Radiation Monitoring at HERA

CERN LHC radiation monitoring workshop
April 6th, 2004

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(Columbia University)

ZEUS

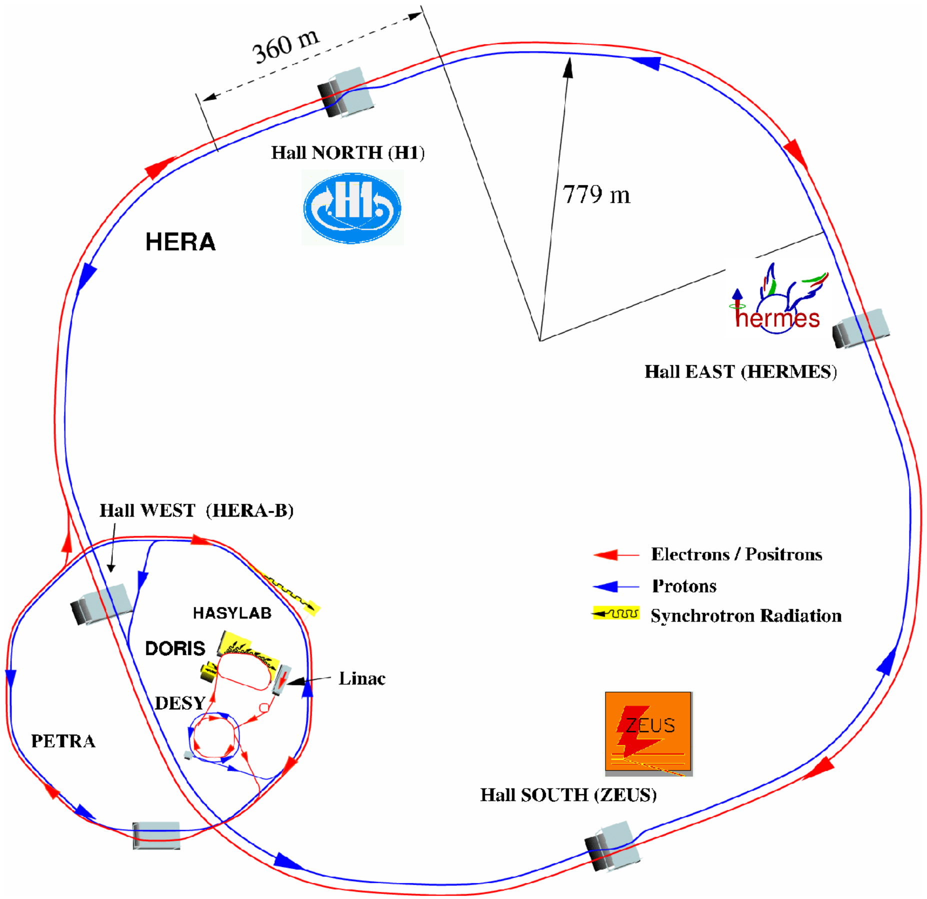
- Radiation background at HERA
- Radiation monitoring at
  - ZEUS (main focus)
  - H1
  - HERMES
  - HERA / DESY
- Summary/Conclusions

HERA accelerator

$e^+(e^-)$ → ← p

27.5 GeV   920 GeV

$\sqrt{s}$=318 GeV



HERA parameters (post upgrade)

- 6.3 km circumference
- 174 colliding bunches
- 96 ns between bunch crossings
- 21 μs cycle
- 1.5 μs consecutive empty bunches
- I_e=58 mA, I_p=140 mA (design values)
- L_{inst}=7.5 x 10^{31} cm^{-2} s^{-1} (design value)

Controlled beam aborts

- p beam: within ~ 20 μs, triggered by HERA
- $e^{+/-}$ beam: within ~500 μs, triggered by HERA and experiments

HERA Upgrade 2000/2001

- 5x increase of instantaneous luminosity, achieved by:
  - Redesign of beamlines, installation of superconducting magnets inside H1 + ZEUS
  - Increase of currents
- Longitudinally polarised lepton beam for H1+ZEUS
- New detector components in the experiments

➔ Machine operation more challenging
➔ Detectors more vulnerable to radiation damage

Radiation background at HERA

Radiation sources at HERA

- Direct and backscattered synchroton radiation
  - mean critical energy $<E_{crit}> = 85$ keV
  - Scales ~linearly with $e^{\pm}$-beam current
- $e^{\pm}$/p-beamgas interactions
  - Scale ~quadratically with beam currents
  - Depend on vacuum conditions
- $e^{\pm}$/p beam-loss accidents
- Radiation from ep interactions negligible (unlike LHC!)

➔ ~50 Gy/year expected for inner detector components (average normal running 1994-2000)

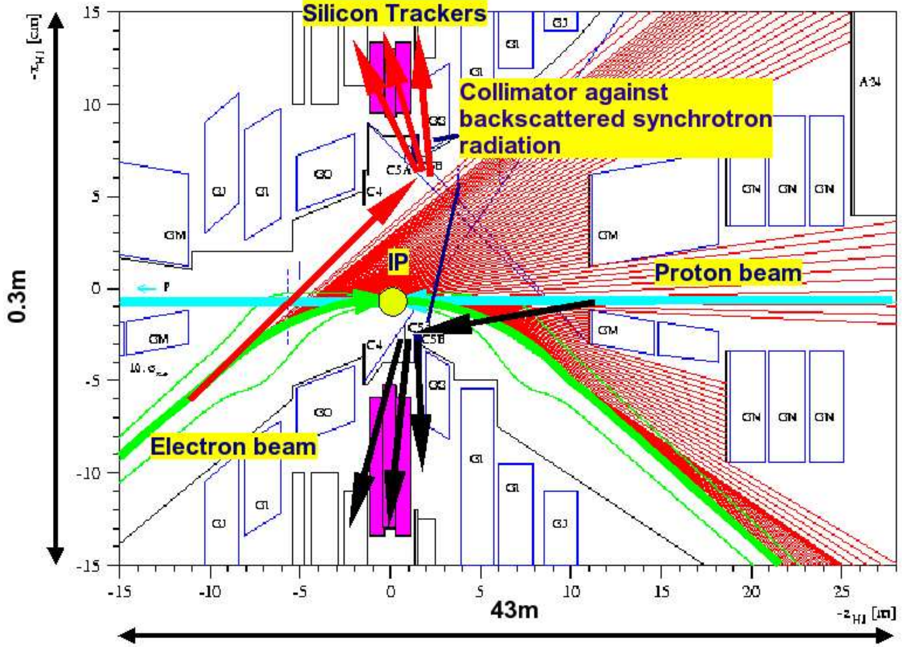
Radiation-background effects

- Reduces lifetime of detector components (wire chambers, Si detectors)
- Increases trigger rates

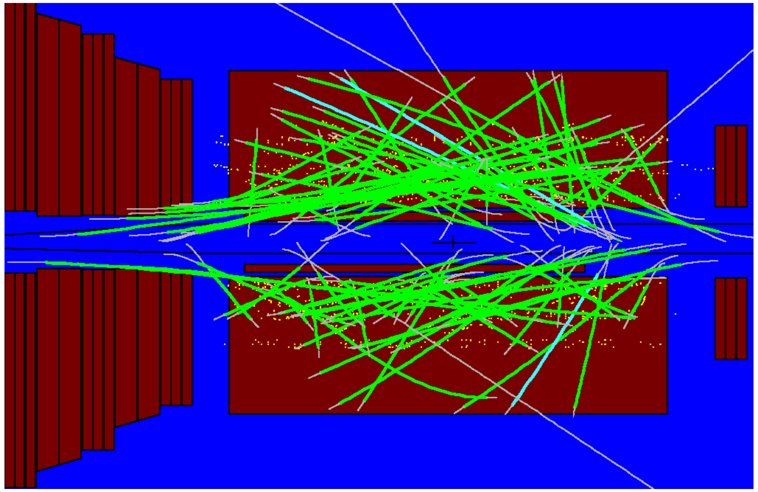
HERA-II commissioning

- 1st commissioning July 2001 - March 2003
  - Instable background conditions
  - High synchrotron and particle backgrounds observed in collider experiments
- Shutdown March 2003 - July 2003
  - Improved synchrotron-radiation shielding
  - Improved vacuum conditions
- 2nd commissioning since July 2003
  - Reduced background rates
- Luminosity operation since Oct. 2003
  - Delivered L_{int} ~28 pb^{-1} (until March 2004)
  - ~200 pb^{-1} per year expected until 2007

Beamline at H1

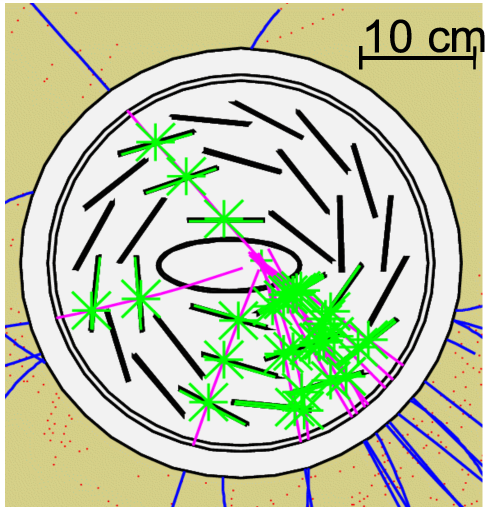


ZEUS beam-gas event



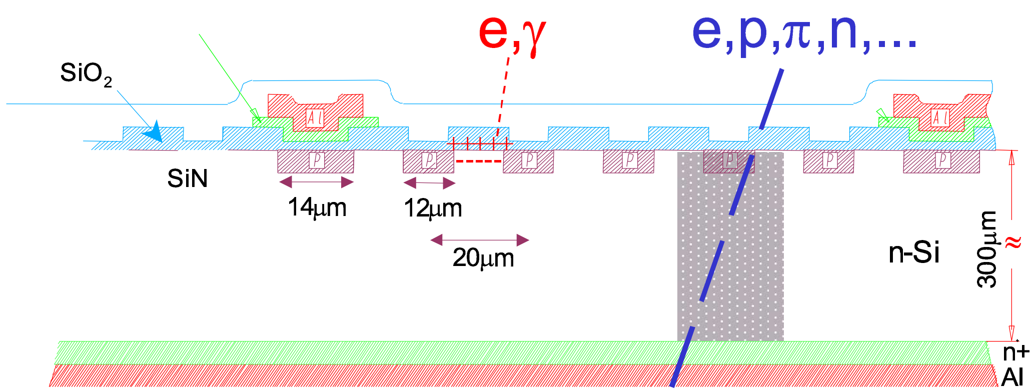
ZEUS Silicon Microvertex Detector

- New silicon microvertex detector (MVD)
  - 712 strip detectors with capacitive charge division, 20 μm strip pitch
  - Central- and forward-region
- Installed close to interaction point (~4 cm distance)
- Impact-parameter resolution ≈ 100 μm (at θ=90°)



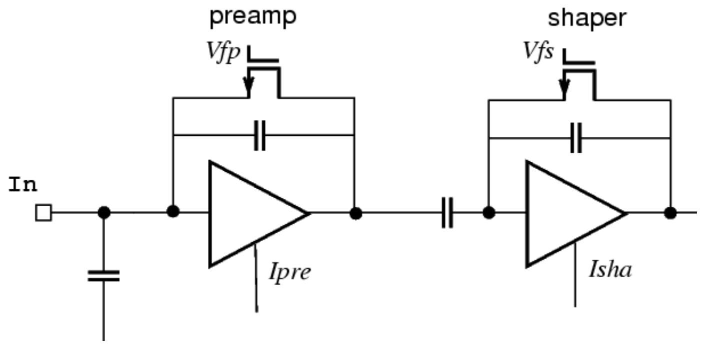
Radiation damage for MVD

- Ionising radiation
  - Surface damage
  - ➔ influences detector performance
  - Max. tested: 3 kGy
    - Surface damage observed (electrical meas.)
    - no change in performance (testbeam)
- Hadronic radiation
  - Bulk damage
  - ➔ affects detector biasing
  - Tested up to $\phi_{max}=1\cdot10^{13}$ 1 MeV equiv. n / cm^2

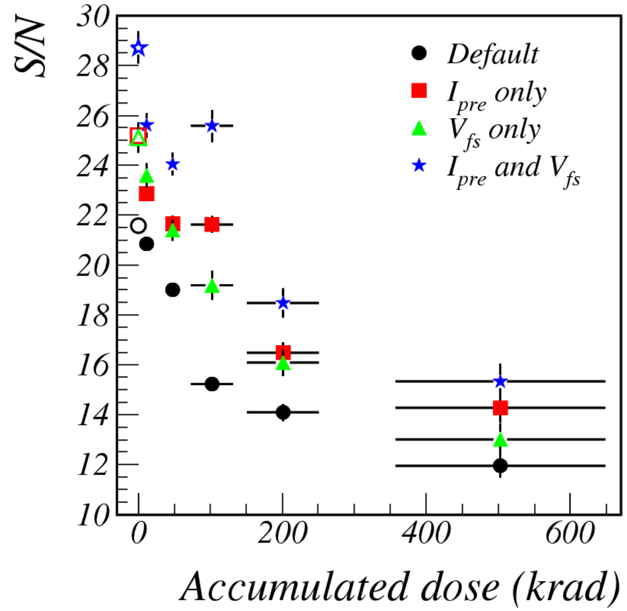


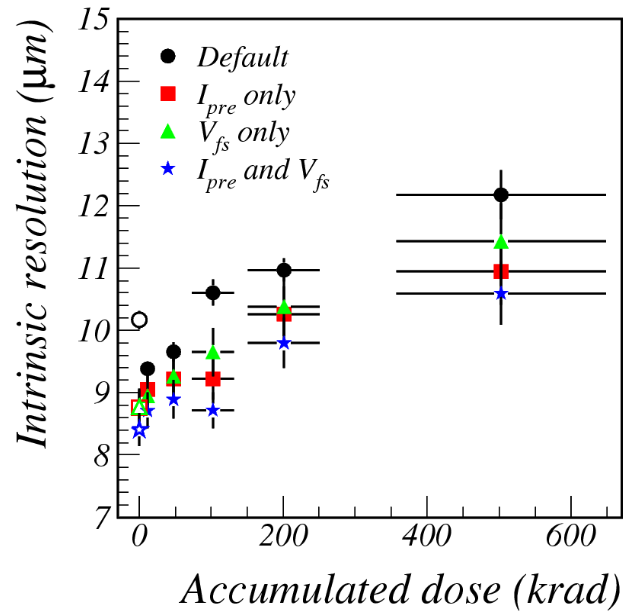
MVD readout electronics

- HELIX 128-v3.0 analog readout chips
  - AMS 0.8 μm, 16 nm gate oxide
  - mounted inside active volume
  - Sensitive to surface damage from ionising radiation
  - Radiation hardness tested with ^{60}Co photons up to 5 kGy
  - S/N decreases after irradiation
  - Resolution worsens after irradiation
  - Decreased performance partially recoverable by optimisation of programmable readout parameters:
    - I_{pre}: bias current of the preamplifier
    - V_{fs}: feedback resistor of the preamplifier



→ Aim for D_{max} < 3 kGy during MVD lifetime





ZEUS Radiation monitoring

Aim

- Protect MVD and readout electronics from radiation damage

Requirements

- Automatic dump of the lepton beam for high rates
- Provide online information for ZEUS and HERA shift crews
- Measure and archive integrated dose from ~ms to years
- Monitor surface- and bulk-damage

- Space and material constraints
- Radiation hardness
- Independent readout

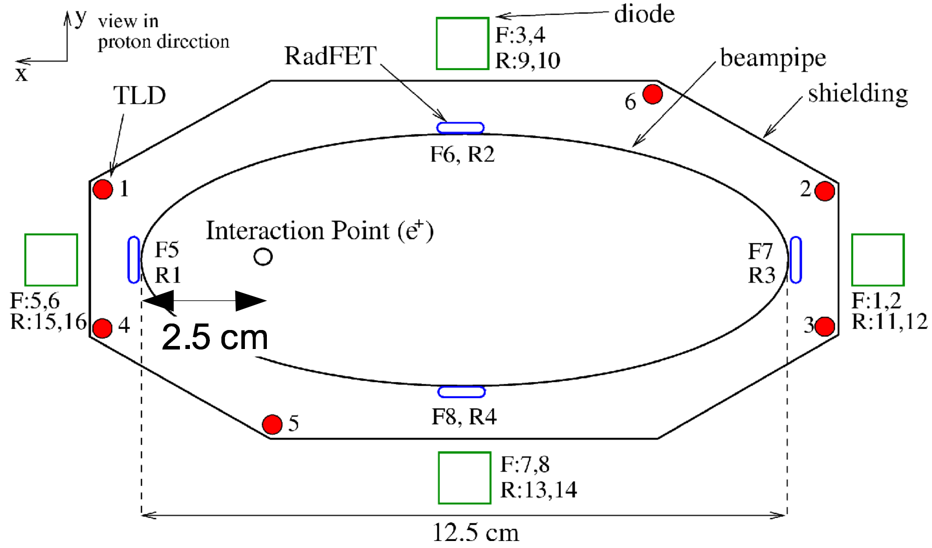
Concept

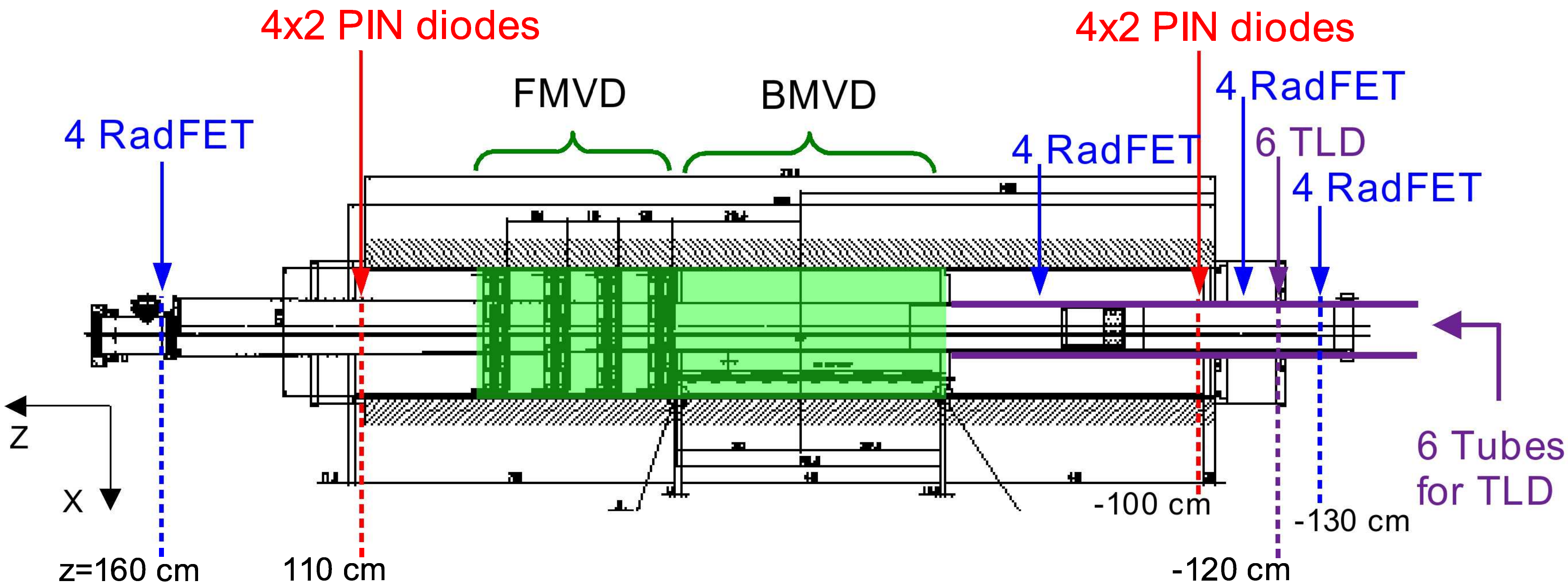
- Silicon PIN diodes
  - → Instantaneous dose rate from signal current
  - → Bulk damage from offset leakage-current
- Radiation Field Effect Transistors (RadFETs)
  - → Monitor surface damage from shift in threshold voltage
- Thermo-Luminescense Dosimeters (TLDs)
  - → Control measurement of integrated dose of ionising radiation and neutrons

http://www-zeus.desy.de/components/mvradmon/

Radiation monitor layout

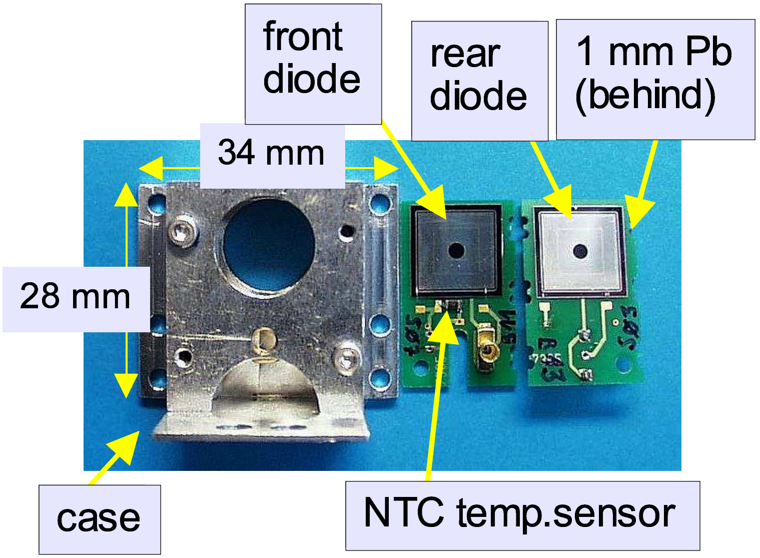
- Place as many components as close as possible to the MVD area:
  - 16 silicon PIN diodes
  - 16 RadFETs
  - 6 TLDs
- Combine with information from other detector components, e.g.:
  - Leakage currents in the MVD
  - Current in central tracking drift chamber
  - Scintillator counters outside the main det.



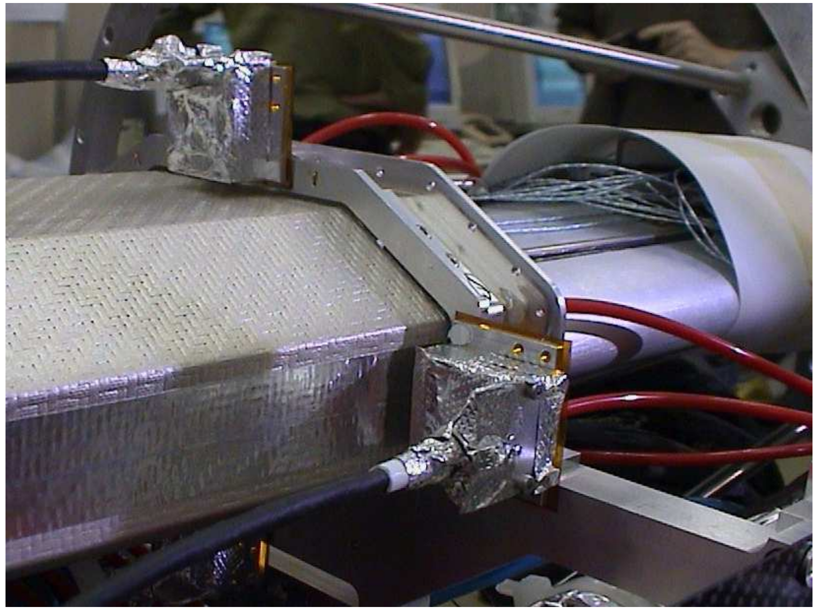


Silicon diodes

Module before assembly



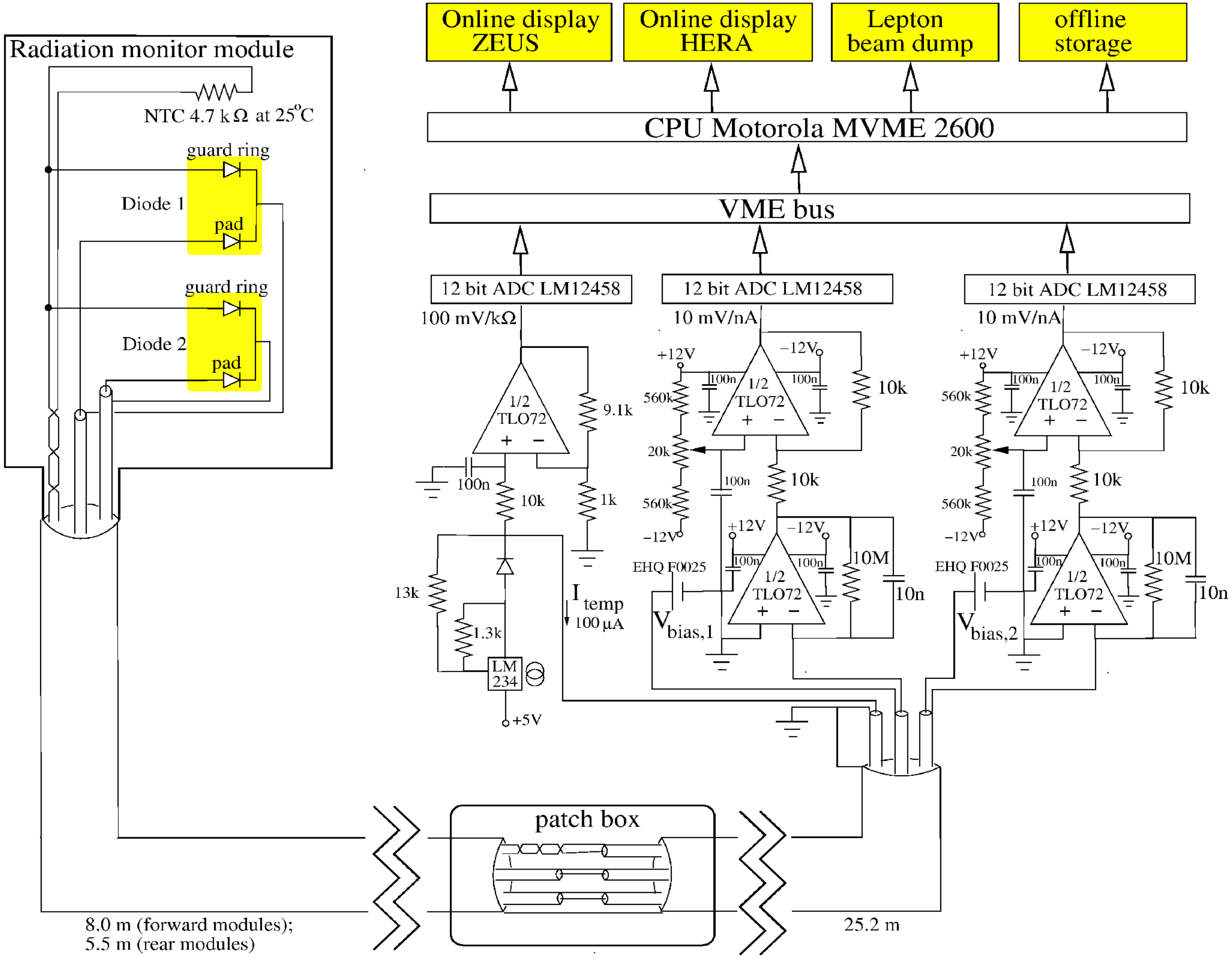
Silicon diode modules



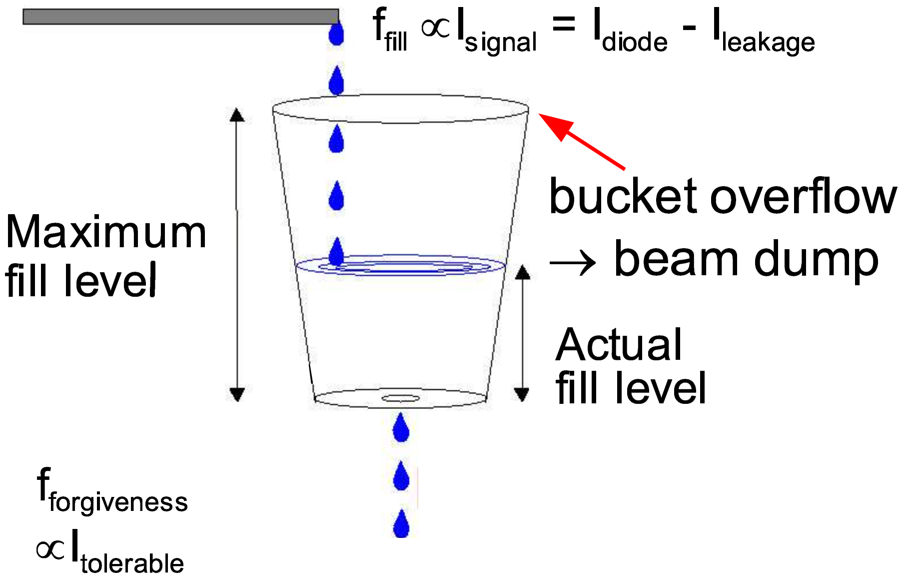
- 16 Silicon PIN diodes in 8 modules
- Producer: SINTEF
- 1 cm^2, high-resistivity, n-type silicon, 300 μm thickness, p+ implant, 1 guard ring
- Initial depletion voltage: V_{dep}~80 V
- Redundancy: 2 diodes back-to-back
- Lead absorber, d=1 mm (1/10 attenuation for E_γ=80 keV)
- Readout electronics outside active volume (~30m distance)
- Signal current measurement: 1 nA ⇔ 50 μGy/s
- NTC temperature sensors
  - ➔ Correct for temp. induced changes in $I_{leakage}$

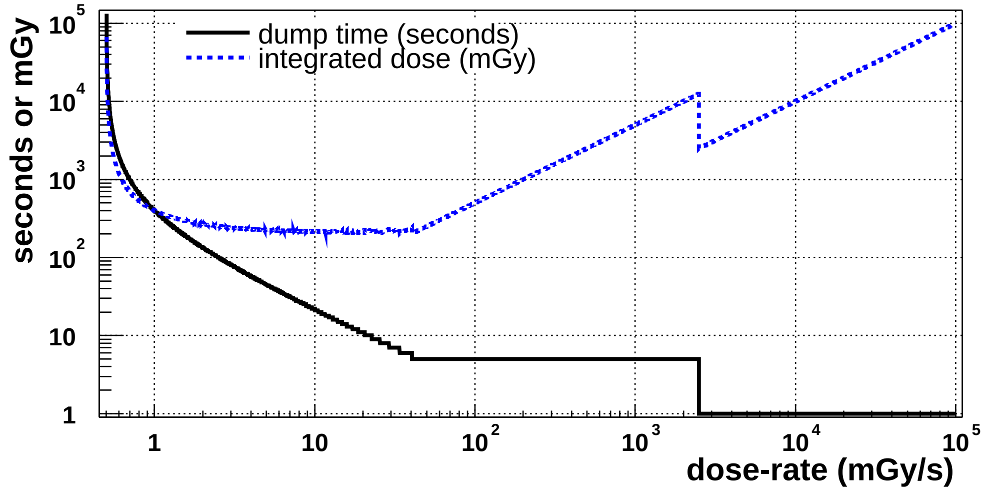
Silicon diode readout

- No active components in detector volume
- ~30m cable to readout el.
- All diodes biased and readout individually
- Preliminary readout for moderate integrated radiation levels:
  - Integr. amplifier (t~0.1s)
  - 12 bit ADC
    - I_{min}=244 pA ⇔ 12 µGy/s
    - I_{max}=1 µA ⇔ 50 mGy/s
  - DAQ software: 1 s readout interval
  - Beam dump implemented in software, t_{min}~1 s
- Online information and warnings for ZEUS and HERA shift crews on 1 s time scale
- Offline storage of temperature and current information on 1 s to years time scale



Leaky bucket beam-dump concept





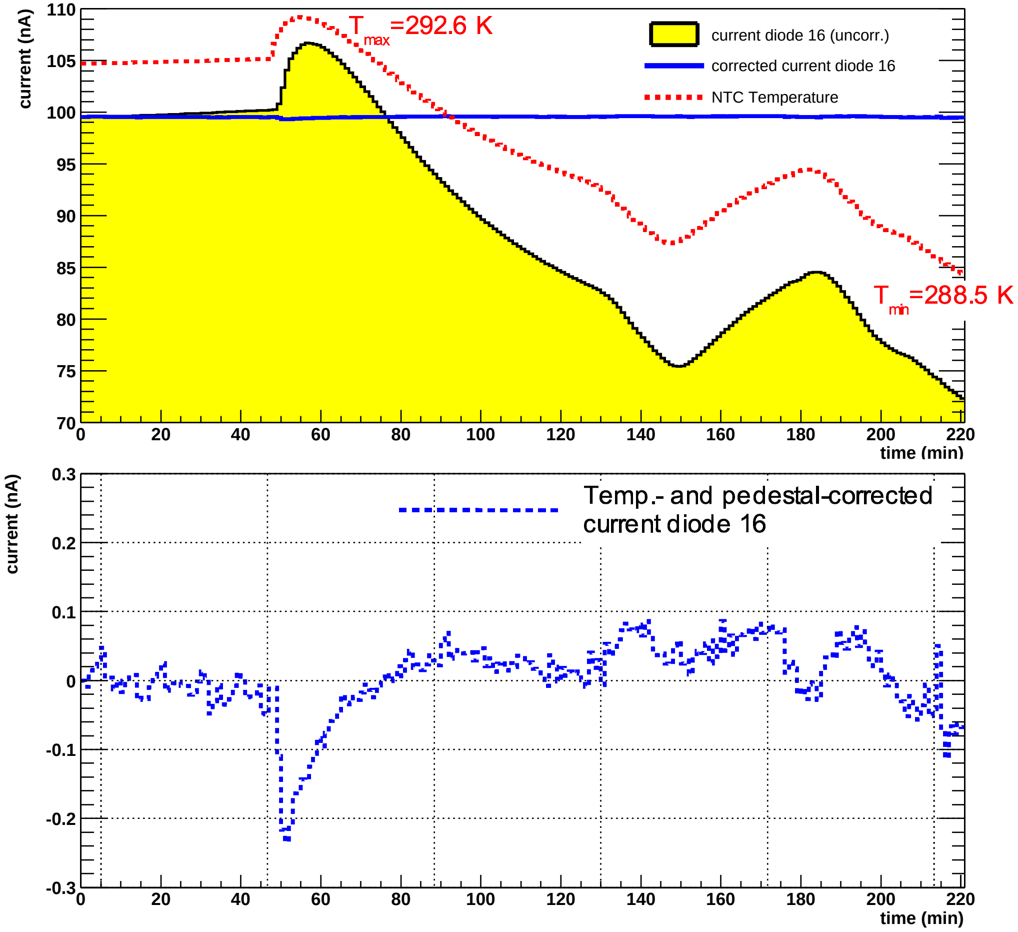
- Trigger beam dump on integrated dose
  - Allow for moderate constant background (forgiveness rate $f_{forgiveness}$)
  - Allow for short-term increases,
    e.g. during lepton-beam injection (Maximum fill level)

cf. BaBar radiation monitor,
T.I. Meyer, Int. J. Mod. Phys.
***A16S1C**, 1084 (2001)*

NTC temperature correction

- Offset leakage current in diodes increases exponentially with Temp. (~8% / K at room temperature)
- Offset current adds to radiation-induced signal current
- → Reliable temperature correction crucial for precise dose-rate measurement
- Semiconductor resistors with negative temp. coefficient (NTCs) are used to measure and correct for temp. induced changes in offset currents
- Correction coefficients extracted from fit: MVD cooling-sytem cycles during HERA shutdowns
- Coefficients change with absorbed radiation dose
- Corrected current stable within 0.2% (limited by high gradients)
- → Sufficient for moderate offset currents ~ hundreds of nA

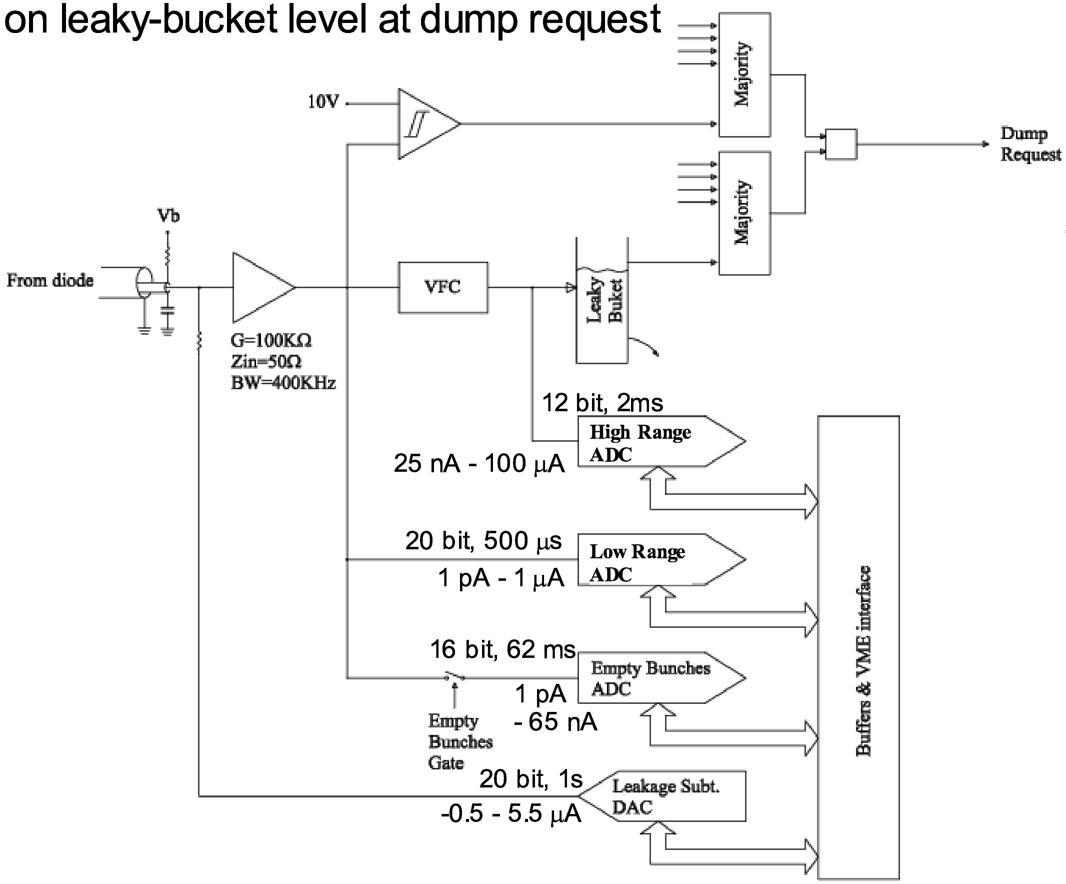
diode leakage current



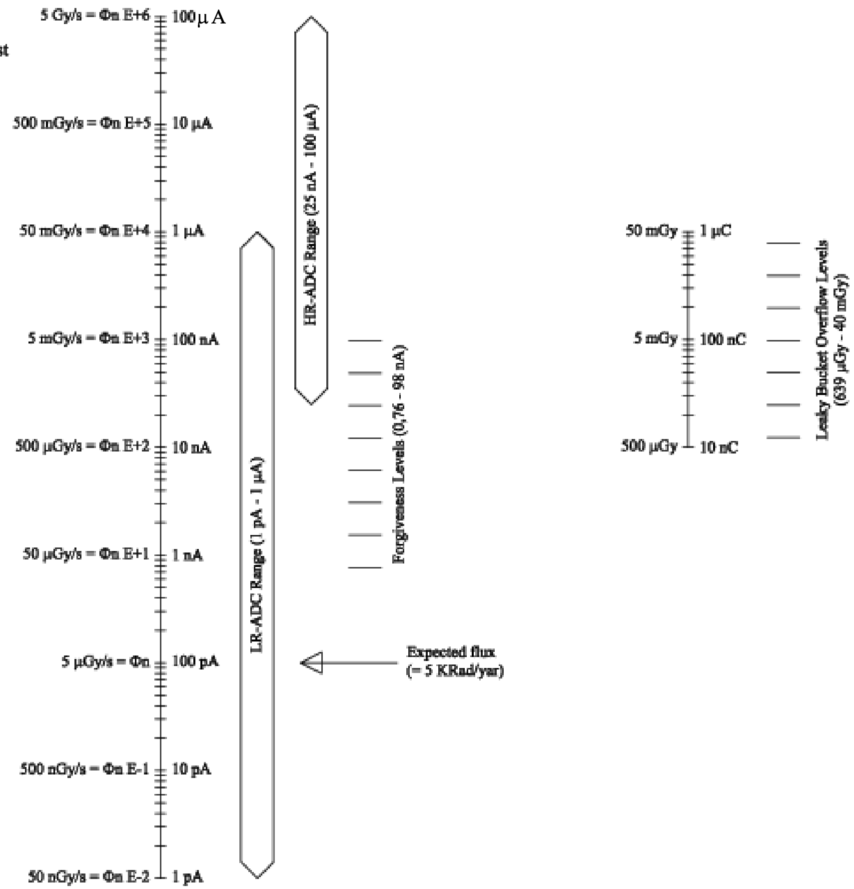
- Corrected current stable within 0.2%

Silicon-diode readout upgrade

- Leaky-bucket concept implemented in FPGA
- ~1 ms minimum dump time
- Empty HERA bunches (1.5 μs) for $I_{leakage}$ subtraction
- 20-bit DAC removes $I_{leakage}$ up to 6μA with 6 pA resol.
- FIFO for ±10 ms post mortem information on leaky-bucket level at dump request



- Larger dynamic Range:
  - low-range 20-bit ADC:
    - 500 μs integration time, deadtime-less readout (2 interlaced integrators)
    - 1 pA - 1 μA
  - high-range 12-bit ADC
    - 25 nA - 100 μA
  - Discriminator: dump for I>100 μA

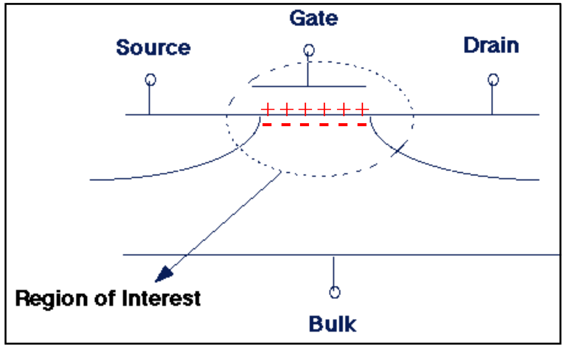


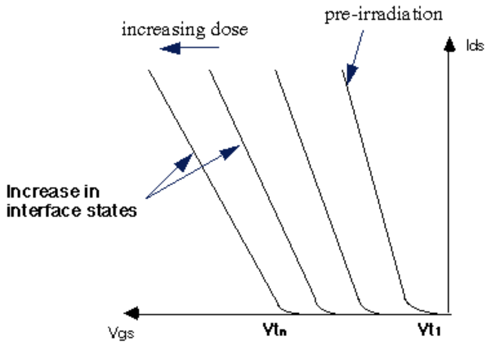
- Design finished
- Prototypes tested

→ Production started

RadFETs

Radiation Field Effect Transistor (RadFET) principle



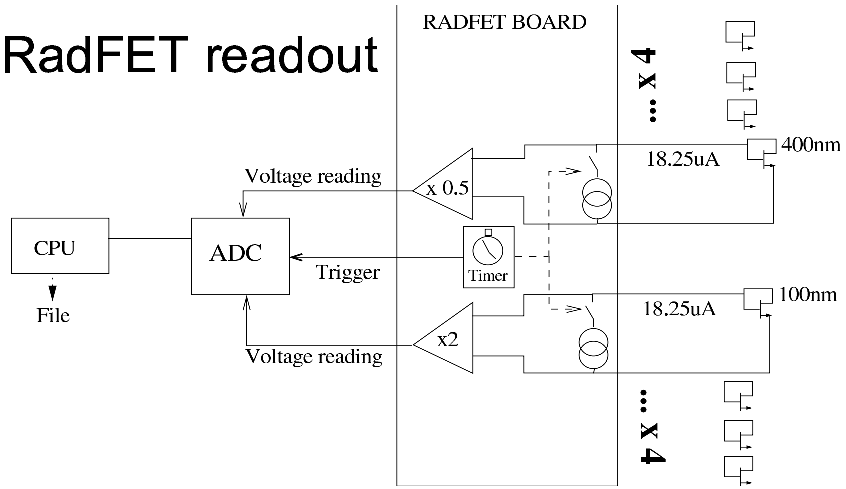


- Ionising radiation creates e$^-$-hole-pairs in SiO_2 layer of PMOS transistor
- Holes trapped in defects in SiO_2 and at Si-SiO_2 interface form positive space charge
- Electron accumulation layer forms below gate oxide

➔ Threshold voltage, V_{th}, increases with accumulated radiation dose

➔ RadFETs are used to monitor surface damage from ionising radiation

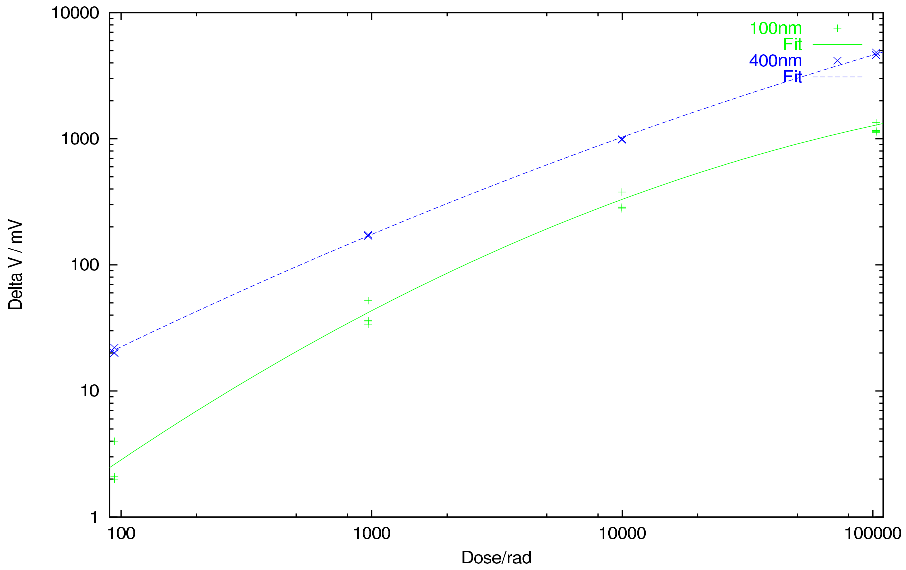
RadFET readout



- RadFETs used for ZEUS radiation monitoring:
  - Producer: NMRC
  - unimplanted and implanted gate-oxide
  - 8 RadFET of two different gate-oxide thicknesses used initially:
    - d=100 nm (low sensitivity)
    - d=400 nm (high sensitivity)
  - 17 min readout cycle
  - I=18 μA applied for readout
  - Upgrade during March 2003 shutdown:
    - 16 new RadFETs:
      - d=400 nm, unimplanted gate-oxide readout as before
      - d=400 nm, implanted gate-oxide continous negative biasing, 128 Hz readout

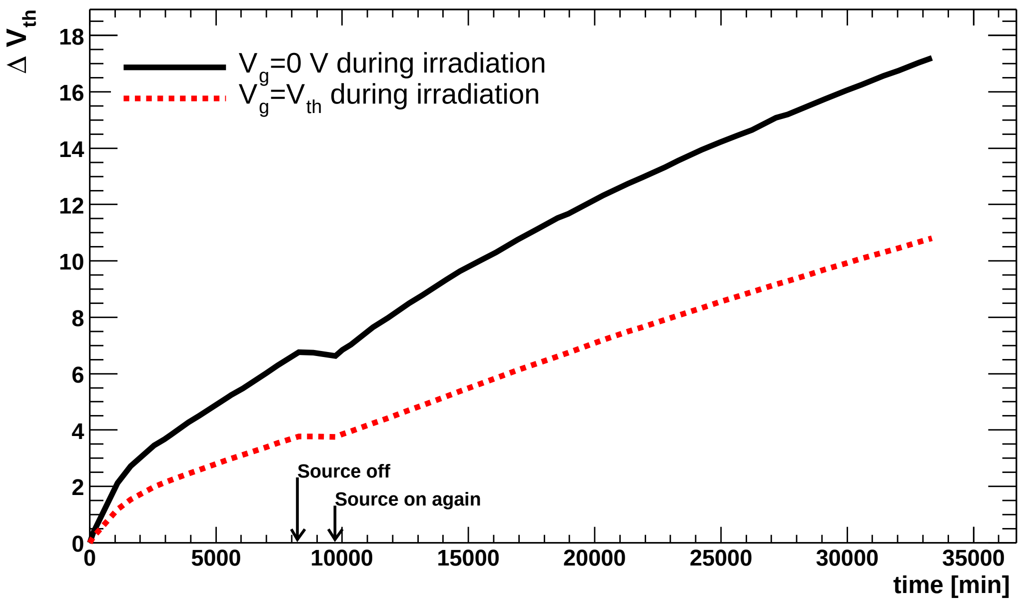
http://www.nmrc.ie/projects/radfets/index.html

RadFET calibration



Calibration at manufacturer

- 100 nm and 400 nm, non-implanted types
- No bias voltage applied during irradiation (V_g=0)
- ^{60}Co γ irradiation up to 1 kGy
- Initial change in V_{th}:
  - 1.5 mV/Gy (100 nm)
  - 18 mV/Gy (400 nm)
- Estimated uncertainty from device-to-device variation: ~±50%

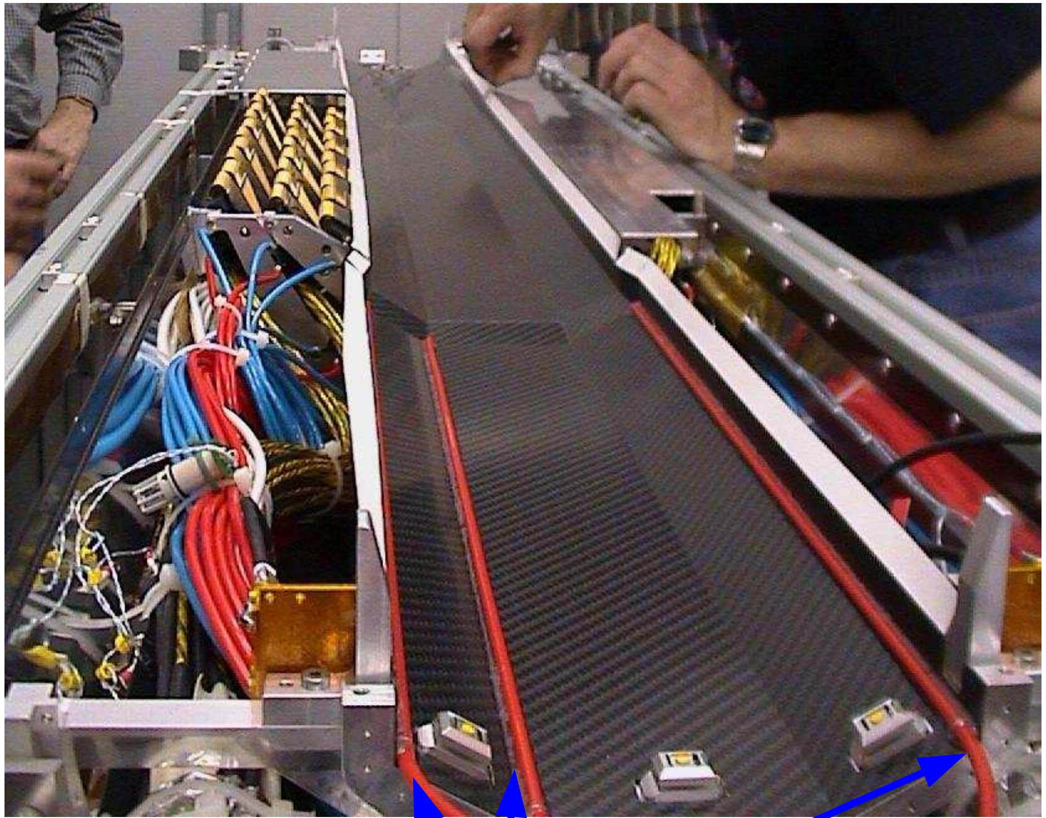


Calibration at DESY

- 400 nm, implanted gate oxide types
- V_g=0 and V_g=V_{th} during irradiation
- ^{137}Cs γ irradiation at 65 mGy/min up to 2.4 kGy
- Initial change in V_{th}:
  - 35 mV/Gy (V_g=0)
  - 20 mV/Gy (V_g=V_{th})
- Annealing for V_g=0: ~130 mV/day

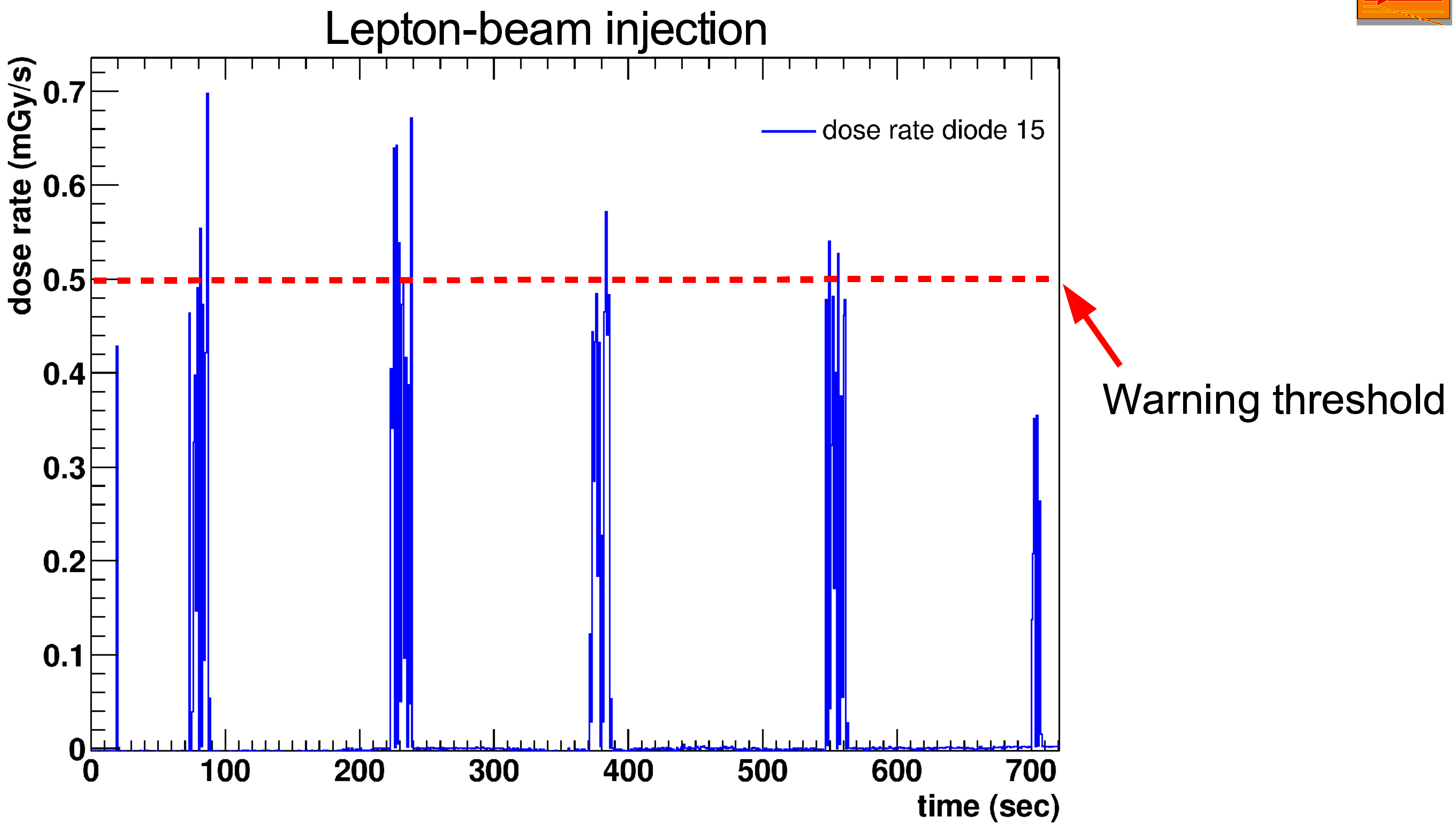
Thermo-Luminescense Dosimeters

- 6x2 Thermo-Luminescense Dosimeters (TLDs)
- ^{6}LiF (TLD-600):
  - sensitive to ionising radiation+neutrons
  - D_{max} = 1 Gy
- ^{7}LiF (TLD-700):
  - sensitive to ionising radiation
  - D_{max} = 10 Gy
- Monthly exchange and on-site readout
  - ➔ Control measurement of integrated dose of photons and neutrons



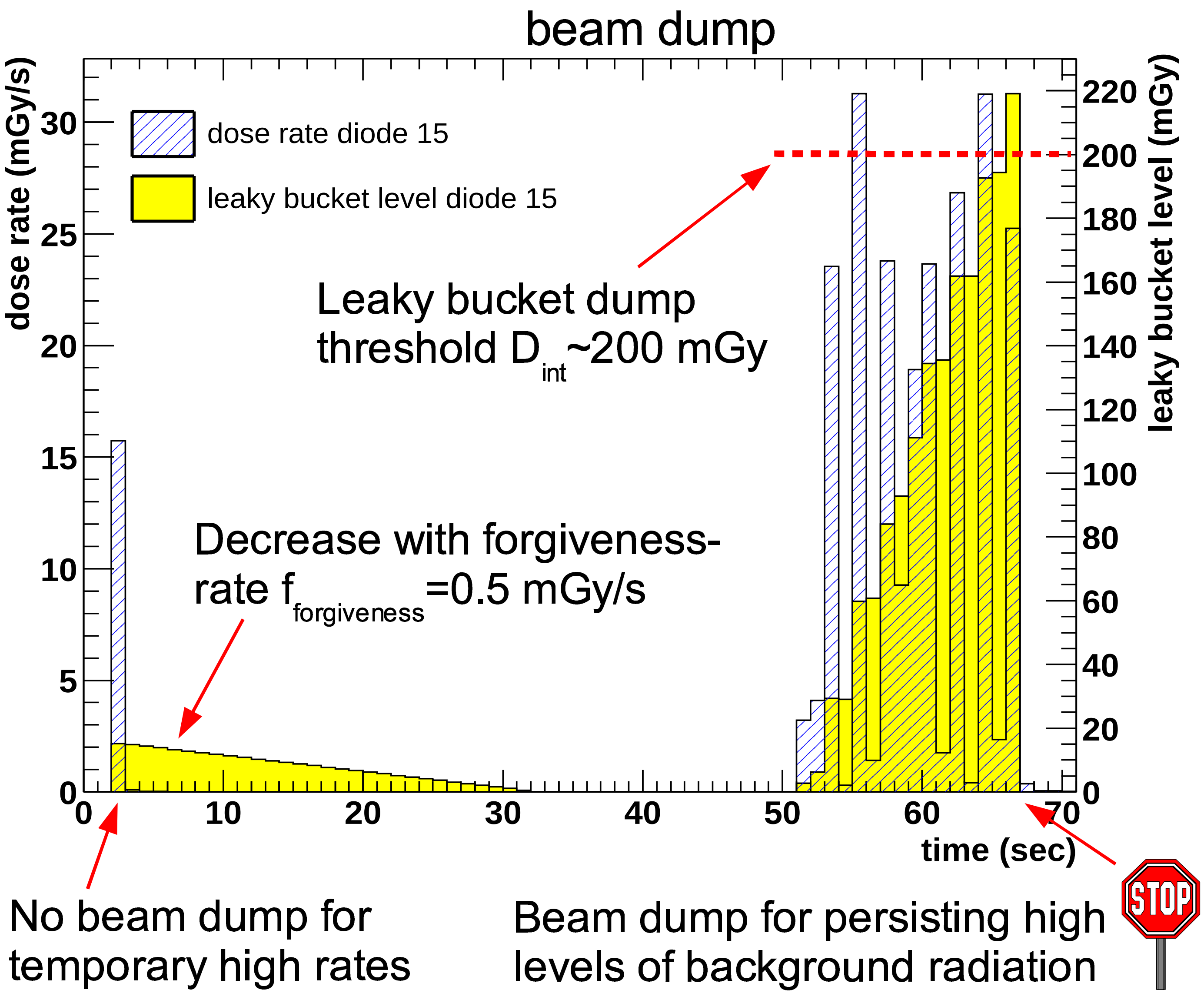
Plastic tubes to insert TLDs

Instantaneous dose-rate



- Moderate background levels during normal injections
- Warning threshold for HERA/ZEUS shift crews: 0.5 mGy/s (10 nA)

Automatic beam dump

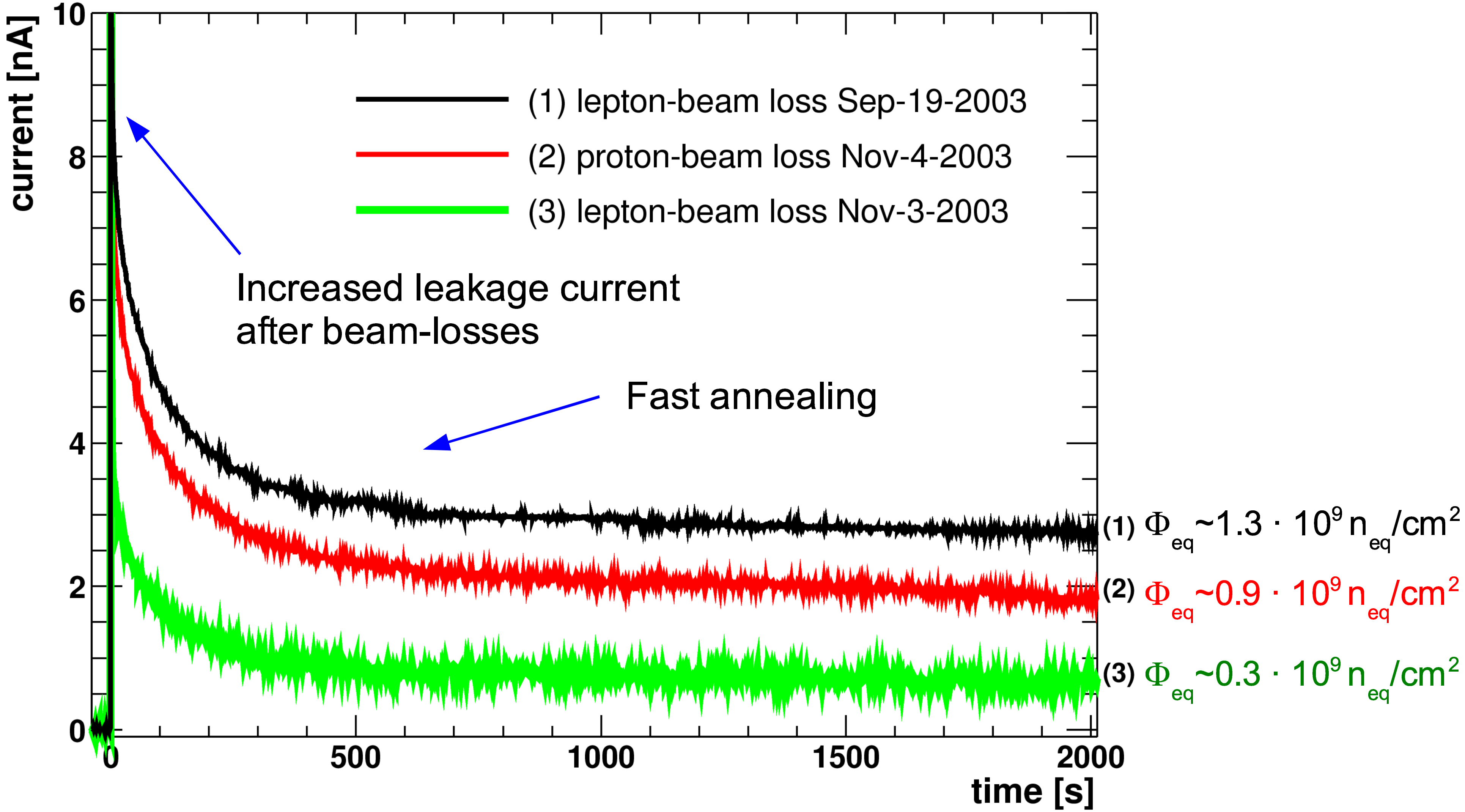


No beam dump for temporary high rates

Beam dump for persisting high levels of background radiation

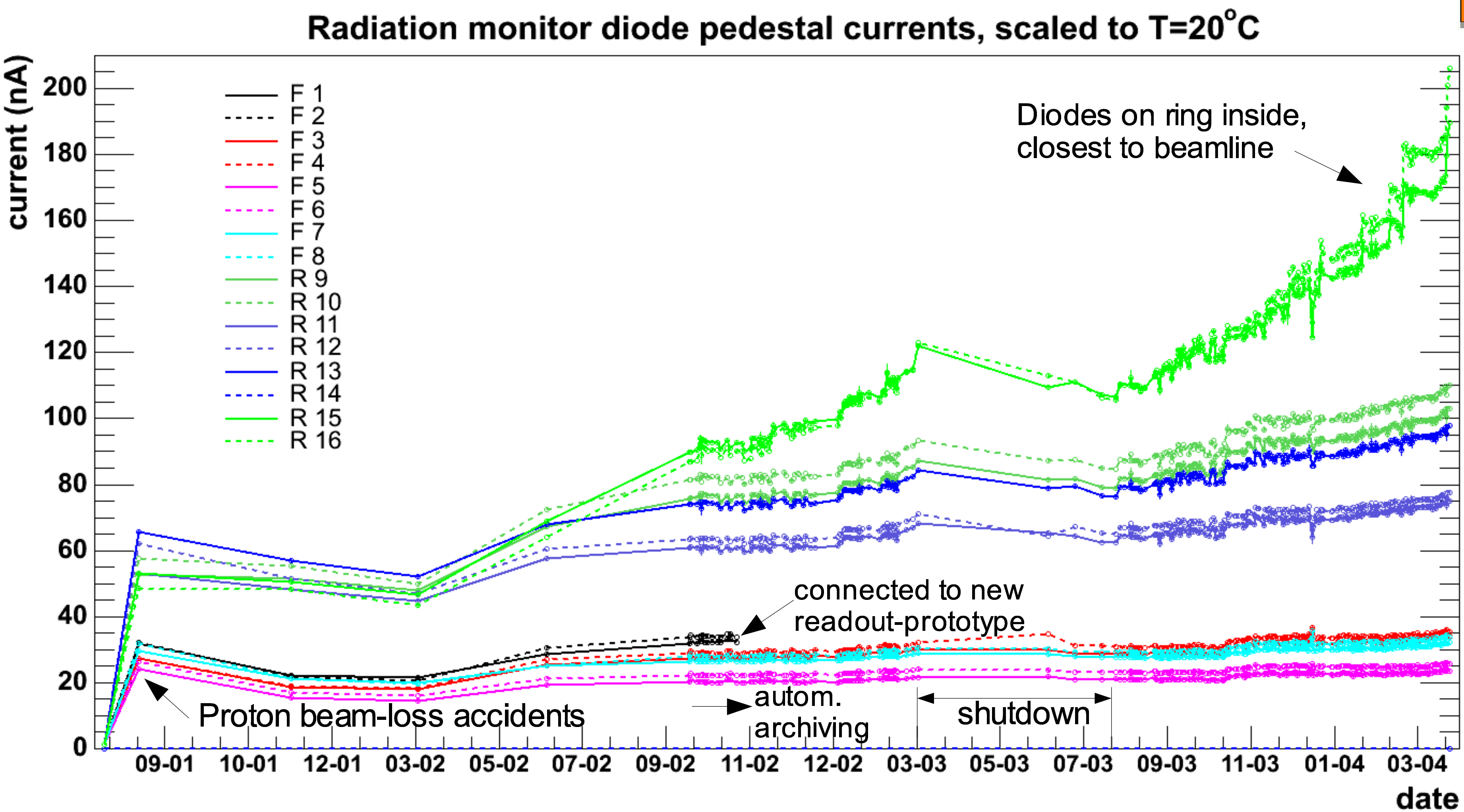
Short-term bulk damage

Si-diode offset leakage current after radiation spikes



→Estimate bulk damage from offset increase after single beam-loss accidents

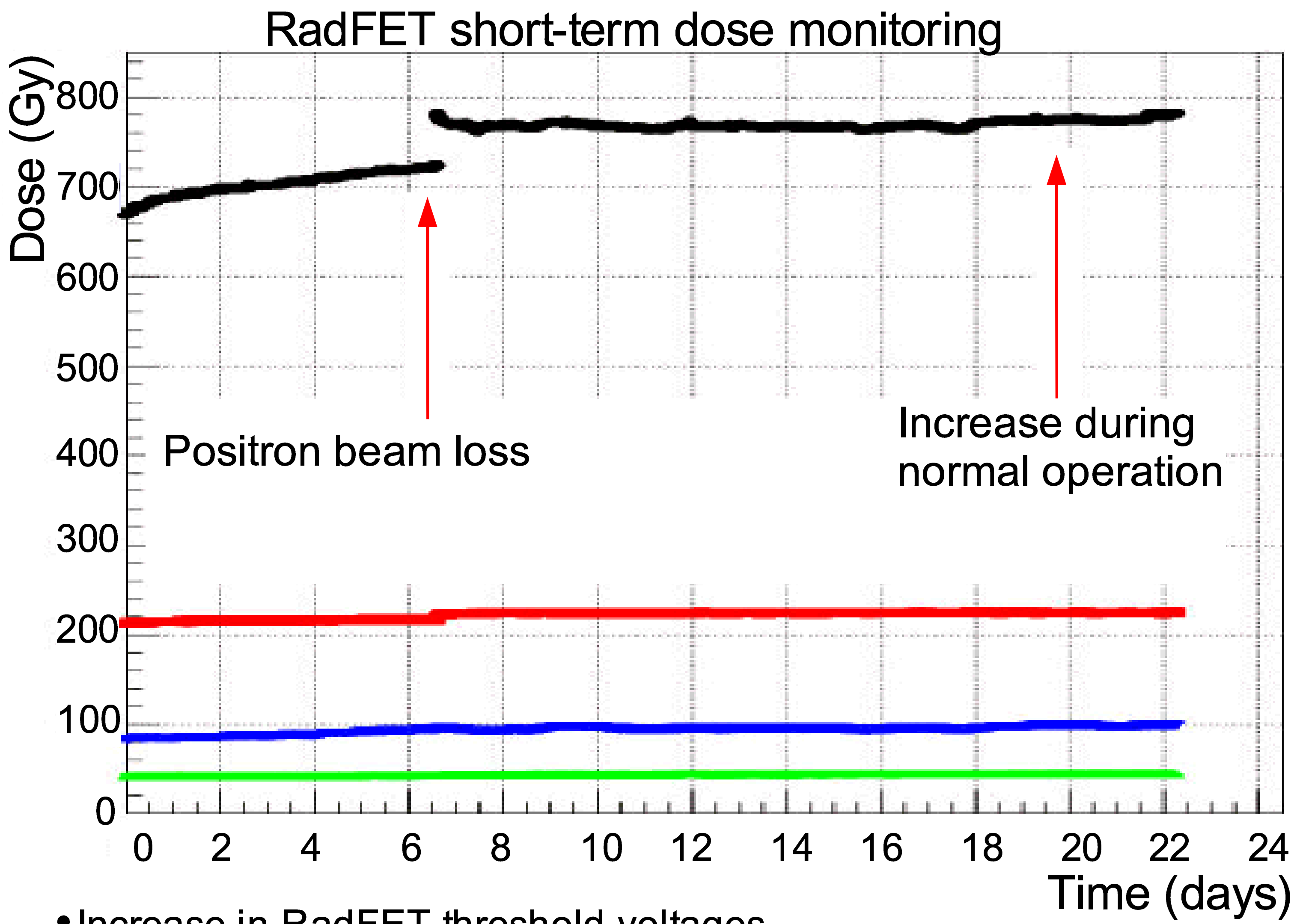
Long-term bulk damage



- Long-term increase and annealing of leakage current
  ➔ Estimate accumulated bulk damage
- Moderate fluence observed so far (~1% of ϕ_{max})

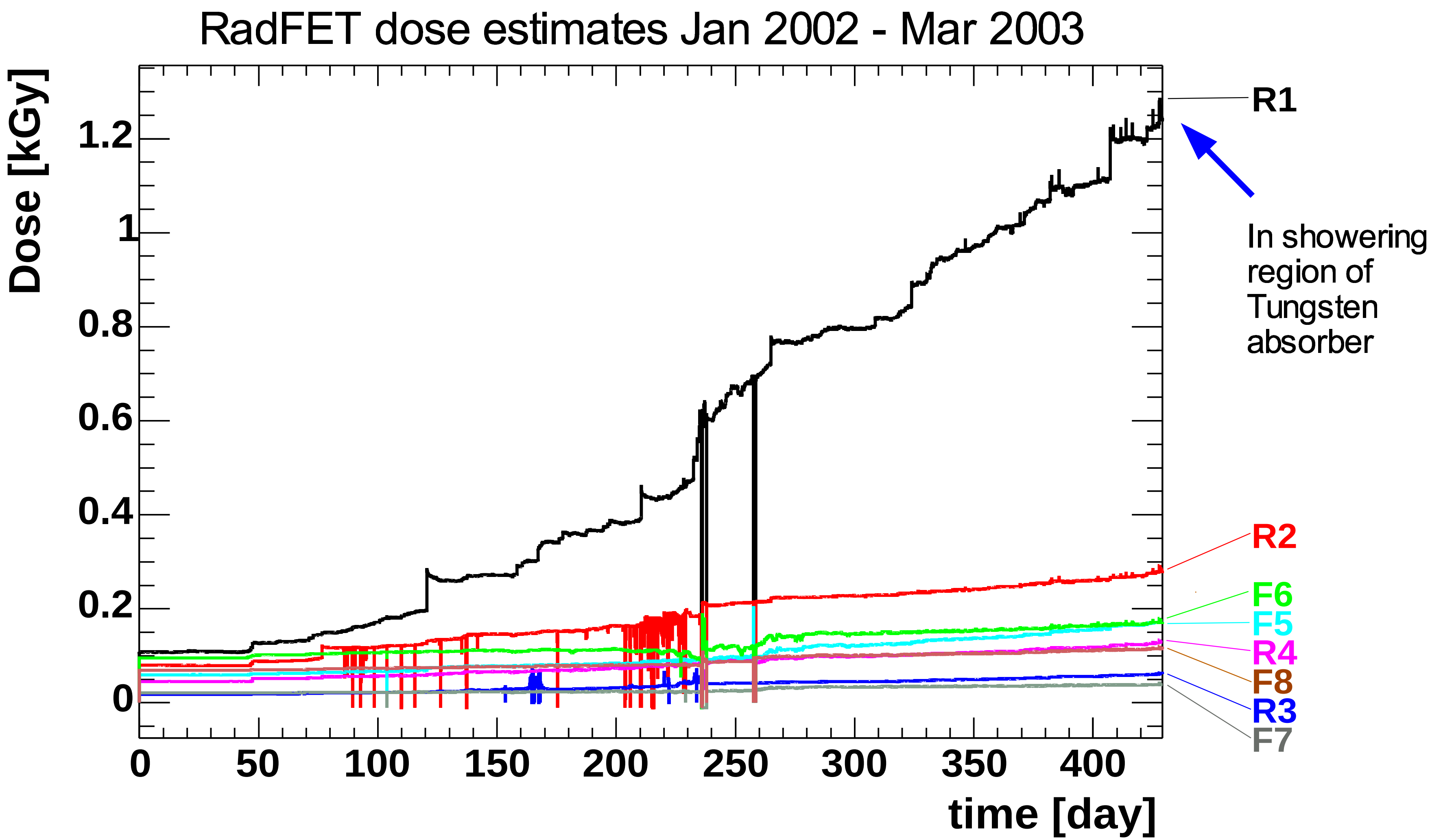
- In agreement with TLD measurements
- Confirmed by leakage current increase in MVD sensors, also ϕ-,z-dependence

Surface damage (I)



- Increase in RadFET threshold voltages
  - ➔ Estimate accumulated dose of ionising radiation
- Steady increase during normal beam operation
- Step-like increases from single beam-loss accidents

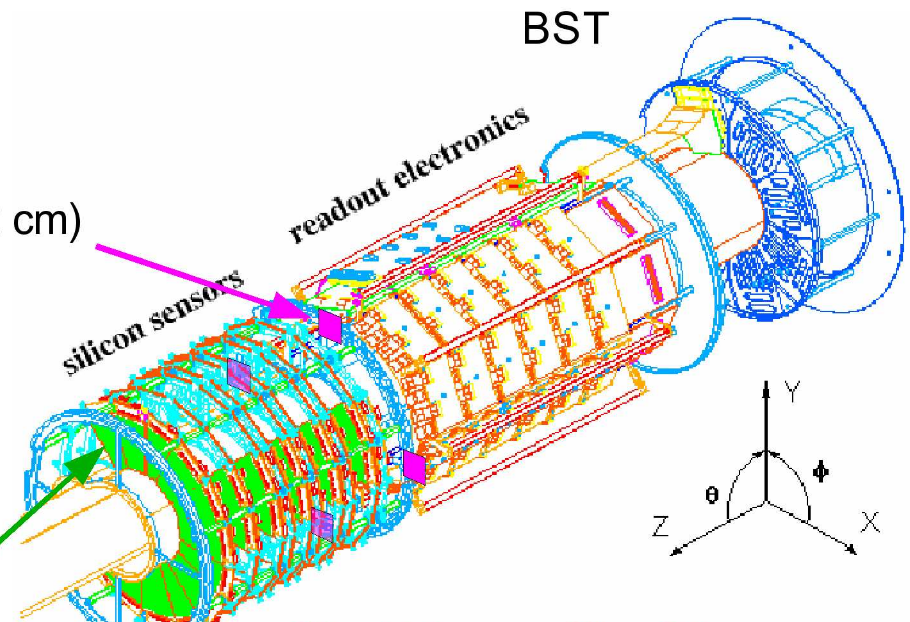
Surface damage (II)

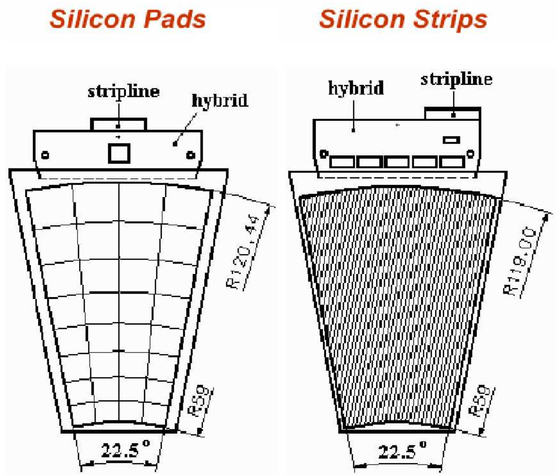


- Moderate integrated dose observed so far (~10% of D_{max})
- In agreement with TLD measurements
- Confirmed by moderate S/N decrease for MVD (~1-8%, confirms also ϕ-,z-dependence)

H1 radiation monitoring concept

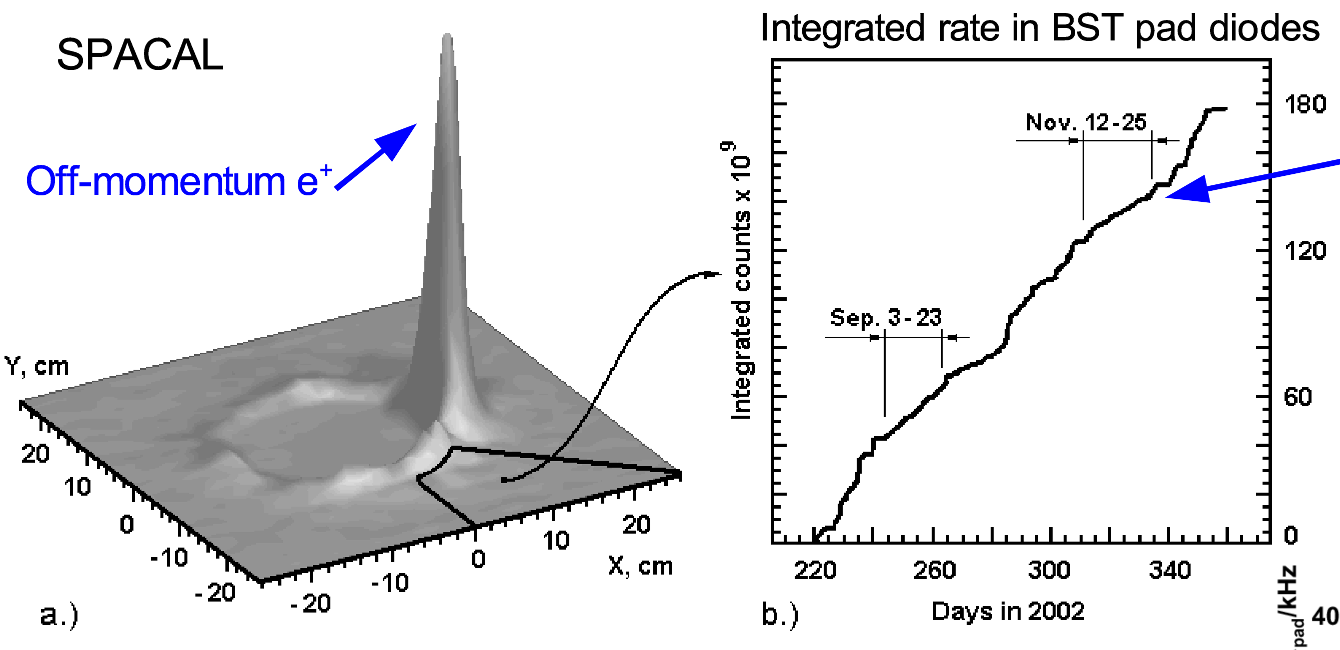
- Aim: Protect Si Vertex Detector and readout electronics from radiation damage
  - Dedicated independent online monitoring:
    - 4 Si PIN diodes Hamamatsu S3590-08 (1 cm^2) + charge sensitive preamp. and line drivers mounted behind backward silicon trackers (z=-62 cm)
    - Count particles, E_{th}=100 keV
      - ➔ insensitive to soft synchrotron radiation
    - Dynamic range: 0.1Hz - 600 kHz (~110 µGy/s)
    - Manual beam-dump requests after ~2min @ 10 kHz summed rate
  - New additional monitoring since 2002:
    - Use Backward Silicon Pads (512 channels)
      - ➔ Additional Trigger Output: Sum of hits per BC (@ 10 Mhz L1 rate)
      - ➔ Upper dose-rate limit ~90 µGy/s
      - ➔ In use now as main radiation monitor
      - ➔ Automatic beam dump trigger under investigation, with additional coincidence (e.g. drift chamber alarm)
  - Long term calibration and control:
    - Radiophotoluminescent glass dosimeters (RPL) and TLD, readout during long shutdowns





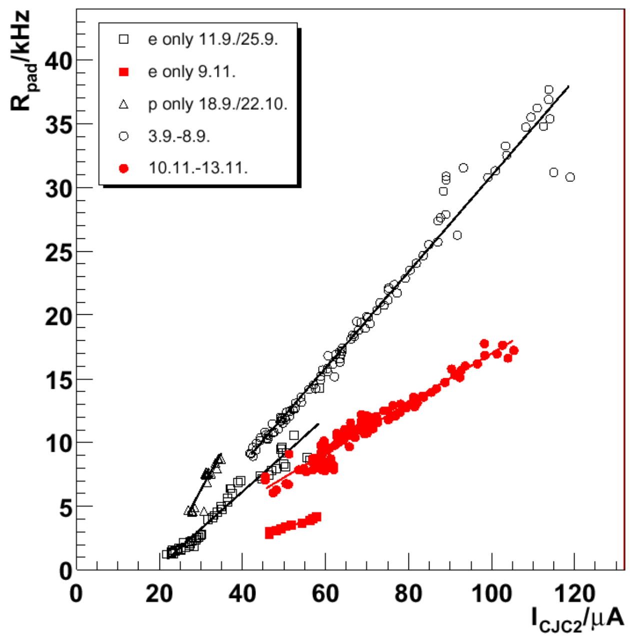
http://www-h1.desy.de/~blist/talk-vertex2003.pdf

H1 radiation monitoring results



- ~1 Gy/month during normal running

- Background rates correlate with drift-chamber currents:



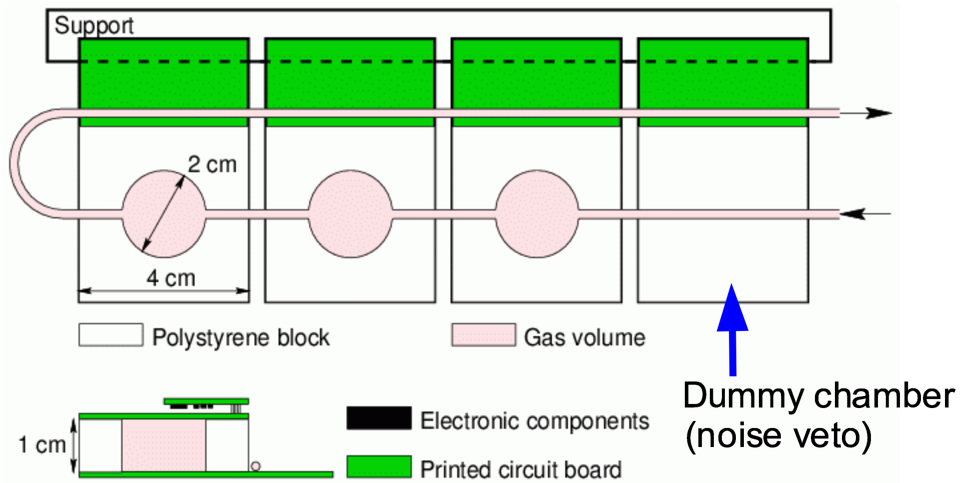
http://www-h1.desy.de/h1/www/publications/bgrep2.pdf

- Radiation damage during HERA-II commissioning:
  - D=8-24 kGy in backward Si detector
    - ➔ Synchr. rad. backscattered off absorbers
  - D~100 Gy for central and forward parts
  - $e^{+/-}$ / p - beam-loss events lead to damage in (replaceble) readout chips
  - Readout components partially replaced
    - ➔ Radiation-hard (DMILL) Version of APC-128 readout chip in use now for central silicon tracker
  - No change in Si leakage currents observed

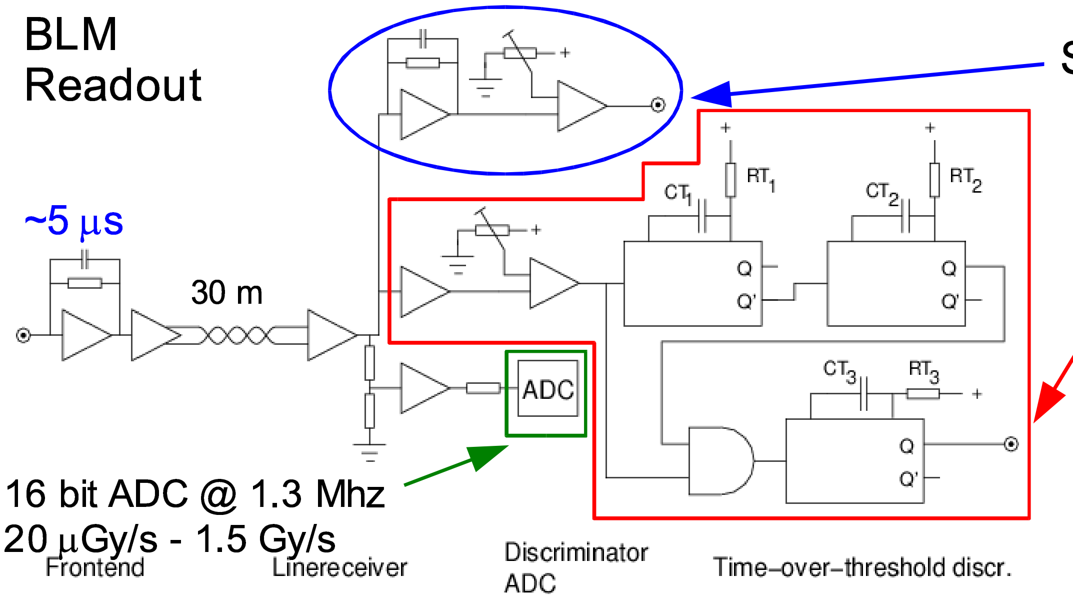
HERMES radiation monitoring concept

- HERMES: study spin structure of the nucleon
  - ➔ polarised $e^{+/-}$ on fixed polarised gas target
- New Si Detector since 2001: 'Lambda Wheels'
  - 2 disks of double-sided strip detectors
  - 34 cm diameter, DCA to $e^{+/-}$ beam ~4 cm
  - Non rad.-hard front end chips at outside
- Beam Loss Monitor installed to prevent Si Detector from radiation damage:
  - 2 sets of Argon ionisation chambers in the horizontal plane
  - Triggering automatic $e^{+/-}$ beam dump

Argon ionisation chambers (2x3)



BLM Readout



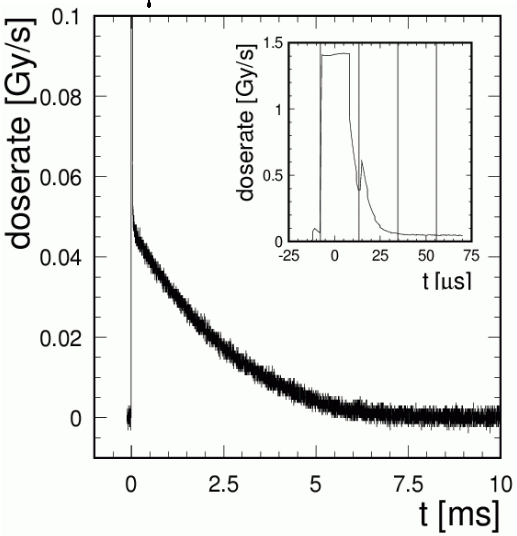
Slow trigger: 1 s integration, > 0-1 Gy

Fast trigger: >0-500 mGy/s and 1-10 µs time over threshold

- Additional Radmon components:
  - RPL/TLD longterm monitoring
  - Scintillators for beam-tuning
  - RadFETs on Hybrids for new Si strip recoil detector (in preparation)

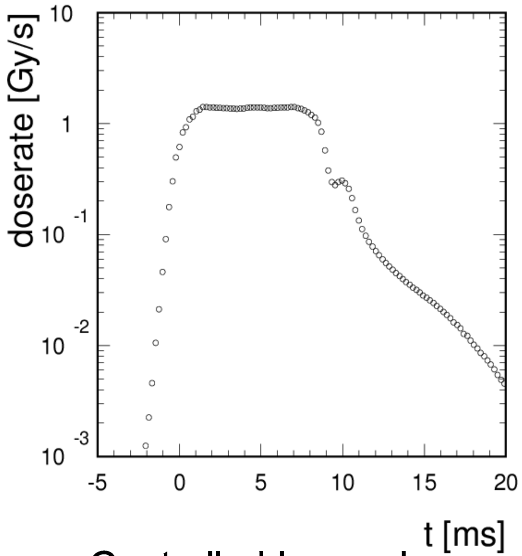
HERMES radiation monitoring results

μs beam loss



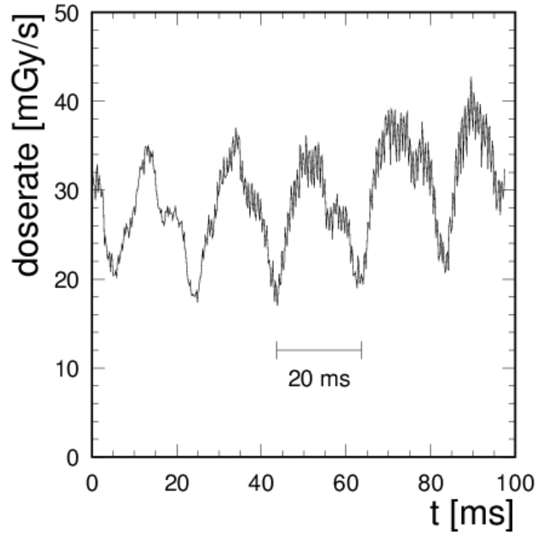
- Loss within ~1 revolution
- No protection from BLM
  (rise time of dump kicker ~0.5ms)

ms beam loss

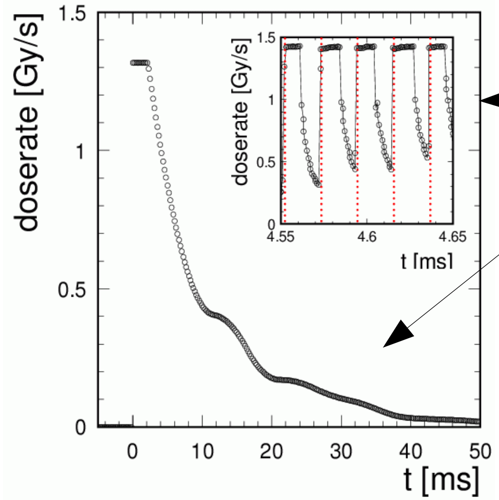


- Controlled beam dump through fast time-over-threshold trigger

beam loss within ~seconds



- Current drop in the main dipoles
  - ➔ Increased rate over ~30 s
  - ➔ Large integrated dose
- Beam dump from slow trigger



e^+ injections

- 21 μs machine cycle visible
- Increased radiation levels persisting for ~30 ms
- Beam-dump trigger disabled during injection

- High radiation events on time scales from μs to seconds observed
- Activates beam dump ~ 2 times/year
- Integrated dose (RPL/TLD) 4/2002 - 3/2004 ~ 5-100 Gy
- No significant damage observed in Si detectors up to now

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HERA radiation monitoring

- Main purpose of HERA radiation monitoring:
  - Protect beamline instrumentation from radiation damage
  - Quench-protection for superconducting p magnets
  - Optimise beam quality
  - Monitor dose from beam-induced activation

- Various devices for beam monitoring
  - Beam profile monitors (wire scanners), beam loss monitors, beam position monitors (striplines), DC+AC beam current monitors (toroids, pickup electrodes), OTR beam imaging, temperature sensors, ...

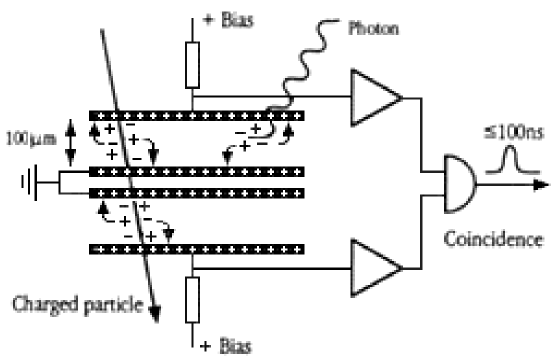
- Legally required dose monitoring (DESY D3)
  - Online dose measurement
    - 84 stations: electronic neutron counters, Ar ionisation chambers (γ)
    - trigger automatic beam dump (for pre-accelerators)
  - Passive long-term dose monitoring
    - 256 stations, TLDs and Th foils in various moderators (γ,n up to ~200 MeV)
    - Monitor air, water activation
  - Personal dose monitoring
    - RPL glass-dosimeters (γ)
    - Nuclear track emulsion (n)

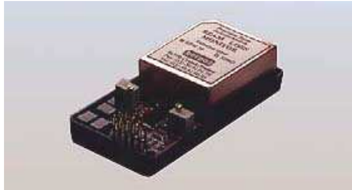
- Refined web interfaces and archiving tools on different time scales
  - ➔ Online and offline correlation with radiation monitoring in the experiments

HERA beam loss monitors (BLM)

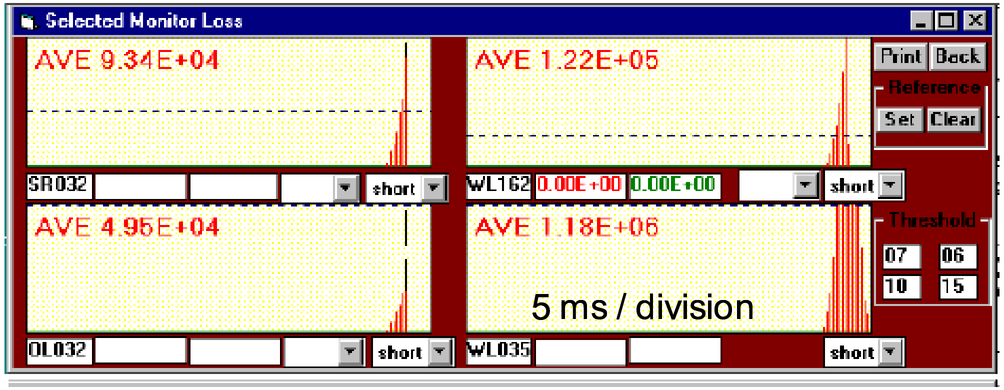
- quench-protection for superconducting quadrupols in HERA p-ring
- controlled p-beam dump within 5 ms for high p-beam loss rates
- 282 pairs of Si diodes, mounted mostly at superconducting quadrupols around the HERA ring
- 214 modules for e-ring, used for background diagnostic
- Temic BPW-34 (0.08 cm^2) and Hamamatsu S 2662 (1.5 cm^2) diodes in use
- Rad.-hardness tested up to 10^6 Gy
- Count single MIPs, 0.1 Hz .. 10 Mhz, >30% MIP efficiency
- Require coincidence for diode pair
  - → insensitive to γ's
- Also used for:
  - Monitoring vacuum conditions (beam-gas interactions)
  - Monitor p-background at collimators
  - Time resolved post mortem analysis of uncontrolled beam losses
  - correlation with radiation monitoring in the experiments

Operating principle





Example: trip in 208 MHz RF system
→ p-beam dump within ~30 ms



- Recent development:
  - Very fast beam-loss accidents from failures in low-β magnets end of 2003
  - Significant n-doses in the experimental halls
    - → Temporary reduction of p-current

→

- New p beam-dump system:
  - Based on A/C beam current monitors
  - beam-dump within 1 turn (20 µs) for ΔI_p>2 mA
  - Limits loss to max. 10% of beam current
  - Developed and installed within weeks (!)

http://desyntwww.desy.de/mdi

Summary/Conclusions

- ZEUS, H1, HERMES and HERA have successfully built and used radiation-monitoring and beam-dump systems to protect machine and detector components from high rates of background radiation
- Measurements over a wide dynamic range in radiation-type, time and dose rate
- Online information for shift crews helps to optimise beam conditions
- Archived information used to correlate the various components and increase the understanding of the background conditions
- Improvements in radiation monitoring ongoing

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