RFQ and Chopper Issues

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RFQ Requirements

CW RFQ required to accelerate H-minus to 2.5 MeV

Frequency is 162.5 MHz

Up to 10 mA output, CW

Low longitudinal phase space output

Transverse input emittance 0.25 pi mm-mrad, norm, rms

RFQ Characteristics

The RFQ is an electrostatically-focused FDFD strong-focusing lattice with acceleration (E_z) added as a perturbation. The energy bandwidth of the focusing lattice allows unaccelerated beam to be transported to the exit.

There will be a low-energy tail present. About 90% of the beam will be captured and accelerated to full energy.

Subsequent magnetically-focused MEBTs and DTLs get rid of the tail harmlessly: the low-energy tail will not be transported very far.

If a superconducting RF structure follows the RFQ, tail-clipping of the output spectrum may be required.

Compare 162.5 MHz Design

	Proj-X 162	Proj-X 325	KOMAC	
Frequency	162.5	325	350	MHz
Injection Energy	35	30	50	keV
Output Energy	2500	2500	3000	keV
Current	10	10	23	mA
Length	385	287	324	cm
Length/Lambda	2.1	3.1	3.8	
Vane-Vane Voltage	90.8	64.2	100	kV
Peak E-field	20.7	27.6	33.1	MV/m
E-field/Kilpatrick	1.52	1.55	1.8	kilpatrick
Cavity Power	155*	149*	350*/417	kW
Power/Length	40	52	108	kW/m
Avg Wall Power Density	2.1	5.2	13	W/cm^2
r_0 (transverse vane tip radius)	0.61	0.31		cm
minimum longitudinal radius	1.2	0.69		cm
Output rms Momentum Spread	0.2	0.15		percent
Output rms Longitudinal Emittance	0.050	0.046	0.246	MeV-Degree
Output Transverse Emittance	0.030	0.028	0.023	cm-mrad
Transmission	94	90		percent

*=Calculated

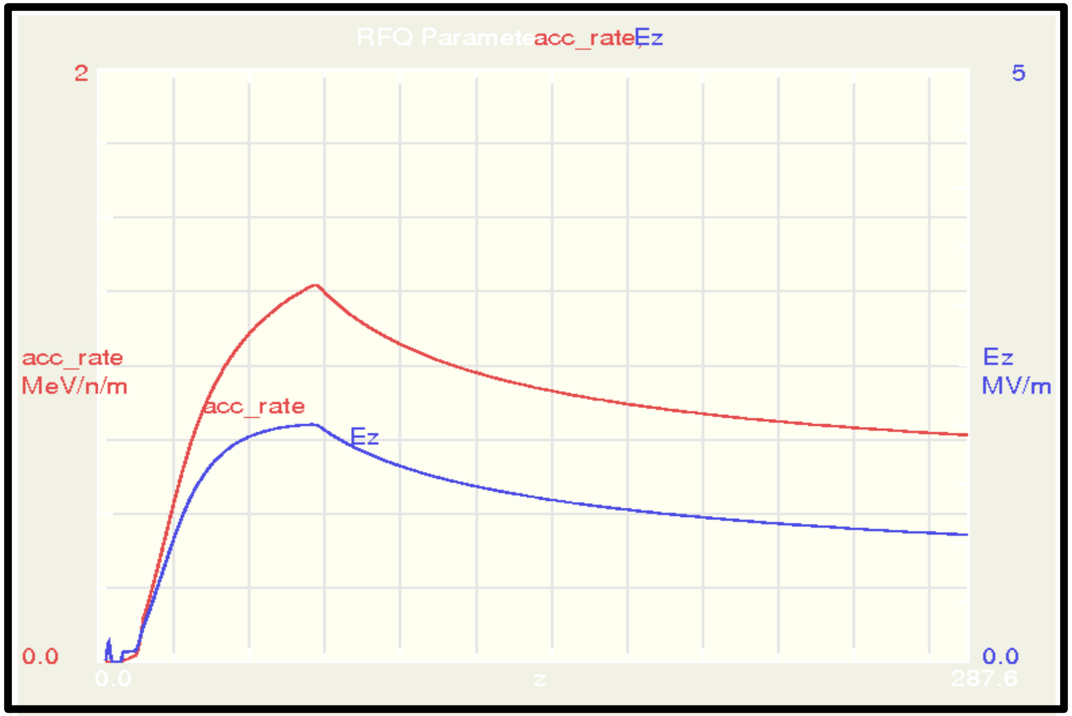
162.5 MHz RFQ Beam Dynamics

The kick-buncher design (Staples, Linac94) has several advantages for lower current designs.

This results in a shorter design using lower power.

Most of the RFQ is the acceleration section.

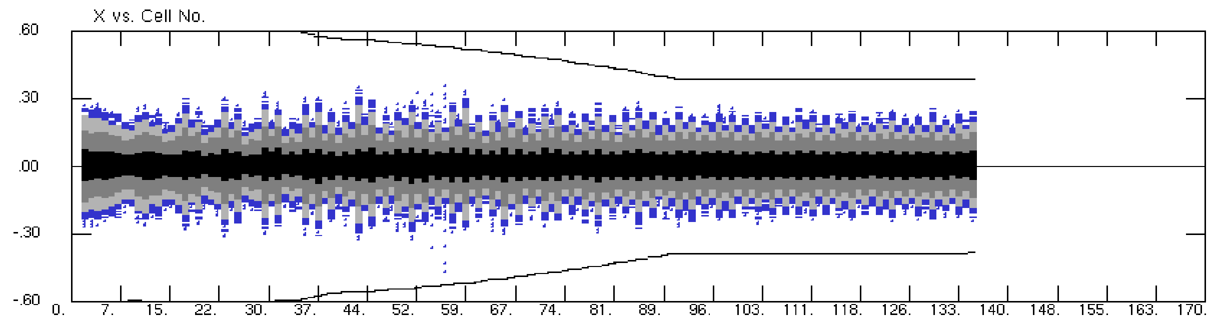
The longitudinal output emittance is significantly lower than a K-T design.



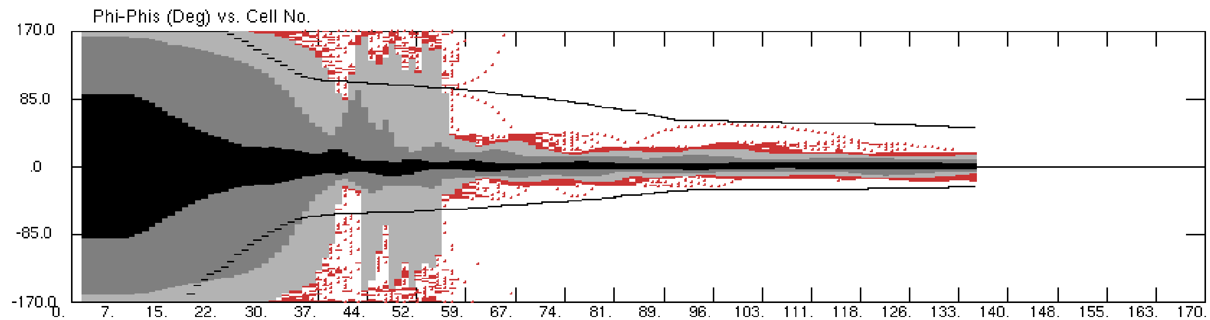
162.5 MHz RFQ Beam Traces

The uncaptured beam, shown here eliminated at cell 58, actually continues to the end.
Input current is 6 mA, acceptance to full energy is greater than 93%.

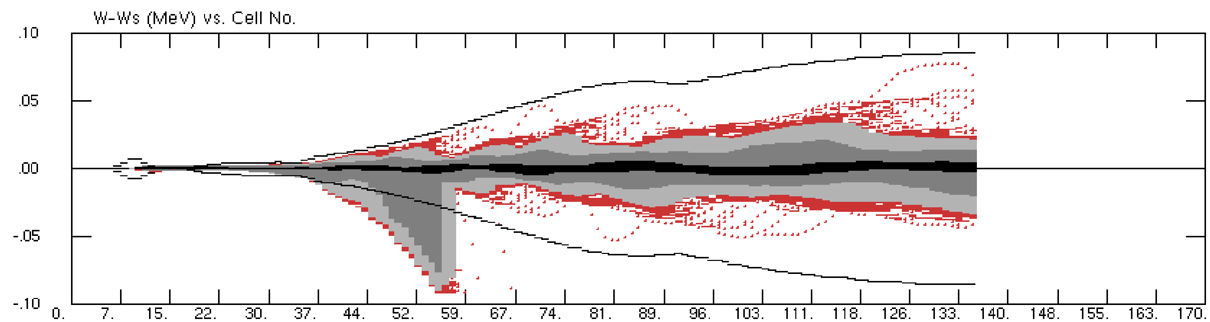
x vs. cell number
normalized emittance
= 0.30 mm-mr



Phase vs. cell number
rms phase spread
= 5.0 deg



Energy Spread
vs cell number
rms energy spread
= 10 keV



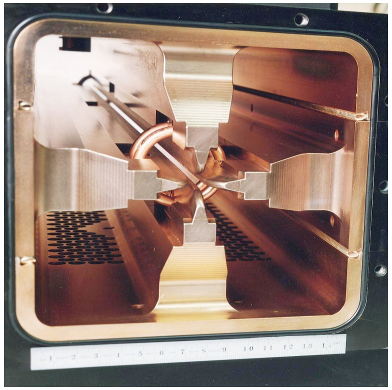
Mode Stabilization

The field sensitivity to local frequency error goes as $(\text{Length/wavelength})^2$.

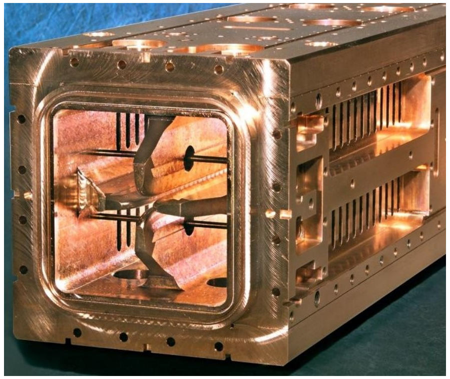
For longer structure (greater than about 2 wavelengths), mode stabilization is recommended.

Transverse stabilization: LBNL method

Longitudinal stabilization: LANL approach



Vane Coupling Rings. Used on 4 LBNL RFQs. Not suitable for high average power.



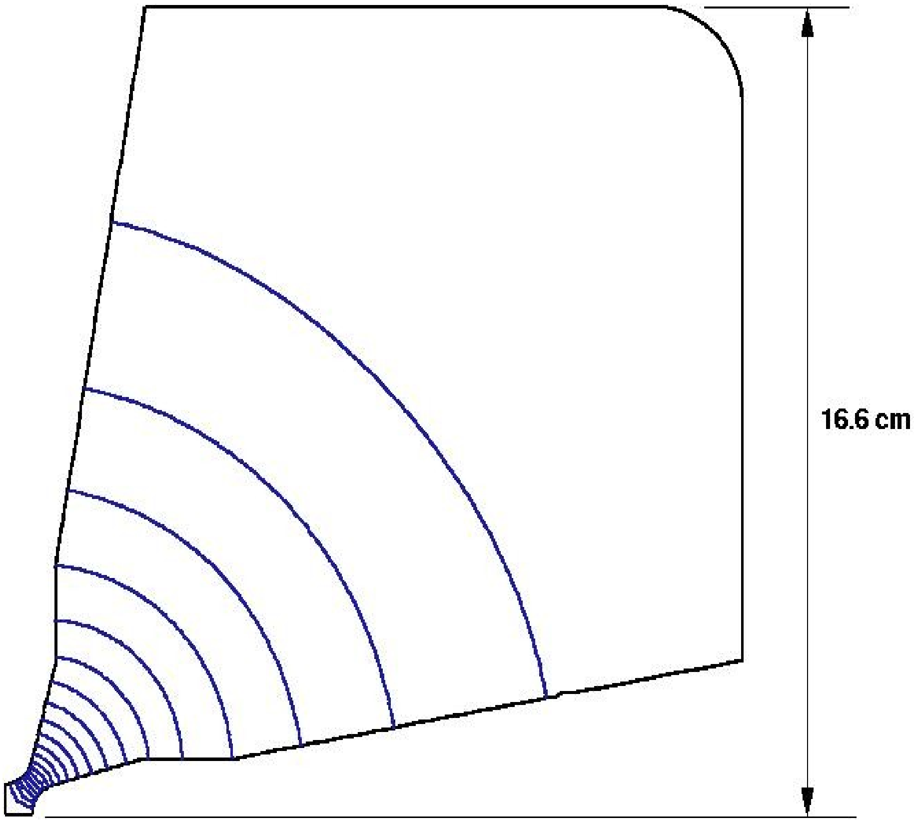
pi-mode stabilizers. Used on SNS RFQ.

162.5 MHz RFQ Cavity Shape

The cavity is just over 33 cm full inside width.

The one clear advantage of the 162.5 MHz RFQ is the lower wall power density and larger transverse acceptance.

The 162.5 MHz structure would use loop couplers. (The 402.5 MHz SNS RFQ uses loop couplers running around 400 kW per coupler at 7% duty factor.) Another LBNL project will transmit up to 60 kW CW per coupler at 187 MHz with no coupler cooling required.



Chopper Requirements

A very complex series of requirements satisfying several users.

Maintain average beam through SCL at 1 mA (2 MW power) with a time structure that allows keeping a constant gradient in the SCL and avoiding pulsing.

This implies rapid switching of a time-averaged beam among several users on time scales ranging from 10 Hz to ten's of MHz.

Users: (example)

Kaon (A) and “other” (B), 27 MHz, 777 kW
Mu2e, 1 MHz 10% duty factor, 518 kW (C)
RCS, 10 Hz pulse of 2.6 x 10^{13} H-minus (D)

Path to a Solution

Fast chopping in the 35 keV LEBT does not seem possible

- laser or e-beam e- detachment: not a chance
- choppers with several MHz bandwidth: TTF limitation
- neutralization problems and 3-stream instability

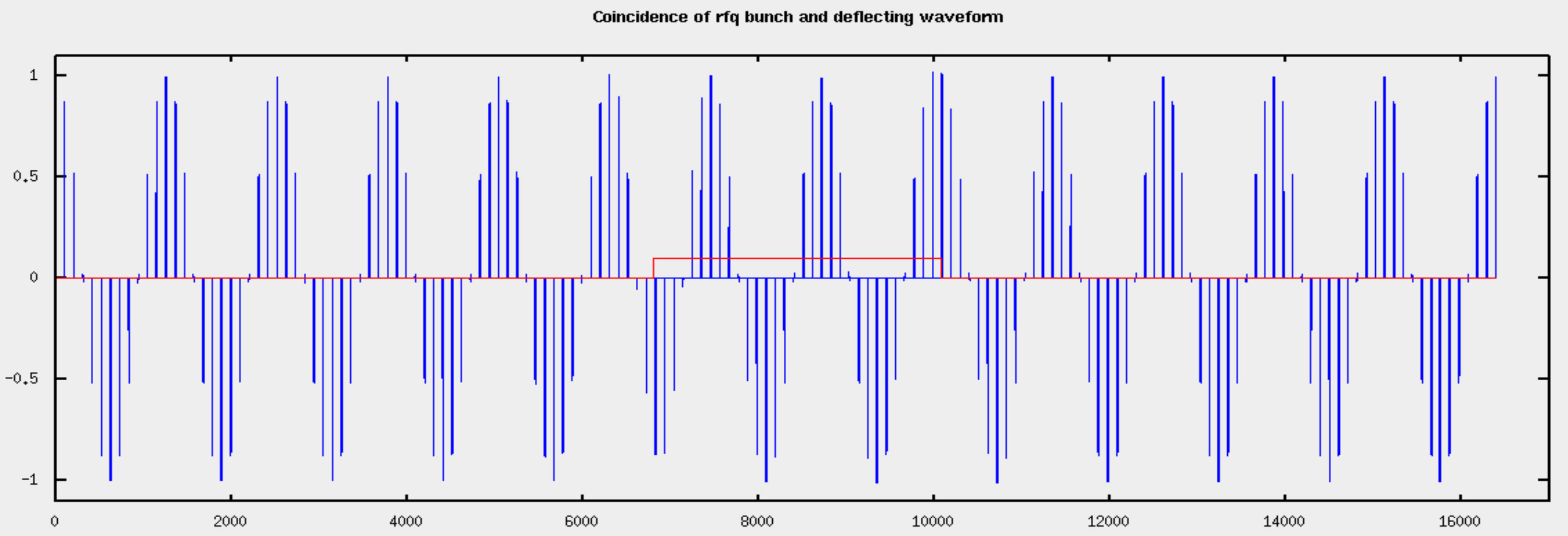
Chopping in 2.5 MeV MEBT seems only possible scenario

- Beam is fairly rigid
- 6 mA CW packs a 15 kW punch, 5/6th to absorber
- Beam has a few tens of micron range in absorber

Very wide-band transverse kickers are difficult to design and require state-of-the art electronic drivers. Narrow bandwidth kickers may offer a solution.

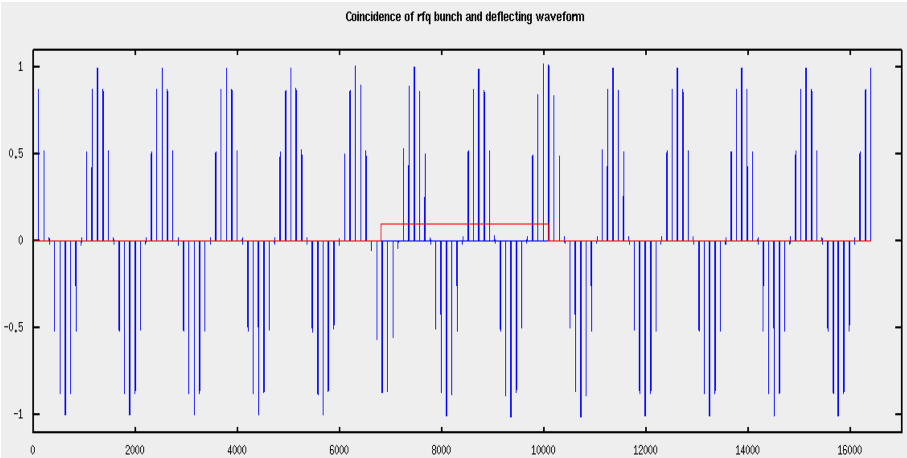
Subharmonic Phase-Shift Chopping

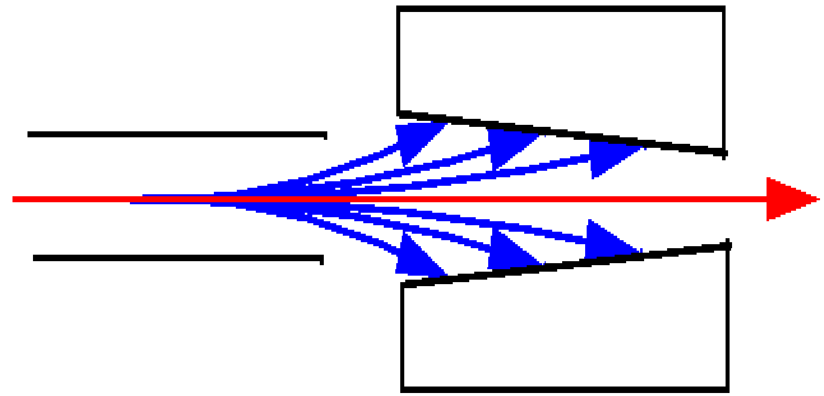
Following the 162.5 MHz RFQ, a 13.54 (162.5/12) MHz deflector with periodic pi/6 phase shift at a 1 MHz rate at 10% duty factor.



The 162.5 MHz bunch structure from the RFQ is deflected by a 13.54 MHz traveling-wave deflector onto a slit. The beam that crosses the baseline goes through the slit. A pi/6 phase shift of the 13.54 MHz occurs at 1 MHz for 100 nsec, and shifts the zero-crossing by 1 RFQ micropulse. The bandwidth in this case extends to 28 MHz.

Subharmonic Phase-Shift Chopping





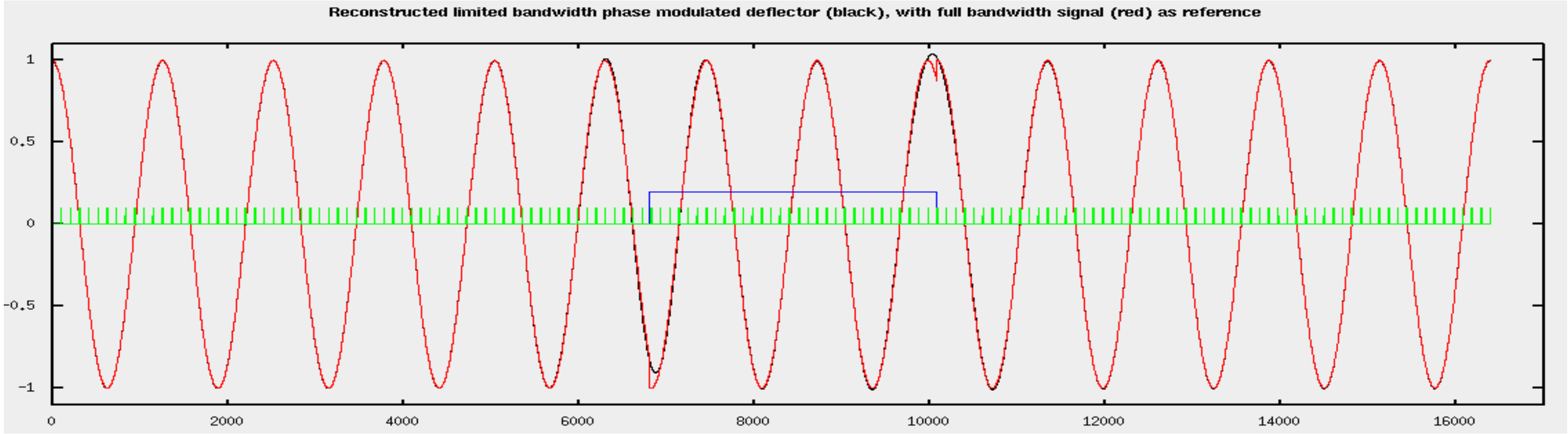
The chopper amplitude of sin(30, 60, 90, 120, 150,...) spreads beam on slit.

At the 2 GeV end of the linac a 1.3 GHz TM110 RF deflector whose frequency is f_{rfq} (m±¼) deflects the "normal" zero-crossings to users A, B, and the phase shifted zero crossing to user C.

The beam power is divided up to provide 777 kW at 27 MHz to A, B, and a pulsed beam of 518 kW at a 1 MHz, 10% duty factor to user C. The average power through the linac is 2 MW with a smooth average time structure.

Chopper Bandwidth Requirement

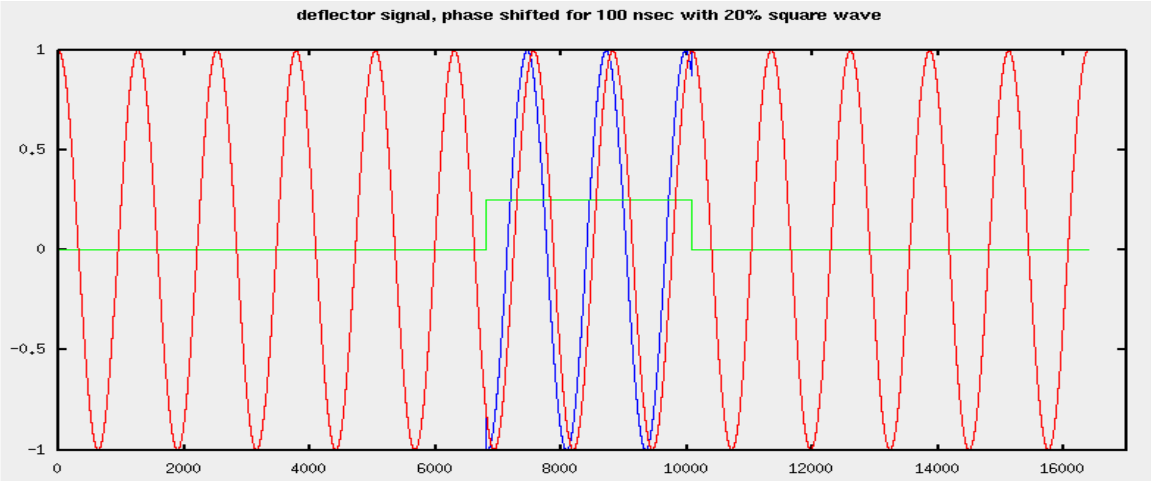
A phase shift of pi/6 degrees at a 1 MHz rate generates sidebands around the 13.54 center frequency. Residual phase error at the zero crossing deflects the beam or may cause actual beam loss on the slit. In addition, bandwidth limitation maay cause the overall 13.54 MHz envelope to be modulated.



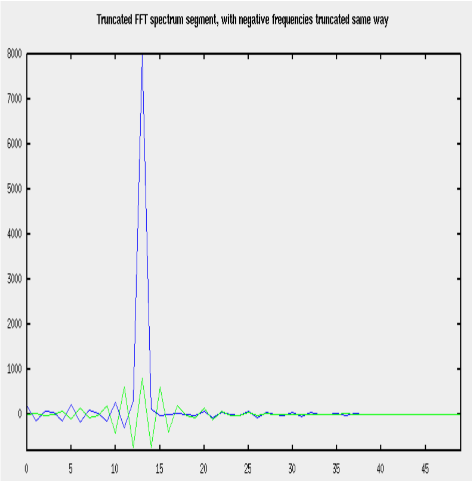
The red curve is the full-bandwidth 13.54 MHz signal, phase shifted pi/6 over the central part of the waveform (blue pulse), and the black curve is the 28 MHz band-limited waveform. The green pulses are the 20 degree-wide 162.5 MHz RFQ micropulses. Bandwidth limits shift the exact zero crossing of the deflector waveform when the RFQ beam pulse is present.

Generating Bandwidth-Limited Simulation Waveform

The chopper/amplifier bandwidth is simulated by generating a time-shifted wave, Fourier analyzing it, and then removing the sidebands above the simulated bandwidth (for both positive and negative frequencies). The resultant is then Fourier transformed back to time space.



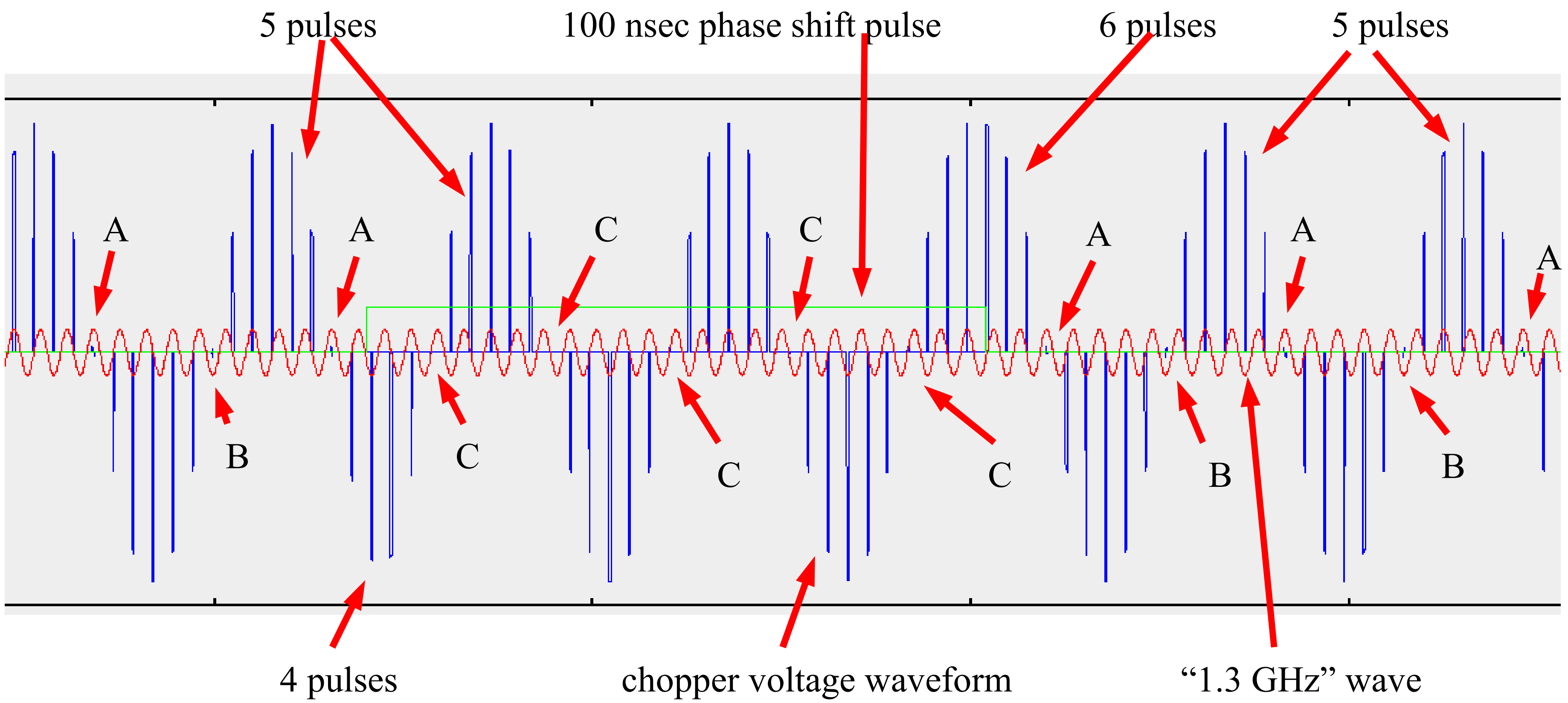
13.54 MHz waveform with pi/6 phase shift



Truncated Fourier Components

Approximation: the Fourier cut-off is sharp, and phase shifts are not taken into account that a real frequency roll-off may have.

Detail of Chopper waveform, phase shift and 1.3 GHz RF Deflector



Detail of 20 degree RFQ beam pulse convolved with 13.54 phase shifted chopper waveform, and 2 GeV RF separator waveform showing deflection of A, B and C bunches. The "C" pulses (Mu2e) are undeflected by the "1.3 GHz" waveform. 28 MHz bandwidth.

Implications of Chopper Bandwidth Limitation

The beam is directed by the 1.3 GHz RF deflector at the end of the 2 GeV linac to users (A,B) or C by the pi/6 phase shift of the 13.54 MHz deflector.

The chopper waveform will have 1 MHz sidebands.

Bandwidth limitations change the phase of the 13.54 MHz chopper zero crossings with respect to the 162.5 MHz bunch structure from the RFQ.

A phase error shifts the zero crossing, which causes a beam deflection at the slit, increasing transverse emittance in the plane of the deflection, or reducing the beam intensity.

Bandwidth limits in the 30-40 MHz range result in very good phase performance on the chopping slit, while allowing selection of individual RFQ micropulse to the 1.3 GHz RF separator.

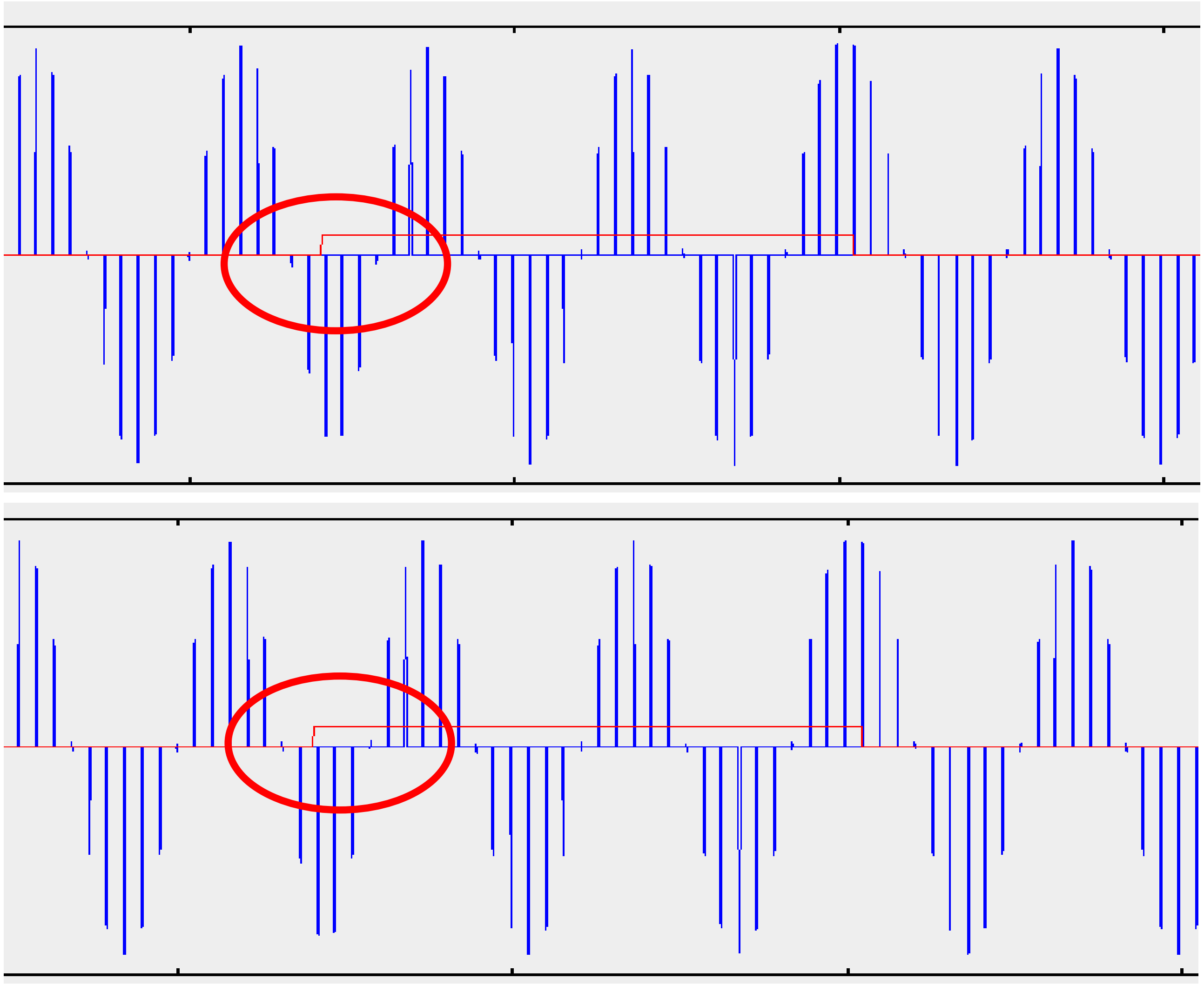
Zero-crossing Quality vs. Bandwidth

28 MHz bandwidth

Wider bandwidth produces more accurate zero-crossing of the RFQ bunch on the slit.

Note one RFQ microbunch shift at start and end of phase shifted region

40 MHz bandwidth



Further Implications of a low-bandwidth chopper

The TW chopper need not have nanosecond risetime. SNS chopper had 2.4 nsec rise: here only $1/10^{th}$ of that is required.

The driver electronics bandwidth extends from near DC to 30-40 MHz only.

The dispersion in the chopper becomes less important. Break the chopper in two or more longitudinal sections, each with its own amplifier.

The chopper impedance can be higher than 50 ohms, reducing the CW power required from the amplifier and dissipated in the TW structure terminating load.

100 ohm system requires about 1300 watts CW from each of four 40-MHz bandwidth solid-state drivers (almost a ham-radio HF linear amplifier).

The deflected beam for 13.54 MHz chopper is deflected to 6 spots, three on each side of the slit, spreading the beam power.

Example MEBT Design

As simple as possible

Two 0.5 meter TW choppers, placed near each other

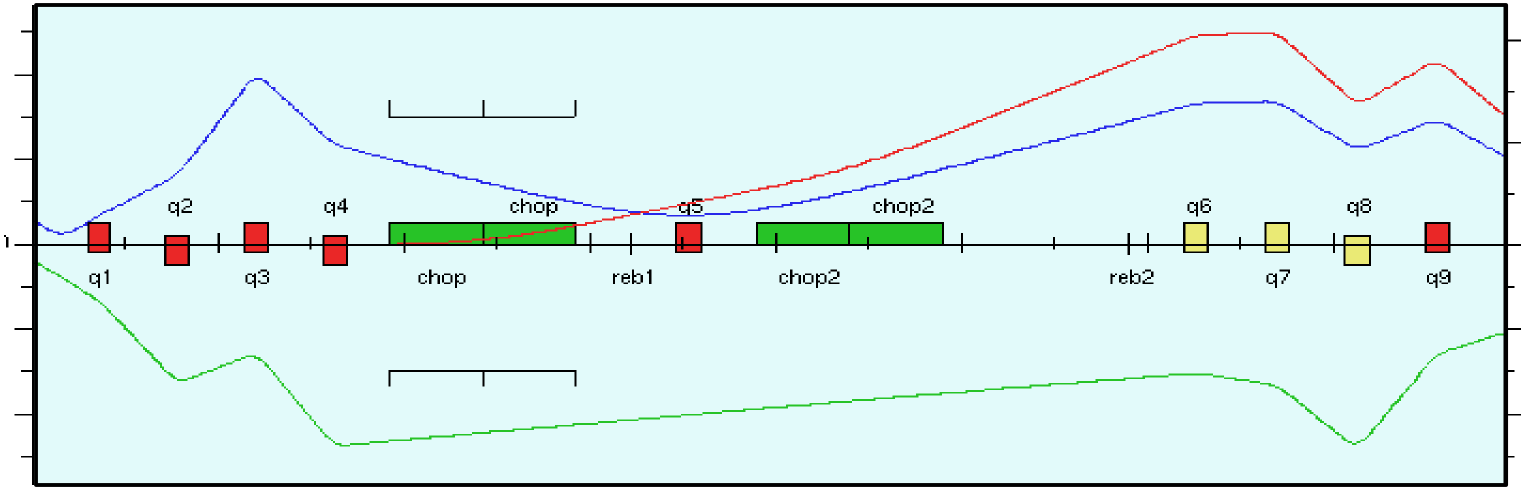
Two rebuncher cavities

Four quads at each end, trim quad in the middle

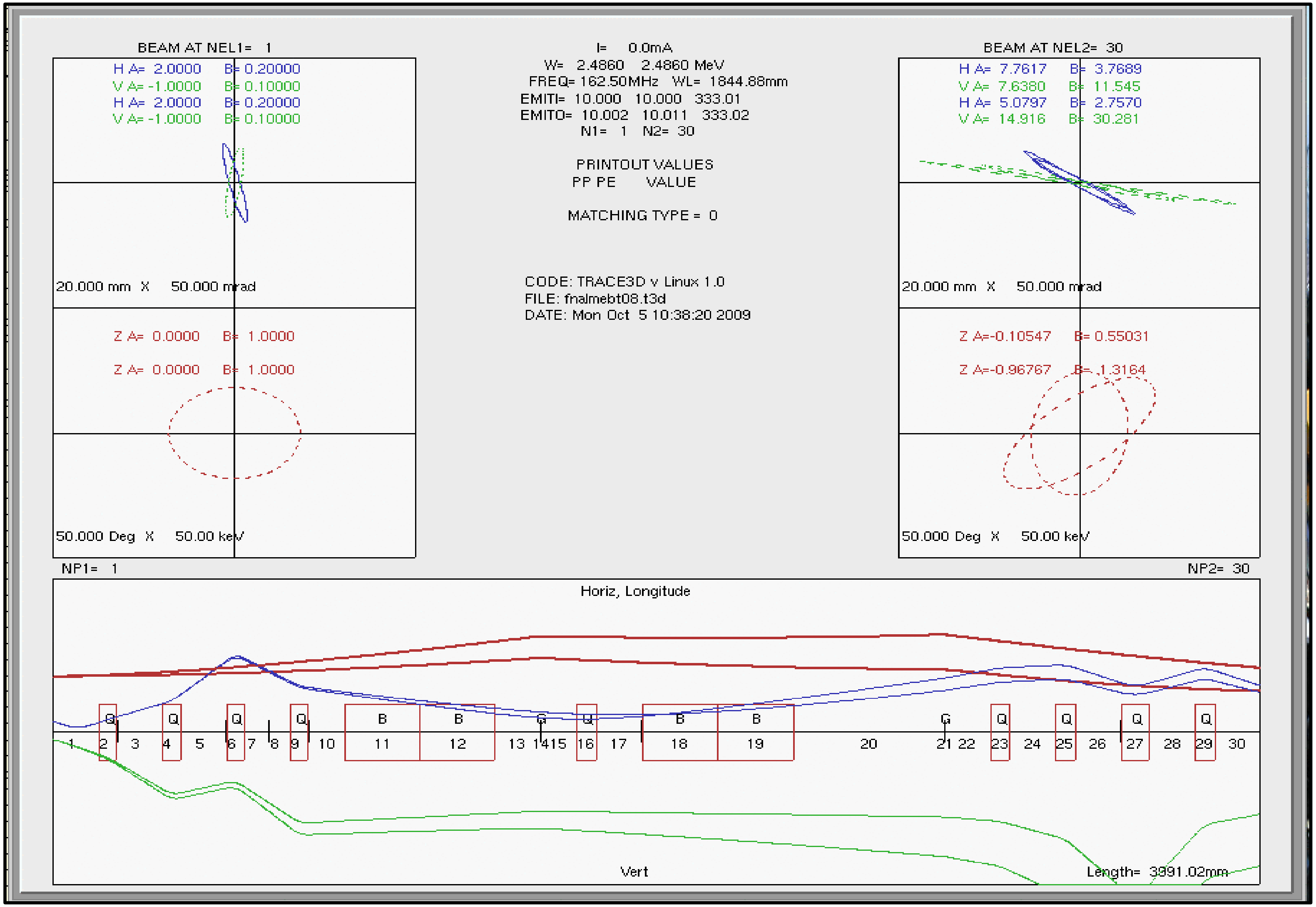
"Ribbon" beam shape in choppers and chopping slit

No diagnostic boxes, etc. included yet

About 4 meters long



MEBT in TRACE3-D: 0, 6 mA H-minus beam



10 Hz RCS Beam

In the C (Mu2e) line, insert a 10 Hz kicker

Kicker requires a notch for the finite kicker risetime
RCS requires a 10% 513 kHz gap for extraction kicker

Both the notch and the gap can easily be placed on the waveform.
The 513 KHz is similar to the 1 MHz wave, but easier
because more sidebands are included within the same bandwidth

The “discarded” beam goes to beamlines A and B

Limitations

The chopped beam goes to either C or (A, B)

Actual microbunch control not possible. Switching at the 1 MHz rate is easy.

Inability to alter the A/B intensity ratio.

More complex patterns may require gating or chopping in the LEBT or additional fast choppers in the MEBT.

Summary

162.5 MHz RFQ easy, good acceptance and low longitudinal emittance, integrates well into beam time structure requirement.

6 mA DC H-minus source required, 35 keV pre-accelerator

Low-bandwidth (40 MHz) chopper scenario gives good performance with 1 MHz (A,B), C switching requirement.

Does not give microbunch time-switching capability

RCS time structure is easy to implement.

Chopper and drive electronics fairly low-tech