LEBT, RFQ and MEBT since April Meeting

John Staples and Qing Ji, LBNL

19 May 2011

LEBT Issues

LEBT R&D program

Chopping in LEBT: emittance growth

LEBT Configuration and Requirements

Ion source now tested at TRIUMF with good performance: Qing will report

Use detailed emittance data to generate better RFQ input beam

Transport and focus 20-30 keV beam from ion source to RFQ

Provide for 2 ion sources for redundancy and quick source change

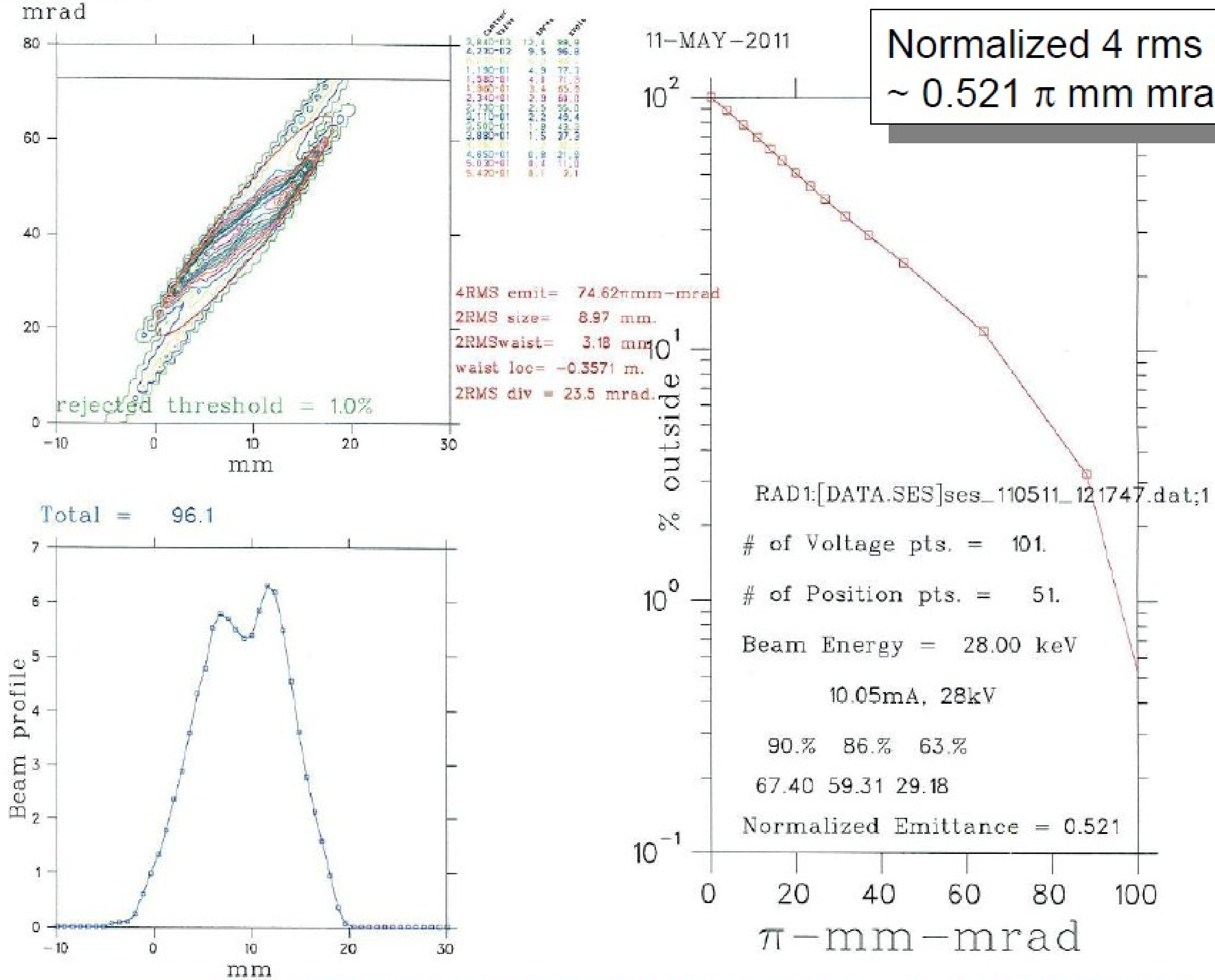
Include chopper for a 500 microsecond gap in beam for HEBT switch magnet

Diagnostics to tune ion source, steer it into RFQ

Investigate higher frequency chopper scenarios

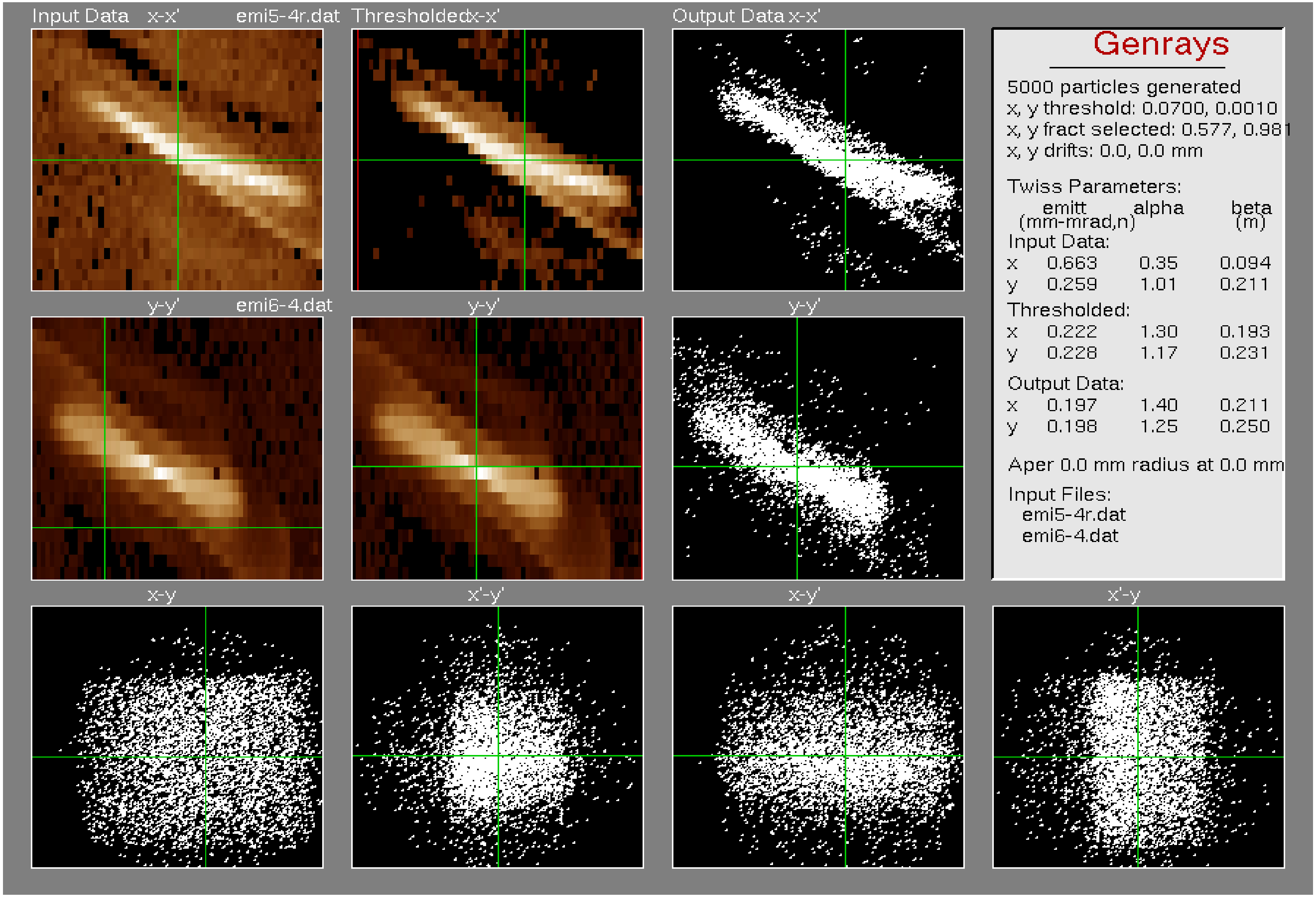
Emittance Measurement – 10mA, 28keV

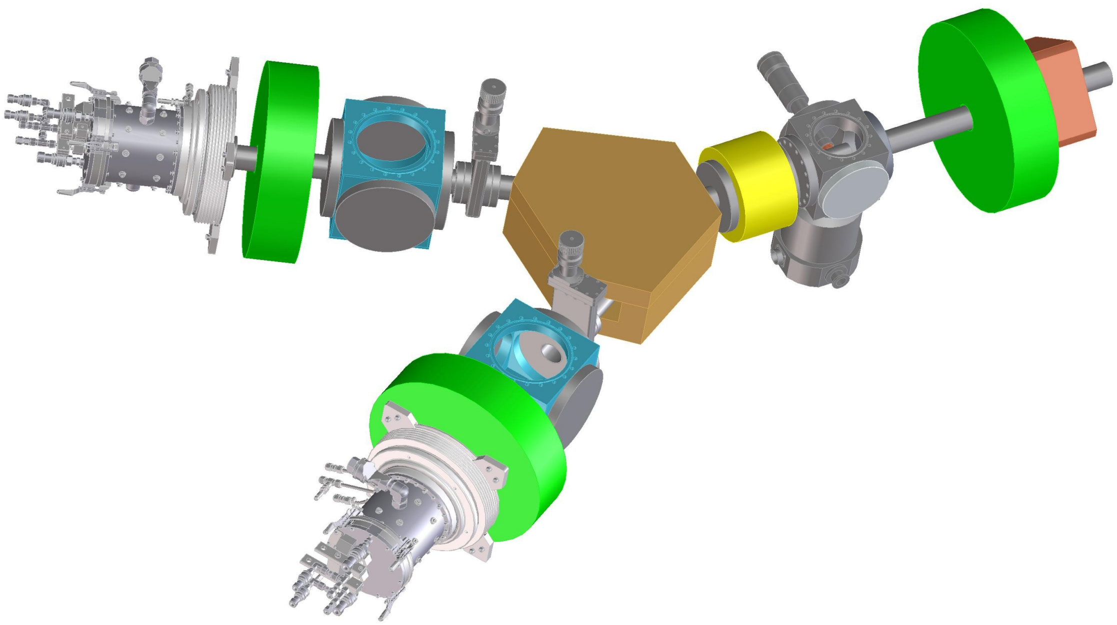
Normalized 4 rms emittance:
~ 0.521 π mm mrad

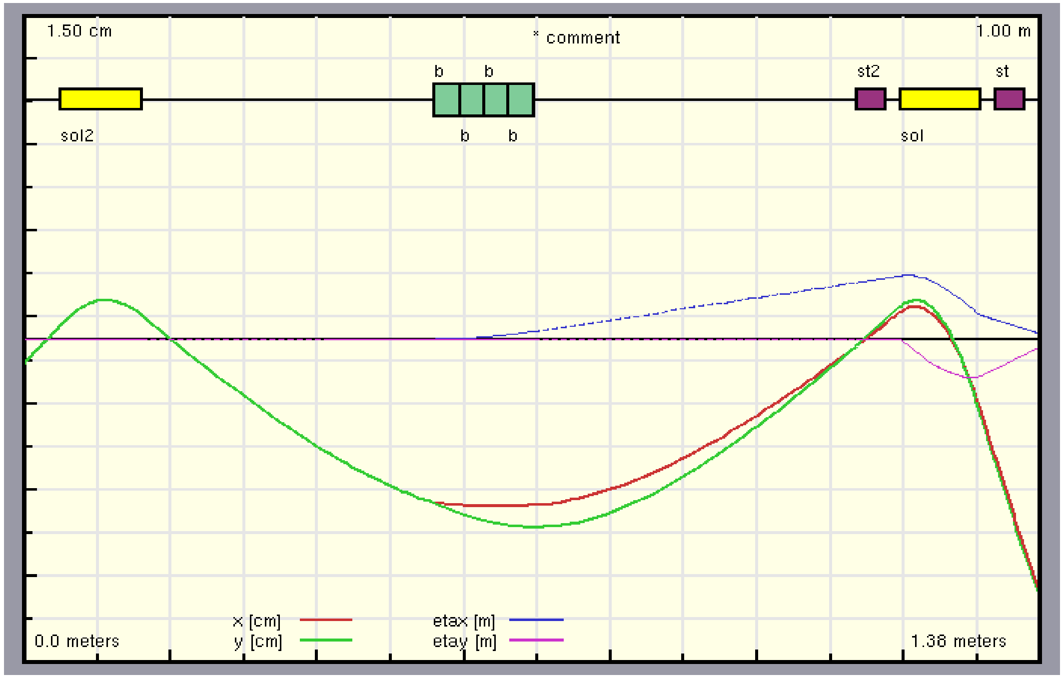


Use detailed emittance data, generate an RFQ input ensemble with same distribution

“Reasonable” distribution of all 6 projections of the 4-dimensional phase space







Working LEBT Configuration

20-30 keV

5-10 mA DC beam

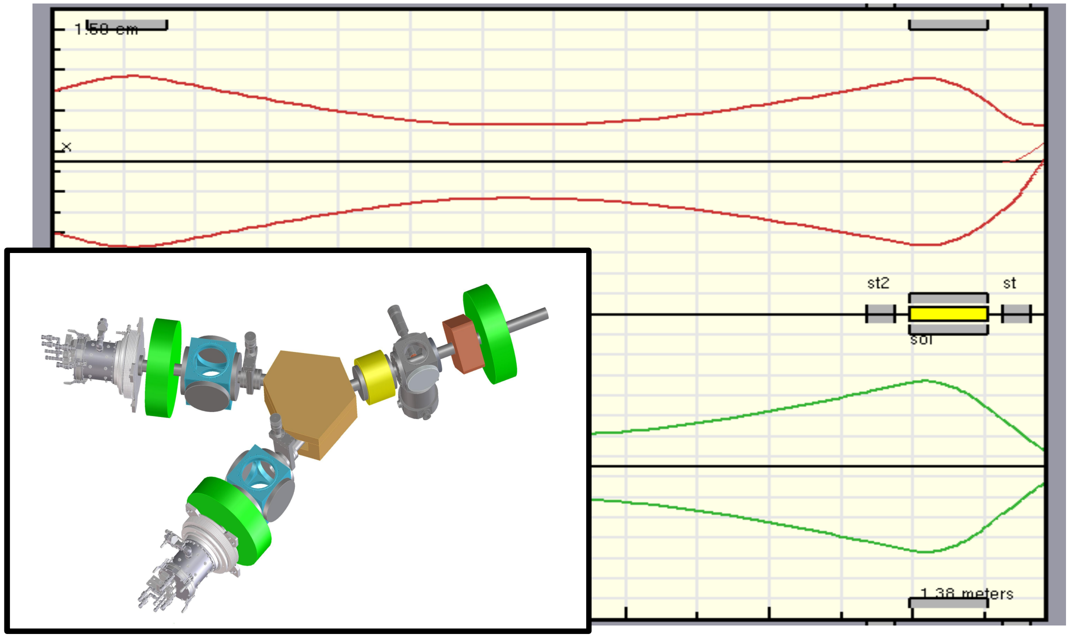
>90% neutralization

2 solenoids
investigating einzel final lens

2 ion H-minus ion sources

±20 degree selector magnet
chopper at end

LEBT Chopper Location Choice



20 keV beam. $\beta = 0.0065$

Two locations considered:

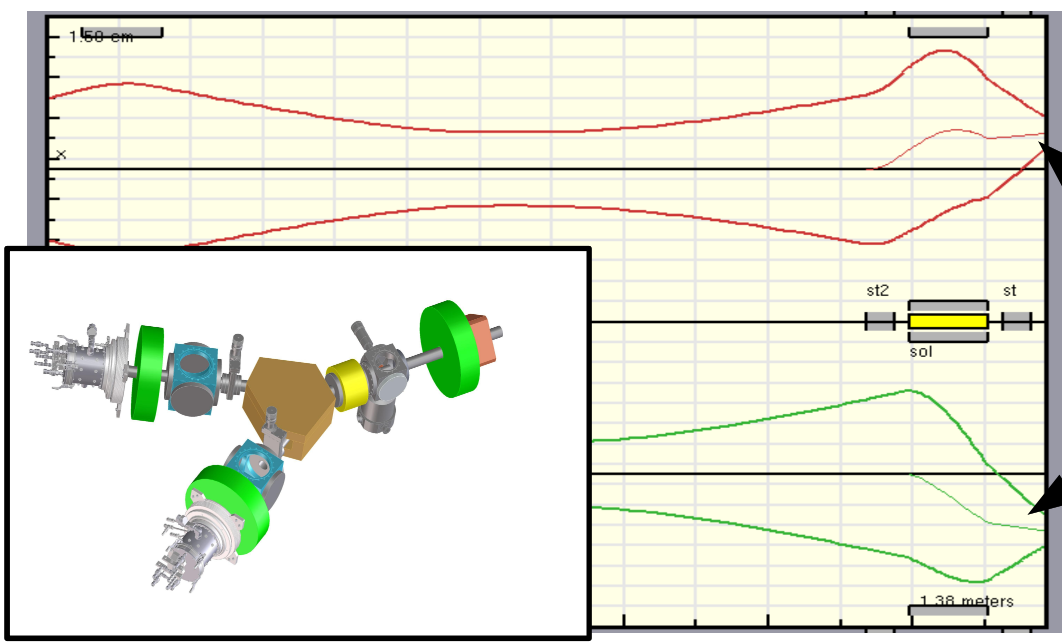
In front of last solenoid

After last solenoid

For position in front of last solenid, plate spacing > 2 cm.

For effective length of 4 cm, transit time is 20 nsec

TW chopper for this beam velocity probably not practical

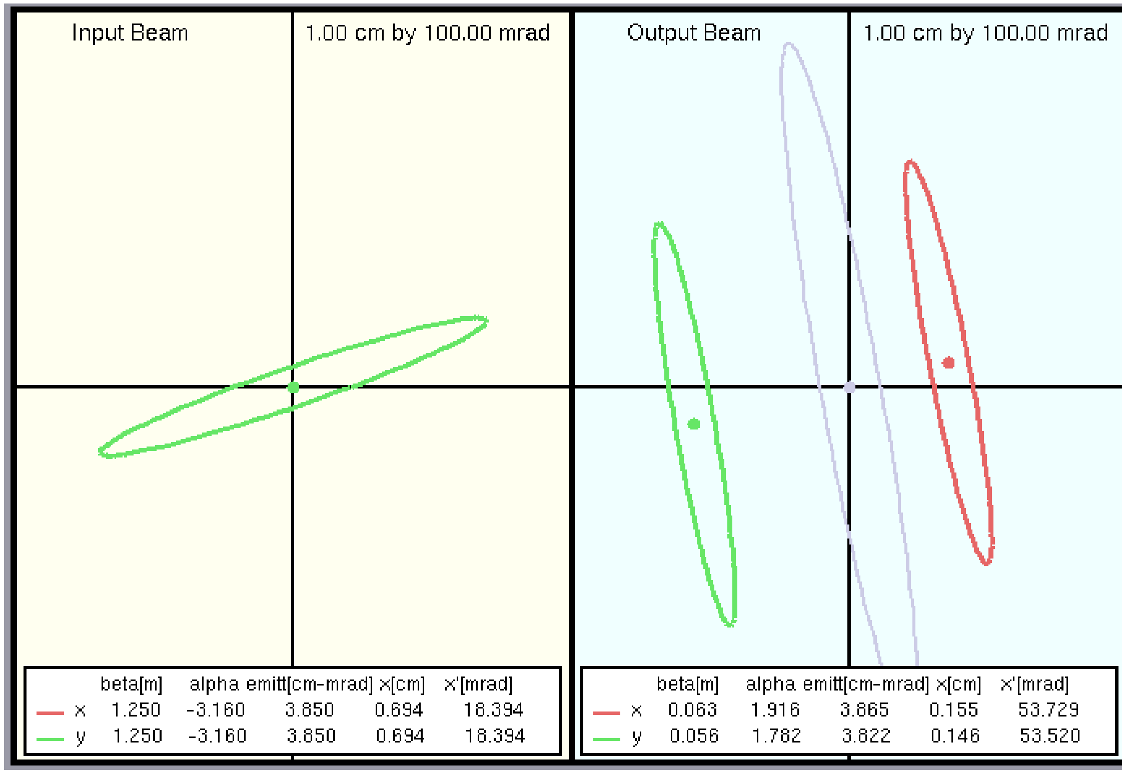


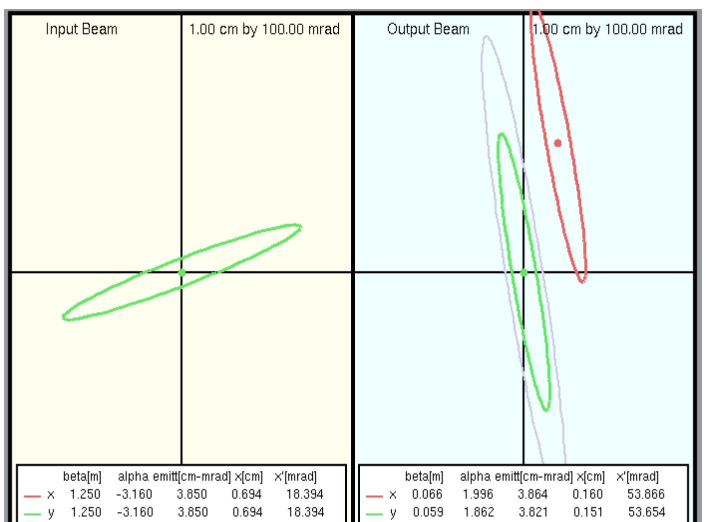
deflection at RFQ entrance from electrodes preceeding solenoid

LEBT Chopper displacement of x and y phase spaces at RFQ Entrance

Chopping ahead of last solenoid in x-direction displaces both x and y ellipses.

Gray ellipse is RFQ acceptance ellipse orientation.





Phase space for post-solenoid chop.

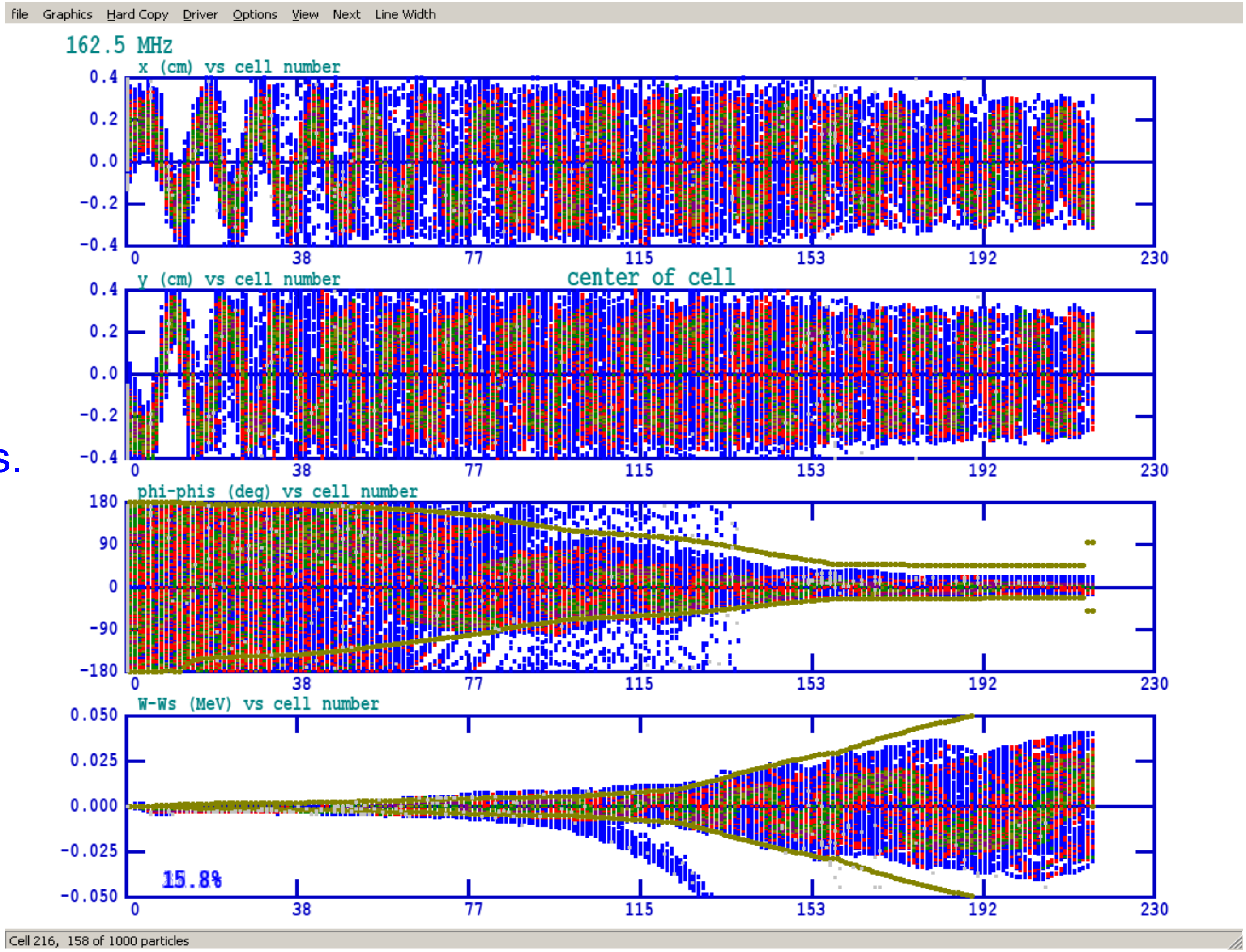
RFQ transmission and output beam characteristics simulated with various chopper deflection field strengths to determine RFQ transmission and effect on RFQ output beam.

Response of RFQ to displaced entrance beam

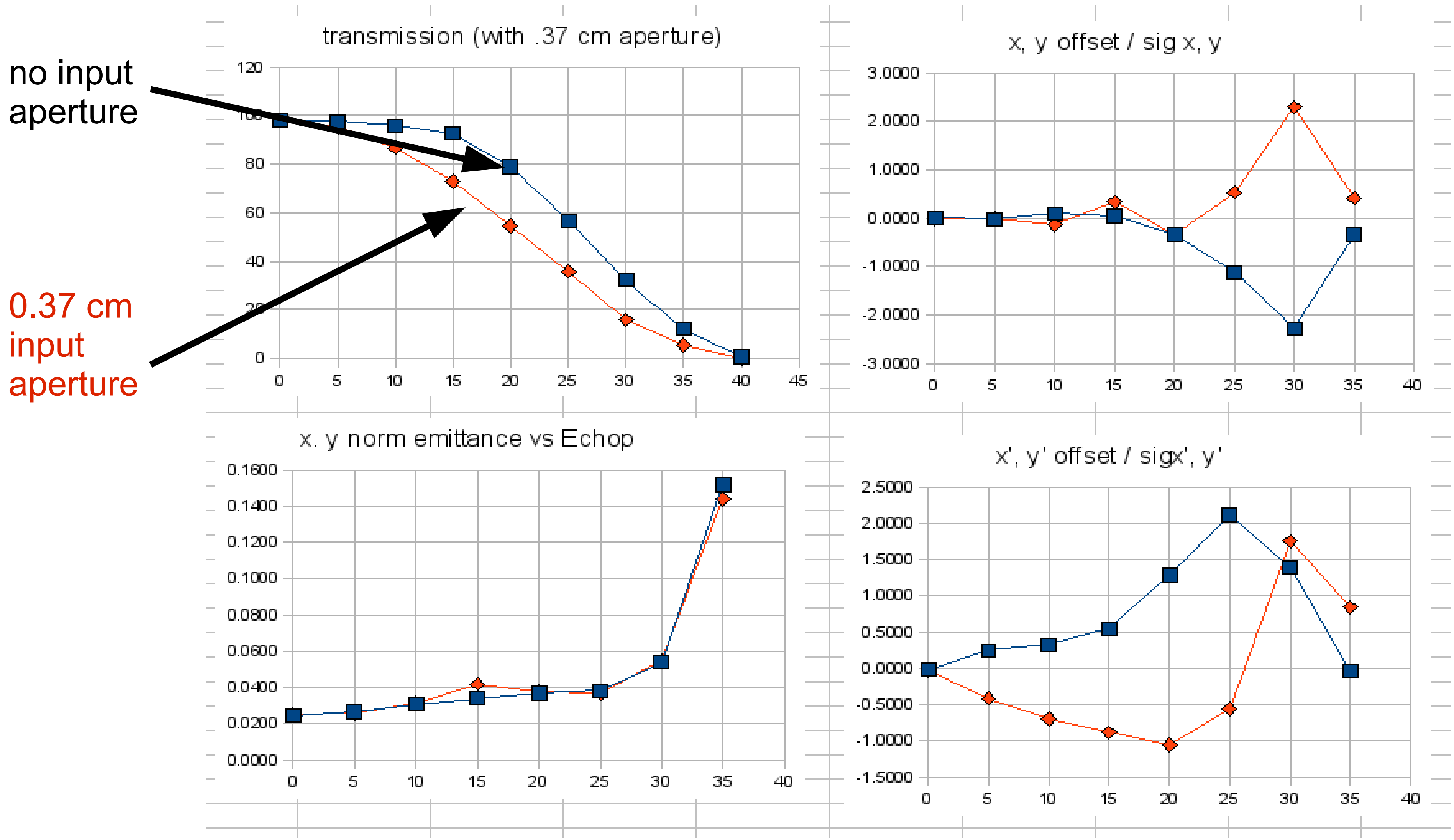
Beam injected into the RFQ off-axis will emerge from the RFQ with strong coherent betatron motion.

Transverse beam undergoes about 17 betatron oscillations.

Output beam offset very dependent on gradient, as number of phase oscillations changes.



RFQ exit beam parameters vs. LEBT chopper gradient



Horizontal axis: transverse chopper field, kV/m for 4 cm long deflector upstream of solenoid.

Details highly dependent on gradient (tune). Input aperture doesn't help much.

Therefore, 20 MHz chopping in LEBT looks difficult.

Issues for Possible 20 MHz LEBT chopper

20 MHz beam chopper with 10 MHz deflector: 2 zero-crossings per cycle

4 cm long chopper 75 electrical degrees of 10 MHz long

β = 0.0065 low for a TW chopper design

For square wave to sharpen edges of chop, next harmonic of 30 MHz is 225 electrical degrees long. Reducing individual longitudinal chopper electrodes reduces their electrical length, but the transverse spacing of the plates reduces the higher-frequency fields on axis.

Plates > 2 cm apart, shorter chopper will still have long effective length and more nonlinear fields.

Time average of RFQ output beam emittance is large

The RFQ phase acceptance $\pm\pi$. Any beam at the RFQ entrance will be accepted into one of the phase buckets.

Longer chop produces satellite bunches.

Shorter chop reduces current within one phase bucket.

Challenges of LEBT Chopping

Off-axis beam at RFQ entrance is reproduced as off-axis beam at RFQ exit

Beam aperture at RFQ entrance is not effective in removing off-axis beam

Don't make the RFQ act as a beam collimator by using a very small aperture

Off-axis RFQ input beam must be cleaned up in the MEBT

For 500 microsecond, 10 Hz chop: remove “bad” edges in MEBT

For possible ca. 1 MHz LEBT chop: MEBT chopper should still apply

Faster LEBT chop: most beam will be off-axis and/or satellite bunches:
just use MEBT chopping

LBNL LEBT chopper: two scenarios:
before solenoid more effective and should be tested
after solenoid but with higher deflection voltage

The H-minus neutralizing plasma includes both positive ions and electrons, due to different production and loss rates, and they have different mobilities. Chopping should be as close to the RFQ as possible. Upstream LEBT transport is neutralized.

LEBT R&D Program

The LEBT to be developed and tested incrementally

Extraction and 20-30 keV acceleration from the ion source
Ion source emittance measurements
Chopper implementation at RFQ entrance
Establish matching parameters required by RFQ
Emittance, neutralization time measurements of chopped beam

The separation of the acceleration, the magnetic transport, and the pulsed electric field chopper will ensure high reliability.

Action Items

Do acceptance test of ion source at TRIUMF

Do detailed end-to-end simulations with measured ion source data

Set up ion source test stand at LBNL, continue testing and characterization

Implement as much LEBT as possible, including LEBT chopper

Measure dynamic characteristics of LEBT chopping and beam neutralization

RFQ Issues

New RFQ beam dynamics designs

RFQ output energy

RFQ cavity for new beam dynamics design

RFQ Cavity engineering

RFQ

Two RFQs in design process

Project-X, INP RFQ

The INP RFQ is on a fast track, and will be similar, perhaps identical to PX RFQ

The 10-15 mA INP RFQ current requirement is higher than PX.
The PX RFQ parameters are compatible with the INP requirements.

The design is based on a low injection energy, which determines the longitudinal output emittance. The output current limit is proportional to the injection energy, so a compromise solution is required.

In addition, for CW operation, low power and power density is desirable as well as very high capture and bunching of the input beam.

A new set of solutions has been found to satisfy both PX and INP requirements.

RFQ Beam Dynamics Designs

Design presented in April highly optimized for PX: 20 keV input, 2.1 MeV out

INP requires higher current, same output energy

INP ion source tests carried out at much higher energy

Try to find a “middle-road” solution for the beam dynamics

Investigating ~30 keV injection energy, but detailed calculations must continue to optimize a higher current design.

Higher injection energy results in a higher longitudinal output emittance

FNAL must specify a maximum acceptable output emittance (distribution)

Try at least to have the same RF structure, but possibly different dynamics details

Compare three different RFQ beam dynamics versions

Version:

1: Last year

2: Last April, PX RFQ

3: PX and INP 10 mA design with lower wall power density

	V1	V2	V3		
Duty Factor	100	100	100	percent	
Input Energy	35	20	30	keV	
Output Energy	2.5	2.1	2.1	MeV	
Length	384	404	395	cm	length of vanes
V_{vv}	90.8	68	68	kV	intervane voltage
N_{cells}	135	212	228		
Input current	5	5	10	mA	
Transmission	93.7	97.8	95.8	percent	
Transverse Loss		0.05	0.15	percent	transverse beam loss on vanes
Longitudinal Loss		2.2	4.1	percent	beam out of bucket
B	9.0	9.0	7.0		focusing parameter
P'/cm	402	180.3	163	watts/cm	copper power per linear RFQ length
P_{copper}	154	73	64	kW	Superfish power, 100% Q_0, no ends
P_{beam}	12.5	10.5	21	kW	beam power
P_d	2.05	0.90	0.82	W/cm^2	max wall power density
L/λ	2.1	2.2	2.1		length/free-space wavelength
E_{max}	20.8	16.4	13.9	MV/m	peak vanetip field
kilp	1.53	1.21	1.03	kilpatrick	peak vanetip field
r_0	0.605	0.521	0.593	cm	average vane tip dist from axis
$r_{long, min}$	1.18	1.87	0.83	cm	minimum long radius of curvature
r_{transv}	0.605	0.391	0.445	cm	vane tip transverse radius
a_{min}	0.395	0.316	0.345	cm	minimum aperture
cavity radius		17.5	18	cm	max outer cavity wall dimension
$\epsilon_{x,y\ in}$	0.250	0.250	0.257	mm-mrad	normalized transverse input emittance
$\epsilon_{x,y}$	0.29	0.254	0.256	mm-mrad	normalized transv output emittance
ϵ_z	0.279	0.158	0.268	mm-mrad	normalized longitudinal emittance
ϵ_z	51.1	28.9	49.0	keV-deg	longitudinal output emittance
ϵ_z	0.88	0.49	0.85	keV-nsec	longitudinal output emittance

2-D Superfish run

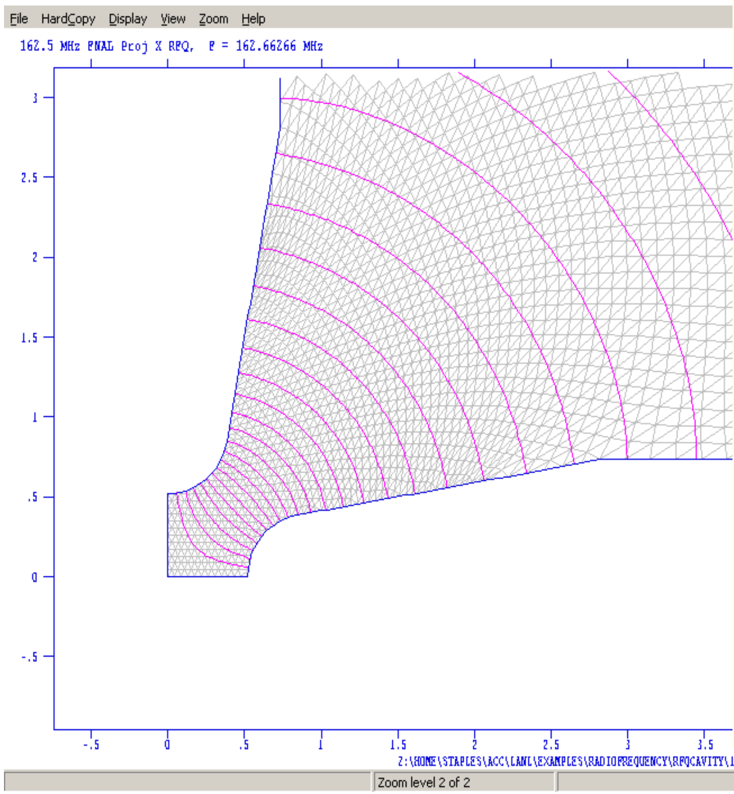
INP design for higher current

Lower focusing parameter B

Wall power density 0.82 W/cm^2

163 watts / cm cavity length

1.03 kilpatrick peak field




```
Mesh problem length [L]  =     .5933 cm
Frequency [f] (starting value = 162.500) =              165.659027 MHz
Eo normalization factor (CON(74)=ASCALE) for  5.731 MV/m =    8298.8
Stored energy [U] (for mesh problem only) =               .66293 mJ/cm
Power dissipation [P] for mesh problem only =               40.74 W/cm
Q (2.0*pi*f(Hz)*U(J)/P(W)) =                                16938
Shunt impedance [Z] mesh problem only, ((Eo*L)**2/P) =    28.37679 Mohm-cm
Shunt impedance per unit length [Z/L] =                   4782.874 Mohm-cm/m
Magnetic field on outer wall =                               2205 A/m,    8.17E-01 W/cm2
Hmax for wall and stem segments at x= 16.33,y= 16.33 cm =     2207 A/m
Hmax for wall and stem segments at x=   .82,y=
Emax for wall and stem segments at x=   .72,y=   .31 cm =    13.863 MV/m
```

ISEG	xbeg (cm)	ybeg (cm)	xend (cm)	yend (cm)	Emax*epsrel (MV/m)	Power (W/cm)	df/dx (MHz/mm)	df/dy (MHz/mm)
Wall								Wall
2	.0000	.5933	.2860	.6974	13.7177	.0022	1.0000	2.5851
3	.2860	.6974	.4382	.9610	13.7761	.0165	2.2669	1.4194
4	.4382	.9610	.6919	2.4000	8.9125	.2961	1.8272	.3222
5	.6919	2.4000	.7855	2.9306	2.5406	.1743	.1618	.0285
6	.7855	2.9306	.7855	4.9306	2.2156	.8526	.1862	.0000
7	.7855	4.9306	1.1796	7.2000	.8761	1.2351	.0198	.0034
8	1.1796	7.2000	2.4000	14.2280	.6302	4.8631	-.1632	-.0283
9	2.4000	14.2280	2.6812	15.8473	.1618	1.2429	-.0562	-.0098
10	2.6812	15.8473	3.3652	17.0321	.0744	1.0680	-.0425	-.0246
11	3.3652	17.0321	4.6508	17.5000	.0448	1.0740	-.0169	-.0465
12	4.6508	17.5000	7.2000	17.5000	.0716	1.9780	.0000	-.0926
13	7.2000	17.5000	13.5000	17.5000	.0755	5.0179	.0000	-.2348
14	13.5000	17.5000	16.3284	16.3284	.0332	2.5484	-.0448	-.1080
15	16.3284	16.3284	17.5000	13.5000	.0335	2.5483	-.1080	-.0448
16	17.5000	13.5000	17.5000	7.2000	.0761	5.0179	-.2348	.0000
17	17.5000	7.2000	17.5000	4.6508	.0721	1.9781	-.0926	.0000
18	17.5000	4.6508	17.0321	3.3652	.0425	1.0740	-.0465	-.0169
19	17.0321	3.3652	15.8473	2.6812	.0766	1.0680	-.0246	-.0425
20	15.8473	2.6812	14.2280	2.4000	.1619	1.2430	-.0098	-.0562
21	14.2280	2.4000	7.2000	1.1796	.6362	4.8630	-.0283	-.1632
22	7.2000	1.1796	4.9306	.7855	.8762	1.2351	.0034	.0197
23	4.9306	.7855	2.9306	.7855	2.2131	.8526	.0000	.1861
24	2.9306	.7855	2.4000	.6919	2.5515	.1742	.0286	.1622
25	2.4000	.6919	.9610	.4382	9.0112	.2962	.3218	1.8251
26	.9610	.4382	.6974	.2860	13.8626	.0165	1.4229	2.2712
27	.6974	.2860	.5933	.0000	13.7530	.0022	2.5810	1.0013
Wall					Total =	40.7381		Wall

RFQ Structure Engineering

Lessons learned from SNS, ADNS, SNS RFQ Replacement engineering studies

RFQ operates CW, but power densities less than half of SNS RFQ at 6% DF.

Peak fields about 1.03 - 1.2 kilpatrick

Relatively small length to free-space wavelength may allow no stabilization (TBD).

Will model structure electrodynamics with MWS, do an extensive error analysis to determine need for stabilization, assembly error tolerances.

RFQ Structure RF Modeling

All previous LBNL RFQs used cold models to assess cavity parameters

SNS RFQ was modeled after the fact with MWS with excellent agreement: D. Li

This structure will be modeled with MWS including:

- pi-mode stabilizers
- vane coupling rings
- extensive mechanical error analysis

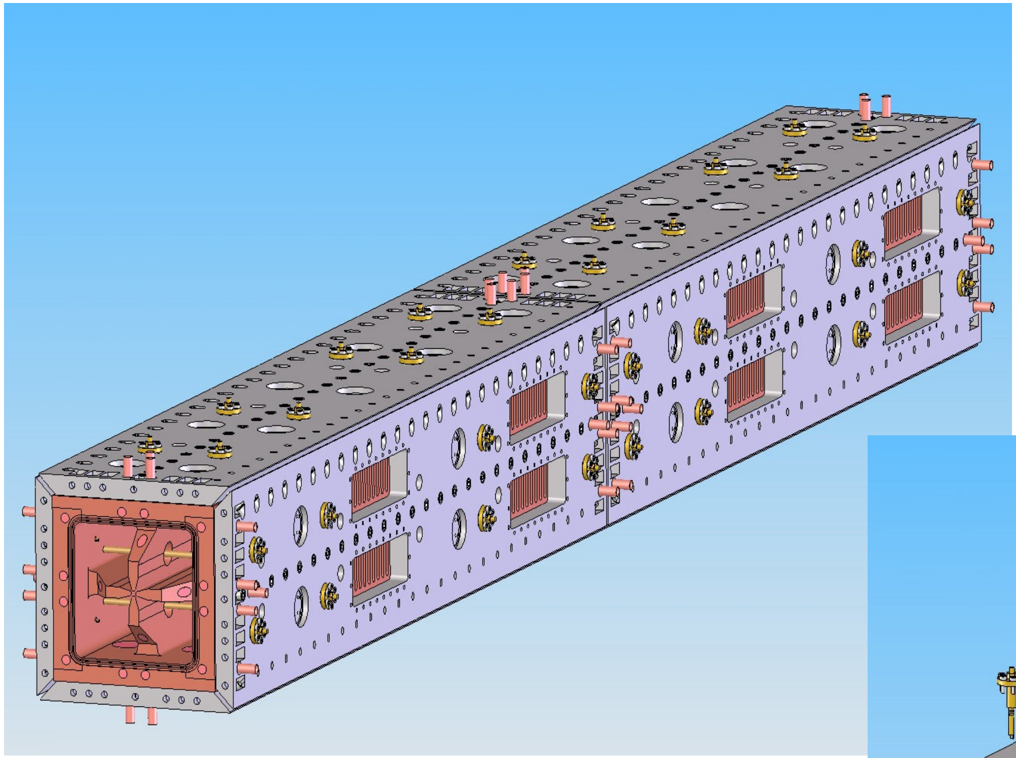
This RFQ operates CW, but the wall power density is 0.8-0.9 W/cm^2
(SNS is 1.7 W/cm^2 at 6% duty factor)

Gennady Romanov will carry out MWS simulations of all of the above options.

From the modeling results we will choose mode stabilizer option, assembly methods and error tolerances.

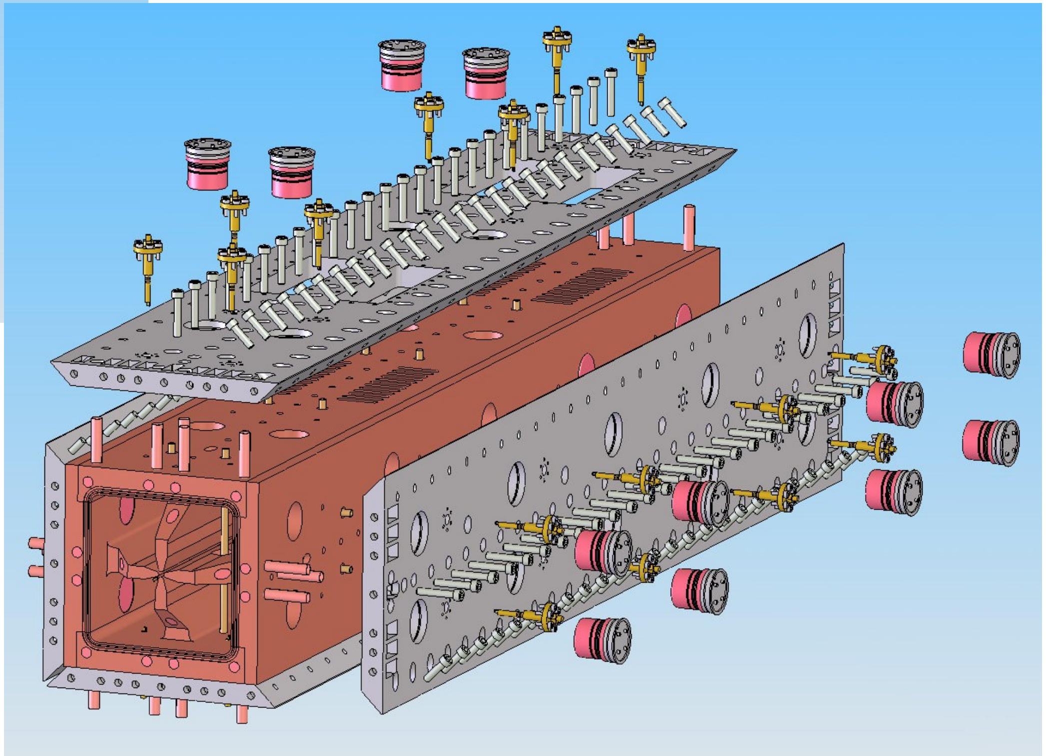
325 MHz RFQ Cross Section Engineering Analysis

162.5 MHz RFQ may use some of these techniques. (Steve Virostek)



Each 133 cm modules has 24fixed tuners, 8 pumping ports.

Brazed copper inner cavity, with a bolted-on stainless steel exoskeleton

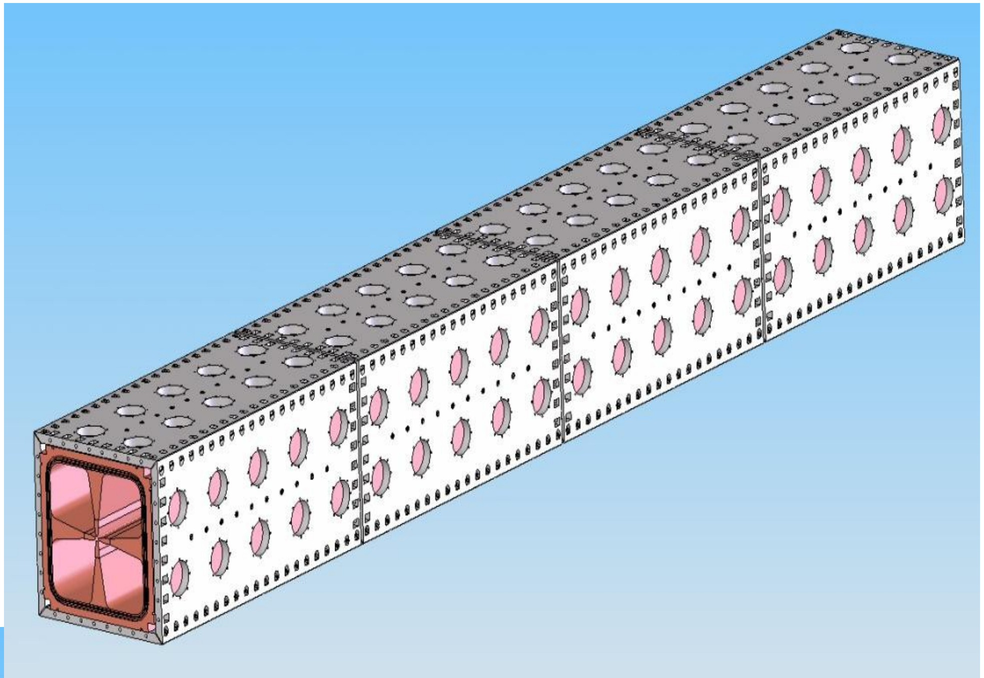


266 cm long, two modules

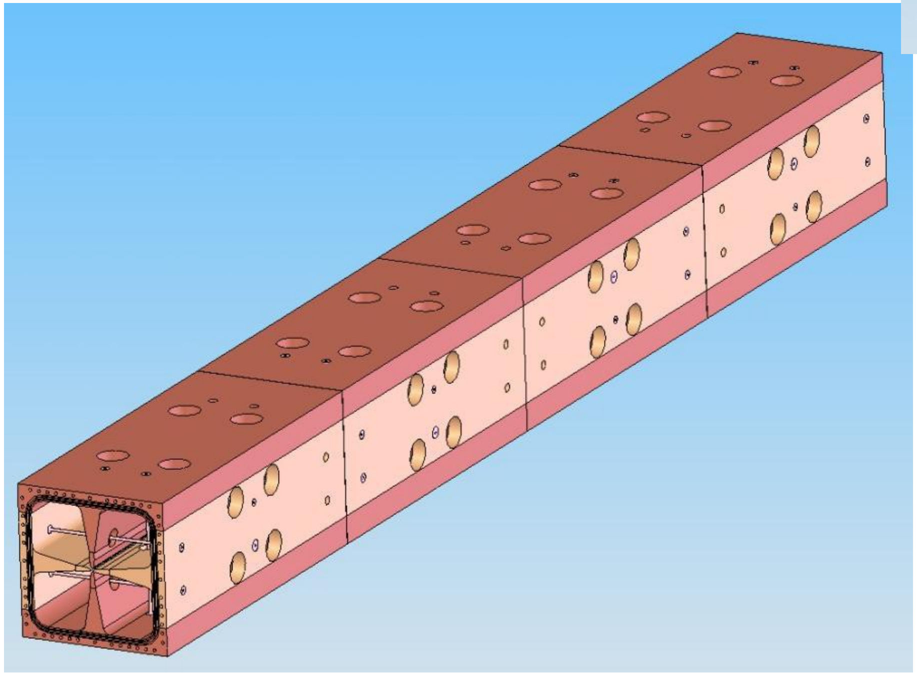
Cooling passages are rifle-bored in the copper substructure.

Two RFQ drive loops provided

Some new ideas of manufacturing the structure are being considered, consistent with the ability of INP to machine the RFQ in their shop. (Matt Hoff)



E-beam welding may be used, if built in the US, which eliminates brazing and keeps a high copper yield strength.



Brazing would require an exoskeleton for strength.

Cooling passages would be gun-drilled.

Action Items

Agree to a set of RFQ parameters

Start engineering analysis of RF structure

Carry out detailed Microwave Studio analysis of structure stabilization, error tolerances

MEBT Issues

New MEBT concept

MEBT modeling with Astra

Emittance Growth

Beam absorber

Limited-bandwidth MEBT chopper modes

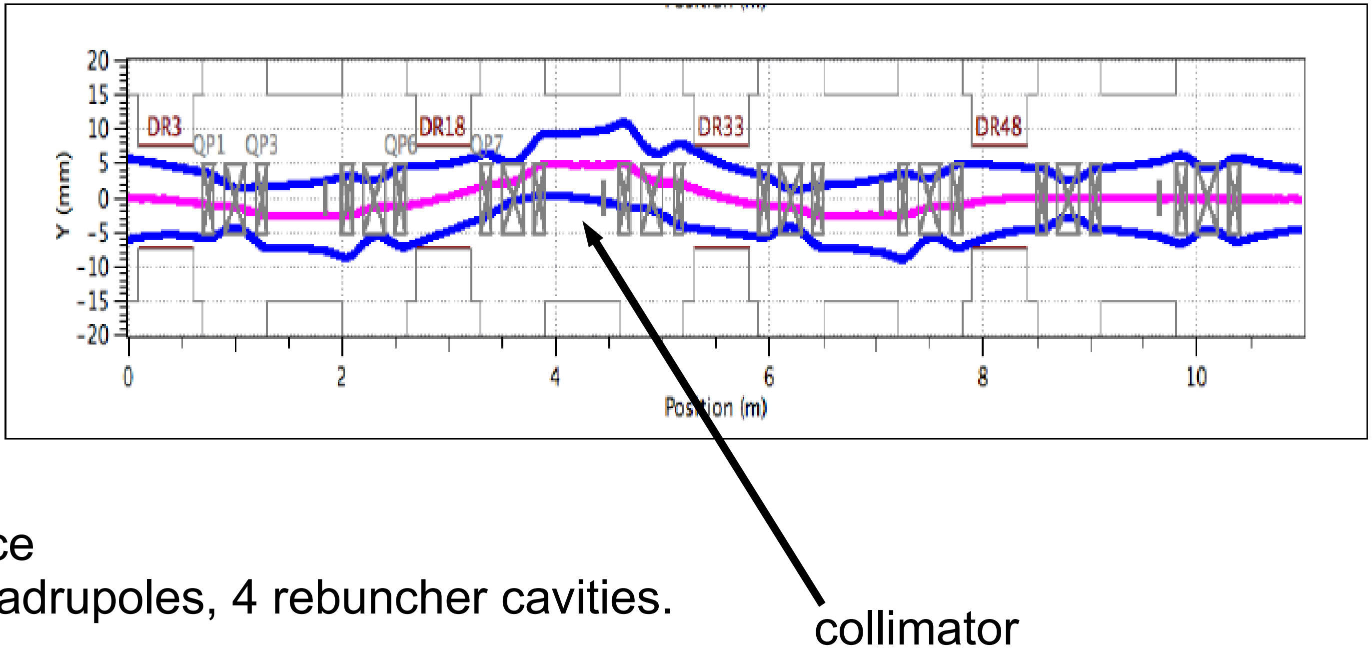
FNAL MEBT Concept

“+ - - +” 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.

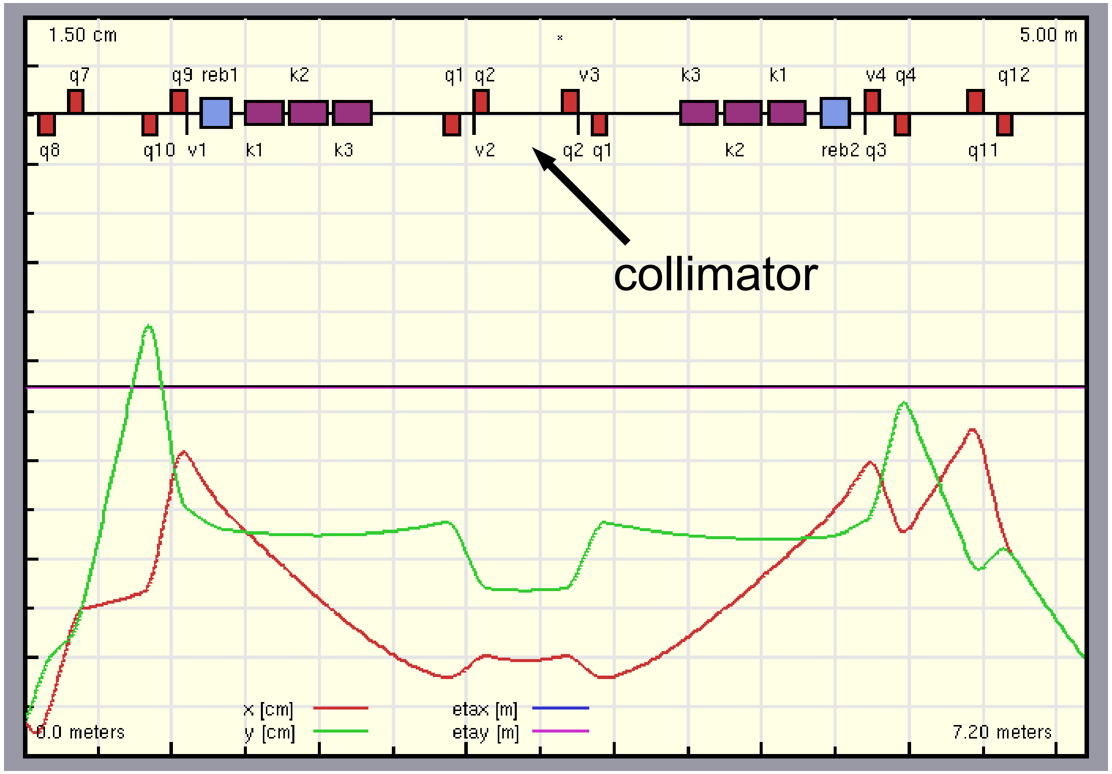


Keeps the lattice of the previous design: 4 periods of 180 degree phase advance per period.   Requires 24 quadrupoles, 4 rebuncher cavities.

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.

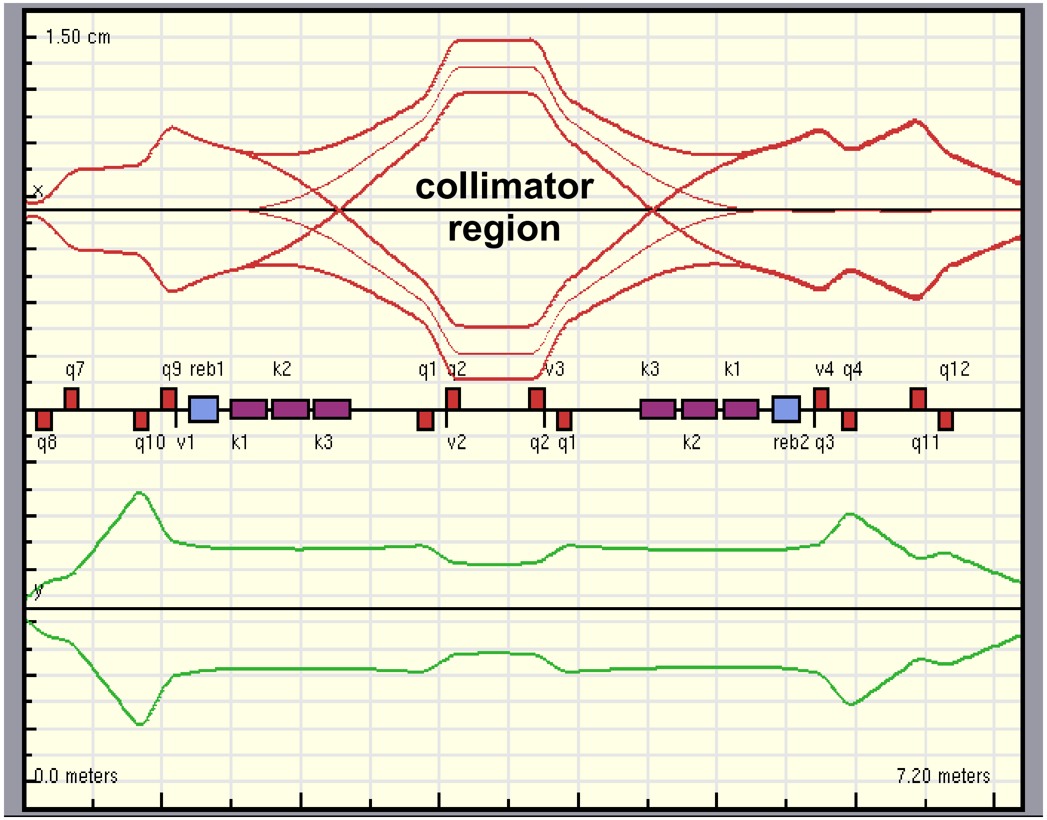
The 50 cm region for the beam stop can easily be extended, as $\alpha_x = \alpha_y = 0$ in the center region bounded by Q2.

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.

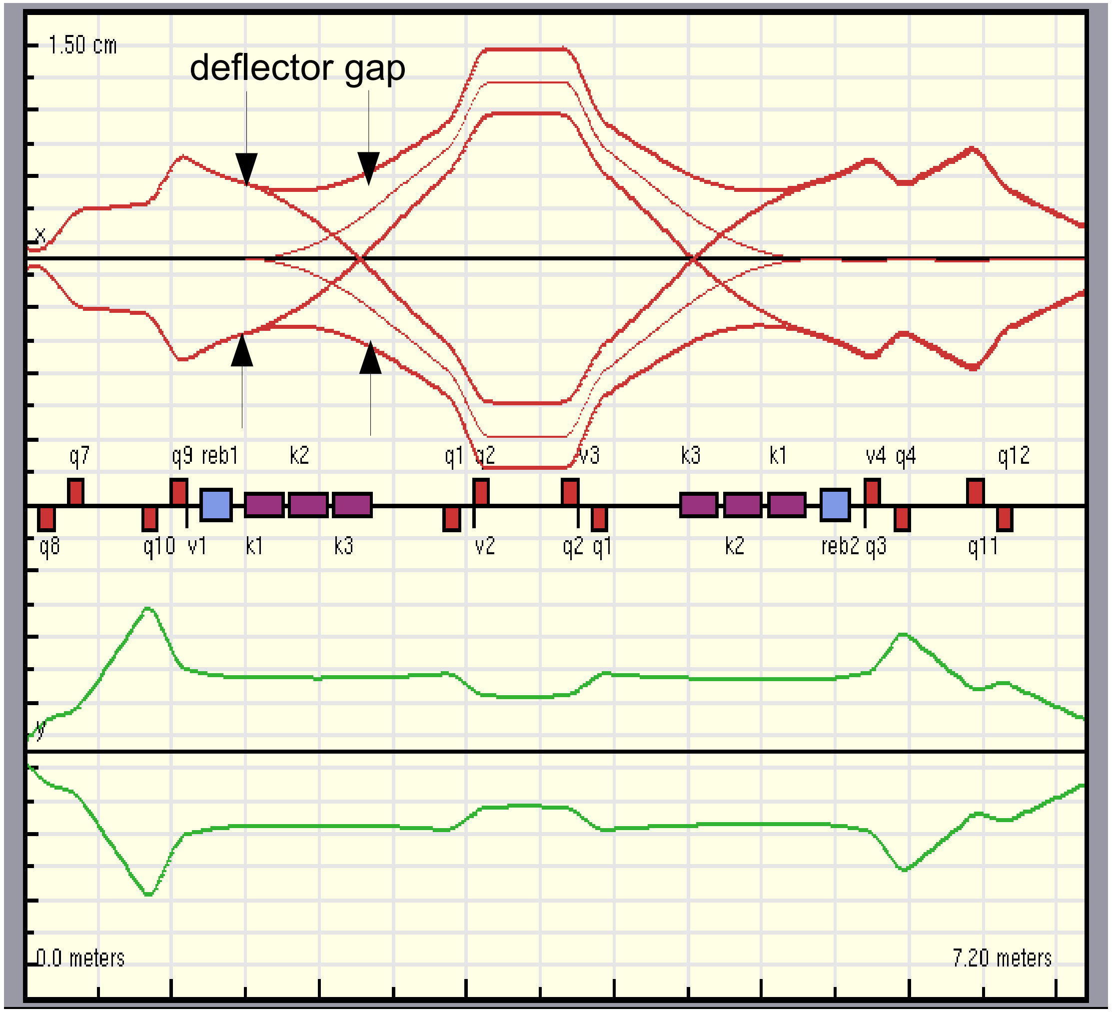
The rebuncher cavities (blue) are 4.2 m apart.   The rest of the 7.2 m is taken up by the input and output matching sections.   The input beam is taken from the RFQ simulation in parmteqm.



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

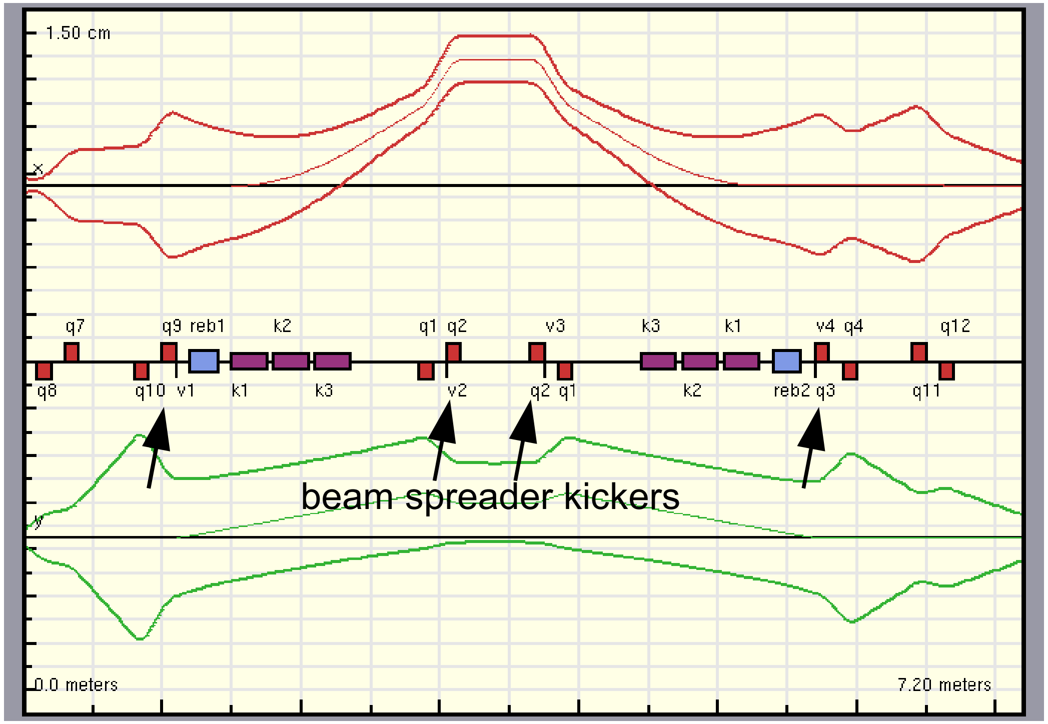
The beam hits the collimator at an angle 87.4 degrees from the normal, which reduces the power density in the beam by cos(87.4) = 0.0454.

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

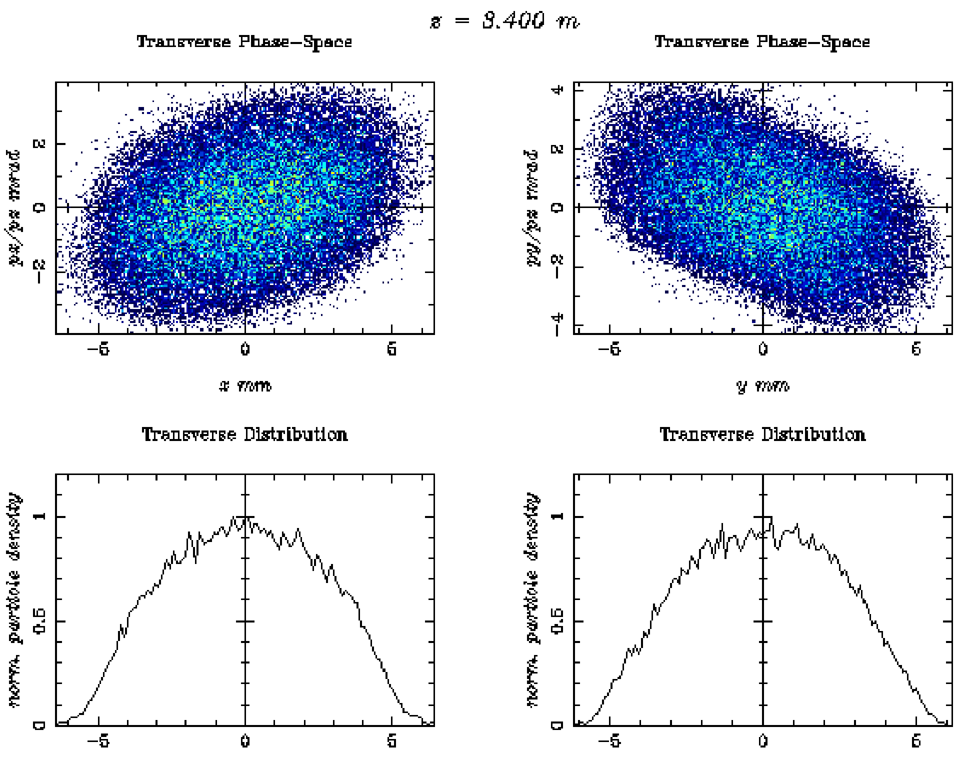
full beam width = 1.4 cm, with tails

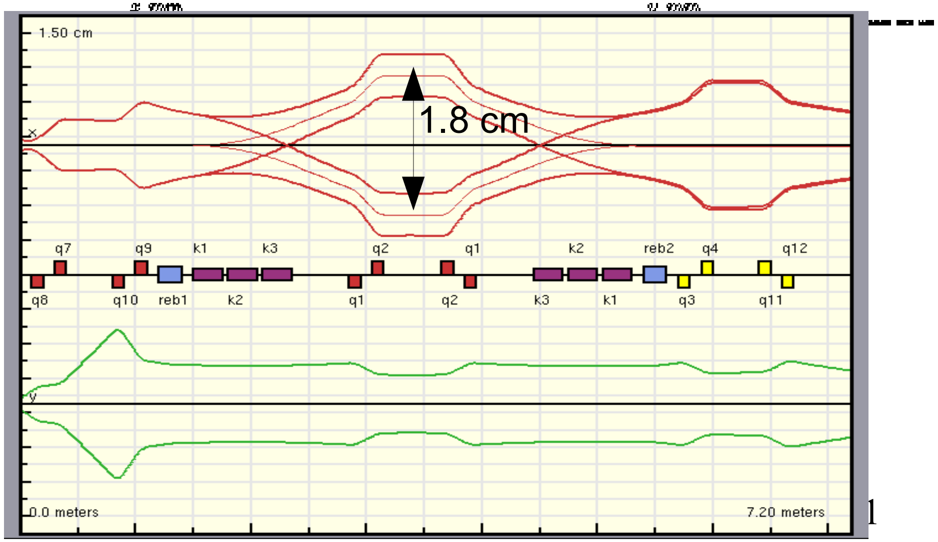
$$\frac{\Delta_{deflection}}{2\,\sigma_{beam}} = \frac{1.8\ \text{cm}}{0.2\ \text{cm}} = 9.0$$

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.

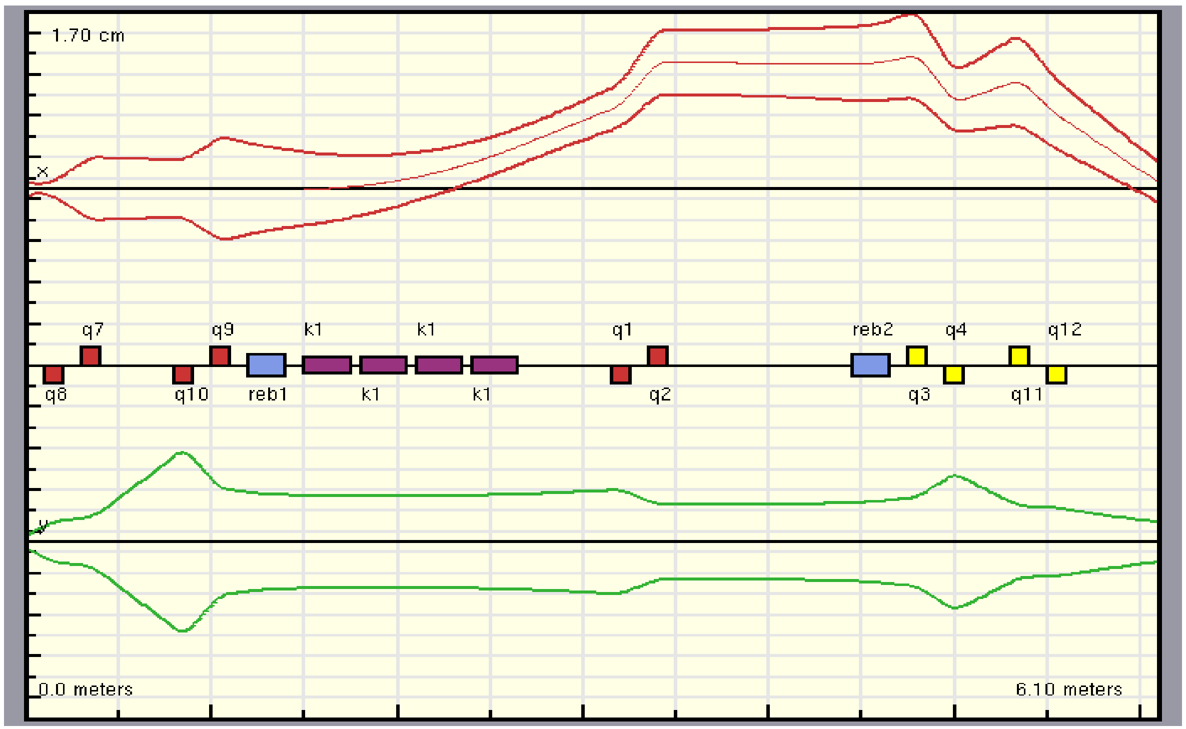
A bipolar suppply of ±250 volts gives the required 33 kV/m field.

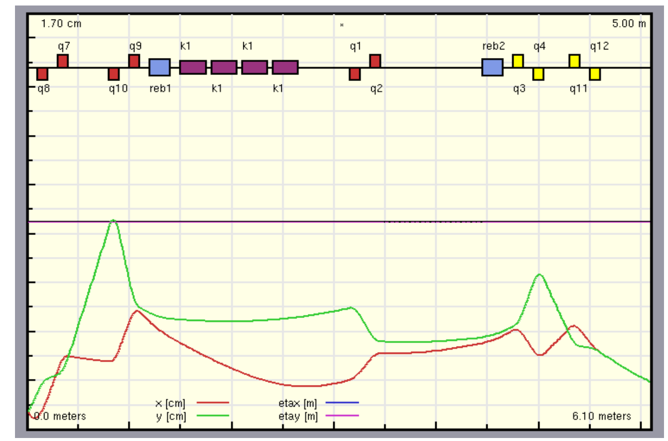




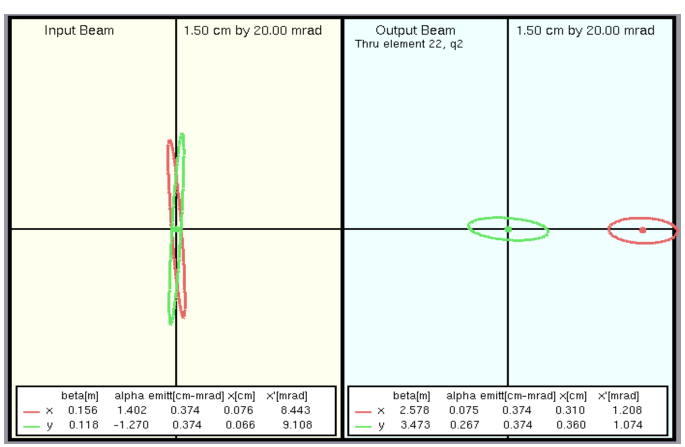
Recent Variant on Chopper-Antichopper MEBT

Remove the antichopper portion: move the rebunchers closer together
Provide 1 meter space for the collimator.   Chopper field is 33 kV/m.

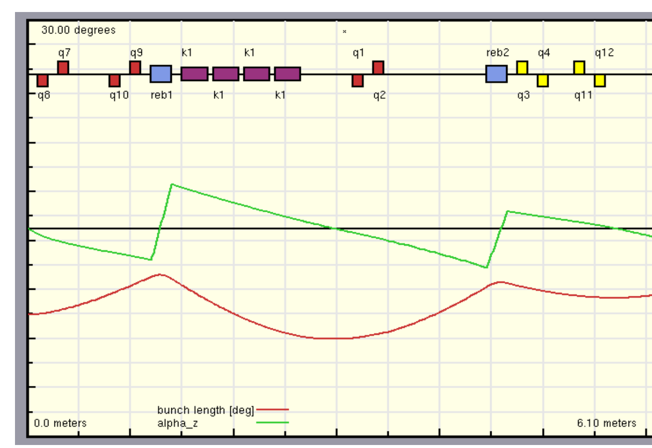




rms beam size with round match to spoke cavity



phase space at collimator entrance



bunch length

Narrow-Band Chopper Examples

Non-resonant structure

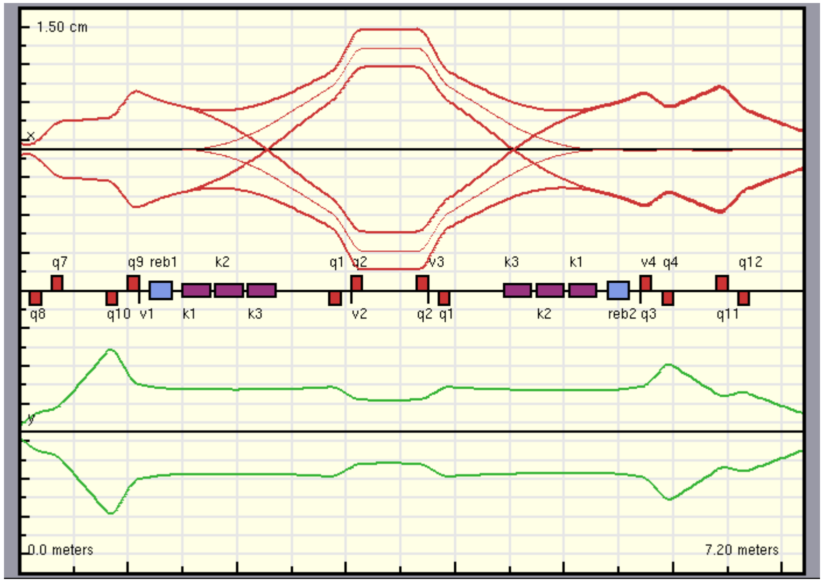
Sinusoidal waveform, amplitude and/or phase modulated.

Can change beam distribution at RF beam separator on a microsecond basis.

Deflects beam into two chopper targets, located symmetrically across beam axis.

Chopped beam deposited on two targets and at several spots.

Beam on axis passes through to linac.



Example of a beam split

Requirement: Split 162.5 MHz microstructure 3 ways:

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

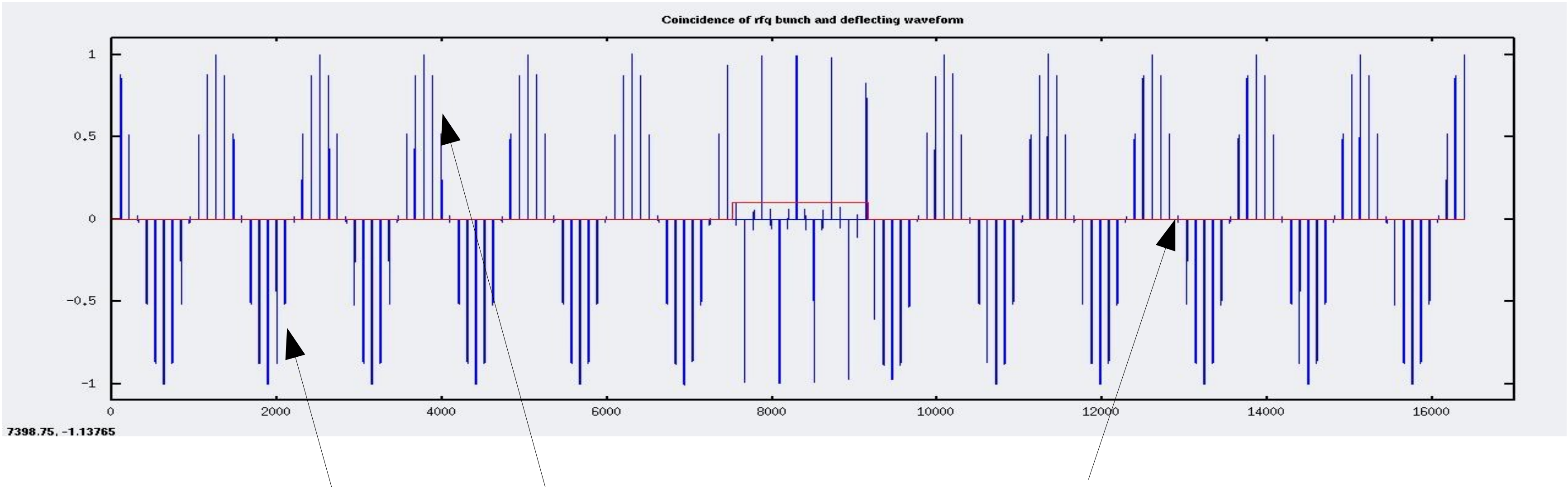
Average beam current over 1 microsecond integration period is 1 mA.

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.

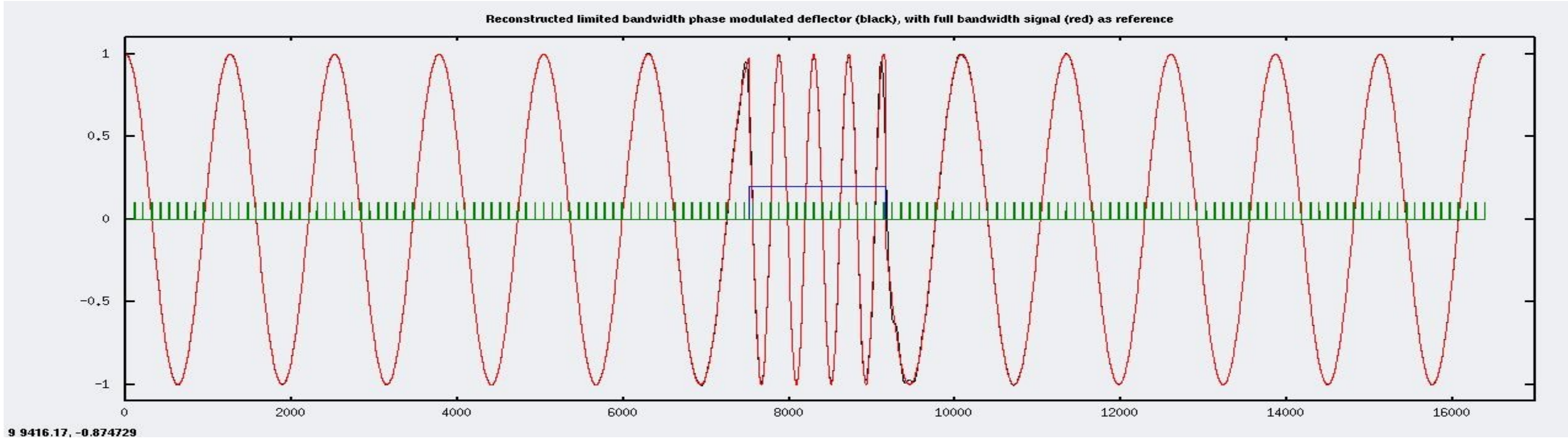
Beam that misses the collimator is returned to the axis, and does not contribute to an increase of transverse emittance .



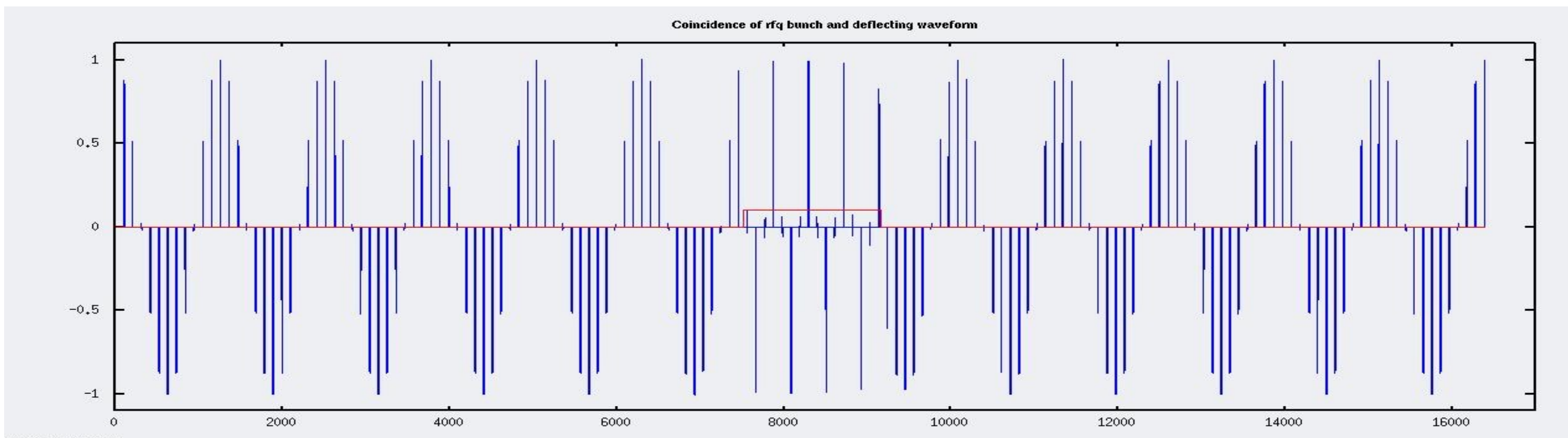
Narrow-band waveform: beam passes collimator on zero-crossing, the rest of the beam is spread out on the symmetric collimators.

Chopper Waveforms
(one of many)

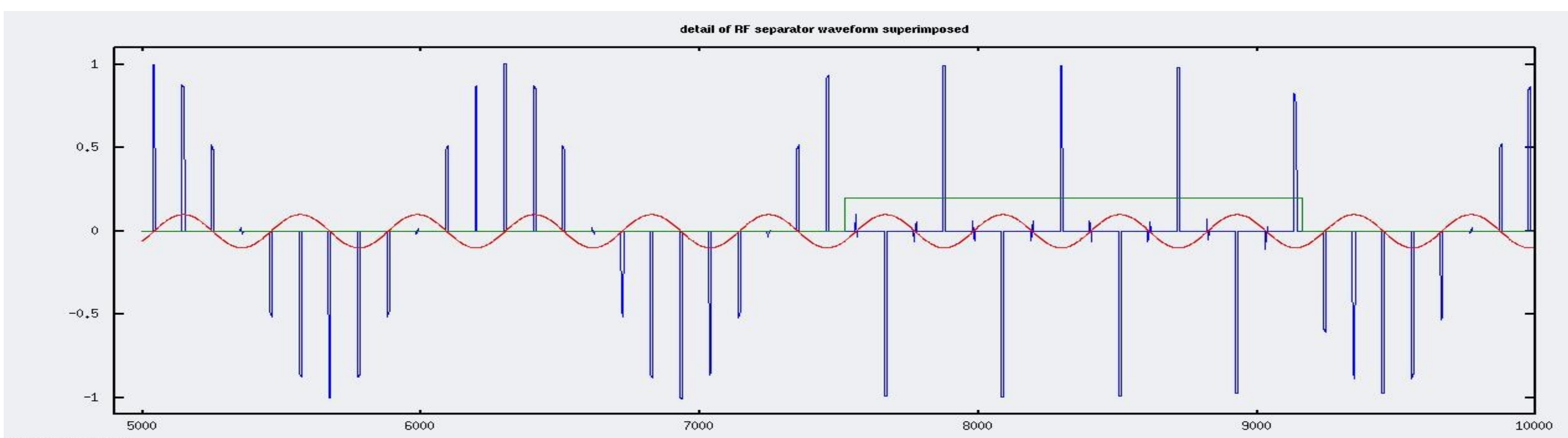
Dual Frequency Chop Example



5/6ths of the pulses removed to collimator



Detail, with RF separator waveform



Real Challenge: Nagaitsev at DOE Talk, 5 May

Split beam:

10.15 MHz to Nuclear, 770 kW
20.3 MHz to Kaon, 1440 kW
81.25 MHz to Muon, 100 nsec, 700 kW

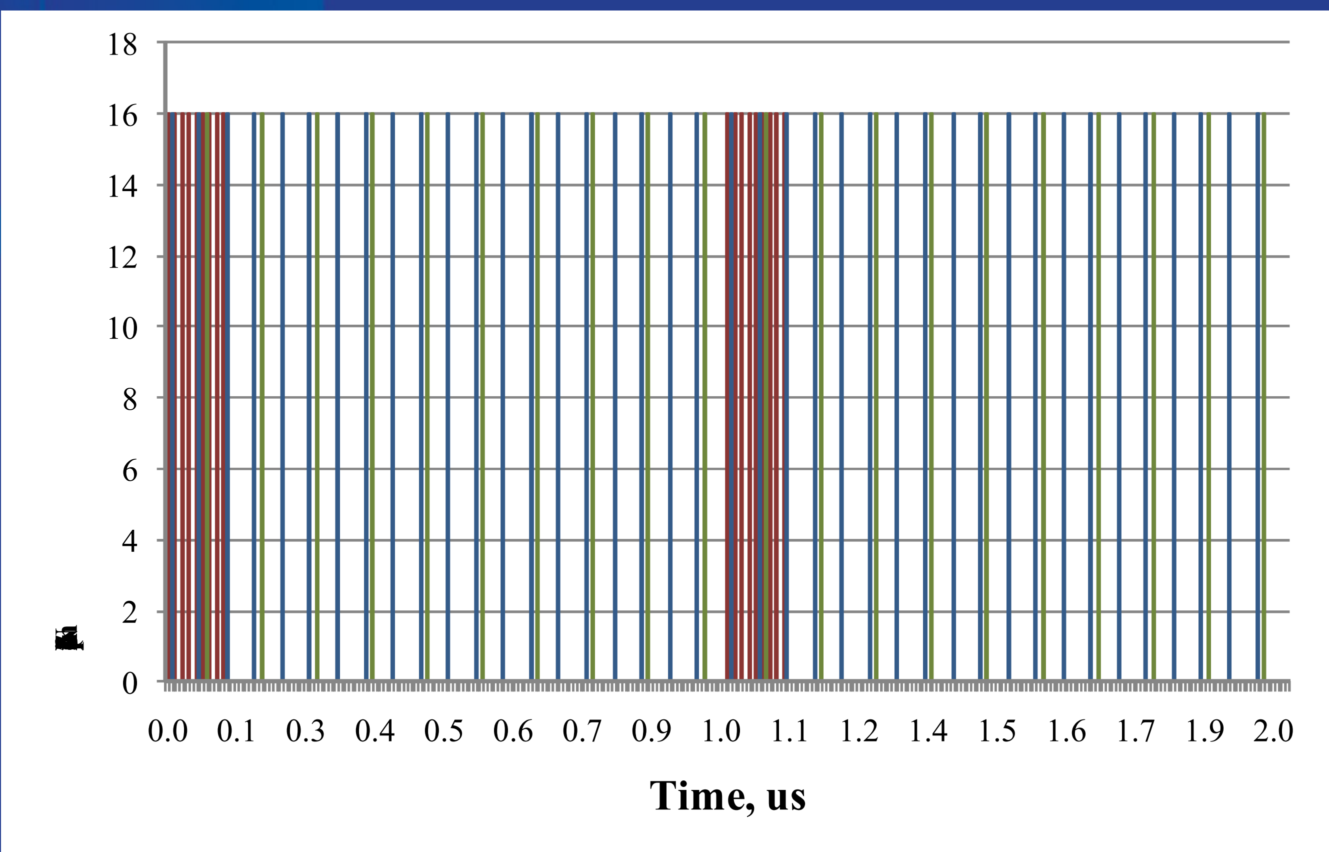
Can do this: generate a waveform that will give this split, and changeable on a microsecond time scale.

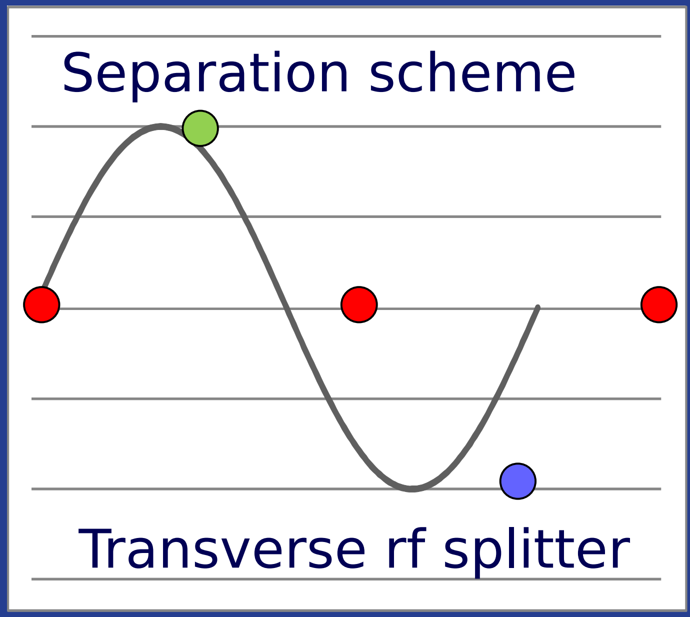
Chopping and splitting for 3-GeV experiments

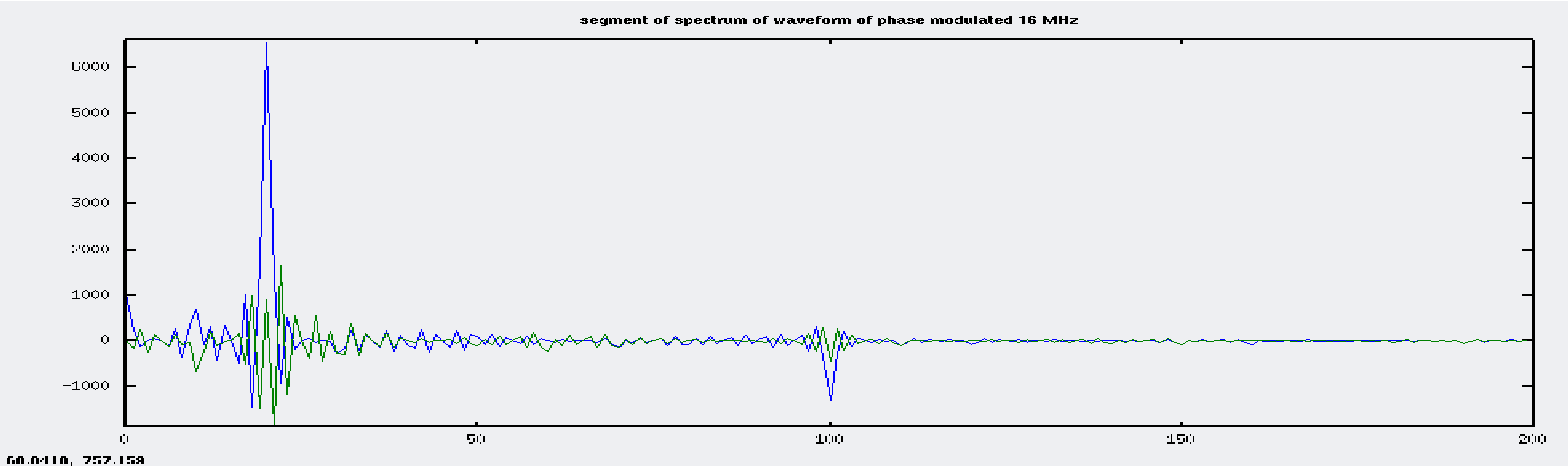
1 μsec period at 3 GeV

- Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz   700 kW
- Kaon pulses (16e7) 20.3 MHz   1540 kW
- Nuclear pulses (16e7) 10.15 MHz   770 kW

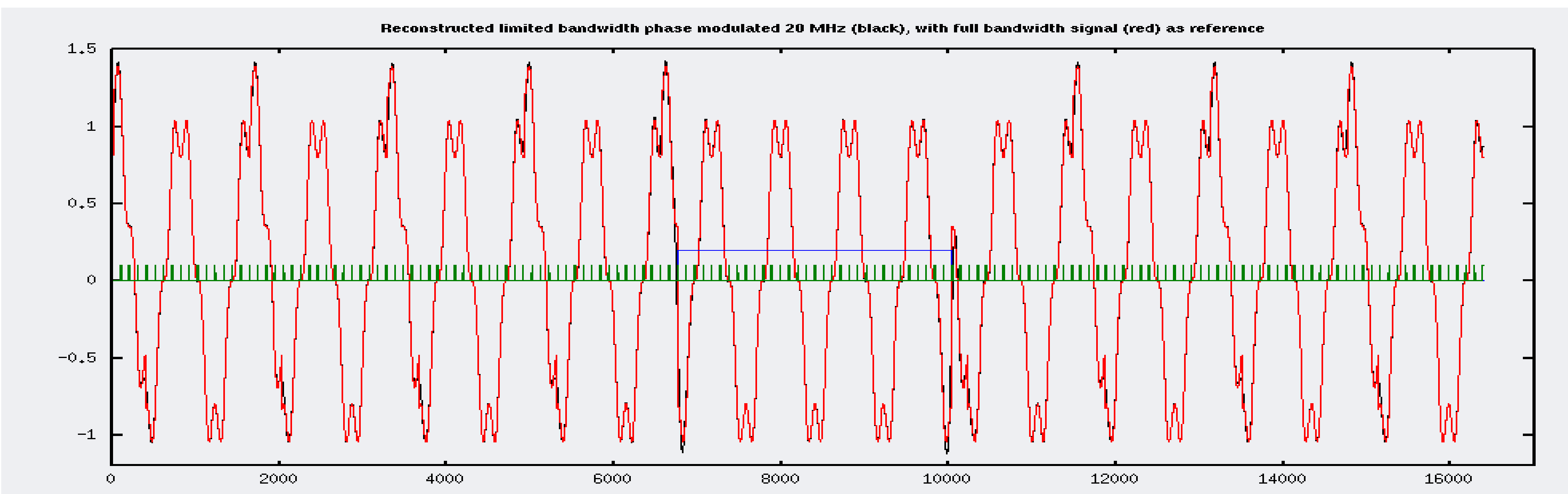
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ



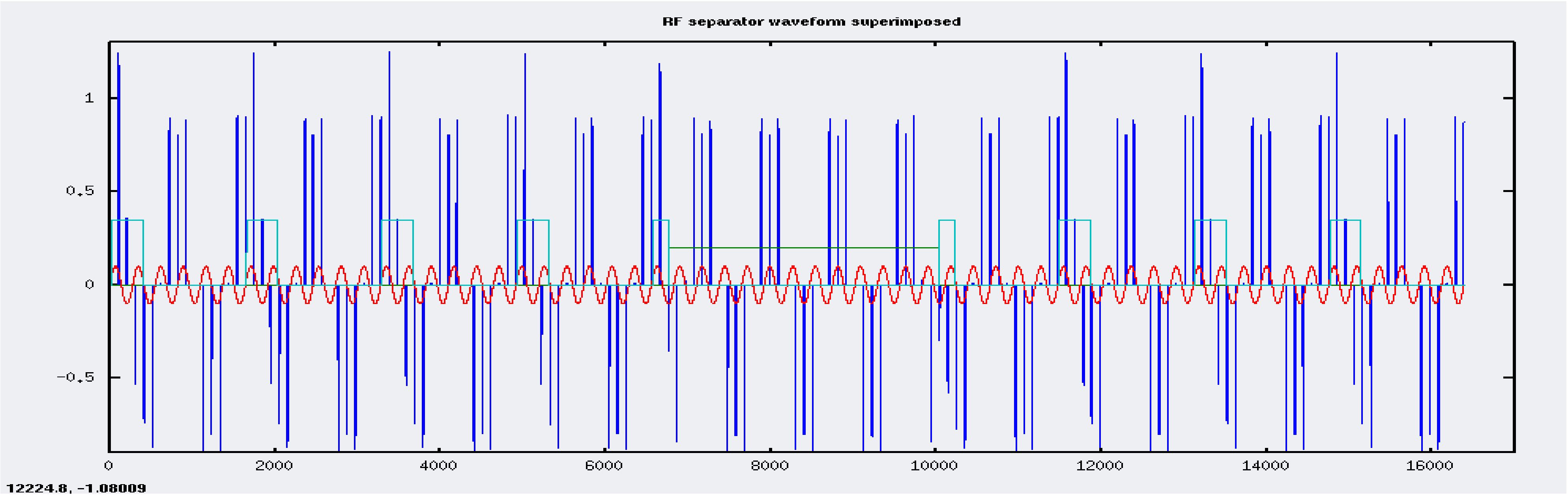




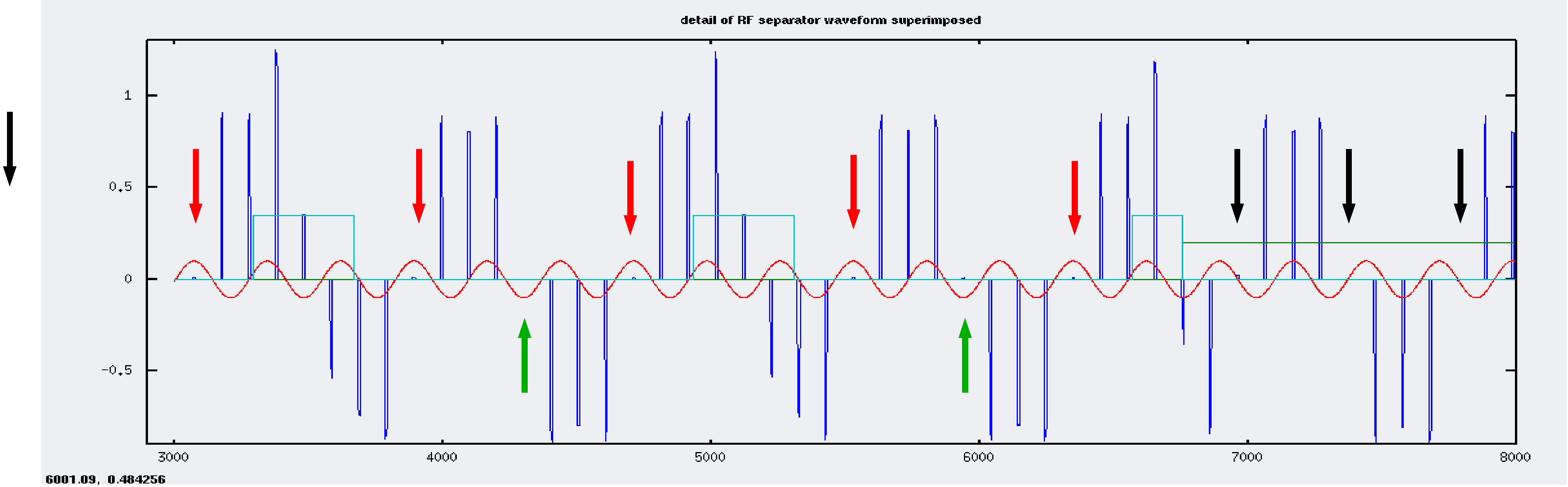
Real and imaginary spectrum of deflecting waveform. This is then band-limited to 150 MHz.



Reconstructed band-limited waveform over 1 microsecond interval. 162.5 MHz RFQ pulses



Beam deflection with RF separator waveform.   Beam is spread out on collimator



Detail of chopped beam: nuclear   kaon   muon   (Superimposed RF separator)

Full or Half MEBT?

The full MEBT returns unchopped beam to the axis.

The half MEBT does not.

The chopping waveform is approximately symmetric across the axis (no dc component)

The beam sweeps across the collimator slit.

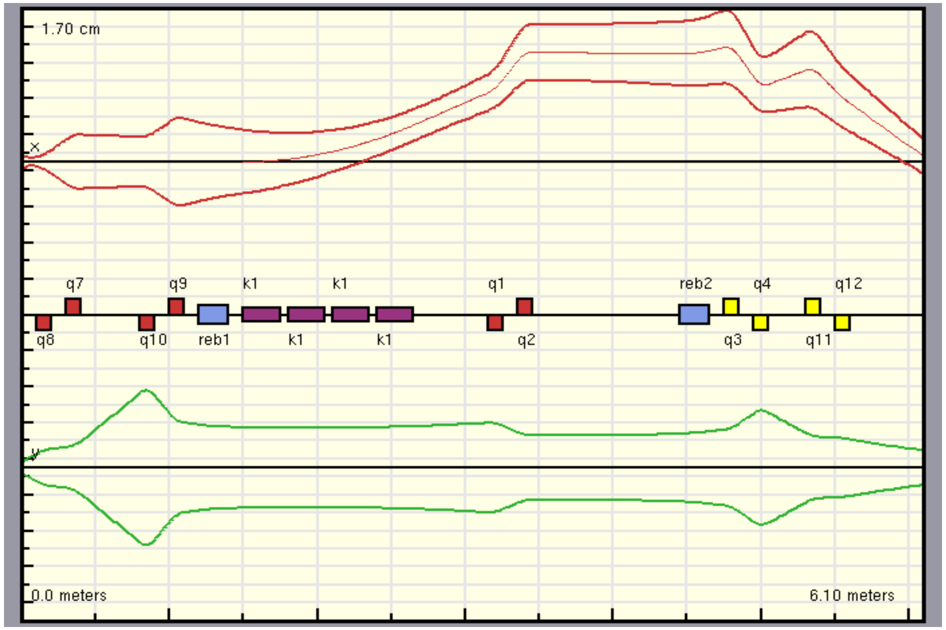
The addition of 4% of 5th harmonic reduces the beam sweeping across the slit

The transverse emittance growth for (example: 30 degree phase width) is smaller.

The rebunchers in the half MEBT are close enough that 50K particle simulations show almost no longitudinal emittance growth.

The half MEBT provides 1 meter for the collimator.

Chopper field is 33 kV/m



Other Examples

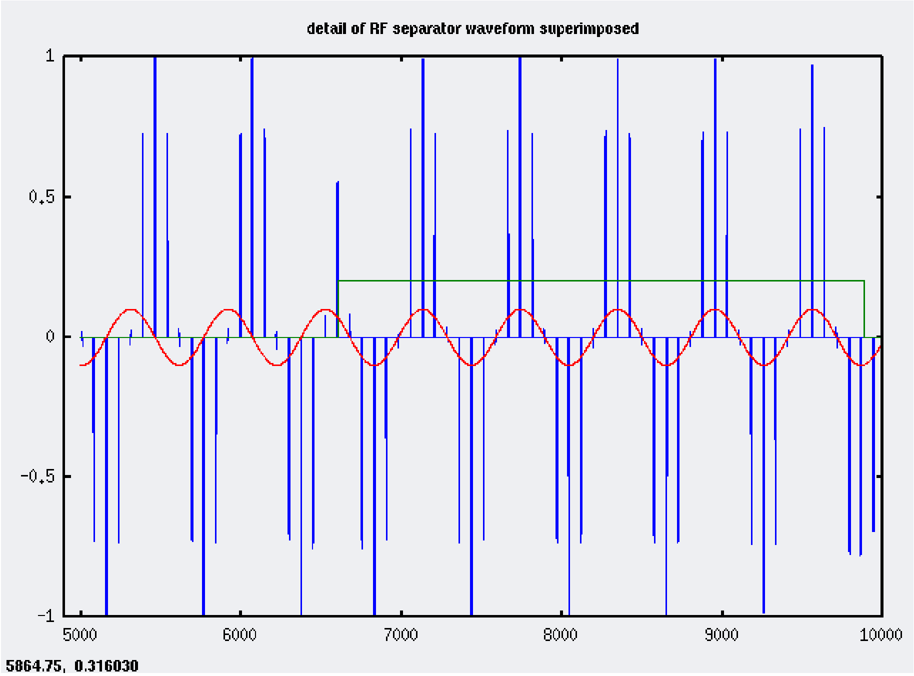
The beam is distributed by the RF kicker in different fractions. (Detail of part of the 1 microsecond cycle.)

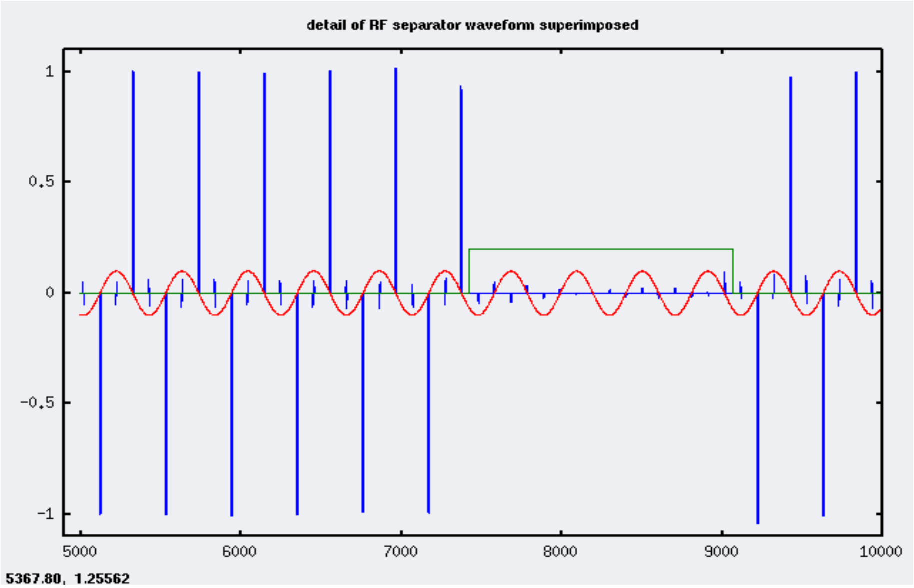
The beam can be directed at one or two experiments at a time.

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.

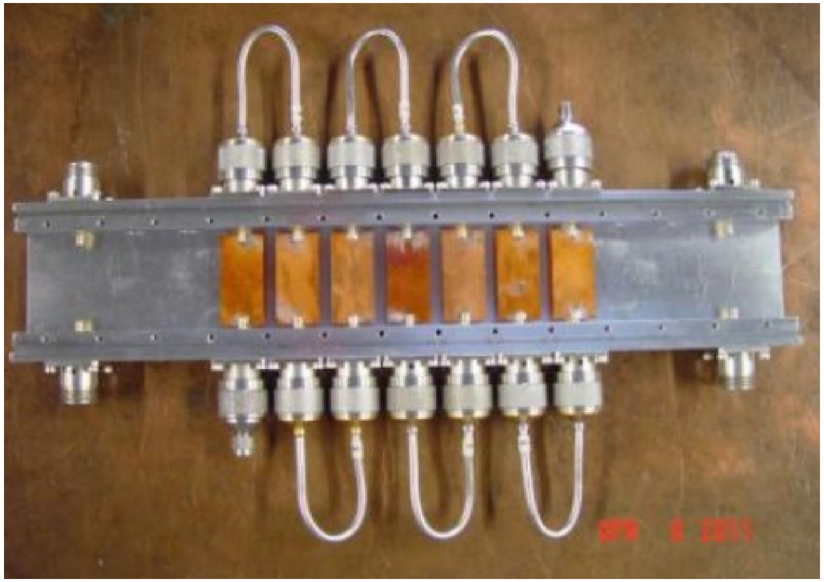
The chopper-antichopper configuration significantly relaxes this, allowing further narrowing of the chopper and electronics bandwidth to give equivalent performance to the older MEBT design.

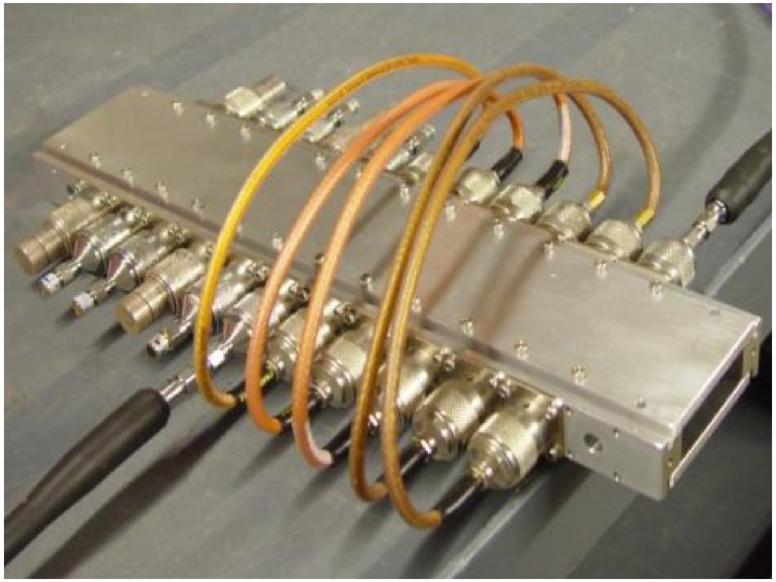




Chopper Technology

Several chopper concepts were presented at the April meeting, all aiming for a GHz bandwidth.





The requirements for a narrow-band chopper are more modest:

- 200 MHz bandwidth sufficient, can compensate for dispersion
- robust mechanical structure to withstand beam sputtering, etc
- 100 ohm impedance would work well with a 1:4 balun from a 50 ohm source.
- ability to handle significant CW power loss

1000 watts into 100 ohm chopper gives 447 volts peak. Symmetric deflectors from balun require 2.7 cm spacing for 33 kV/m deflection for 100% efficiency.

Off-the-Shelf Narrow-Band Chopper Power Source

Use a balun to split output into two-100 ohm push-pull outputs matched to TW deflectors. One unit should give ample deflection in the “half” MEBT configuration.   Still looking for a full-spectrum high-power balun.

back

2500A225

2500 Watt CW, 10 kHz – 225 MHz
(w/DCP, IEEE, RS-232, USB & Ethernet interfaces)
Login to see pricing information.

The Model 2500A225 is a self-contained, broadband, completely solid-state amplifier designed for applications where instantaneous bandwidth and high gain are required. The amplifier is air cooled using internal self-contained liquid cooling for high performance and reliability. Push-pull LDMOS circuitry is utilized in all high power stages in the interest of low distortion and improved stability. The Model 2500A225 is equipped with a Digital Control Panel (DCP), providing local and remote control of the amplifier. The DCP uses a 3 ¾ inch diagonal graphic display, menu assigned softkeys, a single rotary knob, and four dedicated switches to offer extensive control and status reporting. The display provides operational presentation of Forward Power and Reflected Power plus control status and reports of internal amplifier status. All amplifier control functions and status indications are available remotely in GPIB/IEEE-488 format, RS-232 hard wire and fiber optic, and USB and Ethernet. The buss interface connectors are located on the back panel and positive control of local or remote operation is assured by a keylock on the front panel of the amplifier. High efficiency universal input, power factor corrected switching power supplies provide DC to all internal sub-assemblies. Housed in a stylish, contemporary enclosure, the Model 2500A225 provides readily available RF power for typical applications such as RF susceptibility testing, antenna and component testing, watt meter calibration, particle accelerators, plasma generation, communications and use as a driver for higher power amplifiers.

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

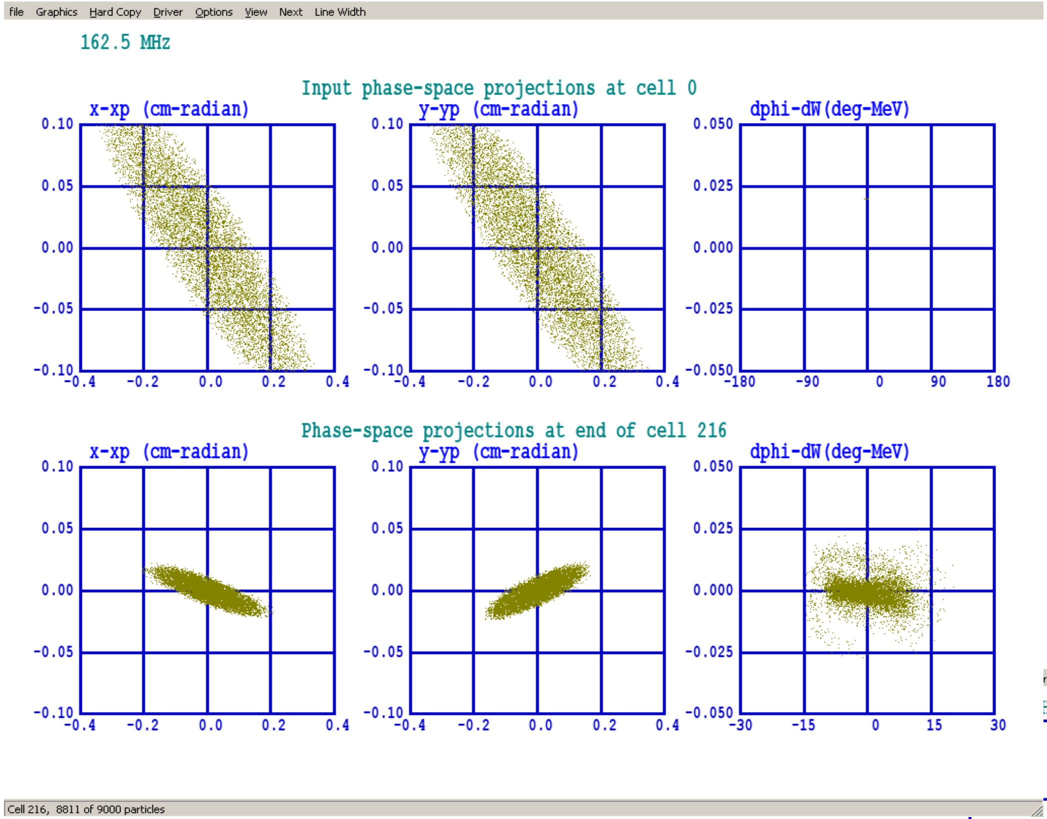
Diagnostics required for setting rebuncher gradients and phases
BPMs and/or striplines

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

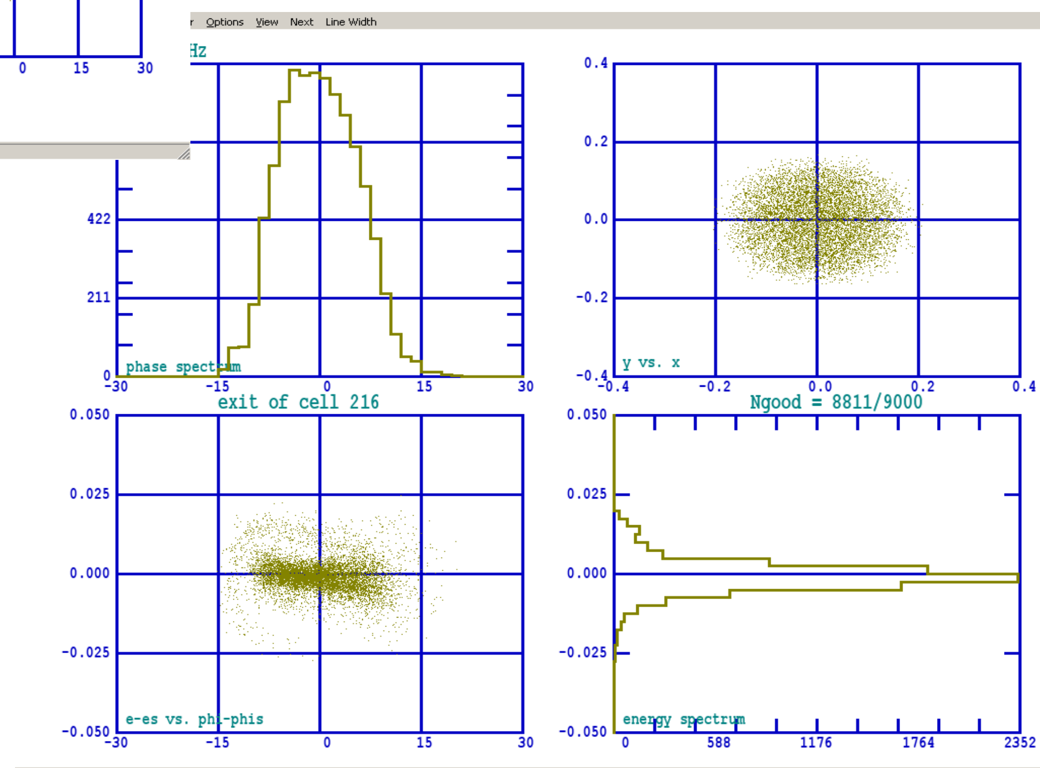


Transverse emittance 0.25 mm-mrad

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 full MEBT

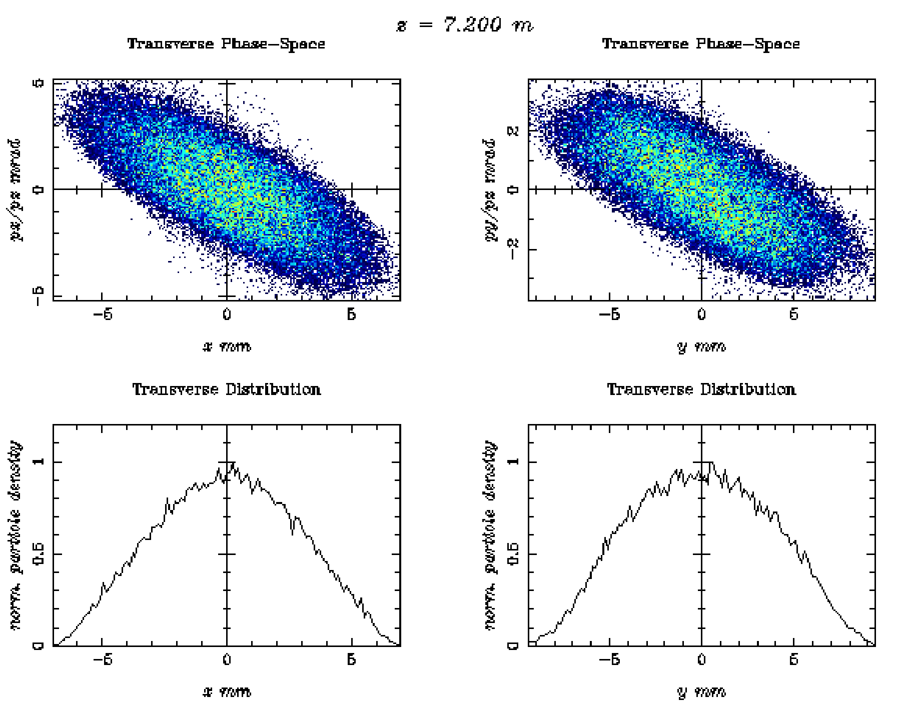
The emittance growth is calculated for 50,000 macroparticles in each bunch with 30 picoCoulomb bunch charge (5 mA) for a 2.1 MeV beam. The particle ensemble is calculated by parmteqm for the 2.1 MeV RFQ that is then transported through the MEBT.

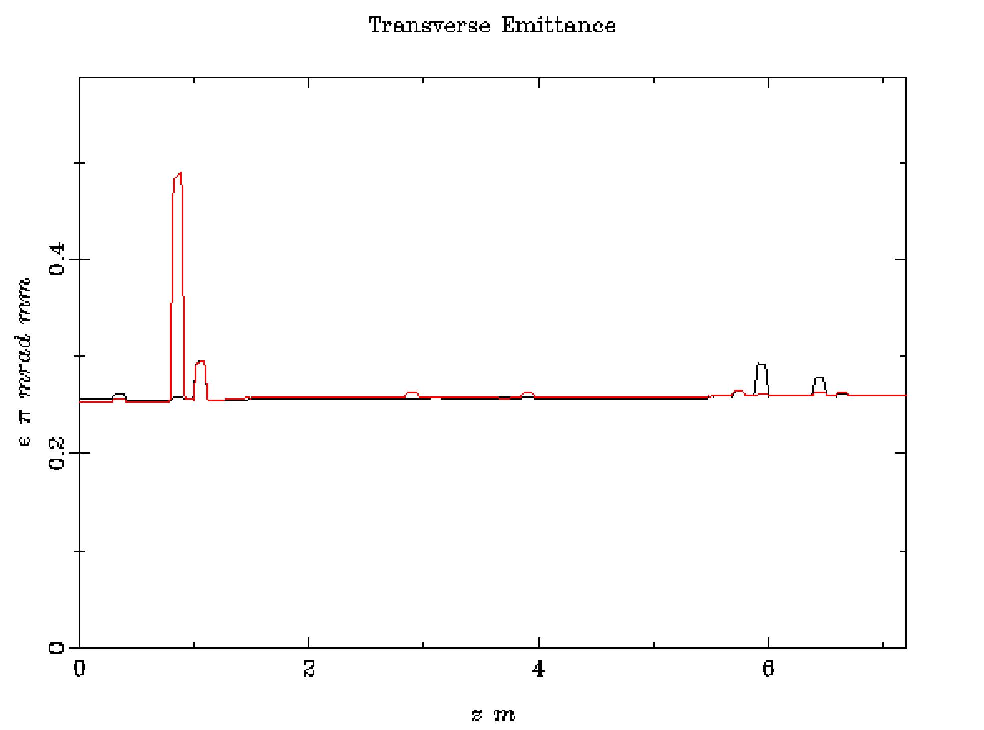
The transport is simulated with Astra, using a full 3-D FFT space charge algorithms.

Transverse emittance growth: less than 5%.

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

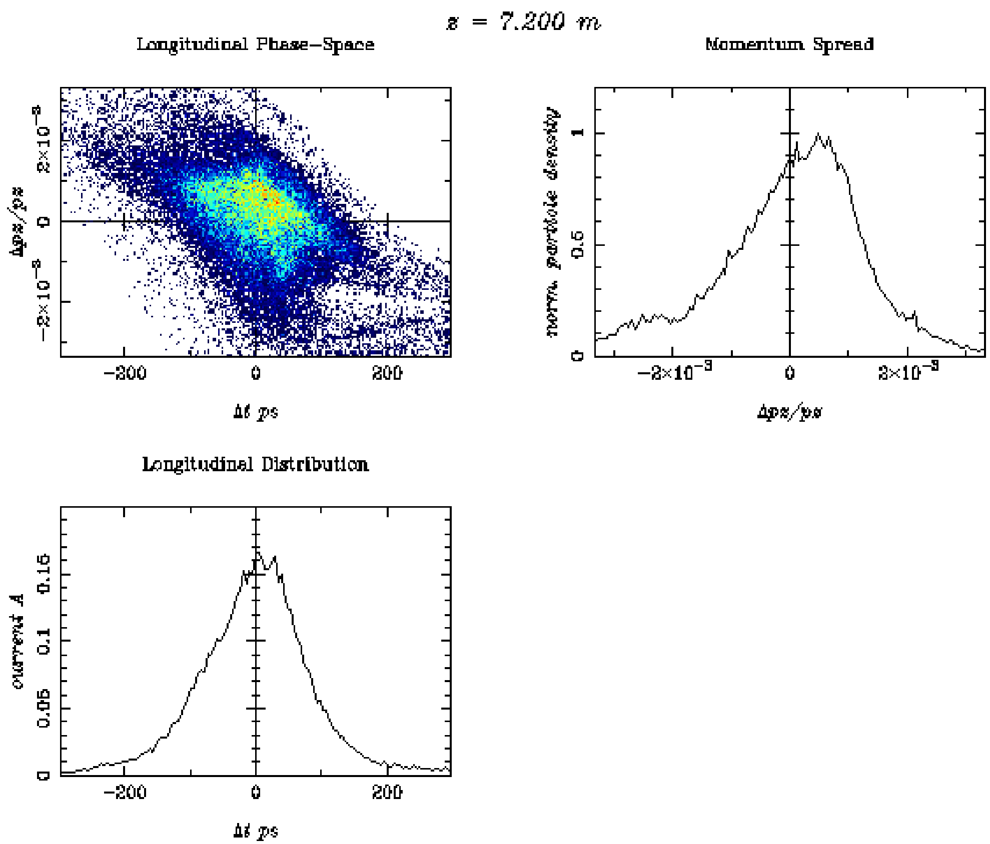
Final phase space distributions shown at the MEBT exit.

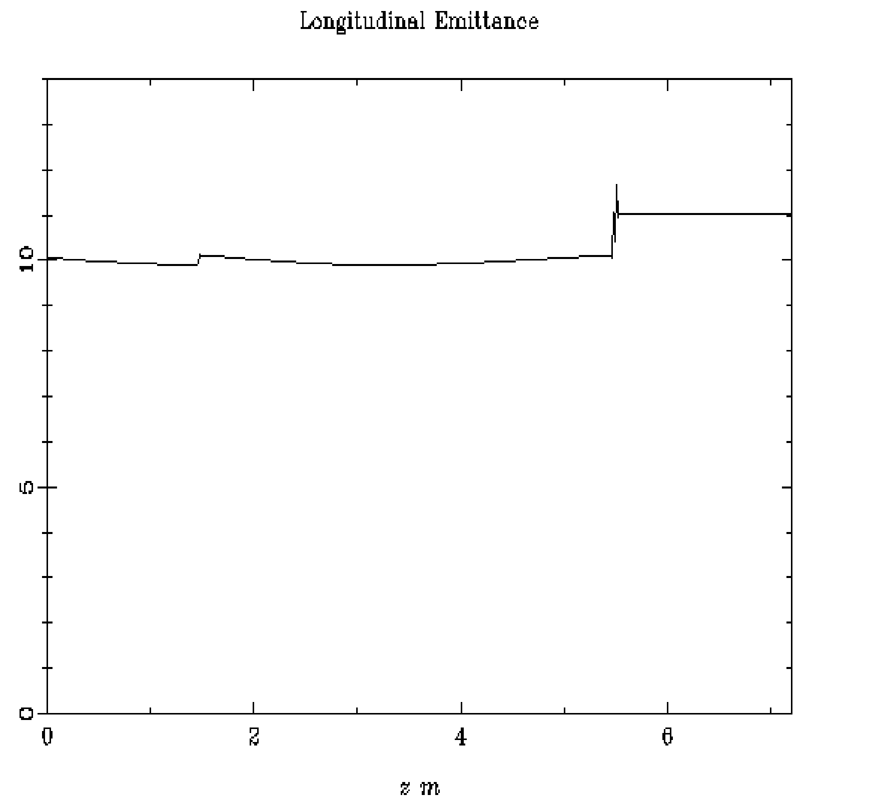




Longitudinal Emittance Growth

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.

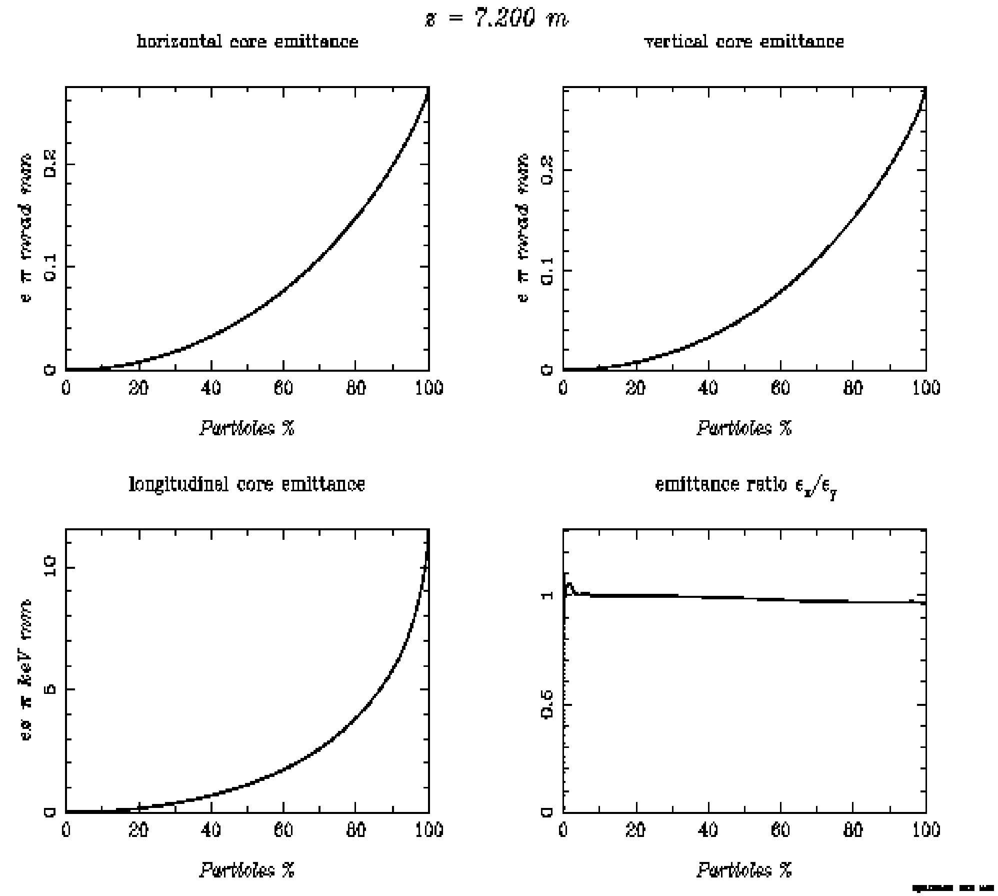


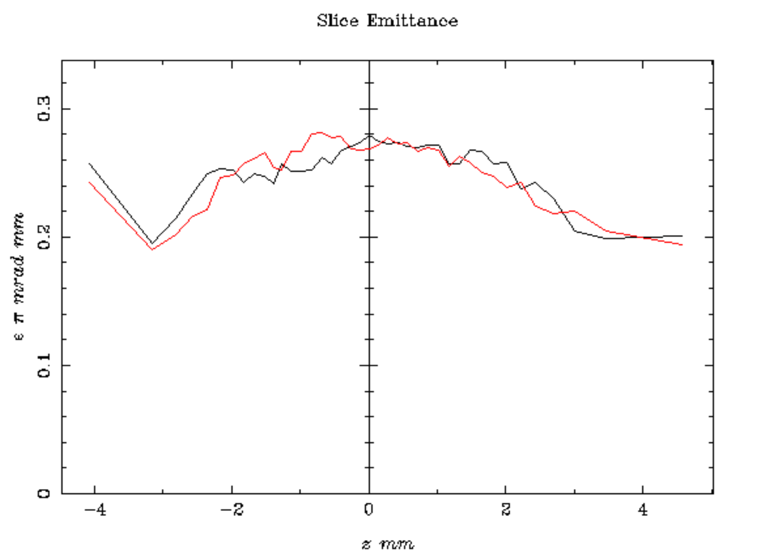


Emittance Distribution

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

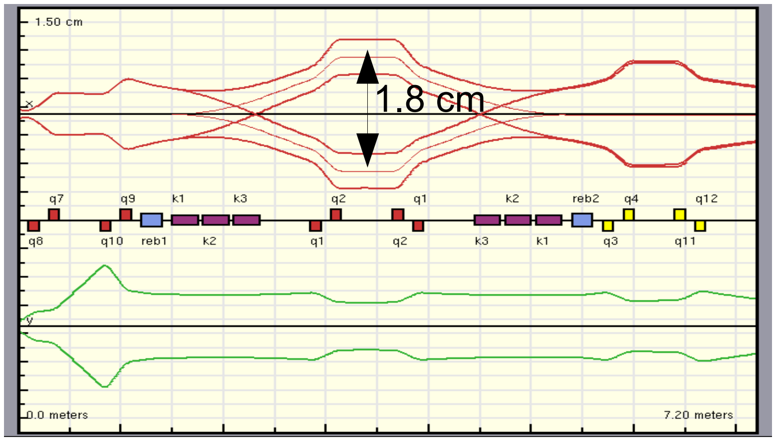
Tuning

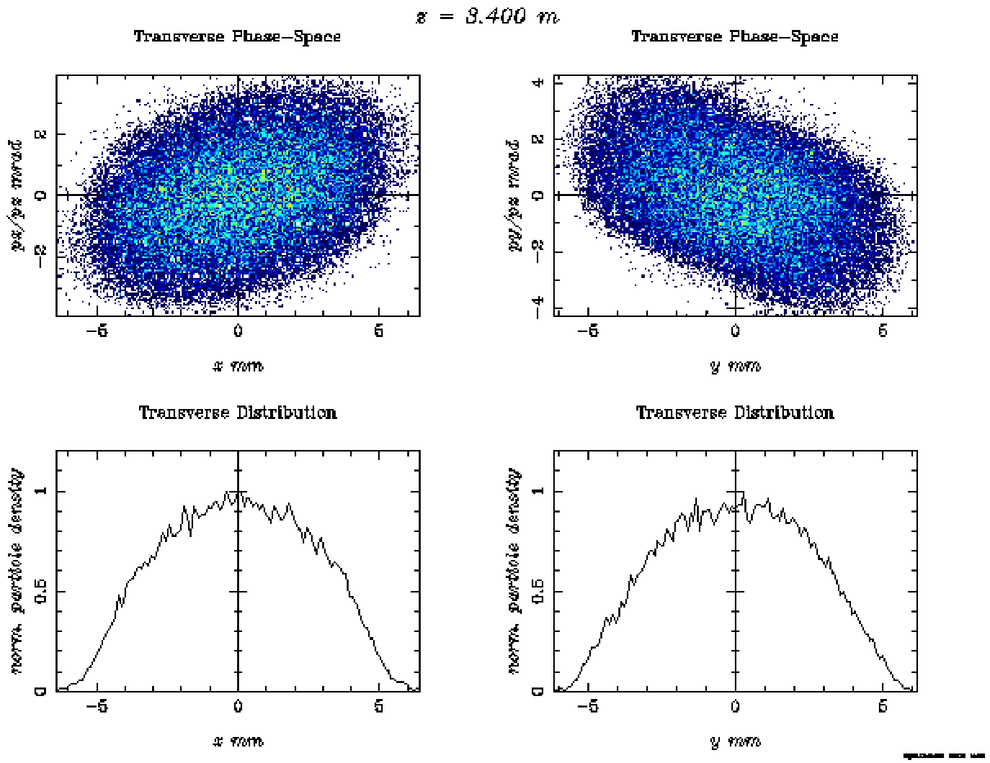
Beam at Beam Stop

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.





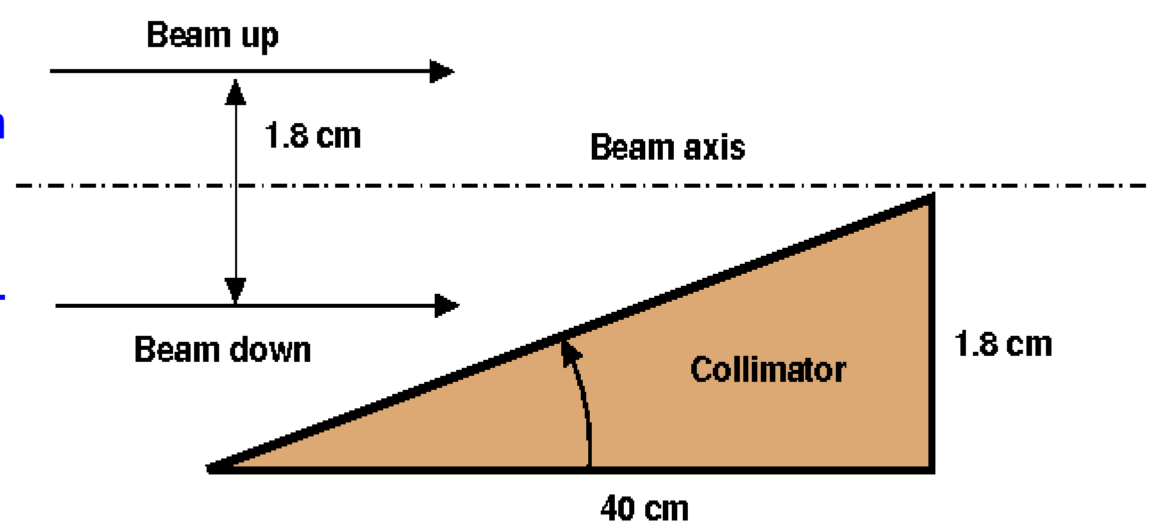
For the narrow-band chopper, the collimator configuration is symmetric across the axis, the beam is deflected both up and down to be stopped, and the undeflected beam passes through.

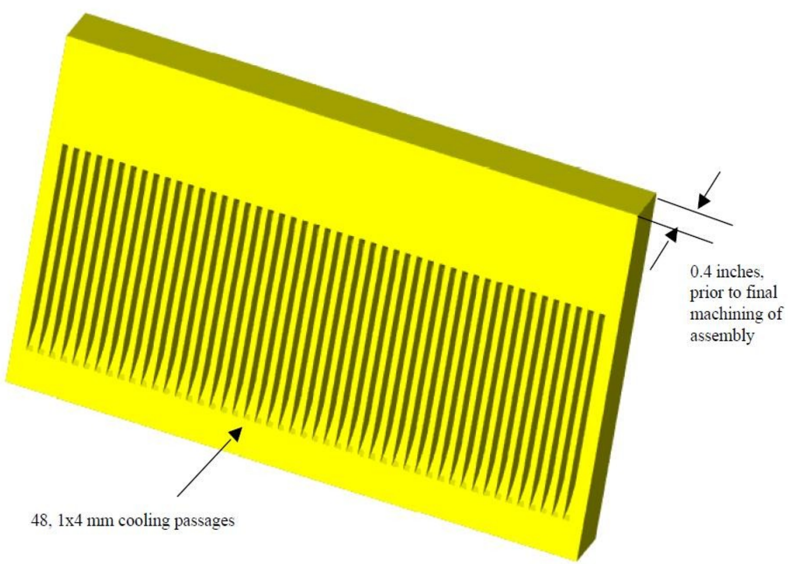
Beam Stop Geometry

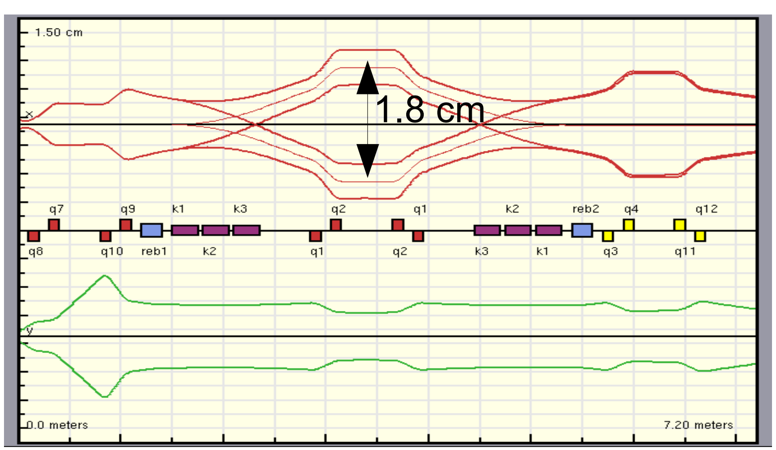
If collimator is 40 cm long, and has a 1.8 cm slope, the slope angle is 2.6 degrees. The beam impacts the beam stop at an angle of 87.4 degrees from the normal.

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.

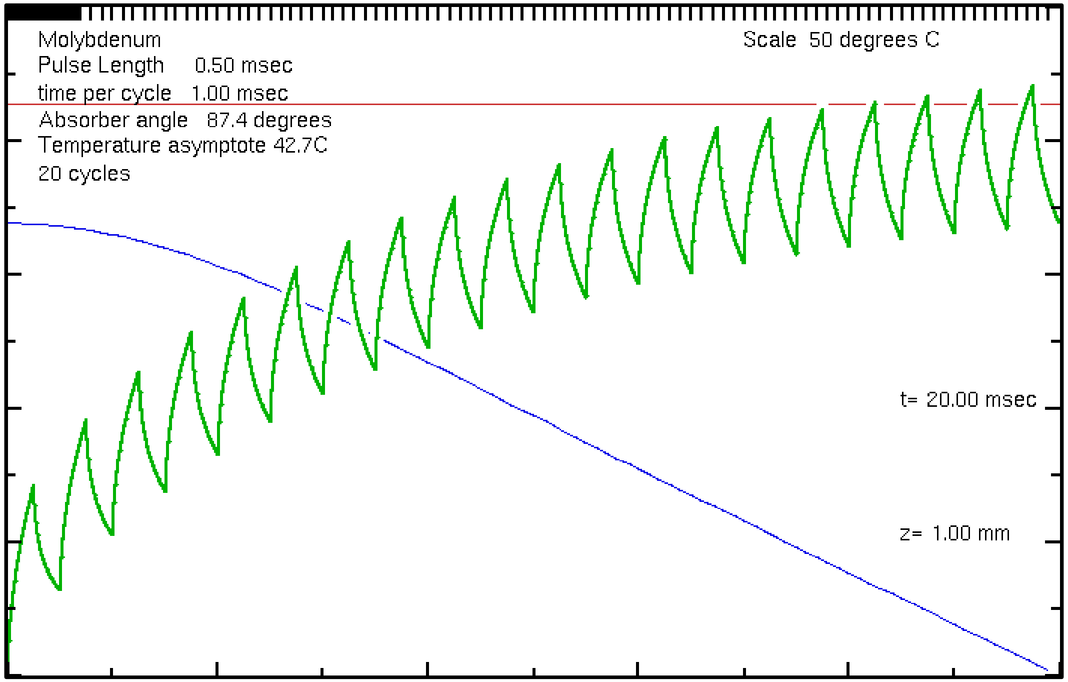
Several materials simulated.
Microchannel cooling with 1 mm spacing between surface and water
Beam impacts 87.4 degrees to normal.

Two time constants modeled:

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

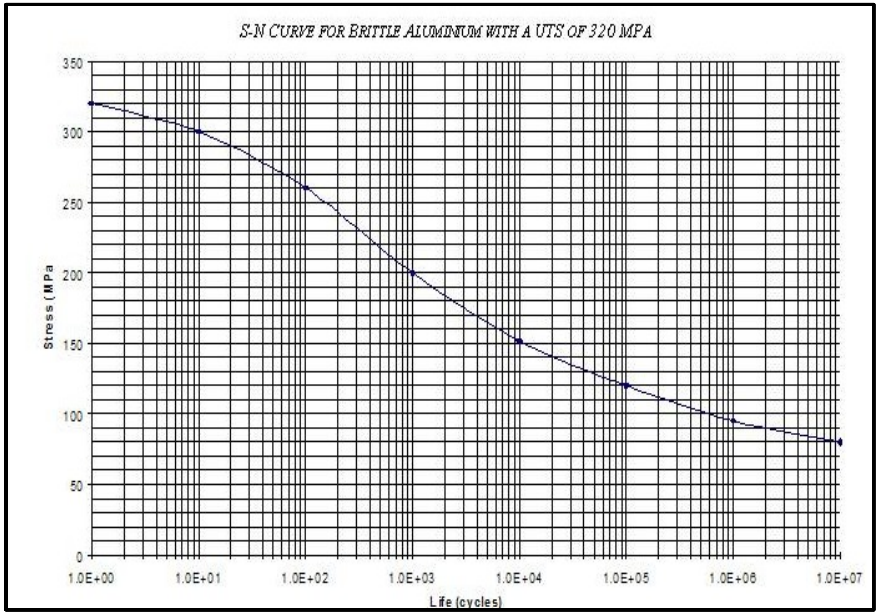
Results for moly, 1 kHz pulse
Does not quite reach equilibrium temperature rise of 42.7C in 20 msec.

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?

Action Items

No LBNL MEBT hardware development at this time.

MEBT strategy still wide open: LBNL, FNAL, something else?

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

MEBT Summary

Two new MEBT concept uses a chopper-antichopper configuration with pi phase advance between them produced by a pair of focusing doublets, or eliminate the antichopper and use a deflection harmonic to reduce motion at the chopper slit.

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 to 100 cm long, as the central region can easily be extended with a slight increase of rebuncher voltage.

12 quads and six 25-cm long deflectors are used with about a 1.6 cm spacing between plates for the full MEBT.

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.