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LIA for the Neutrino Factory at FNAL

1. This memo is to summarize what was done since some activity started early in October with the goal to understand basic features of the Neutrino Factory Phase Rotation Linear Induction Accelerator.

2. The initial requirements were described in the Norbert's memo dated October 7. The most important features of this LIA are:

- particles to accelerate are muons with initial energy range from 50 to 250 MeV; it is necessary to equalize the beam energy spread by differential accelerating or the beam (so called phase rotation procedure); accelerating voltage pulse shape must closely follow (within several percents) the muon input longitudinal energy distribution;
- a LIA energy swing from of about 200 MV is necessary for the phase rotation;
- total muon current does not exceed 100 A;
- a large aperture beam channel for the muon beam is required because large emittance beam coming from the source. The 60 cm free aperture for the muon beam is required with magnetic field 1.25 T;
- LIA length must be about 100 m to avoid excessive muon losses due to decay;
- multiple pulse regime (4 pulses within 2 μsec) has been requested;
- voltage pulse duration is about 150 ns.

3. Taking into the account that required average accelerating field is very high, it is reasonable to talk about a change of the acceleration direction: starting from + 1 MV/m and going to -1 MV/m in the end of the voltage pulse. Some variation of the start and end voltage are possible if to keep the difference equal to 2 MV/m

It is necessary to find an acceptable and simple approximation to the accelerating voltage change with time.

4 Magnetic field solenoid system can be realized based on superconducting wire or cable. DC or water cooled pulsed system does not look attractive. It is possible to consider nitrogen cooled pulsed system later as an alternative to superconducting one.

5. High magnetic field in the transport channel and needed voltage gaps create a problem of a fringe magnetic field in the area where inductor cores are located. Presence of magnetic field in this area can reduce allowed magnetic induction swing of a core that results in lower system efficiency. According to V. Kazacha's (Dubna) experience, properties of nickel alloy ribbon cores that were used commonly for LIA can be significantly compromised by the magnetic field of several hundred gauss in the material. To reduce magnetic field at core location, it is possible:

- to have magnetic system inside cores;
- to increase core inner diameter;
- to minimize voltage length gap;
- to shape coil current density profile;
- to use iron shielding between coil and core.

Preliminary fringe field estimate was done after the first induction cell scheme was generated based on the requirements above (item 2).

To reduce field emission and surface plasma formation problems, it was accepted for voltage gap to have maximum electric field of the order of 100 kV/cm. For pulse duration of 150 ns this field level looks like a reasonable compromise. Because magnetic field solenoid is superconducting, the gap between solenoids is larger than voltage gap to allow helium, nitrogen, and vacuum shielding of a coil. Nevertheless, after several iterations was made, it was possible to find a design solution where fringe field were kept at a reasonable level. Figure 1 shows fringe magnetic field distribution in the area that contains inductor cores. Core material permeability was considered to be about 2000. Transport bore radius was chosen to be 200 mm; internal radius of a core was 460 mm. It is possible to see that magnetic field inside cores does not exceed 150 Gs, which is not so bad because typical value of a magnetic flux density swing is 20,000 Gs for metglasses, nickel alloys, and nanocrystalline alloys. Although it was done not for the final cell configuration, the result is quite optimistic, and even allows some reduction of core radius keeping in mind that it is possible to optimize the design playing with coil shaping and, maybe, adding iron screen.

6. Based on this result, core section layout was modified, and the result of this modification is shown ion the figure 2.

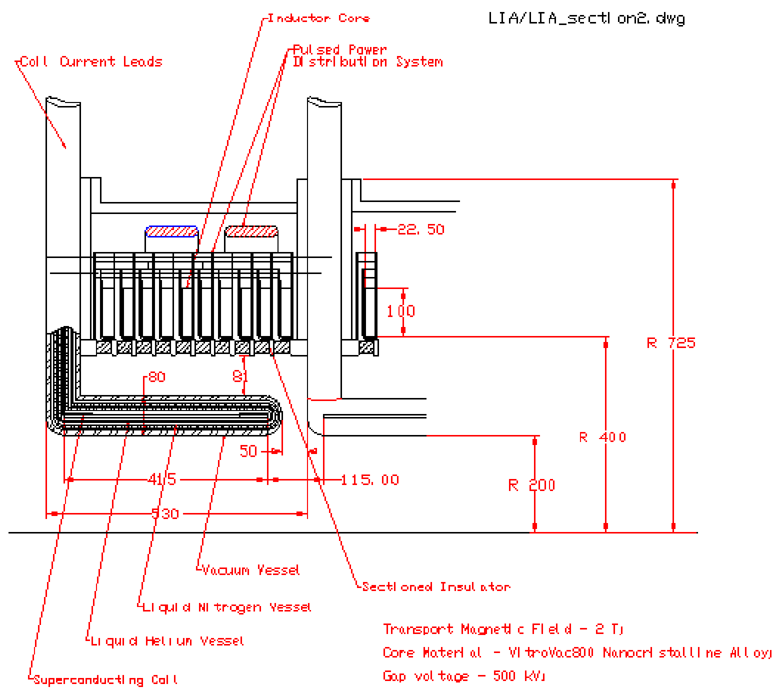

Fig. 2 LIA Cell Layout

The design uses 200 mm bore radius; the cell length is 530 mm. Voltage per cell is about 500 kV; voltage gap is 50 mm. Solenoid is placed inside its cryostat with vacuum, nitrogen, and helium shells. The length of each solenoid is 415 mm. The gap

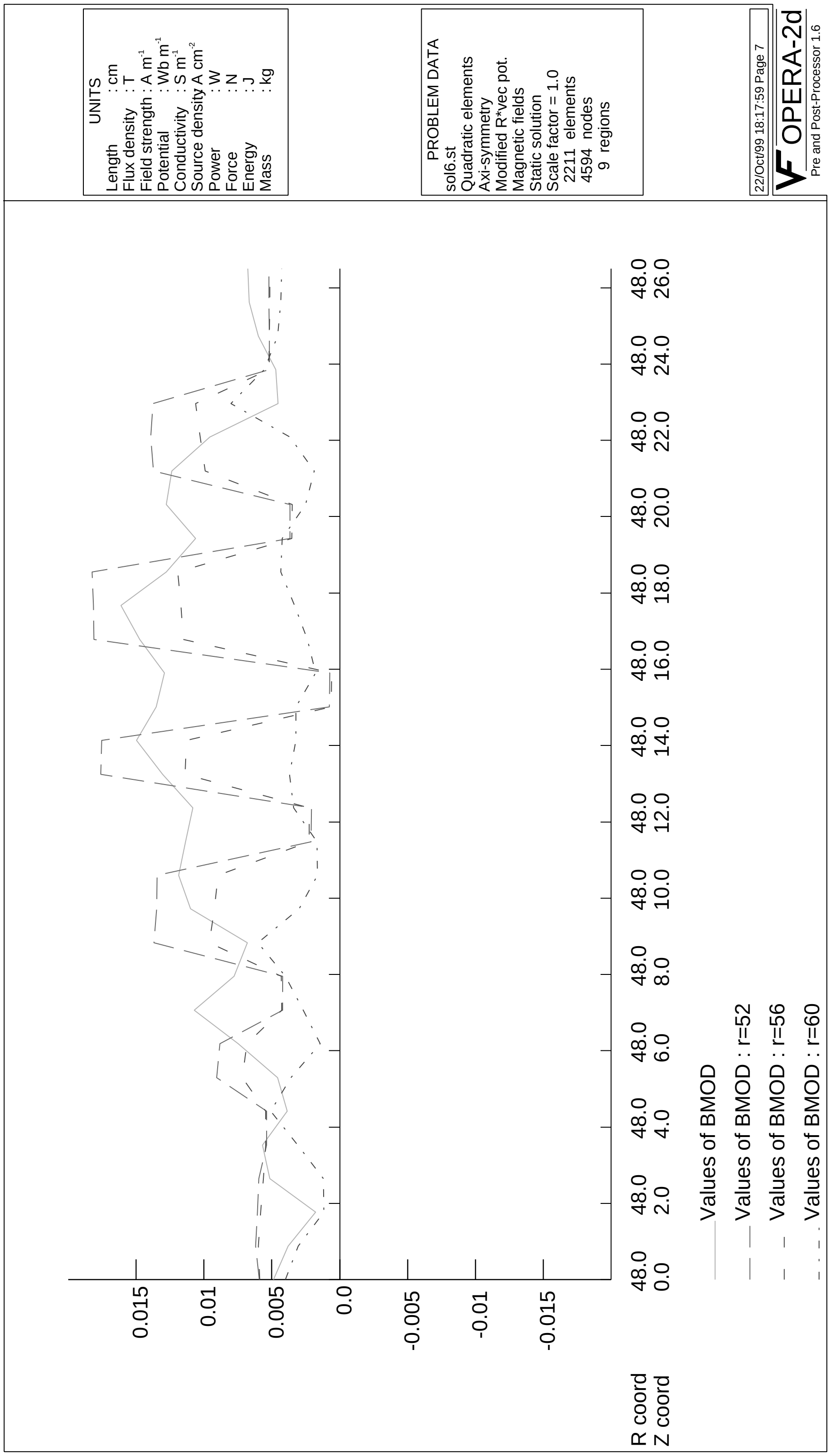

Fig. 1. Magnetic Field distribution in the core area

between the next two solenoids is 115 mm. Radial thickness of the cryostat is about 80 - 90 mm. Magnetic gap results in field penetration into the core area. It is possible to compensate it slightly by shaping the coil profile (it was made in the design shown in the fig. 2, but was not optimized). It will be necessary to work at the solenoid design. It can be a significant advantage if it is possible to make solenoid cryostat lead end section thinner (now it is about 80 mm thick). Final bore diameter and magnetic field must be chosen as soon as possible to finalize solenoid design.
It will be necessary to address transportation issues. Reasonable requirements to field value, quality, and alignment must be generated taking into the account possible emittance growth, and cork-screw and BBU instability development. These issues become very important if one considers the total accelerator length.
Cylindrical, sectioned design of an accelerating tube was used taking into the account that average accelerating gradient is rather high, and that it's polarity changes during the pulse. This results in rather low surface field level of about 17 kV/cm that helps to avoid surface breakdown. Because of large volume of cavity, some measures are required to reduce its quality factor for transverse modes that are responsible for BBU instability.
Ten inductor circuits were considered at this stage each using only one core made from ferromagnetic ribbon. Ribbon width was chosen to be 22.5 mm, cell spacing - 40 mm. Compaction factor is rather low, but the advantage is the relatively low voltage (50 kV per core) that can result in having rather good system reliability.
If to take into the account required pulse shape (change of polarity) and most probable material properties (induction swing of about 2 T), core radial thickness must be about 100 mm, so the volume of the core is well defined that allows making an estimate of its performance.

6. Core material choice is of great importance for LIA cell performance. Traditionally, for pulse length more than 100 ns, soft ferromagnetic ribbon is used made of nickel alloys, metglasses, or nanocristalline alloys. Ferrites are also used, but they do not have much advantages if pulse length is higher than 100 ns. Major parameter to use as a material choice criterion is core power loss. There are several sources of core losses: eddy currents, magnetic domains wall movement, and hysteresis. Eddy current losses scale like the first order of a material specific conductivity and the second order of ribbon thickness, so it is important to have thin ribbon with high value of a specific resistance. Core production technology is very important for reduction of the hysteresis and domain wall movement losses. Because at pulse duration range of about 100 - 200 ns all the components of losses mentioned above are of similar importance, at this stage, it is reasonable to use manufacturer's data to estimate core power loss.
Another important factor is magnetic flux density swing. The more the swing, the less material is required to support needed voltage and pulse length. On the other hand, power losses is a function of maximum induction in a core, so it is necessary to optimize the system configuration taking into the account construction cost and energy consumption cost. Also, pulser and distribution system design approach depends strongly on the required power level to activate LIA.

The latest available LIA core performance data source can be found in [1,2]. It is quite clear from these sources that the best available material suitable for a large-scale LIA core production is a nanocrystalline alloy. There are two vendors that can supply these alloys. They are Hitachi (Japan) that makes FT-1H alloy and Vacuumschmelze (Germany) that makes VitroVac 800. From the point of view of core performance these alloys are similar, so I will use the VitroVac 800 in further power loss estimation. Required magnetization rate to support core voltage of about 50 kV per one core is dB/dt = U/S. Taking into account core packing factor of 70%, maximum field change rate is **$50\cdot10^4$V/0.00157 m^2 = 3.2$\cdot10^7$ T/s**. There are no core loss data available for this magnetization rate. Nevertheless, taking into account linear loss dependence of magnetization rate, it looks possible to extrapolate available data to this magnetization rate. Different sources give different results of the extrapolation. Nevertheless, for the FT-1H nanocrystalline alloy, it is possible to pick loss value of 2500 J/m^3 for 2.0 T flux density swing.. With estimated core volume of $V=2\pi\cdot15.7\cdot45\cdot10^{-6}$ m^3 = 0.00445 m^3, we have total core loss power of

$$P = w\cdot V\cdot(dB/dt)/\Delta B$$

or P = $1.8\cdot10^8$ W. If to take into account 50 kV of a core voltage, it gives effective shunt loss resistance of about 14 Ohm, and maximum excitation current of 3600 A. This current corresponds to core magnetic field of 1300 A/m (16 Oersted). It is necessary to repeat here that the loss estimate made for constant magnetization rate corresponding to rectangular voltage pulse of 50 kV with pulse length that provide 2.0 T of flux swing. In our case voltage varies during pulse, so the excitation current will change. If current that is provided is less than the required excitation current, pulse rise time will increase and gap voltage can become smaller. It will be necessary to understand loss properties of the material to have an option to model voltage-current core characteristics during excitation cycle and to scale them to different pulse shapes and material grades.

7. It is possible to reduce losses if to increase core cross-section. Then we will reduce flux swing and flux change rate. In this case we must gain in power loss proportionally to the flux change rate. It will be necessary to compare LIA construction cost taking into account different core size, power saving, and power source construction cost.

8. Total amount of core material needed is the weight of one core times number of cores: M = 0.00445m^3 $\cdot$ 7.8 T/m^3 $\cdot$ $100\cdot1000/50$ = 70 T. So, we are talking of about 100 T of core material **for LIA** itself.

9. Because magnetization current is significant and efficient impedance is rather small, each core will require its own drive that can be connected to the load using four 50-Ohm 60 kV cables. It will be necessary to develop power distribution system that provides needed impedance matching.

10. There is one feature in the requirements to the system that can simplify pulser design. Multiple pulse regime requires core reset after each pulse. This reset is done by changing the polarity of a voltage in a primary turn. Because one of possible LIA regimes requires voltage polarity change, this reset can be done automatically if to design a voltage pulse in a way that its full integral over the pulse length is zero. Adjusting the pulse shape, it is necessary to take into account pulse rise time. Pulse decay time is not so critical because for the rectangular magnetization curve it will not move residual flux

density below its maximum value. Because required pulse shape is not a symmetrical, we ought to increase maximum voltage at the beginning of the cycle.

References:

1. A.W. Molvik, et al. "Implication of New Induction Core Materials and Coatings for High Power Induction Accelerators", PAC-99, Proc., pp. 1503 - 1505
2. I. Bolotin, et al. "Influence of Technological Process on Parameters of Magnetic Cores Made from Amorphous Alloy Ribbons".