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Approach to Beam Preparation and Distribution System Development

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I. Introduction

Recent discussions about a PX linac beam structure have revealed significant differences in how people understand the beam conditioning and distribution process. Obviously, some discussion is needed to focus on the issue and to choose right path towards solving it; this note attempts to start this process. The next set of beam distribution requirements was accepted for the discussion:

1. Average current in the linac of ~1 mA at any time. This results in 2 MW of average beam power at the exit of the 2-GeV linac.
2. Neutrino physics program requires high energy proton beam. In accordance with the present proposal, acceleration to the final energy will be done by an RCS after initial 2 GeV obtained in the linac. For injection in the RSC, a 10 Hz series of 4 msec macro-pulses of H^- beam is needed; additional chopping within the pulses with the beam circulation frequency (~500 kHz) and RF frequency (50.33 MHz) must also be made. Average beam current within the pulses must be ~1 mA.
3. Mu2e experiment needs 1 MHz, 100 ns pulse sequence. Average beam current within the pulses must be ~3.3 mA.
4. Kaon experiments require 20 to 30 MHz CW bunch sequence. Average current must be ~0.37 mA.
5. There are others, not fully identified experiments that also require 20 to 30 MHz CW bunch sequence with average current of ~0.37 mA.

Having in mind this set of the beam structure requirements, it was common understanding that the beam “chopping” is a very challenging task. Two presentations during PX CW Chopper Webex meeting followed quite different paths in an attempt to come to some decent proposal of the chopping scenario; both proposals relied on chopping in the MEBT part of the linac.

In the first proposal [1], a chopper in the MEBT channel needs to remove individual bunches from a bunch train that follow with 162.5 MHz frequency. This proposal employs three-way RF beam splitting and a wide-band, multi-kicker, quazi-resonant beam deflection system. Beam chopping takes place in the MEBT channel, where 2.25 mA of beam current is directed to a dump at the 2.5 MeV energy level. This corresponds to 5.6 kW of the dumped beam power, which requires removal of the chopped out portion of the beam out of the channel and dumping it in the appropriate stand alone beam dump.

The second proposal [2] makes an attempt to use a relatively narrow-band chopping system. It employs a 13 MHz deflector with periodic phase shift in the MEBT channel to intercept 5/6 of the beam by using a slotted beam intercept. The system bandwidth required for the quick phase change is ~30 MHz, which is a significant plus of the proposal. Nevertheless, the same problem of high dumped beam power requires serious attention.

As recent discussions during AHIPA workshop [3] at FNAL have shown, there is understanding among people involved in developments of high power linear ion accelerators that in order to reduce beam loss in the main linac, it is very important to properly prepare the beam in low energy sections. In particular, LEBT channel is being modified or redesigned at several laboratories to accommodate pre-chopping systems that can significantly relax requirements for the MEBT chopping and power of the chopped-out portion of the beam. It worth to mention about this kind of efforts in Brookhaven [4], in ORL [5], and in India [6]. The importance of a beam conditioning R&D is especially clear when one observe efforts spend for this purpose at CERN [7].

To better understand the issue, we tried to come out with several possible approaches to the beam preparation and distribution with further attempt to analyze the approaches in order to choose one that could be reliably implemented and satisfy the needs of physics.

In the context of the PX program, "beam preparation" means the following:

1. The beam must be structured at low energy in a way that allows reliable distribution between different experiments. To know how to prepare the beam, one must know how it will be distributed; hence we have the combined task of "preparation & distribution".
2. It is quite desirable to make the main work of chopping out parts of the CW beam (that will otherwise be lost) in the lowest energy part of the accelerator, that is in the LEBT section, or even in the ion source (one needs to be sure that this is possible though). Having less beam to be chopped off at the MEBT level helps to mitigate the power dump and radiation problems there.
3. Previous experience with chopper development both at Fermilab and at other laboratories shows how challenging this task can be. This said, we can not avoid using MEBT choppers; to relax requirements to average power and frequency, the choppers (one or several) must be designed to make a fine "cleaning" job of conditioning a pulse train before injection in the main linac.
4. Having in mind the above statesments, the next plan of this study note is proposed with each next step depending on the outcome of the previous one:
   - Make preliminary analysis of LEBT optics to show that it is possible to use one or several insertion devices in this part of the accelerator;
   - Find an initial solution for beam pre-chopping;
   - Find one or more beam-handling solutions that would make the required beam structure.
5. Having agreement on a possibility of implementation of one of the proposed schemes (or other schemes that can emerge during the discussion process), develop an R&D plan to design and test critical elements. Having a devoted test stand, which includes an H^- source, LEBT section, and beam diagnostic equipment, would allow testing different design ideas to choose the most appropriate one.

II. LEBT configuration

Common requirement for all possible schemes for beam preparation and distribution should be providing some space in the LEBT section sufficient for placing pre-chopping systems and/or beam bunchers. It is important to understand what freedom we can have in configuring the LEBT. A long channel built by using focusing elements with gaps between them (for installation of insertion devices) would help to build a distributed pre-chopping system where different chopping (or modulating) functions are executed by different (devoted) devices. There are many way of how to approach the LEBT configuration. One of the main concerns related to the LEBT concept is the presence of positive ions (mostly ions of heavy atoms and molecules of oxygen and nitrogen) that can make it difficult controlling the beam of the H^- ions. The positive ion column will pull the H^- ions back towards the center of the beam channel, thus compromising steering we need for chopping and having its impact on the beam emittance growth. On the other hand, ion focusing can significantly improve requirements for optical elements in LEBT. Here we choose the most difficult path of not relying on the ion column for focusing.

What kind of optical elements to use is another question to answer. Here we will try to understand how a solenoid-based LEBT channel could be built. Mainly this way was chosen because of the availability of a code for modeling transport of long beams of charged particles, which is based on the theoretical model by Lee and Cooper [8]. Comparison of this model prediction with other codes' and theoretical predictions was made for different cases, including free expansion with given charge density and emittance, transport in the longitudinal magnetic field, and others. A transport channel was formed using a series of focusing solenoids. Figures 1 and 2 below show two cases (both with I = 10 mA, $R0_{rms}$ = 3.5 mm, and ε_n = 0.25 mm-mrad): a zero-angle matching with the ion source and a negative angle matching. On both figures, focusing solenoids are spaced 0.3 m, and the first one is 0.15 m from the end flange of the ion source. A root-square radius is used in the figures, so $R0_{rms}$ = 3.5 mm corresponds to the 5 mm outer radius of the uniformly charged beam. The required focusing strength of the lenses is $\langle B^2L \rangle$ = 0.066 T^2-m; in realistic solenoids, this corresponds to the maximum field of ~1.5 T, so the solenoids must be superconducting. A reasonable solution for solenoid configuration can be like following: Ri = 30 mm, Ro = 31.5 mm, L = 48 mm, Dw = 0.3 mm, compaction factor k = 0.5, number of turns N = 510.

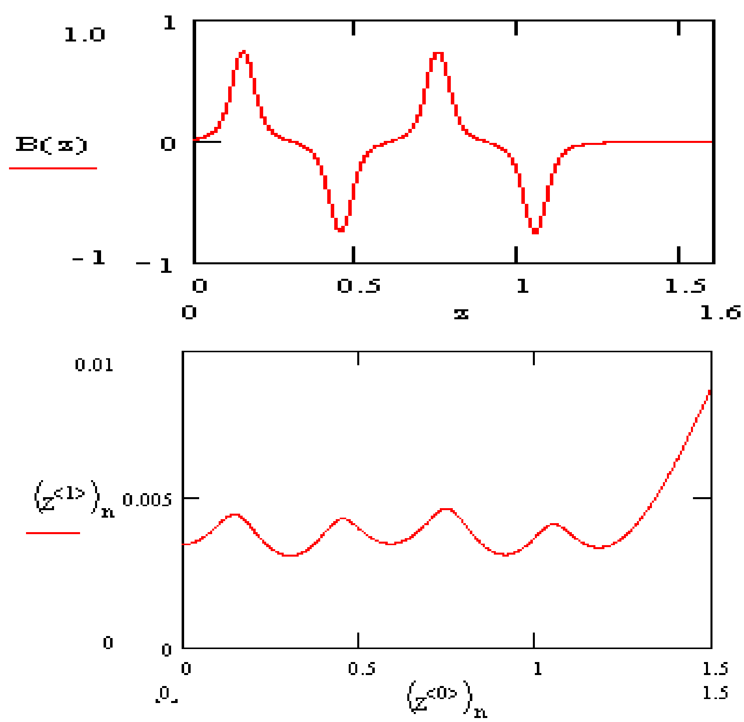

Fig. 1. Zero angle matching

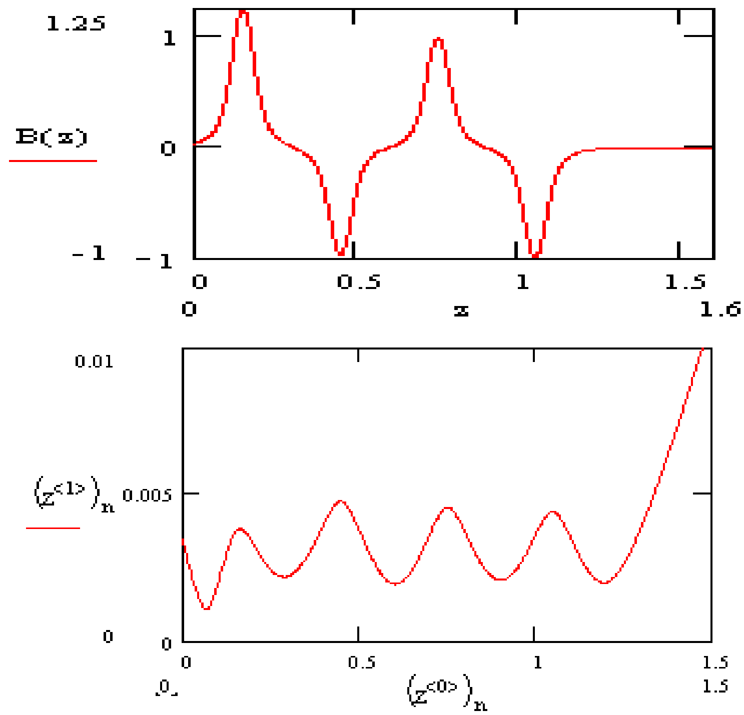

Fig. 2. Negative angle matching: α = -50 mrad

For NbTi strand, the critical current density can be parametrized as following:

$$J(A/m^2) = 8\cdot10^3 - 10^3\cdot Bw(T).$$

At Bw = 0, J = 8000 A/m^2 and at Bw = 5T, J = 3000 A/m^2. The critical current is ~330 A with the critical field on the wire Bcr = 3.4 T. With this current, the magnetic field profile along the axis is like in the graph in Fig. 3.

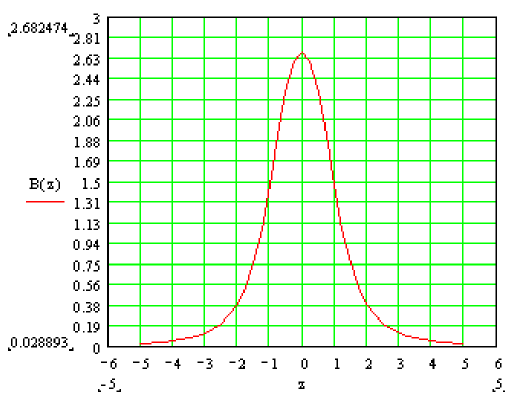

Fig. 3. Magnetic field profile of the lens at I = 330 A.

If needed, the longitudinal extension of the field can be limited by using appropriate flux clamps. The working current will not exceed ~170 A, so standard 200 A current leads seem appropriate for the design.

To understand how this lens can be implemented, a sample design was made (Fig. 4) that includes a cryo-vessel, which is the main labor consuming part of the lens.

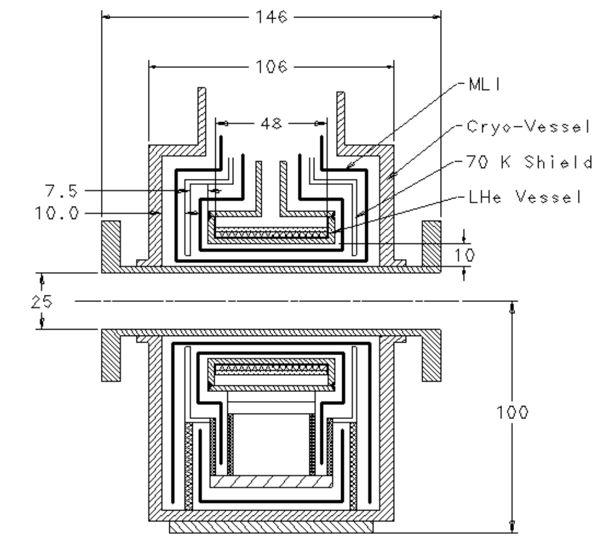

Fig. 4. Sample solenoid lens design layout.

So, the total (flange-to-flange) length of the lens is ~150 mm, which leaves 150 mm for insertion devices in the LEBT channel. A sample configuration is shown in Fig. 5.

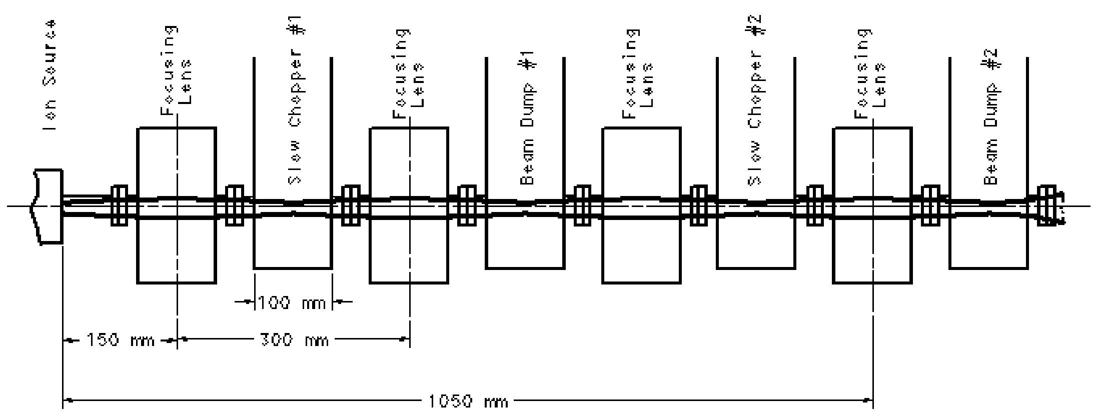

Fig. 5. Using focusing solenoids in LEBT section

Using deflectors in LEBT with solenoids is less efficient than in a beam pipe without lenses. Fig. 6 shows a deflector installed before focusing lens and the radial projection of the beam trajectory (beam rotation in the magnetic field is not shown).

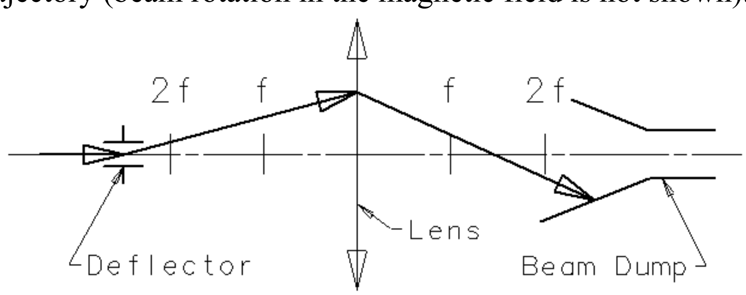

Fig. 6. Deflected beam trajectory.

The maximum beam deflection is observed within the lens, so a deep radial modulation is desirable to make this scheme work, which is in contradiction with the desire to limit the beam emittance growth. So, it is quite desirable to put a beam dump inside the solenoid. With the maximum beam current out of the ion source of 3.3 mA, at 50 kV, the power in the beam is ~165 W. This power does not seem tremendously high to prohibit putting a dump inside each solenoid lens. The needed cooling can be made using water (<0.3 l/min for ΔT = 10º C) inside the warm bore of the lens (the design in Fig. 4 must be modified to allow this arrangement).

The next chopping scheme can be tried. The beam is deflected by a rotating electric field. The rate of rotation is chosen to spread the beam along the surface of a cylinder dump. E.g., if the bunch frequency is 1 MHz, the rotation rate can be ~200 kHz to get the beam move 20 mm (one diameter) azimuthally during 0.9 μs gap between 100-ns pulses. While the deflecting field exists, the beam is deflected to a water-cooled surface of the dump. Zeroing voltage on the deflector by grounding the electrodes (using a semiconductor device) results in the beam passing through the solenoid.
The deflection angle must be ~0.1 radian (15 mm / 150 mm). On the other hand, it is defined by the next expression:

$$\alpha = \frac{E_{\perp} \cdot L}{2 \cdot T(eV)}$$

With the 50 keV beam energy and the length of the deflecting electrodes L = 75 mm, we have $E_{\perp} = 1.33 \cdot 10^5$ V/m or 0.13 kV/mm. With 25 mm distance between the electrodes and with the potential close to zero at the beam axis, we have the maximum voltage of each electrode relative to the ground of ±1.7 kV. The scheme in Fig. 7 can be suggested for further analysis, which must involve detailed design and circuit modeling:

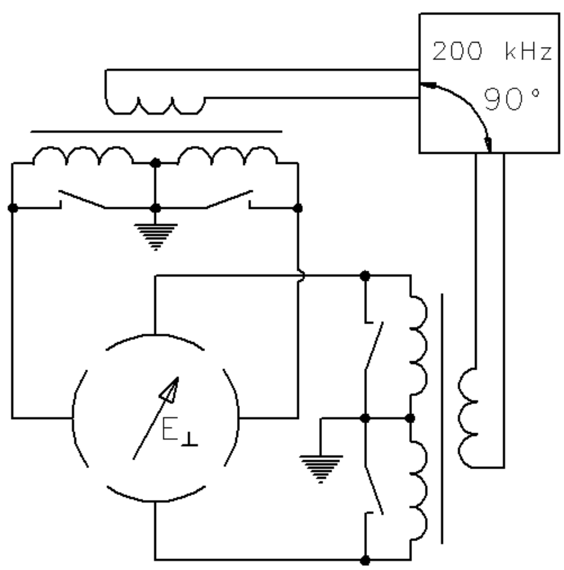

Fig. 7. Concept of a pre-chopper.

Preliminary analysis of the scheme shows that the current in the circuit to charge and discharge the capacitances of the steering electrodes is quite small (order of 100 mA). Semiconductor switches must have switching time of ~5 ns implying a ~200 MHz upper frequency. In accordance with the current requirements to beam distribution, this approach can work for the next systems:

1. 100 ns, 1 MHz pulses for Mu2e;
2. 4 ms, 10 Hz pulses for RCS with embedded 200 ns, 500 kHz gaps

In principle, these two functions can be combined in one device.

So, building an appropriate LEBT using superconducting solenoids as focusing elements does not seem an impossible task. More over, equipment-related issues of this path are quite well understood having in mind extensive focusing solenoid R&D within the HINS program. A reliable solution for the electronic part of the LEBT pre-choppers still to be found and tested; at least at first glance, it seems quite possible to find one.

Having no clear stoppers in building an appropriate LEBT, we can now switch to the next issue – how beam distribution system can be built.

III. Beam preparation and distribution schemes.

While thinking about beam preparation for acceleration in the main linac, one of main considerations is reliability and flexibility. This system must also be simple, which can be in contradiction with the reliability issue if too many functions are loaded onto one system. Several schemes can be suggested for further analysis. The goal of this section is to understand difficulties associated with each of the approaches and a scope of R&D work needed to validate the system design.

1. Using three dedicated ion sources, each corresponding to its own injection channel, would be the most flexible approach. Example of such a system is in Fig. 8. RF combiners are used to bring beam from each source into the main linac, and RF splitters are used to separate the beams after it is accelerated.

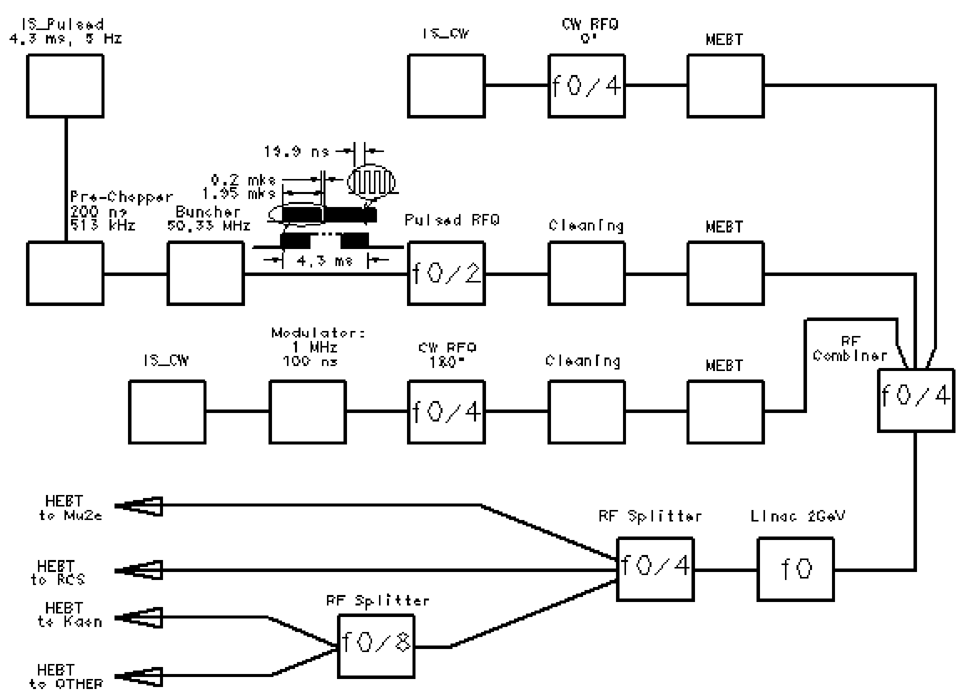

Fig. 8. Beam distribution system using three ion sources

Fig. 9 shows corresponding timing diagram. The main linac frequency is f0. The frequency of the RCS channel's RFQ is f0/2. The frequency of each of two other RFQ-s (Mu2e and KAON) is f0/4; these RFQ-s are phased 180 degrees apart and also phased relative to the first RFQ as shown in Fig. 9 (lower row). This way, one can populate every RF bucket in the main linac by using an f0/4 combiner (traces are similar to shown in the upper row of the diagram for the splitter).

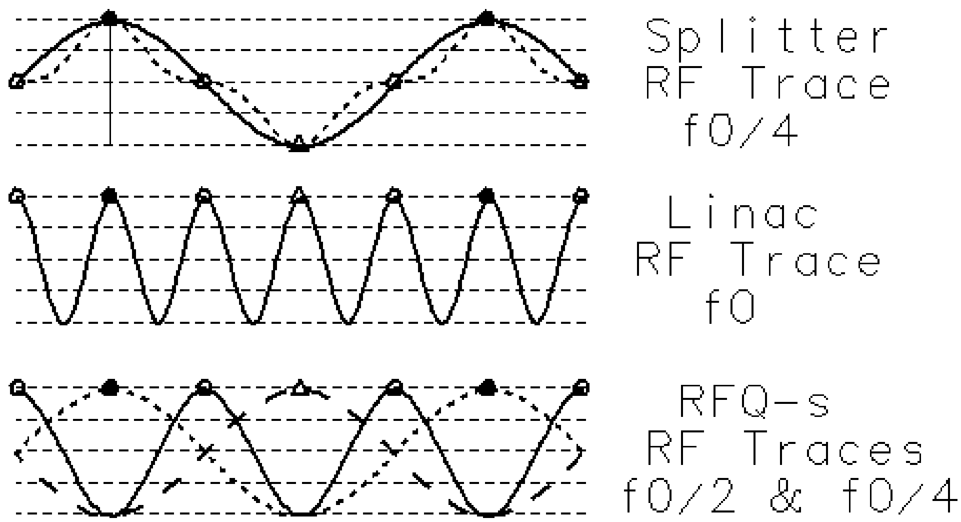

Fig. 9. Phasing linac, RFQ-s and RF combiners/splitters

As the pulsed RFQ uses f0/2 frequency, this channel populates two of every four RF buckets in the linac. The RF splitter is phased to pass these bunches without deflection. To make it simpler, a 3-d harmonic of the f0/4 frequency can be used to provide RF trace as shown in the trace figure in dotted line. This channel must generate quite complex pulse train shown in Fig. 10 below.

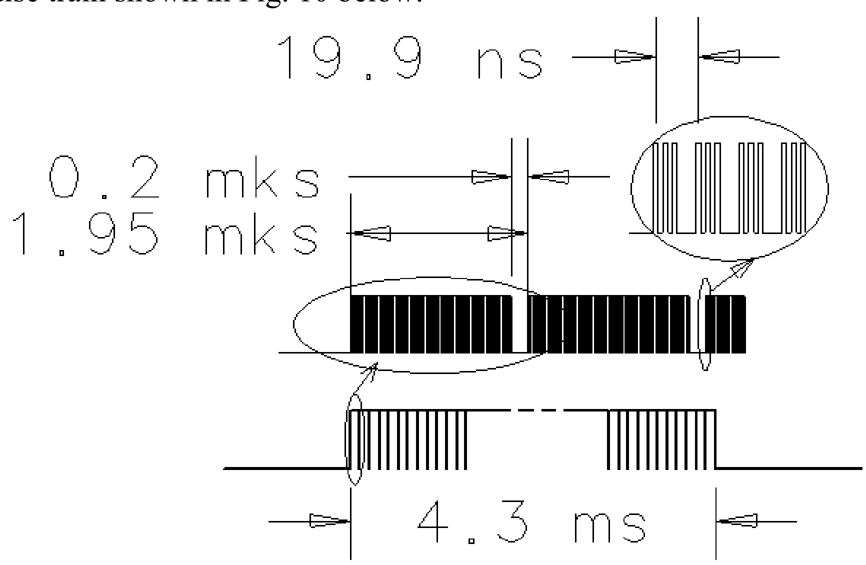

Fig. 10. Bunch chopping requirements for the RCS channel

To generate this pulse train, the ion source and/or LEBT must be heavily used to make most of the dirty work of removing the unwanted part of the initial pulse train at the low energy level. A provision to allow introduction of necessary insertion devices (e.g. pre-choppers) in the LEBT part of the accelerator must be made. Additional cleaning can also be made at the MEBT level.

The Mu2e channel uses a DC ion source and CW f0/4 RFQ. To get the desired bunch pattern (shown in Fig. 11), some bunch train conditioning (by chopping) is required. This chopping can also be made (mainly) at the LEBT level with some post-cleaning in the MEBT section. The required pulse voltage, width, and repetition frequency seem well within what semiconductor-based pulse forming circuits can do. Although one of possible approaches is shown in Fig. 7 above, no ready to go solutions exists at the moment.

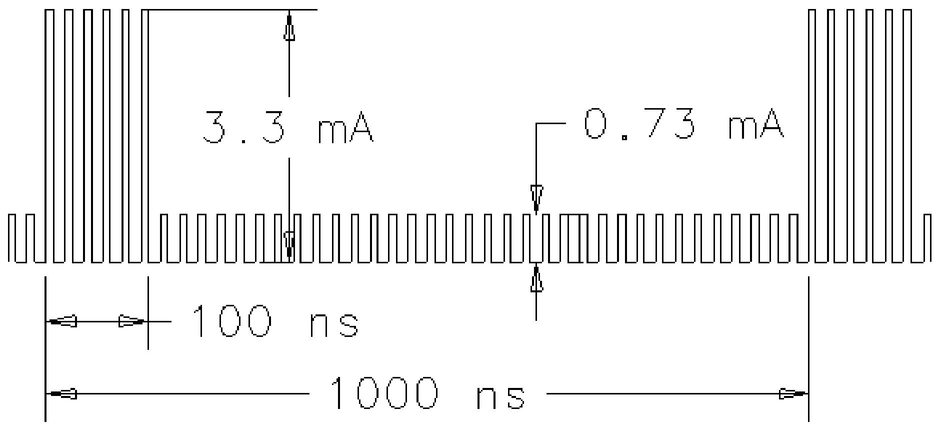

Fig. 11. Beam structure in the CW channel

The third channel also uses DC ion source and CW f0/4 RFQ.

Both CW channels require a 4-ms pause in their operation that can be made using a pre-chopper of a kind described above (see figures 6 and 7).

After acceleration in the linac, the bunches, that are effectively phase-separated, can be space-separated by using an appropriate RF splitter, that can re-distribute the bunches into three channels. Addition of the third harmonic (of the splitter frequency) can simplify requirements for the separator amplitude and phase stability. Because the CW channel will be used by two experiments with the required bunch frequency of ~20 to 30 MHz, an additional RF splitter can be employed here with the frequency of f0/8. E.g., if we choose 20 MHz of the bunch sequence for Kaon experiment, f0 must be 160 MHz. If 320 MHz is the frequency in the linac, we end up with 40 MHz of bunch sequence, and additional buncher will be needed (at the LEBT or MEBT level) to adjust the bunch frequency.

Because of the use of three separate channels, currents in all the channels can be adjusted independently and 4-ms gaps can be added in Mu2e and KAON channels pulse sequence to meet the linac average current requirement. To have 2-GeV beam power distributed evenly between the competing projects, the next time structure of the beam current at the entrance of the main linac is required: 1 mA for the 4-ms pulse, 3.3 mA for the 100-ns pulse, and 0.74 mA for the CW beam, which will be split in two even halves.

2. Two channels of the RF scheme in Fig. 8 use CW RFQ-s with the same frequency. The RFQ-s are phased 180 degrees apart, so that beam combining and separation could be made possible. It seems attractive to try to combine these two channels to reduce the amount of required injection channels. We can try to make this combination by adding a low-Q buncher (of a gate type or deflection type) in the LEBT transport line and changing its phase by 180º for the 100 ns pulse duration and with the 1 MHz frequency required for the Mu2e channel. A block diagram of the system is shown in Fig. 12, and a timing diagram, which explaining the combining/splitting works, is in Fig. 13.

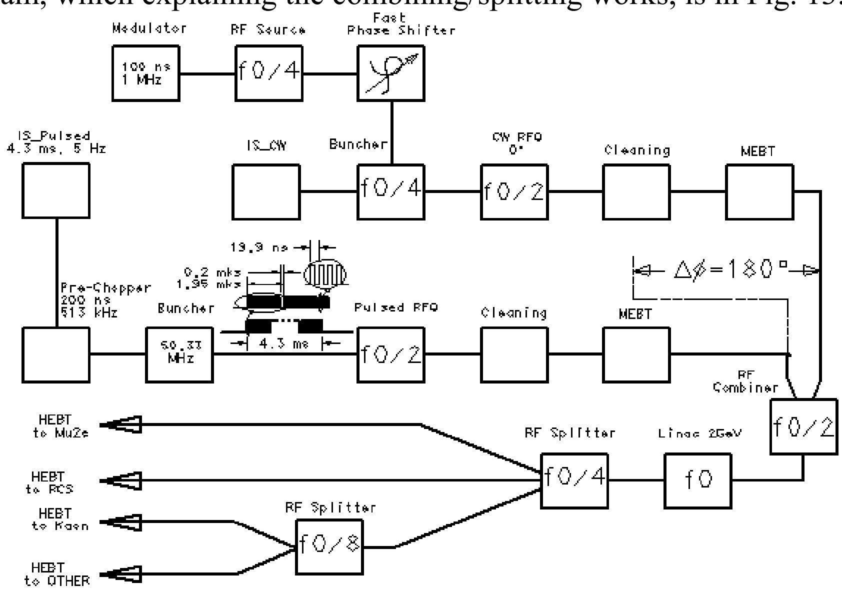

Fig. 12. Two-source beam combining scheme with the use of phase shift

The first row of the diagram in Fig. 13 shows the CW channel: the "kaon" bunches are in red and follow with f0/4 frequency defined the LEBT buncher. The Mu2e bunches are in blue; the timing of these bunches is shifted by 180º relative to the "kaon" bunches by shifting the phase of the bunching cavity. To make the fast shift possible, the quality factor of this cavity must be low; examples of similar approach of using a low-Q cavity for beam chopping can be found in [9].

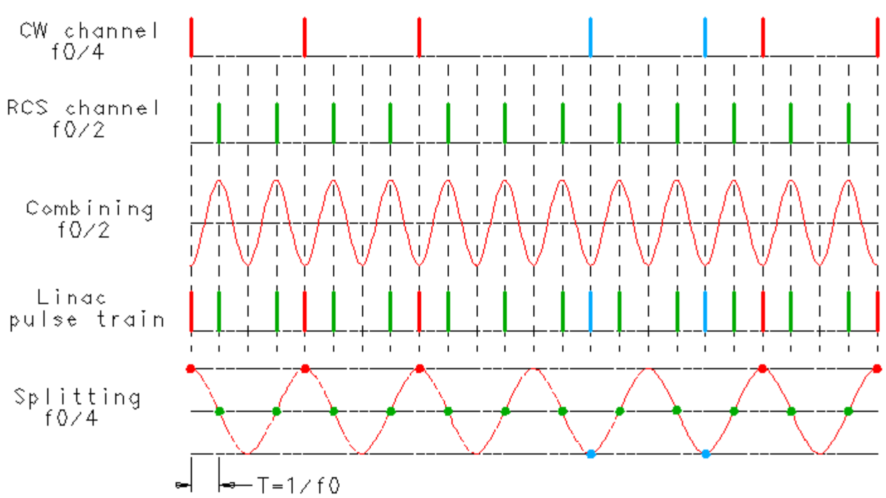

Fig. 13. Pulse timing diagram for the two-channel RF combining/splitting approach

The second row is the sequence of bunches for injection into the RCS (within 4-ms macropulse). Bunches here follow with f0/2 frequency. Several technical gaps within the 4-ms pulse that need to be arranged (see Fig. 10) are not shown in the diagram.

The two channels are combined using an f0/2 RF combiner. The beam structure in the linac is shown in the fourth row. Because splitting must be made into three different channels, an f0/4 splitter is used, as shown in the last row. Addition of the 3-d harmonic of this frequency would help to improve the accuracy of the splitting. It is possible to make additional splitting of the CW (red) channel by using an additional splitter.

To ensure the needed average current, the CW ion source must be built to allow fast current change, like it was required in the case with the use of kickers. With this current modulation, the current structure in the CW channel should be like it is shown in Fig. 11. A 4-ms gap must be introduces in the CW channel current; the gap must be synchronized with the RCS channel pulsing.

3. A different two-source scheme can be proposed that do not require manipulation of the beam phase. This scheme uses both RF-based and kicker-based combining/splitting techniques. Corresponding diagram is shown in Fig. 14. There are two injection channels, each includes CW H^- source, and CW RFQ accelerator. The first channel contains a 3.3 mA H^- source, a 1 MHz, 100 ns pre-chopper, a 162.5 MHz RFQ, and a cleaner after the RFQ. The ion source in this channel must also be modulated by a 4-ms, 10 Hz pulse sequence with the current of 1.0 mA during this mode of operation. The beam for RCS must have the 500 kHz and 50 MHz structure, as shown in Fig. 10.

The second channel contains a 2.1 mA H^- source, a 162.5 MHz RFQ that is 180º phase-shifted with respect to the phase in the RFQ of the first channel, and an RF beam splitter at 162.5·(m±1/3) MHz, that chops out 2/3 of the beam, leaving the bunches with the bunch sequence frequency of 54.17 MHz.

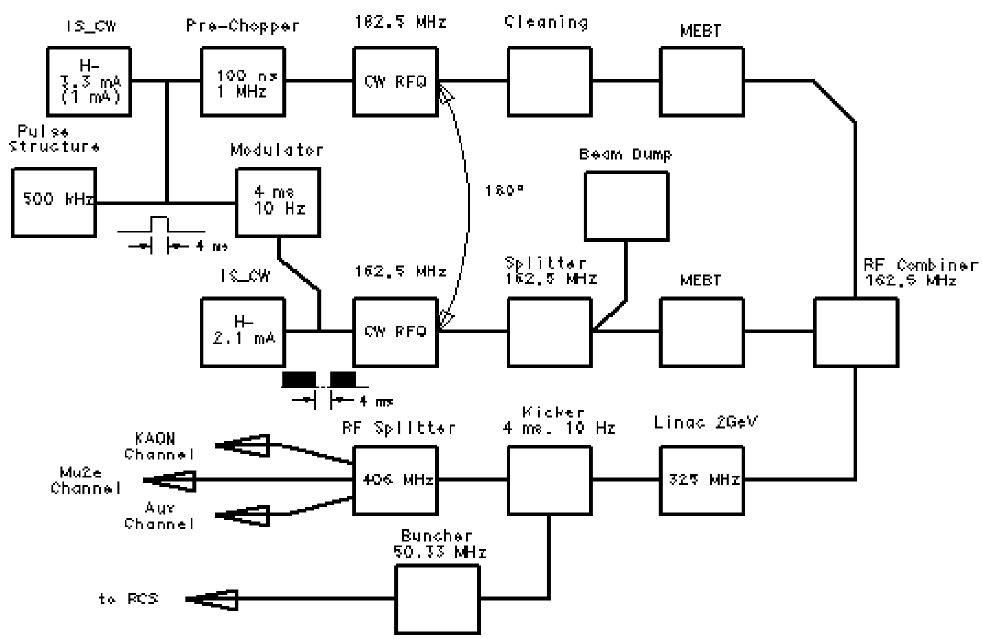

Fig. 14. Two-source beam combining/distribution scheme that employs both RF-based and kicker based deflectors.

RF combiner at 162.5 MHz combines the beams from both channels for further acceleration in the 325/1300 MHz linac. A 4-ms kicker separates part of the beam for injection into the RCS. A 50-MHz buncher can be installed after the kicker. Beam splitting RF system at 81.25 MHz (or 406 MHz) distributes the beam to Mu2e, Kaon, and the Auxiliary channels, providing 1/3 of the total beam power to each of the experiments. Corresponding timing diagram is in Fig. 15.

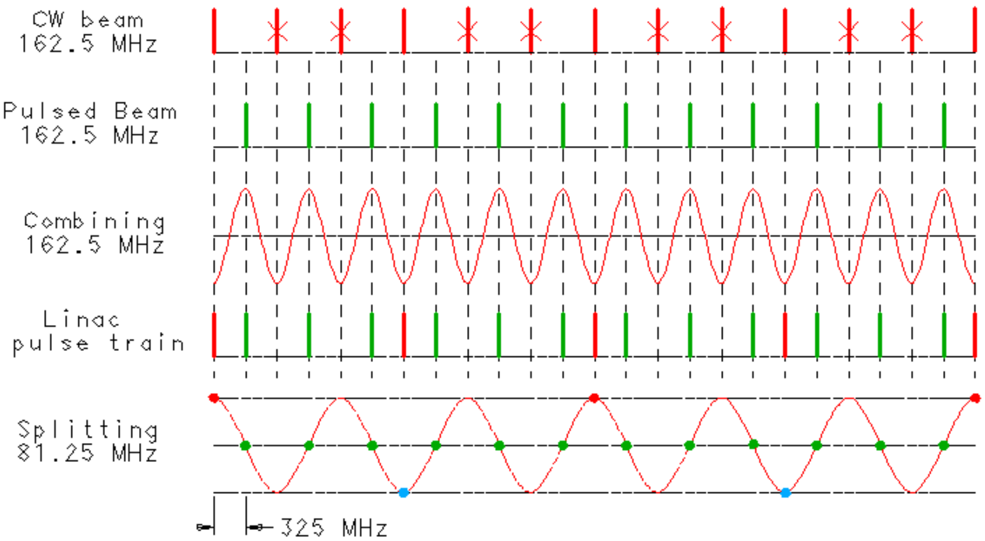

Fig. 15. Timing diagram for combined BPDS scheme

4. The next two-source scheme does not use RF-based separators. Instead it uses kickers for beam deflection. Corresponding block diagram is shown in Fig. 16.

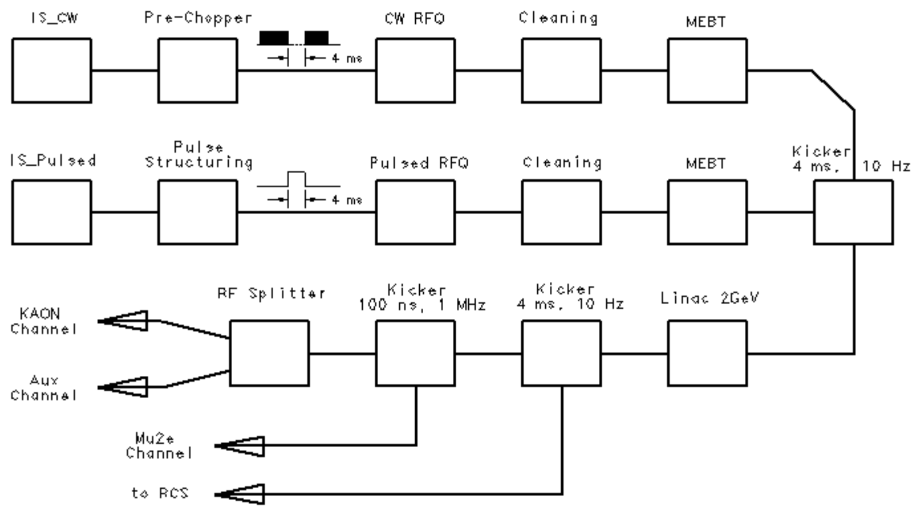

Fig. 16. Two-source kicker-based combining/distribution system.

One of two channels is fully devoted to generation of a pulsed beam for injection in the RCS. As in the previous schemes, the beam structure within this 4-ms pulse must be arranged using additional pre-choppers and/or bunchers. The average current within the 4-ms bunch is 1 mA.

A gap in the CW pulse train of the second channel is made that corresponds to the RCS pulse timing. In this channel, the average beam current linac is also 1 mA. This channel also requires ion beam current modulation, which is made on the LEBT level. Because it is difficult to make front rise and fall time small on the nanosecond level, cleaning sections in LEBT and MEBT must be introduced in the block scheme to deflect low energy parts of the pulses (rise and fall) that will not be accelerated in the linac.

A 4-ms, 10 Hz kicker brings the beams of the two channels into one transport line. The combined beam is then accelerated in the linac. The two beams are separated at the exit of the linac by another 4-ms, 10 Hz kicker that splits out the beam to be accelerated in the RCS. Although the energy of the beam is 2 GeV now, the required 4 ms pulse duration and 10 Hz of repetition rate seems well within the SOA area of this field.

The 100 ns 1-MHz pulse train for Mu2e experiment is generated by deflecting these parts from the CW pulse train by an appropriate kicker. Although quite challenging, these requirements do not seem impossible to meet: several systems were studied and some built to provide similar parameters (e.g., see [10], [11], and [12]).

Further separation of the beams between the KAON channel and another CW channel can be made using an RF splitter.

5. Finally, a one-source scheme can be imagined that combines some features of the 2-source schemes. If current modulation can be arranged at the ion source level (some indication exists that it can [13]), a phase shift option described earlier (Fig. 12) can be added to the scheme in Fig. 14. Corresponding block diagram is shown in Fig. 17.

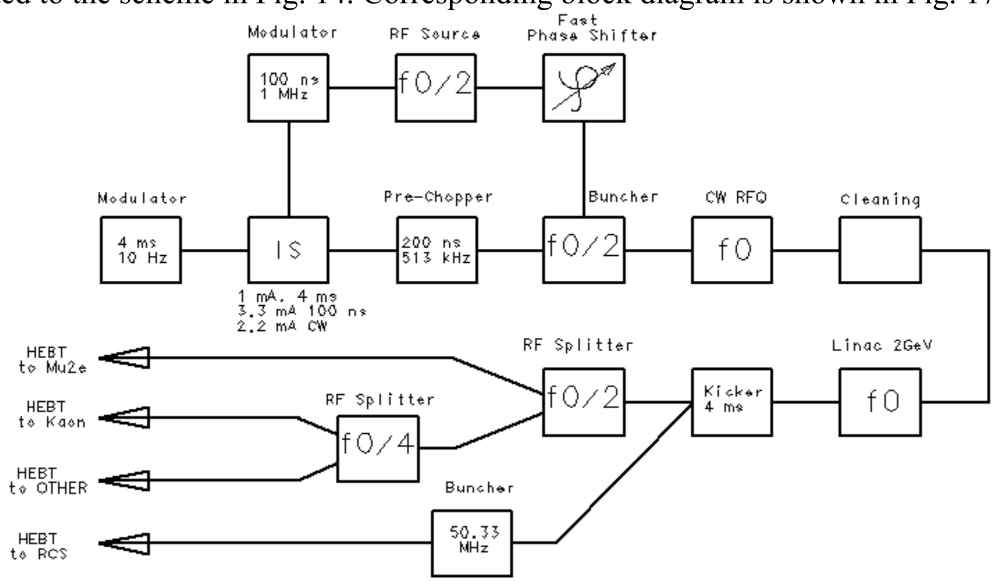

Fig. 17. Block diagram of the one-source system.

During the 4-ms pulse, a 1-mA average current is extracted out of the ion source. This pulse is directed towards the RCS using a kicker (green series in the second row of the diagram in Fig. 18. During the 100 ns pulses, which follow with 1 MHz frequency, the average extracted current is 3.3 mA (blue series in the first row in Fig. 18). The rest of the time, the ion source provides 2.2 mA current (red series). An f0/2 buncher installed before RFQ (f0) can change phase of the bunches in the RFQ by 180º for the timing of the 100 ns pulses. So, the phases of the Mu2e and KAON pulses in the RFQ and linac (both at frequency f0) differ by 360º. After the linac, the Mu2e and KAON bunches can be separated using an f0/2 splitter. Further separation of the KAON bunches into two separate channels will require additional RF splitting.

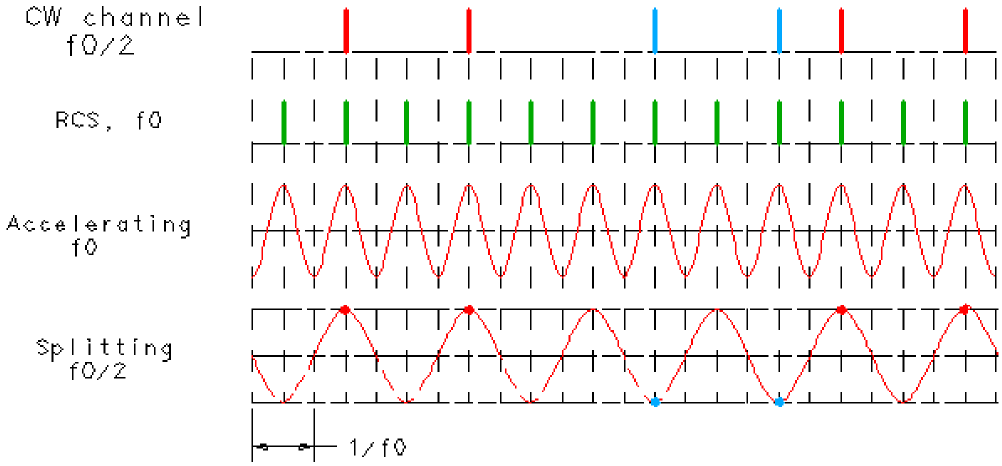

Fig. 18. "One-source" combined pulse diagram

Each of the beam distribution schemes must be analyzed from the point of view of availability and reliability of required technology. As was mentioned, the most critical part of the kicker-based scheme is a 1 MHz kicker system at the 2 GeV end of the linac. For the three sources scheme, RF combiners and splitters need to be developed with the additional requirement to ensure very stable RF amplitude and beam phasing. Some encouraging comes from the fact that similar structures were used at other labs (J-lab). For the scheme that require beam phase shift, the fast phase shift technique paired with low-Q bunching cavity must be analyzed.

A possibility of building an H^- source with current modulation must be evaluated for all schemes except the three-source one.

Common requirement for all the scheme above is providing in the LEBT section space sufficient for placing pre-chopping systems and/or beam bunchers (keep in mind the low frequencies of the bunchers).

IV. Summary

The introductory analysis of the beam preparation and distribution system shows that there exist several ways to approach the problem. Which way is chosen depends on the set of final requirements for beam distribution. This choice must also be made having in mind what kind of R&D-s need to be done to approach design stage in the most optimal way (meaning using mostly known solutions and methods and trying to avoid risky decisions). Definitely, extensive LEBT R&D must be set to address immediate problems critical to the project. Table below summarizes outstanding issues that need to be resolved for each approach mentioned above. Pluses mean that the issue exists and needs to be addressed. Minuses mean that there is ready to go solution or there is no need for the sub-system.

Block Diagram Phase Diagram	Fig. 8 Fig. 9	Fig. 12 Fig. 13	Fig. 14 Fig. 15	Fig. 16 Non	Fig. 17 Fig. 18
Number of Ion Sources	3	2	2	2	1
4 ms Pulse Structure	+	+	+	+	+
1 MHz Pre-Chopper	+	+	+	+	—
CW Ion Source Current : 10 Hz	—	—	+	—	+
CW Ion Source Current : 1 MHz	—	+	—	+	+
LEBT	+	+	+	+	+
1 MHz Kicker	—	—	—	+	—
10 Hz Kicker	—	—	+	+	+
RF Splitter	+	+	+	—	+
RF Phase Modulation	—	+	—	—	+

We can see from the table that the least amount of unknowns exists for the three source option. For the two-source options, additional study is needed to understand status of technology used in the scheme. The ion source configuration, LEBT beam optics, and chopper and dumper design issues are common for each of the mentioned schemes.

References:

1. S. Nagaitsev, http://projectx-docdb.fnal.gov/cgi-bin/DocumentDatabase/, doc 320
2. J. Staples, http://projectx-docdb.fnal.gov/cgi-bin/DocumentDatabase/, doc 319
3. http://conferences.fnal.gov/App-Proton-Accelerator/index.html
4. J.G. Alessi, J.M. Brennan, A. Kronou, “H^- Source and Low Energy Transport for an RFQ pre-injector”, 1989
5. G. Murdoch, et al, “Review of the Mechanical Engineering Challenges Associated with the SNS Power Ramp up”, EPAC-08, Proceedings, pp. 1500–1502, Genoa, 2008
6. V. Sahni, “Linac Accelerator Design in India for ADS”, http://indico.fnal.gov/conferenceDisplay.py?confId=2854
7. C. Rossi, “Chopper line Design and the 3-MeV Test Stand”, HIPPI-07, Sept. 2007.
8. E.P. Lee and R.K. Cooper, “General Envelope Equation for Cylindrically Symmetric Charged-Particle Beams”, Particle Accelerators, 1976, v.7, 83-95.
9. T. Kato, et al, “Beam Study with RF Choppers in the MEBT of the J-PARC Proton Linac”, PAC-03, pp. 1455.
10. H. Kirbie, et al, “ MHz Repetition Rate Solid-State Driver for High Current Induction Accelerators” PAC-99, pp. 625 – 627 (LLNL)
11. A. Mikhailichenko, “Fast Kicker”, Cornell University, rep. CBN 09-03.
12. E.G. Cook, “Review of Solid-State Modulators, LINAC-2000, Monterey, CA, pp. 663 – 667 (LLNL)
13. V. Dudnikov, Private communication