MEBT

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Issues

New MEBT concept

MEBT modeling with Astra

Emittance Growth

Beam absorber

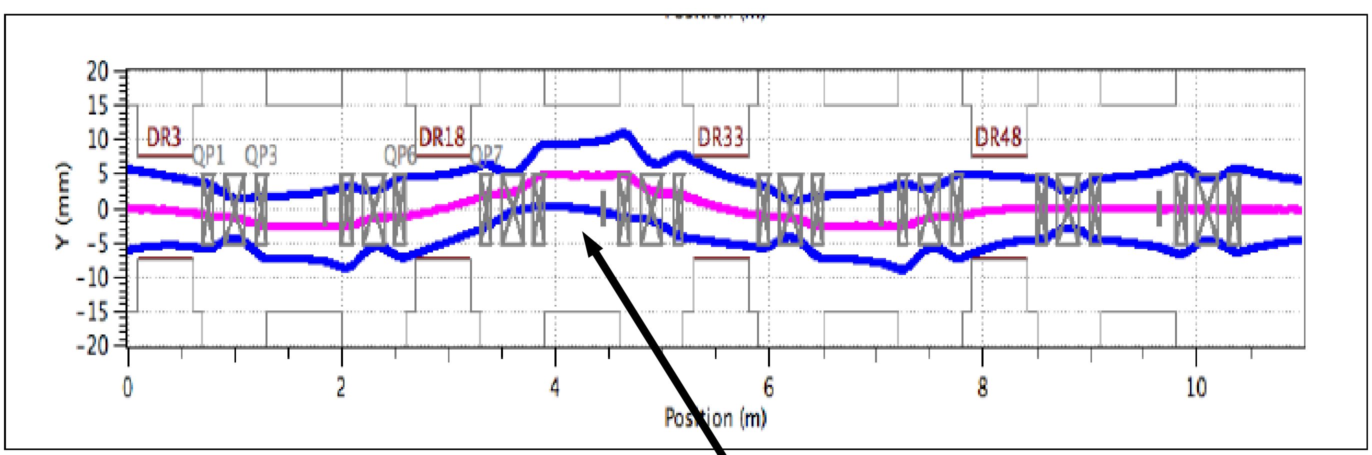
Limited-bandwidth MEBT chopper modes

FNAL MEBT Concept

“+ - - +” design.   Beam deflected to alternate sides.

Beam passes through when deflected one way, stopped on the other deflector polarity.

Reduces the peak field in the deflector by a factor of two.



Beam that misses the beam stop is returned to the axis.

Keeps the lattice of the previous design: 4 periods of 180 degree phase advance per period.   Requires 24 quadrupoles, 4 rebuncher cavities.

collimator

Lattice pretty crowded.

Alternate MEBT Concept

Simulations for 2.1 MeV

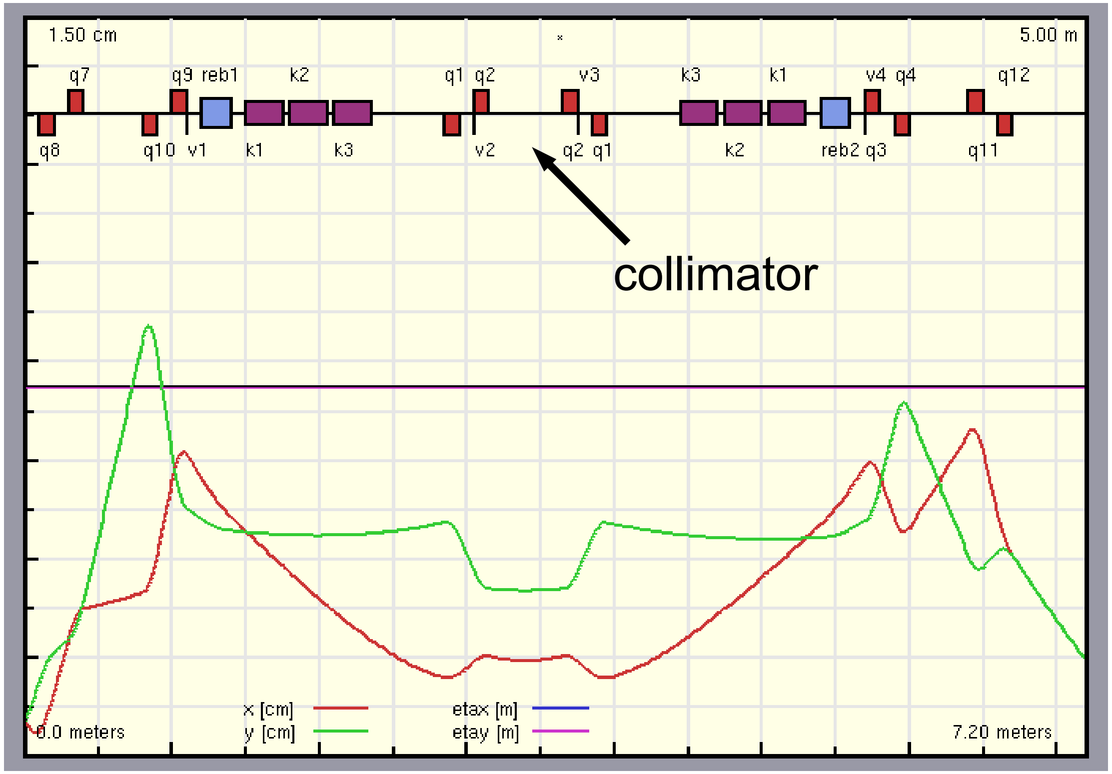
Similar to SNS chopper-antichopper

Accommodates both narrow or wide bandwidth chopper schemes.

Uses 12 quadrupoles (8 in matchers) two 325 MHz rebunchers (blue)

Three 25 cm choppers (purple) in tandem,each side of center, either NB or WB.

"Flat" (α = 0) beam in 50 cm drift space in center for collimator(s).



For wideband chopper, beam is offset in one direction to pass through, deflected in opposite direction to be stopped.

For narrowband chopper, beam is deflected in both directions to be stopped, and goes straight through undeflected. Collimators symmetric across center.

Overall length 7.2m, which includes matchers on each end: from RFQ and round beam to spoke structure on right to spoke cavity.

For wideband chopper, a bipolar waveform moves beam in center region from one side, no collimator, to pass, to the other side, against a collimator in the 50 cm central region. Both up and down deflections are shown.

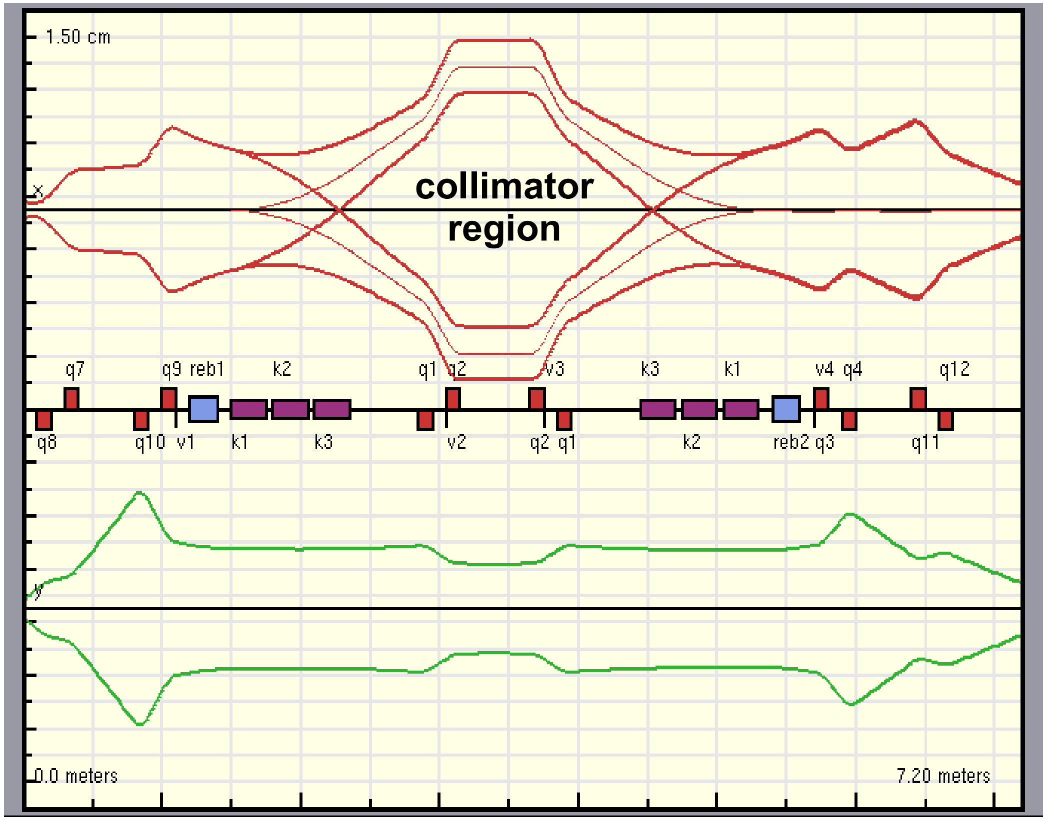
The 50 cm region for the beam stop can easily be extended, as $\alpha_x = \alpha_y = 0$ in the center region bounded by Q2.

The phase advance from the mean center of each deflector (purple) to the other is 180 degrees.

The beam in the y-plane is slightly wider to reduce the power density.

Even wider beam in y produces some emittance growth, however.

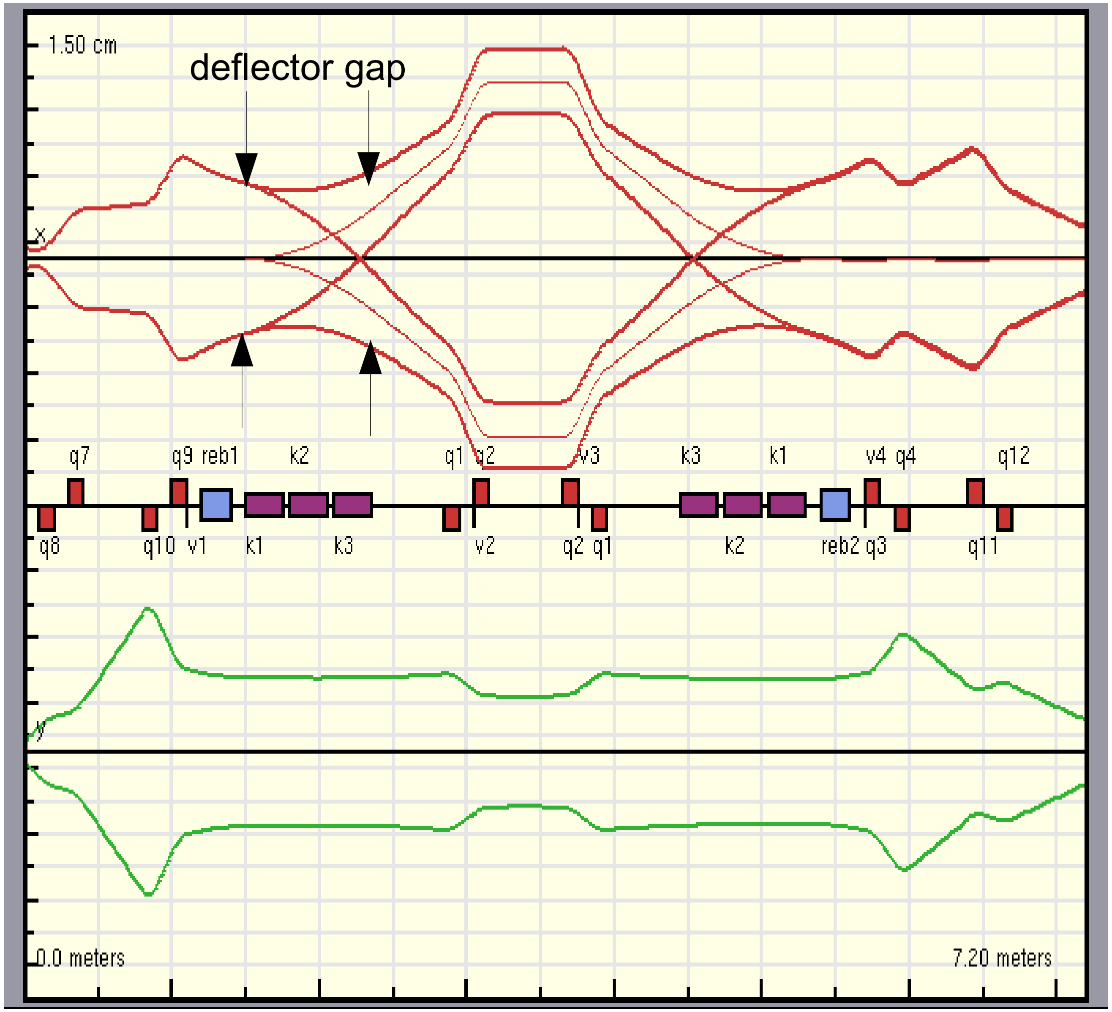
The rebuncher cavities (blue) are 4.2 m apart. The rest of the 7.2 m is taken up by the input and output matching sections. The input beam is taken from the RFQ simulation in parmteqm.



The beam is focused to get smaller as it progresses along the chopper, so the deflected beam clears the chopper and the spacing of the chopper plates is constant along all 25 cm sections. The field is the same in all chopper sections.

A 5 cm space is placed between the three 25 cm chopper sections.

Several places are reserved for diagnostics: between quads in the matcher, and after the deflectors, as well as in the center collimator section.



Additional Deflection Option in Perpendicular Plane

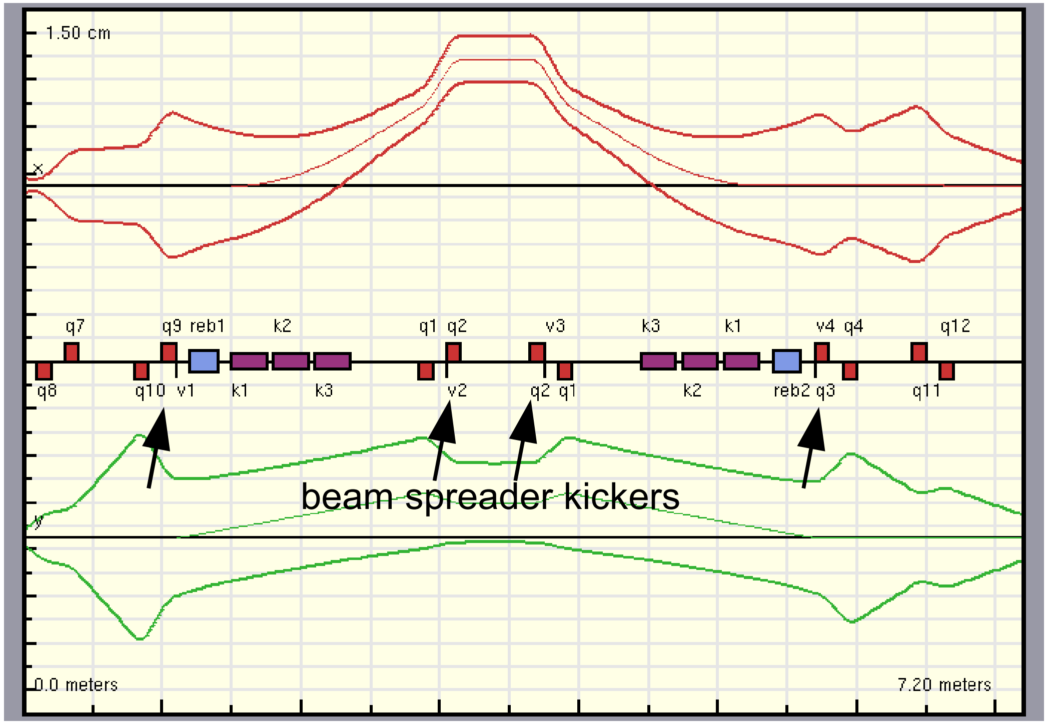
The beam hits the collimator at an angle 87.4 degrees from the normal, which reduces the power density in the beam by cos(87.4) = 0.0454.

The power density can be further reduced by deflecting in the transverse direction to spread the beam.

Small magnetic deflectors are placed at Q9 and Q2 and their symmetry points to deflect the beam in the y-plane. As the betatron phase advance in this plane is small, four deflectors are needed.

2 mrad deflection at Q9 and -1.5 mrad at Q2 give a 0.3 cm shift of orbit at the collimator.

2 mrad requires a field of 420 G-cm. This could be implemented as dipole steering windings on the quadrupoles.



Deflector Gap Spacing

With a field of 33 kV/m (330 V/cm) in each of the deflectors, the beam centroid is displaced 0.90 cm from the axis

For a bipolar excitation of the deflectors, the beam is displaced a total of 1.8 cm.

The beam parameters at the center of the collimator are:

β_x = 1.7 m

σ_x = 0.20 cm

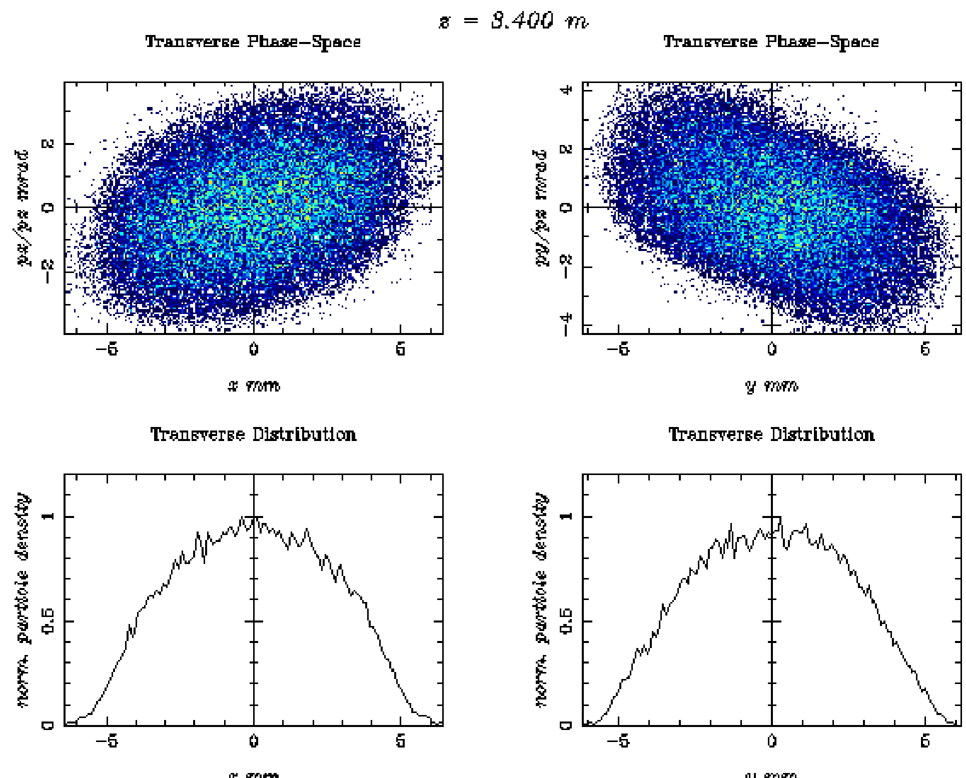
full beam width = 1.4 cm, with tails

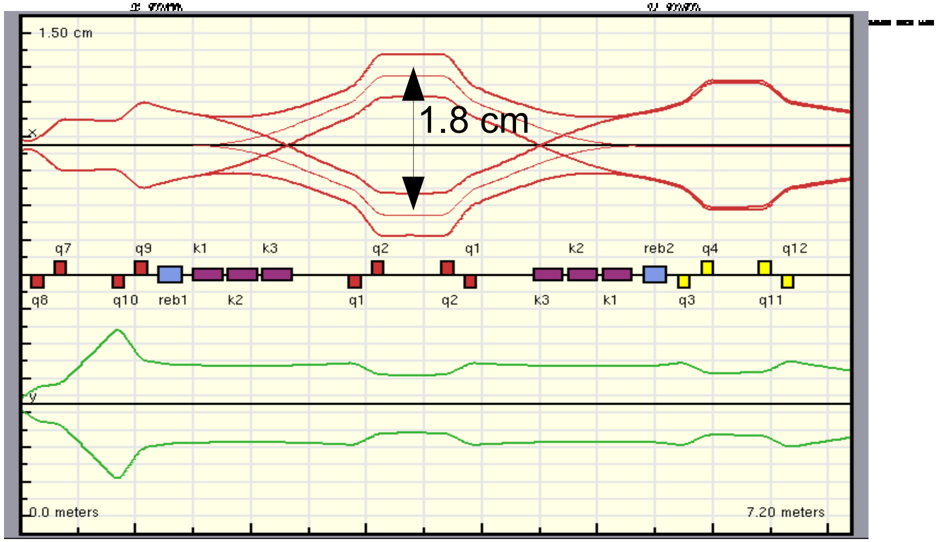
$$\frac{\Delta_{deflection}}{2\,\sigma_{beam}} = \frac{1.8\ \text{cm}}{0.2\ \text{cm}} = 9.0$$

The beam is deflected 9.0 rms radii, or 1.3 times its full width.

The full beam width at each deflector + twice the deflection requires a least a 1.5 cm deflector plate spacing, including some margin.

A bipolar suppply of ±250 volts gives the required 33 kV/m field.



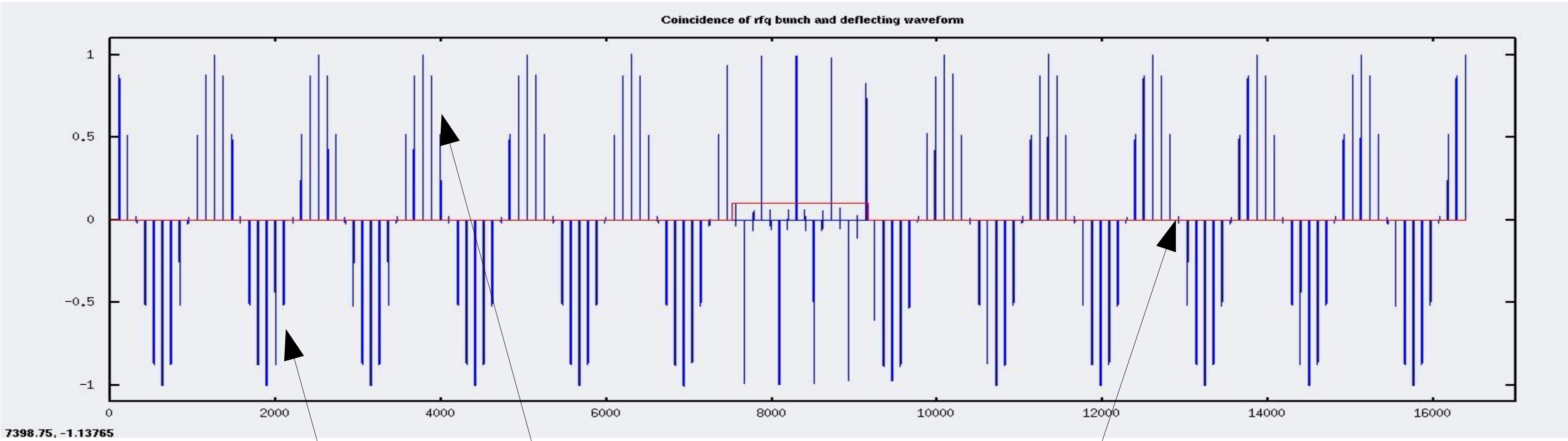


Narrow-Band Chopper Waveform

For the narrow-band chopper, where a larger voltage can be generated, the collimators are on each side, and the undeflected beam passes through.

The waveform the the narrow band chopper deflects the beam over both collimators, and distributes it over a wider area on each collimator, reducing the power density on the collimator.

Beam that misses the collimator is returned to the axis, and does not contribute to an increase of transverse emittance .



Narrow-band waveform: beam passes collimator on zero-crossing, the rest of the beam is spread out on the symmetric collimators.

325 MHz Rebuncher Cavity Example

Two 325 MHz cavities, with peak voltage gain of 25-45 kV. Power about 1 kW CW.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All calculated values below refer to the mesh geometry only.
Field normalization (NORM = 0):     EZERO =      0.21940 MV/m
Frequency                                 =    325.67527 MHz
Particle rest mass energy                 =   938.272029 MeV
Beta =  0.0671960          Kinetic energy =        2.125 MeV
Normalization factor for E0 =  0.219 MV/m =     2511.271
Transit-time factor                       =    0.5698715
Stored energy                             =    0.0023621 Joules
Using standard room-temperature copper.
Surface resistance                        =      4.70818 milliOhm
Normal-conductor resistivity              =      1.72410 microOhm-cm
Operating temperature                     =      20.0000 C
Power dissipation                         =     300.3079 W
Q    =   16095.3           Shunt impedance =       16.029 MOhm/m
Rs*Q =    75.780 Ohm                 Z*T*T =        5.205 MOhm/m
r/Q  =    32.342 Ohm   Wake loss parameter =      0.01654 V/pC
Average magnetic field on the outer wall  =      389.376 A/m, 35.6913 mW/cm^2
Maximum H (at Z,R = 2.57628,3.96744)      =      941.657 A/m, 208.742 mW/cm^2
Maximum E (at Z,R = 0.6,1.97)             =      4.22106 MV/m, 0.236325 Kilp.
Ratio of peak fields Bmax/Emax            =       0.2803 mT/(MV/m)
Peak-to-average ratio Emax/E0             =      19.2391
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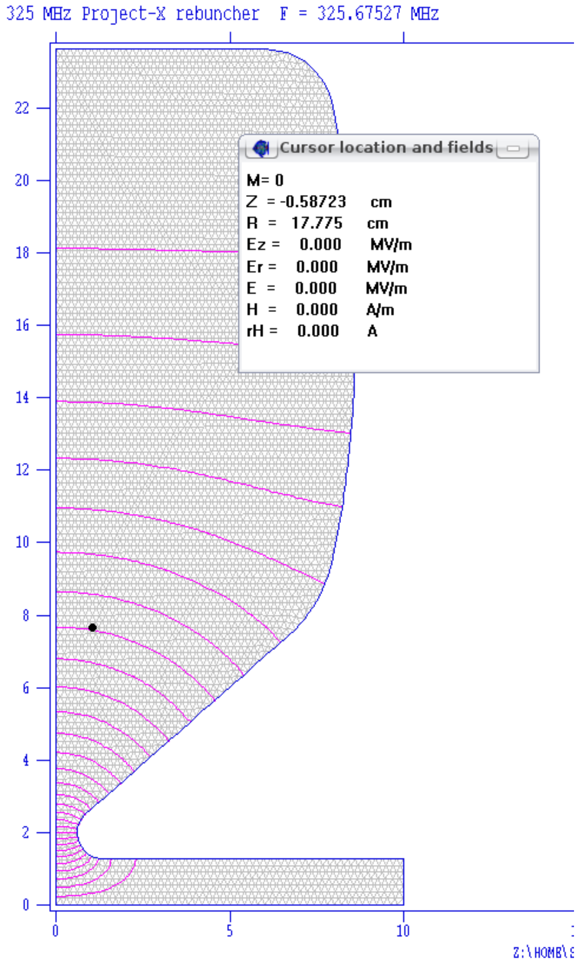
Wall segments:

Segment	Zend (cm)	Rend (cm)	Emax (MV/m)	Power (W)	P/A (mW/cm^2)	dF/dZ (MHz/mm)	dF/dR (MHz/mm)
	0.0000	0.0000					
2	0.0000	23.630	3.139	112.3	64.02	7.142	0.000
3	6.0100	23.630	2.5938E-03	31.85	35.70	0.000	-0.5861
4	7.9700	22.030	1.4319E-02	14.73	37.13	-0.1591	-0.1926
5	8.6000	15.810	7.6335E-02	37.40	50.20	-0.6336	-6.4668E-02
6	7.9650	9.6000	0.1319	40.37	80.93	-0.5613	-5.6462E-02
7	6.5600	7.3400	0.2107	19.33	135.1	-0.2166	-0.1318
8	0.85000	2.5060	2.973	43.31	187.2	2.174	2.568
9	0.60000	1.9700	4.221	0.8357	96.77	3.742	1.558
10	1.3000	1.2700	4.221	0.1855	17.64	2.679	1.180
11	10.000	1.2700	0.8495	1.3368E-03	1.9255E-02	0.000	2.3286E-02
12	10.000	0.0000	1.4992E-07	5.4221E-17	1.0701E-14	7.5767E-16	0.000
			Total	300.3			



Emittance Growth in MEBT

Macroparticle calculations with Astra with space charge

Beam energy is 2.1 MeV
Input beam derived from output of parmteqm.
Format converter written
Parmteqm has a bug in the quadrupole transport element

Emittance growth through MEBT is dependent on details of tune

Diagnostics required for transverse beam size and centering
BPMs and laser wires

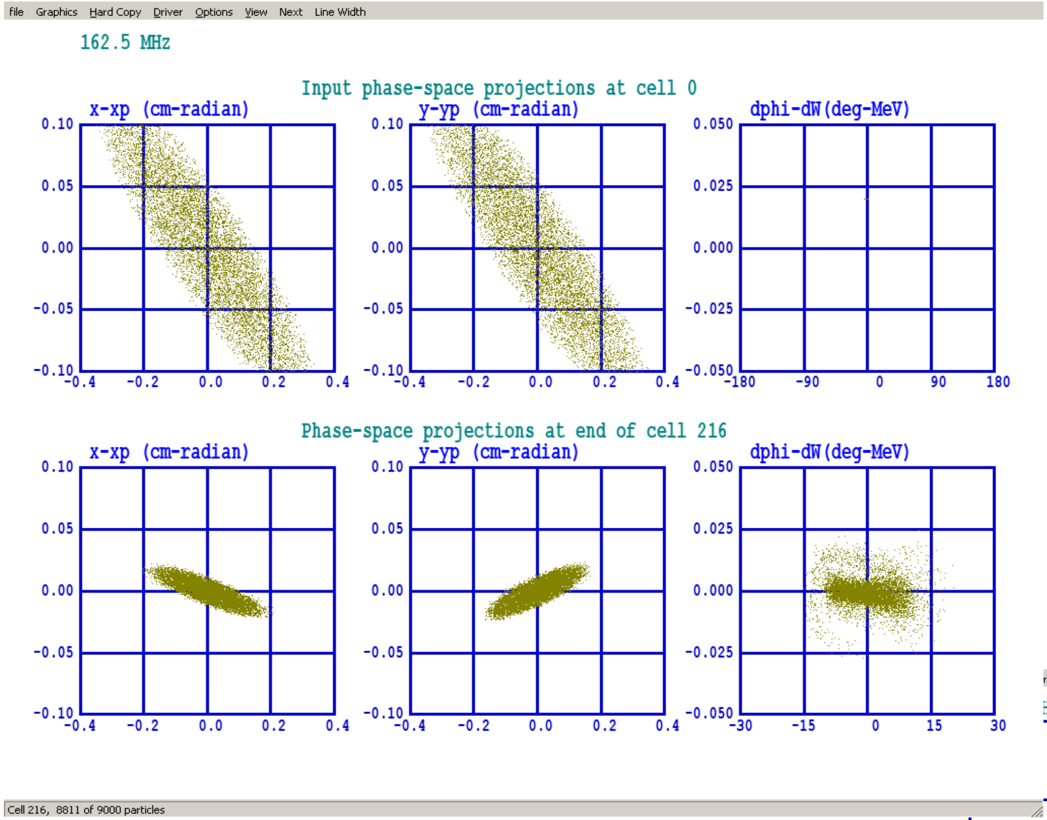
Diagnostics required for setting rebuncher gradients and phases
BPMs and/or striplines

These diagnostics should not take much room

Initial RFQ emittance measurements need to be done only once before the MEBT is appended.

RFQ Output Beam Distribution

parmteqm calculations
5 mA,   2.1 MeV

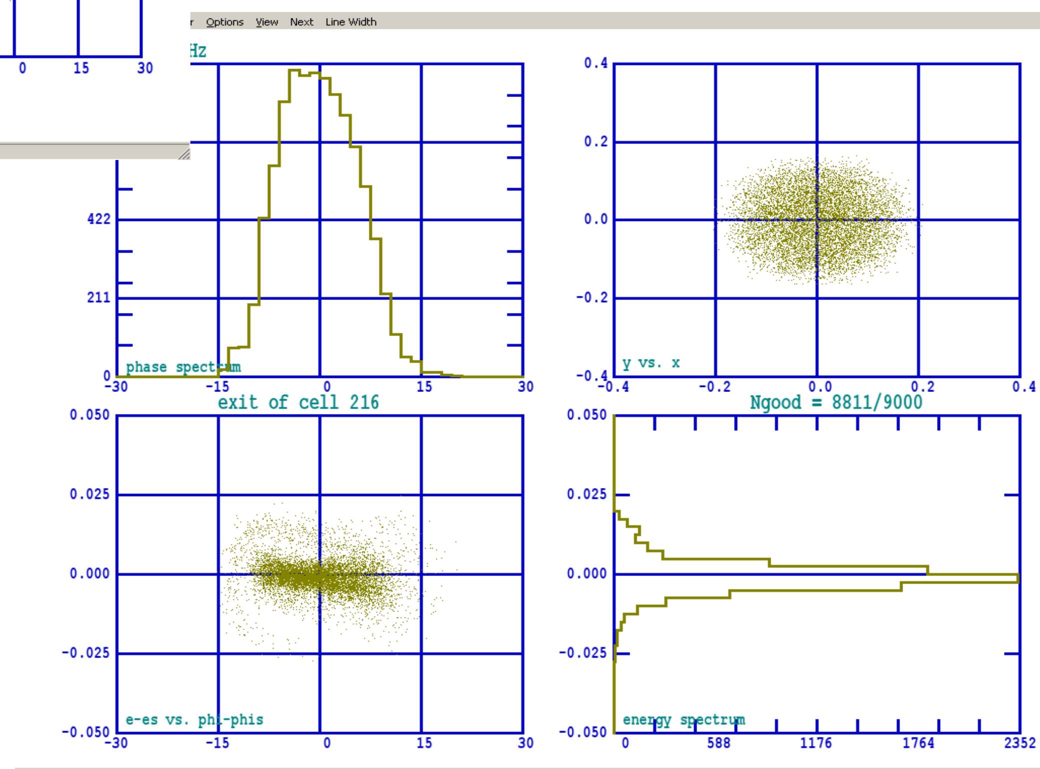


Transverse emittance 0.25 mm-mrad

Longitudinal emittance 0.50 keV-nsec

Transverse phase space at entrance and exit (same scales).

Waterbag input beam distribution, 0.25 pi mm-mrad rms emittance



Emittance Growth in MEBT

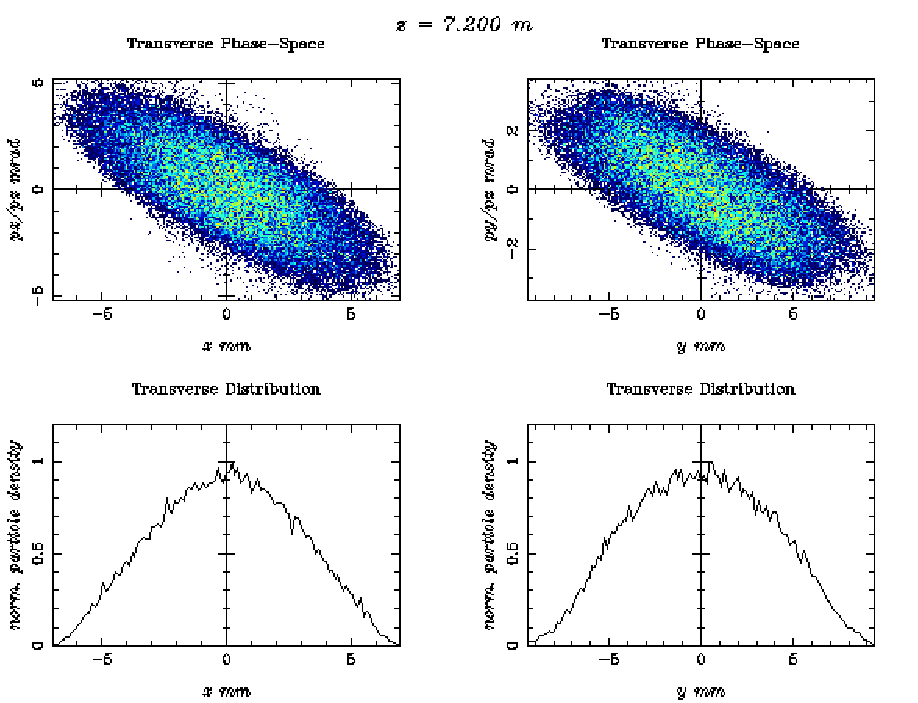
The emittance growth is calculated for 50,000 macroparticles in each bunch with 30 picoCoulomb bunch charge (5 mA) for a 2.1 MeV beam. The particle ensemble is calculated by parmteqm for the 2.1 MeV RFQ that is then transported through the MEBT.

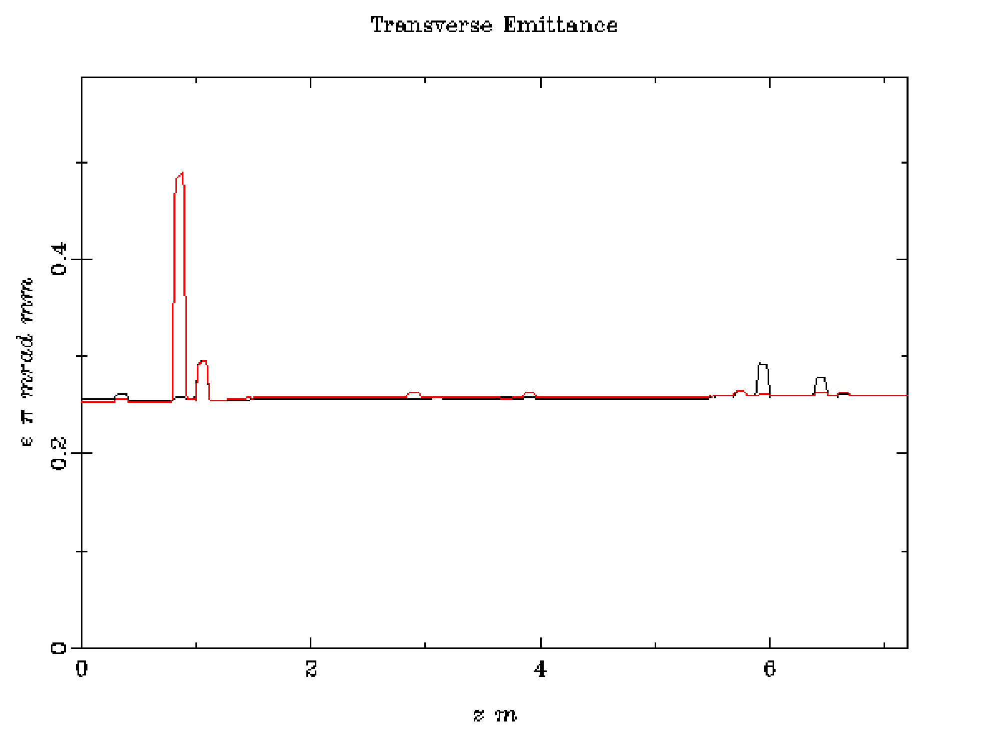
The transport is simulated with Astra, using a full 3-D FFT space charge algorithms.

Transverse emittance growth: less than 5%.

Initial 1 times rms emittance from parmteqm is 0.25 pi mm-mrad normalized.

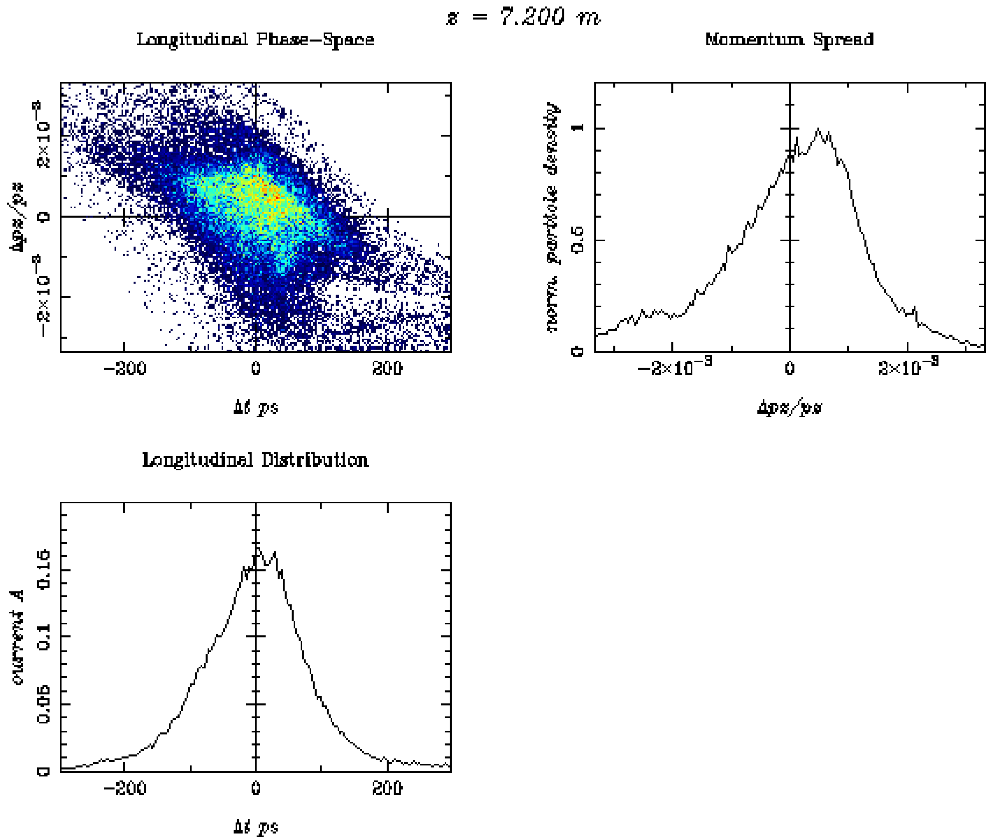
Final phase space distributions shown at the MEBT exit.

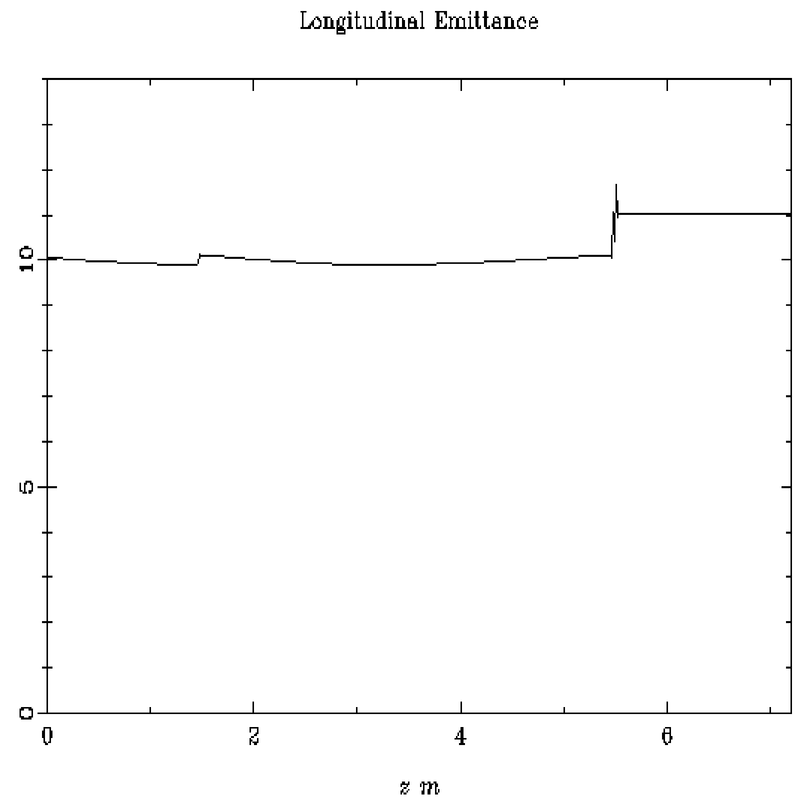




Longitudinal Emittance Growth

Longitudinal emittance growth is 10% with 3-D FFT space charge for 50K particles, or an emittance at the match point at the 7.2 meter point of 0.55 keV-nsec, rms, 30 pCoul charge per bunch. The rebuncher cavity frequency is 325 MHz.

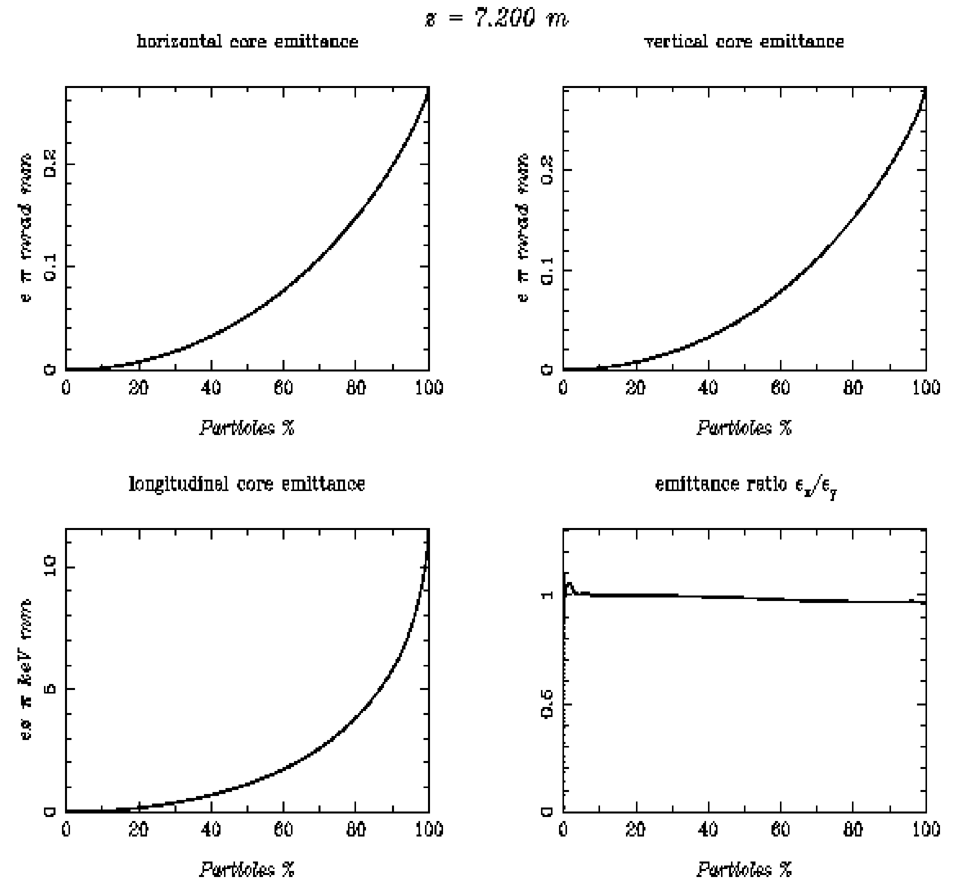


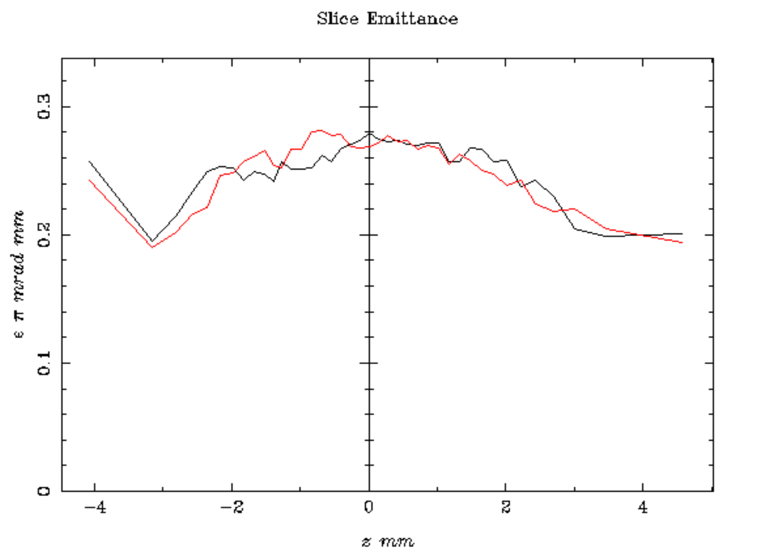


Emittance Distribution

The emittance vs. particle fraction are given here.

For 90% of the beam, the longitudinal emittance is about 6 keV-mm, or 0.3 keV-nsec, for example.





The transverse emittance for 40 longitudinal slices of the beam peaks at 0.28 mm-mrad in the center, and actually falls off towards the ends. The total *projected* emittance is 0.27 (x) and 0.28 (y) for the scheff calculation, and 0.26 (x and y) mm-mrad for the 3-D FFT run, showing that no skewing occurs of the Twiss parameters along the bunch.

MEBT Physics and Engineering

Biggest issue: thermal control on beam collimators

- Materials choice: strength, sputtering, neutron production ...
- Detailed cooling configuration
- Damage, sputtering, spalling, erosion, etc.
- Beam distribution on collimators with wideband and narrow band choppers

TW Choppers

- Interaction of choppers with beam:
  - erosion from beam halo
- Resistive and reactive losses, thermal control
- Robustness of chopper current-carrying elements in hostile environment
- Bandwidth, phase linearity, efficiency

Neutron production

Diagnostics

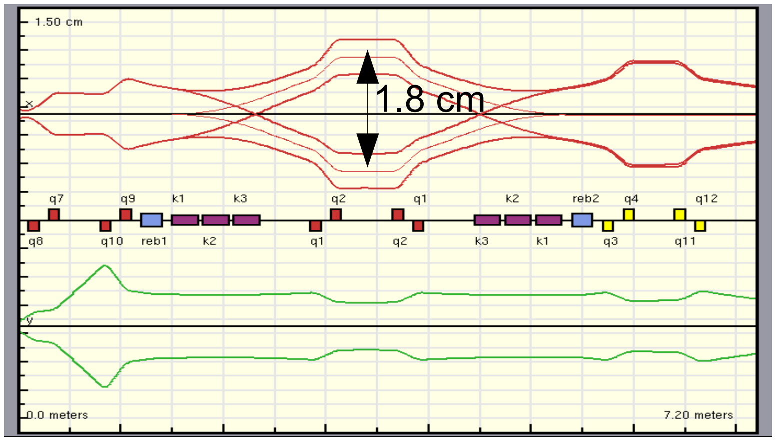
Tuning

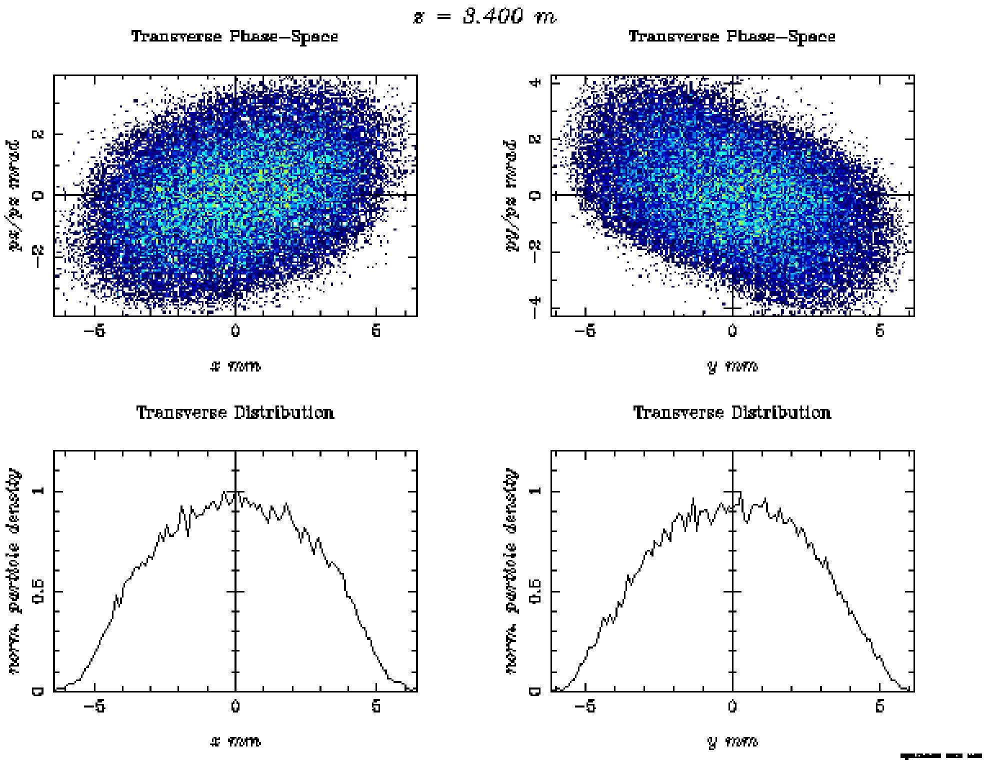
Beam at Beam Stop

Beam stop located in a 50 cm long drift at MEBT symmetry point.

For the wide-band chopper, the beam is deflected 0.9 cm below axis to 0.9 cm above axis. The beam that is deflected up passes, and the beam that is deflected down is stopped.

The full beam width is 1.2 cm.





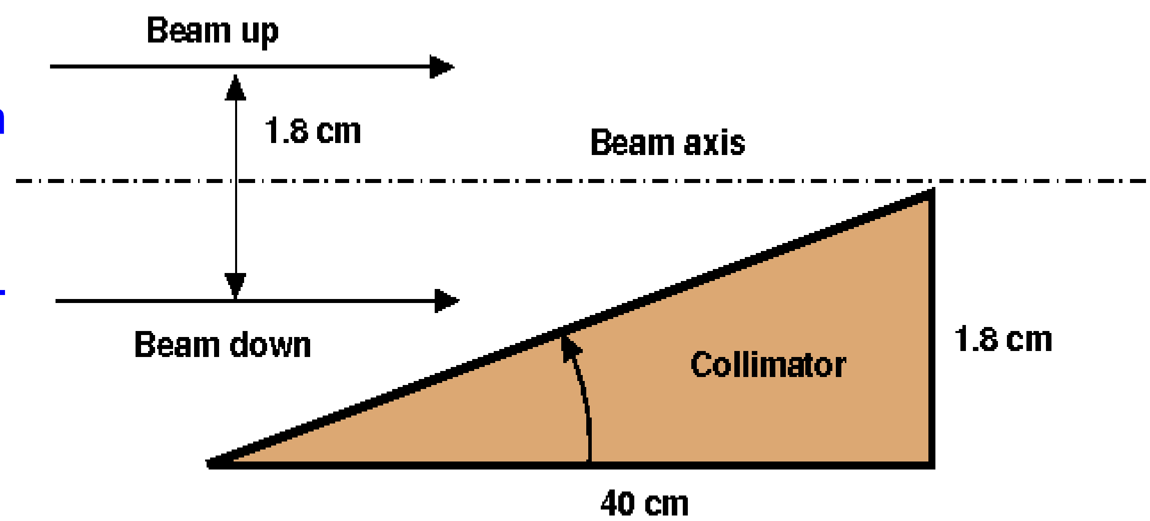
For the narrow-band chopper, the collimator configuration is symmetric across the axis, the beam is deflected both up and down to be stopped, and the undeflected beam passes through.

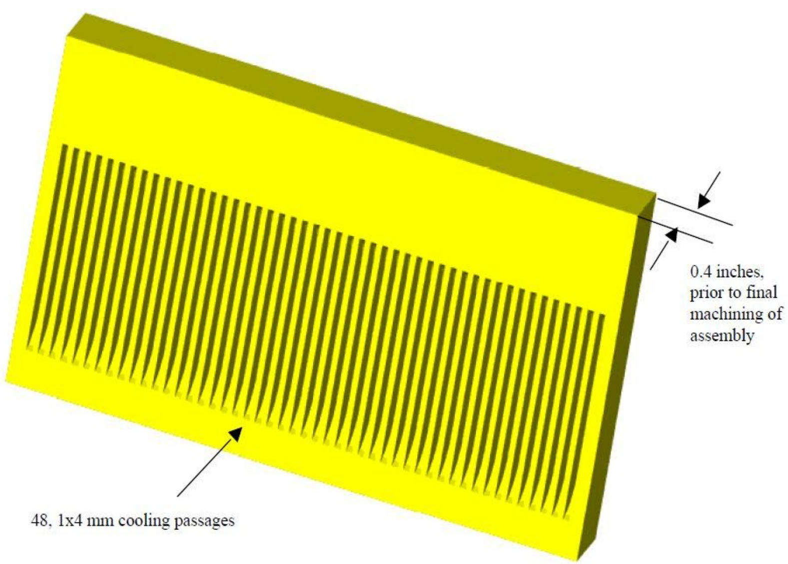
Beam Stop Geometry

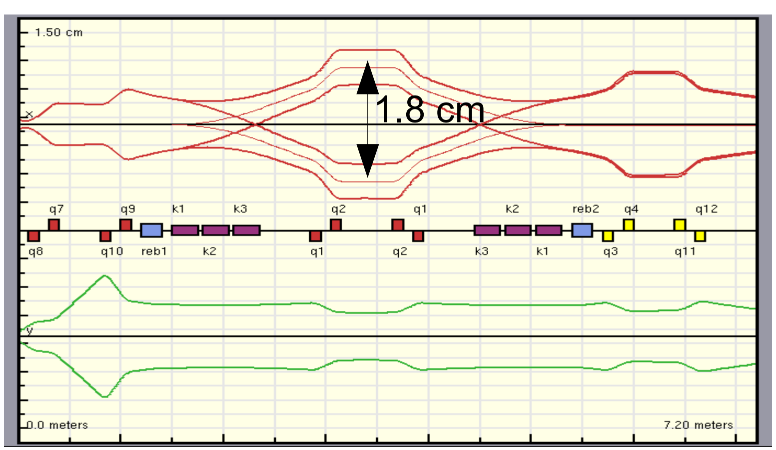
If collimator is 40 cm long, and has a 1.8 cm slope, the slope angle is 2.6 degrees. The beam impacts the beam stop at an angle of 87.4 degrees from the normal.

The collimator could be made of a series of microchannel plates, each a few centimeters long, arranged in a 40 cm long unit. The water is 1 mm away from the target surface.

This eases manufacturing and replacement of individual units.







Beam Power and Power Density on Target

Beam parameters at target location:

σ_x = 0.25 cm, σ_y = 0.35 cm, rms
I = 5 mA, KE = 2.1 MeV

Power density in core of beam = 15.3 kW/cm^2

At an angle of 87.4 degrees the power density = 0.69 kW/cm^2

The choice of target material is determined by:

Neutron production
Mechanical fatigue from pulsed beams over many cycles
Mechanical stress in the material as a fraction of ultimate strength
Machineability

One-Dimensional Simulations of Temperature, Stress in Target

1D model of the time-dependent temperature variation at the core of the beam.
This is a very approximate simulation: 1D, no heat spreading, perfect heat sink at 1 mm, etc, etc. Lots of approximations.

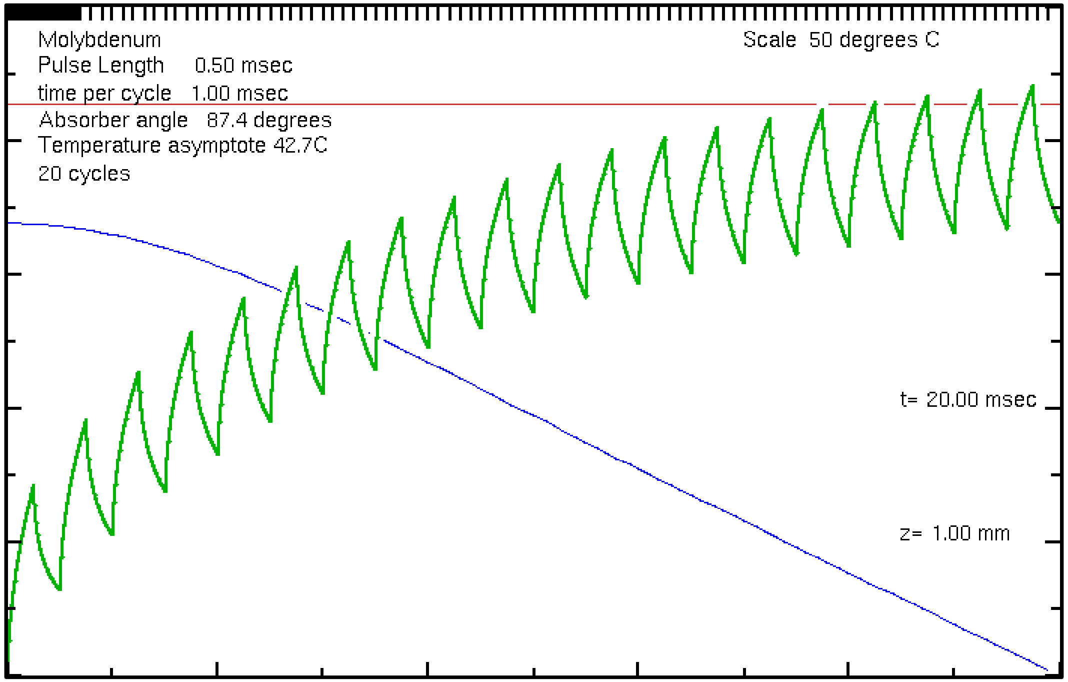
Several materials simulated.
Microchannel cooling with 1 mm spacing between surface and water
Beam impacts 87.4 degrees to normal.

Two time constants modeled:

- 1 kHz transverse beam wobble across the target surface
- 500 microseconds beam interrupt at 10 Hz

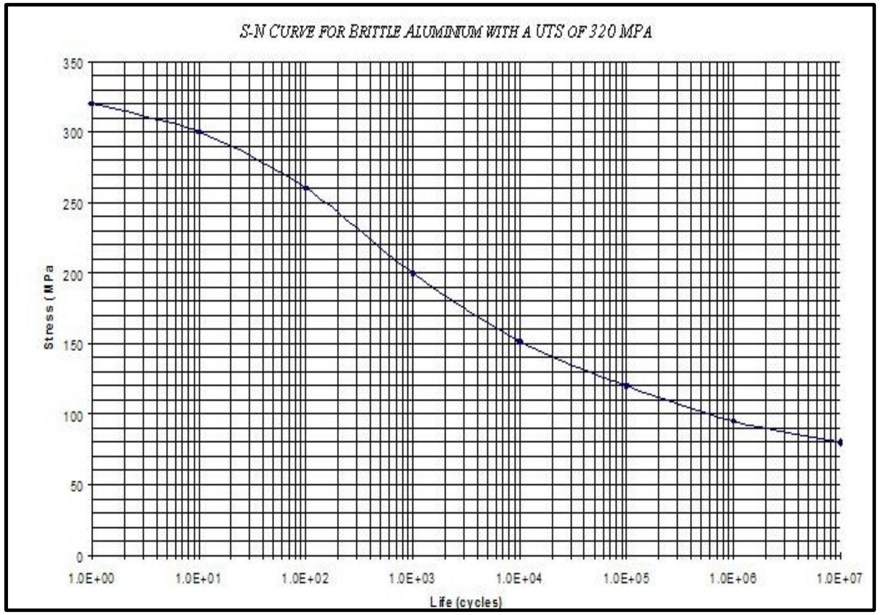
Results for moly, 1 kHz pulse
Does not quite reach equilibrium temperature rise of 42.7C in 20 msec.

Linear stress in core = 59 MPa
Material yield strength = 560 MPa



Derating Material under Periodic Temperature Cycling

Material subjected to periodic stress may exhibit mechanical failure. The curve shows the magnitude of stress to failure as a function of the number of stress cycles for aluminum.



Derating asymptotically to infinite periodic stress reduces induced stress to a small value of the yield strength, perhaps 10%

The effect of a pulsed beam heating the surface depends on the yield stress, the coefficient of expansion, and several thermodynamic properties of the material.

Values in table for 2.5 MeV, 6 mA beam spot unmodulated

Material	Z	range (micron)	temperature rise (C)	Stress (MPa)	Yield (MPa)	Melting Point (C)
Titanium	22	42	70	66	300	1670
Copper	29	24	33	65	70	865
Molybdenum	42	26	85	118	560	2500
Tantalum	73	24	227	275	180	2900
Tungsten	74	21	74	127	500	3400

Moly is perhaps the best if the beam spot is widened (by sweeping). Copper is poor.

Chopper Target Power Density Mitigation

Mitigations:

Bi-directional chopping with sinusoidal waveform.
Spreads beam out over a wider swath: factor of 2-3

Split MEBT tune: ribbon shape in MEBT
Further spreads beam out: another factor of 2 or so. (This may have some problems with emittance growth.)

Sweep the beam laterally at a rate that minimizes cyclic temperature variation.
At least 1 kHz. May require thin beam pipe at sweep magnets.

Possible LEBT chop
If the SCL and experiments can handle it: another factor of 2

Lowered RFQ energy
from 2.5 to 2.1 MeV: a factor of 1.2

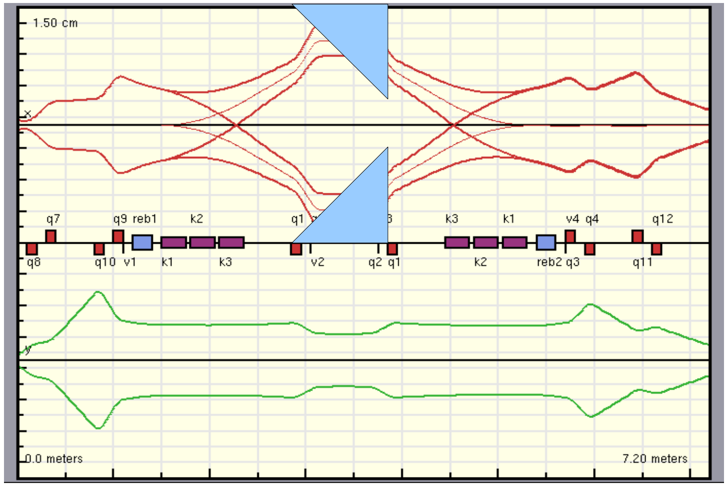
Select best material. Moly?

Total reduction of power density: up to a factor of 10?

Narrow-Band Chopper Examples

Non-resonant structure
Sinusoidal waveform, amplitude and/or phase modulated.

Simulation includes bandwidth limiting (Fourier transform, limit, and transform back). Errors from bandwidth limiting produce timing errors of beam zero-crossing at the collimator.



Can change beam distribution at RF beam separator on a microsecond basis. The frequency spectrum includes many sidebands separated by 1 MHz from carrier.

Beam deflected into two chopper targets, located symmetrically across beam axis.

Chopped beam deposited on two targets and at several spots, along sine waveform.

Example of a beam split

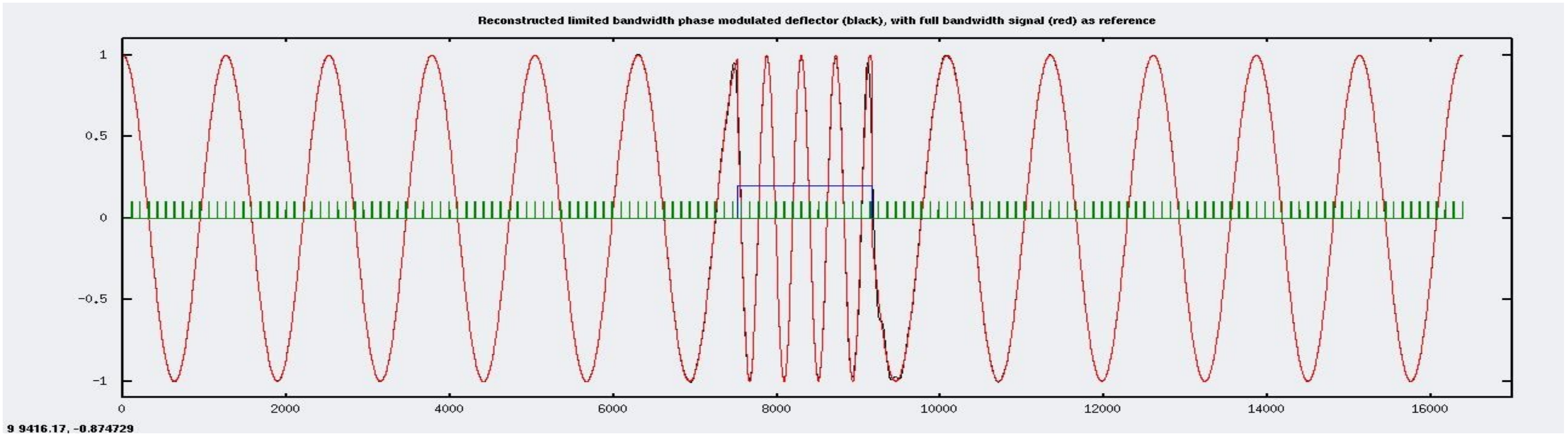
Requirement: Split 162.5 MHz microstructure 3 ways:

one-half to experiment A for 100 nanoseconds
$1/12^{th}$ (0.5 mA) to experiment B for 900 nanoseconds
$1/12^{th}$ (0.5 mA) to experiment C for 900 nanoseconds, simultaneously

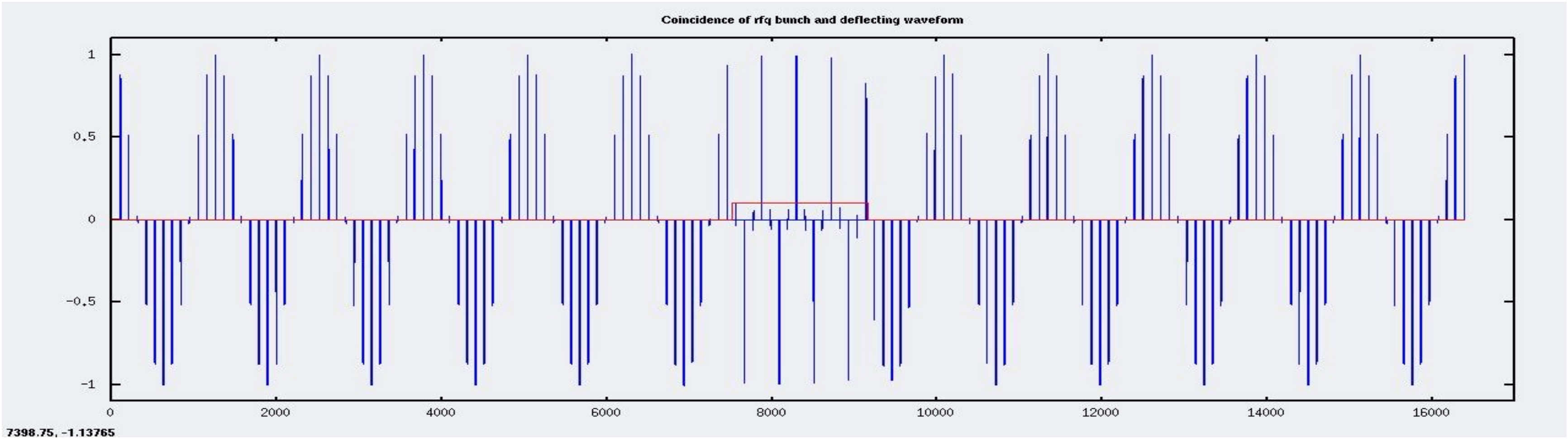
Average beam current over 1 microsecond integration period is 1 mA.

Chopper Waveforms
(one of many)

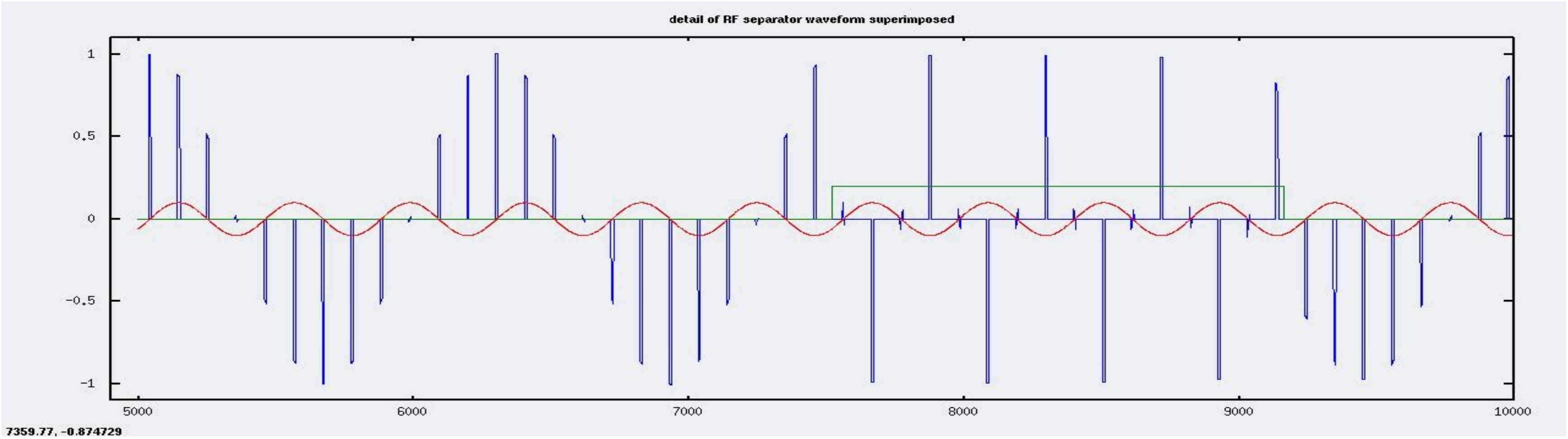
Dual Frequency Chop Example



5/6ths of the pulses removed to collimator



Detail, with RF separator waveform



Other Examples

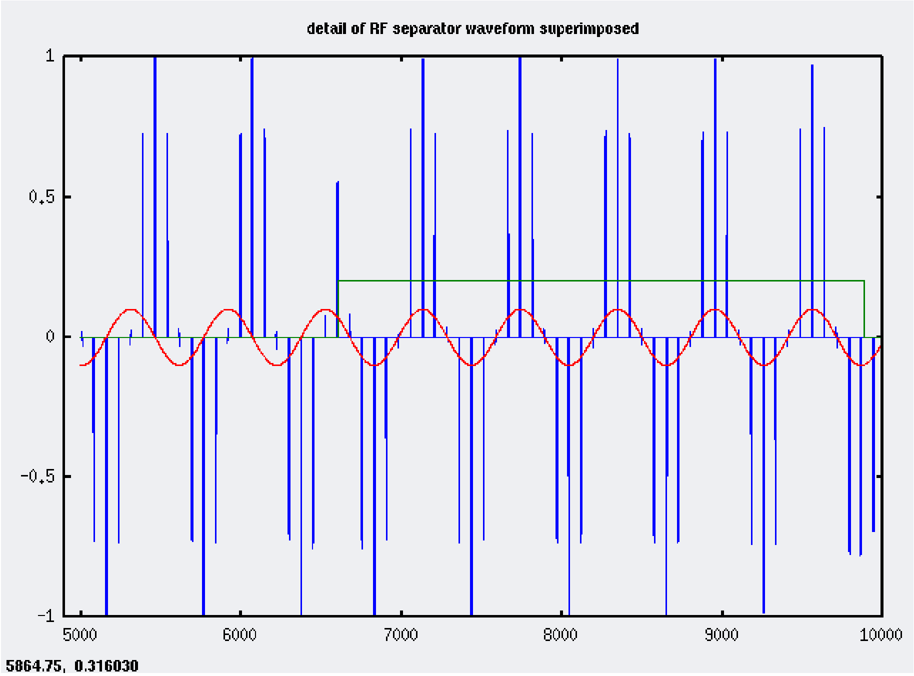
The beam is distributed by the RF kicker in different fractions. (Detail of part of the 1 microsecond cycle.)

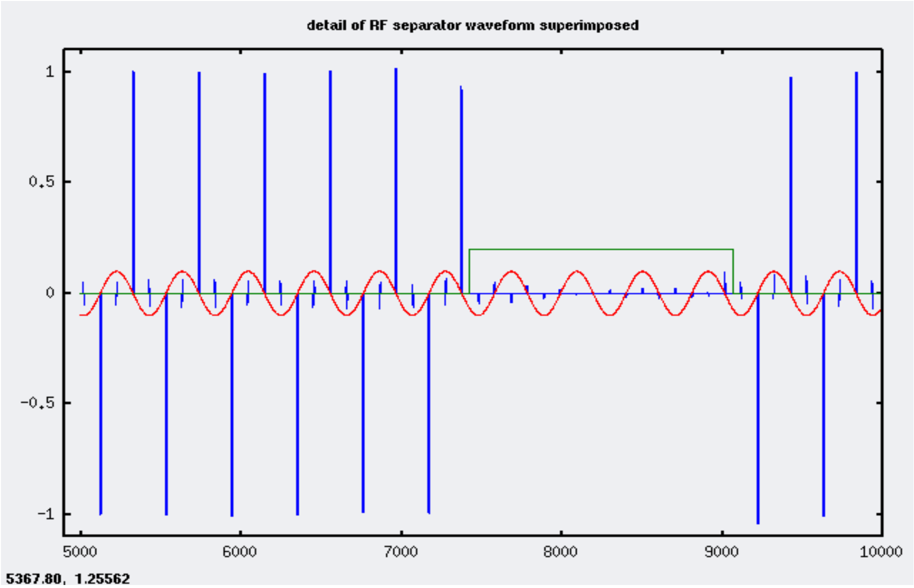
The beam can be directed at one or two experiments at a time.

Additional value of new MEBT design:

Beam that is not removed is returned to the axis. The bandwidth of the NB chopper is determined by the phase and amplitude errors of the zero crossing of the beam.

The chopper-antichopper configuration significantly relaxes this, allowing further narrowing of the chopper and electronics bandwidth to give equivalent performance to the older MEBT design.





Action Items

No LBNL MEBT hardware development at this time.

Freeze RFQ output energy

Detail MEBT beam dynamics, matching, layout

Select technology for narrow-band chopper: TW structure, drive electronics

Develop and simulate more beam chopping scenarios for NB chopper

Develop beam collimator concept, do detailed time-dependent thermal simulations, do materials selection

Develop diagnostics scenario, tune strategy

Develop rebuncher cavity requirements, placement, tuning, hardware concepts

Summary

The new MEBT concept uses a chopper-antichopper configuration with pi phase advance between them produced by a pair of focusing doublets.

The collimator can be placed at one side for the low-voltage wideband chopper or on both sides for the narrow band waveform, spreading the beam out further.

The collimator is 50 cm long, or even longer, as the central region can easily be extended with a slight increase of rebuncher voltage. The chopper voltage remains the same.

12 quads and six 25-cm long deflectors are used with about a 1.6 cm spacing between plates. The deflectors have constant plate spacing along all three 25 cm segments.

The emittance growth for the worst-case beam of 2.1 MeV, 30 picocoulombs per bunch is just a few percent, and the emittances are very low, particularly the longitudinal emittance. The rebuncher cavity frequency is 325 MHz.

Lots of space is available for diagnostics.