Production, Separation and Implantation of ^{163}Ho for Electron Neutrino Mass Measurements

T. Kieck[1], K. Chrysalidis[1], H. Dorrer[1], Ch. E. Düllmann[1;2], K. Eberhardt[1], Ch. Enss[3], Li. Gamer[3], L. Gastaldo[3], T. Day Goodacre[4], R. Haas[1], C. Hassel[3], K. Johnston[4], U. Köster[5], S. Kormannshaus[1], B. Marsh[4], Ch. Mokry[1], S. Rothe[4], J. Runke[2], S. Schmidt[1], F. Schneider[1], T. Stora[4], and K. Wendt[1] for the ECHo Collaboration

[1]Johannes Gutenberg-Universität, Mainz, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[3]Universität Heidelberg, Heidelberg, Germany
[4]CERN, Geneva, Switzerland
[5]Institut Laue-Langevin, Grenoble, France

DFG Research unit FOR 2202/1
NEUTRONS FOR SCIENCE®
CERN
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Electron Capture ^{163}Holmium Experiment

Implication of Non-Zero Neutrino Mass

- Observation of neutrino oscillation (2015 Nobel Prize in Physics)
- Physics beyond the Standard Model

Takaaki Kajita
Arthur B. McDonald

Experimental Upper Limits for the Electron (Anti-) Neutrino Mass:

- $m(\bar{\nu}_e) < 2.3$ eV (MAC-E filter, Mainz)
- $m(\bar{\nu}_e) < 2.12$ eV (MAC-E filter, Troitsk)
- $m(\nu_e) < 225$ eV (inner Bremsstrahlung, Livermore)

C. Kraus *et al.*, Eur. Phys. J. C **40**, 447 (2005)
V. N. Aseev *et al.*, Phys. Rev. D **84**, 112003 (2011)
P. Springer *et al.*, Phys. Rev. A **35**, 679 (1987)

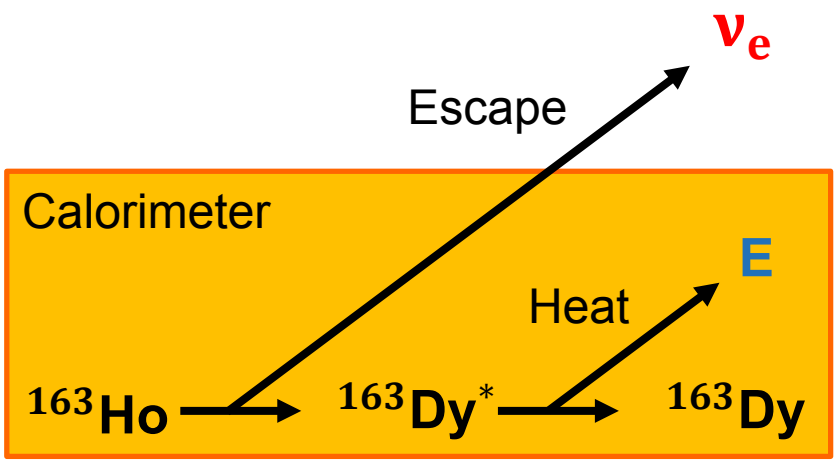
Cosmological Upper Limits

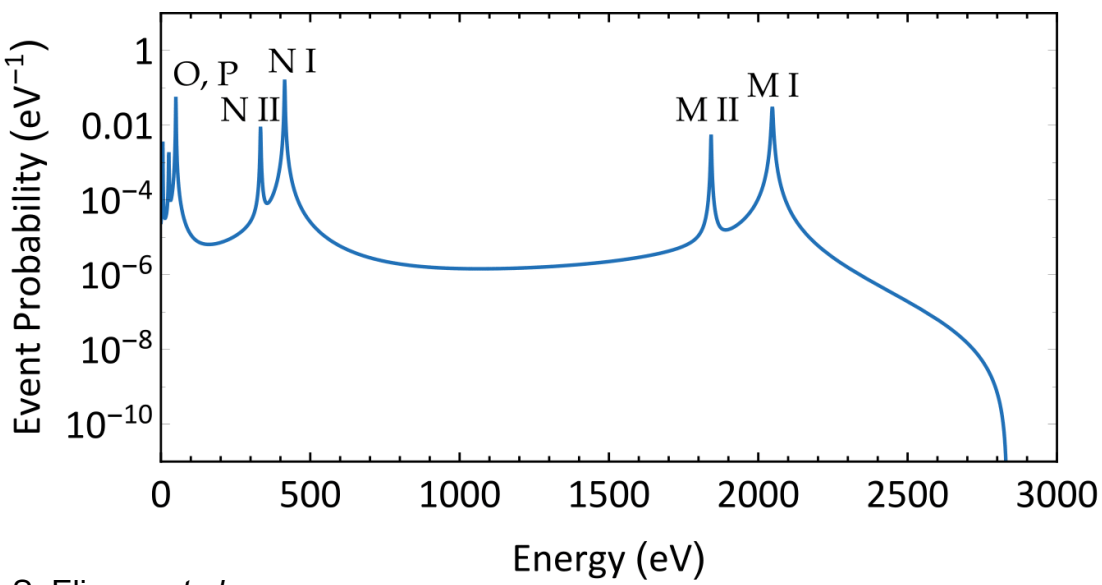
- Strongly depending on model
- $\sum m(\nu_i) < 1$ eV

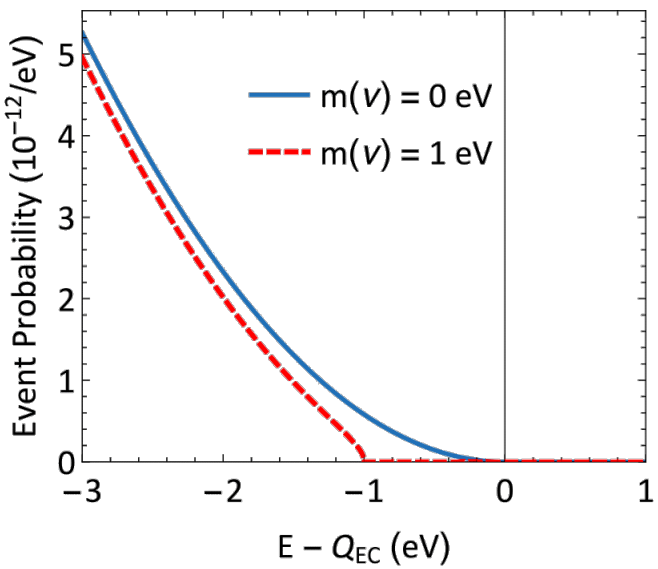
Ø. Elgarøy *et al.* NJP **7**, 61 (2005)

^{163}Holmium Electron Capture

- Electron capture decay with lowest energy: Q_{EC} = **2.833**$(30)_{stat}(15)_{sys}$ keV [1]
- EC decay energy stored in atomic shell
- De-excitation by Auger electrons and X-rays
- Endpoint shifted and shape modified by finite neutrino mass







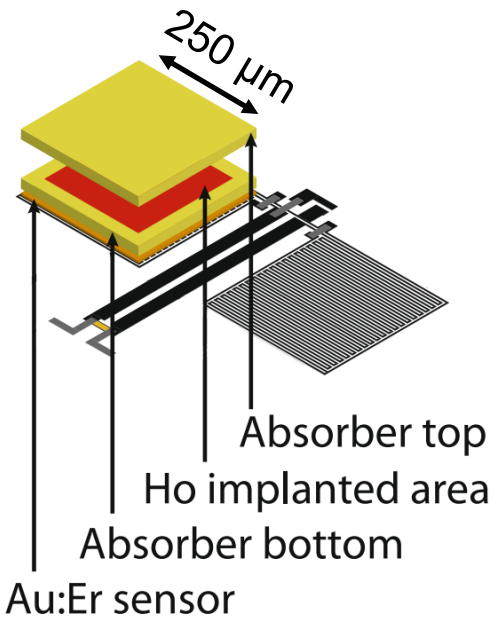
[1] S. Eliseev *et al.*, Phys. Rev. Lett. **115**, 062501 (2015)

The ECHo Detector Setup

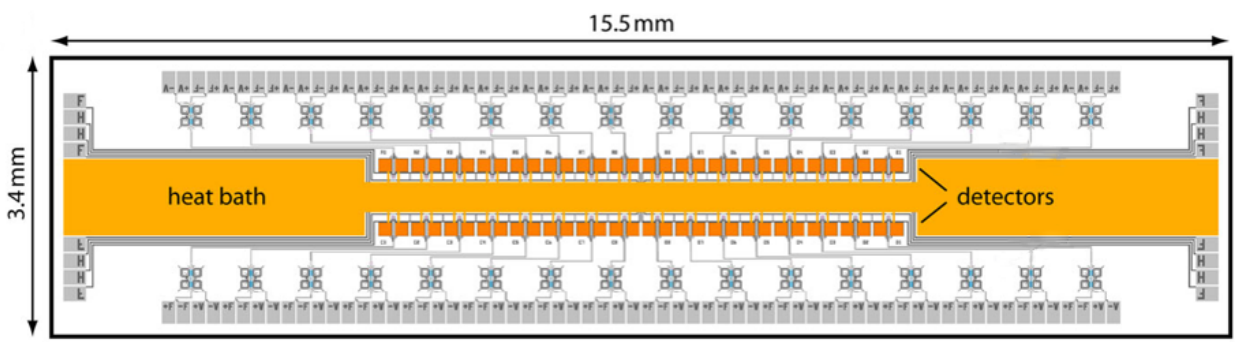
Metallic Magnetic Calorimeters (MMC's)

- Energy resolution: < 10 eV
- Source embedded in gold absorber
- On-Chip dc-SQUID sensor
- Multi detector readout

$$\delta M \cong \frac{\partial M}{\partial T}\delta T \cong \frac{\partial M}{\partial T}\frac{\delta E}{c_{tot}}$$

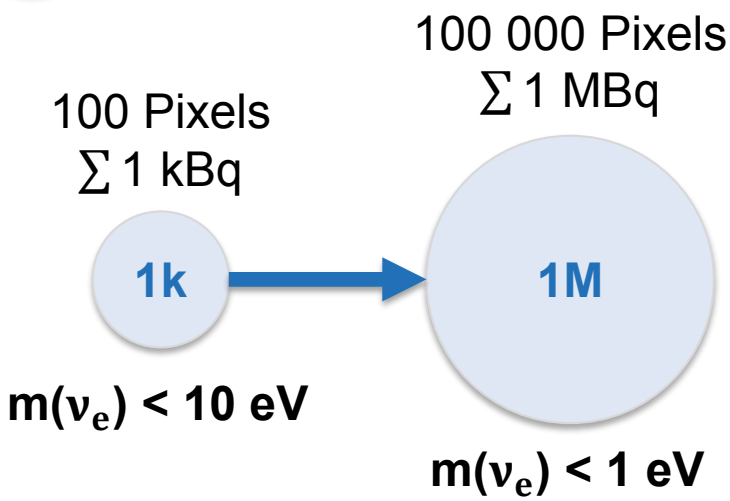


Prototype-Design



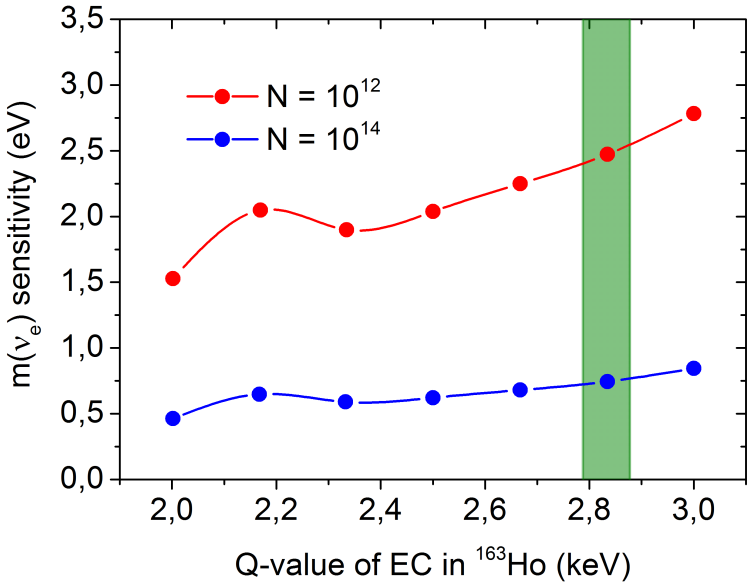
S. Kempf *et al.*,
J. Low Temp. Phys. **184**, 344 (2015)

Scalability of the ECHo Experiment



Next 2 Years (ECHo-1k):

- Proof of technique and scalability
- Production of high purity ^{163}Ho source
- Accumulation of 10^{10} counts (1 year)

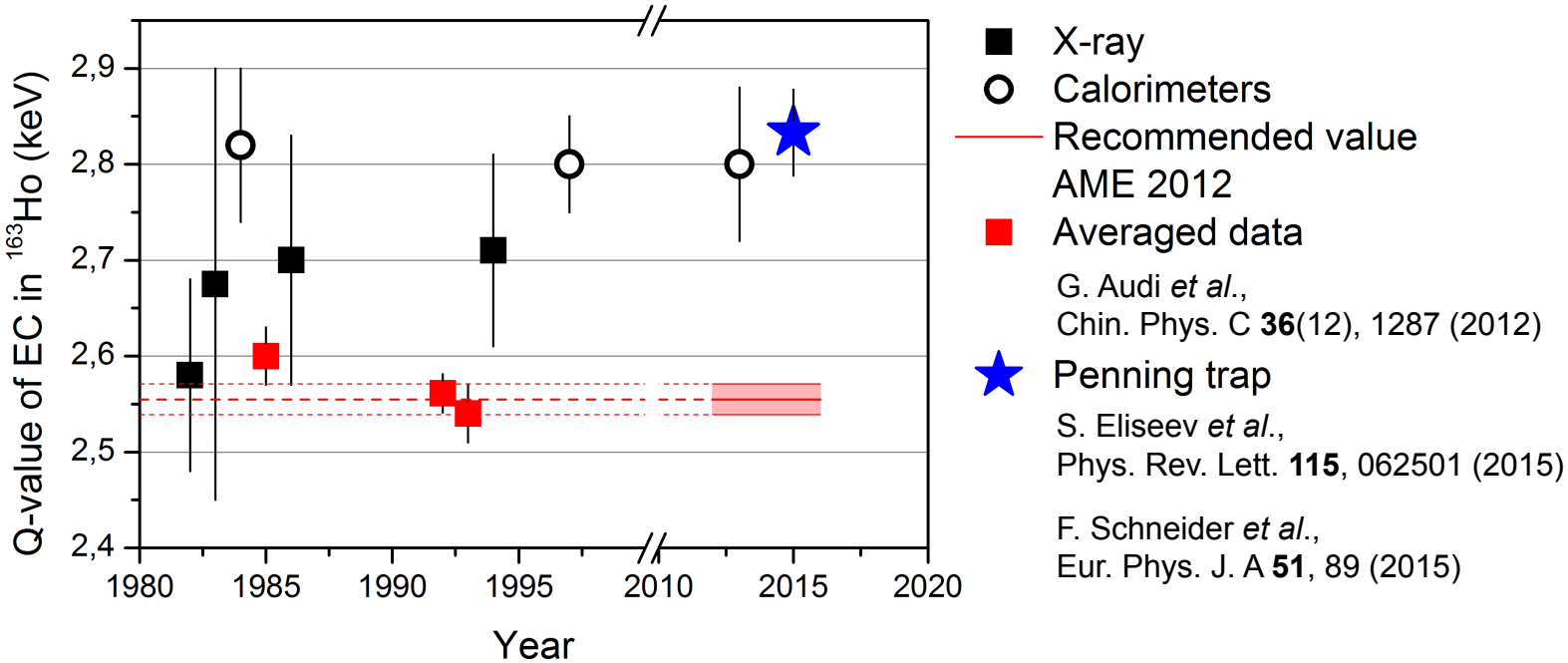


Future (ECHo-1M):

- High statistics
- Accumulation of > 10^{14} counts (3 years)

→ **Towards sub-eV sensitivity**

Precision Measurement of Q-Value of ^{163}Ho EC



Model Independent Determination by Penning Trap Mass Spectrometry

- New measurement at SHIPTRAP, GSI: $2.833(30)_{stat}(15)_{sys}$ keV
- Measurement at eV uncertainty level planned at PENTATRAP, MPI Heidelberg

Reactor Based ^{163}Ho Production at ILL Grenoble

Neutron activation of enriched ^{162}Er sample at high flux reactor:

$$^{162}\mathrm{Er} \xrightarrow{(n,\gamma)} {}^{163}\mathrm{Er} \xrightarrow{(\epsilon)} {}^{163}\mathrm{Ho}$$

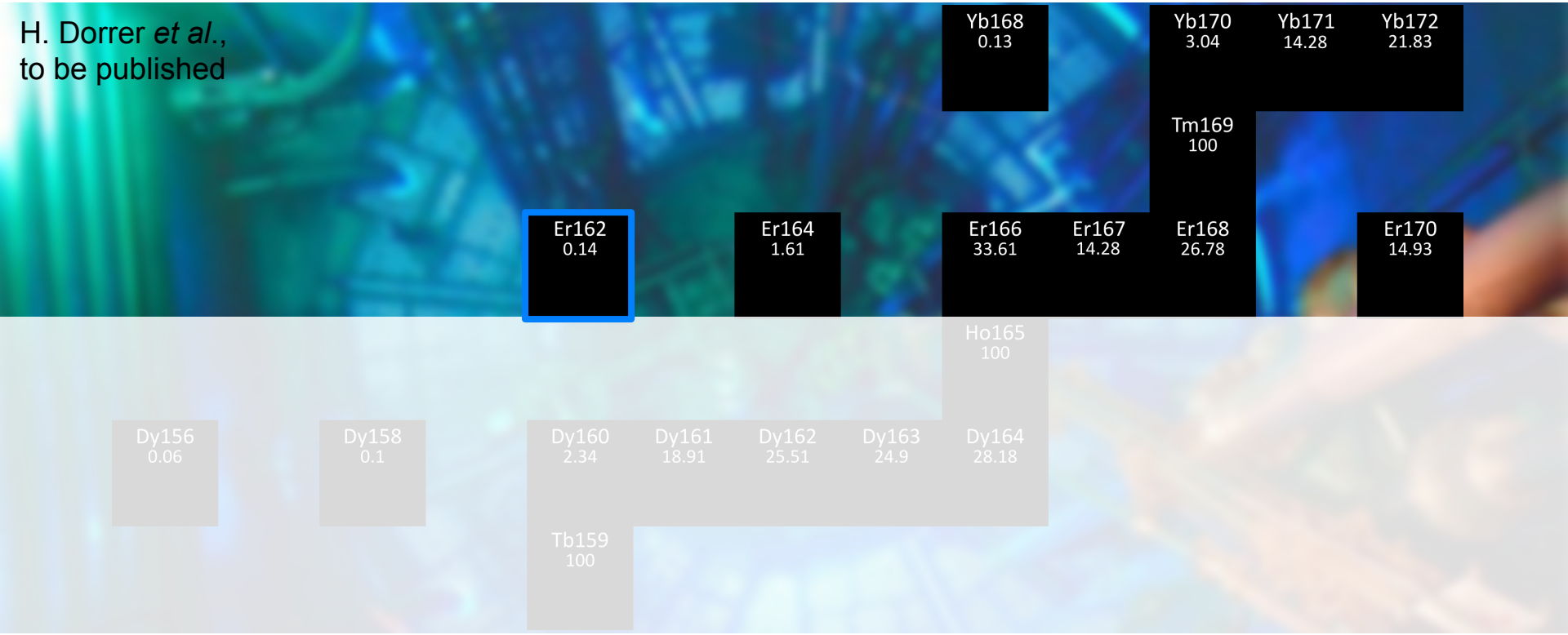
- Production of ^{163}Ho sample completed
- Large-scale production in preparation

Ytterbium 70	Yb163 11.10 m	Yb164 1.26 h	Yb165 9.90 m	Yb166 2.36 d	Yb167 17.50 m	Yb168 0.13	Yb169 32.02 d
Thulium 69	Tm162 21.70 m	Tm163 1.81 h	Tm164 2.99 m	Tm165 1.25 d	Tm166 7.70 h	Tm167 9.25 d	Tm168 93.10 d
Erbium 68	Er161 3.21 h	Er162 0.14	Er163 1.25 h	Er164 1.61	Er165 10.36 h	Er166 33.61	Er167 22.93
Holmium 67	Ho160 25.30 m	Ho161 2.48 h	Ho16[illegible] 15.00 m	Ho163 4570 y	Ho164 28.60 m	Ho165 100	Ho166 1.2e3 y / 1.12 d
Dysprosium 66	Dy159 144.40 d	Dy160 2.34	Dy161 18.91	Dy162 25.51	Dy163 24.9	Dy164 28.18	Dy165 2.33 h
Terbium 65	Tb158 180.00 y	Tb159 100	Tb160 72.30 d	Tb161 6.89 d	Tb162 7.60 m	Tb163 19.50 m	Tb164 3.00 m
	93	94	95	96	97	98	99

$$\Phi_{th} = 1.3 \times 10^{15}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Strategy for Production of Pure ^{163}Ho

H. Dorrer *et al.*,
to be published



1. Chemical separation of Er from all lighter Lanthanides

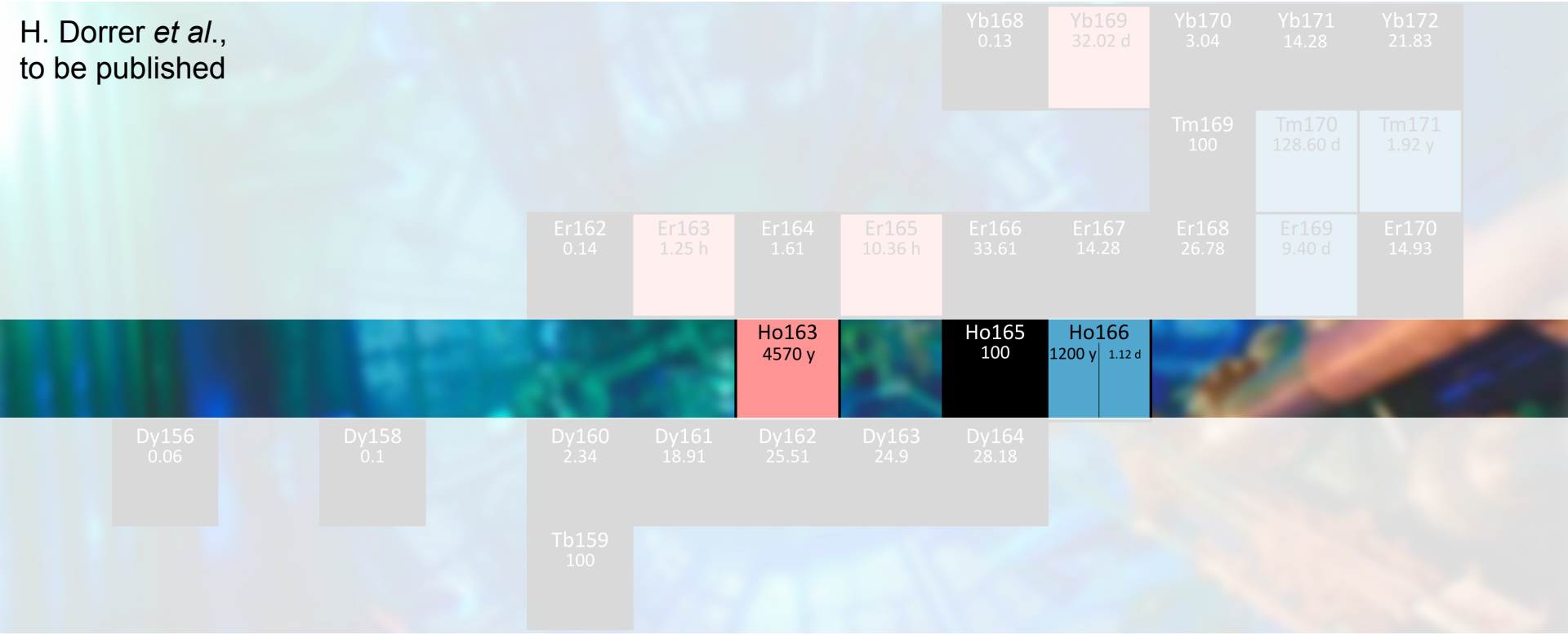
Strategy for Production of Pure ^{163}Ho

H. Dorrer *et al.*,
to be published

1. Chemical separation of Er from all lighter Lanthanides
2. Neutron irradiation of enriched ^{162}Er

Strategy for Production of Pure ^{163}Ho

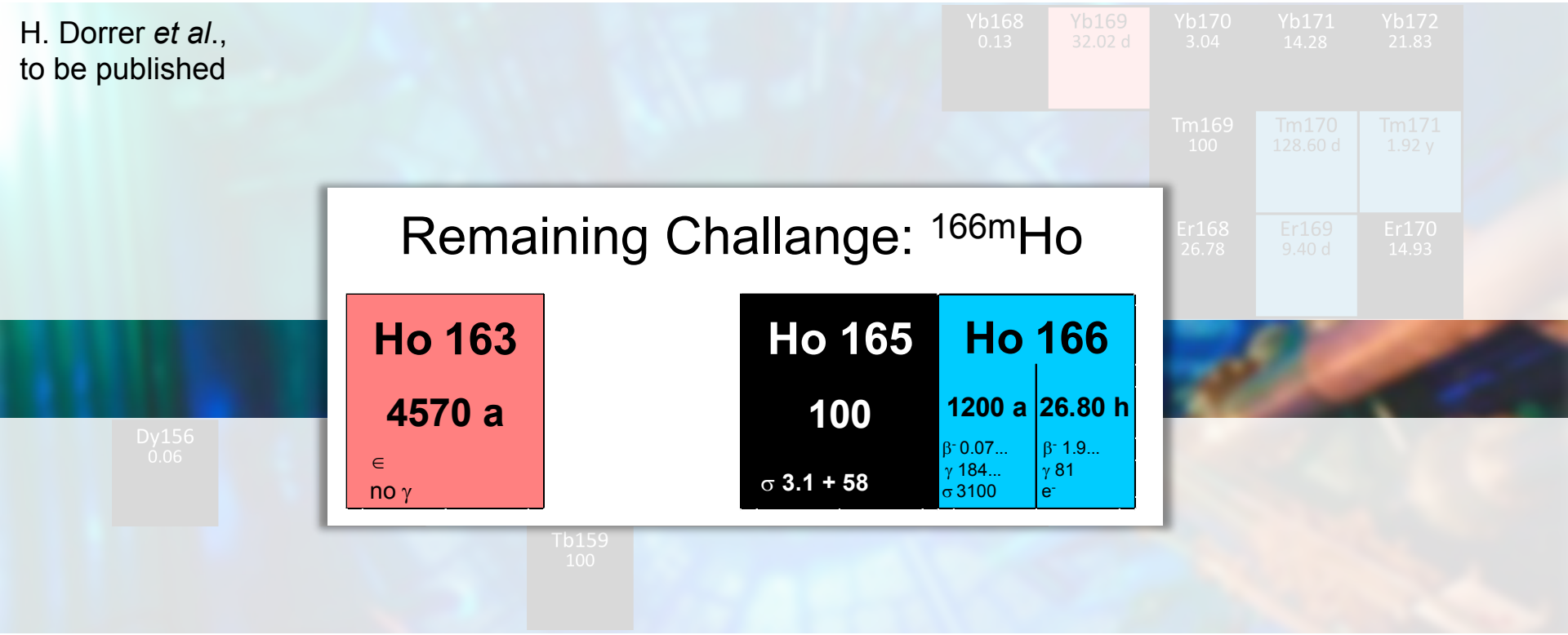
H. Dorrer *et al.*,
to be published



1. Chemical separation of Er from all lighter Lanthanides
2. Neutron irradiation of enriched ^{162}Er
3. Chemical separation of Ho from all heavier Lanthanides

Strategy for Production of Pure ^{163}Ho

H. Dorrer *et al.*,
to be published



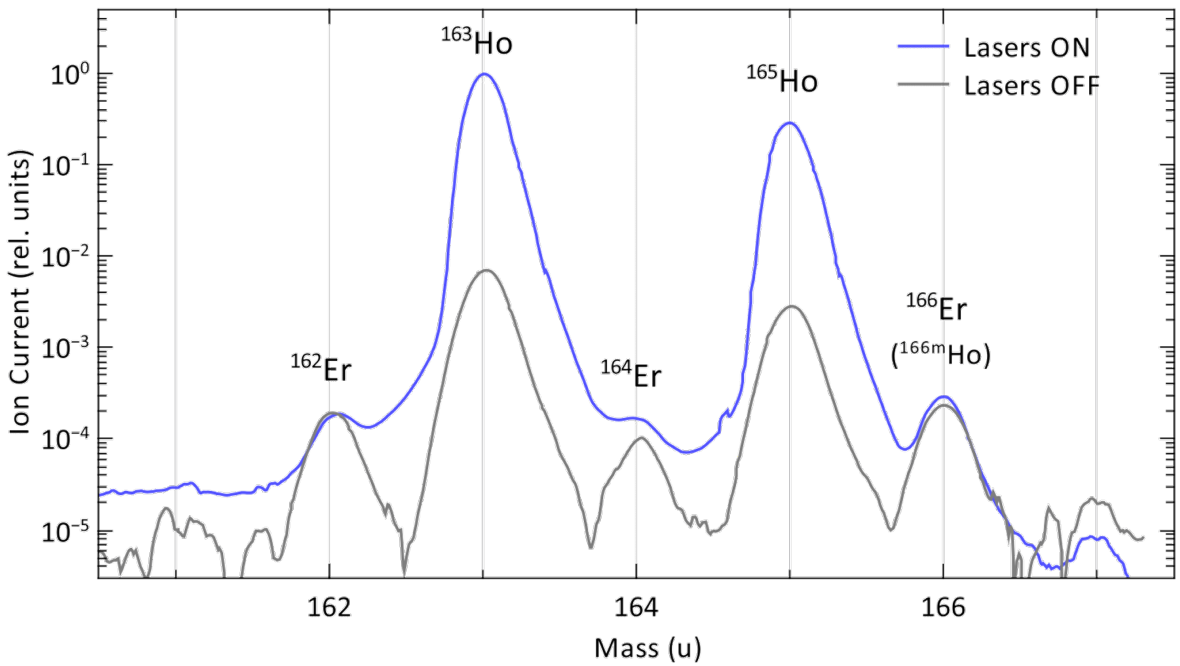
1. Chemical separation of Er from all lighter Lanthanides
2. Neutron irradiation of enriched ^{162}Er
3. Chemical separation of Ho from all heavier Lanthanides
4. Additional isotope separation

Laser Mass Spectrometry for Isotope Selection

Requirements:

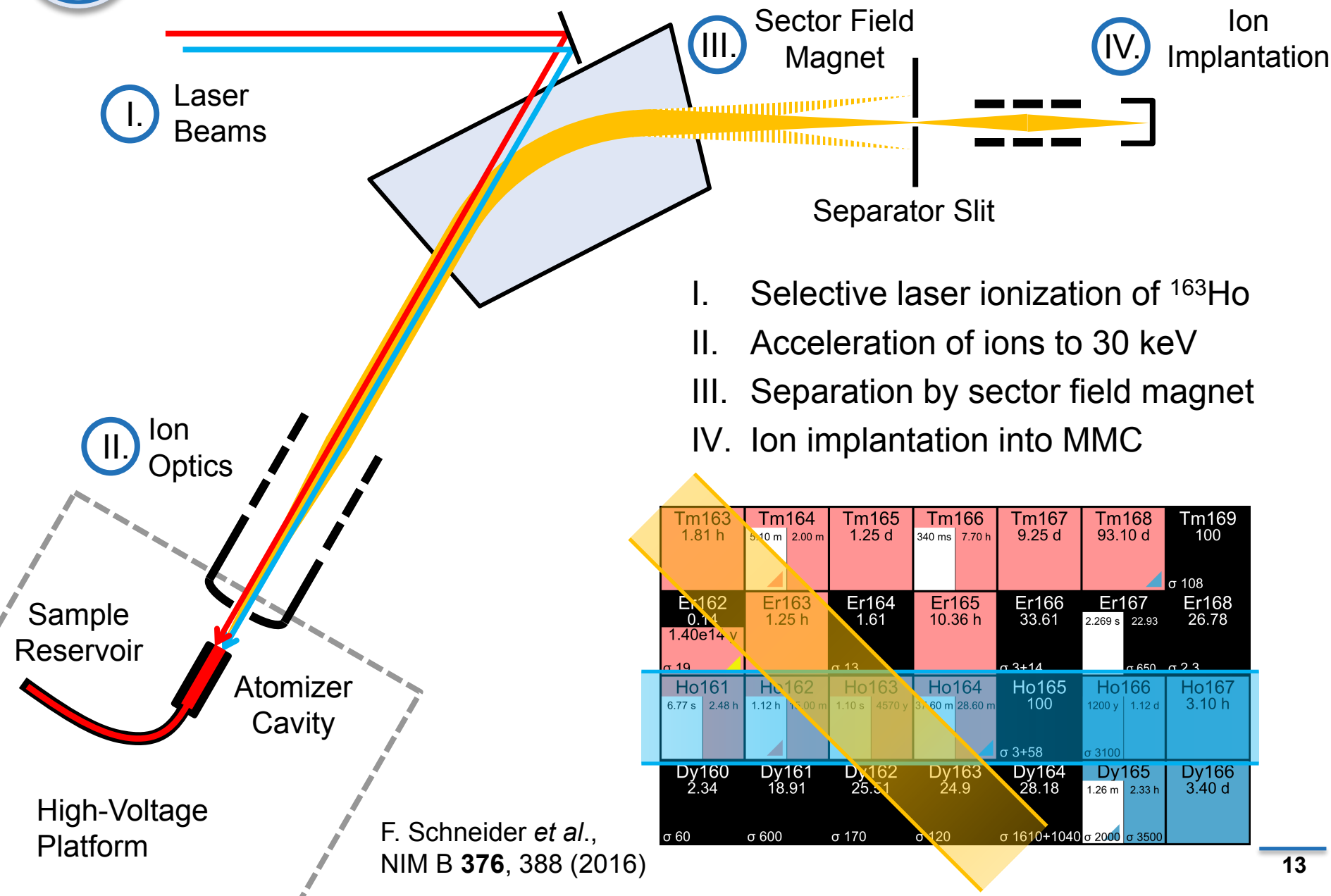
- High efficiency
- High mass selectivity for ^{166m}Ho suppression
- Direct ion implantation

Mass Spectrum by Laser Ionization



F. Schneider,
PhD thesis, JGU Mainz (2016)

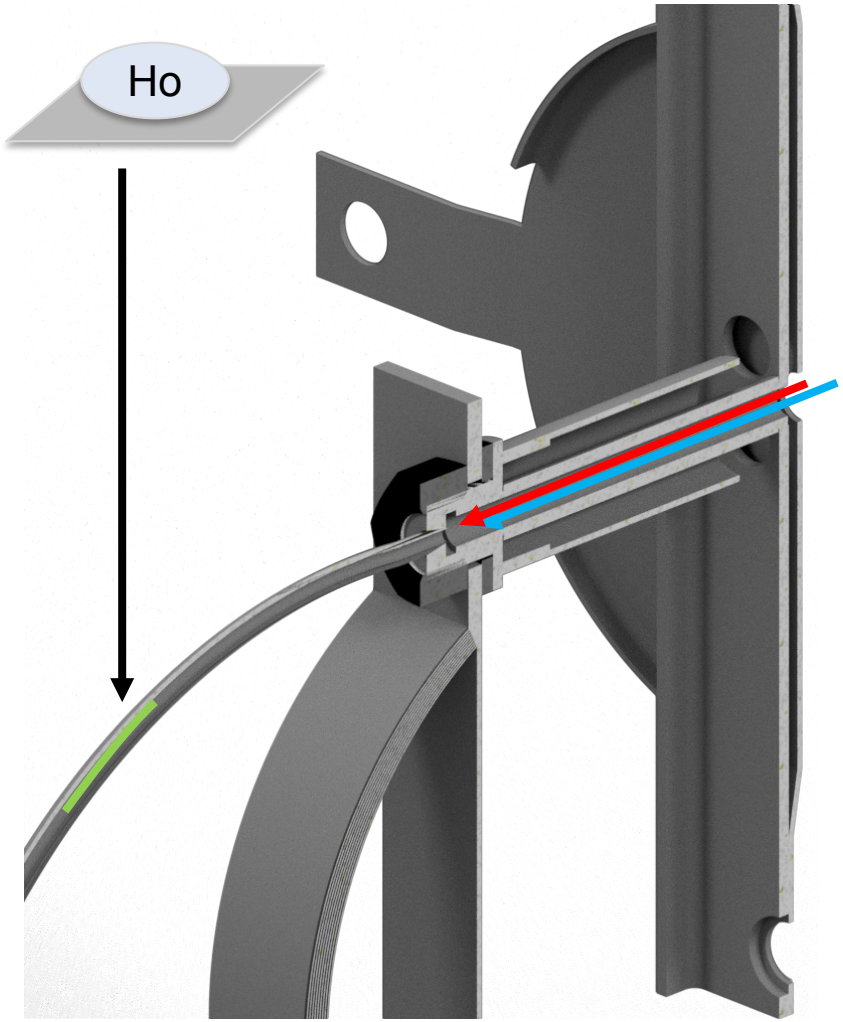
Selective Laser Mass Spectrometric Purification

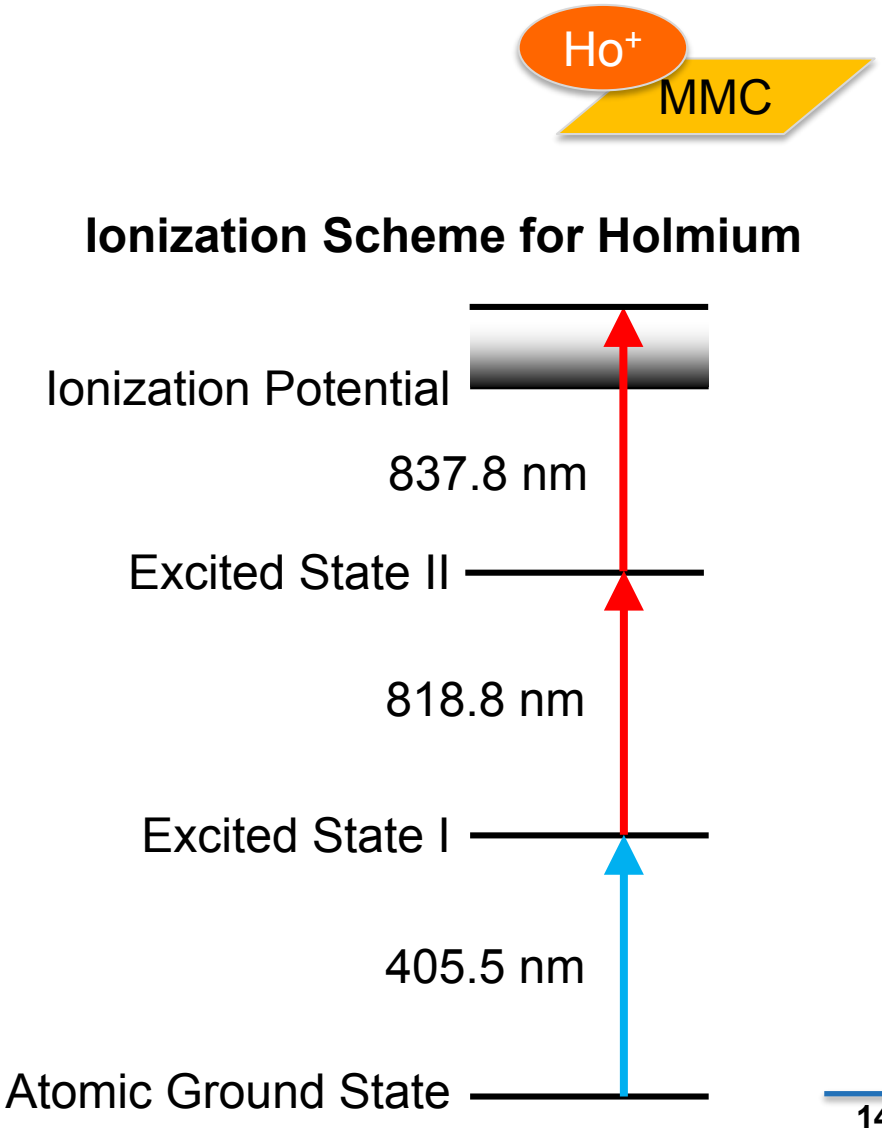


I. Selective laser ionization of ^{163}Ho
II. Acceleration of ions to 30 keV
III. Separation by sector field magnet
IV. Ion implantation into MMC

F. Schneider *et al.*, NIM B **376**, 388 (2016)

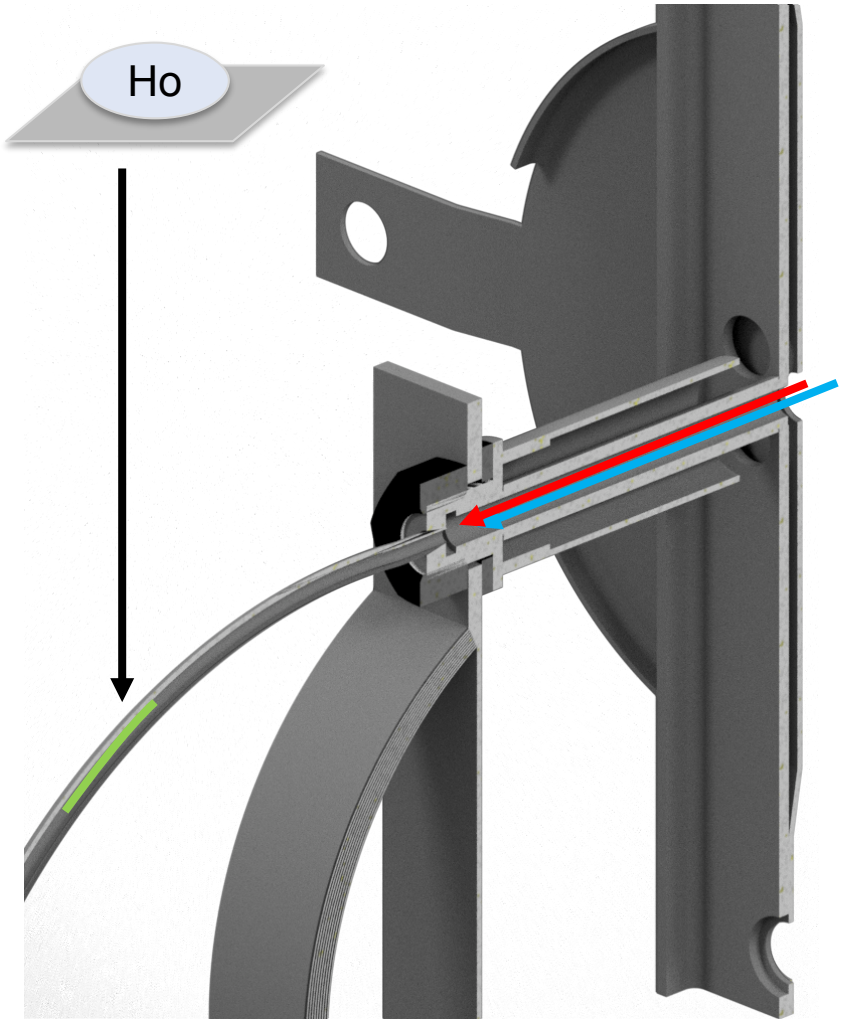
Laser Ion Source for High Efficiency





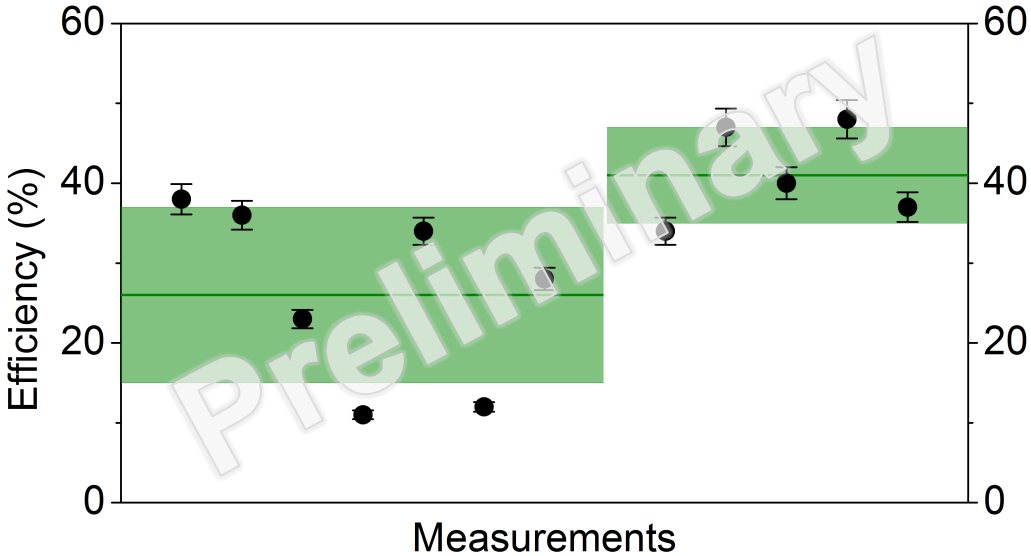
F. Schneider,
PhD thesis, JGU Mainz (2016)

Laser Ion Source for High Efficiency



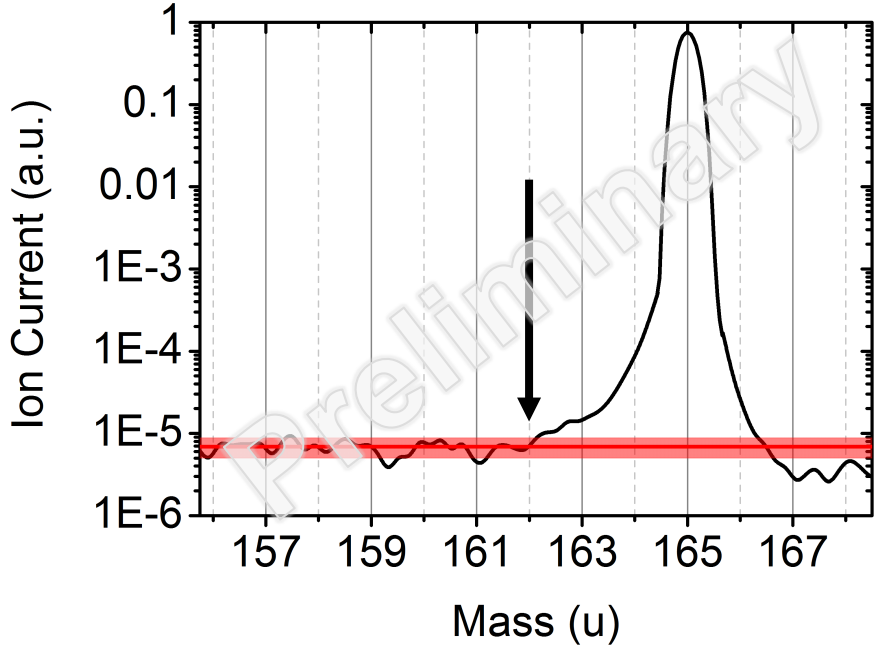
Efficiency Improvements
(stable ^{165}Ho measured)

Conventional Design **26(11) %** → New Design **41(6) %**

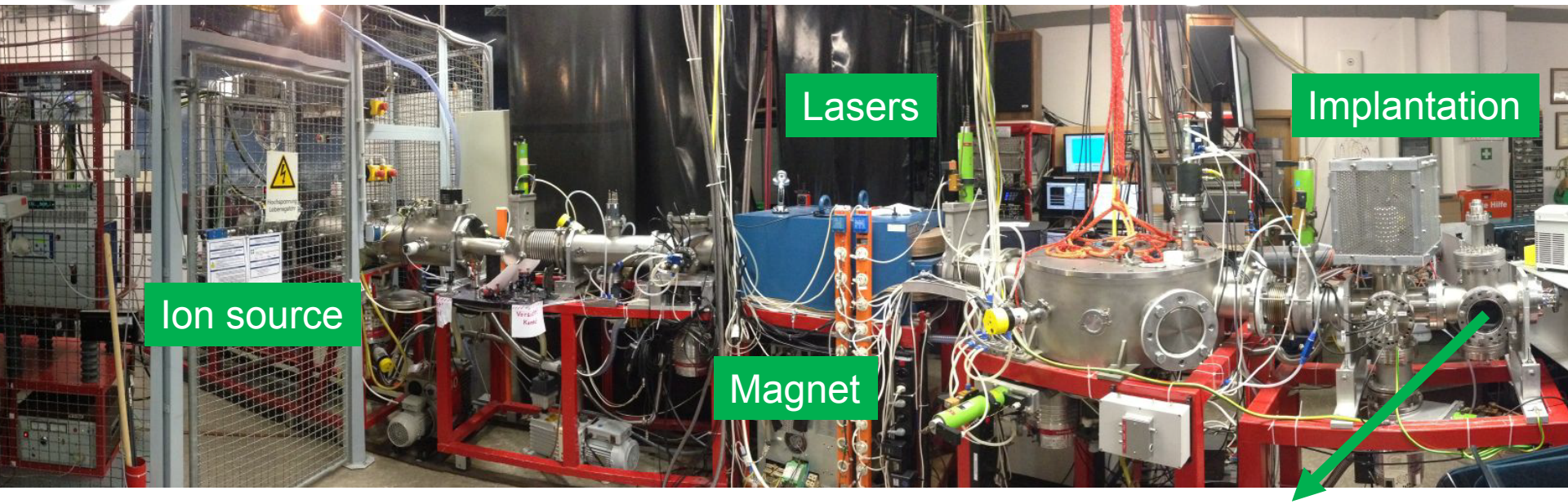


Isotope Selectivity

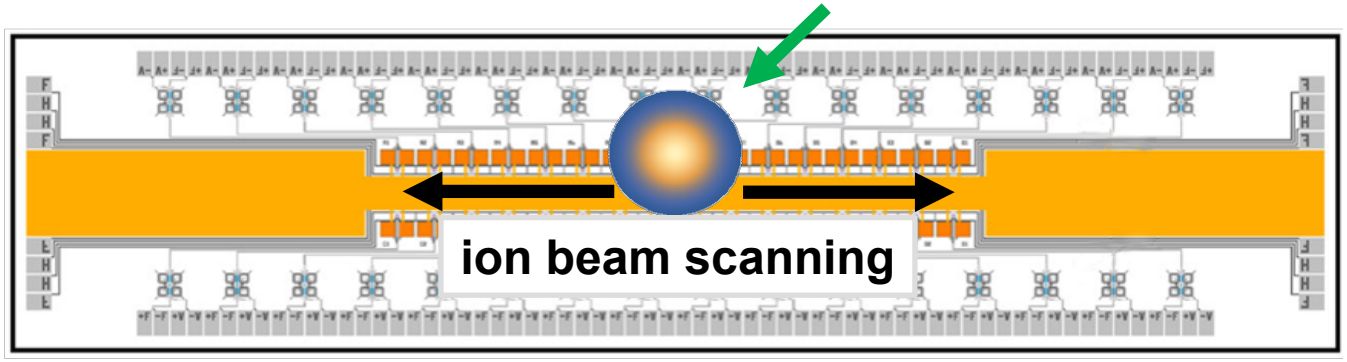
Suppression Demonstrated on Stable Holmium



Direct Ion Implantation – Customized for ECHo



Ion distribution on implantation site: 0.70(2) mm x 0.66(2) mm (FWHM)



Geometric Efficiency of Implantation **18 %**

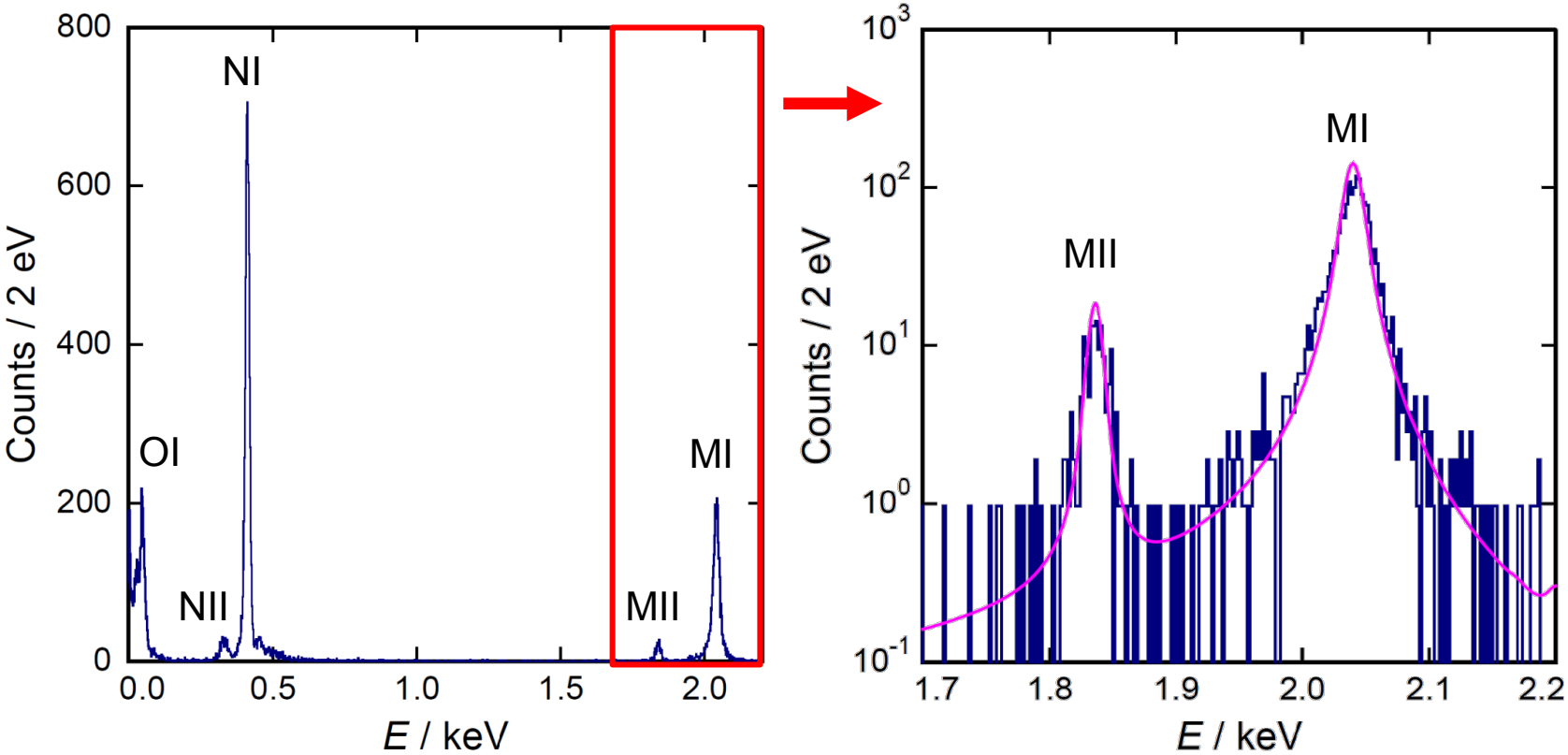
Summary and Outlook

ECHo-1k → • Proof of technique and scalability ✓
• Production of high purity ^{163}Ho source ✓

→ Accumulation of 10^{10} counts

ECHo-1M → $m(\nu_e) < 1$ eV envisaged in the next 5 years

First Results of Prototype Detector: 2 MMC pixels – 0.2 Bq ^{163}Ho – 2 days measured



L. Gastaldo
NuDark2015

Acknowledgements

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

NEUTRONS FOR SCIENCE®

CERN

ISOLDE

Financial support:

DFG Research unit FOR 2202/1

Federal Ministry of Education and Research

JOHANNES GUTENBERG UNIVERSITÄT MAINZ