

# Momentum Spectroscopy in Atomic Collisions

R. Moshhammer

## Target-Ionization

- Virtual Photons
- Many-Electron Continuum

## Projectile-Ionization

- Simulated electron impact

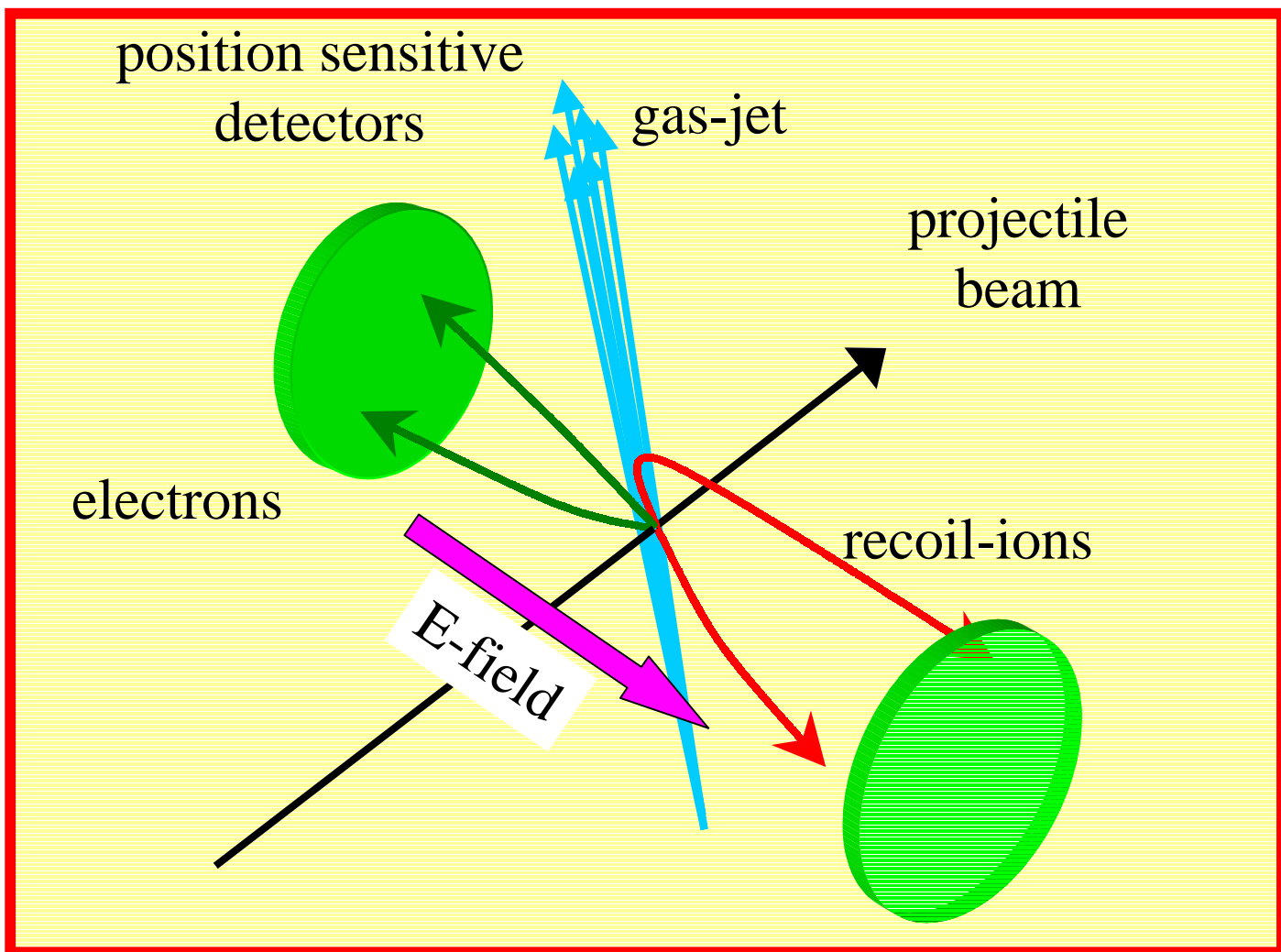
## Capture Reactions

- Spectroscopy
- Dynamics

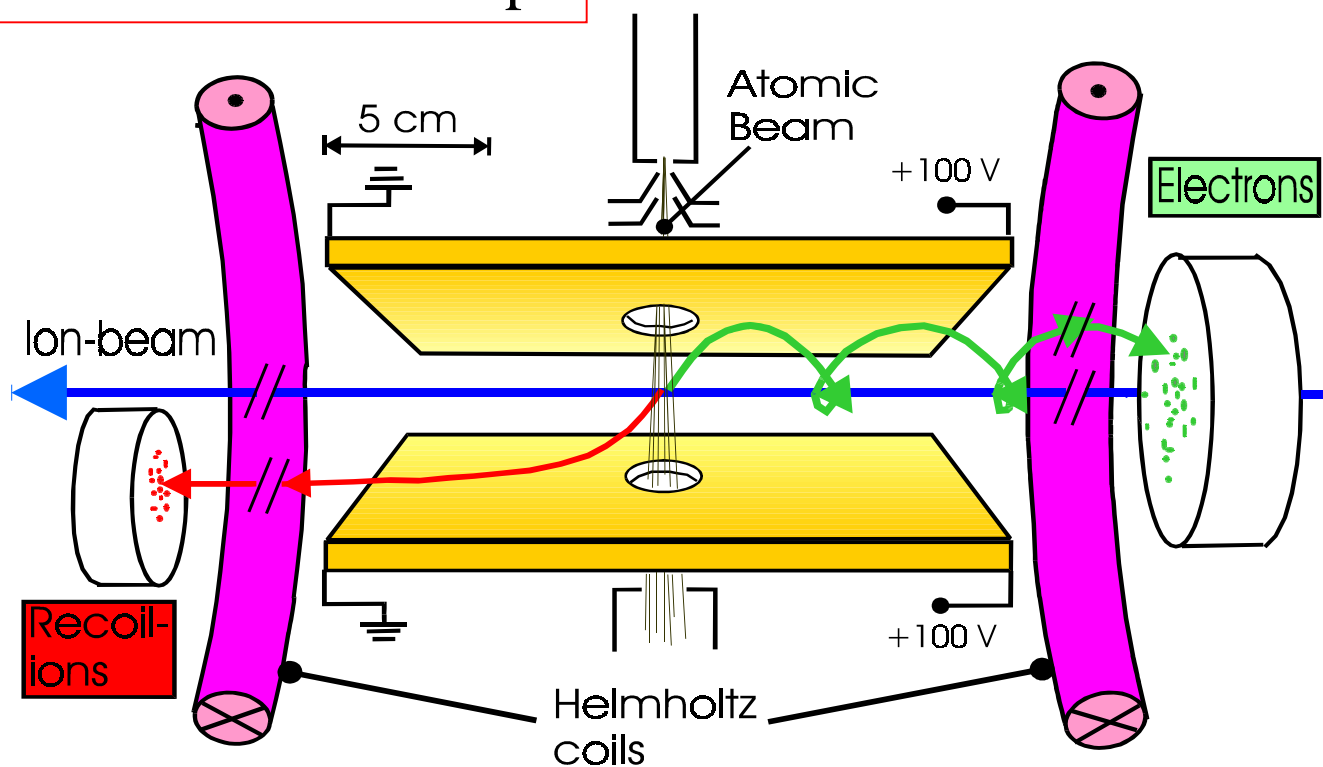
## Implementation into ESR

## Outlook

# Imaging Technique

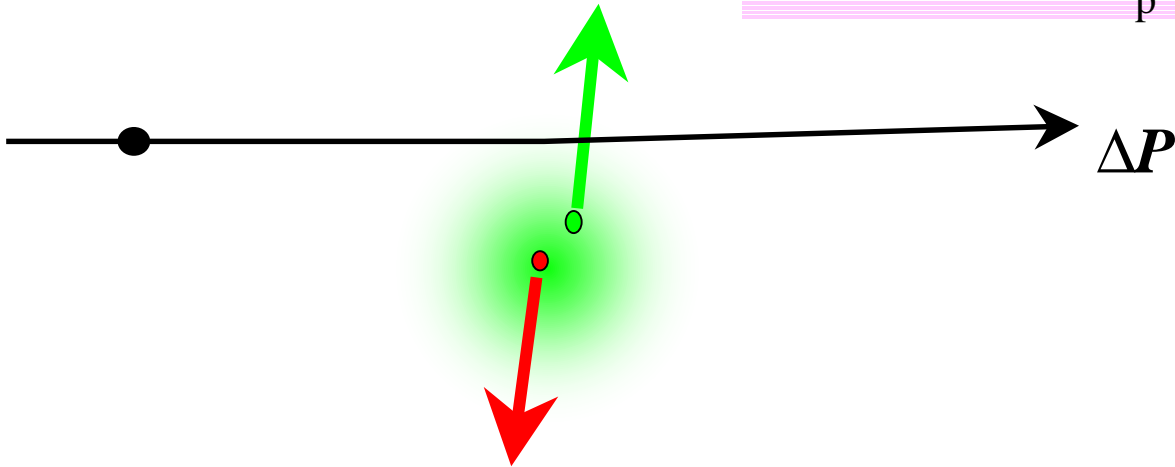


# Reaction-Microscope

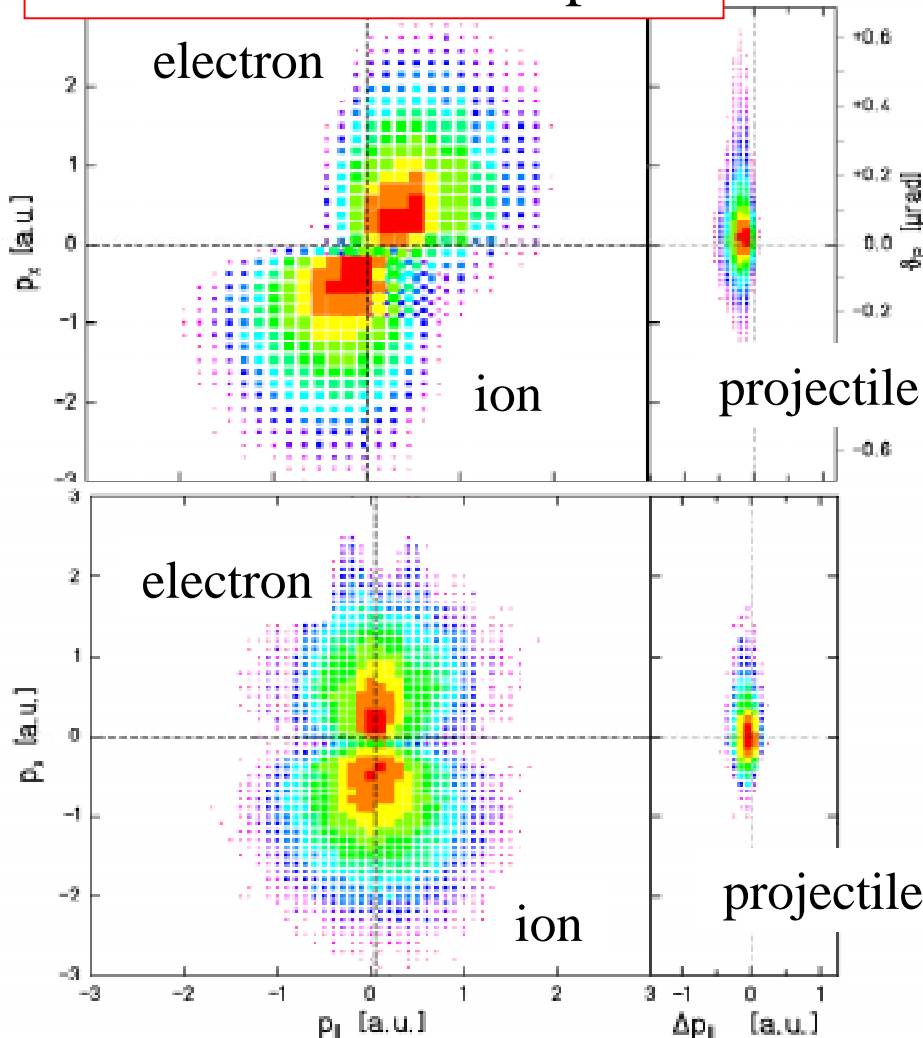


# Ionization in Fast Collisions

$A^{q+} \rightarrow He \quad v_p > 10 \text{ a.u.}$



## View onto collision plane



3.6 MeV/u  $Au^{53+}$   
 $q/v_p = 4.4$

strong

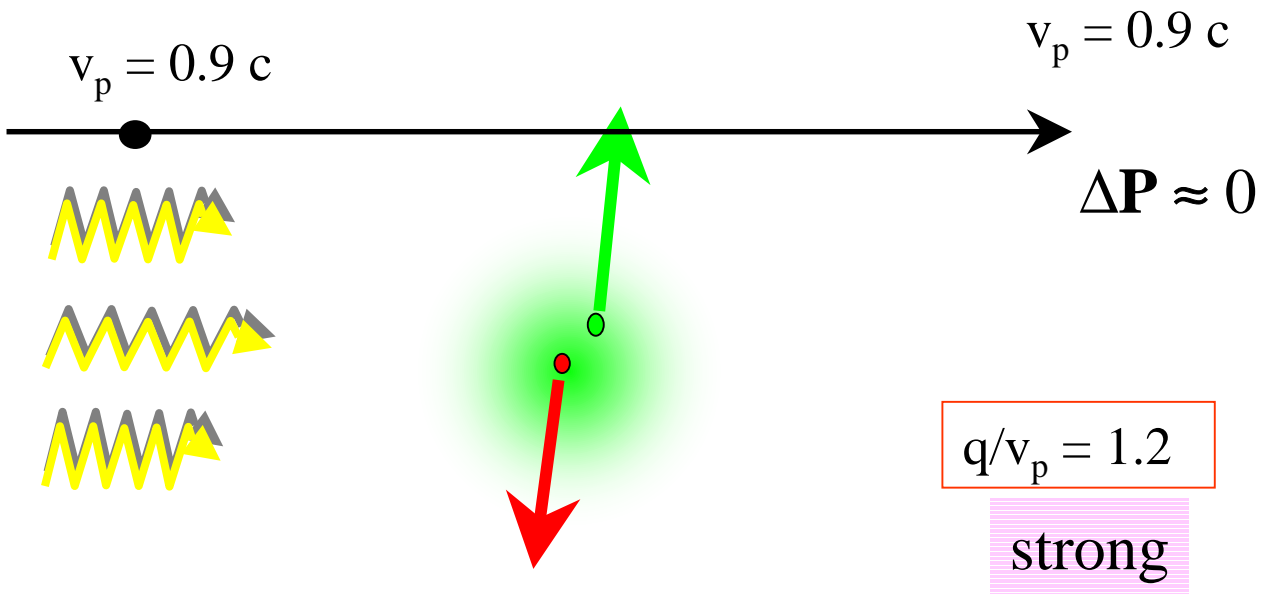
100 MeV/u  $C^{6+}$   
 $q/v_p = 0.1$

weak

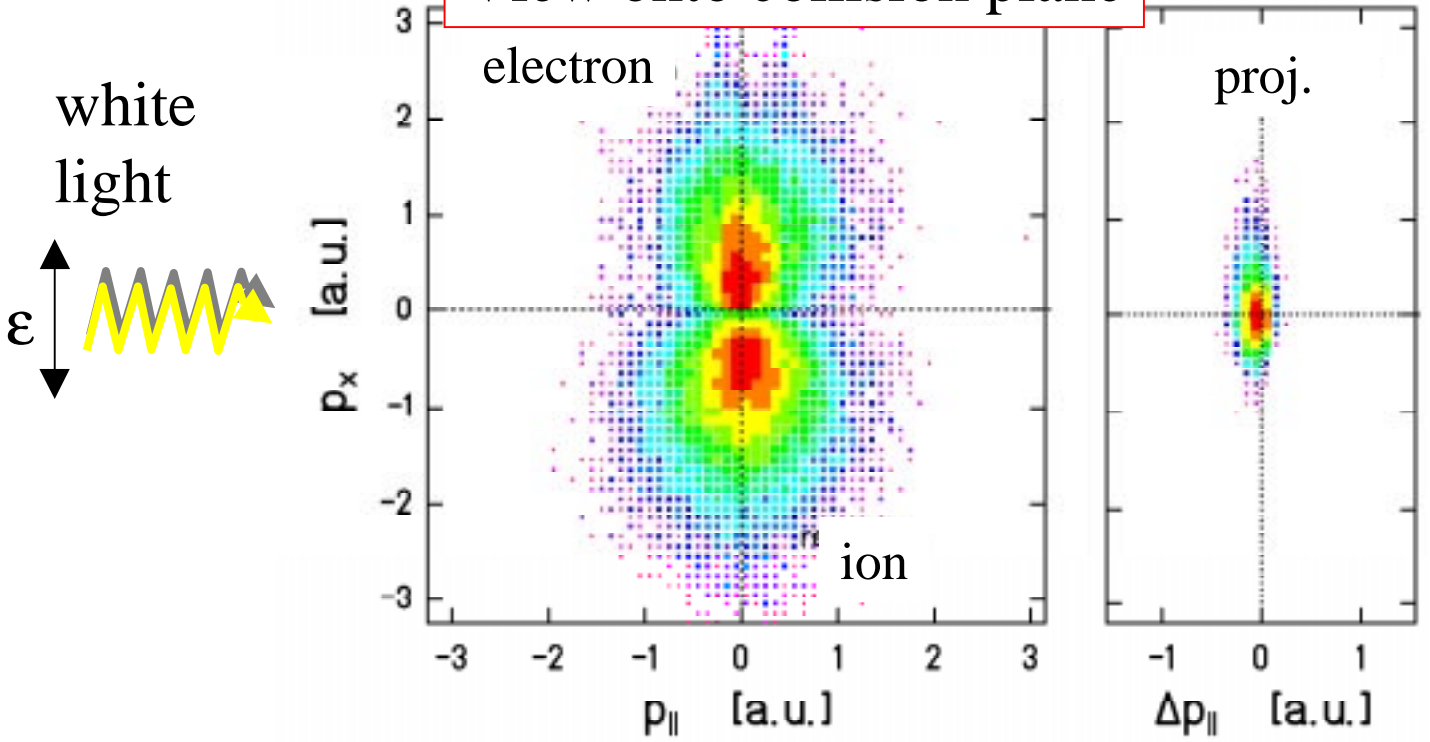
- Projectile transfers (almost) no momentum
- Similarities to Photoionization “optical limit”

**Relativistic collisions**

$U^{92+} \rightarrow He$  1 GeV/u

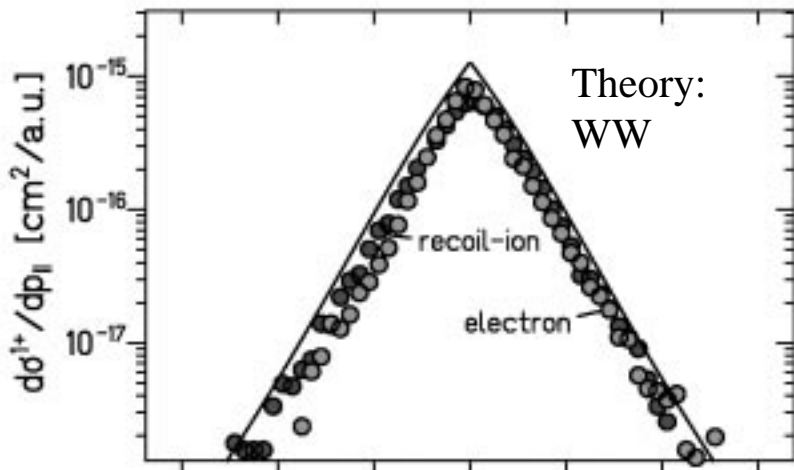


**View onto collision plane**



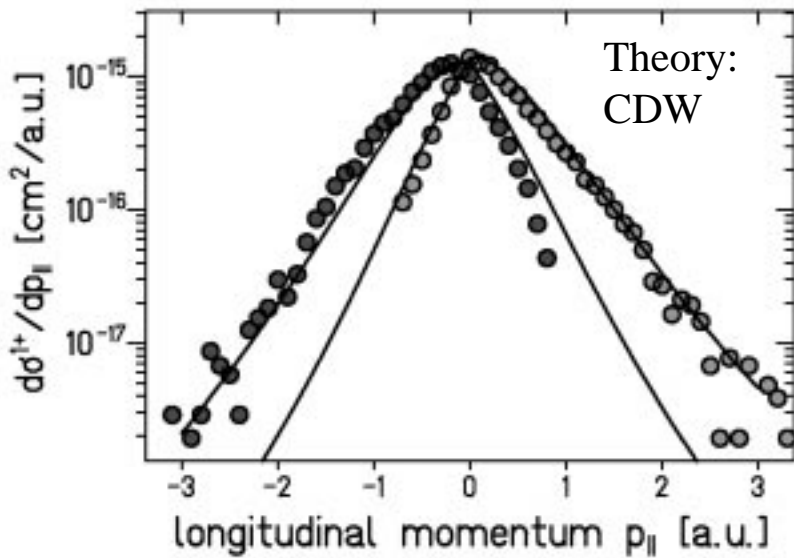
- Atom gets ionized by absorption of virtual photons

# Strong perturbation without PCI



1 GeV/u  $U^{92+}$   
 $q/v = 1.2$

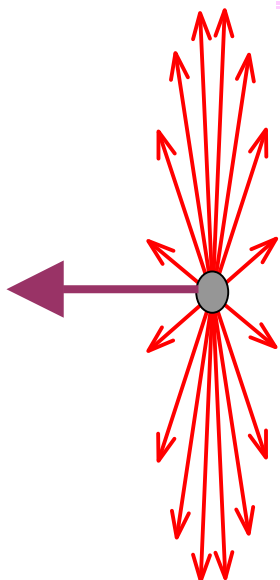
~~PCI~~



3.6 MeV/u  $Ni^{24+}$   
 $q/v = 1.3$

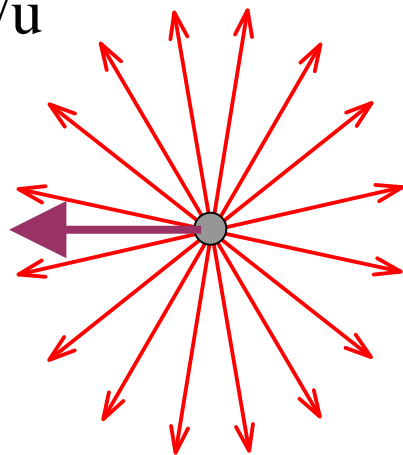
PCI

What makes the difference ?

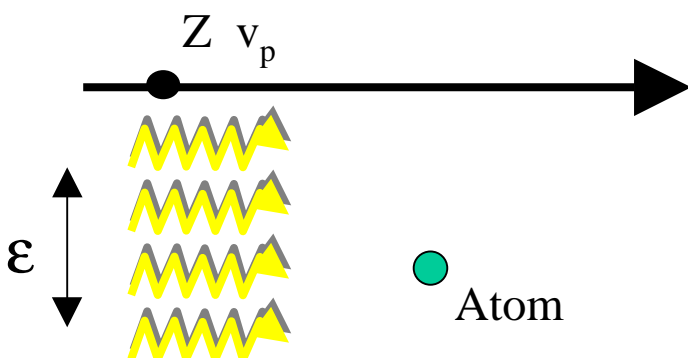
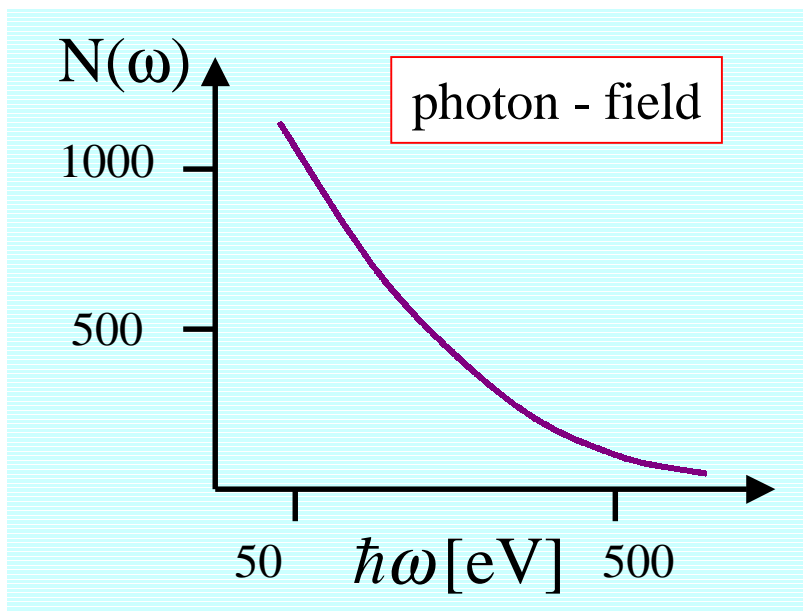
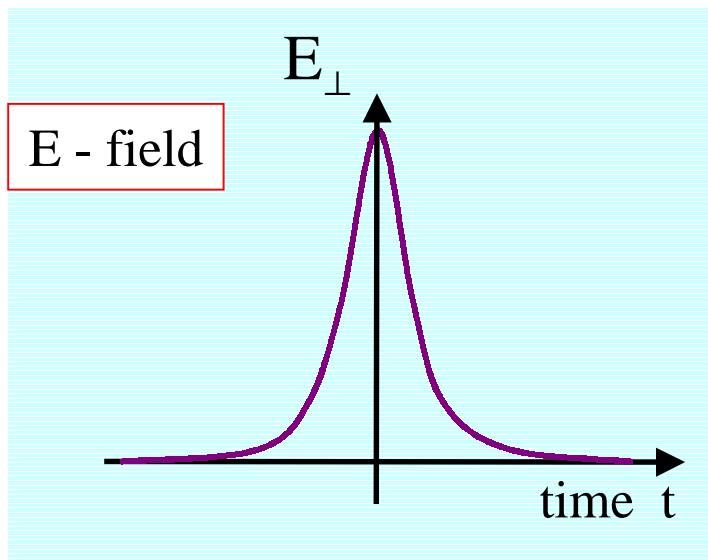
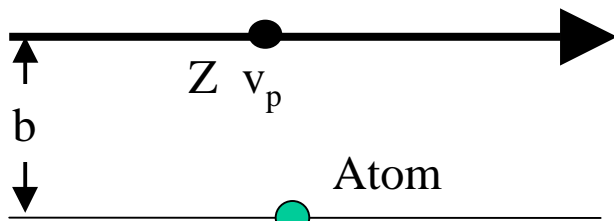


1 GeV/u  
 $\gamma = 2$

3.6 MeV/u  
 $\gamma = 1.003$



# Fast Ion => pulse of virtual photons



$$E(t,b)$$

Fourier-Transformation

$$E(\omega,b)$$

$$dI/d\omega(\omega,b) = (c/2\pi) |E(\omega,b)|^2$$

Integration over b

$$dI/d\omega(\omega) \propto (Z/v)^2$$

Quantisation

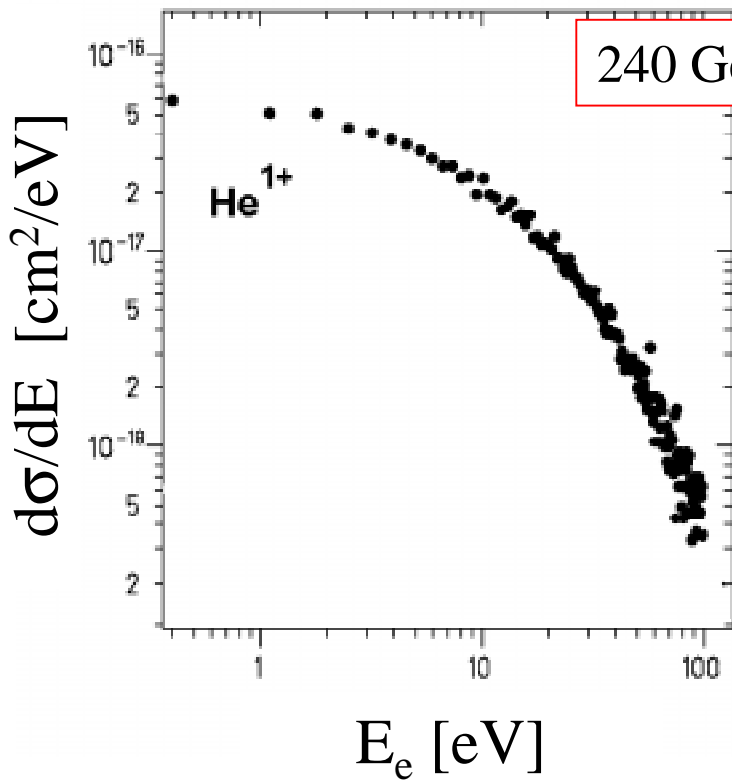
$$N(\omega)$$

Photo-Ionization

$$\sigma_{\text{Ion}} = \int N(\omega) \cdot \sigma_{\gamma}(\omega) / \omega \, d\omega$$

Weizsäcker-Williams 1934

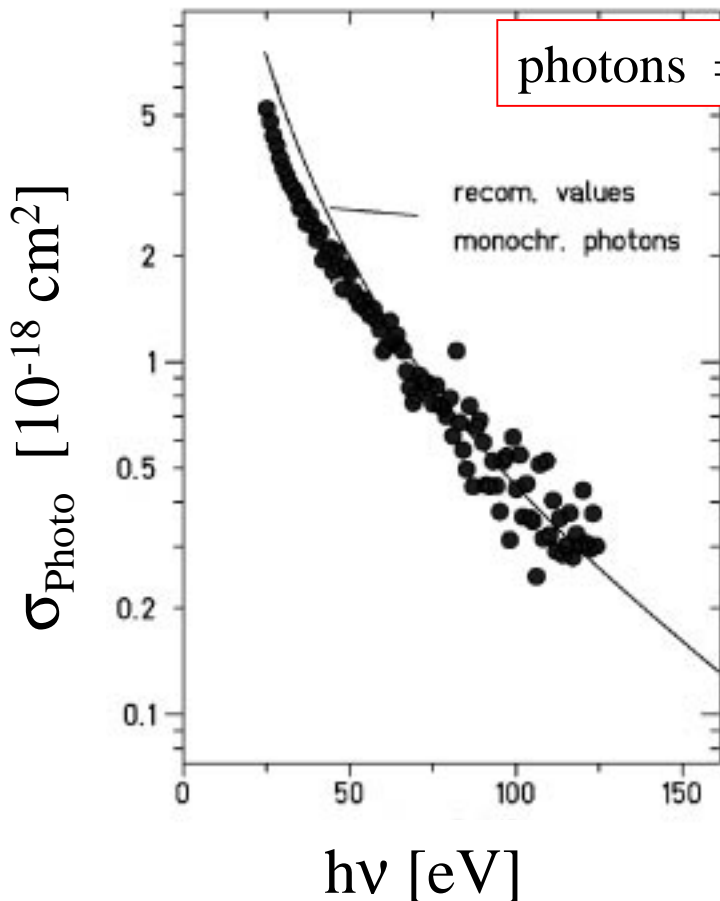
# Equivalence to Photo-Ionization



$$d\sigma/dE_e = N(\omega) \cdot \sigma_{\text{Photo}}(\omega) / \omega$$

$$E_e = \hbar \omega - I_0$$

From Ion-impact extracted photo cross-section



# Sources of intense Photon-pulses

## Strong Lasers

I	$10^{19} \text{ W/cm}^2$
$E_{\text{photon}}$	1-2 eV
$T_{\text{pulse}}$	10 fs

## Free Electron Laser FEL

I	$10^{19} \text{ W/cm}^2$
$E_{\text{photon}}$	10-10000 eV
$T_{\text{pulse}}$	100 fs

## Relativistic Ions

I	$10^{19} \text{ W/cm}^2$
$E_{\text{photon}}$	1-10000 eV
$T_{\text{pulse}}$	1 as

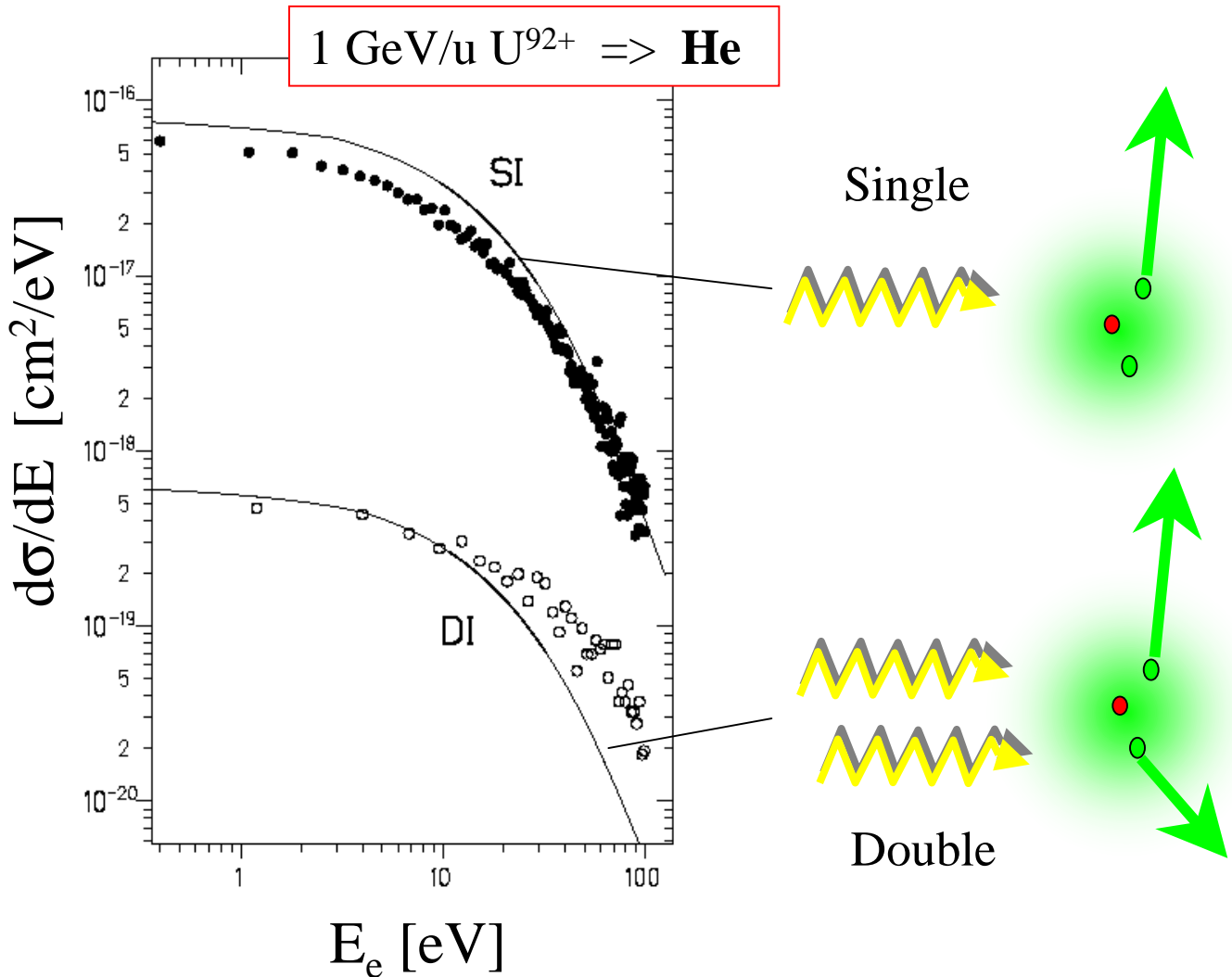


A unique light source

# Double Ionization

Weizsäcker-Williams

Single Ionization : **One** virtual photon



Double Ionization : **Two** virtual Photons

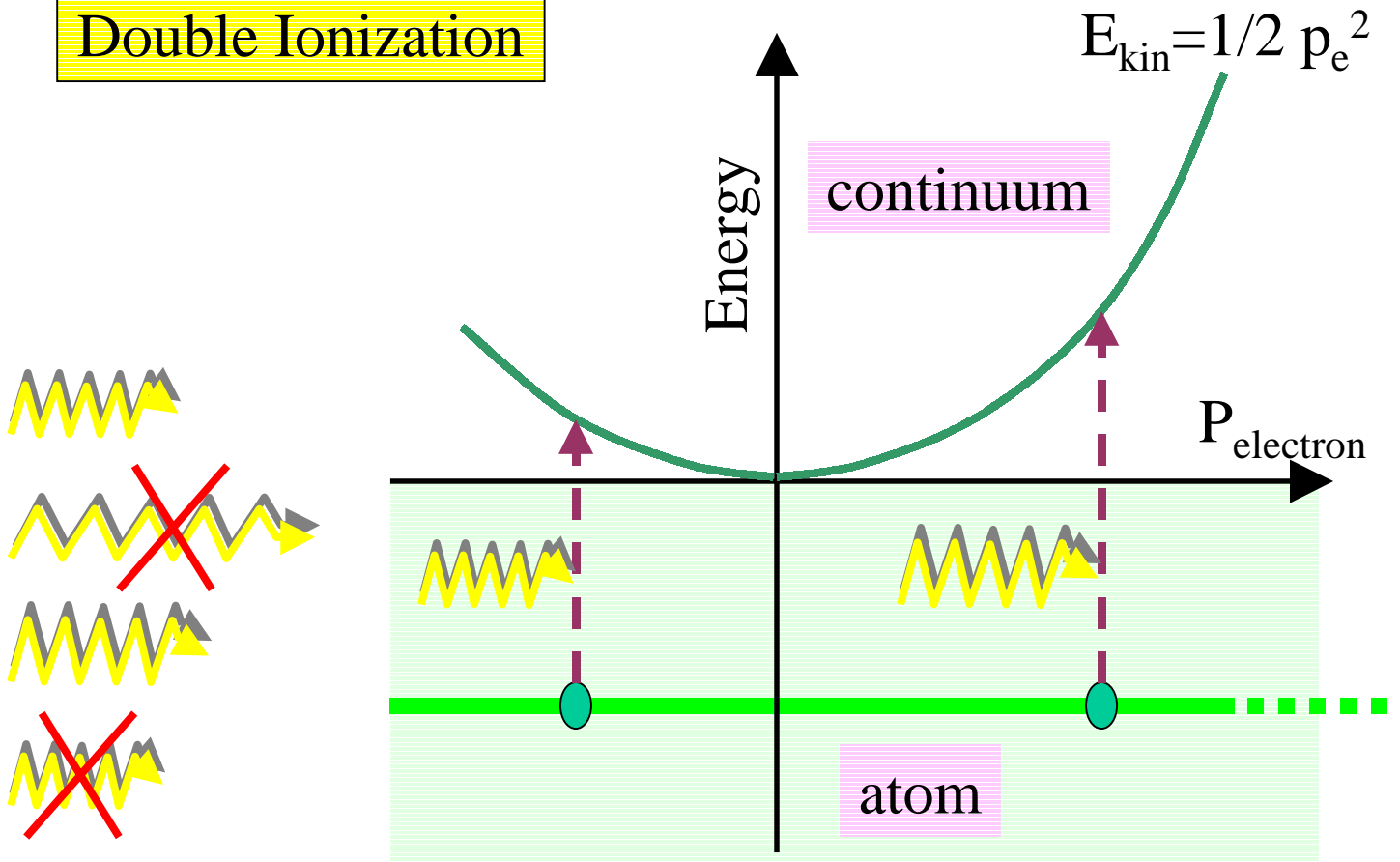
Equivalent Light Intensity  $I \approx 10^{20} W/cm^2$   
high perturbation  $q/v_p \approx 1$

## Images of correlated bound states !?

Instantaneous absorption of 2 photons

$$h\nu = I_o + E_{\text{kin}}$$

## Double Ionization

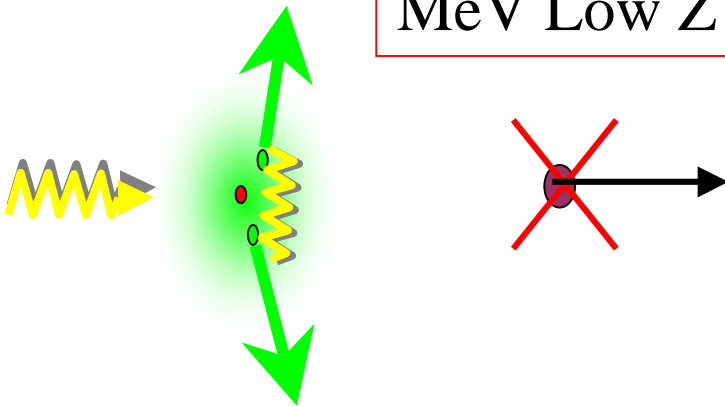


Conditions:

1. Short collision time  $\Delta t_{\text{sto\ss}} \ll t_{\text{atom}}$
2. Small momentum transfer
3. Intense white light

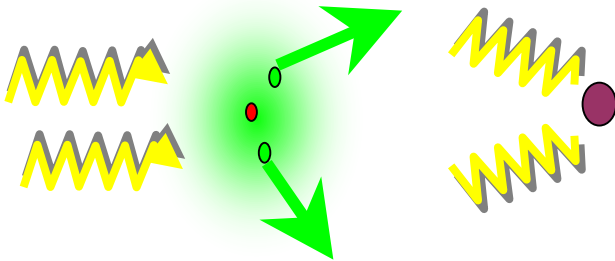
# Double (Multiple) Ionization Mechanisms

## MeV Low Z ions



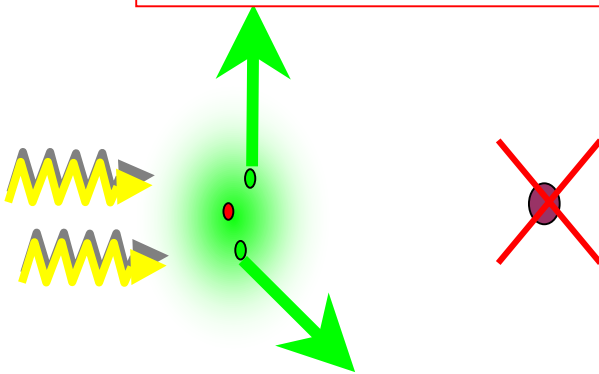
weak perturbation  
1 photon  
no PCI

## MeV High Z ions



strong perturbation  
2 Interactions (photons)  
PCI

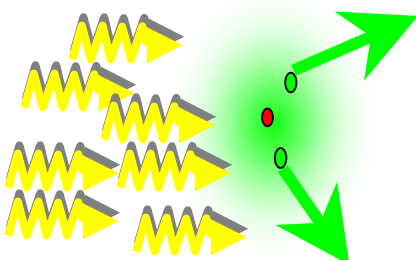
## Relativistic High Z ions



ESR, SIS

strong perturbation  
2 photons  
no PCI

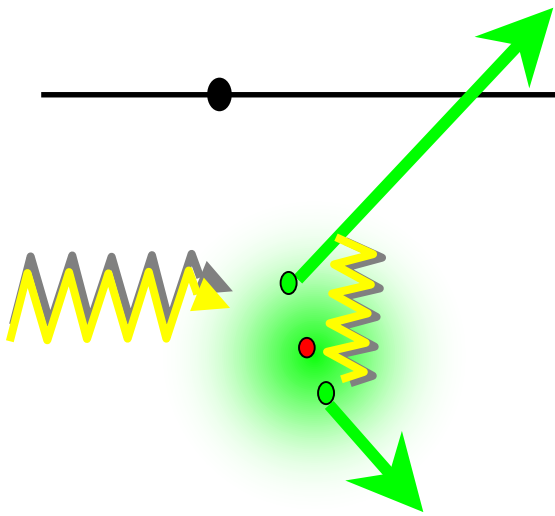
## Intense Lasers



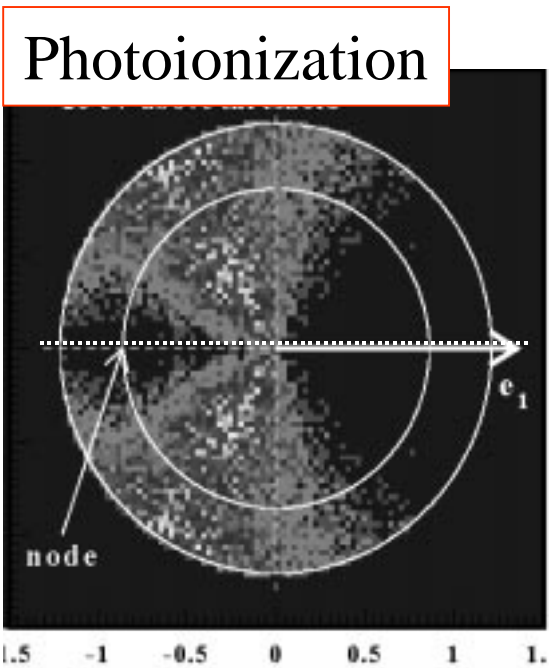
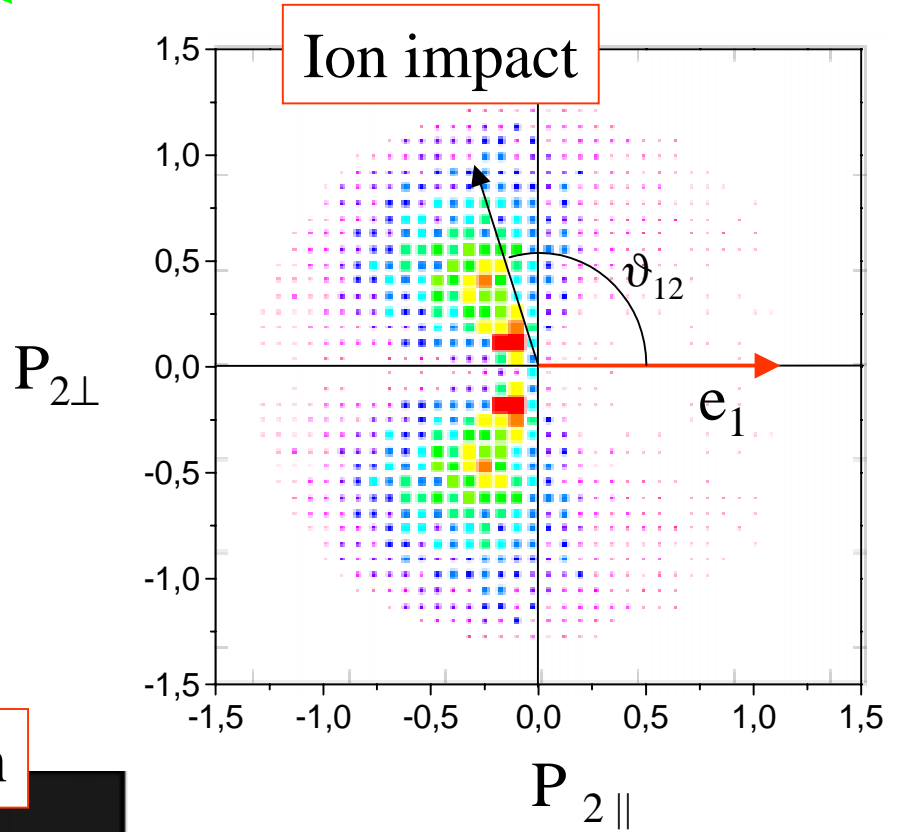
100 (tiny) photons  
no PCI

# Fast Low Z Ion $\Leftrightarrow$ Single Photon

100 MeV/u  $C^{6+}$



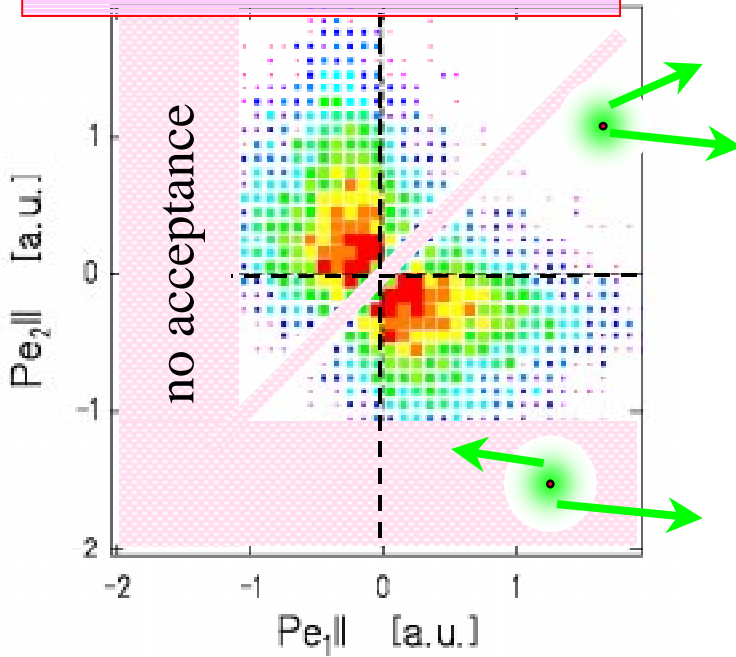
weak perturbation ( $q/v_p = 0.1$ )  
shake-off



R. Dörner et al. (Ffm)

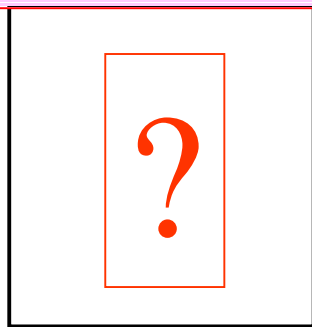
# Electron correlation in double ionization

100 MeV/u  $C^{6+} \rightarrow He$



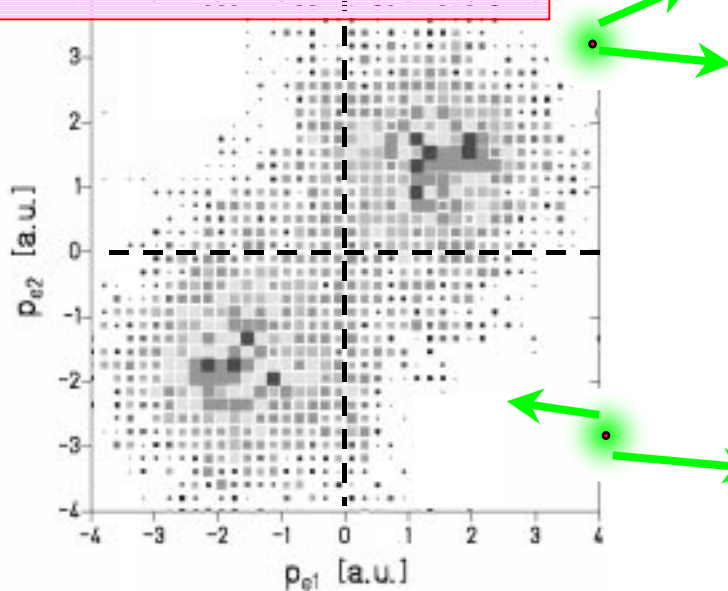
Ion impact  
1 Photon

1 GeV/u  $U^{92+} \rightarrow He$



SIS, ESR  
2 Photons

Intense Laser  $\rightarrow Ne$



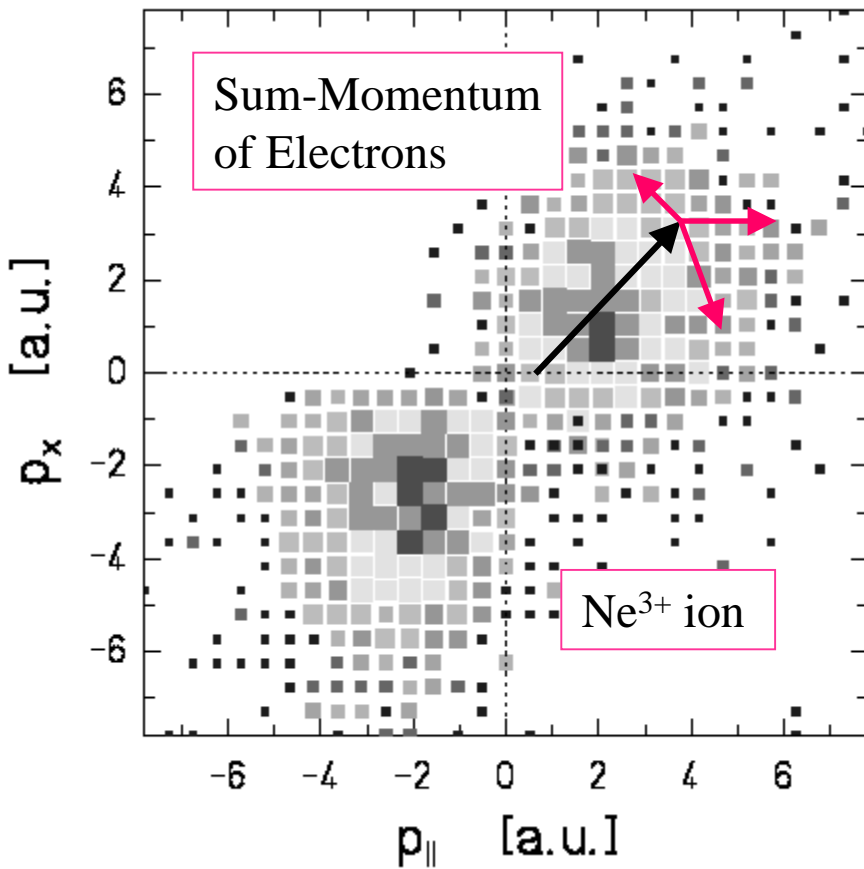
Laser  
100 Photons

$E_{ph} = 1.5 \text{ eV}$   
 $I = 10^{15} \text{ W/cm}^2$

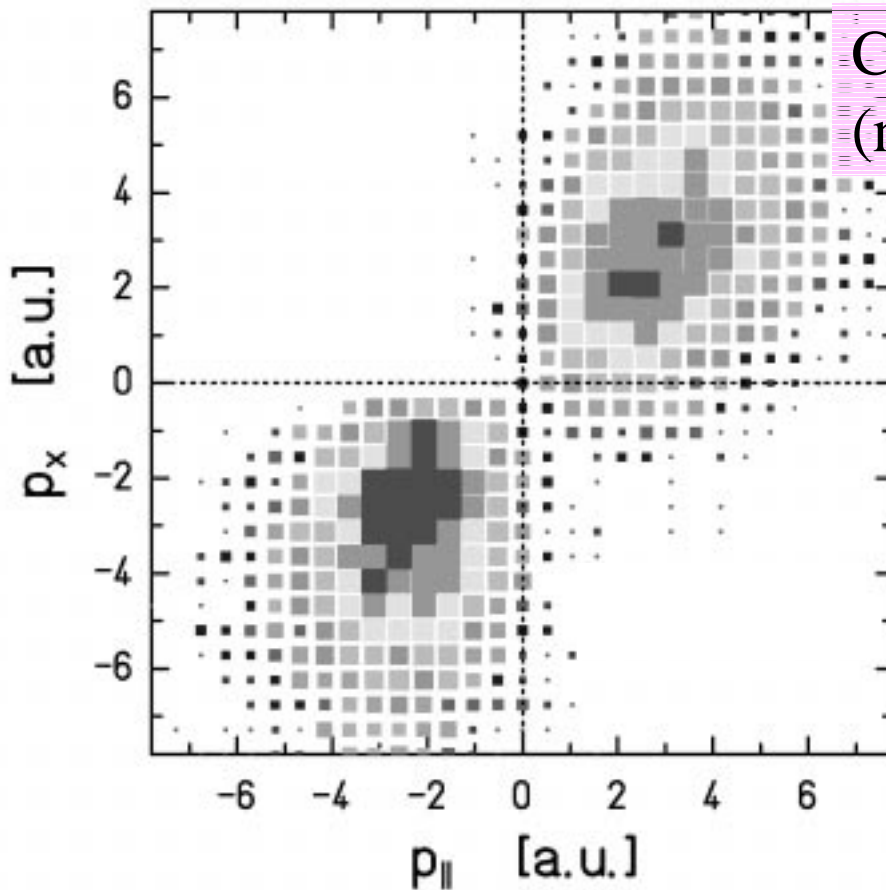
# Triple Ionization

3.6 MeV/u Au<sup>53+</sup> => Neon

View onto collision plane



Experiment

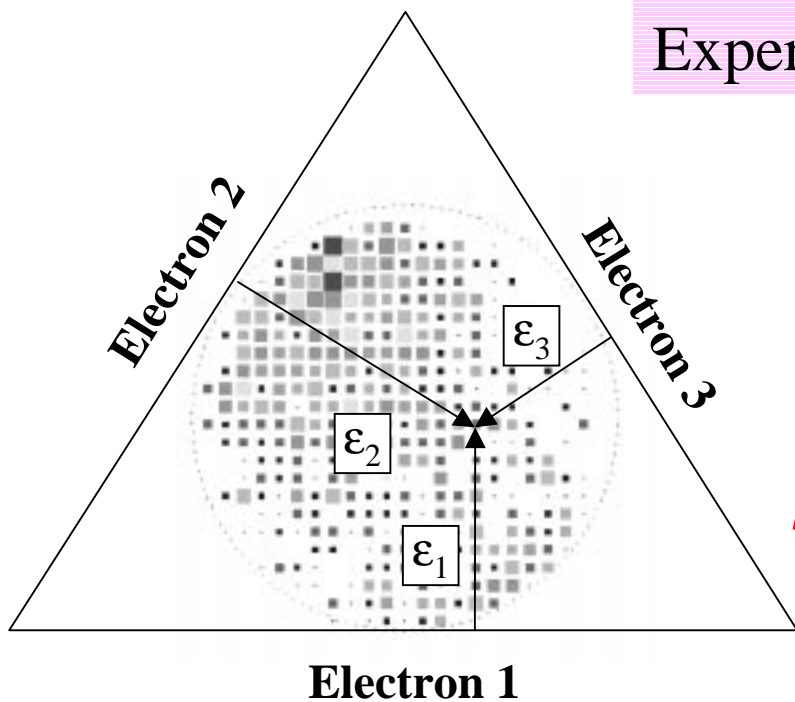


Classical calculation  
(nCTMC) R.E. Olson

# Relative-Motion in Electrons CM-System

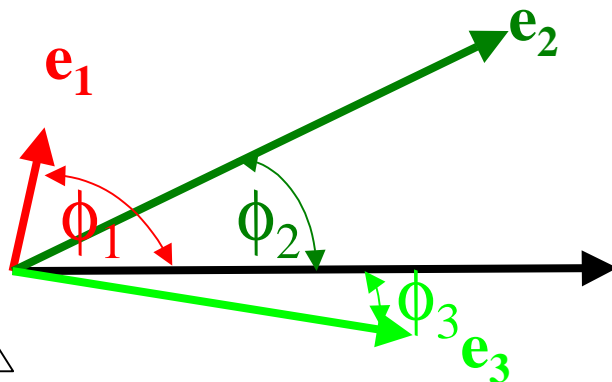
Experiment

Dalitz-Plot

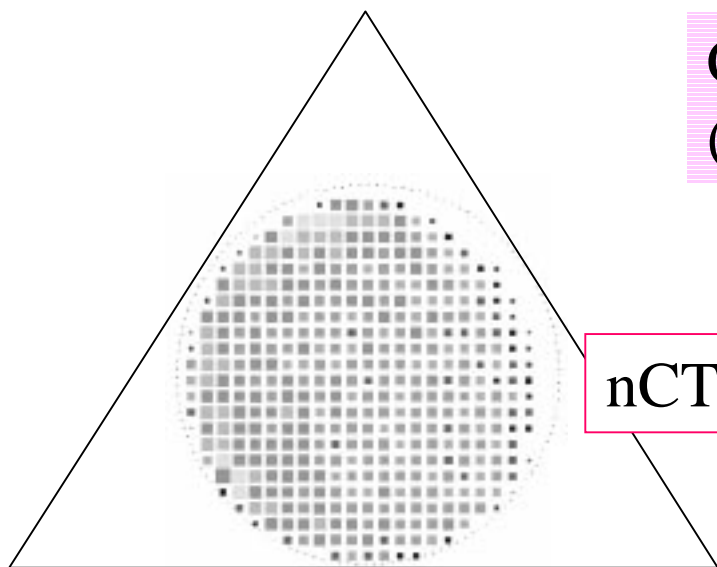


$$\epsilon_i = E_i / (E_1 + E_2 + E_3)$$

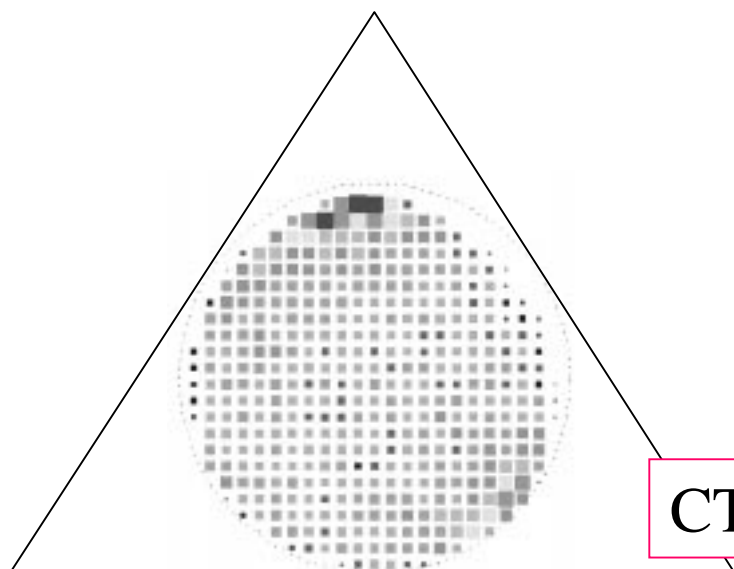
$E_i$ : kin. Energies



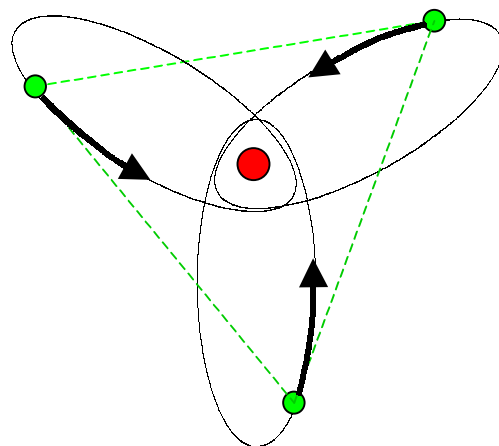
Classical Model  
(CTMC): R.E. Olson



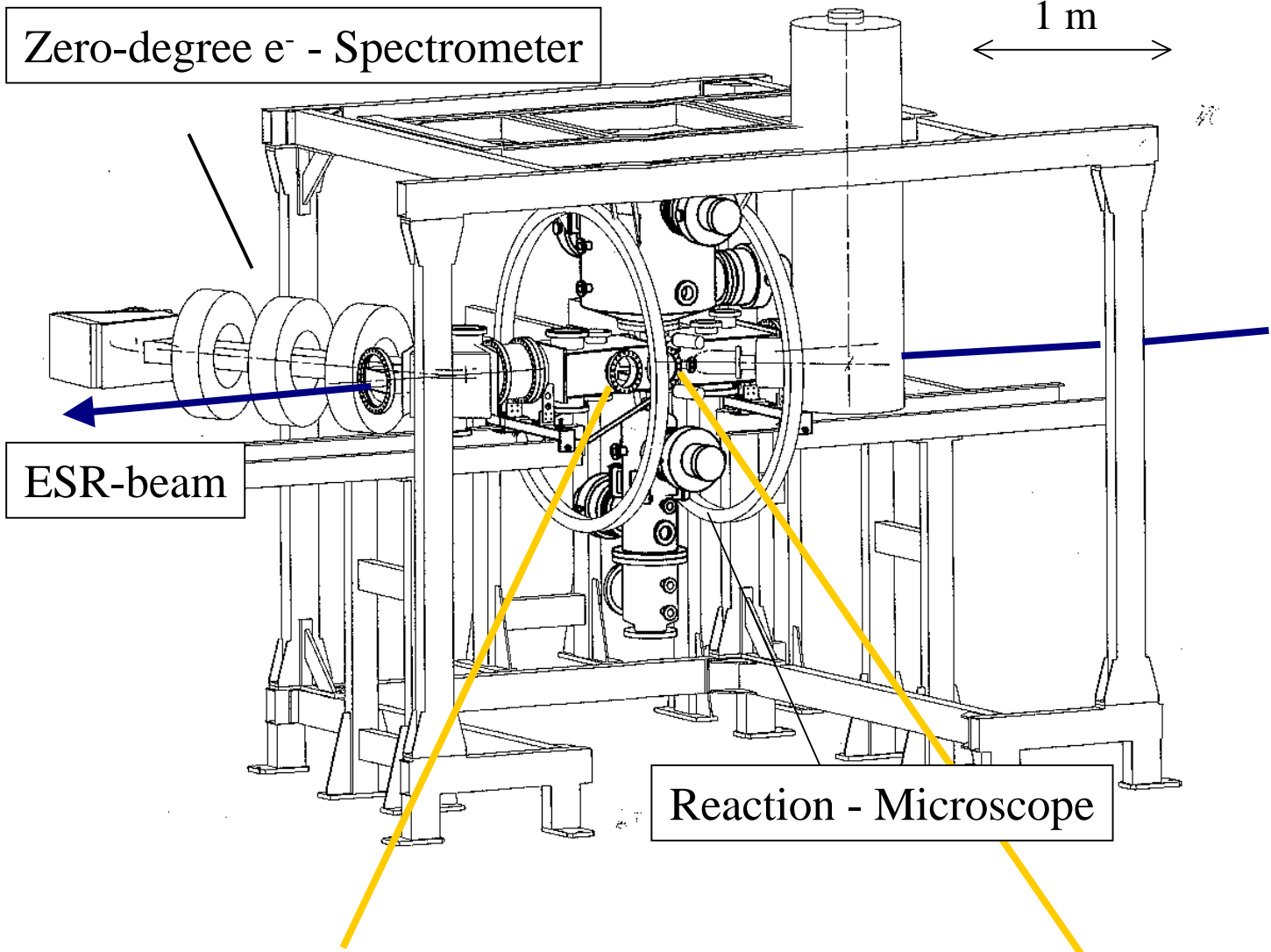
nCTMC without e-e Interact.



CTMC with e-e Interact.



# Implementation into ESR at GSI

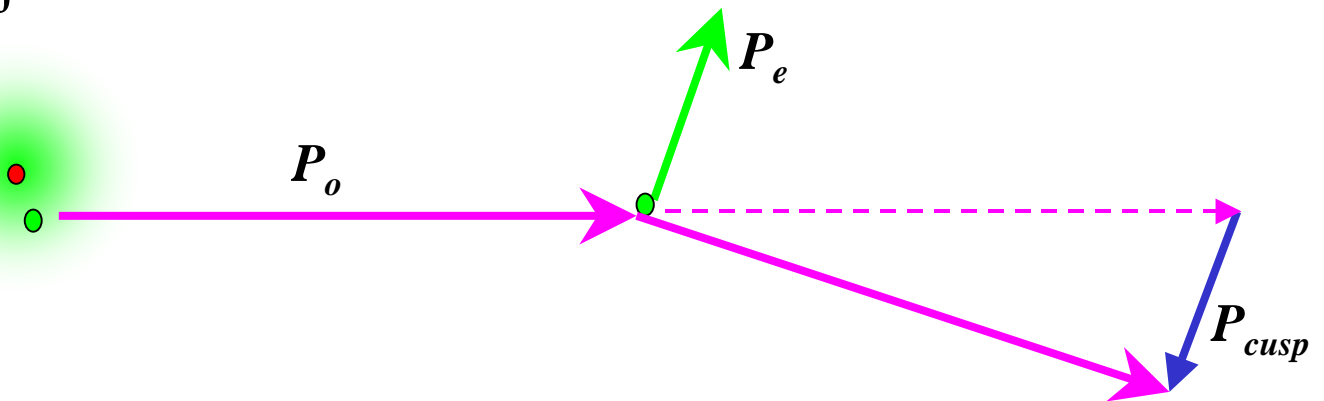


## Ionization of Ions

## Electron impact ionization

Projectile ...U<sup>91+</sup>

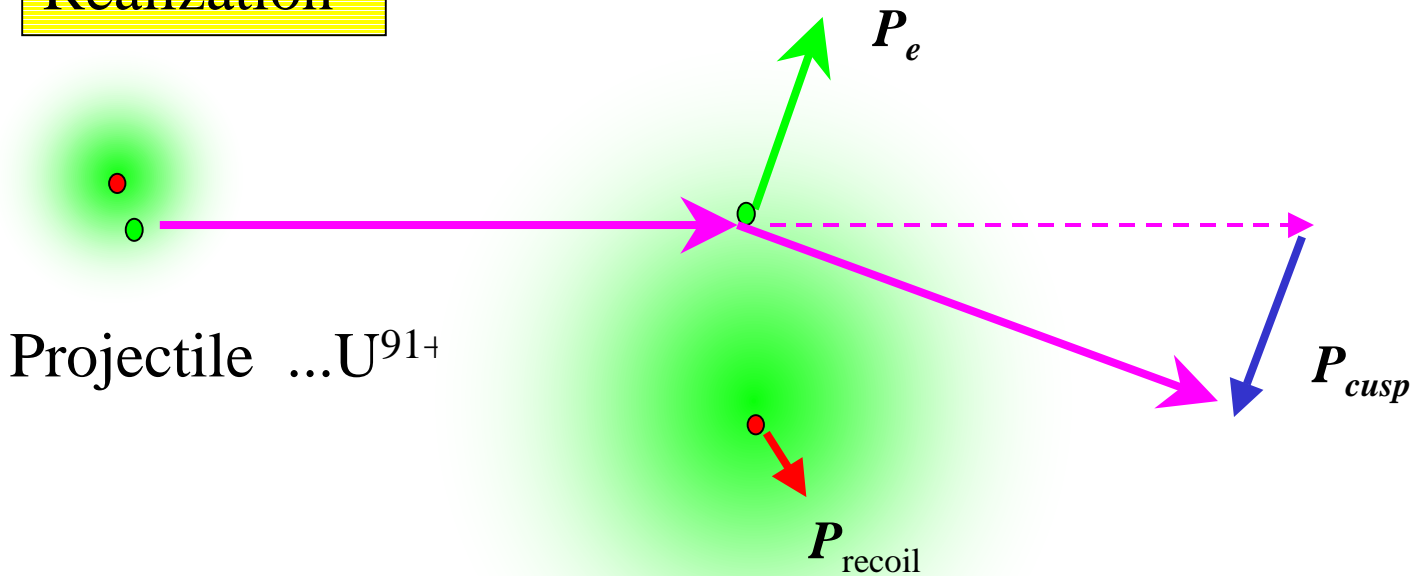
e<sup>-</sup> Target



Binary Collisions :  $P_{cusp} \approx -P_e$

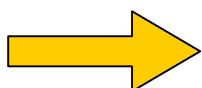
## Realization

Projectile ...U<sup>91+</sup>



He - Atom  
(excited H)

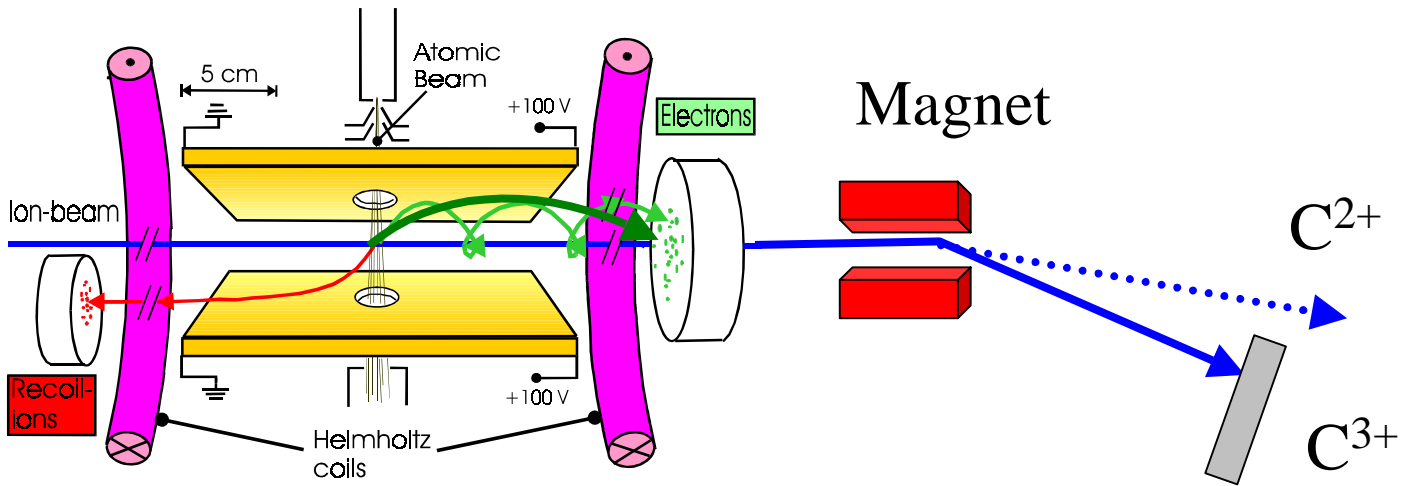
Atomic target  $\Rightarrow$  dense e<sup>-</sup>-Target ( $10^{12}$  cm<sup>-3</sup>)  
Target-ion recoil  $\Rightarrow$  compensates initial momentum



fully differential data for (e,2e) on ions

# Pilot Experiment at the UNILAC

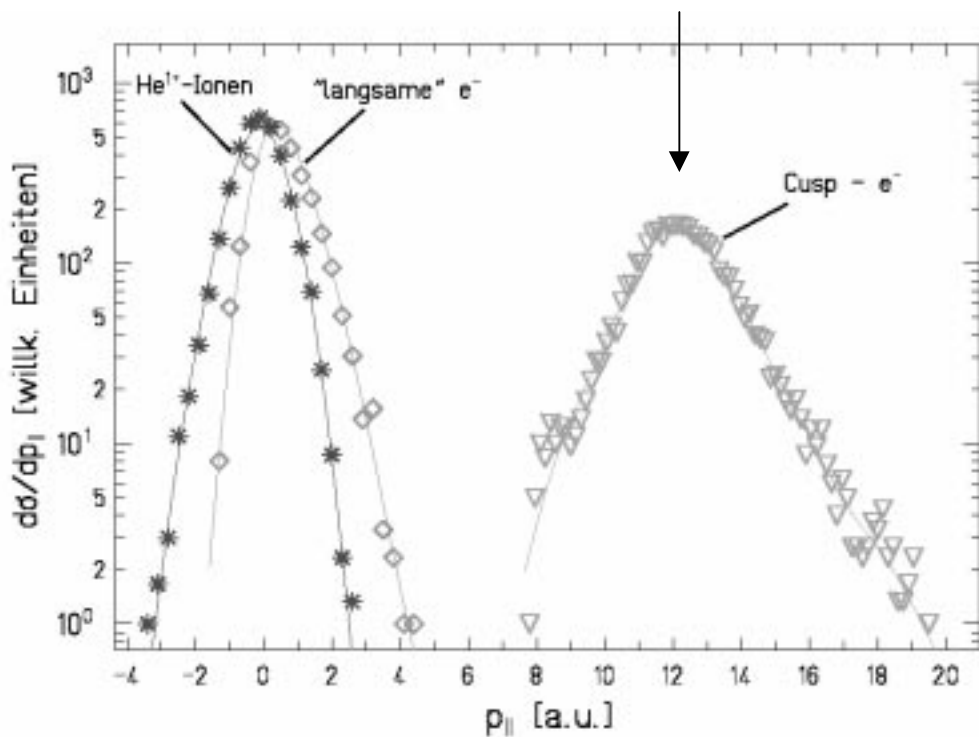
3.6 MeV/u  $C^{2+} \Rightarrow He$

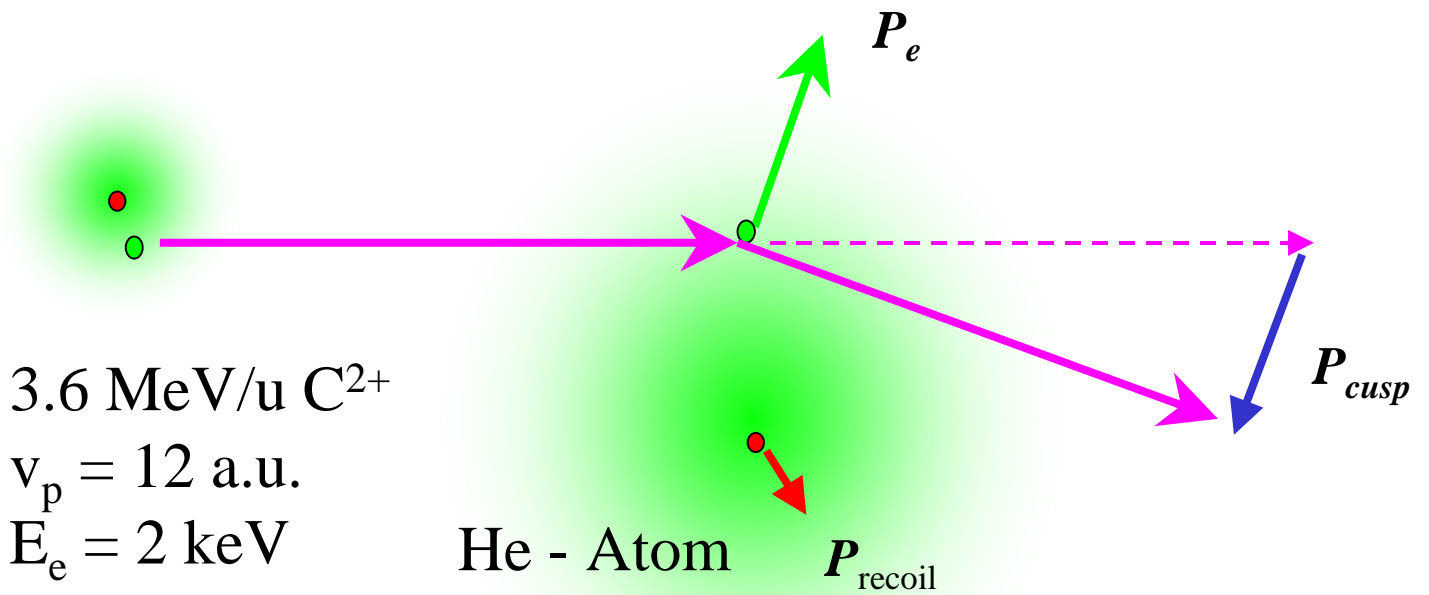


Coincident measurement of:

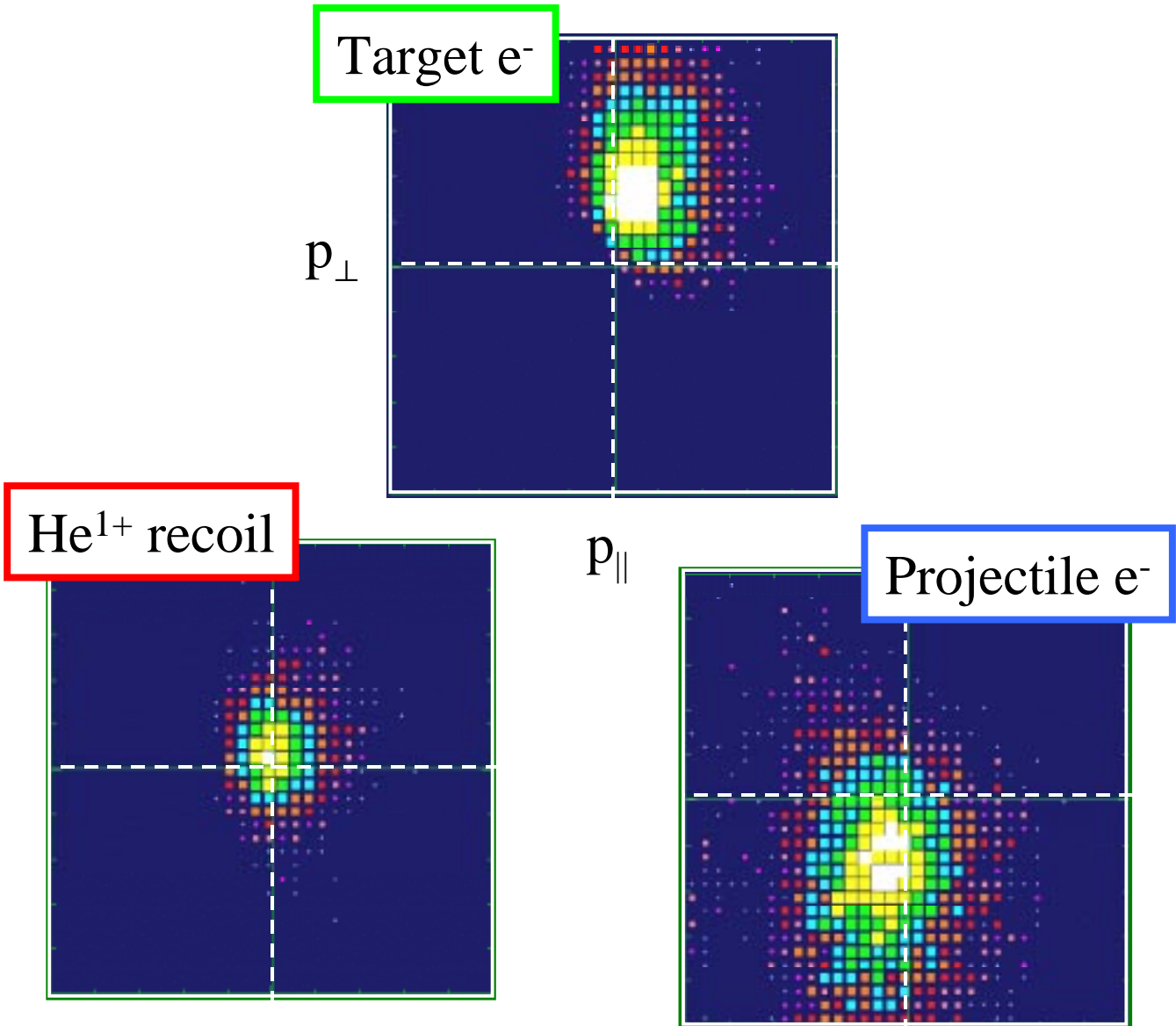
$He^{1+}$  ion - Target Electron - Cusp Electron - Projectile

$v_p = 12$  a.u.

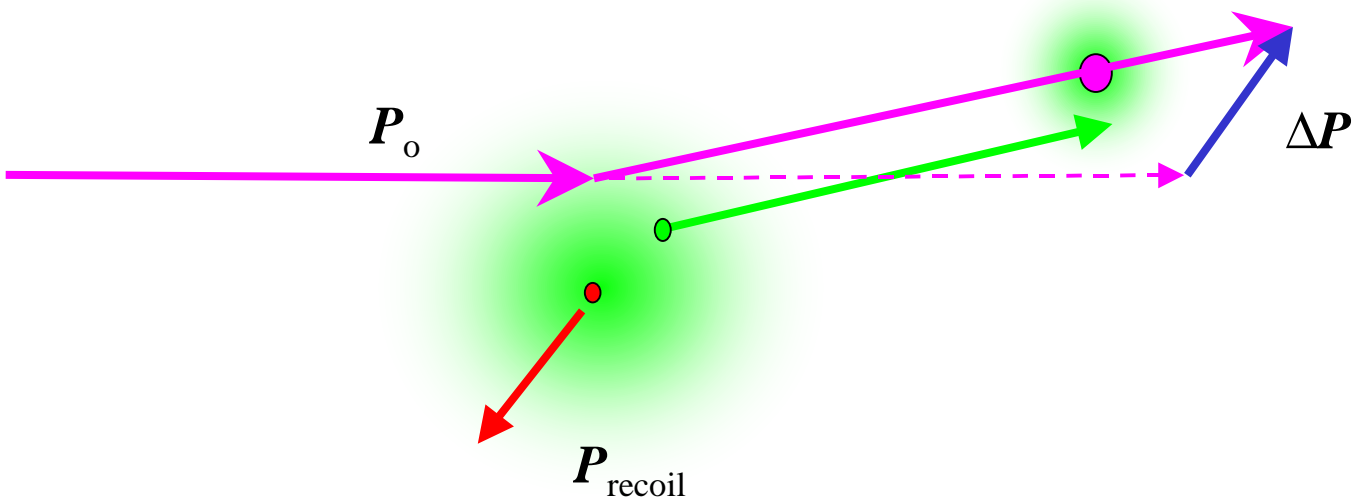




view onto collision plane



## Electron Capture



## Energy gain/loss

Momentum conservation :  $P_{\text{recoil}} = -\Delta P$

### *Recoil Momentum*

Along the beam direction :  $P_{\parallel} = -Q/v_p - 1/2 v_p$

Perpendicular to beam :  $P_{\perp} = P_0 \cdot \vartheta$

$Q$  = Change of internal energy ( $E_i^{\text{bound}} - E_f^{\text{bound}}$ )

$v_p$  = projectile velocity

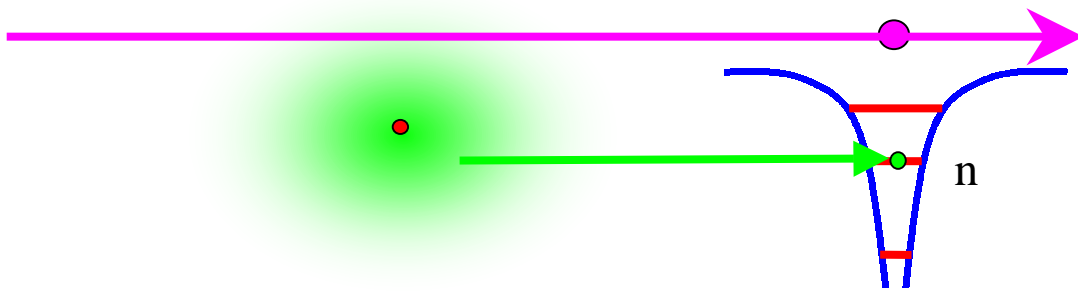
$$Q = -P_{\parallel} \cdot v_p - 1/2 v_p^2 \quad \vartheta = P_{\perp} / P_0$$

### Resolution (100 keV Ne)

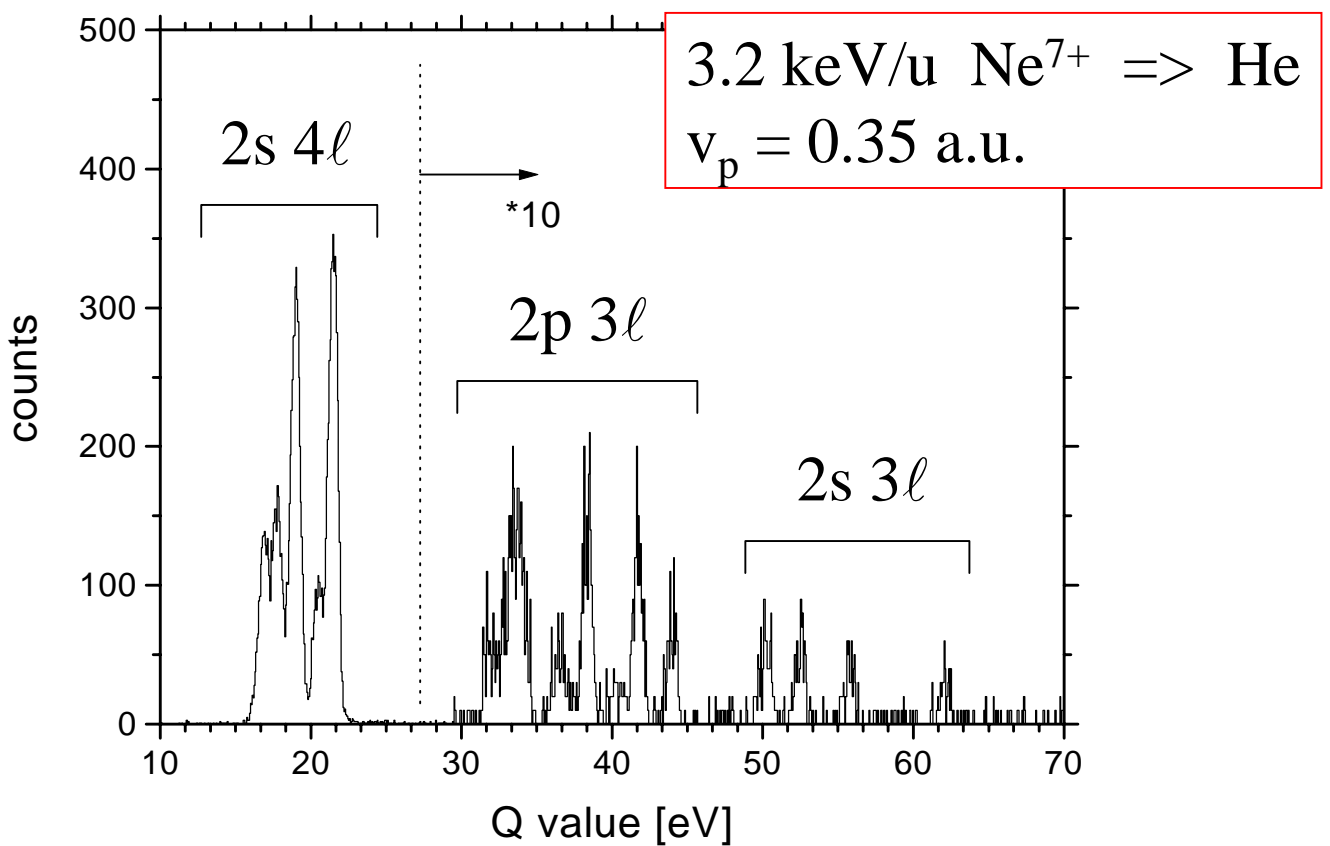
- Energy gain:  $5 \cdot 10^{-6} \Delta E/E$
- Scattering:  $5 \cdot 10^{-6} (1\text{mm}/200\text{m})$

Independent on beam quality !!

# Towards Precision Spectroscopy !?



## Example Low Energy Collisions



$$\Delta E_{\text{FWHM}} = 1 \text{ eV} @ 3 \text{ keV/u}$$

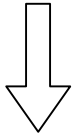


$$\Delta E \propto v_p$$

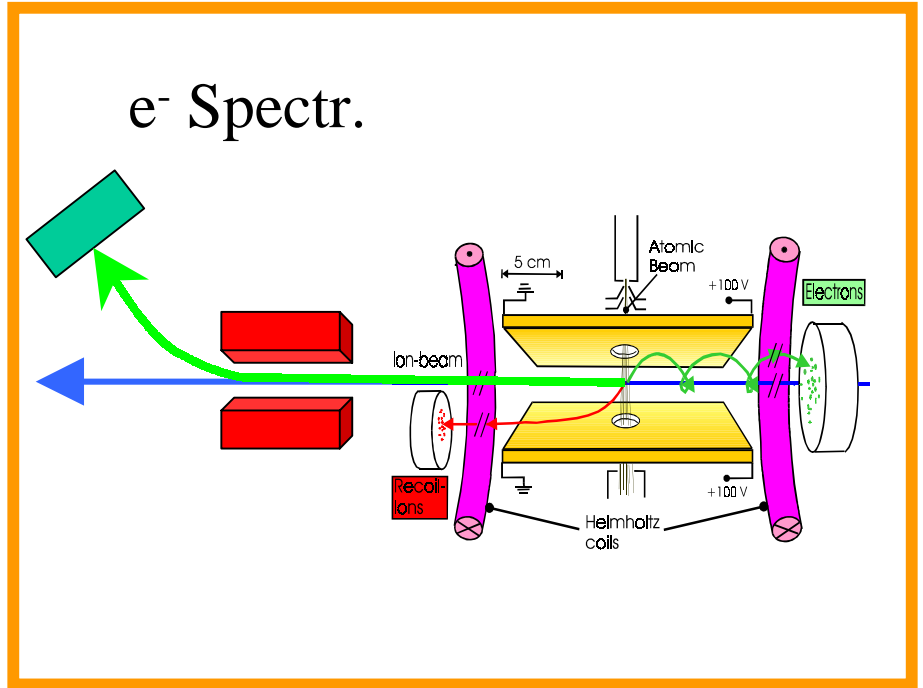
$$\Delta E_{\text{FWHM}} = 100 \text{ eV} @ 50 \text{ MeV/u}$$

# Outlook

Combination with  
e<sup>-</sup> Spectrometer

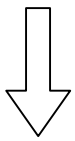


S. Hagmann



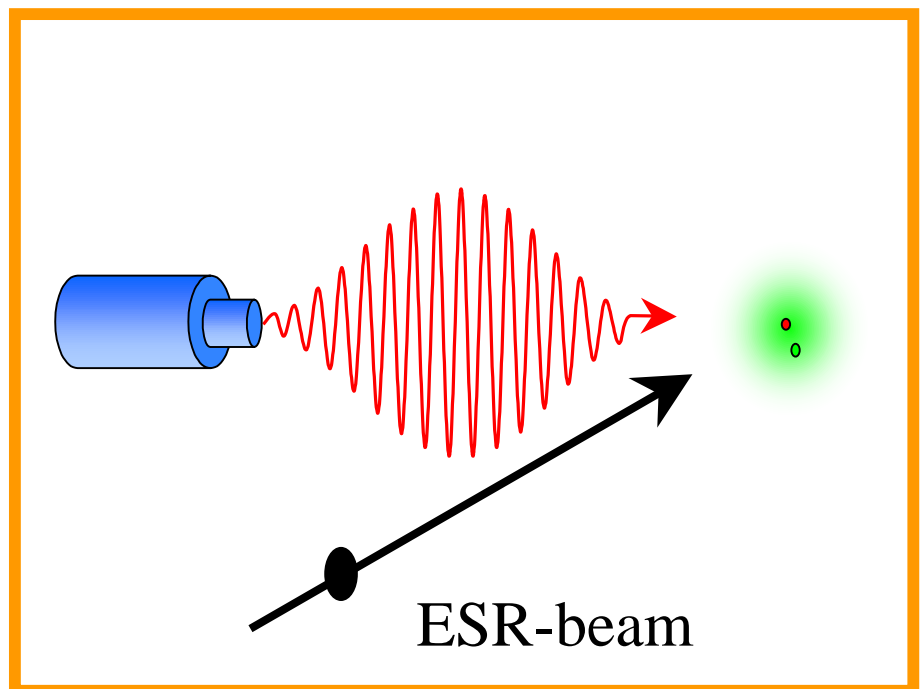
Collisions in a Laser-field

Capture  
Ionization



A. Voitkiv

## Laser assisted collisions

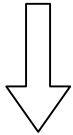


## Other Targets

e.g. Molecules (Clusters)

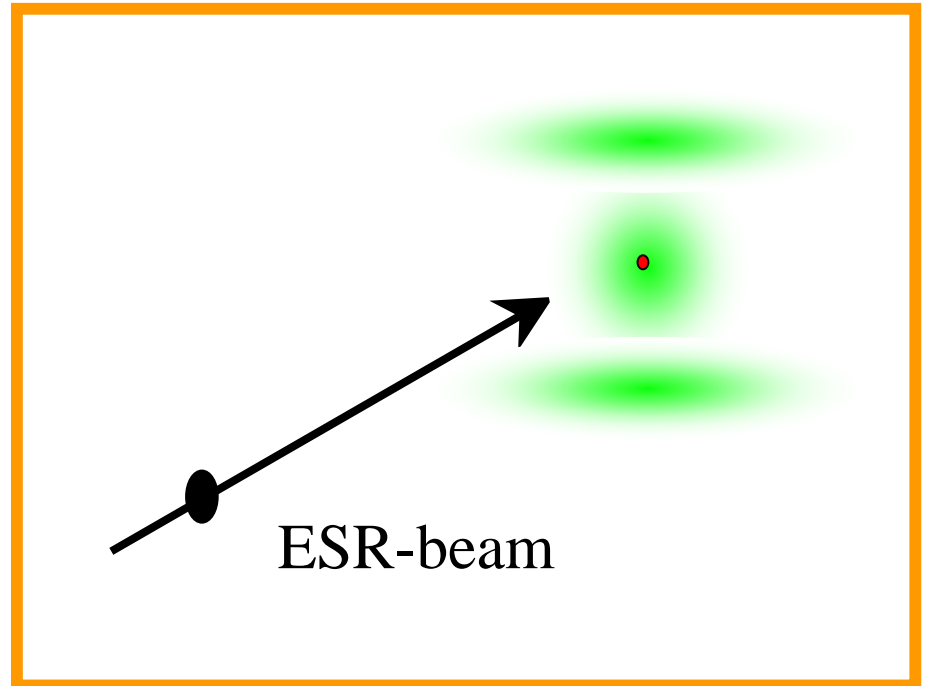
⋮

Metastable He



R. Dörner

## Exotic Targets



## Collaboration

GSI

R. Mann

MPIK-HD

H. Kollmus  
C.D. Schröter  
D. Fischer  
B. Feuerstein  
A. Dorn  
J. Crespo  
J. Ullrich

Frankfurt

R. Dörner  
Th. Weber  
H. Schmidt-Böcking

KSU

S. Hagmann

UMR

M. Schulz