Operational experience with profile monitors for MeV and keV antiproton beams at CERN AD

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Antimatter research at MPI for Quantum Optics

The following people are involved in the detector, laser, and trap development work described here:

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European Science Foundation
Setting science agendas for Europe

Munich-Centre for Advanced Photonics (MAP)

CERN

文部科学省
Ministry of Education, Culture, Sports, Science and Technology-Japan

財団法人 三菱財団
The Mitsubishi Foundation

ASACUSA collaboration

Atomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons

1997 at Antiproton Decelerator (AD) of CERN

University of Tokyo,
Max Planck Institute for Quantum Optics,
RIKEN,
SMI Vienna,
KFKI Budapest,
INFN Brescia,
Aarhus University,
University of Swansea,
Queens University of Belfast,
ATOMKI, Debrecen

Asakusa, Tokyo

We use antiproton beams of various energies for atomic and nuclear physics experiments:

- **5 MeV** -- microwave spectroscopy of antiprotonic helium atoms

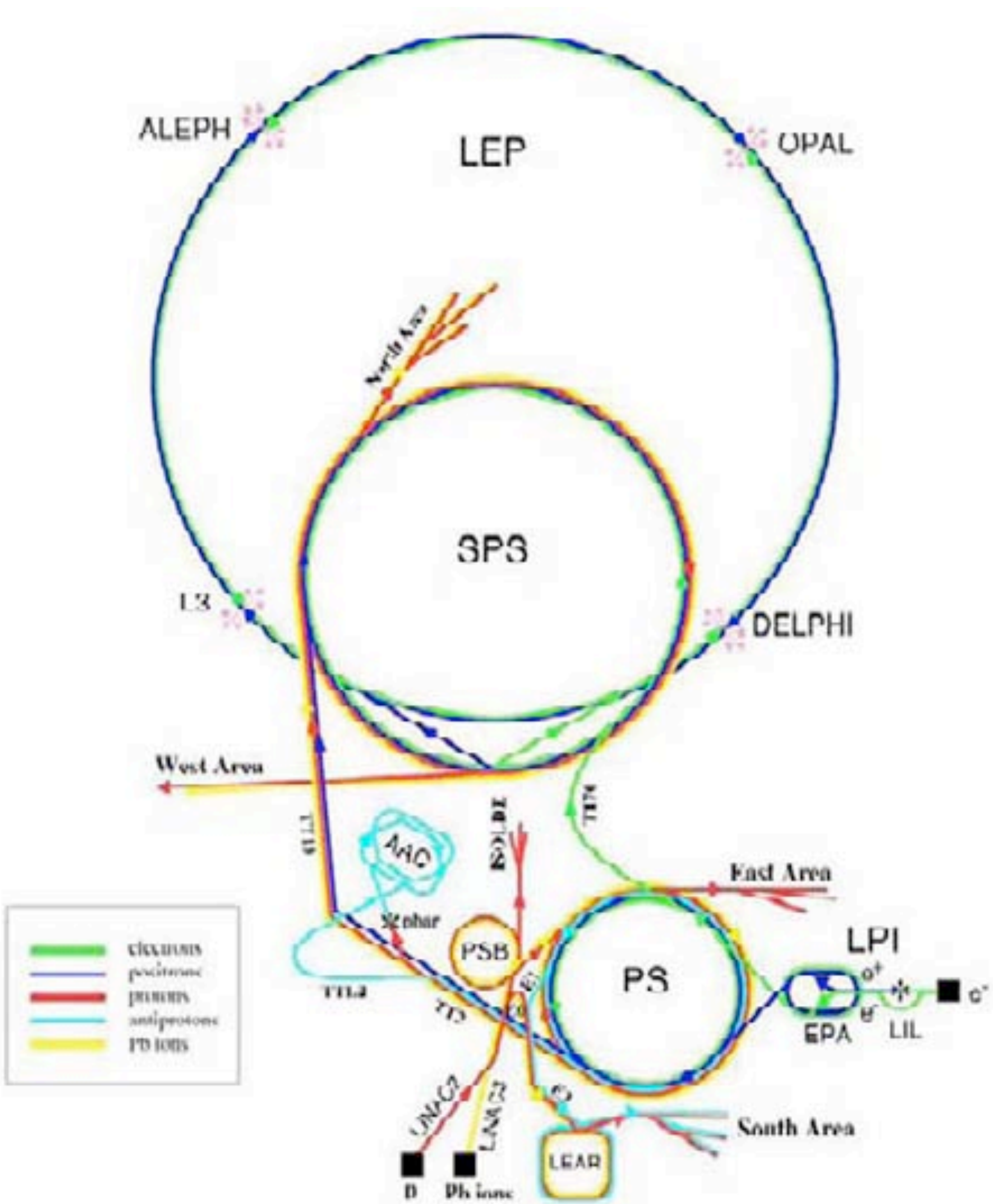
- **60 -100 keV** -- Doppler-free 2-photon-spectroscopy of antiprotonic helium: antiproton to electron mass ratio, CPT test

- **100 eV** -- atomic ionization experiments with antiprotons on hydrogen, helium and argon gases

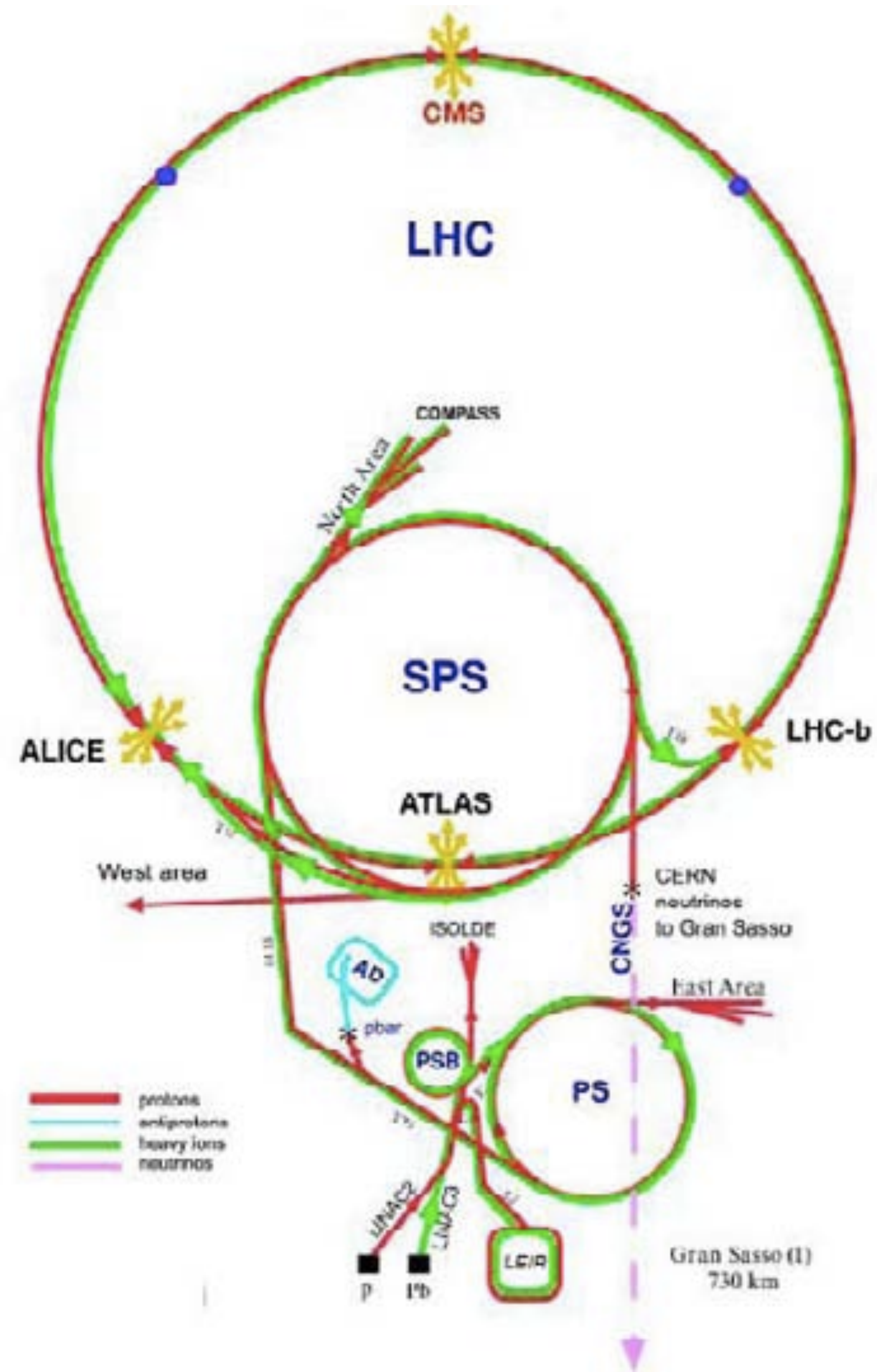
- **< 1 eV** -- antihydrogen production in traps

Accelerators at CERN

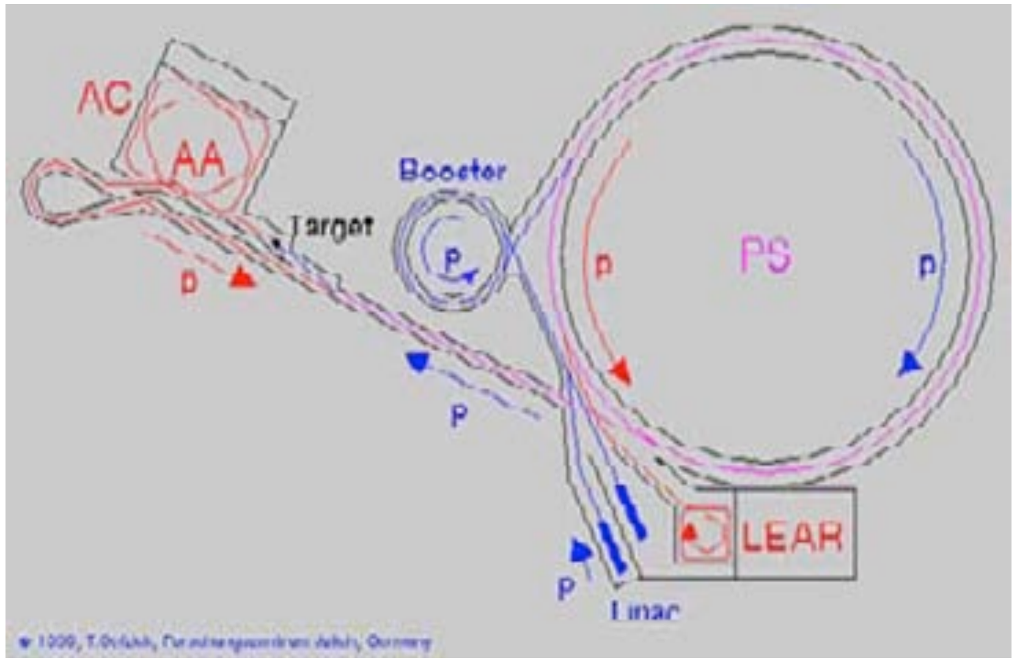
LEAR (1983-1996)



AD (1999-)



History: LEAR (Low Energy Antiproton Ring)

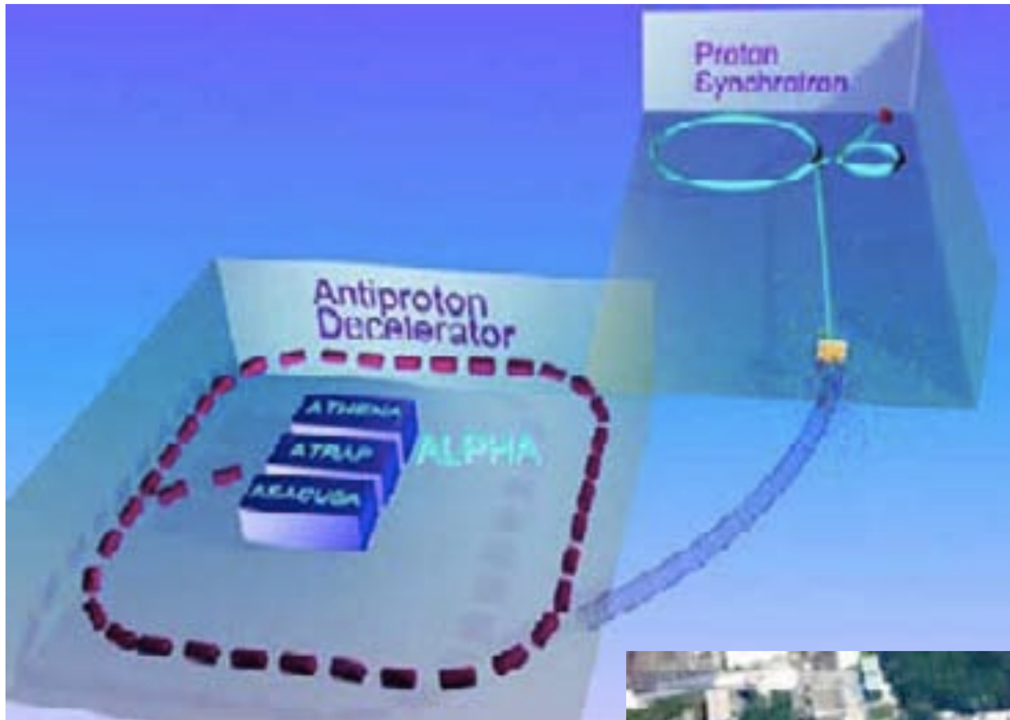


All photos from CERN archives

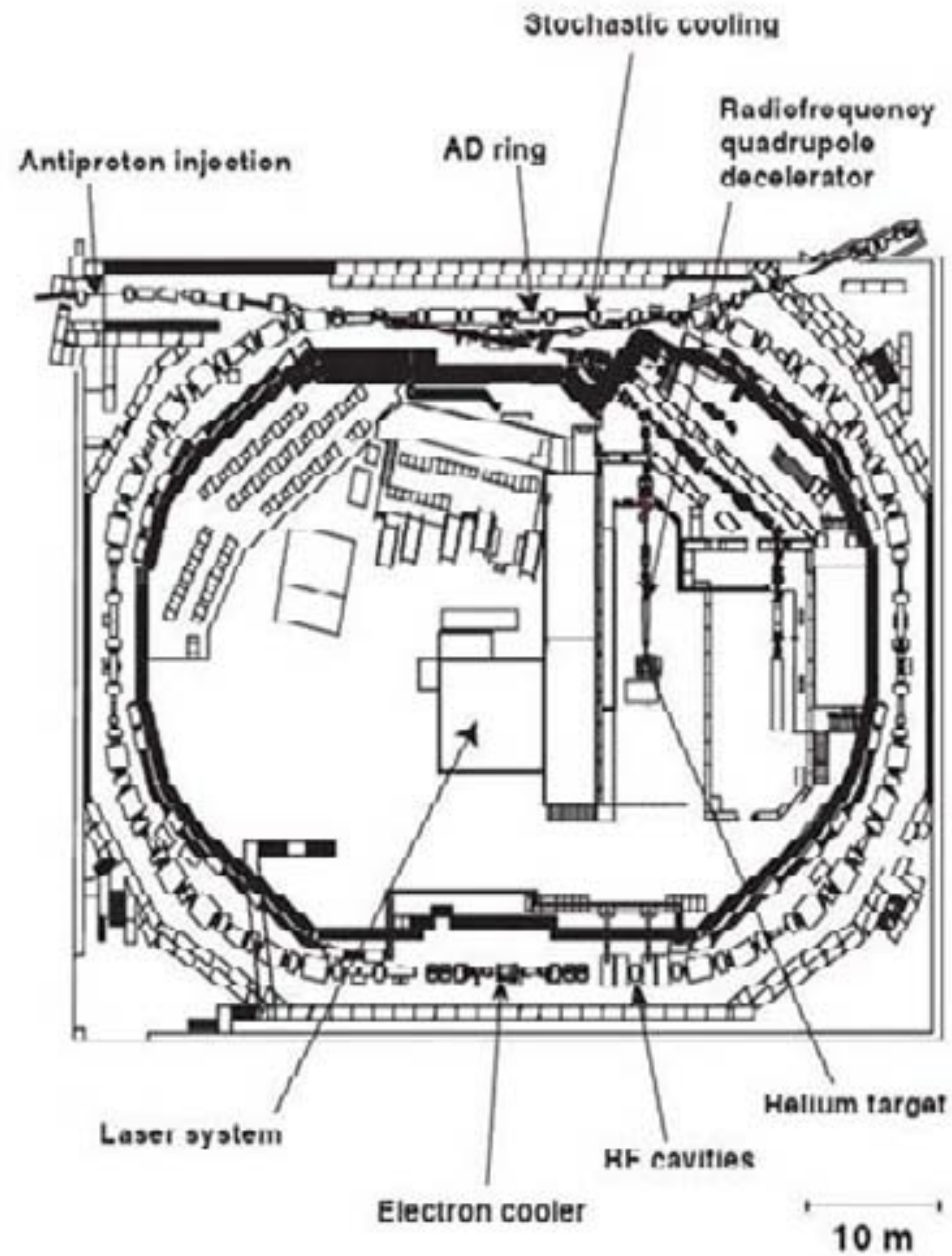
- construction: 1983
- Antiproton production with 26-GeV beam of PS
- Captured by Antiproton Collector
- Stored by Antiproton Accumulator
- Decelerated to 609 MeV/c by PS
- Injected to LEAR.
- Provided 10^{10} antiprotons within 10 minutes
- pulsed and continuous beams
- energy range from 5 MeV above 1 GeV
- shutdown: 1996

The Antiproton Decelerator at CERN

- constructed in 1999 using US, European, Japanese user funding.
- low-cost antiproton facility, dedicated to atomic physics (antihydrogen) experiments,
- 188 m synchrotron
- All-in-one: capture, deceleration, cooling, ejection

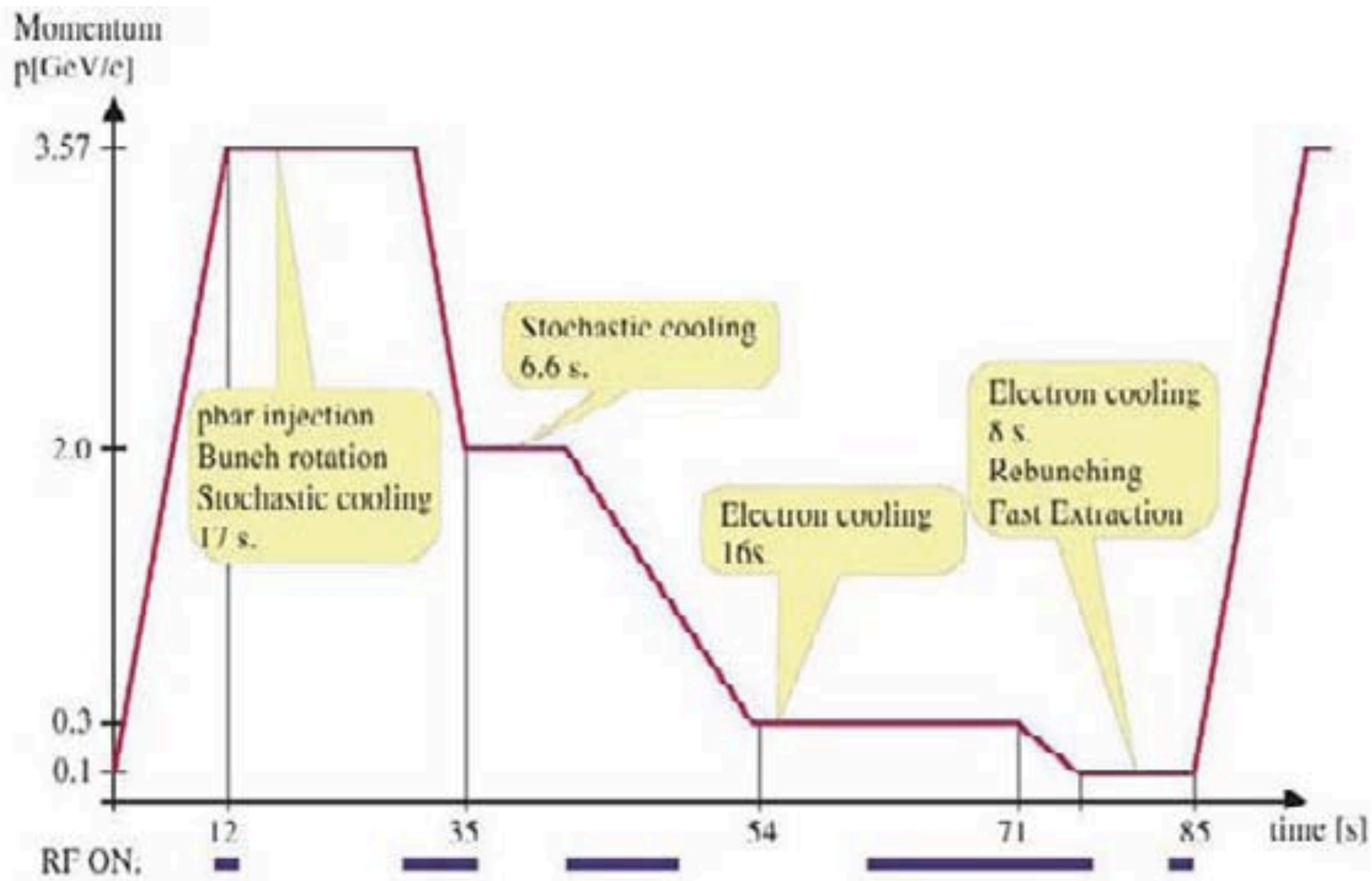


All photos from CERN archives



Cooling and decelerations at AD

- **Injection at 3.5 GeV/c,**
  - transverse acceptance ~ 200 π mm mrad
  - momentum spread Δp/p = 6 %, after pulse stretching 1.5 %
- **After stochastic cooling and decelerations:**
  - deceleration by RF fields in 2 steps (2 GeV/c .... 300 MeV/c), between them stochastic cooling
  - emittance ~ 3-4 π mm mrad
  - momentum spread Δp/p ~ 0.07%
- **After electron coolings and deceleration:**
  - emittance ~ 0.3 π mm mrad
  - momentum spread Δp/p ~ 0.01%

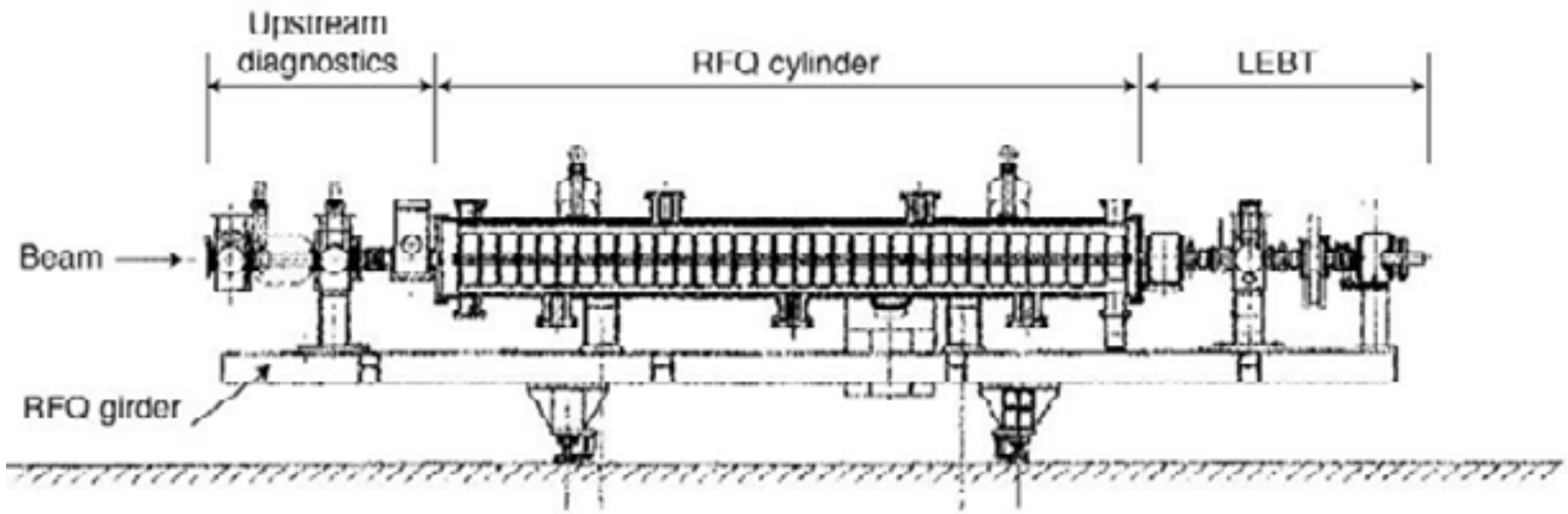


~ 4 × 10^7 100 MeV/c antiprotons every 85 s

Pavel Belochitskii: AIP Conf. Proc. 821 (2006) 48

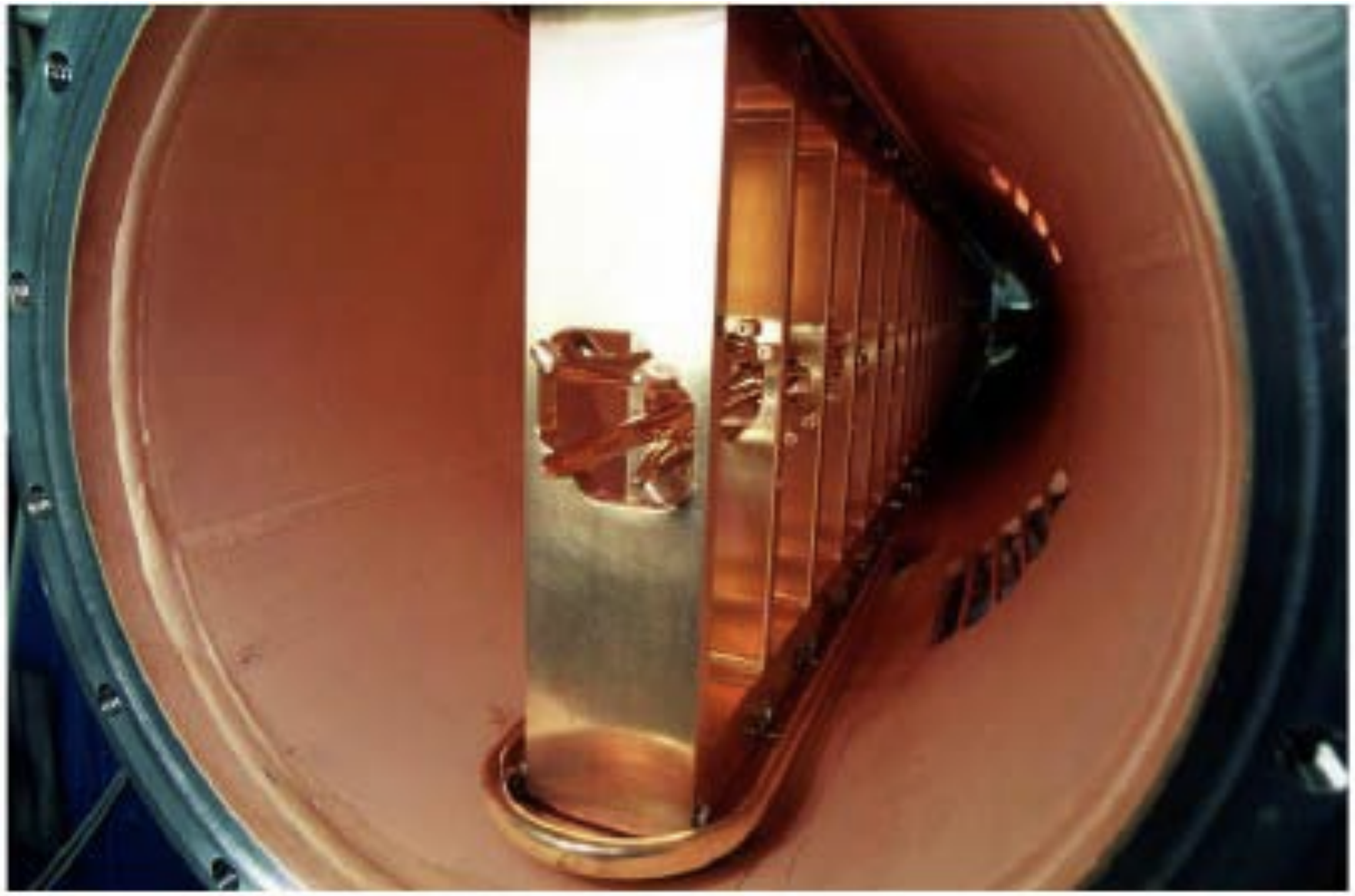
- **Ejection:** 100-ns-long beam, 4x10^7 antiprotons of energy 5.3 MeV

The RFQD



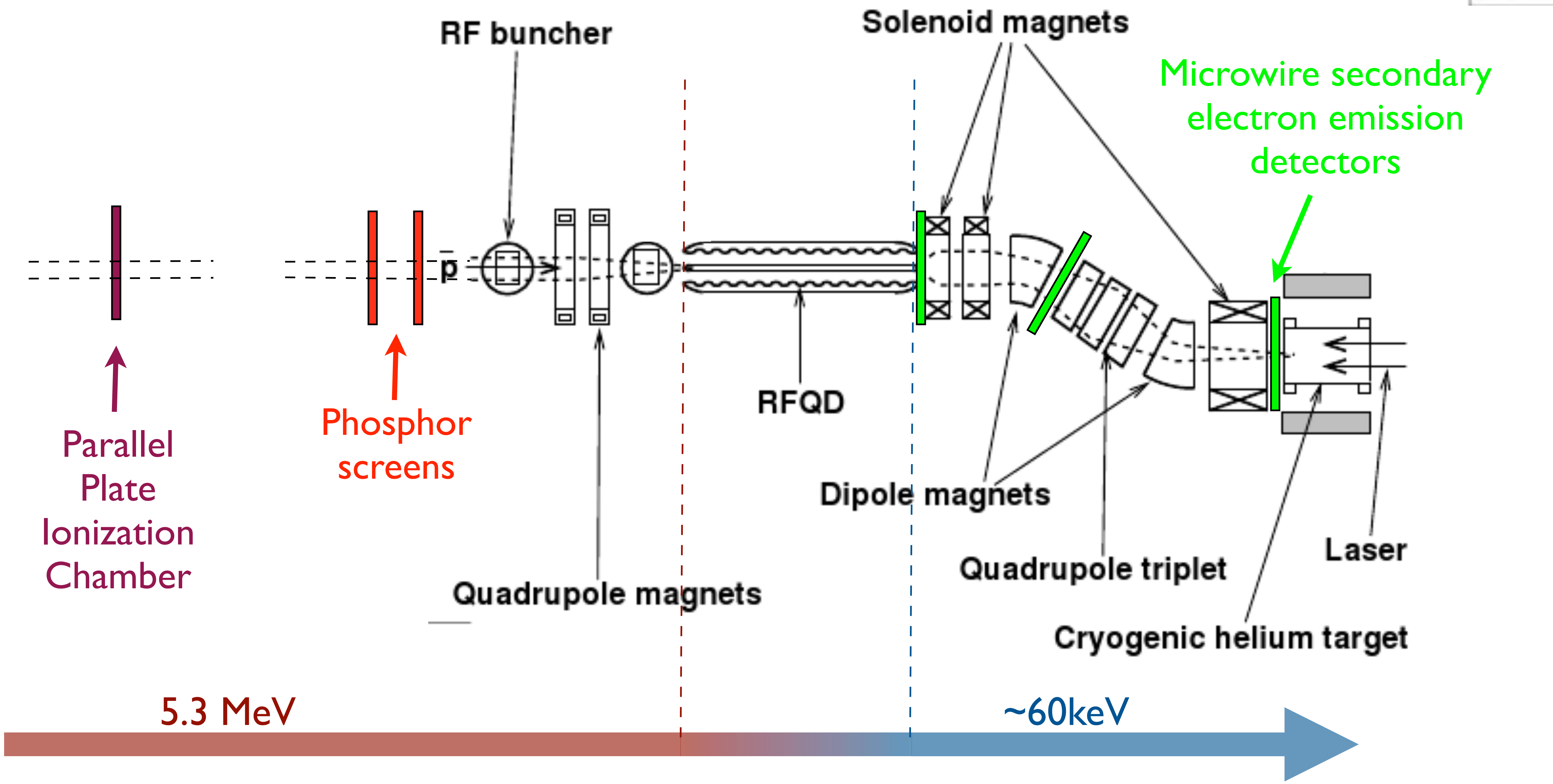
CERN and ASACUSA constructed the **RFQD** (Radiofequency Quadrupole Decelerator) to decelerate the antiprotons from **5.3 MeV** to **keV** energies needed for atomic physics experiments.

- Energy variable 10-130 keV
- f=202.5 MHz
- 3.5 m long, 30 RF cells in ladder structure, 33 MV/m peak electric field
- buncher + energy corrector +RFQ
- Pulse rate 1 Hz
- 30 mm aperature, deceleration efficiency >25%.



All photos from CERN archives

The RFQD and the low-energy beam transport

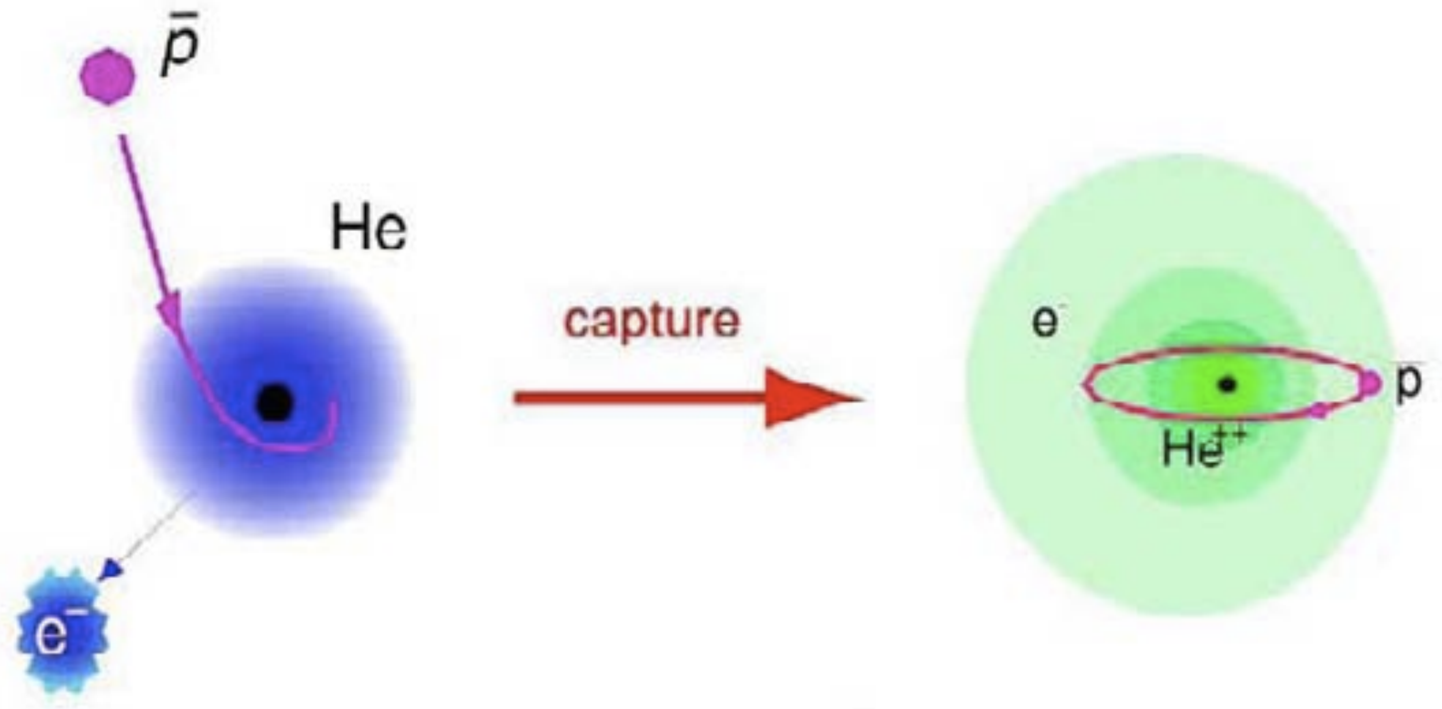


PRL 91, 123401 (2003) M. Hori et al.

the low-energy beam is transported by an acromatic momentum selector:

- 2 dipoles, a matching quadrupole triplet
- point-to-point focus

High-precision spectroscopy of antiprotonic helium



metastable 3-body system

~ 4 µs lifetime

exciting the antiproton transitions with laser beams ⟶ high-precision methods to investigate the antiproton mass and fundamental symmetries.

highlighted results: $m_{antiproton}/m_{electron}$ = 1836.152674(5)
(M. Hori et al, PRL 96, 243401 (2006))

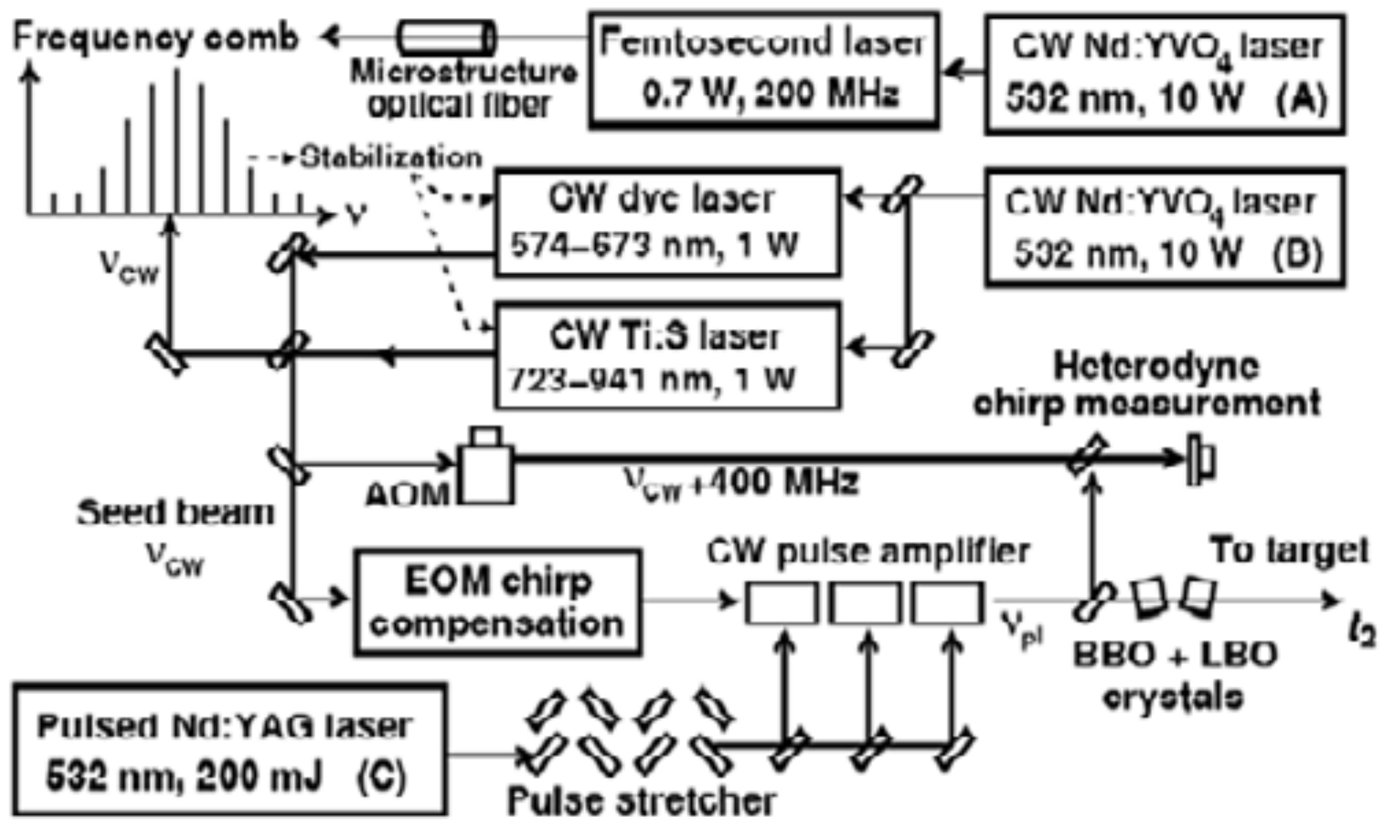
assuming *CPT* symmetry, result was used as one of the data sets in CODATA2006 to determine the $m_{proton}/m_{electron}$ mass ratio

Laser and trap developments

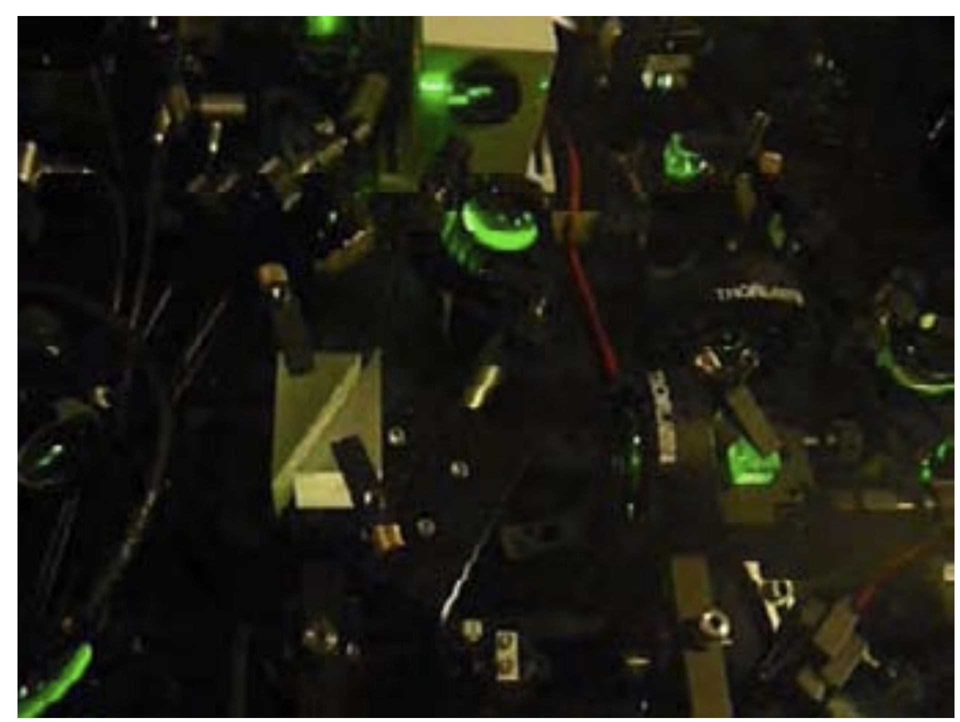
At MPQ and CERN:

• high-precision laser systems (stabilization by frequency comb, chirp-compensated pulse-amplification)

• radiofrequency traps



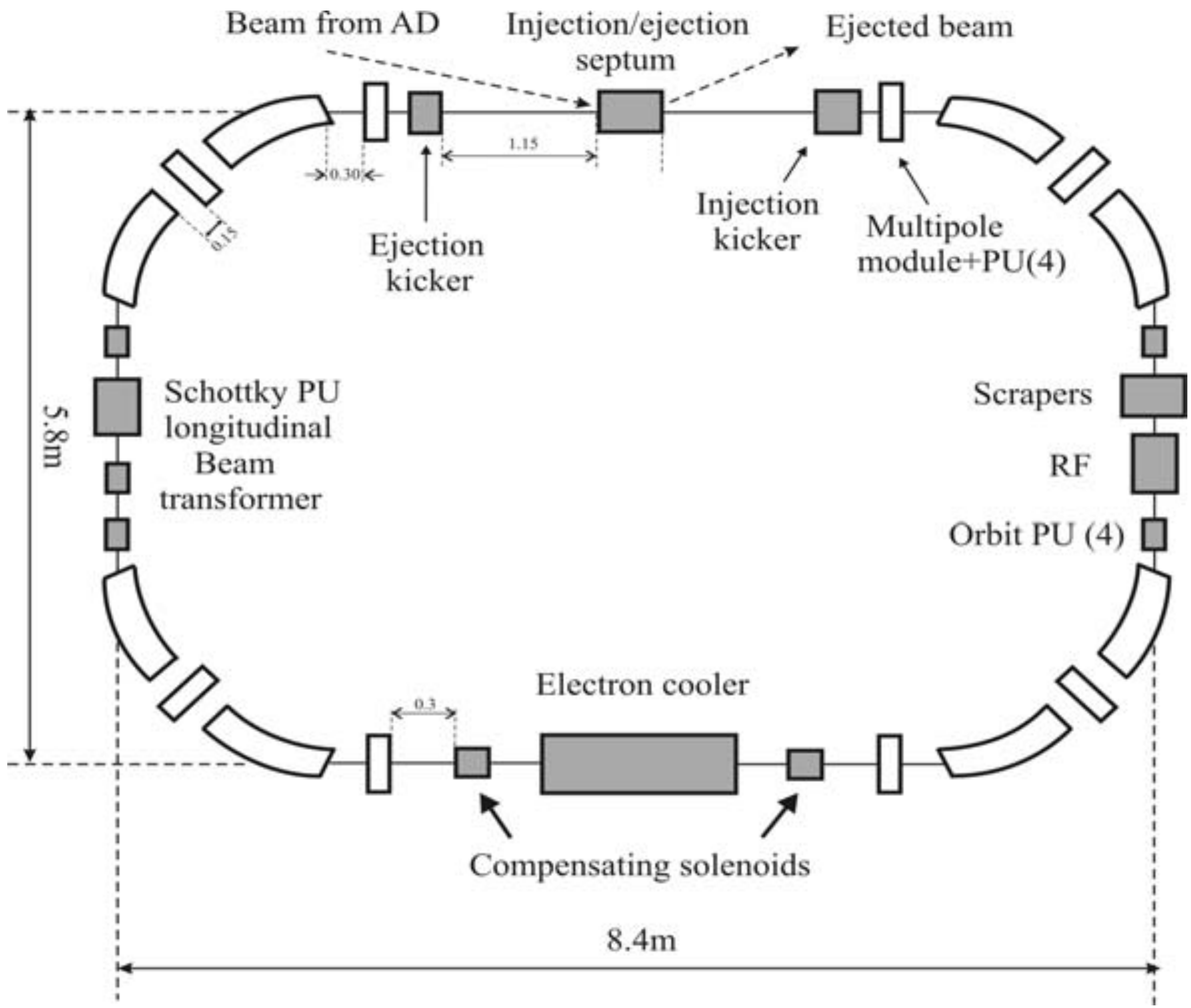
(M. Hori et al, PRL 96, 243401 (2006))



Future: ELENA, the possible extension of AD

Our group is participating in a proposed project to build a new storage ring inside the AD, which can provide:

- 100 keV electron-cooled antiprotons
- intensity up to ~ $2*10^7$
- $\Delta p/p$ ~ 0.2%
- emittance: 5 π mm mrad



(M. -E. Angoletta et. al., CERN-AB-2007-079, 2007)

Measuring antiproton beams

Beam profile and intensity measurements of MeV - GeV antiproton beams were studied in the 1970's to 90's at FNAL and CERN

MWPC's, flying wires, residual gas ionization detectors, Schottky pickups, scintillation and phosphor screens, intensified cameras, parallel plate ionization and avalanche detectors.

keV to eV beams were studied at AD in the 90's and 2000's.

Secondary electron emission detectors, microchannel plates, delay line anodes, pixel detectors.

Design constraints of detectors for AD and beyond

Strong magnetic field and low temperature and UHV: some detectors work in $B>1$ Tesla, $T<5$-77 K and $P<10^{-10}$ mbar.

Low maintenance: few adjustment parameters, don't need specialists to maintain it, if possible avoid detector gases and components that wear out.

Common use: detection of eV to MeV-energy antiproton beams, continuous and pulsed antiproton beams.

Continuity: Parts available after 10-15 years of use in the facility.

Low cost: AD, ELENA, etc. are constructed relying on user funding. 20 kEuro per detector including vacuum chamber, software, manpower costs, etc.

Behavior of antiprotons in detectors

When antiprotons annihilate, following particles are produced:

1): Around 3 charged, minimum-ionizing pions

2): Recoiling nuclear fragments

3): Gamma rays (pi0 decays)

Charged pions are useful for reconstructing annihilation vertex. Can become a backgound in scintillators.

Heavy ions can become background in MCP's (tracks)

Antiprotons produce 0.1 - 3 secondary electrons depending on incident energy 100 keV - 5 MeV and target material.

Pions do not produce very much secondary electrons.

Strategy we adopted at ASACUSA

For 5-50 MeV antiproton beams:

Parallel plate ionization/secondary electron emission chamber

Scintillation screens

Cherenkov detectors

For 100 eV - 100 keV antiproton beams:

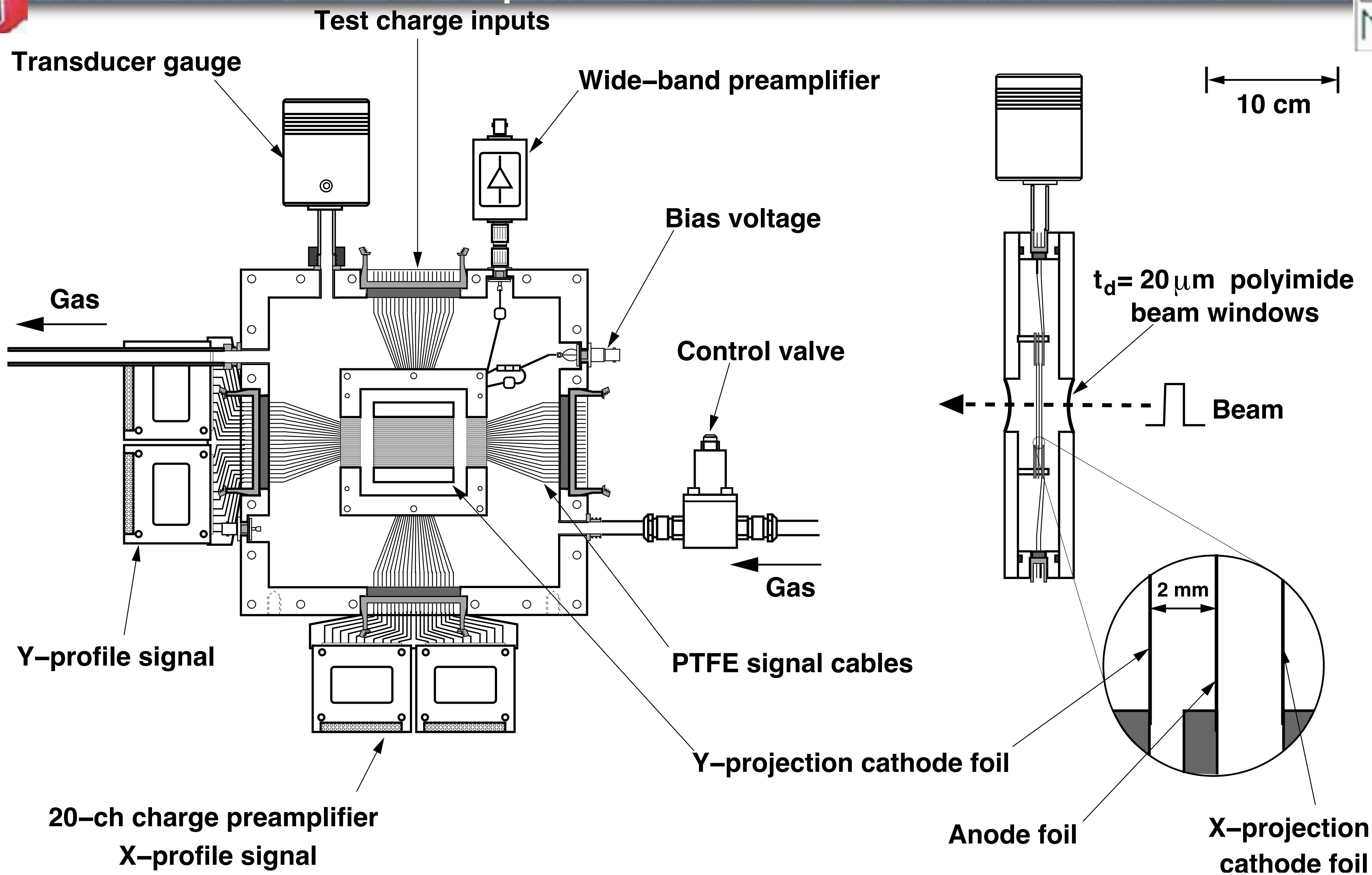
Microwire secondary electron emission detectors

Microchannel plate

Scintillation / phosphor screens

Annihilation vertex reconstruction detectors

Parallel plate ionization chamber

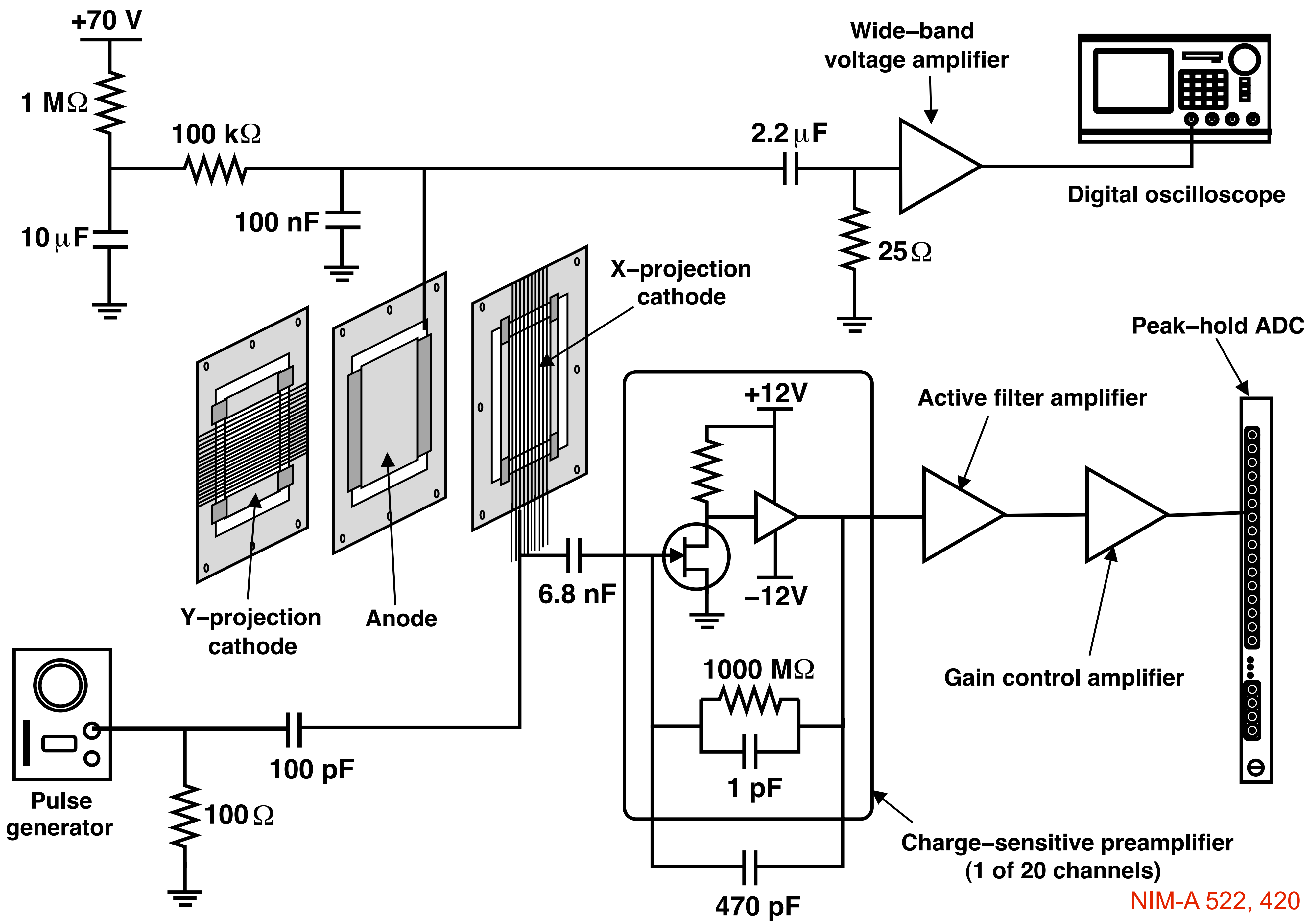


NIM-A 522, 420 (2004) M. Hori

Constant flow of P10 (Argon + 10% methane) gas at pressure 65 mbar.

Parallel electrodes + reduced gas pressure to minimize space-charge effects.

Detector electronics

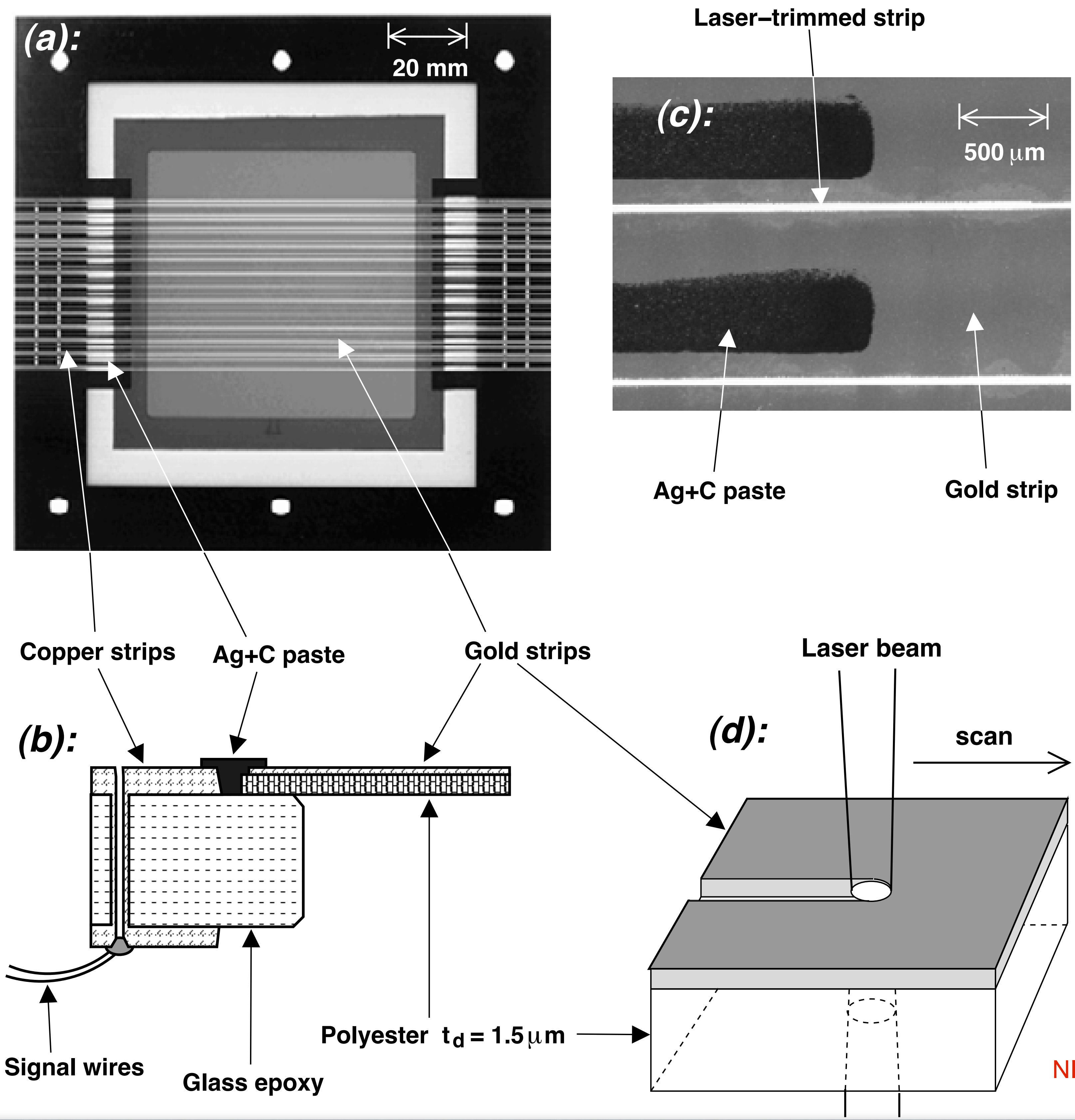


NIM-A 522, 420 (2004) M. Hori

Timing information from common anode read out by voltage amplifier.

Spatial information from X-Y cathodes read out by charge-sensitive preamplifiers.

<2 micron thick electrodes made by laser trimming



Aluminized or gold-sputtered polyester or Mylar foils.

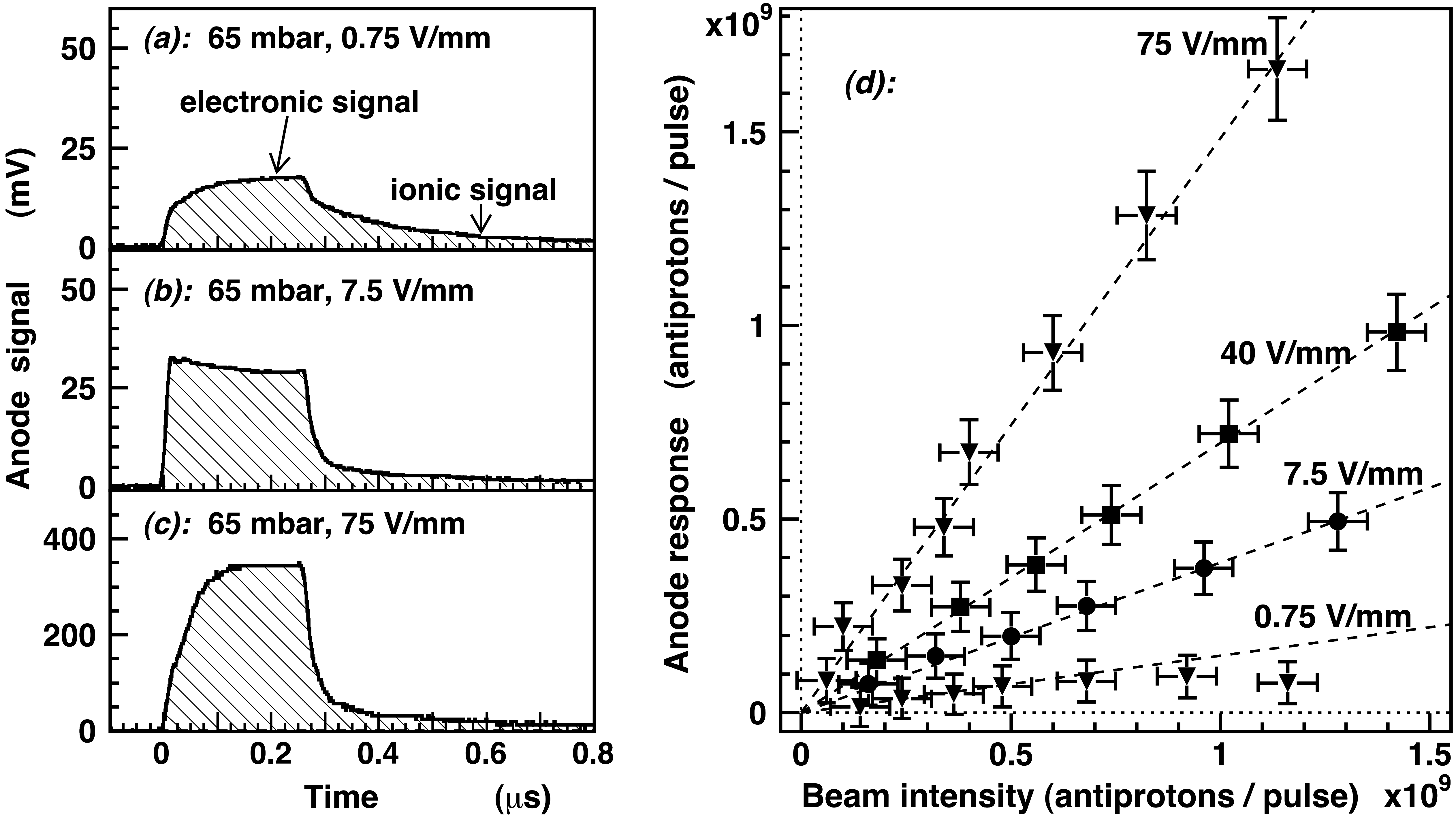
Cutting of 80-um wide strips in metal layer using Nd:YAG or excimer nanosecond laser trimmer.

Transparent Mylar or polyester foils are left intact.

NIM-A 522, 420 (2004) M. Hori

Response of PPIC at high beam intensities

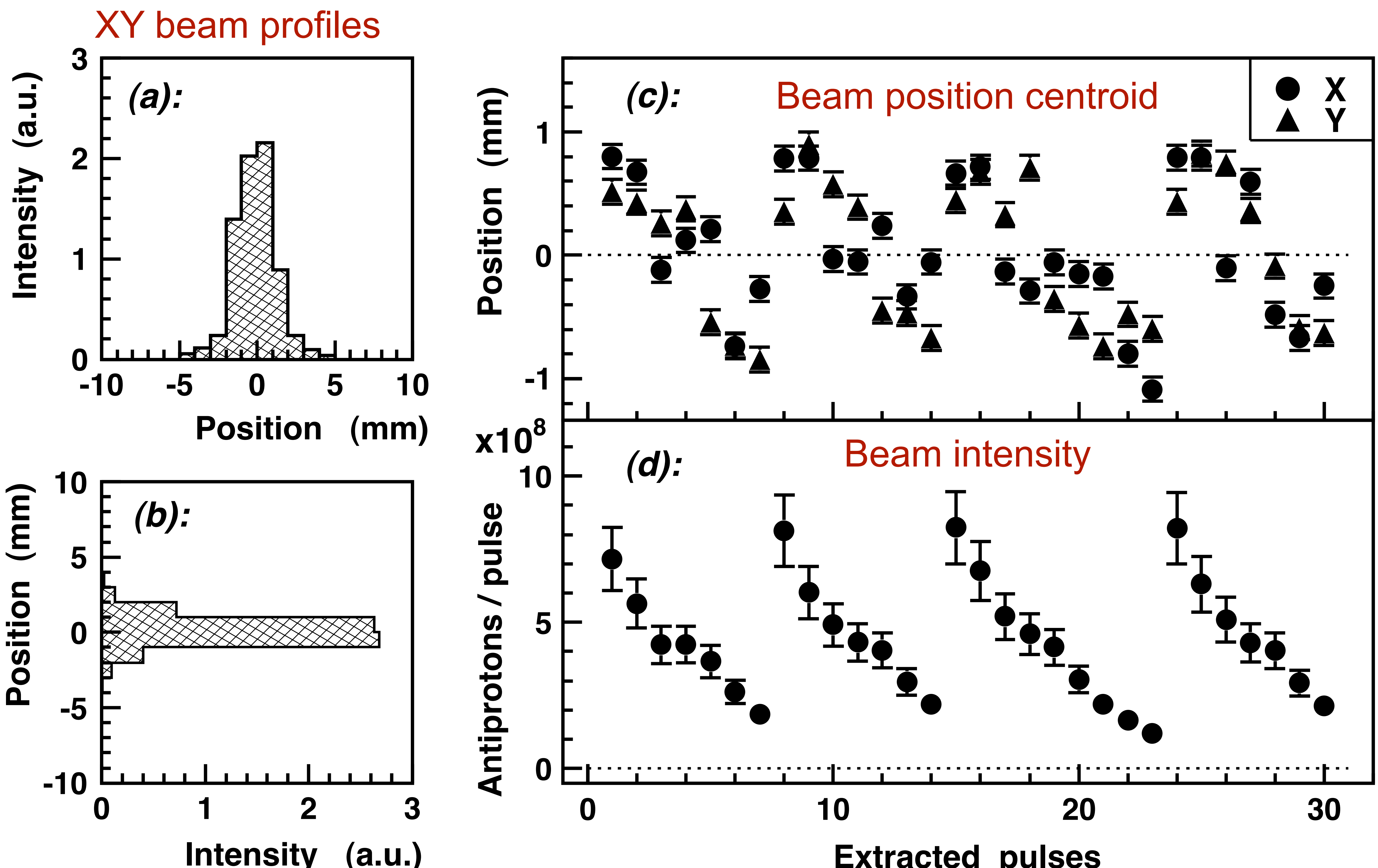
Various P10 gas pressures used.



NIM-A 522, 420 (2004) M. Hori

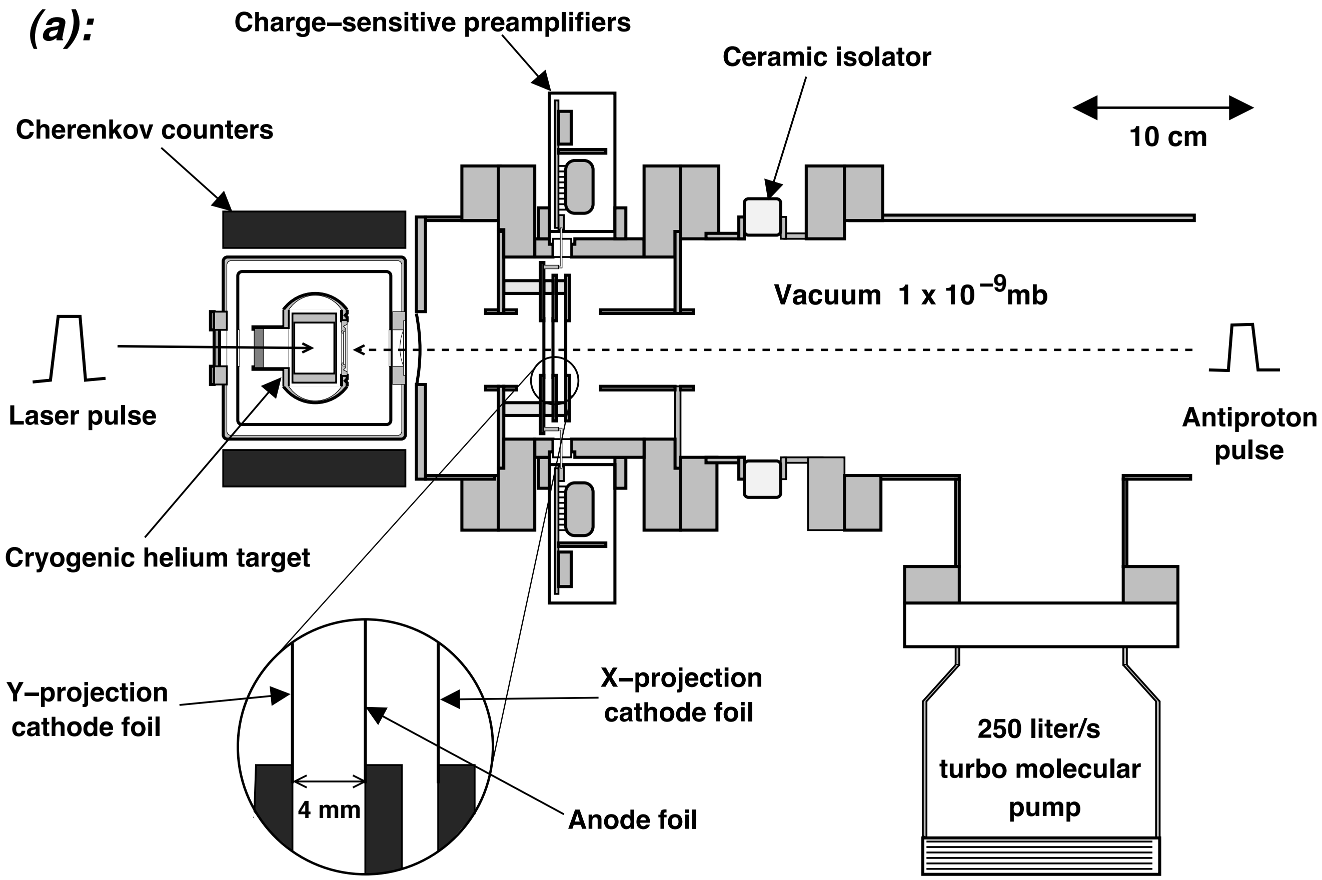
Relatively linear up to 2×10^9 antiprotons/pulse.

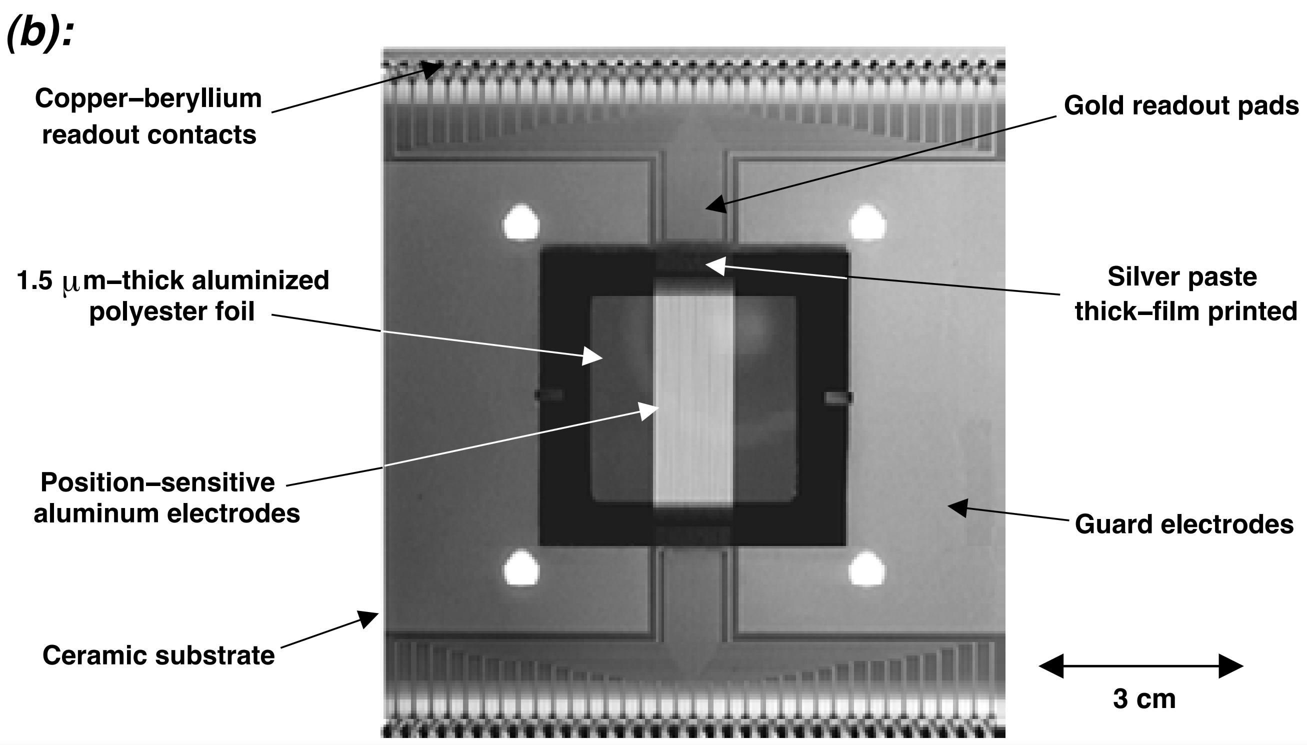
Beam position and intensity measurements at LEAR



NIM-A 522, 420 (2004) M. Hori

Parallel plate secondary electron emission chamber





Avoid using detector gases and beam windows, put detector directly in beamline.

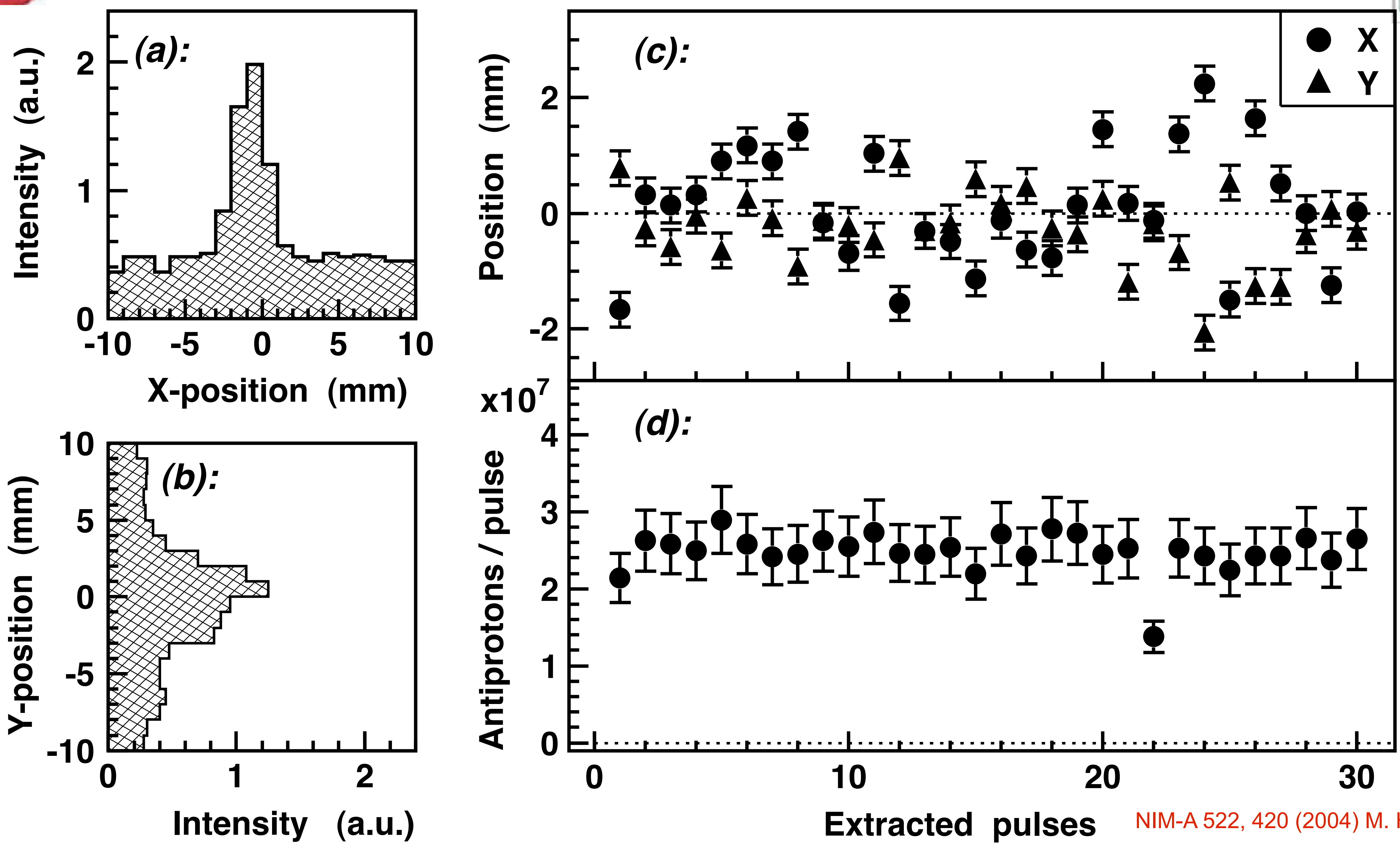
Rely on secondary electron emission.

UHV-compatible materials (ceramic, fluxless solder).

Signal intensity reduced by two orders of magnitude compared to ion chamber.

NIM-A 522, 420 (2004) M. Hori

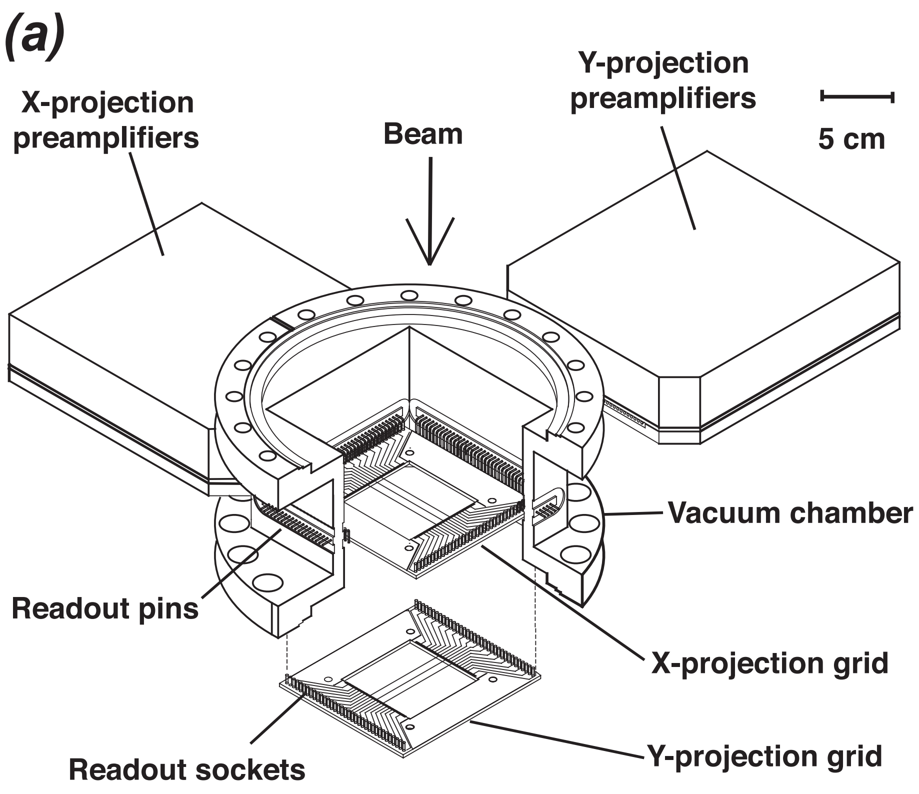
Beam profile and intensity measurements at AD

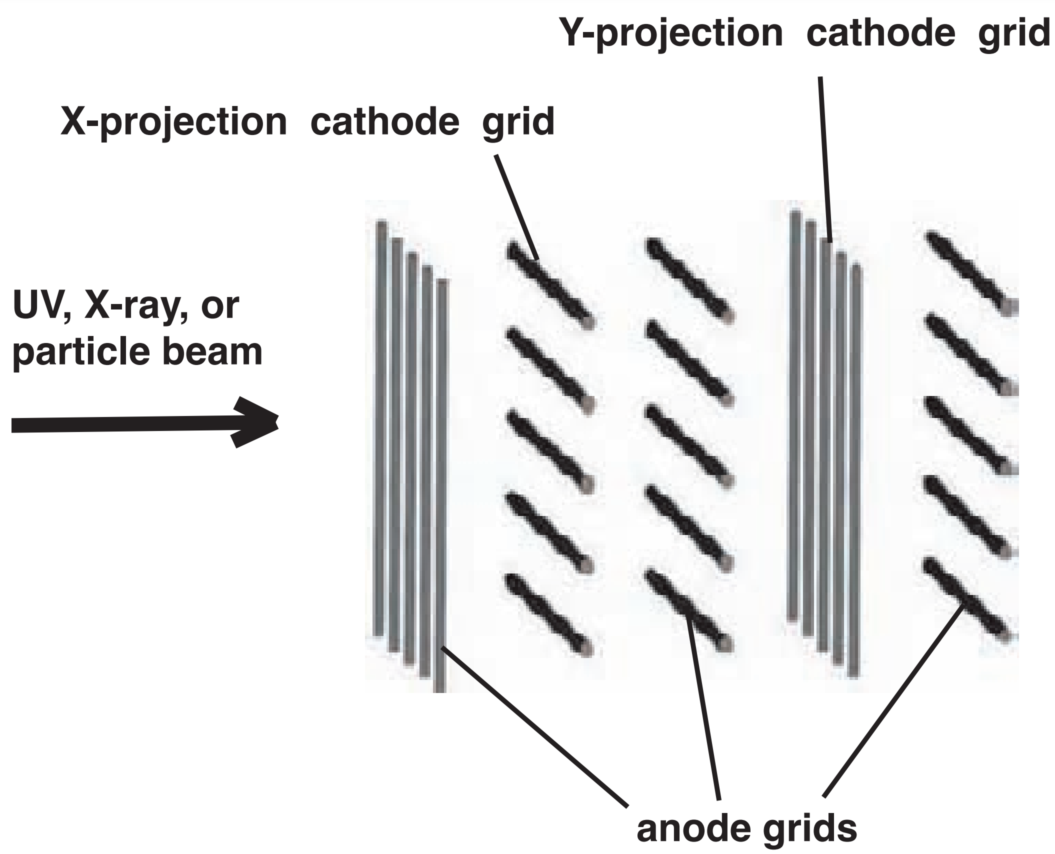


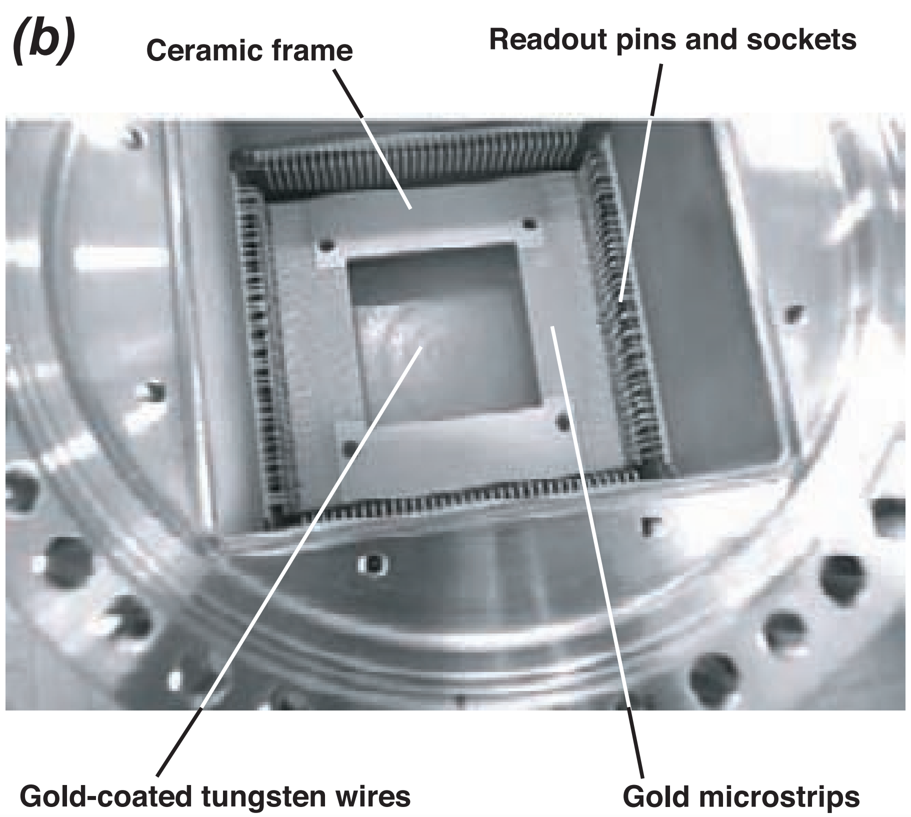
NIM-A 522, 420 (2004) M. Hori

Clear profiles can be observed using the detection of secondary electron emission $2x10^7$ antiprotons/pulse.

Microwire secondary electron emission chamber







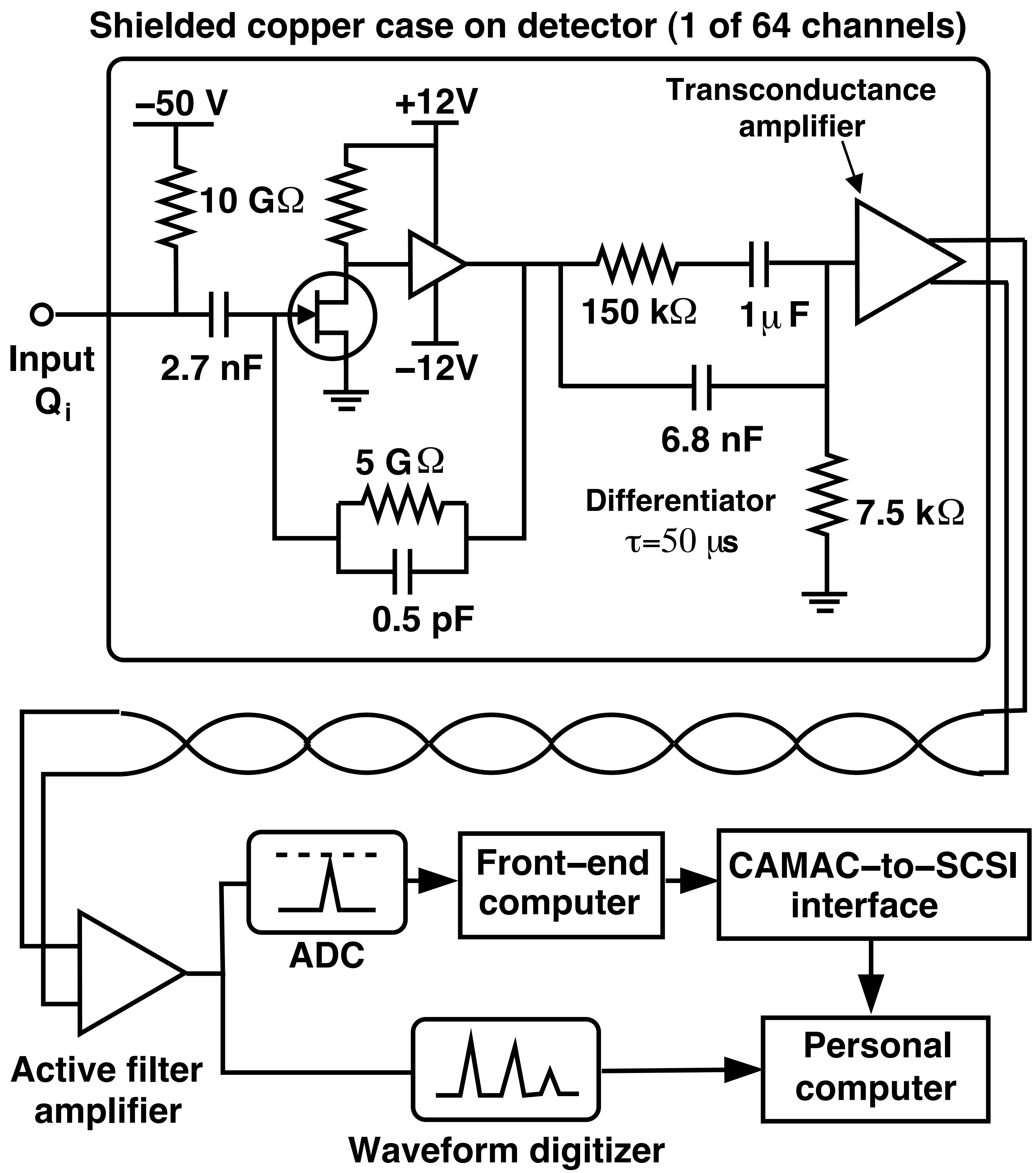
RSI 76, 113303 (2005), M. Hori

Gold-sputtered tungsten wires or carbon filaments diameter 5-30 um placed in UHV.

Wires intercept 1-3% of the beam. 97-99% travel through without being affected.

Secondary electrons detected by preamplifiers.

J-FET based charge sensitive preamplifier system



RSI 76, 113303 (2005) M. Hori

64 discrete junction FET hybrid amplifiers

Cf = 0.5 pF, Rf = 5 GOhm, 2 V/pc.

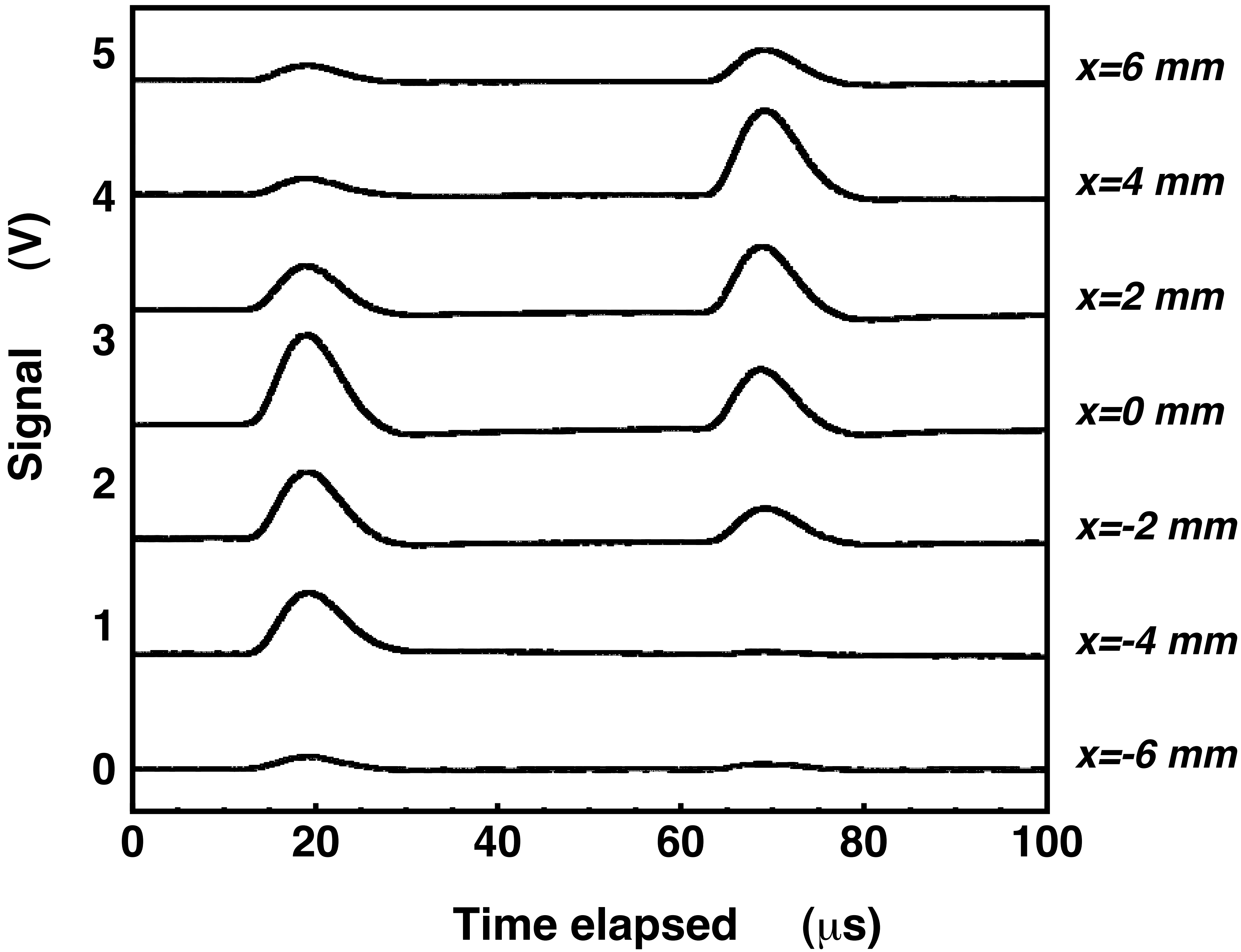
Transmission via 200-Ohm differential transconductance amplifier (minimizes RF interference and ground-loops)

Active filter amplifier t = 2 us.

1 differentiator, 4 integrators

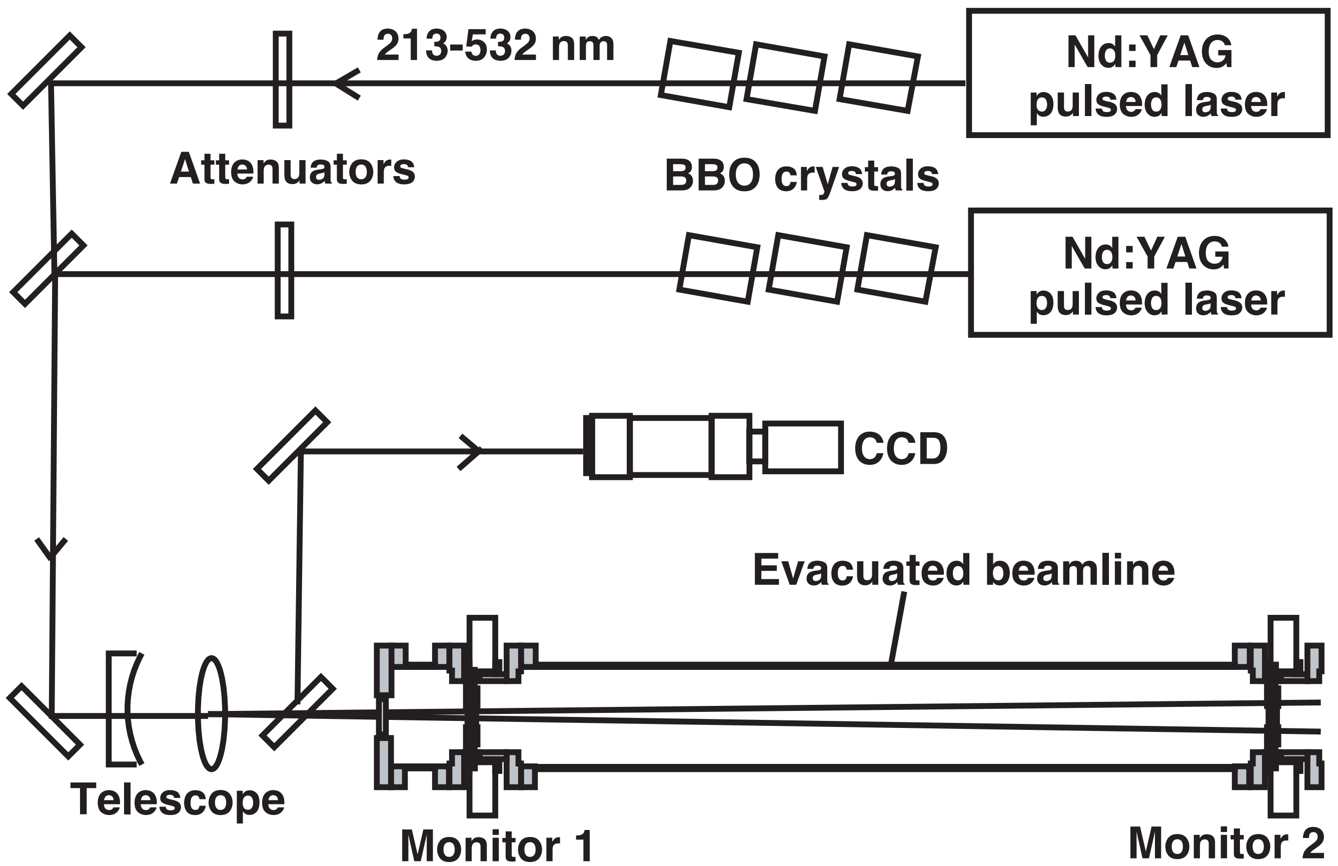
Equivalent noise charge RMS=200. (calibrated with Si detector + 241Am source)

Time/space-resolved measurement



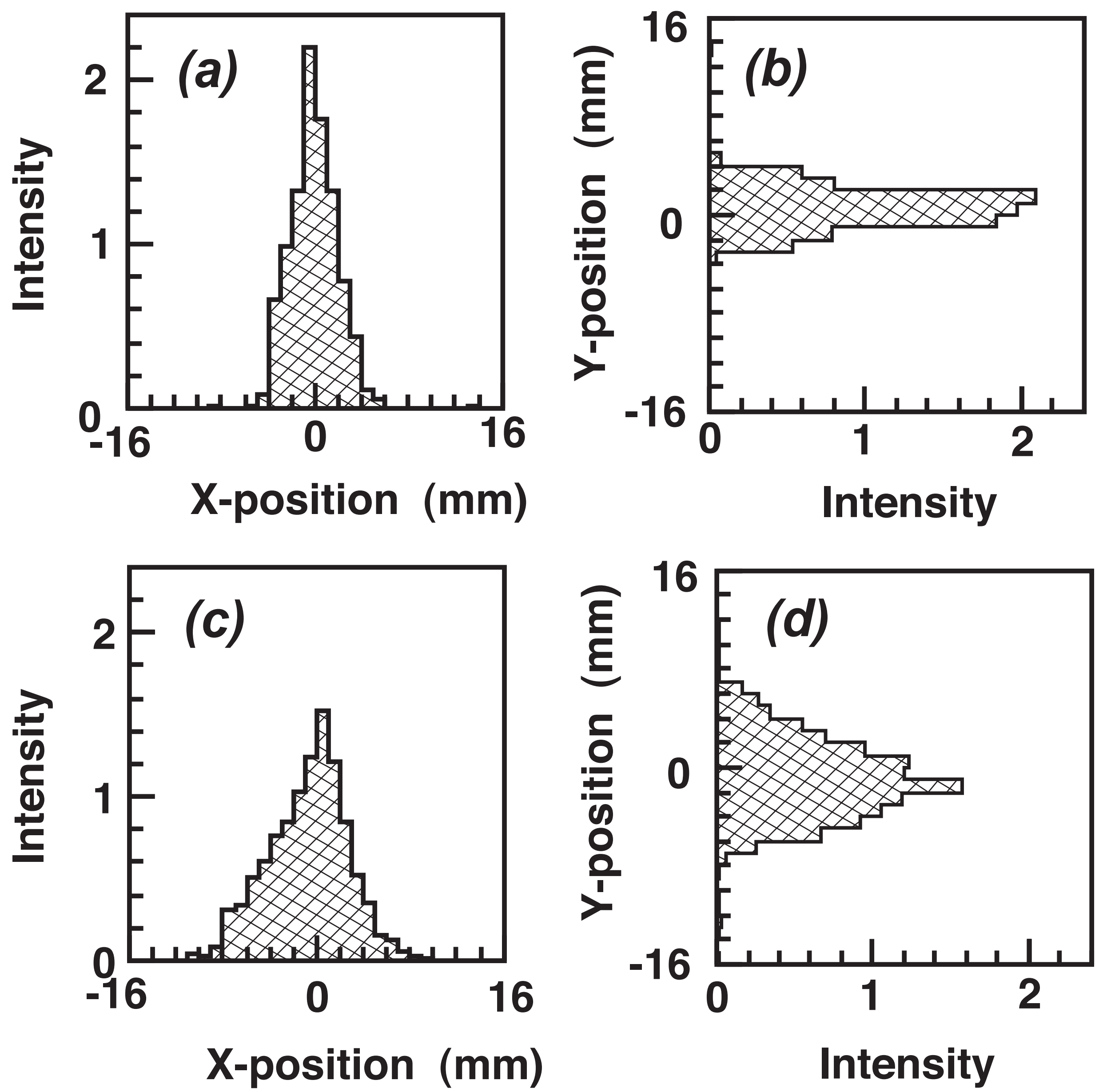
RSI 76, 113303 (2005), M.Hori

Response against pulsed Nd:YAG laser beams



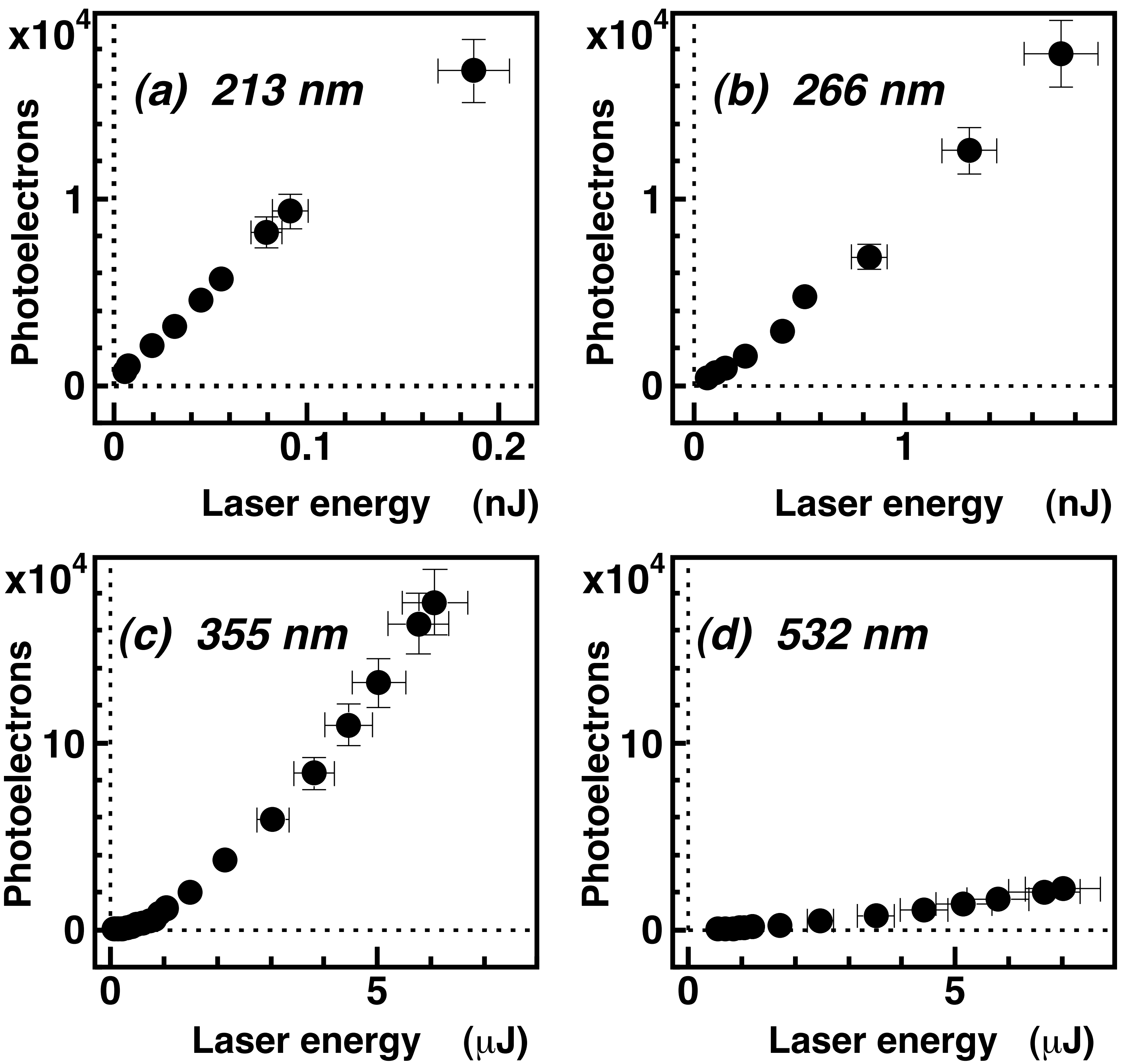
Single-shot measurement of beam profile at several point along beamline.

Enables rapid determination of beam emittance, beam tuning.



RSI 76, 113303 (2005), M. Hori

Photoelectron emission yield measurement



W-value of gold = 4.6 eV

213 nm (5.8 eV) g=10-4

266 nm (4.6 eV) g=10-5

proceeds via single-photon. relatively linear.

355 nm (3.5 eV) g=10-8

532 nm (2.3 eV) g=10-9

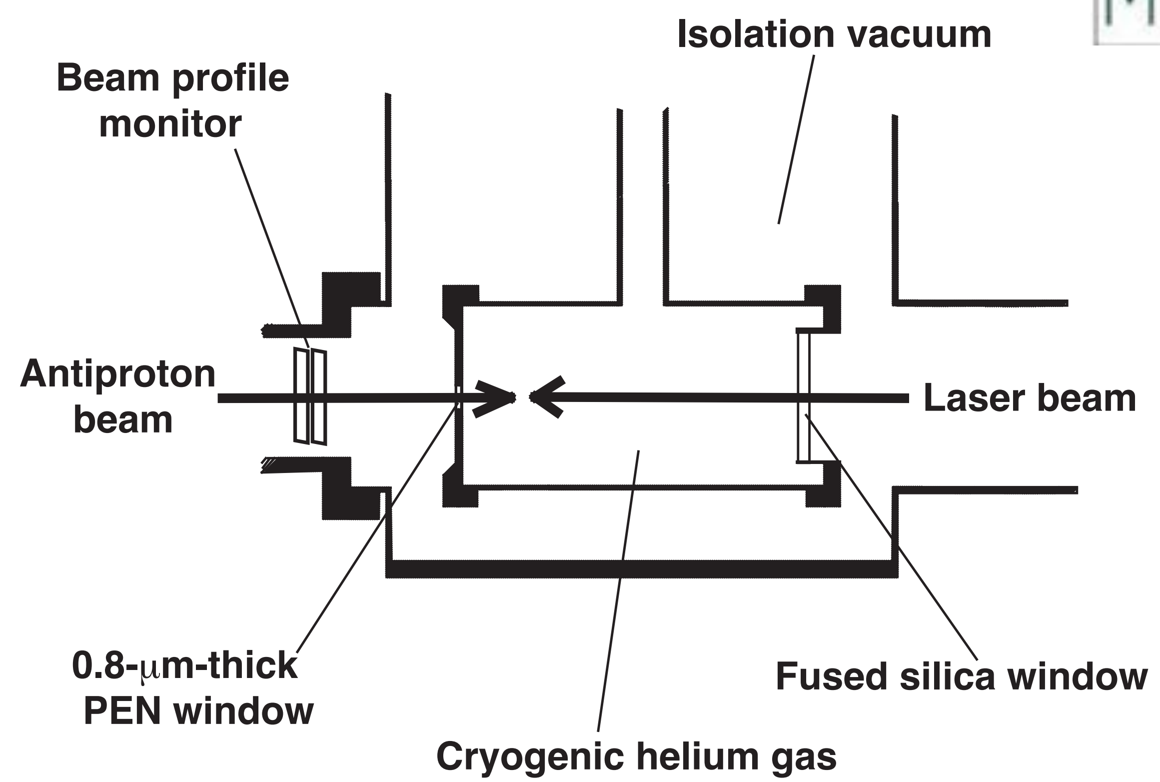
proceeds via two-photon, non-linear. Needed field =50-200 kW/cm2

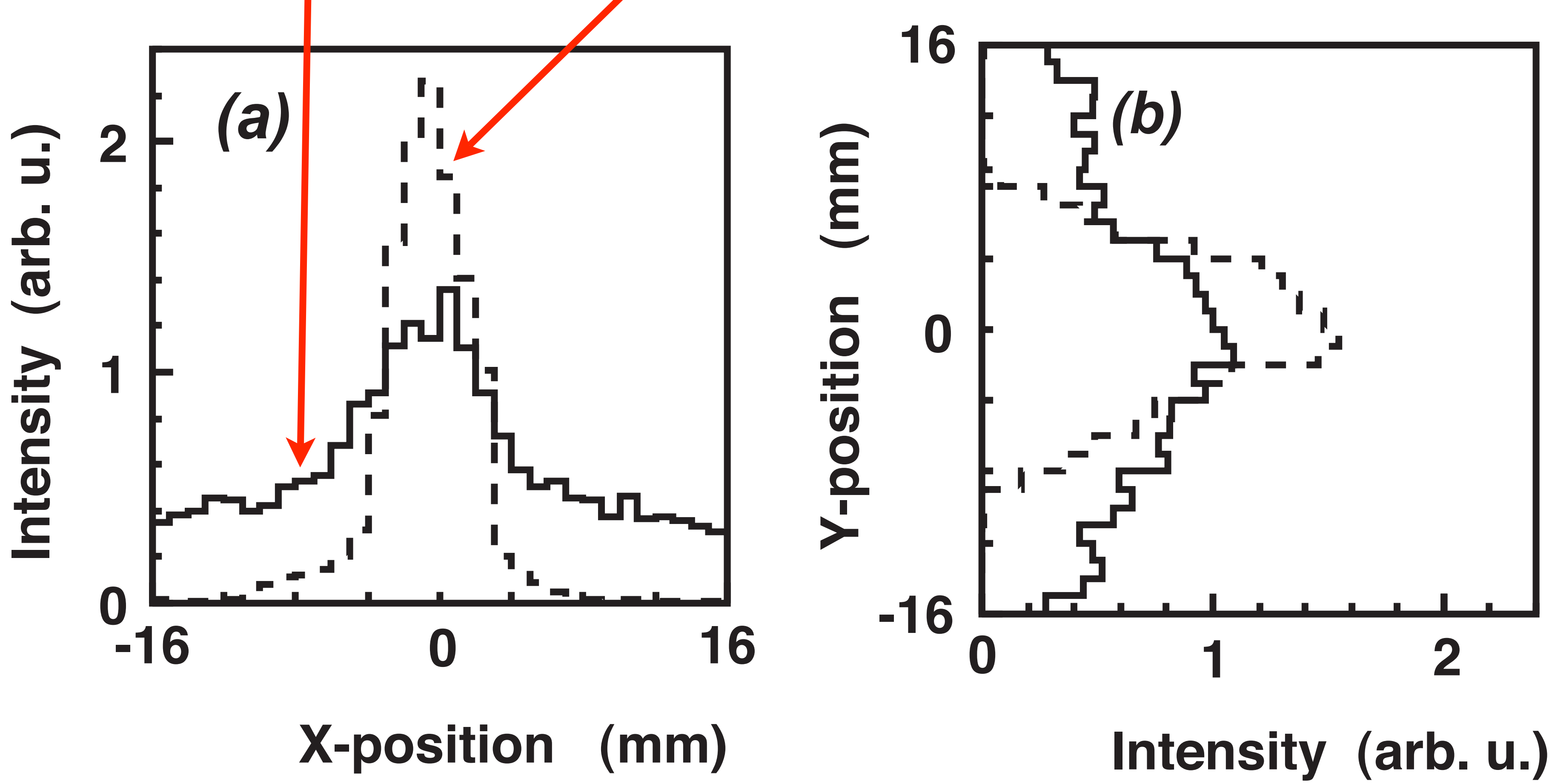
RSI 76, 113303 (2005), M. Hori

Response against <100 keV antiprotons

Detection of 60-100 keV beam of

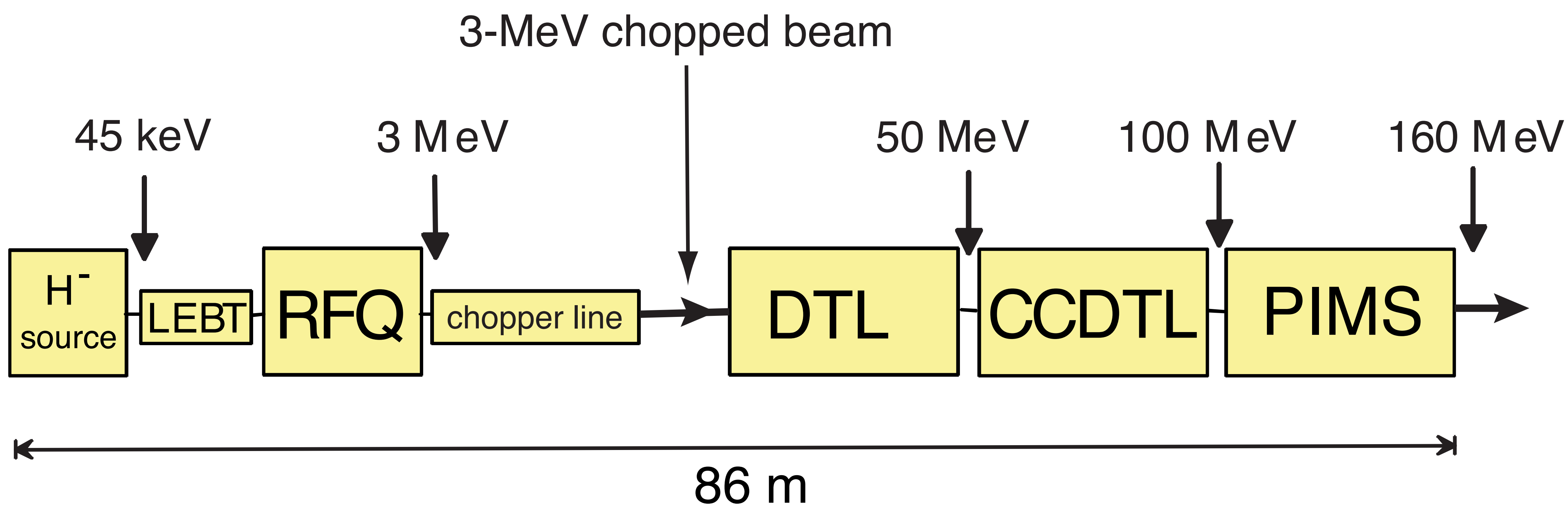
2e6 antiprotons, and 289-nm laser beam

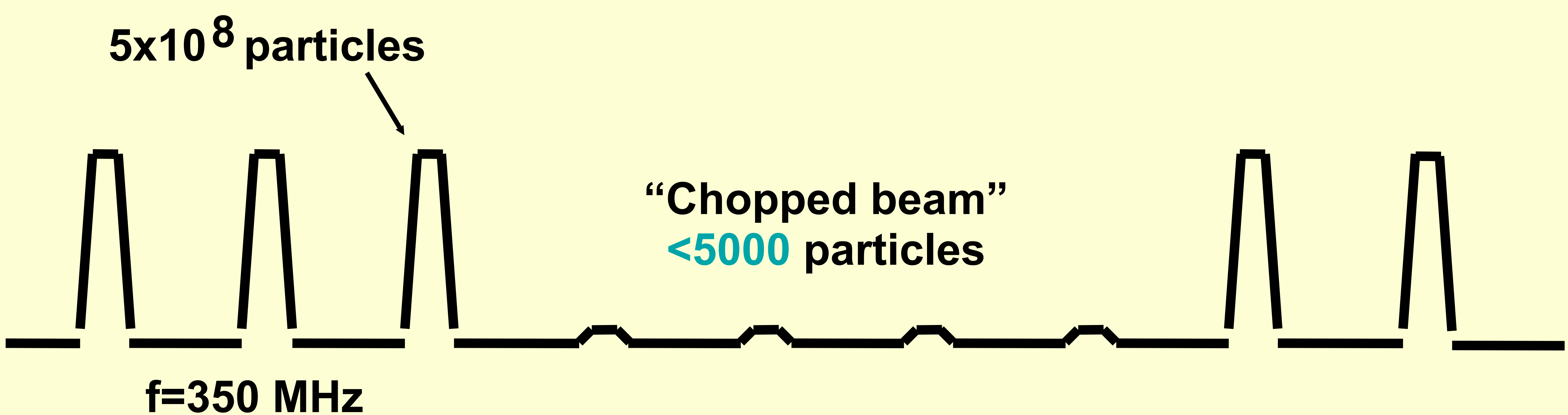




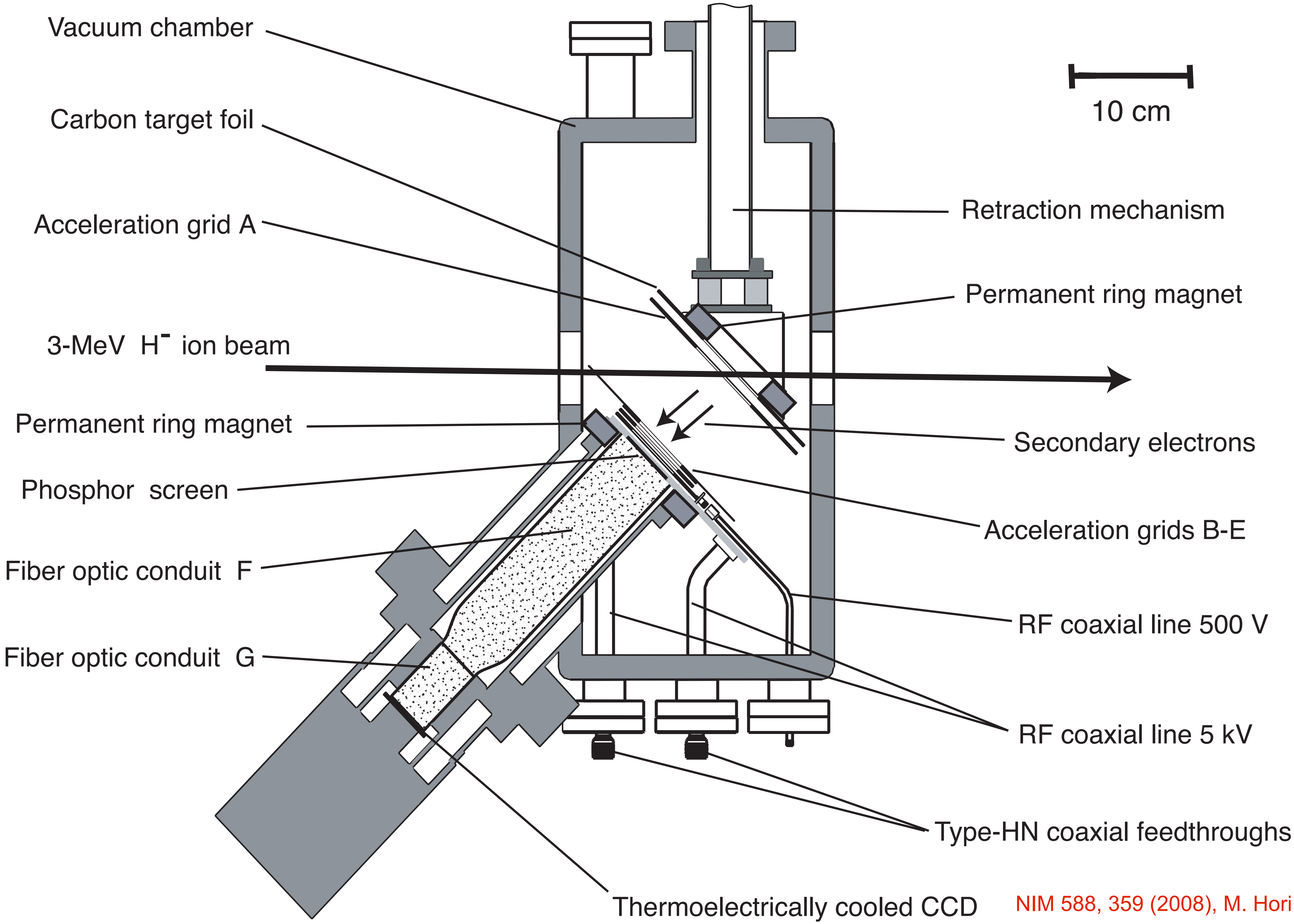
RSI 76, 113303 (2005), M. Hori

Time-resolved measurement of Linac4 chopper





Nanosecond foil detector



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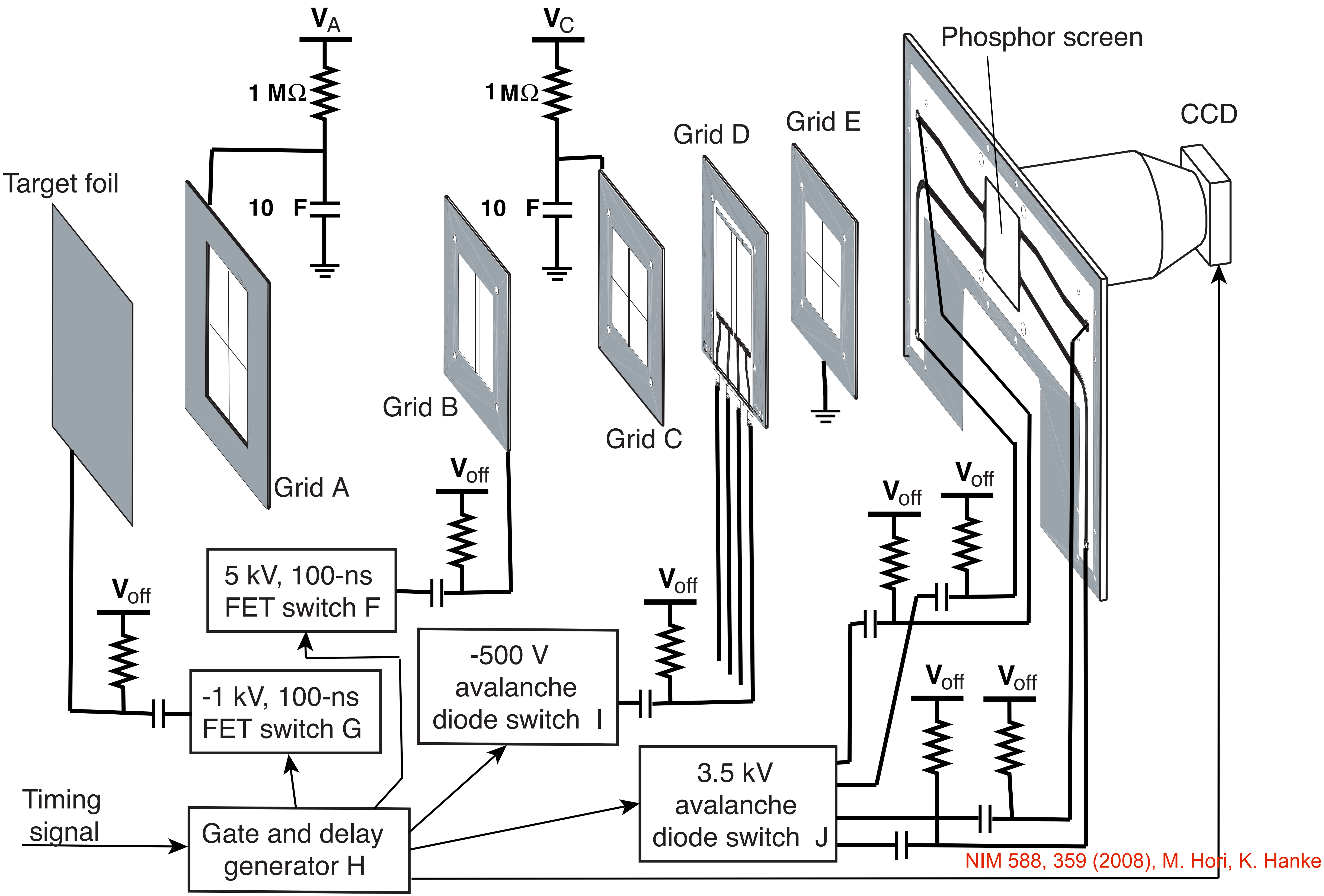
Time-resolved gating system



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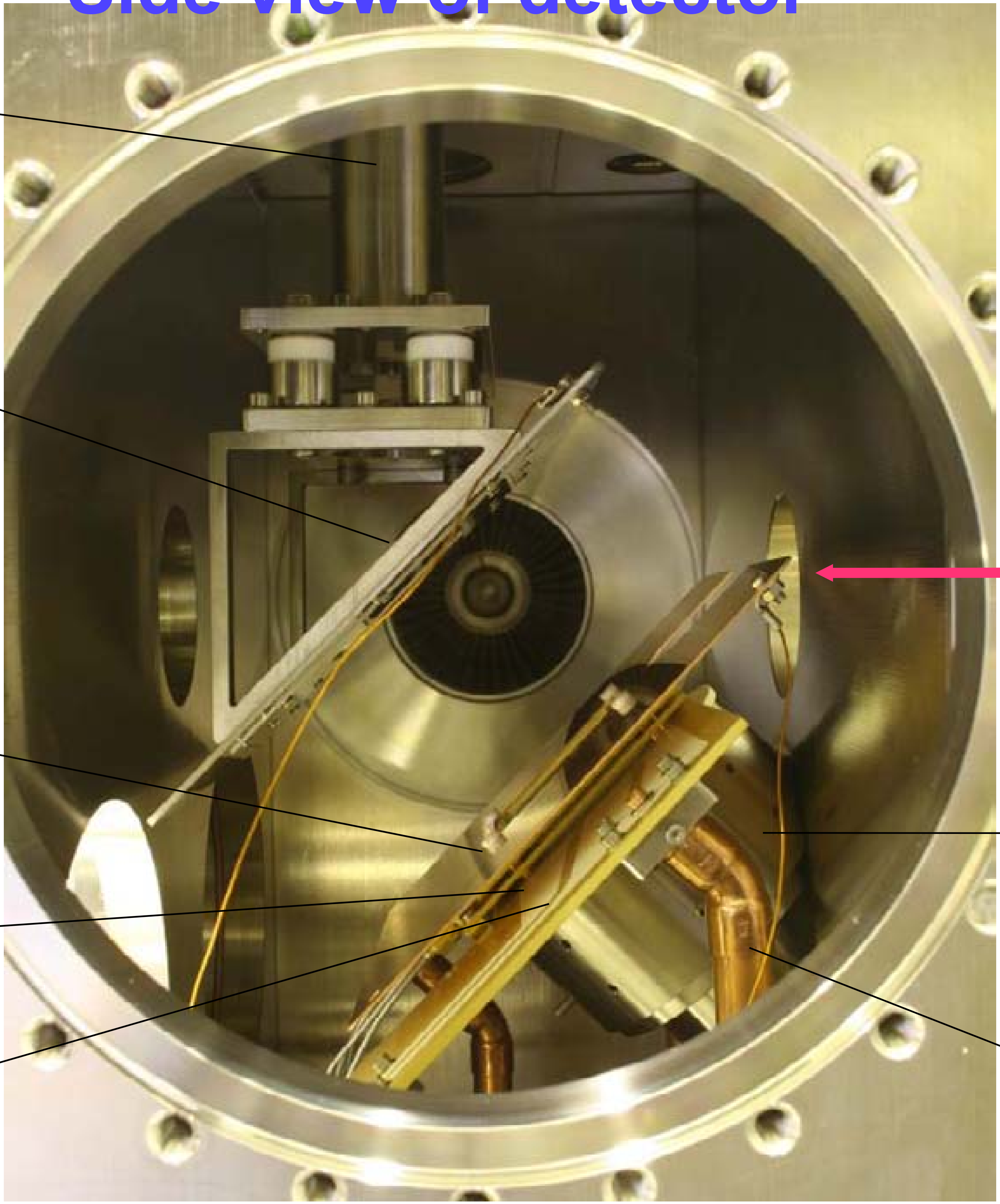
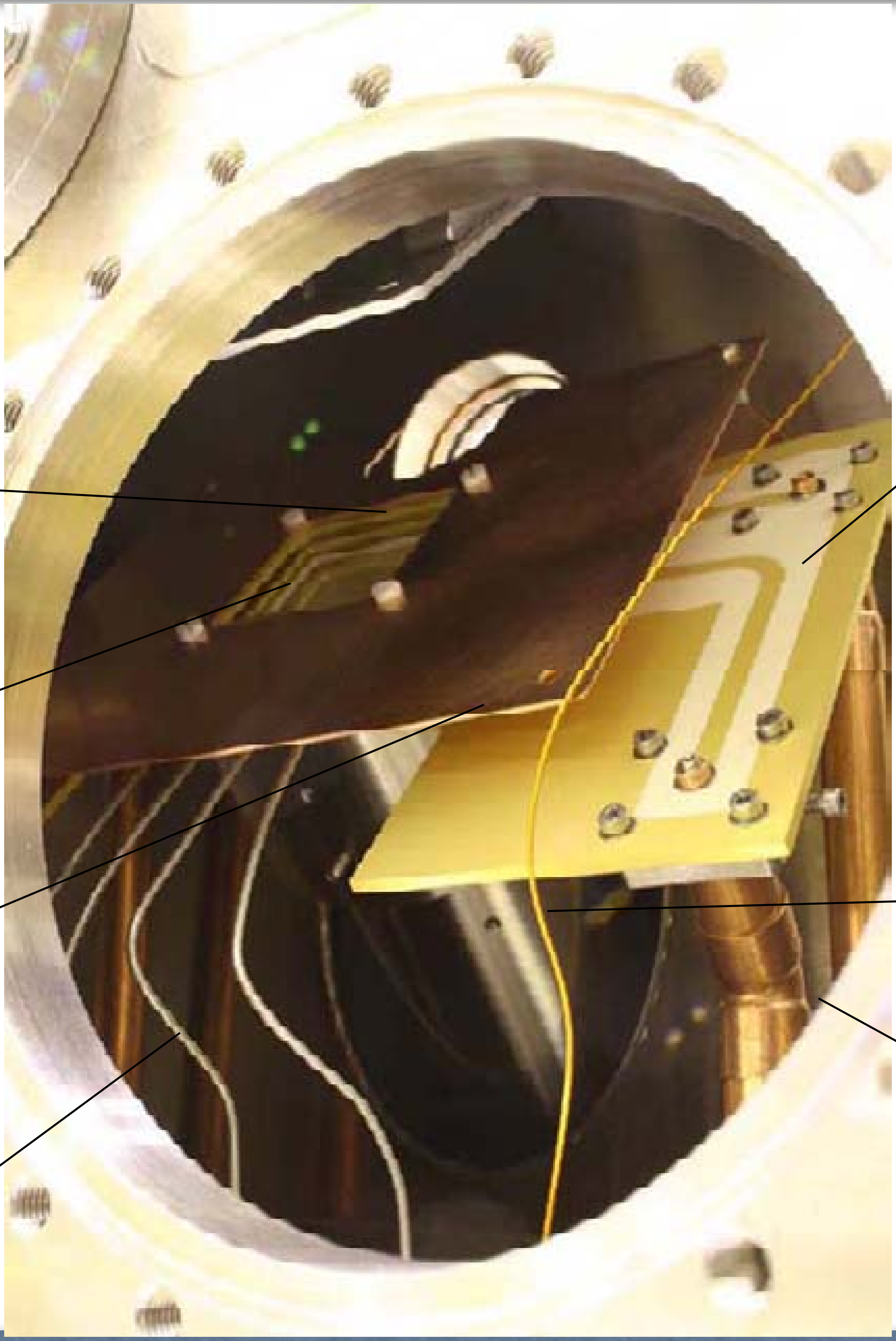
Side view of detector

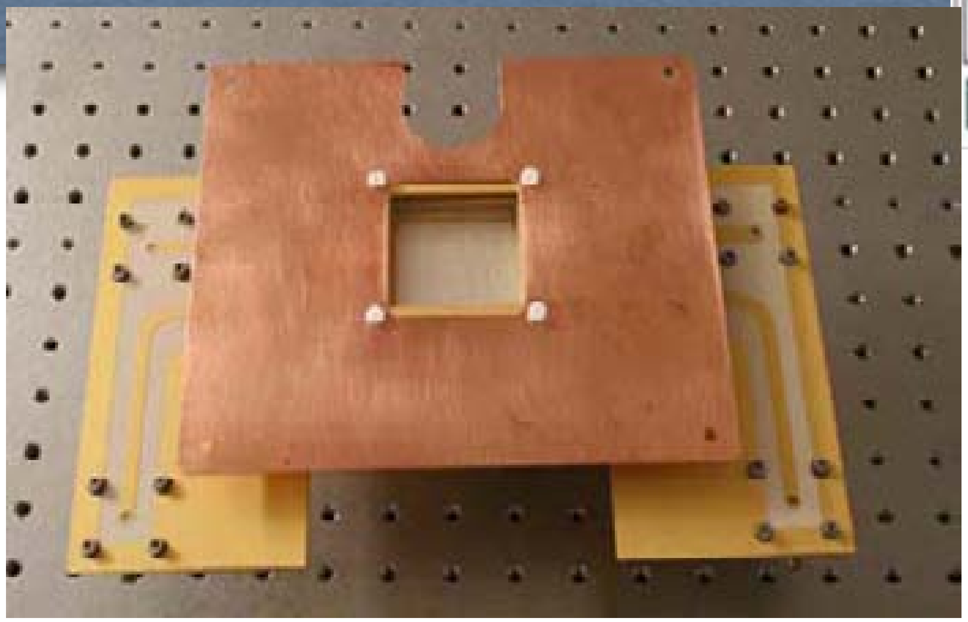


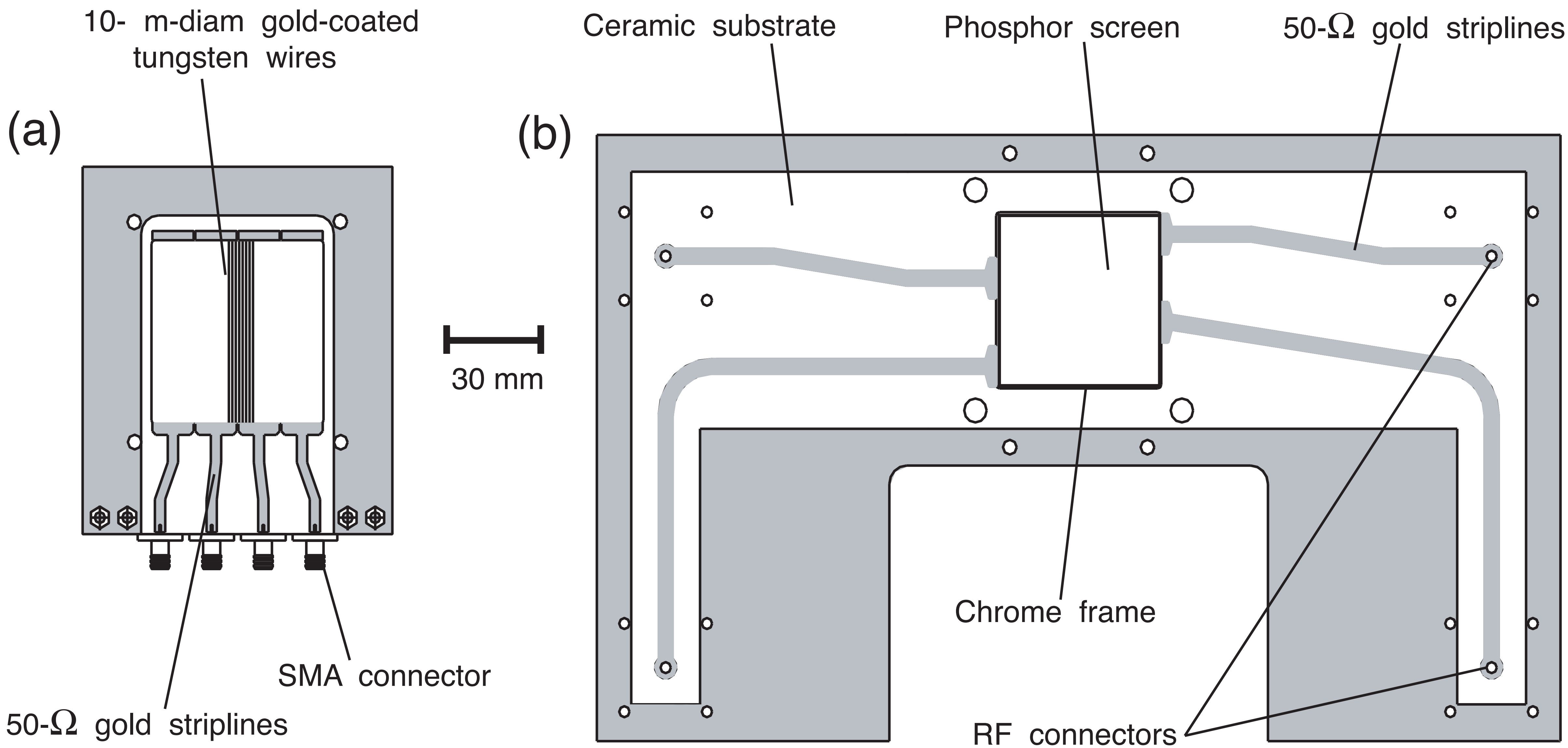
High-speed shutter electrodes



High-speed shutter electrodes

Four parallel 50-Ohm lines for effective impedance 12.5 Ohm allows fast switching of voltage potential





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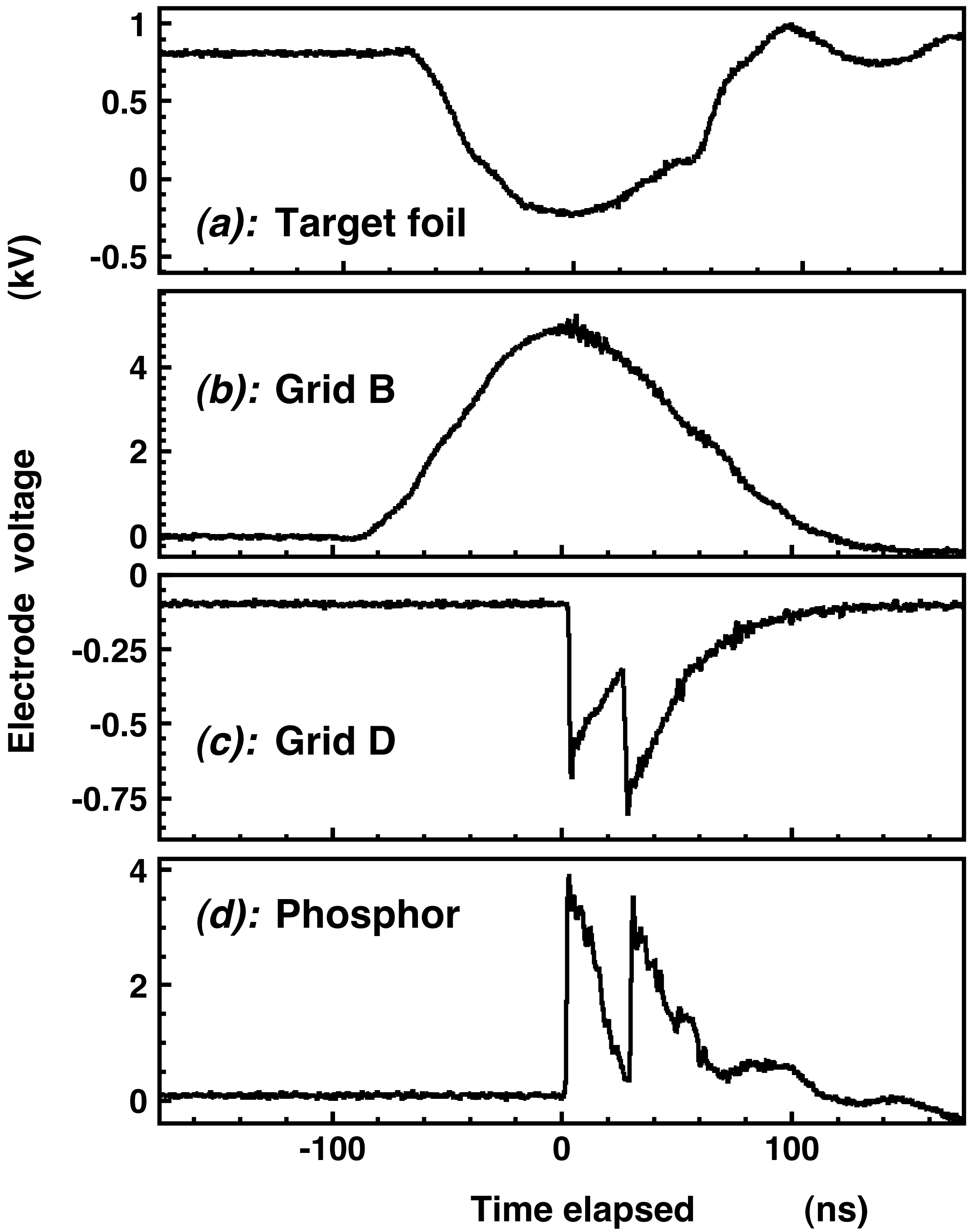
Grid biasing and pulsing scheme



- Two FET switches
- Two avalanche diode switches
- Open circuit at end of coaxial lines.

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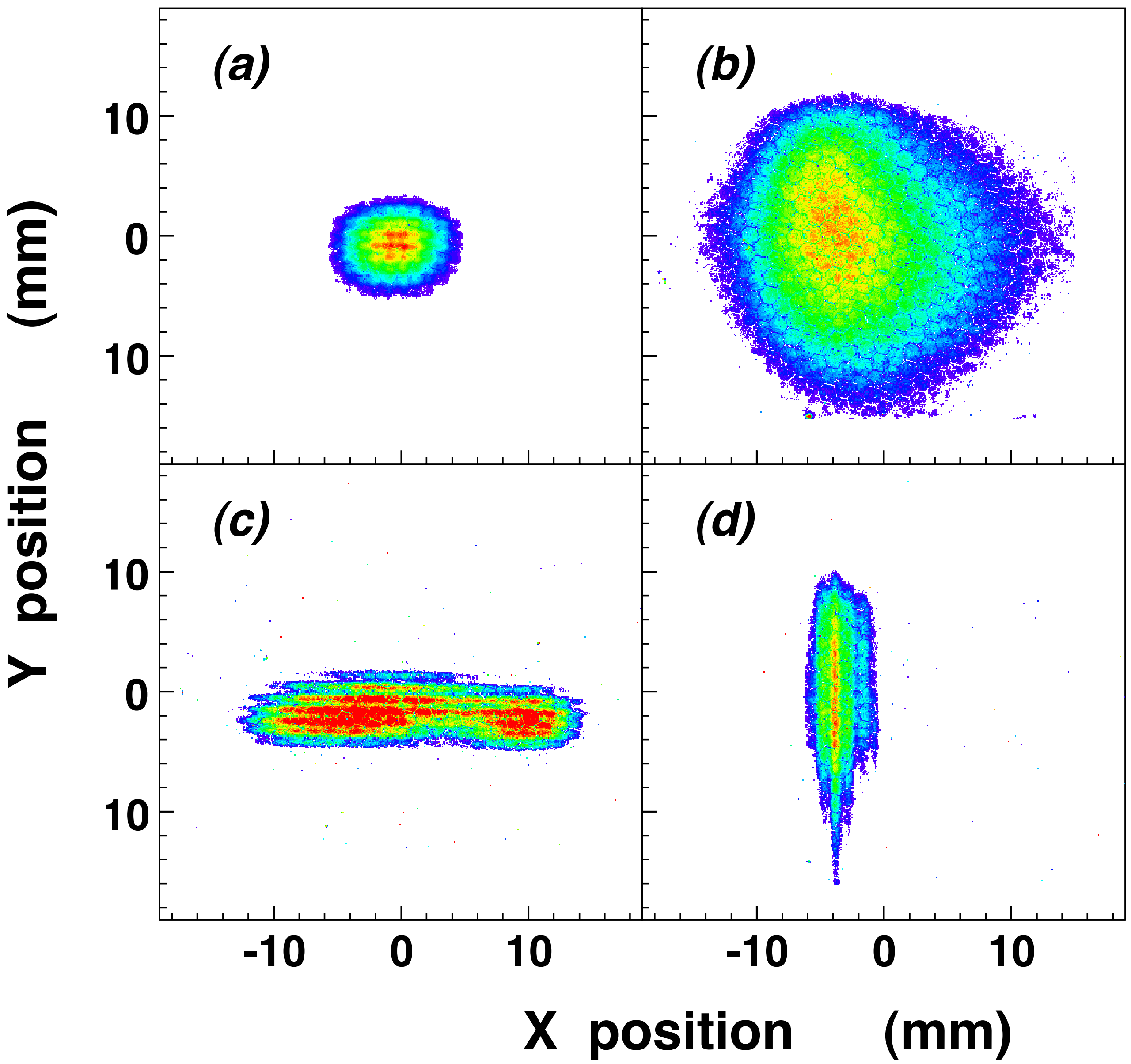
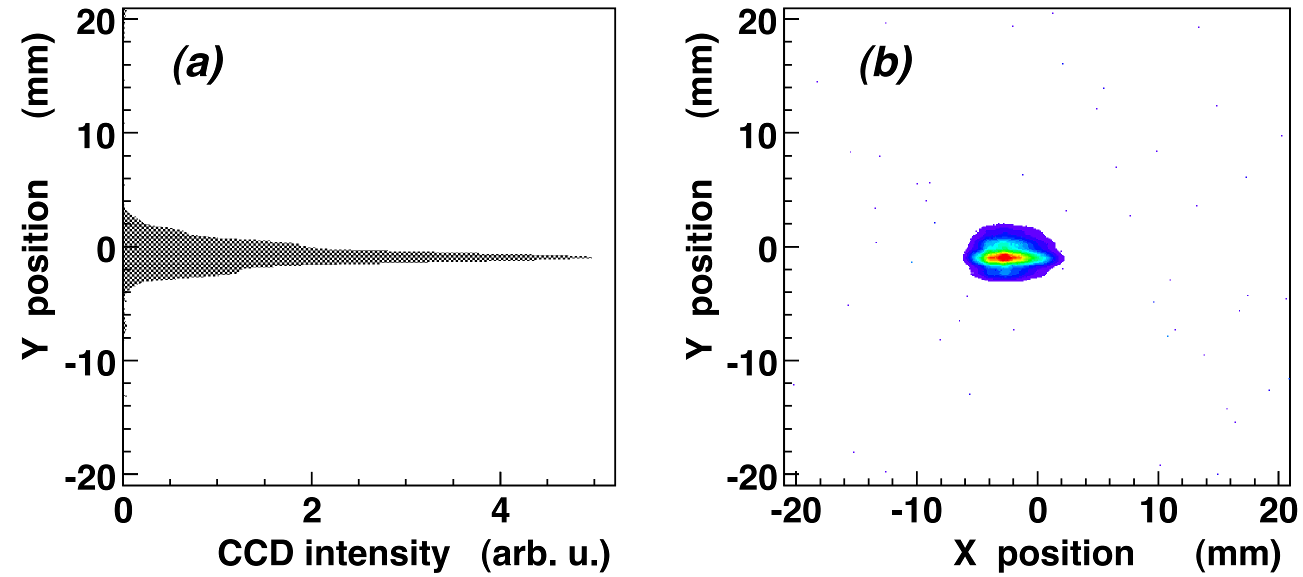
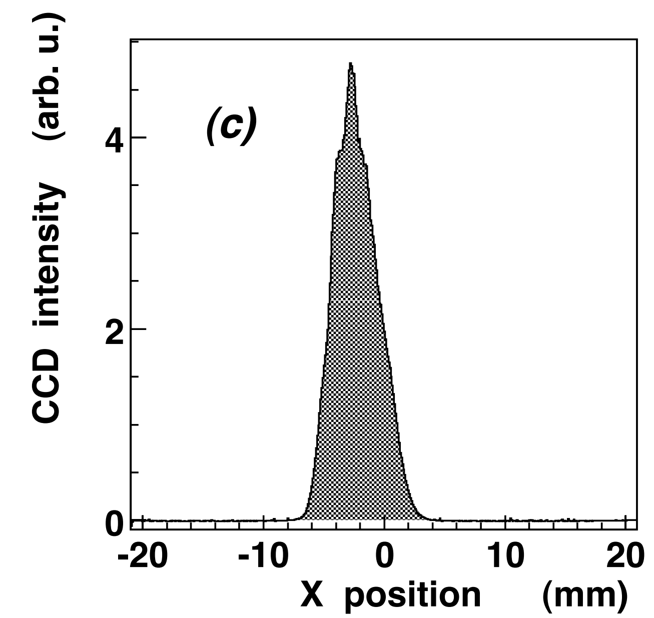
Response against 3 MeV proton beam at Orsay



Beam profile for various focusing settings of the Orsay beamline



5×10^7 photoelectrons
2 mm spatial resolution



Beam profile for pinpoint laser beam

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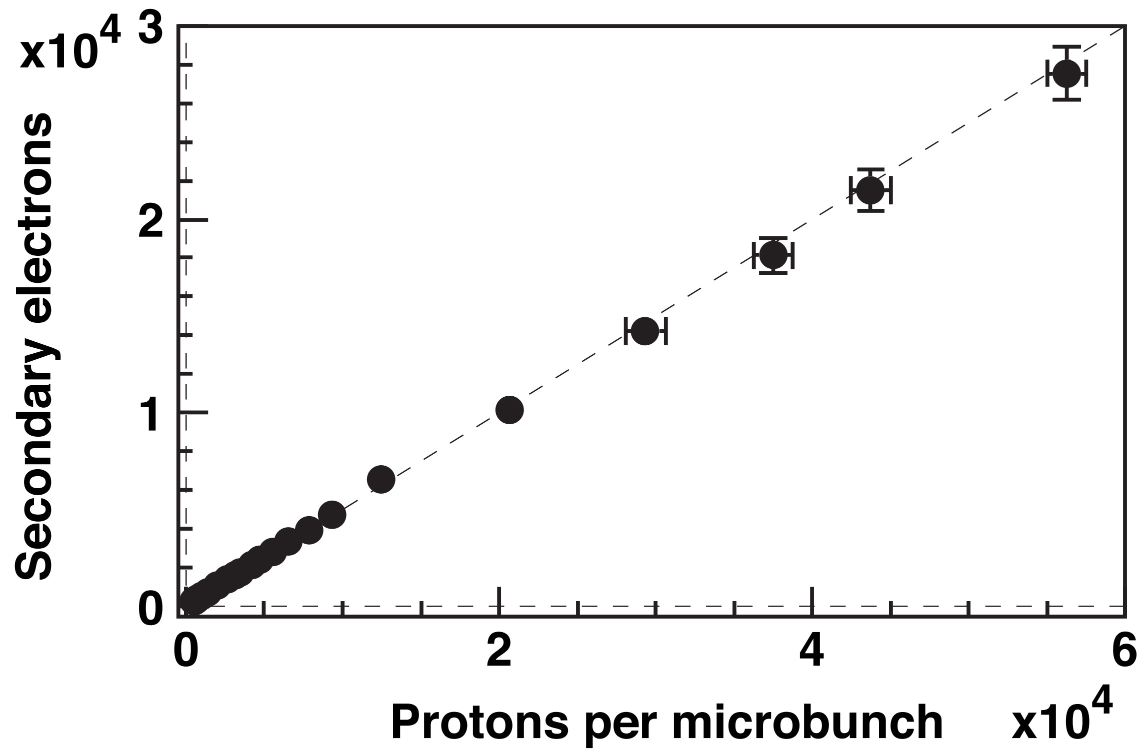
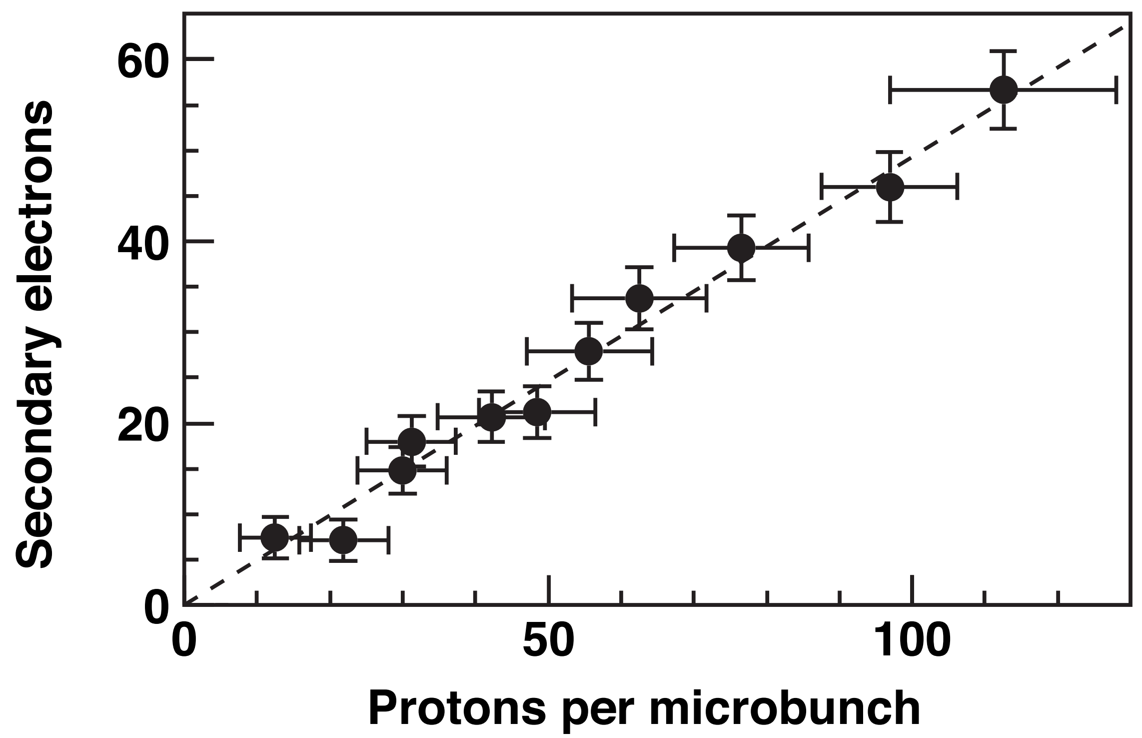
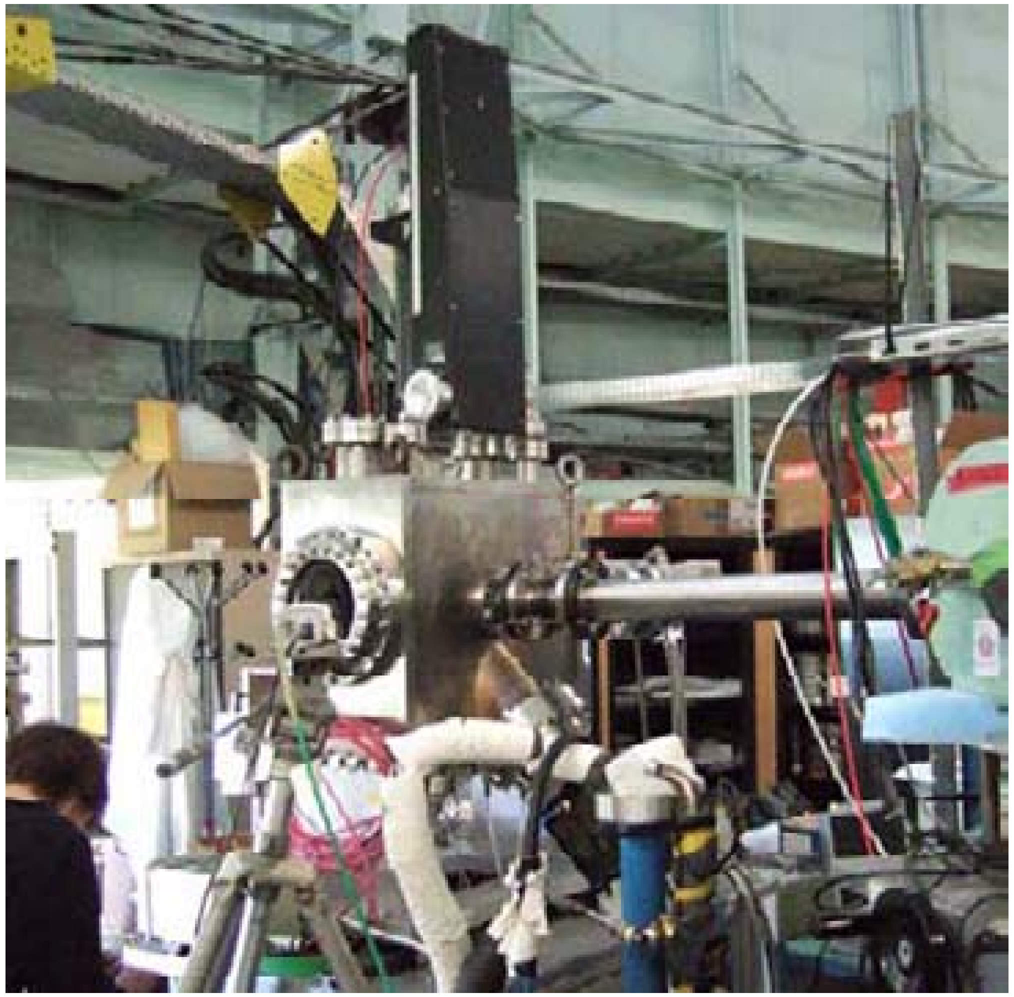
Linearity measurement







Linearity measurements

Beam diam 1 cm, f=10 MHz
Integrated 1000 pulses
Linear response between
N_p=10 and 6x10^4 protons/pulse

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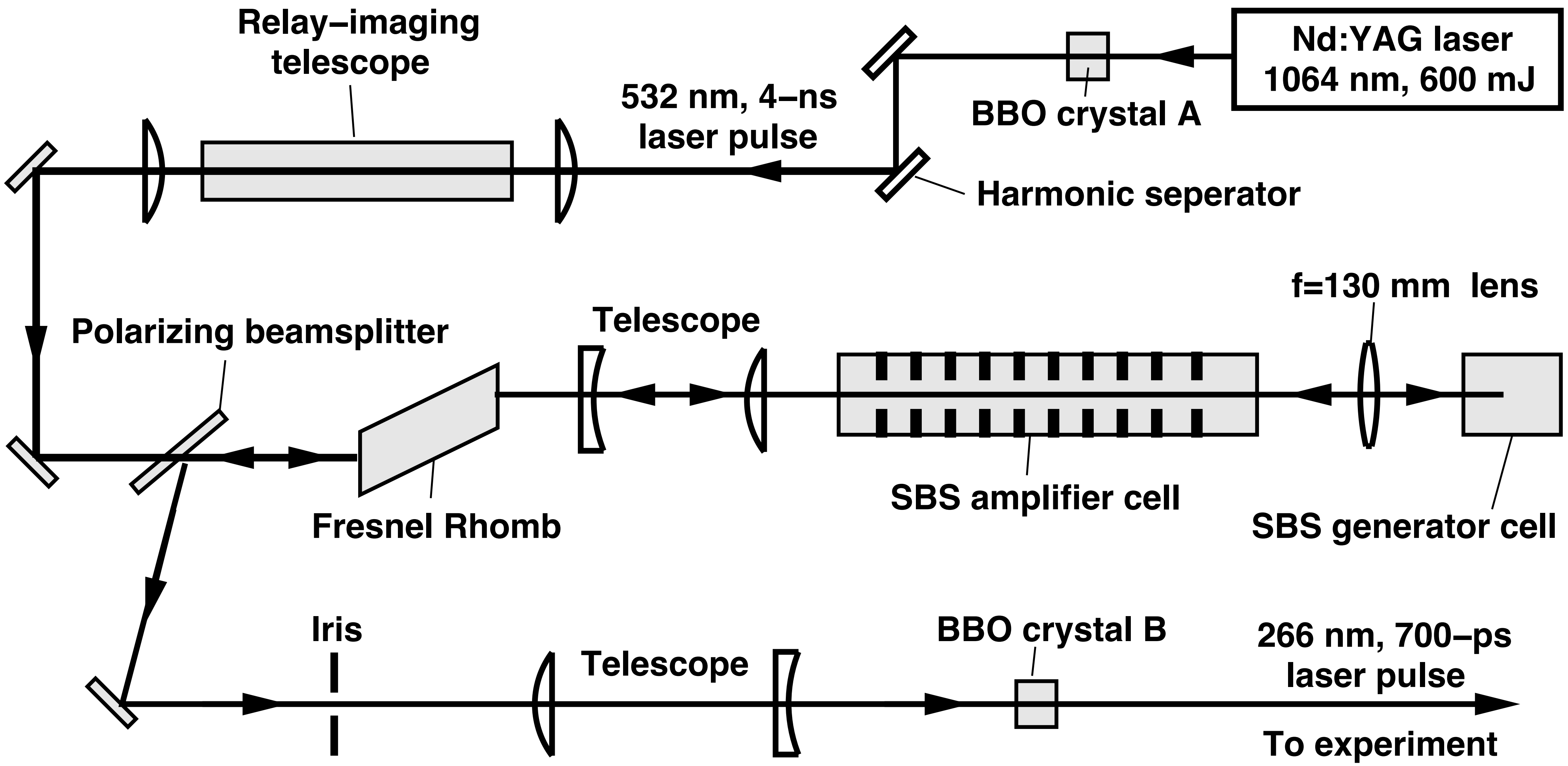
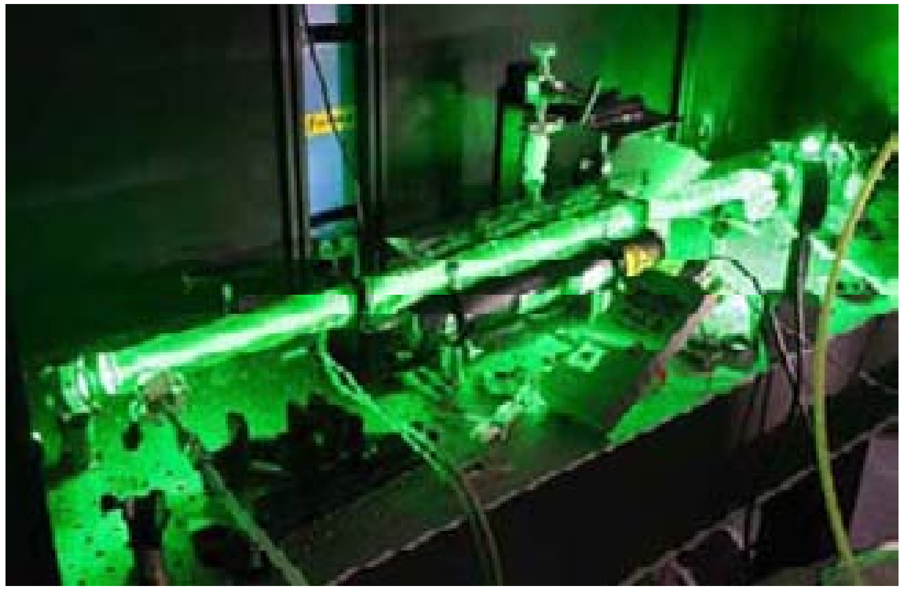
Stimulated Brillion backscattering laser





Ultraviolet laser pulse generator to simulate Linac-4 beam

SBS process to compress Nd:YAG laser pulses to < 700 ps, 266 nm UV laser
10 Megawatt peak power

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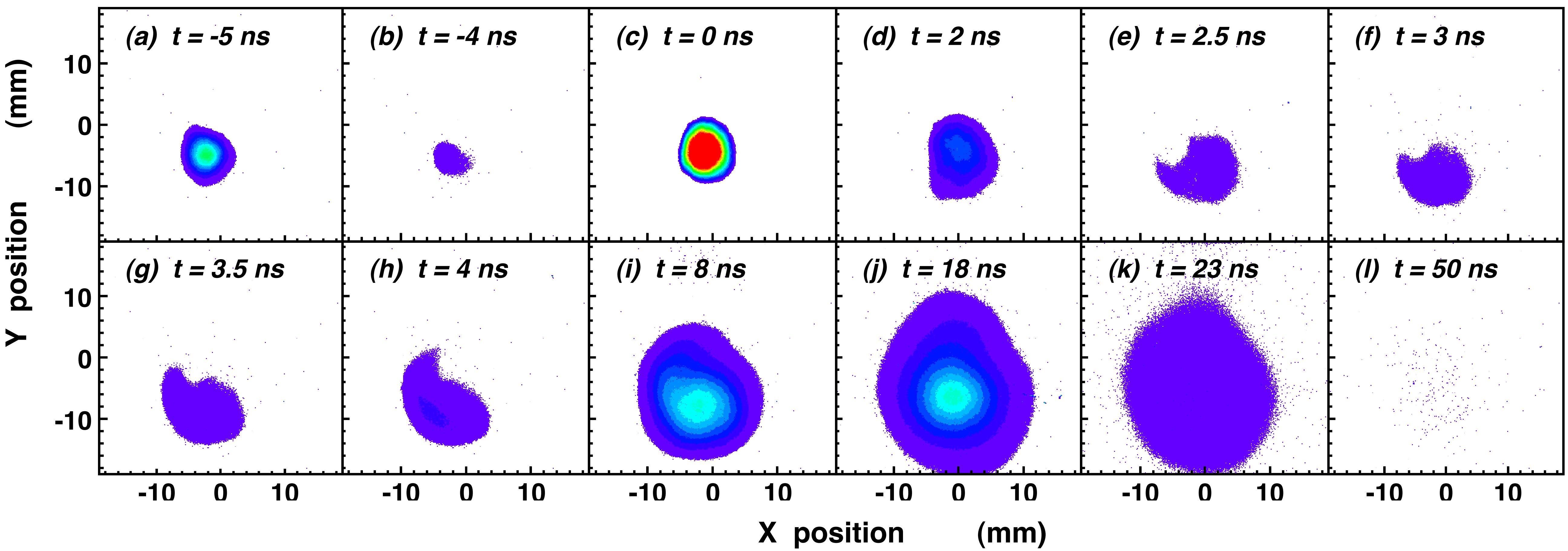
Time/space resolved measurement with B-field

Magnetic field 100 Gauss, acceleration voltage 1 kV

"Stop motion pictures" of the beam



5×10^8 photoelectrons, similar to Linac4 intensites.
"Swirling" effect due to cyclotron motion.

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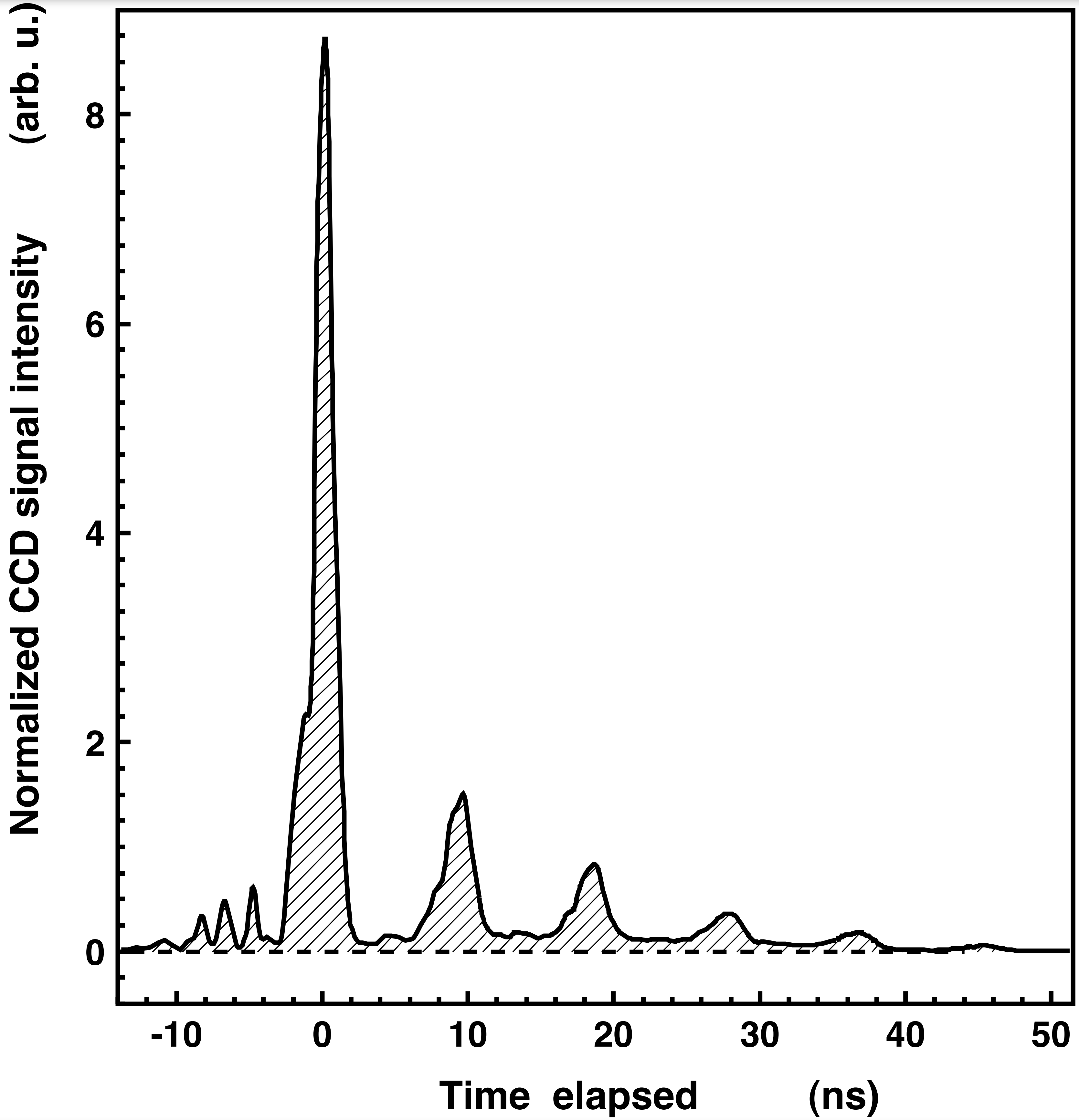
Time resolved measurement with B-field



B=100 Gauss
acceleration voltage 1 kV

$5x10^8$ photoelectrons, similar to Linac4 intensites.

Many prepulses and afterpulses appear at regular intervals !?

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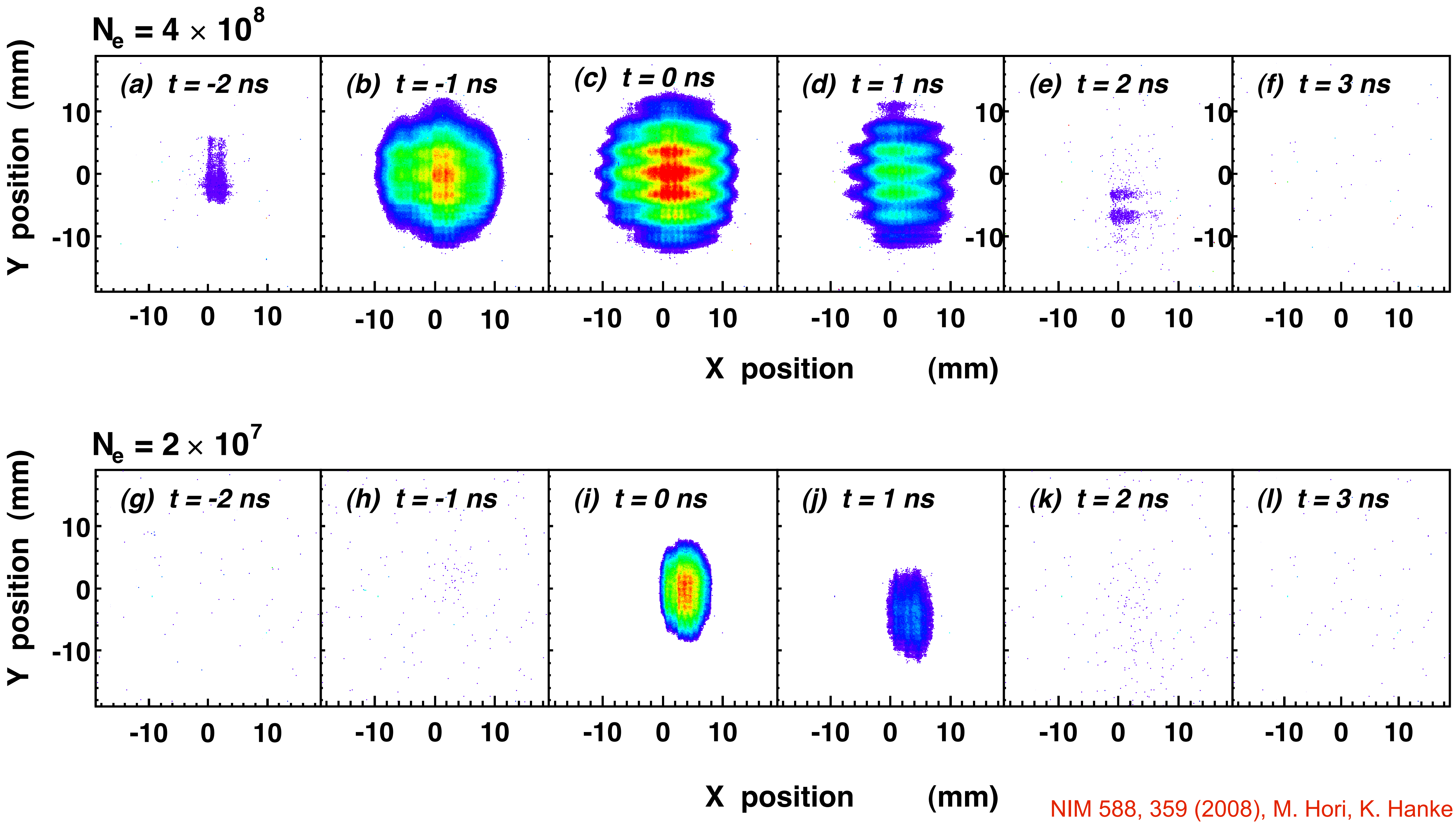
Spatial distortion due to space-charge effects

No magnetic field, lower acceleration voltage
(some distortion due to space-charge seen)



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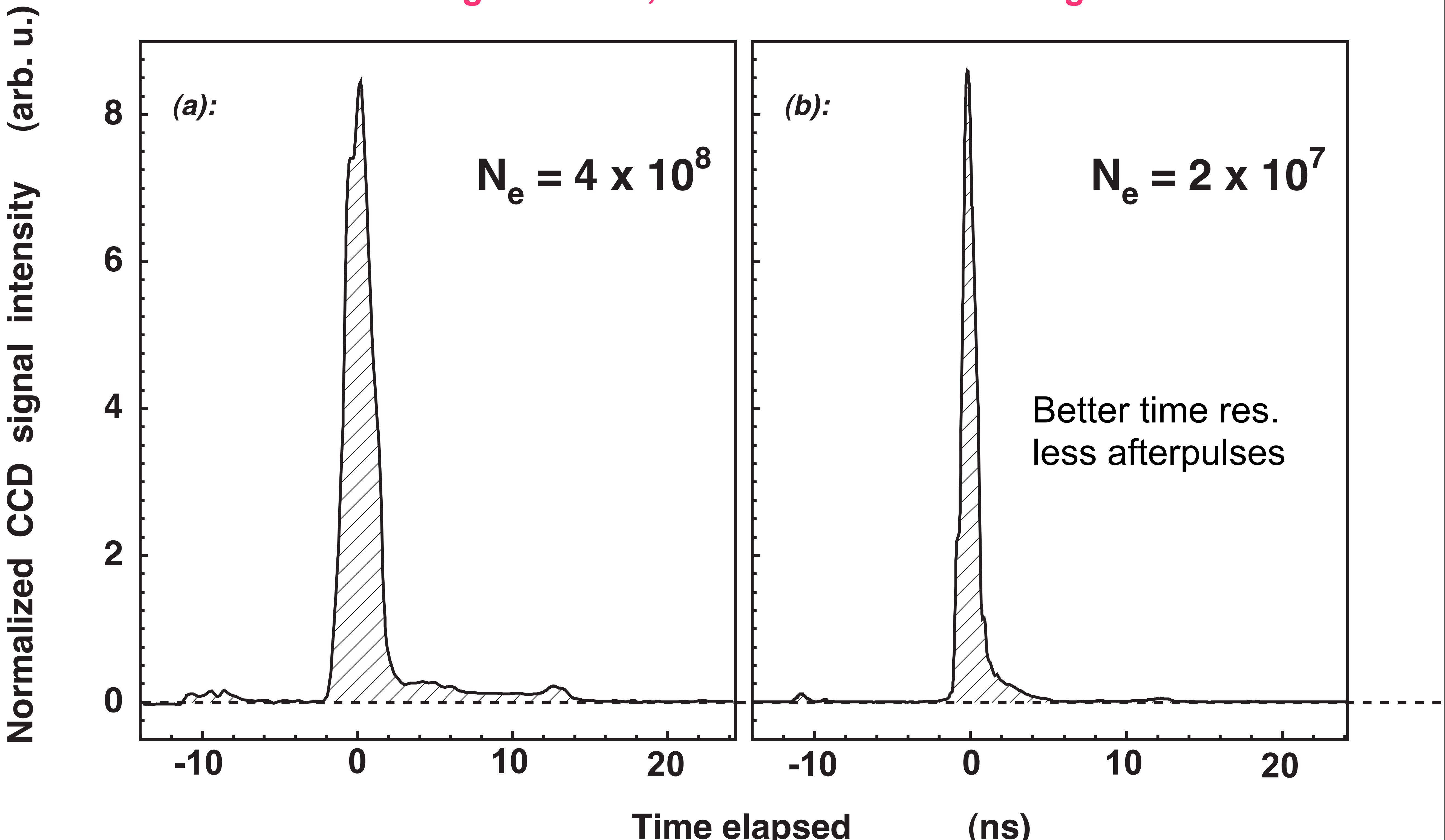
Timing deterioration due to space-charge effects

No magnetic field, lower acceleration voltage



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Future prospects

We are developing several new types of detectors for AD and ELENA:

Extremely low-cost and compact secondary electron emission detectors based on CMOS VLSI readout technologies.

Extruded scintillation bar modules read out by wavelength shifting fibers and Geiger-mode silicon multipixel detectors.

Optical fiber plate detectors.

Laser-ionization based detectors.

Conclusions

We developed scintillation screens, parallel plate ionization chambers, secondary electron emission detectors and used them at LEAR and AD since 1995 to measure both continuous and pulsed antiproton beams of energies 100 eV to 20 MeV.

Some of the detectors are semi-non-destructive and work at cryogenic temperatures and high magnetic fields.

Challenges lie ahead for high intensity, high speed beam facilities.

A new series of detectors are being developed for future experiments, and ELENA at AD.