Statistical Lifetime Analysis of Thyratrons in CERN Kicker Systems

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Contents

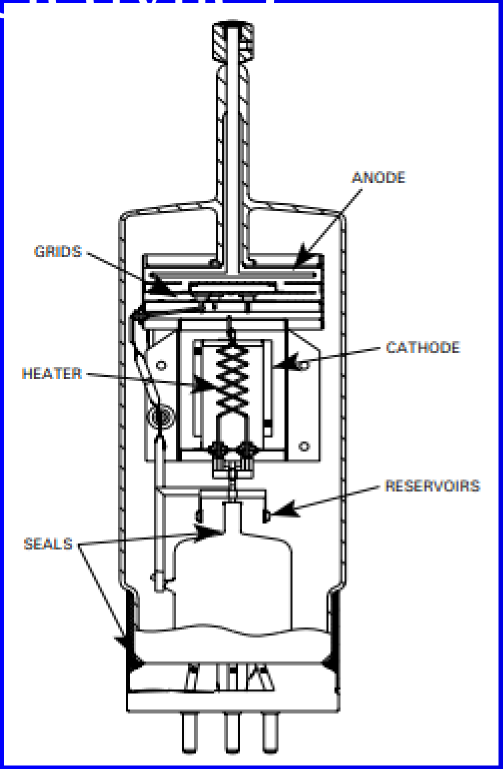
- Reminder about thyratron devices.
- Thyratrons used in CERN kicker systems.
- Operating mode in CERN kicker systems.
- Lifetime statistics.
- Conclusion.

Reminder about thyratron devices

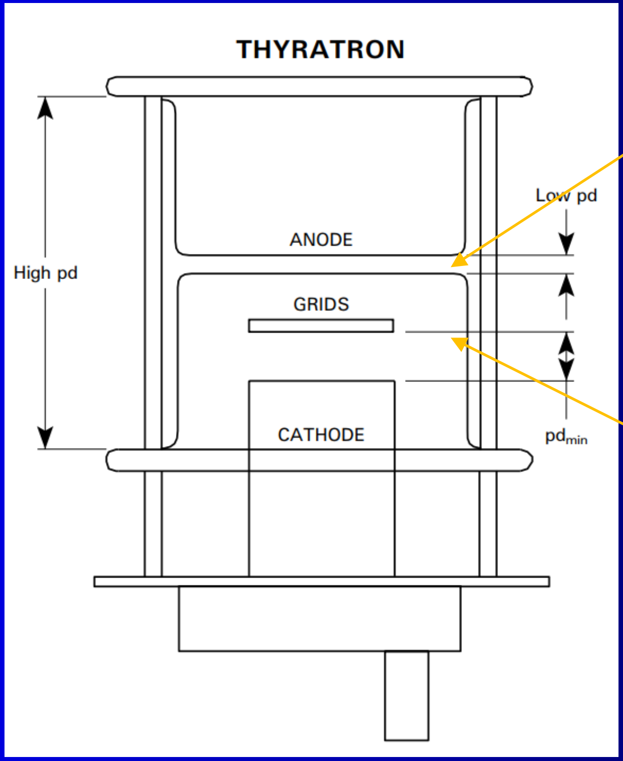
- Tube containing H_2 or D_2 (deuterium) gas at low pressure (~0.5 torr).
- Cathode heated for e^- emission.
- High density plasma in glow mode when on.
- Voltage controlled switching.
- Unidirectional in standard model.
- Gas pressure adjustable using heated titanium hydride reservoir.
- High voltage and high current capabilities (200 kV, 100 kÂ).
- Fast switching (tens of ns). Low jitter (2 ns typical).
- Closing switch only. Needs zero current + recovery time ~50 µs to stop.

Reminder about thyratron devices

For the kickers, we use glass (H_2 filled) and ceramic (D_2 filled) envelope tubes from E2V (now Teledyne)



Glass envelope



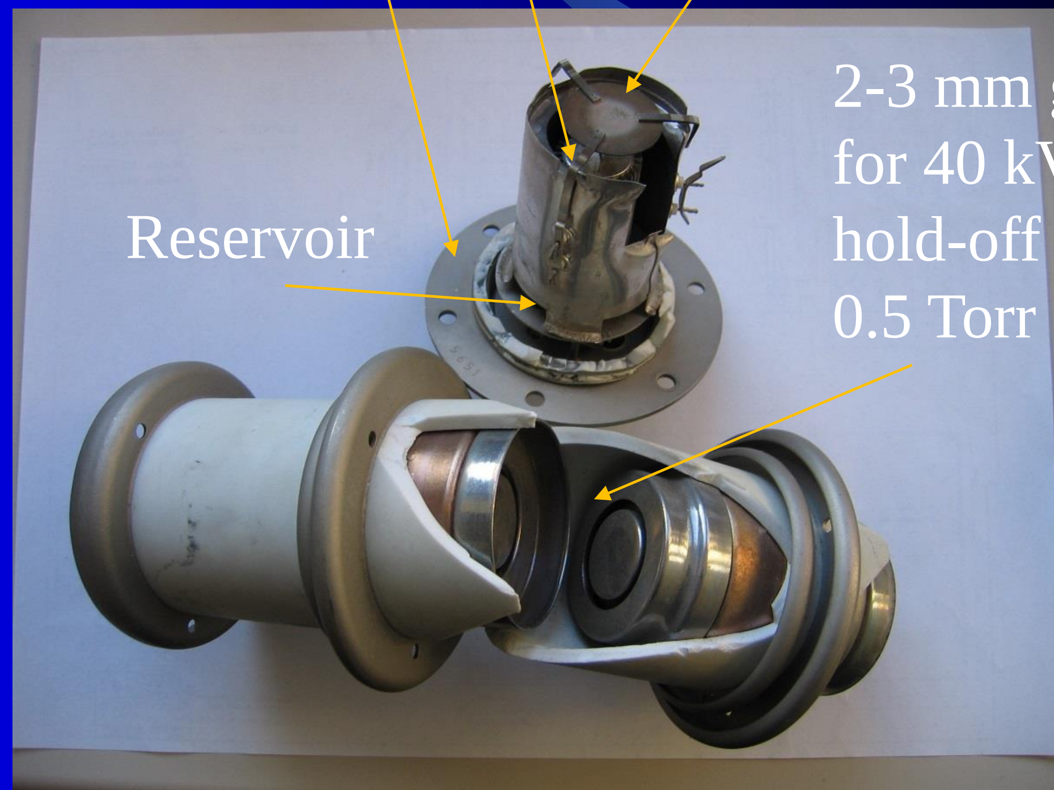
Ceramic envelope (1 gap)

2-3 mm gap for 40 kV hold-off at 0.5 Torr

G0, G1 priming grids,
G2 trigger grid

Reminder about thyratron devices

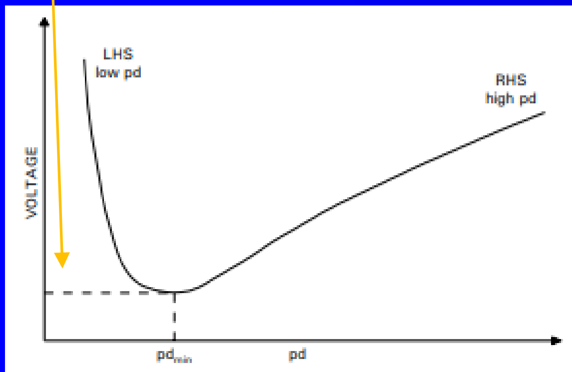
Glass envelope



Ceramic envelope (multi-gap)

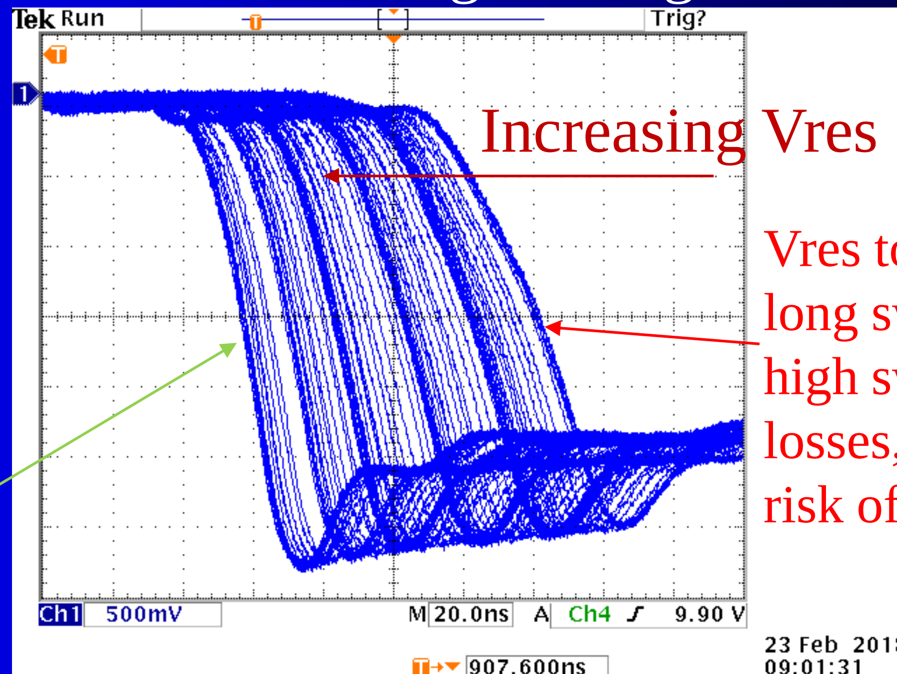
Reminder about thyratron devices

Operating zone (left side)



Paschen curve for H_2

Reservoir voltage management

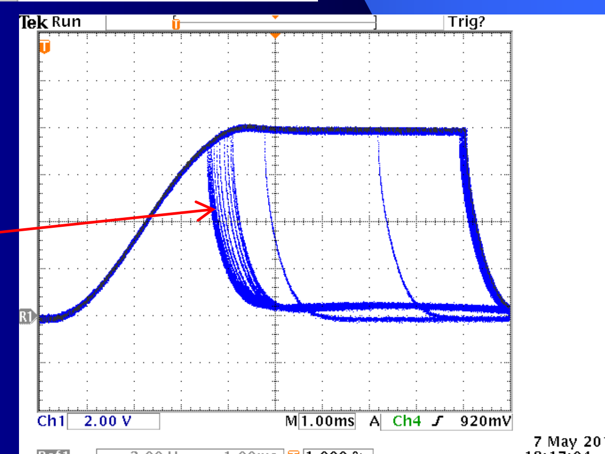


Increasing Vres

Vres too low,
long switching time,
high switching
losses,
risk of quenching.

Vres optimised,
short switching time,
minimum switching losses,
reduced anode delay time.

PFN voltage



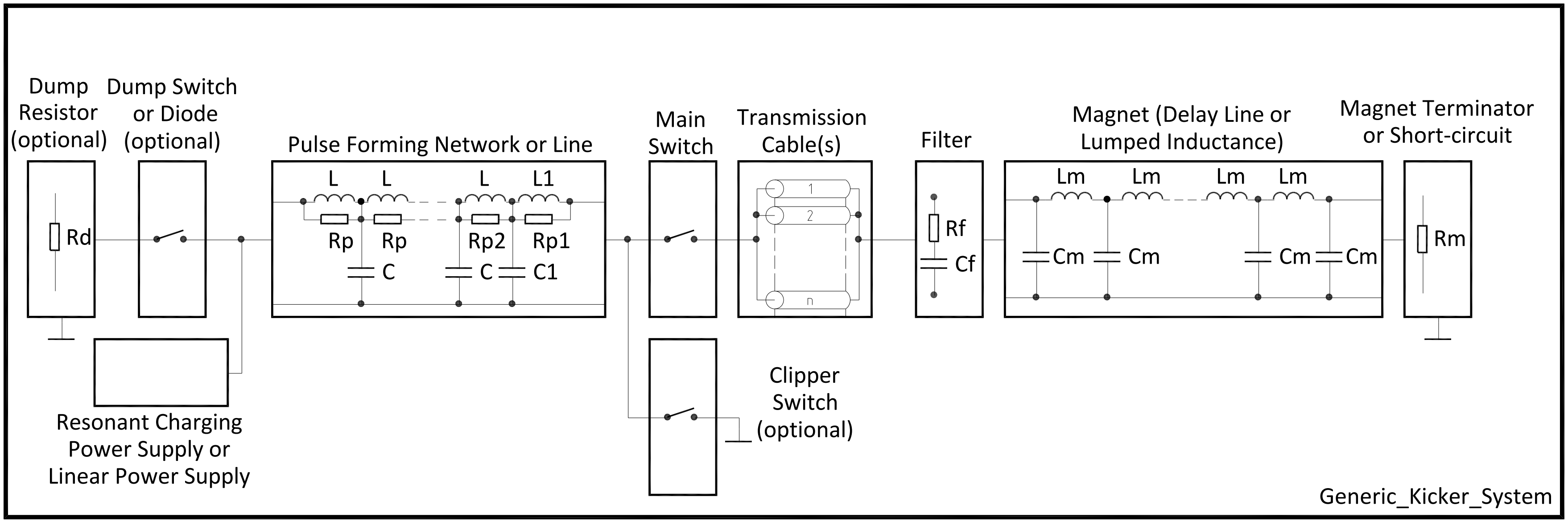
Erratic switching due to wrong reservoir settings (resonant charging case)

Reminder about thyratron devices

Special tube types

- Double Cathode (DC) ceramic: symmetric tube allowing bi-directional current. Needs two heater systems. Longer than the single cathode standard tube (more inductance, slower switching).
- Hollow Anode ceramic (HA): designed to conduct reverse current after forward current conduction if the plasma is still present in the tube. Same length as the standard tube.
- Ceramic metal envelope (X): tube with large reservoir and fixed reservoir voltage along its lifetime. An internal circuit assures the self adjustment of the gas pressure when the tube ages.

Thyratrons used in CERN kicker systems



Thyratron types used at Cern:

- Glass up to 30 kV, 1.8 kÂ.
- Standard ceramic up to 100 kV (3 gaps), 6 kÂ.
- Hollow Anode ceramic up to 100 kV (3 gaps), 6 kÂ.
- Double Cathode ceramic up to 100 kV (3 gaps), 6 kÂ.
- Metal envelope X up to 100 kV (3 gaps), 6 kÂ.

Operating modes in CERN kicker systems

Triggering techniques used:

1) G1 DC priming (100 to 150 mA), G2 negative bias, G2 fast trigger pulse of 1 kV minimum.
2) G1 DC priming (100 to 150 mA), G2 negative bias, G2 fast trigger pulse of 1 kV minimum, RC coupling of G2 pulse to G1 without delay.
3) No G1 DC priming. G1 pulsed with 1 Â picked from G2 trigger pulse which is then delayed by ~550 ns. Negative bias on G2. Needs only one trigger unit.
4) G1 DC priming (100 to 150 mA) + minimum 10 Â/1 µs pulse ~550 ns before G2 fast trigger pulse of 1 kV minimum. G2 negative bias. Needs two separate trigger units and trigger transformers.

Methods 3) and 4) give the best results in terms of jitter and lifetime.

Operating modes in CERN kicker systems

Good practises:

- try to match the system to avoid reflections which may lead to reverse currents in unidirectional tubes. This is not possible with lumped inductance magnets.
- operate tubes at their optimum gas pressure in order to reduce losses and avoid quenching or internal arc.
- use stabilised heater supplies.
- use hollow anode tubes only if you can switch forward current during a minimum of 100 ns before reverse current arrival. If this is not guaranteed, a double cathode switch is necessary.
- use hollow anode or double cathode tubes as Dump Switches to avoid damage (arc) in case of short-circuit in a normally terminated magnet circuit.
- Use an efficient fault detection system to immediately stop operation in case of problem.

Lifetime Statistics

Glass tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
PSB Distributor BI.DIS10	CX1159	5	25	0.5	130	1	MS	$7 \cdot 10^3$	$20 \cdot 10^6$
PS Pedestal PG	CX1159	3	30	1.8	12	1	MS	$10 \cdot 10^3$ to $20 \cdot 10^3$	$3 \cdot 10^6$
PS Staircase NSG	CX1159	12	38	1.52	12	1	MS	$10 \cdot 10^3$ to $20 \cdot 10^3$	$3 \cdot 10^6$
TT2 ERD1	CX1159	2	30	1.2	2.2	1	MS	$25 \cdot 10^3$	$4.5 \cdot 10^6$
TT2 ERD2	CX1191D	12	30	1.2	12	1	MS	$25 \cdot 10^3$	$4.5 \cdot 10^6$

Failure modes: metallisation, short circuit G2-cathode, erratics, gas leak.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (μs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
PSB extraction BE.KFA14L1	CX1575G (2 gaps, HA)	4	-42.5	6.8	1.516	3	MS	$>110\cdot10^3$ still ok	$>180\cdot10^6$
	CX1175G (2 gaps)	4	-42.5	3.4	1.516	1	Diode	$>110\cdot10^3$ still ok	$>180\cdot10^6$
PSB Transfer BT.KFA10	CX1575G (2 gaps, HA)	2	-42.5	6.8	1.516	3	MS	$>120\cdot10^3$ still ok	$>200\cdot10^6$
	CX1175G (2 gaps)	2	-42.5	3.4	1.516	1	Diode	$>120\cdot10^3$ still ok	$>200\cdot10^6$
PSB Transfer BT2.KFA20	CX1574G	1	-28	4.48	2.717	3	MS	$75\cdot10^3$	$125\cdot10^6$
	CX1175G (HA)	1	-28	3.4	2.717	1	Diode	$>120\cdot10^3$ still ok	$>200\cdot10^6$

Failure modes: erratics.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
PS Proton Injection KFA45	CX1171A (3 gaps)	4	80	1.52 (3 if SC)	2.86	1	MS	$70 \cdot 10^3$	$100 \cdot 10^6$
	CX1671A (3 gaps, HA)	4	80	1.52 (± if SC)	0.2 (3 if SC)	1	DS	$70 \cdot 10^3$	$100 \cdot 10^6$
PS Ion Injection KFA28	CX1154A	2	28	2.24	2	1	MS	$>20 \cdot 10^3$ still ok	$>3 \cdot 10^6$
	CX1573 (HA)	2	28	±1.12	2.1	1	DS	$>20 \cdot 10^3$ still ok	$>3 \cdot 10^6$
PS Extraction KFA71/79	CX1171A (3 gaps)	12	80	2.667	2.1	1	MS	$50 \cdot 10^3$	$70 \cdot 10^6$
	CX1671A (3 gaps, HA)	12	80	2.667	0.2	1	DS	$50 \cdot 10^3$	$70 \cdot 10^6$

Failure modes: mainly erratics, not triggering.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
PS MTE extraction KFA13-21	CX1192G (3 gaps)	3	75	6	12.5	3	MS	$>46\cdot10^3$ still ok	$>9\cdot10^6$
PS MTE extraction KFA4	CX1171A (3 gaps)	2	81	2.7	2.1	1	MS	$>20\cdot10^3$ still ok	$>3\cdot10^6$
	CX1671A (3 gaps HA)	2	81	2.7	0.2	1	DS	$>20\cdot10^3$ still ok	$>3\cdot10^6$
AD Injection KFI	CX1171A (3 gaps)	7	80	5.3	0.6	1	MS	$>100\cdot10^3$	$>2\cdot10^6$
	CX1671A (3 gaps HA)	7	80	±2.67	0.7	1	DS	$>100\cdot10^3$	$>2\cdot10^6$
AD Extraction KFE & ELENA Injection	CX1171A (3 gaps)	1	80	2.67	0.6	1	MS	$>100\cdot10^3$	$>2\cdot10^6$
	CX1671A (3 gaps HA)	1	80	2.67	0.1	1	DS	$>100\cdot10^3$	$>2\cdot10^6$

Failure modes: erratics, not triggering.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
SPS Injection MKP	CX1171B (3 gaps, DC)	6	52	3.1	11.5 (0)	1	MS	$35 \cdot 10^3$	$10 \cdot 10^6$
	CX1171B (3 gaps, DC)	6	52	6.2	0.2 (0)	1	CL	$>50 \cdot 10^3$ still ok	$>10 \cdot 10^6$
	CX2503X (3 gaps, X)	6	52	±3.1	2 (11.5)	4	DS	$>30 \cdot 10^3$ still ok	$>8 \cdot 10^6$
	CX2503X (3 gaps, X)	2	38	3	3	4	MS	new	new
SPS MKQV MKQH	CX1154B (DC)	2	25	2	<23	1	MS	$80 \cdot 10^3$	$10 \cdot 10^6$
	CX1154B (DC)	2	25	±2	<23	1	DS	$80 \cdot 10^3$	$10 \cdot 10^6$
	CX1154B (DC)	2	25	4	1	1	CL	$80 \cdot 10^3$	$10 \cdot 10^6$

Failure modes: switching too slow, erratics, cathode heater.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
SPS DUMP MKDV	CX1171B (3 gaps, DC)	3	47	~7.5	~2	1	MS	$55 \cdot 10^3$	$10 \cdot 10^6$
SPS Extraction MKE6	CX2003X (3 gaps, X)	1	31	3.1	8	4	MS	$>60 \cdot 10^3$ still ok	$>10 \cdot 10^6$
SPS Extraction MKE4	CX2003X (3 gaps, X)	1*	33	3.3	8	4	MS	$>60 \cdot 10^3$ still ok	$>10 \cdot 10^6$
	CX2503X (3 gaps, X)	0*	33	3.3	<8	4	CL	$>60 \cdot 10^3$	$>10 \cdot 10^6$

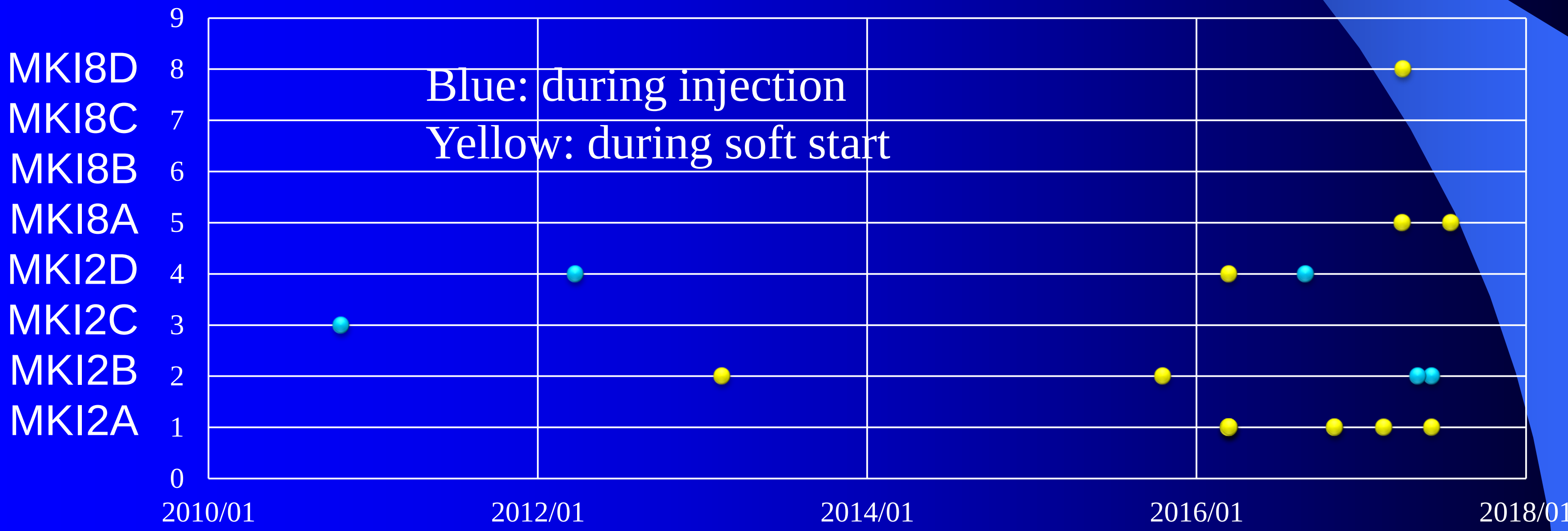
* Prior to December 2015, we had 5 systems.

Failure modes: erratics.

Lifetime Statistics

Ceramic Tubes

System	Tube Type	Qty	PFN Volt (kV)	Switch current (kA)	Pulse duration (µs)	Trigger method	Switch use	Life Time (h)	Life Time (Shots)
LHC Injection MKI	CX2003X (3 gaps, X)	8	54	5.4	7.5	4	MS	$>45\cdot10^3$ still ok	$>3\cdot10^6$
	CX2503X (3 gaps, X)	8	54	5.4	0.5	4	DS	$>45\cdot10^3$ still ok	$>3\cdot10^6$



Main concern: erratics to be avoided to prevent loss of the beam

Conclusion

Thyratron lifetime in normal operating conditions depends mainly on product: peak current × pulse duration × shots.

For extended life, G1 trigger before G2 is highly recommended.

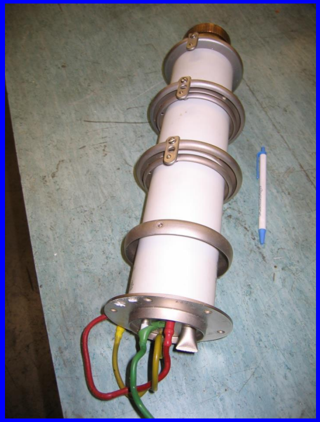
Filament failures are very rare.

For the best tubes without erratic problems, end of CERN life is decided when the rise time becomes out of specification due to gas depletion. A large reservoir voltage supply dynamic from ~3 to 8V is recommended for extended use of non X tubes.

Thyratrons are reliable devices in kicker systems if they are properly operated by well trained people.

Extra Slides

Thyratron CX1171A



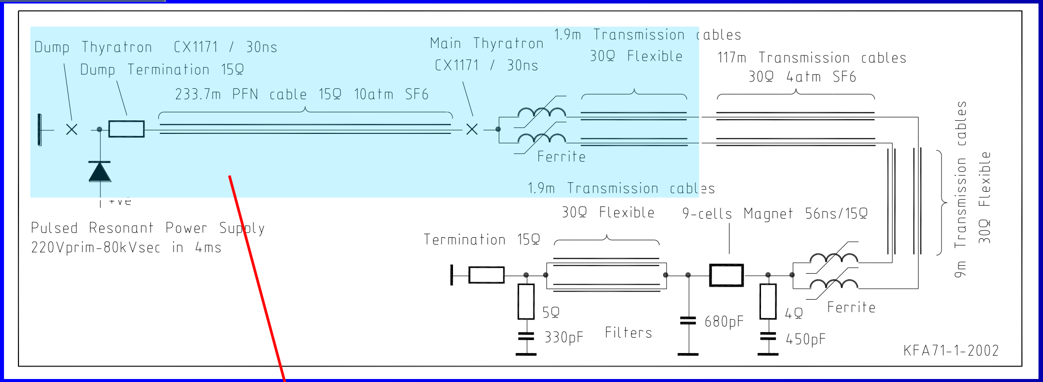
Features

- deuterium filled switch (gas discharge technology)
- deuterium pressure adjustable (reservoir)
- 100 kV max operating voltage
- 3 kA max current
- switching time ~ 30 ns (10-90)%, jitter <5 ns
- triggered with ~1 kV pulse
- single supplier (E2V technologies)
- cost ~11000 GBP (~17000 CHF)
- lifetime from 50000 to 100000 filament hours (more than 10^7 shots)
- for the time being no equivalent switch in other technologies (semi-conductors or else)

Main concerns

- long term availability (the supplier has recently reduced his catalog offer)
- continuous optimization of gas pressure necessary for a good compromise between voltage hold-off (low pressure) and rise-time (high pressure)
- inherent self firing

KFA71-79 system description



Generators in B359

100 kV Thyratron

SF_6 filled Pulse Forming Line