Advanced Topologies 4
Magnetic Switching

Pulsed Power Engineering
Michigan State University
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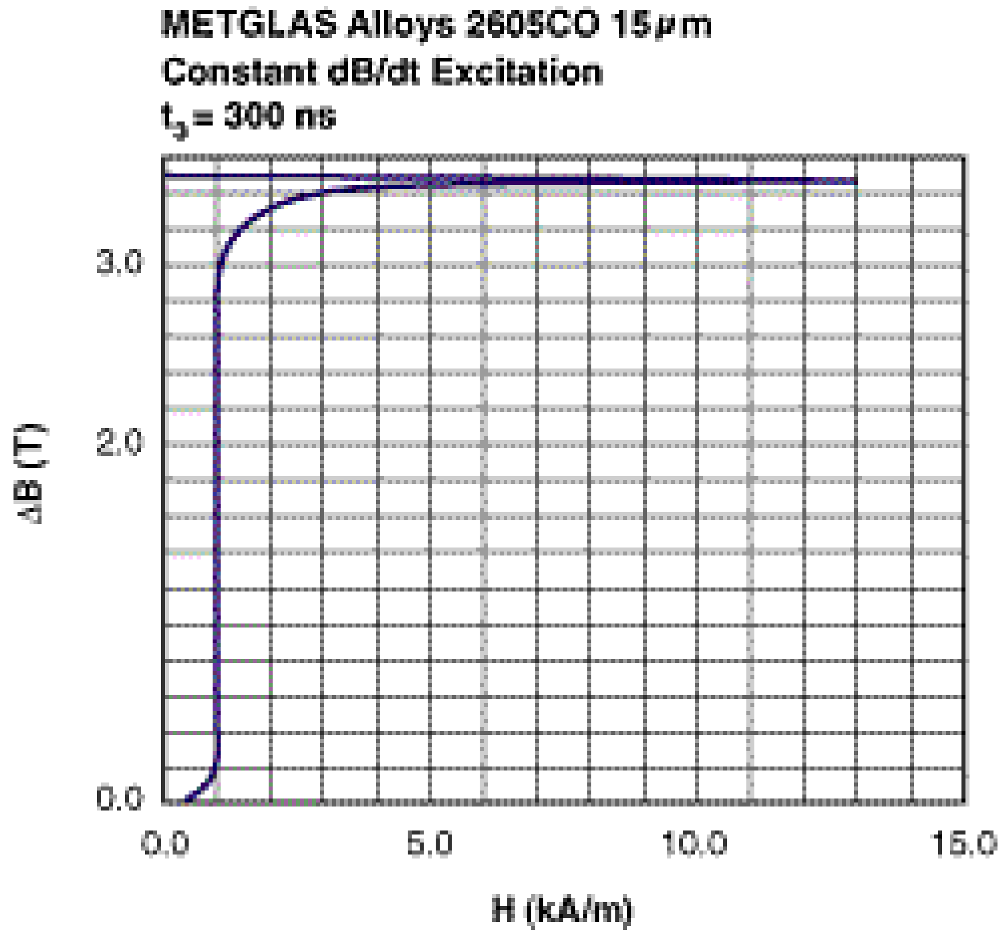
Magnetic Switching and Magnetic Pulse Compression Circuits

- Basics
- Relevant Equations
- Limitations
- Other Practical Considerations
- Mechanical Design
- Examples
- References

Magnetic Switch Principles

- A magnetic switch is a device, usually constructed as a winding around a magnetic core, that uses the non-linear properties of magnetic materials to achieve a large change in impedance
- The impedance of a magnetic switch varies from a large inductance (high permeability when magnetic core is unsaturated) to a small inductance (low permeability when magnetic core is saturated)
- With few exceptions, a magnetic switch needs a "real" switch somewhere in the circuit ahead of the magnetic switch to initiate magnetic compression . This real switch will need to be capable of handling the same energy as the magnetic switch but at much lower peak power levels.

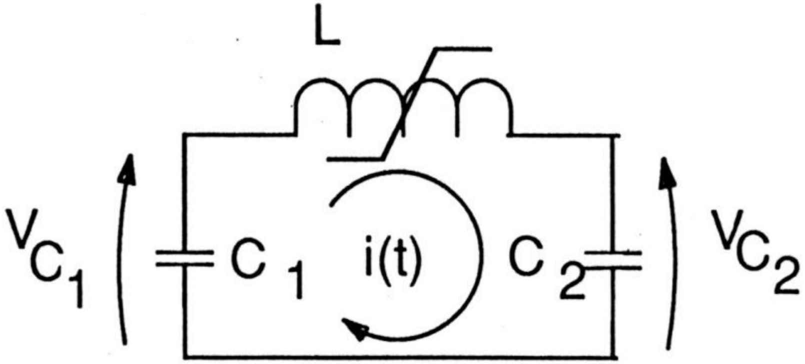


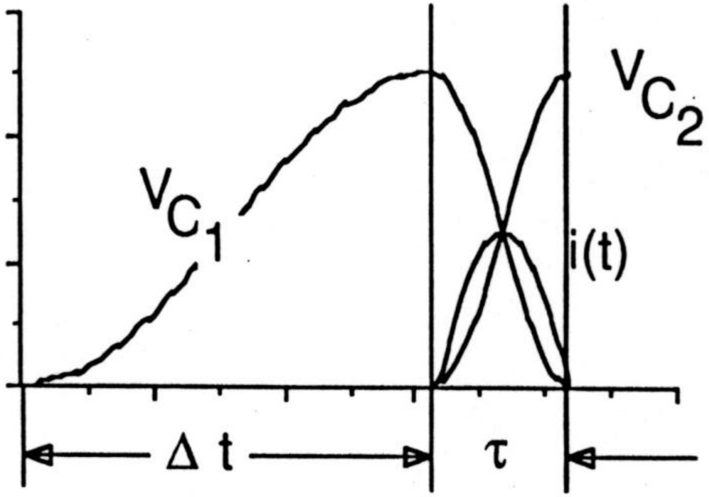
Definition of Terms

Term	Definition	Units
L_n	the n^{th} stage of magnetic compression	
Vol_n	minimum magnetic core volume of L_n	meters^3
A_n	magnetic cross-sectional area of L_n	meters^2
OD	outer diameter of magnetic core (toroid)	meters
ID	inner diameter of magnetic core (toroid)	meters
ΔB_s	usable change in core flux density	tesla
N_n	number of turns on the L_n winding	
w_n	axial length of L_n winding	meters
Δr	radial thickness of magnetic core	meters
$\langle r \rangle$	mean radius of magnetic core	meters
pf	packing factor - cross-section area of magnetic material divided by total area enclosed by windings	
L_n^{sat}	saturated inductance of L_n	henries
$Gain_n$	ratio of charge to discharge time for L_n	
C_n	capacitance at the input of L_n	farads
E_{Cn}	per pulse energy stored on C_n	joules
$\langle V_{Cn} \rangle$	average charge voltage on capacitor C_n	volts
τ_{Cn}^{chg}	time required for capacitor C_n to charge to peak voltage	seconds
$\tau_{Ln}^{\ sat}$	hold-off time - time required to saturate L_n at a given average charge voltage	seconds
t_{prop}	total propagation delay through the modulator - equal to the sum of the hold-off times of all the stages	seconds
μ_o	free space permeability $= 4\pi * 10^{-7}$	henries/m
μ_r	relative permeability	
μ_r^{sat}	saturated value of relative permeability	
$\langle \mu_r^{sat} \rangle$	average relative permeability during saturation	
Δt	time jitter	seconds
Δv	pulse-to-pulse variations in peak charge voltage	volts

Magnetic Switch Operation

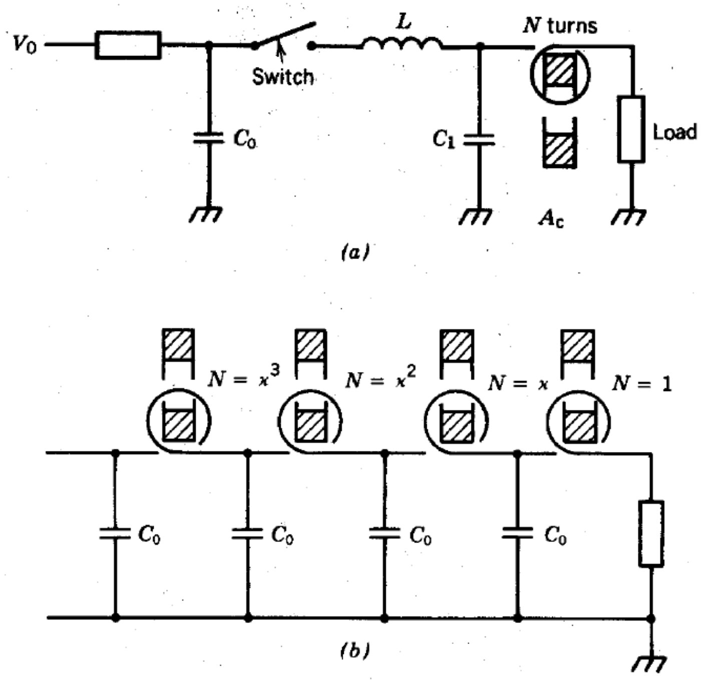
- **The Magnetic Switch is designed to saturate at the voltage peak on C_1 and transfer all the stored energy to C_2**

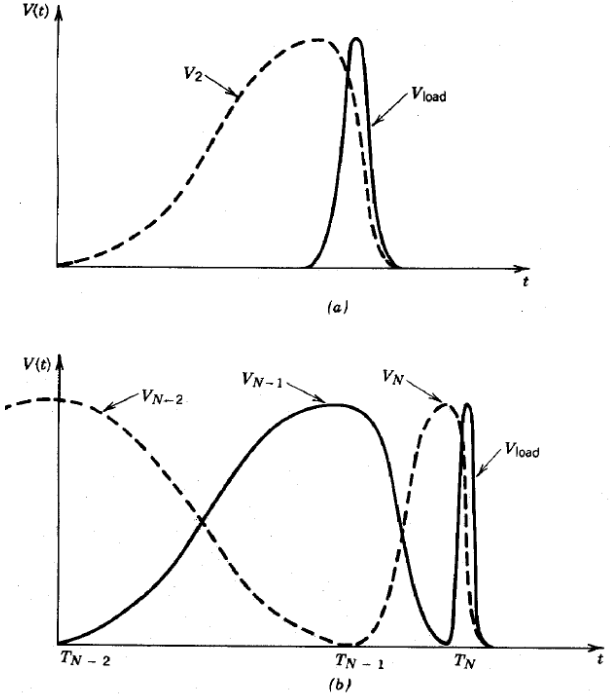




$$\text{GAIN} = \frac{\Delta t}{\tau}$$

Magnetic Pulse Compression Systems





- Windings around a magnetic core can be used as a switch
- OPEN = unsaturated core state
- ON = saturated core state
- By using various materials and winding configurations, one can control the timing of core saturation (transition from OPEN to CLOSED) and therefore the amount of compression in time

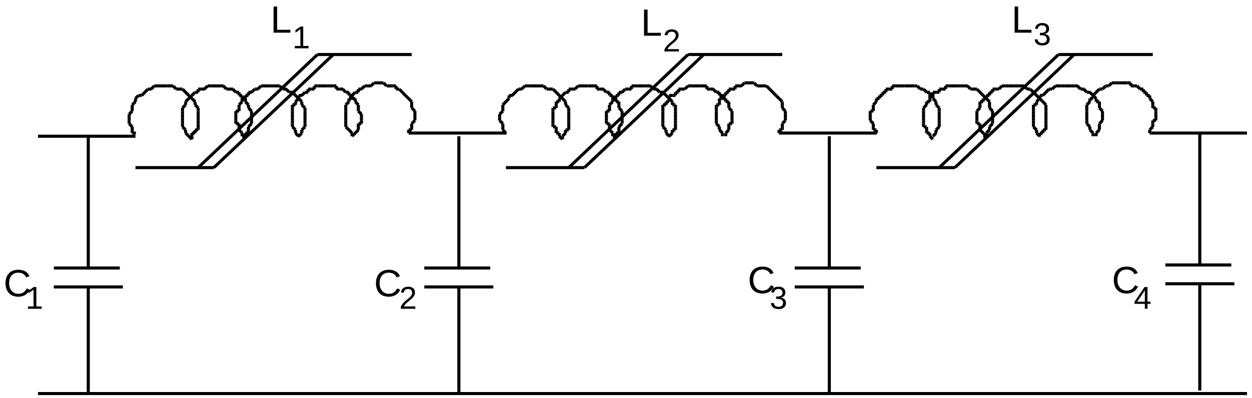
S. Humphries, Principles of Charged Particle Acceleration, 1999

Magnetic Compression Circuits

- To achieve higher overall gain, multiple switches may be used
    - Switches are designed to saturate sequentially
    - Multiplying individual switch gains yields the overall gain

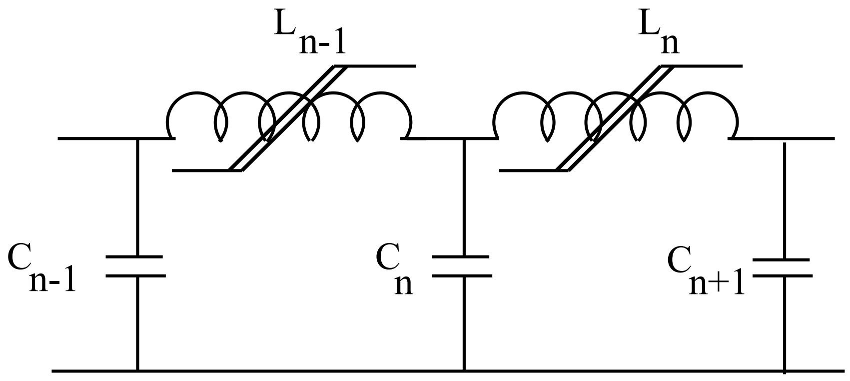
- Capabilities of magnetic compression systems
    - High repetition rate
    - High average power
    - Very high peak power
    - High reliability

- A “real” switch (one than can be controlled by external trigger) is required to initiate the magnetic compression sequence



Basic Compression Circuit Equations

$$\tau_{C_n}^{chg} = \pi\sqrt{L_{n-1}^{sat} C_{eq}} = \pi\sqrt{L_{n-1}^{sat}\frac{C_n}{2}} \qquad (1)$$



$$C_{n-1} = C_n = C_{n+1}$$

$$\tau_{C_n}^{chg} \approx \tau_{L_n^{sat}} = \frac{N_n A_n \Delta B_s}{< V_{C_n} >} \qquad (2)$$

where:

The resonant charging voltage waveshape of this circuit has the form:

$$V(t) = \frac{Vpk}{2}(1 - \cos(\omega t))$$

And for this waveshape $<V_{C_n}>$ is equal to Vpk/2 when integrated to the time of peak voltage.

Combining the equations (1) and (2) and solving for L_{n-1}^{sat} gives:

$$L_{n-1}^{sat} = \frac{\left(\frac{2N_n A_n \Delta B_s}{\pi}\right)^2}{\frac{1}{2} C_n V_{pk}^2} = \frac{\left(\frac{2N_n A_n \Delta B_s}{\pi}\right)^2}{E_{C_n}} \qquad (3)$$

Where E_{C_n} is the peak energy stored in C_n

Basic Compression Circuit Equations

- The previous equations define switch parameters as functions of circuit values and magnetic material properties. Into these equations we need to incorporate equations defining switch geometry.

- The inductance of a toroid of rectangular cross section is given by:

$$L = \frac{1}{2\pi}\mu_r\mu_o w N^2 \ln\left(\frac{OD}{ID}\right) \qquad \textbf{(4)}$$

- Substituting the saturated value of L$_n$ into this equation gives:

$$L_n^{sat} = \frac{1}{2\pi}\mu_r^{sat}\mu_o w_n N_n^2 \ln\left(\frac{OD}{ID}\right) \qquad \textbf{(5)}$$

- Dividing this into the relation for L$_{n-1}^{sat}$ (Eq. (3))yields:

$$\frac{L_{n-1}^{sat}}{L_n^{sat}} = \frac{2\Delta B_s^2 A_n^2}{10^{-7}\pi^2\mu_r^{sat} w_n \ln\left(\frac{OD}{ID}\right) E_{C_n}} \qquad \textbf{(6)}$$

Basic Compression Circuit Equations

- However:

$$\frac{L_{n-1}^{sat}}{L_n^{sat}} = \left(\frac{\tau_{C_n}^{chg}}{\tau_{C_{n+1}}^{chg}}\right)^2 = Gain_n^2 \qquad \textbf{(7)}$$

- and therefore:

$$Gain_n^2 = \frac{2\,\Delta B_s^2 A_n^2}{10^{-7}\,\pi^2 \mu_r^{sat} w_n \, ln\left(\frac{OD}{ID}\right) E_{C_n}} \qquad \textbf{(8)}$$

- Using the expansion for the natural log term in Eq 5: $w \ln(OD/ID) \approx w\,\Delta r/\langle r\rangle = A_n/\langle r\rangle$

$$L_n^{sat} \approx \frac{\mu_r^{sat}\mu_o N_n^2 A_n}{2\pi \langle r \rangle} = \frac{\mu_r^{sat}\mu_o N_n^2 A_n^2}{Vol_n} \qquad \textbf{(9)}$$

- Substituting eq. (3) and (9) in (7) and rearranging gives:

$$Vol_n \approx \frac{Gain_n^2 E_{C_n} \pi^2 \mu_r^{sat}\mu_o}{4\,\Delta B_s^2} \qquad \textbf{(10)}$$

Basic Compression Circuit Equations

- Vol_n in Eq. (10) represents the minimum volume of magnetic material (and therefore minimum loss) required for a switch, L_n, given a required gain, per pulse energy, and ΔB_s. Eq. (10) assumes that the entire toroidal volume inside the winding is filled with magnetic material. This is never achieved in practice and the term packing factor (pf) is defined:

pf = the cross-section area of magnetic material divided by the total area enclosed by the windings (which includes air, insulation, etc.)

This modifies the minimum volume equation to the following:

$$Vol_n \approx \frac{Gain_n^2 E_{C_n} \pi^2 \mu_r^{sat} \mu_o}{\text{pf}\, 4 \Delta B_s^2}$$

Magnetic System Limitations- Jitter

- Time Jitter - caused by variations of voltage and ΔB as per: $\tau_{C_n}^{chg} \approx \tau_{L_n^{sat}} = \dfrac{N_n A_n \Delta B_s}{< V_{C_n} >}$
  - Jitter is proportional to the total propagation delay through the magnetic system (sum of the individual switch hold-off times)
    - Example: If the total propagation delay is 10µs and the average input voltage variation is 1% the minimum time jitter (ΔB variation is zero) is:
      - $\Delta t \sim 10\mu s * .01 = 100ns$
  - Jitter can be minimized by:
    - Precisely resetting the magnetic cores prior to the next pulse (stable ΔB)
    - Precise voltage regulation or real-time adjustment of trigger pulse to compensate for ΔV (stable V)
- Jitter of < ± 2ns can be reasonably anticipated for systems having propagation delays < 10 µs

Magnetic System Limitations - Risetime & Repetition Rate

- Risetime: the pulse risetime is determined by the saturated inductance of the winding geometry. It is possible to obtain single turn inductance in the nH range. In practice, output risetimes in the range of 10-20 ns are routinely achieved for high voltage systems

- Repetition Rates:
  - Burst Repetition Rate
    - Parallel systems (Branch Magnetics) can operate at 10's of MHz
    - Single pass systems can probably work up to ~100 kHz (the limitation is that all the magnetic cores need to be reset between pulses
  - Constant Repetition Rate
    - Single pass systems can operate into the 10-20 kHz region (liquid cooling is required to remove heat generated in the magnetic cores and capacitors)
      - Metglas™ is limited to < 5 kHz for the fastest saturation rates (output stages) but may easily be used for earlier stages. Another limitation of Metglas™ at fast saturation rates (high $\Delta B/\Delta t$) is voltage breakdown between laminations
      - Ferrites are often used for the output stages in high rep-rate systems

Magnetic System Limitations - Number of Stages

- The total gain required by the system determines the number of stages where the total gain is the product of the individual switch gains
  - Individual switch gain is restricted by the core volume relationship: $Vol_n \approx \frac{Gain_n^2 E_{C_n} \pi^2 \mu_r^{sat} \mu_o}{4 \Delta B_s^2}$
    - Maximum reasonable core gain:
      - ~3 for ferrite
      - 5-10 for Metglas™ and other amorphous materials

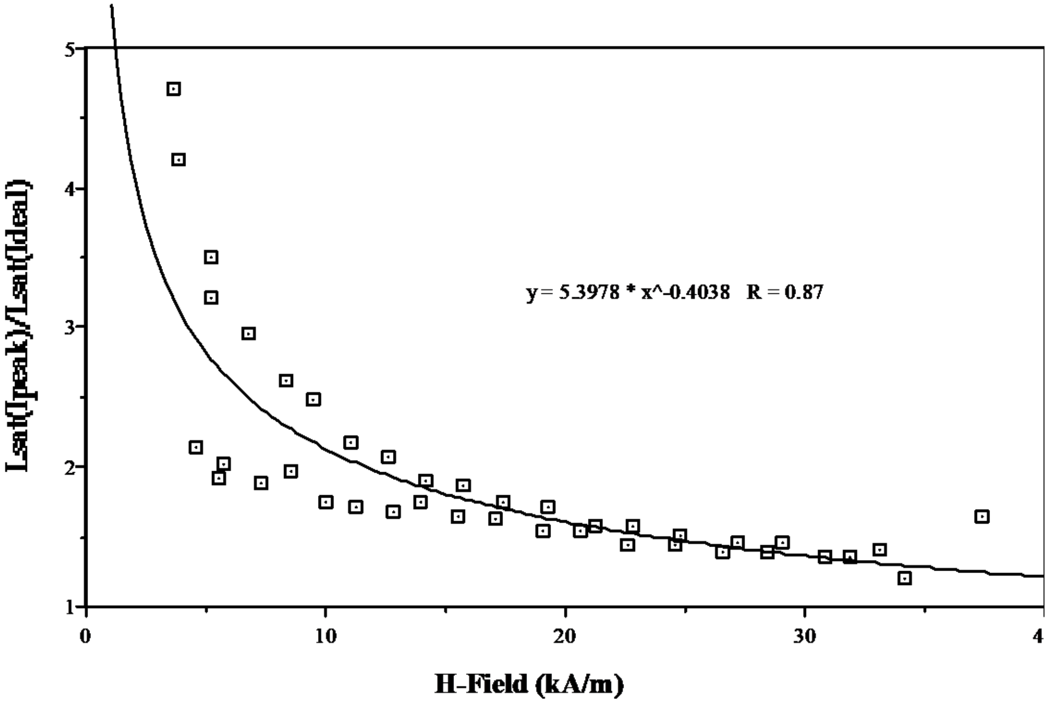
- When more than two switches are required, a step-up transformer is normally needed (to better match impedances and optimize efficiency)

- Usually, only 3 magnetic switches are required to cover the range of microseconds (initial conduction time) to nanoseconds (output risetime)

Other Practical Considerations - μ_r^{sat}

- Saturated permeability - The assumption is that the saturated inductance of a magnetic switch may be calculated by assuming that μ_r has the value of unity (free space). While this is a valid assumption when the H field is high enough, empirical data indicated that surprisingly large values of ampere turns are required to fully saturate a magnetic core. The net effect is that during the time of saturation and energy transfer through the magnetic switch the average value of saturated permeability should be considered as having a value somewhere between 1 and 2. The actual value will be dependent on the magnetic core material chosen and the geometry of the winding around the core.

This curve is generated by allowing a magnetic switch to ring in a resonant, low loss circuit. The average saturated inductance (calculated from the peak current of the oscillations) is divided the calculated air core inductance for $\mu_r = 1$ and plotted versus the peak H-field corresponding to each value of peak current. Note that the inductance ratio levels out at ~1.5 for a peak field of ~25kA/m: this indicates that the core is fully saturated and that the winding geometry is responsible for the measured inductance being higher than the calculated value.



Ratio of Inductance Values versus Peak H-Field (Ferrite Core)

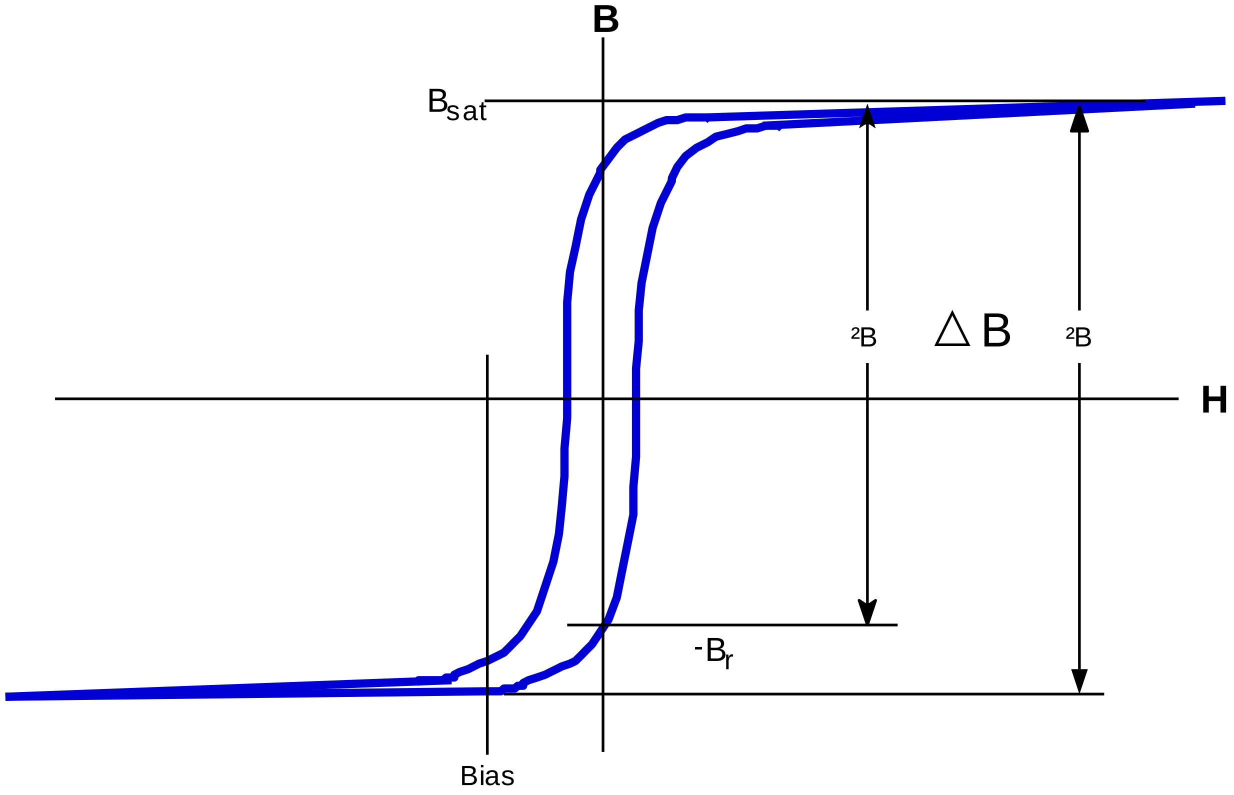
Other Practical Considerations - Reset/Bias

Achieving consistent performance from a magnetic switch requires that the initial state of the magnetic core be known and the easiest way to know the initial condition of the magnetic is to force it to a known position. This is usually the task of the reset/bias circuit.

The magnetic cores must first be reset - in essence the volt-seconds used by the switch must be replaced by voltage applied of the opposite polarity such that the volt-second product is equal to or greater than that used during the initial energy compression.

The cores can be reset by voltage applied to the main windings or to a turn through the core that is not part of the pulse power circuit (in essence a secondary winding as the magnetic switch will function as a transformer until the core material is again saturated). In either case the reset circuit must be protected/isolated from the high-voltage pulses generated during normal operation. Isolation is usually achieved by using large inductors although diode isolation can be used.

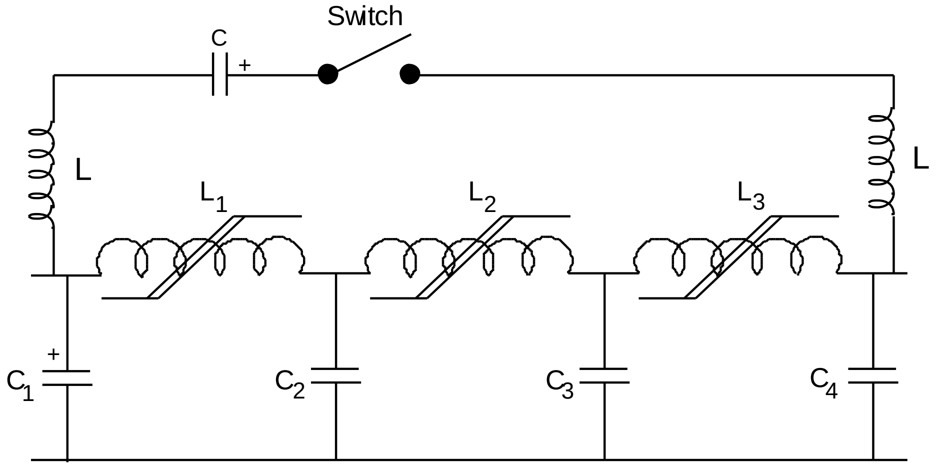
DC bias is used to hold the magnetic core at a particular point on the BH curve and provides the additional benefit of increasing the useable ΔB for a given core. Note the polarity of the bias current is opposite the switch discharge current.

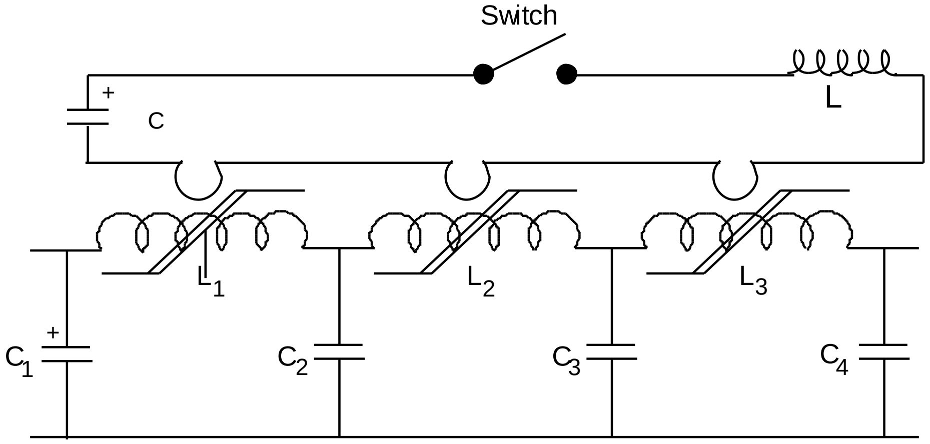


Other Practical Considerations - Reset/Bias Circuits

Two different type of reset circuits can be used:

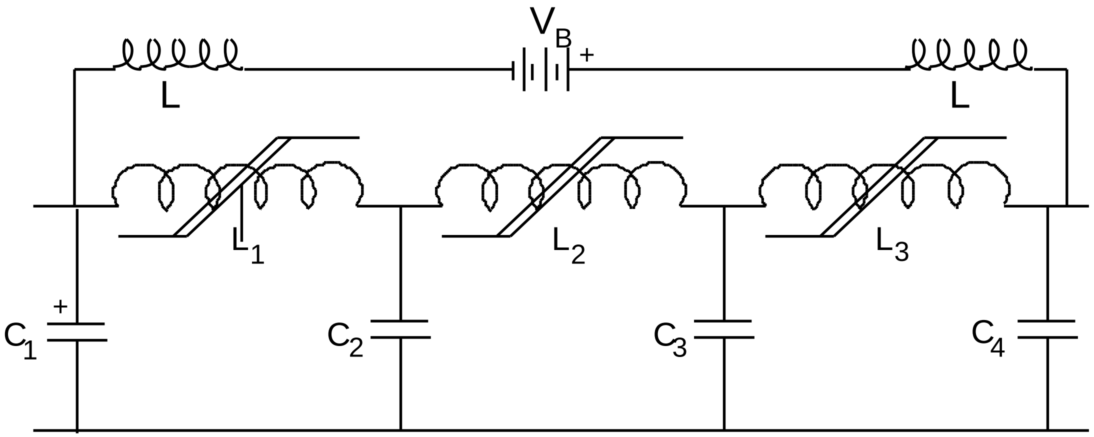
- Pulsed reset: a voltage pulse (usually having an amplitude substantially less that the operation voltage) is applied to the core
  - Advantages:
    - fast: the core can be reset quickly if needed for high repetition rates.
    - efficiency: only the energy needed to reset the core is required
    - increased ΔB: the core can be driven all the way to $-B_{sat}$
  - Disadvantages:
    - complexity: requires a switch, extra capacitors, power supply, and a properly timed trigger signal
    - circuit cannot be allowed to ring or the magnetic switch must operate while the reset pulse is on (still at $-B_{sat}$)

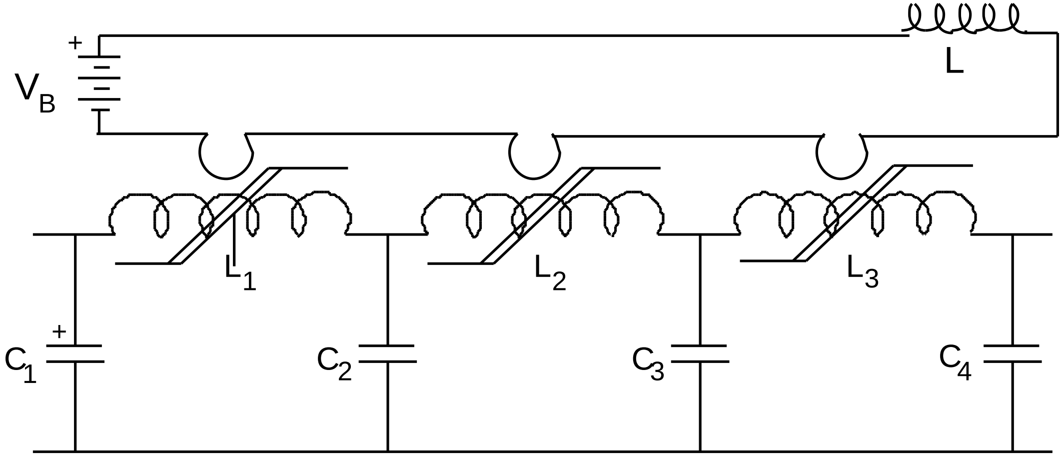




Other Practical Considerations - Reset/Bias Circuits

- DC reset: a low voltage DC power supply is connected to the magnetic switch through an large inductor (compared to the pulse duration) thereby creating a current source
  - Advantages:
    - simplicity: few components and no timing requirements
    - inexpensive: components not costly
    - reliability: not much to break
    - Increased ΔB: the DC reset also serves as a DC bias
  - Disadvantages:
    - efficiency: the power supply is usually on all the time





Mechanical Design

- The mechanical design of a magnetic switch is more complicated than the electrical portion of the design

- The mechanical is guided by two contradictory requirements:
  1. the need to minimize inductance of the winding structure (including connections to capacitors and other switches) in order to optimize the performance of the magnetic switch
  2. the need to ensure reliable performance of a winding structure that must operate at high voltage

- In addition, the mechanical design must have sufficient mechanical robustness to adequately support the magnetic material (which may have substantial weight) and ensure that the position of the windings is controlled and the inductance of the mechanical structure is fixed and repeatable (particularly if production quantities are envisioned).
  - In general, turns of wire around a core are not going to meet these requirements.

Mechanical Design

- A common method of constructing a magnetic switch on a toroidal core of rectangular cross-section is to use metal rods on the inside diameter (ID) and outside diameter (OD). Crossover links on the ends of the switch may be fabricated with metal bars or may be attached to a printed circuit board.

- For calculating inductance, use the dimensions to the middle of the rods (for ID and OD)

- When only a few turns are needed, use multiple sets of parallel windings to enclose the core as completely as possible and minimize saturated inductance

- When using NiZn ferrite (high intrinsic resistance), the turns can be touching the core
- When using MnZn ferrite (low intrinsic resistance), the turns must be insulated from the core

- Connections between the magnetic switch and capacitors should be as short and wide (such as a parallel plate layout) as possible to minimize inductance

- The spacing between conductors at high voltage should be adequate to prevent electrical breakdown and all edges of high voltage conductors should have as large a radius as possible in order to reduce field enhancement

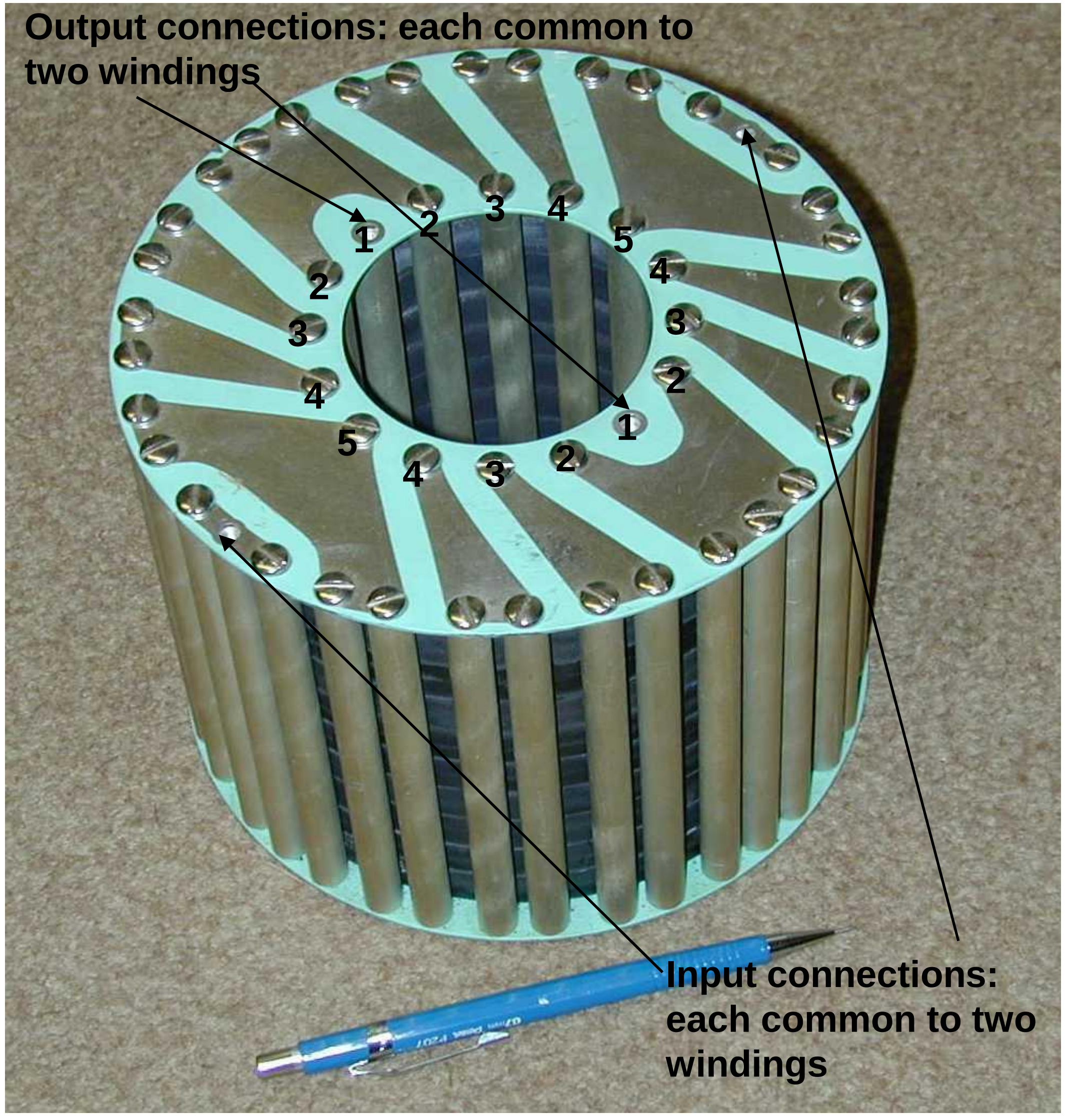
Mechanical Design - Example

5-Turn Switch
(configured as 4 sets of 5 turns)

20kV hold-off for 1μs with gain of 3.0 using ferrite toroids

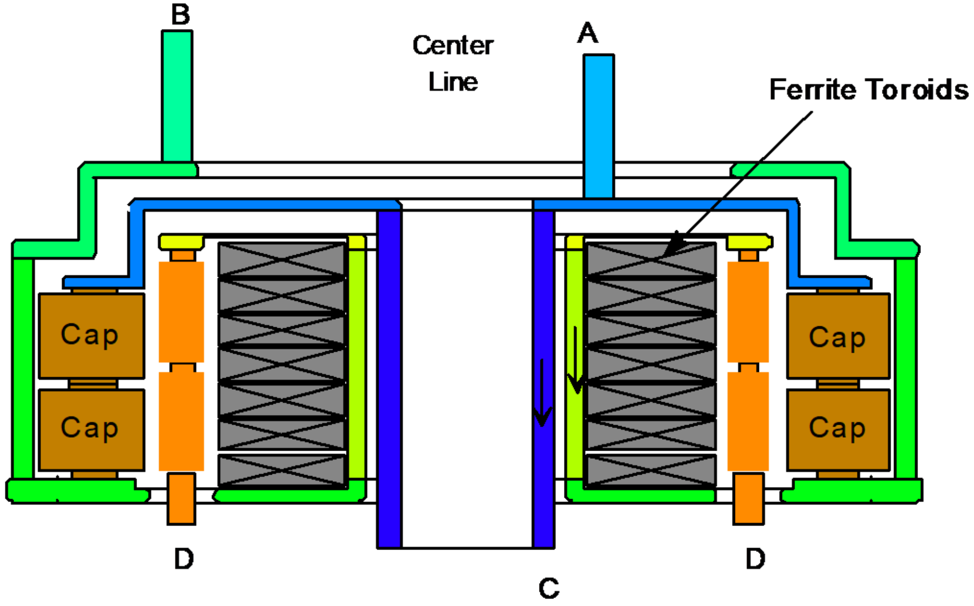
Inside and outside turns are fabricated of 0.375” diameter rod

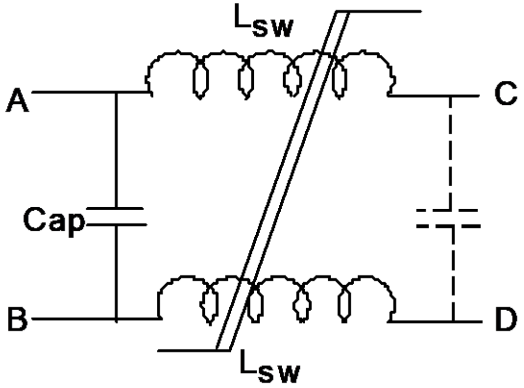
Crossover connections between inside and outside rods are patterns on printed circuit boards. Board pattern on top and bottom boards are different.



Mechanical Design - Example

- When only one or two turns are required, tubes and concentric tubes can be used as the turns through the center of the core
- Remember that the current return on the outside of the core needs to be close to the core to minimize the inductance
- Cross-section of 2-turn magnetic switch with turns split as shown in the schematic. This approach is used to reduce maximum field stress to ground by operating at positive and negative input voltages with respect to ground.

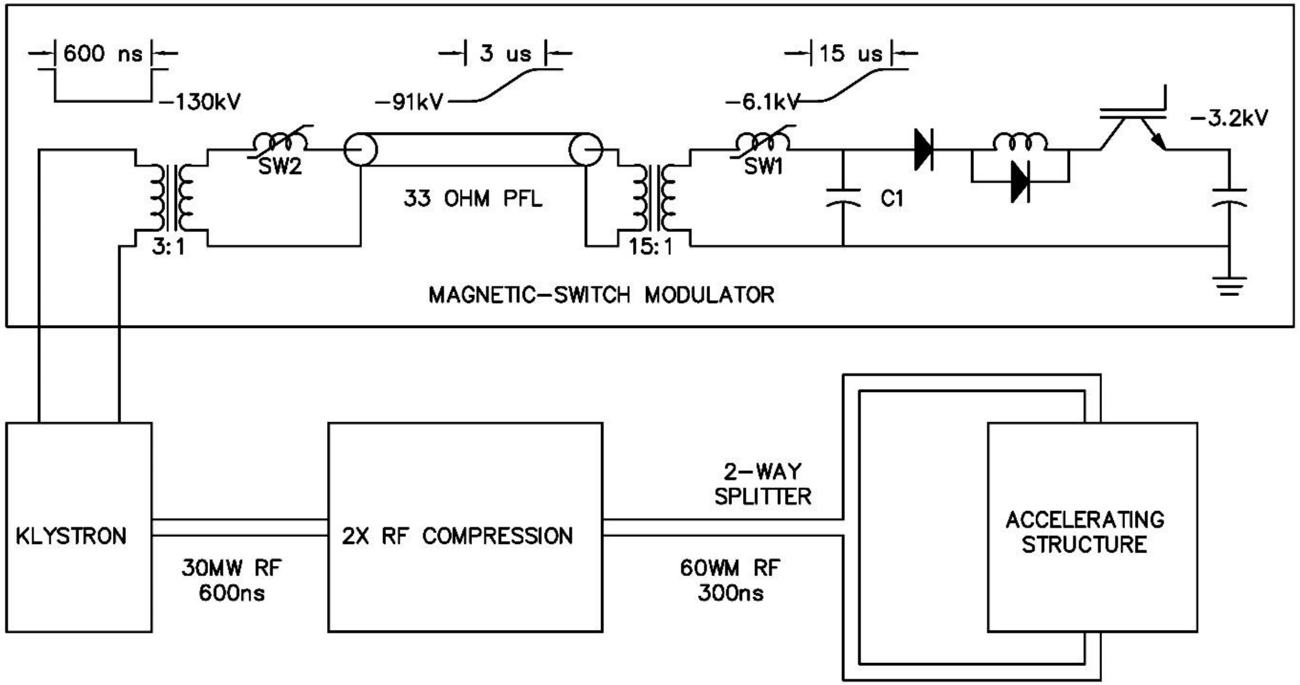




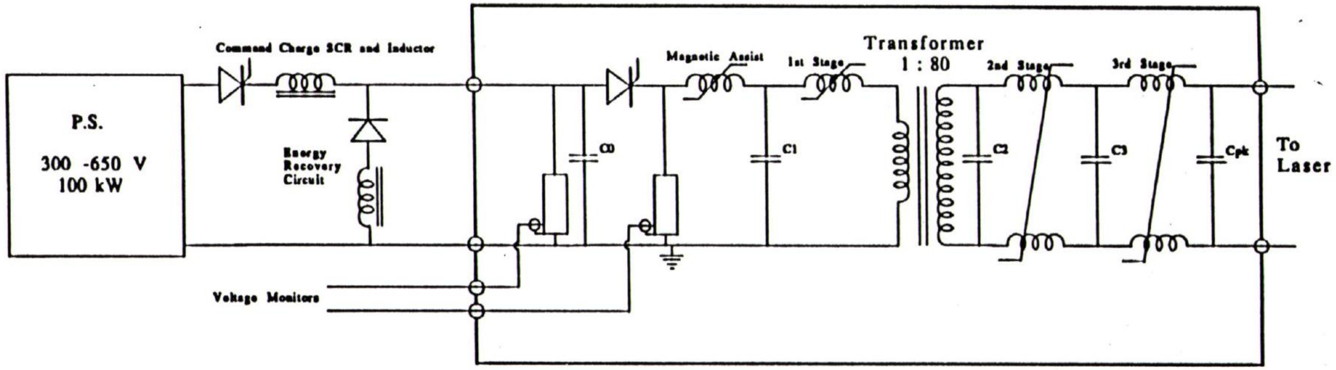
Electrical Schematic

Conceptual X-Band Klystron Magnetic Modulator (SLAC)

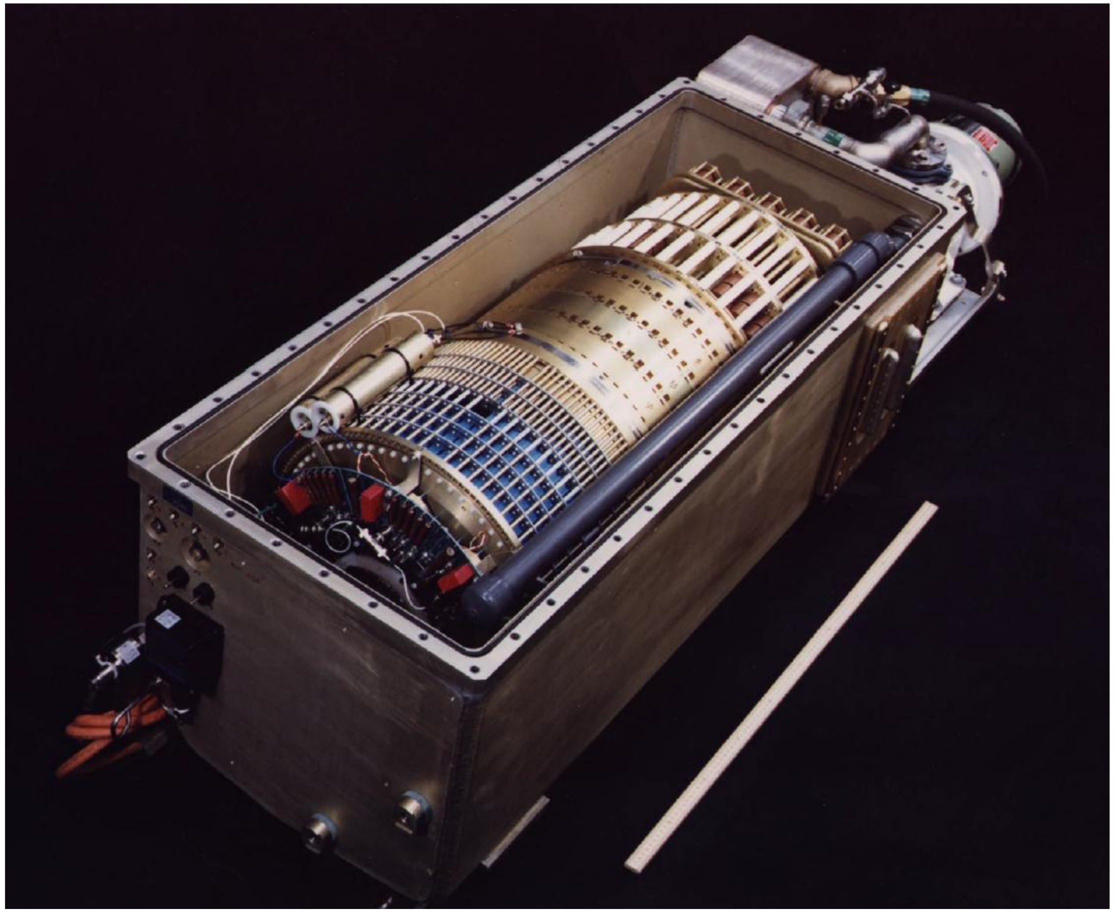
- IGBT module for 1st stage switching
- 1st magnetic switch charges water PFL through HV pulse transformer
- 2nd magnetic switch discharges PFL through pulse transformer to match klystron impedance
- Very high perveance, X-band MBK load
- Short modulator pulse minimizes Rf pulse compression costs/losses



Atomic Vapor Laser Isotope Separation (AVLIS) - LLNL



Modulator In PPE Tank



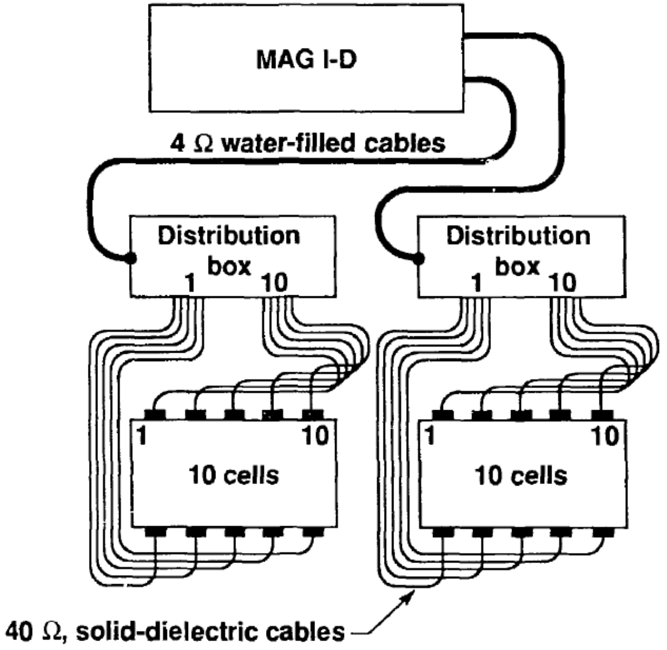
Operating Parameters:

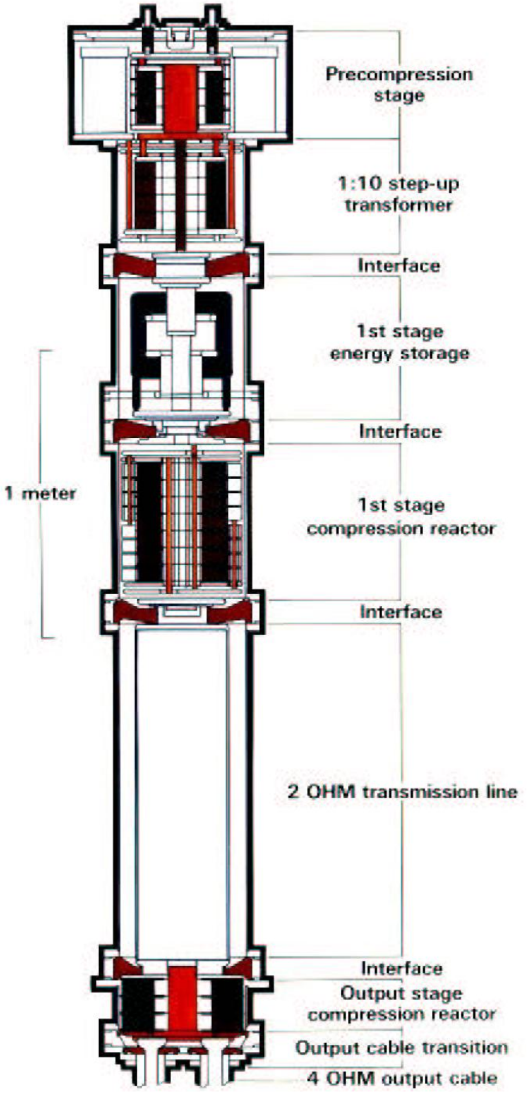
- 80 kV @ ~4 kA_{peak} (non-linear load)
- τ_{rise} ~ 30ns
- > 4 kHz continuously
- liquid cooled
- MTBF > 5000 hours

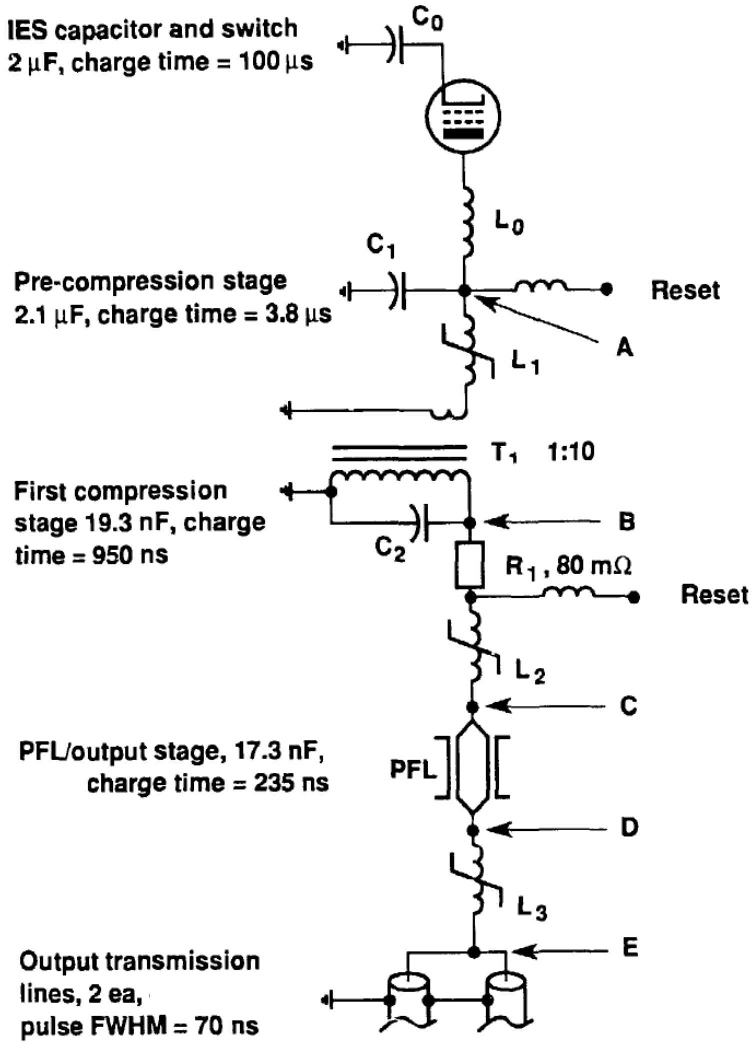
Note that commercial pulsed gas lasers are a widely deployed application of MPC

ETA-II Induction Accelerator Driver (LLNL)

- Pioneering use of magnetic pulse compression for induction accelerators
- 125kV, 70ns pulse into 2 ohms
- 5kHz burst mode (50 shots)

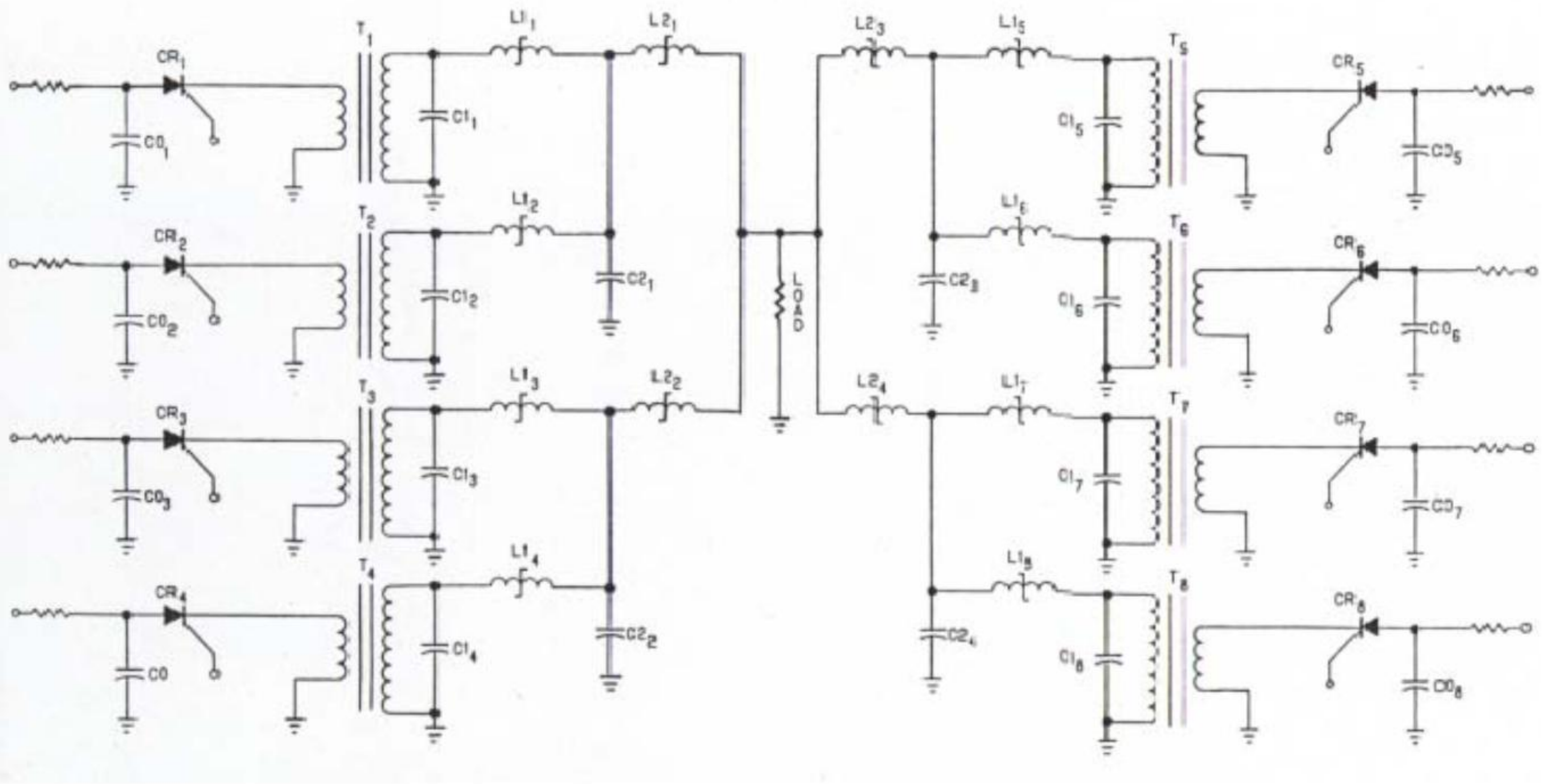






W. Turner, Magnetic Pulse Compression Workshop, Vol. 2, 1991

Branch Magnetics 8-pulse Burst Generator (35MHz burst frequency) – Birx, LLNL



Firing Sequence - CR1, CR3, CR5, CR7, CR2, CR4, CR6, AND CR8

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