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IMPROVING THE RELIABILITY OF THE PSI PROTON ACCELERATOR RF SYSTEMS

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- Introduction: The PSI 590 MeV proton accelerators
- Beam trips, caused by RF- cavity voltage trips; and unscheduled interruptions (component failures).
- Sparks in cavities: characteristics
- Measures to reduce the effects of RF- sparks
- Conclusion, outlook

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FACT:

RF systems and components are responsible for roughly 1/3 of the total down time of the PSI accelerators.

Measures are taken to improve **two distinct areas** of the performance:

increase the ⇒ *Mean **T**ime **B**etween **F**ailures:* ***rf voltage breakdown: → beam trips***

reduce the ⇒ *Mean **T**ime to **R**epair:* ***The number and duration of (unscheduled) machine down times for repairs***

WHAT ARE THE MEANS FOR IMPROVEMENTS?

Reduce Component Failures:

- ORGANISATIONAL & TECHNICAL IMPROVEMENTS:

  ⇒ ***fault diagnostics, comprehensive data- & rf- voltage transient event logging***

- TECHNICAL IMPROVEMENTS:

  ⇒ ***protection circuitry at all levels***

- DESIGN:

  ⇒ ***Employ modern quality control management techniques at all levels***

Reduce the Absolute Number of Beam trips:

- ***Condition RF cavities***, Try to avoid breaking vacuum with air (breaking RF windows)!
- ***DO NOT turn off beam*** during **self-recovering μ- sparks** in a cavity (≤ 200 μs).
- ***Use resonance tuning, pulsing and ramping procedures*** to re-establish full resonator voltage within 4…6 s; and full beam after 20 s.

Handling RF System Component Failures:

- ***To shorten down time after failure:***
  - ⇒ ***use fault diagnostics and event logging data***
  - ⇒ ***have ready-to-operate replacement units available*** *(spares)*
  - ⇒ ***design for fast interchangeability of units and components***
  - ⇒ ***Employ modular design at all levels***
- For (sub)systems with ***limited*** lifetime: (≤ 3yrs); like rf- power tubes:
  - ⇒ ***Perform preventive maintenance! (replace after a predetermined operation time)***
- Systems with ***'unlimited'*** lifetime (> 3yrs):

  e.g.: standard power supplies (PS), high voltage PS, air- & water-cooling systems, control systems, frequency tuning systems, RF power amplifiers, etc.:

  - ⇒ ***Periodic Inspections, Testing !***
  - ⇒ ***Analyse each component failure: improve design if needed !***

Reduce Spark Damage to Coupling Windows:

What happens?

After a number of sparks at a coupling window, the evaporated metal coating the insulator will lead to increased losses on the ceramic window: → heat → cracking/breaking !

What can be done?

⇒ **reduce the amount of evaporated metal in each spark by actively detecting it, and shutting down the rf drive within μs.**

- Coupling windows ***redesigned***, with ***electron detection pick-ups*** and new ***protection circuitry.***

⇒ *Lifetime of couplers is now > 4 years!)*

(4 Couplers are operating at typically 600 – 650 kW RF power (CW))

CONCLUSIONS:

Different methods and strategies have to be employed for the different problem areas:

Sparking in cavities

Challenge: Reduce the number of µ- sparks and non-recovering sparks:

- Find causes for these events, look for possibility to prevent sparking completely !
- Investigate breakdown mechanisms in more detail.

Usual methods for cavity conditioning – except overvoltage operation and vapour-cleaning – are difficult to apply because of size of cavities: → find other ways for conditioning.

Kilpatrick- limit is not reached: in our case, $E_{max} \leq 3.0$ MV/m; even for the new 1 MV cavity, E_{max} will be only 3.3 MV/m.

Component failures

- Technical measures to reduce components failures even further require new levels of quality control during design and manufacturing of RF systems.

  This proves to be difficult, because many subsystems (parts, components) already employ mature technologies (i.e.: power amplifiers, high voltage and high power supplies, low level control systems, etc.)
- For existing machines, careful analysis of each failure can lead to a continuing elimination of weak components, unreliable or unsuitable materials or designs:→ this is a very time-consuming procedure and requires staff qualified not only to perform maintenance, but capable of carrying on continuous improvement and redesign programs (this strategy has been chosen at PSI over the past ≈ 15 years)
- Redundancy for some of the systems may reduce the overall failure rate somewhat.

Possible effects of µ-sparks on other components (secondary beam trips)

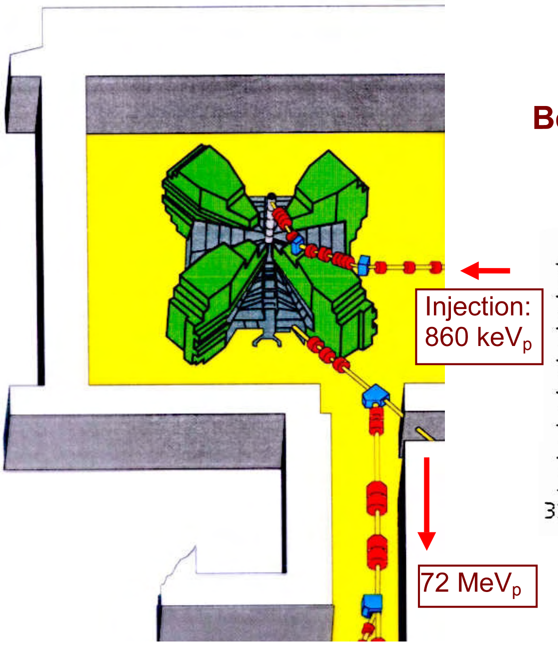
Sparks may be a problem at higher beam currents (extractor elements are 'swept' by beam during µ- sparks)

With the exact timing information of rf- events, possible correlations to HV- trips of electrostatic deflection devices can eventually be established. Such HV-discharges could be caused by the extracted beam, sweeping through (and hitting) the extraction elements during the 100-200 µs of a µ-spark (one cavity voltage missing).

LAYOUT OF THE PSI- ACCELERATORS & TURN PATTERNS AT EXTRACTION

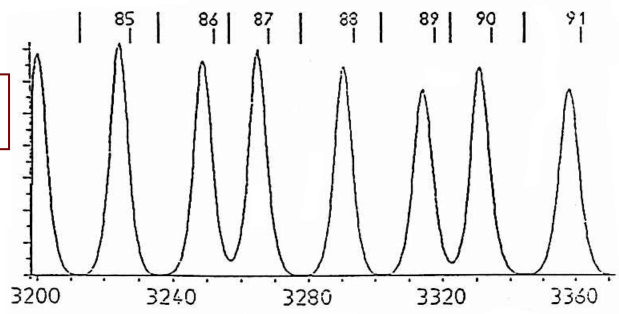
72 MeV Cyclotron (Injector II)

(Maximum beam current extracted: 2.1 mA)



Beam profiles of last 8 turns at 1.5 mA

Turn numbers

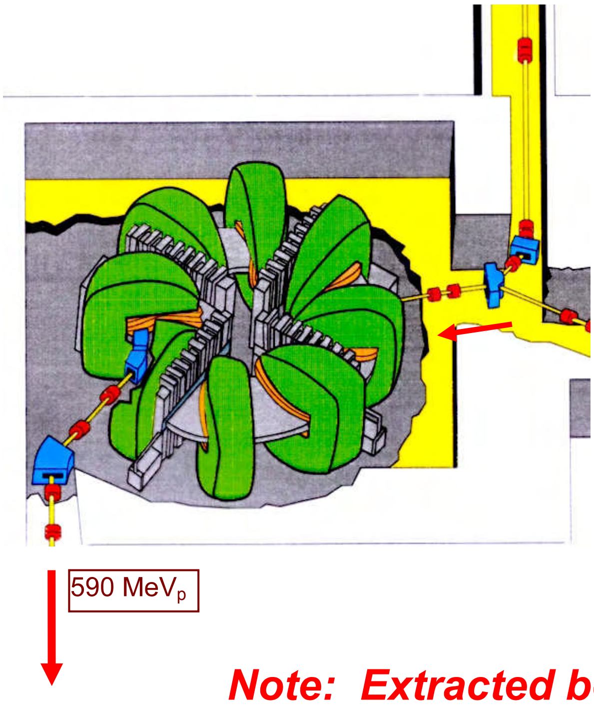


Radius in mm

Extractor location

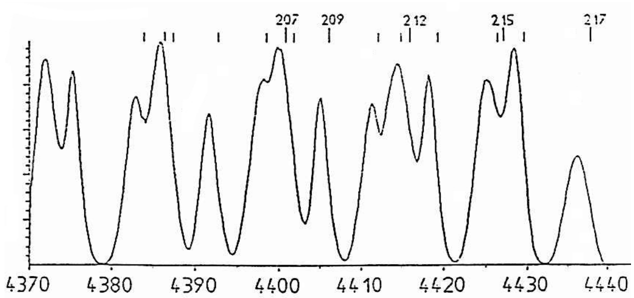
590 MeV Ring Cyclotron

(Maximum beam current extracted: 2.0 mA)



Turn pattern at extraction: the last 19 turns (at 1.5 mA)

Turn numbers



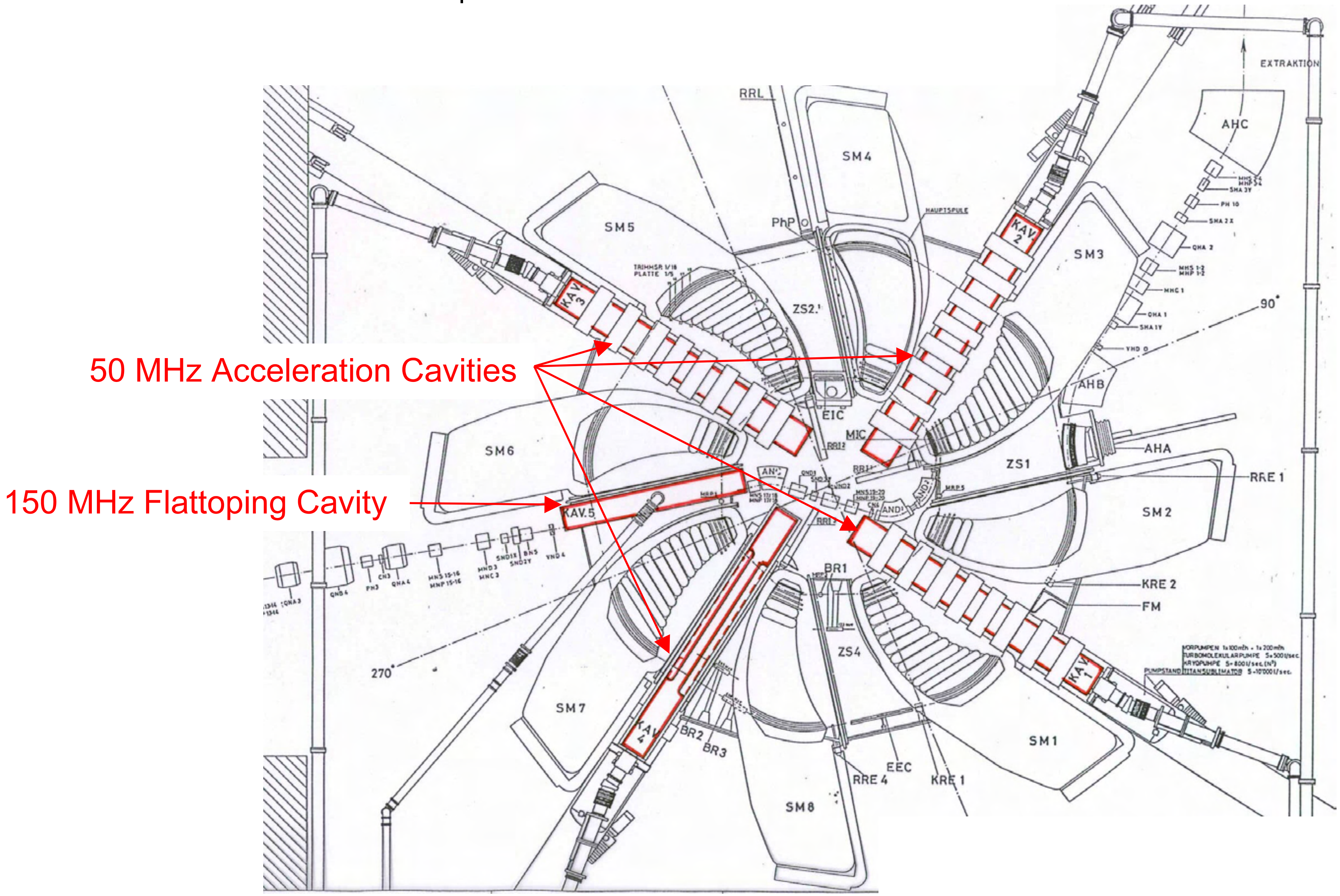
Radius in mm

Extractor location

Note: Extracted beam power: $P_{Beam} \geq$ 1MW !

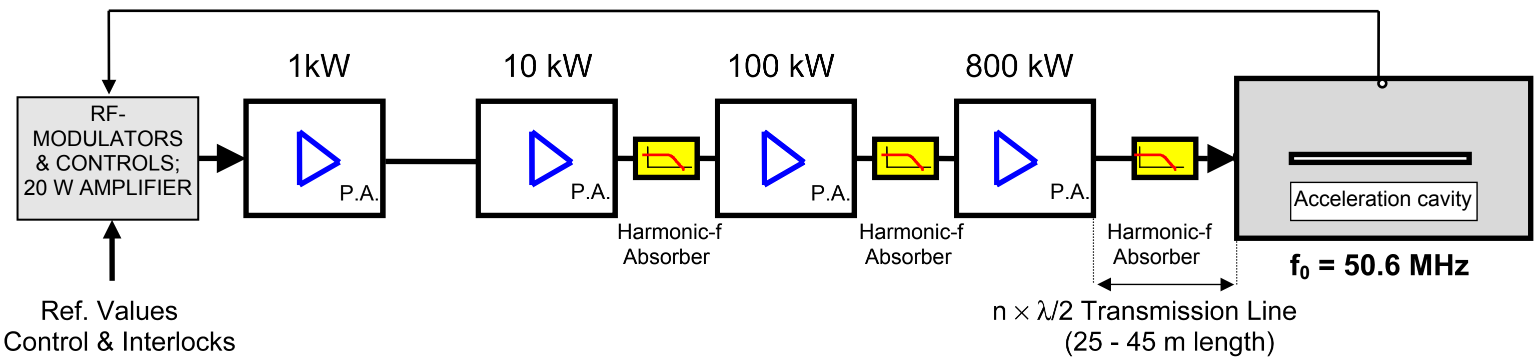
(1.18 MW @ 2mA)

PSI 590 MEV$_P$ RING CYCLOTRON LAYOUT



PSI RING CYCLOTRON RF- SYSTEMS

4- STAGE POWER AMPLIFIER CHAIN, EMPLOYING POWER TETRODE TUBES



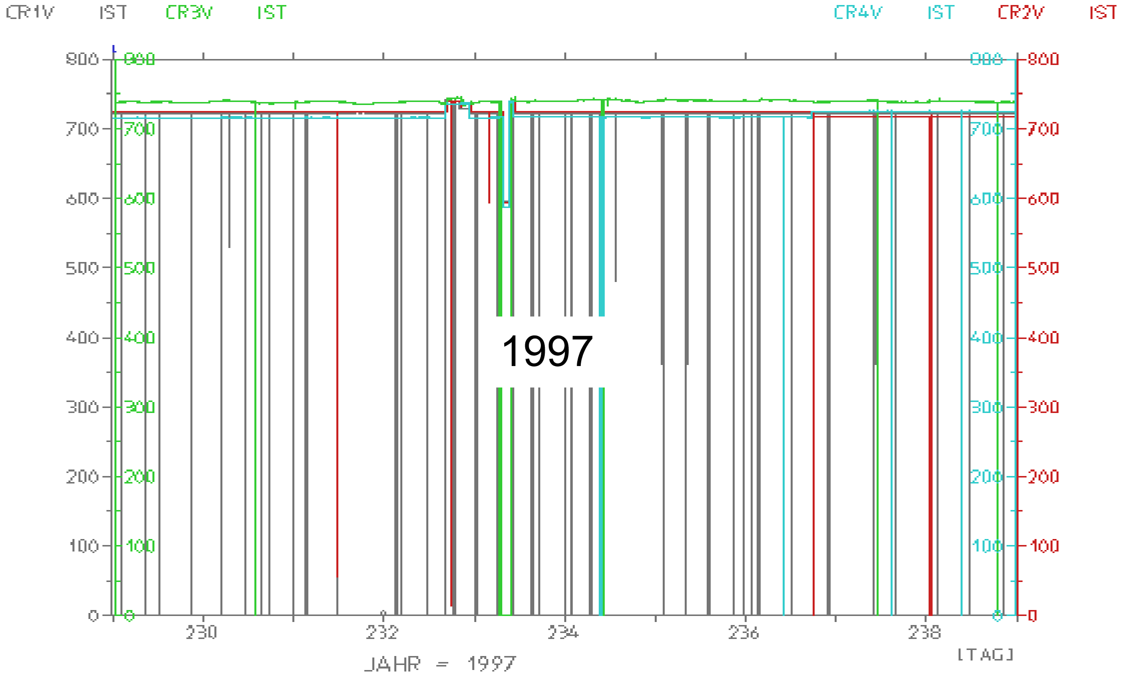
KEY AMPLIFIER DATA IS AS FOLLOWS:

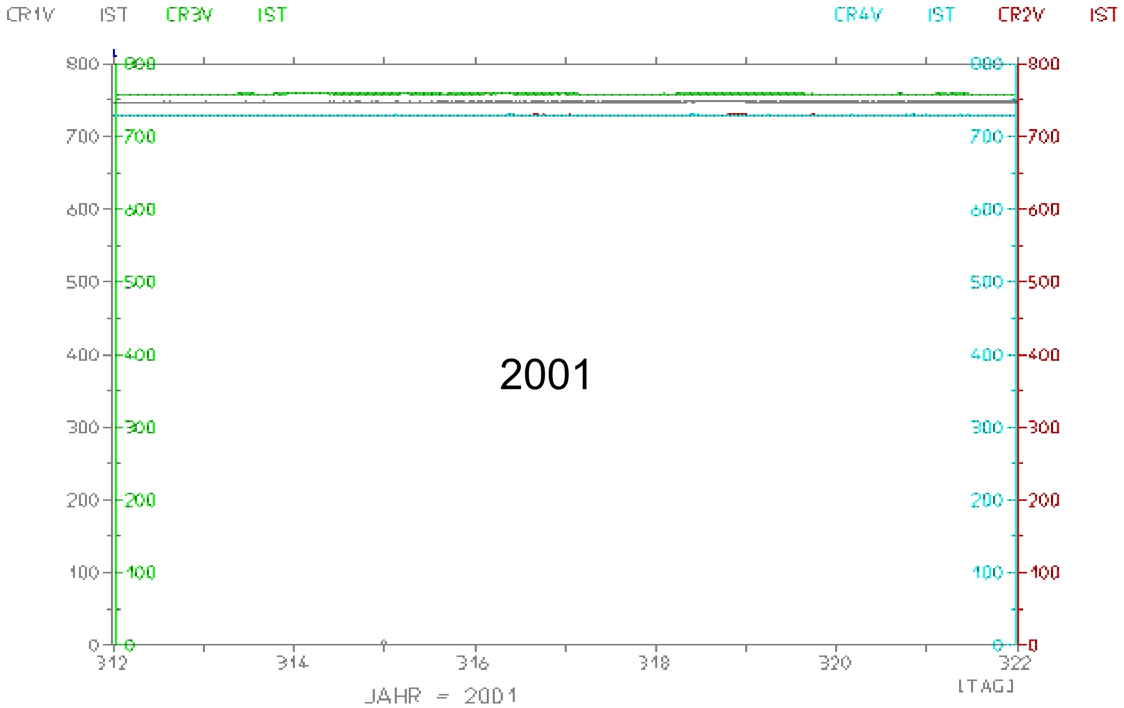
Tube Types:	**YL 1056**	**RS 2022 CL**	**RS 2074 HF**	**RS 2074 HF**
Cooling Method:	forced air	forced air	water	water
RF- POWER, (I_{BEAM} = 0):	0.15 kW	2.0 kW	10 kW	310 kW
RF- POWER, (I_{BEAM} = 1.8 mA):	**0.20 kW**	**4.4 kW**	**35 kW**	**610 kW**

Notes:
- All power tetrodes are transmitter tubes; of coaxial, metal-ceramic design, manufactured by '*Thales' (Siemens)*
- In case of tube failure, ***tubes*** are replaced in amplifiers with air-cooled tubes; but ***amplifiers*** are exchanged when one of the water-cooled tubes fails.
  Time required for *tube* change: ≈ 1 hr.; for *amplifier* change: ≈ 2 hrs.

590 MeV RING CYCLOTRON CAVITY VOLTAGES

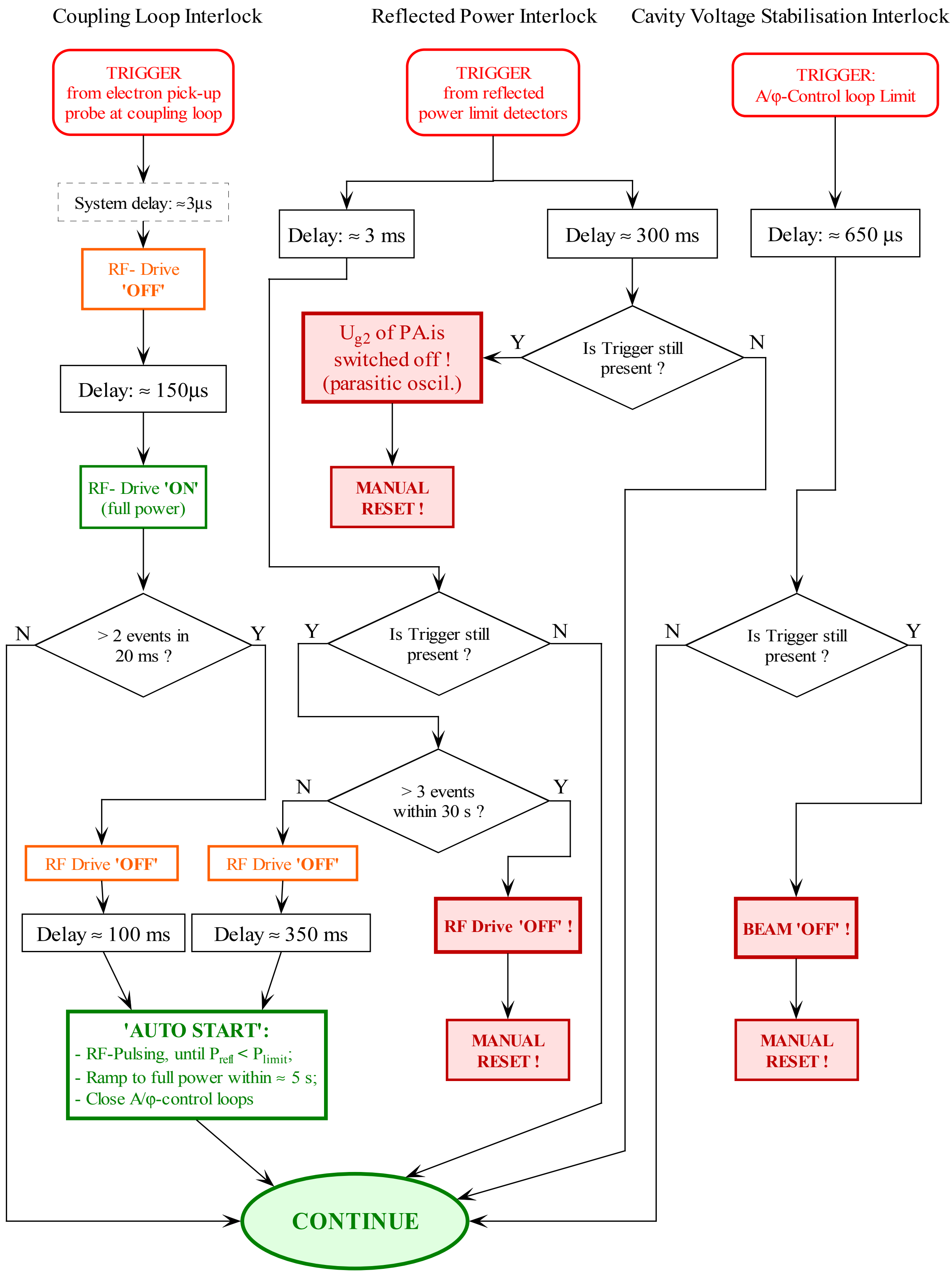
*Cavity voltages over a **10- day period**, in 1997 at **1.5 mA** beam current (before new rf-spark control system came into operation), and in Nov. 2001, at **1.8 mA** beam operation.*





***Note**: Only events (interruptions) of ≥ 1 min.duration are recorded! (in both diagrams)*

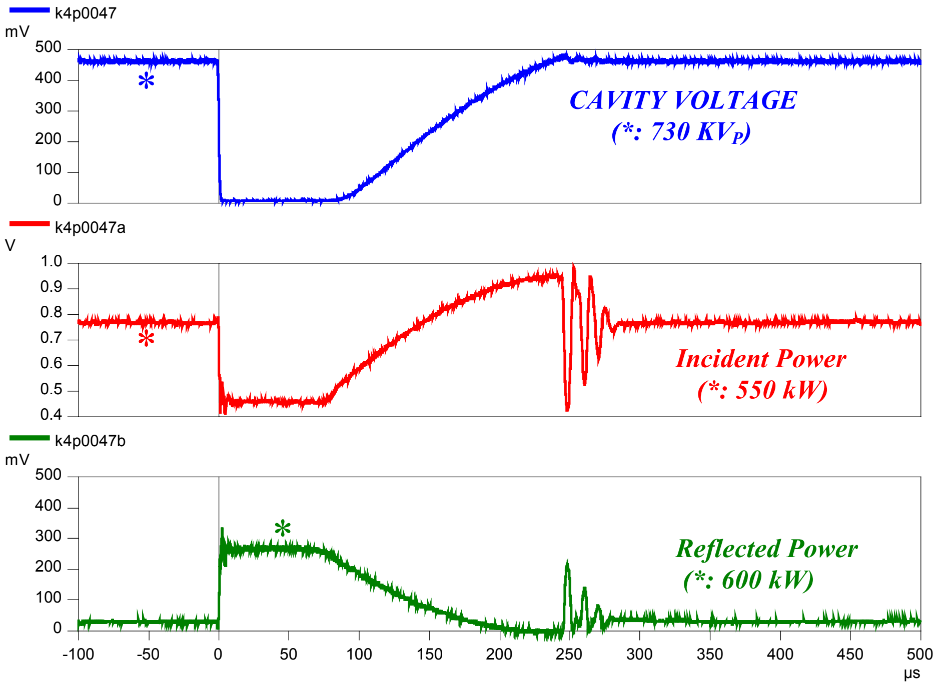
RF- CAVITY SPARK CONTROL PROCEDURES



SPARK RECOVERY IN A RING CYCLOTRON CAVITY

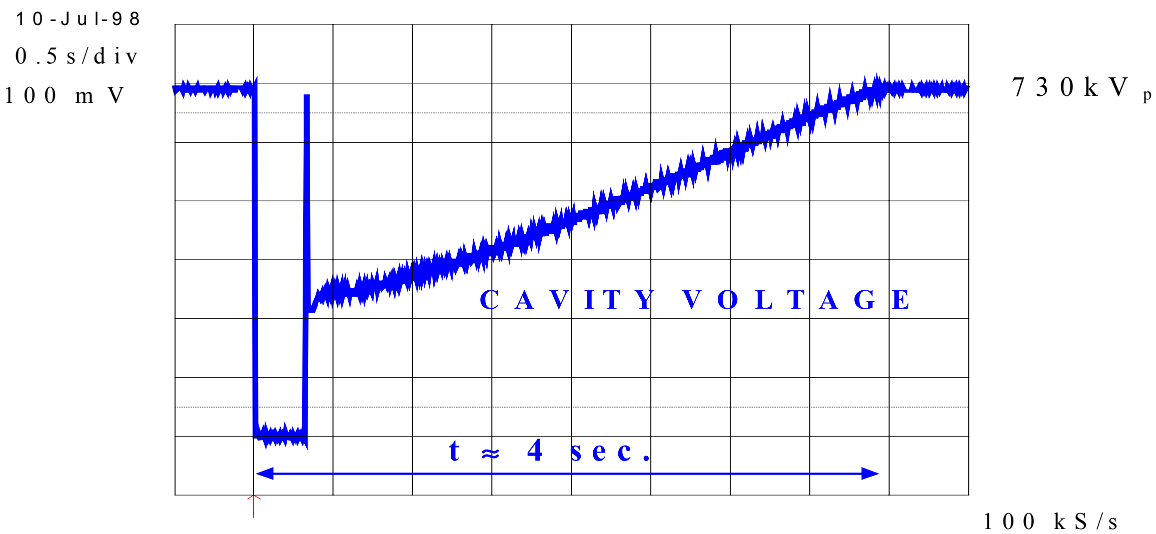
SELF-RECOVERING SPARK ("µ-spark") IN CAVITY

(RF power and beam stay on)



PULSING AND RAMPING PROCEDURE AFTER NON-RECOVERING SPARK IN CAVITY ('Auto-Start')

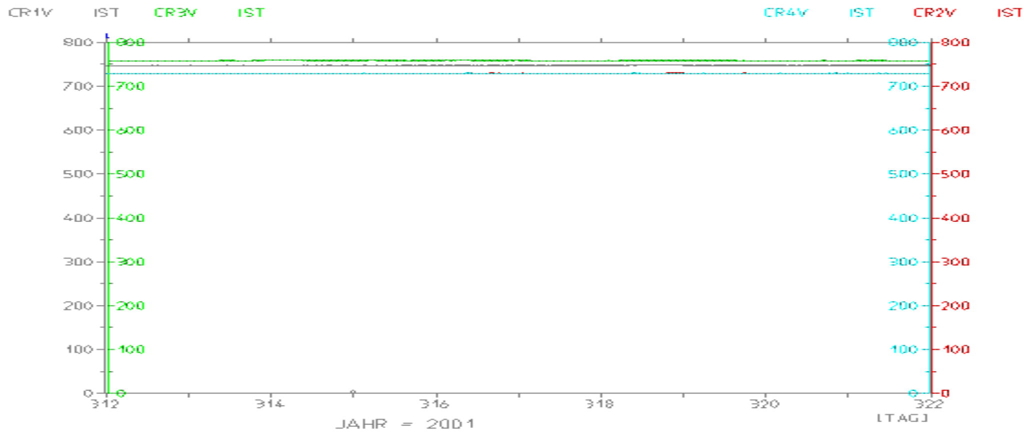
(Beam off after ≈ 1ms; RF turn-on after only one pulse)



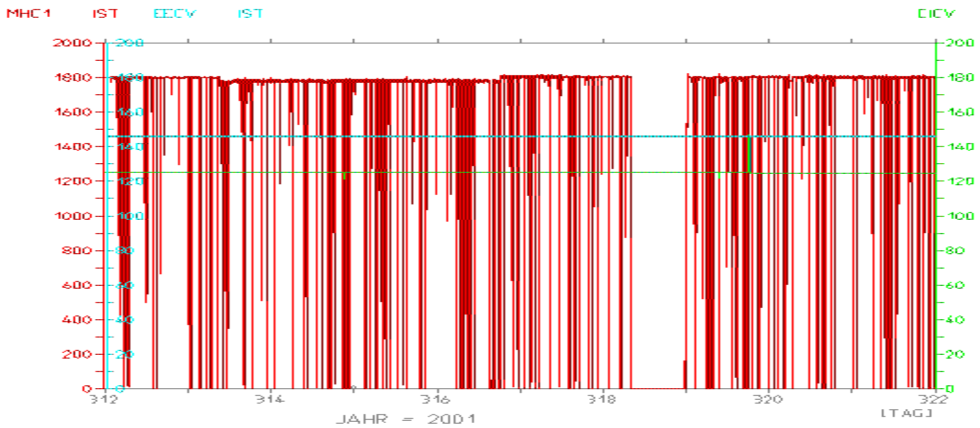
CAVITY VOLTAGE TRIPS OVER A 10 DAY- PERIOD

(590 MeV Ring cyclotron, Nov. 8 – 18, 2001)

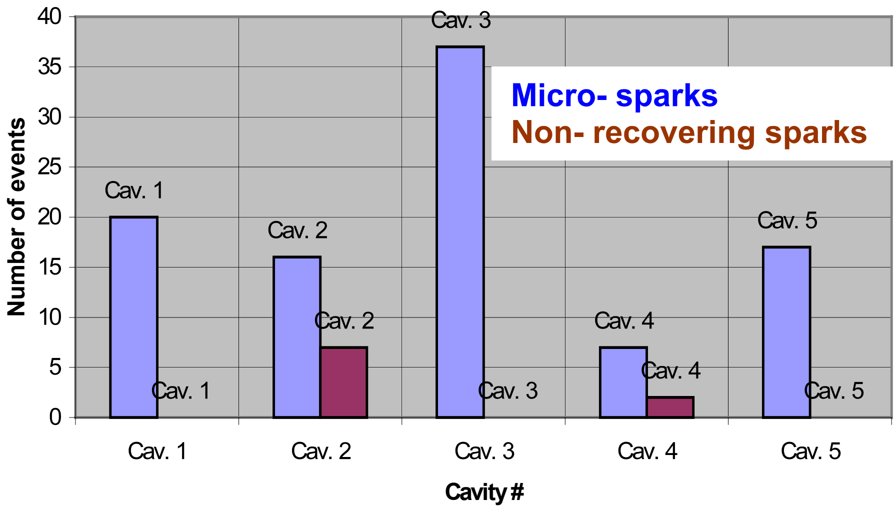
Voltages of acceleration cavities # 1- 4 *(sampling rate ≈ 1min.)*



Extracted beam current, injector- & extractor voltages *(sampling rate ≈ 1min.)*

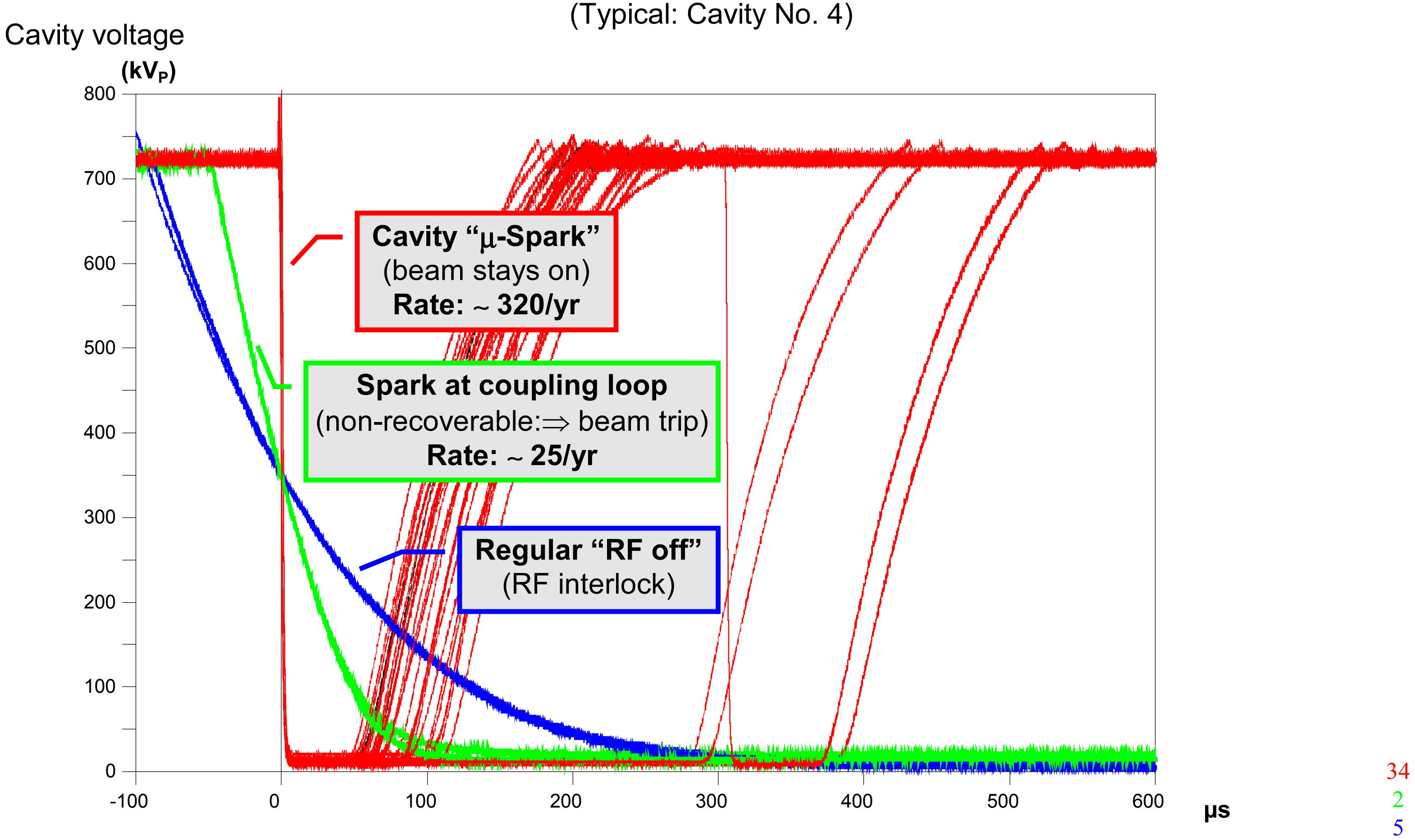


Cavity voltage trips, all events ≤ 1 min *("µ-sparks", non-recovering sparks, etc.)*



PSI-RING CYCLOTRON CAVITY, SPARK- & TURN-OFF EVENTS

(Typical: Cavity No. 4)



50 MHz RING CYCLOTRON CAVITY: RF- POWER COUPLER (WINDOW)