

REVIEW OF FAST BEAM CHOPPING

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- Introduction
- Review of several fast chopping systems
 - ESS-RAL
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 - JAERI
 - CERN-SPL
- Discussion
- Conclusion

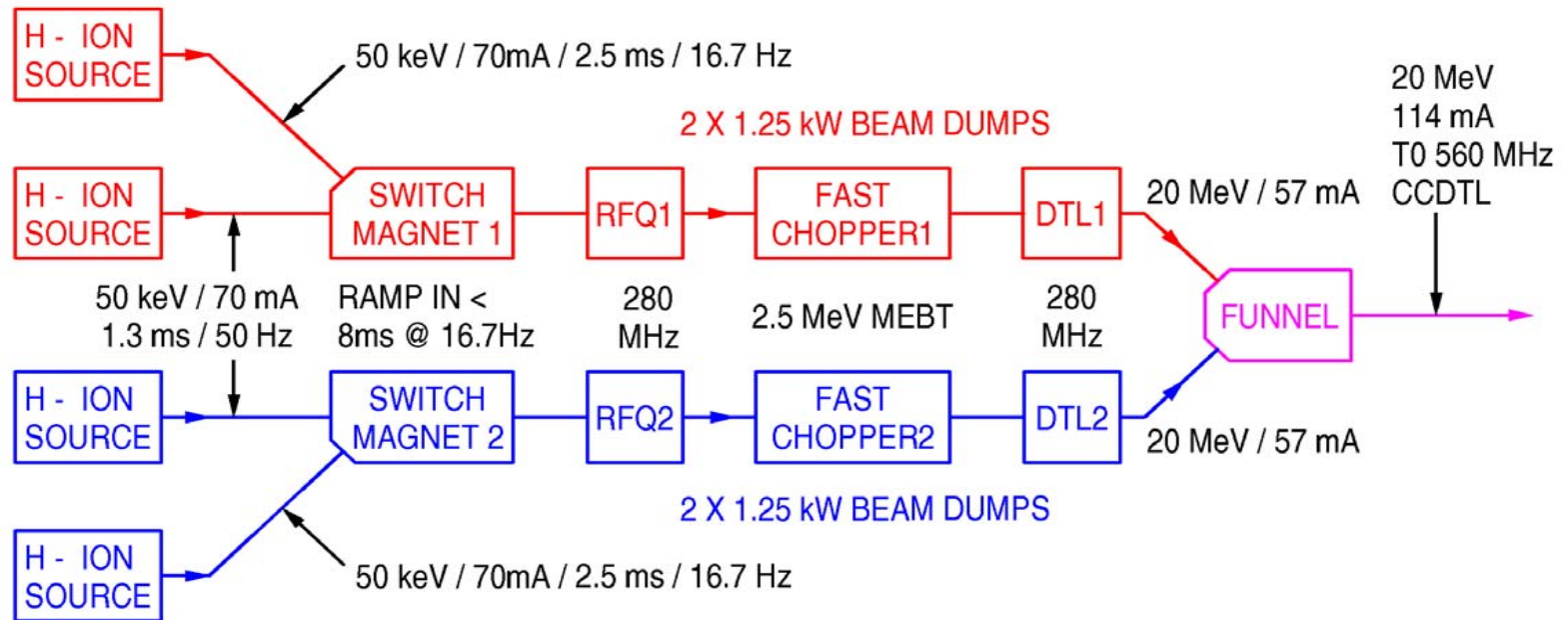
Introduction

- Beam choppers are typically used for $\beta = v/c$ values between 0.05 and 0.1
- Chopping is oft often done by deflecting the undesired part of the beam into a dump or against of wall of the MEBT (medium energy beam transfer line)
- Deflecting elements can be implemented as slow wave structures (meander type delay line)
- Also properly phased individual electrodes are used for chopping
- Fast Energy modulation is another means to cut out parts of the beam (driving it beyond momentum acceptance of a downstream section)
- There is no unique solution! Large range of parameters and parameter setting requirements depending on application

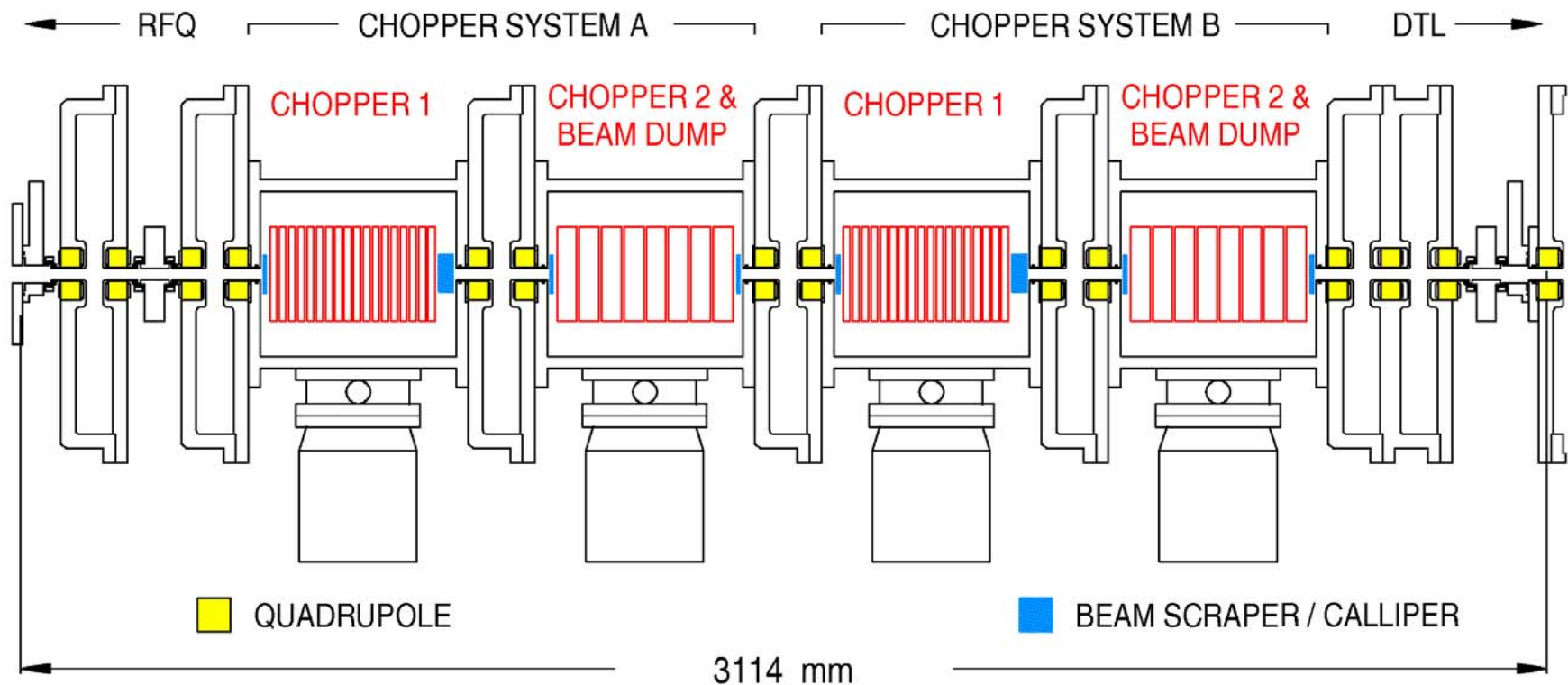
Review of several fast chopping systems: RAL-ESS

Key parameters for RAL-ESS	Prechopper	Chopper
Beam energy	2.5 MeV	
Chopping factor	30 % (ring stacking regime)	
Electrode voltage	± 2.2 kV	± 6.0 kV
Electrode length	340 mm	360 mm
Electrode gap	14 mm	11 mm
Deflection angle	16 mrad	66 mrad
Pulse transit. (10-90%)	~ 2 ns	~ 12 ns
Pulse duration	12 ns	240 ns-0.1 ms
Pulse repetition freq.	2.4 MHz	1.2 MHz
Burst duration	1.5 ms	
Load impedance	50 Ω	35 pF / 60 nH
Repetition rate	50 Hz (two systems @ 25 Hz)	
Beam power on dump	2.5 kW (2 systems @ 1.25 kW)	

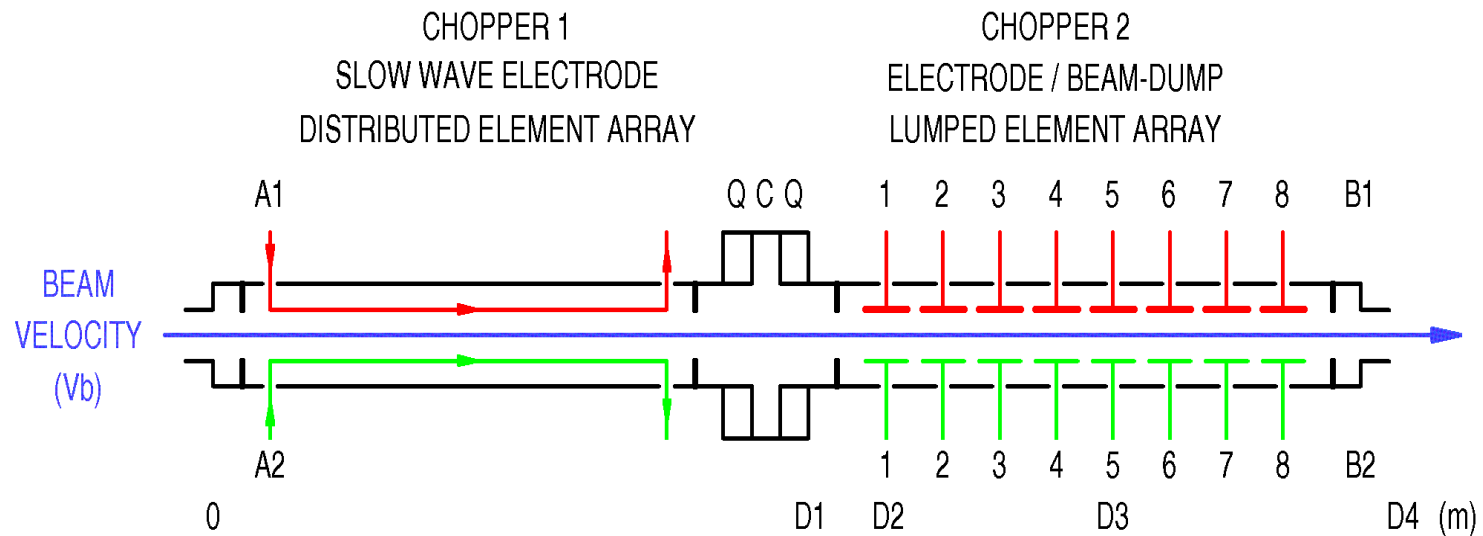
The RAL-ESS system: ESS Front-end



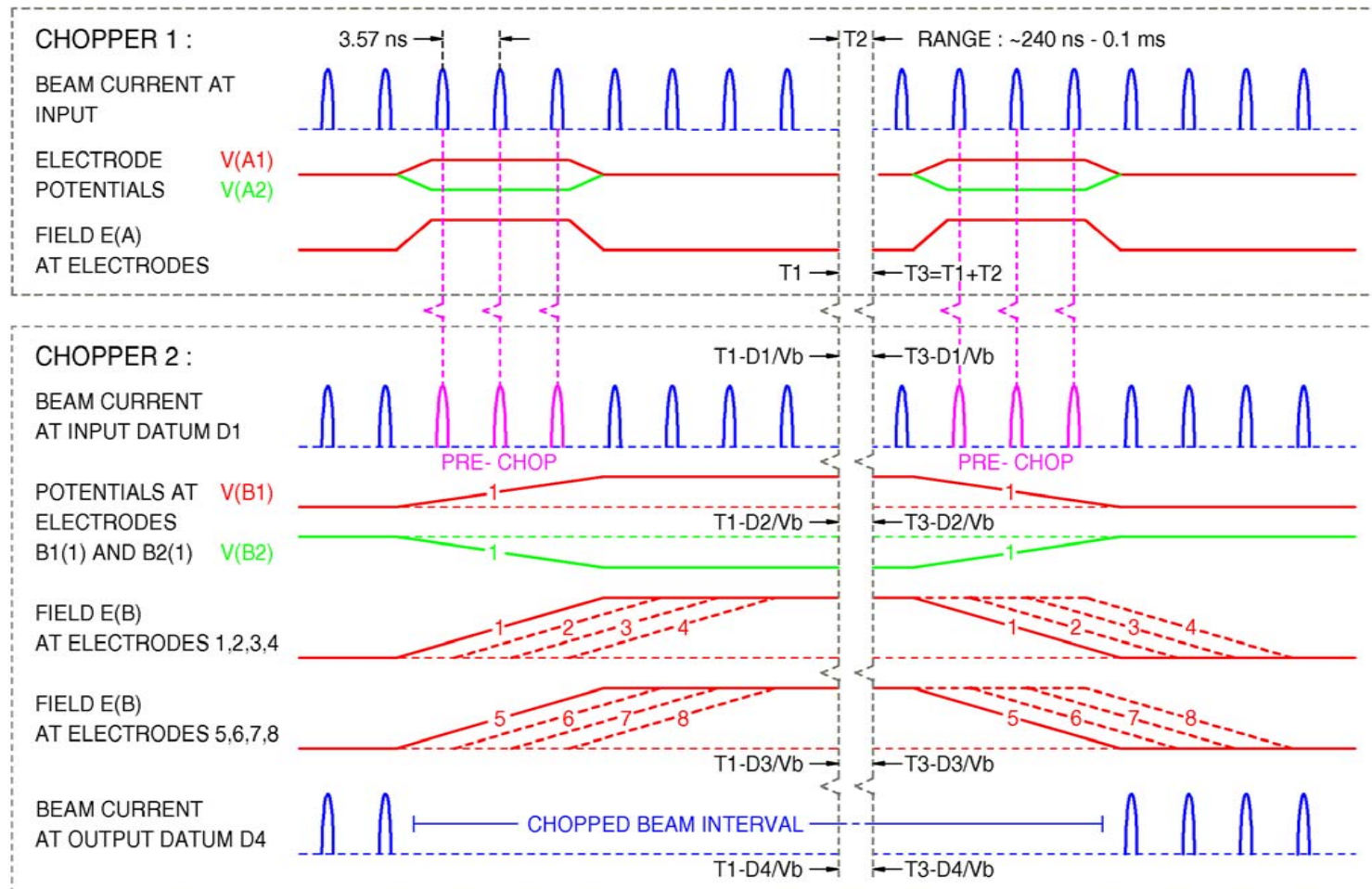
The RAL-ESS system: ESS-MEBT line with “Tandem” chopper



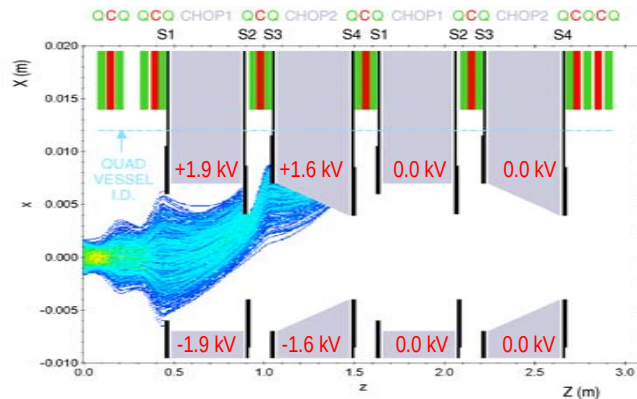
The RAL-ESS system: ESS-MEBT line with “Tandem” chopper details



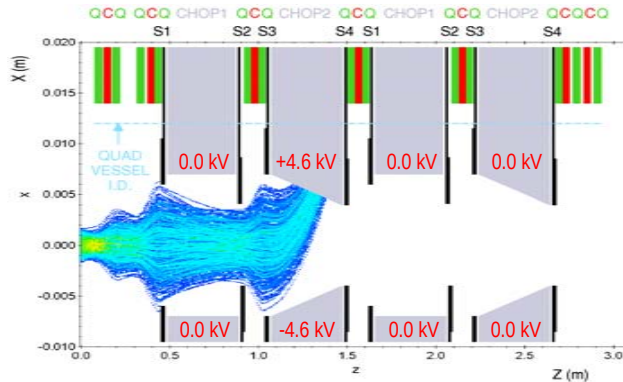
The RAL-ESS system: ESS-MEBT line with “Tandem” chopper timing



The RAL-ESS system: Tandem chopper fast and slow chopping scheme



GPT (General Particle Tracer)
Simulations for fast chopping
Bunch 1-3 and 63-66 chopped



GPT (General Particle Tracer)
Simulations for slow chopping
Bunches 4-62 are chopped

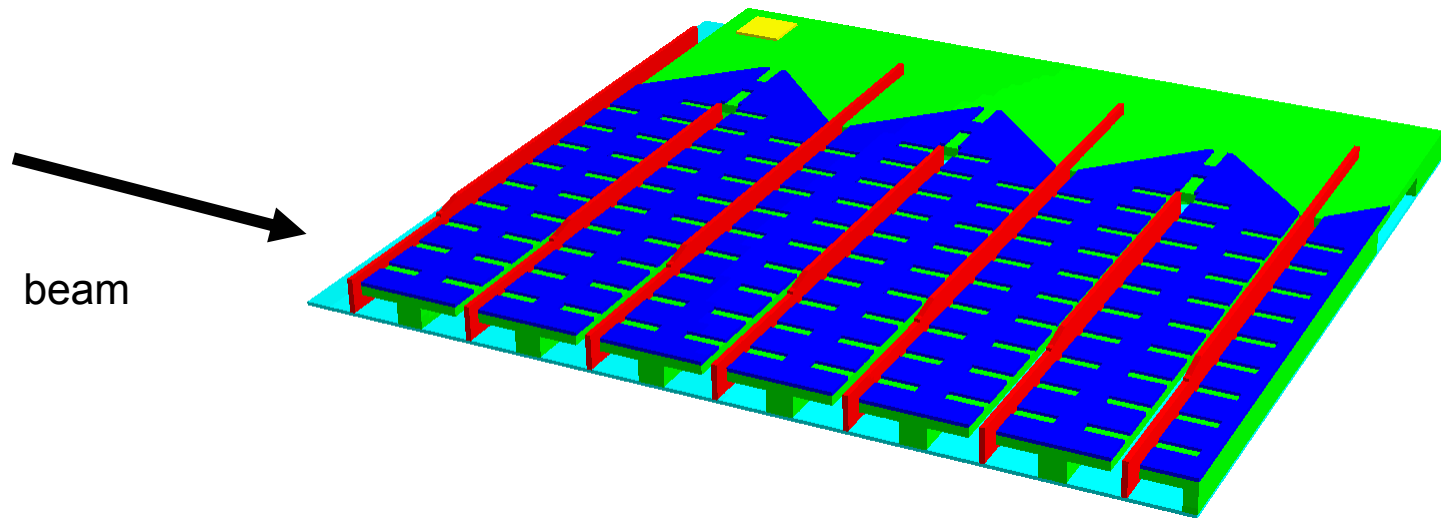
The RAL-ESS system: Tandem chopper driver (pulse generation) scheme

- The slow-wave electrodes (meander type structure) of chopper 1 are driven by fast transition (~ 2 ns), short duration (~ 12 ns) quasi-trapezoidal, uni-polar high voltage pulses of (± 1.4 kV) into $50\ \Omega$ loads. The modular configuration makes extensive use of high power transmission line transformers (TLT's) for efficient wide-band impedance transformation and combination of the outputs of 18 solid-state high voltage pulse generator cards, consisting of two, nine card modules
- With additional modules the output voltage can be increased to ± 2.2 kV
- The lumped element slow wave electrodes of chopper 2, are driven by 12 ns transition, uni-polar, trapezoidal, high voltage pulses (+6.0 and -6.0 kV). Pulse duration will be programmable in the 240 ns to 0.1 ms range. The 120W air-cooled modules will be close-coupled to the electrodes, to preserve pulse fidelity.

The LANL-SNS system: key parameters

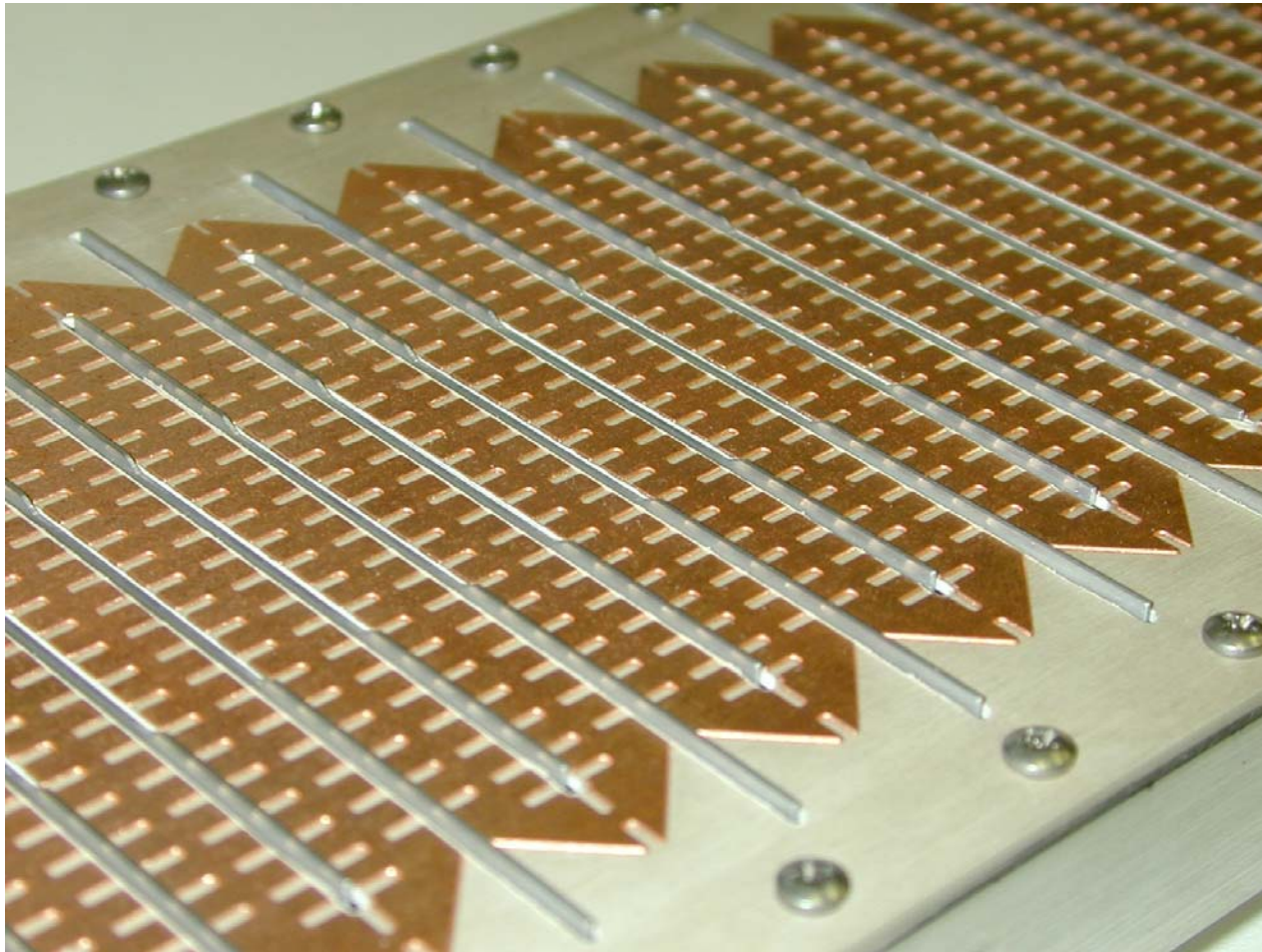
Parameter	Value	Comments
Beam energy	2.5 MeV	$\beta=0.073$
Structure length	35 cm	
Meander width	96 mm	
Gap	18 mm	Adjustable
Pulser voltage	± 2350 V	Max. ± 2500 V
Deflection angle	18 mrad	
Chopping period	945 ns	
Duty factor	32 %	Beam on: 68 %
Structure rise/fall time	1.5 ns	
Pulser rise / fall time	10 ns	2-98 %

The LANL-SNS system: deflector structure (1)



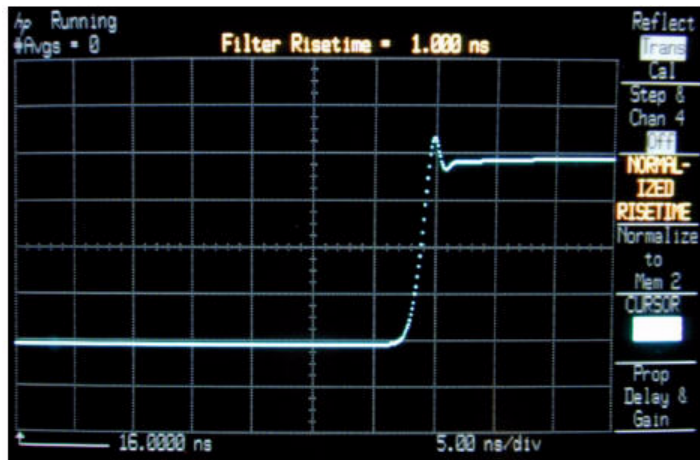
Part of the meander type structure model:
notched metal meander strip (dark-blue) on dielectric supports (green),
metal separators (red) are connected to the ground plate (light-blue, below).

The LANL-SNS system: deflector structure (2) close up view (photograph)

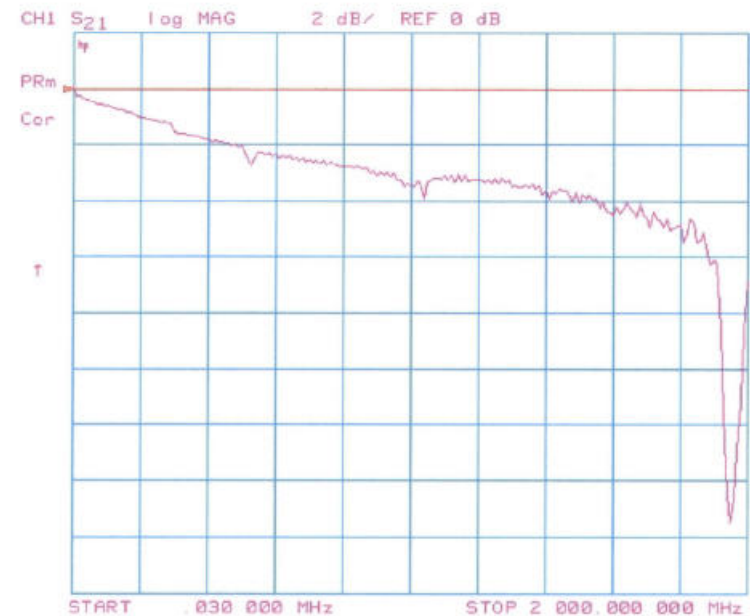
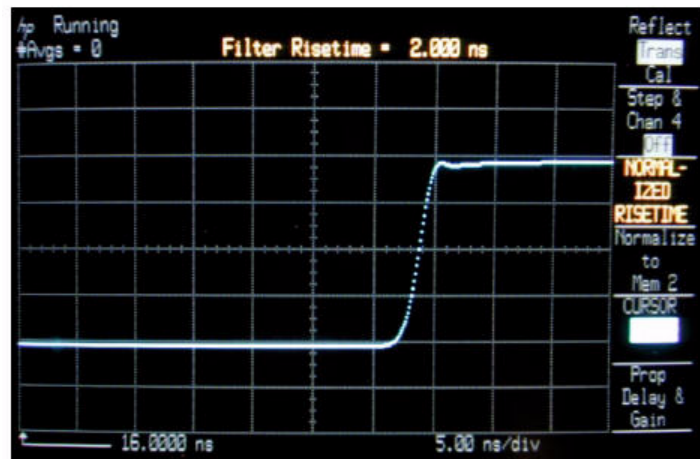


The LANL-SNS system: deflector structure (3) time and frequency domain response

Input
1 ns

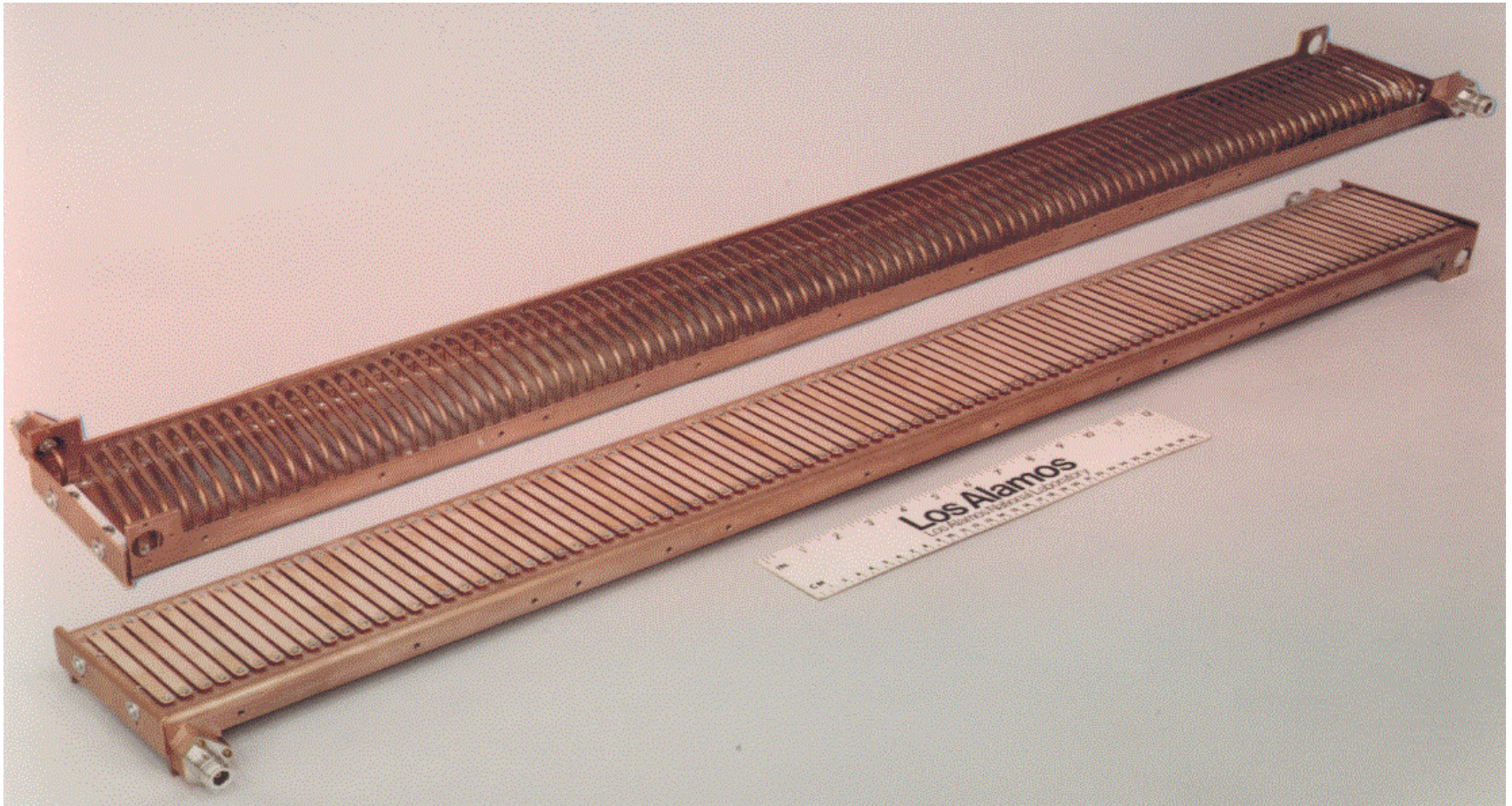


Input
2 ns



Frequency domain transmission measurement
0-2 GHz ; 2 dB/div vert.scale
50 cm structure length, delay =22.65ns
Note the typical notch for meander type
structures around 1.9 GHz

The LANSCE deflecting structure



Pulsers used for LANL-SNS and LANSCE

- The chopper pulser for the SNS-MEBT has a peak voltage of 2.35 kV, higher by a factor 2.6 compared to its original specification of 900 V, so that the peak current through the meander line is about 47 A.
- The requirements for this pulser voltage was set to 2.35 kV with a rise and fall time below 10 ns, thus allowing up to 3 partially-chopped bunches in the beginning and at the end of each chopper pulse, which lasts around 300 ns.
- The pulser was developed by Directed Energy Inc. (Fort Collins, CO); it uses 4 FETs in series for each voltage source, positive and negative.
- The SNS MEBT chopper system was tested with beam at ORNL in 2003. All the results satisfy the chopper system requirements
- The LANSCE pulse modulator was developed in the early 80s as a fast vacuum-tube-driven device. In the 90s it has been revised to a solid-state model, which is easier to maintain at peak performance, but with a slower rise time. Both LANSCE pulsers give 500 V.
- The old LANSCE pulser used 8 vacuum tubes in parallel; it was very fast (about 2.5 ns rise / fall “on a good day”, typically 50% slower), but its tuning was fairly difficult. Its reliability was a serious issue, so it has been replaced later with a slower, but more reliable solid-state pulser.

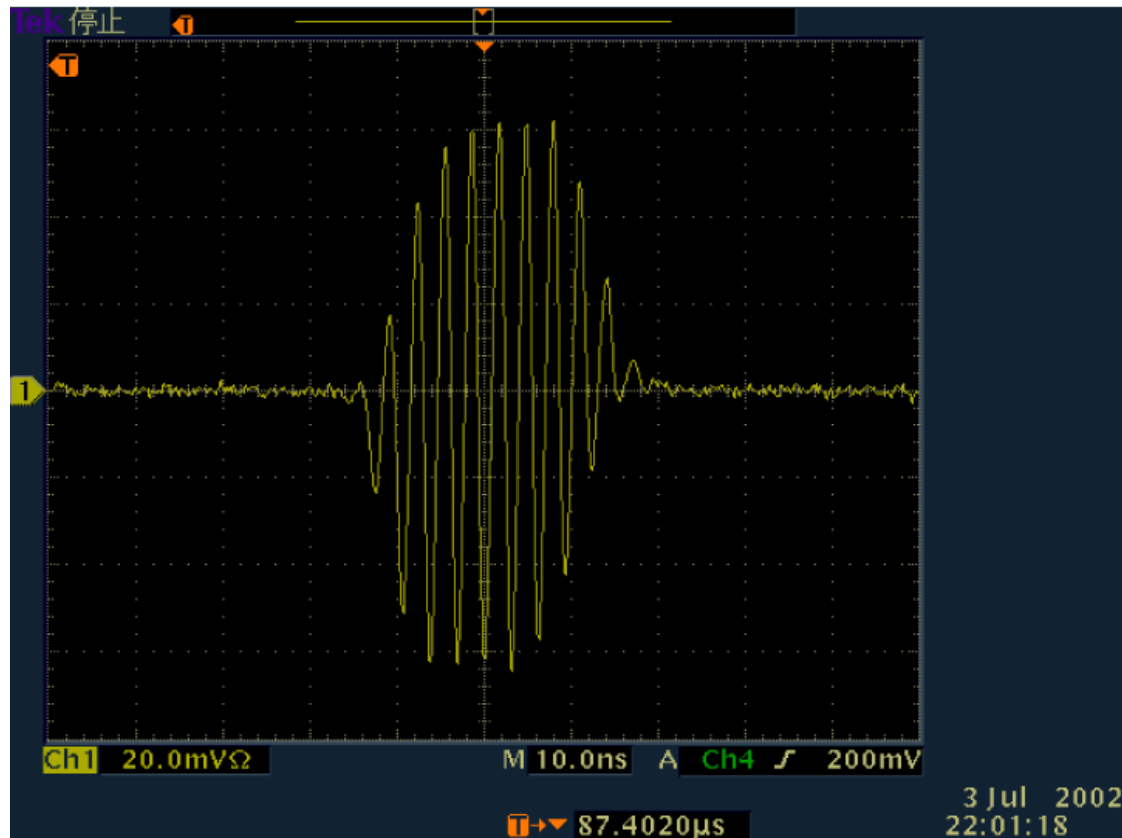
The J-PARC chopping system; key parameters

Beam energy	3 MeV
Type	RFD
Operation frequency	324 MHz
Operation mode	TE11
Number of cavities	2
Number of gaps per cavity	1
Cavity length	172 mm
Bore radius	5 mm
Gap length	20 mm
Full rise / fall time	15 ns
Deflection field voltage	1.6 MV/m
Beam-on duty factor	56 %
RF power source type	Solid state amp.
Number of cavities per RF source	2
Peak RF power per cavity	30 kW

The J-PARC chopping system; key parameters

- The J-PARC linac has a two-stage chopping system with an LEBT pre-chopper and an MEBT chopper.
- The LEBT pre-chopper is an energy modulation induction cavity, with which one can drive bunches beyond the longitudinal acceptance of the RFQ. The MEBT chopper is an RFD (RF deflection cavity) with short time-constant or low Q -value (around 10) driven by fast RF bursts from a high power RF amplifier.
- Bunches are kicked horizontally with the RFD and removed with a collector downstream.
- With the cavity modulating the LEBT beam energy, the downstream RFQ operates as an “energy filter” by letting the off-momentum beam arrive outside the momentum acceptance of the RFQ.
- The MEBT chopper has been tested [see next slide] and the design rise/fall time of 10 ns has been achieved
- It has also been confirmed that the residual current during “chopper-on” periods is less than 10^{-4} of the nominal current (5 mA).
- Further testing of the chopper performance is now in progress during beam commissioning of the J-PARC linac front-end at KEK

The J-PARC chopping system; performance

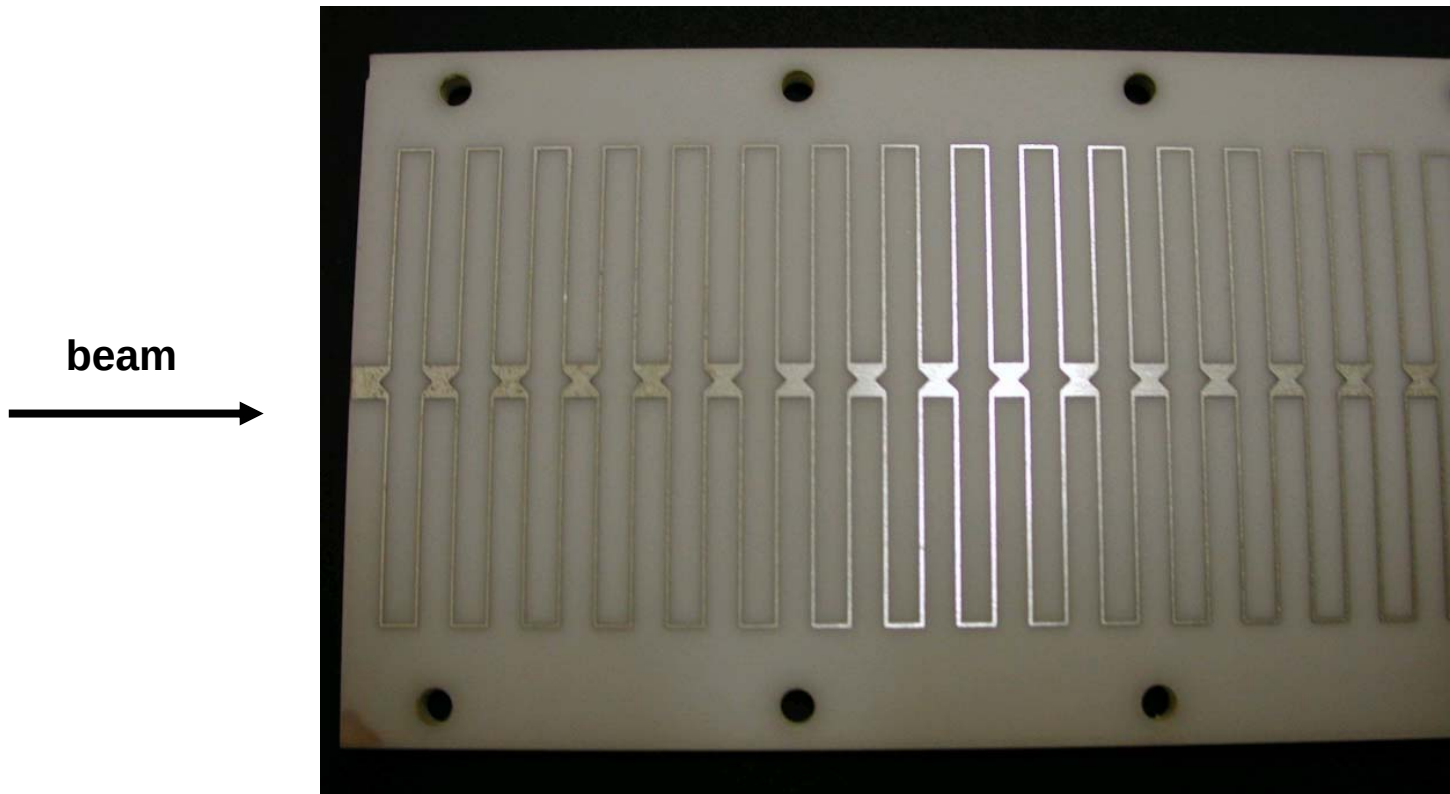


Waveform of a chopped beam obtained with a beam position monitor in MEBT. The horizontal scaling is 10ns/div. The pulse duration is shortened to demonstrate the chopper performance

The CERN-SPL system parameter list

Beam energy	3 MeV
Overall length	3.7 m
Number of chopper structures	2 inside quads
Number of quadrupoles	11
Chopper plate length	400 + 400 mm
Chopper plate distance	20 mm
Separation chopped/ un-chopped beam	15 mm
Chopper structure rise-and fall time	<2ns (10-90%)
Chopper voltage pulse (per plate)	500 V
Effective chopper voltage pulse	400 V
Max. chopper frequency	44 MHz
Pulse length	8-1700 ns
Max chopping factor (duty cycle)	40%
Repetition rate	1-50 Hz
Output transverse emittance (rms, norm)	0.27 π mm mrad with collimator
Chopper deflection angle	6.8 mrad

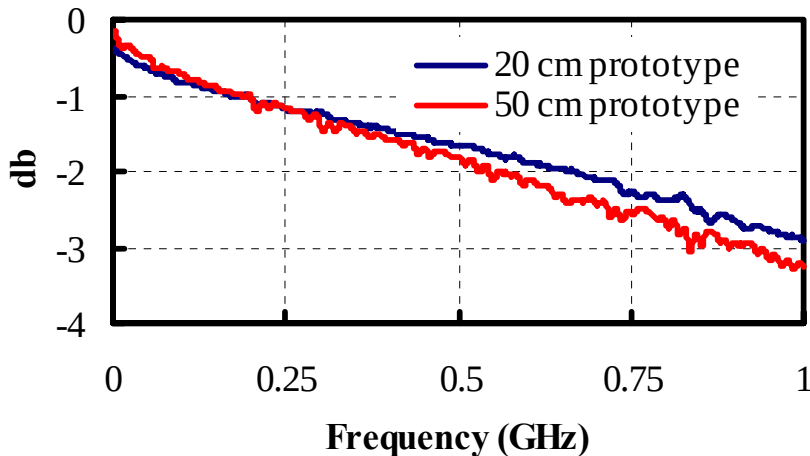
The CERN-SPL system deflecting structure



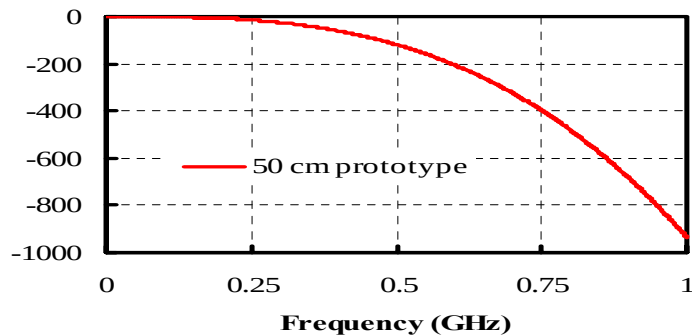
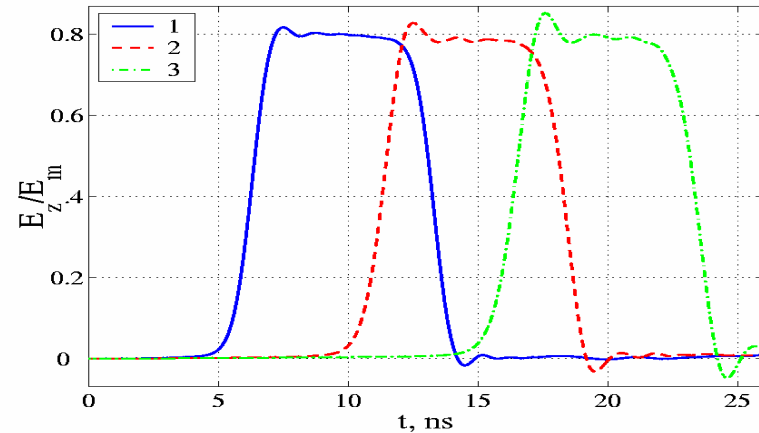
The alumina ceramic plates with printed meander structure (MoMn + 30 micron Ag); mounting holes for M 2.5 screws are at the sides

The CERN-SPL deflecting structure pulse transmission properties

Attenuation vs frequency



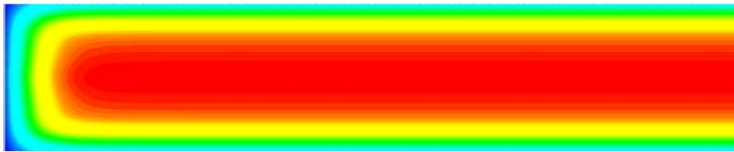
Pulse distortion vs. travel-time



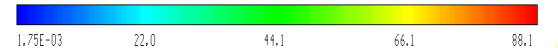
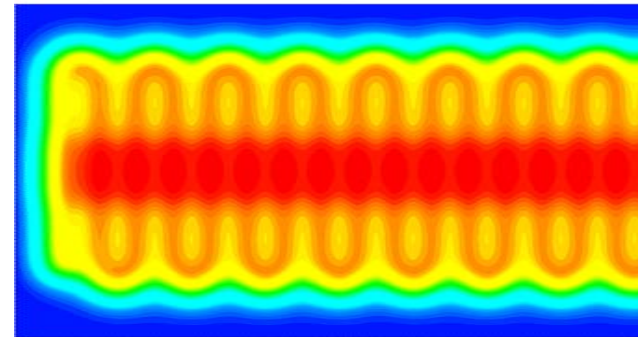
The nonlinear phase shift (dispersion) is the main reason for the pulse distortion as well as for ringing and overshoot

The CERN-SPL system deflecting structure “coverage factors”

The coverage factor is defined here as the ratio of deflecting electric field from the meander structure as compared to the field from a homogeneous infinite metallic plane (ideal capacitor without fringe field)

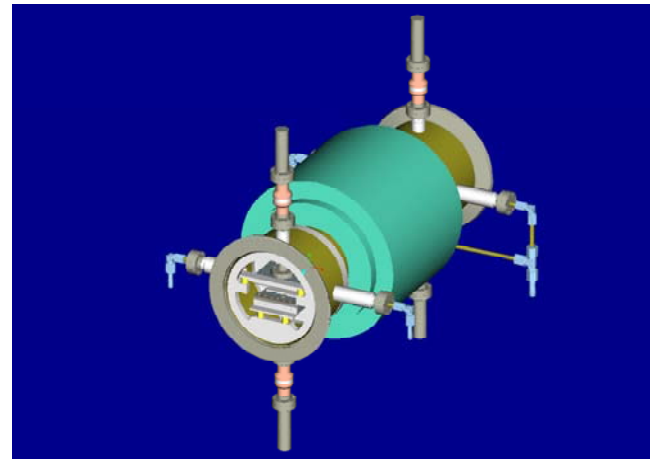
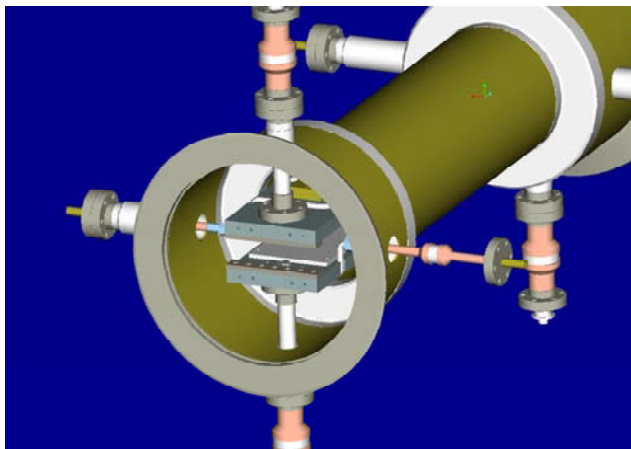
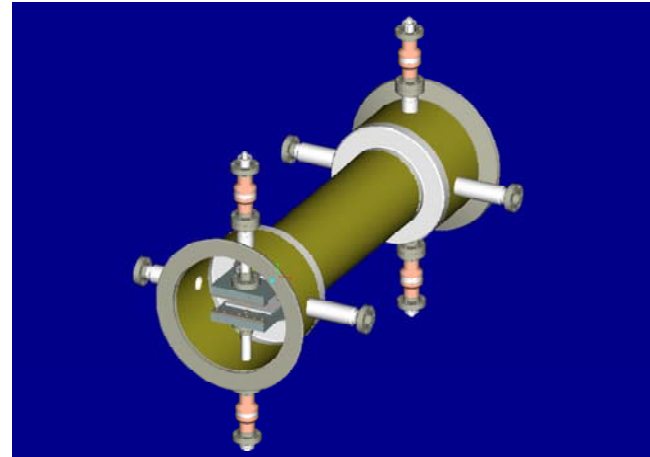
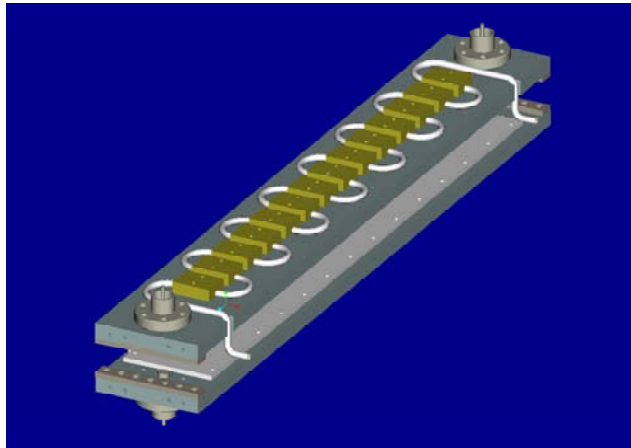


SPL 50 Ohm meander, max 82%



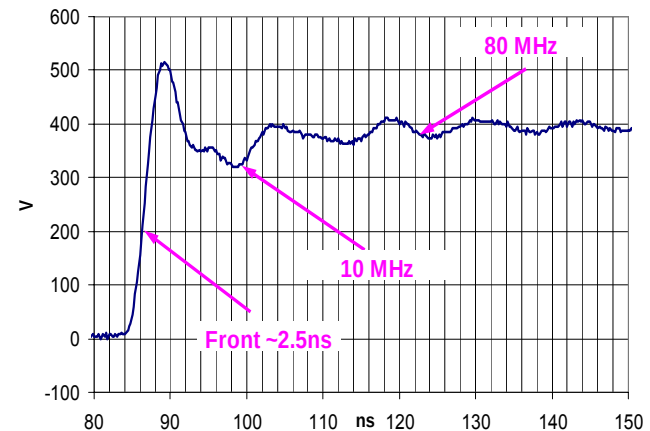
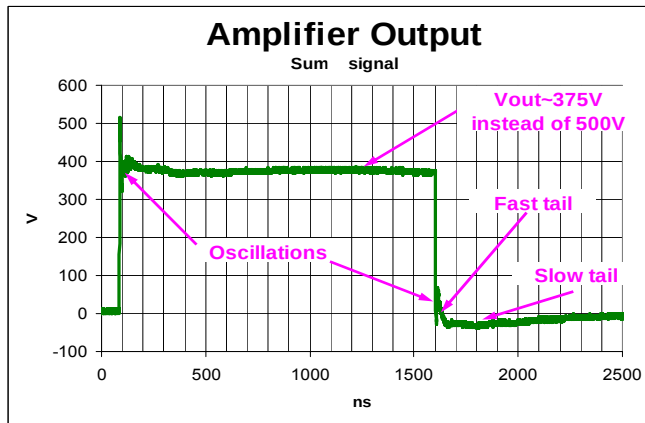
LANL meander, max 89%

The CERN-SPL system deflecting structure 3D views

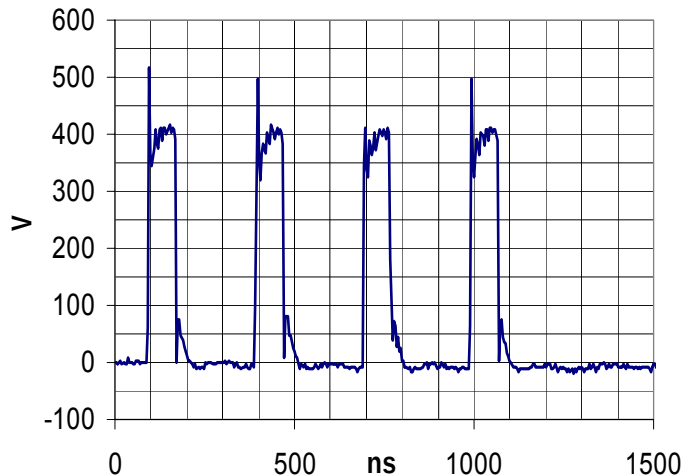


The CERN-SPL system power amplifiers

High frequency(>10 MHz) vacuum tube amplifier performance



80 ns pulse burst



Since high power dissipation during long flattops is to be avoided, the chopper plates are operated in a high impedance quasi-static mode below about 10 MHz and simultaneously in traveling wave mode above 10 MHz; 2 amplifiers! Triax feed-throughs

Discussion

- A certain number chopper concepts developed or implemented in the past years are based on slow wave structures (meander like delay lines) which are synchronous with the beam and/or using electrostatic deflection.
- In the case of the RAL-ESS chopper the slow-wave line and electrostatic deflection are physically separated and for the CERN-SPL chopper there is simultaneous traveling wave and electrostatic deflection foreseen.
- Cavity type (low Q) structures are in use for the JAERI design, both for beam deflection(deflecting mode, used in JAERI MEBT) and particle momentum change (accelerating mode in LEBT) for application of a longitudinal kick to bring particles beyond the momentum acceptance range.

Conclusion

- The main technological challenges for present developments are the pulse driver or power amplifier.
- The actual deflecting (or accelerating) structures are often designed following what is available from the driver units.
- Depending on the technology used, reliability of the driver may be an issue.
- Progress in fast solid state switching technology can be expected
 - This may lead in turn to modifications of the deflector hardware
- Management of beam losses in the MEBT line is very important

Acknowledgements

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RAL-ESS:

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CERN-SPL

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