HIPPI Work Package 4 (WP4): The RAL[†] Fast Beam Chopper Development Programme
Progress Report for the period: January 2007 – June 2008

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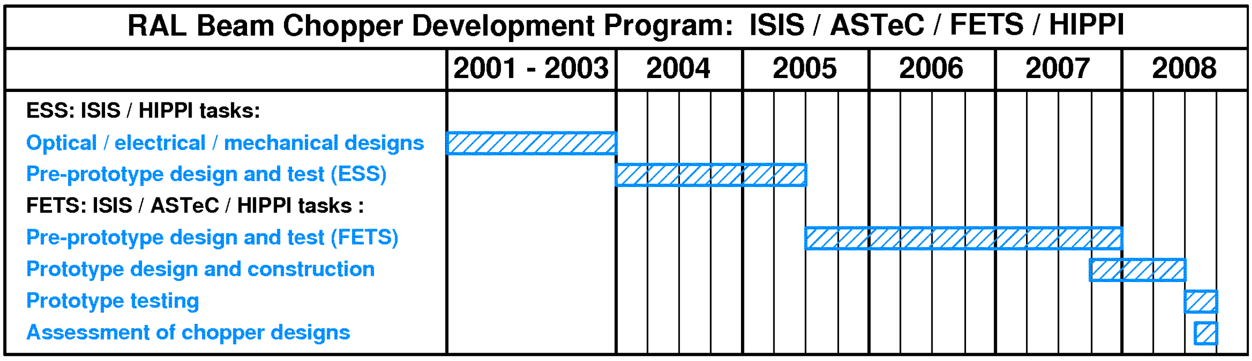
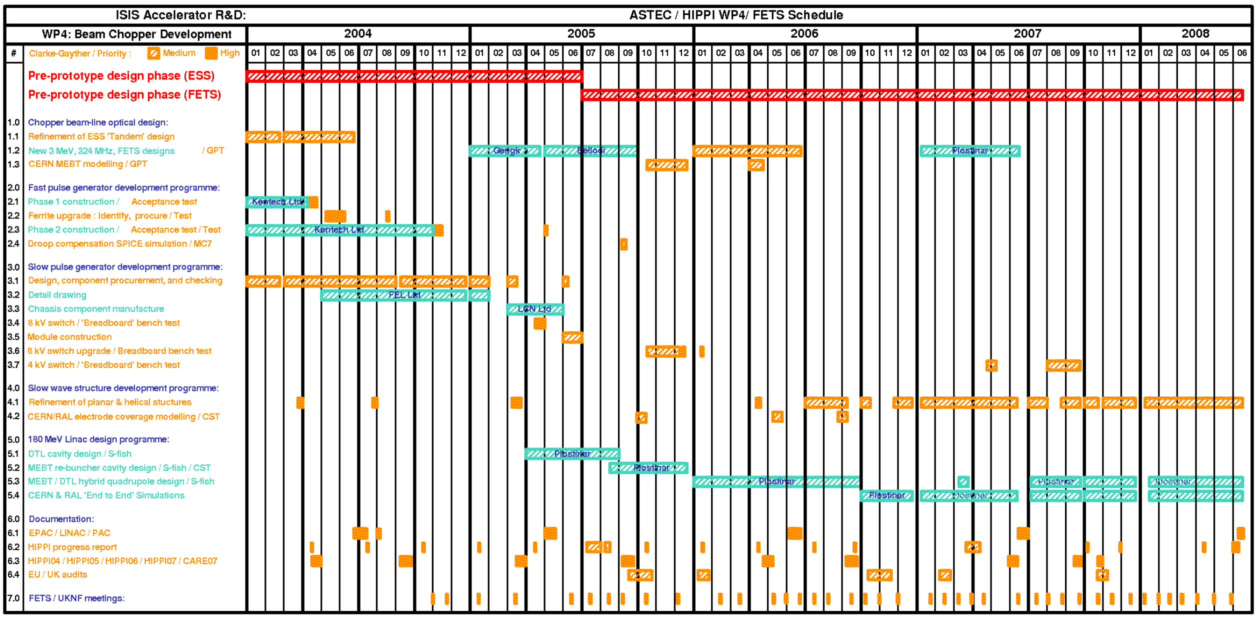
Abstract

The STFC (formerly CCLRC) Rutherford Appleton Laboratory, joined the European High Intensity Pulsed Proton Injector (HIPPI) collaboration in January 2004, and acknowledges the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395). This final report describes the progress made on the development of a fast beam chopper for next generation high power spallation sources (WP4), during the period: January 2007 – June 2008, and includes material drawn from previous reports [29], where necessary. The format, as used in previous reports, has been retained, and includes a summary, and reference section.

Project plan / Overview:



Project history / Detail:



WP4 Prototype design and Construction phase (RAL FETS)

RAL effort is divided into the following key areas of activity:

1.0 Chopper beam line optical design
2.0 Fast pulse generator (FPG) development programme
3.0 Slow pulse generator (SPG) development programme
4.0 Slow wave structure development programme
5.0 Conference activity
6.0 HIPPI meeting activity

Description of WP4 activities and status for the period January 2007 – June 2008

1.0 Chopper beam line optical design

During the period January 2007 – June 2008, a decision was made to adopt and develop MEBT scheme 'A' for the FETS project [3]. The scheme utilises the optical 'amplification' of beam deflection provided by a defocusing quadrupole, placed immediately downstream of the chopper electrodes, to significantly lower the chopper field required by the previous ESS MEBT design [4]. In addition, beam aperture has been increased, and dedicated beam dumps have been included. The initial scheme 'A' design has been developed into a preliminary engineering layout using the GPT code [5], and this work formed the basis of a paper submitted to the EPAC 2006 conference [6]. A comparative 'end to end' study of the CERN Linac 4 beam dynamics using the CERN and RAL MEBT designs was initiated during the reporting period, and this work formed the basis of a paper submitted to the PAC 2007 conference [24].

1.1 Extract from reference [6]: RAL FETS MEBT Chopping Schemes

The FETS project [1], a UK based collaboration involving RAL, Imperial College London, and the University of Warwick, will test a fast beam chopper in a high duty factor MEBT line. The key components, as shown in Figure 1 are: an upgraded ISIS 'Penning' ion source, a three solenoid Low Energy Beam Transport (LEBT) line, a high duty factor 324 MHz Radio Frequency Quadrupole (RFQ), a novel 'Fast-Slow' beam chopper, and a suite of beam diagnostic instruments. The specification, as shown in Table 1, calls for significant technical development, in attempting to address the generic, and specific requirements for a next generation proton driver and a 0.16 to 0.5 MW upgrade for ISIS [7], respectively.

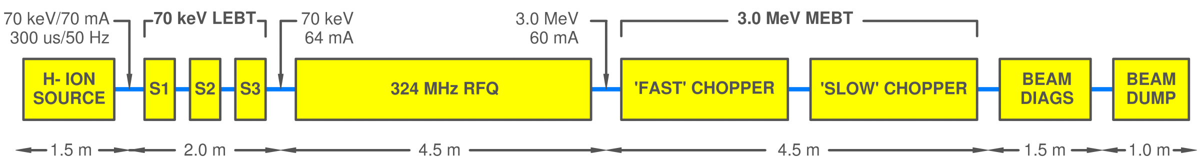


Figure 1: FETS beam line block schematic

Table 1: Key FETS Parameters

Parameters		Parameters	
Ion species	H^-	RF frequency	324 MHz
RFQ output energy	3.0 MeV	Pulse repetition frequency	50 Hz
Pulse duration	0.3 - 2 ms	MEBT chopper field transition time (10-90 %)	2 ns
RFQ input energy	70 keV	Chopped beam duration	0.1-100 µs
Beam current	60 mA	Chopper pulse repetition frequency	1.3 MHz

The RAL 'Fast-Slow' chopping scheme for the 2.5 MeV, 280 MHz, ESS MEBT [4] is evolving to address the requirements of the 3.0 MeV, 324 MHz, FETS project. Three candidate optical designs have been identified, and two of these, schemes A and B, make use of the optical amplification of beam deflection in a downstream defocusing quadrupole, to significantly lower the chopper field requirement, a key feature of the proposed Linac 4 MEBT design at CERN [8]. The preliminary FETS schemes 'A', and 'B', and the ESS scheme 'C', have been refined in the GPT code [5]. The scheme 'A' design, as shown in Figure 2, contains three plots, scaled in the z-plane to a schematic of the component layout, showing simulated beam trajectories for the conditions of no chopping, 'fast' chopping, and 'slow' chopping, respectively. Input and output doublet matching sections, and CCL type re-bunching cavities [9] control emittance growth in the transverse and longitudinal planes.

FETS Scheme 'A'

In this case, the configuration of the 'fast' and 'slow' choppers is symmetrical, each operating independently and each followed by a defocusing quadrupole and a dedicated beam dump. 'Fast' and 'slow' chopping fields are uniformly low, but emittance growth is higher than in scheme 'B'.

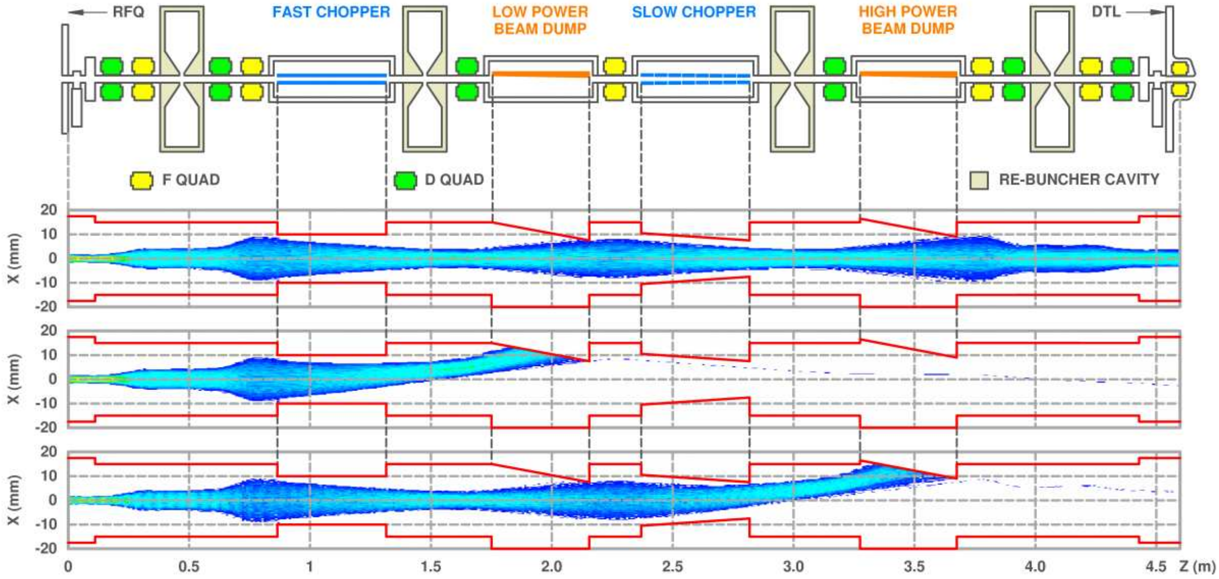


Figure 2: FETS scheme 'A' / Beam-line layout and GPT trajectory plots

MEBT line parameters used in GPT simulations of scheme 'A' are shown in Table 2.

Table 2: FETS MEBT line parameters (GPT simulations)

Parameters	Scheme 'A'	Parameters	Scheme 'A'
Beam line length (mm)	4810	Fast chopper electrode effective length & gap (mm)	450 x 0.82 20
Beam current (mA)	60	Fast chopper potential (kV)	± 1.3
RMS input emittance in X/Y (π-mm-mr) & Z planes (π-deg-MeV)	0.25 / 0.25 0.18	Slow chopper electrode effective length & gap (mm)	450 x 0.85 18
RMS emittance growth in X/Y & Z planes (%)	6 / 13 2	Slow chopper potential (kV)	± 1.5
Quadrupole length / aperture (mm)	70 / 35	Beam dump length (mm)	2 x 400
Cavity field max. (keV/mm) / gap (mm)	4.5 / 21.5		

1.2 Summary

A candidate optical design for the FETS MEBT chopper line has been identified, and refined. Scheme 'A' addresses three weaknesses in the original ESS MEBT optical design, these being: the high chopper field requirement, the absence of a dedicated chopper beam dump, and an overly compact component layout. Studies indicate that scheme 'A' can address the above mentioned weaknesses without incurring excessive emittance growth in the MEBT line.

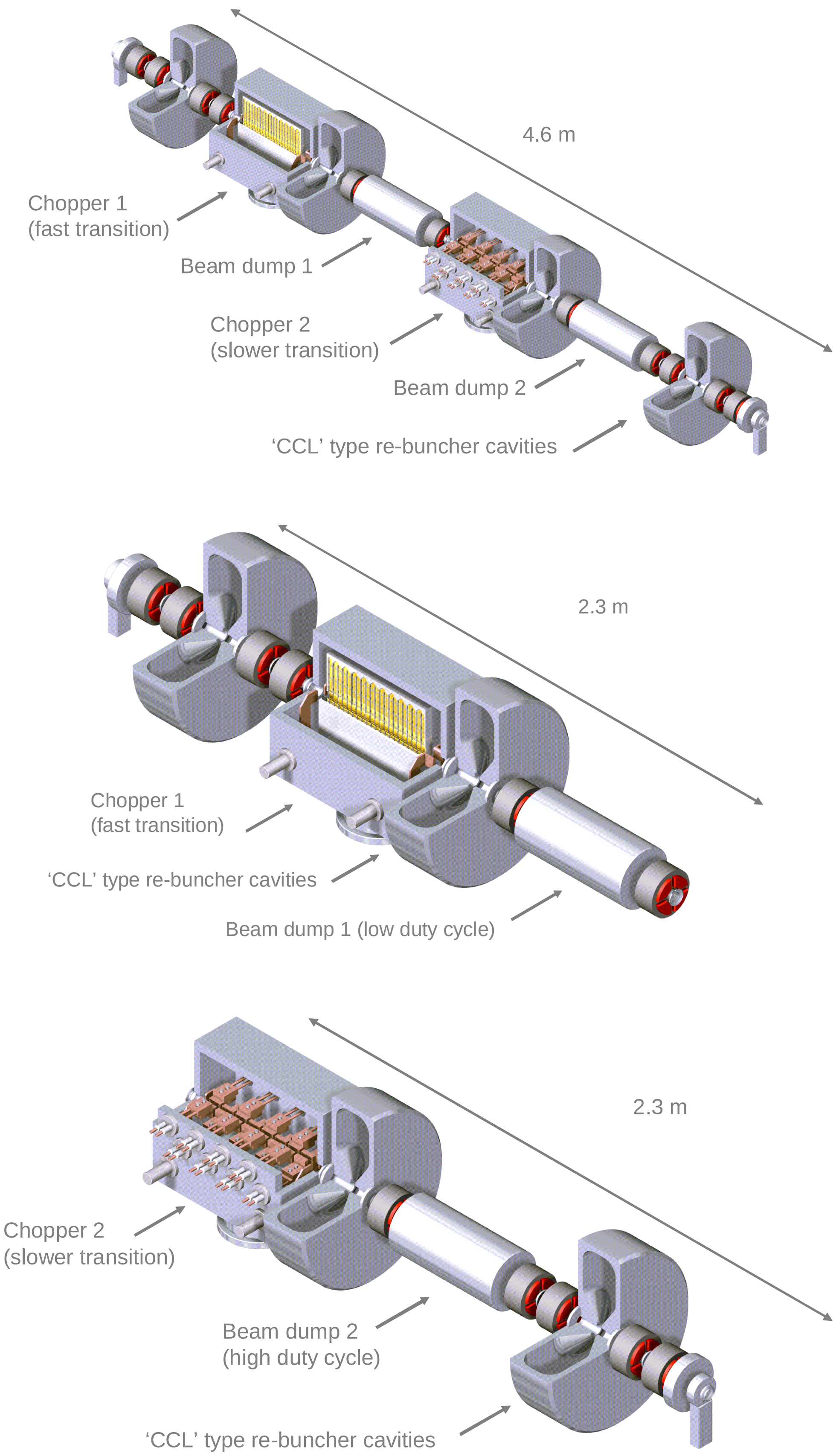


Figure 3: The proposed RAL FETS MEBT line / Scheme 'A'

1.3 GPT code verification

As a precursor to the work on the refinement of the FETS MEBT schemes, a comparison of the GPT, and original 'TraceWin' [10] simulations of the CERN Linac 4 MEBT line [8] was made, with good agreement between codes being demonstrated [11]. Selected results from the GPT simulation of the CERN MEBT line are shown in Figures 4, and 5.

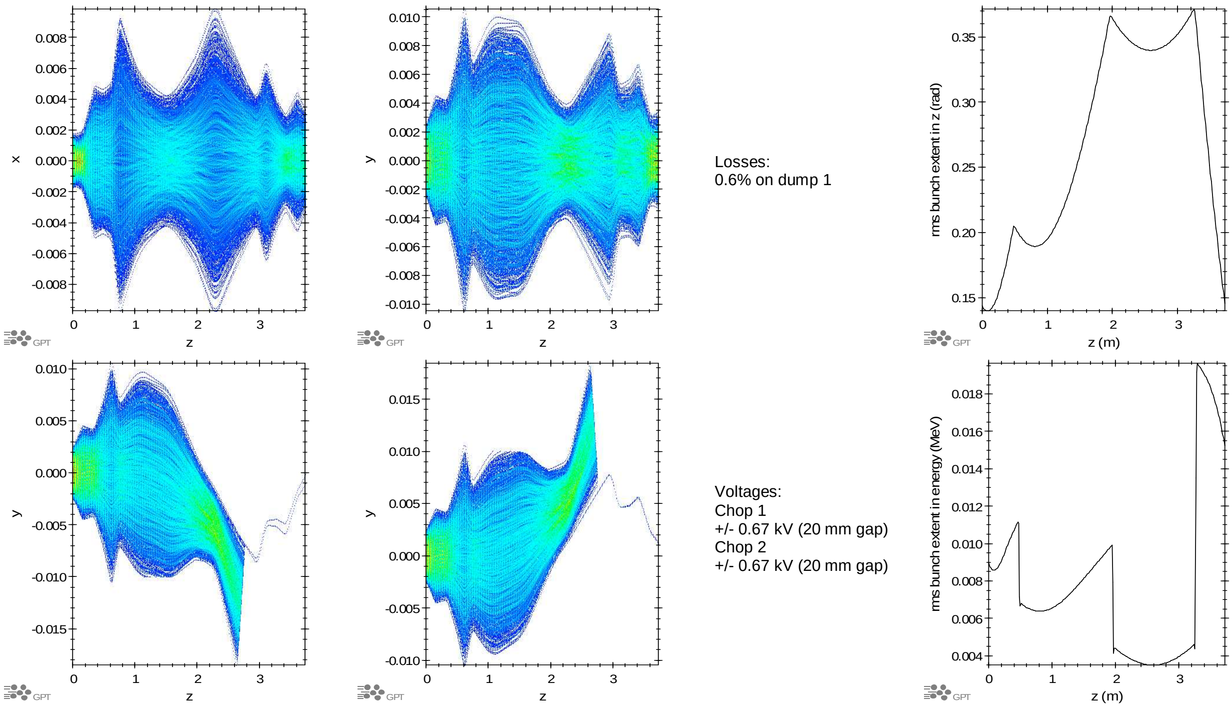


Figure 4: CERN MEBT / Trajectories & RMS bunch parameters in z plane (GPT)

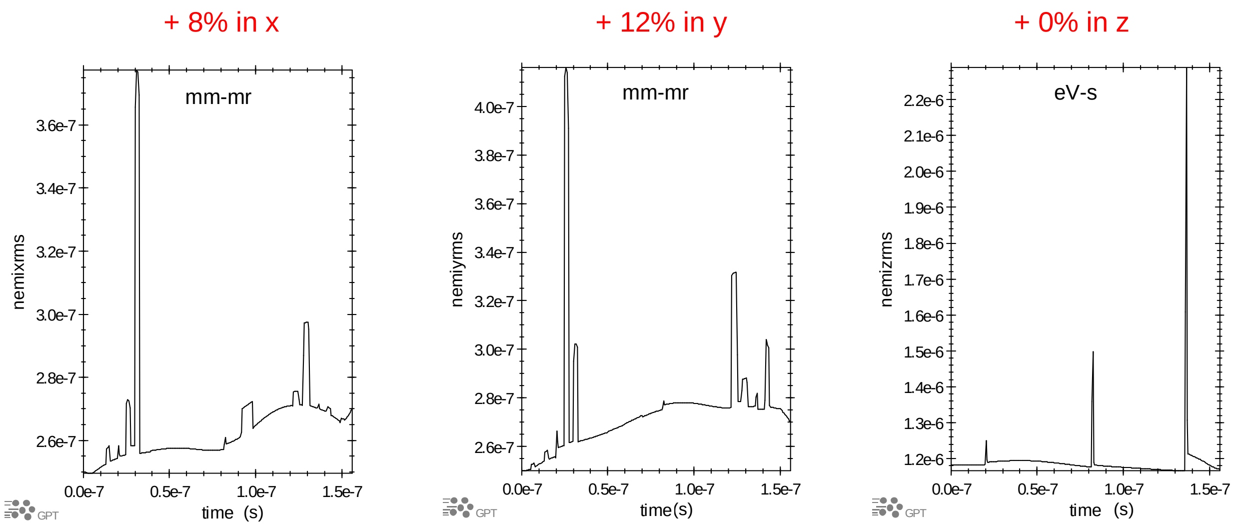


Figure 5: CERN MEBT / Emittance growth (GPT)

1.4 RAL chopper tests on the CERN MEBT line

Following the successful verification of the GPT code [11], a study was initiated, to investigate the possibility of conducting preliminary 'in beam' tests of the RAL choppers on the CERN MEBT line. A modified optical scheme for the CERN MEBT was subsequently developed [11]. Selected results from the GPT simulation of this modified scheme are shown in Figures 6, and 7.

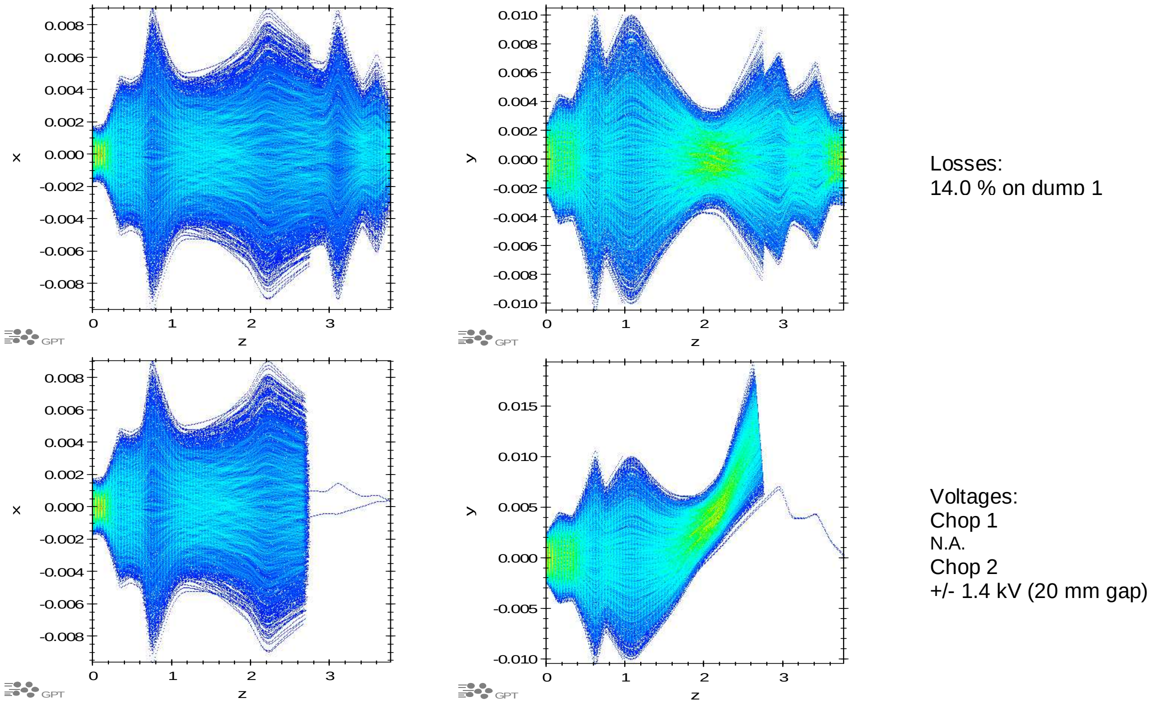


Figure 6: CERN MEBT / RAL set-up /Trajectories (GPT)

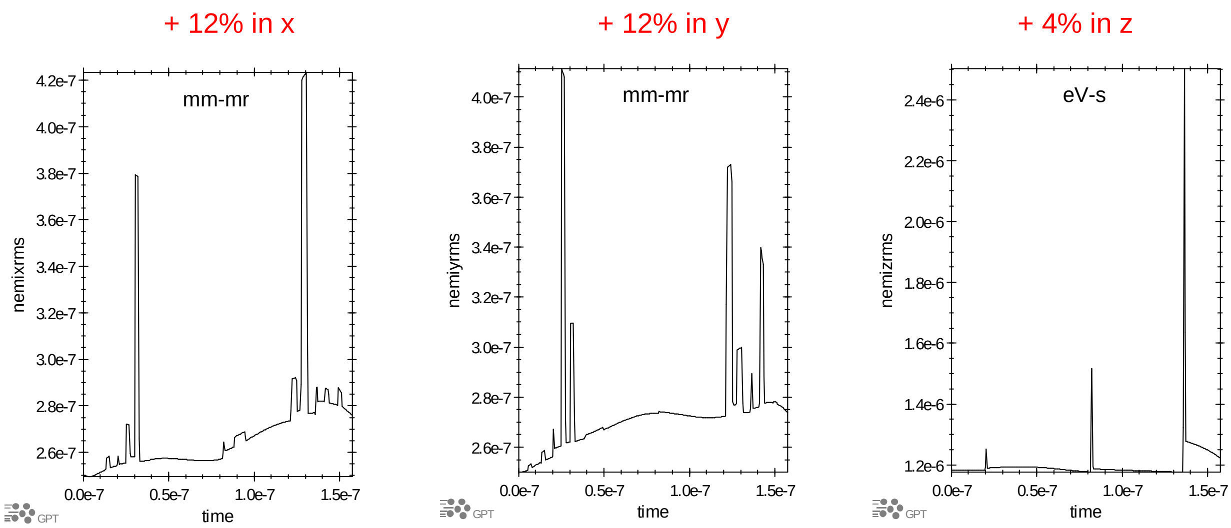


Figure 7: CERN MEBT / RAL set-up / Emittance growth (GPT)

2.0 RAL Fast Pulse Generator (FPG) development

The RAL FPG [12] is available for testing slow-wave electrode structures (Z_0=50 Ohm). The range of available pulse amplitudes, and durations are: +/- 200 to +/- 1500 V, and 8 to 15 ns, respectively. FPG layout and output waveforms are shown in Figures 8, and 9, respectively. RAL has offered to conduct high voltage tests on the new CERN meander structures, when they become available. In addition, RAL has received a request to consider the logistics of shipping the RAL FPG to CEA Saclay [13] for preliminary tests of the CERN chopper system, and has made a request for space to be pre-allocated at CEA Saclay for this purpose.

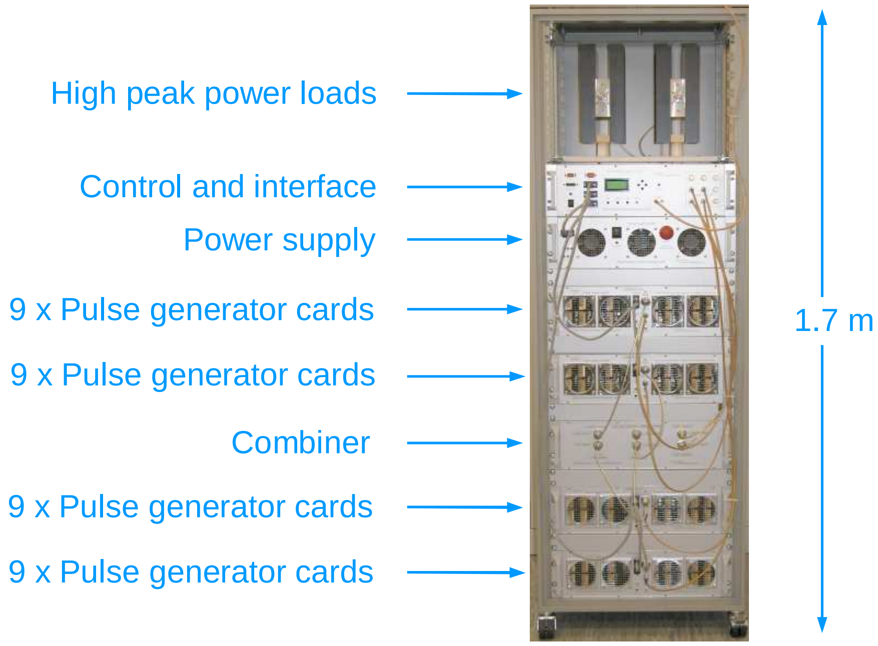


Figure 8: FPG / Front view

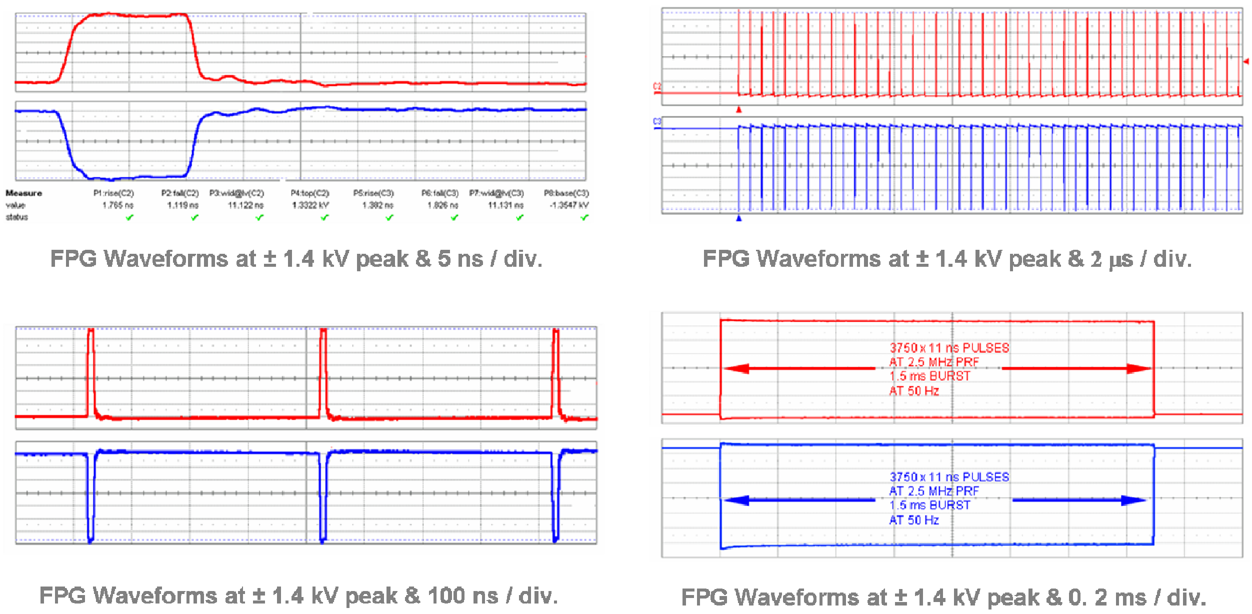


Figure 9: FPG waveforms at ± 1.4 kV peak

Table 3: Summary of measured performance parameters for the 'Phase 2' FPG systems

Pulse Parameter	FETS Requirement	Measured	Compliancy	Comment
Amplitude (kV into 50 Ohms)	± 1.4	± 1.5	Yes	Scalable
Transition time (ns)	≤ 2.0	T_{rise} = 1.8, T_{fall} = 1.2	Yes	10 – 90 %
Duration (ns)	10 - 15	10 - 15	Yes	FWHM
Droop (%)	2.0 in 10 ns	1.9 in 10 ns	Yes	F_{3dB} ~ 300 kHz
Repetition frequency (MHz)	2.4	2.4	Yes	
Burst duration (ms)	0.3-1.5	1.5	Yes	
Burst repetition frequency (Hz)	50	50	Yes	Duty cycle ~ 0.27 %
Post pulse aberration (%)	± 2	± 5	No	Reducible
Timing stability (ps over 1 hour)	± 100	± 50	Yes	Peak to Peak
Burst amplitude stability (%)	+ 10, - 5	+ 5, - 3	Yes	

2.1 FPG / FETS chopping characteristics at 324 MHz

Measurements of the output waveforms of the phase 2 FPG, of an upgraded 8 kV, and more recently, of a 4 kV SPG have been made, and the impact of some of these results on the choice of RF frequency for the RAL FETS has been discussed [14]. A decision to adopt the 324 MHz RF frequency option for the RAL FETS project was made, based on the availability of a high power, high duty cycle, pulse rated Klystron [15]. A FETS chopper timing schematic, based on a slow pulse generator (SPG) transition time of ~ 12ns, is shown in Figures 10. The transition times demand an FPG pulse duration of ~ 15 ns, being determined by the requirement to remove (chop) five bunches at the FETS RF frequency of 324 MHz.

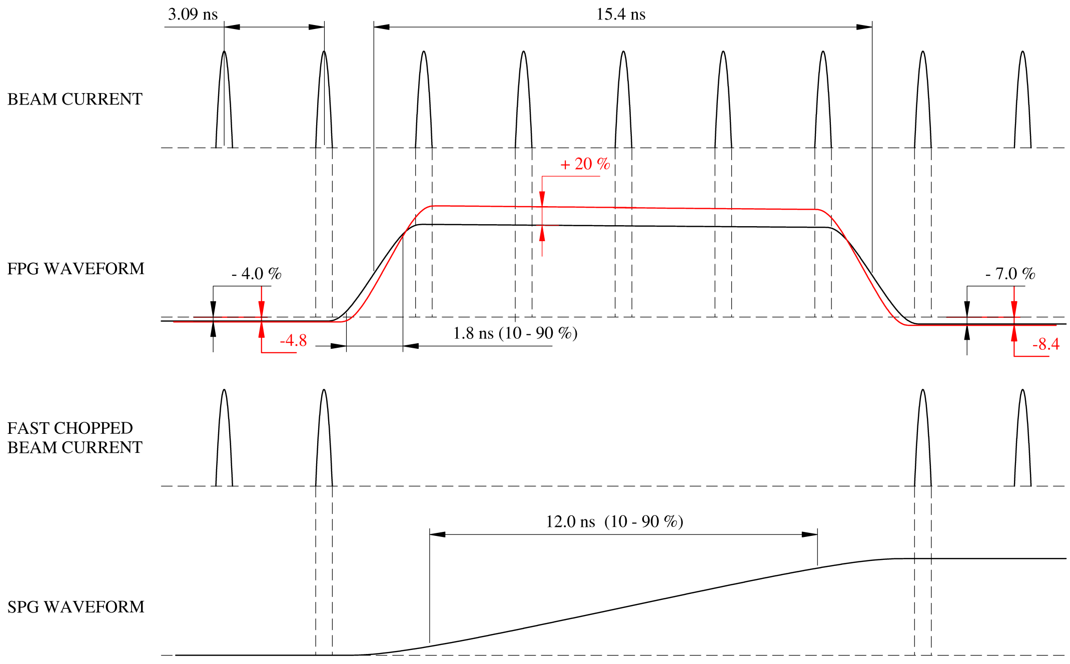


Figure 10: Timing schematic for 324 MHz FETS chopping scheme with 4 kV (12 ns) SPG

Figure 10 indicates that the FETS RF frequency of 324 MHz is only marginally compatible with measured FPG transition times. A strategy for improving transition time compatibility is shown in red but this strategy calls for an increase in pulse amplitude and results in an increase in the effective amplitude of the baseline shift and pulse top droop.

2.2 FPG duty cycle induced baseline shift compensation

Calculated values of duty cycle induced baseline shift, and low frequency (LF) cut-off induced pulse top droop are shown in Table 4, for the 324 MHz FETS chopping schemes, where the FPG pulse length is determined by 4 kV SPG transition times of 9 ns or 12 ns (10 -90%).

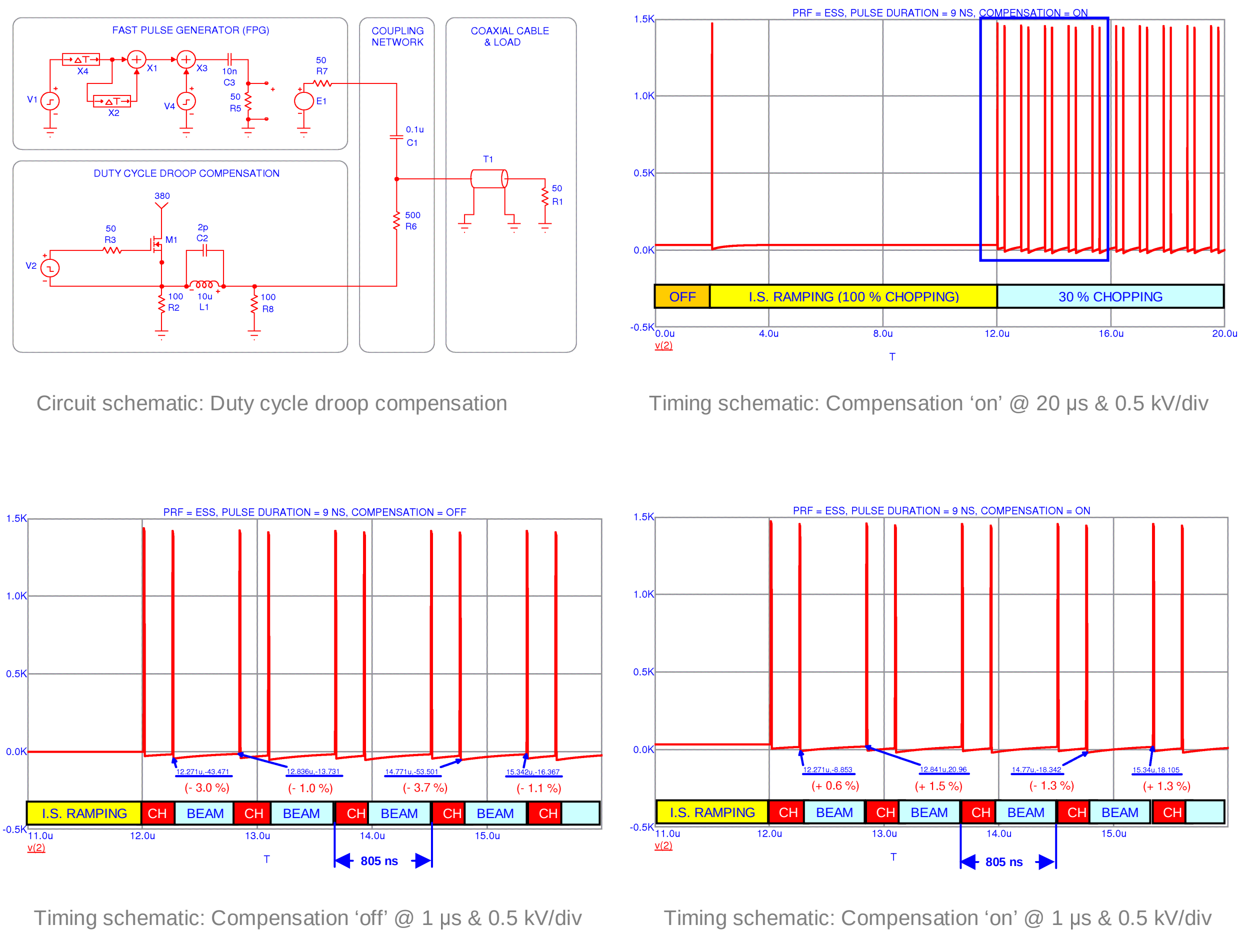
Table 4: FPG duty cycle and LF droop for the 324 MHz FETS chopping schemes

	RFQ	Ring	FPG											
	RF	RF	Pulse				Duty cycle droop		LF cut-off			Total droop	
			PRF	Period	Duration				τ	Droop			
	MHz	MHz	MHz	ns	ns		%		μs	%		%	
					†	††	†	††		†	††	†	††
FETS	324.0	1.3	2.6	384.5	12.3	15.4	3.2	4.0	0.5	2.4	3.0	5.6	7.0

† Assumes 4 kV SPG with ~ 9 ns transition time (10 – 90 %)

†† Assumes 4 kV SPG with ~ 12 ns transition time (10 – 90%)

A scheme to compensate for the duty cycle induced baseline shift as shown in Figure 10 has been described [16]. The resulting residual baseline shift due to LF cut-off can be balanced around the zero volt level, to give values of ± 1.2 %, and ± 1.5 % for 4, and 5 bunch chopping, respectively. Accurate compensation can only be achieved for fixed or slowly varying chopper duty cycles.



Circuit schematic: Duty cycle droop compensation

Timing schematic: Compensation 'on' @ 20 μs & 0.5 kV/div

Timing schematic: Compensation 'off' @ 1 μs & 0.5 kV/div

Timing schematic: Compensation 'on' @ 1 μs & 0.5 kV/div

Figure 11: FPG duty cycle induced baseline shift / Compensation scheme

3.0 RAL Slow Pulse Generator (SPG) development

Work to develop the RAL SPG was restarted during this reporting period, following the development of an efficient optical scheme (scheme A) for the RAL FETS MEBT line. The previous testing of an upgraded 'off the shelf' 8kV SPG MOSFET switch [17] had shown that measured pulse transition times increased, and durations decreased, during the first 20 us of the burst, characteristics that were significantly non compliant with the switch specification and also very difficult to correct for. However, the new RAL MEBT optical design (scheme A) significantly lowers the SPG voltage requirement, and so the most recent developments have been based on a lower voltage, ‘off the shelf’ 4 kV MOSFET switch [23].

Views of the 4 kV and 8kV MOSFET switch, and the 4kV SPG test set-up are shown in Figures 12, and 13. Measured waveforms and parameters, at pulse amplitudes of ± 4 kV, are shown in Figure 14, 15, and Table 5, respectively.

Figure 12: 'BEHLKE' 4 kV & 8 kV MOSFET switches

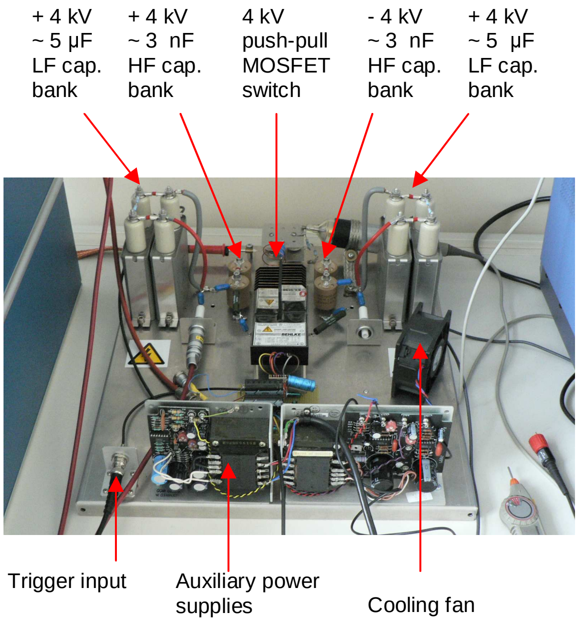


Figure 13: Pre-prototype SPG test set-up

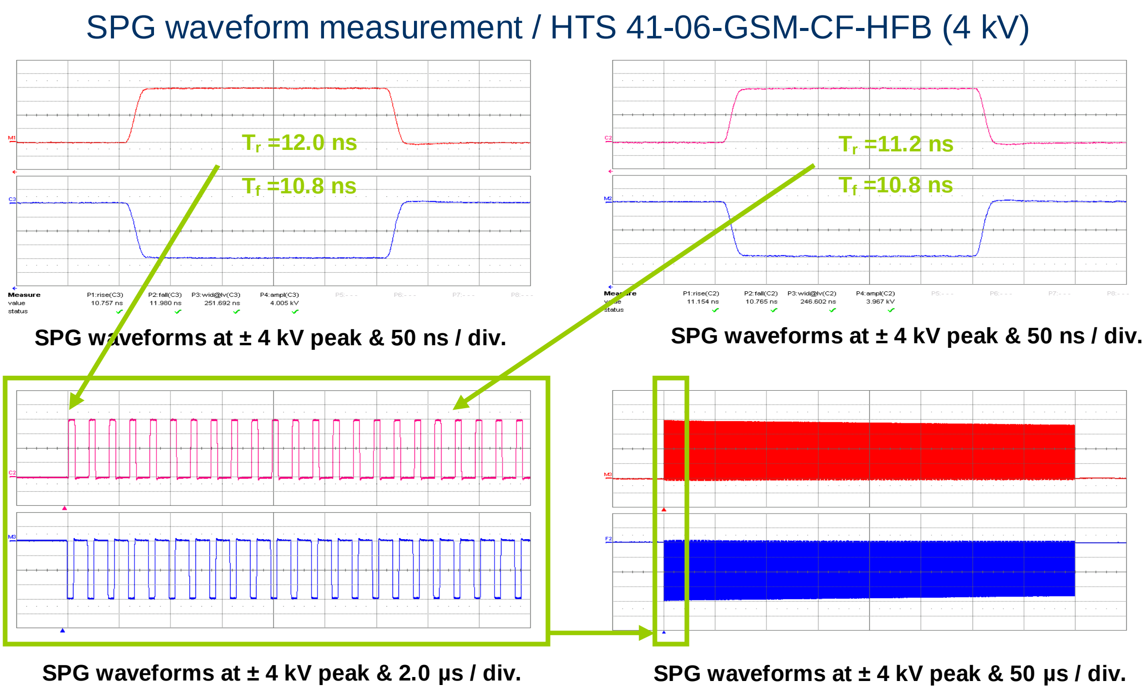
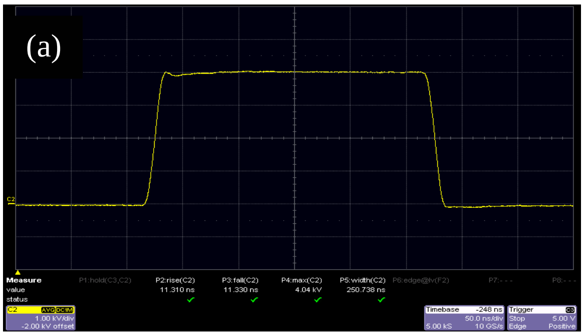
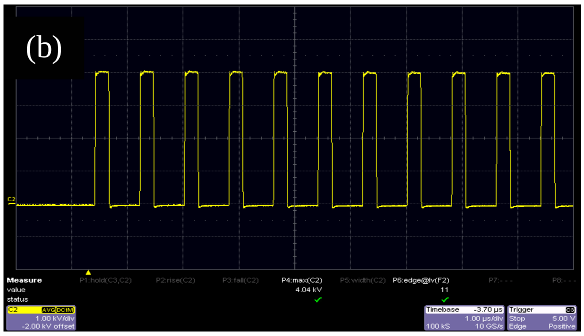


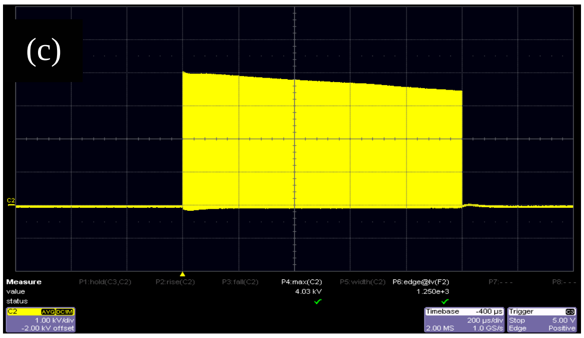
Figure 14: Pre-prototype SPG waveform measurement / HTS 41-06-GSM-CF-HFB



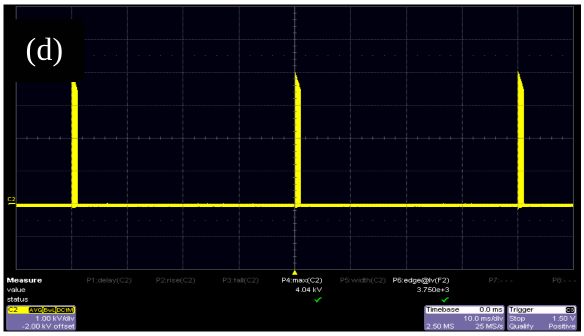
First 250 ns pulse in 1 ms burst   2 kV & 50 ns / div.



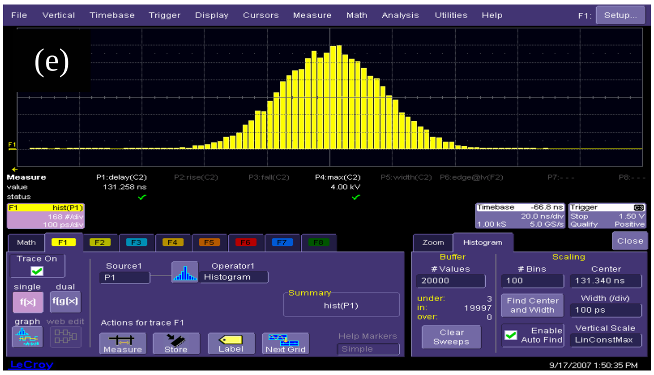
250 ns pulses at 1.3 MHz PRF   2 kV & 1 us / div.



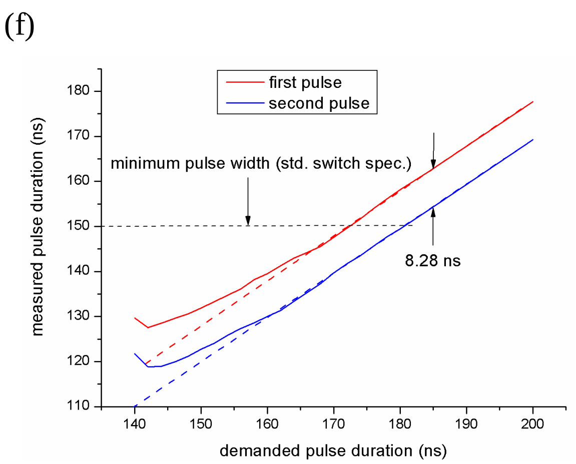
1 ms burst at 1.3 MHz PRF   2 kV & 200 us / div.



1 ms burst at 25 Hz BRF   2 kV & 10 ms / div.



Timing stability / Trigger to first pulse   20k events &100 ps / div.



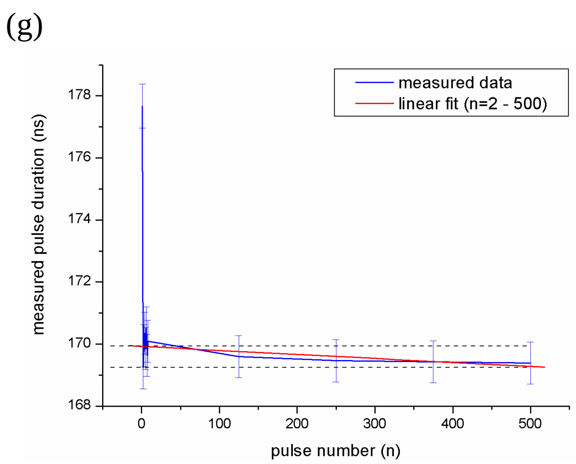
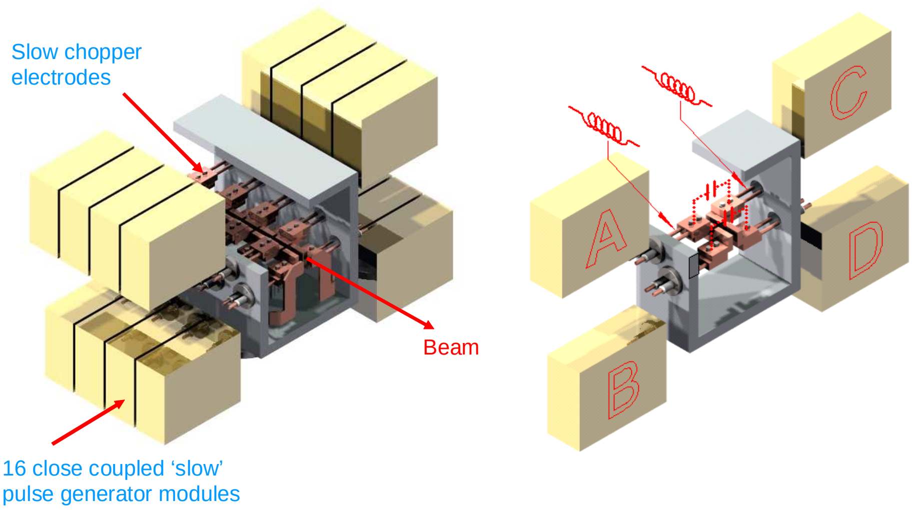


Figure 15: Pre-prototype SPG waveform measurements / HTS 41-06-GSM-CF-HFB

Table 5: Summary of measured performance parameters for the pre-prototype SPG

Pulse Parameter	FETS Requirement	Measured	Compliancy	Comment
Amplitude (kV into 50 Ohms)	± 1.5	± 4.0	Yes	± 4 kV rated
Transition time (ns)	~ 12.0	T_{rise} ~ 12, T_{fall} ~ 11	Yes	500 pulses
Duration (µs)	0.2 – 100	0.17 – 100	Yes	FWHM
Droop (%)	0	0	Yes	DC coupled
Repetition frequency (MHz)	1.3	1.3	Yes	1 ms burst at 20 Hz
Burst duration (BD) @ 1.3 MHz	0.3 - 1.5 ms	1.0 ms	Close	Limited by cooling
Burst repetition frequency (BRF) (Hz)	50	25	Close	Limited by cooling
Pulse width stability (ns)	± 0.1	8.2 ns (n = 1 to 2)	Limited	Can be corrected
Negative pulse width stability (ns)	± 0.1	≤ ± 0.1	Yes	Note transition time limitation
Post pulse aberration (%)	± 2	≤ ± 2	Yes	Damping dependent
Timing stability (ns over 1 hour)	± 0.5	± 0.3	Yes	First ~ 10 pulses in burst
Burst amplitude stability (%)	+ 10, - 5	< + 10, -5 (0.4 ms)	Yes	Limited by HV power regulation

These 4 kV SPG test results are encouraging. A power supply upgrade, and improved cooling have enabled testing at high duty cycle, and measurements of transition time and trigger jitter, as shown in Figure 15, show important improvements when compared to the previous 8 kV rated switches. Modification of the existing 8 kV euro-cassette module, as shown in Figure 16, should enable testing at full duty cycle.



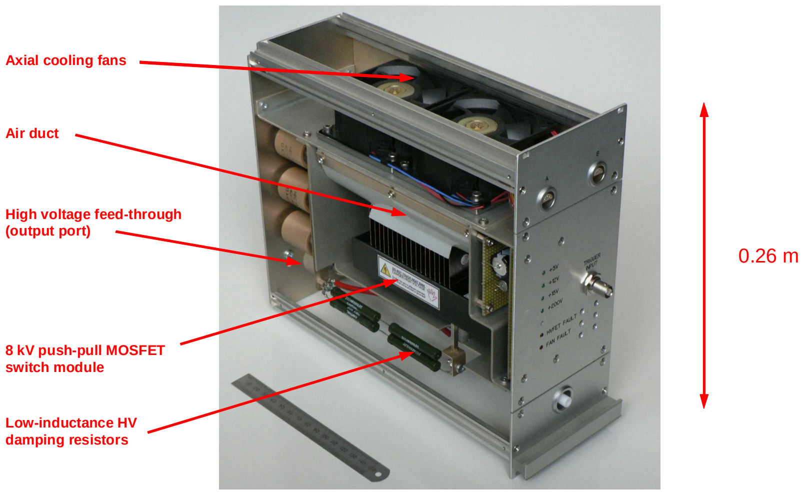


Figure 16: SPG Beam-line layout / Load analysis / 8 kV euro-cassette module

4.0 Slow-wave structure development

The RAL 'slow-wave' chopper structure design work was restarted during the second half of the last reporting period, following the development of an efficient optical scheme (scheme A) for the RAL FETS MEBT line. As a precursor to the main task of modifying the RAL ESS structures to meet the new FETS requirements, an analysis of the so called 'coverage factor' of the CERN and RAL slow-wave structures was undertaken, prompted by a discussion on the subject, at the annual 3rd WP4 meeting [18]. This work was subsequently refined (see section 4.5), and formed the basis of a presentation given at the 3rd HIPPI general meeting [19].

4.1 The RAL slow-wave structure development programme / Redefinition of objectives

Objectives for the programme, redefined to meet the new FETS and CERN MEBT requirements, were as follows:

- Modify ESS 2.5 MeV 'Helical B' and 'Planar' designs to meet the FETS requirement
  - Reduce delay to enable 3 MeV operation
  - Increase beam aperture to ~ 20 mm
  - Maximise field coverage and homogeneity
  - Simplify design - minimise number of parts
  - Investigate effects of dimensional tolerances
  - Ensure compatibility with NC machining practise
  - Optimise choice of materials

- Modify ESS 2.5 MeV 'Helical B' design for the CERN MEBT requirement
  - Shrink to fit in 95 mm ID vacuum vessel

Work on this task commenced in July 06, following the EPAC conference activity, with the modification of the RAL ESS helical B design, initially for the CERN MEBT requirement. This design (Helical B1) was then 'scaled up' to meet the FETS requirement (Helical B2). Engineering drawings of these designs are shown side by side, in Figure 17. This work formed the basis of a paper submitted to the PAC 2007 conference [25].

Effort during the current reporting period has been directed towards the design, manufacture, and test of three preliminary assemblies that are viewed as an essential first step on the path to the realisation of the full scale planar and helical slow-wave structures. The manufacture and test of these assemblies is expected to provide important information on the following:

- Construction techniques.
- NC machining and tolerances.
- Selection of machine-able ceramics and of copper and aluminium alloys.
- Electroplating and electro-polishing.
- Accuracy of the 3D high frequency design code.

The development of the so-called Coaxial, Planar, and Helical B 'test assemblies', is detailed in sections 4.2, 4.3, and 4.4, respectively.

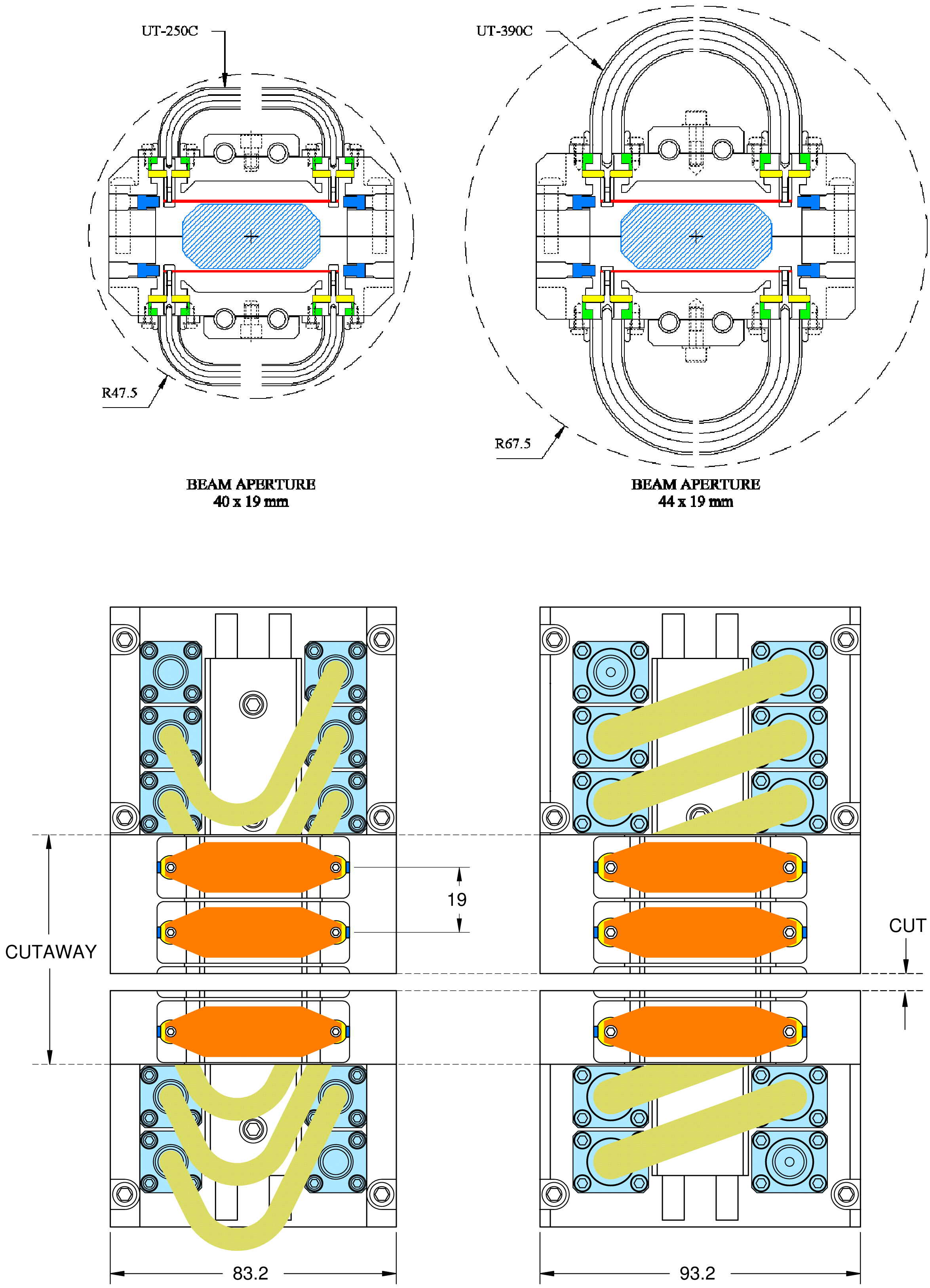


Figure 17: RAL Helical B1 and B2 slow - wave structures / Composite views

4.2 Coaxial test assemblies / High frequency models and measurements

The RAL planar and helical electrode designs make use of machine-able ceramic pillars and discs to support and align the transmission line structures. The characteristic impedance of the transmission line at the position of these supports must be carefully controlled using compensating techniques if reflections are to be minimised. Two candidate ceramic materials have been identified, 'Shapal-M' [26], and BN (HBR) [27], and an interchangeable set of coaxial test assemblies, as shown in Figure 18, has been designed, manufactured, and tested during this reporting period. These assemblies are viewed as an essential first step on the path to the realisation of the full scale planar and helical slow-wave structures.

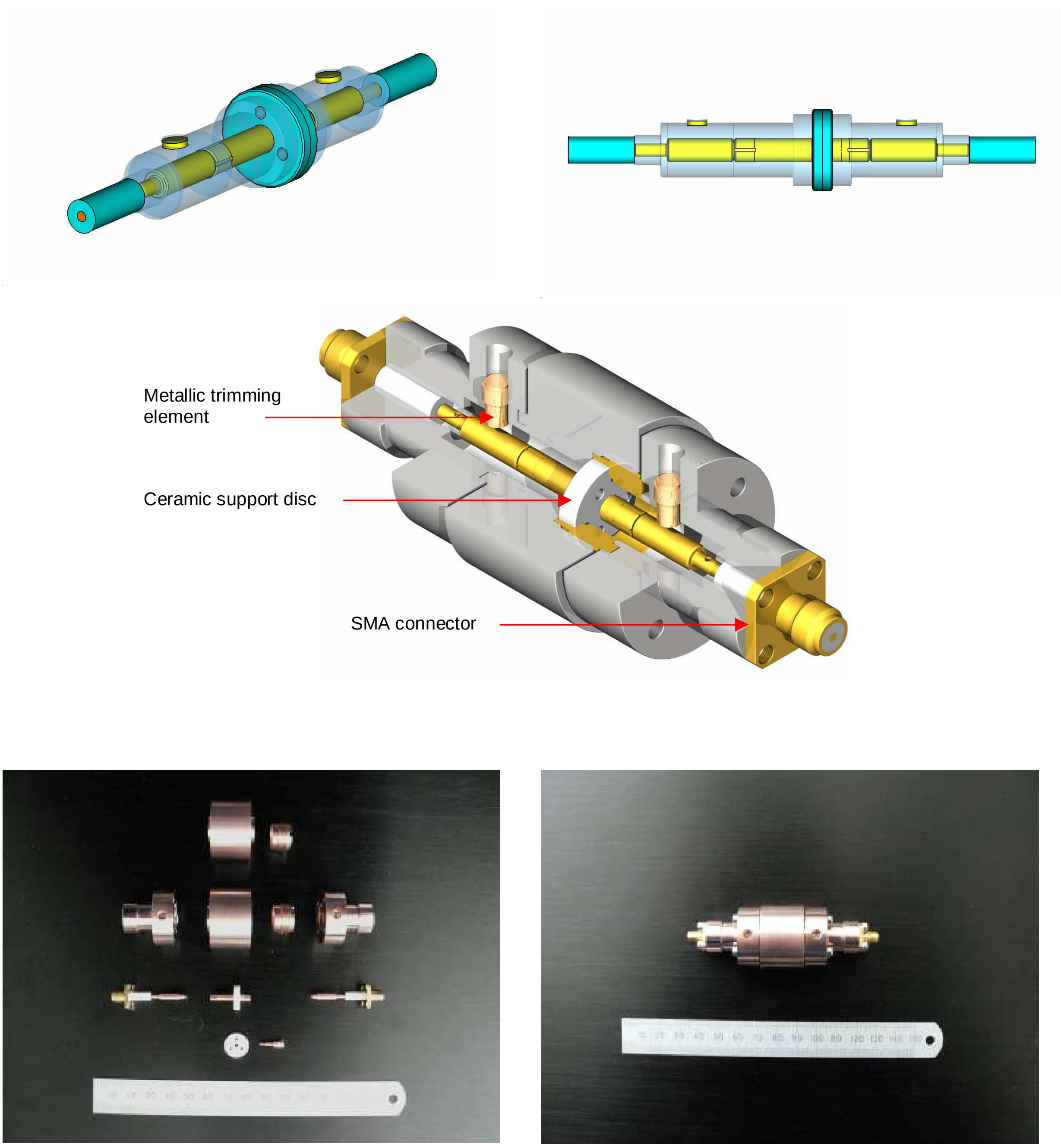


Figure 18: Coaxial test assembly / HF model / 3D CAD view / Photographs

Measurements of the high frequency characteristics of both coaxial test assemblies, in the time and frequency domains, as shown in Figure 19, show generally good agreement with modelled characteristics, and have helped to verify the predictive accuracy of the 3D HF design code [20].

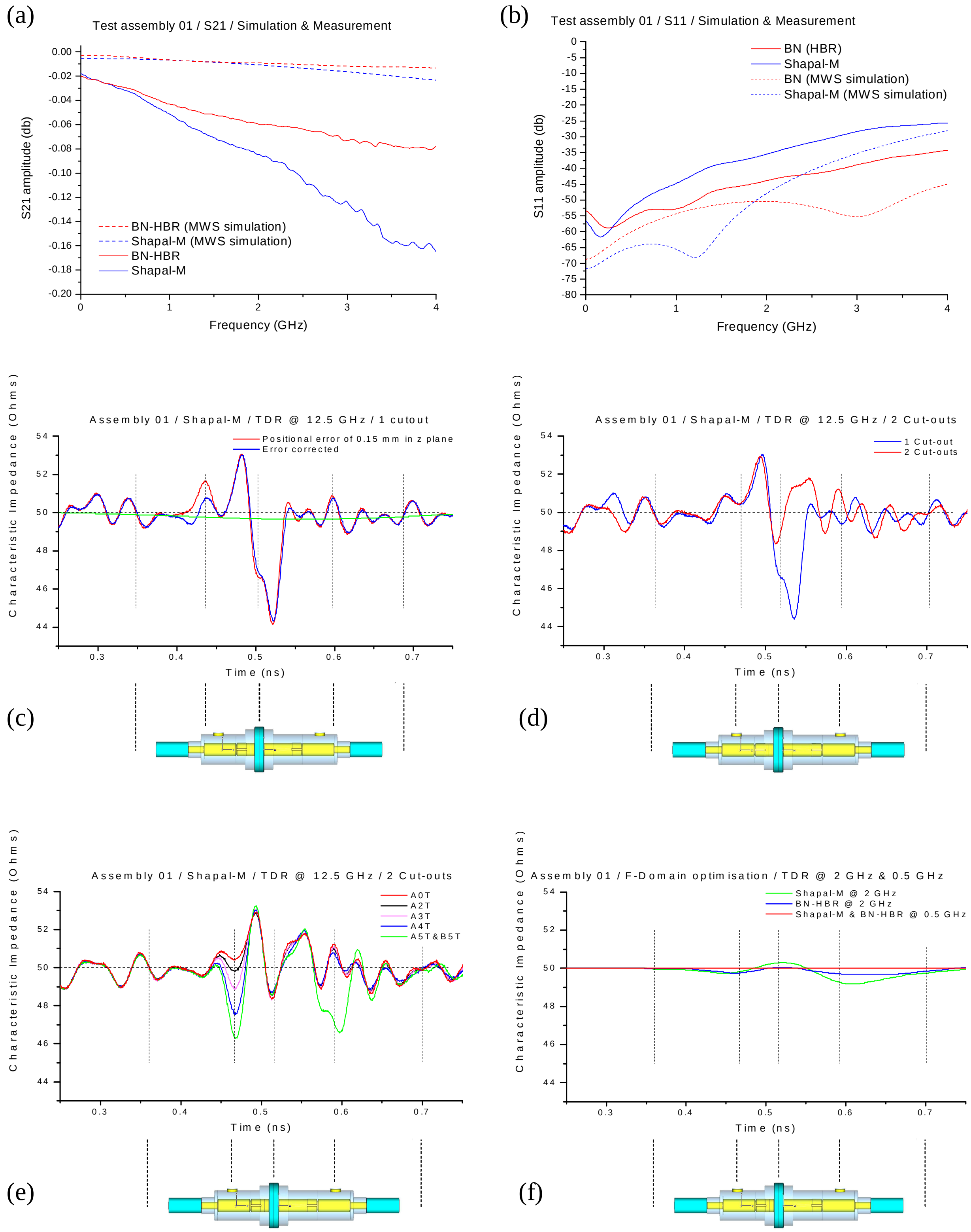


Figure 19: Coaxial test assembly / Measurements in the frequency and time domains

4.2 Helical B2 / High frequency model

A high frequency 3D model of the Helical B2 structure has been developed and analysed in the CST Microwave Studio code [20]. The model is a development of the earlier RAL Helical B structure for the ESS MEBT [21], and has been designed to meet the objectives listed in section 4.1. Views of the model, where the background material is specified as a perfect conductor, and simulated high frequency characteristics in frequency and time domains, are shown in Figure 20. The development, and high frequency analysis of this structure is ongoing.

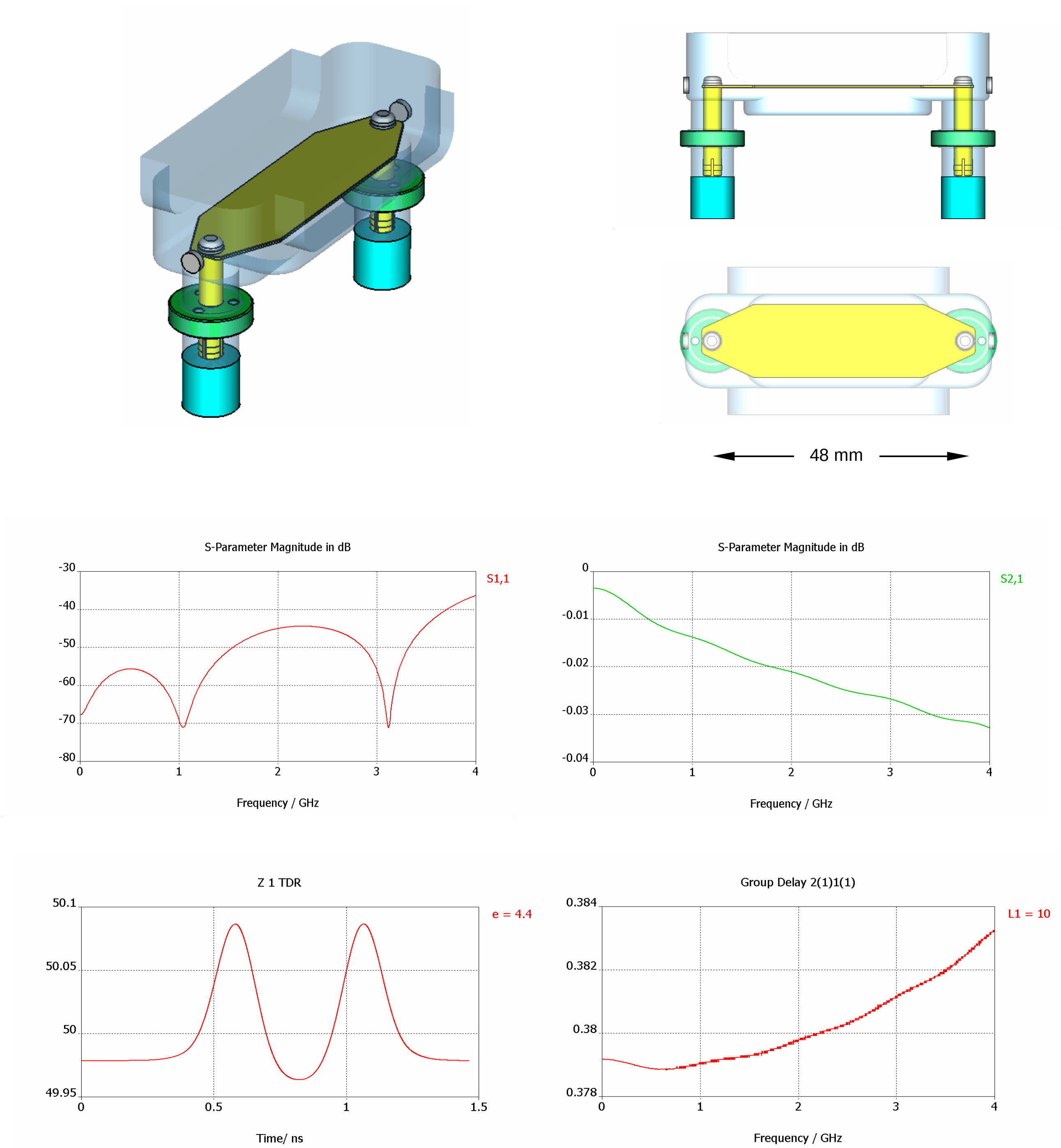


Figure 20: RAL Helical B2 / High frequency model and HF characteristics

4.3 Helical B2 / Test assembly

A Helical B2 test assembly, as shown in figure 21, has been designed and is currently being manufactured. The assembly is viewed as an essential step on the path to the realisation of a full scale helical slow-wave structure, and will serve as a 'test bed' for NC machining practice, material selection, and the effect of manufacturing tolerances. In addition, high frequency measurements in the time and frequency domains will help to evaluate the predictive accuracy of the 3D HF model(s) [20].

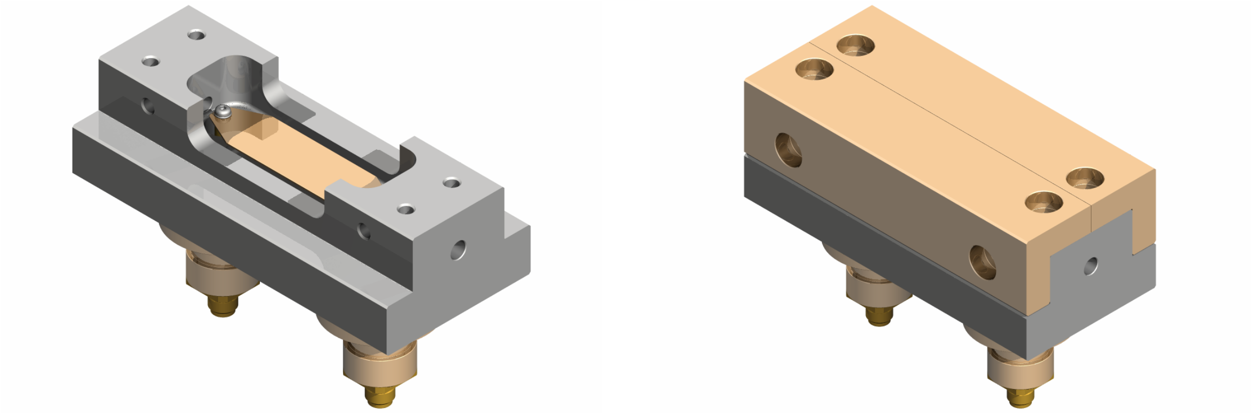


Figure 21: RAL Helical B2 / Test assembly / CAD view

The design, manufacture, and test of the subsequent helical 'short length' prototype structure, as shown in Figure 22, will build on the experience gained from the helical test assembly, and should facilitate the choice of a candidate design for the full scale structure.

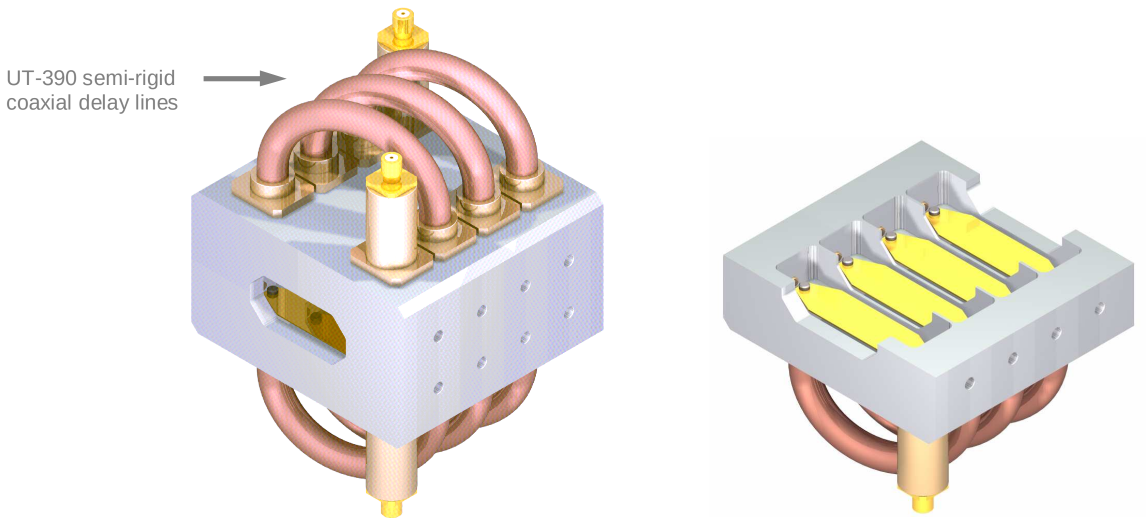


Figure 22: RAL Helical B2 / Short length prototype / CAD view

4.4 Planar / High frequency model

A high frequency 3D model of the RAL planar structure has been developed and analysed in the CST Microwave Studio code [20]. The model is a development of the earlier RAL planar structure for the ESS MEBT [21], and has been designed to meet the objectives listed in section 4.1. Views of the ‘half’ model of a test assembly, where the background material is specified as a perfect conductor, and simulated high frequency characteristics in frequency and time domains, are shown in Figure 23. The development, and high frequency analysis of this structure is ongoing.

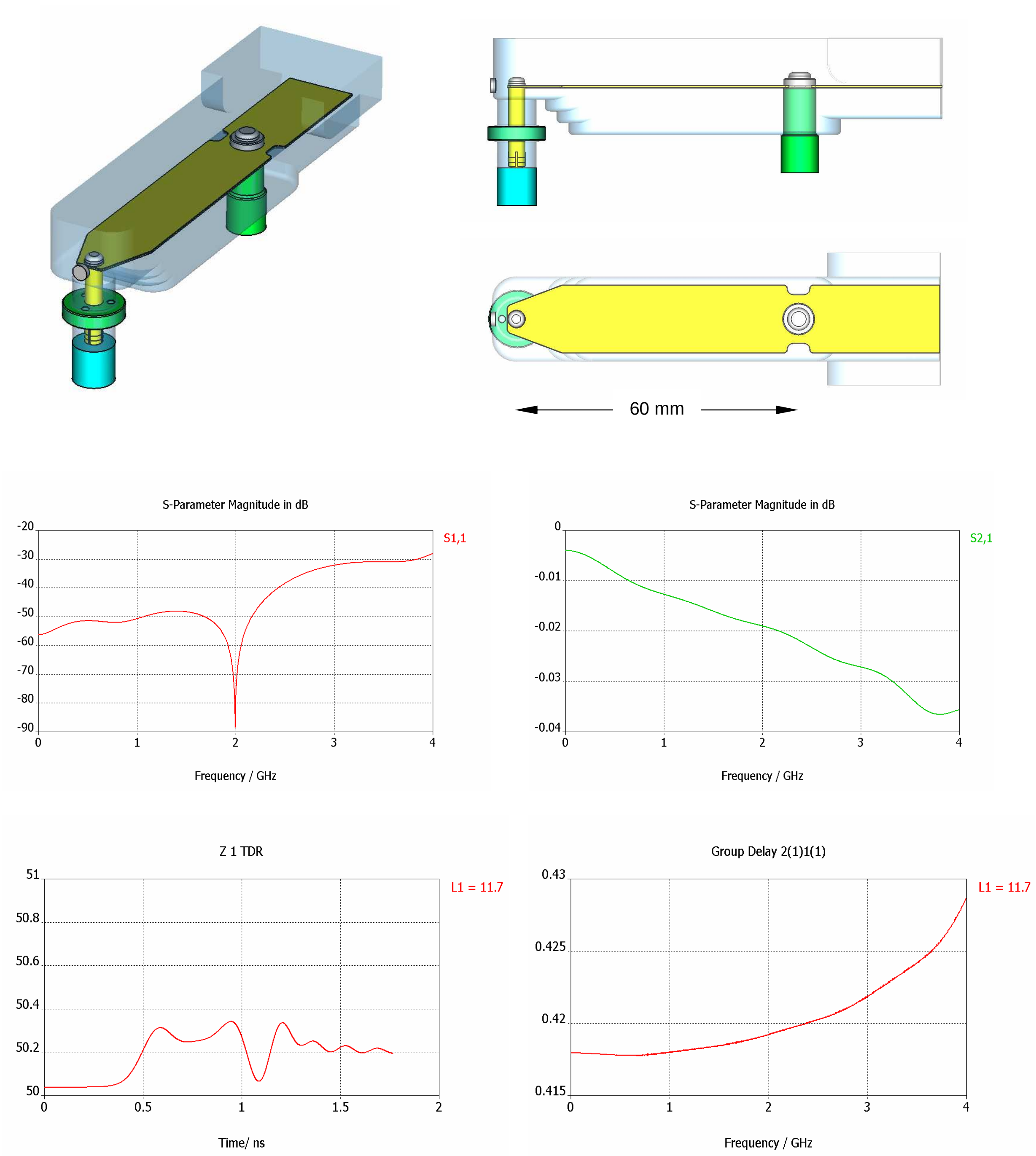


Figure 23: RAL Planar / Test assembly / High frequency half model and HF characteristics

4.4 Planar / Test assembly

A planar test assembly, is being designed, and will be manufactured in the 3rd quarter of 2008. The assembly is viewed as an essential step on the path to the realisation of a full scale planar slow-wave structure, and will serve as a 'test bed' for NC machining practice, material selection, and the effect of manufacturing tolerances. In addition, high frequency measurements in the time and frequency domains will help to evaluate the predictive accuracy of the 'Microwave Studio' model(s).

The design and manufacture of the subsequent planar 'short length' prototype structure, as shown in Figure 24, will build on the experience gained from the planar test assembly, and should facilitate the choice of a candidate design for the full scale structure.

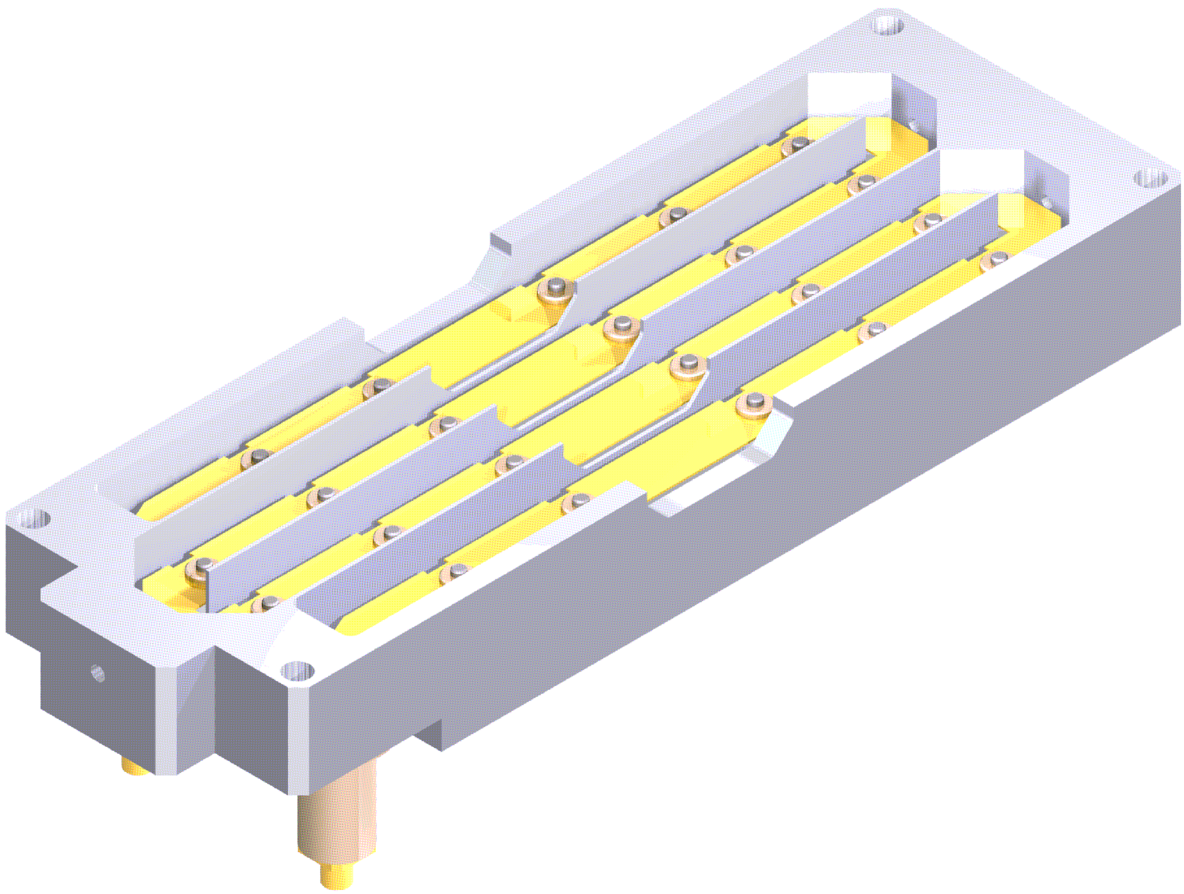
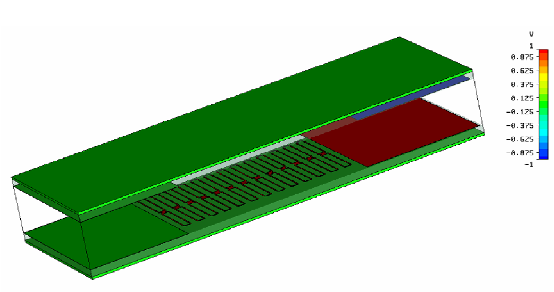


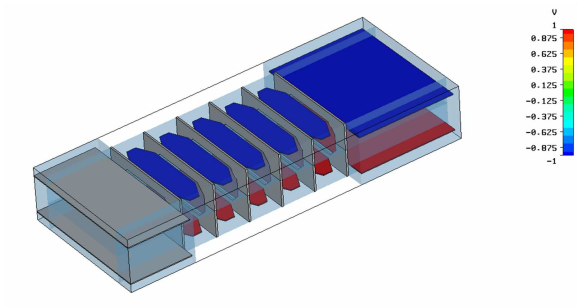
Figure 24: RAL Planar / Short length prototype / CAD view

4.5 Analysis of slow-wave structure 'coverage factor'

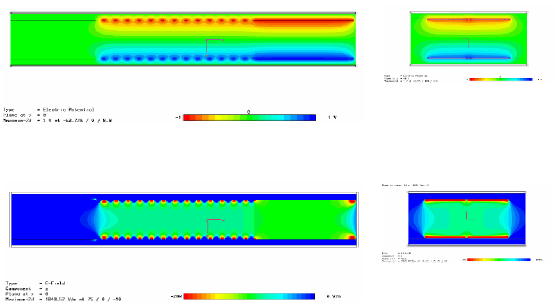
The 'coverage factor' of the CERN and RAL slow-wave structures has been analysed, by simulation of 3D static electric fields in the 'CST EM Studio' code [22]. Extracts from this analysis [19] are shown in Figures 25, and 26.



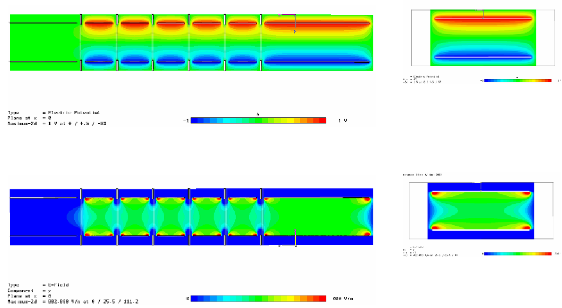
CERN structure / 'CST EM Studio' model



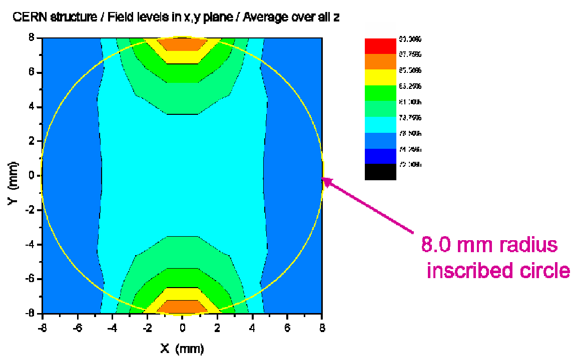
RAL 'Helical B1' structure / 'CST EM Studio' model



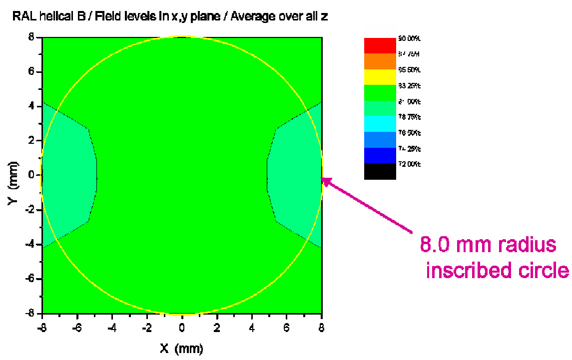
CERN structure / Potential and E field / 2D



RAL 'Helical B1' structure / Potential and E field / 2D



CERN structure / E field integrals in z-plane



RAL 'Helical B1' structure / E field integrals in z-plane

Figure 25: CERN & RAL slow-wave structures /Coverage factor analysis

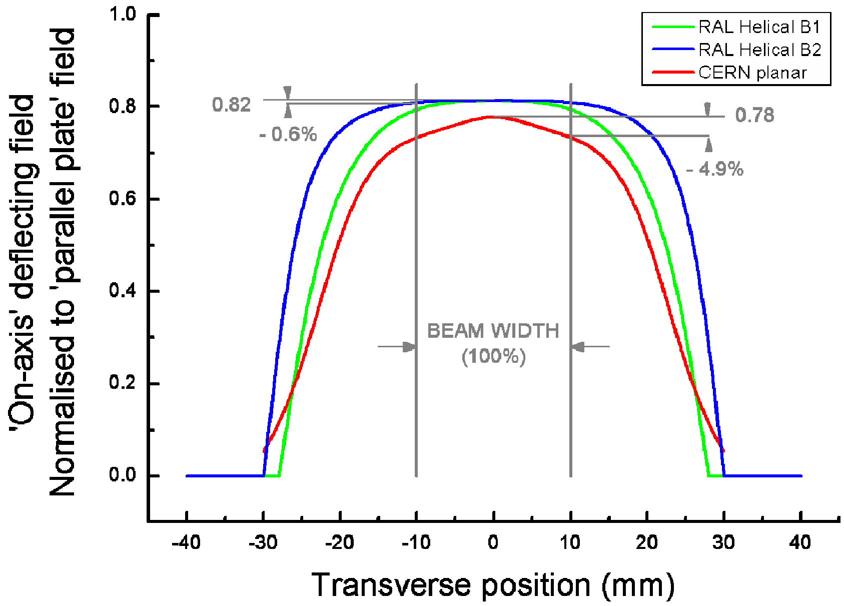


Figure 26: CERN & RAL slow-wave structures / Coverage factor analysis

Table 6: CERN & RAL slow-wave structures / Key parameters & coverage factors†

Design parameter	CERN Planar	RAL Helical B	RAL Helical B1	RAL Helical B2
	Linac 4	ESS	FETS	FETS
H^- beam energy (Mev)	3.0	2.5	3.0	3.0
Beam velocity (m/s)	2.39032e7	2.18292e7	2.39032e7	2.39032e7
Beam width / 100% (mm)	20	10	18	18
Beam aperture (mm)	20	11	19	19
Cell periodicity (mm)	6	19	19	19
Cell delay (ns)	0.251012	0.870394	0.794874	0.794874
Coverage factor: Centre / Edge (%)	78 / 73	80 / 75	81 / 79	82 / 81
Characteristic impedance (Ω)	~ 50	~ 50	~ 50	~ 50
External dimensions (mm)	< 48 radius x 450	< 75 radius x 400	< 48 radius x 450	< 70 radius x 450

† Derived from CST EM Studio analysis

Key parameters and coverage factors for the CERN and RAL slow-wave electrode structures are shown in Table 6. This analysis of coverage factor indicates that the RAL structures (B1 and B2) are expected to produce a higher and more uniform field than the CERN design. However, if the mechanical complexity of the designs is compared, the CERN design appears to be simpler in concept. Field uniformity in the transverse plane has a direct impact on the FPG voltage and MEBT line beam aperture requirements, and on the design of the downstream beam dump. A more comprehensive comparison of these designs will be made when tests on the prototype RAL structures have been completed.

5.0 Conference activity

The following conference papers were submitted during the period January 2007 to June 2008:

'Slow-wave chopper structures for next generation high power proton drivers',
M. A. Clarke-Gayther, CCLRC/RAL/ISIS, Chilton, Didcot, Oxon., UK
Proc. of PAC 2007, Albuquerque, New Mexico, USA, 25-29 June, 2007, pp. 1637-1639
CARE-Conf-07-028-HIPPI

'Status report on the RAL front end test stand'
A. P. Letchford, M. A. Clarke-Gayther, A. Daly, D. C. Faircloth, CCLRC/RAL/ISIS
C. Gabor, D. C. Plostinar, CCLRC/RAL/ASTeC, Chilton, Didcot, Oxon., UK
Y. A. Cheng, S. Jolly, A. Kurup, P. J. Savage, Imperial College, London, UK
J. K. Pozimski, CCLRC/RAL/ASTeC & Imperial College, UK
J. J. Back, University of Warwick, Coventry, UK
J. Alonso, R. Enparantza, Fundacion Tekniker, Elbr (Guipuzkoa), Spain
J. Bermejo, Faculty of Science and Technology, Bilbao, Spain
J. Lucas, Elytt Energy, Madrid, Spain
Proc. of PAC 2007, Albuquerque, New Mexico, USA, 25-29 June, 2007, pp. 1634-1637
CARE-Conf-07-027-HIPPI

6.0 HIPPI meeting activity

The following talks were presented during the period January 2007 to June 2008:

' Beam chopper development for next generation high power proton drivers',
4th HIPPI WP4 meeting, Meyrin, CERN, Geneva, Switzerland, 13th June, 2007.
See document at:
http://hepunx.rl.ac.uk/uknf/wp2/WP4%20talk%20on%2013th%20June%2007.ppt

'RAL chopper status',
4th HIPPI general meeting, IPN Orsay, France,
26th - 28th September, 2007. See document at:
http://www.fz-juelich.de/ikp/hippi/autumn2007/ClarkeGaytherFinal.pdf

'Comparative study of Beam Dynamics in Linac4 using CERN and RAL MEBT lines', Dan Ciprian Plostinar (STFC/RAL/ASTeC), E. Sargsyan, (CERN/AB), 4th HIPPI general meeting, IPN Orsay, France, 26th - 28th September, 2007.

'Beam chopper development for next generation high power proton drivers', 4th CARE annual meeting, Meyrin, CERN, Geneva, Switzerland, 29th - 31st October, 2007. See document at:
http://indico.cern.ch/getFile.py/access?contribId=11&sessionId=0&resId=1&materialId=slides&confId=15901

'Fast - Slow chopper animation', 4th CARE annual meeting, Meyrin, CERN, Geneva, Switzerland, 29th - 31st October, 2007. See document at:
http://indico.cern.ch/getFile.py/access?contribId=11&sessionId=0&resId=0&materialId=0&confId=15901

7.0 Summary

The STFC (formerly CCLRC) Rutherford Appleton Laboratory (UK) joined the European High Intensity Pulsed Proton Injector (HIPPI) collaboration in January 2004. Now, as this collaborative effort draws to a close, a brief summary of the progress of the WP4 task to develop a fast beam chopper for next generation high power proton drivers will be presented.

Central to the RAL FETS chopper design is the novel concept of a two-stage pulsed E-field device, the so called ‘Fast - Slow’ chopping scheme originally developed for the European Spallation Source (ESS) [28]. The requirements for high deflecting E fields, together with a combination of fast field transition times, and long pulse durations, are very difficult to meet with the current high voltage pulse generator technologies. This problem is neatly side-stepped by breaking the task into two stages, whereby an upstream AC coupled pulse generator (FPG) provides a fast transition time, short duration E-field that deflects (chops) five bunches at the beginning and end of each chopping interval, creating two precisely defined 18 ns gaps in the beam bunch train. These gaps ensure that partial chopping of beam bunches is avoided by a downstream set of DC coupled pulsed generators (SPG) that provide a slower transition time, long duration E-field that deflects (chops) the remaining bunches in each chopping interval.

The RAL two stage chopping scheme is considered to be an elegant solution that promises to meet the challenging requirements of the next generation of high power synchrotron or accumulator ring based proton drivers. Central to the efficiency of the scheme is the significant lowering of both FPG and SPG power requirement. The FPG is constrained to drive a resistive (50 Ohm) load, but power requirement is low because duty cycle is low. The SPG has a higher duty cycle requirement, but drives a capacitive load, and so power requirement is again, low. The low power requirement eases the pulse generator design task, and makes possible the utilisation of ‘state of the art’ high voltage semiconductor switch technologies.

7.1 The MEBT optical design as detailed in section 1

The optical design of the RAL MEBT has undergone a complete re-design during the period of this collaboration [3]. The current FETS scheme ‘A’ design, borrows an important feature from the CERN MEBT design [8], namely, the optical amplification of beam deflection provided by a strategically placed defocusing quadrupole. The FETS design is, as a result, more efficient than the previous ESS design, in that beam aperture is significantly increased, chopper fields are much reduced, and emittance growth has been adequately constrained. In addition, space has been found for dedicated beam dumps.

7.2 The fast pulse generator (FPG) as detailed in section 2

The RAL FPG is an AC coupled high voltage pulse generator, designed and manufactured by Kentech Instruments Ltd, UK [12]. The range of available pulse amplitudes, durations, and transition times are: +/- 200 to +/- 1500 V, 8 to 15 ns, and 1.2 to 1.8 ns respectively. FPG layout and output waveforms are shown in Figures 8, and 9, respectively. Measured performance parameters as listed in Table 3, indicate that the design is generally compliant with the RAL specification. Passive techniques to reduce post-pulse aberration can, in principle, be implemented when the precise configuration of the load is determined. The AC coupled unipolar nature of the FPG, places an upper limit on output pulse duration, and introduces a LF cut-off and duty cycle dependent shift in baseline potential, as detailed in section 2.1. A compensation scheme to minimise these effects is outlined in section 2.2. The duty cycle dependent component of baseline shift can, in principle, be eliminated, by utilising an FPG with a bipolar output pulse [28]. This would of course result in alternate beam bunches, or sets of beam bunches, being deflected, in opposite directions.

7.3 The slow pulse generator (SPG) as detailed in section 3

The RAL SPG is a DC coupled high voltage pulse generator, based on a commercially available 4 kV ‘push-pull’ MOSFET switch module, manufactured by Behlke Electronic GmbH [23]. The range of available pulse amplitudes, durations, and transition times are: 0 to +/- 4 kV, 150 ns to ∞, and 11 to 12 ns, respectively. SPG output waveforms and layout are shown in Figures 14, 15, and 16, respectively. Measured performance parameters as listed in Table 4, indicate that the design is generally compliant with the RAL specification at a burst repetition frequency (BRF) of 25 Hz. Further upgrades to power supplies and cooling should allow testing at the full BRF of 50 Hz. Figures 15 (f), and 15 (g) indicate that there is a step change in the trigger to output pulse delay time between the first pulse in the burst and subsequent pulses, and that the magnitude of the change in delay time between the second pulse in the burst and the subsequent 500 pulses is then less than ~ 1 ns. Although these shifts in delay time are not compliant with the required specification, they can, in principle, be corrected by a programmable compensation technique.

7.4 The slow-wave structures as detailed in section 4

The beam ‘chopper’ is required to produce precisely defined gaps in the bunched linac beam, and the upstream ‘fast’ chopping field must therefore rise and fall within, and be synchronous with, bunch intervals that are typically less than three nanoseconds in duration. The proposed RAL slow-wave electrode designs [21, 24] are transmission line structures that avoid partial chopping of beam bunches by ensuring that the deflecting E-field propagates at the bunch velocity. Work on the design of the RAL electrode structures was frozen following the decision to upgrade the optical design of the FETS MEBT line [3]. Although significantly delayed, the work recommenced following the redefinition of key parameters for the MEBT line. The analysis of coverage factor, as shown in section 4.5, indicates that the RAL structures should produce a higher and more uniform field than the current CERN planar design, however the CERN design appears to be mechanically simpler in concept. The two RAL electrode structures, currently being developed in parallel, to a fully representative prototype stage, are the so called planar ‘A’ and helical ‘B2’ designs. The designs have different strengths and weaknesses. The planar design has a lower number of coaxial to strip-line transitions as the transmission line is a ‘one piece’ strip-line structure. However, the planar design has a large number of support pillars, and manufacturing tolerances of the ‘one-piece’ strip-line structure may be difficult to maintain for the full scale structure. In addition, in the case of the planar design, there is no way to adjust the total delay of the structure, and so the predictive accuracy of the high frequency model must be adequate. The delay of the helical design, on the other hand, can be easily adjusted by changing the lengths of the coaxial ‘plug-in’ sections, and the design is probably more tolerant of large scale dimensional errors.

Effort during the current reporting period has been directed towards the design, manufacture, and test of three preliminary assemblies that are viewed as an essential first step on the path to the realisation of the full scale planar and helical slow-wave structures. The manufacture and test of these assemblies is expected to provide important information on the following:

- Construction techniques.
- Machining tolerances.
- Selection of machine-able ceramics and of copper and aluminium alloys.
- Electroplating and electro-polishing.
- Accuracy of the 3D high frequency design code.

The design and manufacture of the subsequent planar and helical ‘short length’ prototype structures, will build on the experience gained from the preliminary test assemblies, and should facilitate the choice of a candidate design for the full scale structure.

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9.0 Acknowledgement

I would like to thank Mat Beardsley, and John Spencer of the RAL Millimetre Wave Technology Precision Development Facility for their helpful comments concerning the design and manufacture of the slow-wave test assemblies.

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

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June 2008