Project-X Front-End Update

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LEBT Requirements

The most challenging physics in the Front-End is in the LEBT

(The most challenging engineering is in the MEBT)

The LEBT will transport a 30-35 keV H-minus beam from 1 or 2 ion sources to the RFQ

LEBT functions

Match beam out of the ion source to the transport channel
Dispose of electrons emitted along with the H-minus ions
Match beam into the RFQ
Provide diagnostics and test facilities

Provide fast switching between two possible ion sources
(Optionally) provide 50-100 nsec on/off switching before the RFQ to introduce short gaps in the beam

LEBT Design Progress

Qing Ji: started to acquire D-Pace ion source

Will use to characterize the ion source, and the response of the LEBT
Measure the beam parameters
Prove the diagnostics devices
Measure neutralization parameters under various conditions

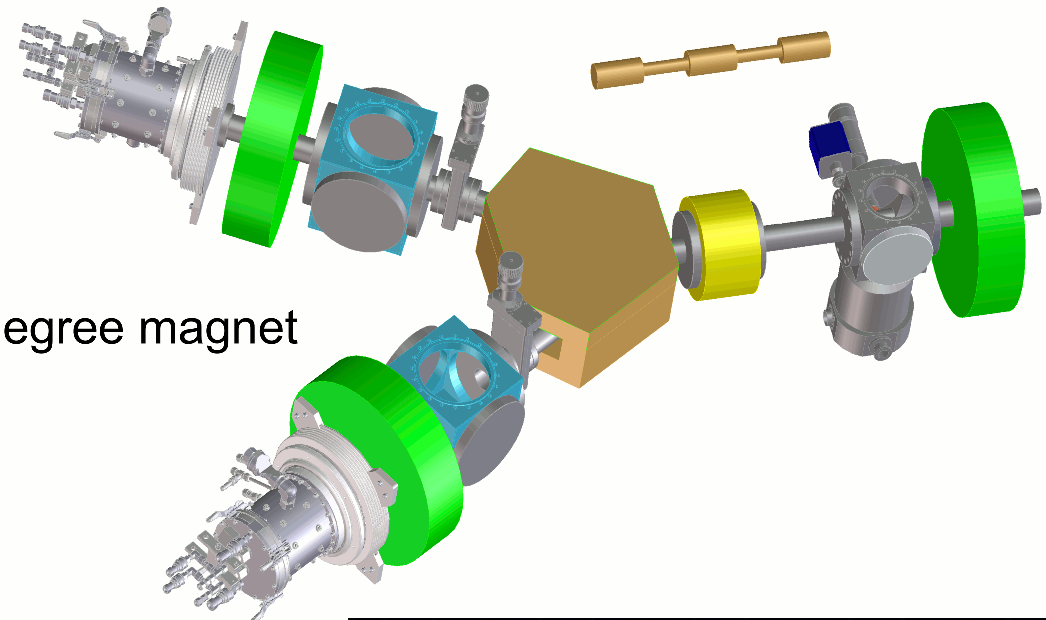
Define the ion source / LEBT / Chopper configuration

What elements in the beamline will be required?

Lay out the LEBT beamline configuration

Carry out beam dynamics simulations

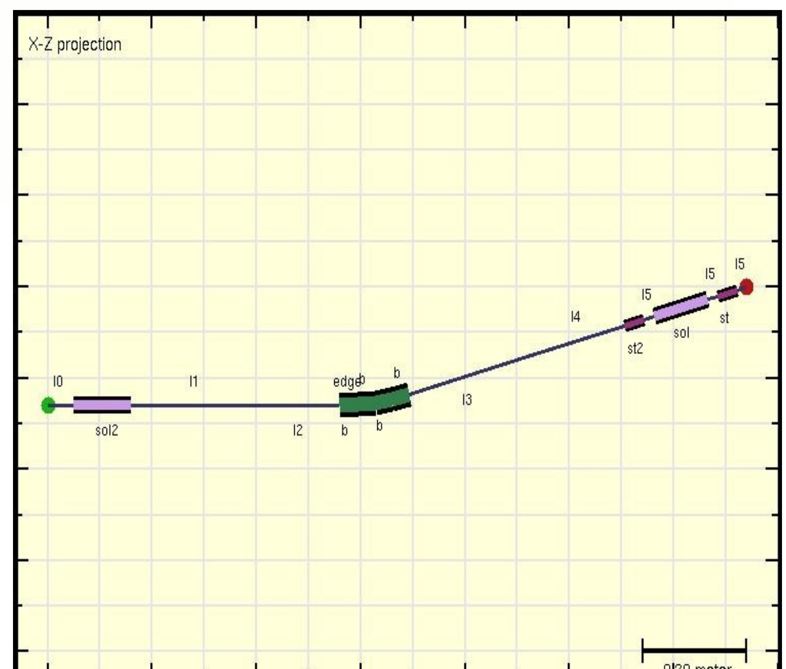
Proposed LEBT Configuration



Two ion sources, selected by a 20 degree magnet

Solenoid focusing
- after the ion source
- in front of the RFQ

The H-V tune split in the dipole is small, and no quadrupoles are required.

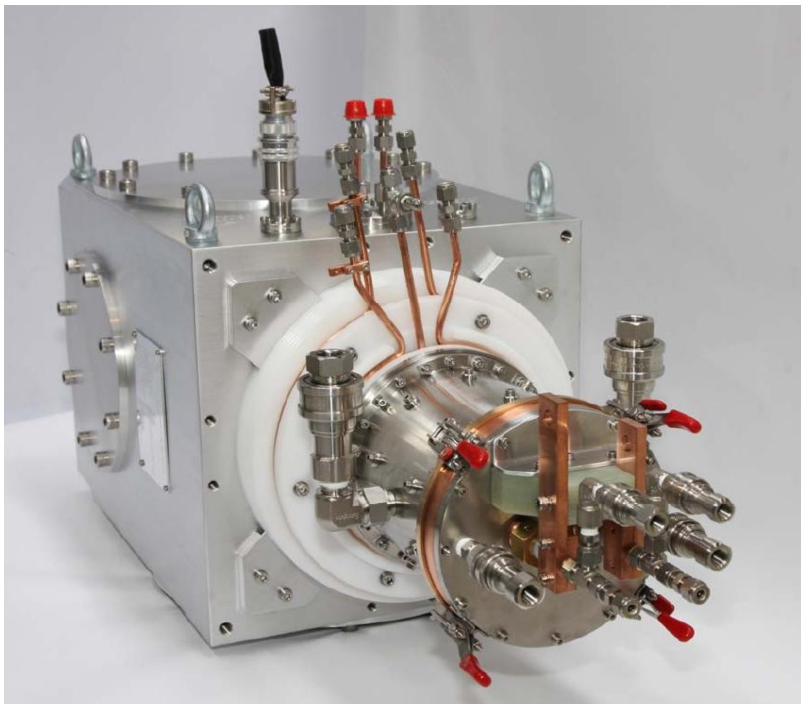


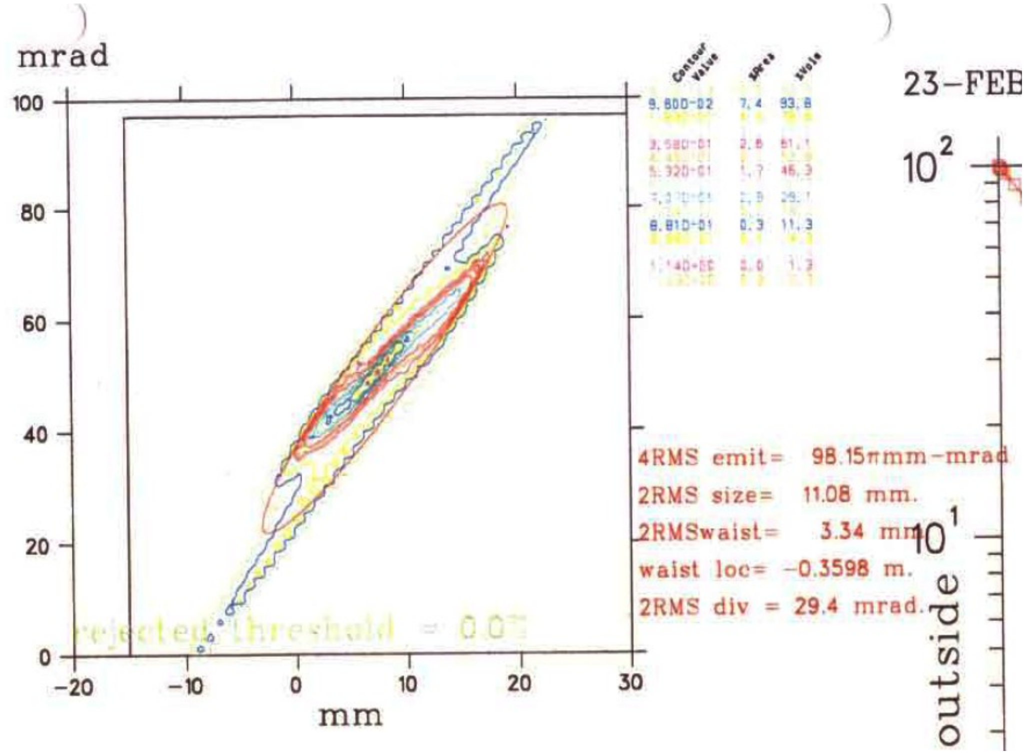
The first implementation will omit the dipole, and use just two solenoids.

An electrostatic chopper will be located near the RFQ entrance, either before or after the last solenoid.

LEBT Beam Dynamics Simulations

Initial beam parameters obtained from D-Pace performance specification.





With a measured beam current of 10.6 mA, at the point of the emittance measurement

β = 1.25 meters, α = -3.16, 4 x ϵ_u = 9.8 cm-mrad, ϵ_n = 0.189 mm-mrad

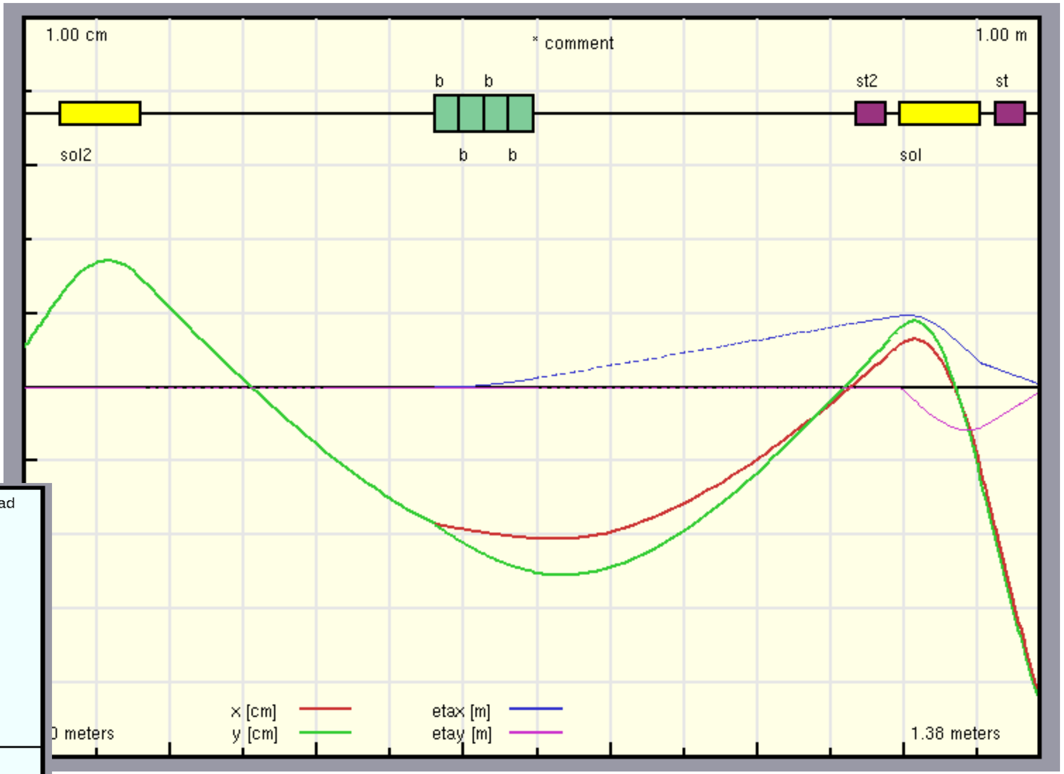
RFQ Matched Input Beam Requrirement

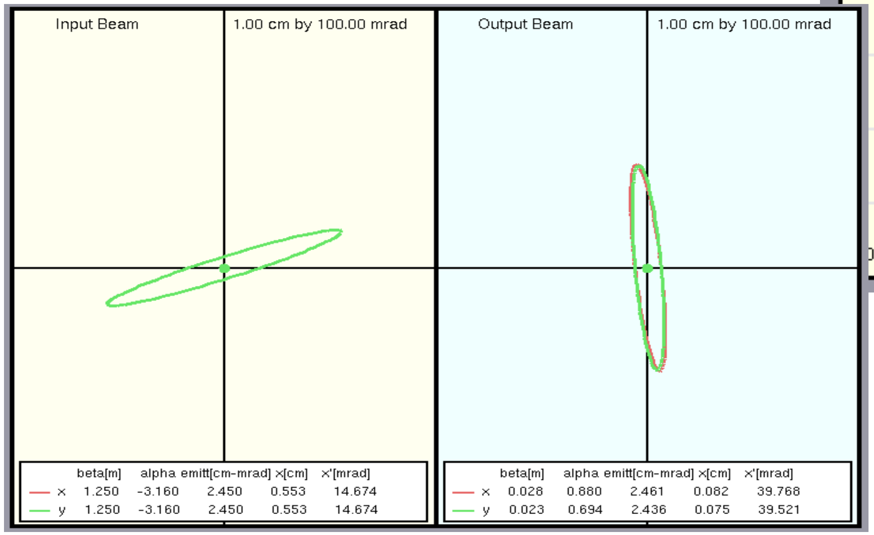
At the beginning of the radial matcher of the 325 MHz RFQ example, the matched beam is

$$\beta = 0.0226 \text{ meters}, \quad \alpha = .913$$

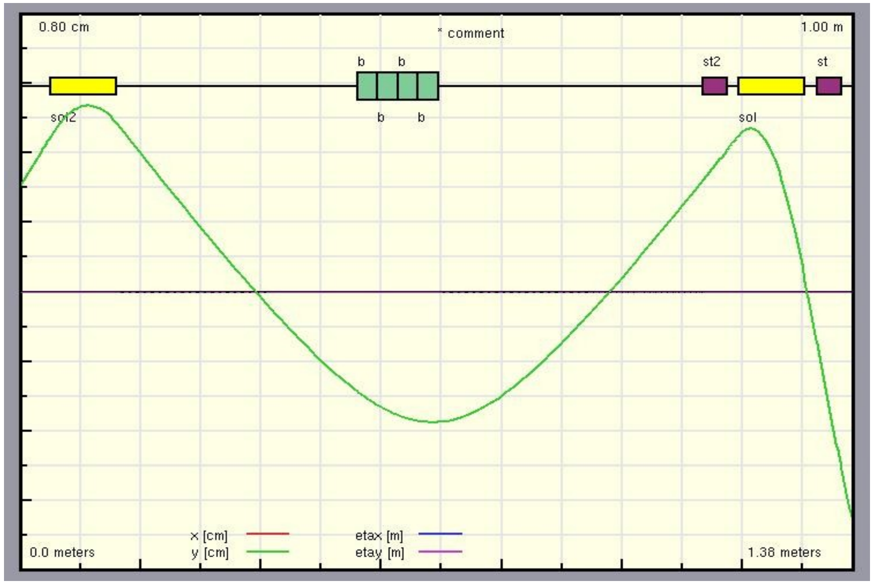
RMS envelope of the beam with 20 degree magnet. The dipole entrance edge angle is 20 degrees.

The H-V tune split is reduced in the final solenoid without additional quadrupole correction.

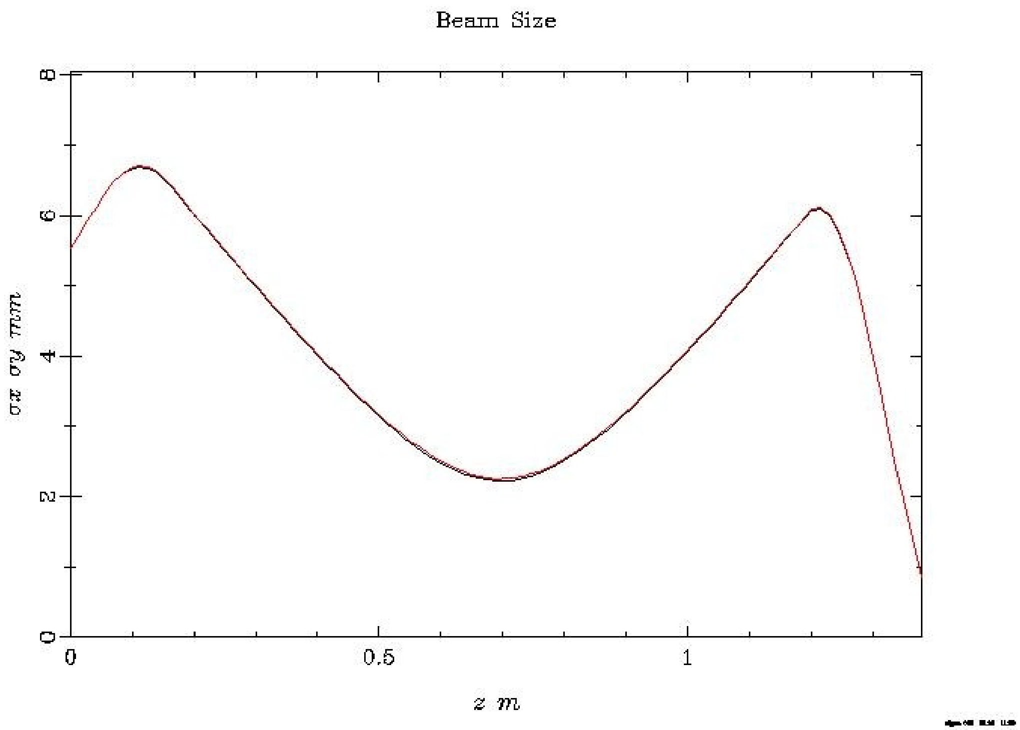




Simulation Codes Used that incorporate Space Charge



TLAT

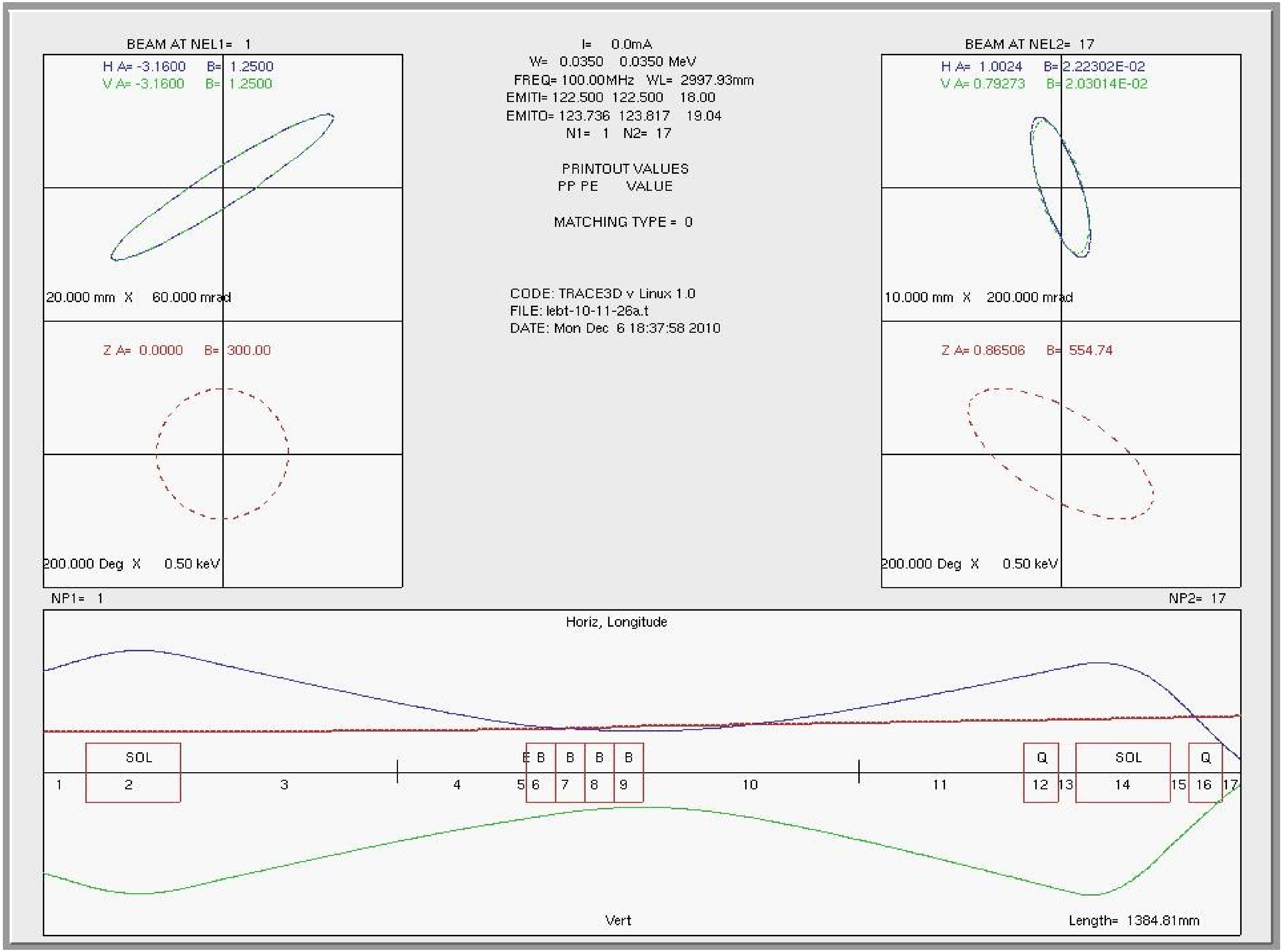


Astra

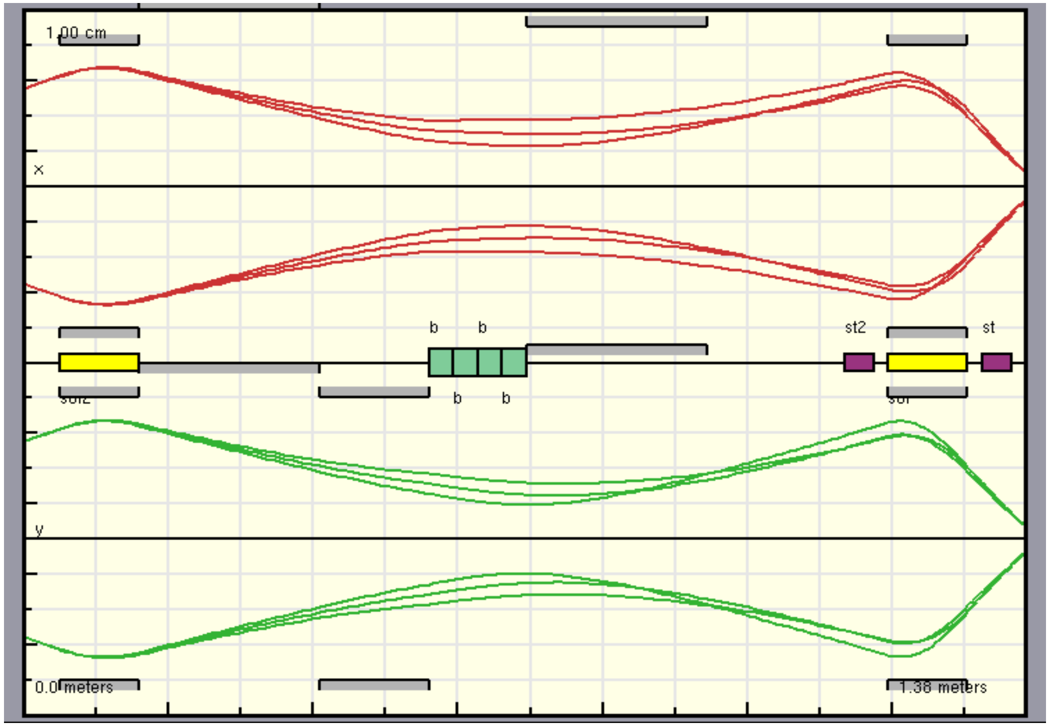
TLAT is a new code, based on a TRACE3D physics model. It is an envelope code that correctly incorporates both 2-D and 3-D space charge, deflectors, steering, etc.

Astra is a workhorse of the electron community. It is a macroparticle code with PIC space charge. It works as well with hadrons and offers extensive graphics and analysis facilities.

TRACE3-D Plot



Response to Varying Amounts of Neutralization



10 mA beam current

Neutralization percentage in 3 plots
- 100%
- 90%
- 80%

The beam parameters at the RFQ entrance are quite stable over varying amounts of neutralization.

We expect that the neutralization will approach 99%. For active beam switching in the 20 degree dipole and the fast LEBT chopper, the neutralization build-up time will be measured.

LEBT Chopper

Chopping in the LEBT:

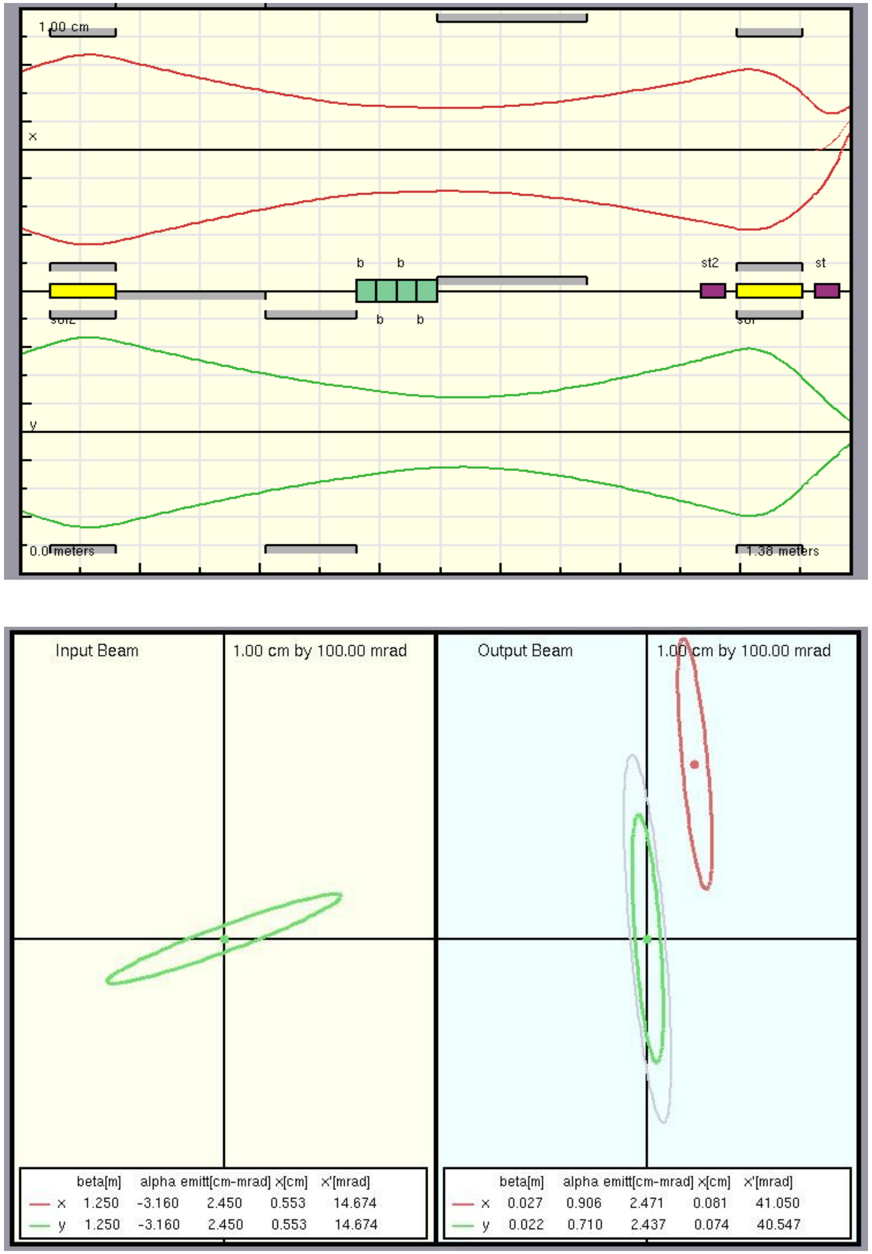
Insert gaps for the 3 GeV switching magnet at the linac exit

Reduce average current on a 1 MHz pattern to reduce MEBT collimator power?

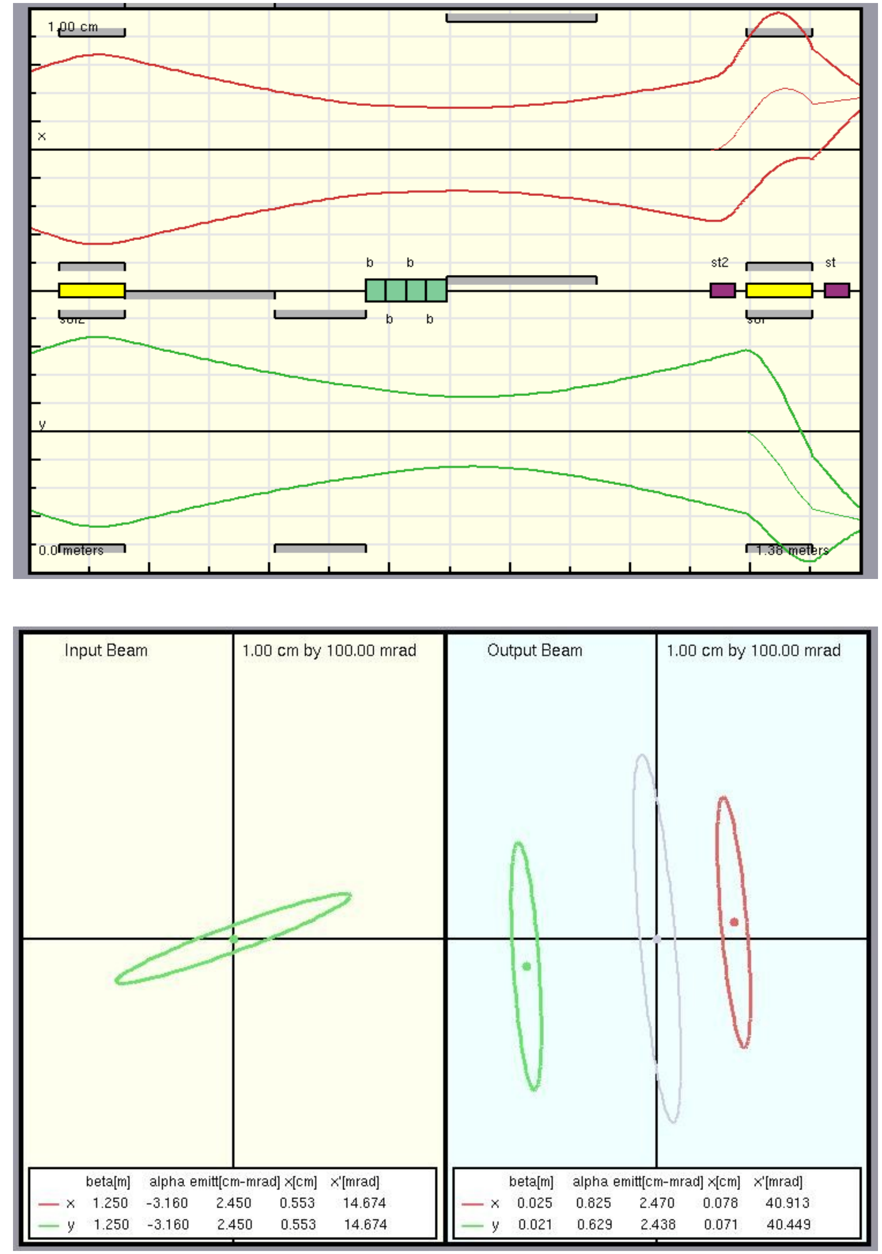
LEBT will use neutralized transport with solenoid focusing. Chopper must be at the end of the LEBT for the shortest path with time-varying neutralization fraction.

The chopper will comprise a time-varying transverse electric field. It could be a simple unidirectional deflection, or possibly a 4-phase system similar to SNS.

Location of LEBT Chopper



Chopper after solenoid



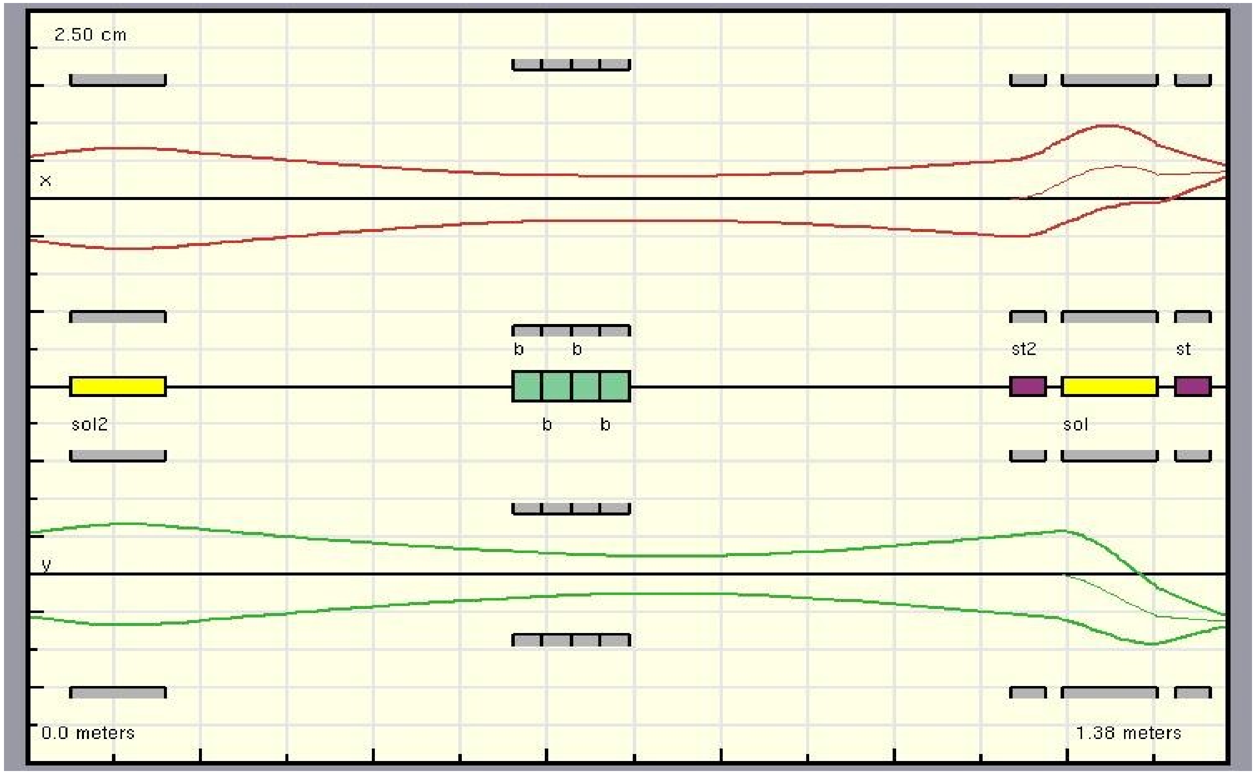
Chopper before solenoid

Chopping Through a Solenoid

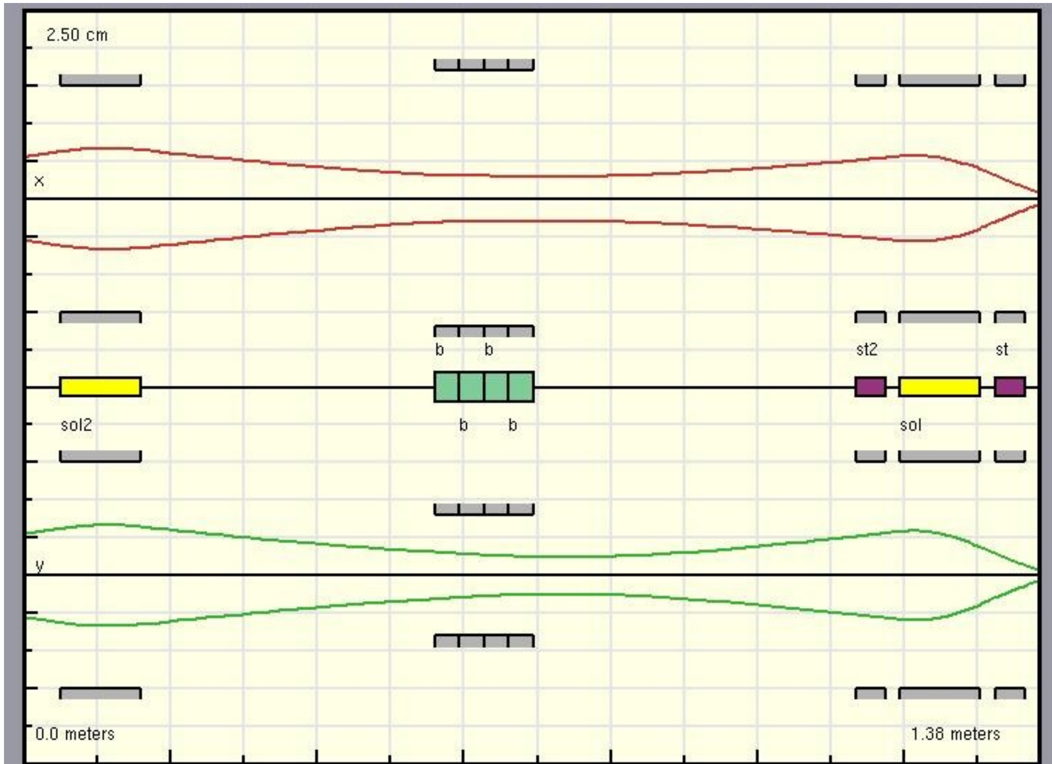
If the chopper is moved back before the final solenoid, its effectiveness is doubled.

It must be determined what the effect of chopping a neutralized beam (before the chopper) has on transport of a partially and time-dependent neutralized beam after the chopper and through the solenoid.

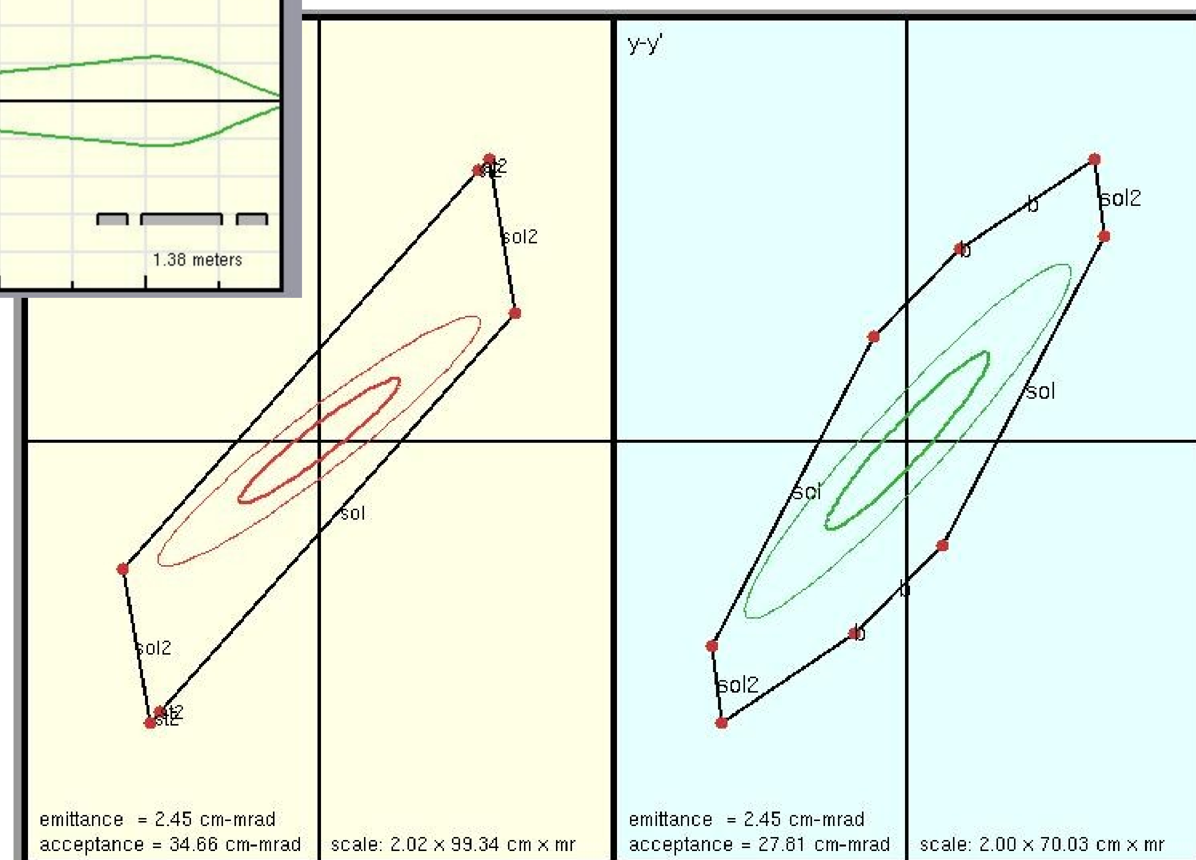
This must be experimentally determined. There is a lot to be gained if it works.



Required Aperture



We require at least a 3σ stay-clear. The solenoid aperture radius should be at least 2 cm clear.



RFQ Response to LEBT Chopper After Solenoid

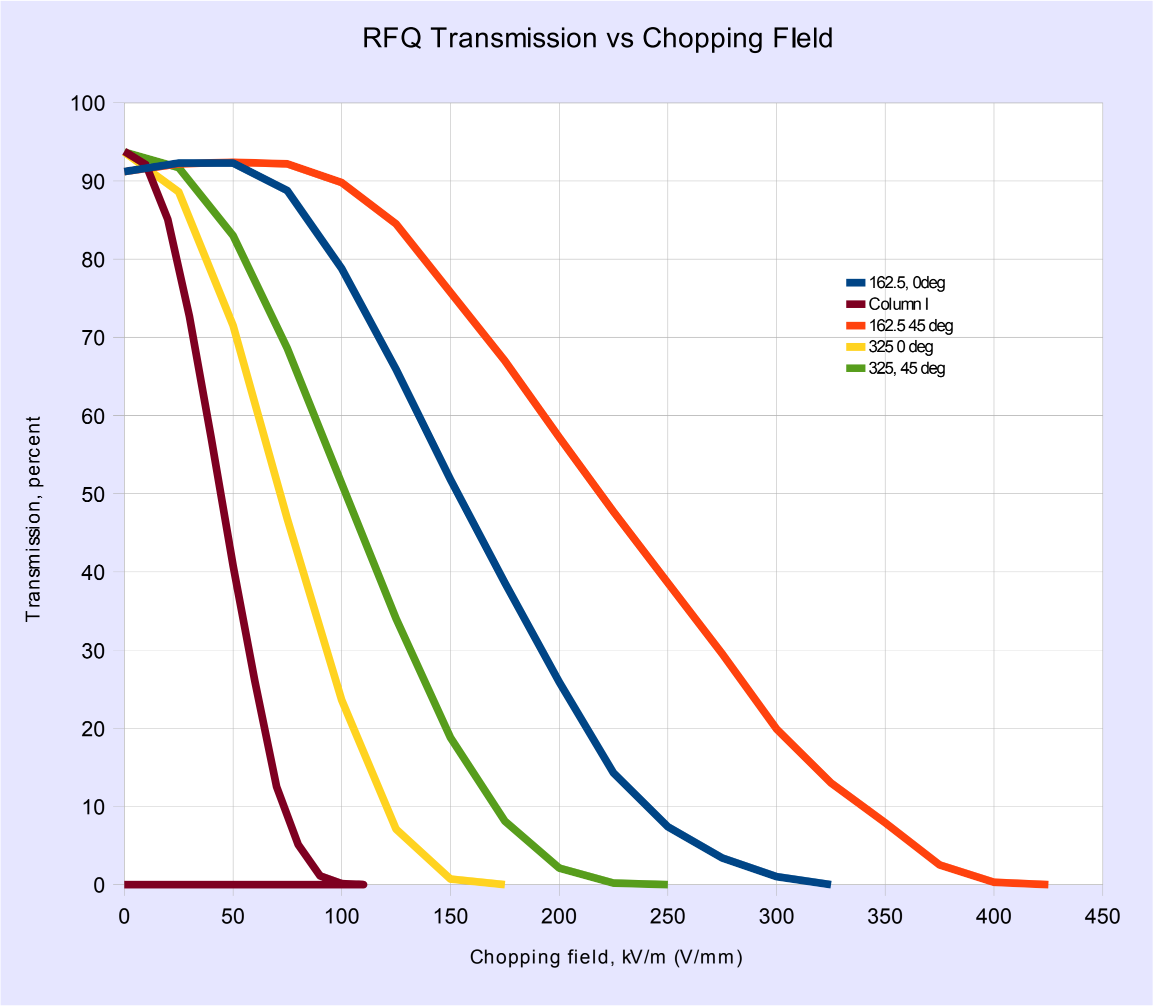
The RFQ Transmission to an ideal waterbag input beam is plotted for the 162.5 and 325 MHz RFQs.

The beam is deflected both in the x-plane, and 45 degrees to the x-plane.

The 45 degree deflection requires a larger deflection.

The 162.5 MHz RFQ has a larger transverse acceptance, requiring a large deflection.

Fields up to 500 kV/m (V/mm) are required for the 162.5 MHz RFQ.



Placing the deflector ahead of the solenoid reduces the field requirement for the 325 MHz RFQ by a factor of two (brown trace)

LEBT Chopper Frequency

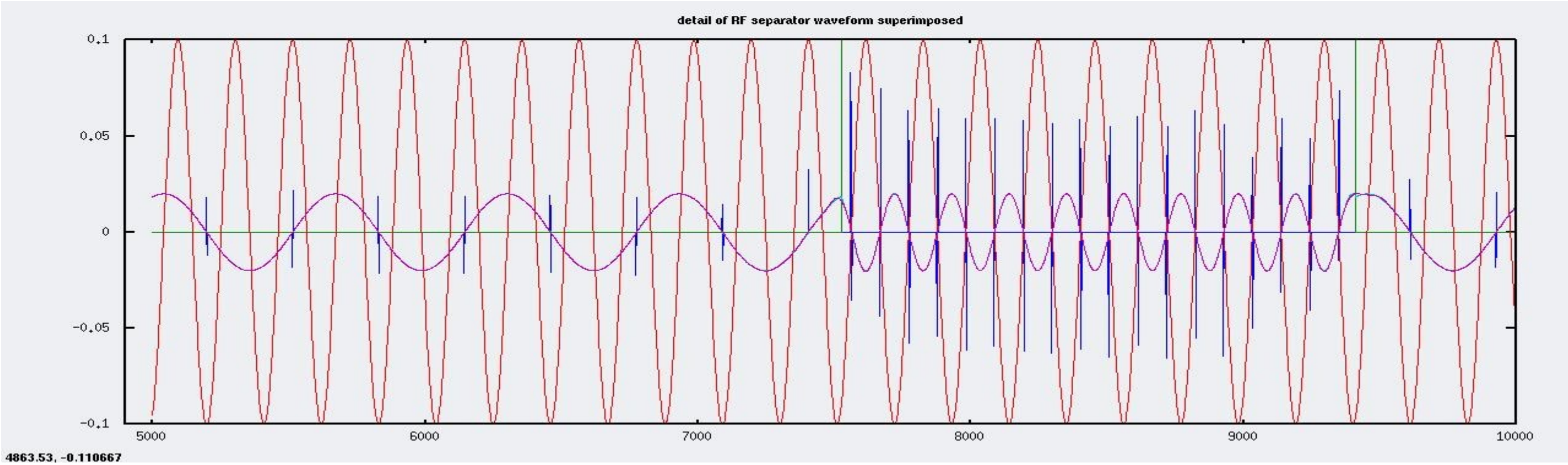
Can the LEBT chopper insert a 500 microsecond gap in the RFQ beam?

Yes. This should be easy.

Can the LEBT chopper reduce the thermal load on the MEBT beam stops?

No, unless beam is crammed into a fraction of the 1 microsecond cycle.

The beam delivered to the linac with the narrow-band choppers is spread out over the 1 microsecond repeat cycle. Most of the beam is thrown away so the average current is 1 mA in the linac. The pulses that are passed to the linac are distributed fairly evenly over the 1 microsecond repeat cycle.



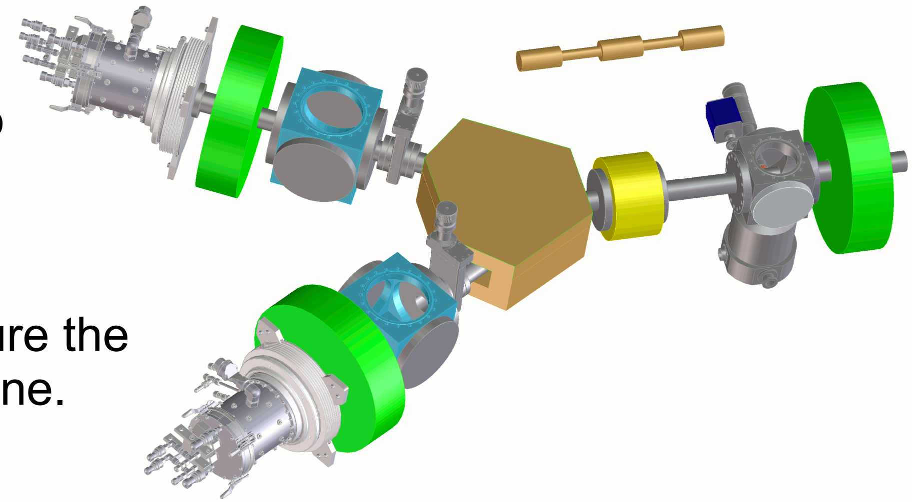
30% detail of one 1-microsecond cycle. The micropulse rate here is 162.5/6 = 27 MHz. Five of every 6 micropulses from a 162.5 MHz RFQ are collimated out.

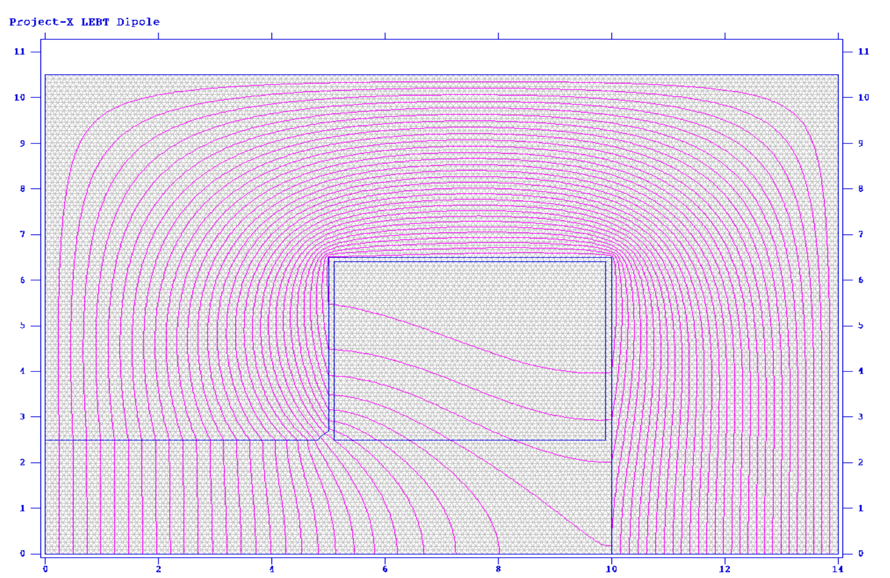
Two Ion Sources

Two ion source will be provided.

This produces redundancy and the ability to replace one ion source while the other is in operation.

Each branch will have diagnostics to measure the ion source performance before it is put on-line.





A question to answer is whether fast switching between ion sources is required.

The design of the $\pm$20 degree dipole depends critically on whether it is a fast or a slow magnet.

The nominal design is a 20 cm long magnet, 700 gauss field, and a 5 cm full gap.

20 degree Selector Dipole

A slow magnet design is very modest, with a power of about 10 watts. It can be made even smaller with a reduced vertical gap.

The magnet is of rectangular geometry, with a ±20 degree entrance angle for the two ion source orbits, and normal exit angle.

A fast magnet will be more challenging. The switching time of 500 microseconds requires laminating the core with high silicon steel, and the power supply must provide a high switching voltage.

As the gap is reduced, the DC current is reduced, but the inductance of the magnet increases, increasing the peak switching voltage. A fast magnet optimizes with a large gap, and a slow magnet with a small gap.

Project-X LEBT Switching Magnet Design

Beam					
	KE	35000	eV	Beam Kinetic Energy	
	pmass	9.38E+08	eV	Beam Mass	
	beta	0.00864		velocity	
	Clight	3.00E+08	m/sec	speed of light	
	Rigidity	0.0270	T-meters	beam rigidity	
	Mu_0	1.26E-06		Mu 0	
Orbit					
	theta	20.0	degrees	bending angle	
	theta	0.349	radians	bending angle	
	L	0.200	meters	magnet length	
	B	0.0471	Tesla	Magnet Field	
	H	37514.3	Amp-turns	Magnet Field	
	rho	0.573	meters	Radius of Curvature	
Magnet					
	full gap	0.040	meters	gap height	
	gw	0.050	meters	gap half-width	
	cw	0.050	meters	coil package width	
	pw	0.040	meters	return leg width	
	ch	0.040	meters	coil package height per pole	
	eta	0.900		magnet efficiency factor	
	s	0.500	meters	steel length of return flux	
	mu_steel	2000		relative to mu_0	
	NI	1677.72		Amp-turns	
	Vgap	8.00E-04	Meters^3	field volume	
	Ugap	0.71	Joules	Stored Energy in gap	
	Vsteel	0.009	Meters^3	Steel Volume	
	Usteel	0.442	Joules	Stored Energy in Steel	
	Full Width	0.280	meters	11.02 inches	
	Full Height	0.200	meters	7.87 inches	
Coil					
	N	50		number of turns, upper and lower coil packages	
	I	33.55	Amperes	Excitation current	
	p	0.70		coil packing factor	
	rho	1.68E-08	Ohm-meter	copper resistivity	
	Lth-winding	30	meters	total winding length	
	Area-wire	5.60E-05	m^2	wire area cross-section, two packages	
	R	0.0090	ohms	coil resistance	
	Pdc	10.13	Watts	DC magnet power	I^2 R
	Volts	0.302	Volts	DC voltage drop	I R
	J	599187	Amps/m^2	wire current density	
	J	0.599	Amps/mm^2	wire current density	
	r_wire	8.444	mm	magnet wire diameter	
Pulse					
	L	2.04E-03	Henries	magnet inductance	2U/I^2
	t_switch	0.0005	seconds	switching rise time	
	dI/dt	134217.78	Amps/sec	switch from + to – field	
	Vpeak	274.07	Volts	switching voltage	L*Idot

Issue: LEBT Magnet

Two ways to go: fast laminated magnet or slow solid-core magnet

2-entry port, 20 degree selector magnet.
20 degree entrance angle, 0 degree exit angle
typically 20 cm long, 700 gauss field.
Entrance gap width 6-8 cm wide

Slow magnet: used to switch to a standby ion source in a few seconds
- small, with small gap, 2.5 cm full gap
- Very modest power
- Solid core construction

Fast magnet: used to dynamically switch two ion sources
- 500 microseconds switching time
- much larger gap to reduce inductance to keep switching voltage reasonable
- laminated core
- may require more complex vacuum chamber to reduce eddy currents
- complex power supply: low static voltage, high switching voltage

Selection will depend on beam requirements.

LEBT Betatron Parameter Match Range into RFQ

The Twiss parameter region with 90% neutralization of 10 mA current:

α = 0.5 to 4.0

β = 0.010 to 0.04 meters

is covered.   The nominal match is α = 0.913, β = 0.0226 meters.

Matching parameters strongly outside the nominal match require larger solenoid aperture.

The beam at the match point is almost independent of the space charge neutralization if above at least 80%.

LEBT R&D Program

The LEBT will be developed and tested incrementally

Extraction and 30 keV acceleration from the ion source
Electron diversion and trapping
Ion source emittance measurements
Pulsed switching magnet then added
Emittance, neutralization time measurements
Matching section into RFQ that accommodates two ion sources operating at different current levels
4-phase chopper implementation at RFQ entrance
Establish matching parameters required by RFQ

The LEBT will be fully configured and tested during the R&D phase.

The separation of the 30 keV acceleration, the magnetic transport, and the pulsed electric field chopper will ensure high reliability.

RFQ

162.5 or 325 MHz? We don't want to engineer two designs. They will be significantly different.

The RFQ uses the kick-buncher design, resulting in a low output longitudinal emittance.

Carry over some mechanical engineering from a recent study for SNS.

Compare 162.5, 325 MHz RFQs

	Proj-X 162	Proj-X 325	
Frequency	162.5	325	MHz
Injection Energy	35	30	keV
Output Energy	2500	2500	keV
Current	10	10	mA
Length	385	287	cm
Length/Lambda	2.1	3.1	
Vane-Vane Voltage	90.8	64.2	kV
Peak E-field	20.7	27.6	MV/m
E-field/Kilpatrick	1.52	1.55	kilpatrick
Cavity Power	155*	149*	kW
Power/Length	40	52	kW/m
Avg Wall Power Density	2.1	5.2	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	MeV-Degree
Output Transverse Emittance	0.030	0.028	cm-mrad
Transmission	94	90	percent

Refinement of the 325 MHz RFQ Design

Lessons learned from SNS / ADNS / SNS RFQ Replacement experience

- Engineering for high power density
- Two-layer construction - brazed vs bolt-on exoskeleton
- Water cooling passage configuration
- ANSYS modeling of temperature distribution, stress, freq shifts

Optimize the beam dynamics

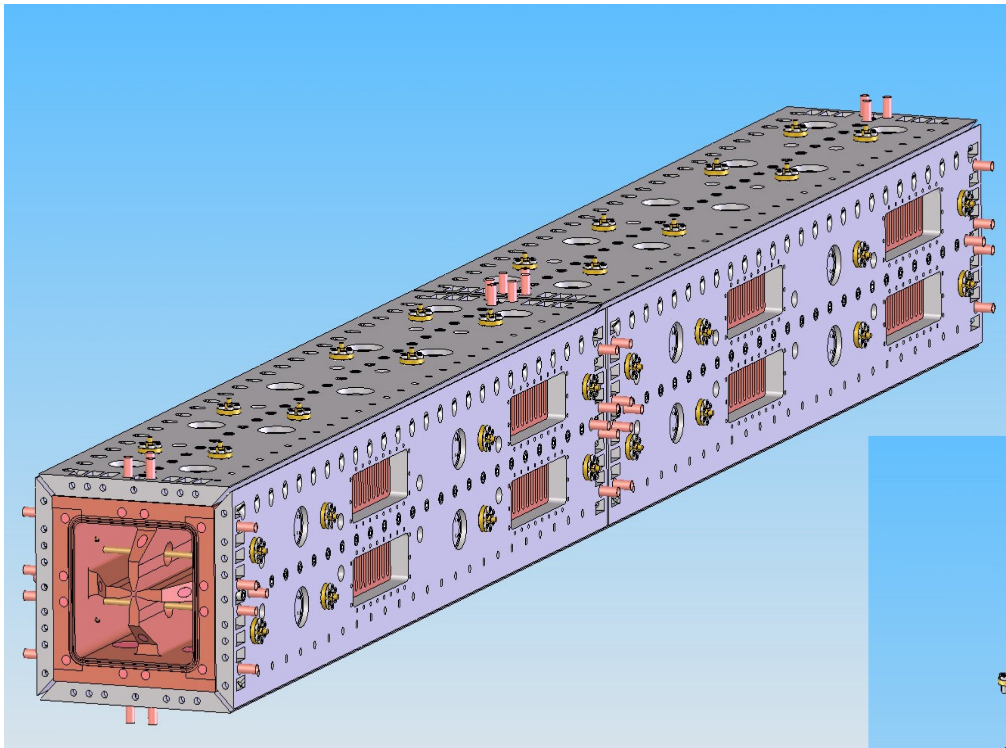
- add more safety margin for the aperture
- improve the 90% transmission
- reduce the losses over 2.1 MeV to minimize neutron production

Assess longitudinal stabilization need, technique

Reduce the peak power density in hot spots

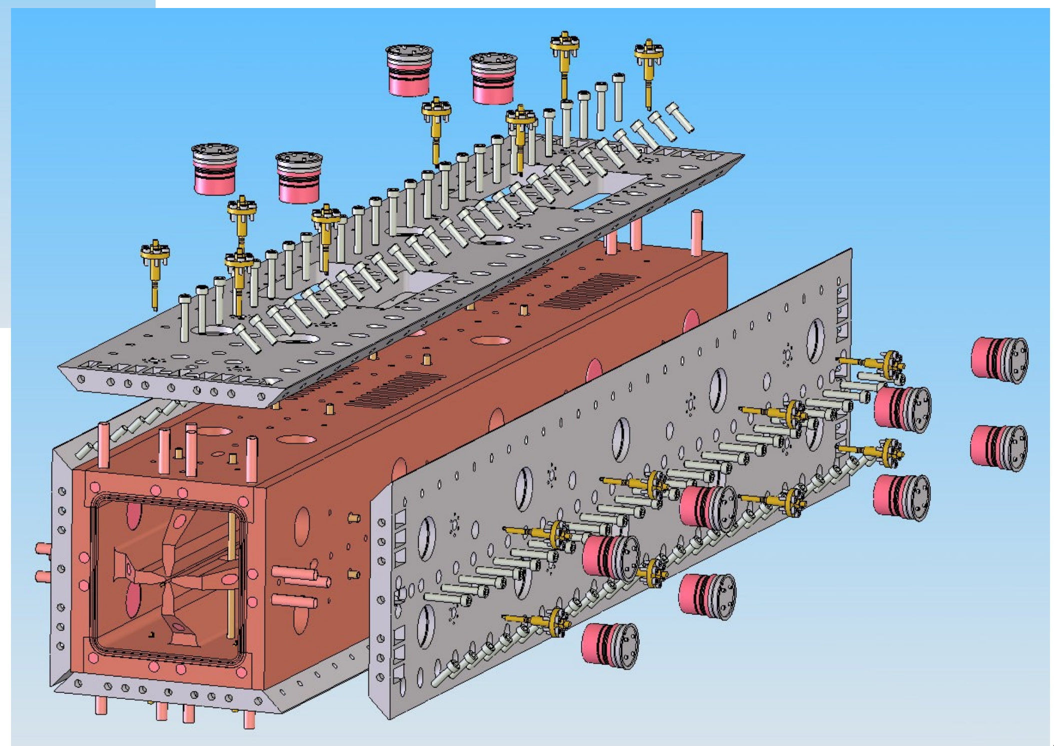
Preliminary engineering study of the RF structure

325 MHz RFQ Cross Section Engineering Analysis



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

RFQ Output Energy

Reducing the output energy to 2.1 MeV should be considered for the following reasons.

I propose to change the output energy of the RFQ to 2.1 MeV for the following reasons:

This is just below the threshold energy of 2.135 MeV for neutron production in copper with the $Cu^{63}(p,n)Zn^{63}$ reaction. Cu^{63} comprises 69% of natural copper.

The deflection angle of the transverse electric field choppers in the MEBT is increased by the inverse energy ratio, or 19% to 5.95 mrad, increasing the extinction ratio of the choppers. Alternately, the chopper voltage may be reduced. The TW chopper phase velocity must be lowered by 8.3%.

The power deposited in the MEBT collimators is reduced to 84%.

The beam collimators in the MEBT are allowed contain copper, with its good thermal conductivity, without generating neutrons. This would allow the MEBT to be unshielded.

The length of the example 325 MHz RFQ is reduced from 269 to 224 cm, a reduction of 17%, and a reduction of power of up to 17%. The shortened RFQ is 2.4 free-space wavelengths long, raising the possibility of eliminating longitudinal mode stabilizers altogether, further reducing the RF power requirement and simplifying the construction. The RFQ could be made in just two modules.

The RFQ, constructed of copper, would not produce neutrons. The 64 keV X-ray bremsstrahlung, if any, is easily shielded locally. The RFQ need not be located in a shielded area.

The transmission through the RFQ is slightly increased, as the exit end has the smallest aperture.

Note that the 0.015% of deuterium component in hydrogen will not be accelerated and thus will not present a radiation hazard as a potential source of neutrons by breakup or (d,d) reactions.

The downsides:

The spoke cavity following the RFQ must accept a beam velocity $\beta = 0.0669$, an 8.3% reduction from 2.5 MeV. Is the phase slip in the first cavity acceptable?

There may be some additional emittance growth in the MEBT due to the lower energy.

MEBT Issues

Chopper configuration: narrow/wideband, deflection angle

Beam Absorber heating

Input / output matching from RFQ to MEBT to spoke cavity

Tune, especially moving y-phase plane to near 0 or 180 degrees/period
generate a ribbon beam in the y-plane

Neutron production

Diagnostics

MEBT

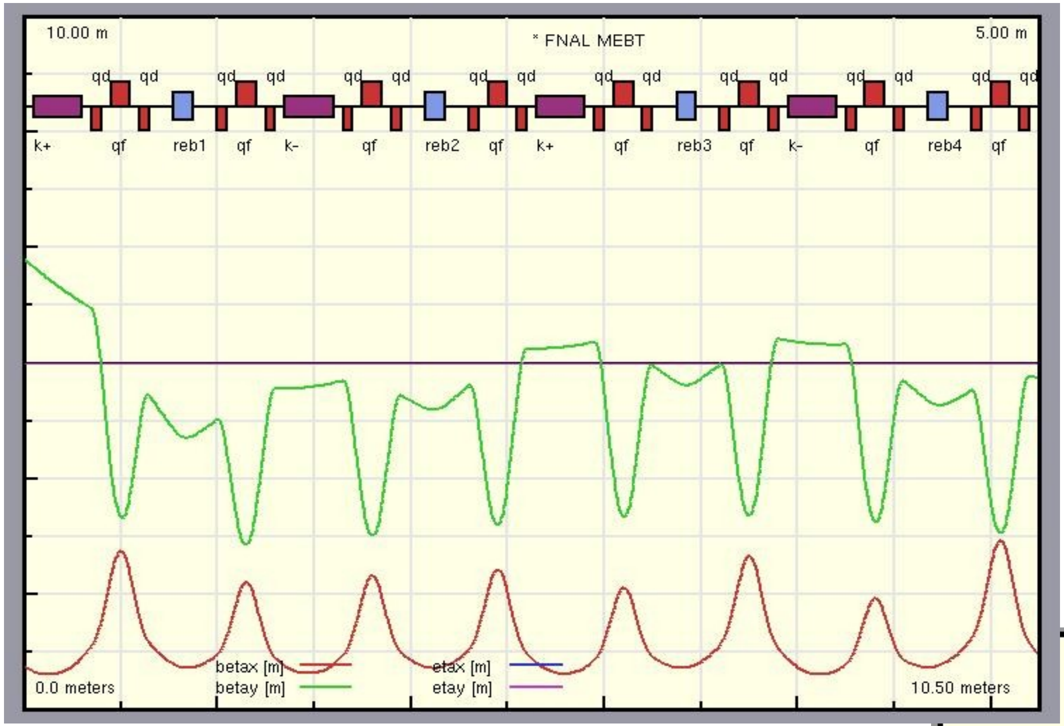
Who builds it?

What is the FNAL progress with the fast choppers?

What is the FNAL progress with the beam collimators?

Suggestions for diagnostics?

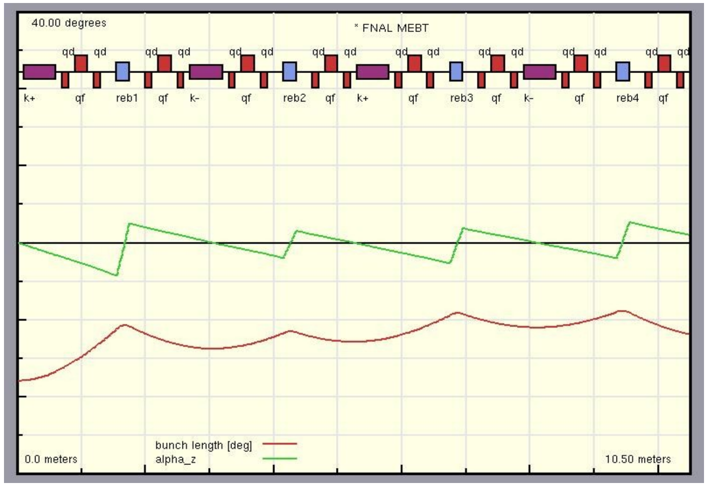
MEBT Beam Envelope



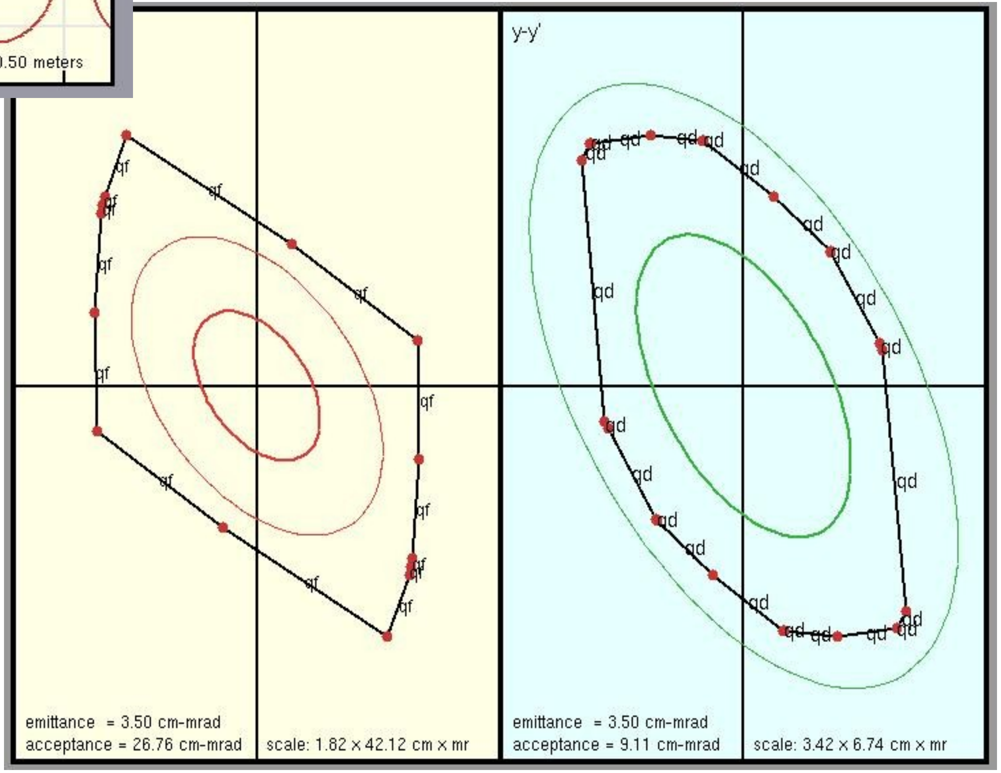
Betatron Functions with split tune.

MEBT acceptance area with 2 cm quad aperture radius. 1 x and 4 x emittance ellipses.

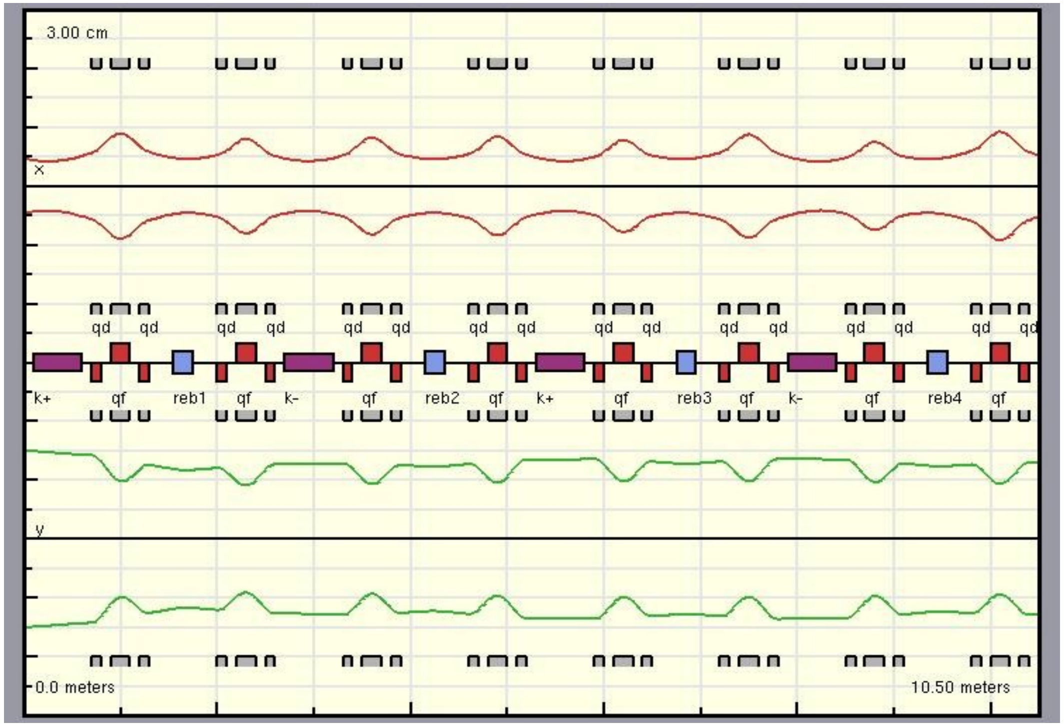
Larger apertures will be needed to go out to at least 3σ.



Bunch Length along MEBT



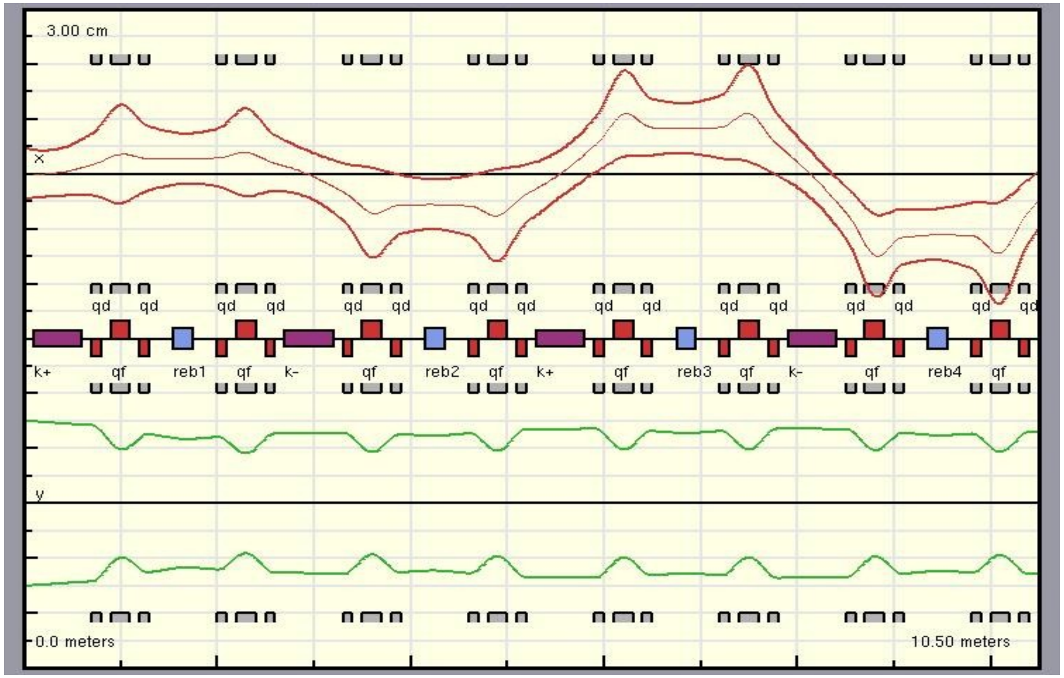
Beam Envelope with Deflection



Split tune used to increase y-width

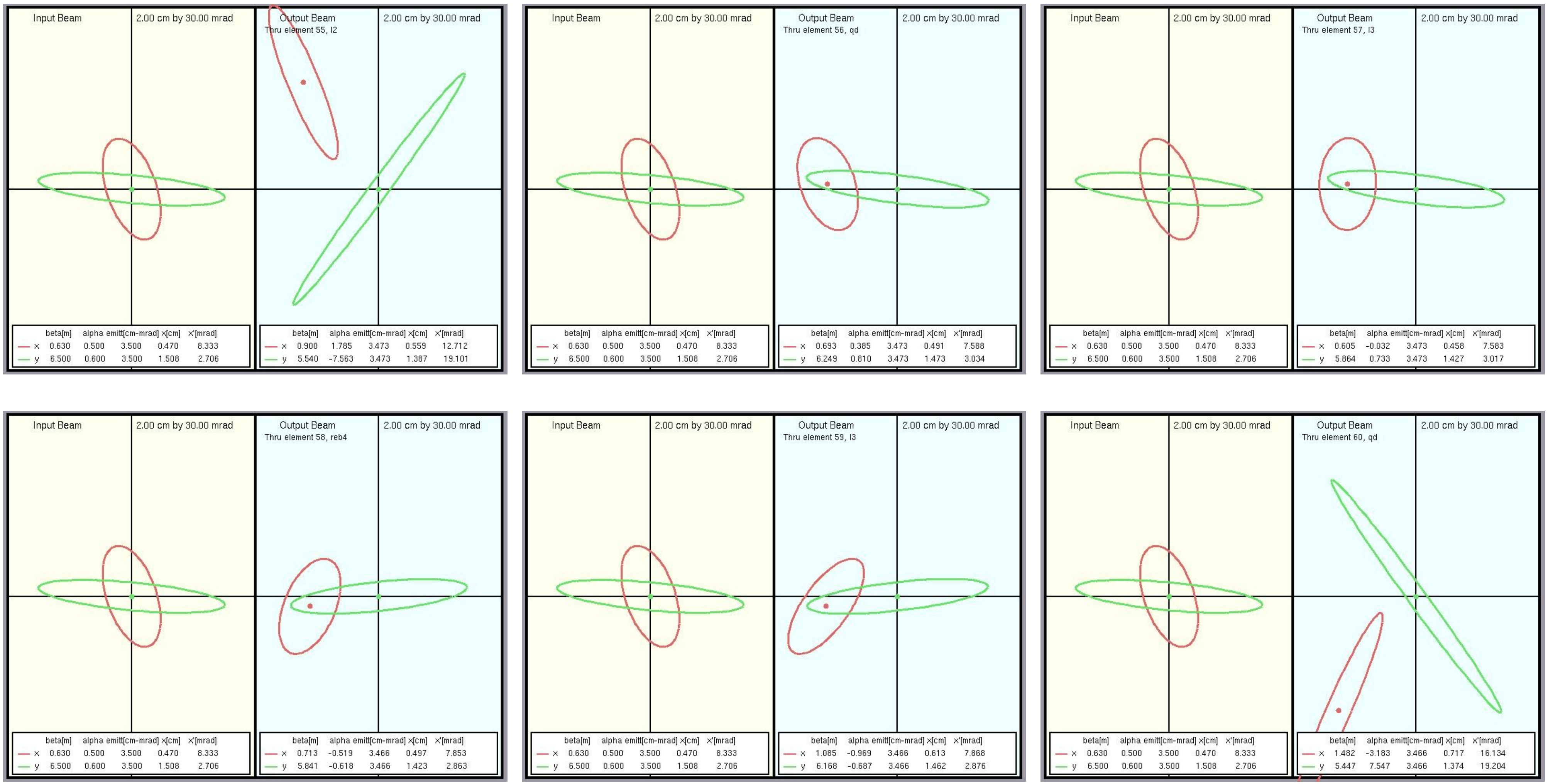
Each deflector is 50 cm long with a transverse field of 50 kV/m (500 V/cm).

1 x rms beam size shown



Beam Phase Spaces around location of maximum deflection

Six locations, centered around the last rebuncher, 10 mA beam current



The best location is that that moves the beam furthest off-axis with the minimum betatron amplitude (upright ellipse). Further improved with the widest beam in the transverse plane.

MEBT Simulations

Start with basic FNAL layout
  periodic lattice, π phase advance per period
  four transverse TW deflectors
  four rebuncher cavities
  needs refinement at ends to match beam from RFQ and into spoke cavity
  include diagnostics

Look into MEBT lattice tune variations
  change tune in y-phase plane to widen beam

Look at deflection amplitude to produce required extinction ratio.
  Use realistic beam with transverse tails.

Establish beam stay-clear and apertures

MEBT 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

MEBT R&D Program

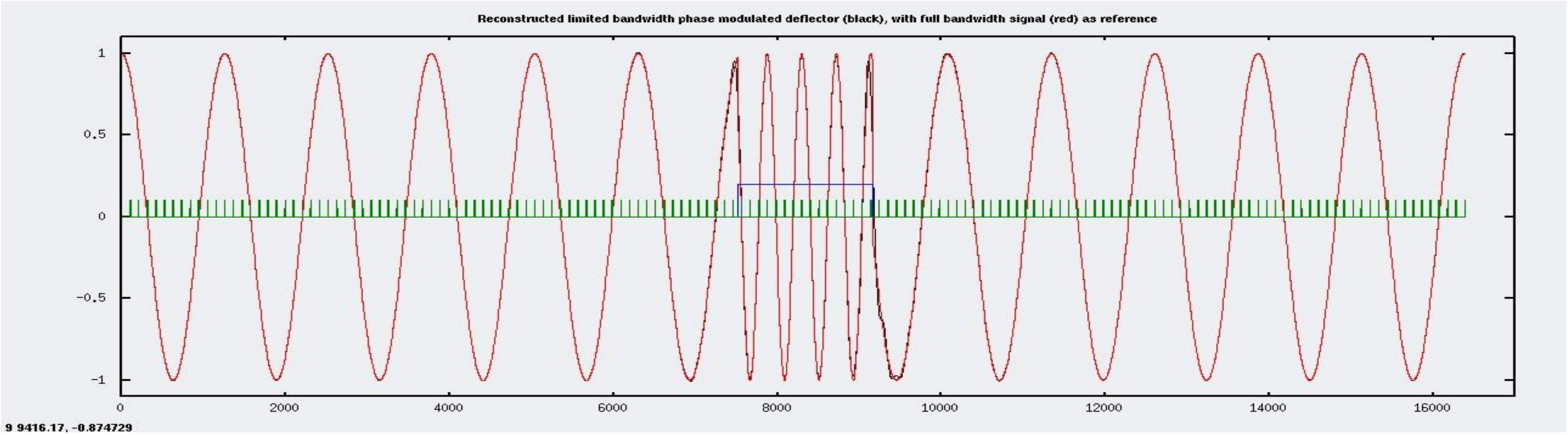
Better define beam requirements
- define what kind of time structure the SCL can handle
- may help with design of a LEBT chopper that mitigates MEBT thermal problems

Choose RFQ frequency and output energy
- Then get on with developing narrow-band chopper scenarios at LBNL

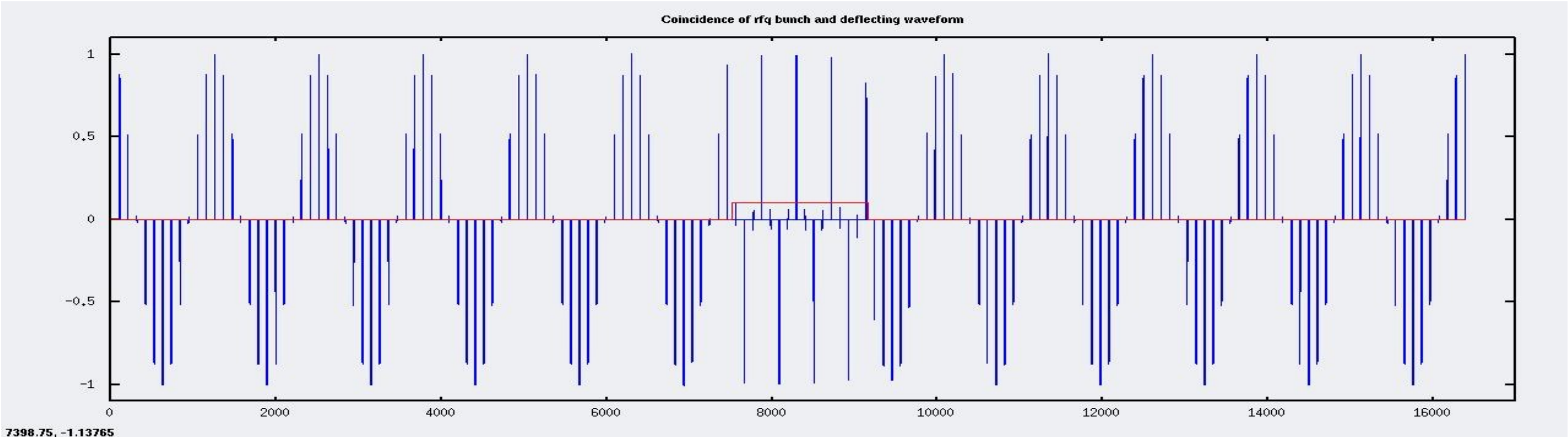
Select leads for critical design issues
- chopper
- chopper power supplies
- beam collimators

Chopper Waveforms
(one of many)

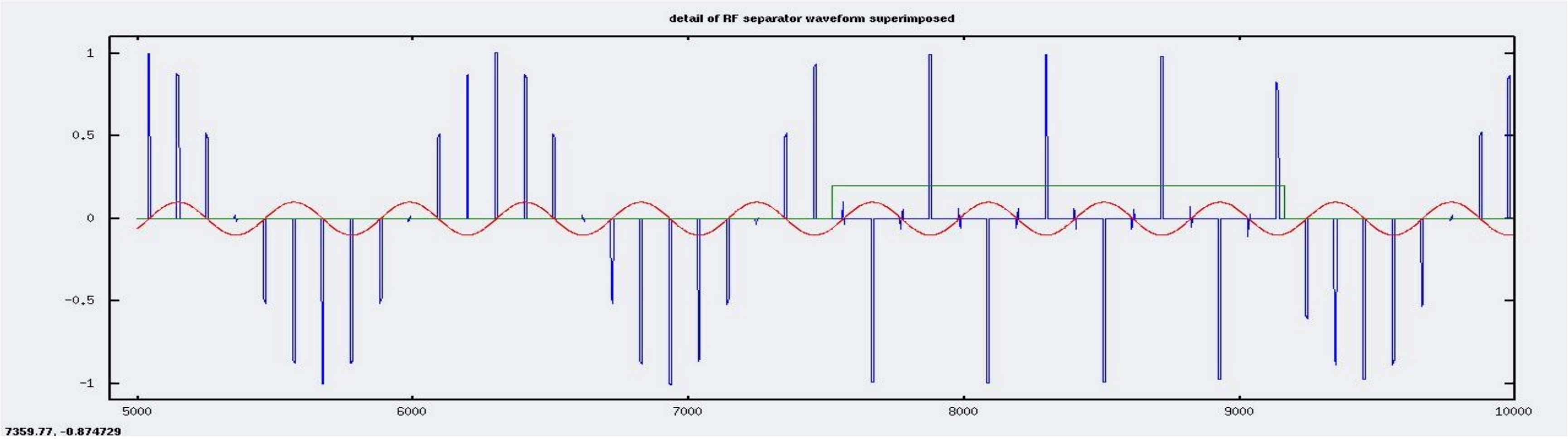
Dual Frequency Chop Example



5/6ths of the pulses removed to collimator



Detail, with RF separator waveform



Chopper Target Power Density Mitigation

Total power is up to 25 kW, steady (10 mA, 2.5 MeV, all chopped out)
More typically 12-20 kW.

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

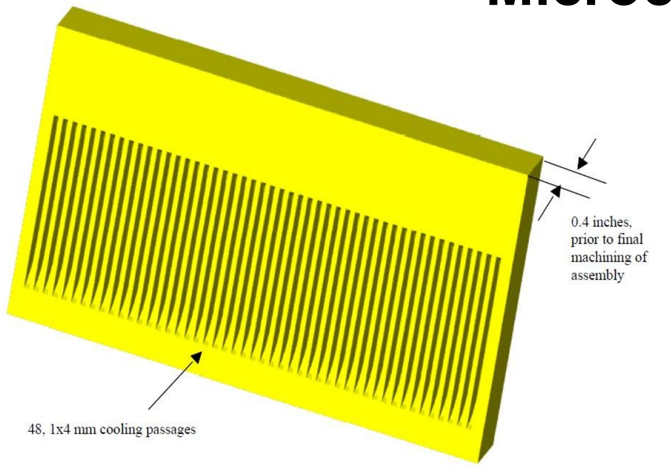
Possible LEBT chop
If the SCL and experiments can handle it: another factor of 2

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

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

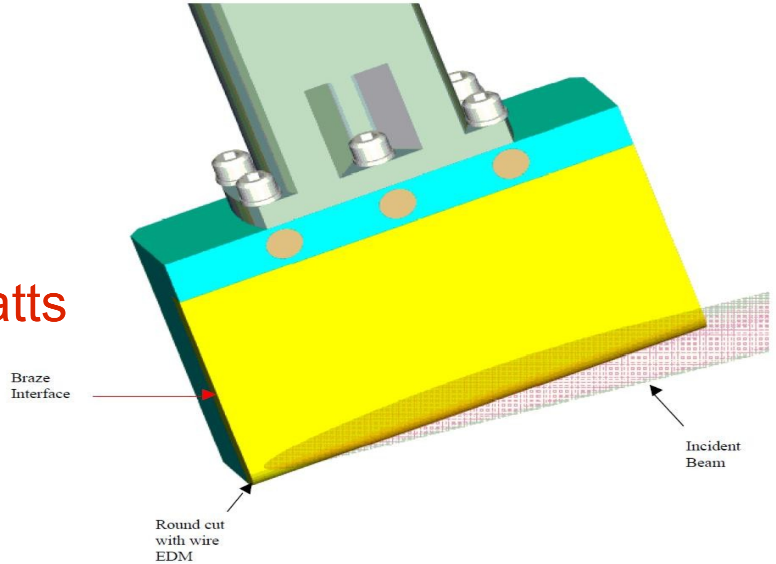
For angle of incidence of, say, 85 degrees, the power density is about 400 W/cm^2 if the beam cross section is 3 cm^2. (4500 W/cm^2 / tan 85 degrees)

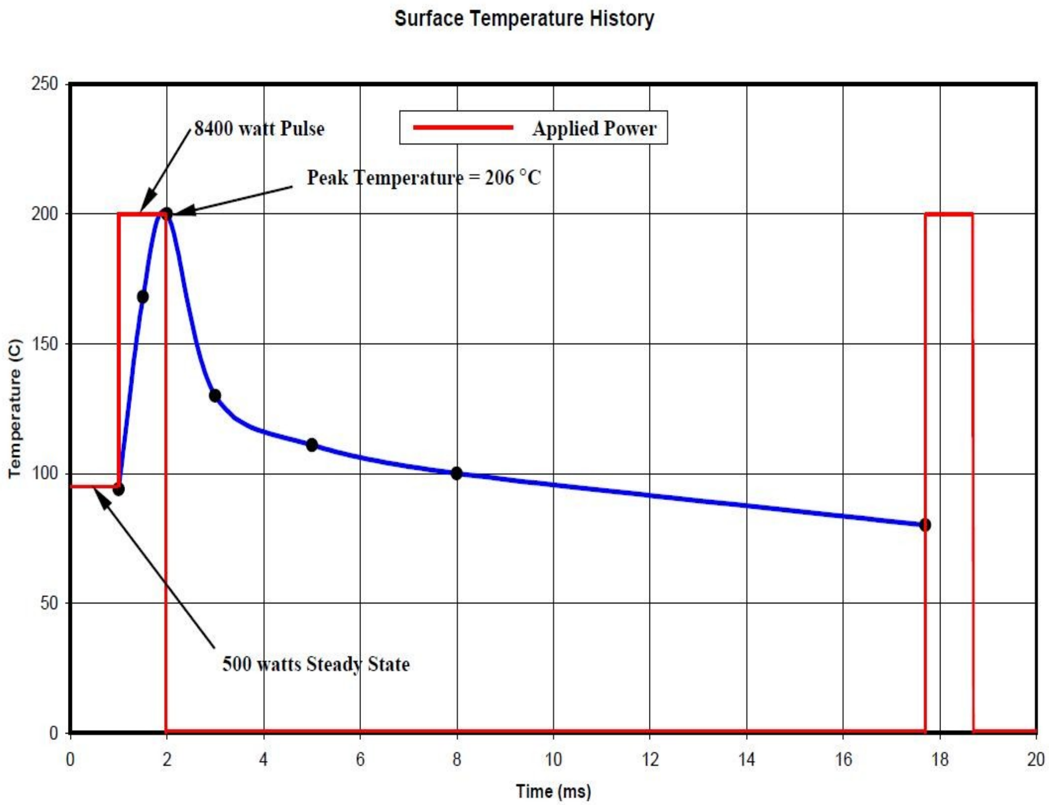
Microchannel Plate Chopper Target for SNS

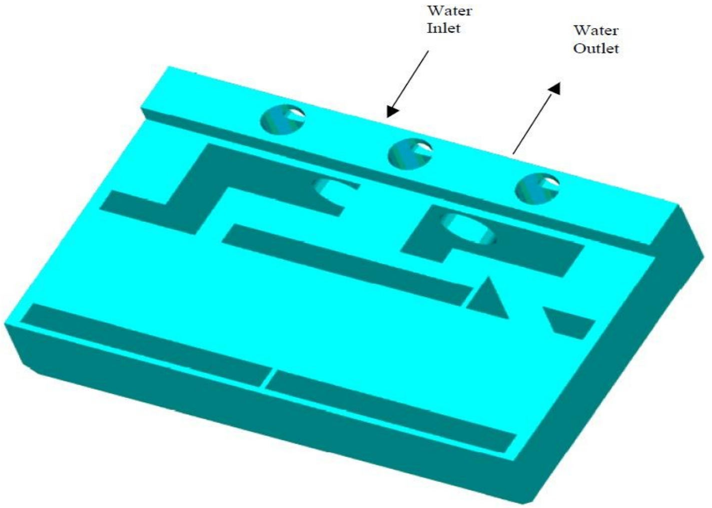


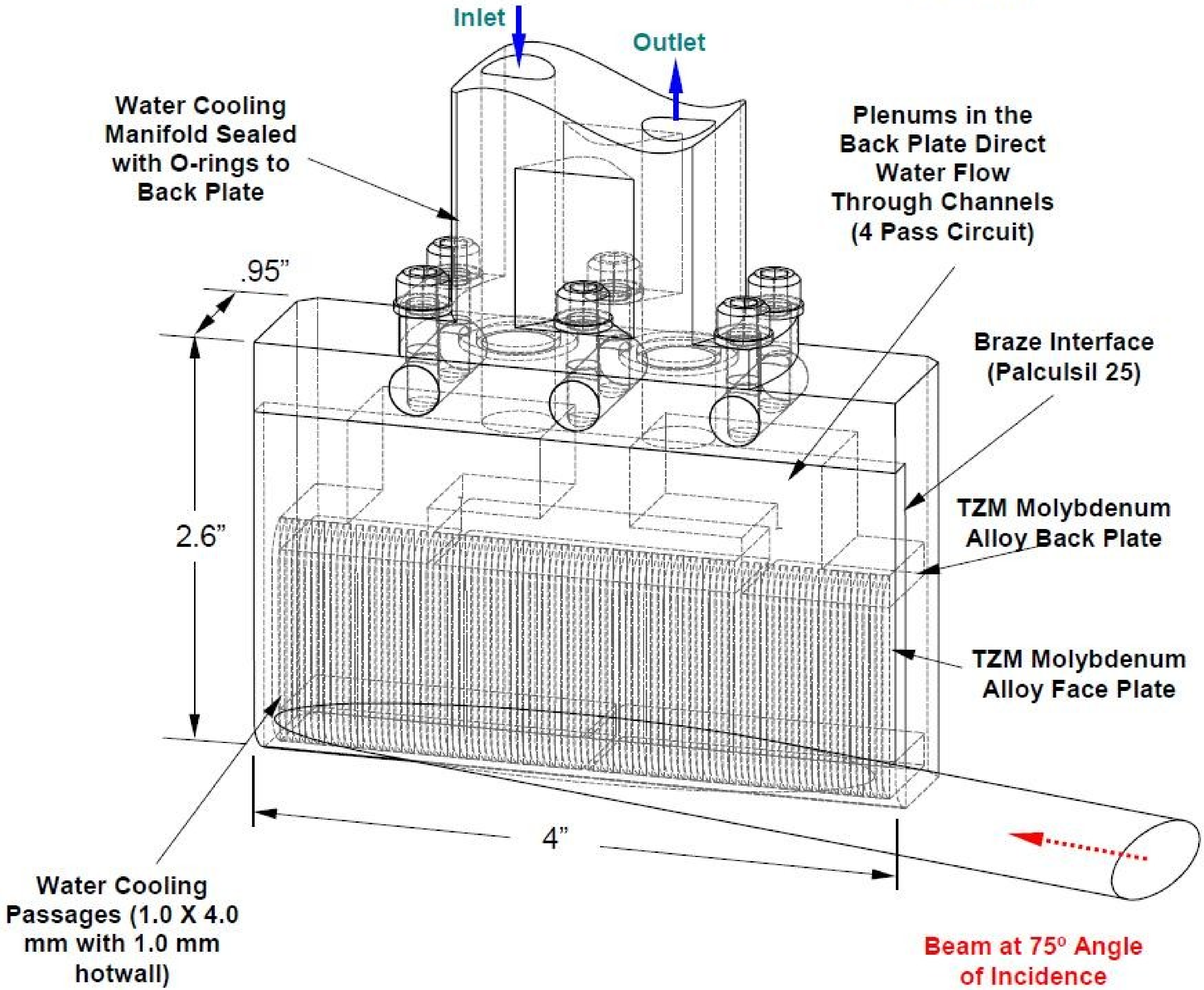
TZM material, developed for high-power X-ray mirrors, adapted for SNS MEBT chopper target.

Average power 500 Watts








Inlet
Outlet
Water Cooling Manifold Sealed with O-rings to Back Plate
Plenums in the Back Plate Direct Water Flow Through Channels (4 Pass Circuit)
.95"
Braze Interface (Palculsil 25)
TZM Molybdenum Alloy Back Plate
2.6"
TZM Molybdenum Alloy Face Plate
4"
Water Cooling Passages (1.0 X 4.0 mm with 1.0 mm hotwall)
Beam at 75º Angle of Incidence

SNS Chopper Target Parameters

Original purpose was to sharpen up the LEBT chop. The LEBT chopper ran at 1 MHz with a 40 nsec transition time. The MEBT chopper removed the 40 nsec beam at each end of a 600 nsec pulse, for an average power of about 500 watts.

Each of 2000 pulses in 1 millisecond repeated at 60 Hz for an individual pulse energy of 4.2 mJ, or 8.3 J/cycle of 60 Hz.

The average power is 500 watts, and the peak power is 100 kW (2.5 MeV x 40 mA).

At the end of a macropulse, the target temperature is 200 C.

The steady-state temperature is 104 C.

The angle of incidence is 75 degrees.

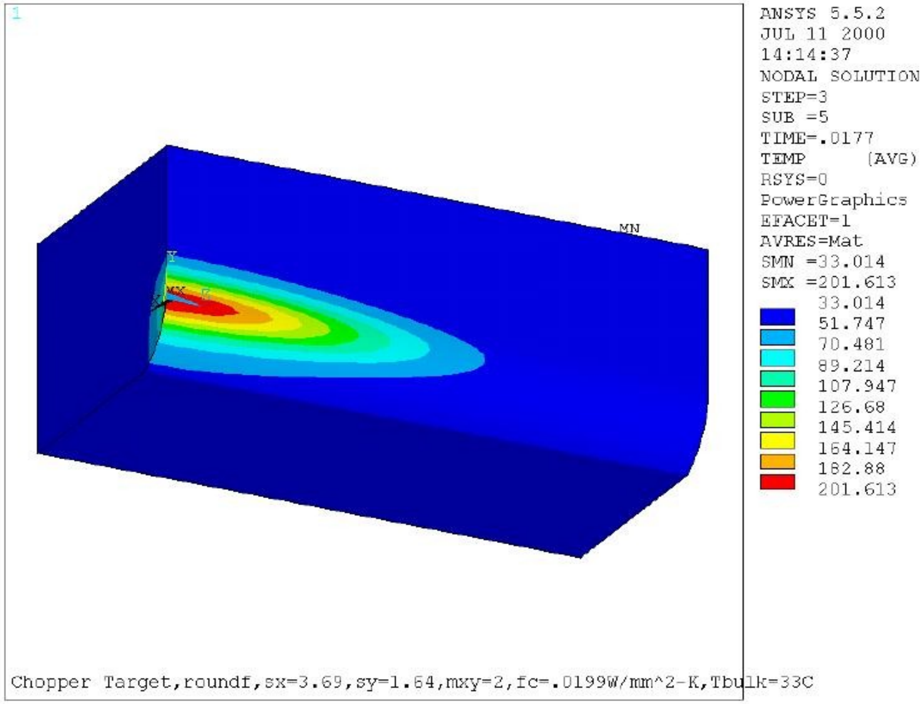
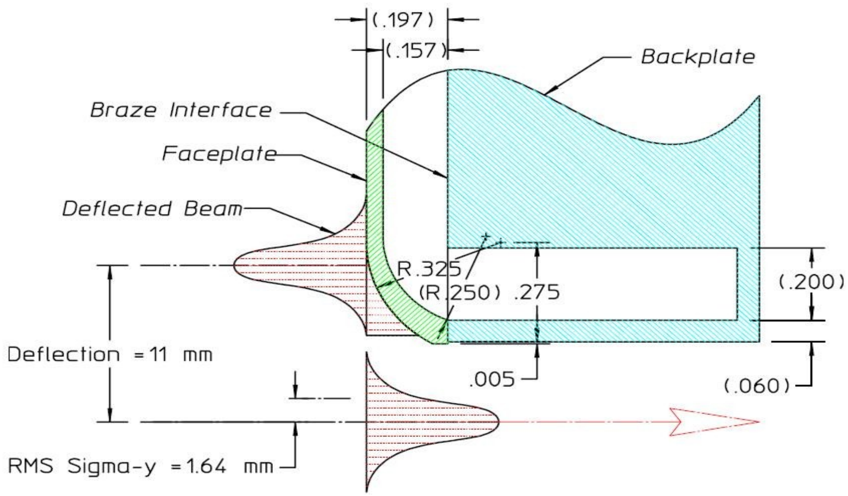
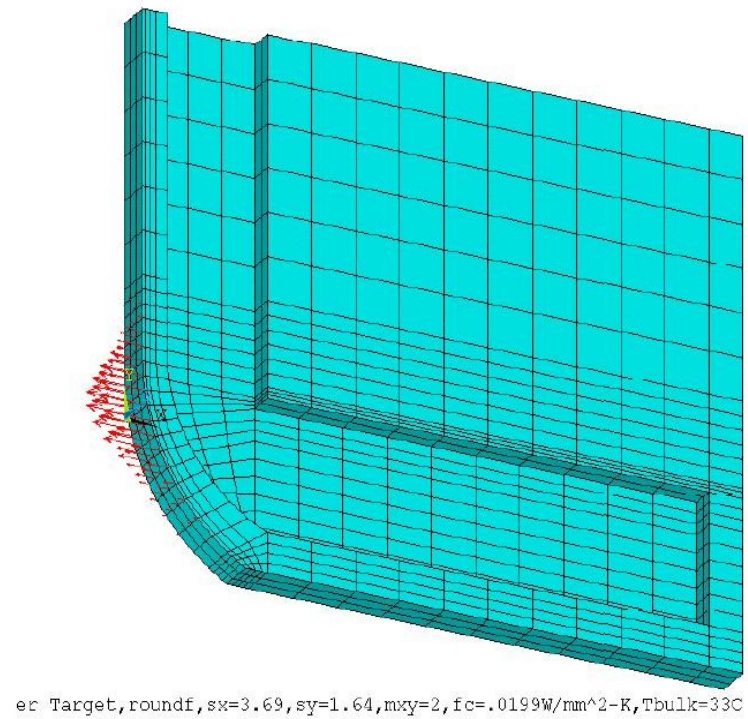


Figure 5 Temperature distribution at the end of a 1 ms 8.4 kW pulse.

Detailed Stress at Maximum Beam Location





The maximum von Mises stress is 246 MegaPascal, below the 420 MegaPascal limit for TZM at 200 C.

This is all for 500 watts average power, 1 msec pulse trains at 60 Hz.

Summary

An ion source will be run and characterized at LBNL

A LEBT with 2 solenoids will be contstructed and operated with an electrostatic chopper and diagnostics.   (The dipole can come later.)

The RFQ parameters will be updated, particularly for the 325 MHz unit.
No engineering can start until a final frequency is chosen.

Much work needs to be done on the MEBT.
Additional scenarios for the NB chopper must be devised, pending definitions of the physics requirements
Details of the NB choppers must be worked out.
The beam collimators for the NB choppers must be developed.