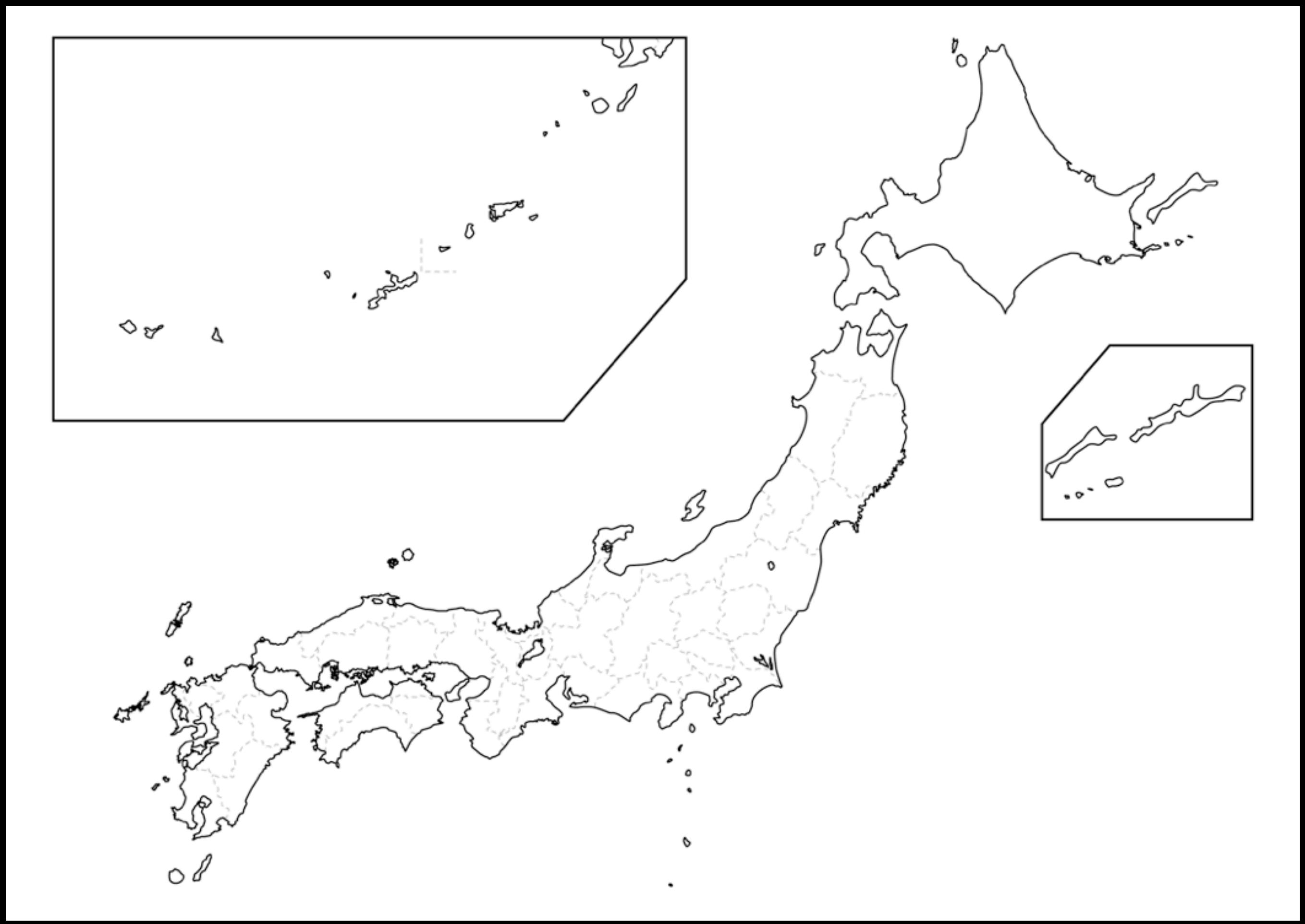
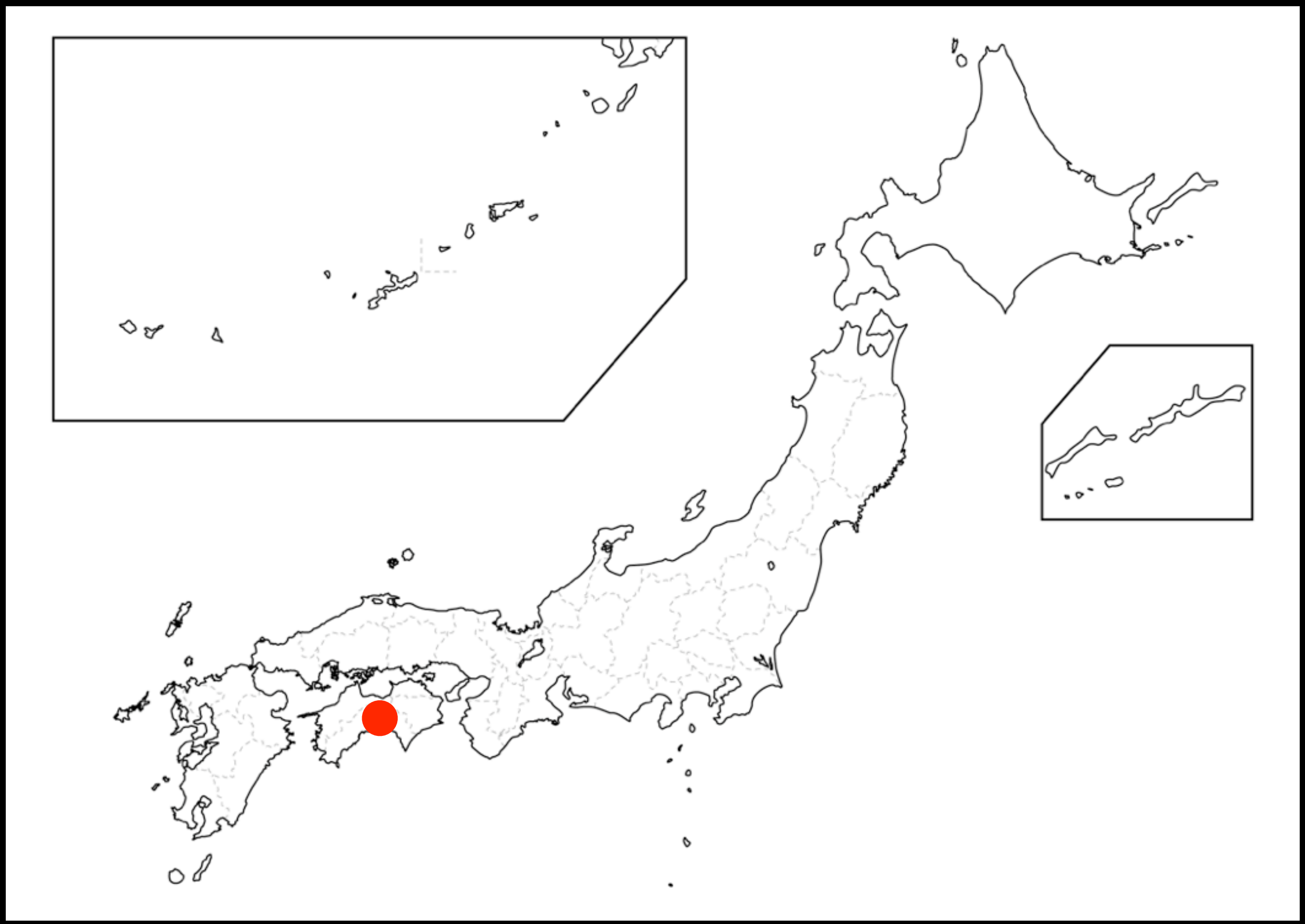
Highly charged ion beams applied to nano-scale fabrication

Sadao Momota
Kochi University of Technology

Kochi?



Kochi?



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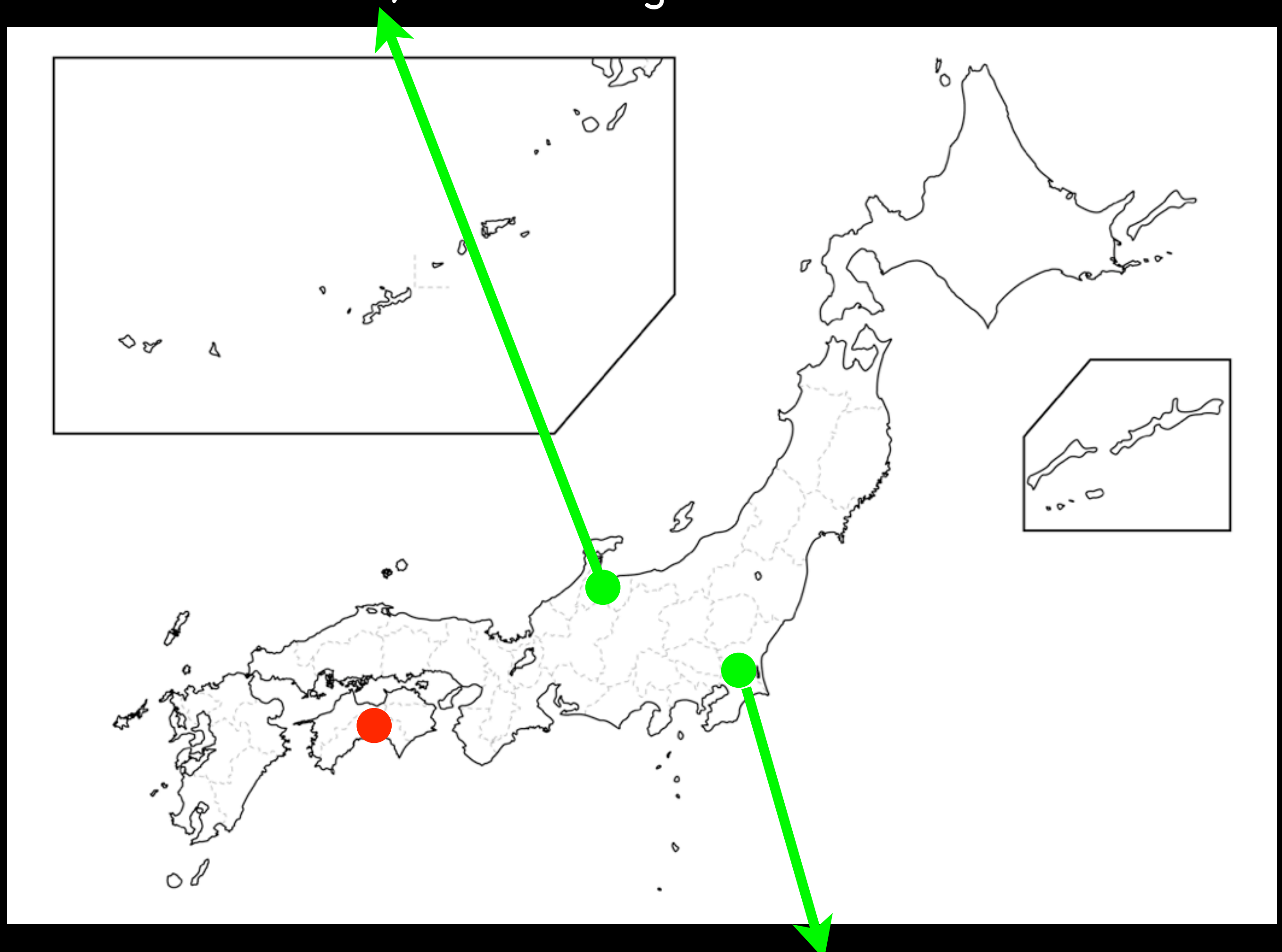
Kochi?

Toyama Univ.
Prof. Morita, Dr. Kawasegi



Tokyo Univ. of Sci.
Prof. Taniguchi, Prof. Satake, Prof. Miyamoto

S. Momota, PT-BMES, Sep. 9-10, 2010 @National Tsing Hua Univ.

Contents

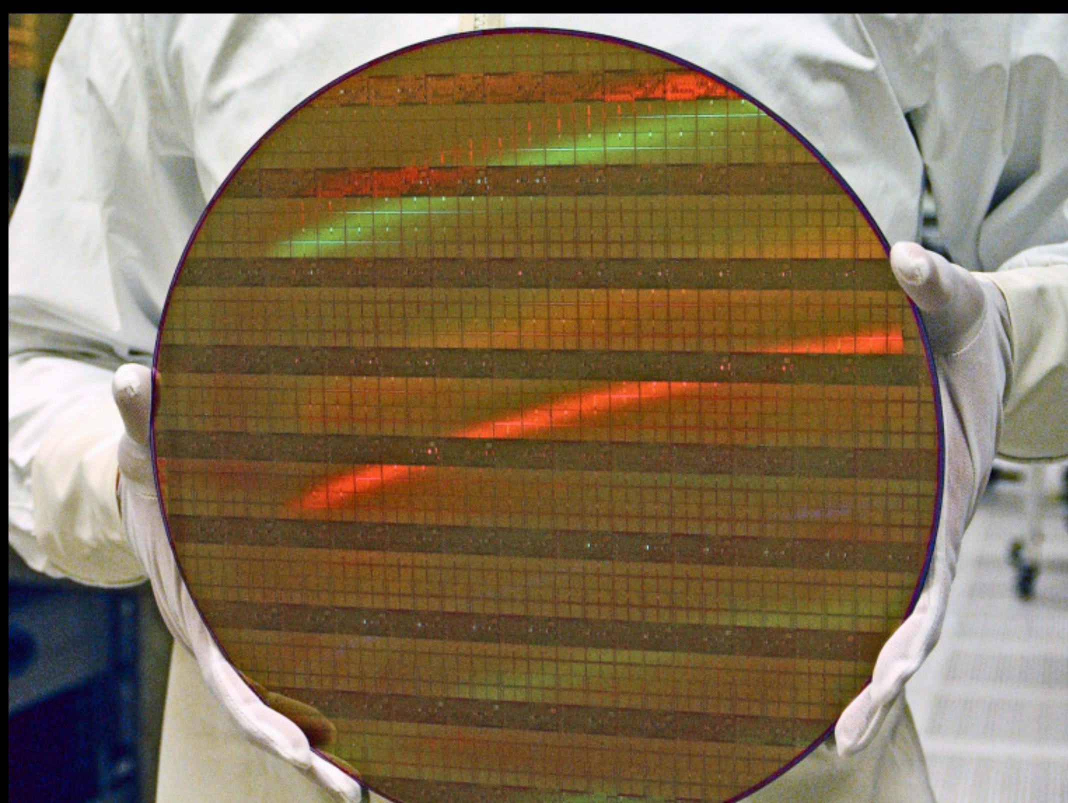
- Motivation and goal
- Features of HCI beams
- Experimental results
- Production of HCI beams
- Conclusions

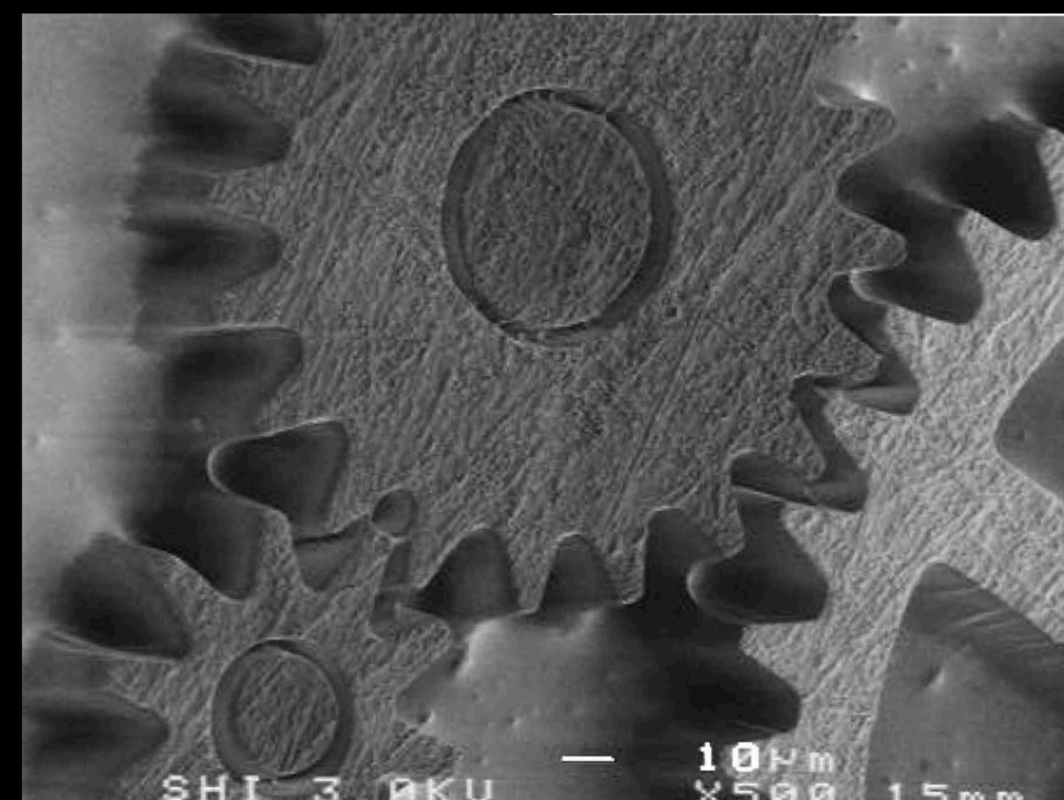
Motivation

Application of IB : 1

Industrial fabrication

- Semiconductor
- MEMS



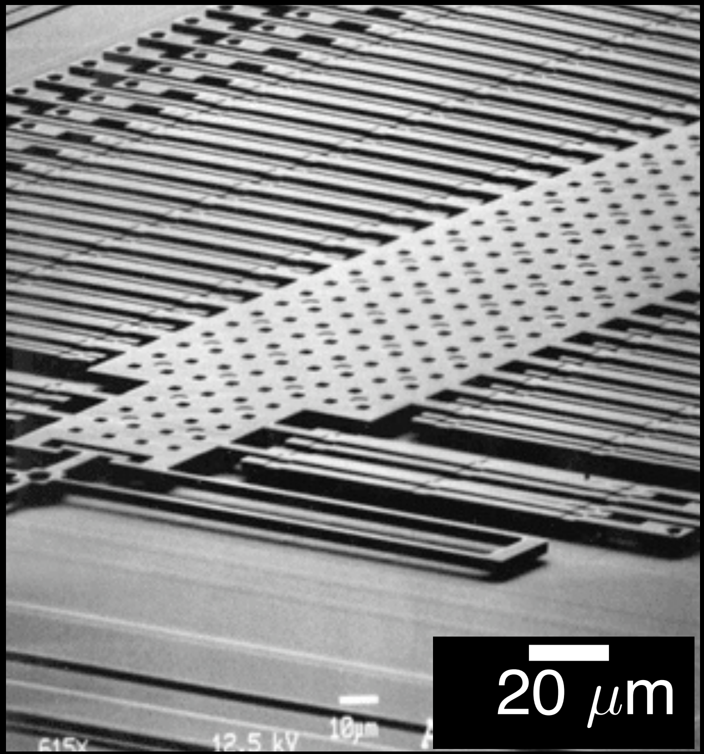


http://www.rise.waseda.ac.jp/proj/sci/S98S08/j-S98S08.html

3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Micro-machining tool
- Mold
- Optical device
- Biochip

3-Axis Accelerometer



Analog Devices Co.

3D micro-nano structures

- MEMS
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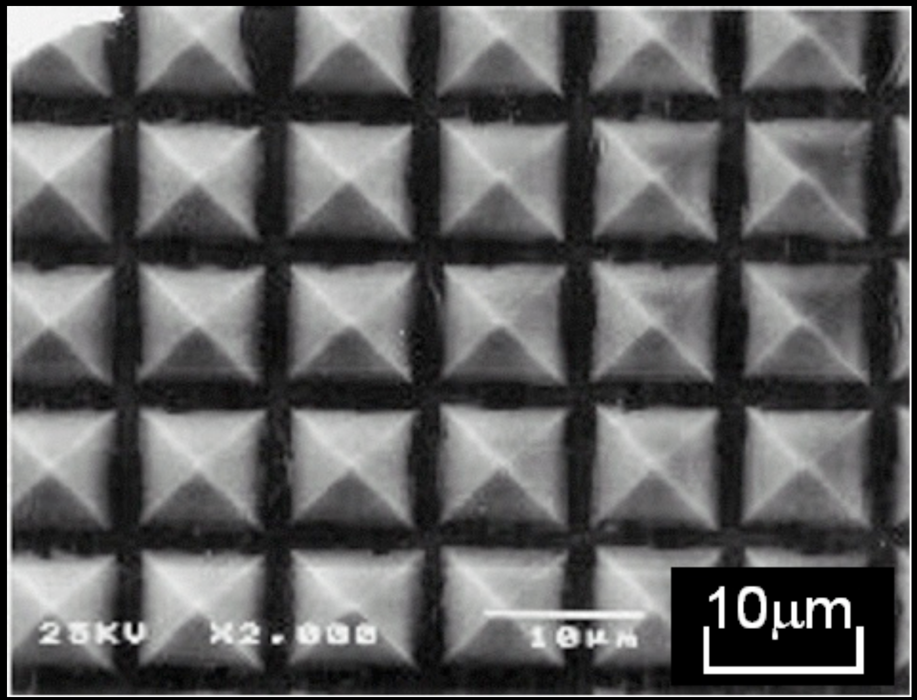
Diamond array tool



Morita Gr. (Toyama Univ.)

3D micro-nano structures

- MEMS
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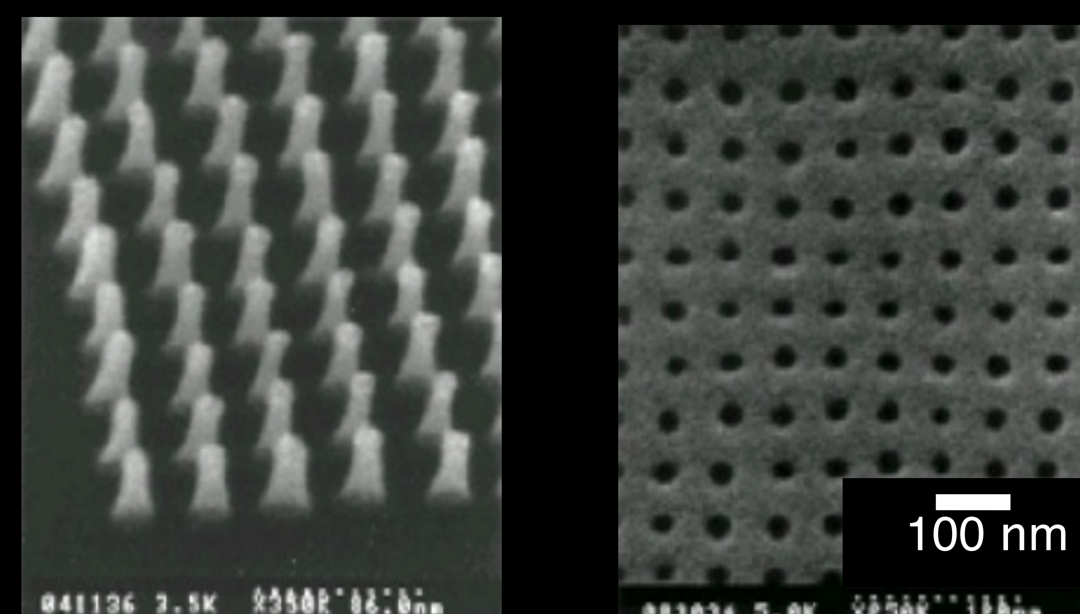
Pattern transfer

SiO_2/Si ⟶ PMMA



10nm diam. & 60nm pitch

S.Y. Chou et al.

J. Vac. Sci. Technol., B15(1997)2897

3D micro-nano structures

- MEMS
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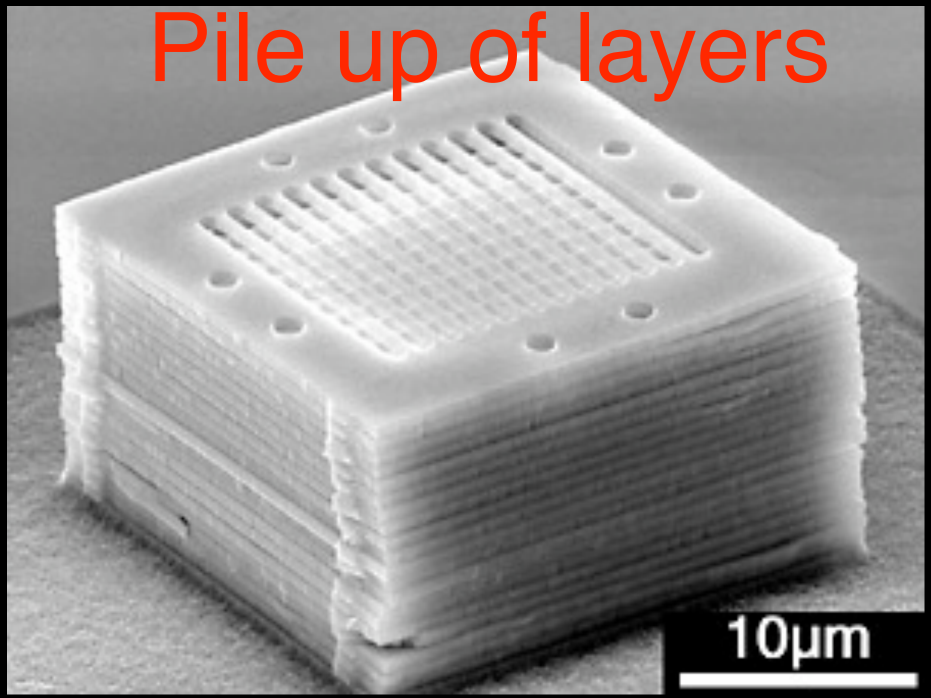
Photonic crystal



National Inst. for Material Science
http://www.nims.go.jp/jpn/news/nimsnow/Vol4/2004-03/05.html

3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Micro-machining tool
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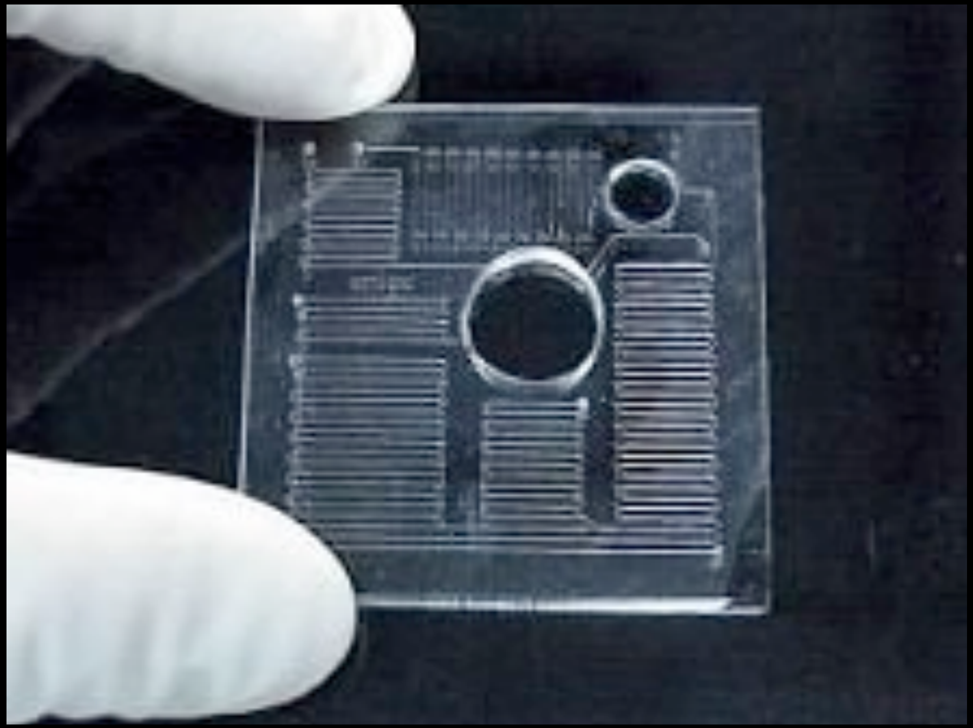
Micro inspection chip



Hitachi, Ltd.

Application of IB : 2

Biomedical application

- Breed improvement

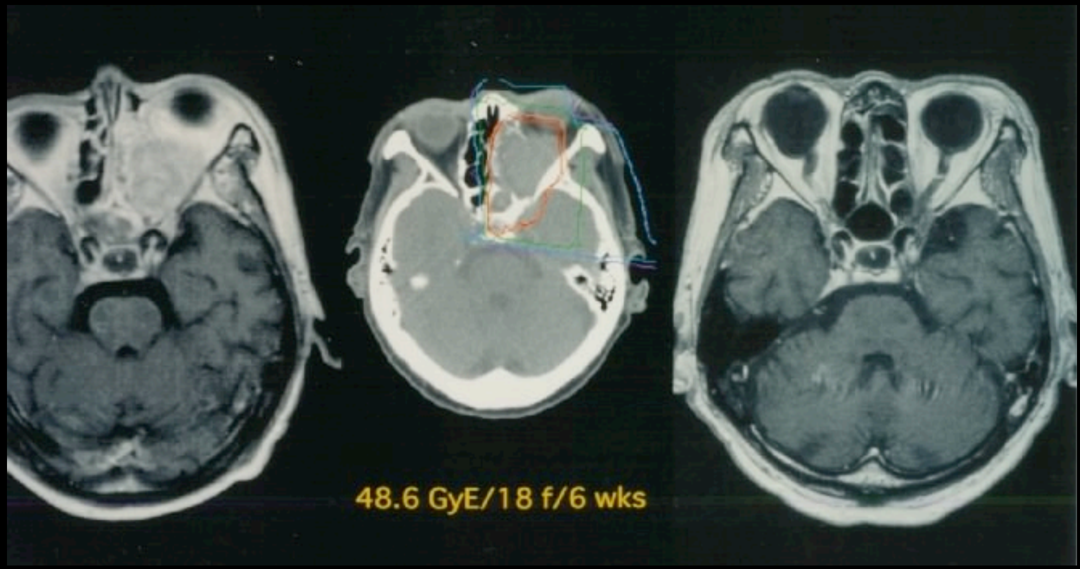
Blue carnation
Bred by RIKEN

Application of IB : 2

Biomedical application

- Breed improvement
- Cancer therapy

Blue carnation
Bred by RIKEN

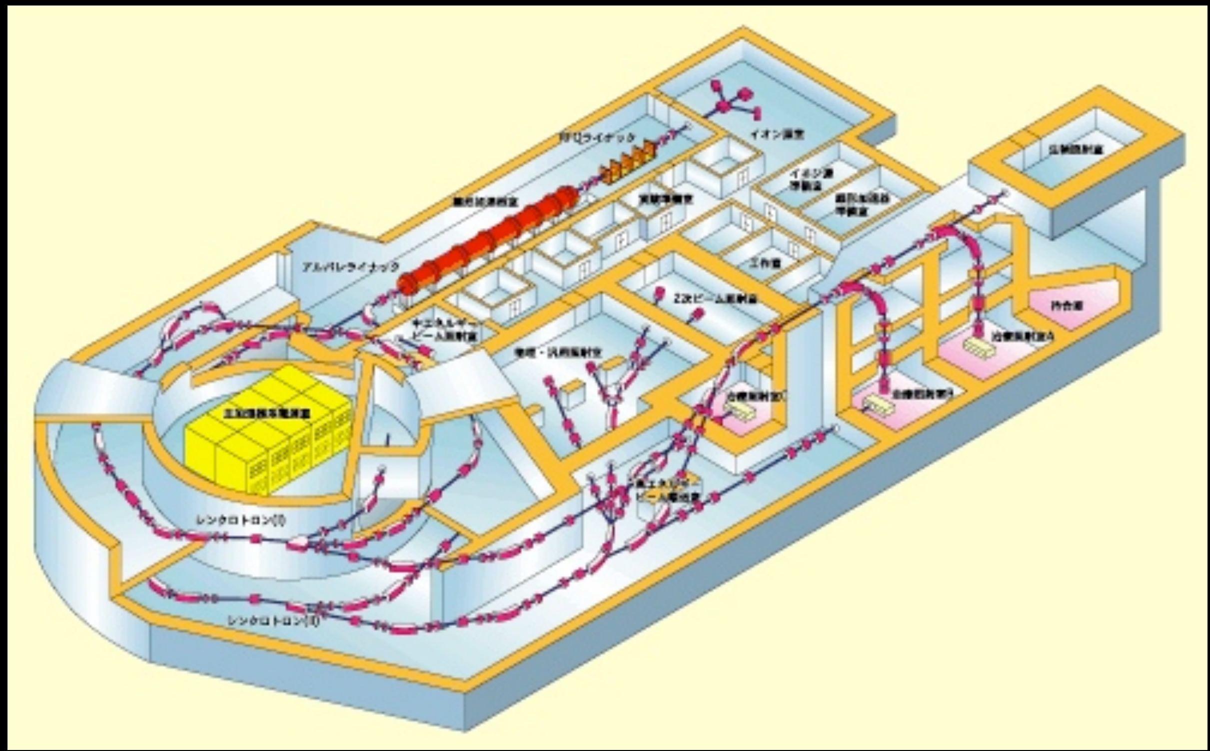


before after 36 months

Treatment at National Inst. of Radiological Sci.

Items to be developed

- Efficient and simple process
- High precision/controllability in vertical direction
- Reduction of footprint



50m x 100m

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Hopeful candidate

Highly Charged Ion beams (HCI beams)

Owing to unique features

- Remarkably high reactivity with materials
- High acceleration efficiency

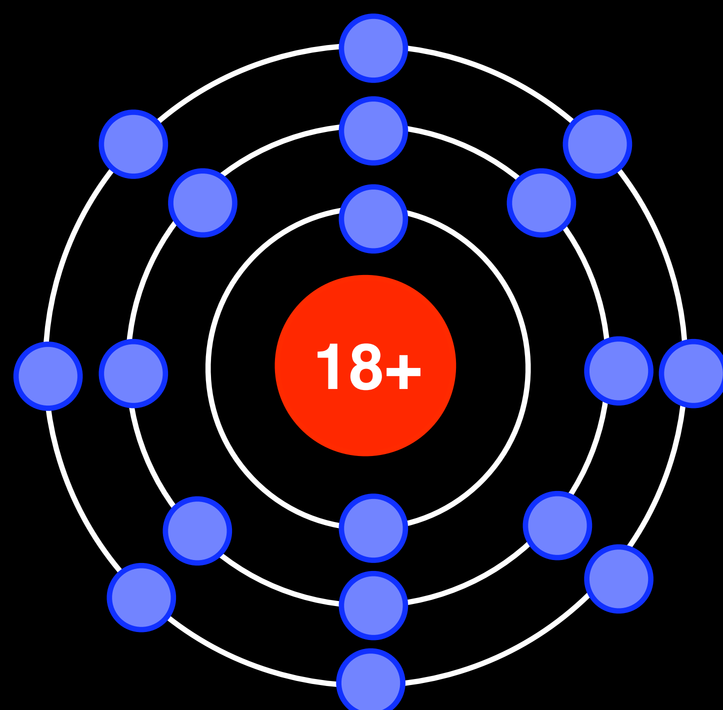
Purpose of this talk

To promote the application of HCI beams

- Prove feasibility of HCI beams
- Produce intense HCI beams

Features of HCI beams

Highly charged ions



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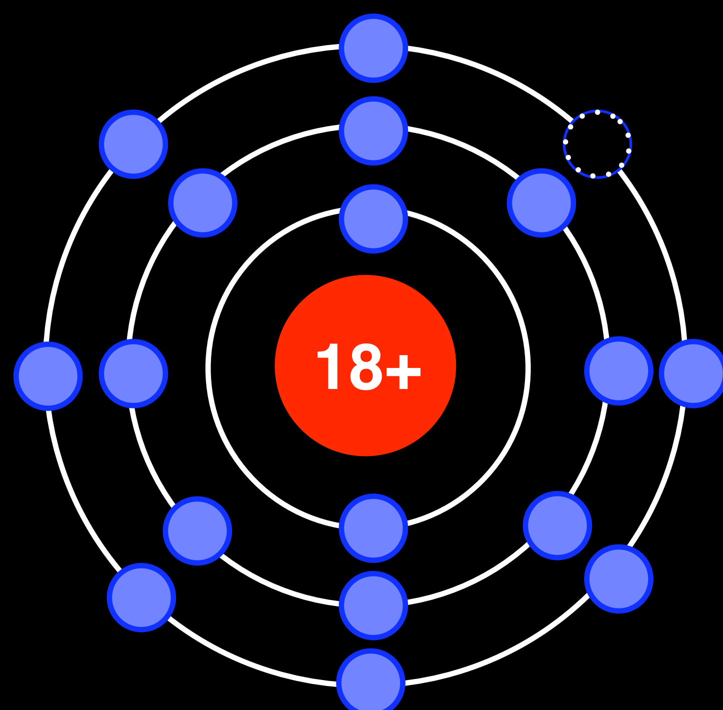
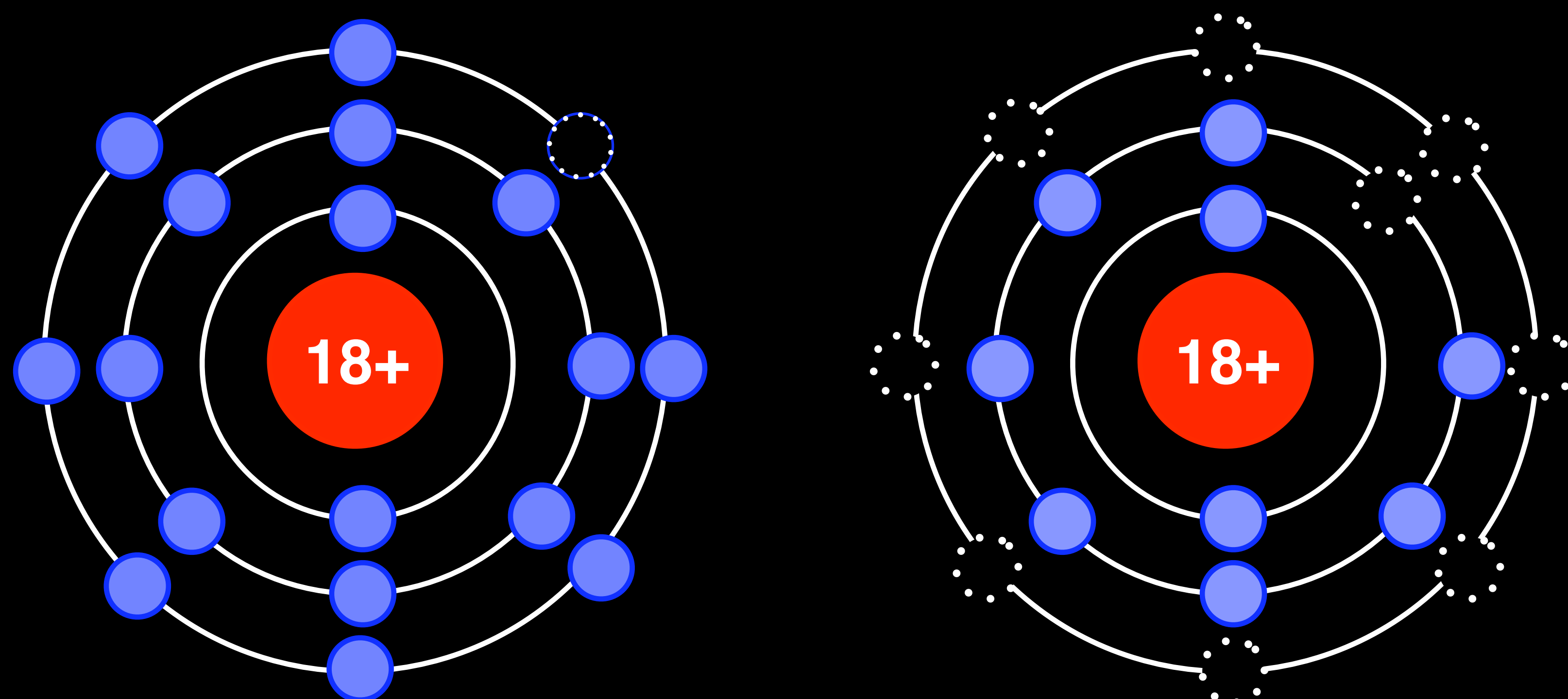
Highly charged ions



Ar^{1+}

Highly charged ions



Ar^{1+} Ar^{9+}

Energy of HCI beams

- Kinetic energy

  $E_{Kin.} = 1/2mv^2$

Energy of HCI beams

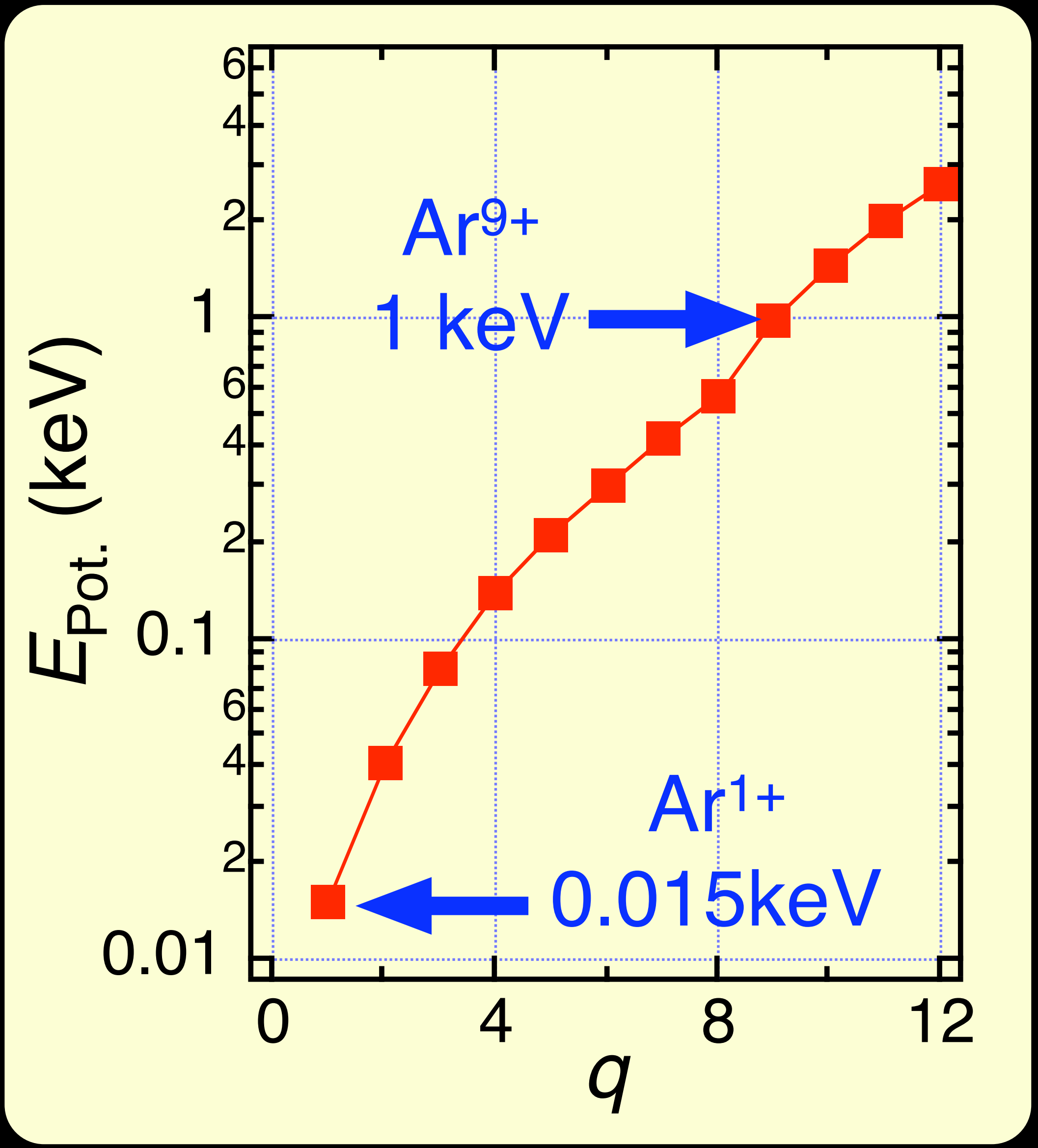
- Kinetic energy

  $E_{Kin.} = 1/2mv^2$

- Potential energy

  $E_{Pot.} \propto q^{2.8}$

$E_{Pot.}$ of Ar ions



http://www.dreebit.com/en/highly_charged_ions/data/

Energy of HCI beams

- Kinetic energy

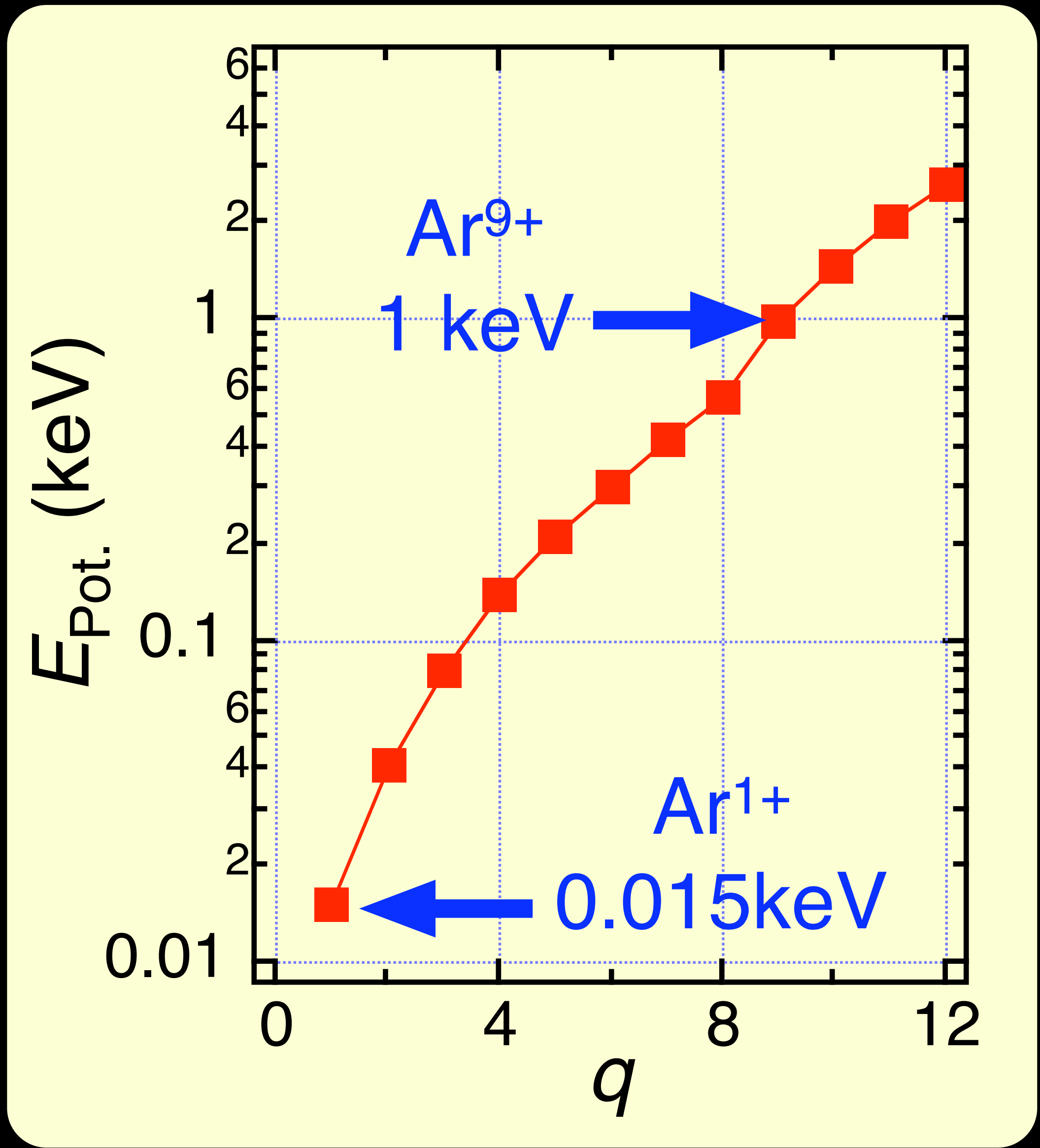
  $E_{Kin.} = 1/2mv^2$

- Potential energy

  $E_{Pot.} \propto q^{2.8}$

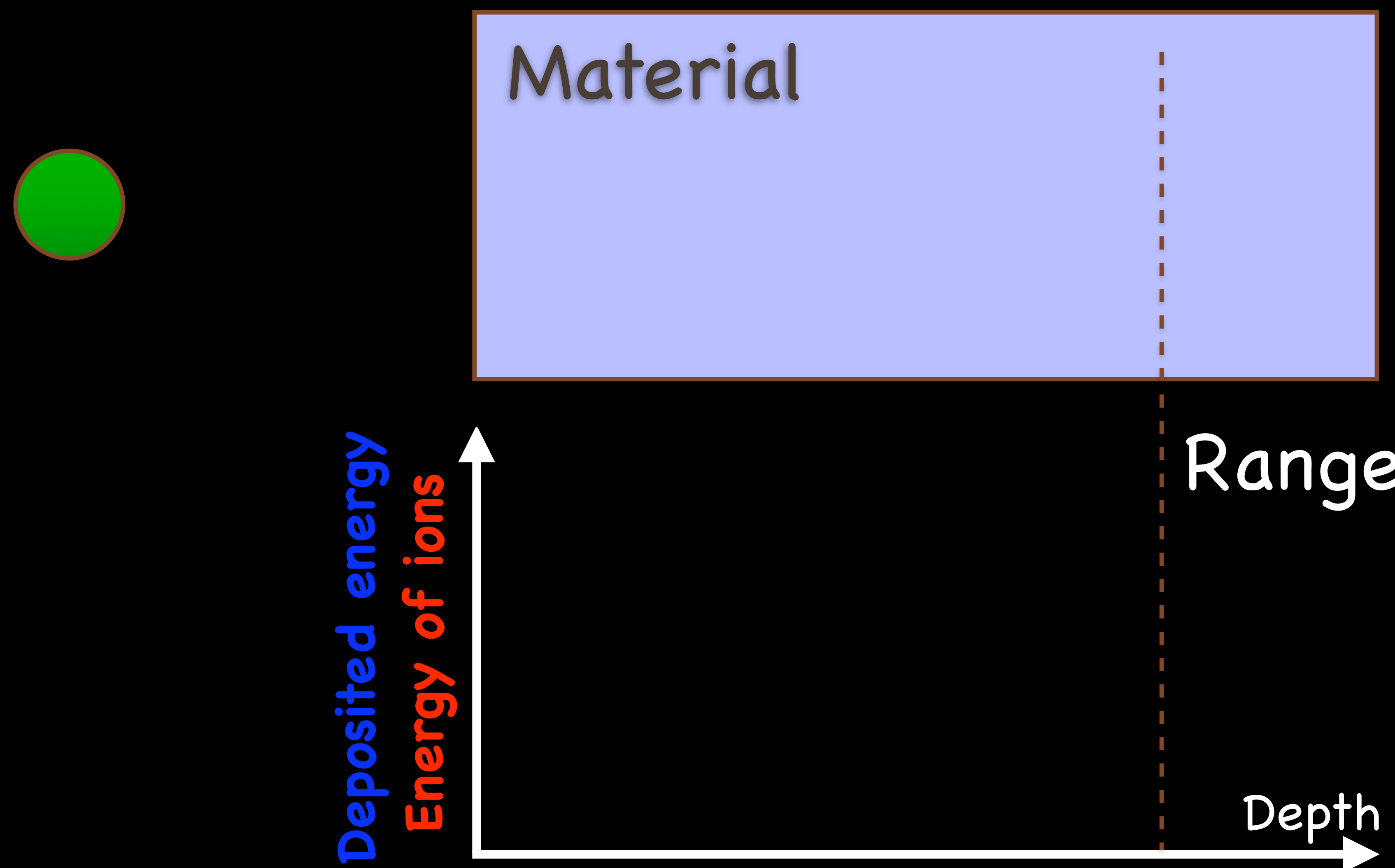
Deposited at surface

$E_{Pot.}$ of Ar ions

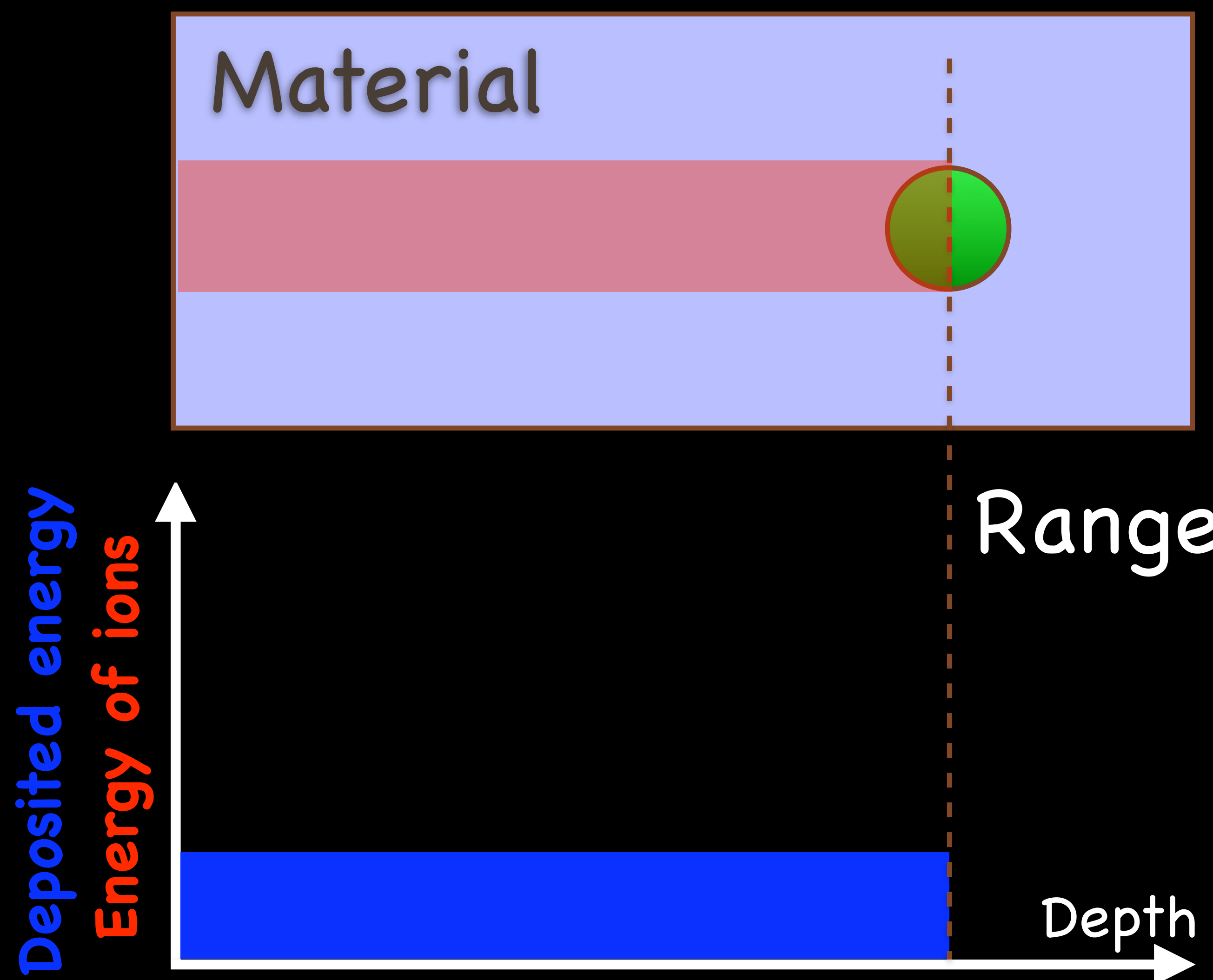


http://www.dreebit.com/en/highly_charged_ions/data/

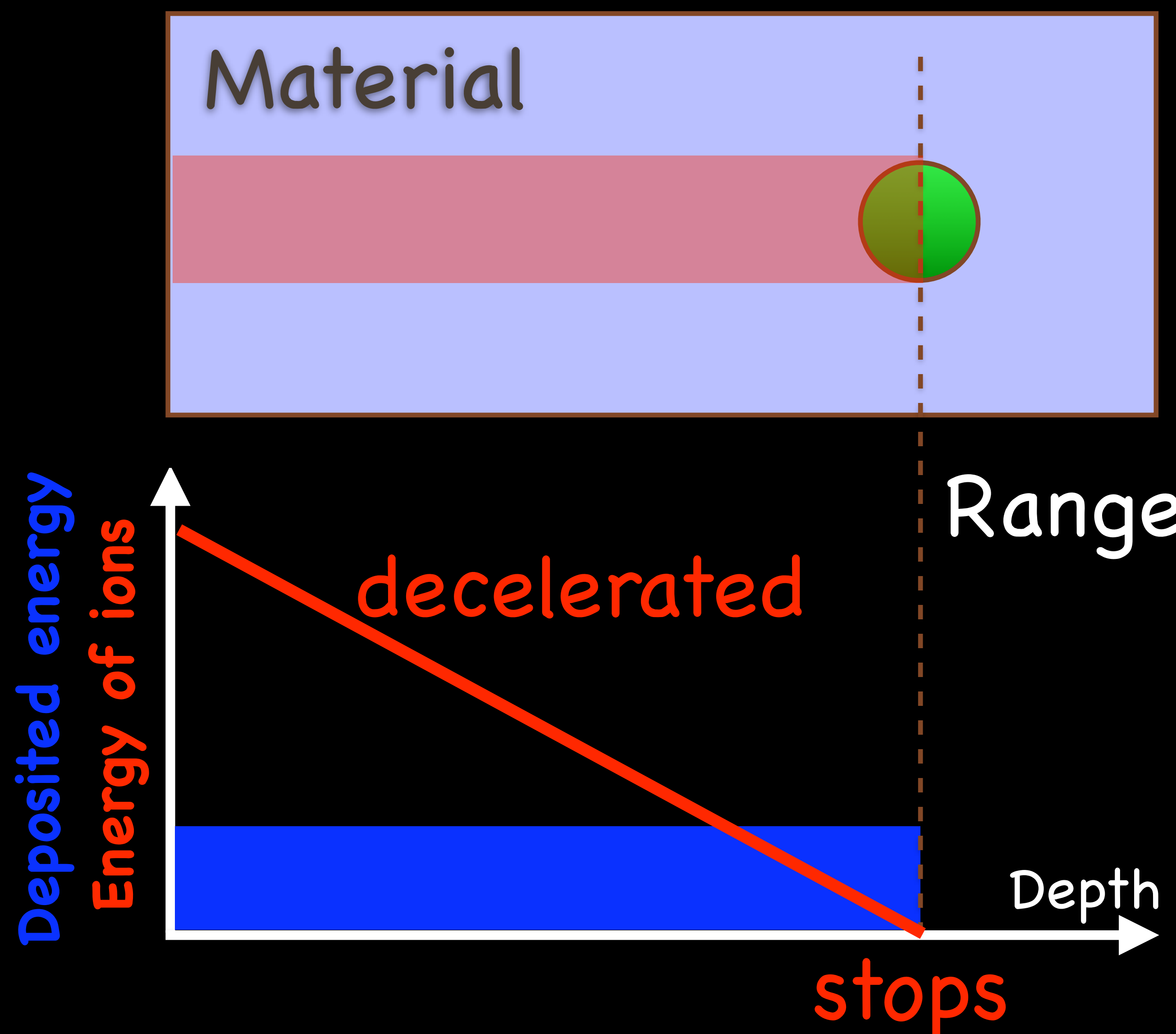
E deposition in materials



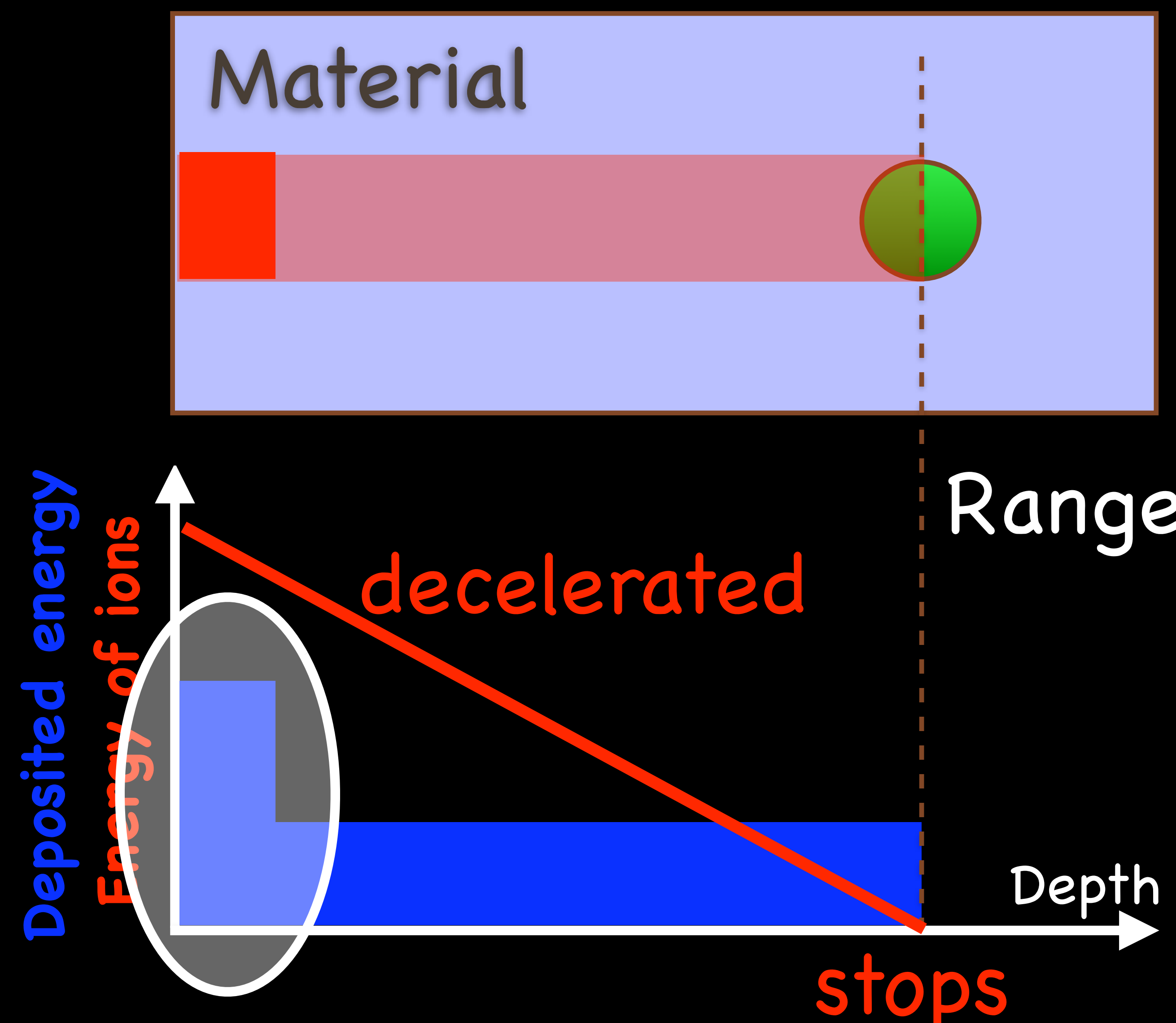
E deposition in materials



E deposition in materials



E deposition in materials



Additional E dep. at surf.

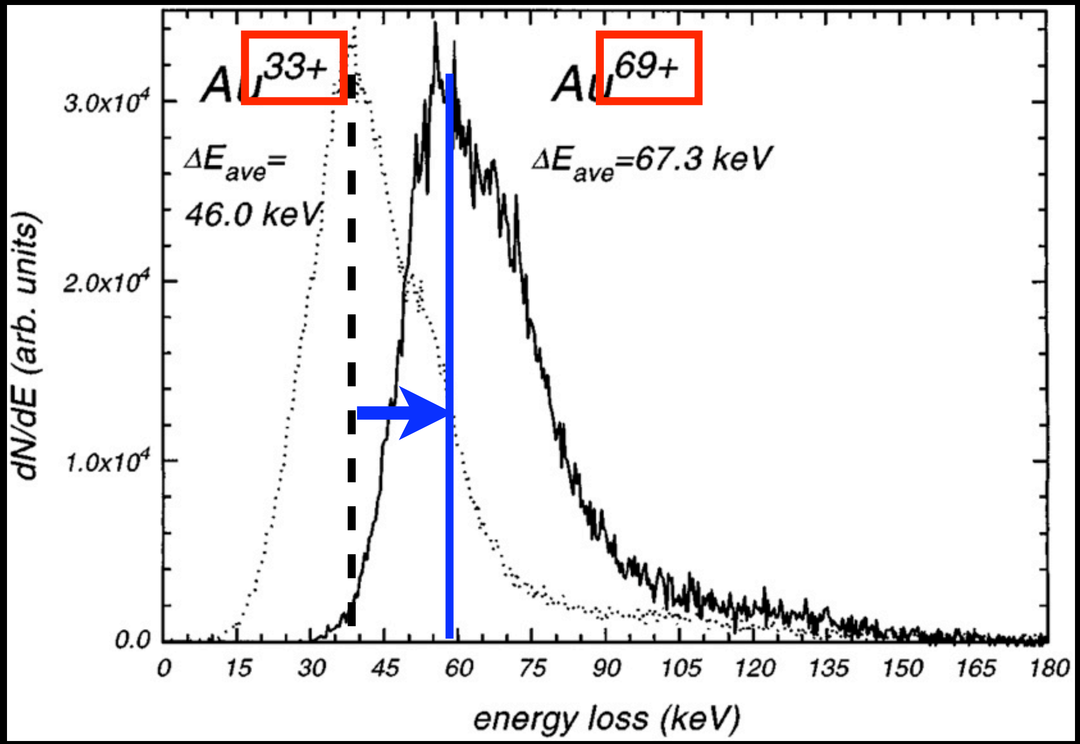
⇒ Enhancement of irr. effect

Unique phenomena induced by HCI beams

- Enhancement of dE
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

  etc.

Enhanced dE of Ar-ions in C foil



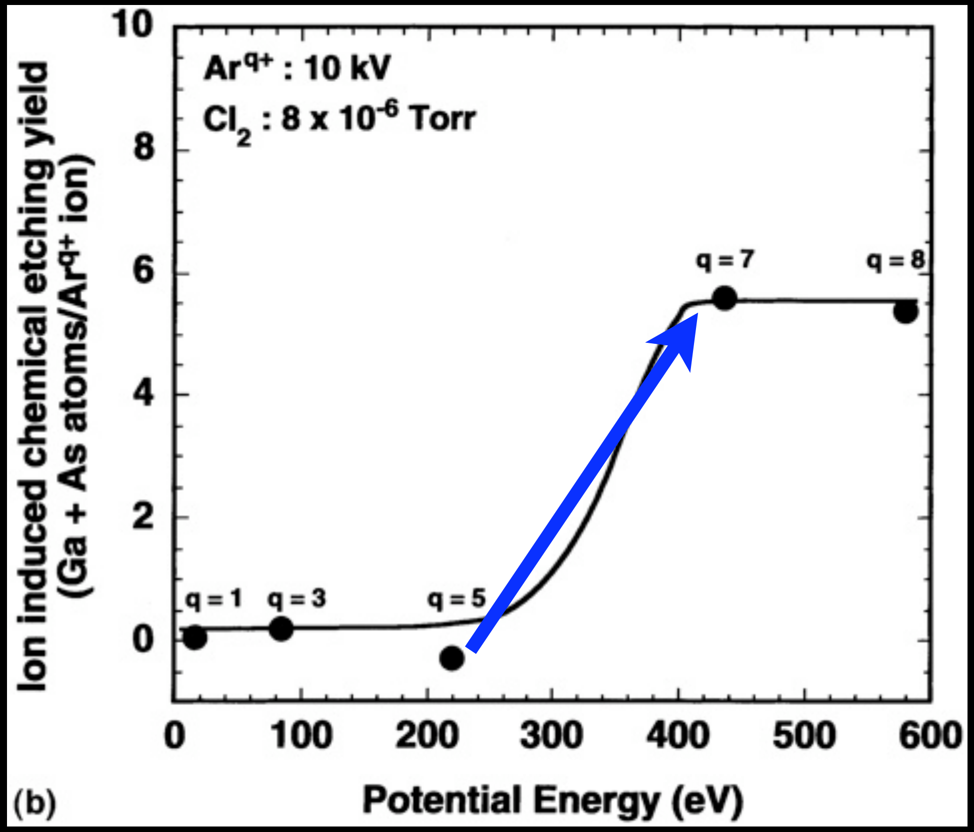
Phys. Rev. Lett. 79 (2000) 2030, T. Schenkel et al.

Unique phenomena induced by HCI beams

- Enhancement of dE
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

etc.

Promoted dry etching rate of GaAs

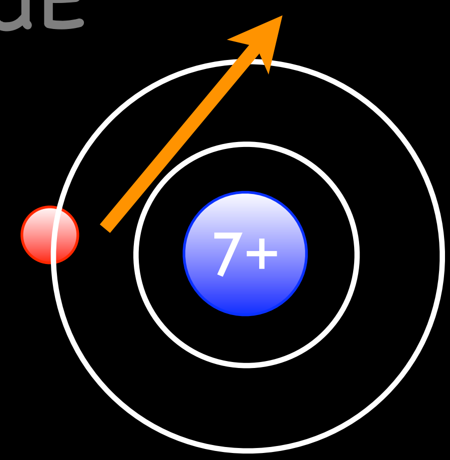


Mat. Sci. Eng. B74 (2000) 40 T. Meguro et al.

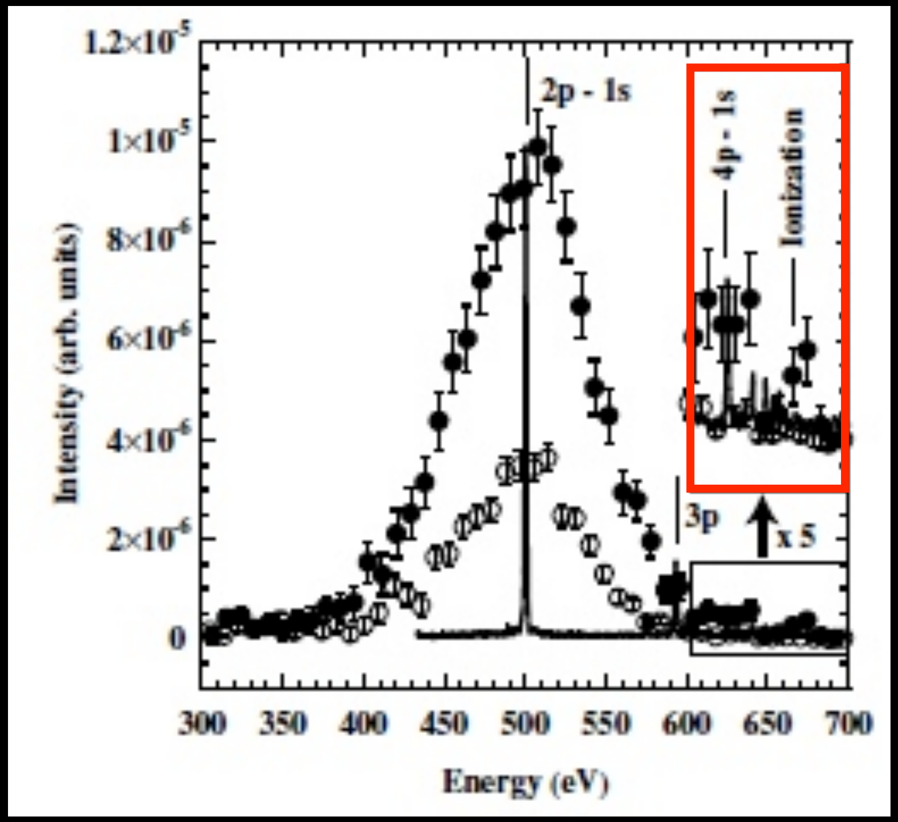
Unique phenomena induced by HCI beams

- Enhancement of dE
- Pot. emission
- **Hollow atom**
- Local modification
- Coulomb explosion

etc.



X-ray from hollow N atom



Nucl Instr. Meth. B 235 (2005) 468, Y. Iwai et al.

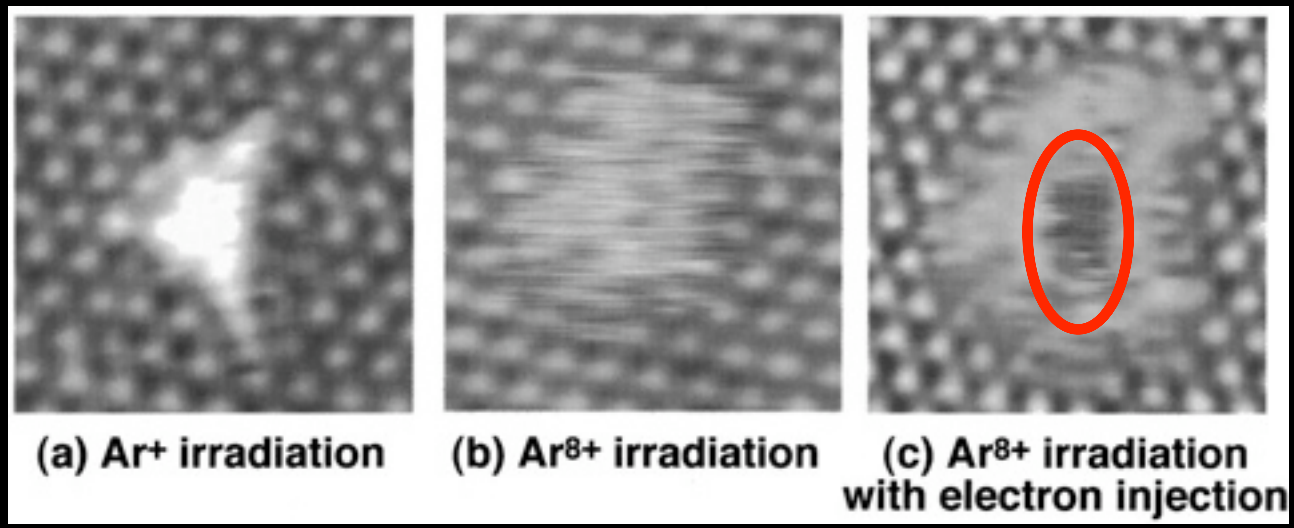
Unique phenomena induced by HCI beams

- Enhancement of dE
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

  etc.

Nano-diamonds created in HOPG

sp_2 -> sp_3



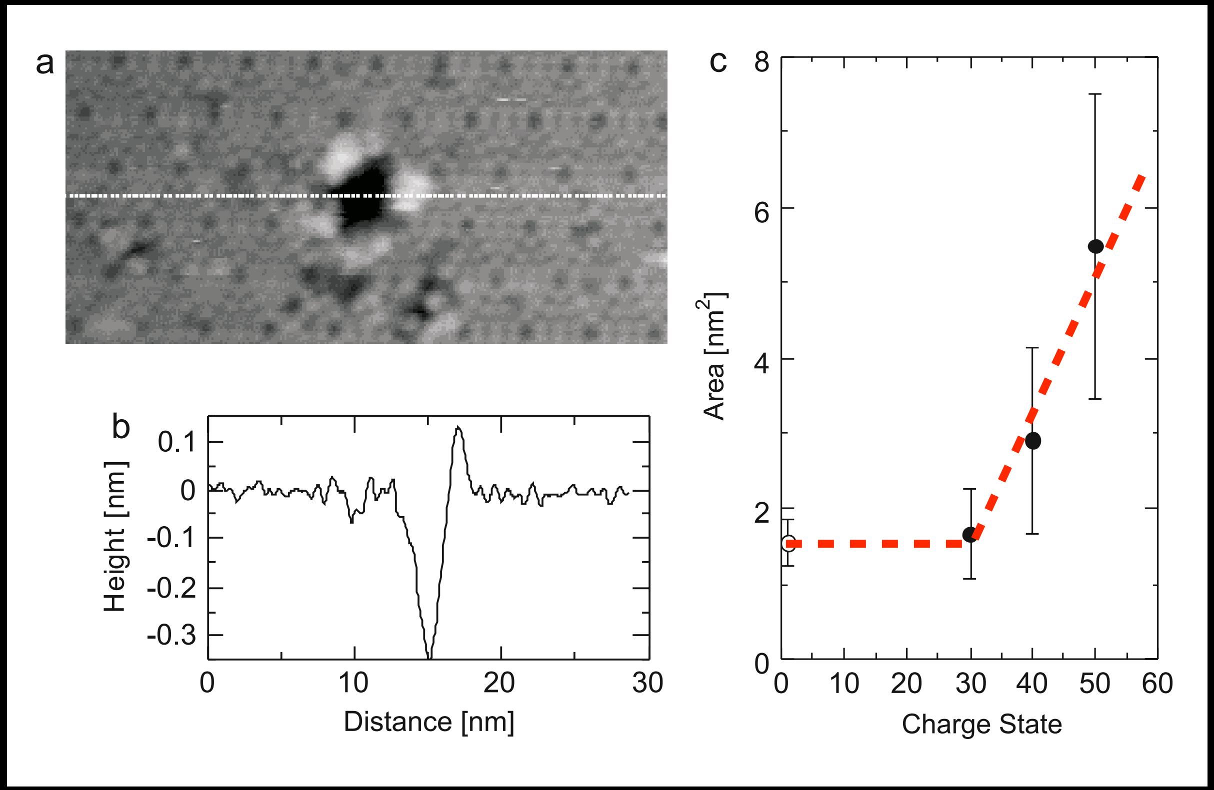
Appl. Phys. Lett. 79 (2001) pp. 3866, T. Meguro et al.

Unique phenomena induced by HCI beams

- Enhancement of dE
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

  etc.

Coulomb explosion of Si-surface



Surf. Sci. , 601 (2007) pp.723-727, M. Tona et al.

High acceleration eff.

- Enhancement according to charge state

$$E = qeV$$

High acceleration eff.

- Enhancement according to charge state

$$E = qeV$$

Ex. $^{40}Ar^{q+}$ on Si, V=100 kV

q	E (keV)	Range (nm)
1+	100	~100
10+	1000	~1000

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Reduction of footprint

NIRS facility 50m x 100m
1994-

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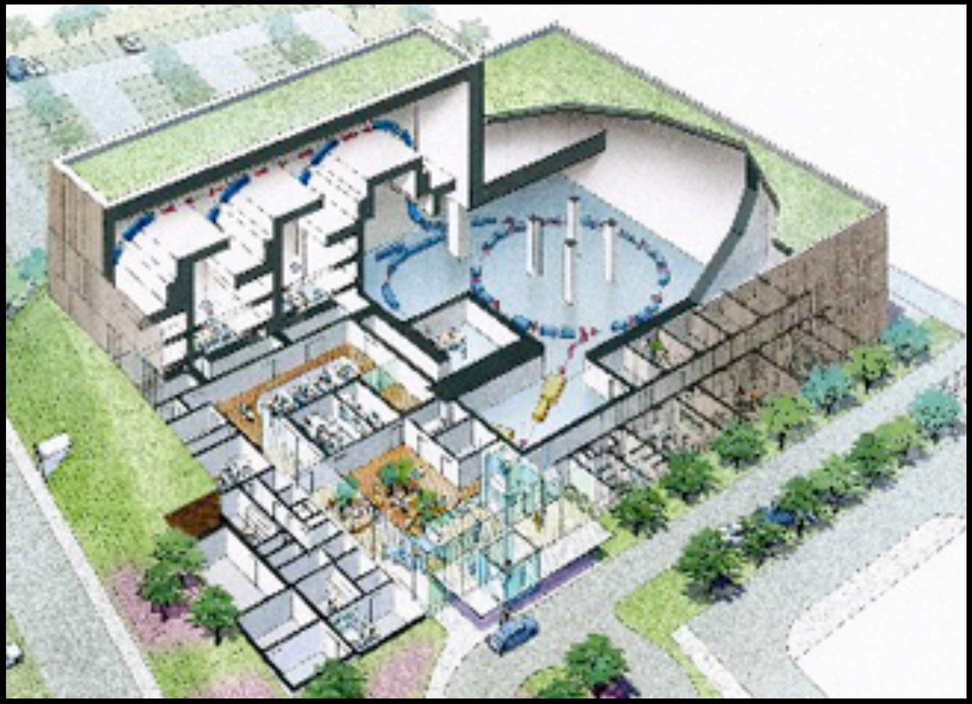
Reduction of footprint

NIRS facility 50m x 100m
1994-

↓

Gunma Univ. 45m x 65m
HI medical center
Mar./16/2010-



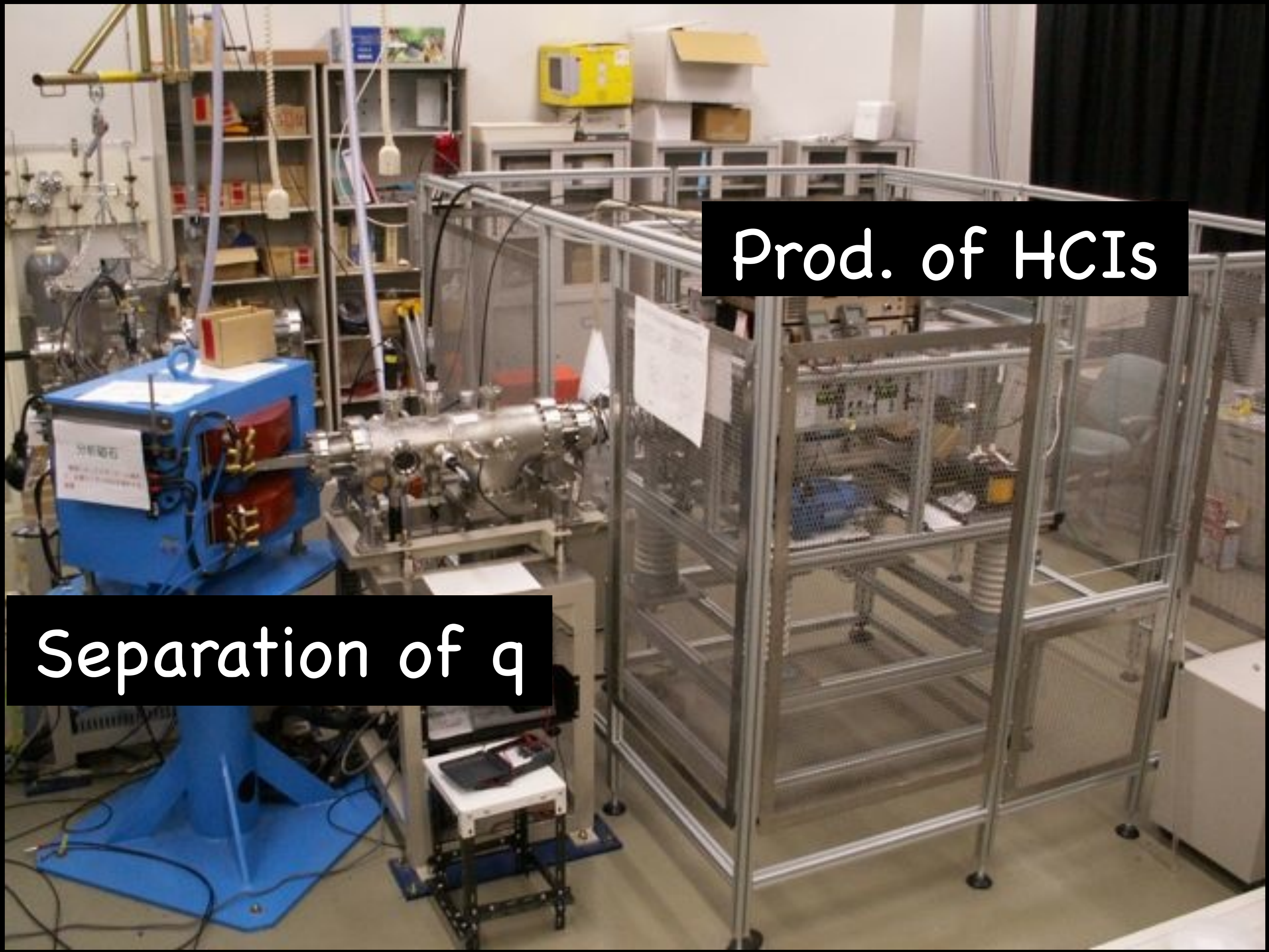
Feasibility of HCI beams

1. High irr. effect
2. High acceleration eff.

- Efficient and simple process
- High precision/ controllability in vertical direction
- Reduction of footprint

Experimental results

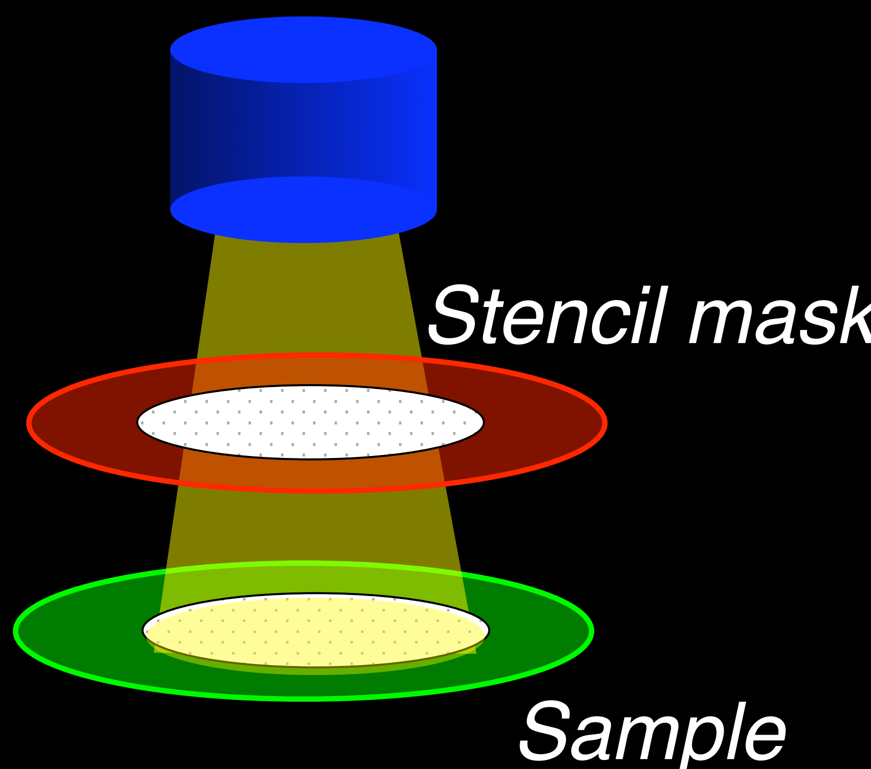
HCI beam facility

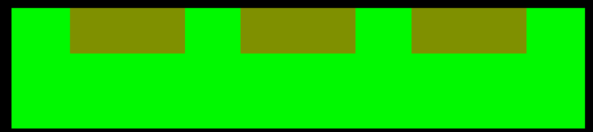


Rev.Sci.Instr. 75(2004) pp. 1497, S. Momota et al.

Procedure

- Irr. of Ar-beam
  modification of chemical structure
- Etching by BHF/HF
  Difference in etching rate





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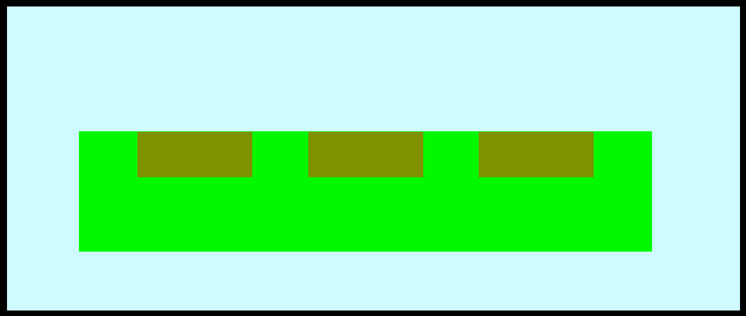

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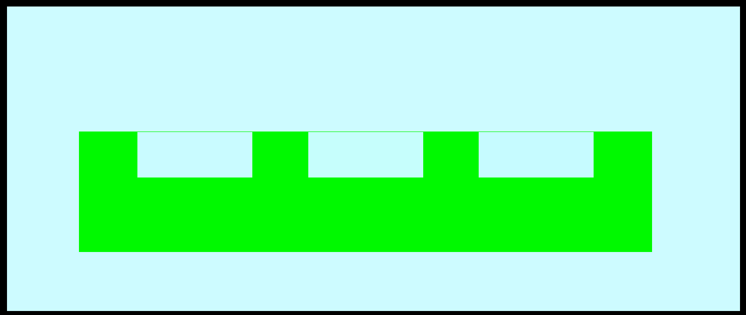
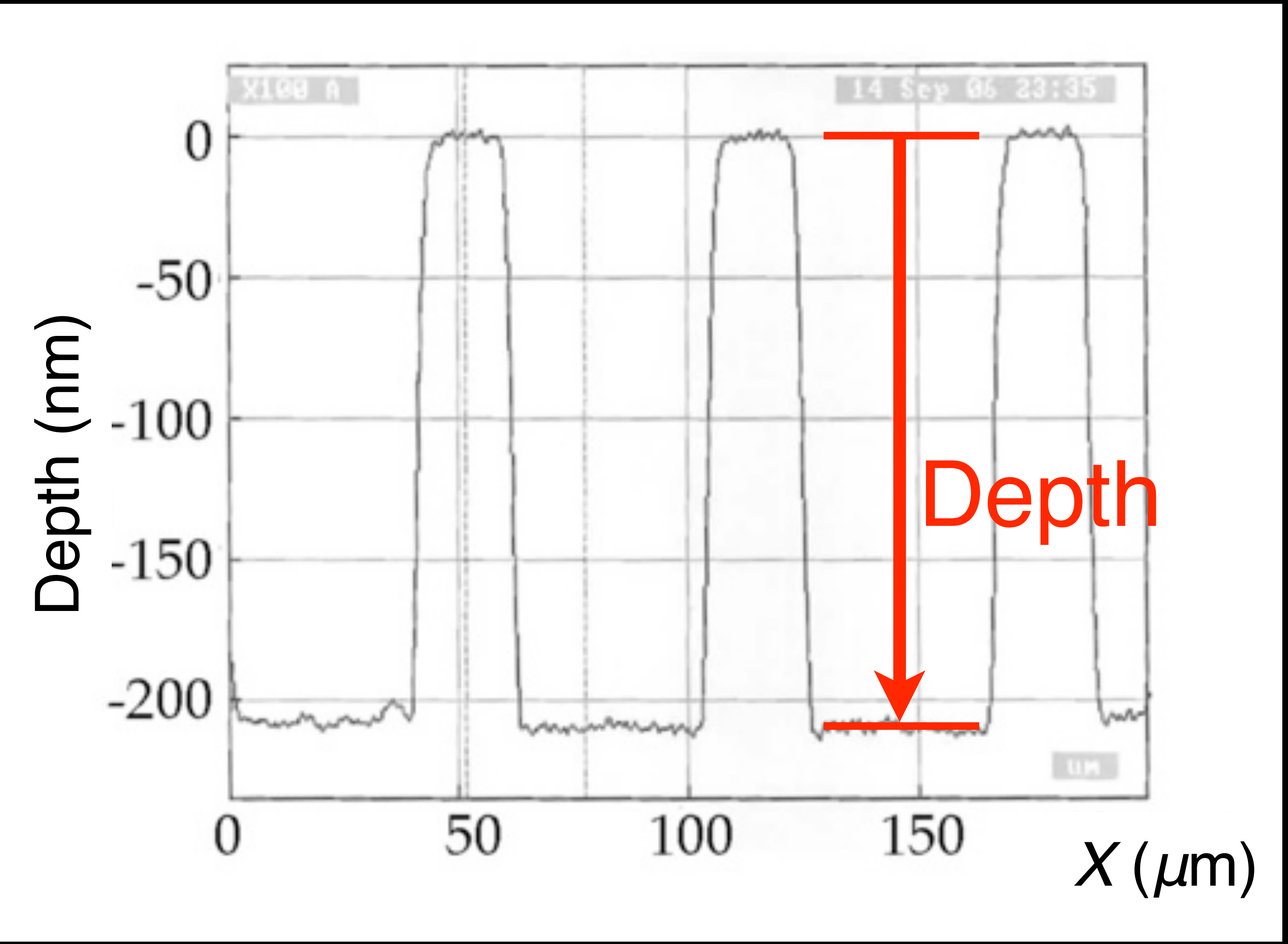


In case of SOG

- Irradiation of Ar^{q+}
  - q = +1~9
  - 90 keV
  - Cu-Mask (43×43 μm)
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

Surface profile



observed by Alpha step

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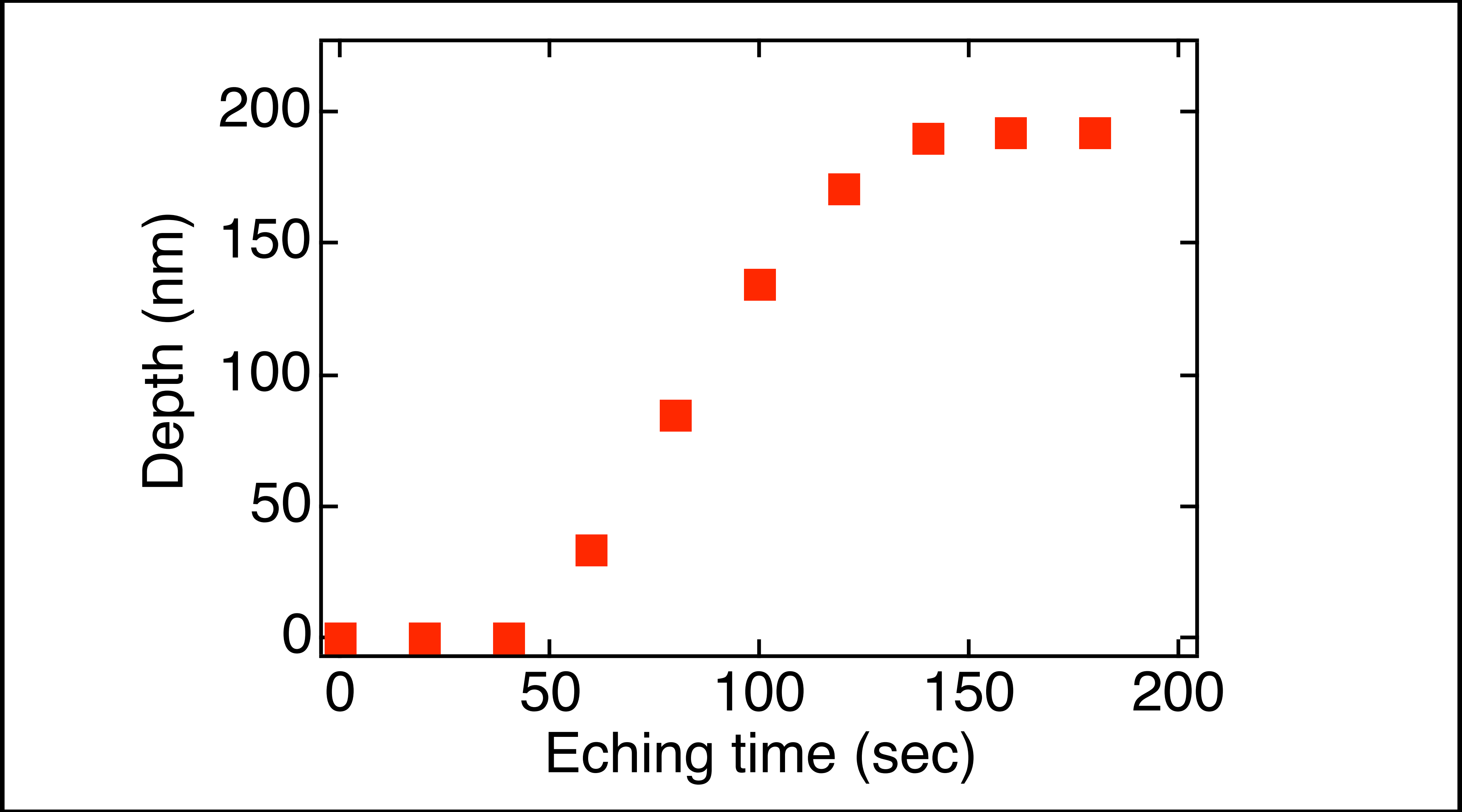
Etching process of SOG

- Ar^{1+}: 90 keV, 6.3×10^{13} ions/cm^2



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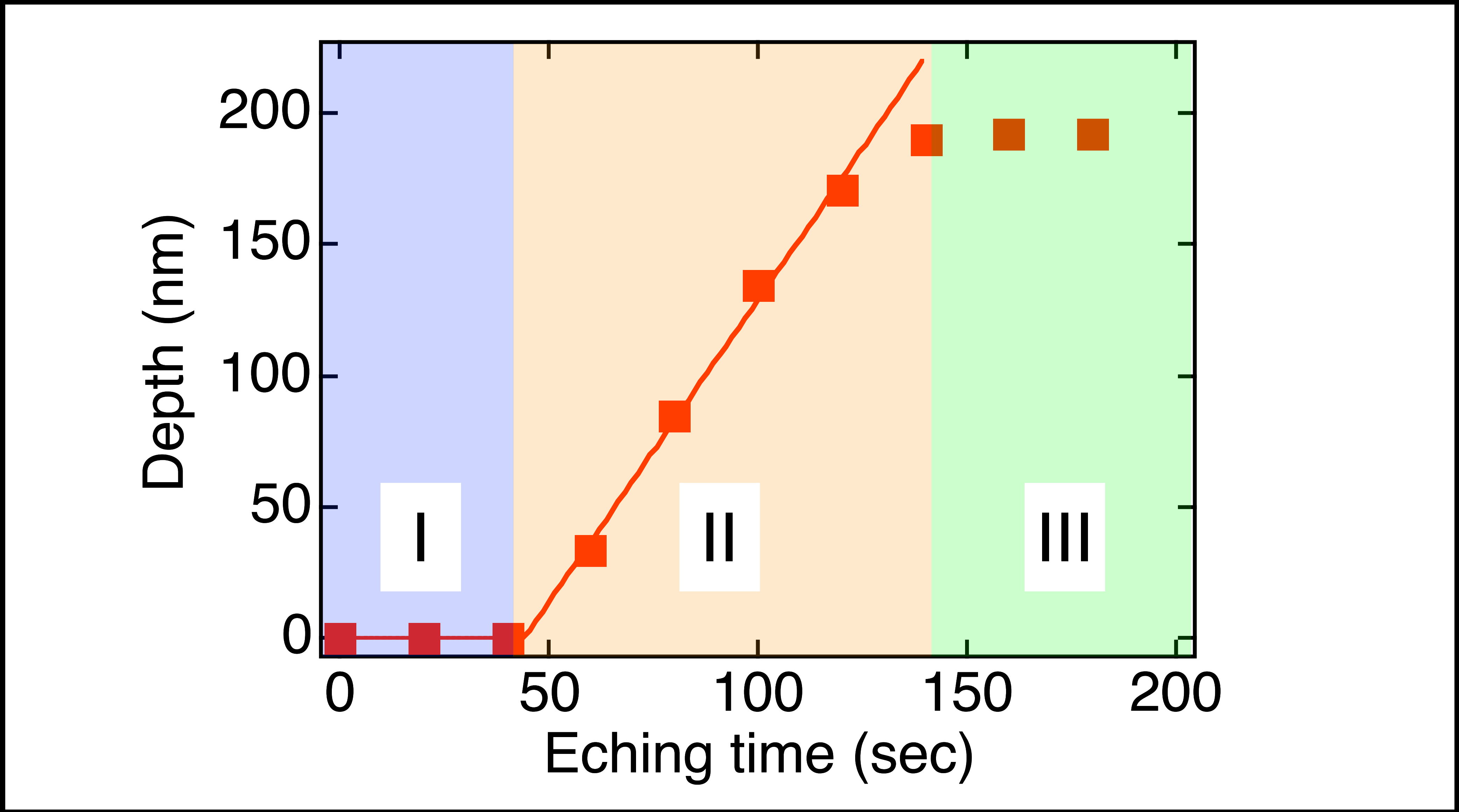

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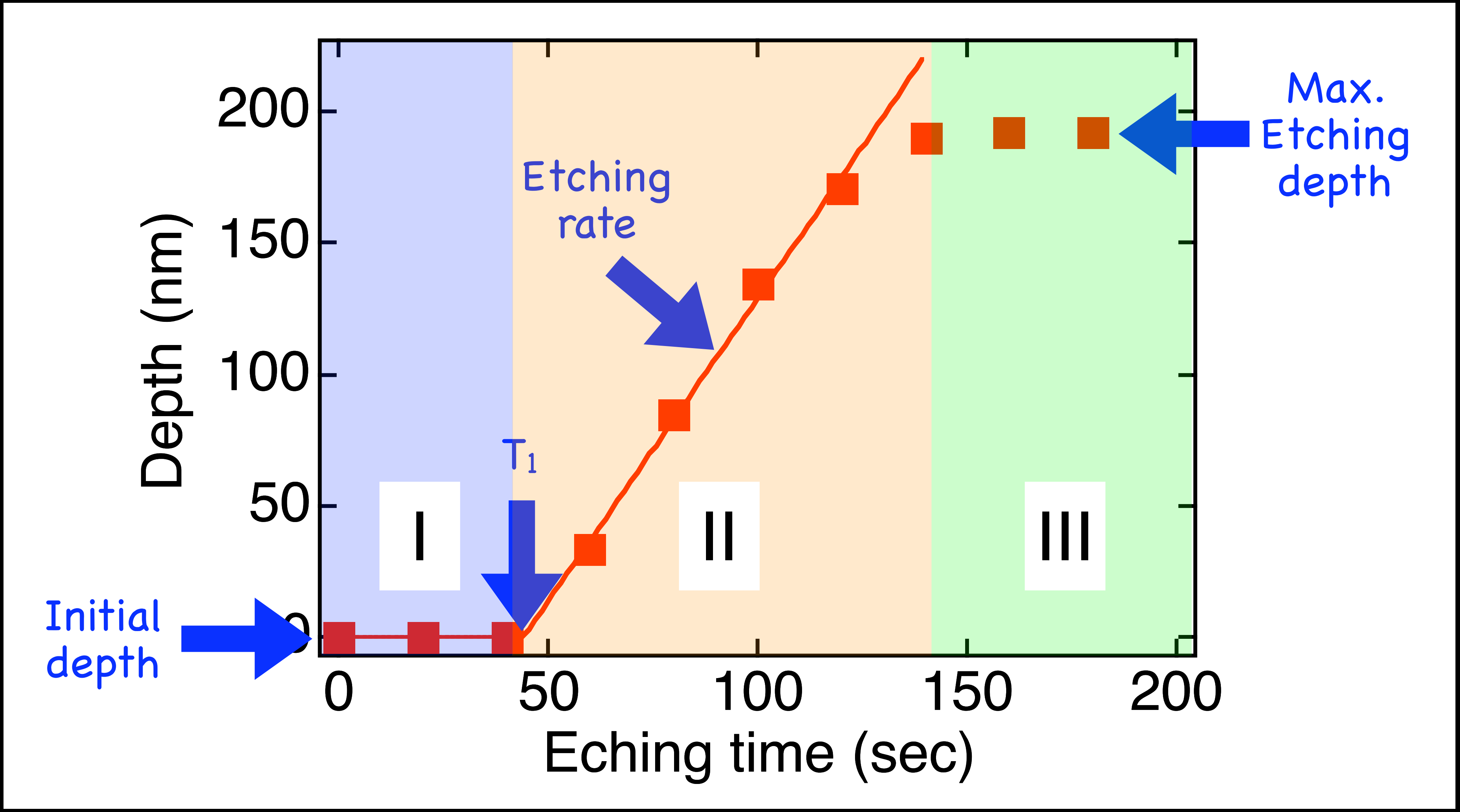
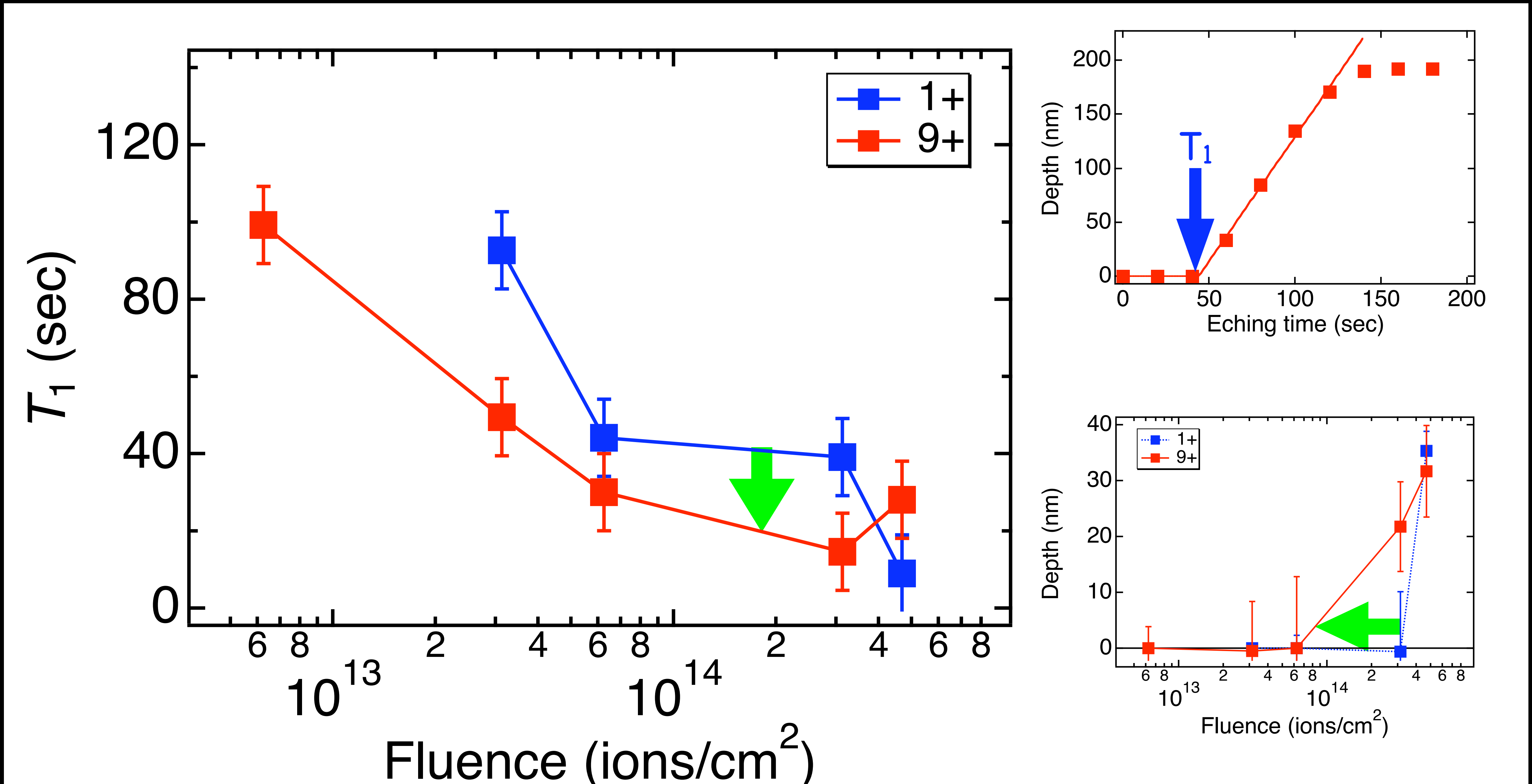


T_1 of SOG

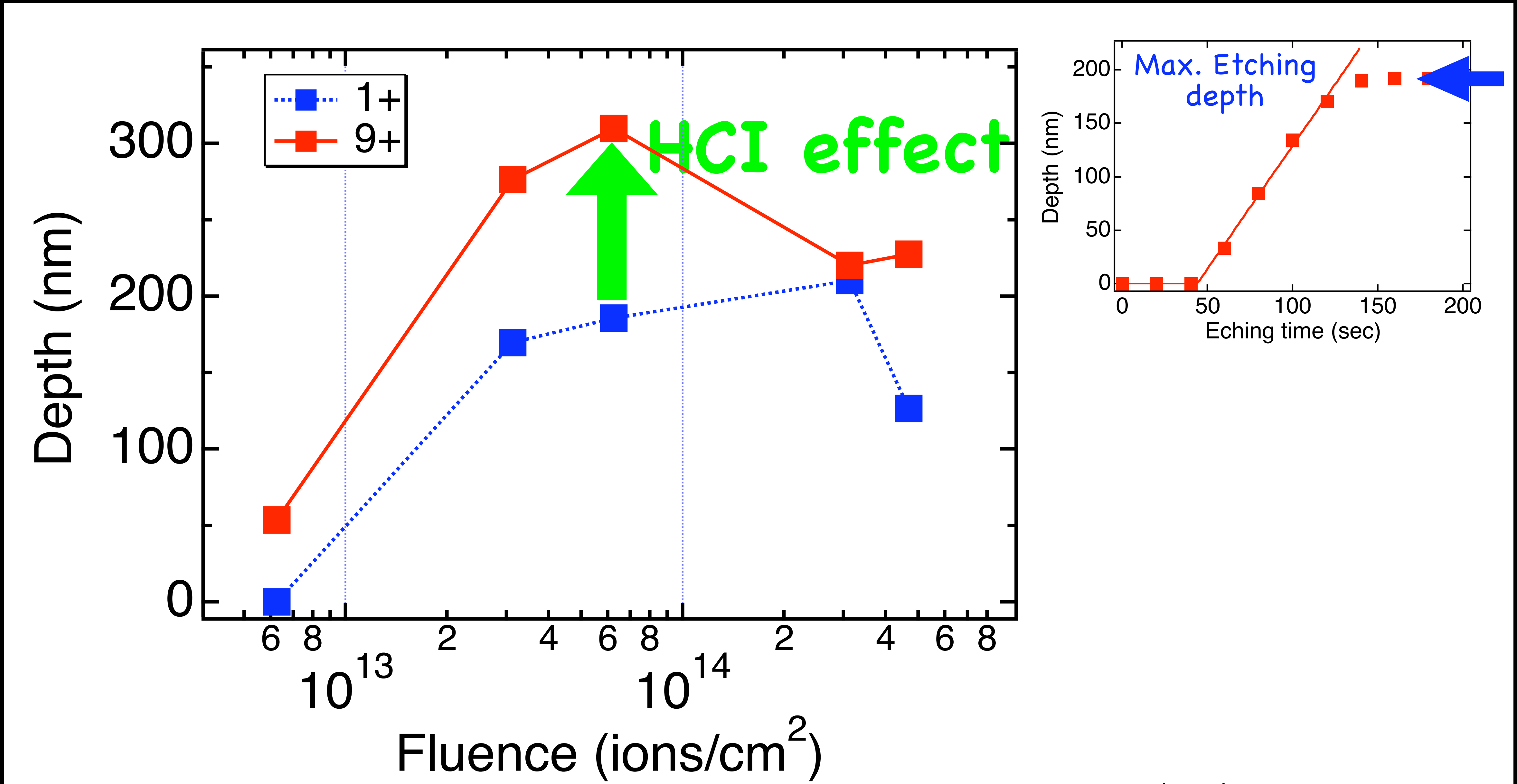
- $Ar^{1+,9+}$, E = 90 keV



Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

Max. Etching depth of SOG

- $Ar^{1+,9+}$, E = 90 keV



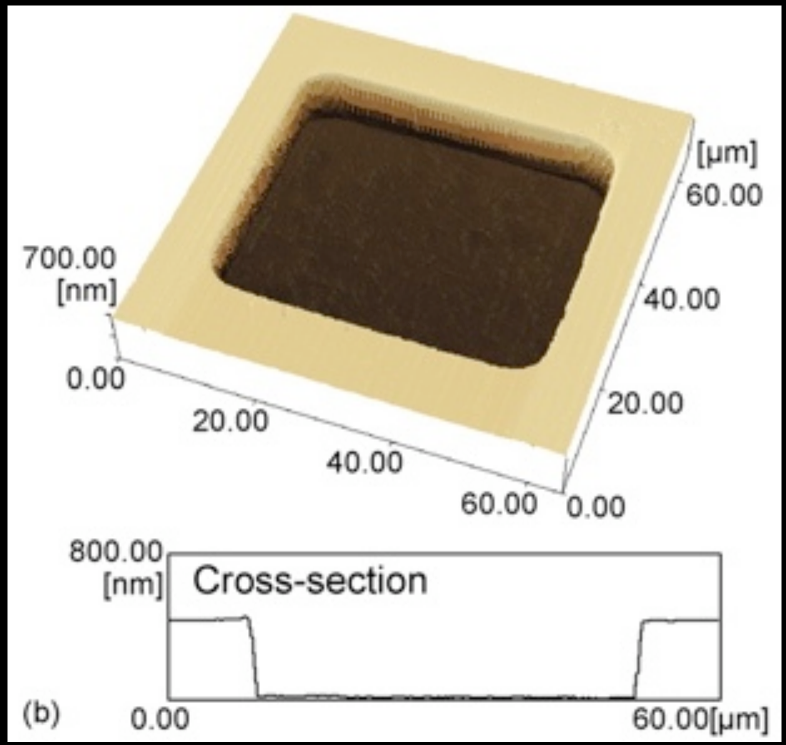
Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

In case of Si

- Irradiation of Ar^{q+}
  - q = +1~9
  - V = 60 kV
    E = 60~540 keV
  - Cu-Mask (43×43 µm)
- Etching
  - 46mass% HF
- Surface profile
  - AFM

Ar^{4+}

240 keV, 1.3×10^{15} ions/cm^2

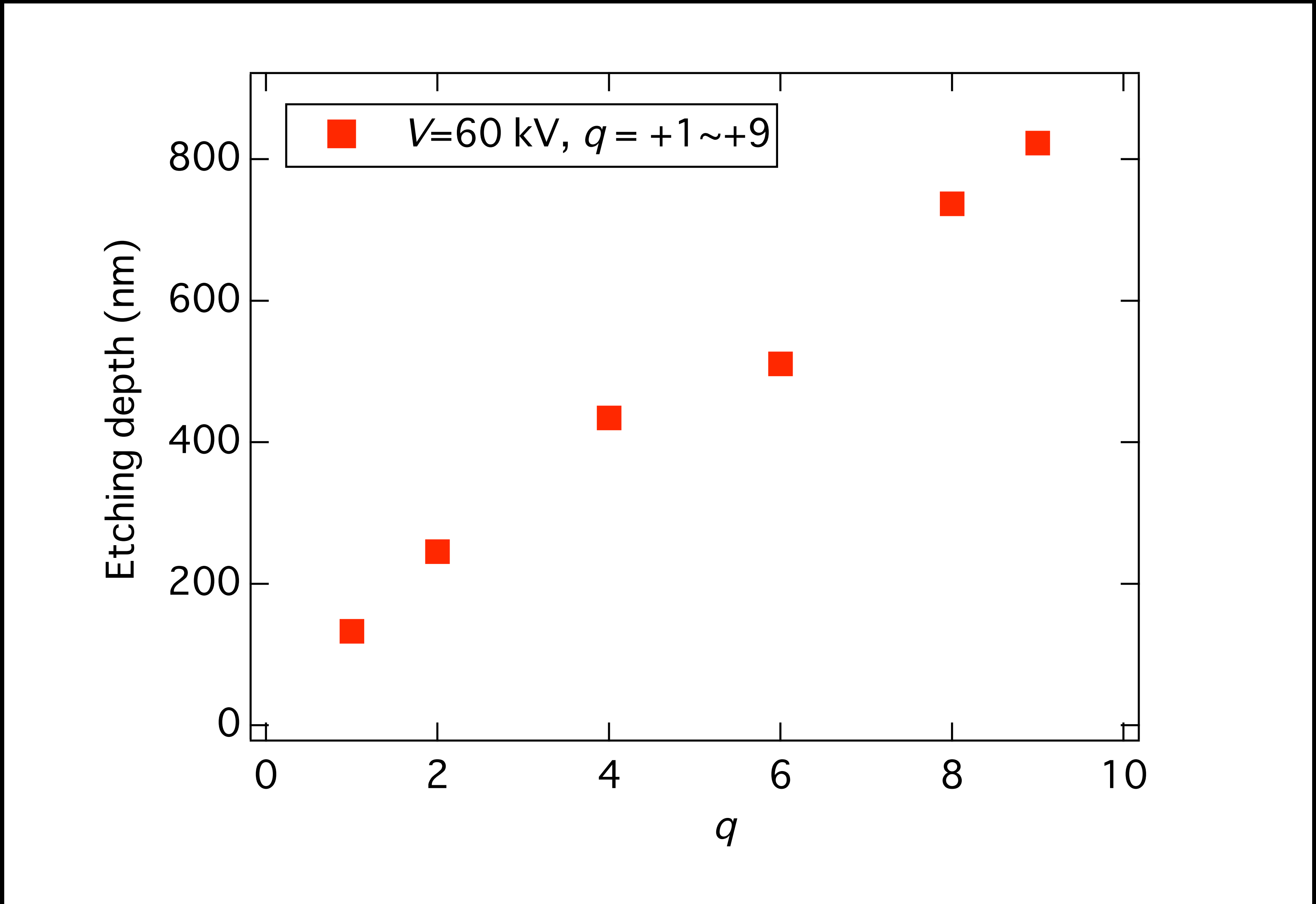


$T_{etch.}$ = 120 min.

Appl. Surf. Sci. 253 (2007) pp. 3284, N. Kawasegi et al.

Etching depth of Si

- $Ar^{1\sim9+}$ on Si



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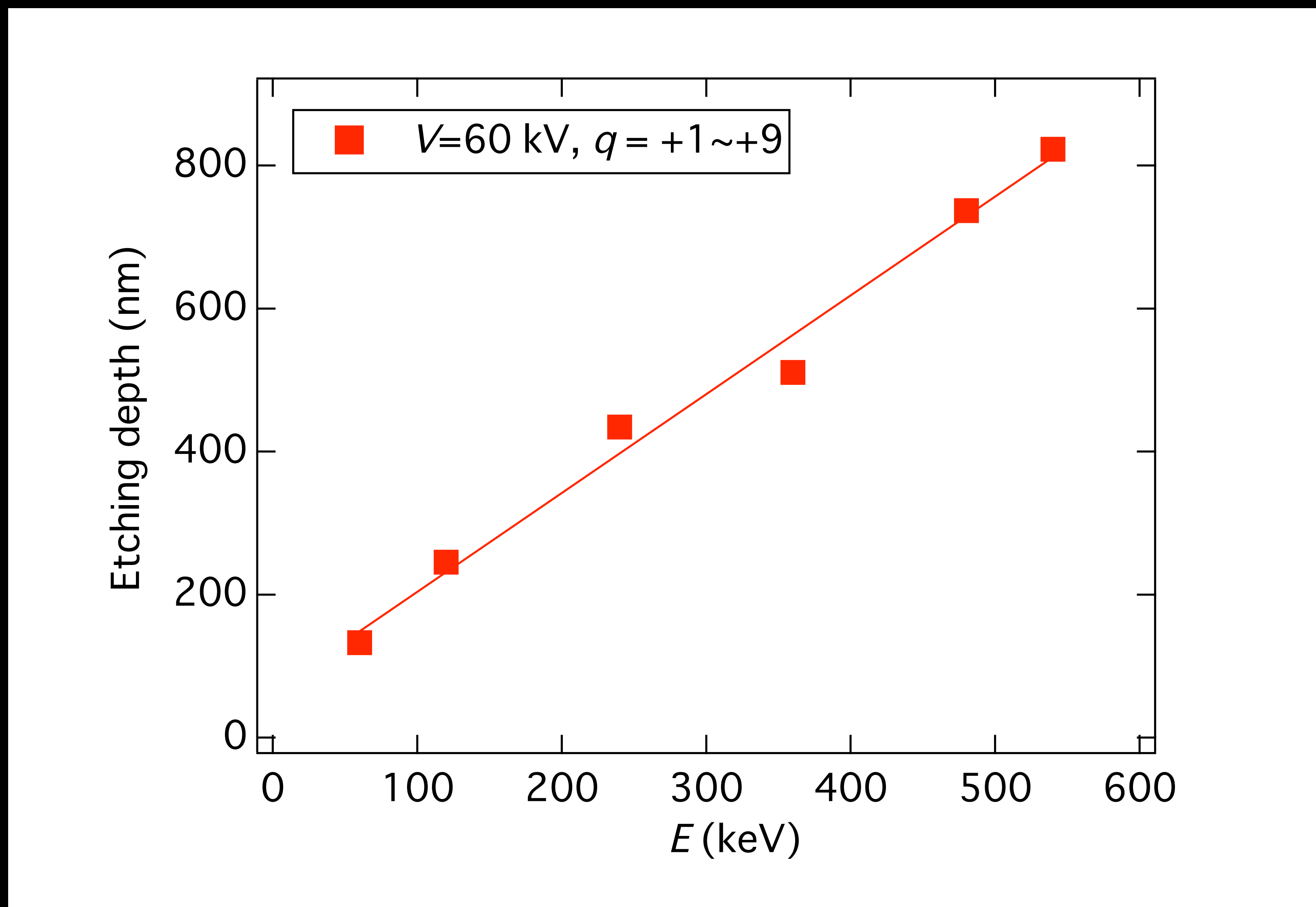

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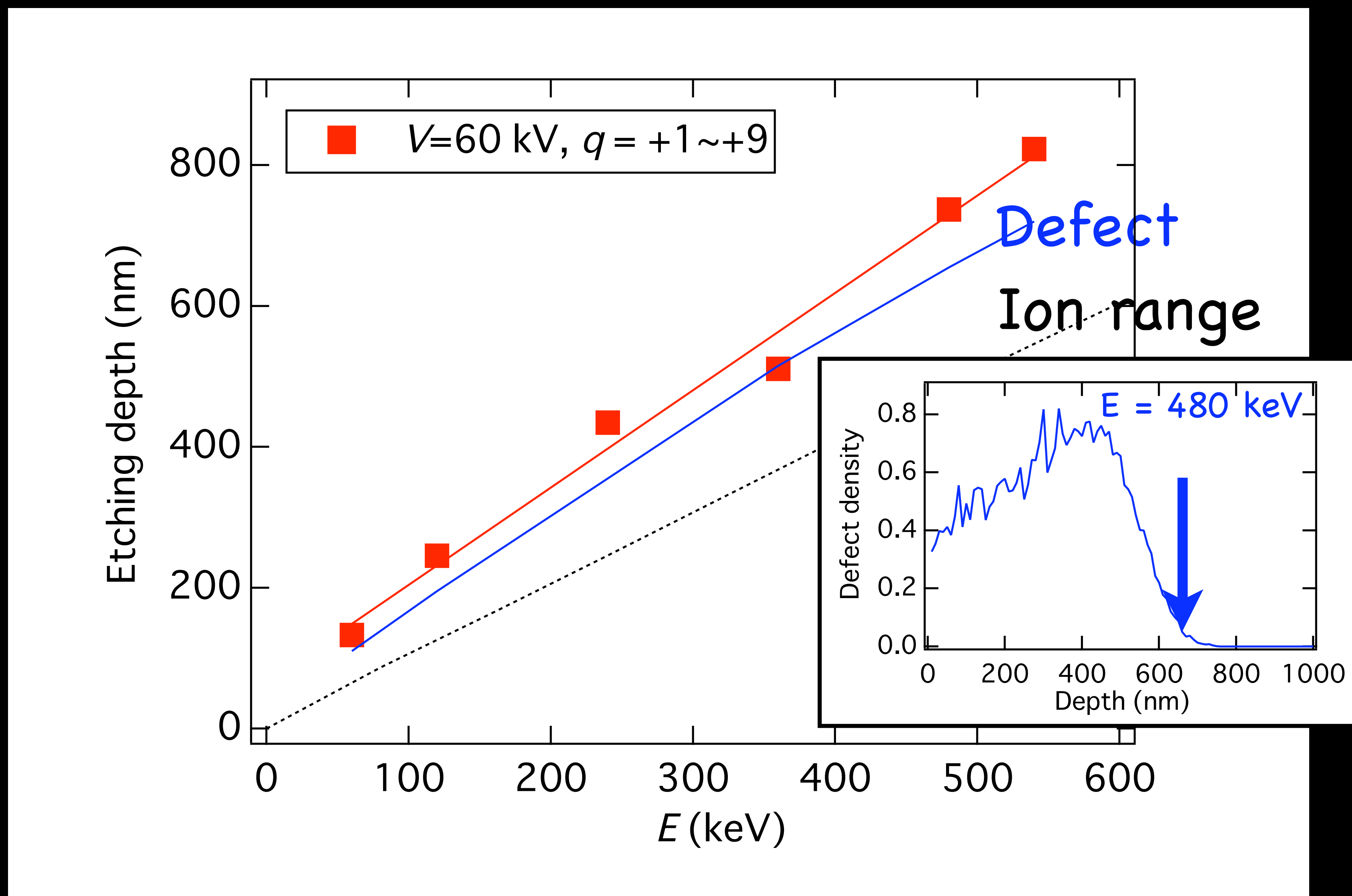
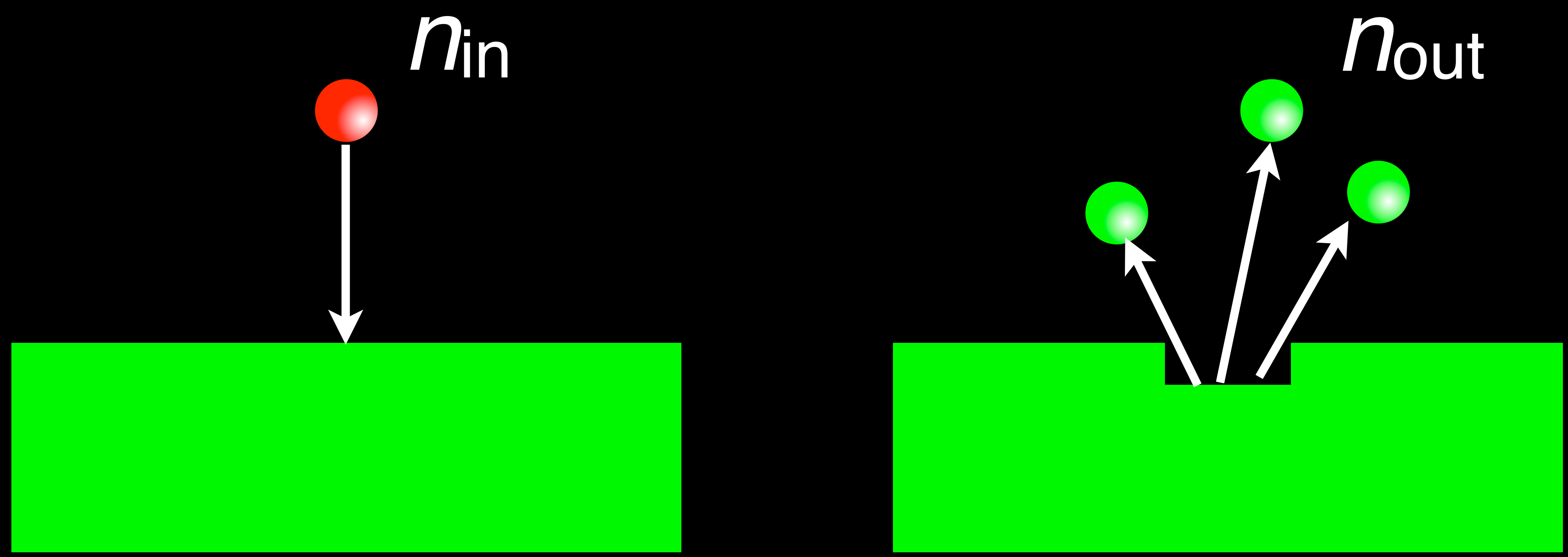


Sputtering rate



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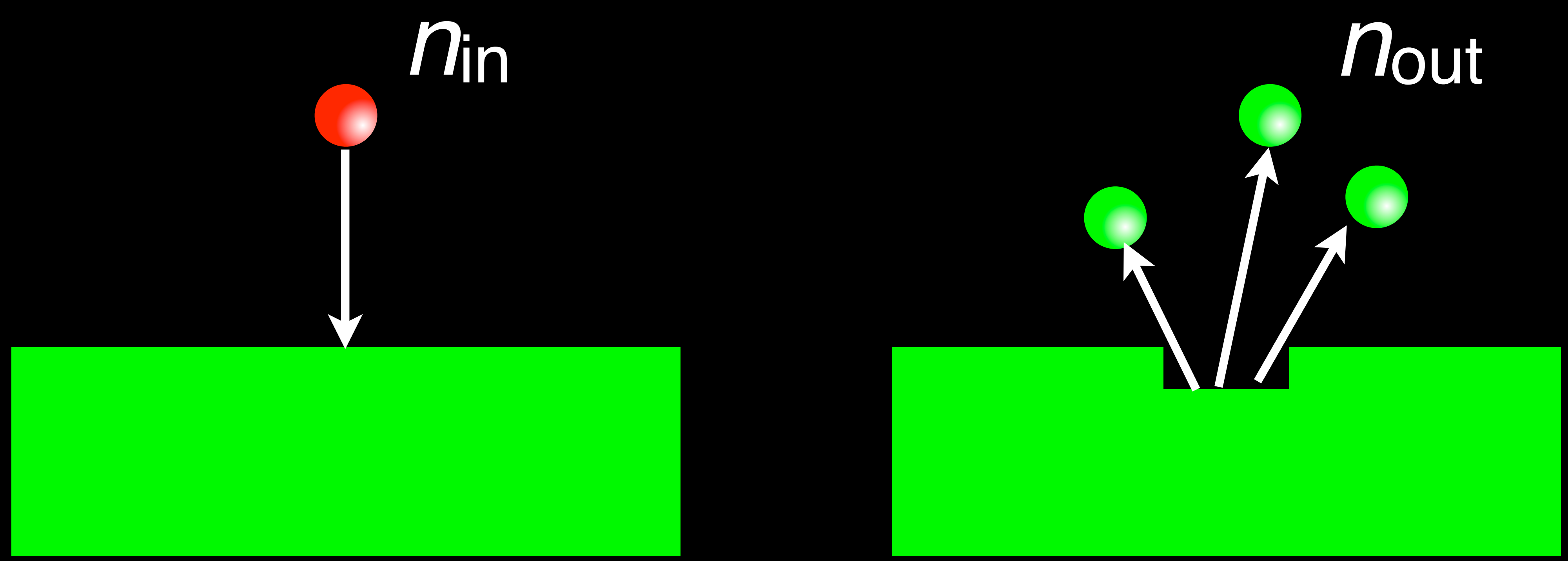


$$S = \frac{\text{Emitted atoms}}{\text{Irradiated ions}} = \frac{n_{out}}{n_{in}}$$

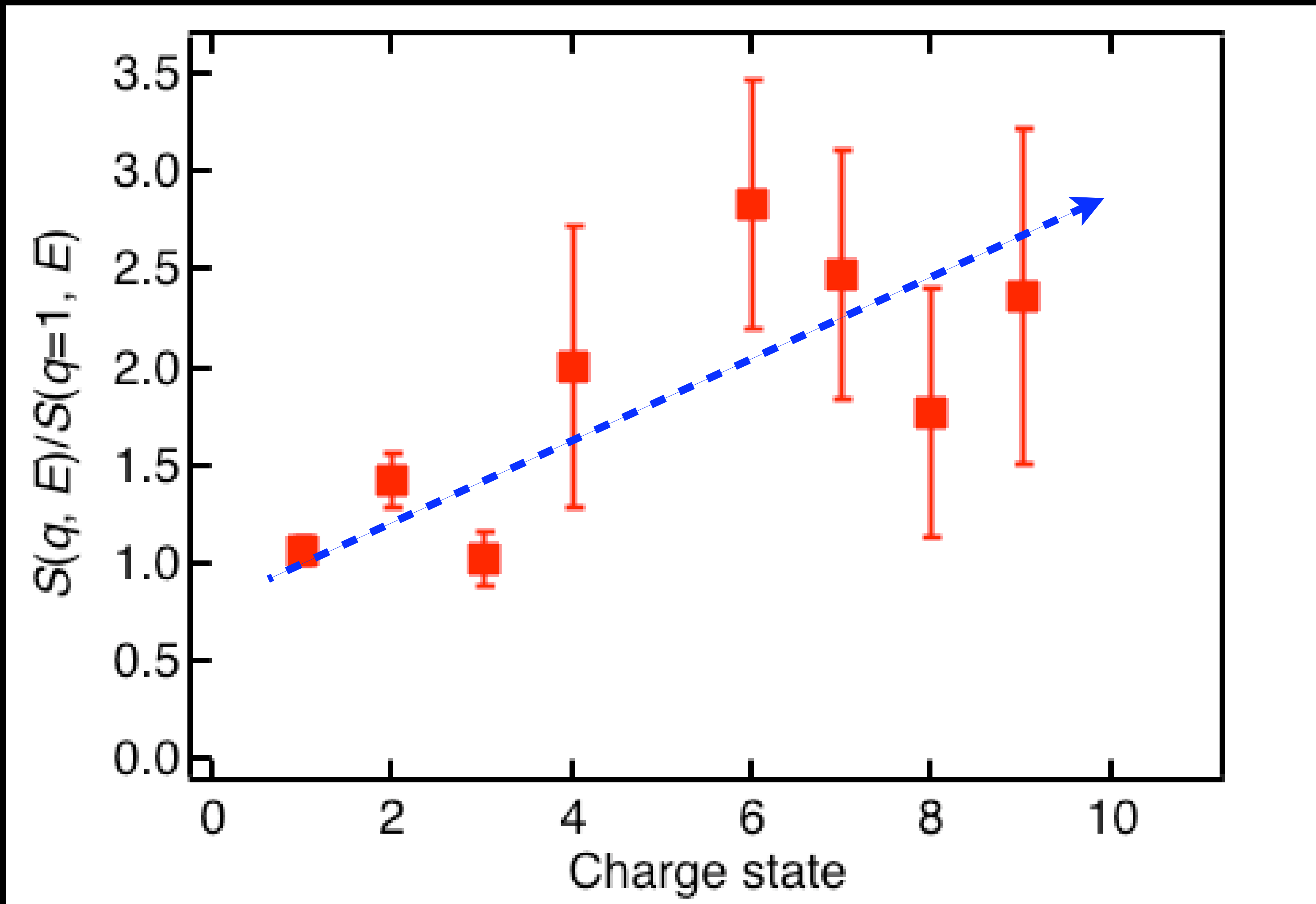
Measurement of S

1. Irradiation of Ar^{q+}
   - q = +1~9
   - 100 ~ 900 keV
   - Number of irradiated ions (A)

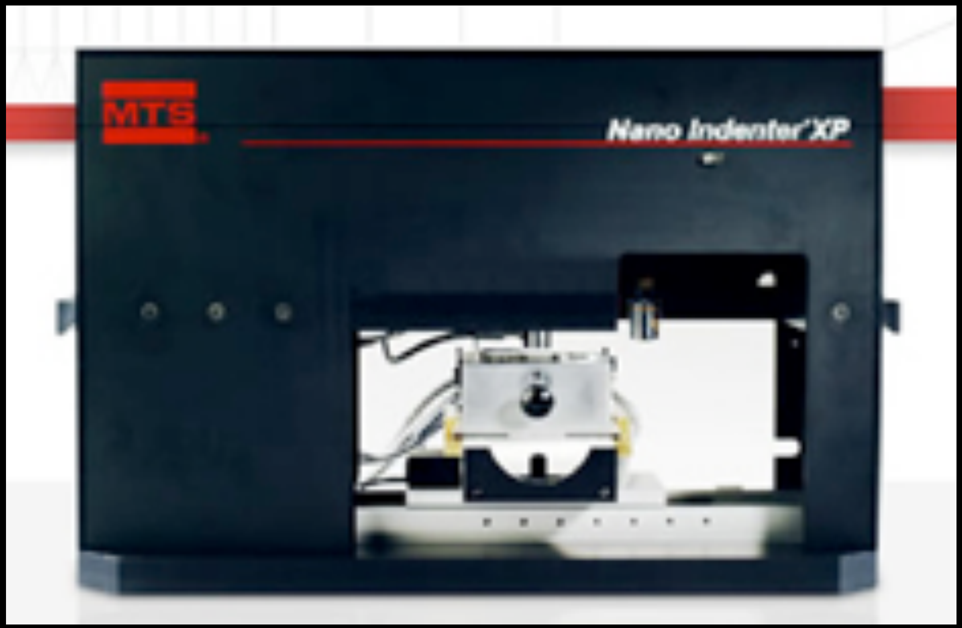
2. Meas. of mass before/after irradiation
   - Number of sputtered Ag atoms (B)

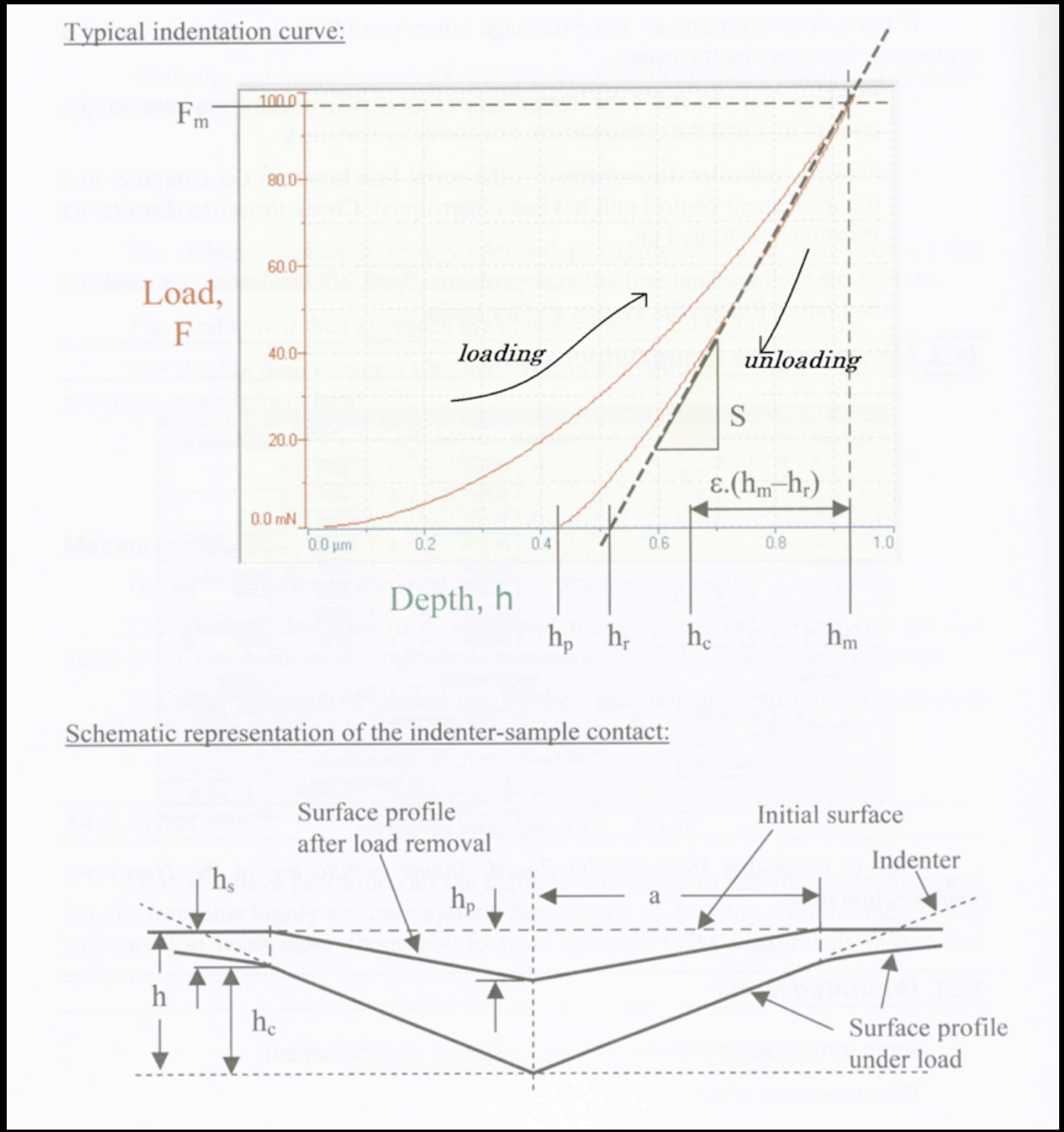
$$S = \frac{(B)}{(A)}$$

Sputtering rate vs. q



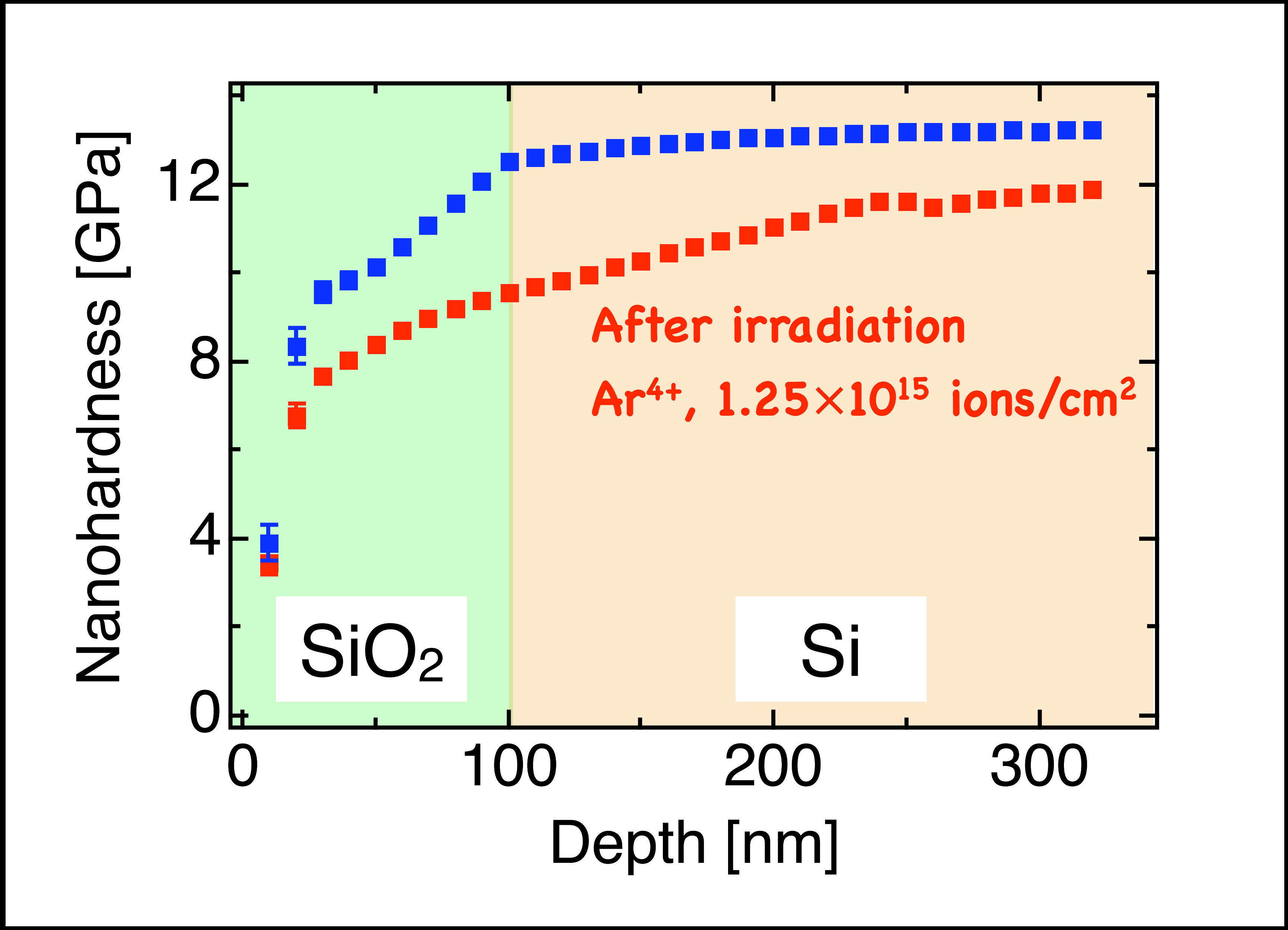
Nano hardness





Softening of Si crystal

- Nano-indentation meas.



Ref. S.A. Pahlovy, Ph.D Thesis, Kochi Univ. of Tech., 2008

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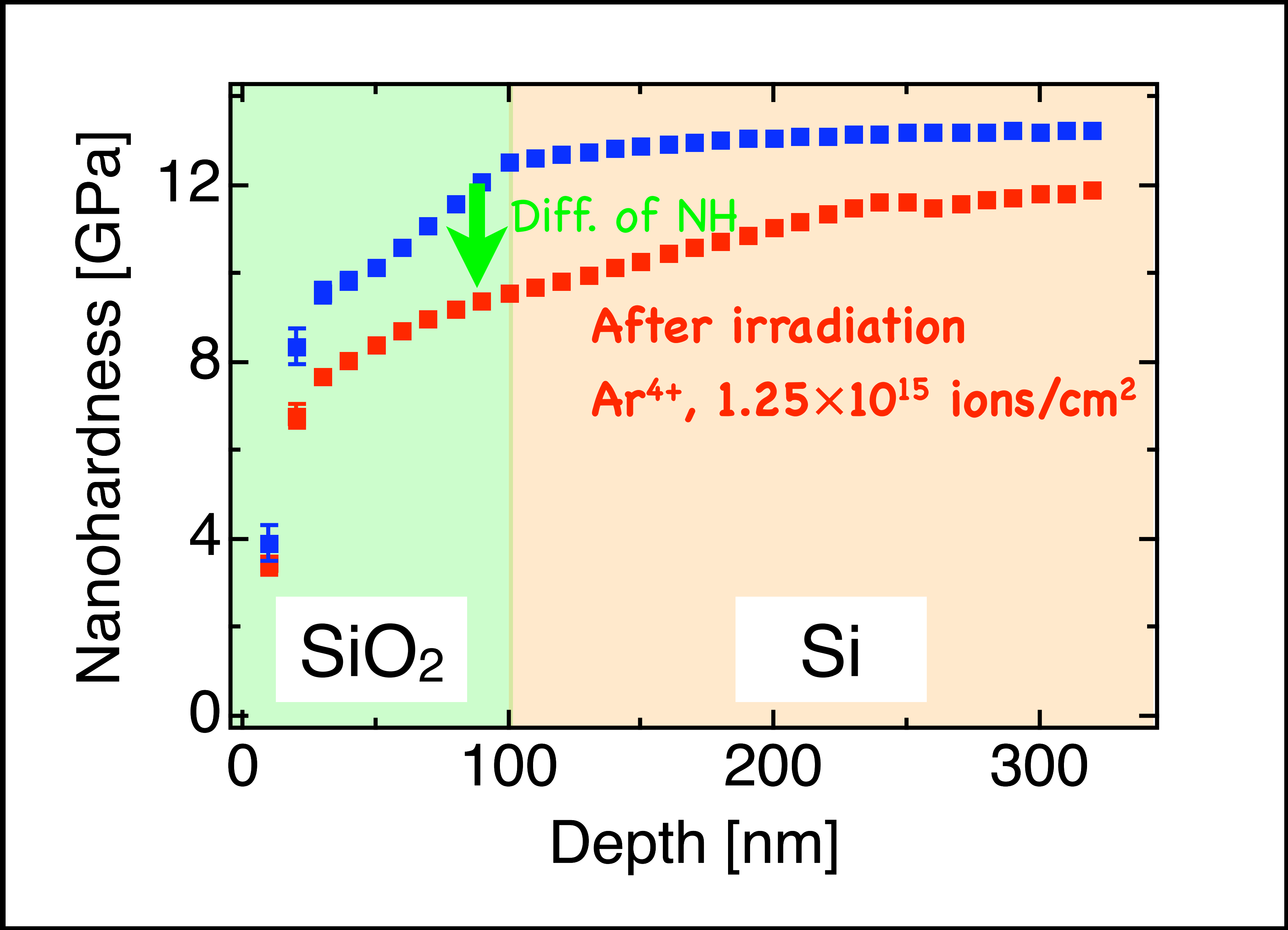

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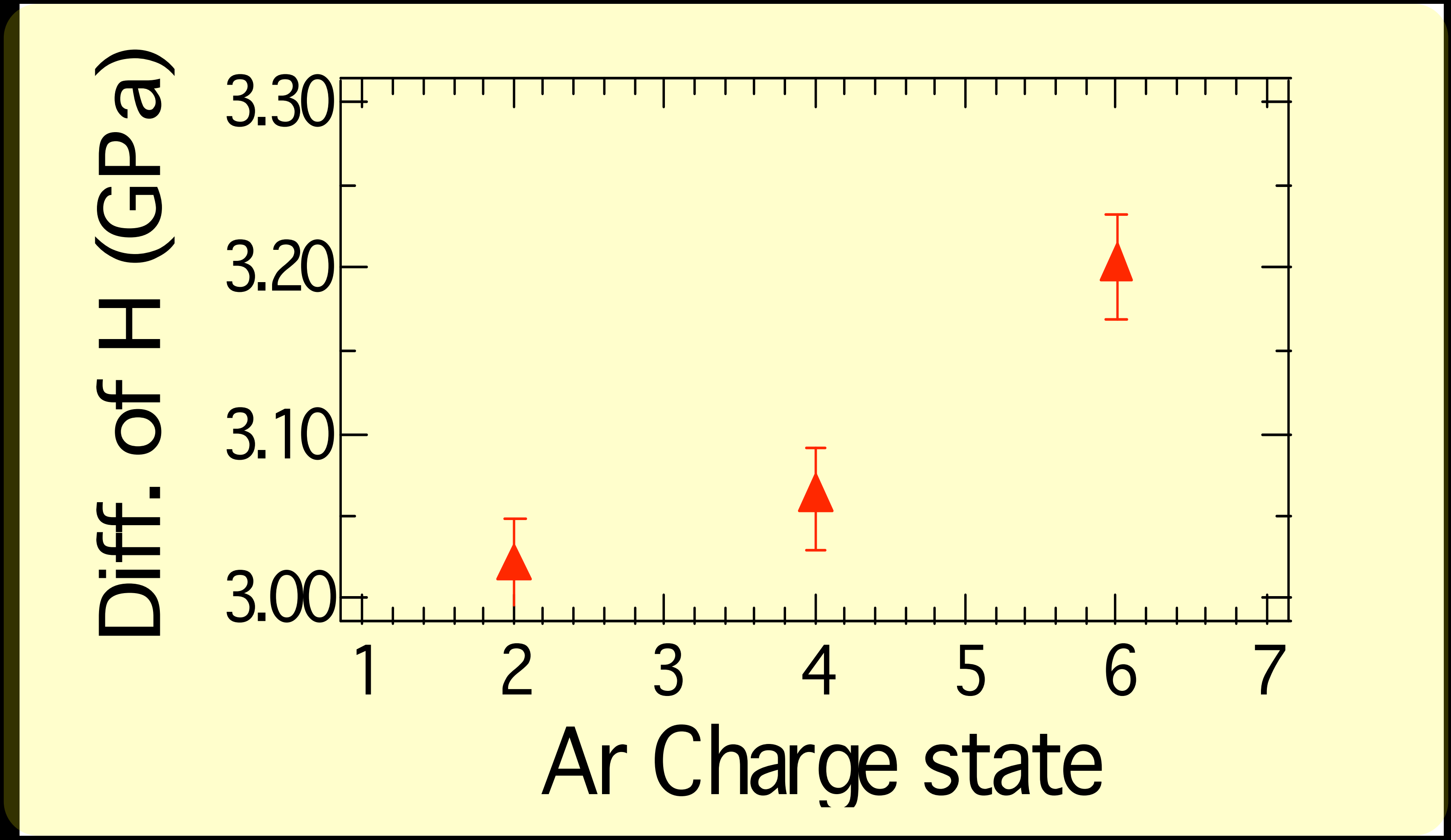
Charge state dep. of modification of NH

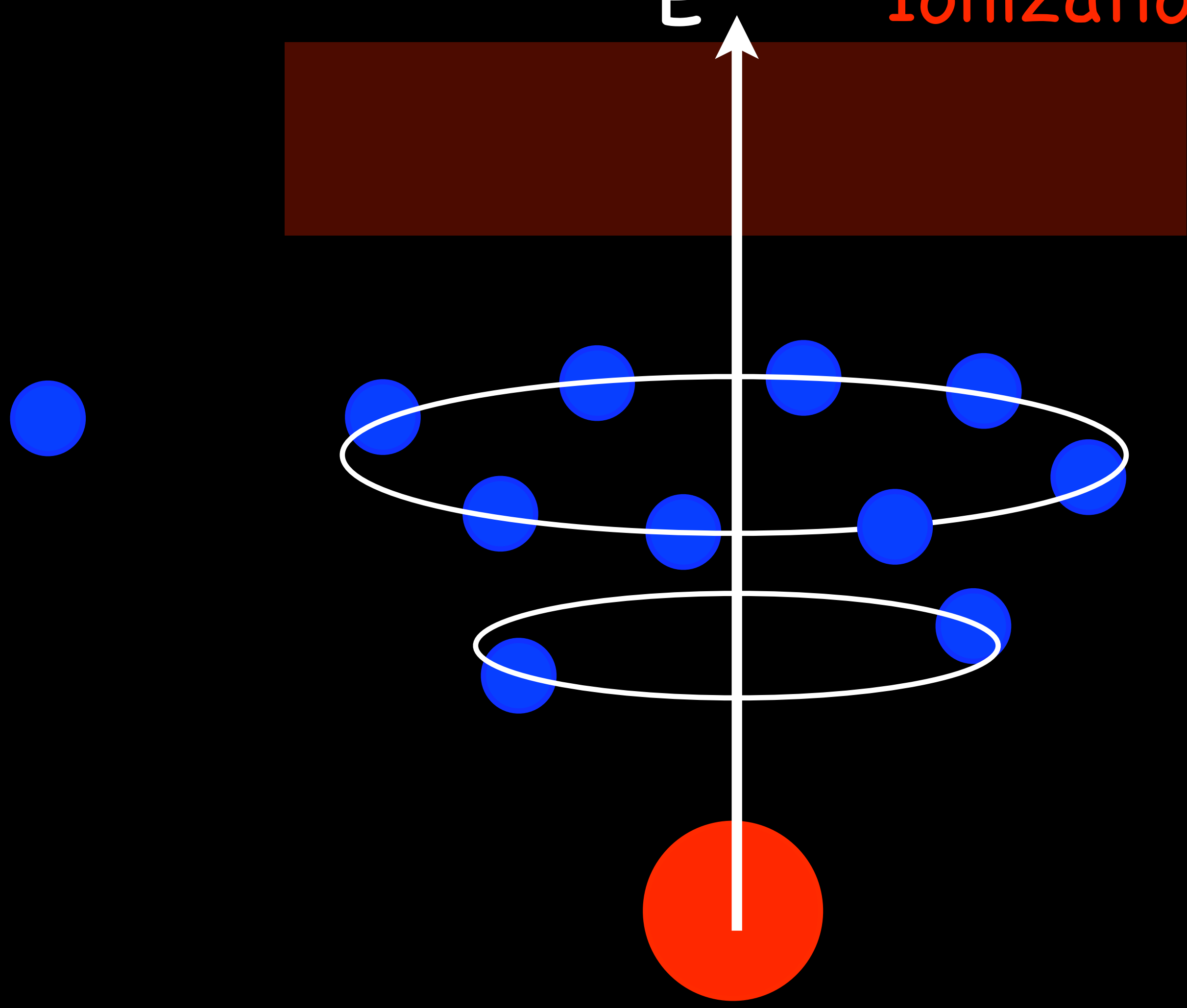


Ref. S.A. Pahlovy, Ph.D Thesis, Kochi Univ. of Tech., 2008

Production of HCI beams

Multi-ionization

- Sequential electron impact



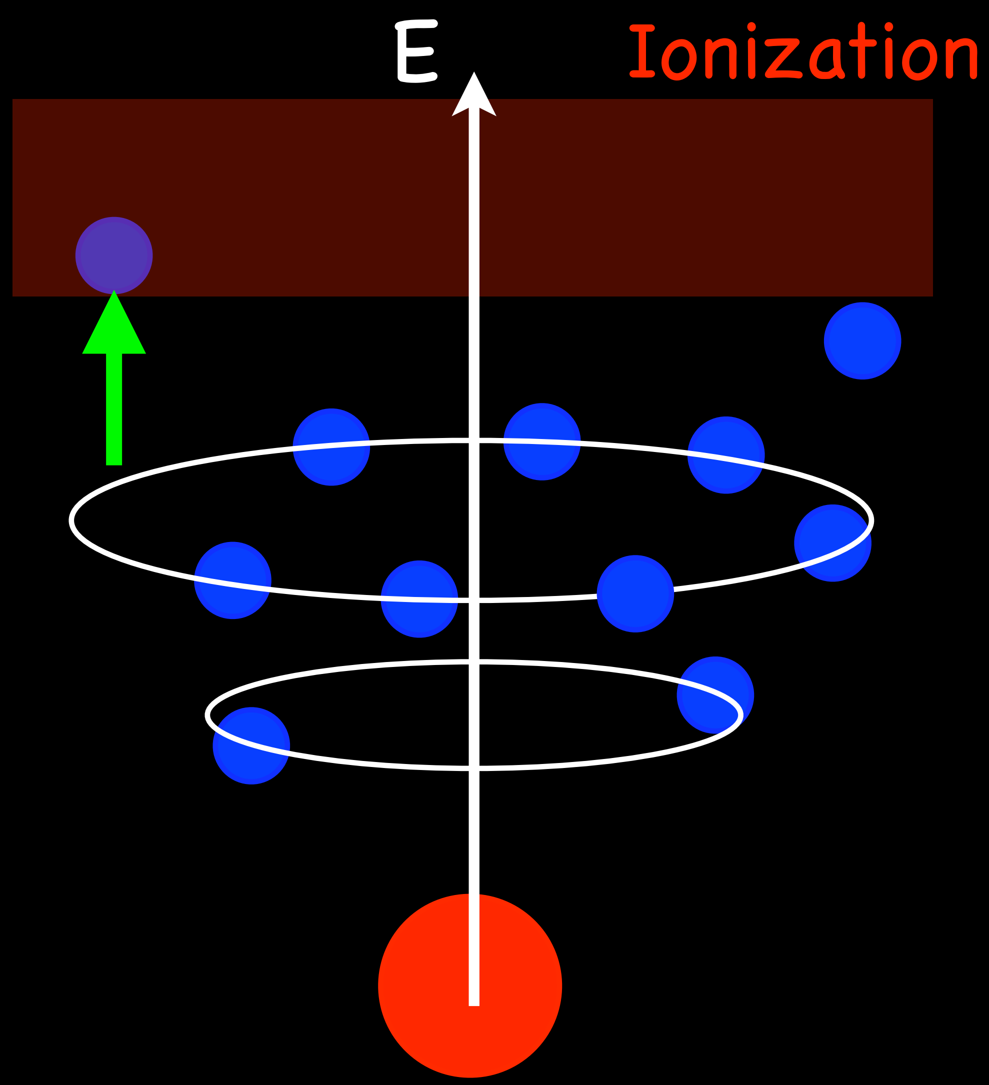
Requirements

A) e^- with high energy/density

B) confinement of ions

Multi-ionization

- Sequential electron impact



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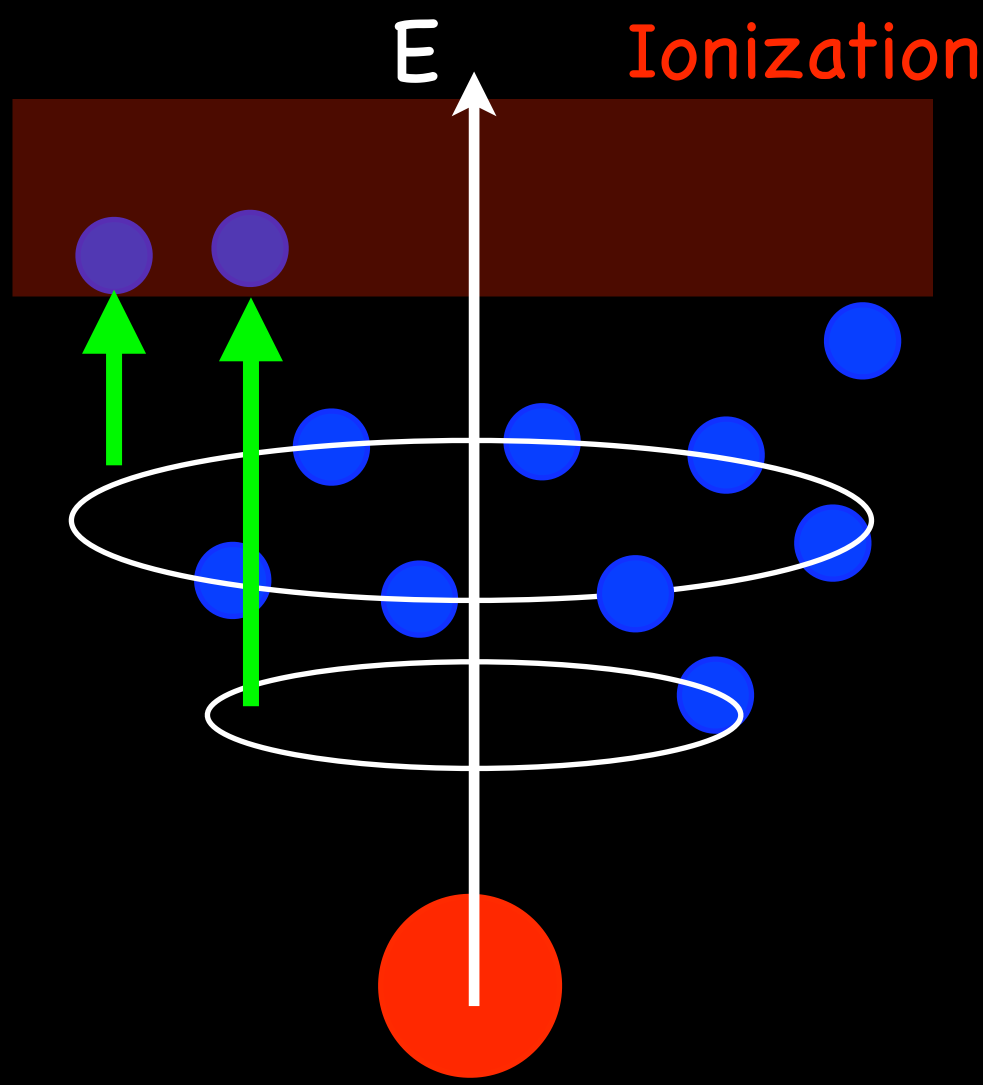
Multi-ionization

- Sequential electron impact



Requirements

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S. Momota, PT-BMES, Sep. 9-10, 2010 @National Tsing Hua Univ.

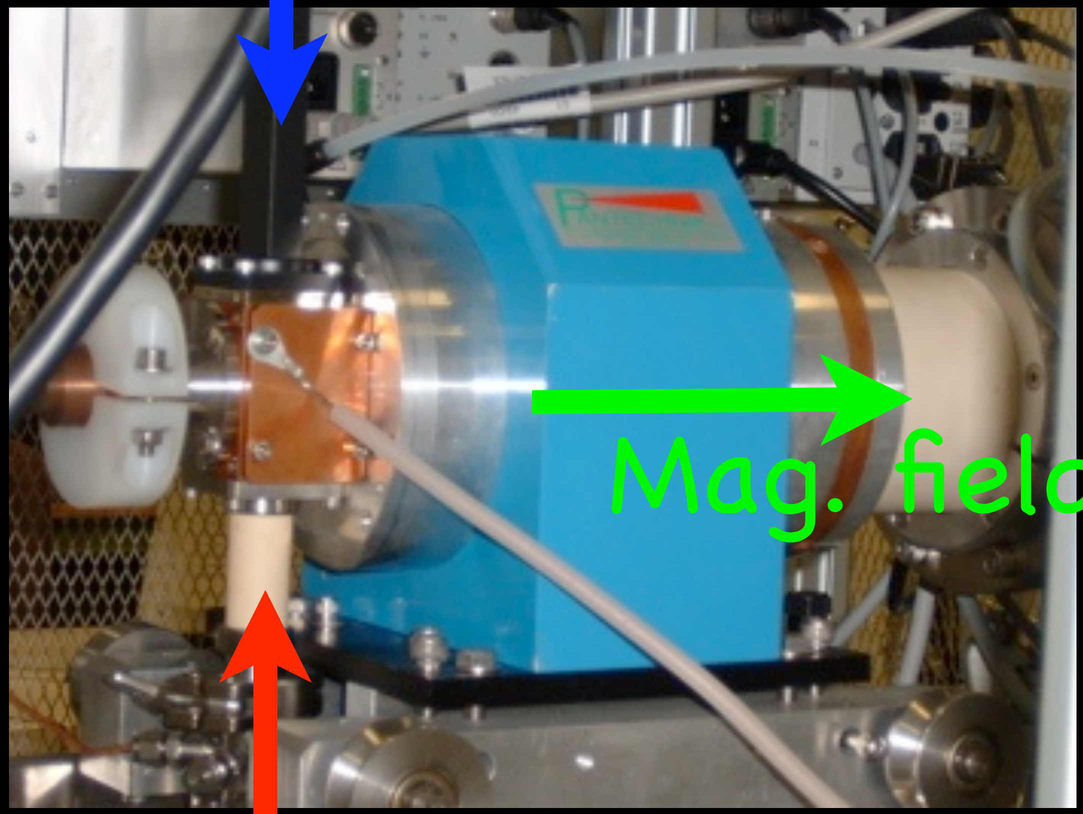
ECRIS (ECR ion source)

NANOGAN by PANTECHNIK

PANTECHNIK

http://www.pantechnik.fr

- e^- with high E
  acceleration by ECR process
- confinement of ions
  Mirror mag. field



EBIS (Electron beam ion source)

dresdenEBIS by DREEBIT

Electron & Ion Beam Technologies

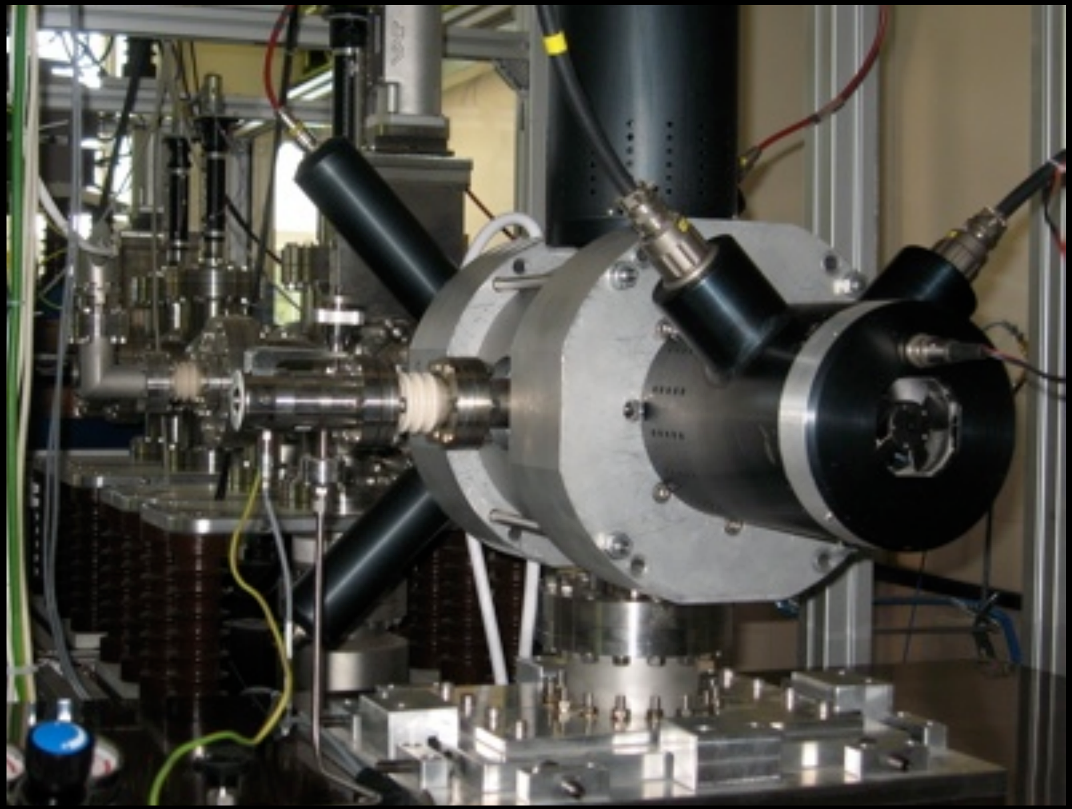
http://www.dreebit.com/

- e^- with high E

  e^--beam (~10μmφ, >10keV) produced by electron gun

- confinement of ions

  Trapped by ele. field induced by electrodes and e^--beam



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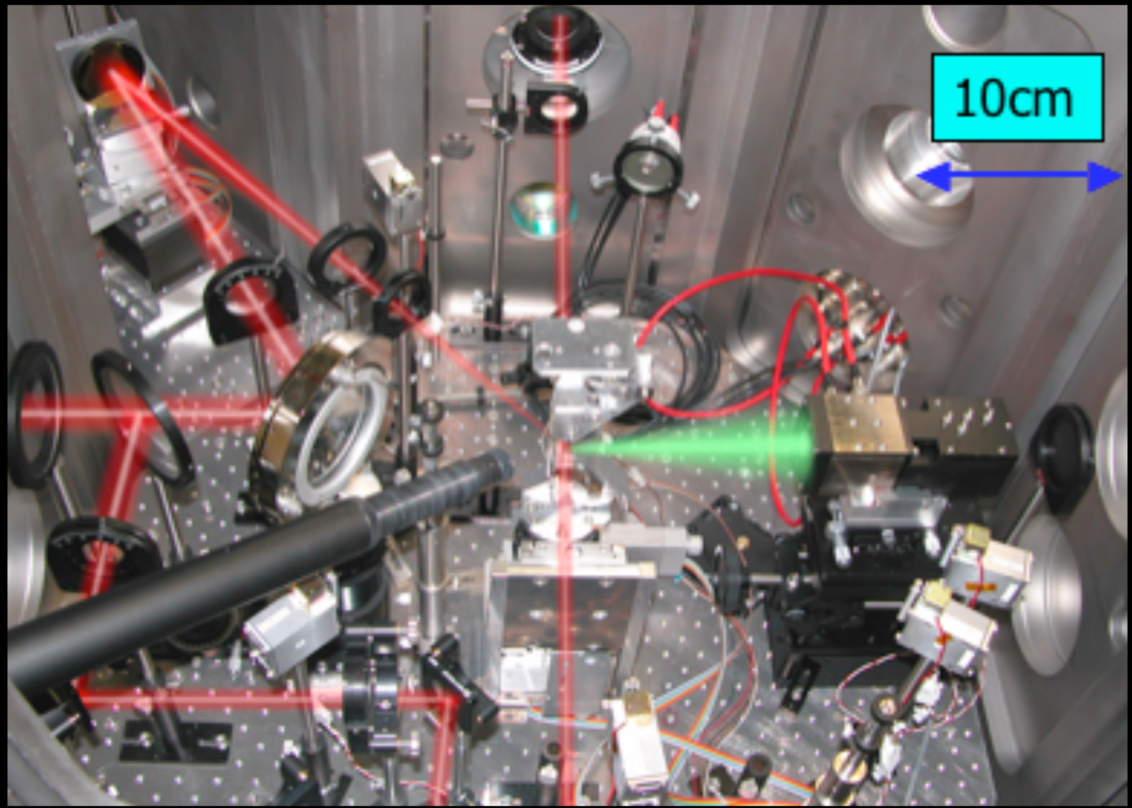
ILIS (Intense laser ion source)

At present no industrial products,
but in future …

- e^- with high E
  Heated by intense laser

- confinement of ions
  No fields for confinement
  because of high density of e^-



http://www2.gpi.ac.jp/JSPF/JAEA%20ion/JAEAion.html

Conclusions

Present status and ...

Feasibility of HCI beams

- confirmed
  IBL, sputtering, NH

Prod. of HCI beams

- developed
  NANOGAN, dresdenEBIS

Present status and ...

Feasibility of HCI beams

- confirmed
  IBL, sputtering, NH
- and further
  higher precision
  crucial application
  theoretical support

Prod. of HCI beams

- developed
  NANOGAN, dresdenEBIS
- and further
  higher intensity/q
  lower cost

Microscopic simulation

- Inclusion of HCI effect in MD calculation