Energy loss measurements of swift ions penetrating hot and dense plasma at the UNILAC

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4th NoRHDia

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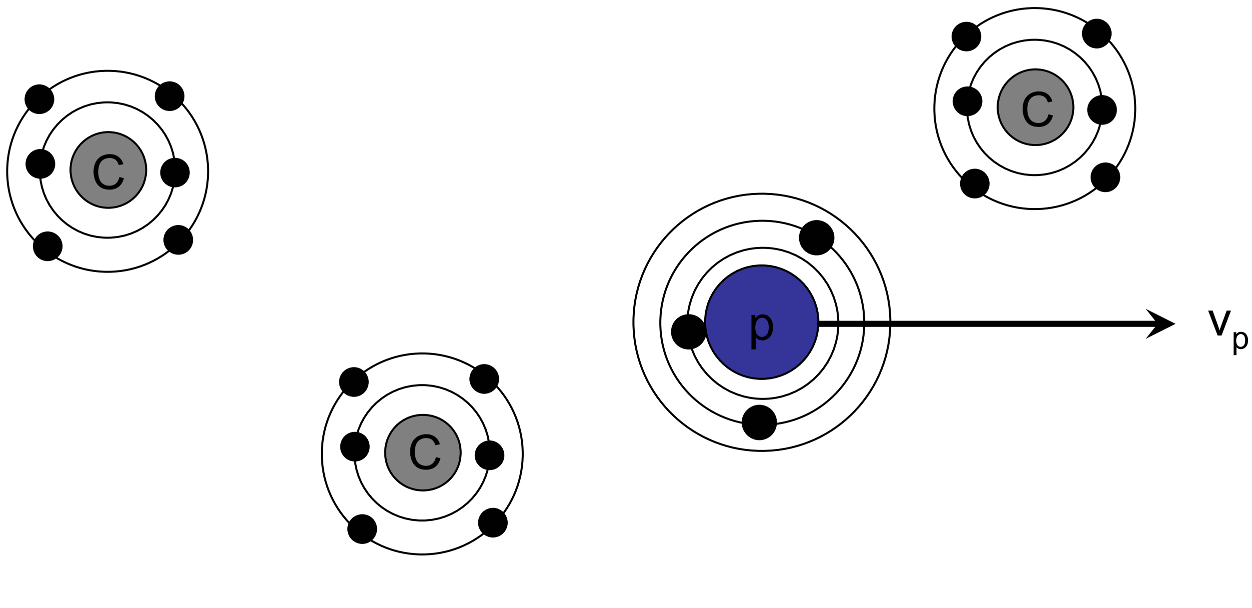
GSI Darmstadt

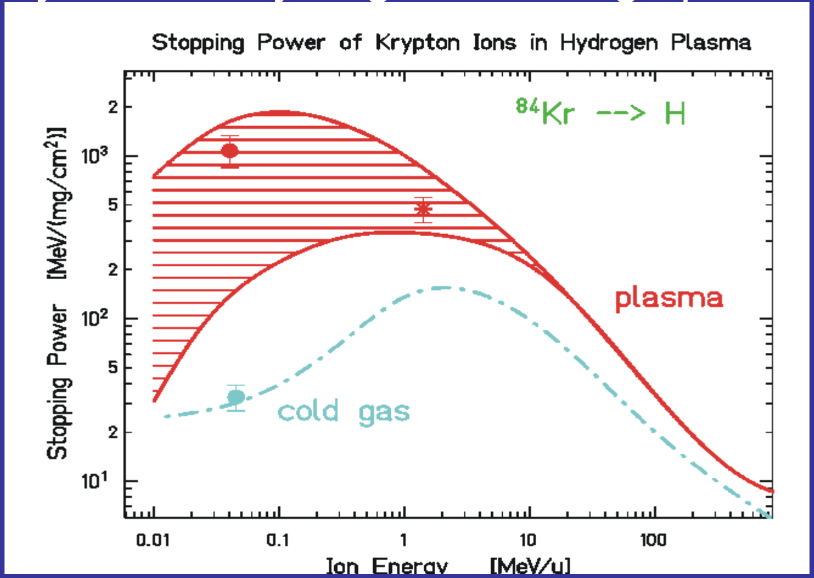
Projectile - solid/plasma matter interaction



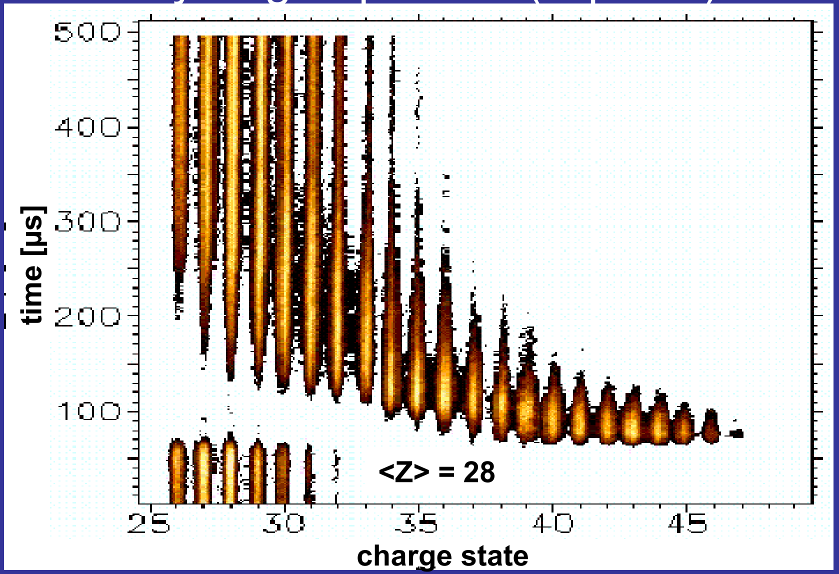
$$-\frac{dE_p}{dx} = \frac{16\pi a_0^2 I_H^2 Z_{p,eff}^2}{m_e v_p^2}\left[\underbrace{\sum_{Z=0}^{Z_t}(Z_t - Z)n_Z \ln\left(\frac{2m_e v_p^2}{\bar{I}_Z}\right)}_{\text{bound electrons}} + \underbrace{n_e \ln\left(\frac{2m_e v_p^2}{\hbar\omega_{pl}}\right)}_{\text{free electrons}}\right]$$

Interaction of heavy ions with a dense plasma

Enhanced stopping power of Kr ions in a fully ionized Hydrogen discharge plasma



Gold charge states in a fully ionized hydrogen plasma (Z-pinch)



Goal:	**To understand the interaction of heavy ions with hot, dense laser generated matter**
Therefore:	**Study the energy loss and charge state evolutions of heavy ions interacting with solids and plasma (GSI).**

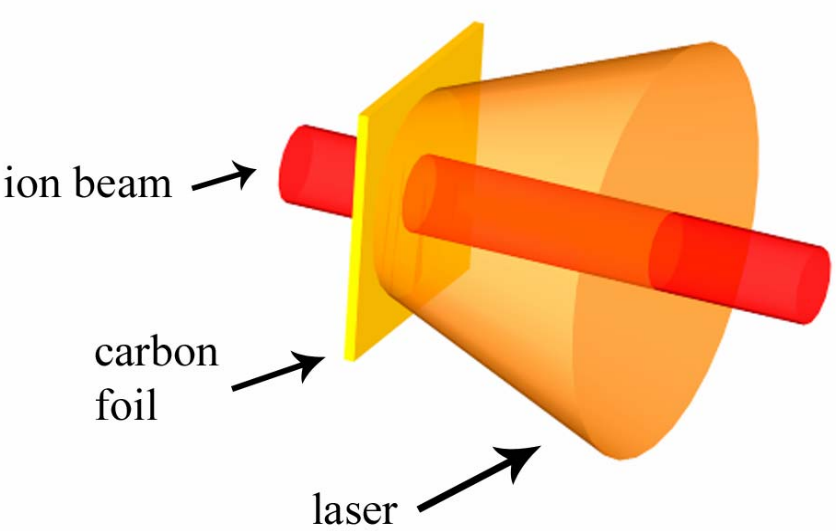
Outline

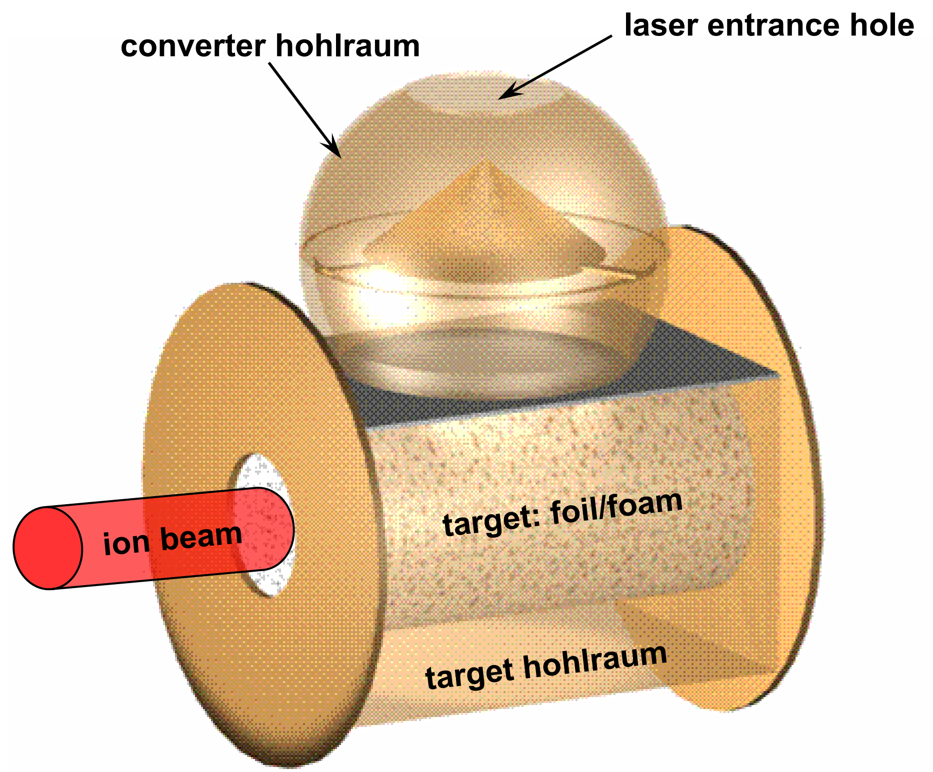
- Experimental setup at GSI
- The CVD diamond ion stop detector
- Results on energy loss in carbon plasma
- First MC simulation on ion-plasma interaction
- Summary

Generation of plasma with a laser

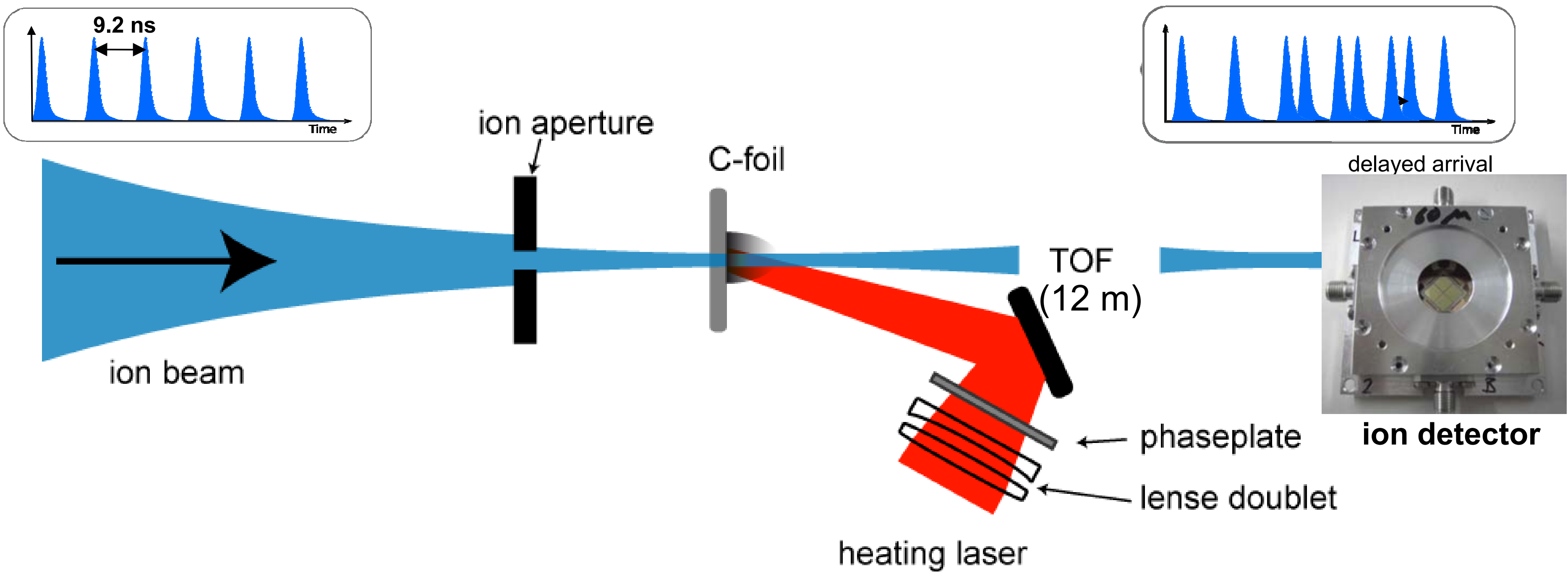
a) direct heating → high T_{pl}
high q_{pl}
low ρ

b) hohlraum heating → lower T_{pl}
lower q_{pl}
high ρ
homogeneous





Experimental schema



- **projectile**:
  - 36Ar^{16+}
  - E= 4 MeV/u
- **target:**
  - C foils
  - 100 – 300 μg/cm²

- **laser parameters:**
  - λ=1.064 μm
  - E=50 J
  - T_{pulse}=10 ns (FWHM)
  - d_{focus}=1 mm (random phase plate)

- **stop detector:**
  - polycrystalline CVD diamond
  - thickness: 19 μm
  - 1 mm², segmented 4 x (0.5x0.5 mm²)

Detector requirements

Temporal resolution:

- ❖ For 30% increased energy loss @ 5 AMeV, after 12 m drift:
- ❖ Expect TOF shift of $\Delta t_{plasma} - \Delta t_{cold} \leq 1.5$ ns between arriving micro pulses.

$\Rightarrow$ Need **temporal resolution $\leq$ 100 ps** $\Rightarrow \Delta E/E = 0.2$ %!

Sensitivity for heavy ions:

- ❖ Beam current @ ion detector: reduced by aperture to
  $10^2 - 10^3$ ions / micro pulse @ 108 MHz (≈1-2 μA)

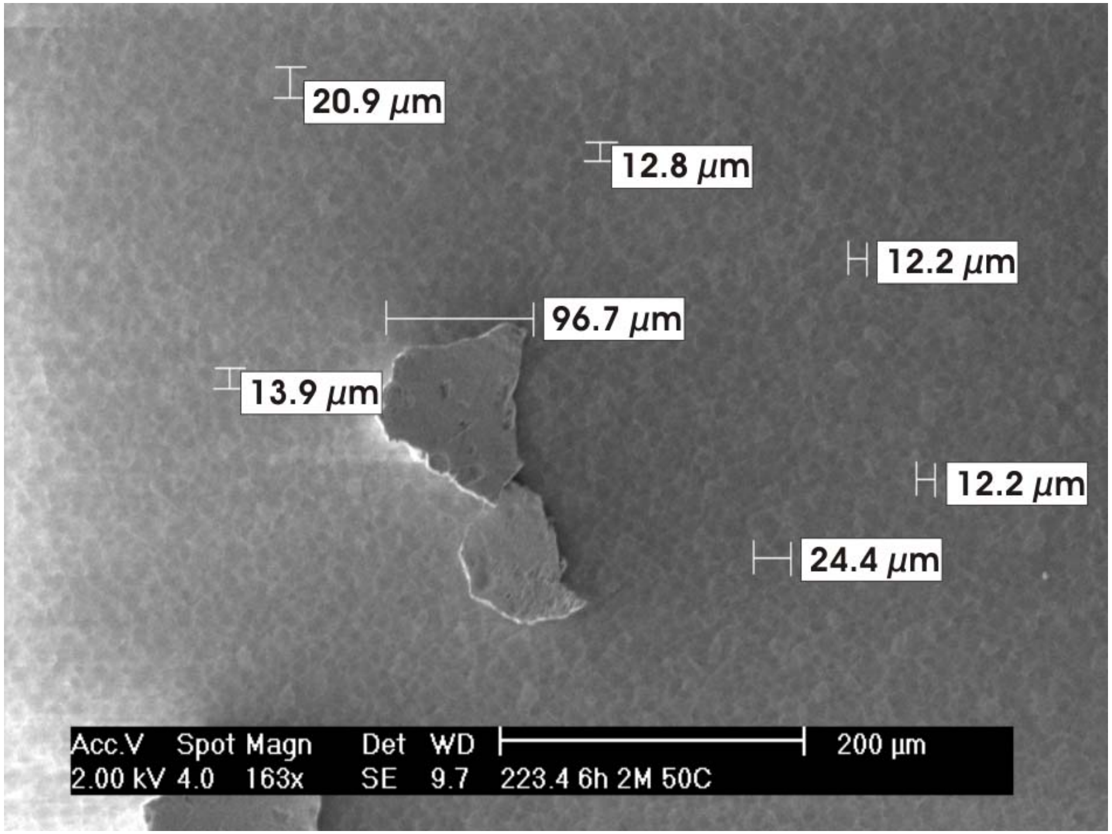
General:

- ❖ Heavy ions (^{20}Ne to ^{86}Kr) 5AMeV $\Rightarrow$ **radiation hardness** desirable.
- ❖ Intense X-radiation from plasma $\Rightarrow$ **low photosensitivity** desirable.

Solution:	PC CVD Diamond. (SC not available yet at ~1 cm²)

PC CVD Diamond

4 'thin' samples from FIAF: ☆



- size: 1x1 cm²
- ~3 μm of substrate side removed
- oxygen etching
- mechanical polishing
- thickness: **13**, **19**, **20.5** and **60** μm

☆

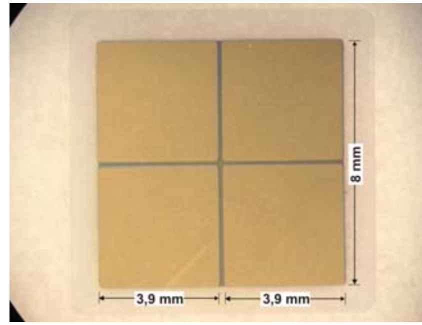
IAF Institut Angewandte Festkörperphysik

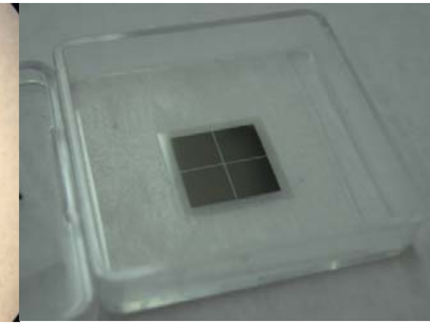
Fraunhofer Institut für Angewandte Festkörperphysik, Freiburg

Construction & assembly

Metallisation:

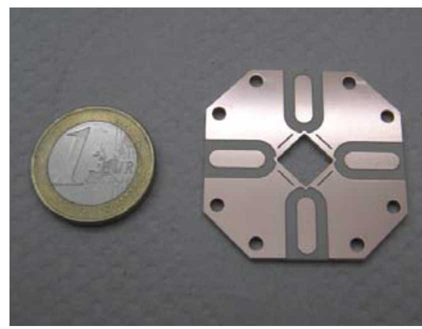
- ❖ 4-pixels beam-side, 3.9*3.9 mm²
- ⇒ reduce capacitance / time constant
- ❖ 1-pixel backside, 8*8 mm²
- ❖ Ti/Pt/Au: 20/30/100 nm, Al: 100nm
- ❖ Annealed in N_2 @ 500°C

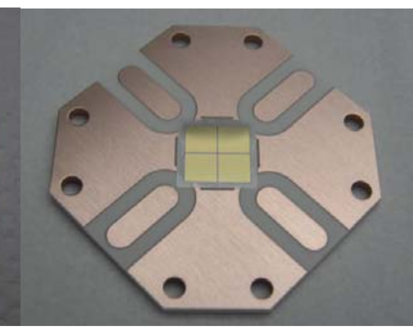




Contacting:

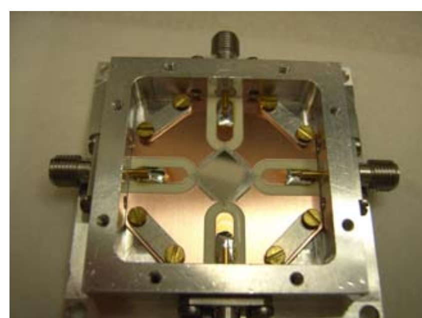
- ❖ RO 4350B™ HF-circuit board
- ❖ 50 Ohm impedance geometry
- ❖ Silver conductive glue
- ❖ Aluminium bonding wires

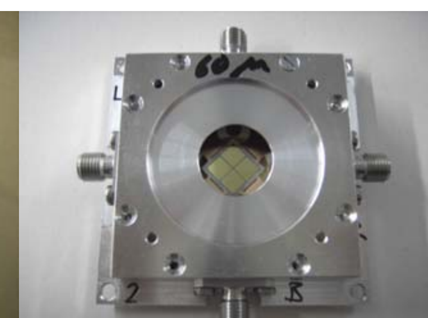




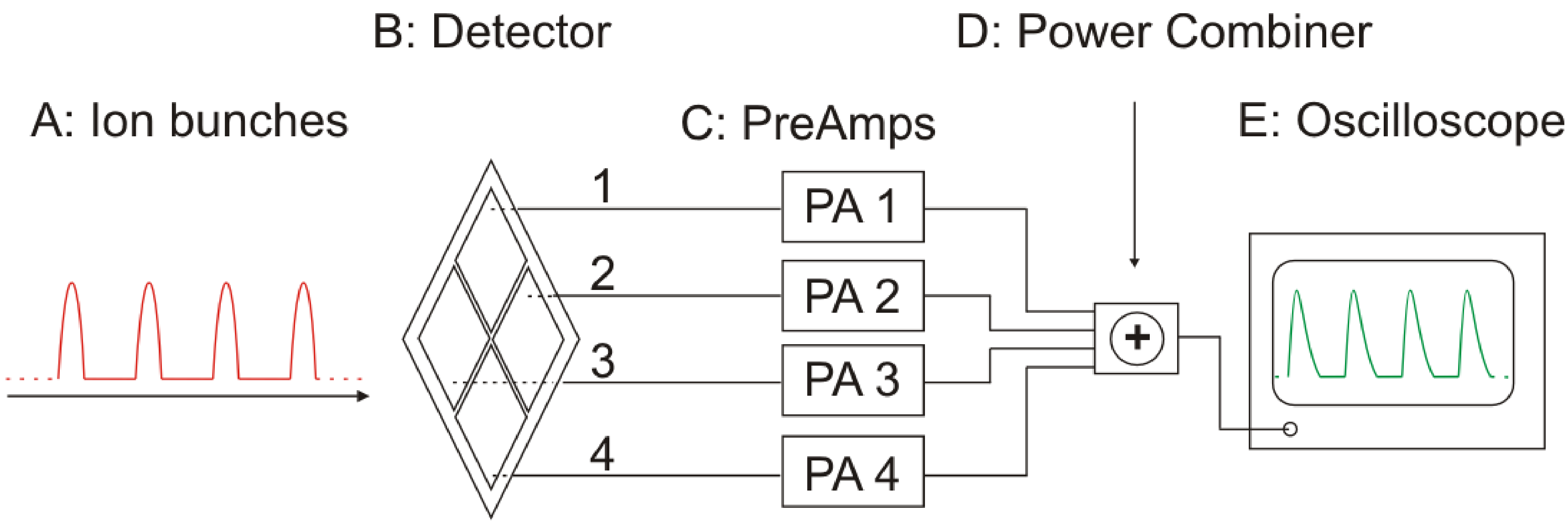
Aluminium housing:

- ❖ CF100 beam pipe suitable
- ❖ SMA connectors
- ❖ Caps and beam apertures





Data acquisition

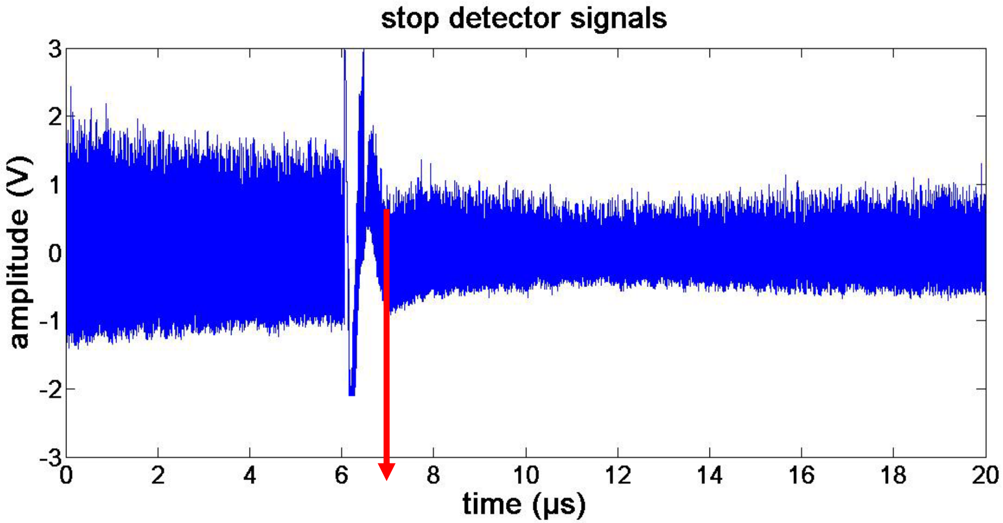


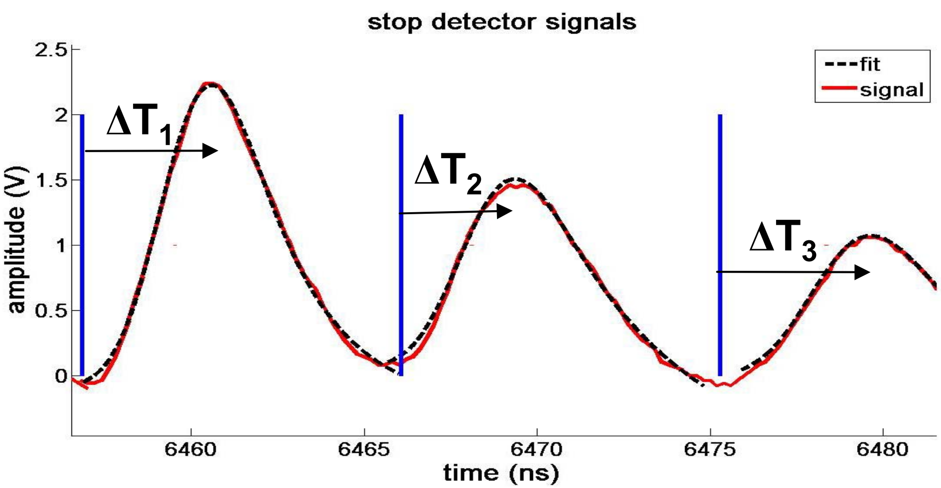
- **DBA4 broadband amplifiers** (by GSI).
- 10 GS/s oscilloscope.

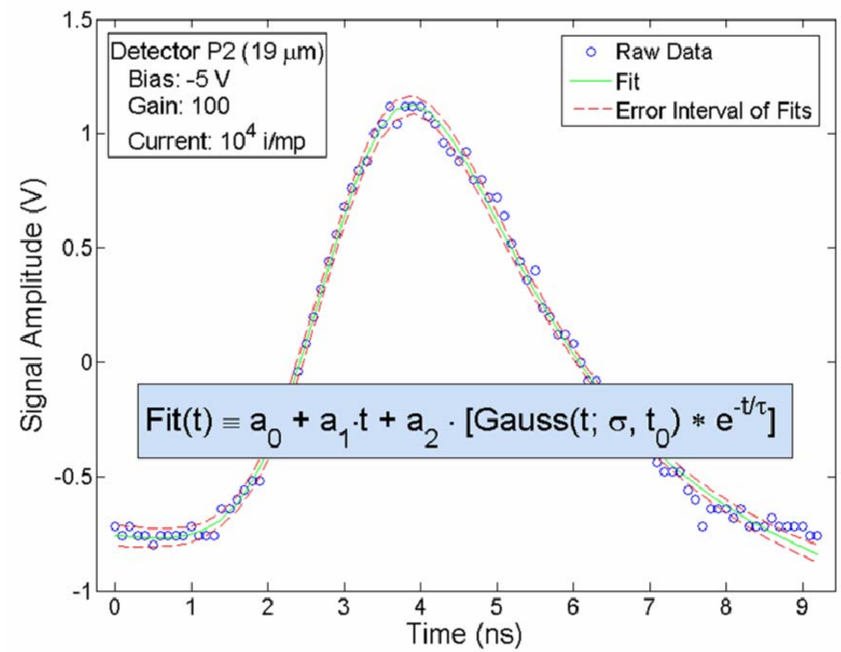
Experimental parameters:

- Beam current: 3.6 μA to 280 nA ↔ ~ 10^4 to 10^2 ions / micro pulse (**i/mp**).
- Detector thickness (4 different detectors: 13, 19, 20.5 and 60 μm).
- Detector bias voltage (-2 V/μm to + 2 V/μm).
- (PreAmp gain: 100 or 10 absolute)

Experimental data analysis







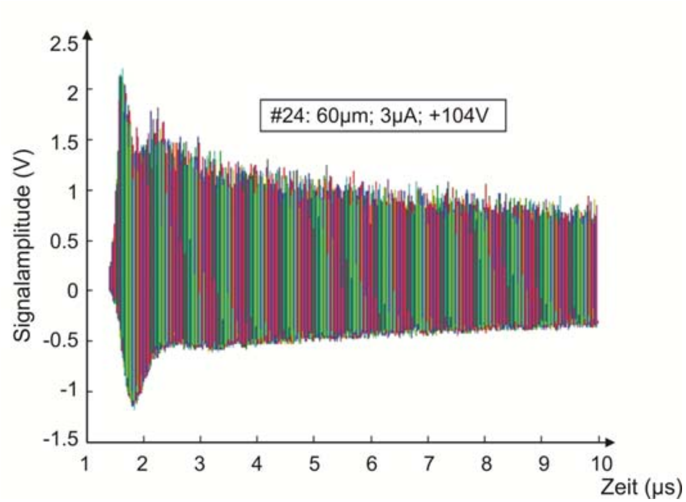
- **Fit function**: Convolution of Gaussian with detector response (exp. decay).
- **Fit parameters:**
  Gaussian: centre $\mathbf{t_0}$, width σ, amplitude $\mathbf{a_2}$
  Baseline: slope $\mathbf{a_1}$, offset $\mathbf{a_0}$.

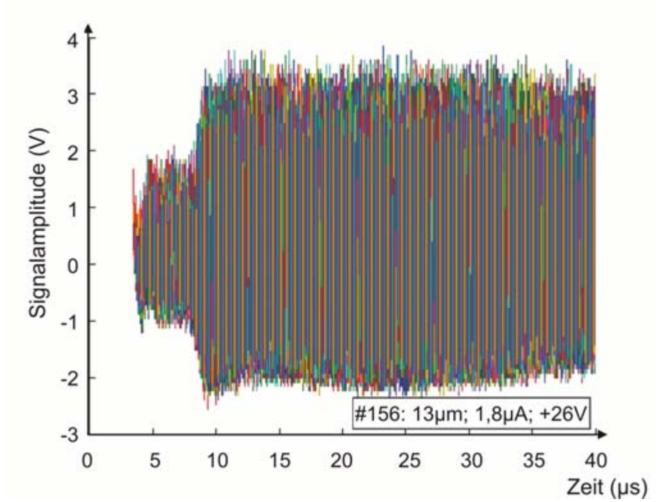
Thickness of diamond sample

60 µm

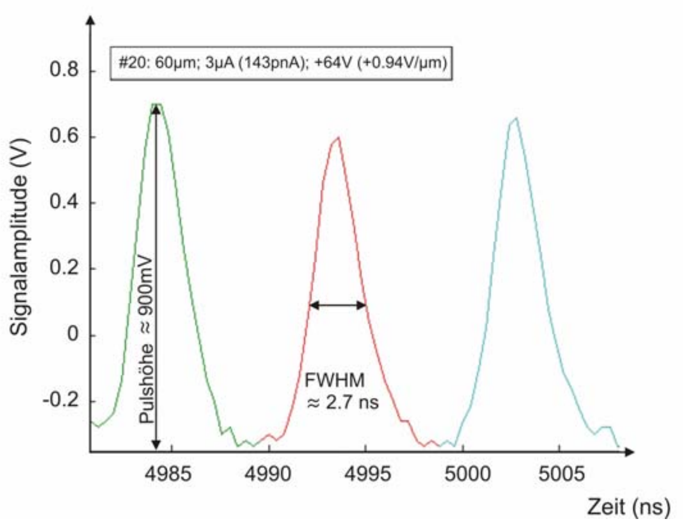
13 µm

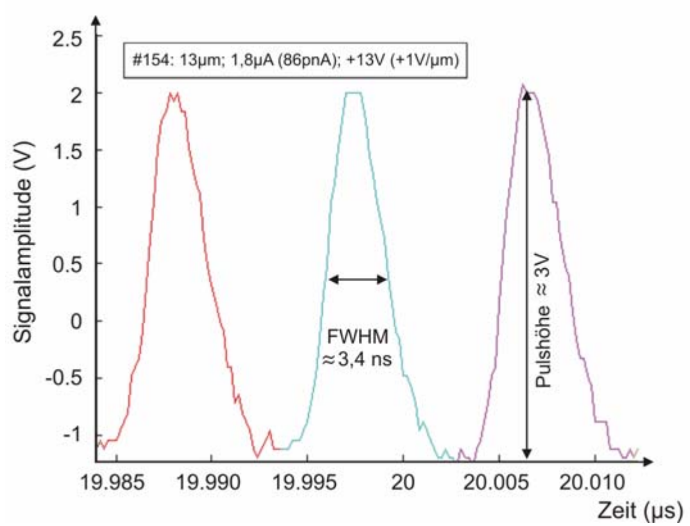
macro shape





micro shape

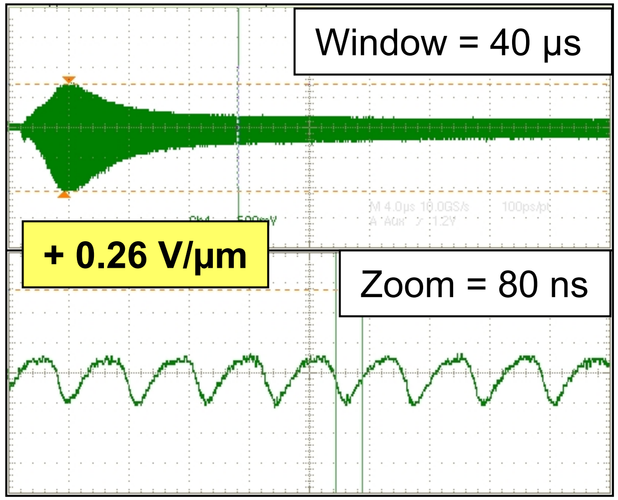


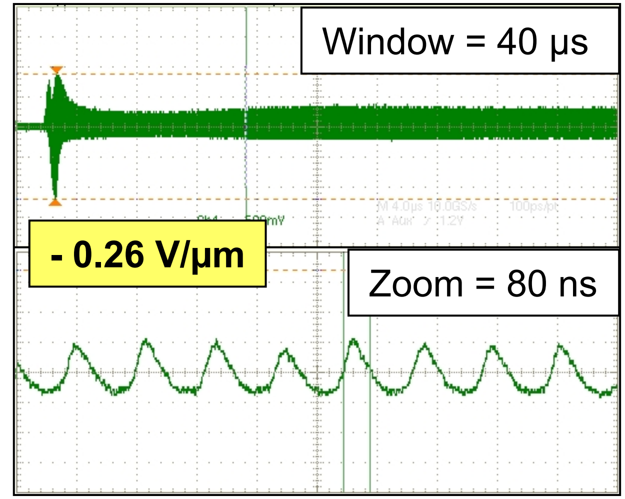


Detector bias

Bias polarity:

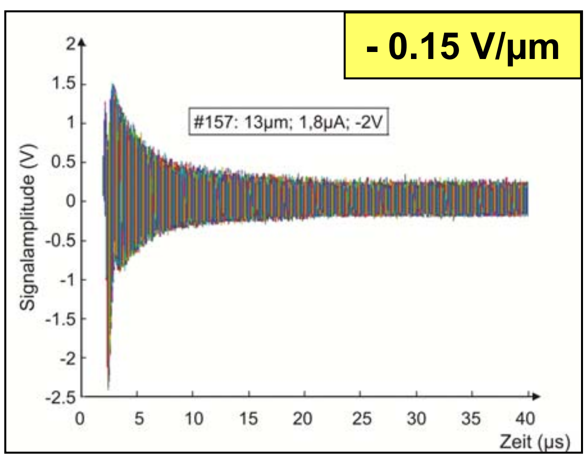
19 µm detector
Gain: 10
Current: ~10^4 i/mp

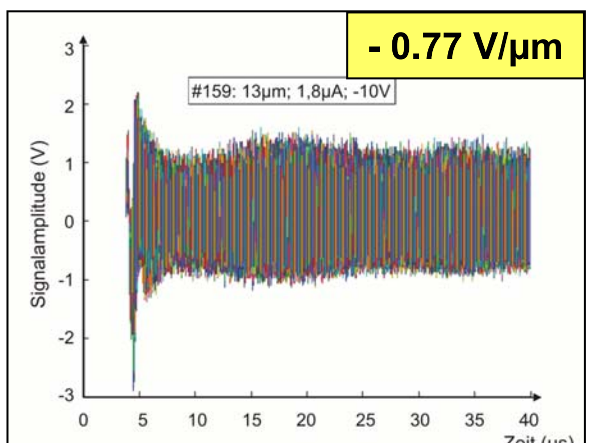


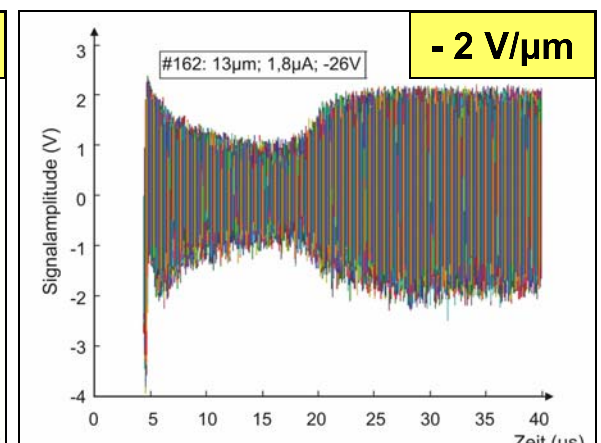


Bias value:

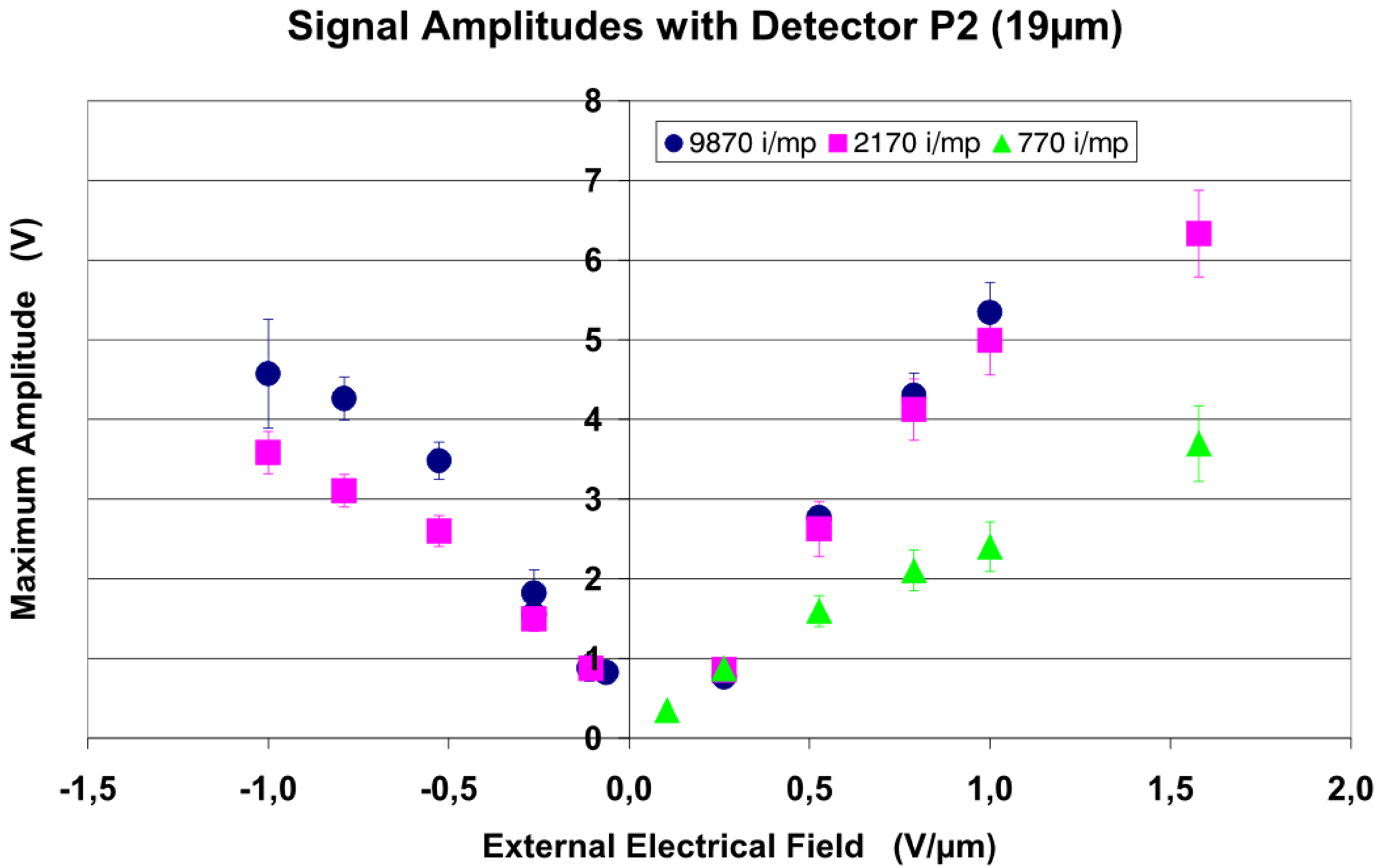
13 µm detector
Gain: 10
Current: ~10^2 i/mp





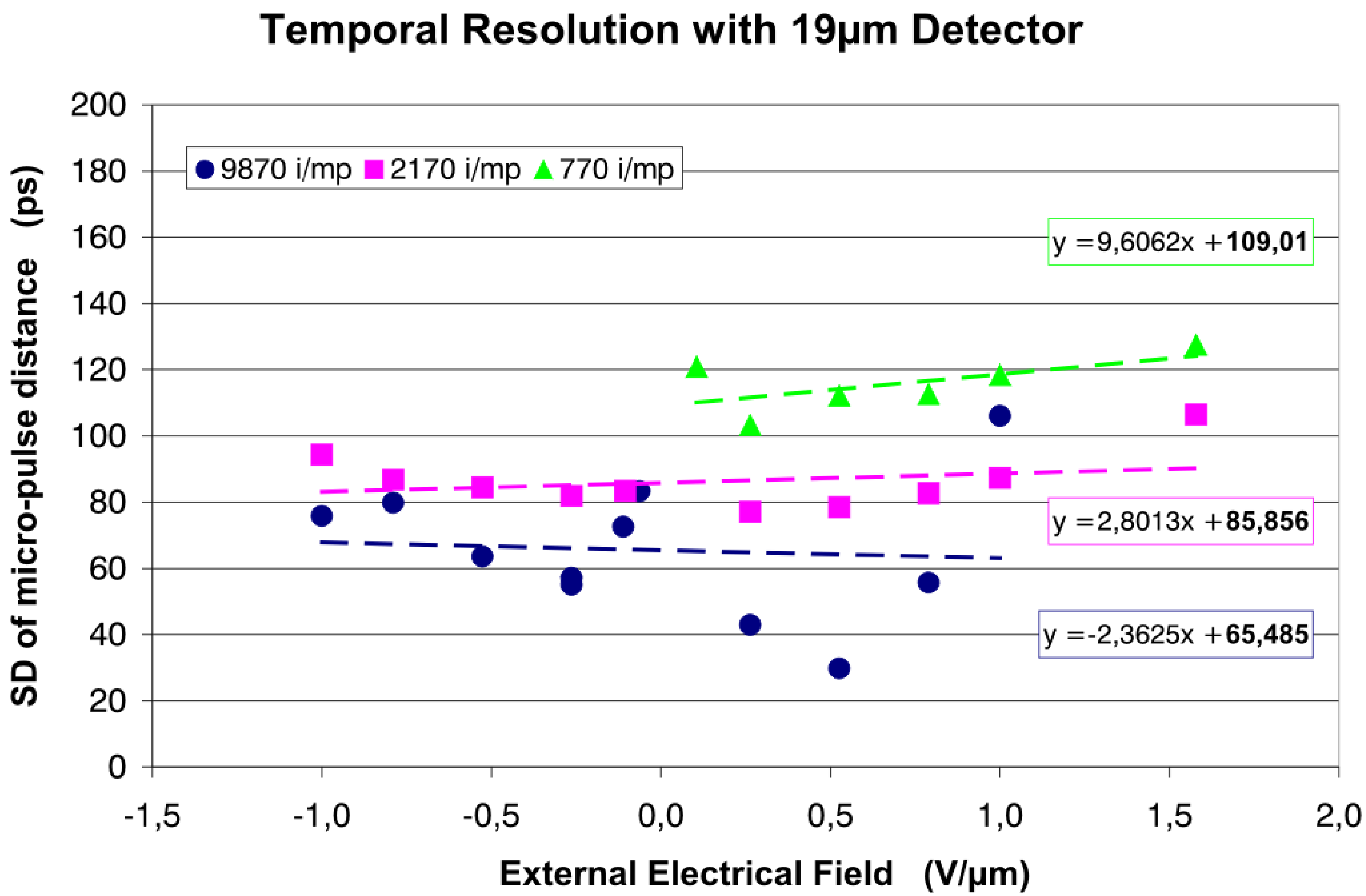


Signal amplitudes



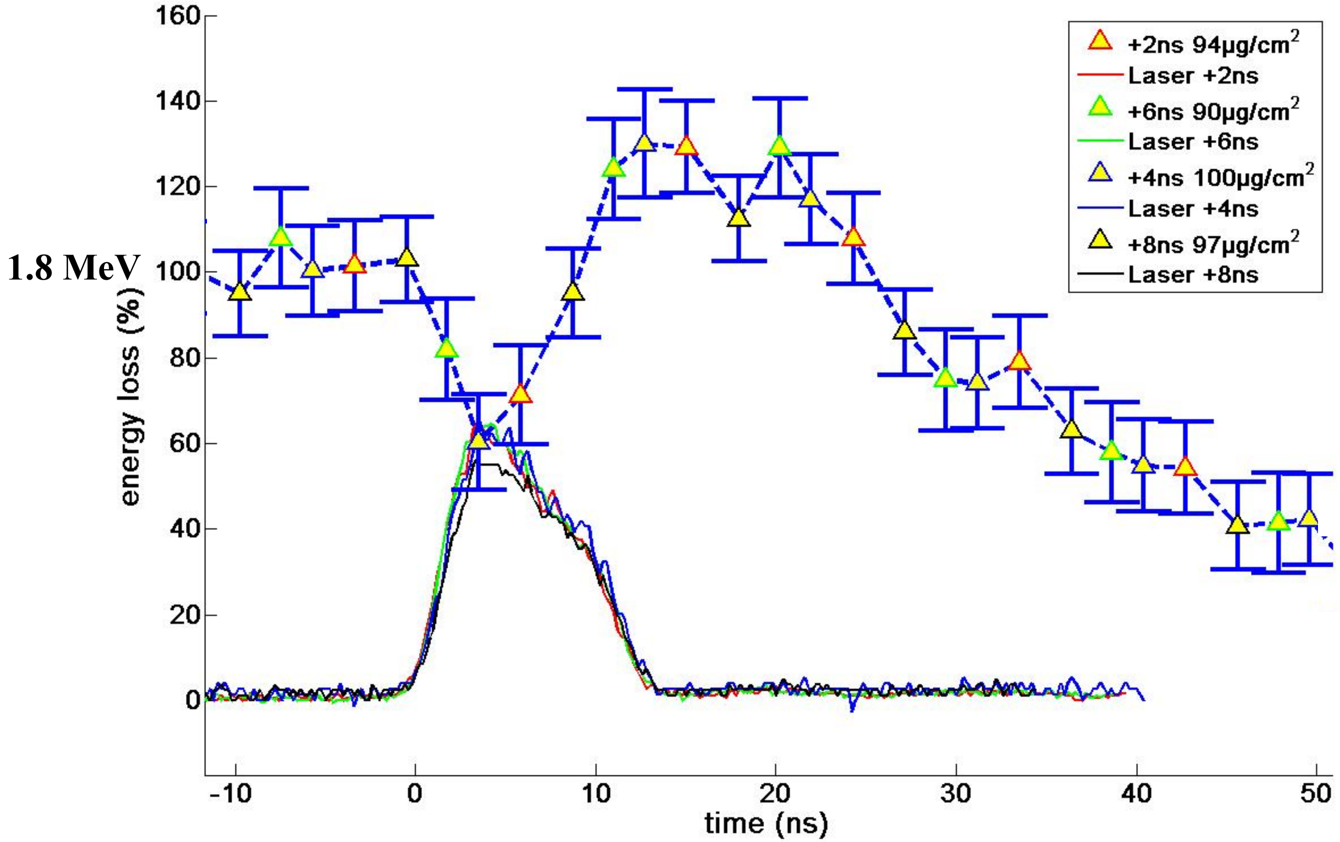
Higher amplitudes for **positive** bias voltage.

Temporal resolution



- ❖ Analyse the temporal distance between micro pulses in one macro pulse.
- ❖ Take the **standard deviation** of the mean (9.224 ns) as temporal resolution

ΔE(^{36}Ar, 4 MeV/u) in C (0.5 μm) plasma



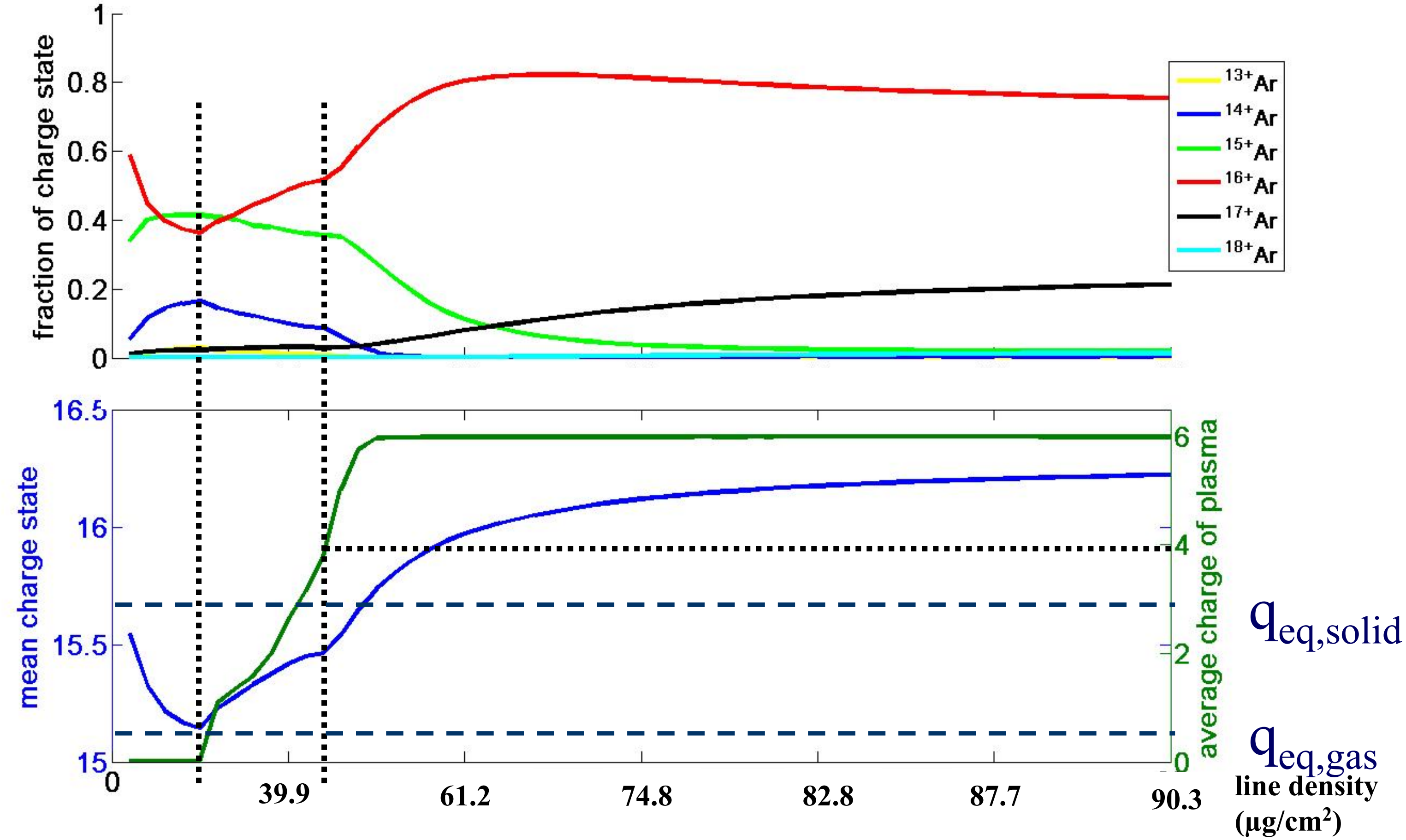
Theoretical investigation of the Ar charge state evolution in carbon plasmas

- plasma diagnostics
- plasma hydrodynamic simulation:
  - electron density
  - electron temperature,
  - ion density and
  - plasma mean charge state
- Experiment at HMI:
  - cross sections for all relevant charge exchange reactions, (i.e. electron capture, ionization, excitation, decay) for Argon @ 4 MeV/u in C
  - charge dependent stopping powers, S(q), for Ar in C

- ETACHA cross section calculations are scaled to plasma conditions by adjusting target screening and the amount of bound electrons to the actual plasma state
- Cross sections for collisions with free electrons added:
  - electron-impact ionization (Y. Zhao Journal of Quantitative Spectroscopy & Radiative Transfer 77 (2003) 301–315)
  - dielectronic recombination (K. B. Fournier, Phys. Rev A **56,** 6 (1997))
  - three-body recombination (T. Peter, MPQ 105 (1985))

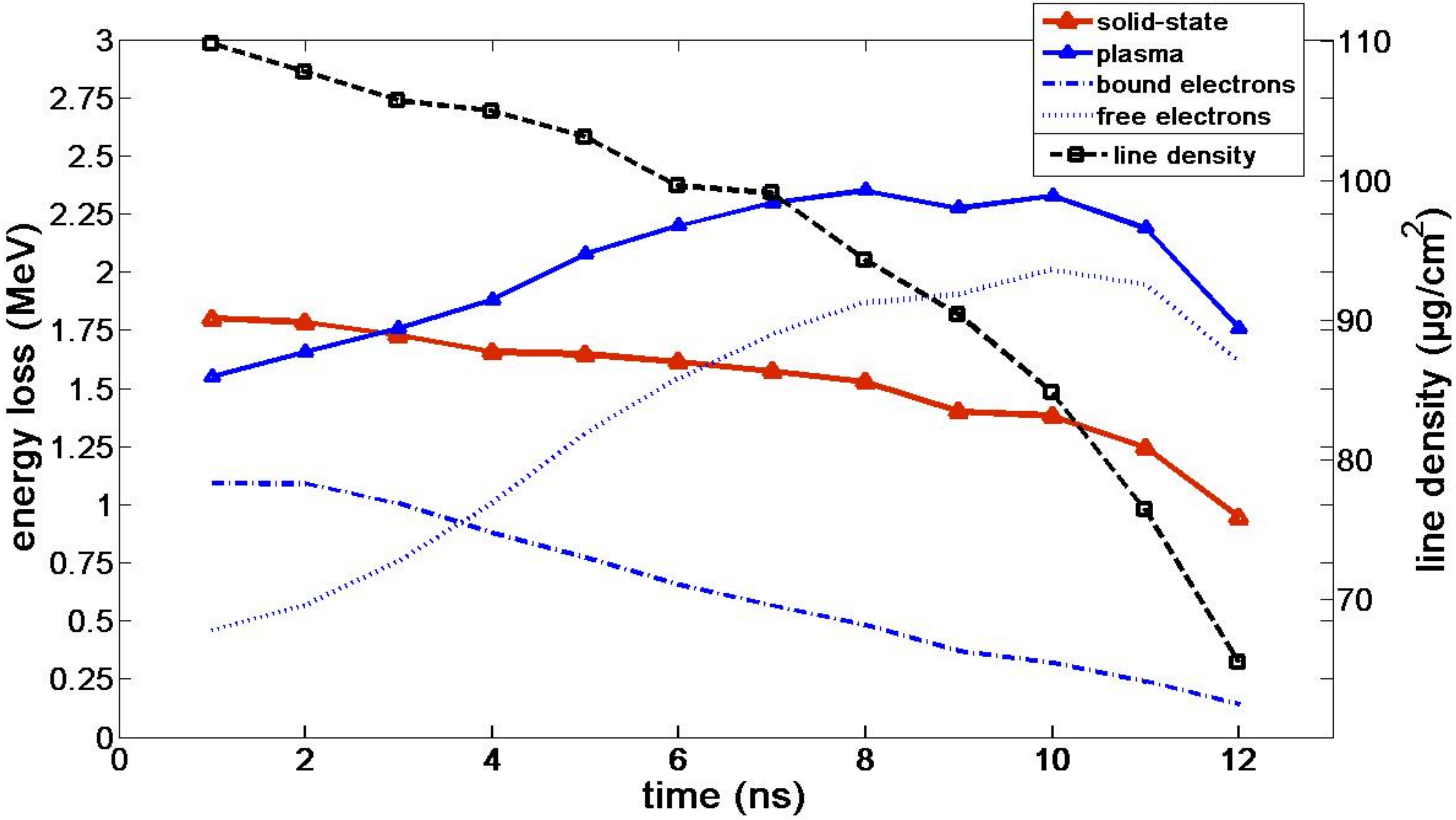
Plasma charge state evolution

Ar^{16+} in C plasma (100 mg/cm²) @ t = 9 ns



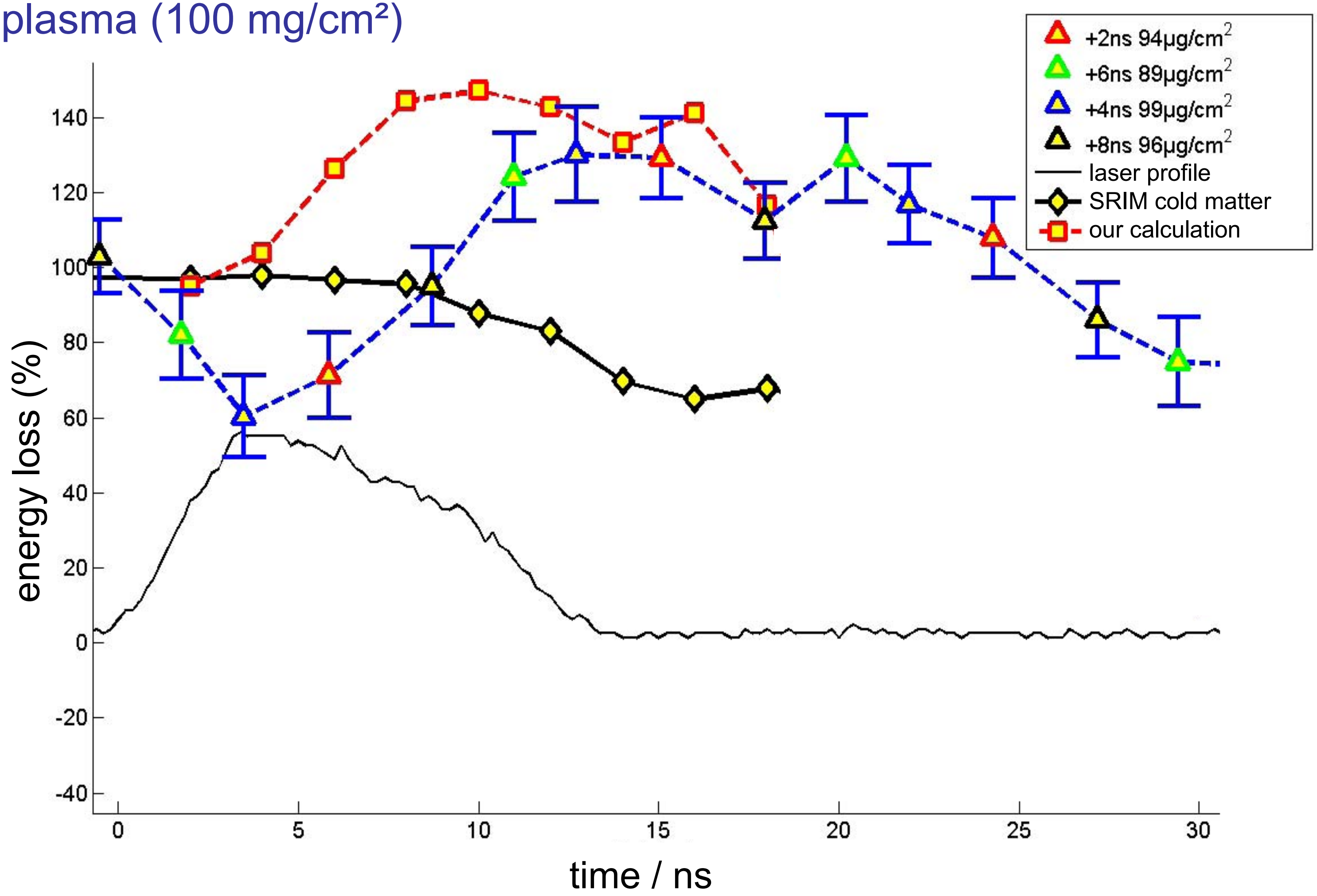
Theoretical description of the energy loss

Ar in C plasma (100 mg/cm²)



Comparison with experimental data

Ar in C plasma (100 mg/cm²)



Summary & Outlook

- ✓ Successful use of PC diamond detector for recording the temporal structure of the UNILAC macro pulse
- ✓ Best signal form when adapting detector thickness to ion range
- ✓ Detection of 10^2 to 10^4 ions per microbunch (FWHM 3 ns) @ 108 Mhz
- ✓ Temporal resolution of Gaussian peak detection < 100 ps
- ✓ Short death time due to X-ray flash

- o Develop a new diamond based charge state detector to measure the projectile charge state distribution after the plasma interaction
- o Experiments with Phelix laser (E < 500 J)

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