EMITTANCE EXCHANGE AT FNPL*

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Abstract

An experiment is being developed at the Fermilab NICADD Photoinjector Lab (FNPL) to demonstrate the exchange of longitudinal emittance, ε_z, with a transverse emittance, ε_x. Placement of a TM_{110} RF cavity in the dispersive region of a magnetic chicane will ideally zero the momentum spread, reducing ε_z. In zeroing the momentum spread in the dispersive region, the cavity's $E_z(r)$ field converts the transverse excursion due to dispersion with that of transverse betatron amplitude, hence increasing ε_x, thereby facilitating the exchange of ε_x with ε_z.

INTRODUCTION

Generating an electron bunch of a small transverse emittance is crucial for the operation of high-gain free electron lasers. It is typically found that photocathode guns can produce an extremely small longitudinal emittance compared to the transverse emittances. An emittance exchange scheme proposed by Emma and Chornachia [1] that utilizes a deflecting mode RF cavity placed in a dispersive region to realize the longitudinal to a transverse exchange. The Photoinjector consists of an RF photocathode gun and a TESLA Type I 9-cell superconducting RF cavity, both operating at 1.3GHz. Typical round beam operation can produce un-normalized transverse emittance, ε_x and ε_y of 0.1π mm-mr and a longitudinal emittance of 6π mm-mr. Although the Photoinjector produces the preferred ratio of a small transverse to larger longitudinal emittance, the principle of emittance exchange can demonstrated.

A 3.9 GHz superconducting TM_{110} deflecting mode cavity (DMC) operating in the π mode has already been developed at FNAL for other applications [2]; however, the construction and operation of a copper cavity is significantly easier than a niobium version. We show that a copper version of the same cavity geometry, requiring only moderate RF power, will provide the necessary longitudinal electric field to realize the emittance exchange.

EXCHANGE OPTICS

Considering only the bending plane phase space and the longitudinal phase space the two halves of the chicane can be written as:

$$M_D = \begin{bmatrix} 1 & L & 0 & \pm\eta \\ 0 & 1 & 0 & 0 \\ 0 & \pm\eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where η is the dispersion and ξ is the momentum compaction term. The thin lens approximation of the TM_{110} mode cavity can be taken as:

$$M_C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$$

Where k is related to the cavity voltage, V_o, by:

$$k = \frac{V_o}{aE_0}$$

and a is the radial offset and E_o is the average beam energy [1]. It can be seen with appropriate values of k and V_o that ε_x and ε_z are approximately exchanged after propagating through:

$$M_{exch} = M_D(-\eta)M_C(k)M_D(\eta)$$

This emittance exchange scheme is not exact due to a non zero transverse-to-longitudinal coupling term discussed in [1]. The effects of this emittance dilution are presently being studied.

The proposed emittance exchange experiment at the FNPL Photoinjector will utilize a 15MeV electron beam with a $\delta p/p \sim 3\times10^{-3}$ arising from a time-energy correlation imparted by off crest acceleration in the 9-cell. An off-momentum particle's transverse excursion in the region of maximum dispersion is linearly proportional to the momentum offset.

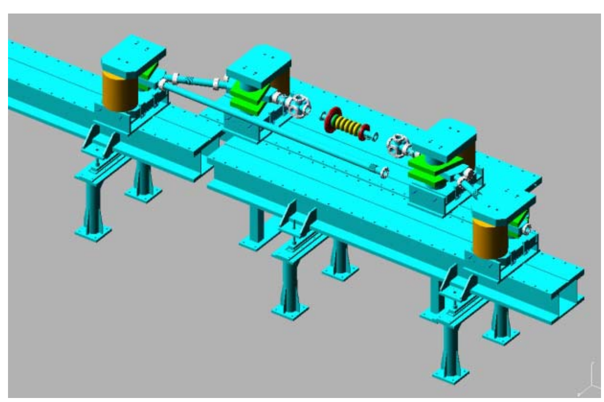

Figure 1: Proposed FNPL layout: deflecting cavity located in maximum dispersive region of magnetic chicane.

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The Magnetic Chicane

The planned chicane is comprised of four dipole magnets, shown in Figure 1. The magnets are being recycled from a previous bunch compression experiment at the photoinjector. Their bend angle is 22.5° with magnets 1 and 2, and 3 and 4 longitudinally spaced approximately 0.8 m to develop a dispersion of 0.33 m. The spacing between magnets 2 and 3 will be set by the space needed for the TM_{110} RF cavity and beam diagnostic currently being determined.

The four vacuum chambers that reside in the magnet gaps are of identical construction making prodigious use of symmetry. The chambers provide a straight through, "chicane off" mode.

The beam line optics are being designed to minimize the betatron function at the center of the cavity and are otherwise optimized for beam diagnostics. This uniquely includes consideration of the existing pole tips on the chicane dipoles, as they have edge angles optimized for transverse focusing in the previous setup. Preliminary calculations suggest that the existing angles are tolerable.

TM_{110} RF CAVITY CONSIDERATIONS

Cavity Power Requirements

Presently proposed values for the experiment require an integrated longitudinal kick of 45.5kV at a radial offset of 1mm from the cavity's central axis.

RF power requirements can be determined from scaling of the superconducting DMC. The following relates both the peak deflecting gradient and longitudinal kick to the applied RF power [2]:

$$V_T = \sqrt{2\left(\frac{R}{Q}\right)' PQ_{ext}} = \frac{c}{r\omega} V_L(r)$$

The shunt impedance, (R/Q)', for an individual cell is 27Ω. Due to the copper construction of this cavity, Q_o will be on the order of 14,000 at 300K. The fill time is less than 5 μsec and as a matter of economy we strive to make the coupling coefficient, β=1, the condition which provides the maximum gradient for a given RF power level.

This experiment is constrained to 80kW of 3.9GHz RF power from an already existing pulsed klystron. This value is further reduced to 50kW in our calculations to allow for circulator and transmission line losses. Since gradient scales with the square root of the power, but the available power to a given cell drops by the number of cells in the structure, it becomes clear that the net integrated gradient grows faster with the addition of cells then does the gradient decrease from the reduction in available RF power per cell. However, the practical upper limit on the number of cells that can be incorporated into this structure is determined by the mode spacing, the Q of each of the modes, and input coupler constraints.

Figure 2 shows plots the integrated longitudinal kick at a radial distance of 1 mm. As expected the gradient rises as the square root of the number of cells. The first cavity of multiple cells that will realize our integrated kick with 50kW is found to be near 7-cells.

Mode spacing places an upper limit on the number of cells; conveniently, calculation has shown that this upper acceptable limit is close to 7-cells. An increase in Q_o of the TM_{110} passband modes will cause their bandwidths to shrink, thereby reducing the deleterious effect from exciting the π-1 mode. This suggests cooling the cavity with lN_2.

It was found that unity coupling with an available coaxial input coupler requires a higher Q_o of the 7-cell structure, ultimately forcing lN_2 cooling. With lN_2 cooling, the copper structure should display a Q_o of 36,000.

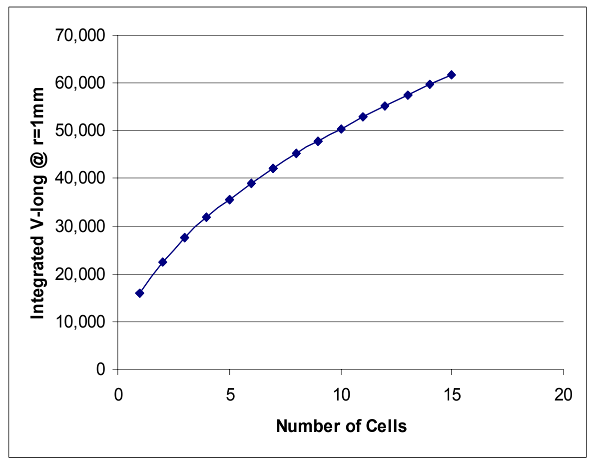

Figure 2: Longitudinal kick at r=1mm vs. number of cells. Q_o = 14,000 and β=1 at 50kW of power.

Input Power Coupling

The superconducting DMC was not designed for use with a "high power input coupler," however, the FNAL/DESY 3.9GHz 3rd Harmonic cavity input coupler has a power handling capacity of 80kW pulsed. It is planned that the TM_{110} copper cavity will utilize this input coupler. The longitudinal location on the beam pipe and penetration into the beam pipe determines the coupling coefficient. The lower the cavity Q_o the lower the Q_{ext} must be, and hence the greater the coupling must be to realize β=1.

A coupling study was performed using HFSS to determine the placement of the 3rd Harmonic input coupler for critical matching [4]. A 7-cell cavity with long beam pipes was modeling in the HFSS 3-D modeler. Two input couplers were incorporated to thoroughly simulate the input and pickup couplers through S_{21} measurements. To reduce the computation time, the modeled cavity structure was taken to be superconducting thus taking advantage of the ideal condition: $Q_L = Q_{ext}$. The input coupler location was optimized for an S_{21} measurement reporting a Q_L (thus Q_{ext}) of 36,000.

It has been concluded that the centerline of the input coupler should reside 20mm from the edge of the end cell for a 7-cell structure with a Q_o of 36,000. Adjustment in the radial direction (penetration into the beam pipe) will allow for fine tuning through β=1.

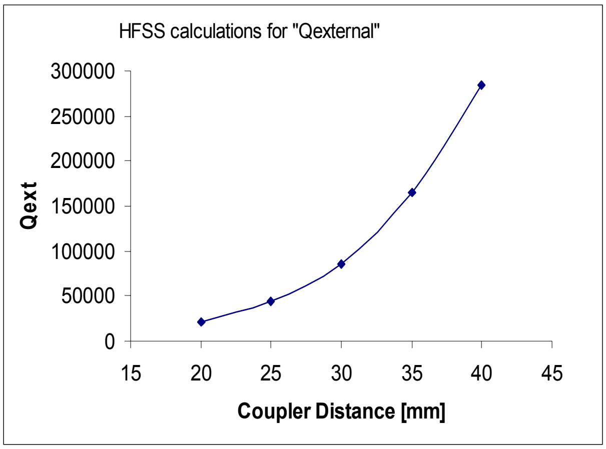

Figure 3: HFSS results: Q_{ext} vs. coupler placement.

Four Cell Prototype

A four cell prototype cavity is being built in order to verify our coupling expectation. A low power, to scale, input coupler and pickup probe are included in the prototype to confirm our RF modeling. Figure 4 shows the 4-cell. The 4-cell will not include a lN_2 jacket, rather the entire assembly will be directly placed into a LN_2 bath.

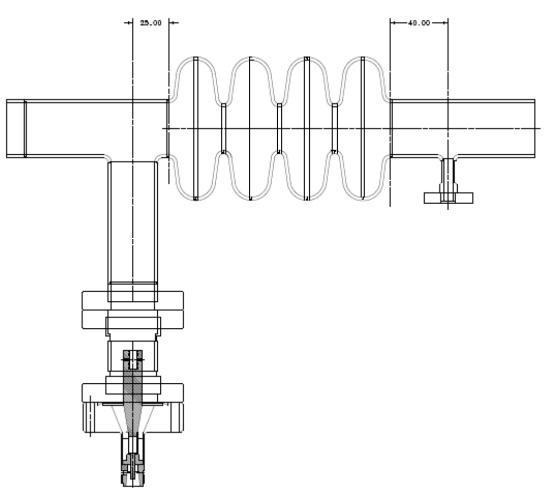

Figure 4: 4-cell prototype cavity setup for unity coupling.

Because of the fewer numbers of cells, the coupler will reside further away from the end cell. Scaling from the 7-cell HFSS simulations place the required coupling location for β=1 coupling with the 4-cell prototype at 25 mm from the end cell. There will be a linear slider to allow adjustment of the antenna's penetration into the beam pipe for fine adjustment of β.

7-cell Cavity Structure

The 7-cell construction will follow from the knowledge and experience gained with the 4-cell. To satisfy installation and safety requirements, the 7-cell will be fashioned with a lN_2 jacket and cryogenic supply system.

All copper-to-copper joints will be vacuum brazed. Due to the close proximity demanded of the input coupler to the end cell, the half end cell, LN_2 jacket flange, a portion of the beam pipe, and input coupler port will be machined out of a single copper block.

High Level RF System

A pulsed 80kW CPI Varian model ### klystron in hand and is being prepared for service. The small physical dimensions of the klystron conveniently permits the installation of it into a portable standard 19-inch equipment rack. This lends to the possibility of directly locating the klystron next to the cavity in the cave, thereby minimize transmission line losses.

Low Level RF System

It is planned to use a modified version of the DESY SimCon3.1 Low Level RF control system [4]. The modifications include algorithm development for the increased bandwidth (compared to typical control of superconducting cavities) and up and down conversion between 3.9 and 1.3 GHz.

CONCLUSIONS

FNPL is developing an experiment to demonstrate the exchange of longitudinal with a transverse emittance. Beam line layout, simulation and hardware construction are presently underway. The manufacting of two copper TM_{110} RF cavities is planned, first a 4-cell prototype, which is presently under construction, and finally an operational 7-cell.

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