Detectors for Single-Photon counting applications at visible and near-infrared wavelengths

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Outline:

- Application: The SPECTRAP experiment
- Detector test setup in Münster
- Characterization of APDs (1100 nm detection)
  → Results for RMD S0223 APD
- Test setup calibration for Single-Photon measurements
- Detectors for NIR (1500 nm) Single Photon detection

Laserspectroscopy with SPECTRAP

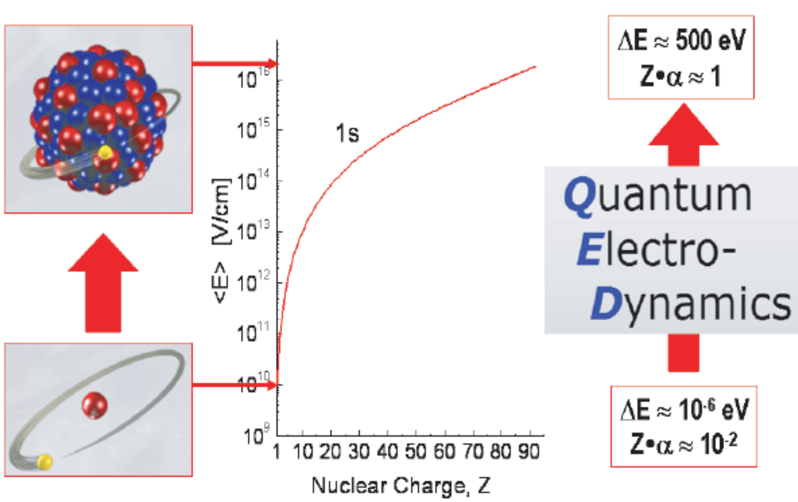
Laserspectroscopy experiments at GSI:

- Probing QED in extreme electromagnetic fields (up to 10^{16} V/cm and 10^{5} T) of **H**ighly **C**harged **I**ons, where QED cannot be described by perturbation theory

  → Precise measurements of Hyperfine-transitions in HCI (H-like, Li-like ions)

- HCI to observe: H-like $^{207}Pb^{81+}$

  H-like $^{209}Bi^{82+}$ and Li-like $^{209}Bi^{80+}$: Measurements of HFS transitions in two bismuth charge states allows to disentangle nuclear structure effects and QED effects

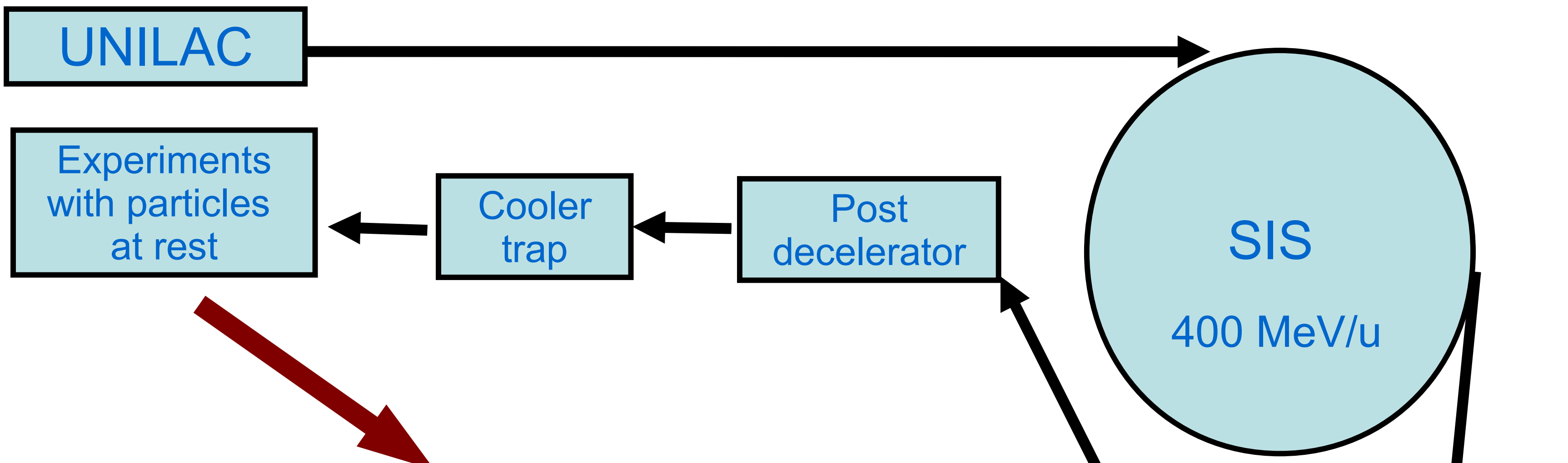


Nuclear structure and QED contributions:

$$\Delta E_{\mathrm{HFS}} = \alpha g_I \frac{m_e}{m_p} \frac{F(F+1) - I(I+1) - j(j+1)}{2j(j+1)} m_e c^2 \times \frac{(Z\alpha)^3}{n^3(2l+1)} \left[\mathscr{M} \, A(Z\alpha)(1-\delta)(1-\varepsilon) + \left(\frac{\alpha}{\pi}\right) \Delta\mathscr{E}_{\mathrm{QED}} \right].$$

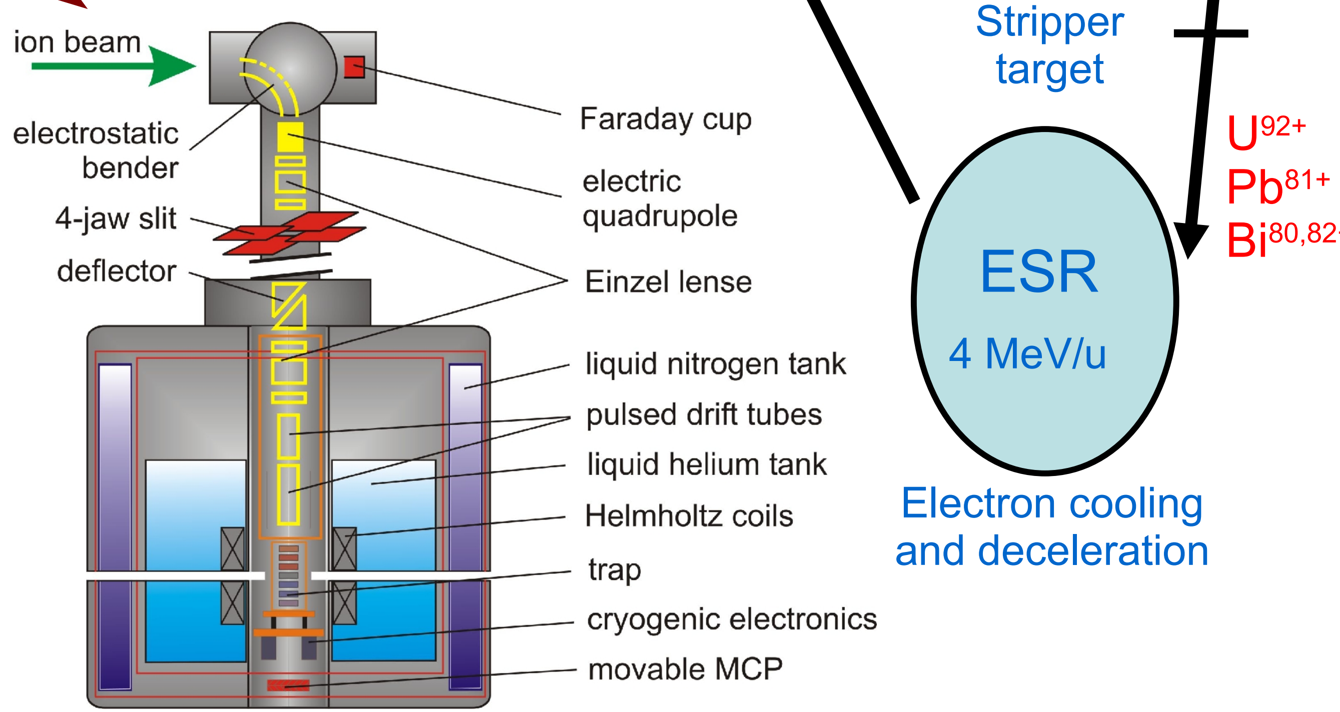
Nuclear Mass Effect ($\mathscr{M}$) · Relativistic Effects ($A(Z\alpha)$) · Breit-Rosenthal Effect ($1-\delta$) · Bohr-Weisskopf Effect ($1-\varepsilon$) · QED Contribution ($\left(\frac{\alpha}{\pi}\right)\Delta\mathscr{E}_{\mathrm{QED}}$)

Laserspectroscopy with SPECTRAP



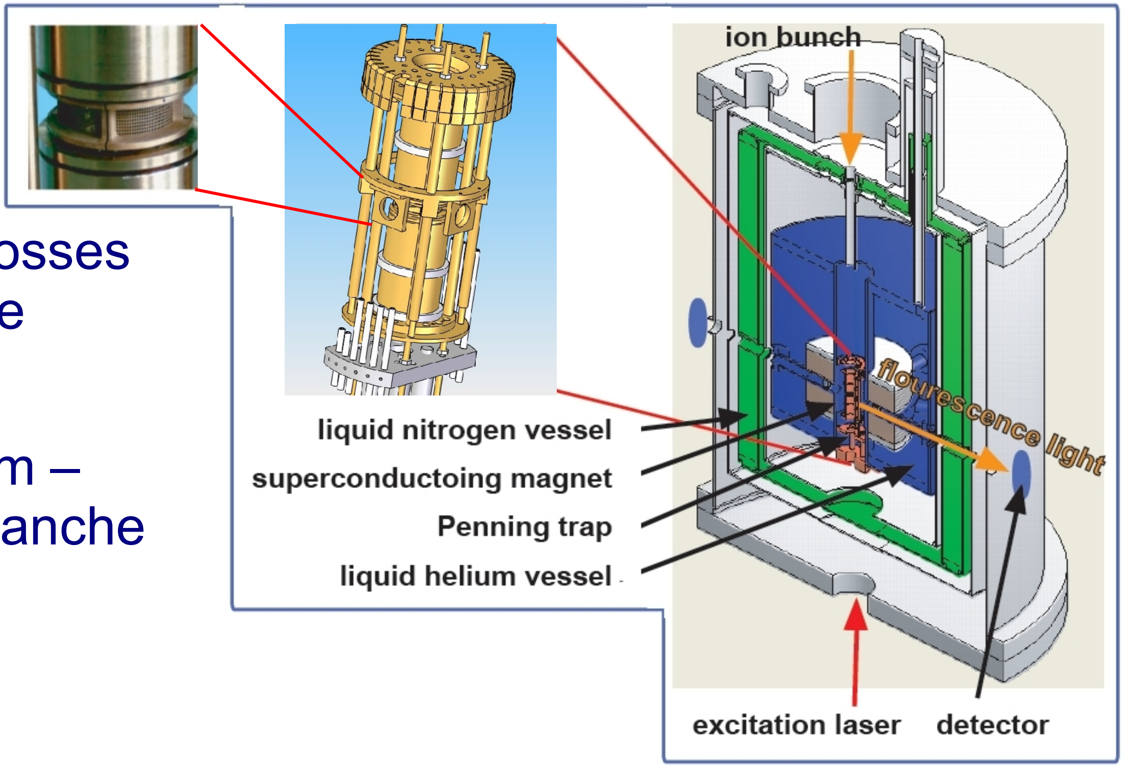
SPECTRAP:

- 10^5 ions nearly at rest in a penning trap
  → narrow line width
- Exitation of HF transition with tunable laser
- Difficulty: Photon wavelengths from UV to NIR have to be detected



Why Single-Photon Counting?

- Count rates depend on the lifetimes of the observed hyperfine states
- Due to small solid angle and light losses count rates of $\mathcal{O}$(kHz) and lower are expected
- The wavelength region from 300 nm – 1100 nm could be covered by Avalanche Photodiodes (APDs) → higher QE compared to PMTs



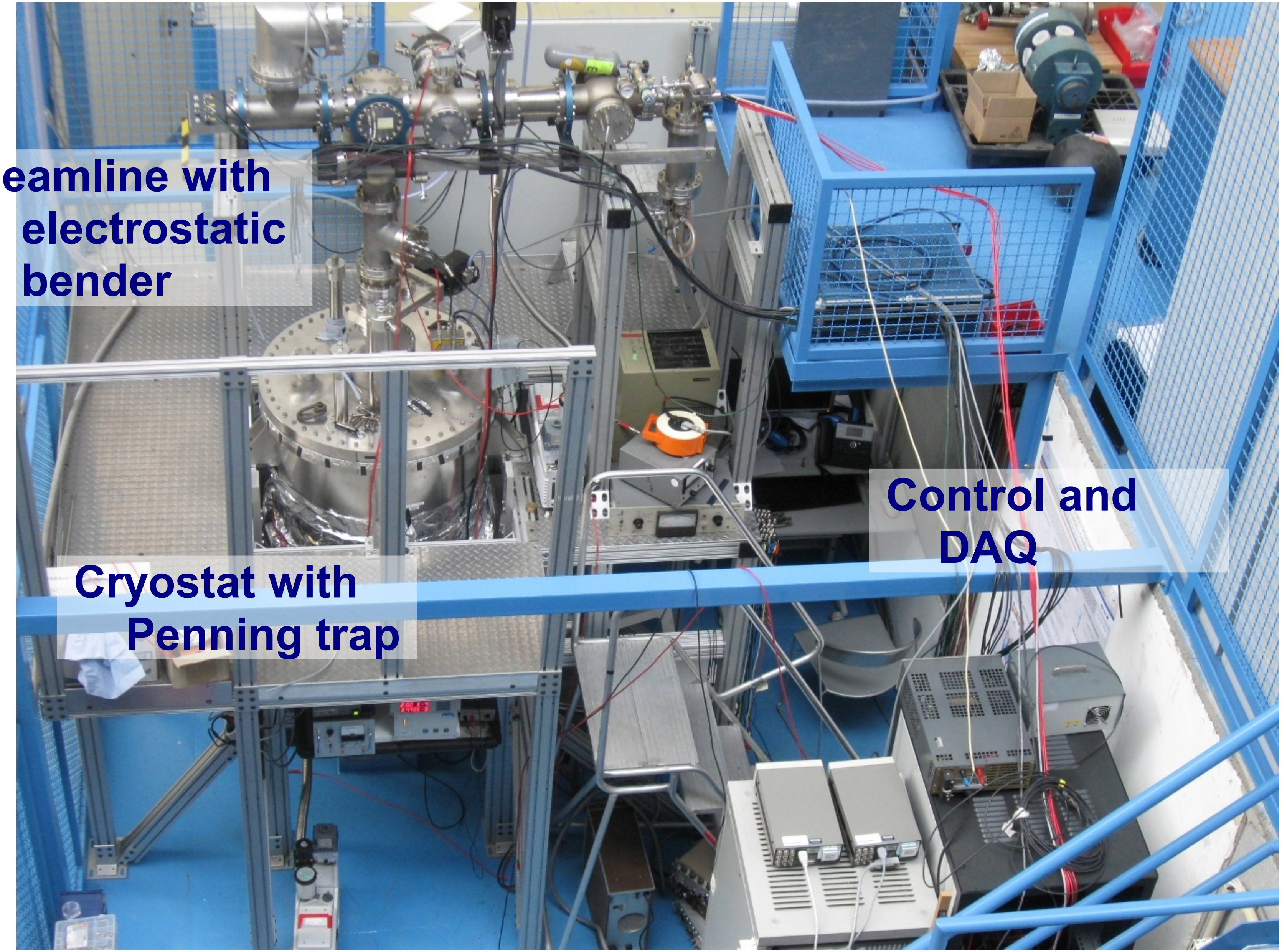
Count rate estimates:

isotope	wavelength	photon rate	detector	expected count rate
$^{209}Bi^{82+}$	244 nm	(625 ± 225) kHz	CPMs	(125 ± 45) kHz
$^{207}Pb^{81+}$	1020 nm	$(6,5 \pm 2,1)$ kHz	APDs	$(1,3 \pm 0,4)$ kHz
$^{209}Bi^{80+}$	1555 nm	$(3,4 \pm 1,0)$ kHz	Hybrid PMTs	(440 ± 130) Hz

Thesis D. Hampf, WWU Münster, 2008

→ Single photon counting capability required

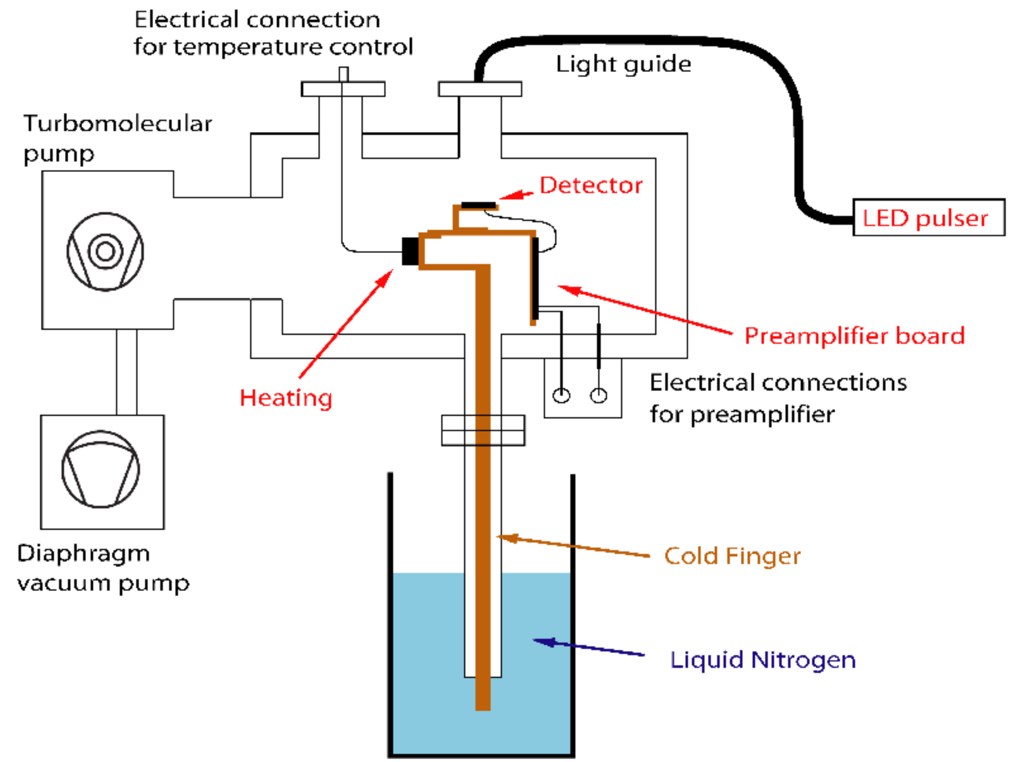
SPECTRAP: Setup

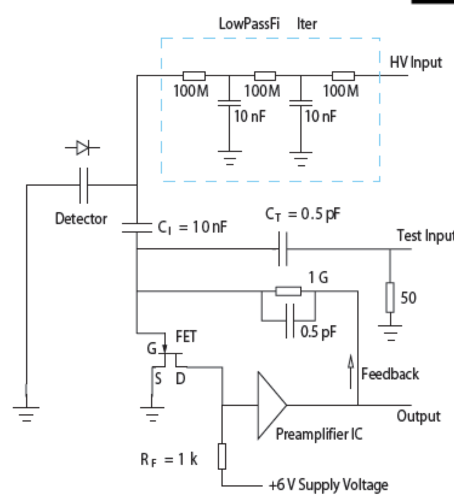


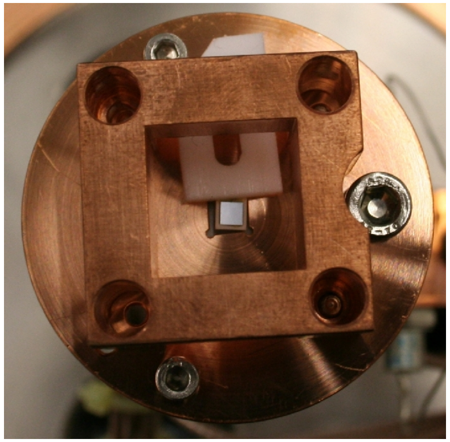
Characterizing APDs: Test Setup

- 10^{-7} mbar vacuum chamber
- Cryogenic cooling to near LN_2 temperature (-178°C @ detector)
- HV supply up to 4 kV, adjustable on 0.1 V scale
- LabVIEW based temperature control
- Single photons produced by applying 20 ns wide pulses (800 mV amplitude) to a LED
- Grating spectrograph for determination of spectral response using a continuous light source
- Specially designed preamp layout:

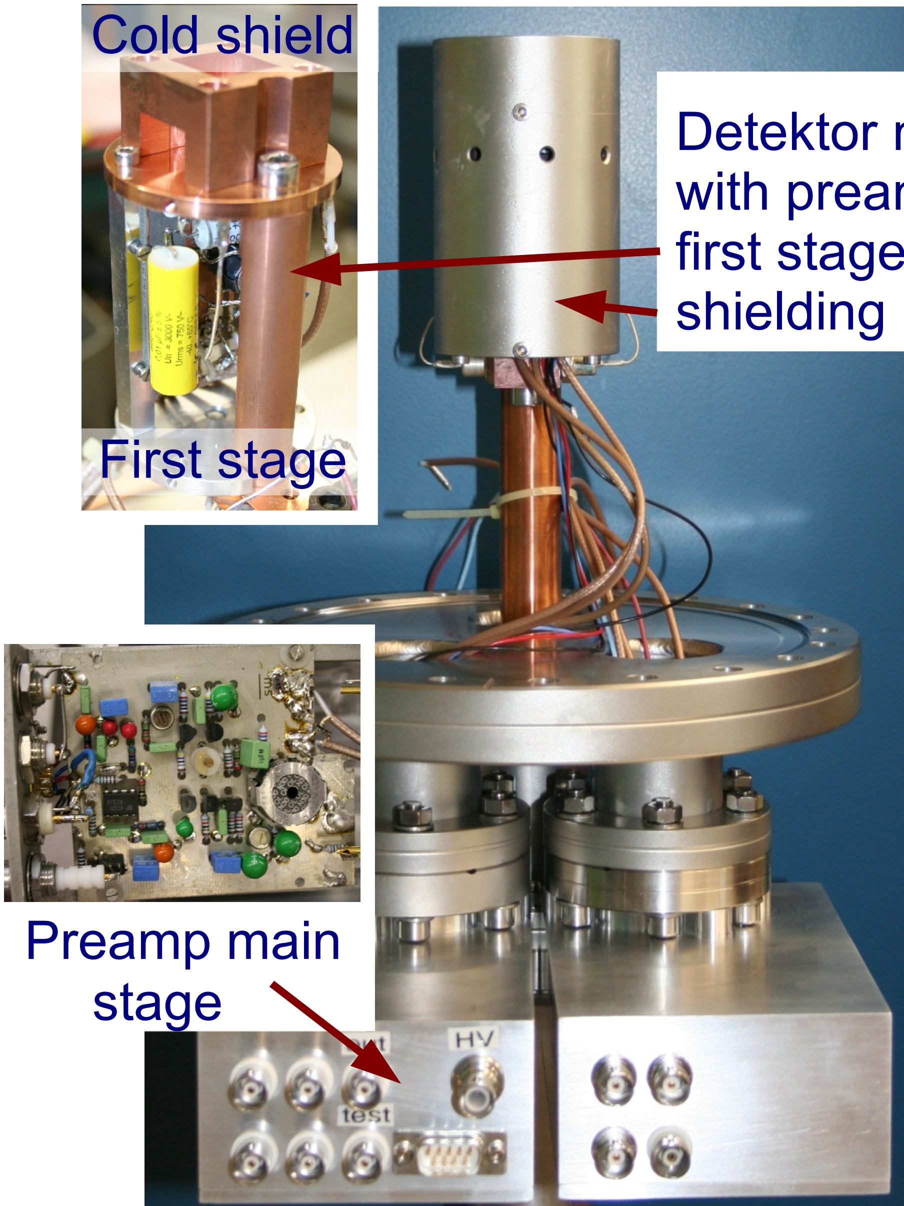
→ **Preamp equivalent noise level below 1 keV FWHM (without detector)**

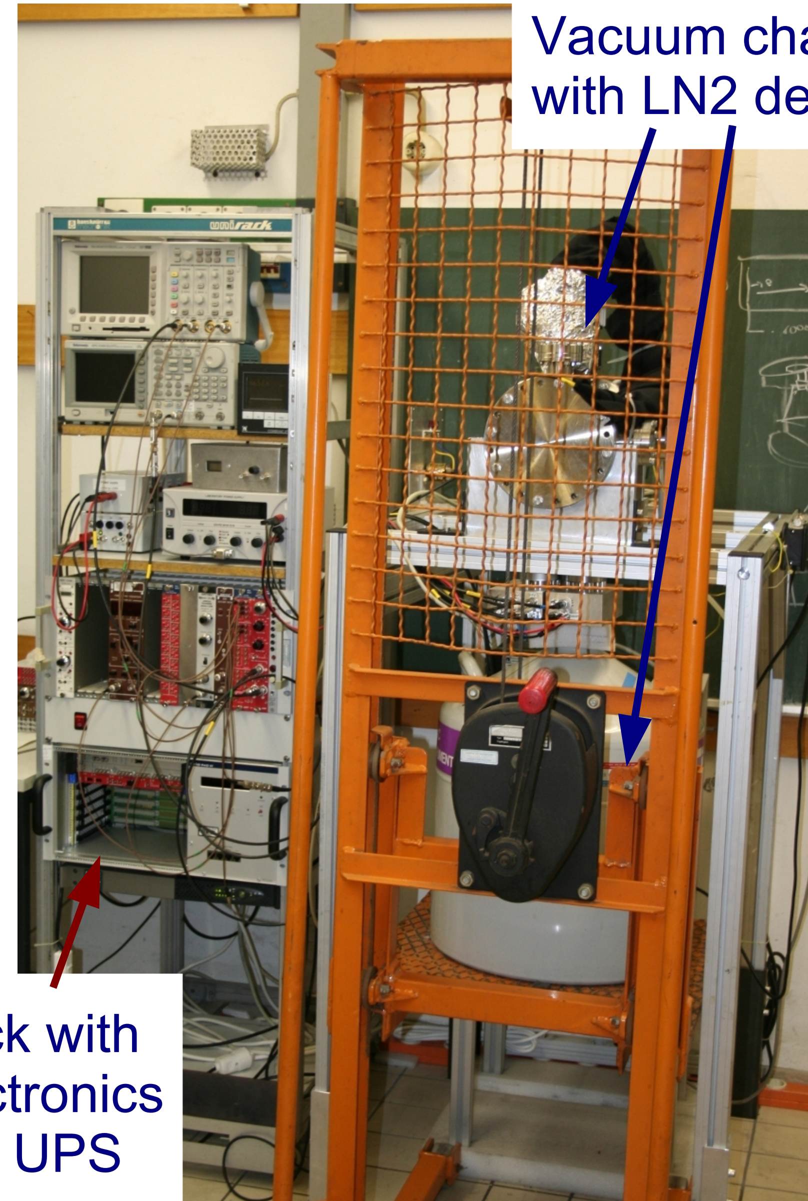






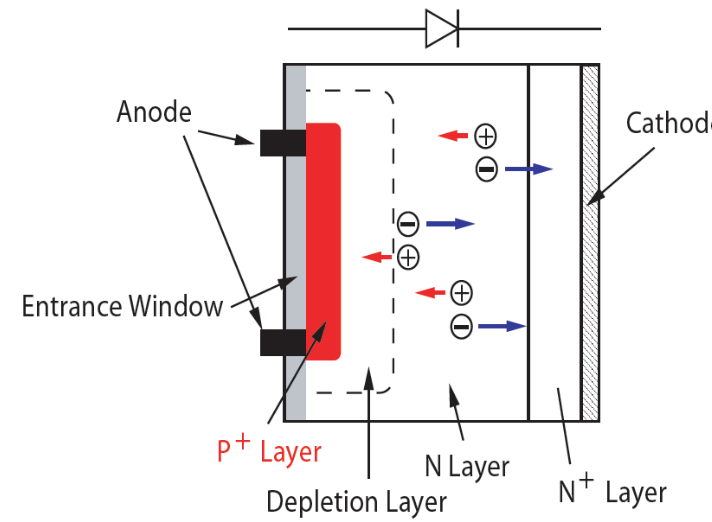
Characterizing APDs: Test Setup





Investigated APD Types

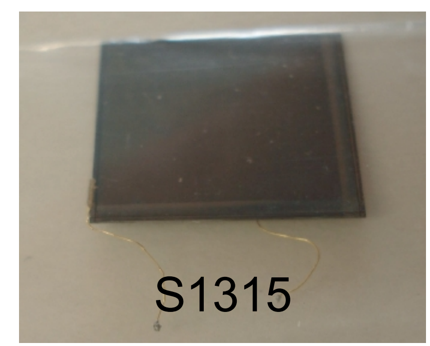
Avalanche **P**hoto **D**iodes are a special type of PIN diodes, operated at high bias voltages. Primary charge carriers are amplified by an internal avalanche process



Suitable for 300 – 1100 nm
→ H-like $^{207}Pb^{81+}$ transition at SPECTRAP (1020 nm)

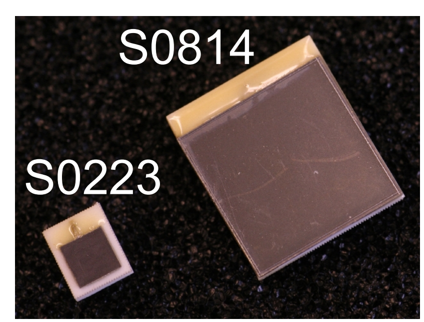
Investigated APD types:

1) RMD S1315 (13 x 13 mm^2, without substrate):
- Have been investigated for ESR measurements due to their large area
- Problems: No stable operation achieved



2) Hamamatsu S8664-20K (2 mm diameter)
- Problems: Gain at best SNR not sufficient

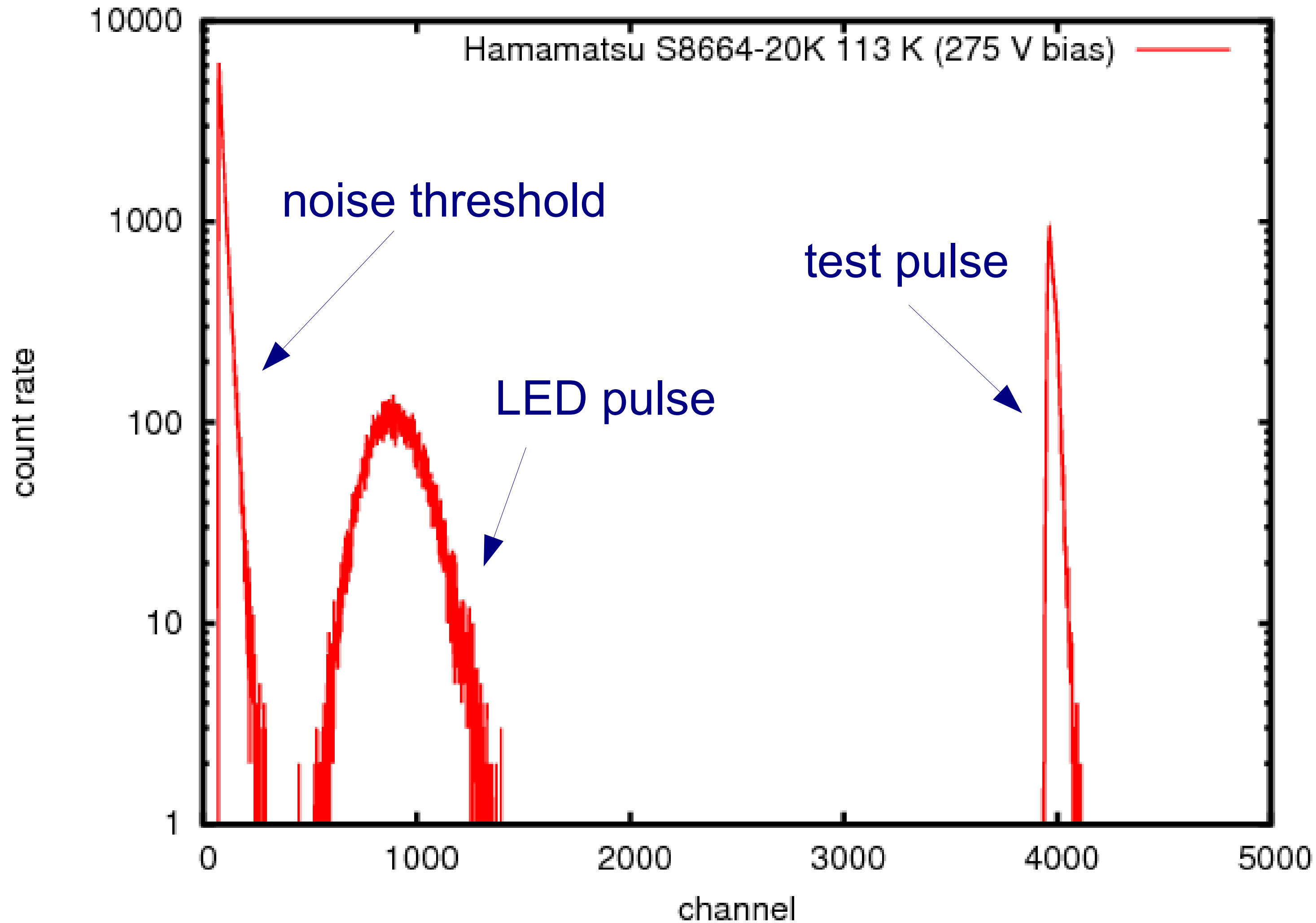
3) RMD S0223 (2 x 2 mm^2, Al_2O_3 backing,)
- High gain at optimum Noise to Gain Ratio
- Stable operation



Characterizing APDs: Measurements

- Photon Gain measured with short LED pulses which are coupled to the APD via light guide
- Gain determination by comparing amplitudes of LED pulses at different bias volages
- Mean amplitude of LED pulse at low bias voltage is defined as gain = 1
- Electronic test pulse simulates 100 keV (1 MeV) signal

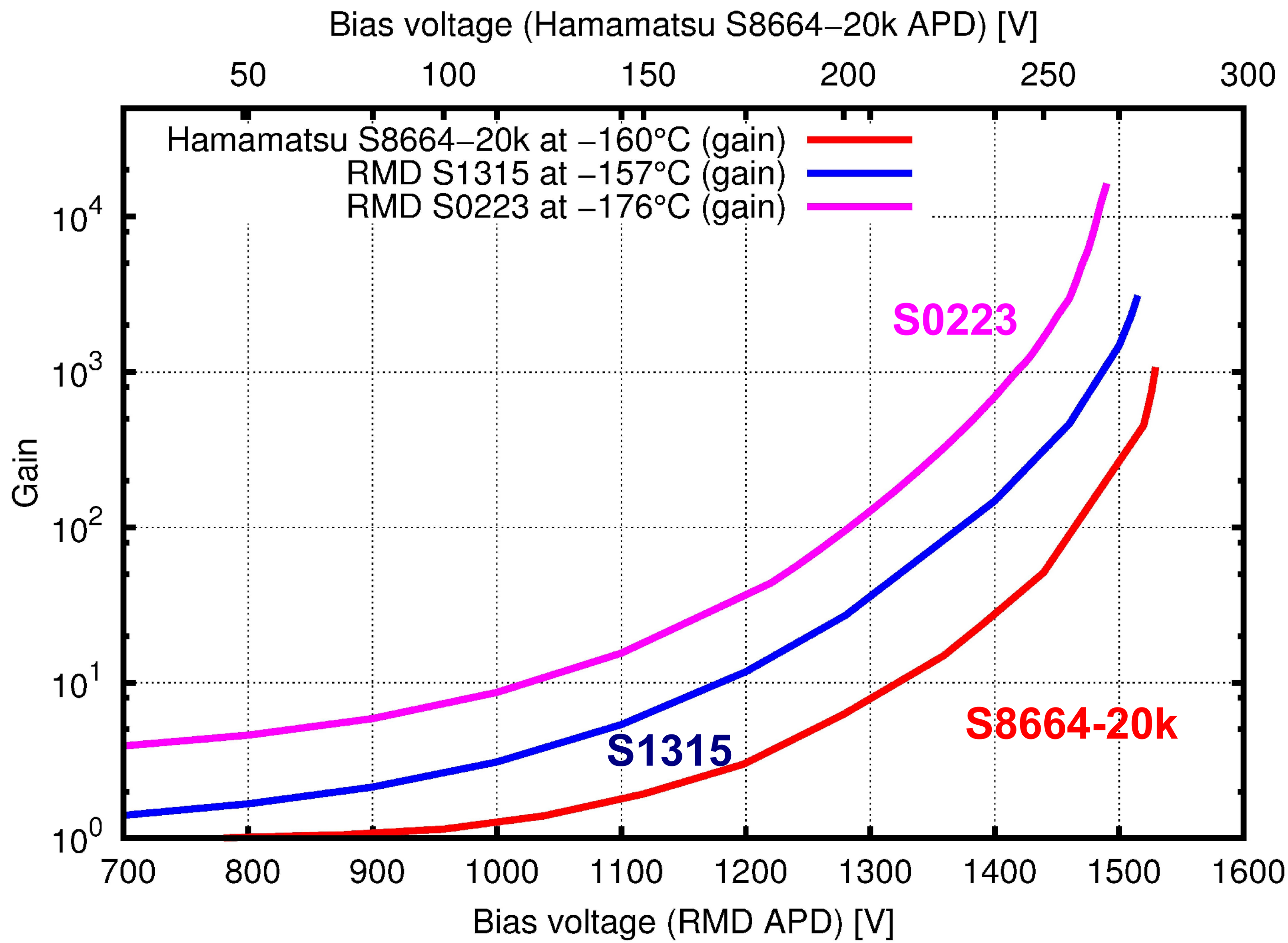
Peak sensing ADC spectrum of preamp signal



Investigation of APD gain

- Noise value is given by FWHM of the LED pulse
- Best Noise to Gain Ratio of S0223 APD at temperatures around -178°C and at 1480V bias
- Gain of about 7500 at best SNR achieved with S0223 APD
- S8664-20k and S1315 APDs exhibit large fluctuations in measured noise characteristics
- Stable operation with S0223 APD

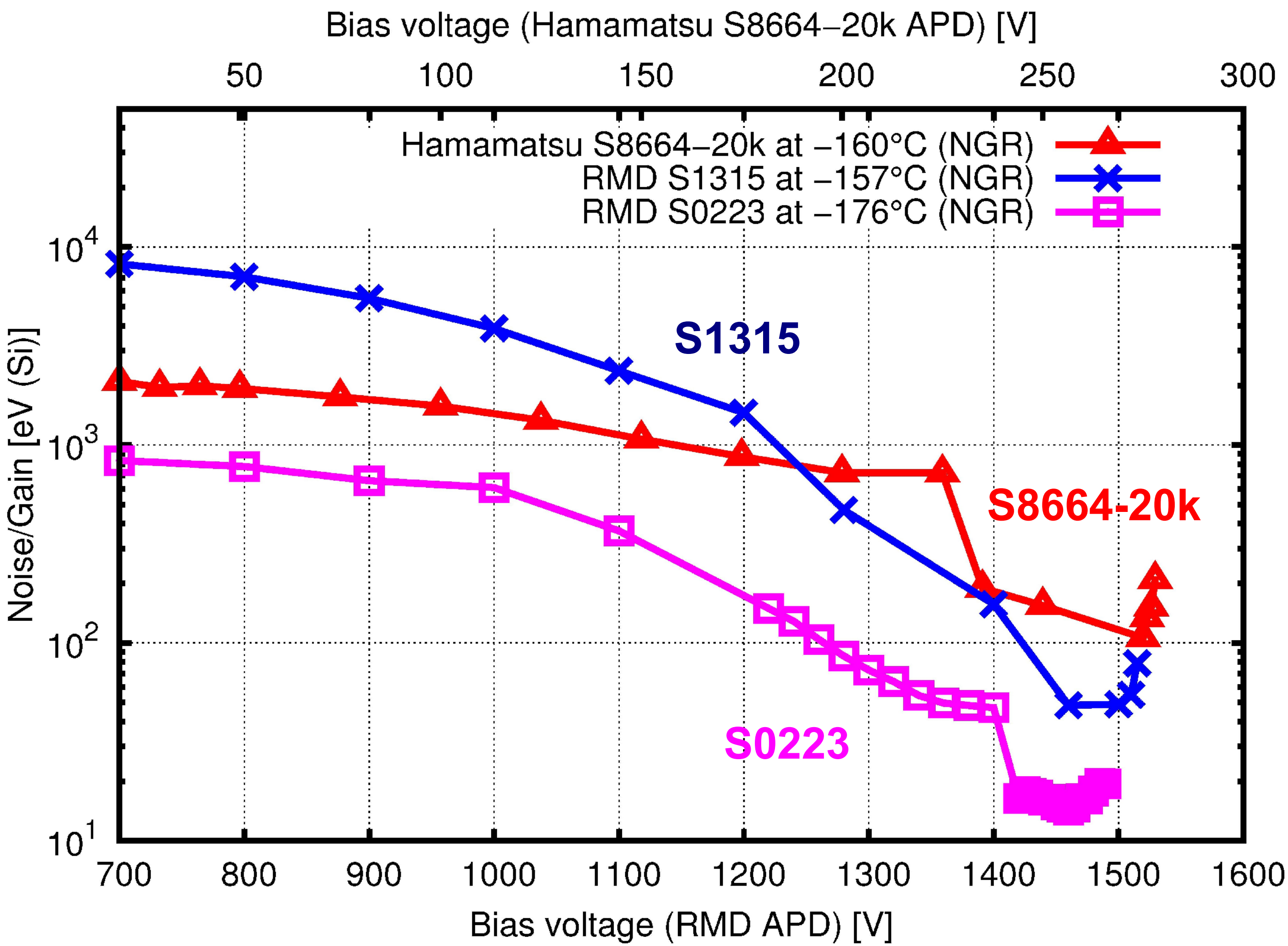
Gain of Hamamatsu S8664-20k type APD and RMD APD types S1315 and S0223



Determination of APD working point

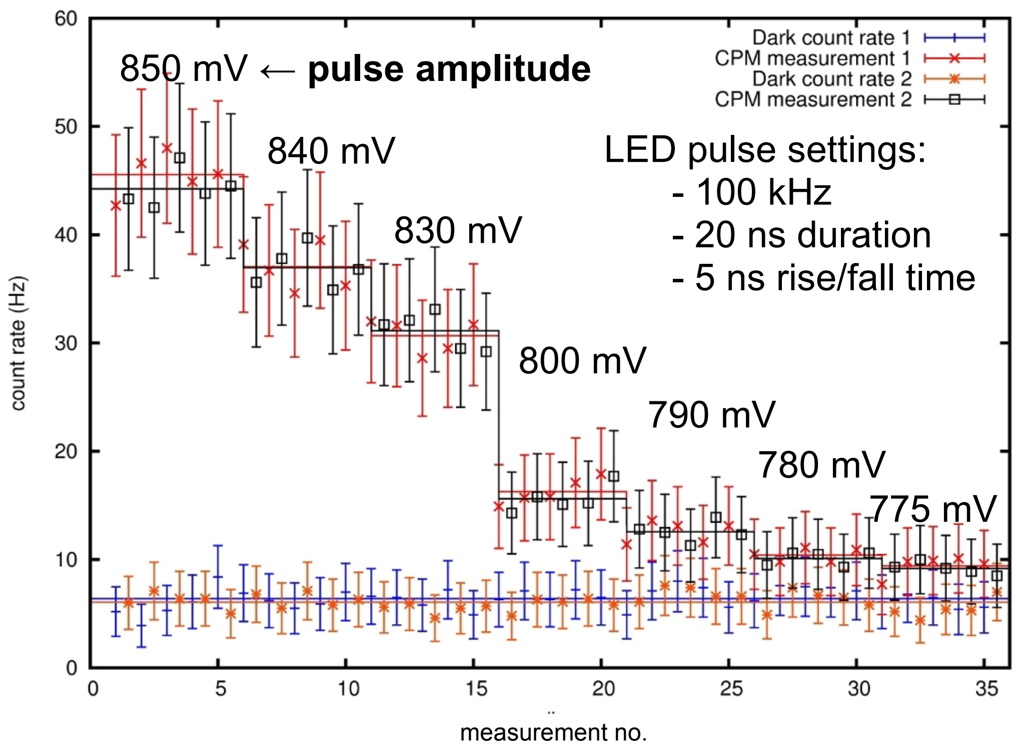
- Noise value is given by FWHM of the LED pulse
- Best Noise to Gain Ratio of S0223 APD at temperatures around -178°C and at 1480V bias
- Gain of about 7500 at best SNR achieved with S0223 APD
- S8664-20k and S1315 APDs exhibit large fluctuations in measured noise characteristics
- Stable operation with S0223 APD

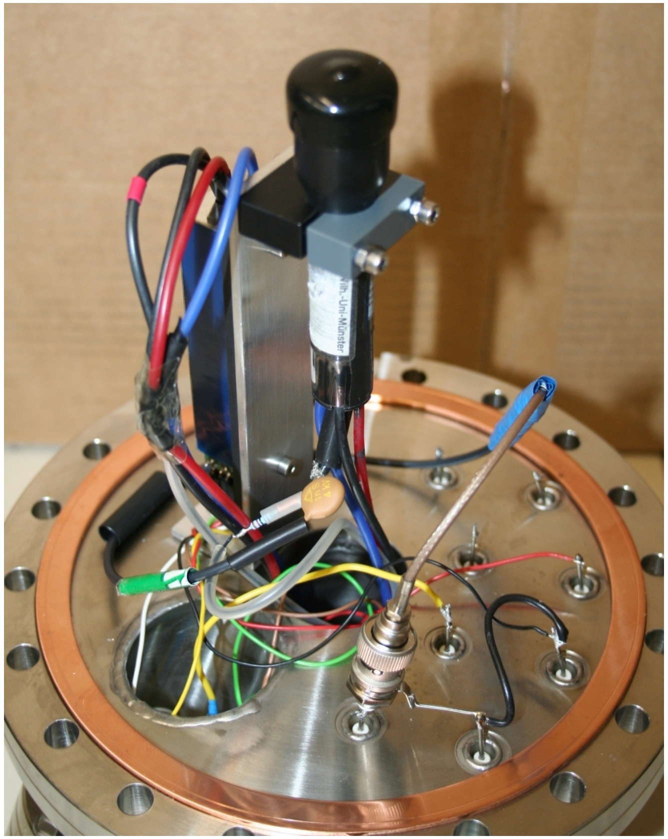
Noise to Gain Ratio of Hamamatsu S8664-20k type APD and RMD APD types S1315 and S0223



Calibration of photon rates

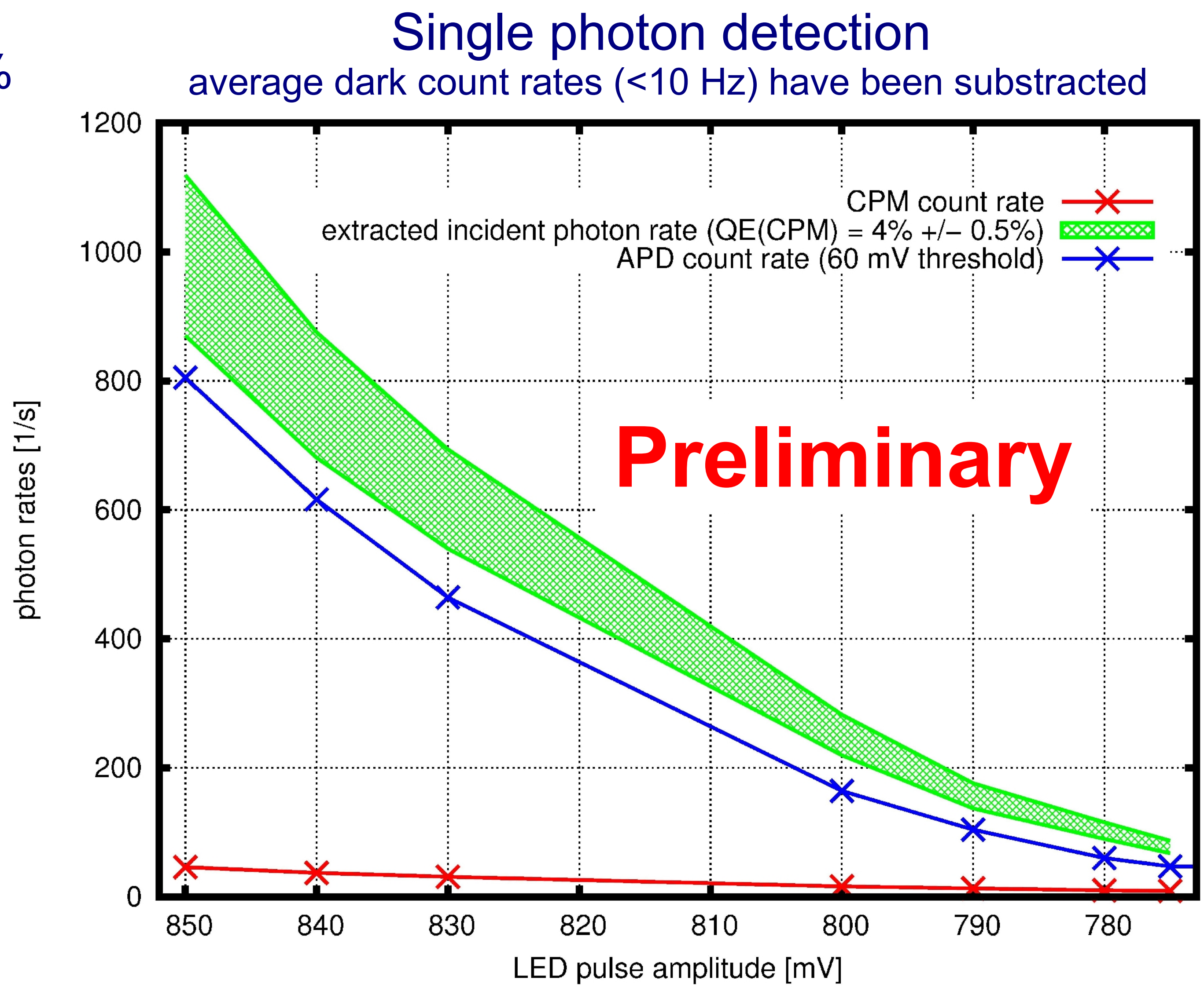
- Channel Photomultiplier as reference detector for Single-Photon sensitivity tests (well known single photon response and QE)
- PerkinElmer CPM 1993 with 2 mm aperture at the same position as S0223 APD
- Determine dark count rate and signal rate for different settings of pulsed LED
  → extract photon rates incident on APD





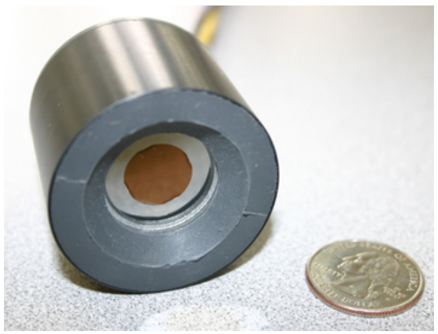
Extracted photon rates

- Assuming a QE = (4±0.5)% for the CPM at 635 nm, we can calculate incident photon rates for the given 2 mm aperture
- APD dark count rate < 10 Hz at 60 mV threshold
- Mean value for Photo Detection Efficiency of S0223 APD at 635 nm: 62% - 79%
- Consistent with QE = 68% from RMD datasheet



Detectors for 1500 nm Transitions

Intevac Intensified Photodiodes (IPD)



- Active diameter: Ø 1 mm
- Dark counts: ~2 MHz @ -40°C
- QE @ 1500 nm: ~20%
- Measuring time per wavelength:

$$t = \frac{n_\sigma \cdot (dark\ counts)}{S^2 \cdot \epsilon^2} = 92\text{s}$$

with S = 3.4 kHz, n_σ = 3 and
ε = QE • CE (65%) = 0.13

→ Status: 2 devices ordered

Hamamatsu NIR PMT Module

- Active diameter: Ø 18 mm detection diameter for collimated light, Ø 1.6 mm effective PMT diameter
- Dark counts: ~200 kHz @ -60°C
- QE @ 1500 nm: ~2%
- Measuring time per wavelength:

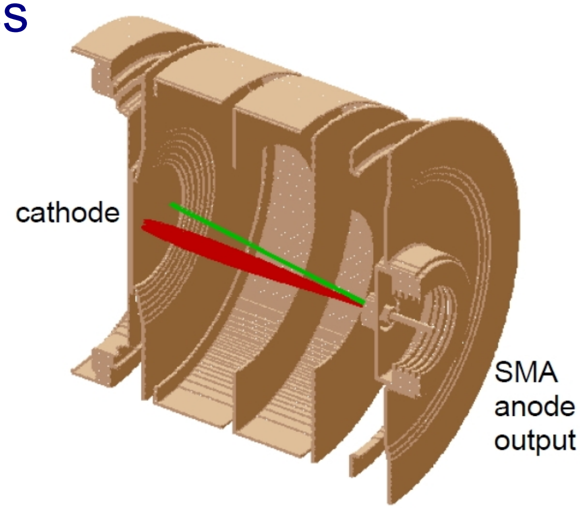
$$t = \frac{3 \cdot 2 \cdot 10^5\ 1/s}{3400^2\ 1/s^2 \cdot 0.017^2} = 538\text{s}$$

→ Status: Device obtained on a loan basis from Hamamatsu and tested

Intevac IPD

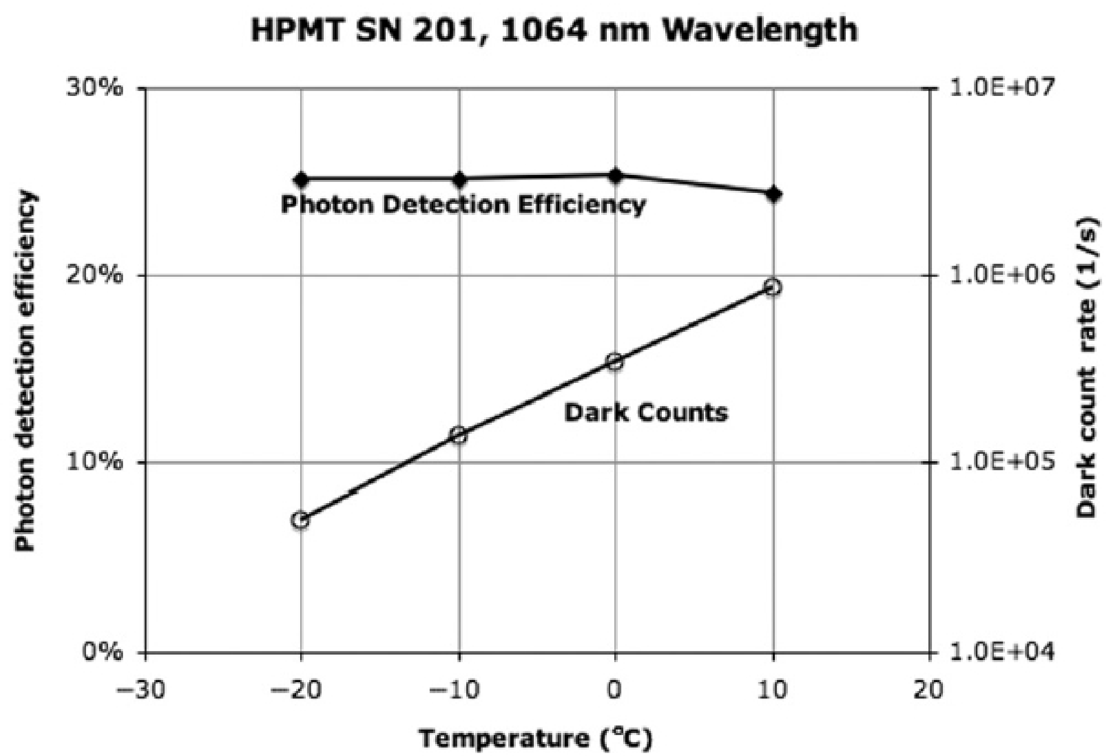
Operating principle:

- Primary electron from InGaAs Cathode (930 nm – 1650 nm)
- Electrostatic acceleration of primary electron onto an APD
- Up to 1000 charge carriers per incident electron
- Another amplification by factor ~10 due to the APD's avalanche process



Road map:

- Build custom housing for operation and cooling
- Investigate dark count rate as shown for InGaAsP type IPD (up to 1300 nm):

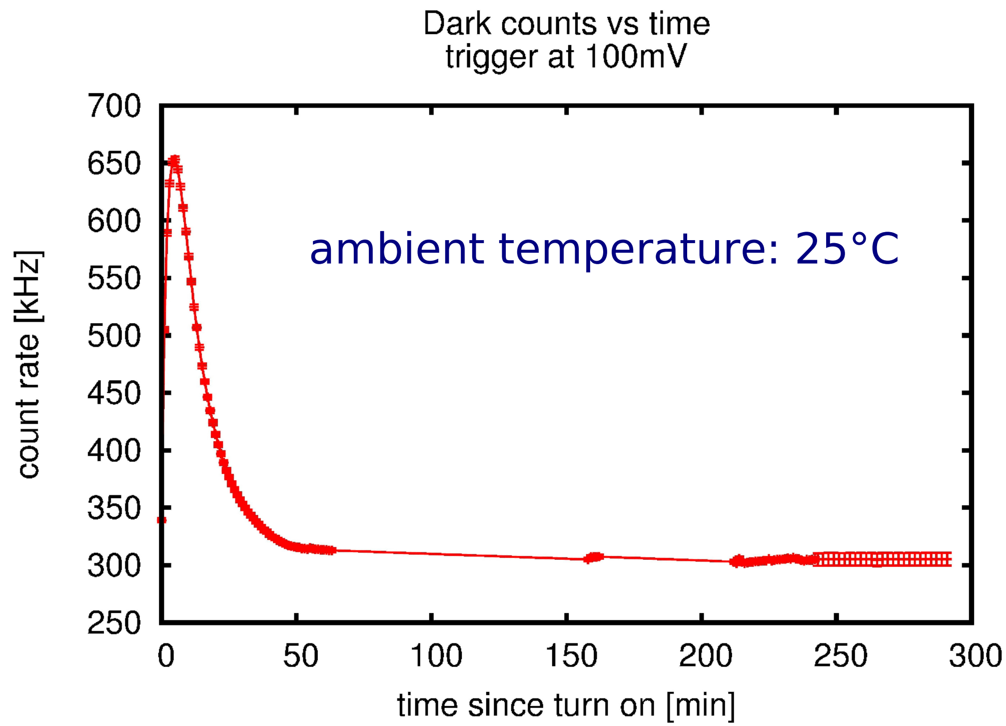


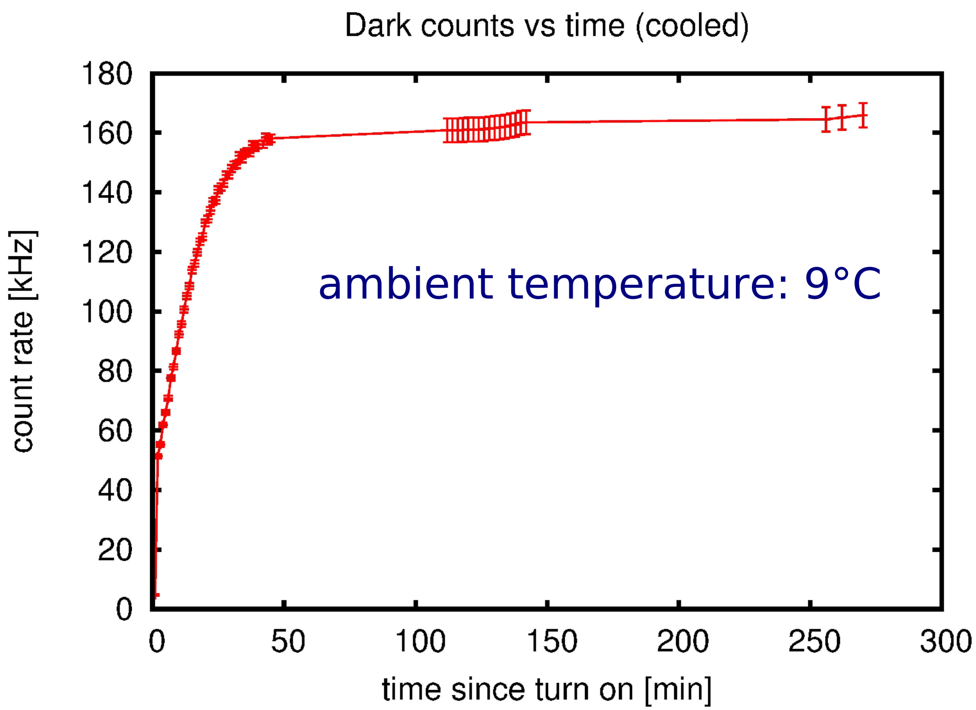
Xiaoli Sun *et al*., Journal of Modern Optics, Vol. 56, Nos. 2–3, 2009, 284–295

Test: Hamamatsu NIR PMT Module

Test results:

- Dark count rate of 300 kHz observed at 25°C ambient temperature
- At 9°C ambient temperature: 160 kHz dark counts, but signal rate decreased by factor 2





→ More investigation required

→ Find best operating temperature i.e. best QE to noise ratio

→ PMT module is fall back solution in case Intevac IPDs exhibit problems

Summary

- The SPECTRAP experiment will perform precision measurements of hyperfine transitions in selected H-like and Li-like HCI to test QED
- Due to long lifetimes of these states and limited solid angle we expect fluorescence photon rates in the kHz region
  → Single-Photon detection capabilities required
- APDs provide high QE and moderate gain at visible and NIR wavelengths up to 1100 nm (SPECTRAP: H-like $^{207}Pb^{81+}$ transition at 1020 nm)
- Current tests at 635 nm have shown a Photo Detection Efficiency (PDE) in the 62% - 79% range at dark count rates < 10 Hz
- Determination of PDE at 1020 nm requires a calibrated Single-Photon source at that wavelength
  → Possibility of using correlated photons
- Detectors for 1555 nm Li-like $^{209}Bi^{80+}$ transition under investigation