Pulsed Modulators

Concepts and trade-offs

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Intro

- Modulator specification
  - Criteria and concepts
- Modulator design
  - Topology selection
  - Commercial v in-house
  - Prototyping
- Conclusion

RF Powering

- The RF specification – starting point for modulator
  - example from ESS requirements

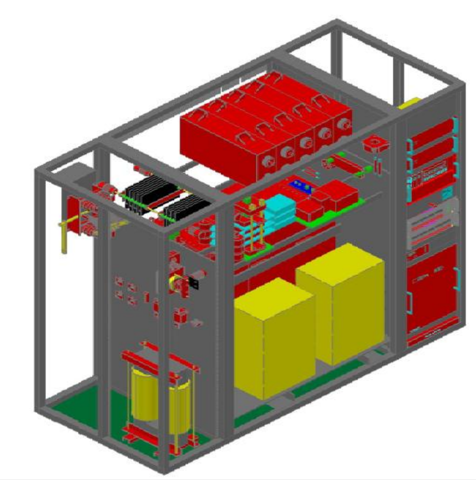
	RFQ+DTL 352MHz	Spoke 352MHz	Elliptical 704MHz low-Beta	Elliptical 704MHz high-Beta
Max power/klystron	2.6MW	400kW	700kW	1100kW
Min power/klystron	1.2MW	130kW	65kW	700kW
Beam time	2.9ms			
Cavity fill+empty time	0.3ms + 0.3ms			
Repetition rate	14Hz			
Klystron efficiency	58%	<60%	<60%	60%
Phase precision	0.5°			
Nb of klystrons	4	28	64	120
Max energy of arc	20 J			

Pulsed v CW

Why a pulsed modulator?

LEP 4MW CW Modulator: 250 m^3
(4 MJ/s)

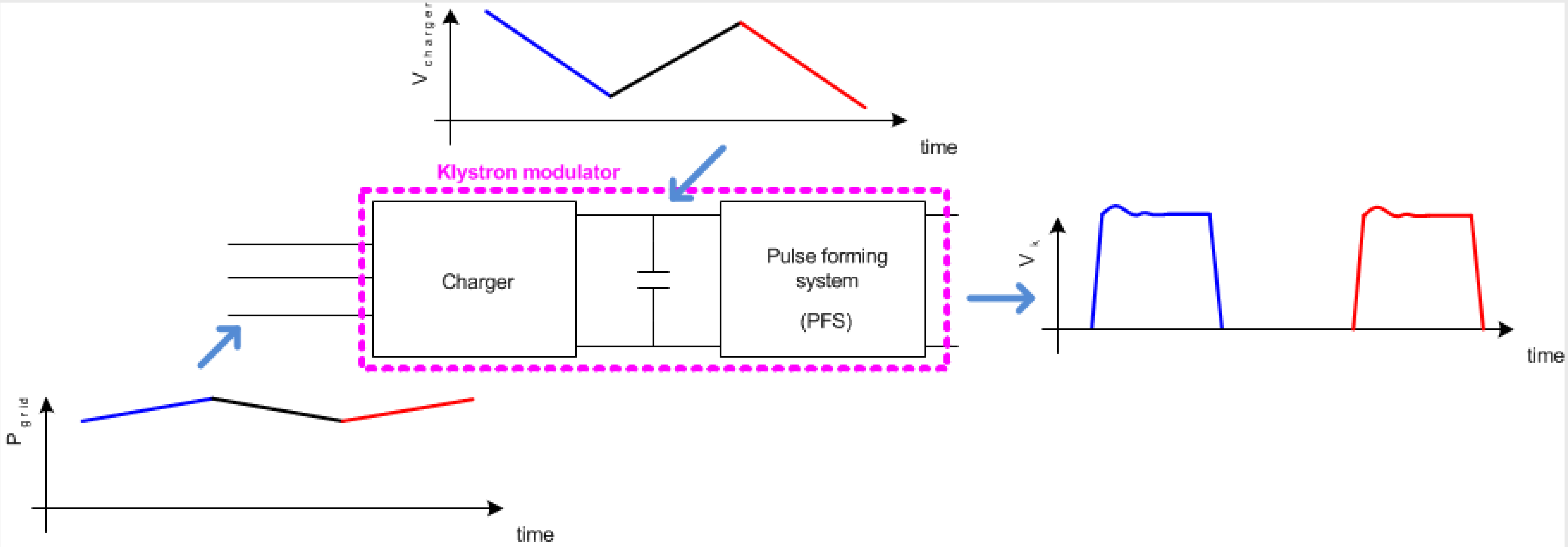
ESS 4.5MW Pulsed Modulator: ~35 m^3
(>200kJ/s)



LINAC4 5MW Pulsed Modulator: 7 m^3
(20kJ/s)

Pulsed Modulators

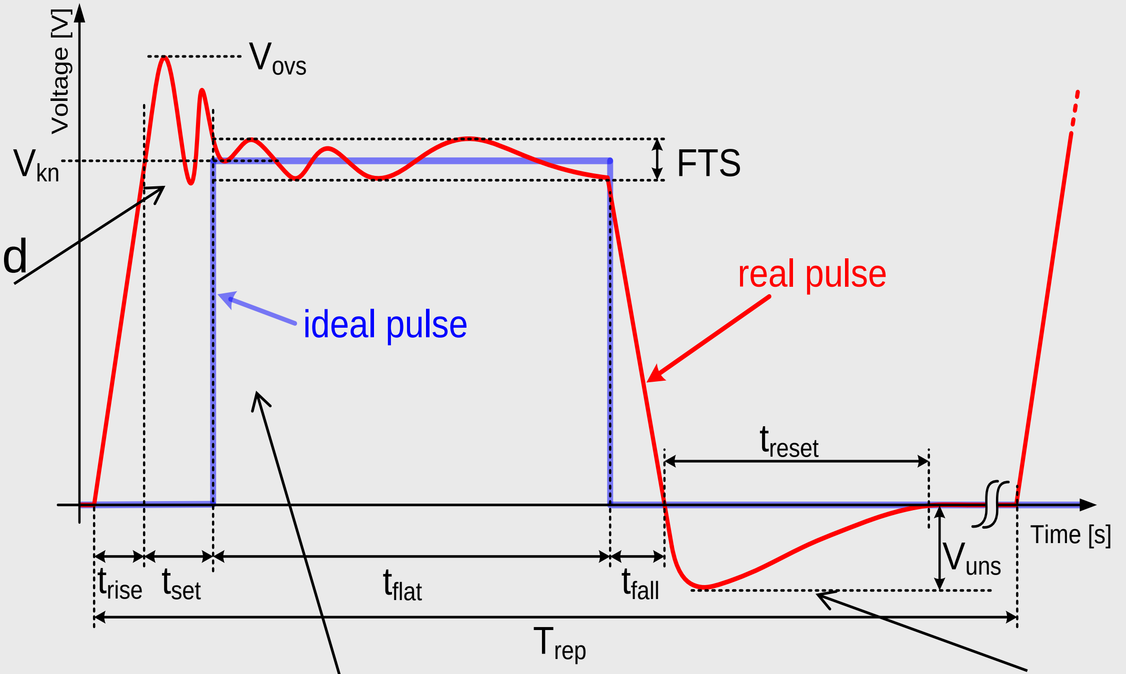
- Can be separated into three principle sections
  - AC/DC ‘Charger’
  - Energy storage
  - Pulse Forming system



Pulsed Modulators

- Pulse definition

Sources of energy loss:



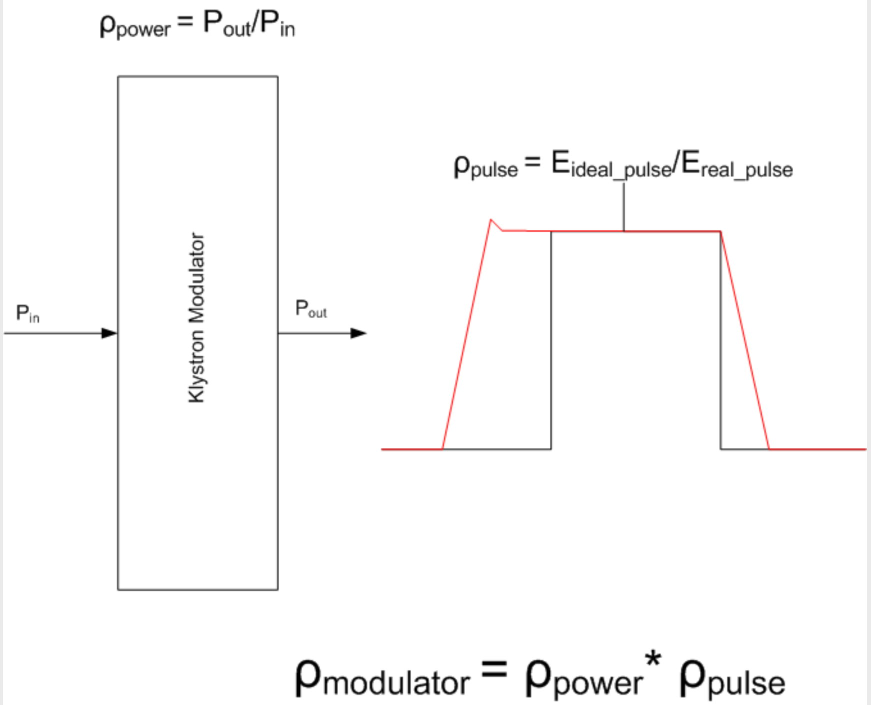
t_set for LLRF and modulator

t_rise and t_fall

t_beam + t_fill + t_empty

reset of pulse transformer (if used)

Pulsed Modulator Efficiency



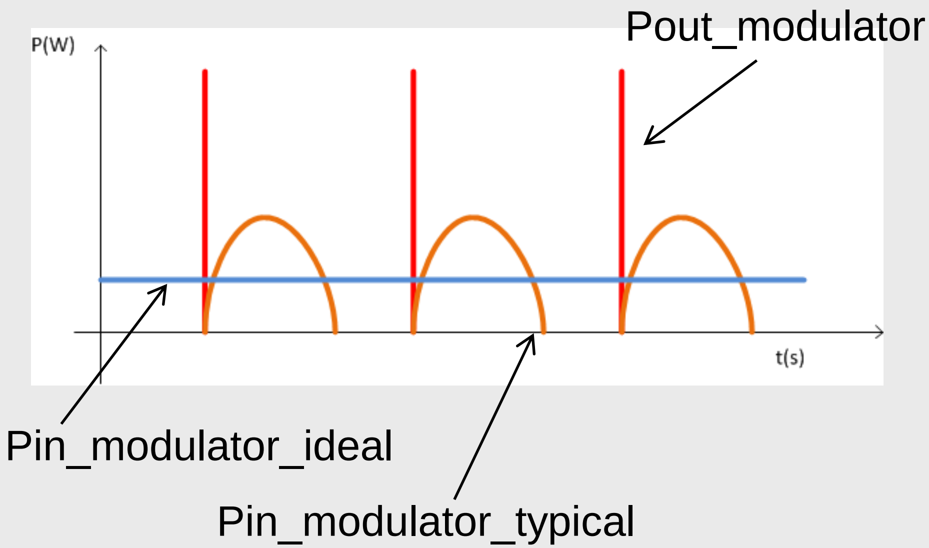
Useful flat-top Energy	**4.5MW*3.5ms = 15.8kJ**
Rise time energy	4.5MW*300µs*1/3= 0.45kJ
Fall time energy*	4.5MW*300µs*1/3= 0.45kJ
Set-up time energy	4.5MW*300µs = 1.35kJ
Pulse efficiency	**0.88**
Pulse forming system efficiency	0.98
Charger efficiency	0.96
Power efficiency	**0.94**
Overall Modulator efficiency	**80%**

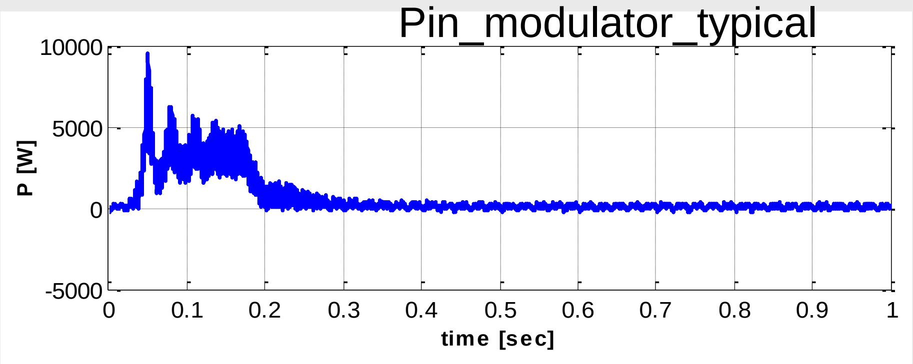
*Does not include pulse transformer magnetizing energy

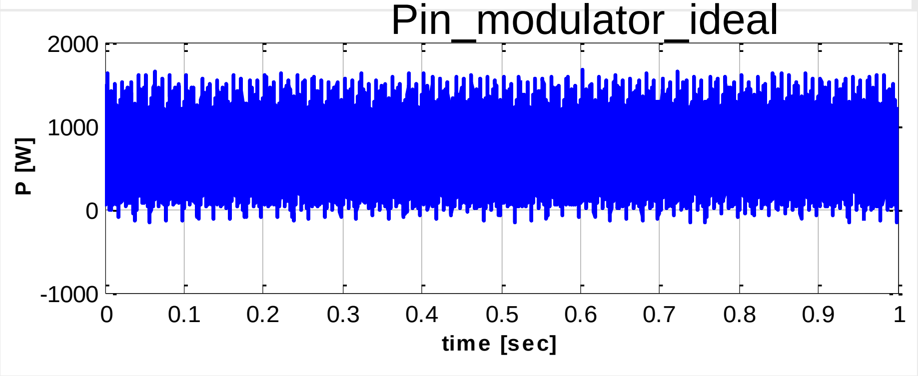
- Modulator can optimize electrical systems
  - however greatest efficiency savings from RF pulse optimization (eg klystron efficiency, control overhead, setup time, etc)

Power from distribution network

- Modulator charging is usually completed before the output pulse generation.
    - This will induce power fluctuations on the power network, affecting distribution power quality.
- A large modulator installation should implement a constant power load consumption with good power quality.
- Strategies for startup and shutdown should also be considered to limit load transients







Reliability and availability

- For large installations, availability is an important criteria
  - Reliability typically specified as Mean Time Between Failure (MTBF)
  - Repair time defined as Mean Time To Repair (MTTR)
  - Availability as a function of reliability and time to repair:

$$Availability = \frac{MTBF}{MTBF + MTTR}\%$$

  - Modular systems may have lower MTBF but higher *availability* due to redundant architectures that significantly reduce the MTTR. In many cases, repair can be scheduled for a future date.
  - Repair time can be significant for high voltage systems unless considered at the design stage (oil, large components, etc).

Modulator specification

1. Maximise charger efficiency and power quality
   - Objective: better than 95% efficiency with near unity power factor and low harmonics
2. Minimise rise, fall and settling time
   - Objective for 3.5ms pulse: less than 750us total for rise, fall and setup time
3. Maximise operational reliability and availability
   - Objective: design for 99.8% availability (1hour intervention every 14 days)
4. Design for good pulse-to-pulse voltage reproducibility
   - Objective: 100ppm (?) from pulse$_{n-1}$ to pulse$_{n}$ (RF feedback gives long term performance)
5. Consider integration issues (machine layout, maintenance, etc)

Modulator specification

Other important specifications to consider

1. Voltage ripple requirement will come from LLRF requirements
   - Requires to be specified in frequency and amplitude (typically 0.1%)
2. Parallel connection of klystrons
   - Verify sharing/balancing for several klystrons per modulator
   - However already done in SNS using LLRF
3. Operation over a wide power range required
   - Pmax ≥ 10x Pmin
   - Light loading may preclude some topologies (eg bouncer)
   - Connection of systems in parallel will resolve most issues

Modulator for RF Powering

- The following parameters follow from RF specification…
  - example from ESS requirements

Max power/modulator	4.5MW
Min power/modulator	65kW ?
Nominal voltage	110 kV
Flat top (fill + beam time + empty)	3.5 ms
Rise/fall time	0.3 ms / 0.3ms?
Repetition rate	14Hz
Droop	1% ?
Voltage Ripple (magnitude and frequency)	0.1% above 10kHz ?
Nb of modulators	~110
Max energy delivered to arc	<10 J
MTBF	100 000 hrs ?
Availability	99.8 % ?

Modulator topology overview

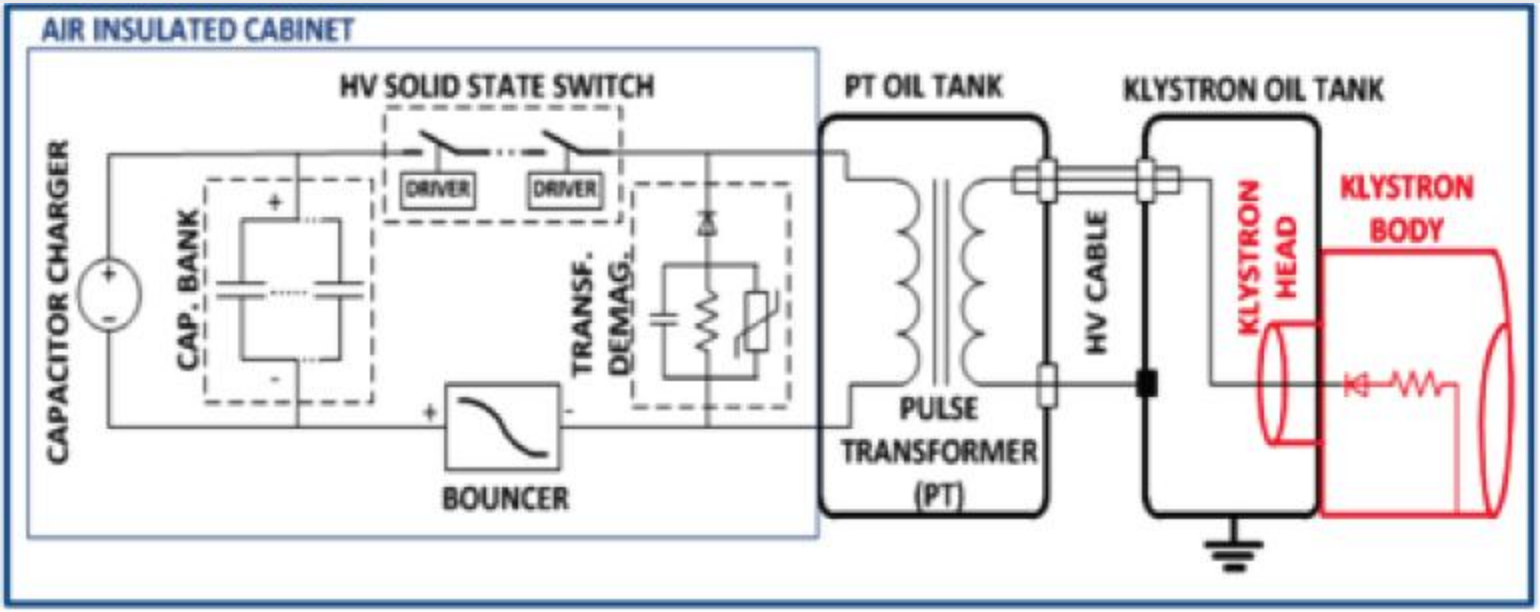
5 topologies highlighted

- Topologies known to already operate with long pulse applications
- Future topologies thought to be well adapted to long pulse applications
- Assessment of some advantages and disadvantages of each topology
- Some topologies in the market are a mix of more than one concept

- I do not claim this list is exhaustive!

Bouncer and pulse transformer

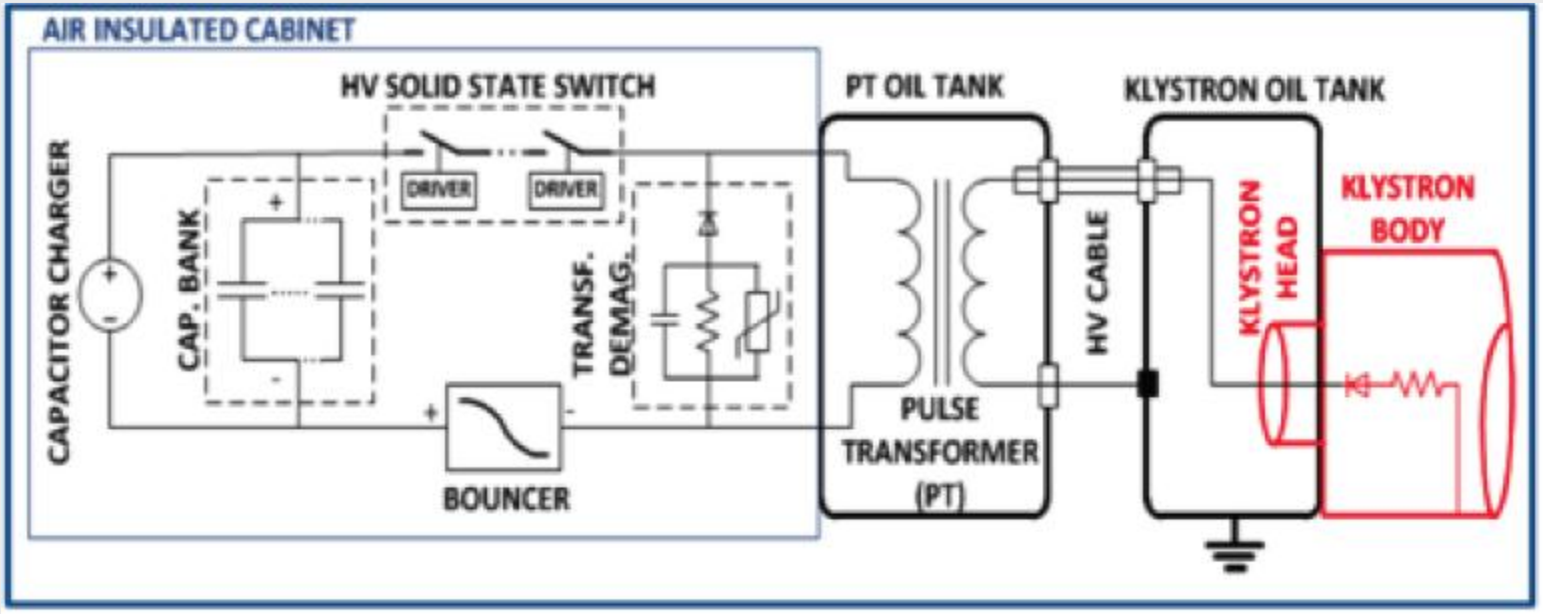
- Charger: Classical resonant topology for charging the capacitor.
- Storage capacitor: The pulsed power is collected by an intermediate storage capacitor before being transmitted through the switch.
- Switch: High voltage, high current solid state switch.
- Pulse transformer: The pulse is generated at high current lower voltage at the primary side of the pulse transformer.
- Voltage droop compensation: Voltage compensator for the droop occurring in the storage capacitor during the pulse discharge.



Bouncer and pulse transformer

- Used by:
  - Fermilab (Tevatron)
  - CERN (LINAC4)

  - Pulse transformer size scales with voltage and pulse width
  - Primary voltage and current is mainly determined by switch technology, capacitor volume, transformer design
  - Oil volume (transformer): ~800 litres



Bouncer and pulse transformer

Advantages

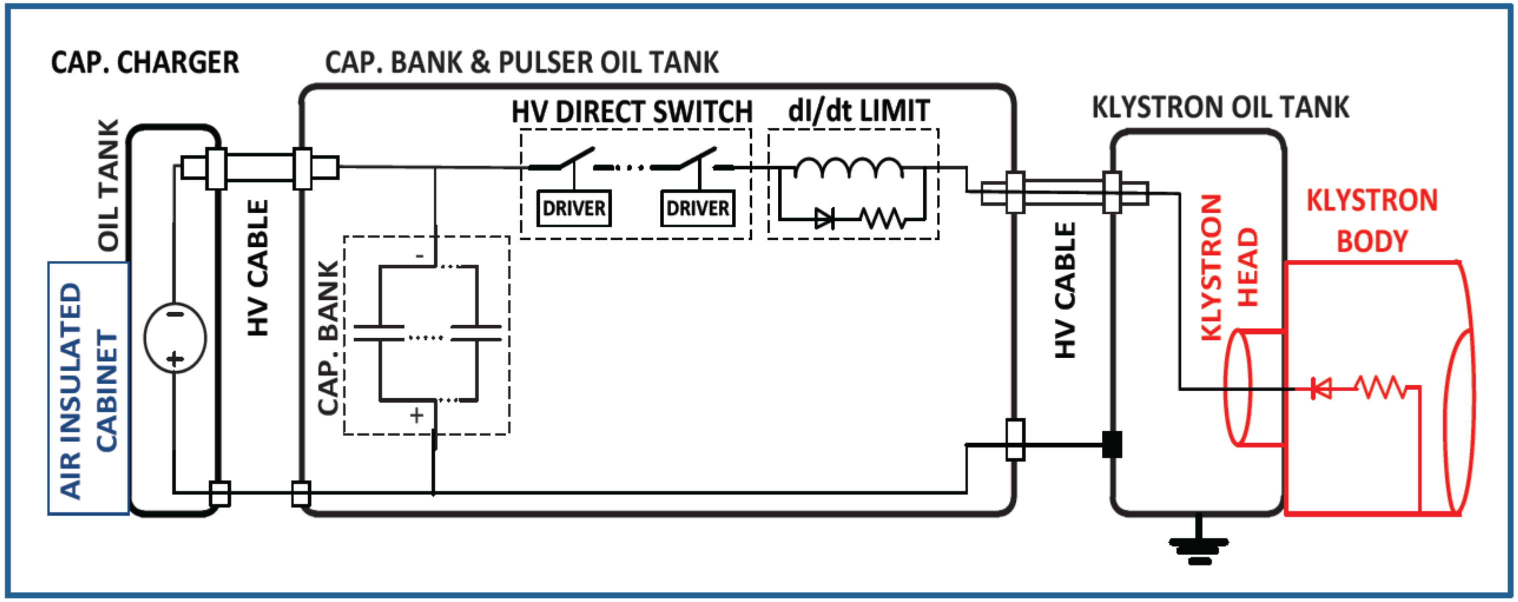
- The power circuit is simple and reliable.
- All electronic active devices are at medium voltage level
- No voltage ripple on the flat-top

Disadvantages

- Large pulse transformer and LC resonant bouncer volume for long pulses
- Limited sources for pulse transformer
- Slow rise and fall times
- Reverse voltage on the klystron to demagnetize the pulse transformer limits the duty cycle

Direct switch

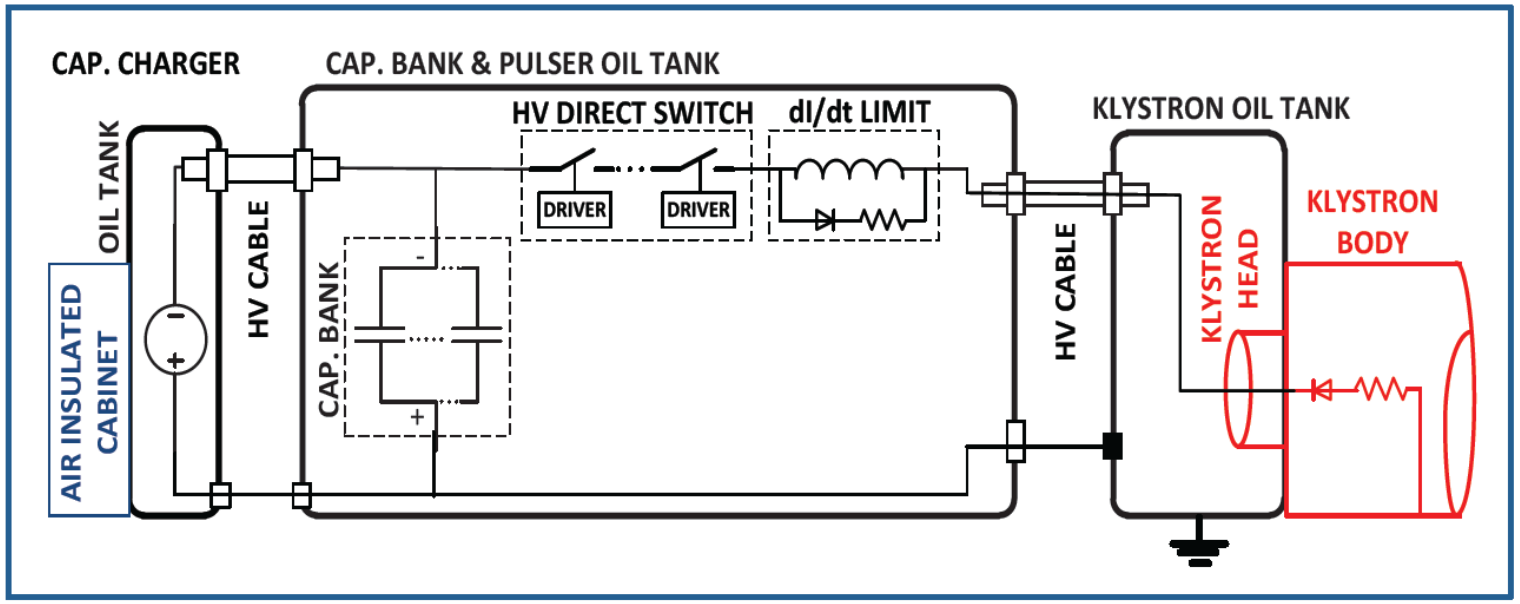
- Charger: Very high voltage capacitor charger.
- Storage capacitor: Capacitors rated for the full voltage. Very high energy storage.
- Switch: Full rated voltage slid-state switch.
- Voltage droop compensation: None. The droop is determined by the capacitor bank size.



Direct switch

- Other accelerator users
  - RAL
  - APS

- Modulator oil volume: ~2000 litres



Direct Switch

Advantages

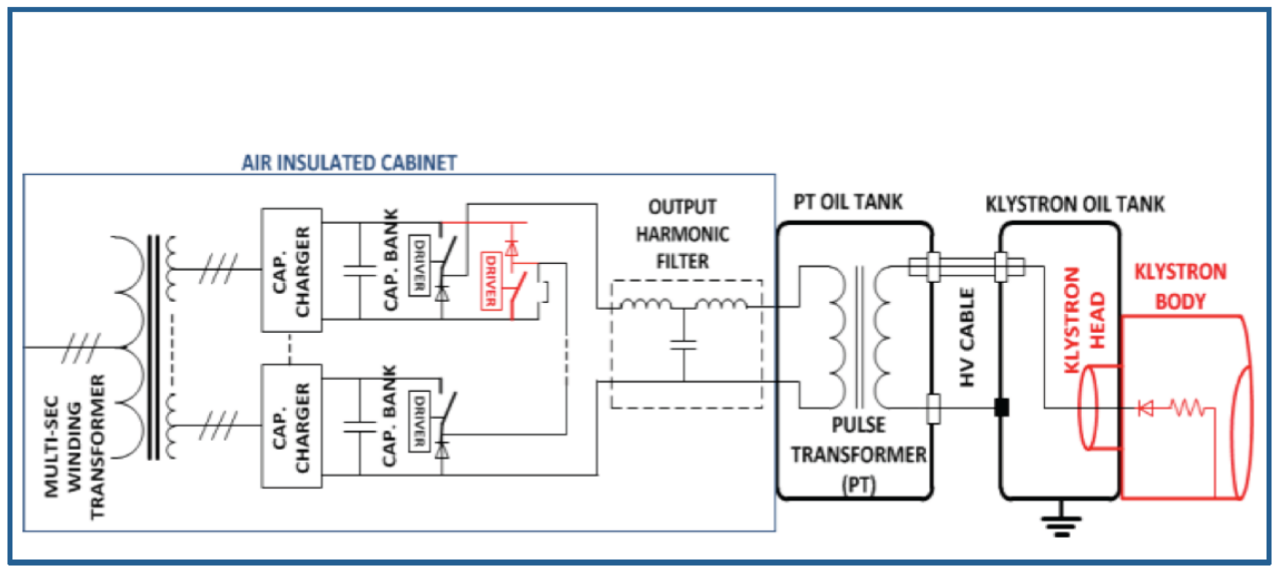
- Fast rise/fall times
- Large range of pulse lengths and pulse repetition rate
- No reverse voltage (no pulse transformer)
- Relatively compact due to most parts being in oil
- No voltage ripple on flat top

Disadvantages

- All components immersed in oil, problematic for operation
- Reliability in arc is entirely dependent on switch
- 100kV IGBT switch assembly required (not widely available)

Interleaved DC/DC

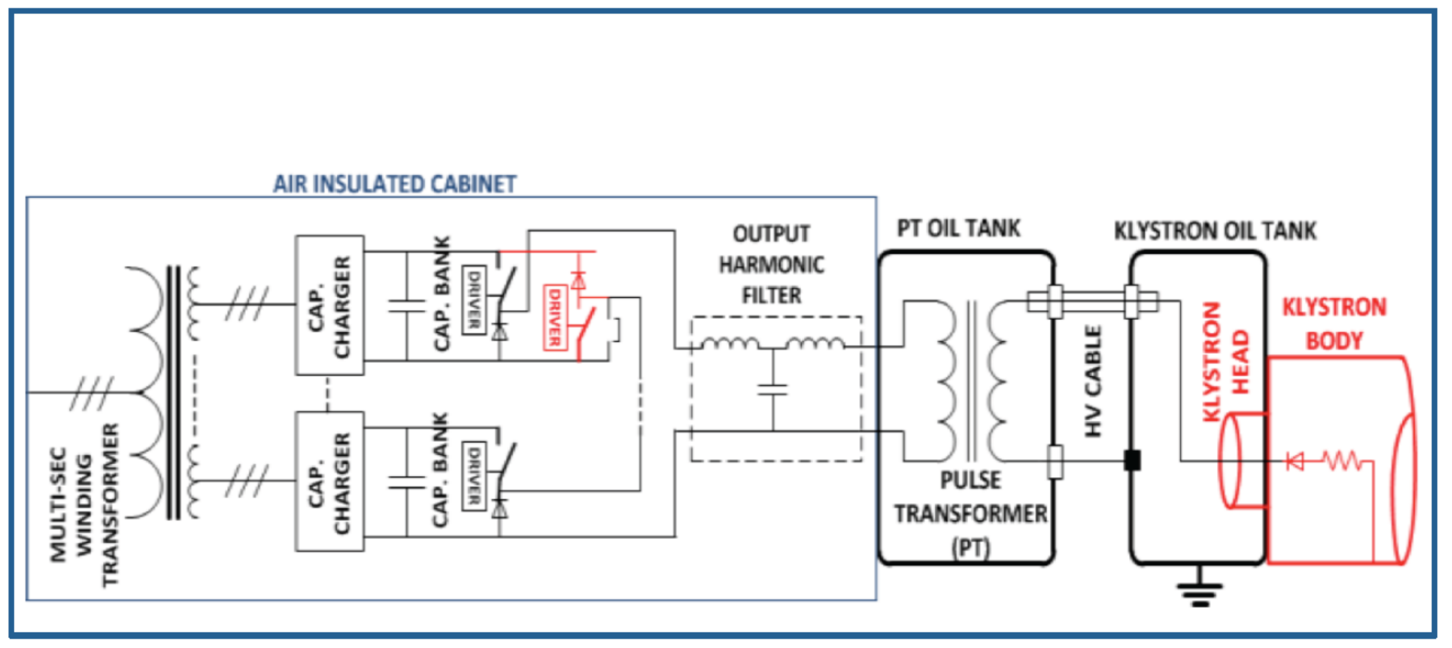
- Charger: Distributed across many smaller modules. Connected to multi-secondary winding interface transformer (also possible to have multiple primaries)
- Storage capacitor: Smaller ~1kV rated capacitors distributed across many modules.
- Switch: Standard solid-state switch.
- Voltage droop compensation: Can operate without compensation, or by using a pulse-modulation technique to obtain desired output characteristics.



Interleaved DC/DC

- Used by
  - DESY (XFEL)

- Oil volume (transformer): ~800 litres



Interleaved DC/DC

Advantages

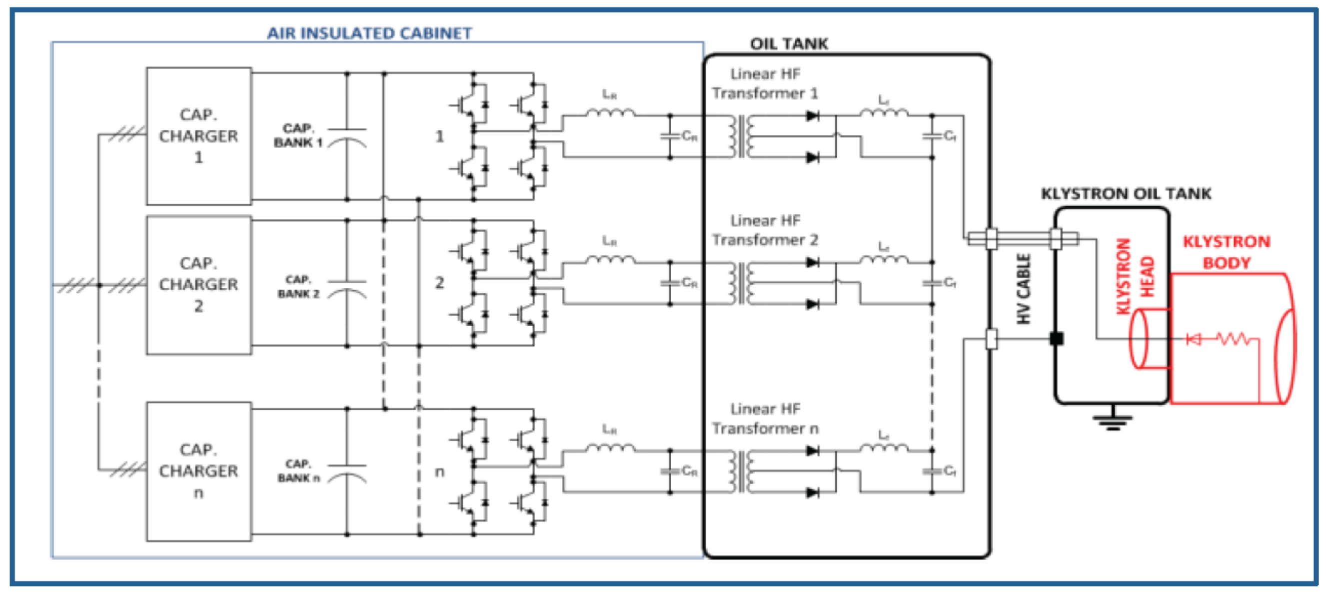
- Active demagnetization of the pulse transformer possible
- Intrinsic active droop compensation
- Active klystron arc extinction possible
- All electronics at medium voltage

Disadvantages

- HF ripple in flat-top
- Thermal cycling of semiconductors in hard switching
- Two special transformers (input and output)
- Large pulse transformer for long pulses
- Limited sources for pulse transformer

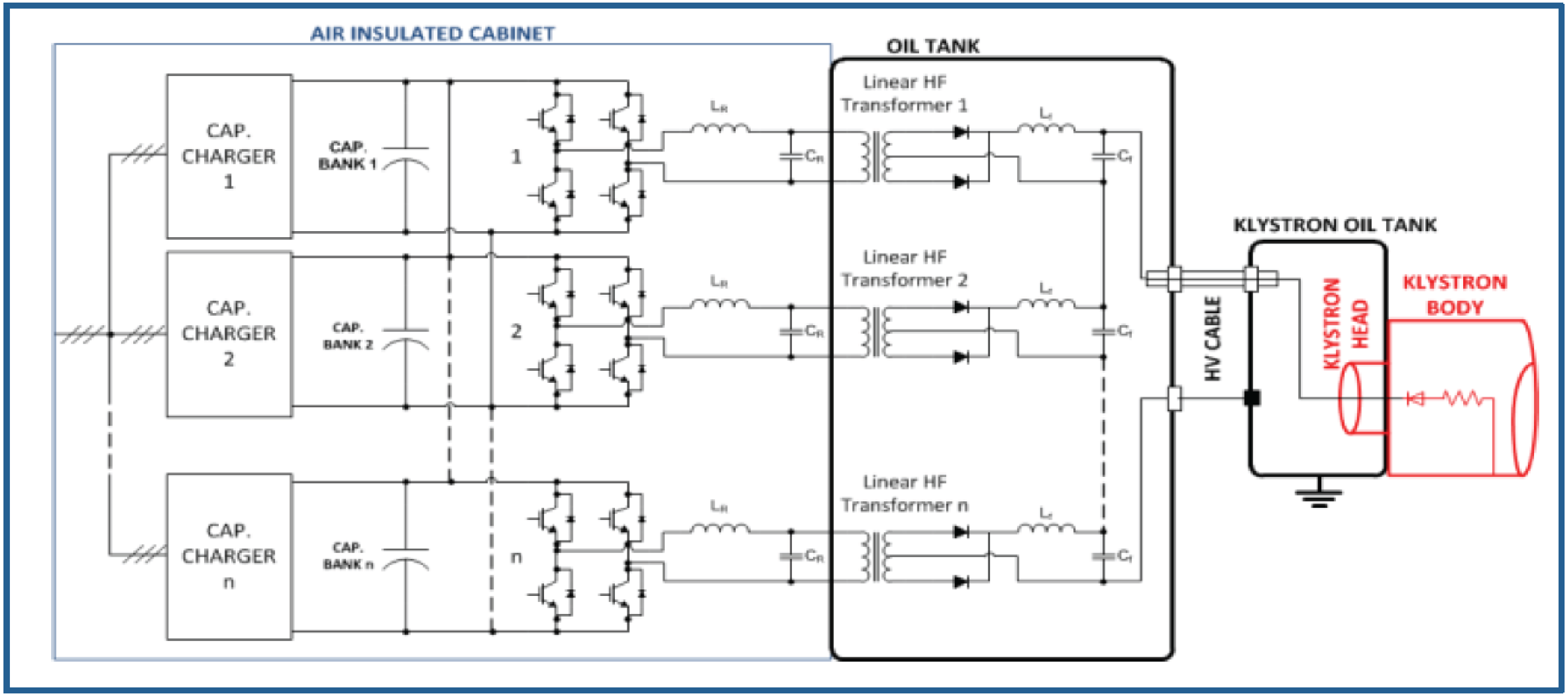
Multiple Resonant DC/AC/DC

- Charger: Distributed across many smaller modules.
- Storage capacitor: Smaller capacitors distributed across many modules.
- Switch: Standard solid-state switch.
- Voltage droop compensation: Flat-top control is inherent in topology



Multiple Resonant DC/AC/DC

- Used by
  - SNS
- Oil volume (transformer): not yet known



Multiple Resonant DC/AC/DC

Advantages

- All electronics at medium voltage
- Standard semiconductor switches
- No demagnetization required
- Intrinsic active droop compensation
- In klystron arc the resonant circuits become de-tuned
- Modular

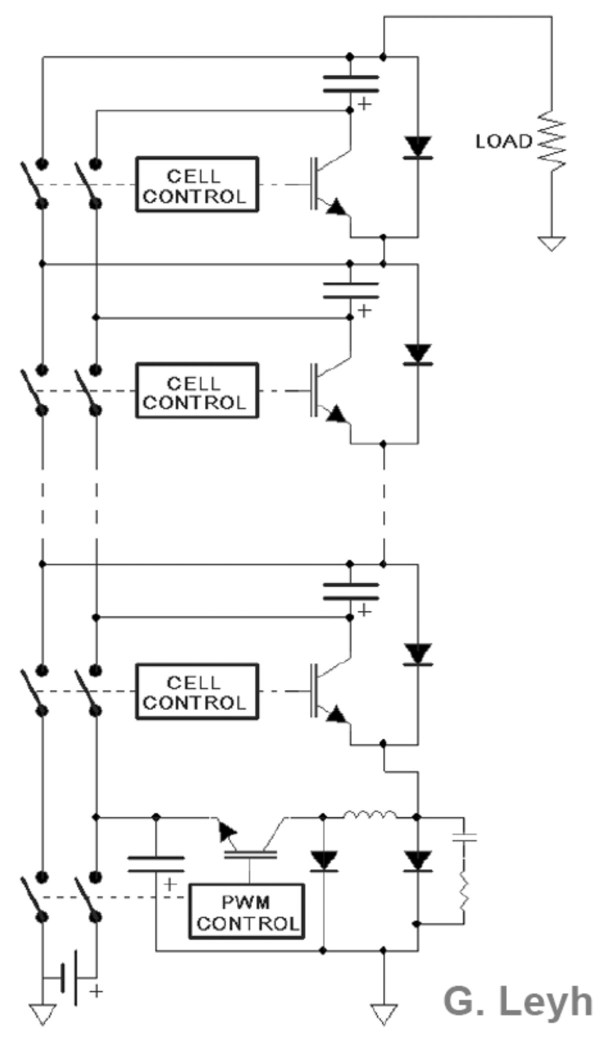
Disadvantages

- High frequency transformer design difficult
- Reactive power in H-bridges (some over-rating required)
- Relies on IGBT soft switching but this is complex
- Ripple on flat-top – to check if it meets reproducibility requirement

Solid State Marx

- Developed for ILC project
- Several years of development already completed

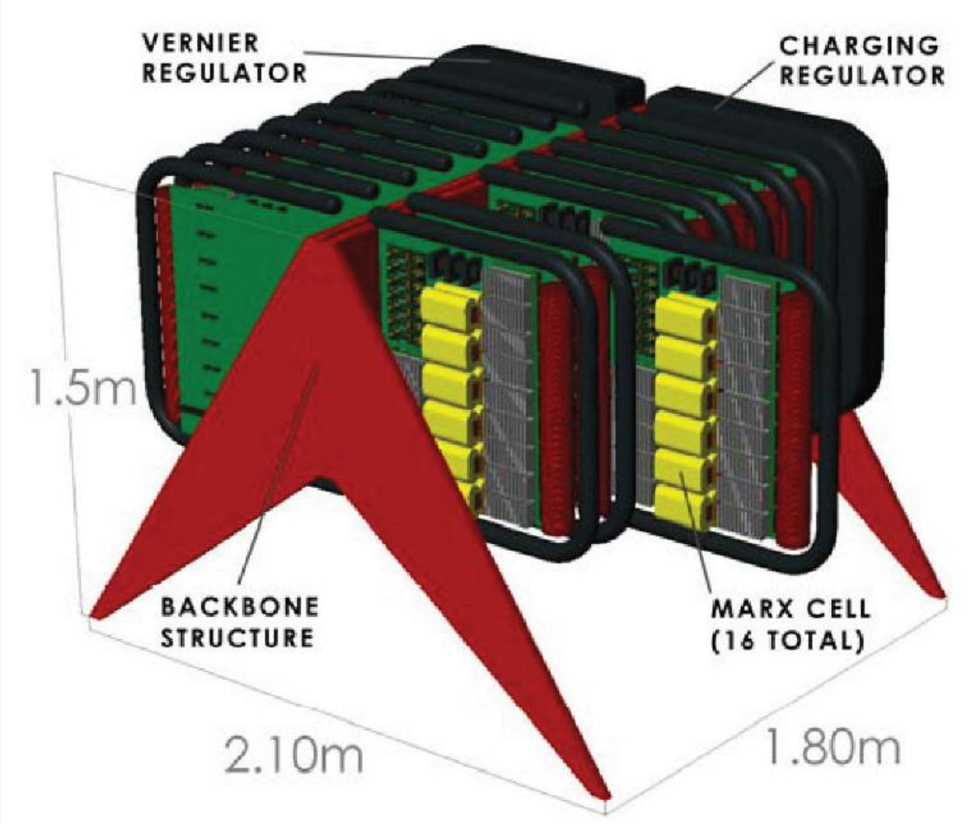
- Charger: Normally main charger for all systems.
- Storage capacitor: Capacitors distributed across many modules.
- Switch: Standard solid-state switch in each module.
- Voltage droop compensation: Flat-top control using switch-mode stage – creates a low amplitude 'sawtooth' waveform

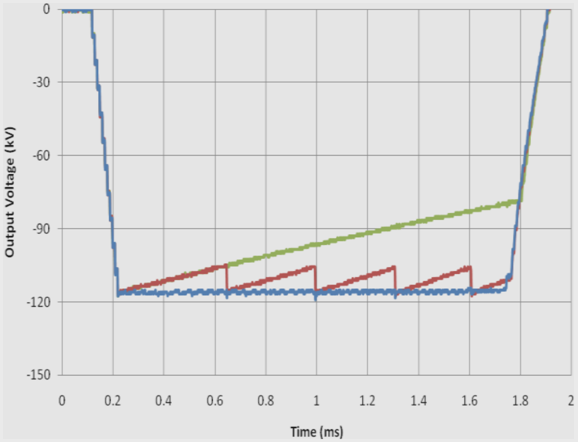


Solid State Marx

- Used by
  - SLAC (advanced prototype only)
- Oil volume: none

120 kV, 140A, 1.6 ms, 5 Hz





Solid State Marx

Advantages

- No oil or pulse transformer
- Standard semiconductor switches
- Intrinsic active droop compensation
- Low arc energy due to fast turn-off
- Modular and fault tolerant solution
- Development almost complete
- Potential to license design from SLAC?

Disadvantages

- Fairly complex
- Electronics are at high voltage (EMC issues)
- A lot of silicon (cost?)
- To be validated for (even) longer pulses

Cost Comparison

- See some cost scaling rules presented previously

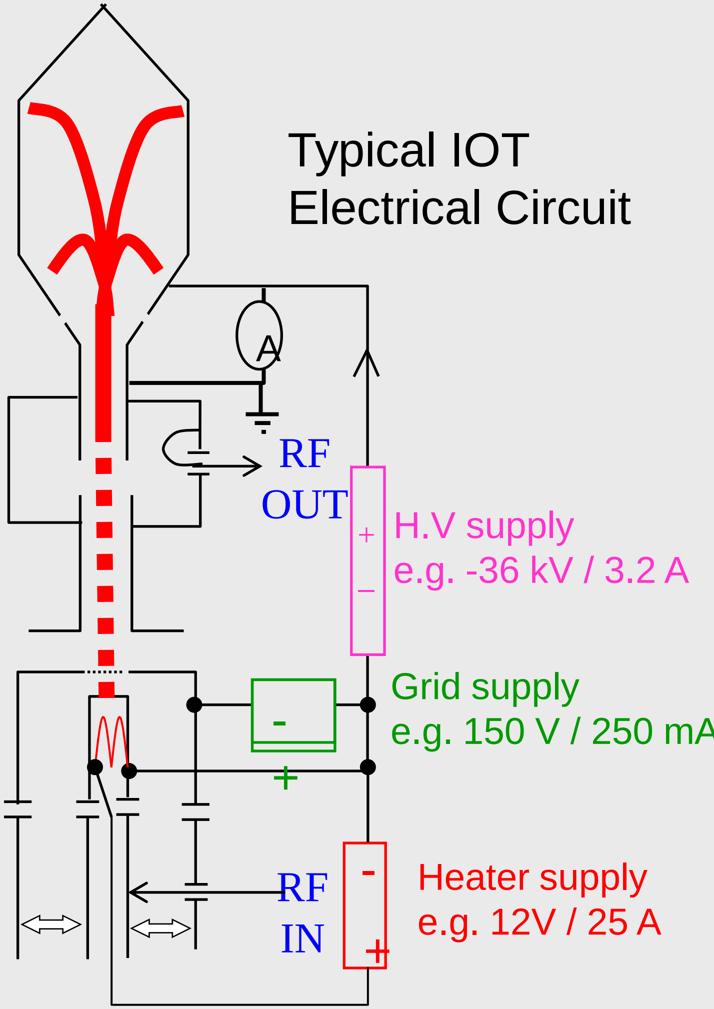
Topology	Comment
Bouncer	Conventional technology; Pulse transformer;
Direct Switch	Simplest solution; Proprietary technology;
Interleaved DC/DC	Modular; Conventional semiconductors; Special transformers;
Resonant DC/AC/DC	Modular; Conventional semiconductors; Special transformer;
Marx	Modular; Conventional semiconductors;

- The cost of each solution should align for industrial production quantities
  - Resonant topology has additional R&D costs compared to other solutions
- Modular systems may benefit additionally from increased quantities

‘Spoke’ Modulators

- Tetrodes and IOTs are being considered for the lower power spoke cavities, potentially several powered from the same modulator
- Modulators for these generally use DC electrical power
    - The power source is essentially the front half of a pulsed modulator (without pulse forming system)
    - IOT’s now widely used in TV signal transmission
    - Associated CW technology well proven

- IOT’s and tetrodes typically operate between 10kV and 50kV
    - Should be straightforward to find technical solution for powering of tetrodes/IOTs
    - However important to ensure reliability and availability (and hence modularity) is considered as part of the technical solution

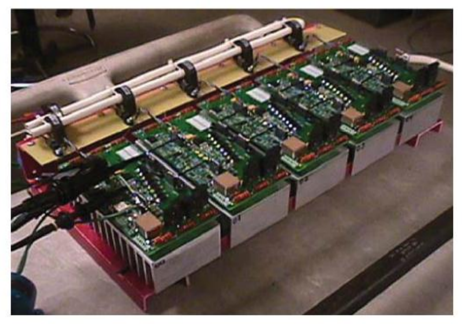


Typical IOT Electrical Circuit

P Sanchez, ALBA

Modulator R&D

- As with any project, several phases to consider
  - Ensure you get what you want!
    - Project management is a critical aspect to develop appropriate specifications and make prudent compromises where necessary
  - Develop specific technologies (eg transformers, inverters, etc)
    - Requires knowledge of HV, electromagnetics, semiconductors,…
    - Domain for experts: designers, teams and companies
  - Validate full scale prototype
    - Requires general knowledge of complete RF system
    - Develop system level electronics and software
    - Initial modulator testing on a passive High Voltage load
    - Subsequent testing on a klystron (without cavity)
    - Final validation in compete mock-up



In-house v commercial development

- In-house development allows facility to confidently maintain and operate equipment for the long term
  - Enables personnel to be highly knowledgeable of technology in operation
  - Requires investment in people and test facilities
- Commercial development is protective of intellectual property and prefers ‘black box’ approach
  - Can be problematic for long term operation of specialized equipment
  - However ability to optimize design and cost for production facilities
- LHC R&D and production model
  - Impose topology (you need to know which one…)
  - Allow companies to develop specific (optimized) solutions
  - Competitive tender on validated prototypes
  - All design data made available to buyer to allow long term support

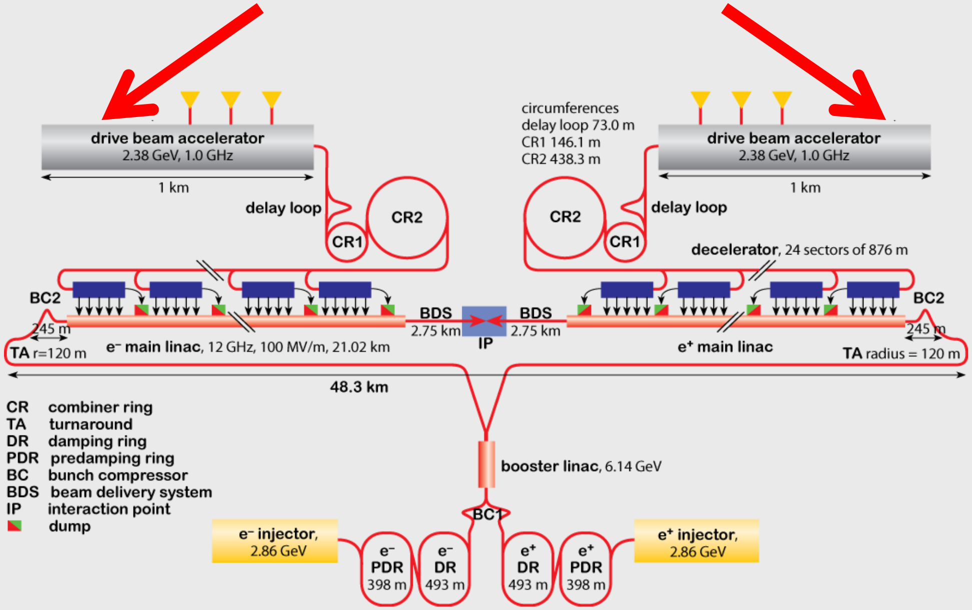
Modulator and RF optimization

- Further activity is encouraged to fully identify the complete RF system
  - At the design stage, the transfer function for the RF High Power system should also include a model of the klystron and modulator
    - Allows certain specifications to be refined and optimized
  - Typically attention is given to the RF resonant frequency
    - However the modulator and other components will generate perturbation (if any) in a lower frequency band
  - Some activity is starting at CERN and SLAC to identify LINAC4 and CLIC type klystron structures
    - Every RF system is likely to be different

CERN CLIC Modulator Development

- Challenging project with stringent specs for modulators
  - Some issues common to other accelerator projects
- R&D will be conducted in several centers, coordinated by CERN
- Intend to evaluate at least 2 different topologies as part of TDR phase

~1600 klystron Modulators required here



- 2-3 years of R&D at component and sub-assembly level
- 2-3 years to construct and test full scale prototypes
- Regular workshops with collaboration participants to share and direct progress

Modulator development efforts

- The following labs have made, or are making, progress on modulator technology
  - SLAC (ILC)
  - CERN (CLIC)
  - DESY (XFEL)
  - Los Alamos (SNS)

- While each project has specific requirements, there are many common technical challenges
- The many large linear collider studies ongoing today would benefit from a coordinated approach to the modulator development
- The ESS requirements for long pulse modulators is larger than all previous projects combined
  - Opportunity to interact with international modulator community
  - Needs an ESS representative/team to follow progress

Conclusion

- The ESS modulator requirements represents a greater financial investment than the power systems for the entire LHC!
  - The LHC powering was a 10year project from conception to installation
  - Due to good concept and design, excellent availability of power systems

- Experience from other large installations, such as SNS, identify the modulator as one of the key reliability/availability drivers
- Development time for new systems is significant
  - Both SNS and ILC developments for long pulse modulators have taken >5yrs

- The modulators are a significant cost driver in long pulse LINACS
  - It is in the interest of large LINAC projects to have a dedicated modulator team

- The proposed strategy for initial construction with a conservative modulator design seems sensible
  - For subsequent phase, recommend considering 2 (or more) alternative topologies

THANKYOU