RFQ, LEBT and MEBT Issues

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Project X Collaboration Meeting

Front-End Working Group

Project X Front End Systems

LBNL has been asked to design, manufacture, acceptance test and deliver an accelerator system to FNAL comprising:

1 or 2 CW H-minus ion sources

30-35 keV LEBT including chopping and ion source switching capability

2.5 MeV, 325 MHz CW RFQ, and/or an alternative 162.5 MHz RFQ

2.5 MeV MEBT comprising focusing, rebunching, chopping, collimation and diagnostic elements

LBNL would take primary responsibility for the R&D, design, fabrication and testing of the system that meets FNAL requirements

RFQ Requirements

The CW RFQ design is based on previous designs and manufactured RFQs, and lessons learned from those designs: in particular, SNS, the SNS replacement, and a deuteron RFQ designed and engineered for national security applications.

Output Energy	2.5	MeV
Intensity	10	mA, CW
Transverse emittance	$\leq 0.2\,\pi$	mm-mrad, rms, 1 x normalized
Longitudinal emittance	$\leq 0.1\,\pi$	MeV-degree, rms
Frequency	325 (162.5)	MHz
Duty Factor	100	Percent

Compare to SNS RFQ: 2.5 MeV at 402.5 MHz, 6% duty factor
Design/operational current: 56 / 35 mA
640 kW RF + 95 kW beam loading
38 kW average cavity thermal power

Beam Dynamics Solutions

Requirements call for up to 10 mA, CW, with the lowest possible longitudinal emittance

Two frequencies of interest: 325 MHz, preferred, 162.5 MHz as an alternative, easing the requirements on the MEBT fast choppers, but requiring more charge per microbunch than the 325 MHz RFQ.

Four beam dynamics approaches investigated:

- "Traditional" LANL 4-section solution
- Chuan Zhang 4-section solution – excellent for very high current
- Kick-buncher solution – IUCF RFQ – developed for low current
- Modified kick-buncher – moderate space charge solution – ADNS proposal

Beam Dynamics Design Examples

All calculated with 64 kV vane-vane voltage, 10 mA H-minus current

Not fully optimized 325 MHz solutions

	LANL	Zhang	Kick Buncher	
Length	391	390	266	cm
Transmission	92	91	92	Percent
Long. Emitt	0.105	0.087	0.075	MeV-deg

The RF power requirement scales as the length.

The kick-buncher design best satisfies the FNAL requirements. Further refinements in the beam dynamics design to be made.

Compare 162.5, 325 MHz RFQs

The Komac RFQ was the FNAL baseline before LBNL propose the 162 and 325 designs.

	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

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

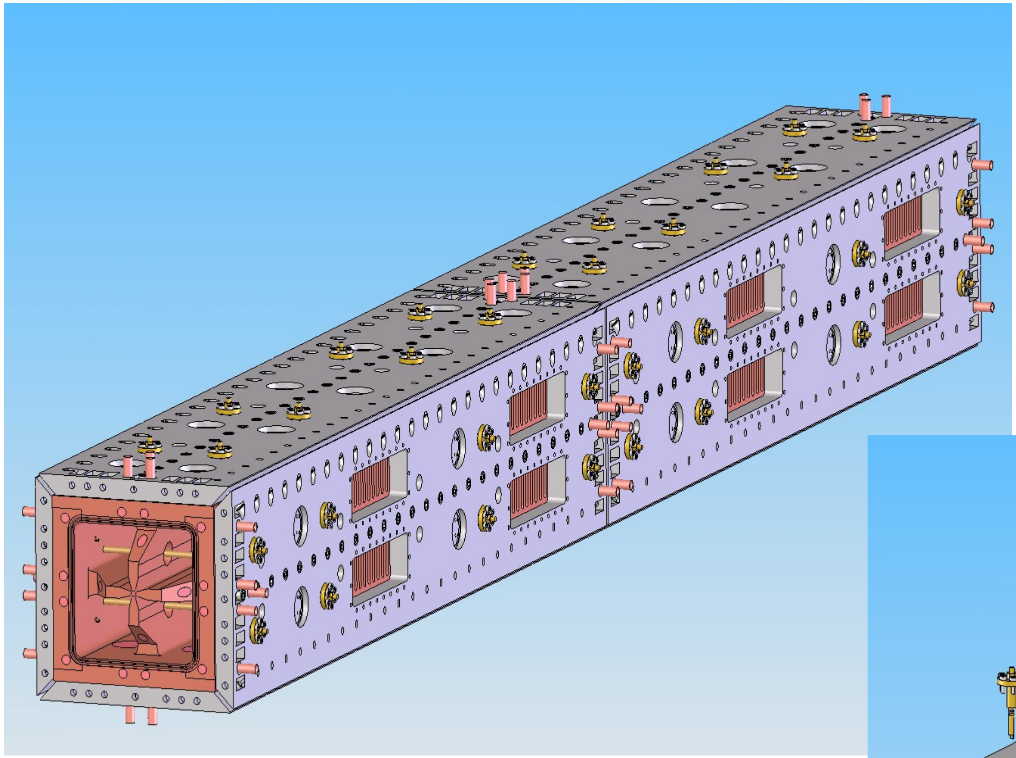
- add more safety margin for the aperture
- improve the 90% transmission
- reduce the losses over 2.1 MeV to minimize neutron production

Assess longitudinal stabilization need, technique

Reduce the peak power density in hot spots

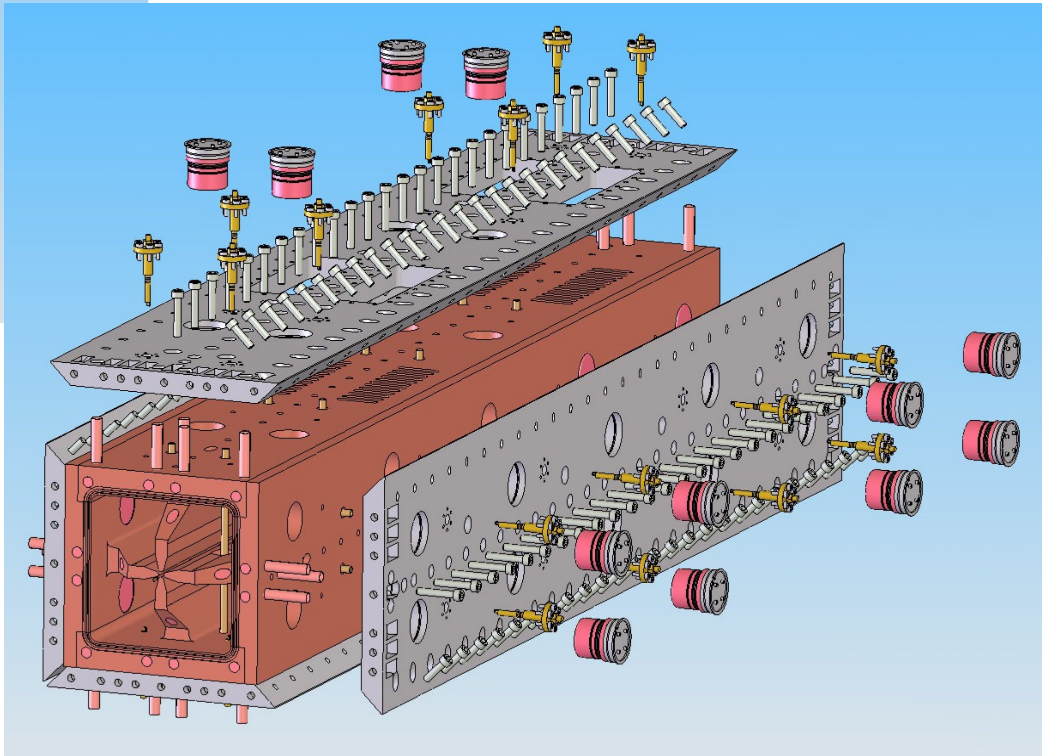
Preliminary engineering study of the RF structure

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.

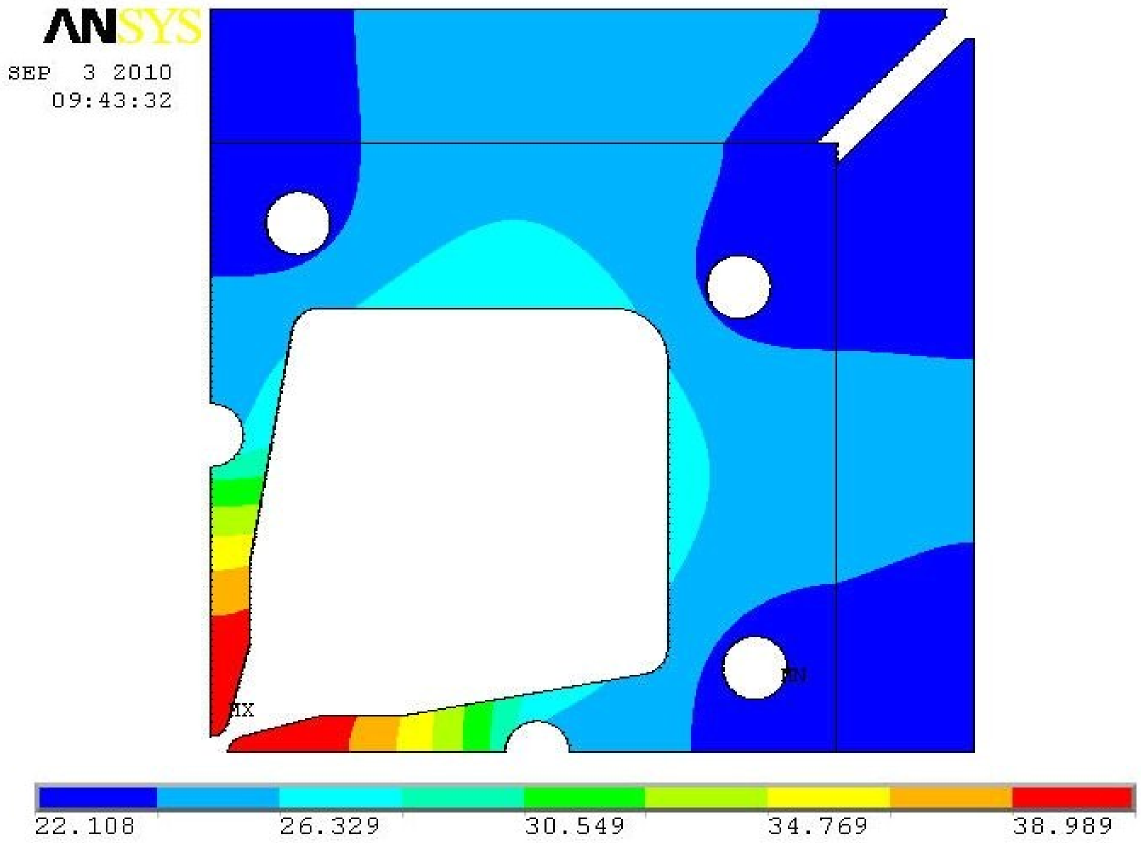
Two RFQ drive loops provided

ANSYS Simulation of Temperature Distribution

The 325 MHz RFQ surface power density, calculated with Superfish, is used in ANSYS to simulate the temperature and stress with the proposed cooling passage configuration.

At nominal gradient the vane tip temperature is 39C.

Full 3-D simulations will be carried out with MWS, ANSYS and other codes.

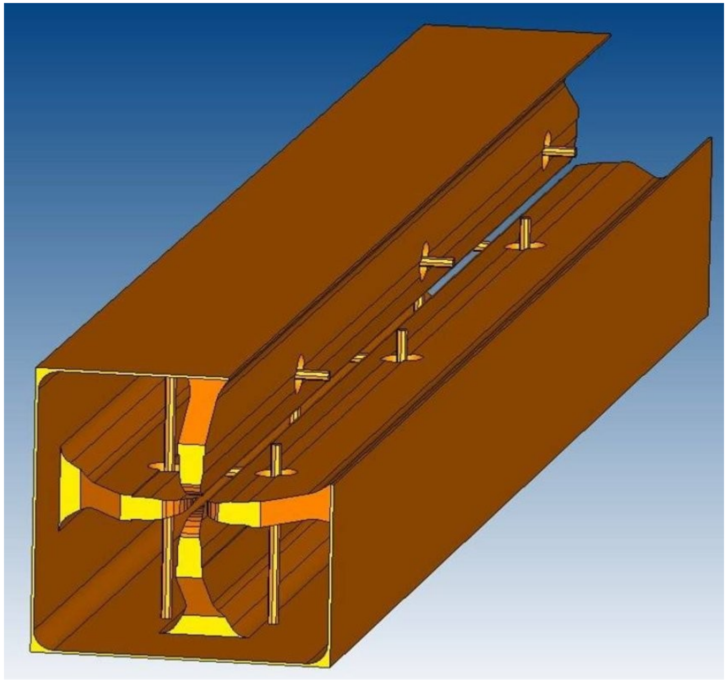


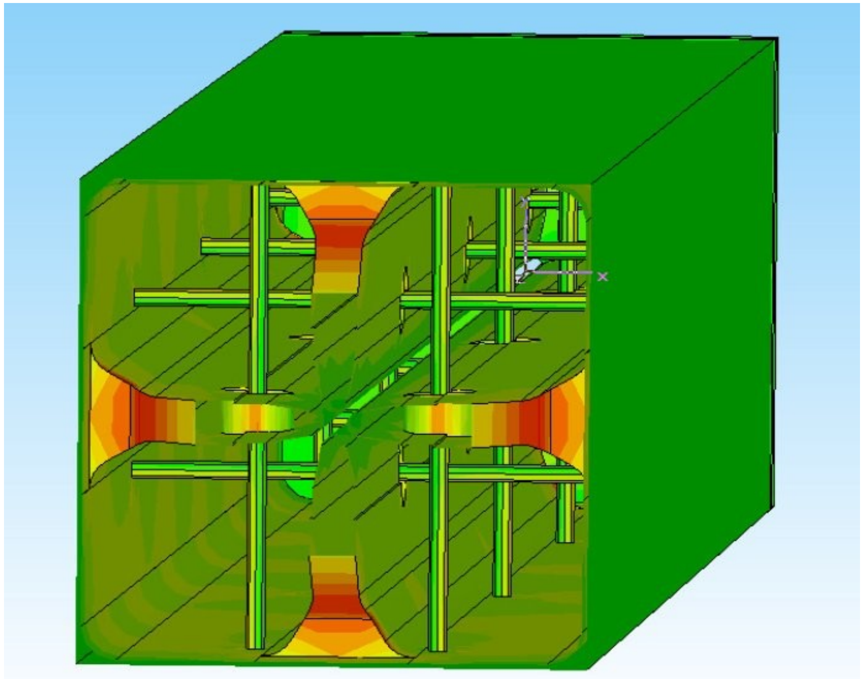
Electrodynamics Simulations of the RFQ Structure

MicroWave Studio used to calculate detailed cavity frequency and field distribution

MWS includes all fine structure, including stabilizers, tuners, end cutbacks, and calcuates the power density on all the structures.

150 kW copper power, <5.1 W/cm^2 on most of cavity, except cutback regions, which will be adjusted to reduce peak power density.





LEBT Requirements

Ion source to be covered by Qing Ji in her talk

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

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 Issues

A hybrid magnetic-electrostatic LEBT offers versatility and redundancy

Two ion source, 1.7 and 10 mA, switched by $\pm$30 degree fast dipole magnet

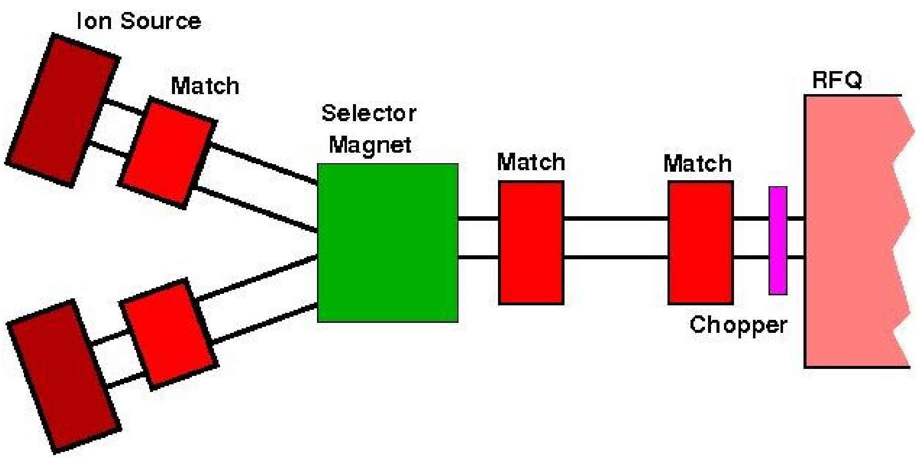
> versatility of current switching, redundant source on-line
> BL = 0.014 Tesla-meter magnet strength required

Possibly a 4 phase deflector near RFQ entrance for 20-30 nsec chopping

Neutralization times following switching magnet low 100's of microseconds

Carry out hardware tests of effects of fast dipole switching. Measure:

- emittance preservation
- neutralization times
- matching beam to RFQ entrance
- electron trapping and removal



LEBT R&D Program

The LEBT will be developed and tested incrementally

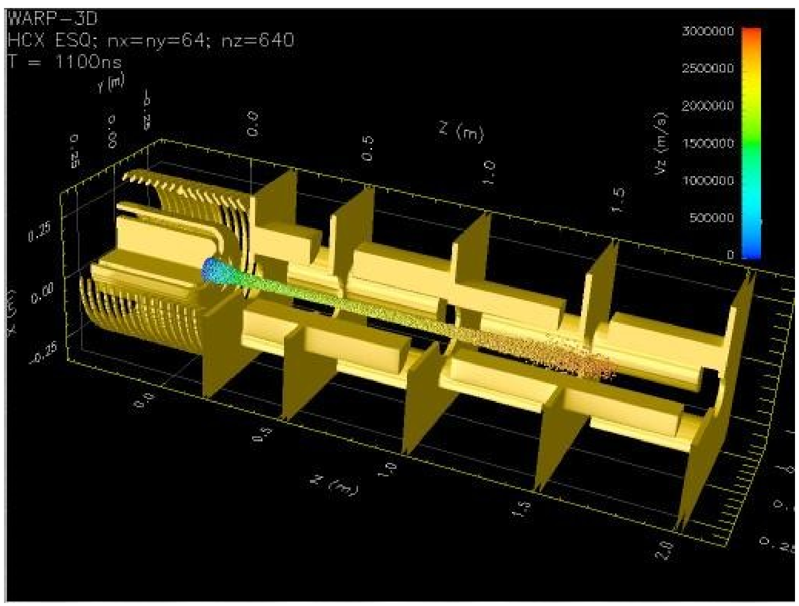
- Extraction and 30 keV acceleration from the ion source
- Electron diversion and trapping
- Ion source emittance measurements
- Pulsed switching magnet then added
- Emittance, neutralization time measurements
- Matching section into RFQ that accommodates two ion sources operating at different current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

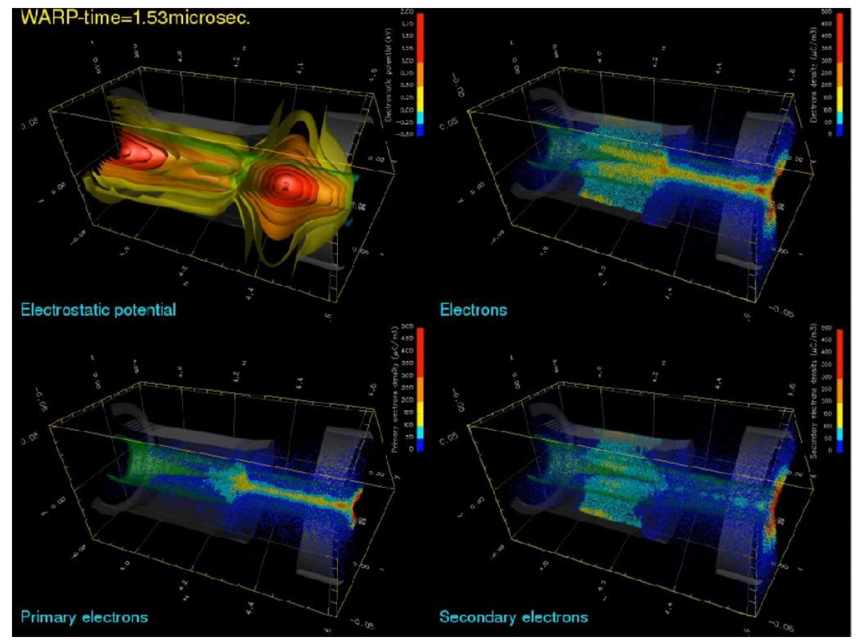
The LEBT will be fully configured and tested during the R&D phase.

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

WARP-3D will be used extensively in LEBT Simulations

- WARP is a multidimensional intense beam simulation program being developed and used at the Heavy Ion Fusion Virtual National Laboratory.
  - Developed to study the propagation of the high-current, space charge dominated beams in induction accelerators
  - Combines the particle-in-cell (PIC) technique commonly used for plasma modeling with a description of the "lattice" of accelerator elements.
  - Allowing nearly all sections of an accelerator to be modeled, both steady-state and time-dependent

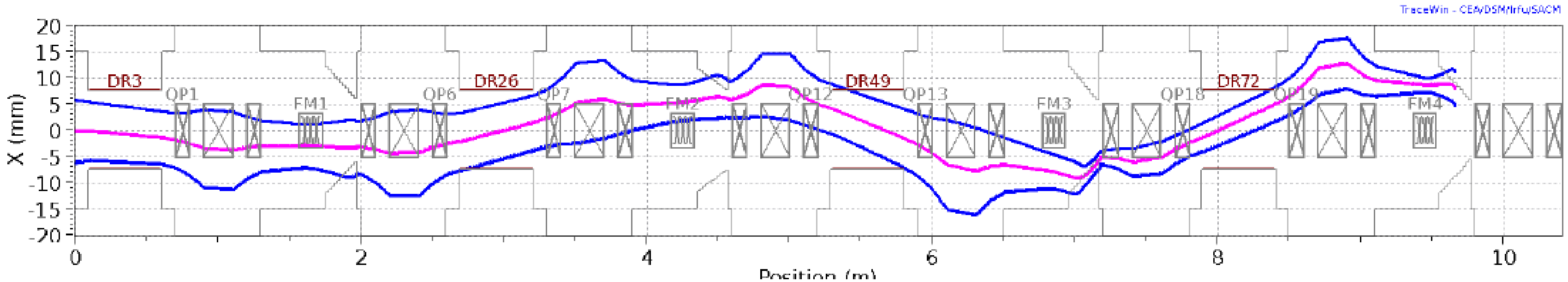




MEBT and MEBT Chopper

FNAL has developed a MEBT lattice structure: we will use that.

regular lattice of 4 periods
180 degree phase advance per period
Each period contains a TW deflector and a rebuncher cavity
Clipping apertures included in each period



Each of the 4 chopper/deflectors adds deflection in phase

FNAL design uses wide-band TW deflectors with 50 kV/m transverse field: 5 mrad each

LBNL would implement the FNAL beam dynamics design with wide-band deflectors designed by FNAL, or as a backup solution, narrow-band deflectors designed by LBNL.

MEBT Beam Chopping and Control

Experimental requirements impose severe constraints on beam time structure.

Control pulse microstructure through linac to provide average beam power with time structure compatible with SC linac beam loading constraints

Control microstructure so RF separator at end linac directs beam to various users.

Provide sufficient micropulse switching versatility compatible with experiments.

Provide sufficient extinction of unwanted microbunches for background-sensitive experiments.

Pulse-by-pulse microbunching switching is the ultimate goal, and the chopper/deflector hardware is state-of-the-art.

- Very fast high-power drivers required
- Low dispersion traveling-wave deflectors at high average power
- Beam collimators must absorb very high power densities

Alternate Chopper Scenario

LBNL presented a scheme last year based on limited bandwidth (100 MHz) choppers and drivers that satisfied the requirements presented at that time. The users were the Kaon, mu2e and “other”.

The beam from a 162.5 MHz RFQ is prepared in the MEBT with transverse TW choppers powered from a frequency-modulated sine wave source, that in conjunction with an RF separator at the high energy end of the linac, divided the beam to three experiments with the required time structure.

A simulation that included a 100 MHz bandwidth, including distortions in the chopper waveforms, show that the beam can be split successfully to the three users.

The hardware included relatively low-power (700 watt) amplifiers with 100 MHz bandwidth, and meander-line TW choppers.

The narrow-band choppers are compatible with the FNAL MEBT design.

The beam is deflected 10 mrad (twice the WB scenario) and bipolar, spreading the beam out over a much larger area on the collimators, reducing the peak power density

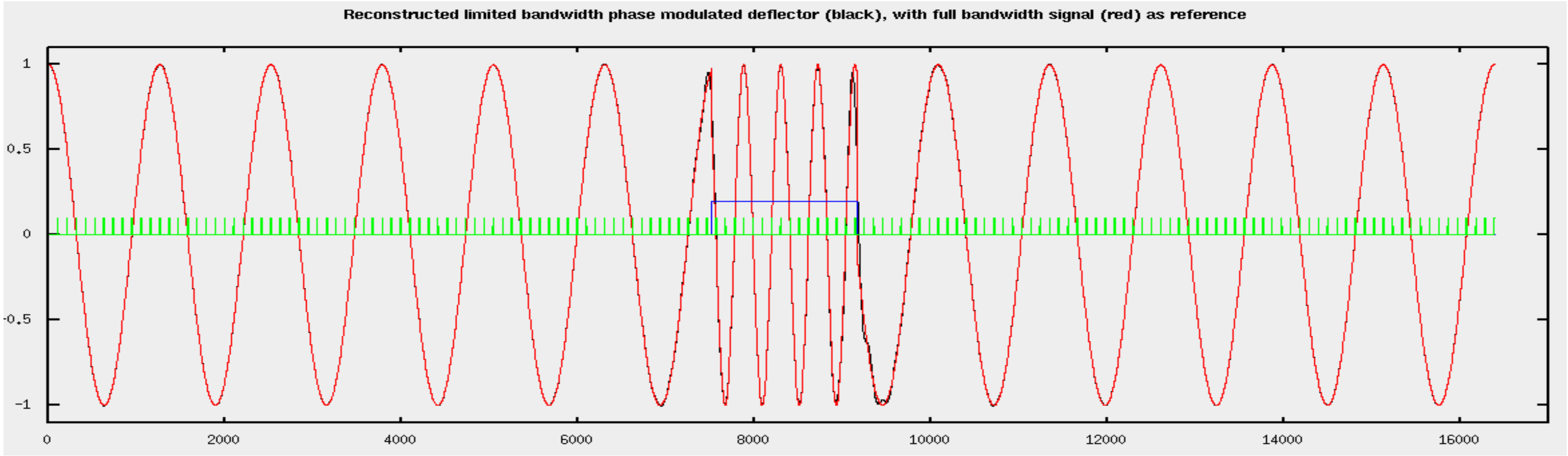
Experimental program requirements still in flux, further development awaits.

One Scenario to chop beam three ways in limited BW

The phase, amplitude and frequency of the MEBT deflector is agile, and is modulated at a 1 MHz rate. The bandwidth of the deflector must be adequate to reproduce the required waveform. 100 MHz bandwidth of voltage waveform simulated here.

To split the beam as required, the micropulses from a 5 mA, 162.5 MHz RFQ are deflected as follows:

900 nsec: 13.54 MHz for beams A, B, 750 kW to each user
100 nsec: 3 * 13.54 = 40.62 MHz for beam C, and phase shifted pi/2, 500 kW

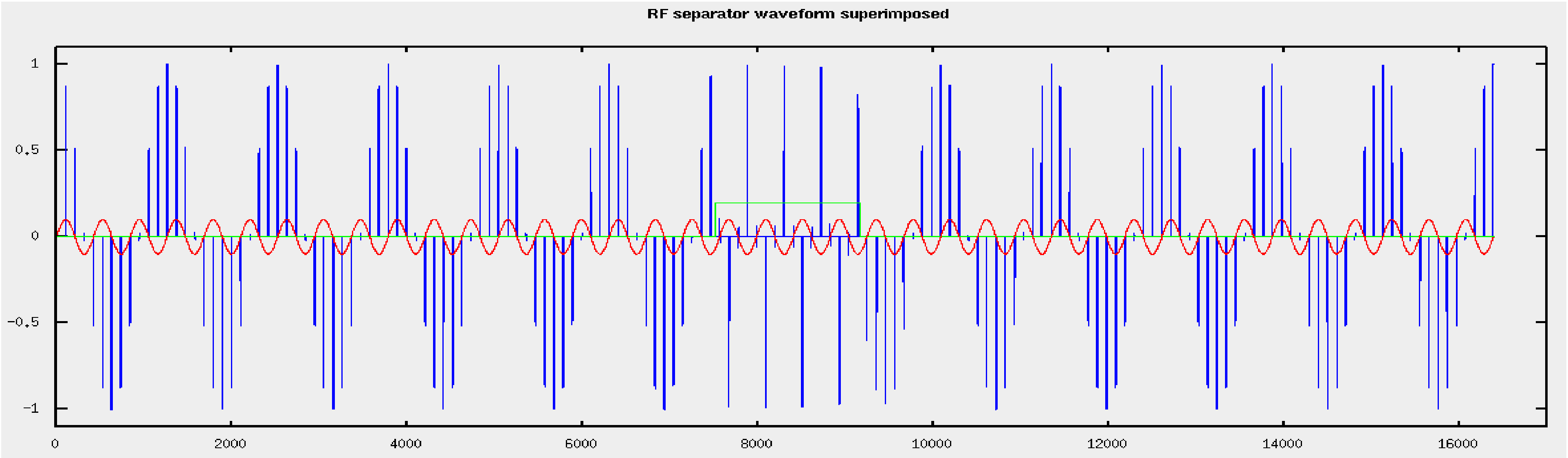


The red is the full-bandwidth, the black the 100 MHz band-limited deflector signal.
The green pulses are the 162.5 MHz RFQ microbunches.

Add in 2 GeV RF Separator Waveform

The phase of the L-band RF separator is added to show its relationship to the zero-crossings. f_sep = f_rfq (m+1/4). The A and B beams come with the separator voltage at +V or -V.

Note that the beam is delivered to A and B 90% of the time, or to C 10% of the time.



For a 5 mA RFQ current, the power in the beams is:

Each A and B: 5 mA * 0.9 * 1/12 * 2 GeV = 750 kW
C: 5 mA * 0.1 * ½ * 2 GeV = 500 kW

Total SCL power : 2 MW Power on the 2.5 MeV slits: about 10 kW distributed to 6 spots.

Narrow-bandwidth chopper

The narrow-band chopper uses the same FNAL MEBT lattice, replacing the WB deflectors, as a backup solution.

The TW meander-line deflector need not have nanosecond risetime and consequently low dispersion. 100 MHz bandwidth is sufficient.

The driver electronics bandwidth extends from near DC to about 100 MHz.

A 100 ohm TW deflector requires about 700 watts per chopper with a 15 mm full gap and a 10 mrad deflection angle, using the same length and gap as the WB chopper, but twice the transverse field.

The deflected beam is deflected to 6 spots, three on each side of a slit, as the waveform is sinusoidal around zero, spreading the beam power over the face of the collimator on each side of the beam line. Very high beam extinction ratios possible with 10 mrad deflection angle using multiple collimators.

Pulse-to-pulse control not possible, but different frequency modulation schemes can provide beam control on the tens of nsec time scale.

Summary

LBNL has the expertise and resources to provide the Front End System

- LBNL provides the Ion source, LEBT, RFQ, MEBT
- FNAL provides the WB choppers and fast chopper drivers
- LBNL can provide NB choppers as a backup solution

With lessons learned from SNS, and engineering ADNS and SNS replacement, we can provide a CW RFQ with beam dynamics uniquely suited to Project X longitudinal and transverse emittance and intensity requirements.

A modest ion source and LEBT hardware development program is slated for next year's R&D activities.