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INDUCTION LINEAR ACCELERATOR TECHNOLOGY FOR SDIO APPLICATIONS

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Introduction

During the past two decades, the induction linear accelerator (Linac) has been the primary tool at the Lawrence Livermore National Laboratory for carrying out a number of research activities in charged particle beams. During the past several years, the major activity has been the investigation of converting a high quality electron beam directly to laser radiation. In trying to produce relativistic electron beams to carry out its research, the program needs dictated a number of advancements in the design of the induction cells, pulse compression techniques, high repetition rate switches and electron sources. These technological innovations have not only allowed us to meet program goals but have produced side benefits to such fields as food irradiation and microwave plasma heating of fusion machines.

Accelerator Research

The properties of the induction linear accelerator qualify it as the frontrunner for generating high current, high energy electron beams whose energy can be efficiently converted to coherent electromagnetic radiation for the SDIO mission.

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The research effort concentrated primarily on three major activities. The first was aimed at improvements in the accelerator drive system to meet the high repetition rate requirements not possible with spark gaps. The second activity was centered around a redesign of the accelerator cells to eliminate the beam breakup instabilities resulting in optimized beam transport. The third activity sought to improve the source of electrons (the injector) to achieve a higher quality beam to satisfy the requirement of the Free Electron Laser.

Drive System

Induction accelerators, like RF linacs, require a considerable amount of pulse compression. Fig. 1 shows a comparison of the amount of pulse compression required by the two different types of accelerators. Even though the initial and final energies are about the same, the peak power required by the induction linac is over an order of magnitude greater. This type of pulse compression was easily achieved on the ATA accelerator by employing spark gap technology. Fig. 2 shows the charging transformer Blumlein and spark gap used on the ATA to achieve the 70-ns pulse capable of delivering a 250-kV pulse at 20-kA. This technology has operated quite well for the past several years at one hertz repetition rate with a one kilohertz burst capability for ten pulses. An increase in average power or burst rate is impractical because of spark gap erosion and gas blower power requirements.

It was clear that such technology would not be adequate to achieve repetition rates exceeding one kilohertz required by future applications. Research into alternative switching schemes began even before the first spark gap went into operation.

A technique which had been around since the early 50's looked quite promising as an alternative to spark gaps for pulse compression. This technique, magnetic pulse compression, had been used for many years in radar pulsers but at much lower power levels and much longer pulse duration. The pulse required to driving induction accelerator cells required peak power levels three orders of magnitude greater (10^{10}W) and pulses two orders of magnitude shorter (10^{-8}S) than existing technology.

A considerable research and development effort over a period of several years resulted in a magnetic pulse compressor which satisfied all the program requirements and could be used as a direct replacement of two spark gap pulse power units.

When an added requirement for high repetition rates continuously was added, it became necessary to add a pre-compression stage so that the initial pulse requirement could be generated by currently available thyratron switches. Fig. 3 shows the finalized version of the magnetic pulse compression unit. Fig. 4A shows the waveshapes in the compression process and Fig. 4B the efficiencies of different stages. This device would not have been possible without advances in magnetic materials technology at Allied Corporation. The power limits at different repetition rates for the MAG 1D are shown on Fig. 5.

Induction Cells

In order to satisfy the FEL beam requirements and properly tailor the drive of the magnetic pulse compressor (MAG 1D) to the accelerator cells, a complete redesign was undertaken. Accelerator cells for ground based lasers require lower current drive and much lower beam transverse motion down the accelerator. In order to transport the beam through many of these cells without growing instabilities, it is necessary to properly design the coupling and accelerating gaps. The most serious instability which much be controlled is the beam break up (BBU) instability.

This instability occurs because the acceleration gaps which supply energy to the beam also allow beam's self-field to excite the cavity modes. These modes possess a transverse magnetic field which can give the beam a transverse impulse which eventually could kick it into the walls. This beam interaction with the cell is minimized by reducing the beam coupling to the cell and by lowering the cell response of Q. Fig. 6 shows the ATA induction cell with some BBU control added in the form of corner reflectors and ferrite absorbers. This accelerator cell was marginally stable at the higher current levels. The new cell on Fig. 7 shows the tapered accelerating gap and the angled insulator so that TM modes excited are transmitted into the ferrite where they are totally absorbed. The beam pipe diameter was kept large so as to minimize the beam coupling to these modes. Consideration was also given to keeping the voltage pulse flat over the acceleration period which is dictated by the requirements of the Free Electron Laser (FEL). A complete ten-cell set which constitutes the building block of an induction accelerator is shown on Fig. 8.

Injector and Cathode

In order for this type of accelerator technology to be appropriate for FEL systems, the accelerated electrons must have high brightness (low emittance). The low emittance criteria results from the FEL gain being strongly dependent upon electron beam brightness. This of course implies that the extracted beam from a cathode must have high brightness to begin with.

The added requirement of achieving high brightness at high repetition rates (high average power) dictated a change from field emitters to thermal cathodes.

The logical place to start seemed to be with existing well established cathodes used in the SLAC klystrons. Although the high repetition rate requirement was satisfied by these cathodes, the emission density was much lower than that required by the FEL. A number of companies involved in cathode research; Varian, Spectramat, Ceradyne, have shown very promising results in obtaining nearly an order of magnitude greater current emission at very low surface temperatures. Experiments currently in progress indicate that cathode operation will not be the limit on beam brightness.

Detailed code studies using EBQ (Herrmansfeld) and DPC (Boyd) are being carried out in the design of the gun optics for optimum output brightness. Those designs are being implemented in the Accelerator Center (ARC) and are currently under test. A cross section of the current gun optics is shown on Fig. 9. The electron gun is assembled from cells which were developed for the accelerator. The complete injector is shown on Fig. 10.

Conclusion

The SDIO requirements for a Ground Based Laser have stimulated developments in several areas of accelerator technology. The research and development will continue in the Accelerator Research Center (ARC) at LLNL in components, sources and transport. The advances achieved in accelerator technology may also yield side benefits in such fields as microwave heating of plasma and accelerators for radiation processing.

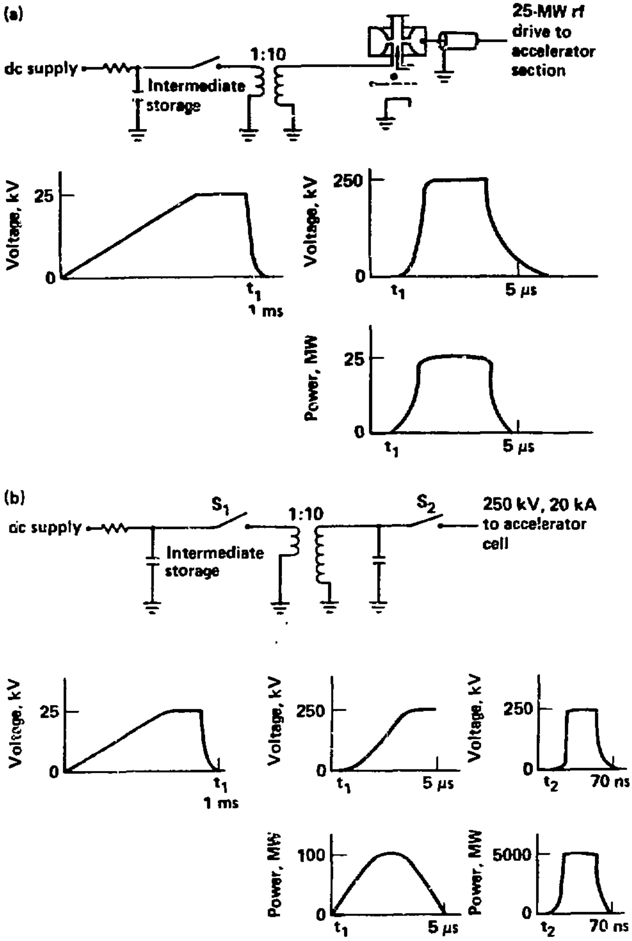
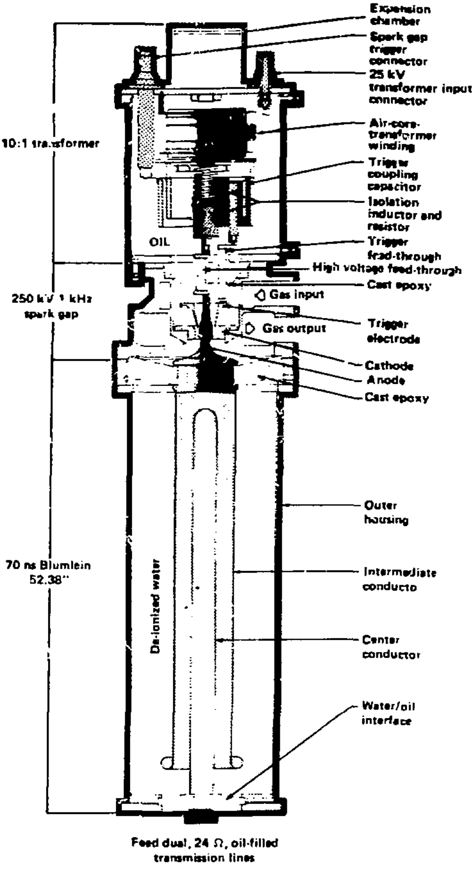

(a)
dc supply
Intermediate storage
1:10
25-MW rf drive to accelerator section
Voltage, kV
25
0
t1
1 ms
Voltage, kV
250
0
t1
5 μs
Power, MW
25
0
t1
5 μs
(b)
dc supply
Intermediate storage
S1
1:10
S2
250 kV, 20 kA to accelerator cell
Voltage, kV
25
0
t1
1 ms
Voltage, kV
250
0
t1
5 μs
Voltage, kV
250
0
t2
70 ns
Power, MW
100
0
t1
5 μs
Power, MW
5000
0
t2
70 ns

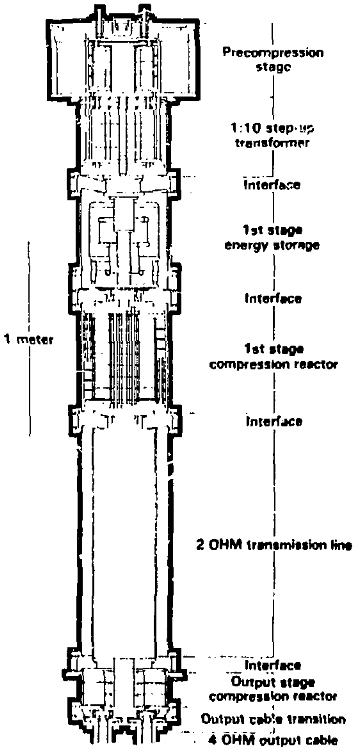
FIG.1



Expansion chamber
Spark gap trigger connector
25 kV transformer input connector
Air-core transformer winding
Trigger coupling capacitor
Isolation inductor and resistor
Trigger feed-through
High voltage feed-through
Cast epoxy
Gas input
Gas output
Trigger electrode
Cathode
Anode
Cast epoxy
Outer housing
Intermediate conducto
Center conductor
Water/oil interface
10:1 transformer
OIL
250 kV 1 kHz spark gap
70 ns Blumlein 52.38"
De-ionized water
Feed dual, 24 Ω, oil-filled transmission lines

FIG.2

MAG-1-D



60 [illegible]-0469

FIG.3

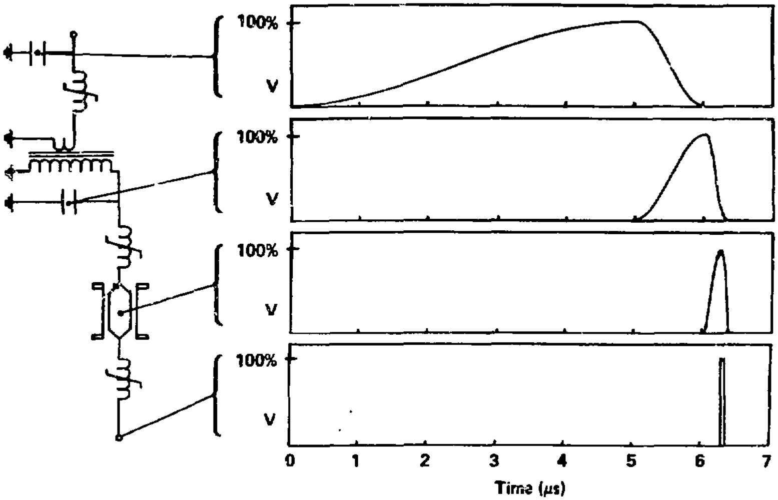
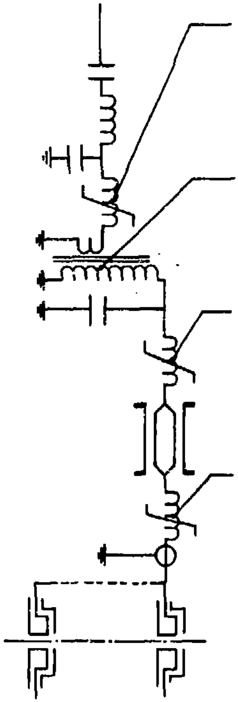


FIG.4a

Estimated core loss per stage MAG-1-D



Precompression stage
50 kG-1 mil-2605CO
Est. core loss — 3.5 J(0.35%)

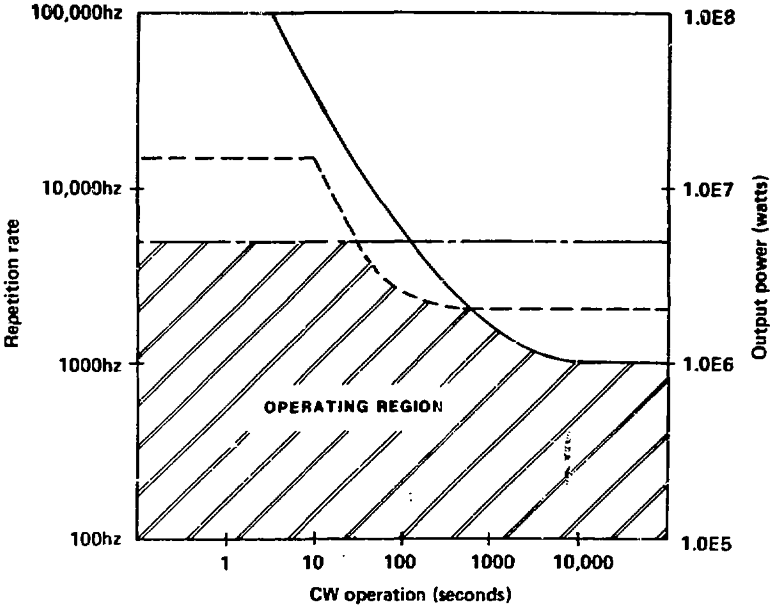
1:12 input xfmr
70 kG-1 mil-2605-S3A
Est. core loss — 3 J(0.3%)

1st stage compression reactor
70 kG-0.6 mil-2605CO
Est. core loss — 9.8 J(0.98%)

Output stage compression reactor
70 kG-0.6 mil-2605CO
Est. core loss — 28 J(2.8%)

Total core loss 44.3 J (4.43%)

FIG.45



Power supply limit (—·—·—)
Thyratron commutator limit (- - - - - -)
Freon cooled MAG-I-D Thermal limit (———)

FIG.5

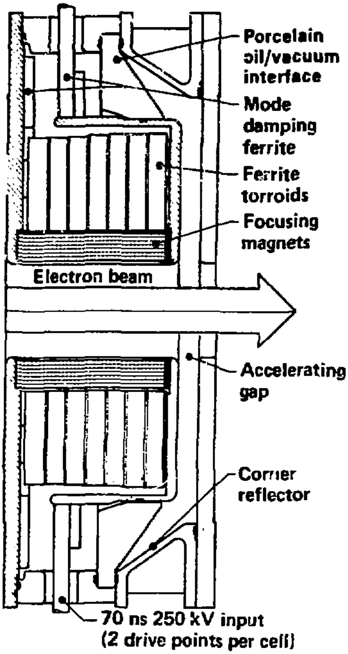
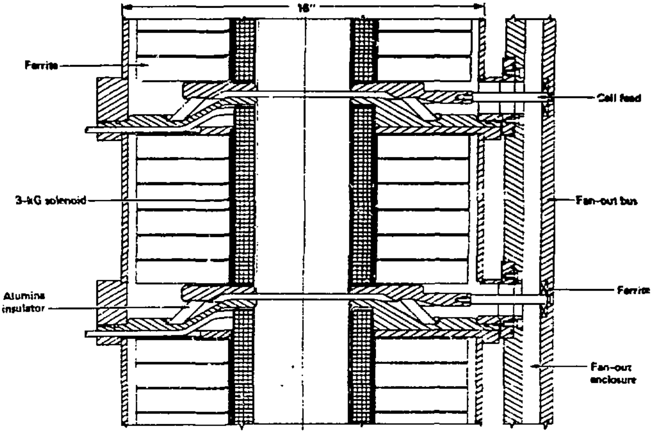

Porcelain oil/vacuum interface
Mode damping ferrite
Ferrite torroids
Focusing magnets
Electron beam
Accelerating gap
Corner reflector
70 ns 250 kV input
(2 drive points per cell)

FIG.6



Typical section of
low-gamma 10-cell module

FIG.7

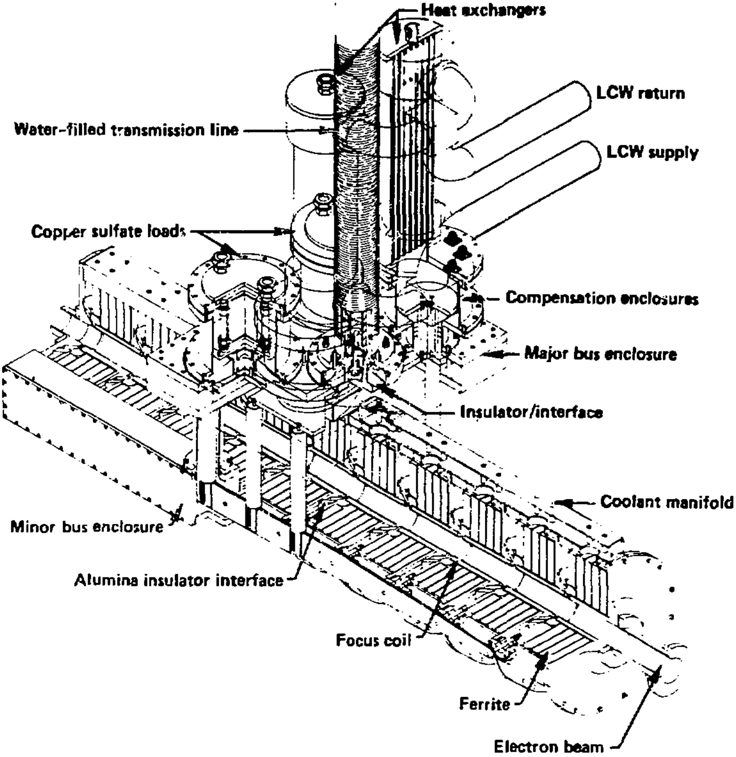
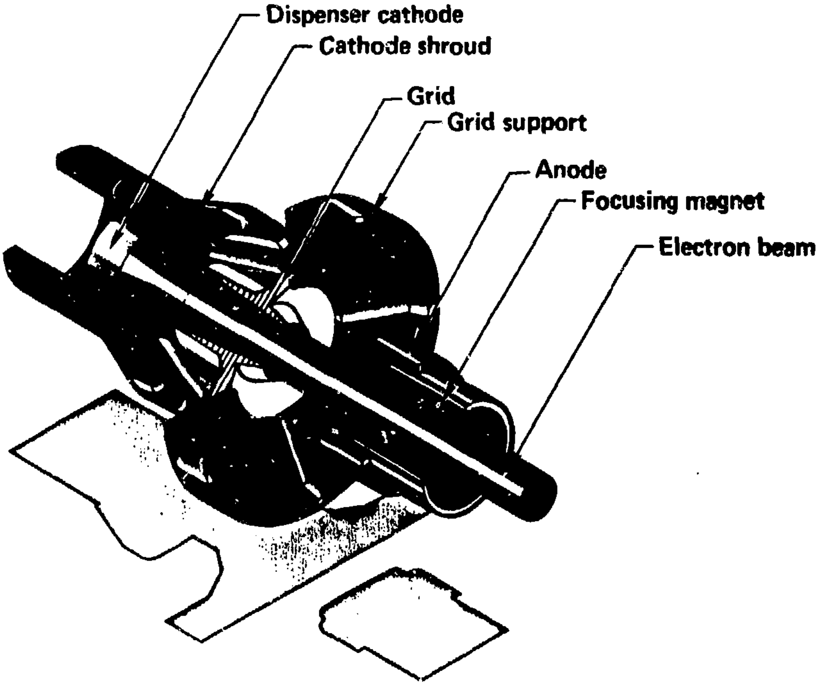

Heat exchangers
LCW return
Water-filled transmission line
LCW supply
Copper sulfate loads
Compensation enclosures
Major bus enclosure
Insulator/interface
Coolant manifold
Minor bus enclosure
Alumina insulator interface
Focus coil
Ferrite
Electron beam

FIG.8

High Brightness Test Stand



**3.50" dia
cathode
initial
configuration**

60-C-0386-0395

FIG.9

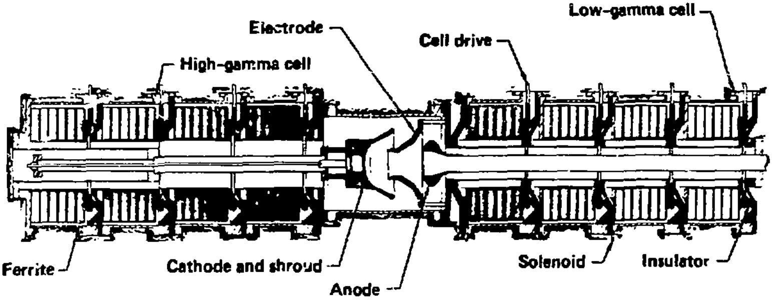

Low-gamma cell
Electrode
Cell drive
High-gamma cell
Ferrite
Cathode and shroud
Anode
Solenoid
Insulator

FIG.10