance | 0.002 | mm mrad |

## MATCHED ENVELOPES WITH SPACE CHARGE

The beam envelopes and lattice functions are obtained by solving the envelope equations by a matrix method, including the linear defocusing effect of space charge [9, 10].

The space charge modified rms envelope equations for the rms beam radii $\sigma_{x,y}$ including dispersion are (see e.g. [2]):

$$\begin{aligned} &\frac{d^2\sigma_x}{ds^2} + \left(\kappa_x(s) - \frac{K}{2X(X+Y)}\right)\sigma_x - \frac{\epsilon_x^2}{\sigma_x^3} = 0 \\ &\frac{d^2\sigma_y}{ds^2} + \left(\kappa_y(s) - \frac{K}{2Y(X+Y)}\right)\sigma_y - \frac{\epsilon_y^2}{\sigma_y^3} = 0 \qquad (3) \\ &\frac{d^2 D}{ds^2} + \kappa_x(s) D - \frac{K}{2X(X+\sigma_y)} D = \frac{1}{R} \end{aligned}$$

where the effective horizontal beam radius is $X = \sqrt{\sigma_x^2 + D^2\delta^2}$ and $K$ is the space charge perveance, which measures the strength of space charge, defined by $K = eI/\left(2\pi\epsilon_0 m\beta^3\gamma^3\right)$, $I$ is the beam peak current, $\beta$ and $\gamma$ are the relativistic factors. $\kappa_{x,y}$ are the focusing gradients and $R$ is the bending radius. $\epsilon_{x,y}$ are the rms emittances. Instead of the envelopes we solve for the the beam matrix $B_s$ along the longitudinal position $s$: $B_s = M.B_{s_0}.M^T$ with $M$ as transport matrix $M\left(s_0, s_0 + \Delta s\right) = M_{\Delta s/2} M_{\Delta s}^{sc} M_{\Delta s/2}$, where $M^{sc}$ is the space charge kick. A matched solution is found using an iteration scheme for the desired envelopes at the exit.

## RESULTS AND DISCUSSION

Figure 2 and Fig. 3 (b) show beta functions of MESA along the longitudinal axis in the absence and presence of space charge effects respectively. As can be seen in Fig. 3 (b), with the inclusion of space charge effects, there appears to be a strong mismatch in beam envelopes in the range (as depicted in Fig. 2) of the PIT experiment.

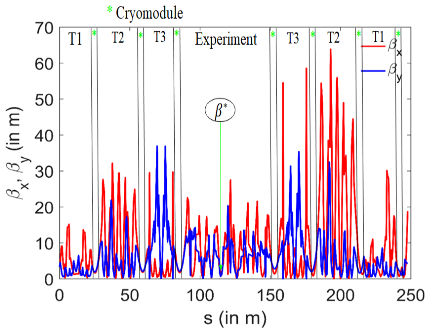

Figure 2: Beta functions of MESA in ERL mode in the absence of space charge effects.

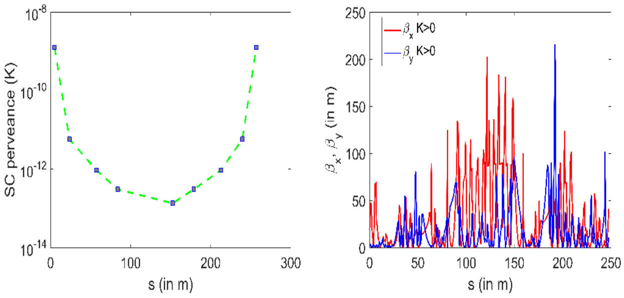

Figure 3: (a) Variation of space charge perveance along the beamline. (b) Beta function of MESA in ERL mode in the presence of space charge effects at design current 10 mA.

Figure 4 (a) shows the Variation of LSC gain function $G(s)$, along the beamline, for four different modulation wavelengths . Microbunching gain at $\lambda = 10\,\mu$m is greater than the gain at three other values $\lambda = 0.1$, 50 and 300 µm, at every point along the beamline. Since impedance is a function of modulation wavelength (see Eq. (2)), an accurate gain analysis requires scanning of the spectral range of modulation wavelengths. Figure 4 (b) shows the variation of LSC gain spectrum $G(\lambda)$ at the exit of the lattice as a function of initial modulation wavelength. As shown in Fig. 5, LSC effect on microbunching gain appears to be increasing in the operating current range of MESA. The preliminary design of MESA for high-current electron bunch is therefore, at risk of microbunching instability. An improved design is required to suppress such instability. Alternatively a modified beam transport scheme may be considered to transport the electron beam through the multi-turn accelerator, while maintaining high beam quality that is necessary for physics experiments in MESA.

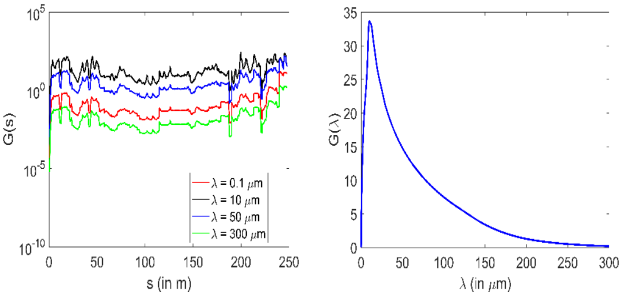

Figure 4: (a) LSC gain $G(s)$ along the beamline shown at four different wavelengths (red) $\lambda = 0.1\,\mu\text{m}$, (black) $\lambda = 10\,\mu\text{m}$, (blue) $\lambda = 50\,\mu\text{m}$, (green) $\lambda = 300\,\mu\text{m}$. (b) LSC gain $G(\lambda)$ as a function of initial modulation wavelength at beam exit.

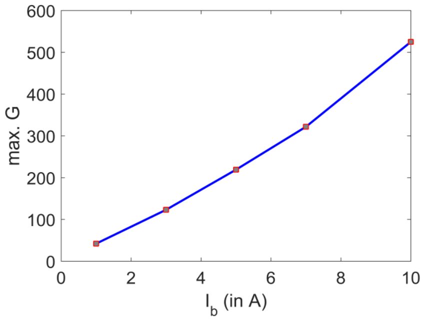

Figure 5: Initial current dependence of the maximal microbunching gains for MESA with space charge effects.

## CONCLUSION AND OUTLOOK

The effect of space charge on the MESA lattice was investigated using a simple beam matrix method with space charge kicks. Since precisely adjusted beam envelopes are a key component of the PIT experiment, the effect of space charge which can create a global mismatch of beam envelopes at different energies, should be well controlled. The microbunching instability is present in the operating range of the accelerator beam parameters. Further optimization of the recirculation arcs for intensity effects is foreseen. Space charge is prominent at low energies during beam injection and extraction. It will therefore be necessary to include 3D space charge in start-to-end simulations.

## ACKNOWLEDGEMENT

We would like to thank D.Simon for providing the MESA preliminary lattice design data. The author (A. Khan) would like to express her sincere thanks to N. Sawhney for fruitful discussions.

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