Scintillating screens for ion beams

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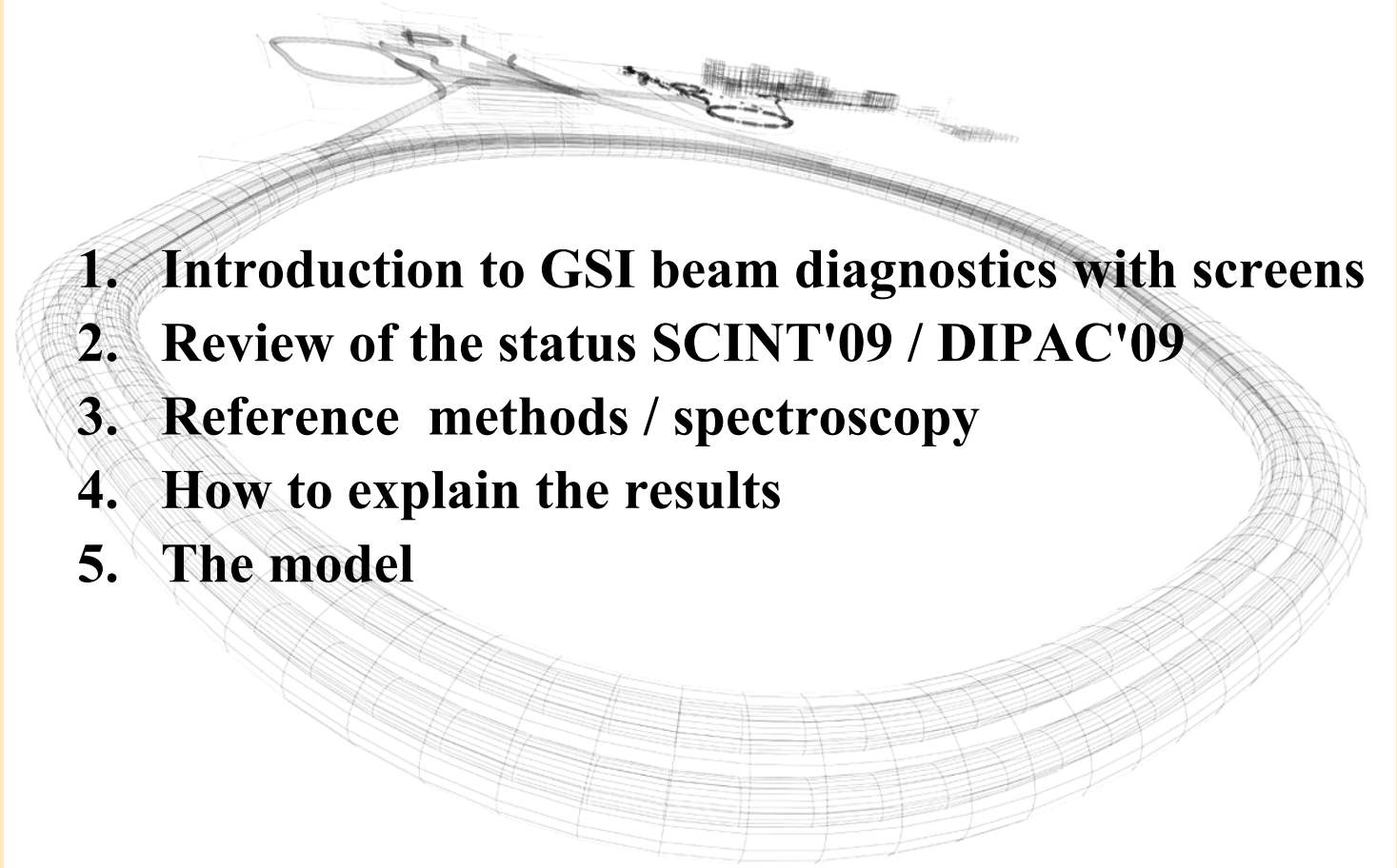
Outline



1. Introduction to GSI beam diagnostics with screens
2. Review of the status SCINT'09 / DIPAC'09
3. Reference methods / spectroscopy
4. How to explain the results
5. The model

Scintillating Screens @ GSI

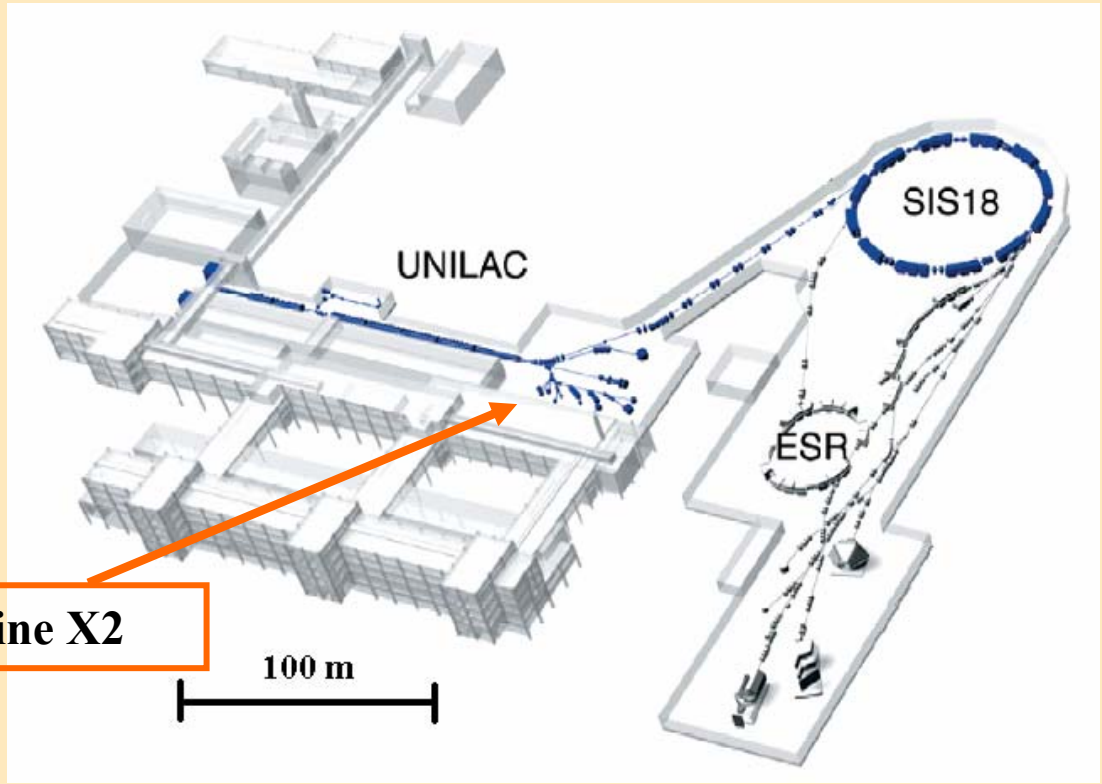
GSI Facility

Linac UNILAC:

- all ions from protons to Uranium
- pulsed currents up to 10 mA
- energies up to 11.4 MeV/u ~ 15.4%c

Synchrotron SIS18:

- ions from protons to Uranium
- up to 10^{11} stored particles
- energies up to 4 GeV/u ~ 98%c



Future extension:

GSI will be the injector for **FAIR: F**acility for **A**ntiproton and **I**on **R**esearch, with high beam currents in the UNILAC

Beam diagnostics with screens @ GSI

Scintillator screens are widely used for qualitative measurements:

- simple profile measurements system (cost efficient)
- complete 2-dimensional beam information (Profile Grid→2x1D)
- used for beam alignment

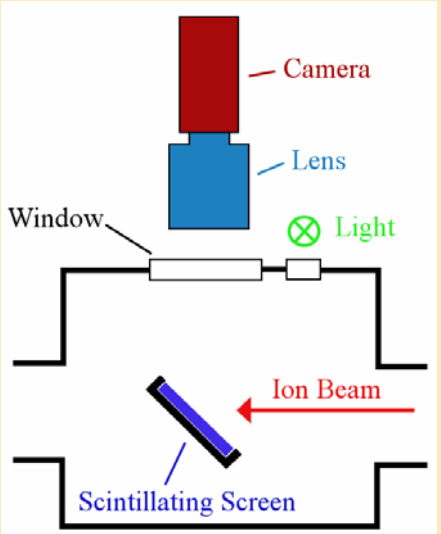
But we want to perform quantitative measurements

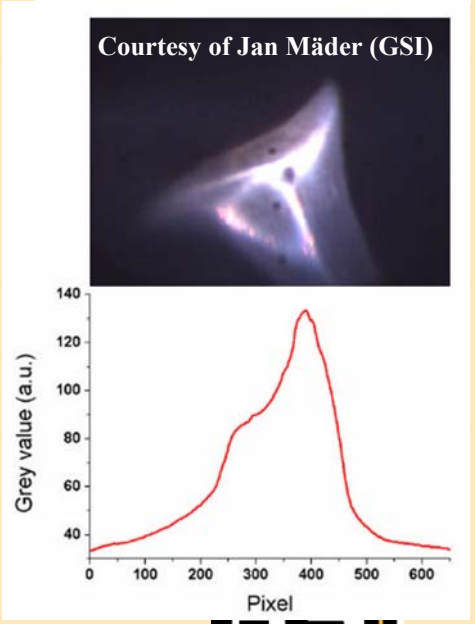
→ Investigation for high currents :

(some mA, for up to 1 ms @ 11.4 MeV/u

→ about 100µm range in matter)

- spatial resolution and linearity
- ageing effects
- dynamical behaviour





Possible application

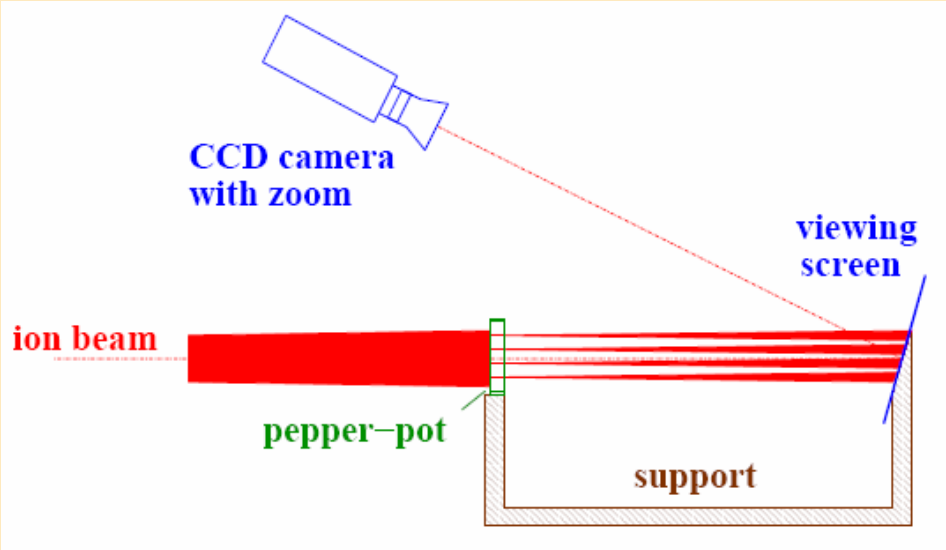
Single shot emittance measurement

-Advantages of the Pepperpot method compared to the Slit-grid method

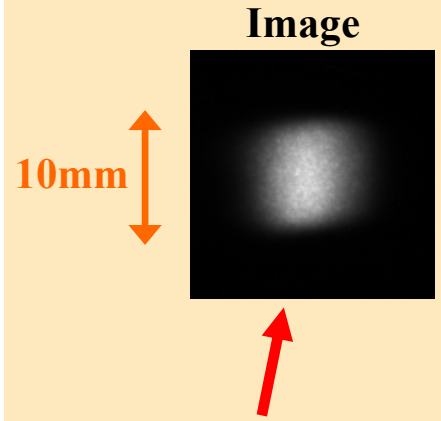
- gain of complete transversal phase space information from one macro pulse

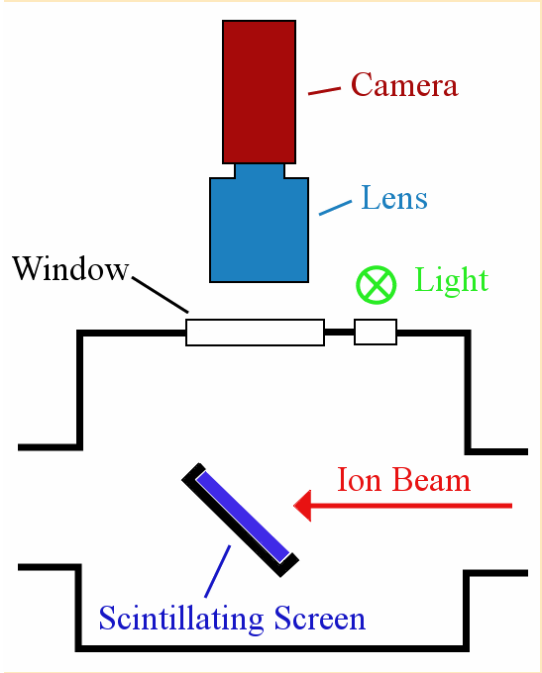
- much shorter measurement time at the UNILAC Pepperpot: ~1 min.
  Slit-Grid: ~30-60 min.

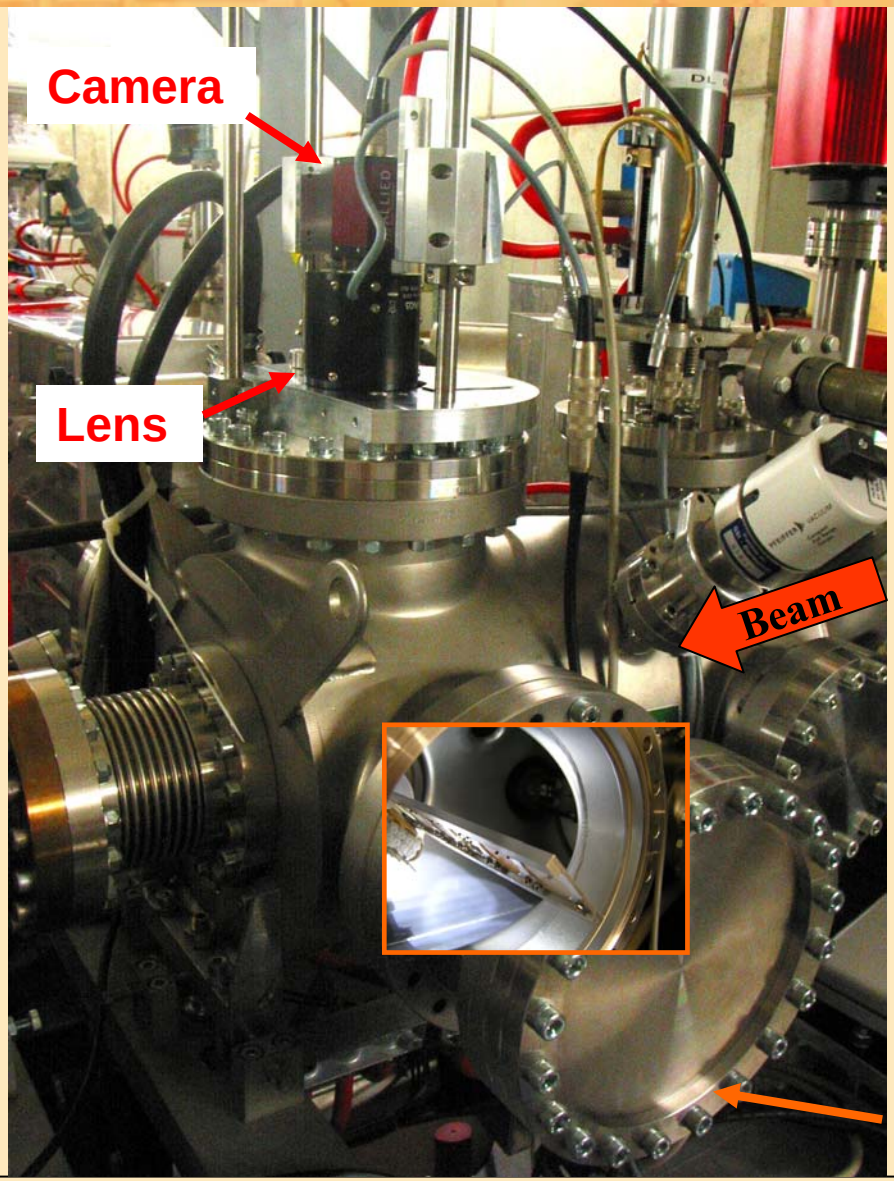
- can be used for machines with low repetition rate



Advanced experimental setup (imaging prop.)





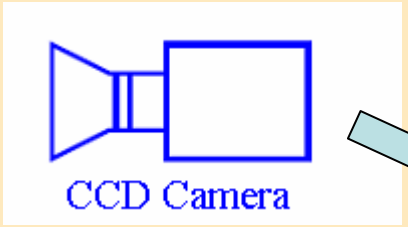


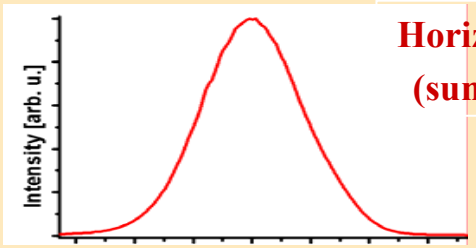
Camera: AVT Stingray F033B (VGA monochromatic), FireWire interface
Lens: Linos ROD Mevis, 2516, stepping motor driven
Resolution: 10 pixel/mm
DAQ: Industrial PC with FPGA

Advantage:

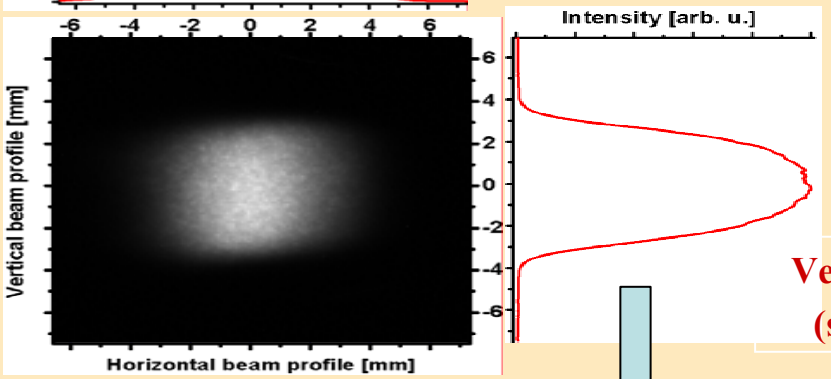
- **back-fitting time from spectrometer to normal camera is about ~25 min.**
- **new DAQ stores the number of particles synchr. for each image → new@GSI**

Observed image parameters



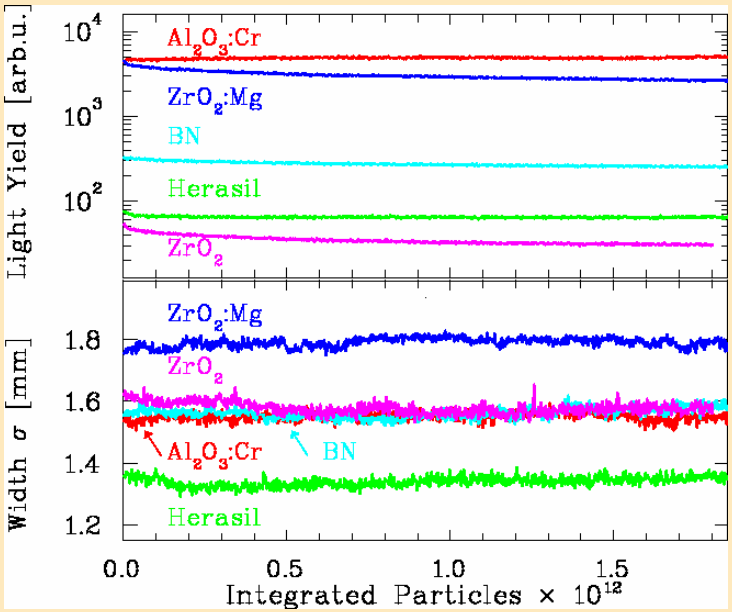


Horizontal projection
(sum over columns)



Vertical projection
(sum over rows)

Comparison of Materials



From the projection:

- Light yield (integral)
- Center of projections (μ, 1st moment)
- Beam width (σ, 2nd moment)
- Skewness (prop. to 3rd moment)
- Kurtosis (prop. to 4th moment)

Scintillators / Ion beams

Desired property: high resistance against high current ion beams

→ **Focus on**

Ceramics: ZrO_2(different doping Y, Mg, Y+Al) , Al_2O_3, Al_2O_3:Cr, AlN, BN

Quartz glass: Herasil

Investigated with **H^+, C^{2+}, Ar^{10+}, Ni^{9+}, Ta^{24+}** and **U^{28+}** Ions with energies between **4.8** and **11.4 MeV/u** and beam currents from some nA to some mA.

4.8 MeV/u ≈ 10%c 11.4 MeV/u ≈ 15.4%c

"Why don't you use crystals" William Moses @ SCINT '09

Application of scintillators in middel energy physics @ PANDA (up to 15 GeV)

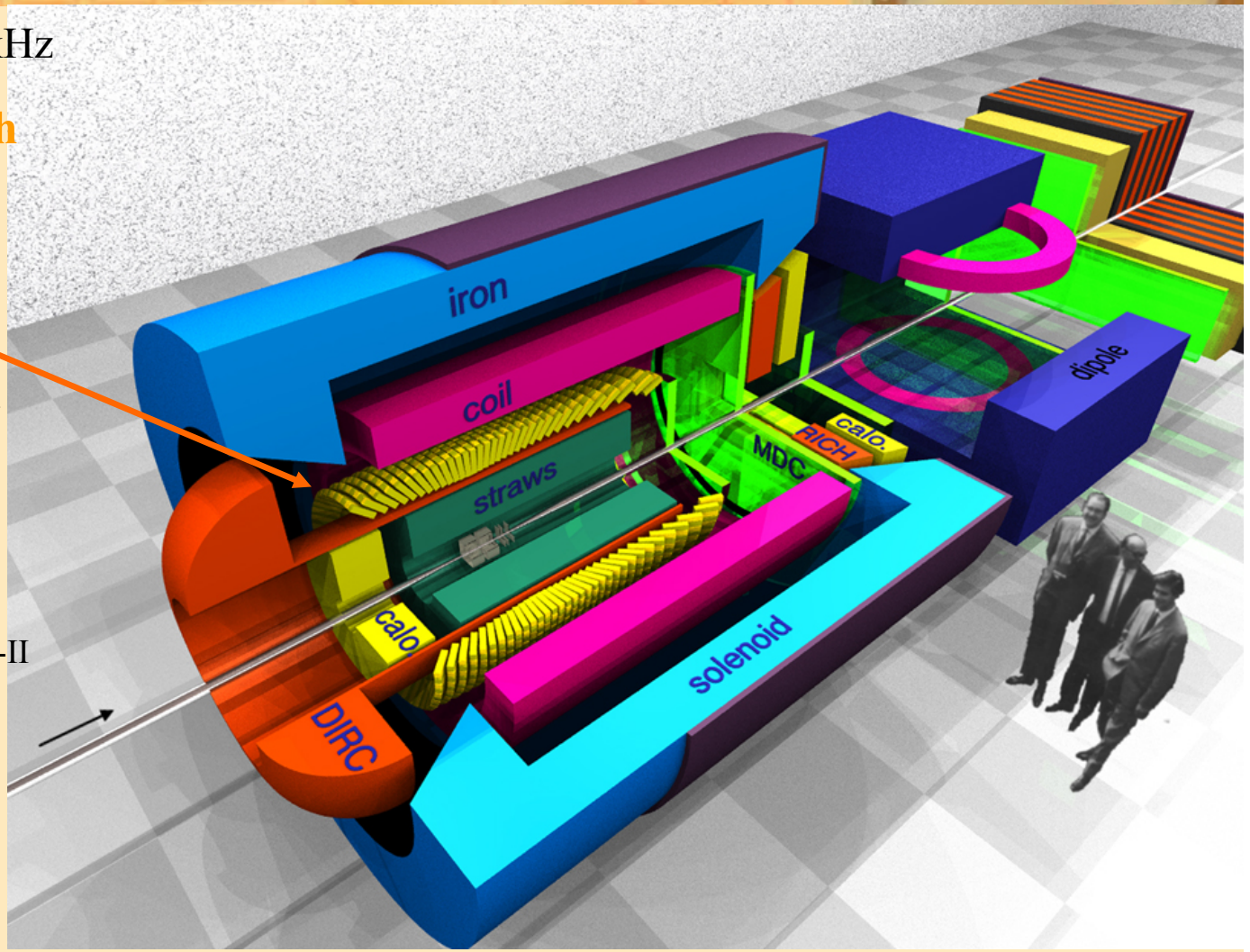
Counting rates: up to 500 kHz

Dose rate: up to **27 mGy/h**

Life time: > 10 years

Crystals: $PbWO_4$

Due to the slow relaxation of color centers in cooled crystals one has to cope with a typical loss in scintillation response between 20 and 30% as an asymptotic value after a deposited dose of 30-50 Gy for typical PWO-II (for γ-rays, ^{137}Cs source)

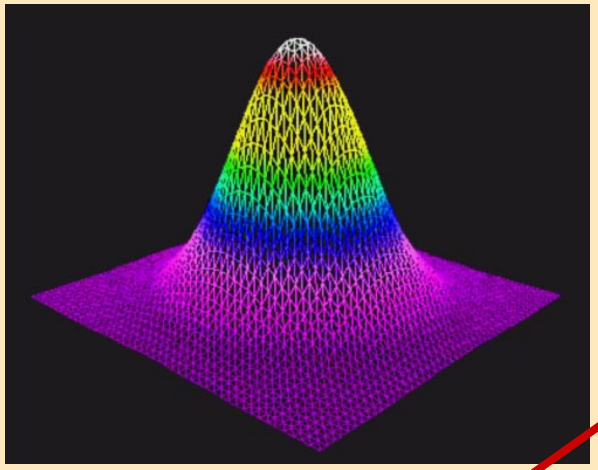


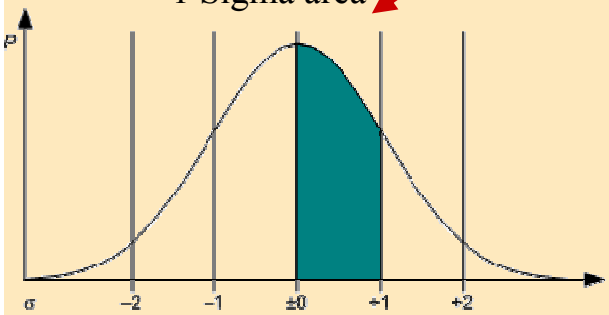
The primary ion beam does not hit the crystals

Dose estimation for scintillating screens in the UNILAC

Due to the stopping power and the intensity distribution of the ion beam, there is a significant difference in the dose within the volume penetrated by the ion beam. → Tumour therapy

Assuming a Gaussian shaped ion beam





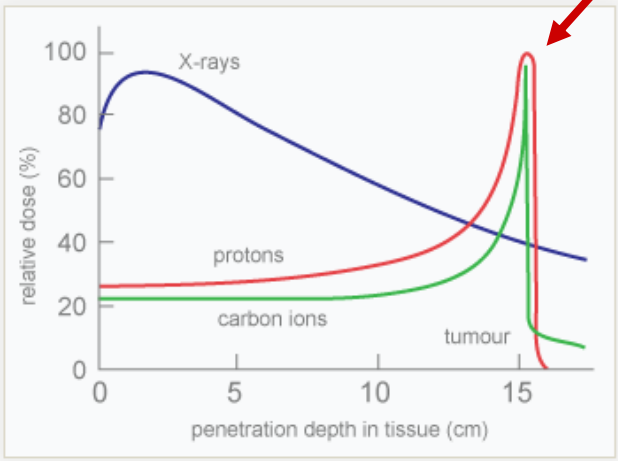
1 Sigma area

- 10^{11} Ar ions @ 11,4MeV/u (160µA for 1ms)
- Screen = Al_2O_3
- σ = 2mm → 1cm beam diameter
- projected range ≈ **85µm**

Average dose within 1 Sigma and over the whole ion trajectory is ~ **10^6 Gy**

for just 1 macro pulse

→ within 1ms !



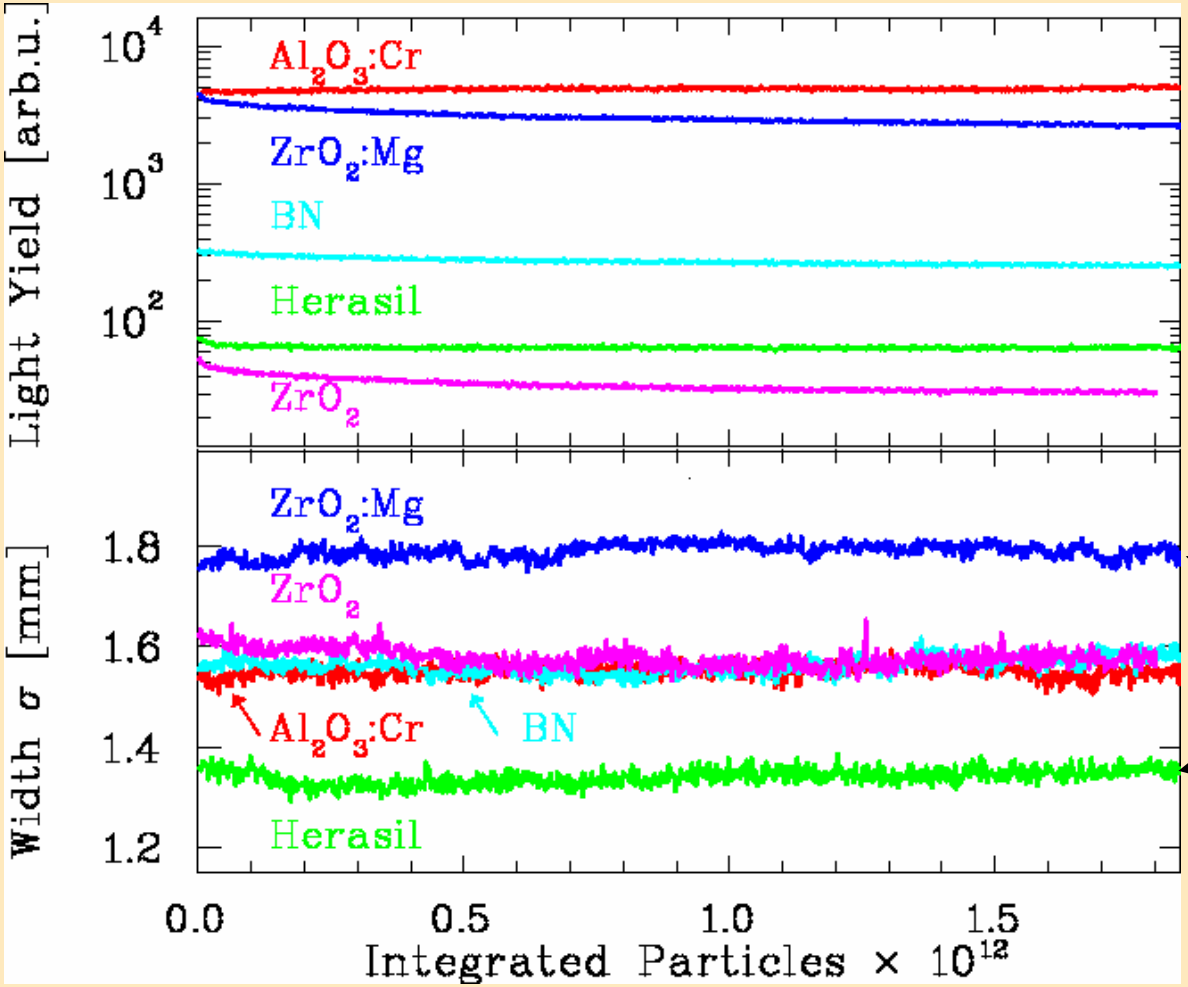
For a 1mA Ar-beam this would be 10^{12} Gy/h @ 50 Hz!

14 orders of magnitude more than for the crystals in PANDA!

Status SCINT'09 / DIPAC'09

Light yield and profile width @ low intensity

Beam parameters: $^{40}Ar^{10+}$, 11.4MeV/u, **2*10^9** Ions/Pulse in 100µs, ~30µA, 2.4Hz, 1000 beam pulses



Results:

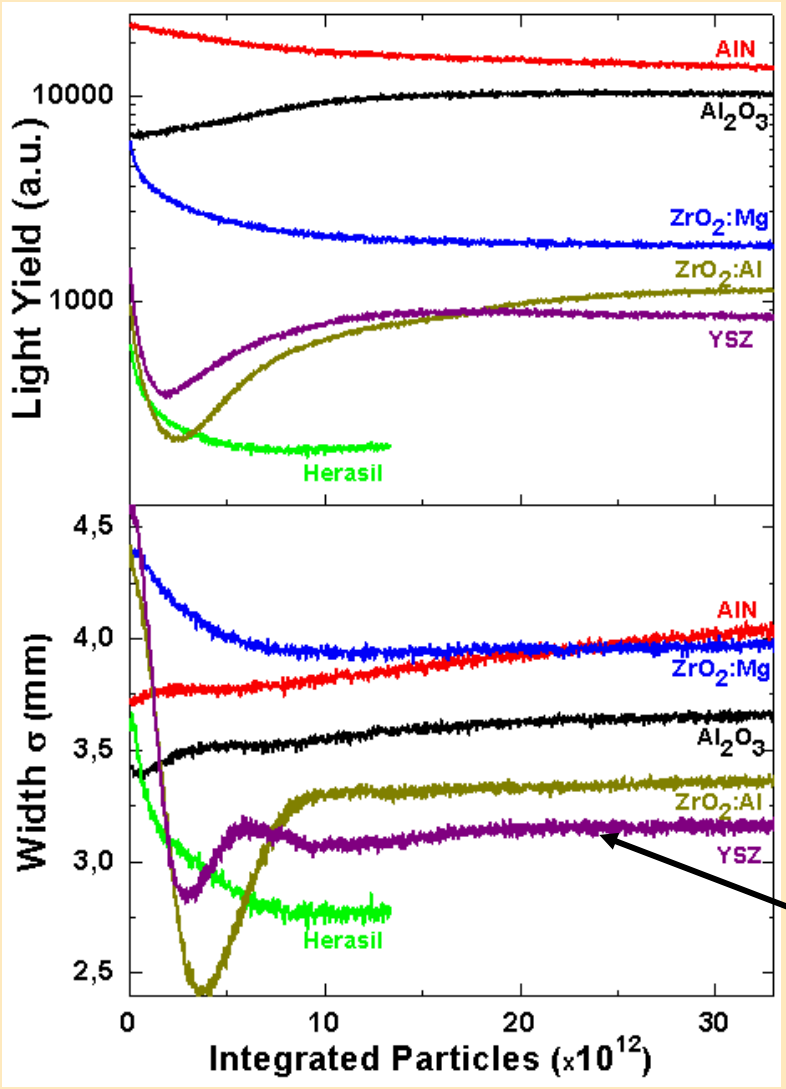
- **reproducible behavior**
- **different light yield and width reading**
- **light yield does not correlate with beam width**
- **different beam shape (from higher stat. moments)**

Difference of 14% in profile width is not negligible for quantitative evaluation

Average temperature: ~47°C (backside of ZrO_2:Mg)

Light yield and profile width @ higher intensity

Beam parameters: Ar^{10+}, 11.4 MeV/u, **$3.3*10^{10}$** Ions/Pulse in 0.2ms, 260µA, 1.7Hz, 1000 Pulse



~10 times higher beam current

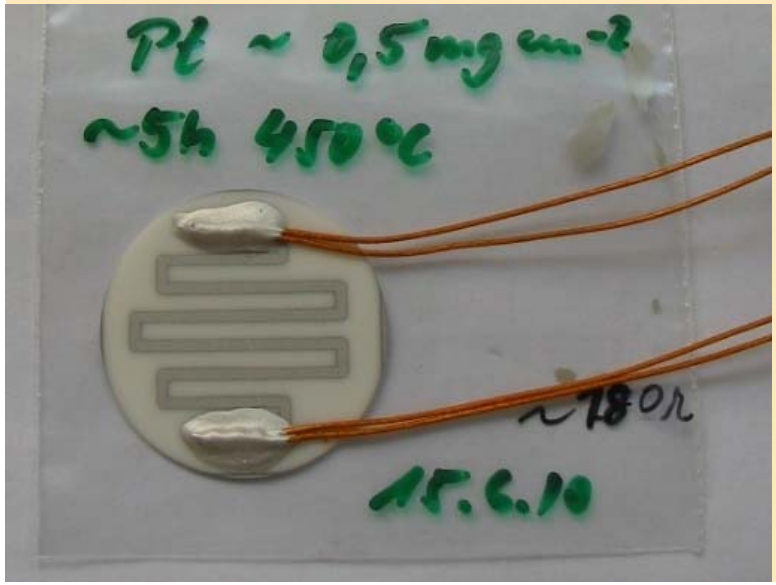
Results:

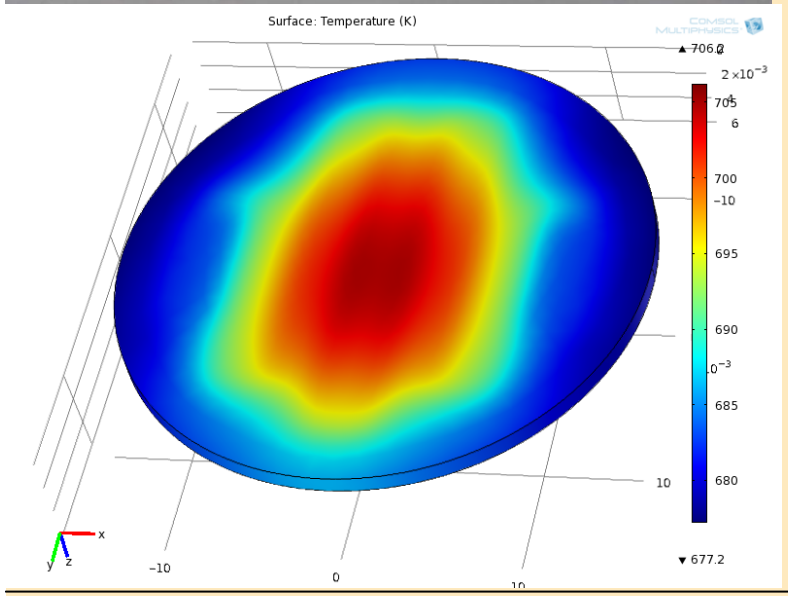
- **light yield and profile width depend on material**
- **different dynamical behavior**
- **possible reasons: material modification and temperature dependency**
- **for the zircon oxides the behavior is clearly temperature dominated**

Difference of 30% in profile width is not negligible for quantitative evaluation

Average temperature: ~200°C (backside of Al_2O_3)

New heating method



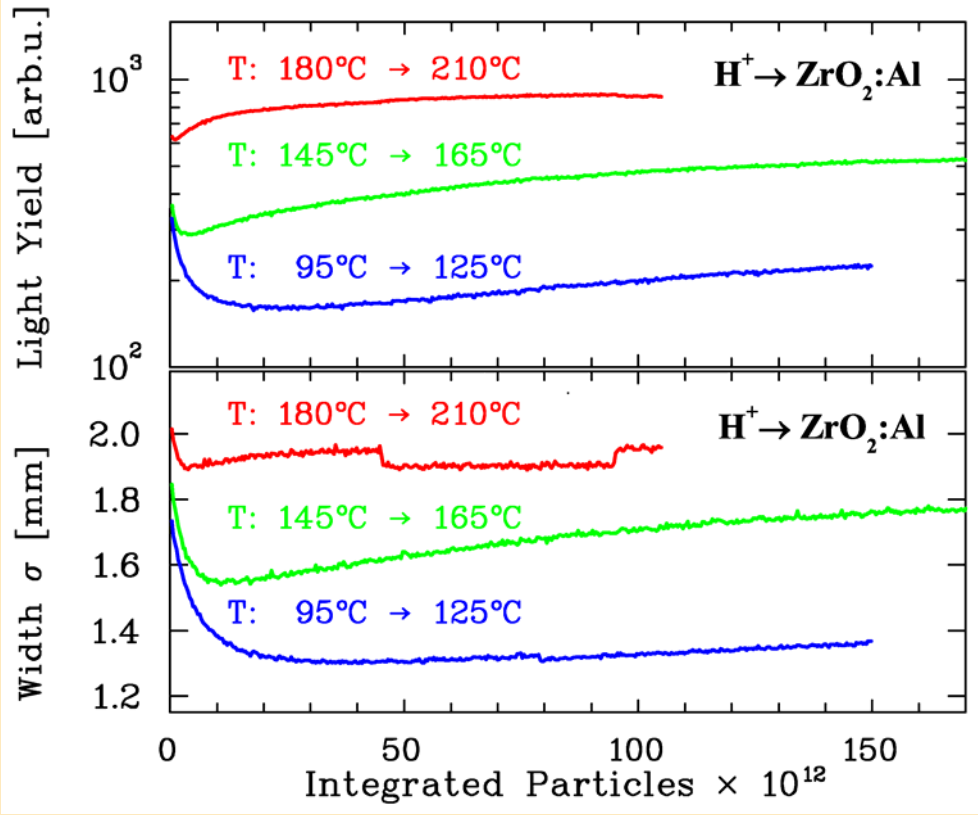


- A Pt layer of 250 nm is sputtered on the backside of the sample.
- The layer is connected to the Capton-wire via high temperature conductive glue Elecolit 327.
- The layer is annealed before characterisation to ensure stable conditions.
- The temperature behavior can be investigated by simultaneous heating and direct 4-point temperature measurement up to 400°C.
- Simulation fit the experimental data
- Temperature difference on the area of the typical beam is always smaller then 10°C (typically 5°C)

350°C
→700A/mm²(Pt)
→1,1W/cm²(Screen)

Temperature dependence – medium current

Beam parameters: H^+, 11.4 MeV/u, **$4.1*10^{11}$** Ions/Pulse in 2ms, ~32.8µA, 2Hz



Result:

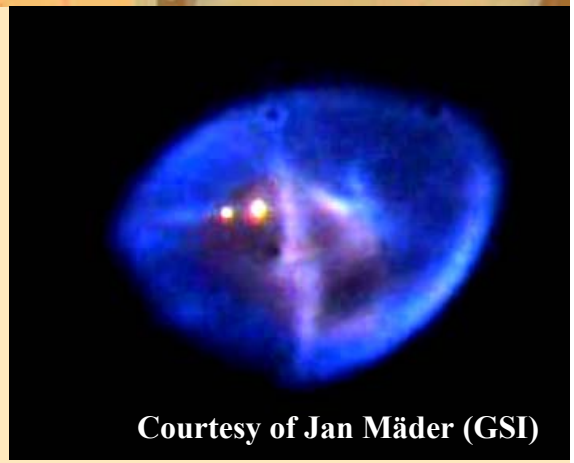
- **Light yield, imaged beam width and spectrum depend on the temperature**

→ **Temperature has to be taken into account for accurate measurements**

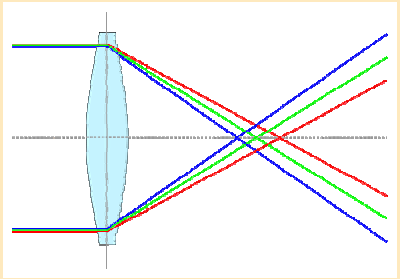
Is it just due to chromatic aberration ? → NO

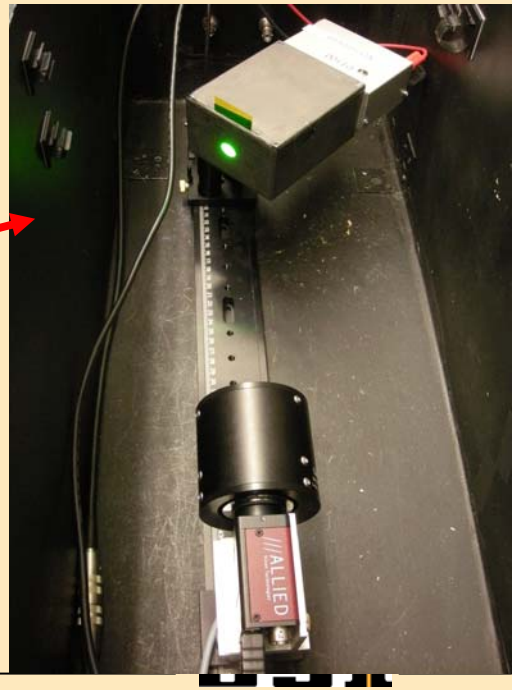
When the spectrum is different between the outer-part and the centre, it could lead to a wrong representation of the ion beam due to:

- **different response of the states to the deposit energy.**
- **the wavelength dependent sensitivity of the CCD-Chip.**
- **the different chromatic aberration (Farblängsfehler) of the lens-system used.**



Up to now, the chromatic aberrations (Farblängsfehler) **of the used lens systems have been investigated in the 400-800 nm region, with a purpose-build light source "beam-spot simulator". → Error in beam width (Sigma) is within 1%**





Linearity of the chip (double integration time → double Pixel value)

Iris values (Blendenzahlen)

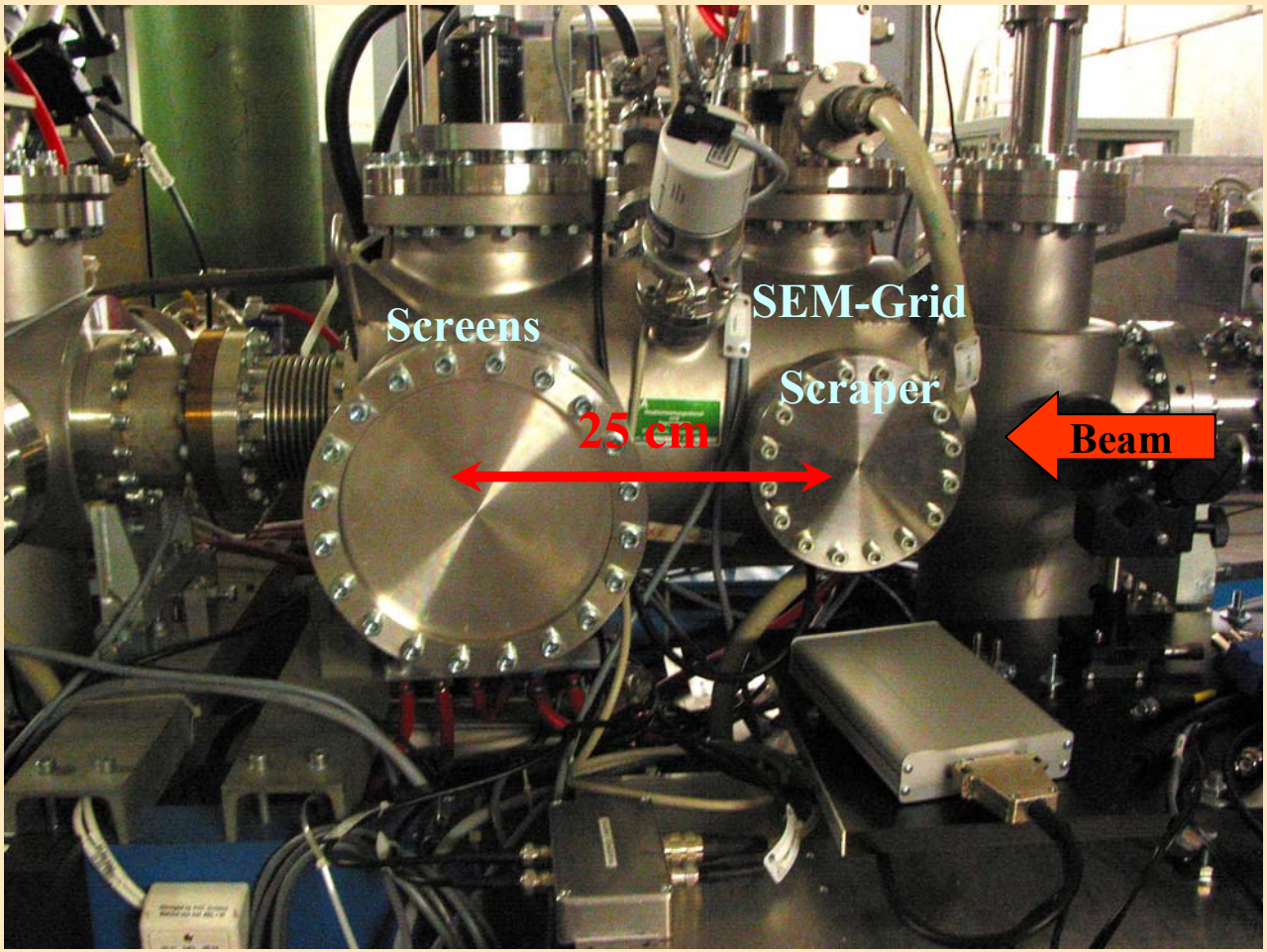
What we have seen up to now

The different materials measure different values for the transversal beam parameters for the same ion beam!

Which one is right, or are they all wrong?

What are the parameters of the ‚real' ion beam ?

Comparison with reference methods



- One can measure a reference profile 25cm in front of the screens.

Limitation:

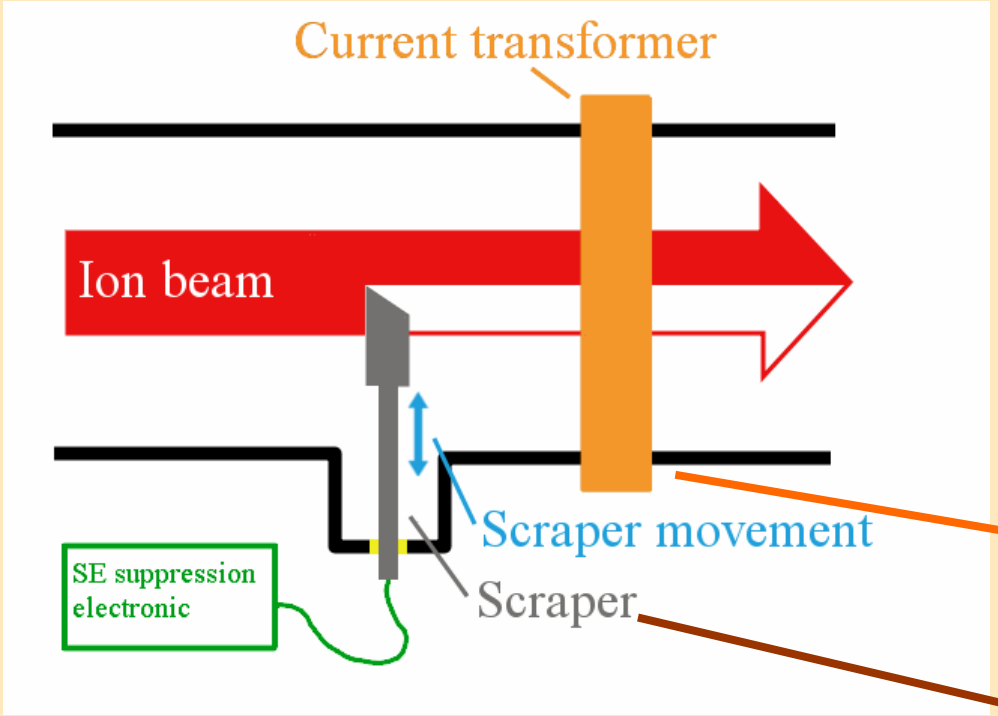
- Due to the lack of space it is not possible to take reference profiles at the same optical position as the screens.
- The profile grid is unable to measure the profile of the entire macro pulse

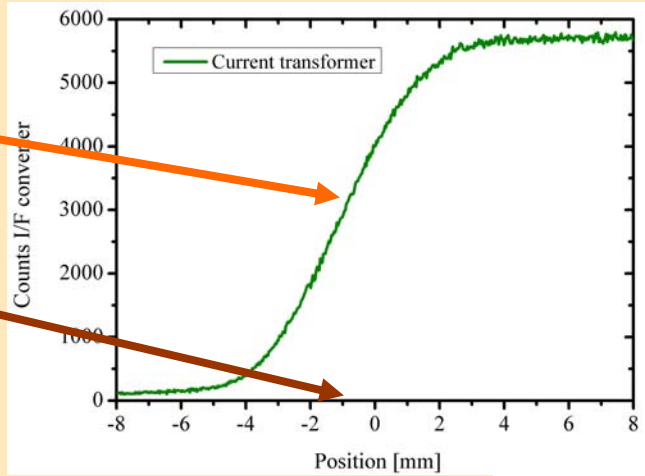
Spatial resolution: SEM-Grid(1.5mm), Screen(0.1mm), Scraper(0.05mm)

The 2nd reference method?

• **How can one obtain a trusted beam profil with a better spatial resolution then a SEM-Grid**

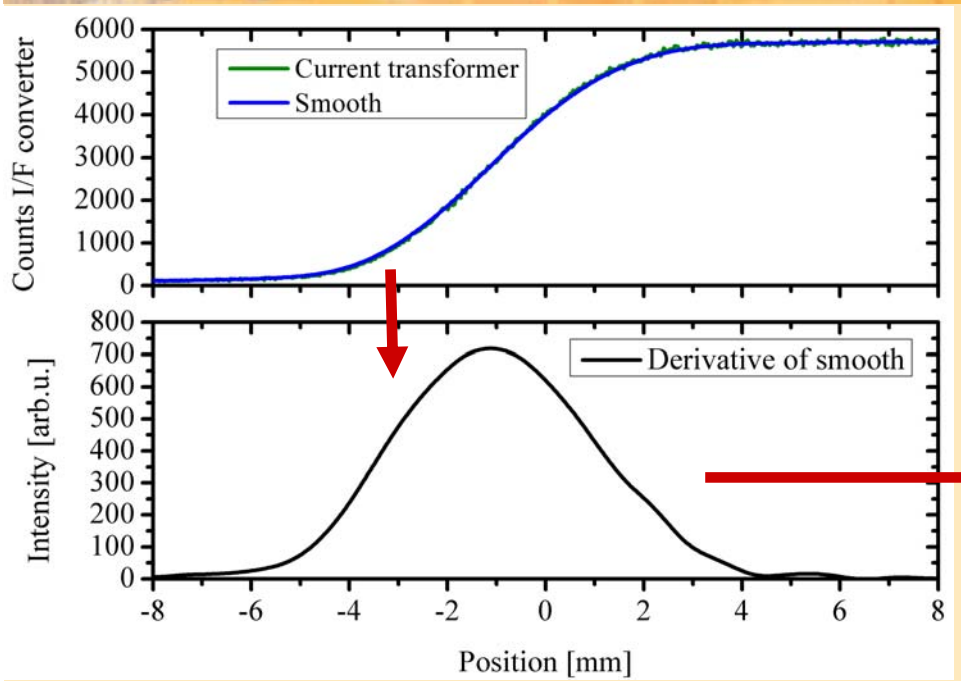
One can try to obtain a beam profile by using a scraper

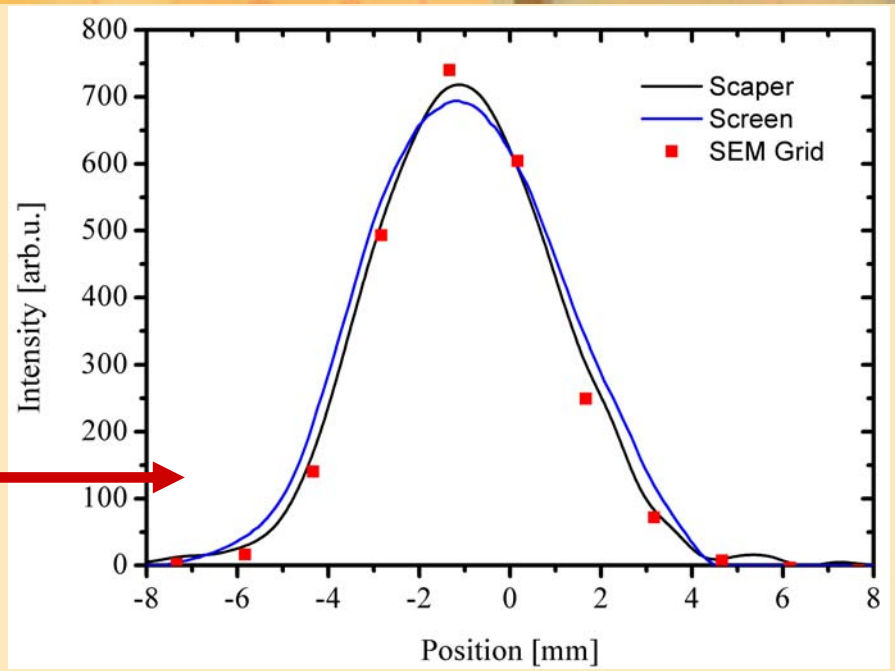




SE suppression electronic ensures that no electrons affect the transformer measurements

Evaluation of data and comparison of diff. methods





Results:

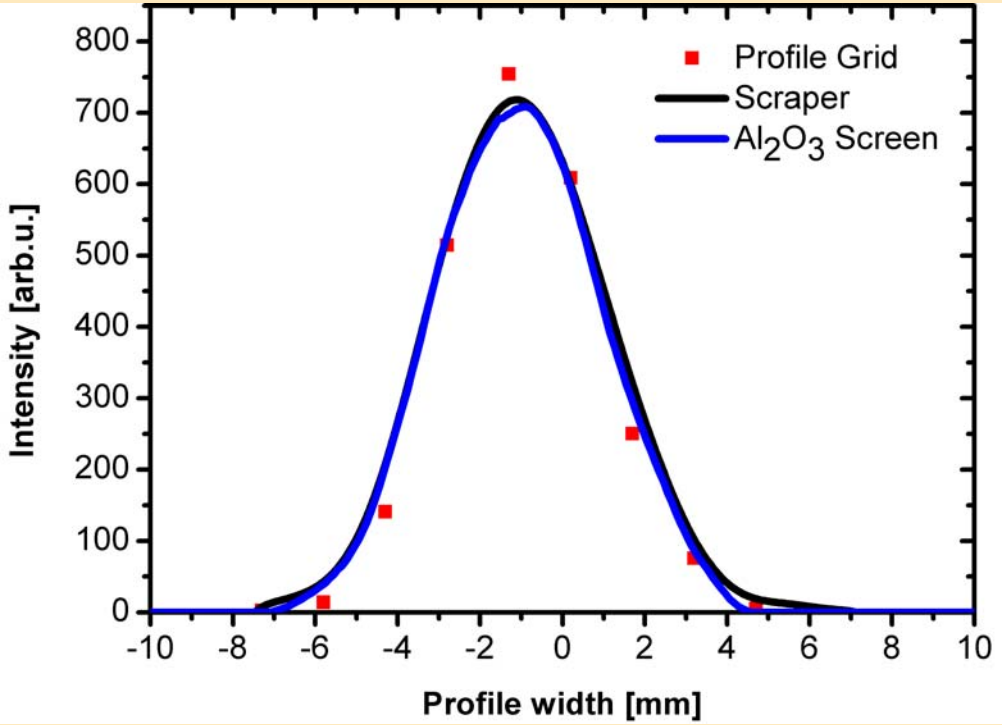
- **SEM Grid and Scraper are in good agreement. → One can obtain a beam profile with a scraper with a much higher resolution then a SEM Grid**

SEM-Grid (1.5mm), Scraper (0.05mm)

- **Allows to determine the response of the scintillator**
- **Method needs a stabile ion beam**

The Al_2O_3 Screen

Beam parameters: Ca^{10+}, 4.8MeV/u, $4.3*10^{10}$ Ions/Pulse in 5 ms



Result: **Methods are in good agreement.**

What about some other materials….

Herasil is not suitable for high current due to:

- Crack formation
- Has a threshold for light-output→ measures wrong (The smallest beam profile is not always the correct one)
- Can have reflections from the back-side, due to its transparency
- Very low light-output

ZrO_2:Mg (Z507) is suitable for high current operation, but

- Has lower light-output then Al_2O_3
- "Saturates" earlier then Al_2O_3

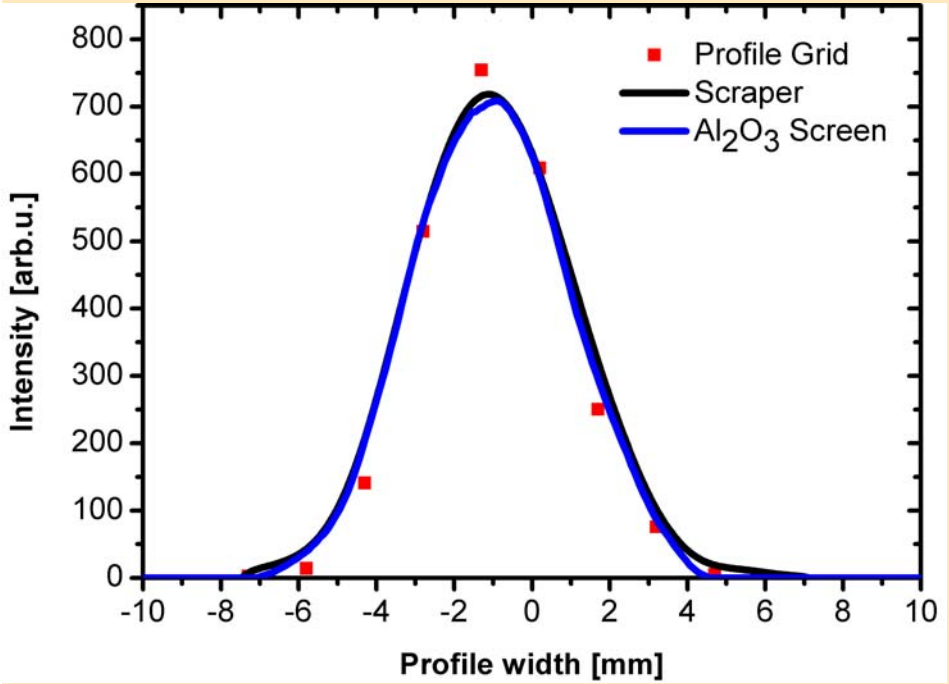
ZrO_2:Y (Z700) is suitable for high current operation, but

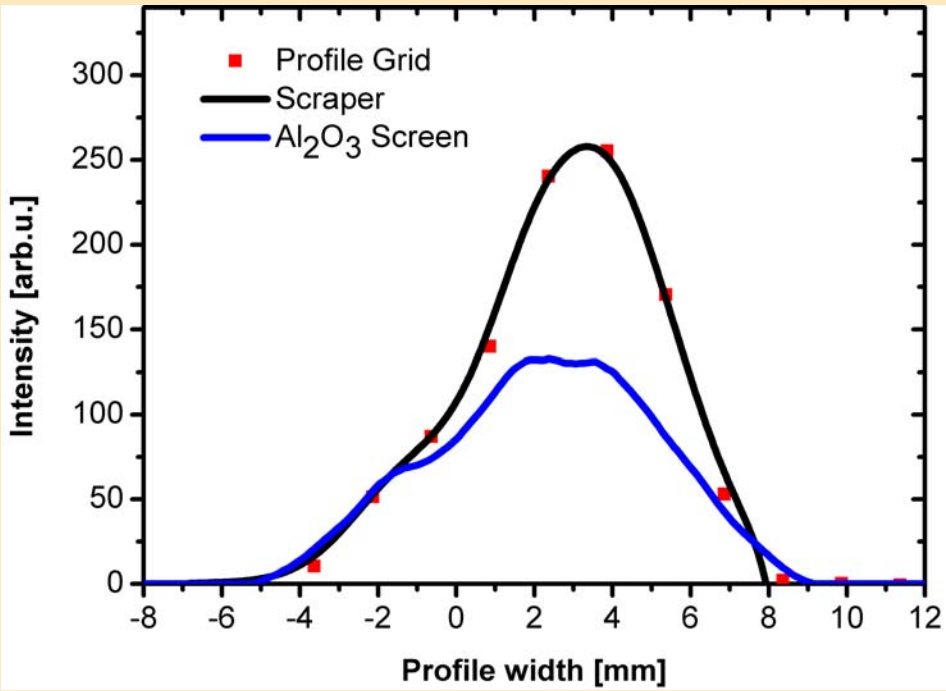
- Has a threshold for light-output→ measures wrong
- Has low light-output

and the winner is: **Al_2O_3**

What is the useful operating range of an Al_2O_3 Screen?

4.8 MeV/u	← Same pulse energy →	11.4 MeV/u
$4.3*10^{10}$ ppp	(~similar flux [ions/(cm² s)])	$1.8*10^{10}$ ppp
5ms		1,2 ms





Result: **Light yield is the same for both energies. For the 11.4 MeV/u case, the imaged beam profile does not math to both reference methods.**

What is the reason for the mismatch in the 11.4 MeV/u case?

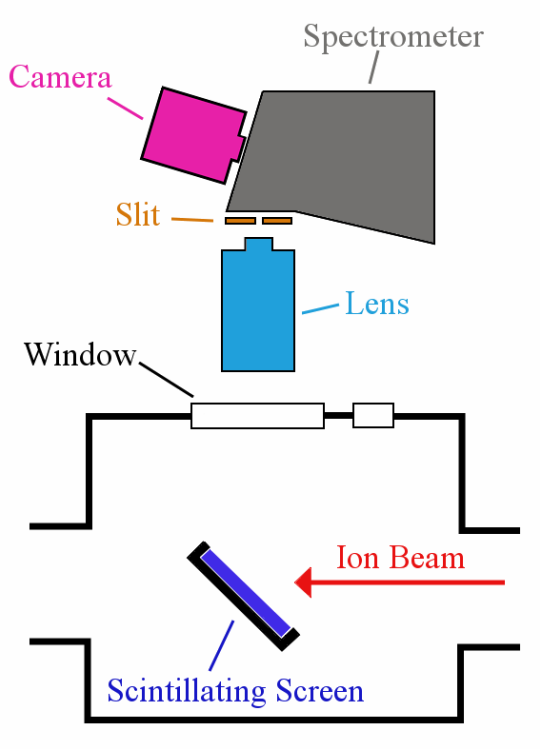
One explanation could give the spectrum of the scintillator

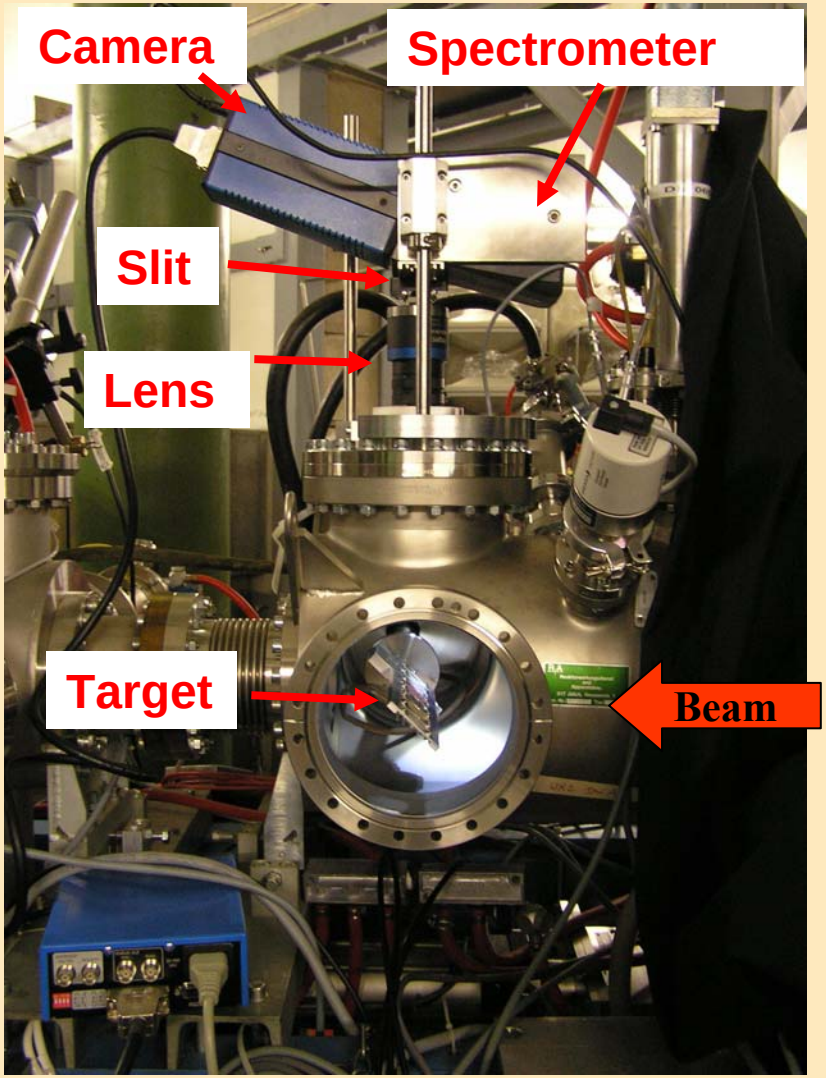
→ if the spectrum in the centre of the ion beam is different from the outer region **and**

the optical system has a significantly different response for each wavelength, it could explain the mismatch.

(Efficiency of not UV enhanced optical system < 10% @ 370 nm)

Advanced experimental setup (spectroscopy)

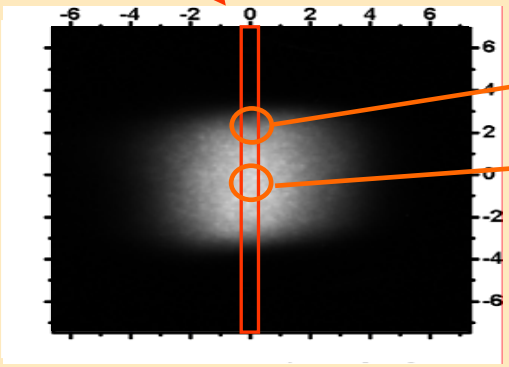




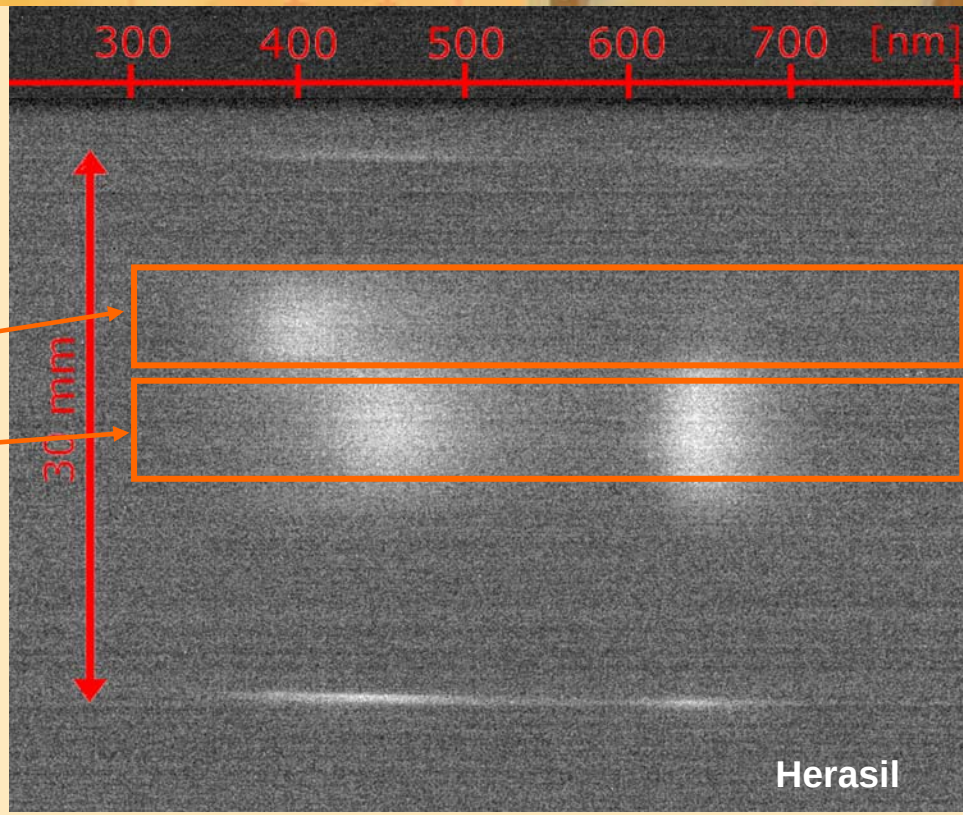
Camera: PCO1600
Spectrometer: Horiba Jobin Yvon CP140-202
Slit: Newport M-SV-0.5
Lens: Linos inspec.x UV-Vis-Lens, 50mm focal length

Spectroscopic investigations

Investigated area of the beam spot for spectroscopic studies



typical width of the stripe is about 1mm and depend on the slit setting

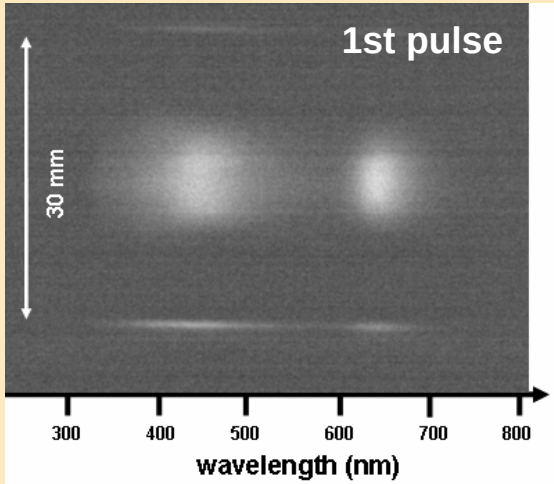


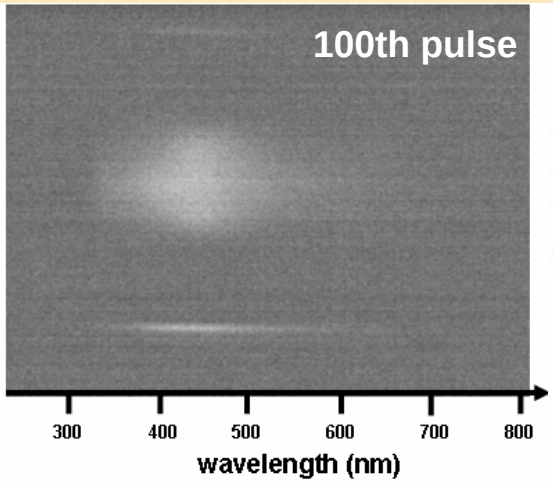
Advantage:

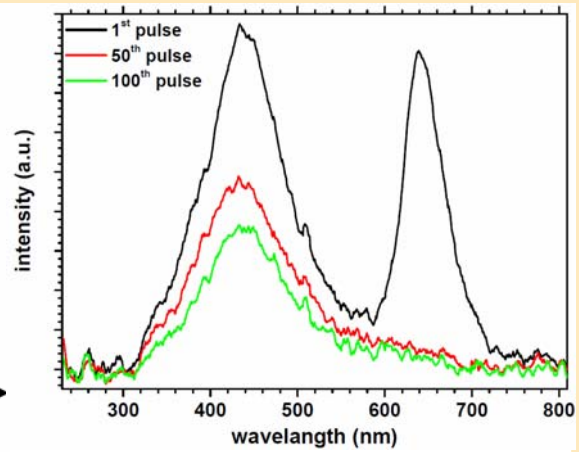
- **influence of the ion flux on the spectra can be analysed over the flounce, for each macro pulse**
- **the whole screen is observed**

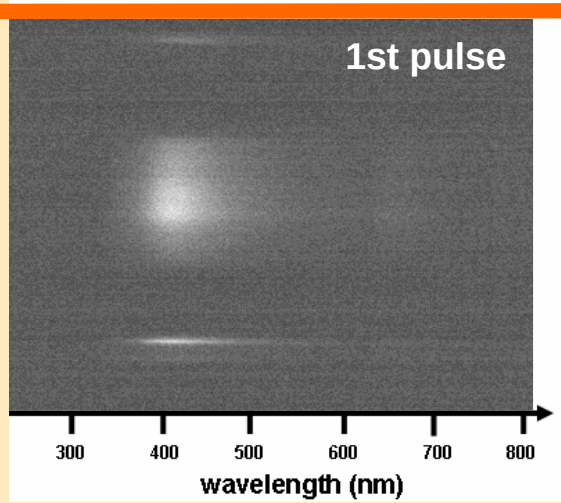
Spectroscopic investigations on Herasil

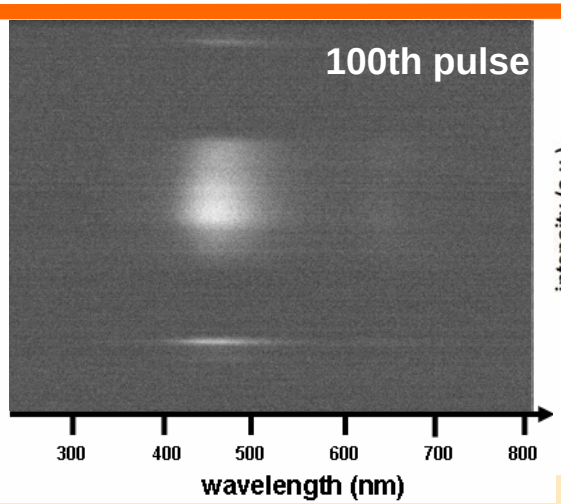
Beam parameters: U^{28+}, 4.8MeV/u, $5.2*10^{10}$ Ions/Pulse in 0.8ms

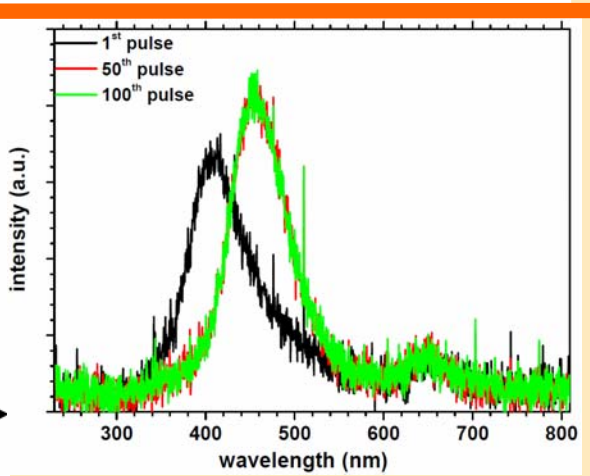










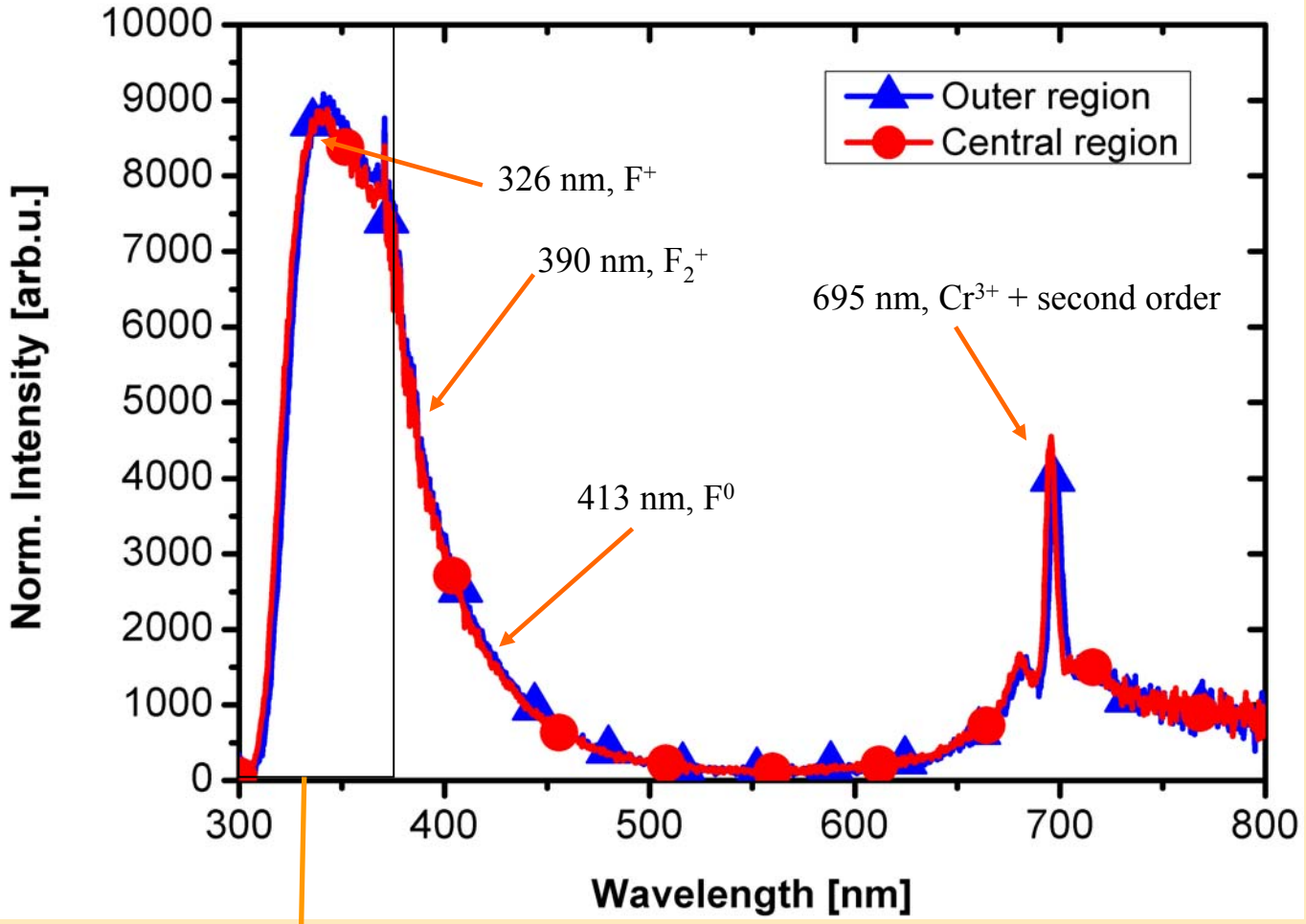


Beam parameters: Ca^{10+}, 4.8MeV/u, $9*10^{10}$ Ions/Pulse in 5.3ms

Result: The Spectrum can depend on the ion and on the dose!

Spectrum of Al_2O_3 for $^{48}Ca^{28+}$ @ 4.8MeV/u

Beam parameters: $^{48}Ca^{10+}$, 4.8MeV/u, 5.2*10^{10} Ions/Pulse in 3ms, 1Hz



Results:

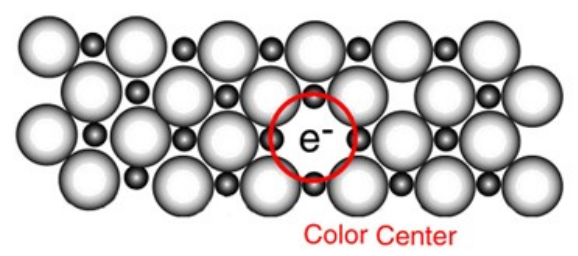
- **Spectra of outer region and centre are very similar in shape**
- **Same behaviour was found for 11.4 MeV/u**
- **No F^0 ←→ F^+ conversion @ 4.8 and 11.4 MeV/u**
- **High current results correspond to low current results in the literature**

Effective response of the optical system for standard measurements @ 370nm is < 10 % of 500 nm

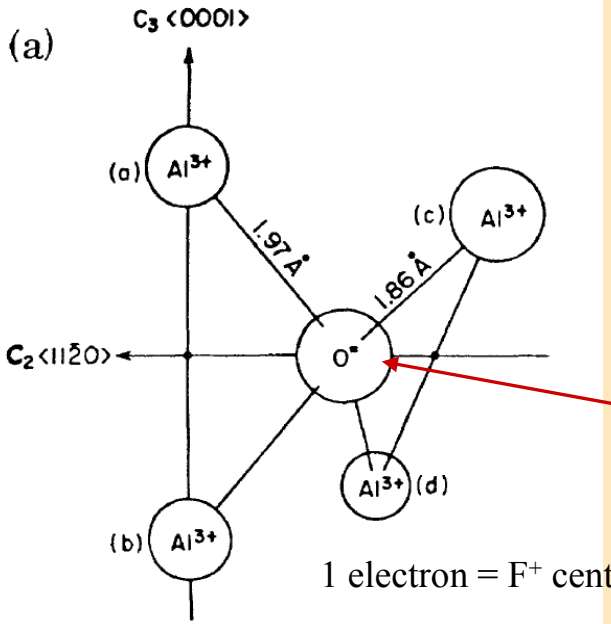
Region that can not be observed with standard, not UV enhanced optics

Colour Centres in Al_2O_3

Example for a color center →



The Al_2O_3 lattice



1 or 2 Electrons

e⁻

1 electron = F^+ centre, 3.8 eV (326 nm), τ=1.7 ns

2 electrons = F^0 centre, 3.0 eV (413 nm), τ=25 ms

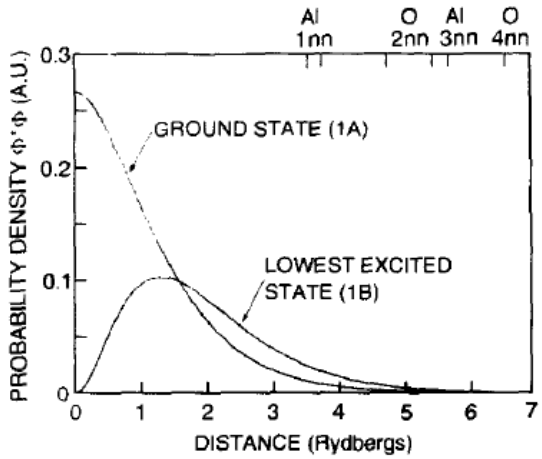


Fig. 2. F^+ center relative probability density $\Phi^*\Phi$ in α-Al_2O_3, calculated from wave functions derived in Ref. [38]. For a typical ground state (1A) distribution, that along the y-axis in Fig. 1 is depicted; the 1B-level distribution shown is along the x-axis, out of the plane of Fig. 1.

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Result: The F^+ emission is might be more resisted against quenching because of the less extended wave function and the shorter live time.

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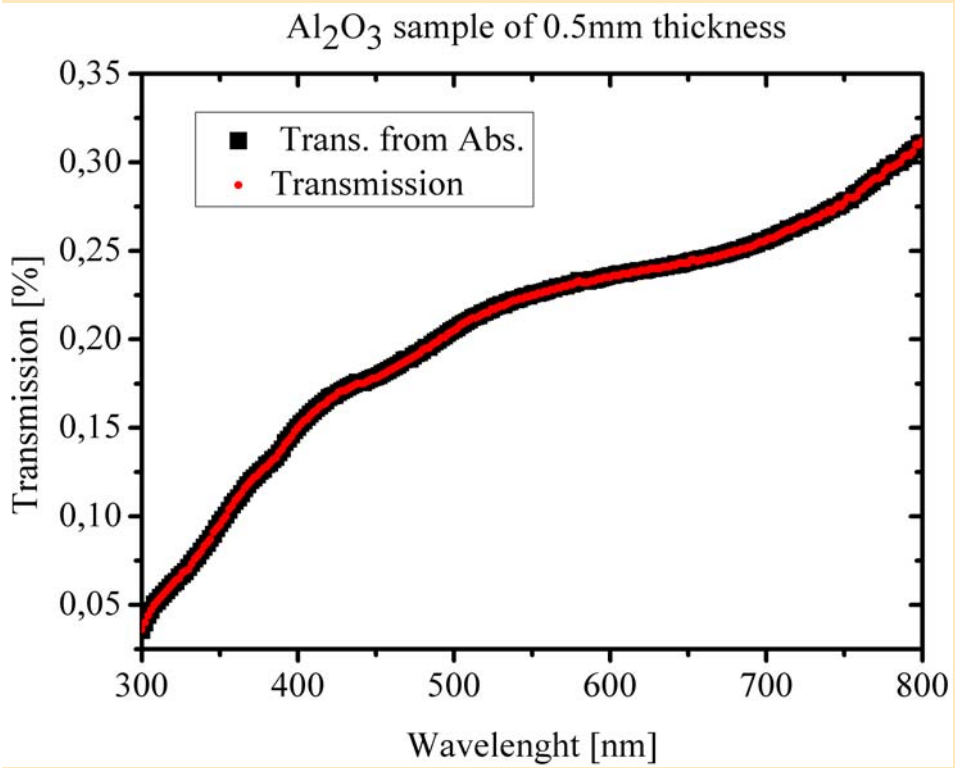
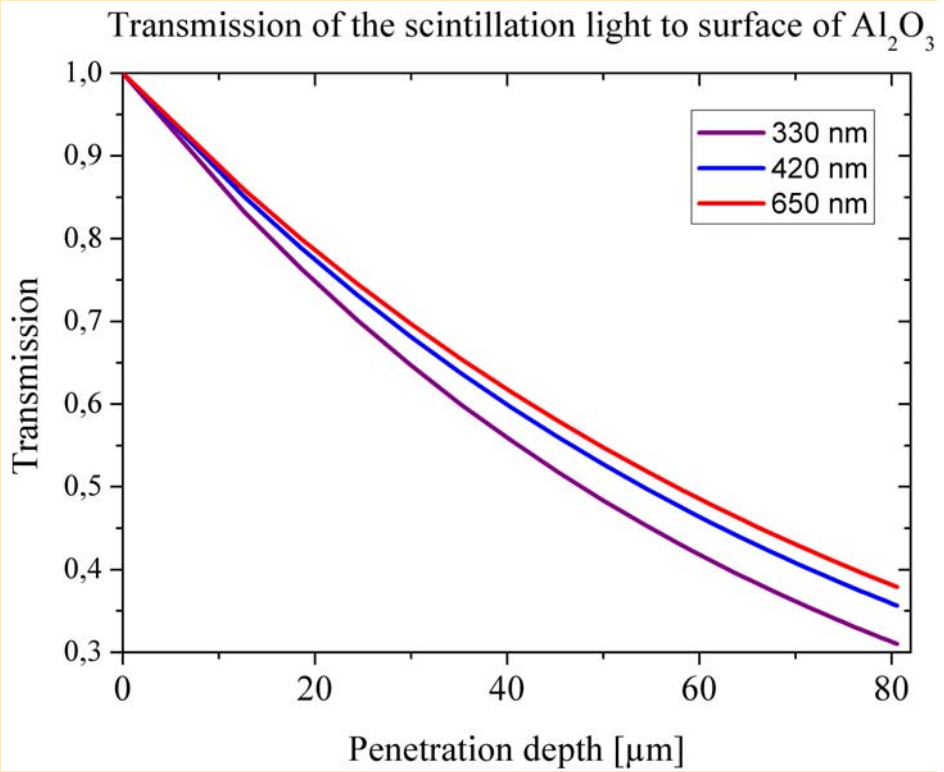
Transmission of Al_2O_3





Result: **There is no important contribution from reflections in the material to the detected scintillation signal. → backside to surface reflection @ 420nm would be reduced to 1E-5, and for 0.5mm sample to 2E-11 for 1mm.**

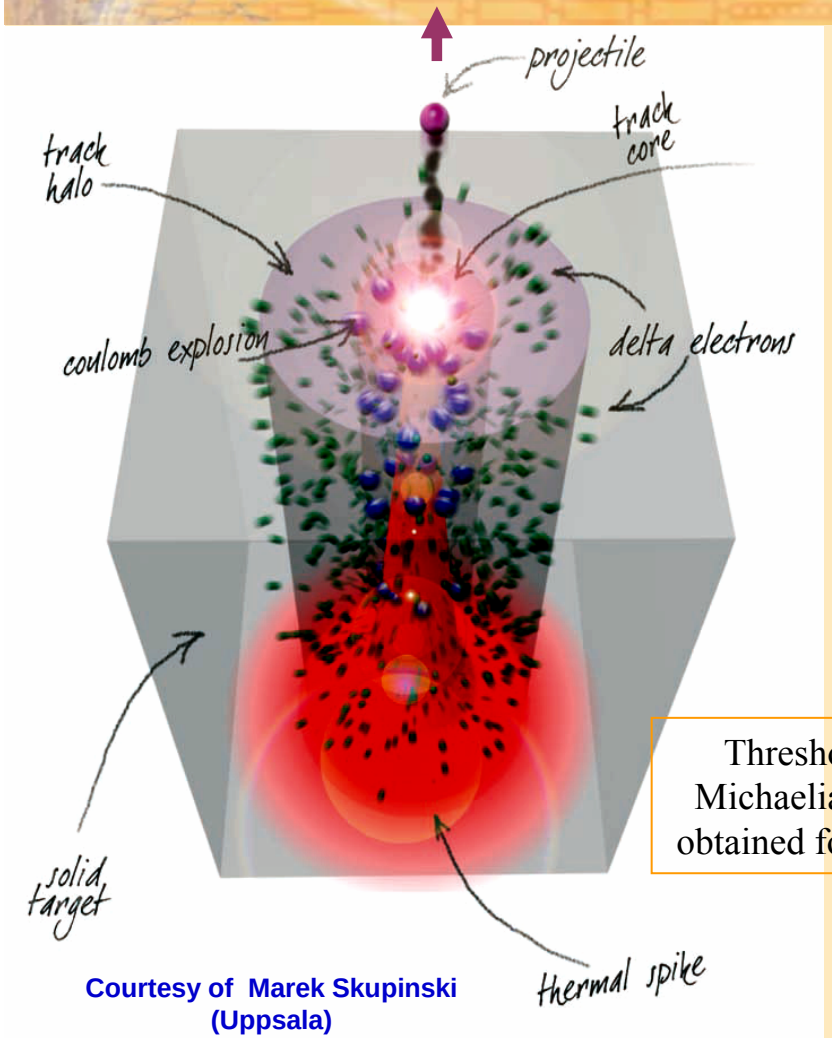
The mismatch of Al_2O_3 at 11.4 MeV/u is not due to a change in spectrum or reflection in the material!

What could be the reason?

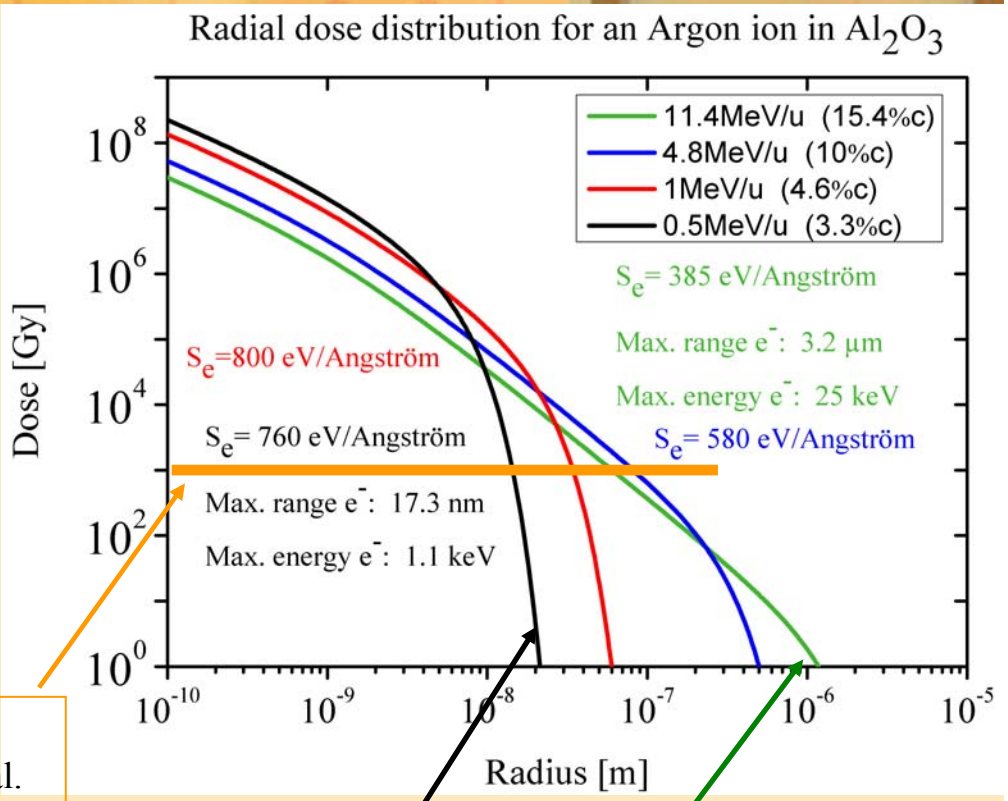
What is the difference between 4.8 and 11.4 MeV/u?

→ **The energy spectrum of secondary electrons**

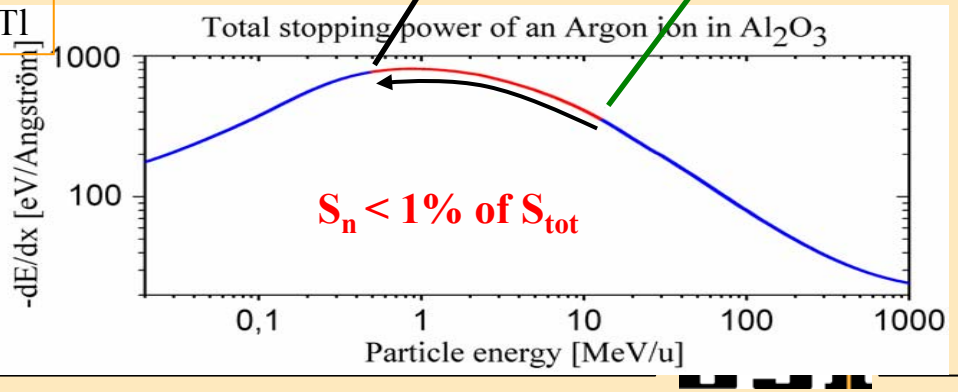
The radial dose distribution of an ion track



Courtesy of Marek Skupinski (Uppsala)



Threshold of Michaelian et al. obtained for CsI:Tl



The camera can see all energies (depth) weighted with a Lambert-Beer absorption

What could be an explanation for the results?

There are models that describe the light output of scintillators, but:

- for single particles
- only one species, e.g. Tl+
- can not predict changes in spectrum for diff. ions
- low doses (no damage)
- .....

Light output is proportional to dose (e-h pairs) up to a quenching density ρ_q , above this dose the light output is constant. Fitting parameter: ρ_q

Different ansatz with δ electrons. 4 fitting parameters

Due to the complexity of the scintillating mechanisms, it is still under investigation

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Nuclear Instruments and Methods in Physics Research A 356 (1995) 297–303

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Scintillation response of nuclear particle detectors

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Response of CsI(Tl) scintillators over a large range in energy and atomic number of ions Part I: recombination and δ-electrons

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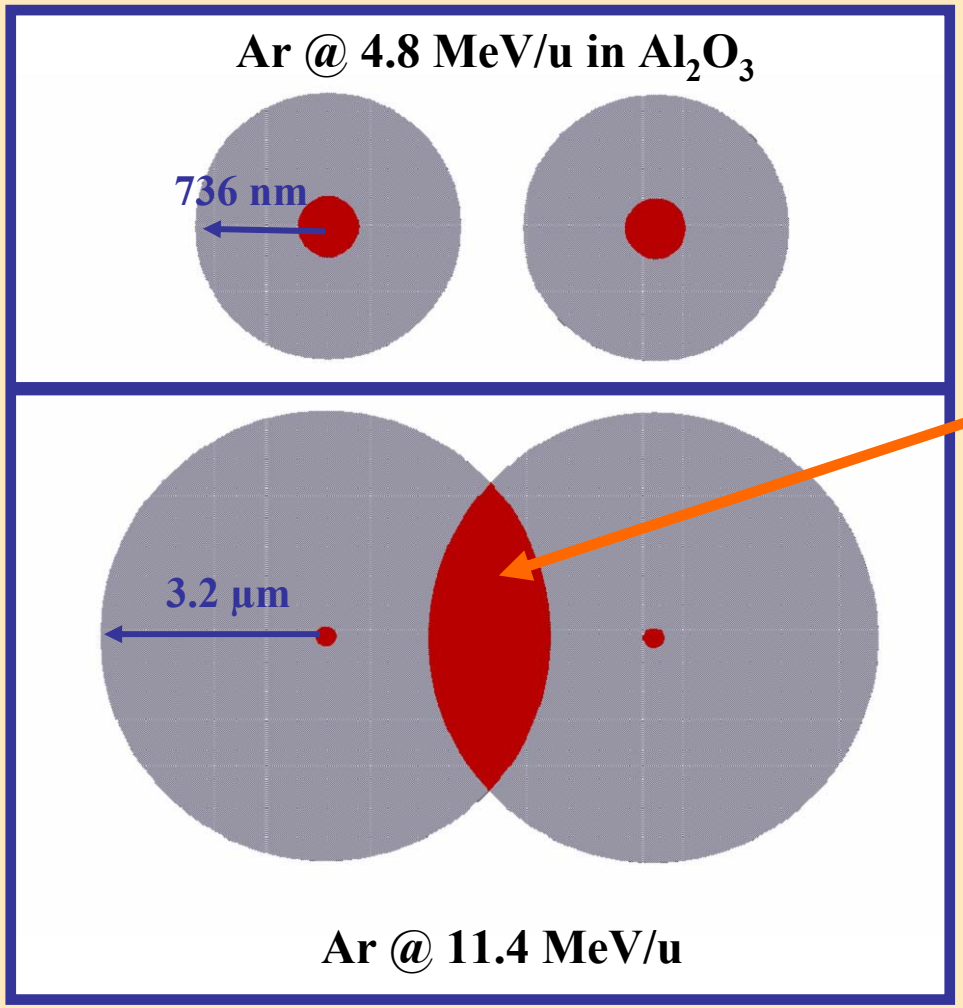
Difference: single particle ↔ ion beam

Schematic overlap of ion excitation tracks in space and time

Ion track radius



What happens in the overlapping regions? Suggestion:

$$F^* + e_\delta \rightarrow F^+ + 2e$$

(Reionization by second hit)

How to model Al_2O_3

For a time dependent 4D Monte Carlo Model, e.g. for Al_2O_3 , one would need in my opinion the cross-sections for:

- Electron capture at F^{2+} and F^{+}
- Hole capture at F^{0} and F^{+}
- Ionization of F^{+} and F^{0}

..... and the hole dynamic of charge carrier production, movement and trapping in the bulk material in dependence of ionization density.

Each one of them is a separate PhD-thesis, and it seem difficult to me to measure them independently of each other.

So lets try an time independent model

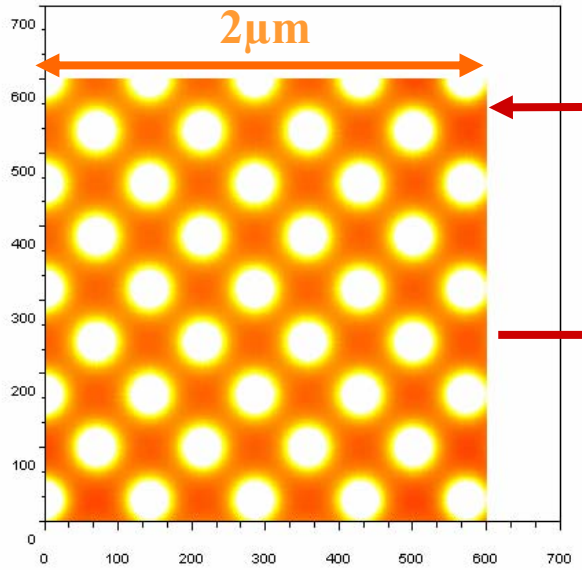
The model for Al_2O_3

Assumption:

1. The radial dose distribution with the parametrization of Katz et al. '96 is valid
2. There is an ionization threshold like the one proposed by Michaelian et al.
3. The re-ionization process has a linear behaviour
4. The pulse length is smaller then e-h recombination+lifetime of the state (at least valid for F^{0*} state of Al_2O_3)

!The only fitting parameter is the ionization threshold ρ_i!

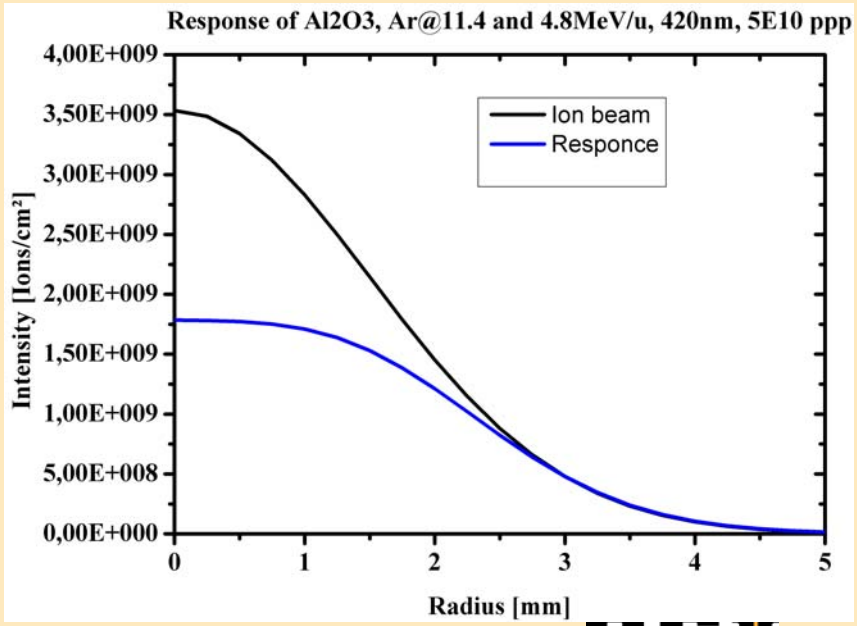
3.5E9 ions/cm²



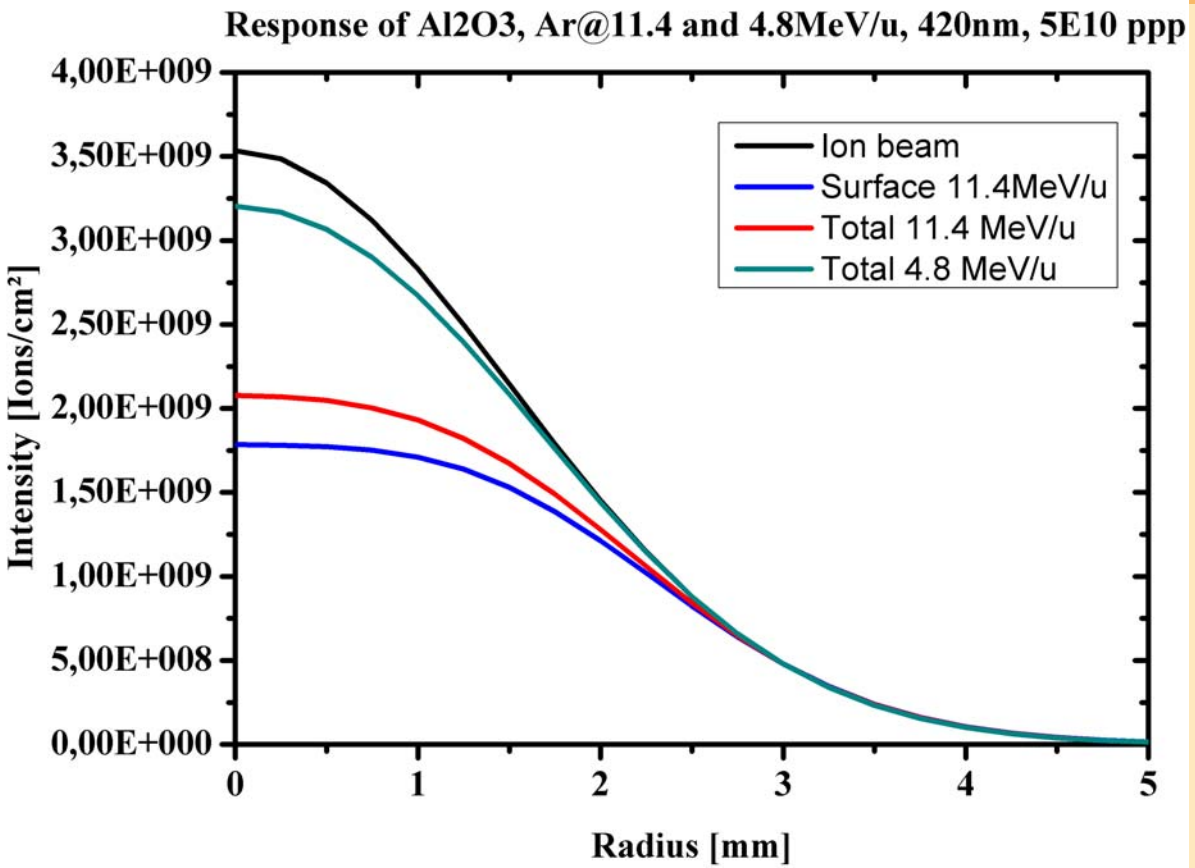
occupation density

response

Only ~800 lines of SciLab-Code ☺



Prediction of the model



5E10 ppp

ionization threshold = 650 Gy

Results: The Model could explain the experimental findings → experiments are needed to determine ionization threshold

(Lambert-Beer absorption of the light in the Al_2O_3 is included in the model)

For a gaussian ion beam, Al_2O_3 screens, Argon @ 11.4 MeV/u, and 5E10 ppp;

The projection of a 4.8MeV/u ion beam is way less deformed then the one of 11.4 MeV/u, if one looks at the F^0 (420nm) emission → F^+ (330)mn. And there is no big contribution to the signal from the end of the ion track.

Summary

- The different materials represent different shapes for the same ion beam → different moments (sigma, and higher)

  → no chromatic aberration
- The screen temperature is an issue for high current beams
- **Al_2O_3** shows promising results for 4.8 MeV/u.

- For the 11.4 MeV/u case:

  → The spectrum and a reflection from the backside of Al_2O_3 could be excluded as an explanation.

- The model for Al_2O_3 shows promising results:

  → Ionization-threshold is the only fitting parameter

  → Detailed measurements are needed to validate the model