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Elettra Injection Development and Troubleshooting

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Accelerators of Elettra

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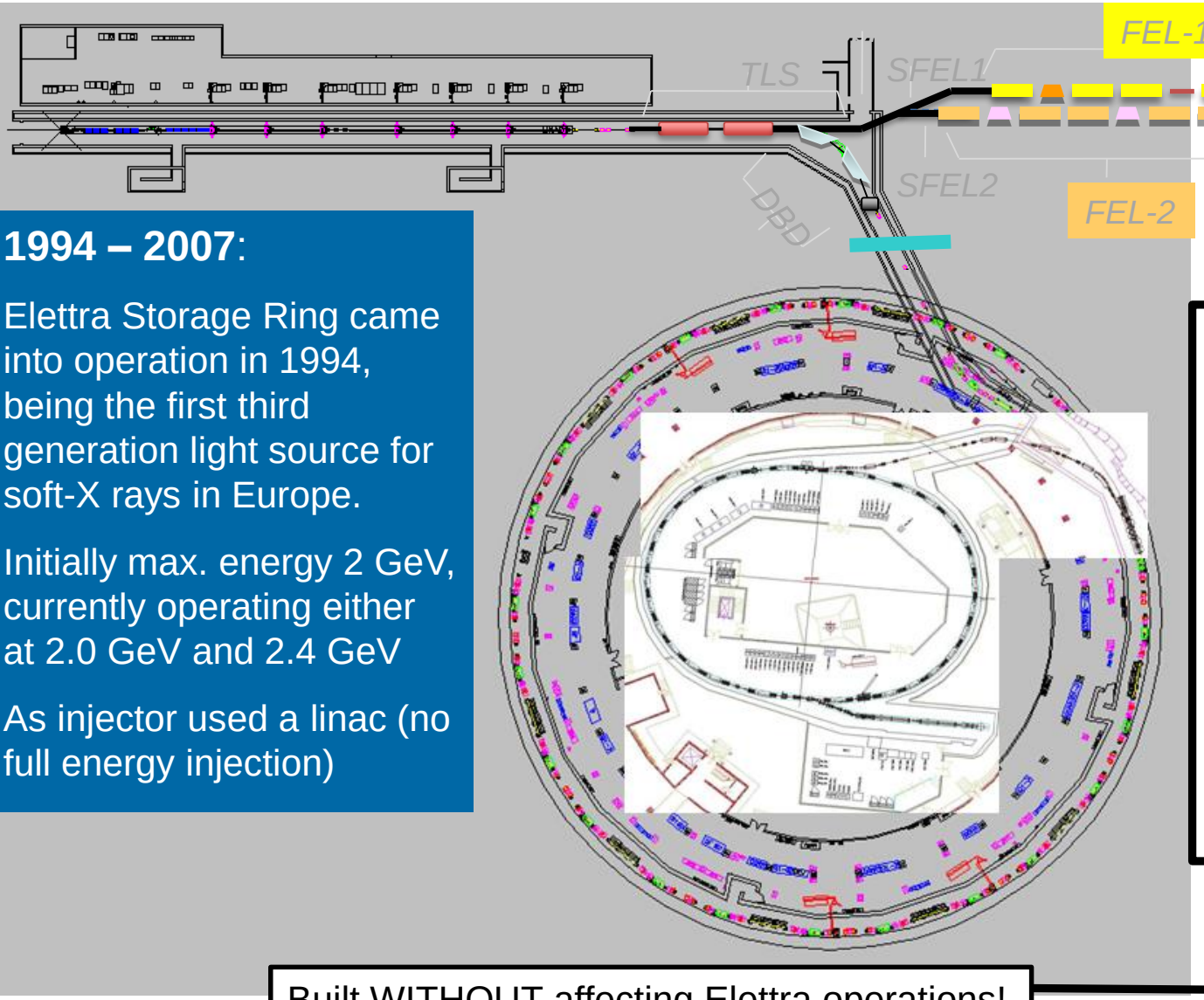


1994 – 2007:

Elettra Storage Ring came into operation in 1994, being the first third generation light source for soft-X rays in Europe.

Initially max. energy 2 GeV, currently operating either at 2.0 GeV and 2.4 GeV

As injector used a linac (no full energy injection)

Since 2011:

4th Generation light source

Since 2008:

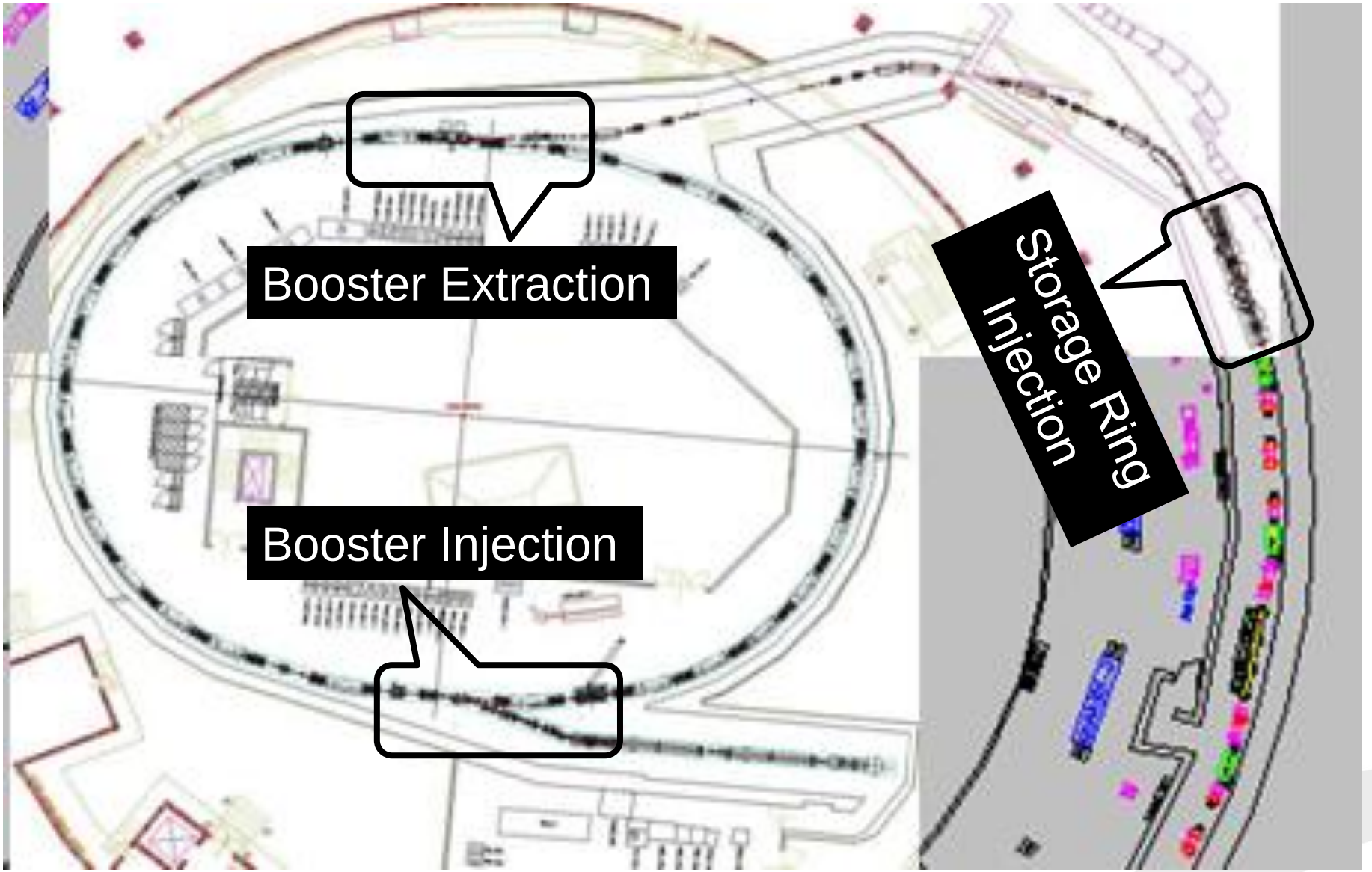
Full energy injector (linac + booster) at 2.0 & 2.4 GeV

Since 2010:

Regular TopUp operations during Users' beam time

Built WITHOUT affecting Elettra operations!

Elettra Injection and Extraction



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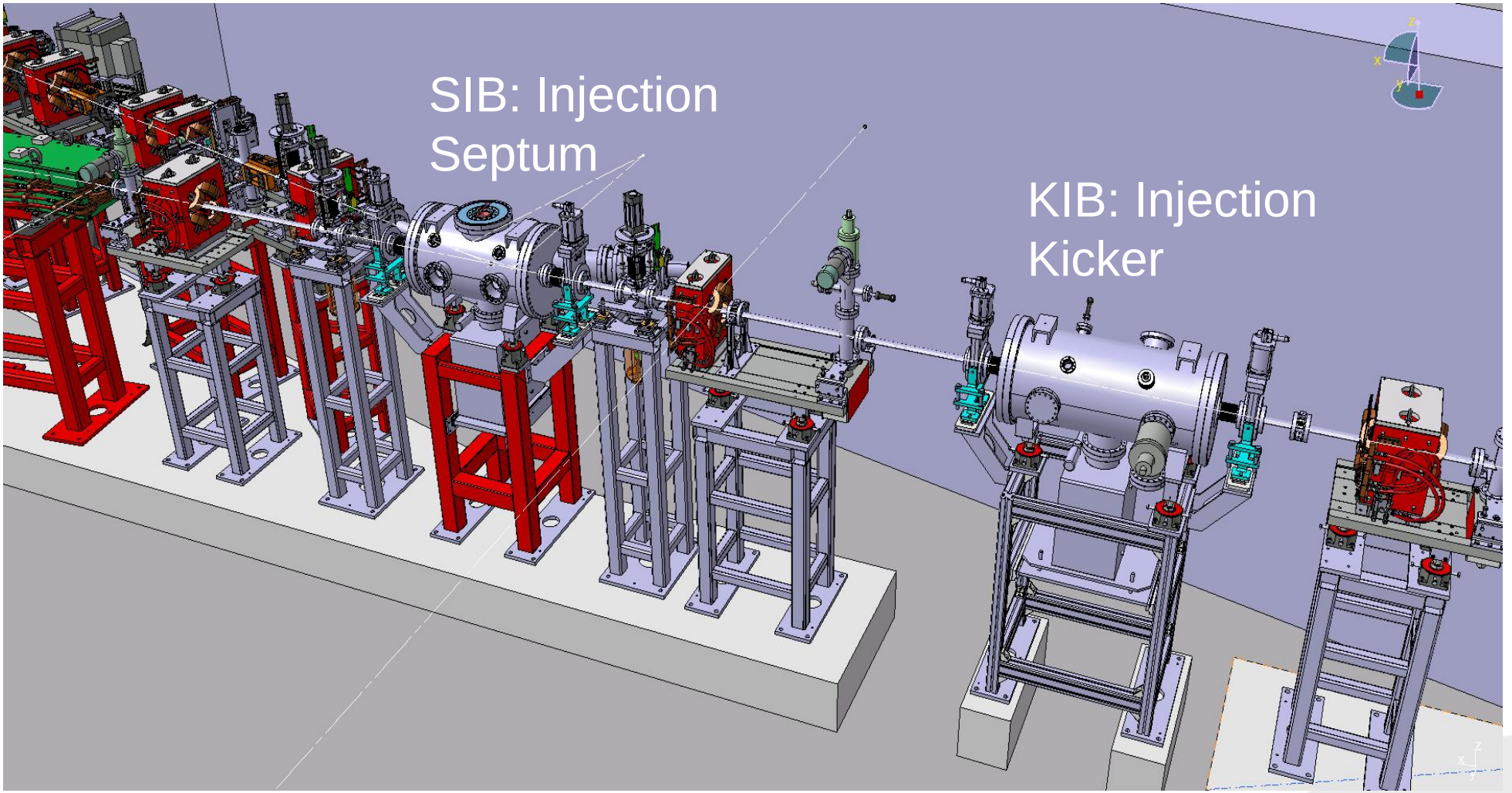
Booster Injection Layout



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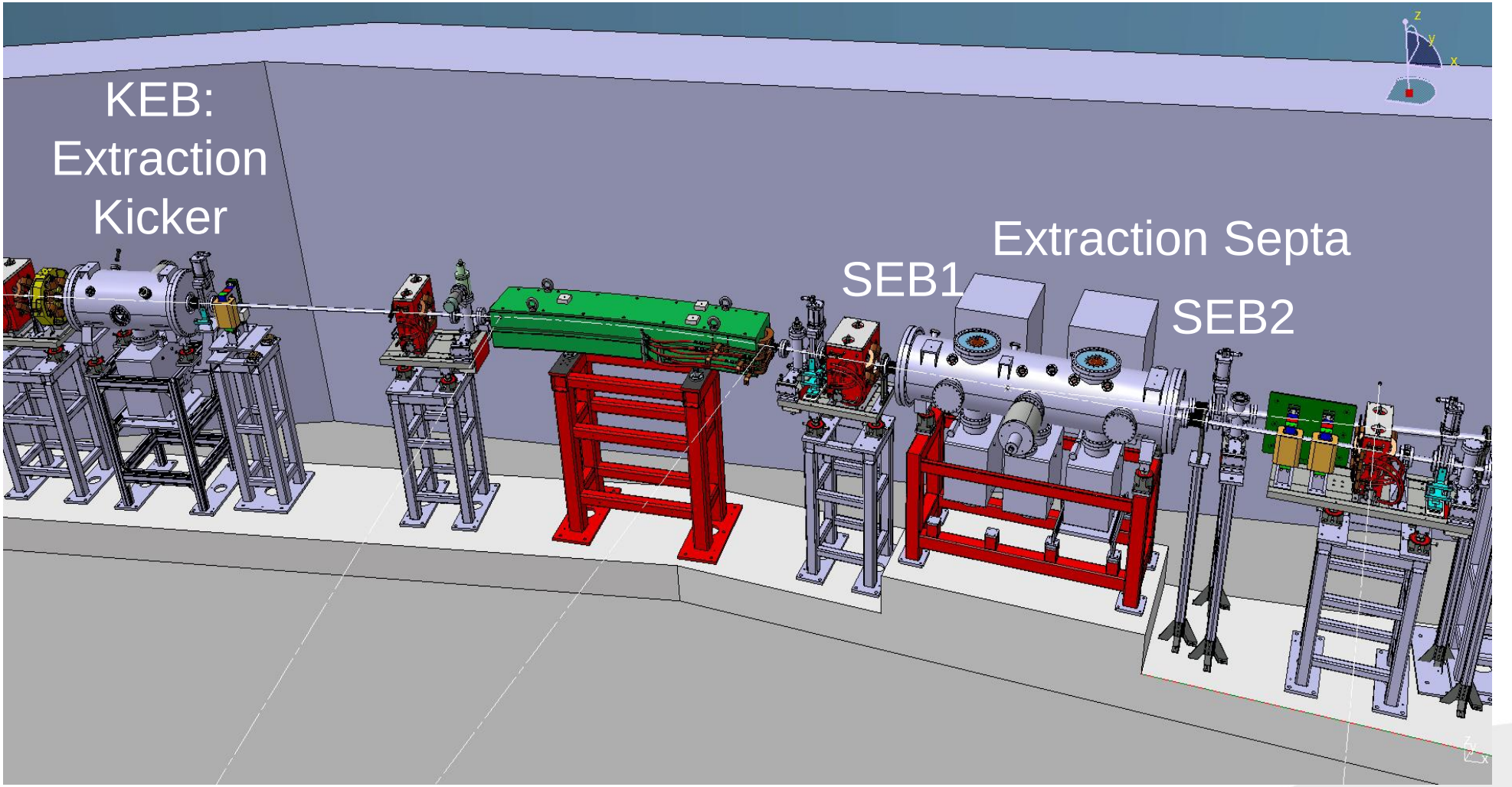
Booster Extraction Layout



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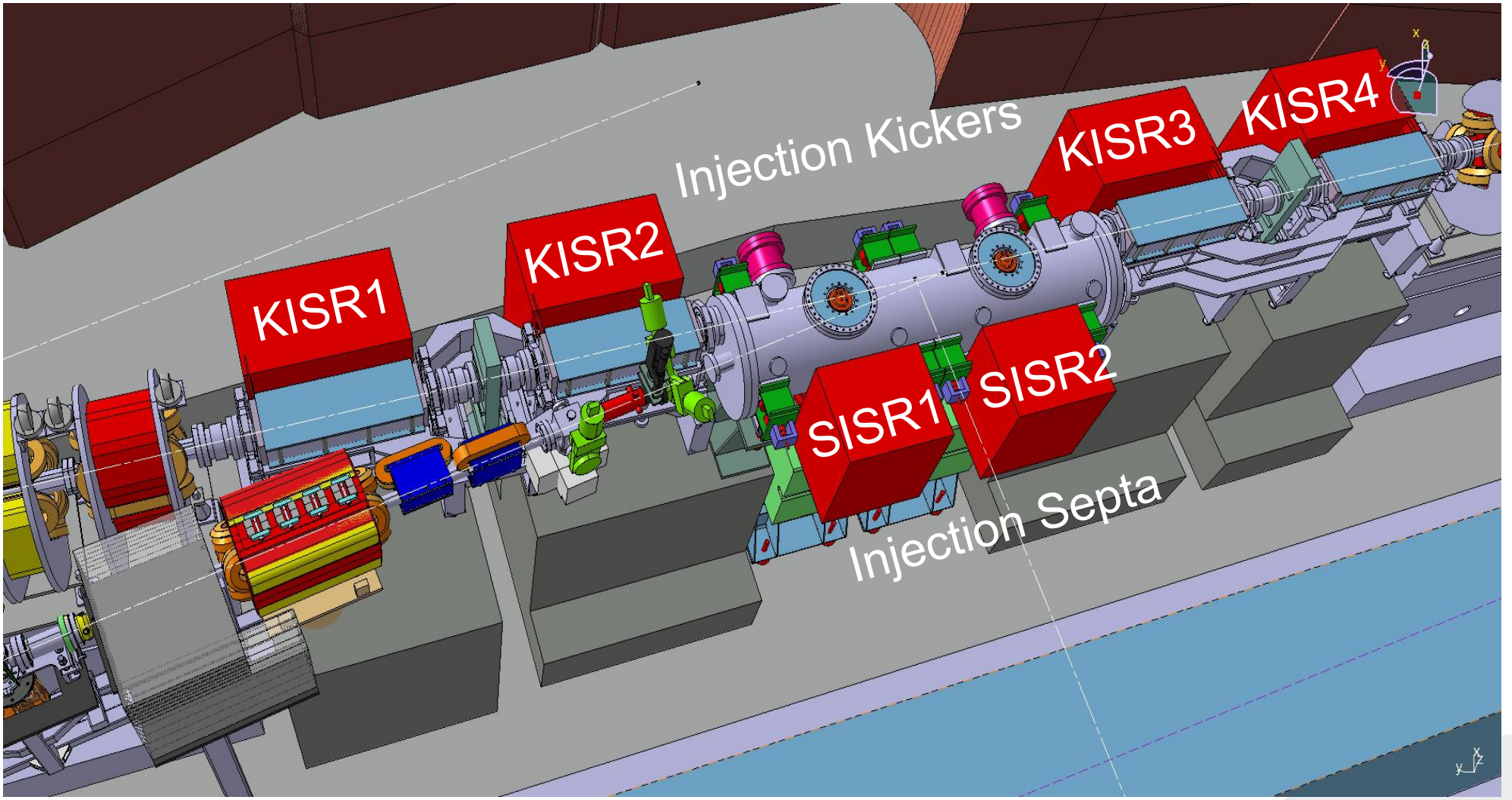
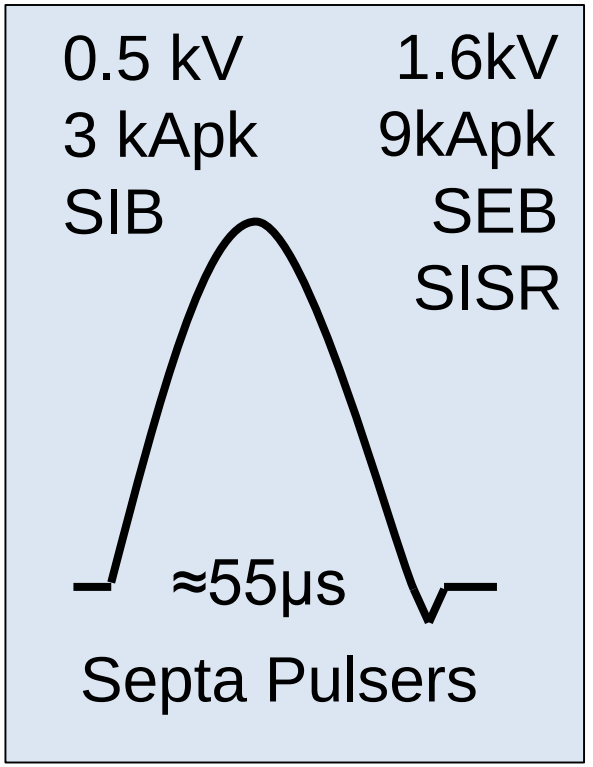
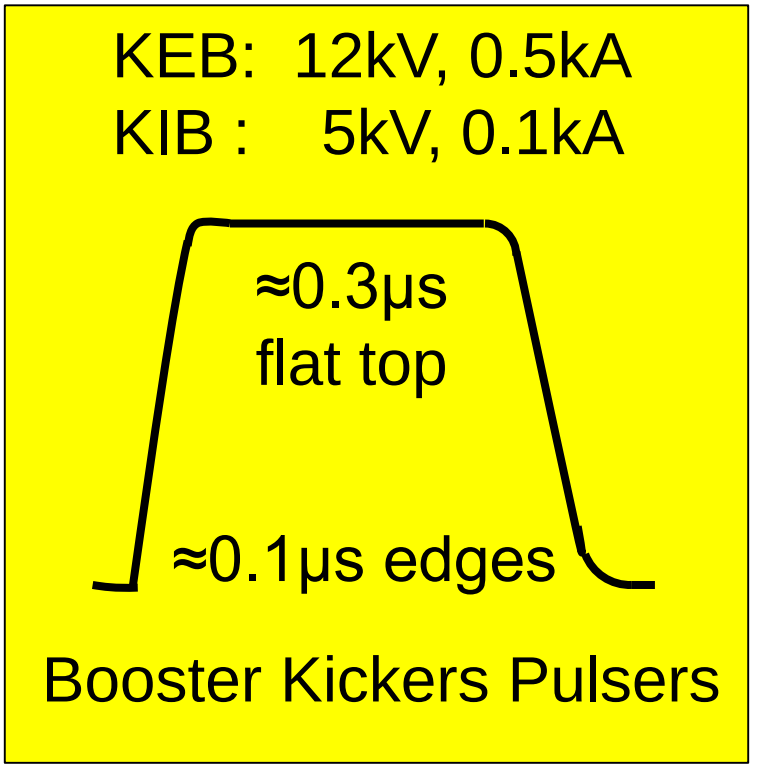
Elettra Storage Ring Injection Layout

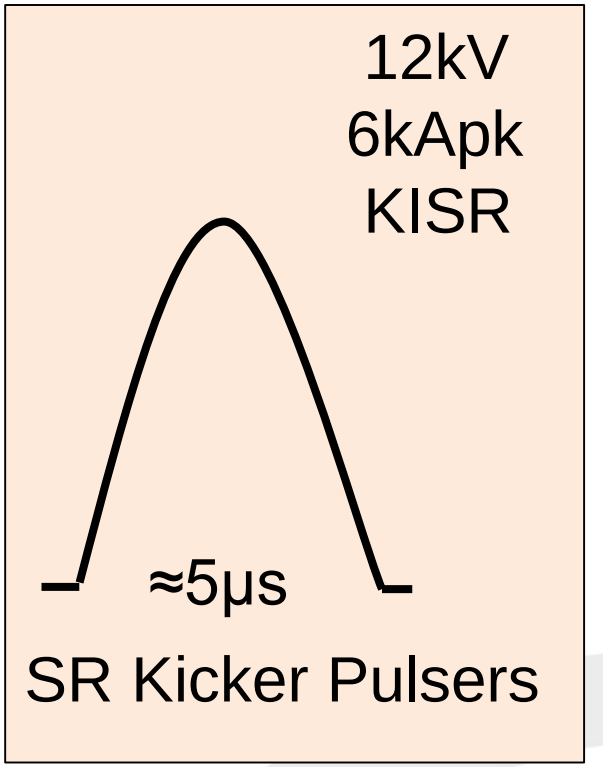


Elettra Injection main electrical ratings

- ✓ Machine Optics decides Injection Magnetics ratings, according to Particle Physics and available technology.
- ✓ Magnet coils often require high, pulsed electrical ratings, with widely adjustable, while accurate and repeatable, waveforms.





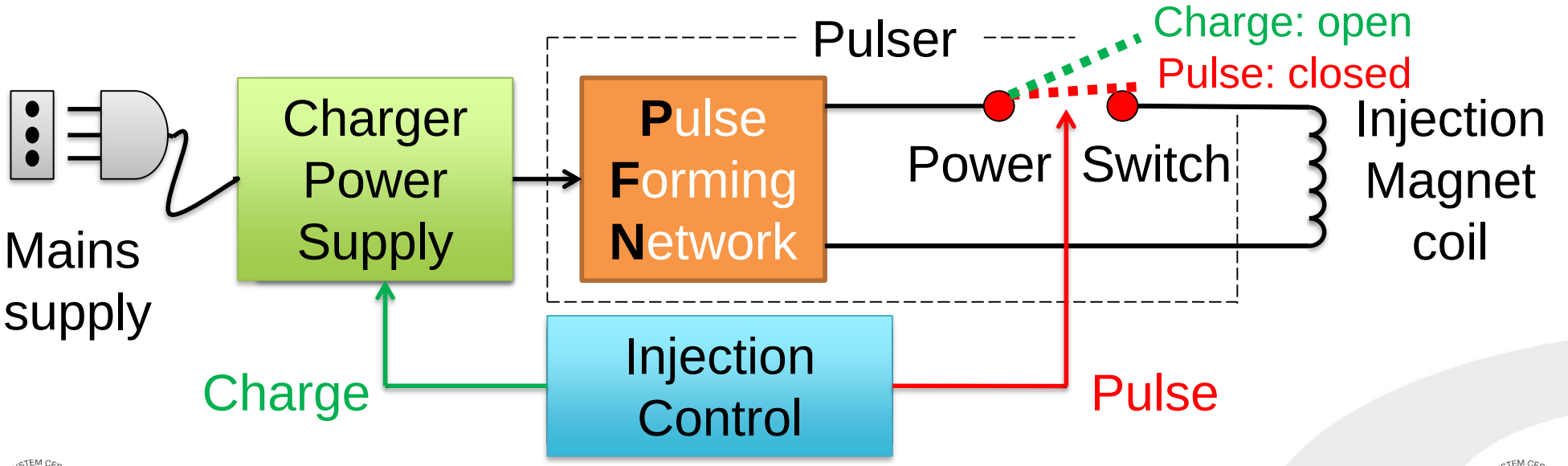


Injection Magnet Pulser configuration

It is impractical to take such high ratings in real time from mains.

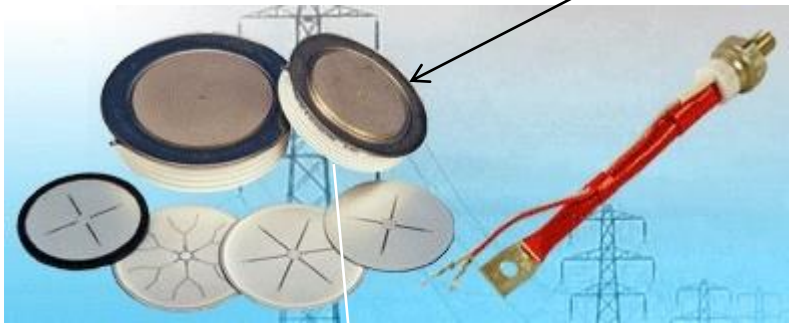
A Pulser circuit is placed close to each Magnet coil. It hosts:

1) a **P**ulse **F**orming **N**etwork (Capacitors, Inductors, Cables...) where energy is gradually stored by a Charger Power Supply
2) a Power Switch between PFN and coil. Its own resistance is:
   - (Charge) High, so disconnecting coil, allowing PFN charge
   - (Pulse) Low, so connecting coil, when trigger commands coil Pulse

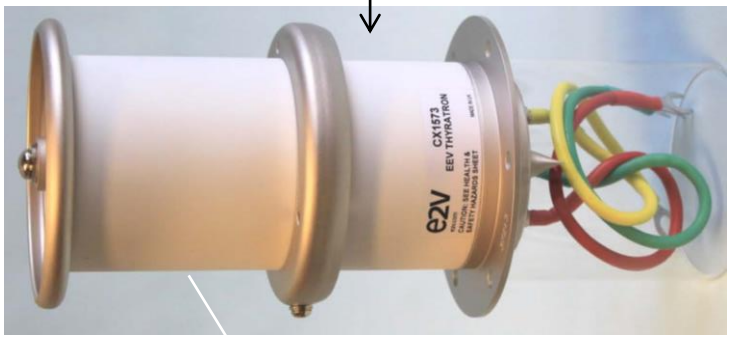


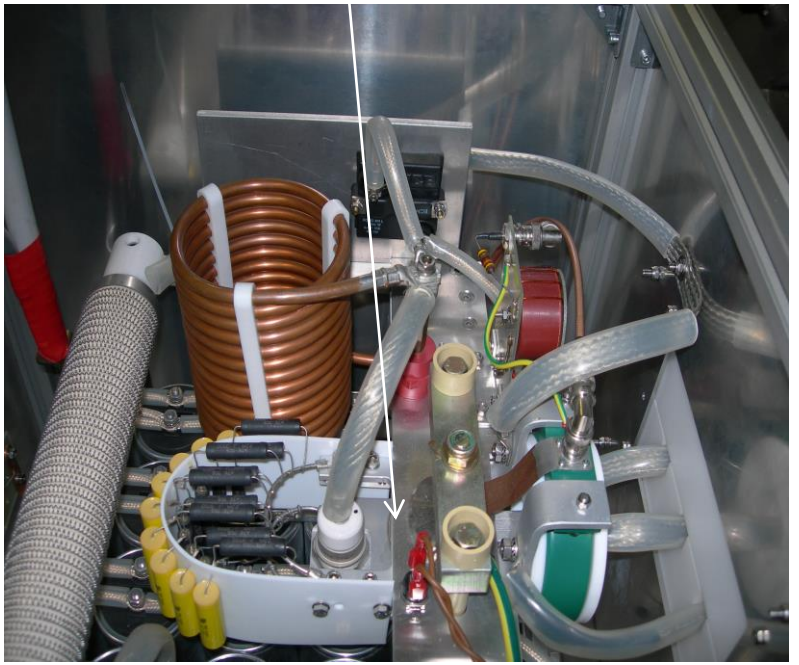
Elettra Injection (and Extraction) Pulsers

All Elettra Injection and Extraction Magnets Pulsers employ latching type Power Switches: Thyristor for Septa and Thyratron for Kickers.

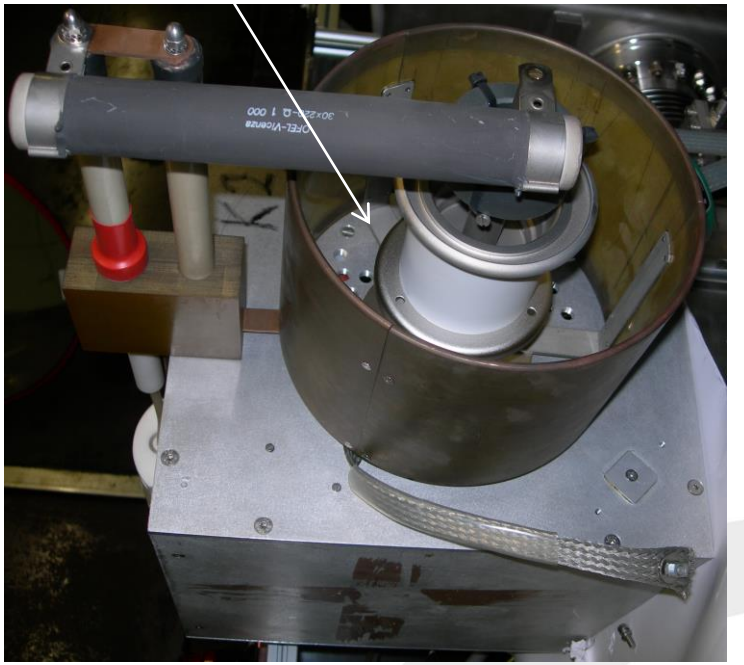


bare Power Switches





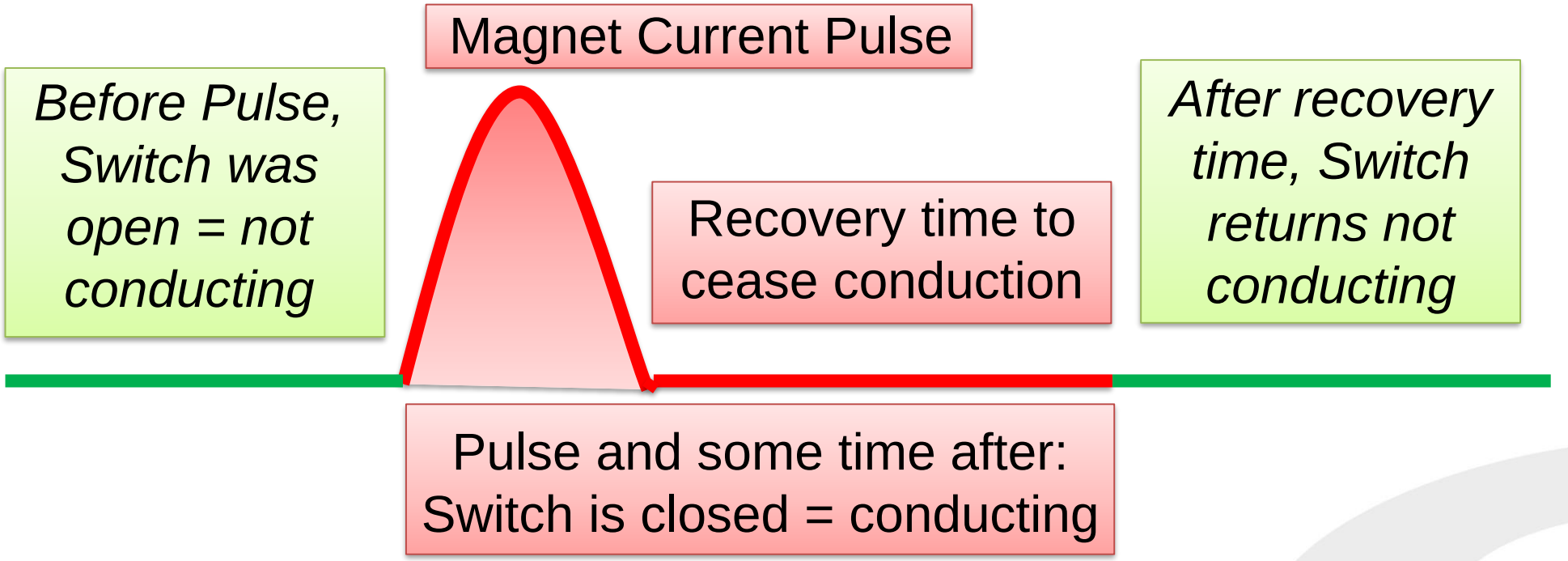
Power Switches installed in relevant Pulsers



Latching type Power Switches

Once closed into conduction for any reason, wanted or not, a latching Switch does not accept any command to open.

The Switch opens by itself only after its current stays under a certain value for a while (recovery time). This is usually provided by suitable Pulse waveform design and/or by temporary stop and appropriately delayed restart of charge.



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Wanted and Unwanted Injection Pulses

Latching type Power Switches (either Solid State Semiconductor Thyristor or Deuterium Tube Thyratron), in apparently normal conditions, *may sometimes not obey to relevant trigger commands:*

1) Missing a wanted Pulse (remaining open) after a valid trigger

2) Producing an unrequested Pulse (closing) with no trigger received.

According to Machine status, the mispulsed Magnet role, its timing and involved ratings, the consequent missing or unwanted particle deflecting Pulse may partially disturb or totally kill the stored beam.

Even few false KISR Pulses per million good ones do molest.

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False Pulses: missing ones

According to Power Switch physics and actual surrounding conditions, some of the *reasons for a missing Pulse may be:*

1) Anode voltage too low (ex: polarity reversed) to correctly turn-on
2) Insufficient trigger pulse length
3) Insufficient trigger pulse current and/or voltage
4) (for thyratrons) Inadequate heaters and/or grids bias ratings
5) Too low temperature

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False Pulses: unrequested ones

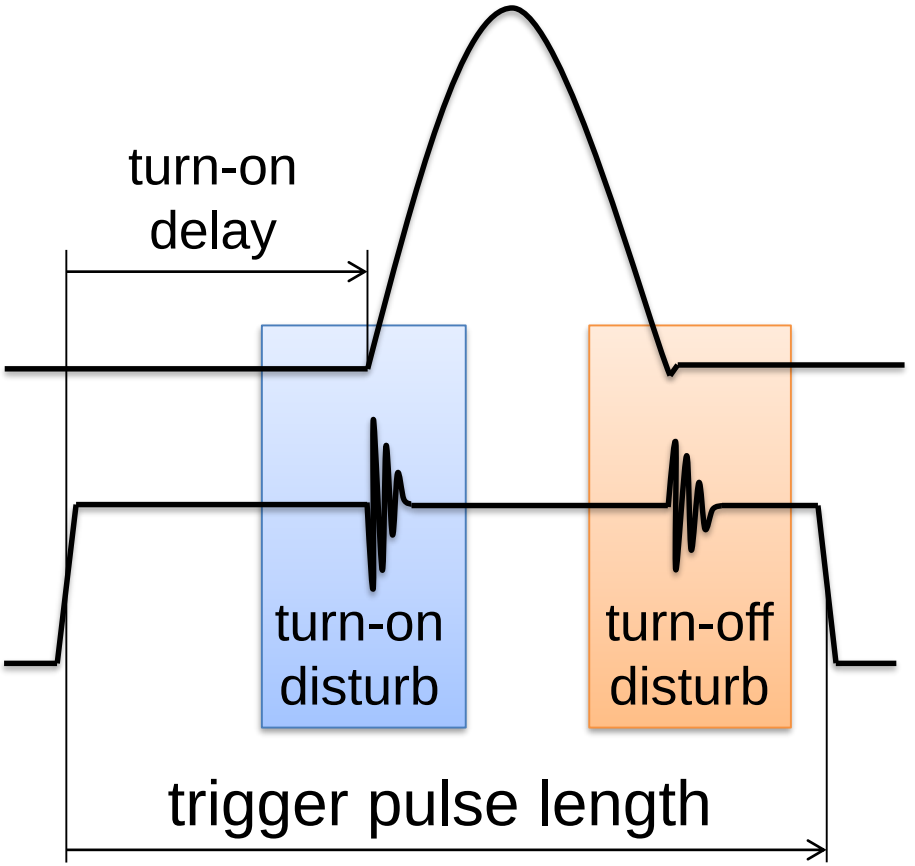
Unrequested Pulses (i.e. Switch self turn-on) may occur caused by:

1) Anode voltage too high and/or its dv/dt too high
2) Enough conducted or radiated radiofrequency or radiation
3) Residual trigger pulse voltage and/or current and/or length
4) (for thyratrons) Inadequate heaters and/or grids bias ratings
5) Switch wear out, due to previous abuses and/or end-of-life
6) Too high temperature

Borderline triggers and self turn-on may damage Power Switches

Power Switch normal turn-on waveforms

Magnet Current Pulse (effect)



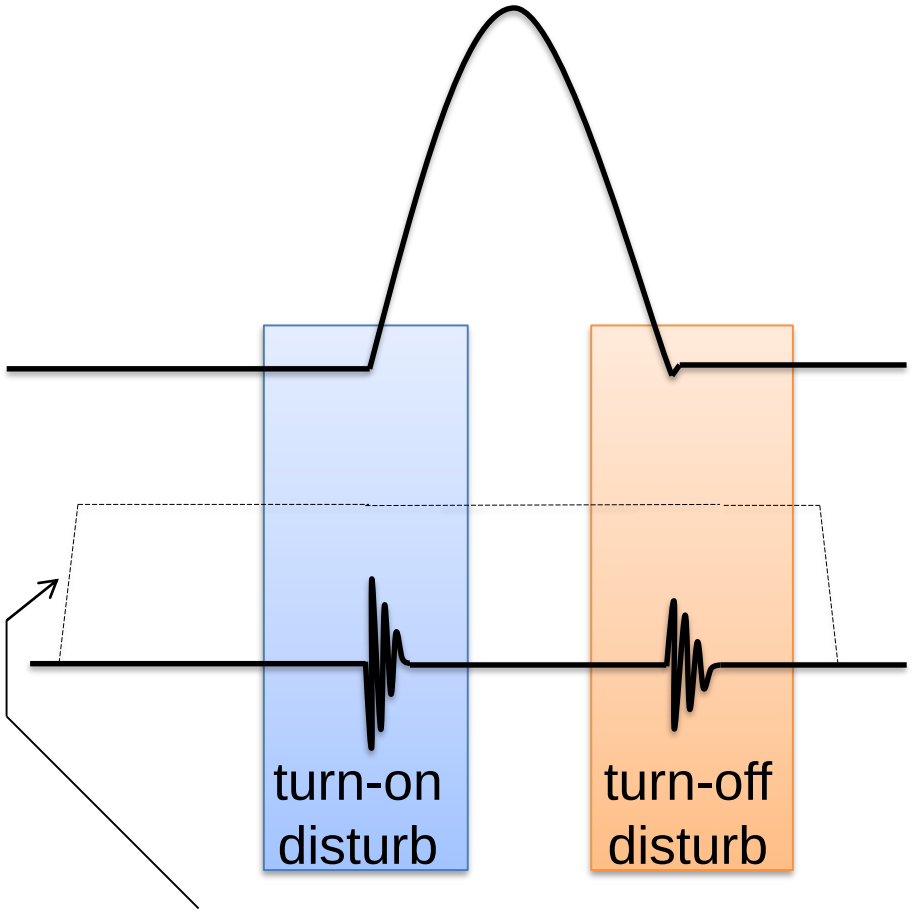
Power Switch trigger (cause)

Simplified normal (i.e. following a valid trigger) Power Switch turn-on waveforms show that current into the magnet coil begins after a turn-on delay. Power Switch turn-on and turn-off cause some trigger waveform disturbs.

Real world measurements must take into account factors that affect signal integrity, such as ground loops and other conducted and radiated electromagnetic interference (EMI), cable delays, probes and attenuator factors, pickup circuits effects...

Power Switch self turn-on waveforms

Magnet Current Pulse (effect)



Missing requesting Power Switch trigger (no cause)

Simplified unrequested (i.e. with no requesting trigger) Power Switch waveforms show that current into the magnet coil starts apparently by itself (self turn-on). Switch turn-on and turn-off still cause some trigger waveform disturbs.

If the oscilloscope is synchronized on the magnet current rising edge, the absence of the previously requesting trigger pulse can be detected and the coil Pulse can be marked as false Injection Pulse.

Real waveforms are not so clean.

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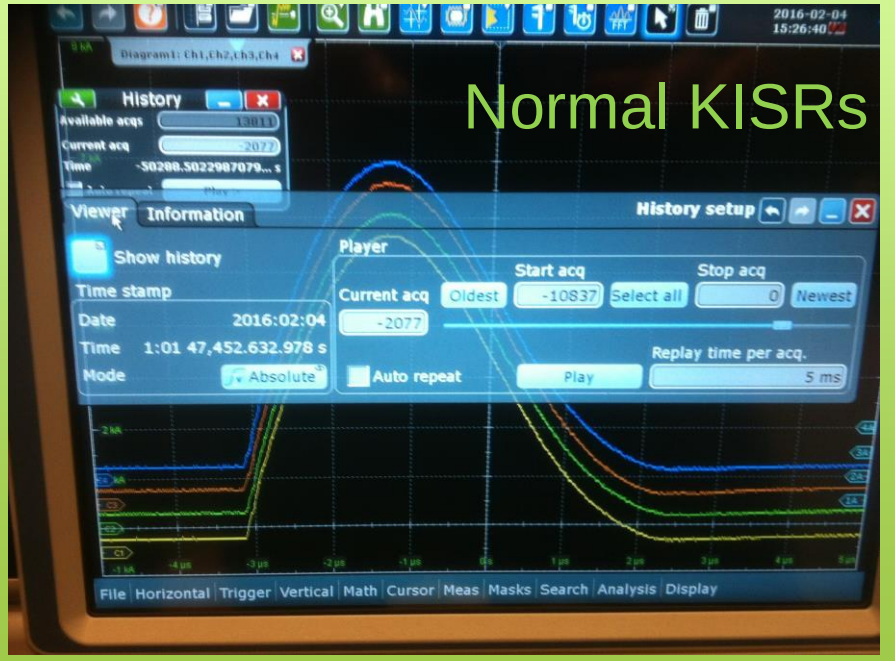
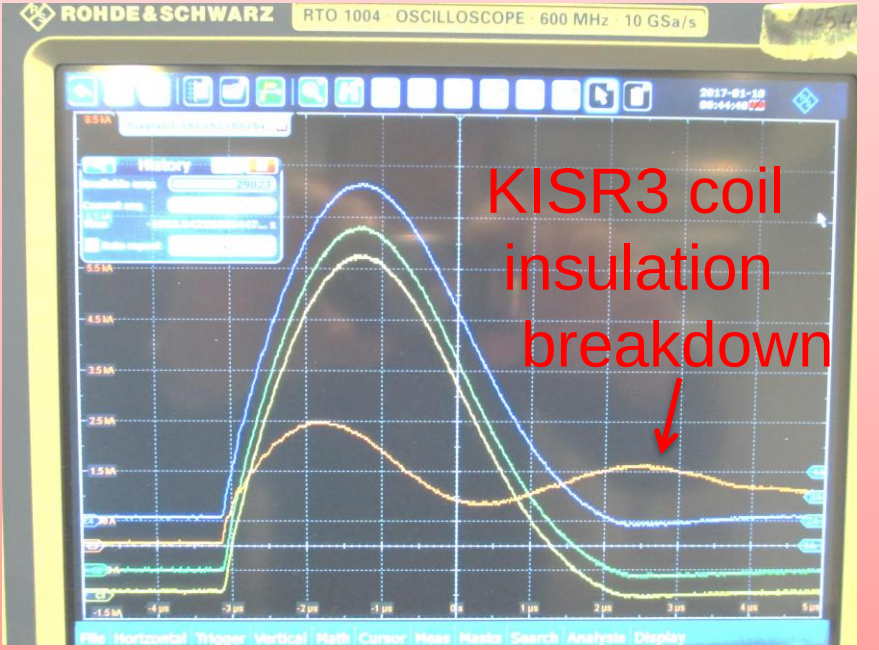
Every Pulse may be a story in itself

Was it requested or not, once started, Pulse is temporarily out of control and it develops according to the actual electrical situation.

If all conductors and insulators do their own duty, waveforms are as designed and expected.



If not, waveforms are distorted and some parts may be affected, *either reversibly or irreversibly.*



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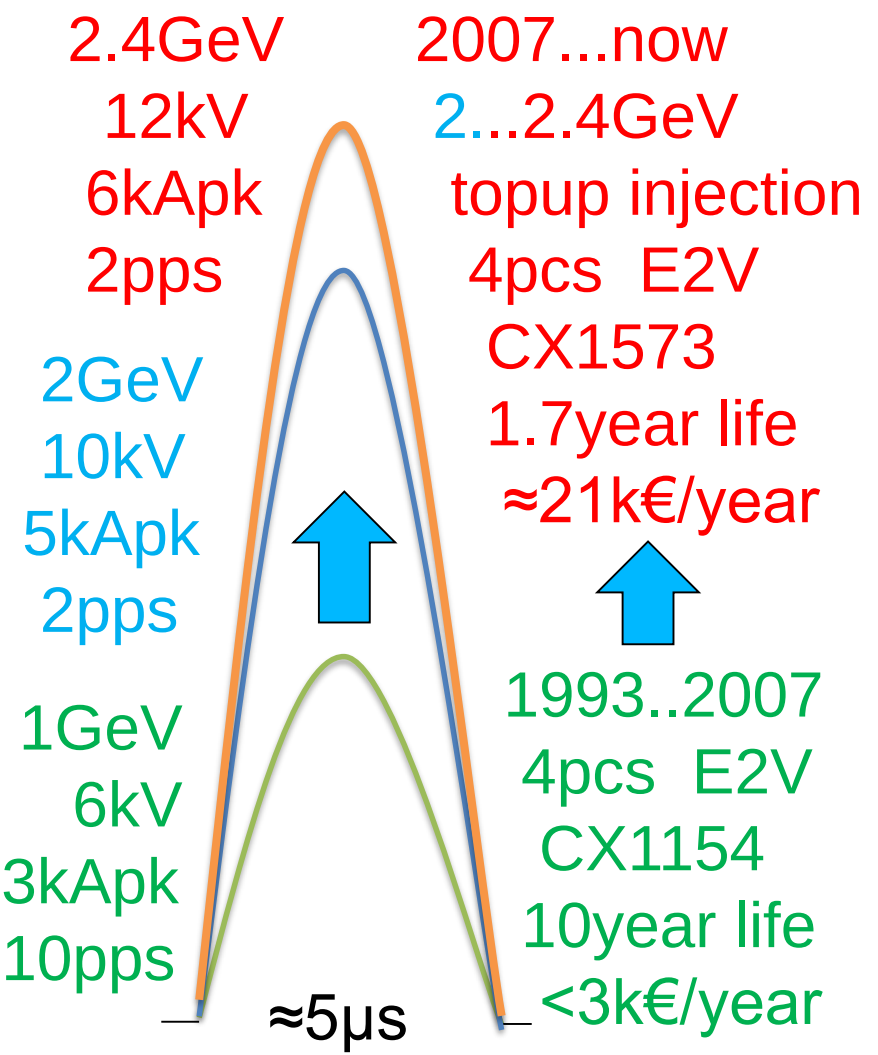
Size, ...pardon..., Ratings Do Matter



Storage Ring Kickers Thyratron story, lifetimes and annual costs

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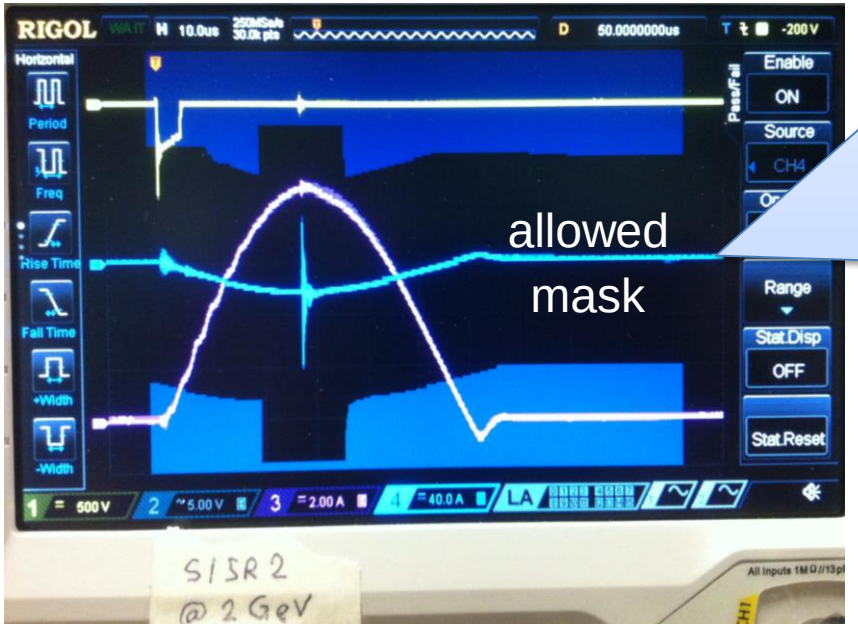
Injection Diagnostics and Fault Recovery

- ✓ It is unpractical to stop present Pulse: Injection Diagnostics can only decide either to proceed towards next pulse or promptly stop.
- ✓ If faulty pulses are promptly stopped, the relevant failure may be faced before worse (long-lasting...irreversible...) damages occur.
- ✓ Injection Equipment design emphasize testability for diagnostics and modularity for fast recovery of Machine Operations.



*Example: SR Inj Septum 2 Coil Earth Current **Waveform Mask Interlock**. If its waveform (mid, blue one) exits allowed mask (black area between top and bottom blue filled areas), the oscilloscope stores it, warns or even stops Pulser Charge, so reducing further coil insulation damages.*

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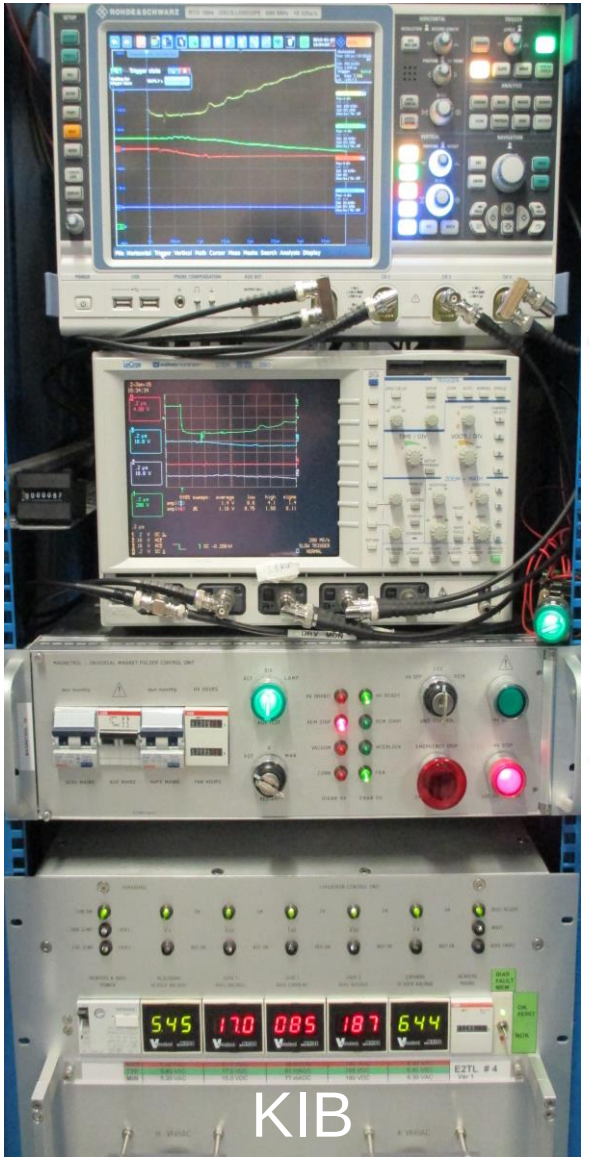
Injection Control Equipment



Provisional Oscilloscopes, monitor Pulse and surrounding waveforms. They can interlock Pulser trigger and/or its High Voltage Recharge to protect equipment, perform vacuum conditioning, search for circuit working limits...

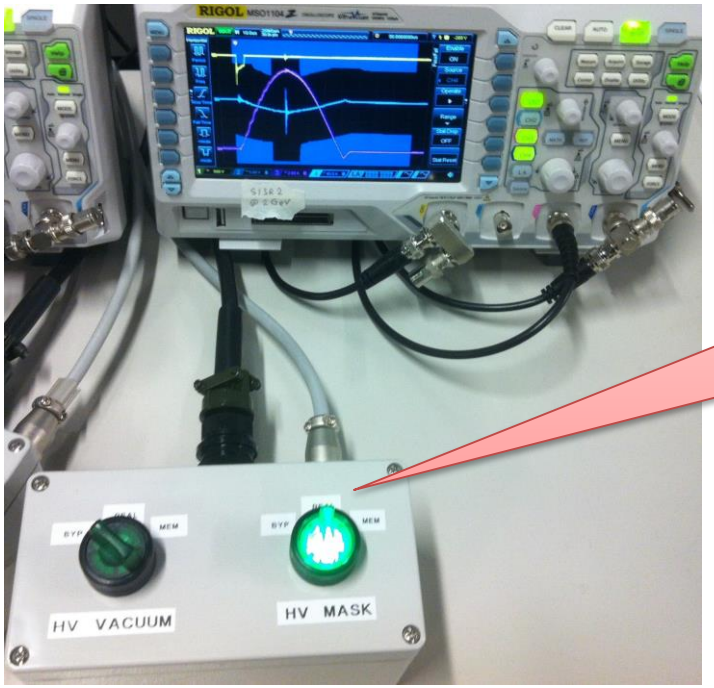
Injection Equipment is tendentially modular and standardized: a Magnetrol Unit, alone, may control either a Septum Solid State Pulser or...

...(passing cables through a Thyratrol Unit), may control a Thyratron based Kicker Pulser, adding relevant interlocks and functions to its basic ones: local/remote, HV recharge STOP/START, automatic or manual restart, vacuum interlock...

Adding further interlocks, controls...

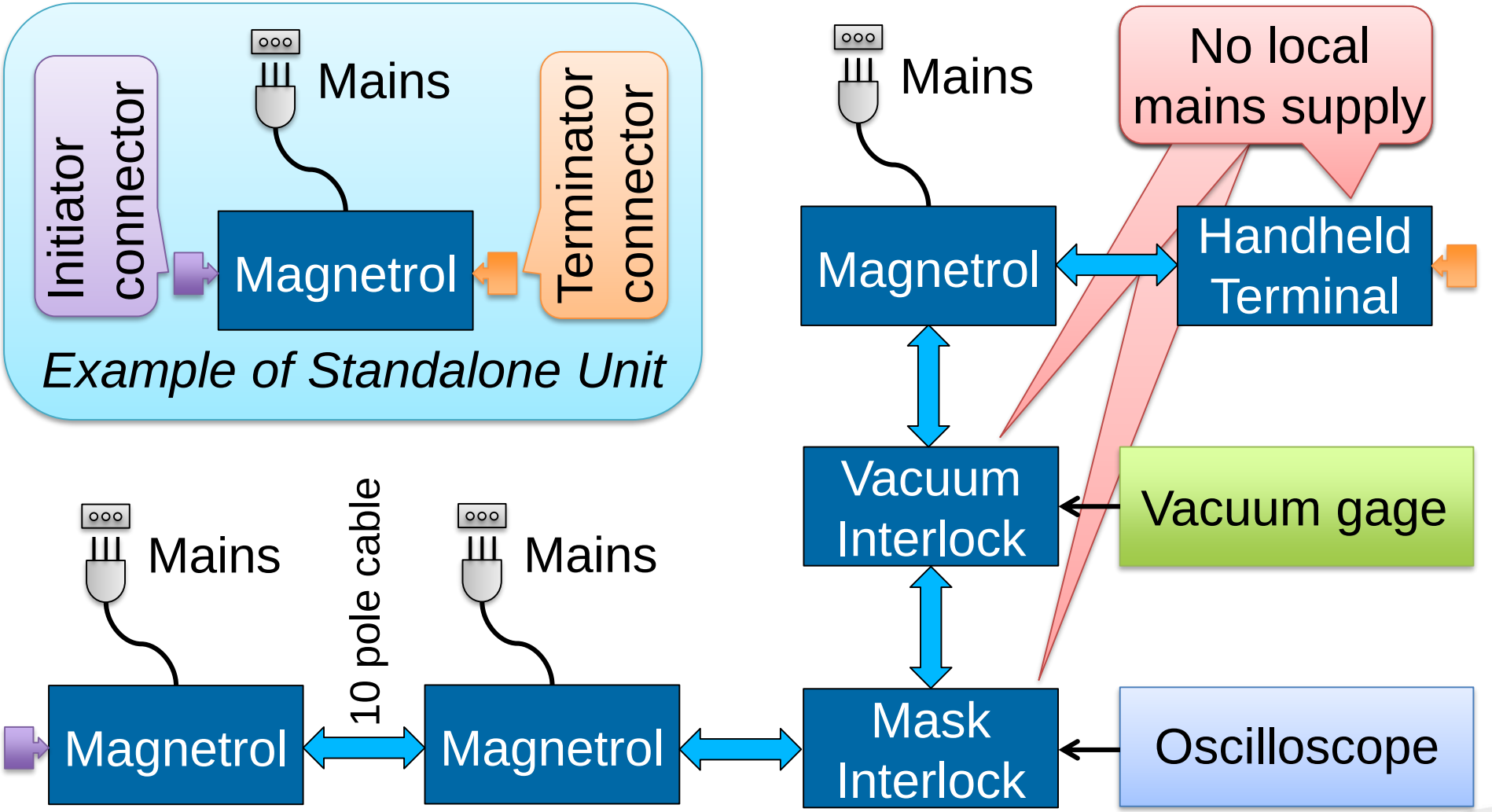
Magnetrol implements Interlock bus logic, which allows to insert, remove, link more units together... sometimes without turnoff.

Mask, vacuum, temperature... interlocks may be easily added/removed, which helps automation in testing equipment, vacuum conditioning, fault finding, routine testing...



Most interlocks have selectors that allow to change relevant effects: BYP= ignore; REAL = self re-enable; MEM = manual re-enable.

Interlock bus layout examples



Example of six Units sharing control via a common Interlock bus

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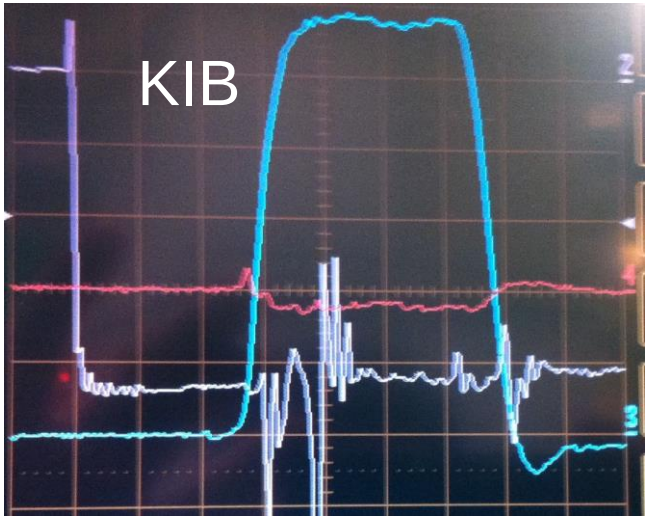
Injection Waveforms Diagnostics

Injection Waveforms may be acquired and observed:

- One plant per oscilloscope, from the requiring trigger to its effects
- Same kind of signal from different Pulser plants

Their time scale depends on the actual detail of interest:

- Nanosecond to tens nanoseconds: jitter, delays, fast pulse edges
- Microsecond to tens microseconds: coil & earth current pulses
- Hundreds microseconds to tens milliseconds: thyratron bias recovery
- Hundreds milliseconds to seconds: charge delay, pulse repetition rate



Injection Waveforms Acquisition History

- ✓ Injection Pulses cannot be controlled by human reaction times.
- ✓ Some fast actions may be done by automatic interlocks.
- ✓ A highly useful ability is to acquire, store and review **all Injection Pulses,** *specially bad ones,* with individual time stamps.

So the acquiring instrumentation (oscilloscopes) should have…

1. **Minimum acquisition blind times** due to selfcalibrations, software updates, data transfers... *This helps the credibility of Injection monitoring, particularly when Injection is suspected for an undefined cause beam dump.*
2. **Tightest time stamp accuracy and synchronization,** *possibly down to submillisecond resolution for realistic time stamps.*
3. **Sufficient number of channels, bandwidth, sample rate, memory depth...** *This allows to picture the surrounding situation for every (bad) pulse, helping to detect possible causes.*

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Elettra Injection: Work in Progress

✓ Main goals:

- Minimization of residual Kicker Beam Dumps
- Lifetime extension of Storage Ring Kickers Thyratrons
- Reduction of Earth Fault Coil Current in Septa Pulsers
- Development / Evaluation of Kicker Solid State Pulsers

✓ Main activities:

- Hunting progress to discover Kicker Beam Dump smoking gun
- Improvements in measurements of Thyratron parameters
- Development of a Storage Ring Kicker Common Supervisor
- Extended lab tests of Septa and Kicker Pulsers for Elettra 2
- Extended Beam-environment tests of dummy Pulser prototypes

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Elettra Injection experience summary

✓ Septa Solid State Pulsers & Kicker Thyratron Pulsers

- After last Westcode Thyristor type refining (2007), Septa Pulsers troublelessly run with minimal preventive maintenance (fans,...).
- SR Kicker Thyratrons, even after migration to CX1573, suffer a limited lifetime (<2 years) while working at 2...2.4GeV topup.
- Same Thyratrons in Booster work more relaxed (>5 years lifetime)

✓ Control Units & Instrumentation

- Robust 48VAC electromechanical logic works fine and undisturbed for basic functions and Interlocks. Ferroresonant mains stabilizers minimizes effects of minor mains voltage variations.
- Migration to fiber optics (out from radiation environment) greatly improved triggers and other fast signals integrity.

Devil is in the details: where applicable, DIY approach pays.

Elettra 2.0: Technical challenges

- ✓ Existing building → “Boundary” constraints
- ✓ Existing photon beamlines → Don’t move

} Keep SR circumference

- ✓ Keep the existing electron injector (Booster) → Keep electrons energy
- ✓ Increase the electron beam intensity (500 mA vs. 313 mA)
- ✓ Reduce the vertical size of vacuum chamber (17 mm vs. 40 mm)
- ✓ High stability & fast feedback and correction of the electron orbit

Elettra 2 SR Injection Pulsers electrical considerations

- ✓ Kickers work more relaxed (less bump, 2GeV only beam energy)
- ✓ Septa work close or slightly above present max ratings (9..10kApk)

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Thank you. Any question?

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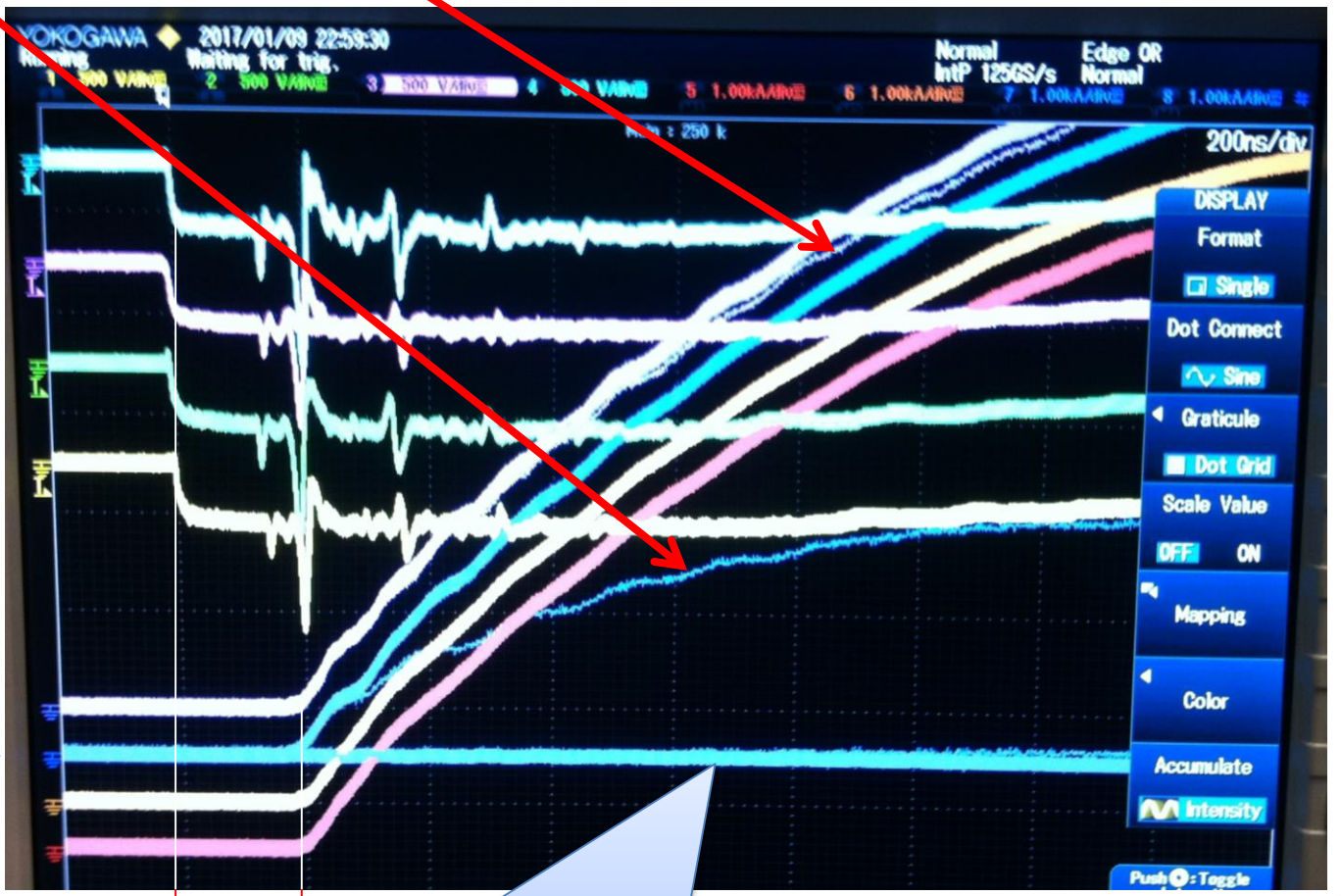
8 channel Oscilloscope KISR waveforms

At least one KISR3 and one KISR4 Pulses had insufficient amplitude

KISR4 trigger →
KISR3 trigger →
KISR2 trigger →
KISR1 trigger →

Display mode: infinite persistence

KISR4 current →
KISR3 current →
KISR2 current →
KISR1 current →



All currents started after delay
➡ No self turn-on Pulses

Some KISR3 Pulses had nearly zero amplitude (little recharge or missing)

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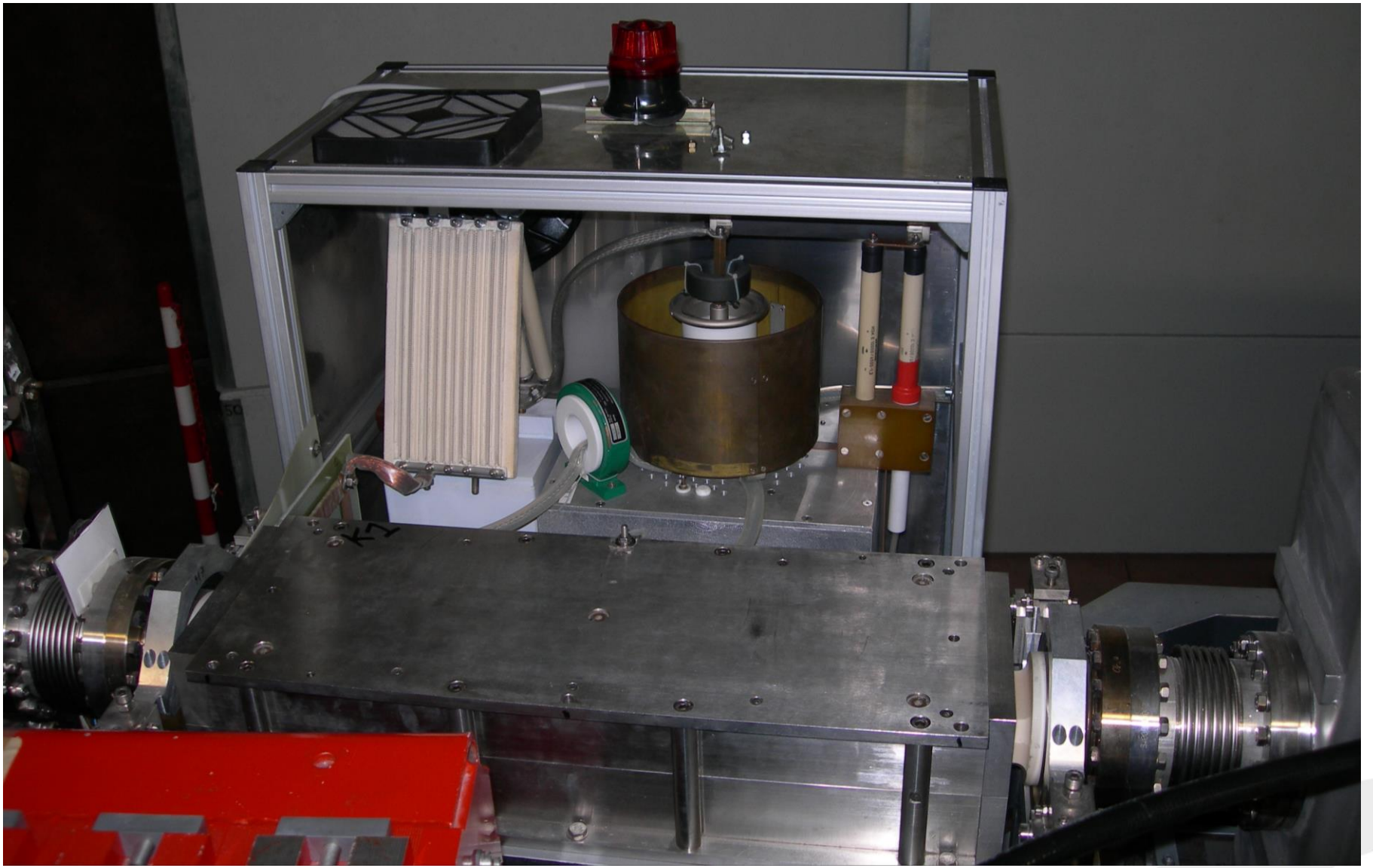
KISR1 Pulser (cover is removed)



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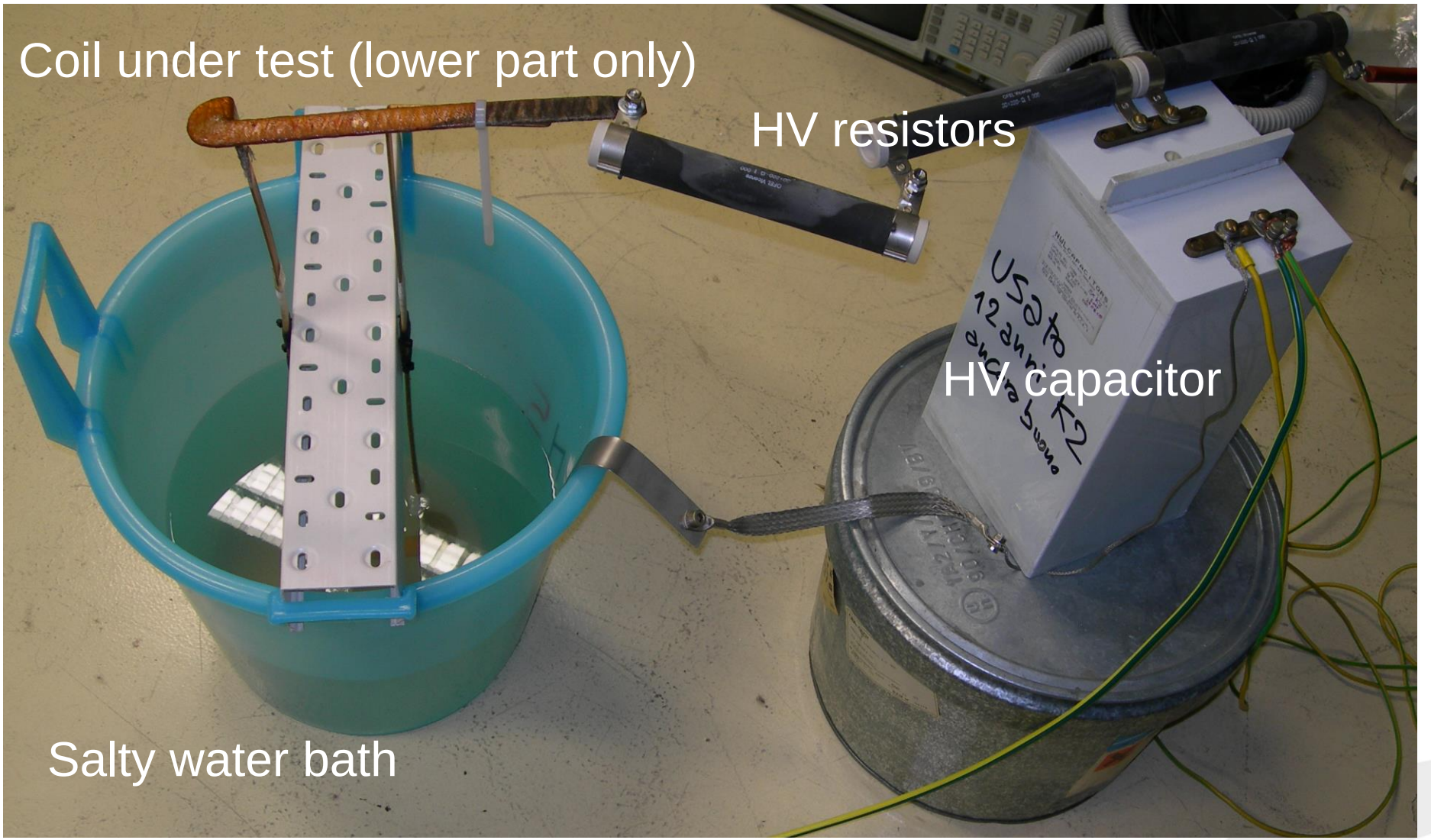
Artisan KISR coil HV insulation test set



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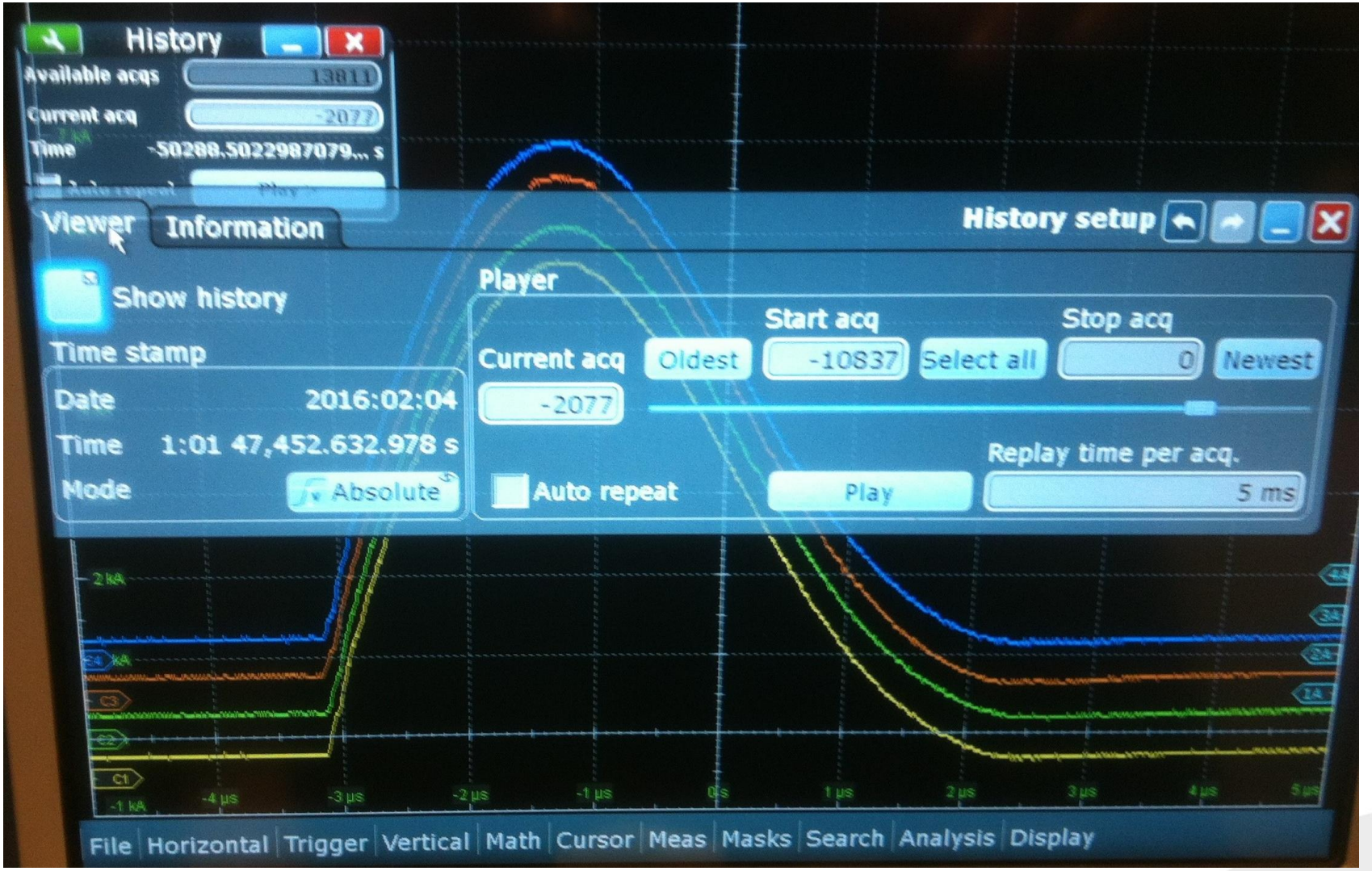
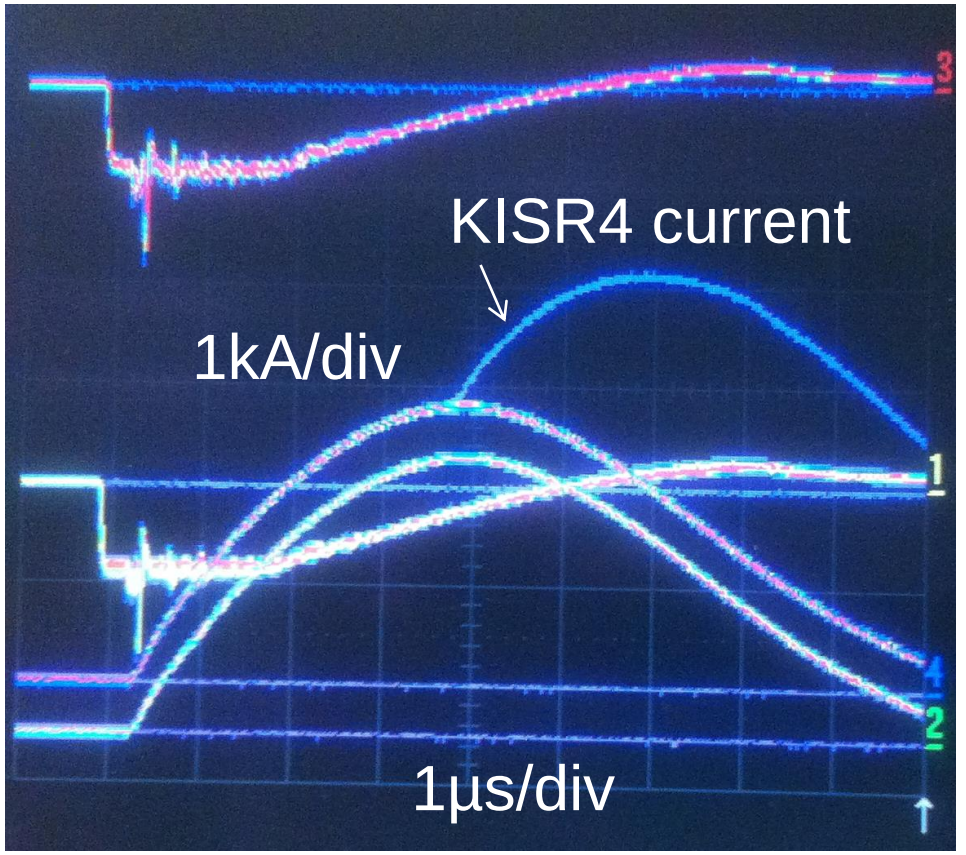
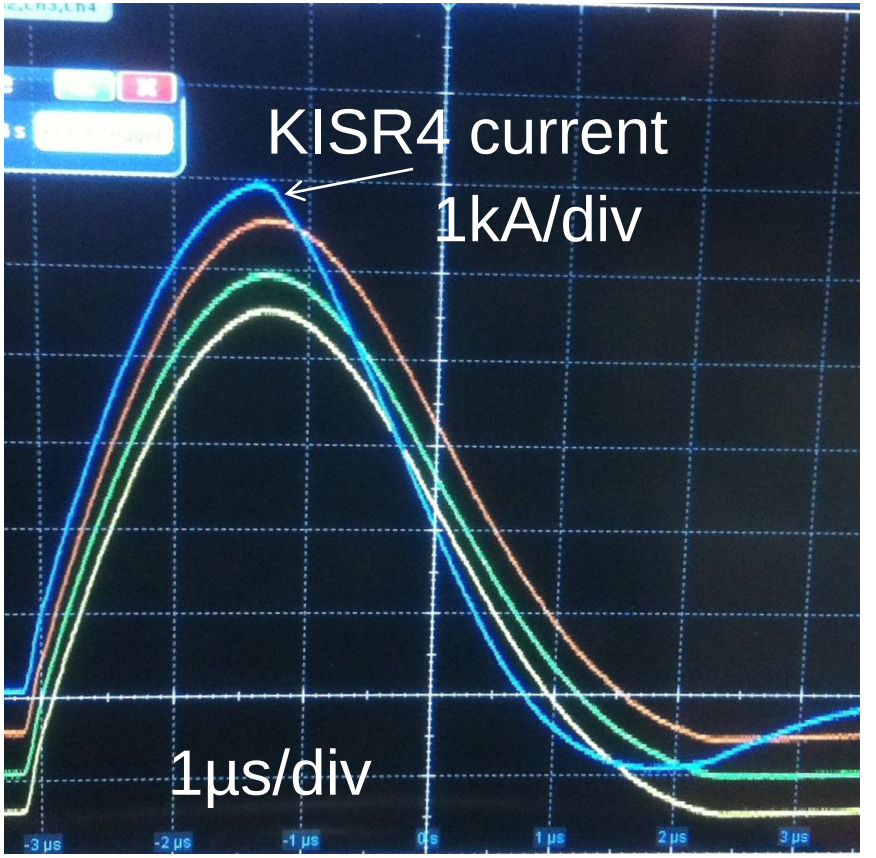
KISR Waveforms History



Signal Integrity Issues may fool Analysis





Uncorrect terminations on remote (≈ 150m coaxial cable) oscilloscopes may suggest unreal faults on working Pulsers

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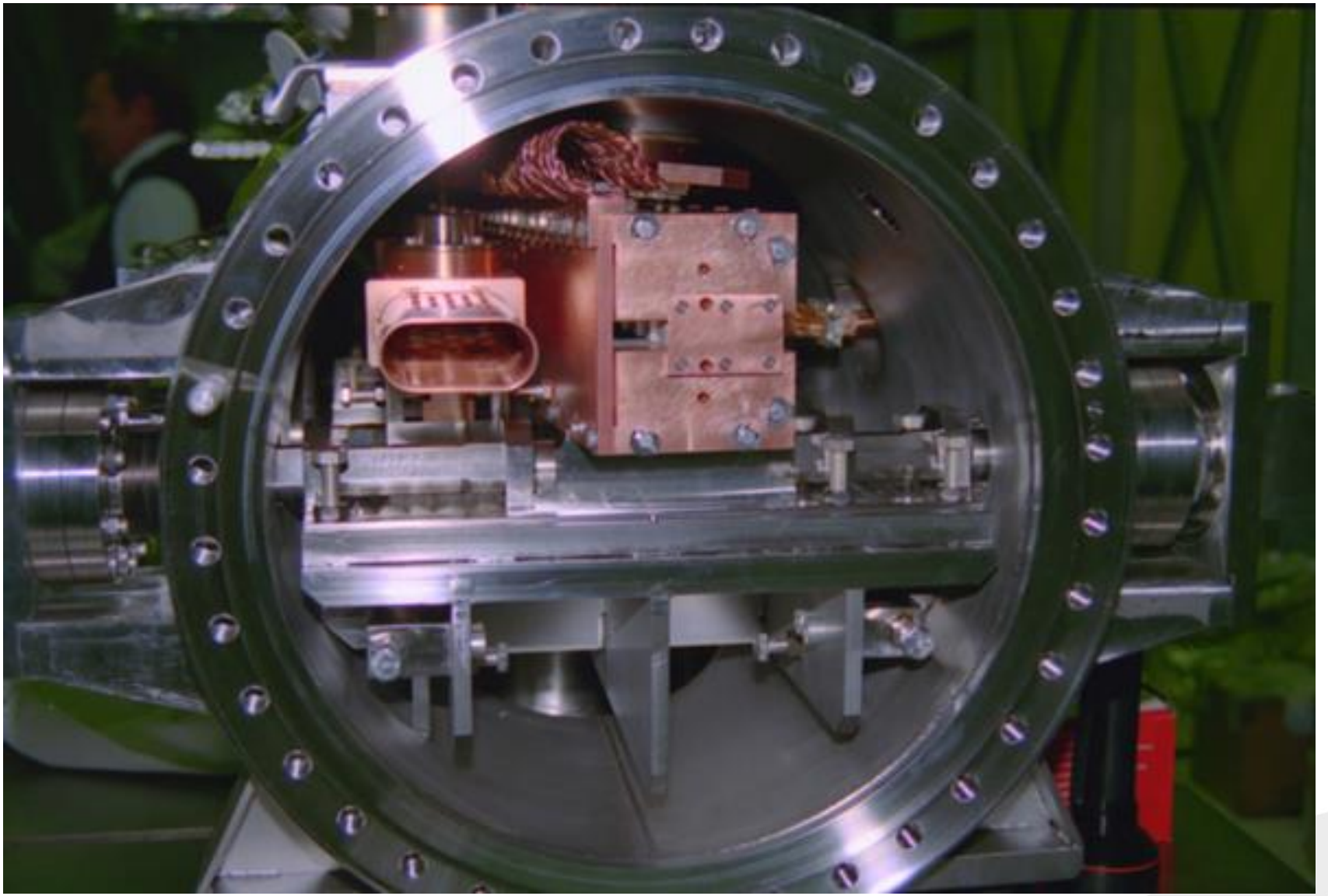
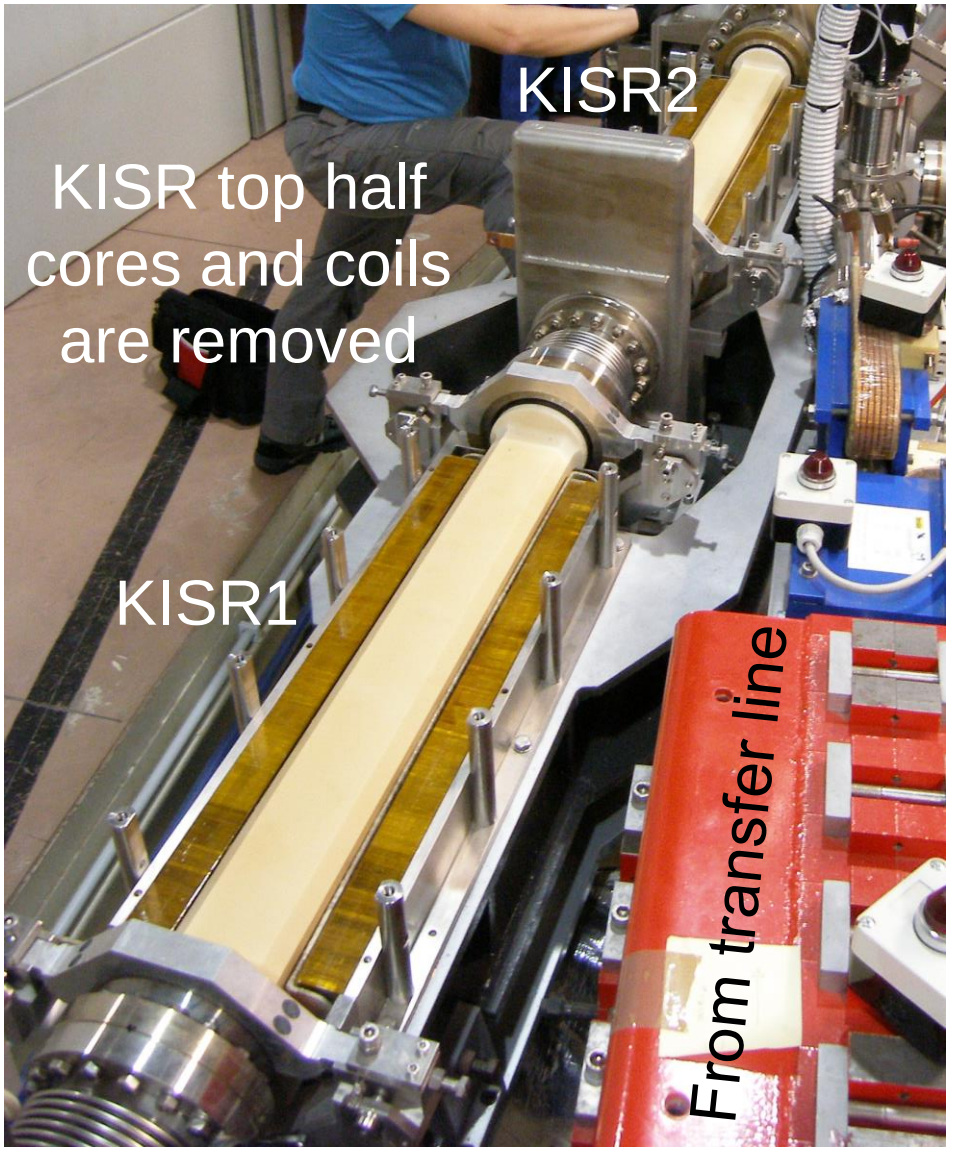
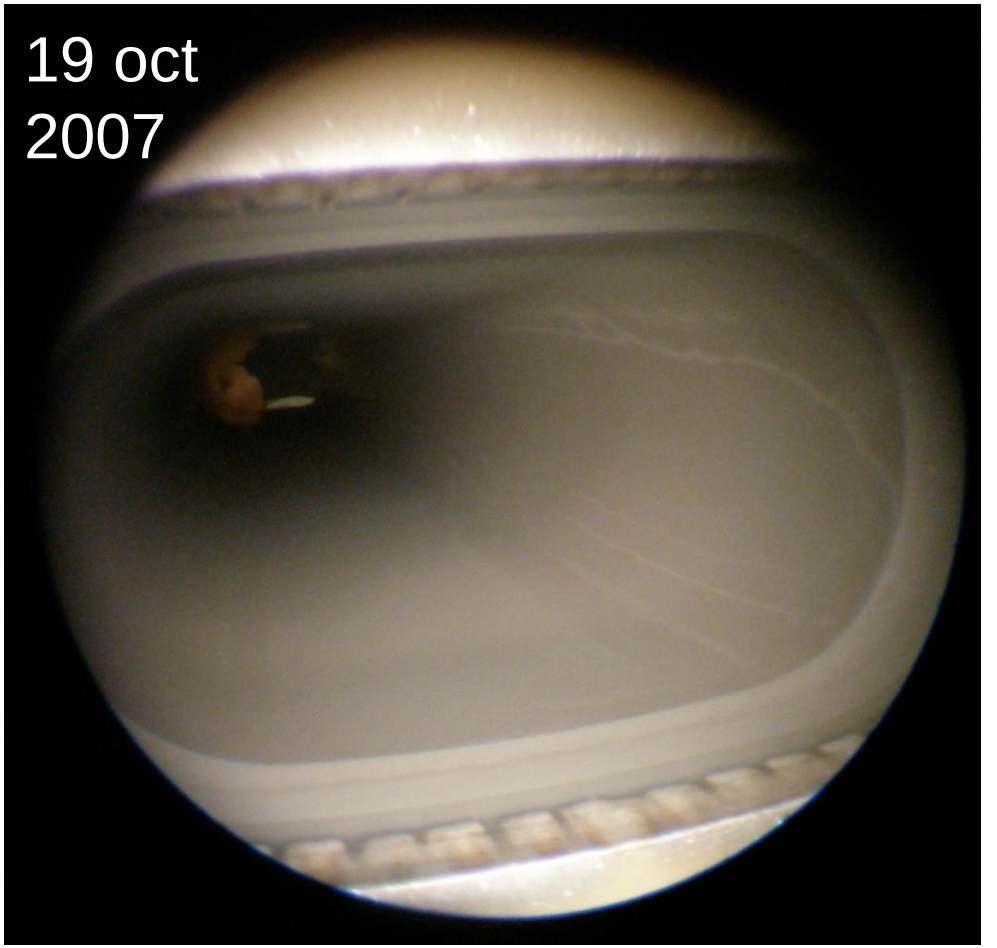
Storage Ring Septa Vacuum Tank (open)



Storage Ring Kickers Ceramic Chambers





3 µm thick Titanium sputtering: endoscope did not evidence any serious wear after 14 years use