DESIGN PROGRESS OF THE RE-BUNCHING RF CAVITIES AND HYBRID QUADRUPOLES FOR THE RAL FRONT-END TEST STAND (FETS)*

C. Plostinar, CCLRC/RAL/ASTeC, Chilton, Didcot, Oxon, UK
M. Clarke-Gayther, C. Thomas, CCLRC/RAL/ISIS, Chilton, Didcot, Oxon, UK

Abstract

The proposed FETS project at RAL will test a fast beam chopper in a 3.0 MeV H^- Medium Energy Beam Transport (MEBT) line. Space restrictions in the MEBT line place constraints on component length and drive the requirement to identify compact component configurations. Two candidate re-bunching RF cavity designs are considered: the space efficient Drift Tube Linac type (DTL) with integrated quadrupoles, and the high shunt impedance Coupled Cavity Linac type (CCL) with external quadrupoles. Preliminary RF simulations in 2D and 3D are presented, and a comparison, emphasising the advantages and disadvantages of each design is made. The compact hybrid quadrupole configurations considered are the 'tandem' combination of permanent magnet (PMQ) and electro-magnetic (EMQ) types, and the concentric combination of PMQ and laminar conductor (Lambertson) EMQ types. The suitability of the compact hybrid quadrupole for implementation in the low energy Drift Tube Linac (DTL) is suggested and discussed.

INTRODUCTION

High power proton accelerators (HPPAs), capable of producing beams in the MW range have many applications including drivers for spallation neutron sources, production of radioactive beams for nuclear physics, hybrid reactors, transmutation of nuclear waste, and neutrino factories for particle physics [1]. These applications require high quality beams, and call for significant technical development, especially at the front end of the accelerator where beam chopping at low energy (2.5 – 3 MeV) and high duty cycle (1 – 10%) is required to minimise beam loss and induced radioactivity at injection into downstream circular accelerators.

The Spallation Neutron Source (SNS) in the USA and the Japan Proton Accelerator Research Complex (JPARC) are both expected to deliver high-power beams in the near future. In the UK, the RAL FETS project [2] represents the national commitment to the development of a next generation HPPA, and prepares the way for a European next generation spallation source and neutrino factory.

One of the key parts of the FETS is the MEBT chopper line. This consists of a series of quadrupoles, RF cavities and a novel “fast-slow” beam chopper system [3]. The MEBT optical design must be as short as possible in order to minimize emittance growth, halo formation and subsequent beam loss in the downstream linac. This constraint drives the requirement for compact beam-line components. Two possible MEBT layouts are illustrated in Figure 1, showing the reduction in length obtained by using a compact combination of PMQs and EMQs.

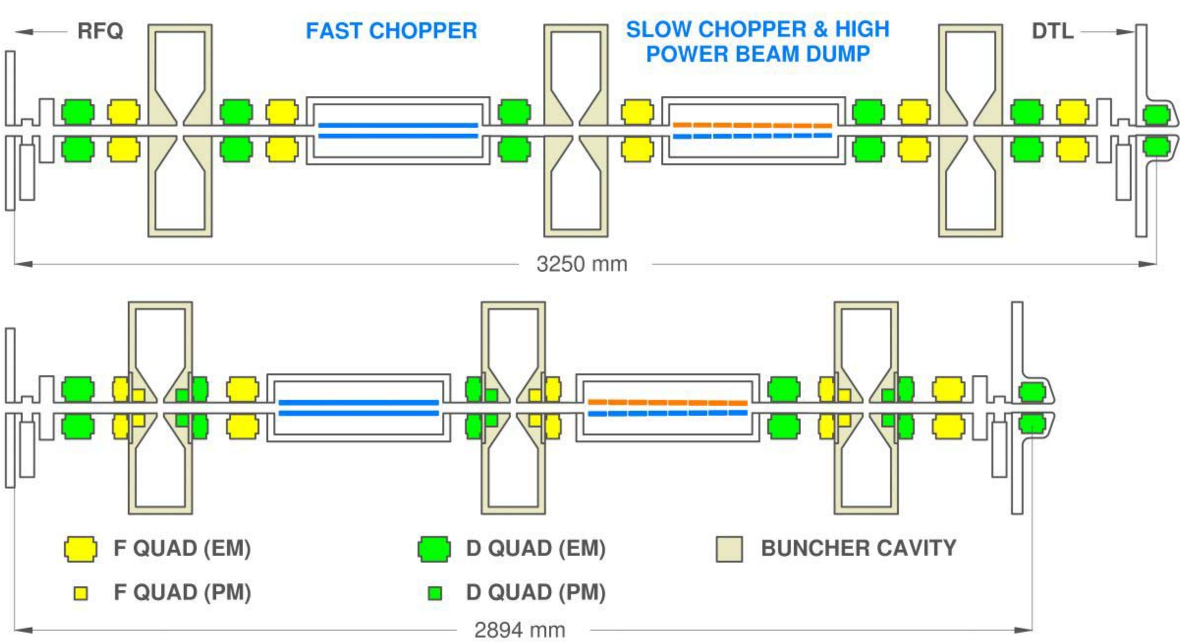

Figure 1: Two possible MEBT configurations showing a reduction in length using compact components.

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RE-BUNCHING CAVITY DESIGNS

The re-bunching cavities maintain the longitudinal focusing as the beam proceeds through the chopper line. In designing the cavities, the optimisation of RF power efficiency (high shunt impedance), Kilpatrick limit (avoidance of electrical discharge) and compactness have been taken into consideration.

Two design options are considered here: the space efficient DTL-type cavity derived from the Drift Tube Linac (Figure 2) and the power efficient CCL-type cavity derived from a Coupled Cavity Linac cell (Figure 3) [4].

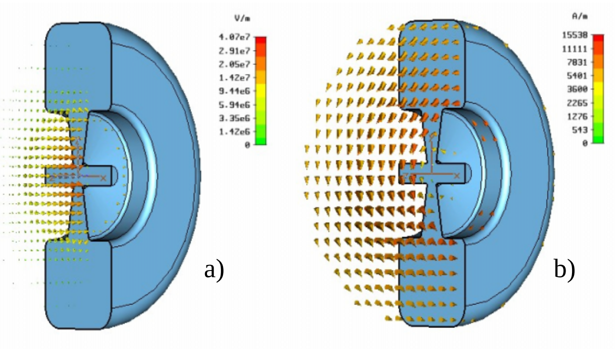

Figure 2: Microwave Studio 3D model of a DTL type cavity: a) Electric Field Vector, b) Magnetic Field Vector.

The preliminary RF design of the two cavity types has been performed using 2D [5] and 3D [6] codes. The 3D simulation is appropriate for designs that lack cylindrical symmetry, and can include the effects of tuning elements and vacuum pumping ports. A comparison of the preliminary 2D and 3D simulations shows good agreement between codes. Representations of the 3D electric and magnetic field vectors can be seen in Figures 2 and 3, respectively for both cavity types.

Considering the space restrictions in the MEBT line, the DTL-type cavity is desirable, because it allows EMQs to be integrated inside the drift tube, whereas the CCL structure is larger and due to its geometry, the nose cone cannot easily accommodate bulky EMQs. To overcome this limitation, a special combination of quadrupoles is proposed, that will be discussed in the next section.

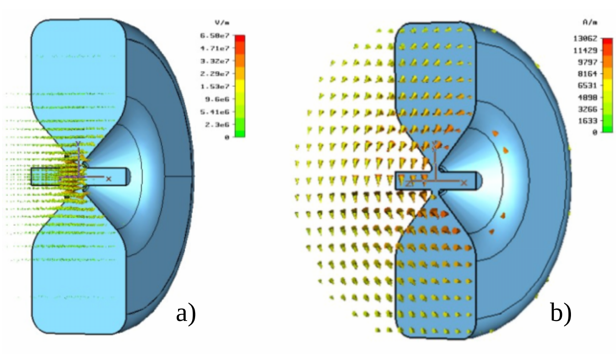

Figure 3: Microwave Studio 3D model of a CCL type cavity: a) Electric Field Vector, b) Magnetic Field Vector.

The main advantage of the CCL buncher cavity is its power efficiency, as shown in Figure 4, where the effective shunt impedance for both structures is plotted for different combinations of cavity lengths and gaps. The Kilpatrick factor variation with gap length for an effective cavity gap voltage of 160 kV is also shown. A region of high shunt impedance is highlighted, allowing an optimal choice for cavity geometrical parameters to be made.

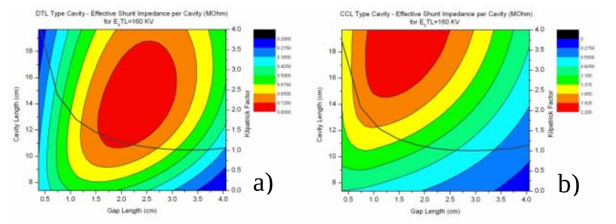

Figure 4: Effective shunt impedance (MΩ) and the Kilpatrick curve for a DTL-type cavity (a) and a CCL-type cavity (b).

Table 1 presents a comparison of RF properties for the two cavity types. Considering the arguments given above regarding the CCL cavity's power efficiency and also practical considerations concerning ease of manufacture, we can conclude that this cavity type is a good candidate for a buncher cavity for the FETS project.

Table 1: RF properties for the re-bunching cavities

Property	**DTL-Type Cavity**	**CCL-Type Cavity**	**Unit**
Energy	3	3	MeV
Frequency	324	324	MHz
E_0TL	160	160	kV
Cavity Length	140	172	mm
Bore Radius	14	14	mm
Gap Length	18	15	mm
Power Dissipation	19.2*	6.8*	kW
Q	17000	26800	-
r/Q	22.3	39.5	Ω
Max Power Density	15	5.1	W/cm^2
Kilpatrick	1.28	1.27	-

*values corrected by 15% from Superfish

HYBRID QUADRUPOLE DESIGNS

The type and design of quadrupole lens to be used in the MEBT line merits special attention. EMQs produce high magnetic fields, and can be adjusted by varying the current flow in the conductors. In this regard, they are preferable to PMQs whose field cannot be changed once they have been installed.. The main advantage of PMQs is their compact size, and if space is limited in the MEBT, these may be preferable over the bulkier EMQs.

Two hybrid quadrupole designs are under investigation at RAL. The main aim is to address the requirement for a compact design, able to efficiently utilise the space inside a DTL drift tube or a CCL nose cone, combined with a (limited) ability to adjust the field gradient. As the CCL-type buncher cavity nose cone cannot accommodate a bulky EMQ, a "tandem" combination of PMQ and EMQ has been proposed, where the smaller PMQ fits inside the nose of the cavity, making good use of the previously 'wasted space'. The EMQ is placed just outside the cavity boundary and provides the required range of field adjustment. As a consequence of the more efficient utilisation of space, the MEBT line length can be reduced by ~ 11% when using the tandem design, and the reduction in beam-line length is expected to provide a corresponding reduction in MEBT emittance growth.

The second hybrid quadrupole design for the MEBT is a combination of PMQ and laminar conductor EMQ (Lambertson quadrupole). Cylindrical, laminar quadrupole magnets, utilising flexible printed circuit techniques, and capable of producing modest field gradients, have been demonstrated [8, 9]. Integration of this structure in the bore of a PMQ should result in the summation of magnetic fields from both elements. As a consequence, the effective field gradient of the PMQ can be adjusted over a limited range, by varying the current in the laminar winding element. Preliminary magnetic field simulations using 2D codes [5, 7] have been made. A 3D finite element analysis model is in preparation as well as arrangements to measure the achievable range of field adjustment, and field homogeneity of an existing PMQ – laminar quadrupole, combination.

In the 2D model, shown in Figure 5, the laminar quadrupole consists of 72 conductors with a cos(2θ) current distribution. For the laminar EMQ alone, a maximum current density of 10 Amm^{-2} allows a maximum field gradient of 0.45 Tm^{-1}. This is approximately 1% of the FETS MEBT quadrupole gradient of 40 Tm^{-1}, and provides only 10% of the required range of adjustment. To achieve the required ±10% range of adjustment, multiple circuit board layers or conductors capable of carrying larger current densities must be utilised.

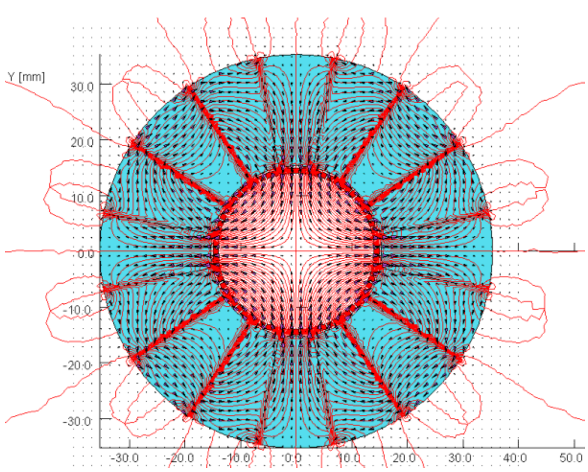

Figure 5: OPERA 2D plot of a PMQ with 16 wedges of material, and an integrated printed-circuit quadrupole.

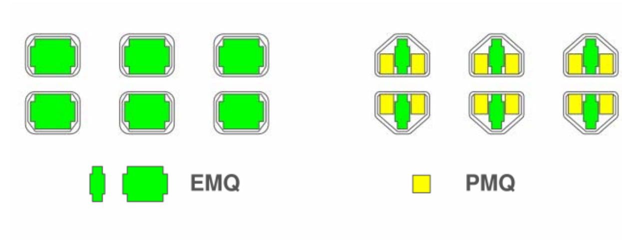

Figure 6: Standard 'low Q' DTL and a higher Q alternative.

The design of drift tubes for the first cells of a low energy DTL places severe constraints on the volume available for the focussing and steering elements. The more space efficient PMQs have been used in this application, but the useful facility for adjusting field gradients is then lost. The two hybrid quadrupoles designs presented here could also be used in a Drift Tube Linac to overcome the limitations mentioned above, if proved that their design complexity and efficiency are acceptable.

SUMMARY

A comparison has been made between two re-bunching cavity types for the FETS and compact hybrid quadrupole configurations have been proposed. The resulting combinations of cavities and quadrupoles offer more design options for the FETS MEBT line.

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