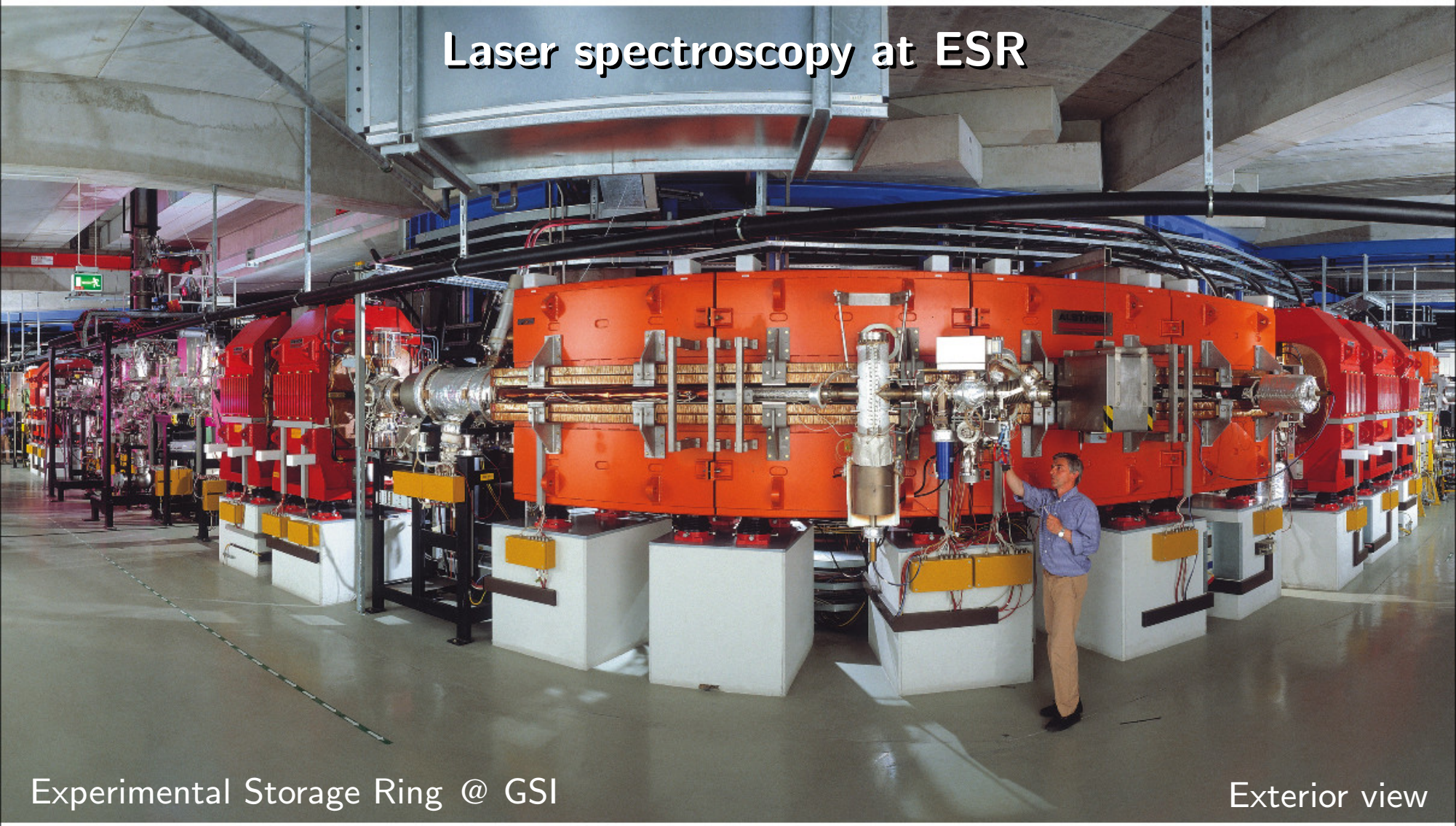
Laser spectroscopy at storage rings
- HESR -

Rodolfo Sánchez

GSI Helmholtzzentrum für Schwerionenforschung GmbH

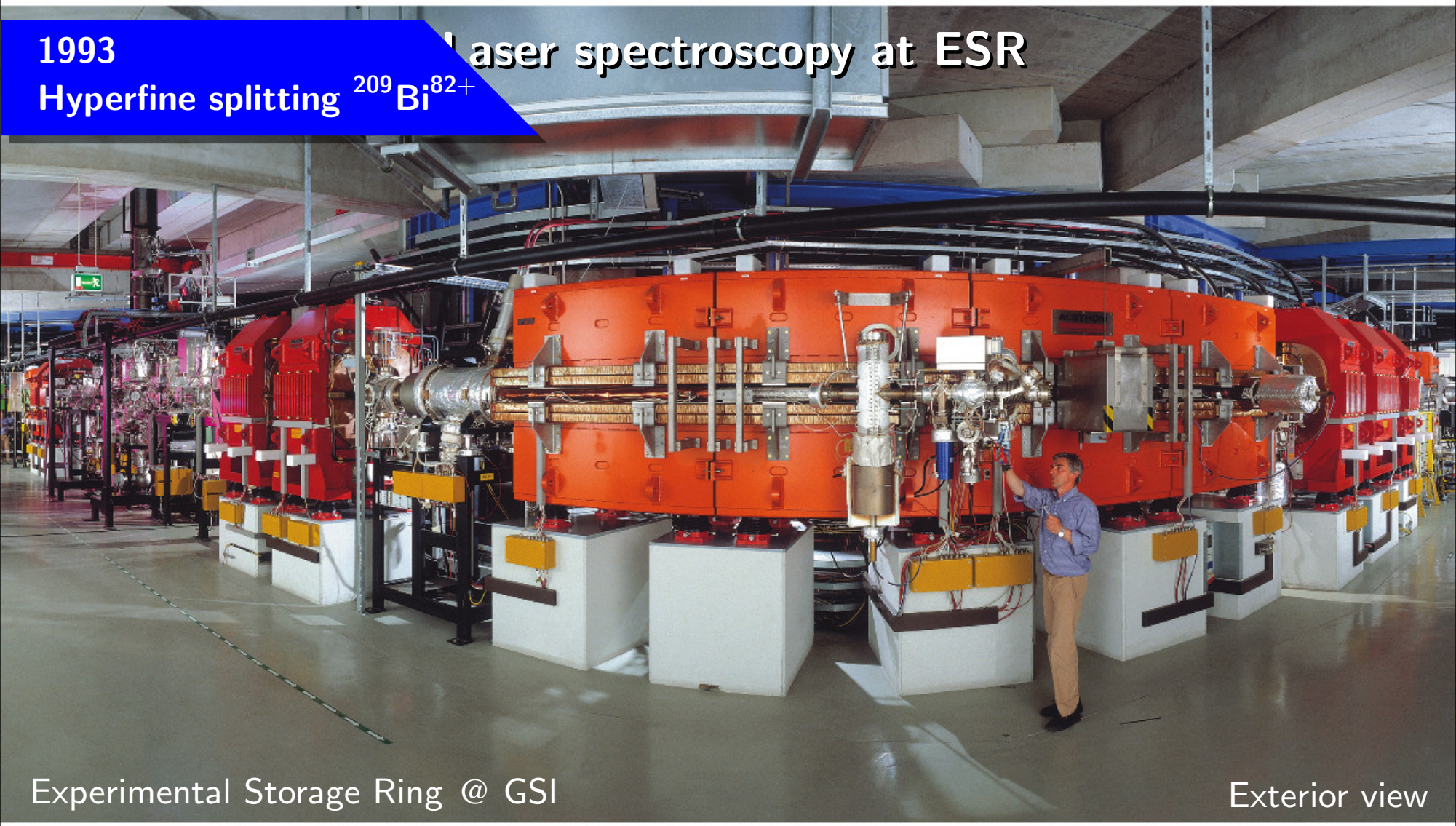
SPARC Workshop 2016 – Kraków, Poland

23 Years


Laser spectroscopy at ESR
Experimental Storage Ring @ GSI
Exterior view

23 Years

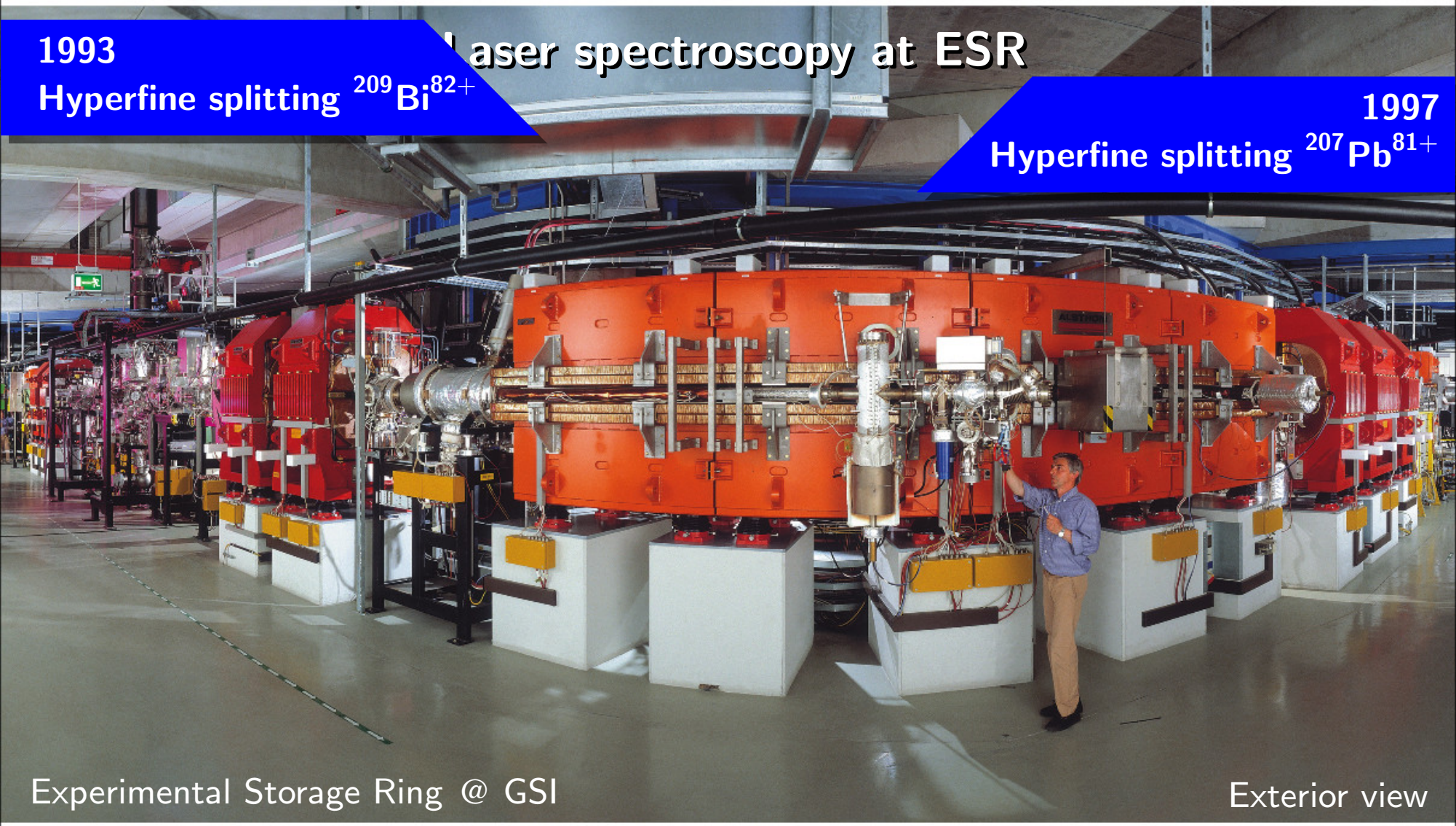
1993
Hyperfine splitting $^{209}Bi^{82+}$



Experimental Storage Ring @ GSI

Exterior view

23 Years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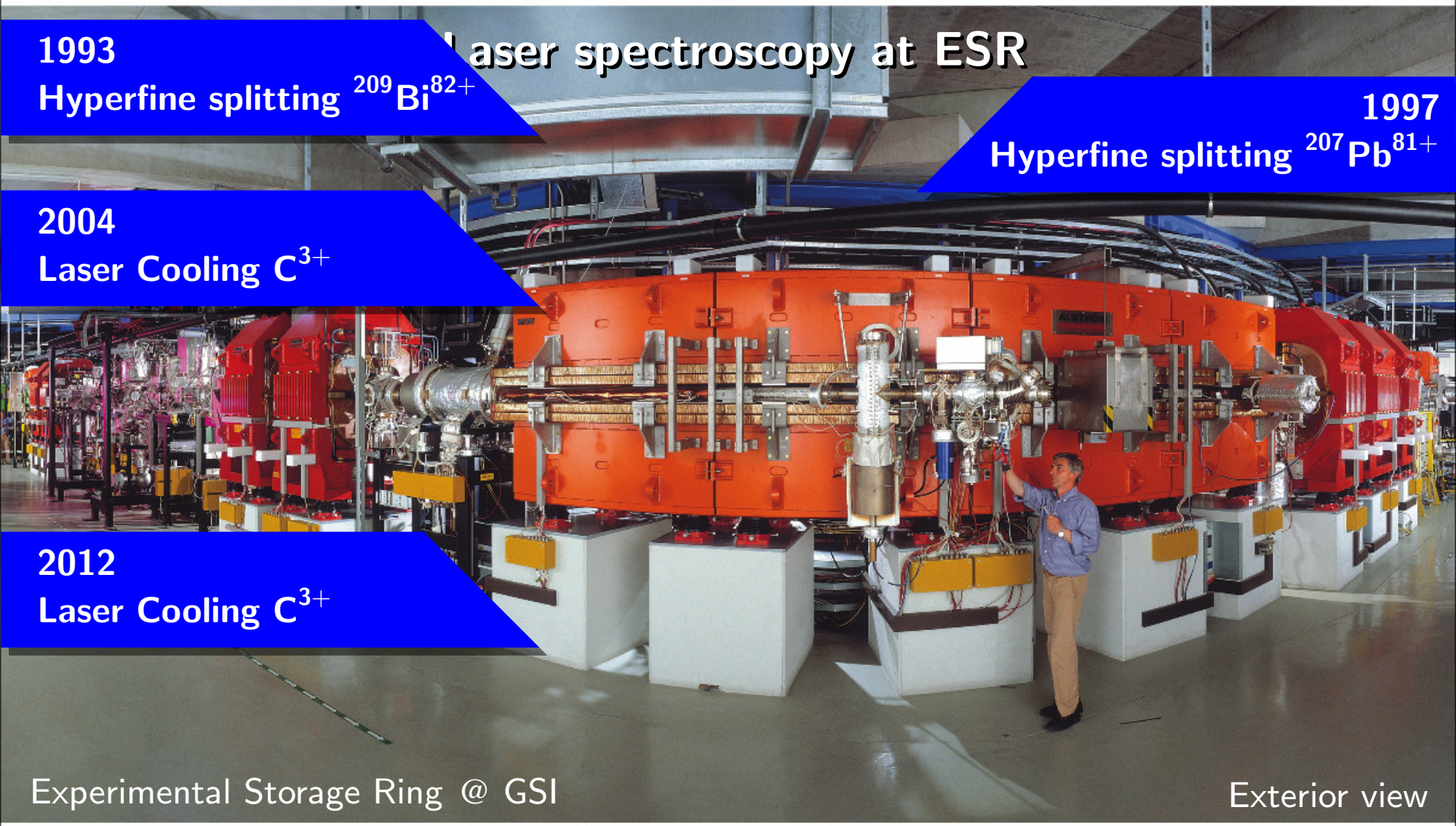
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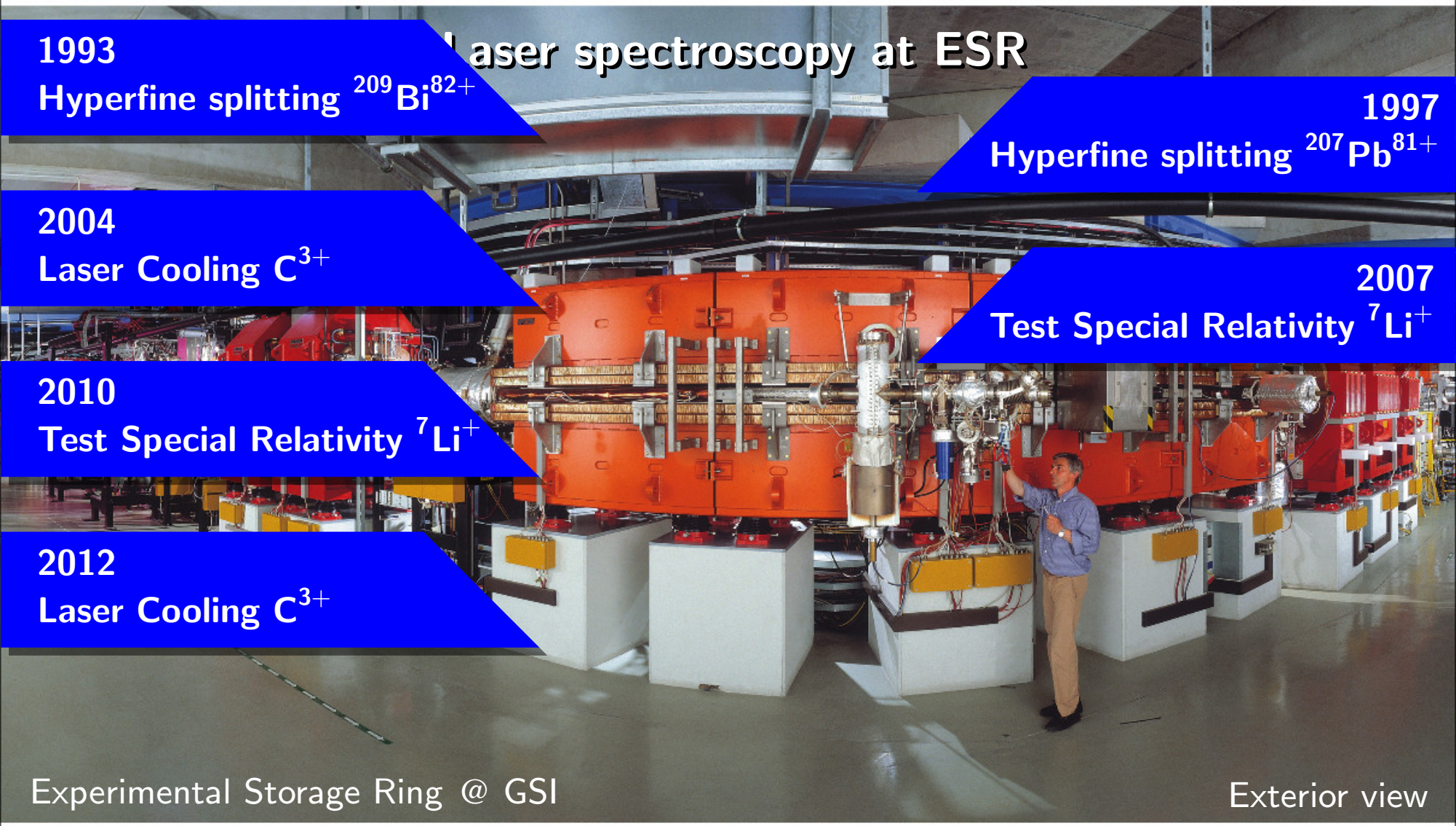
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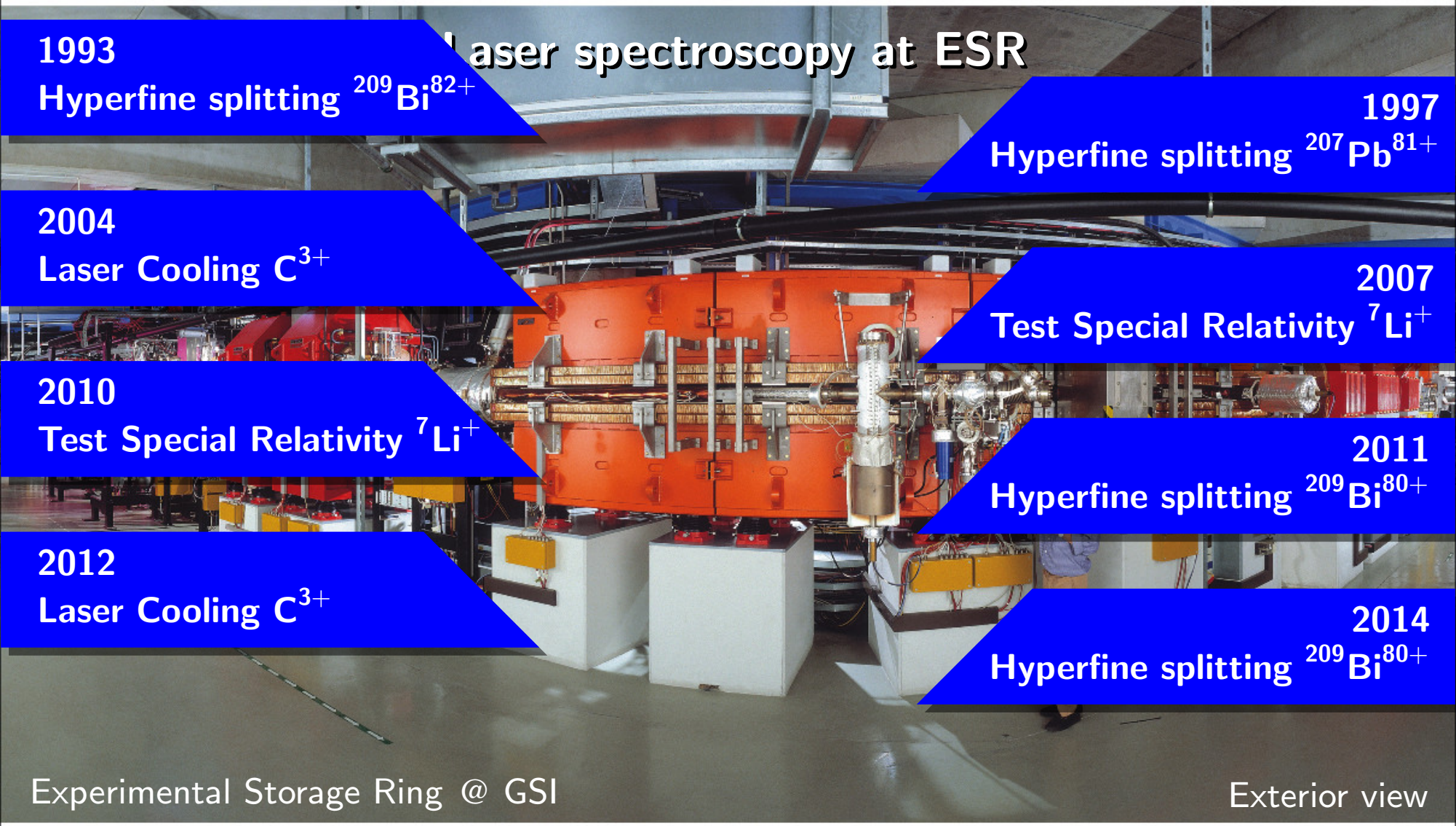
23 Years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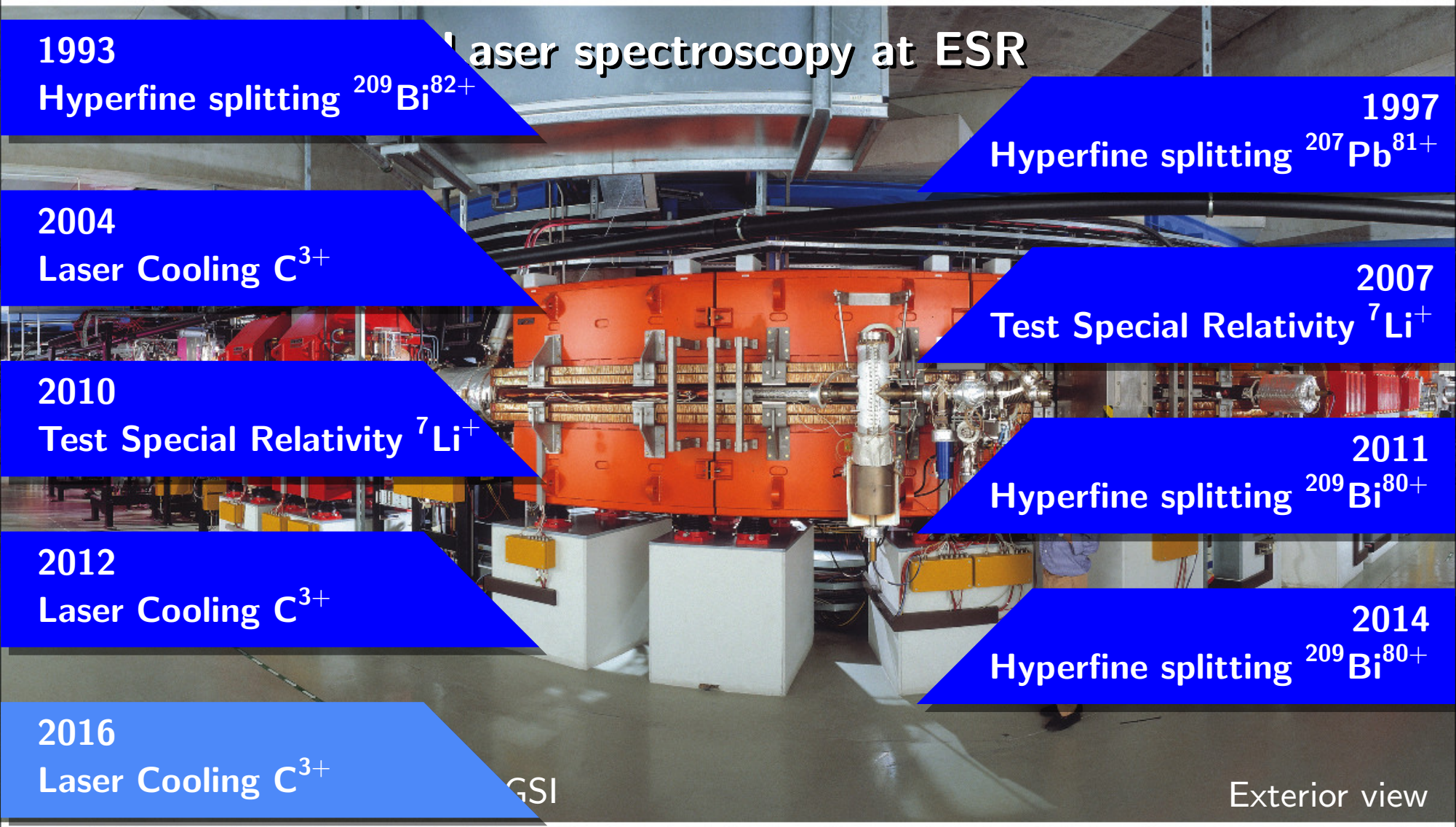
23 Years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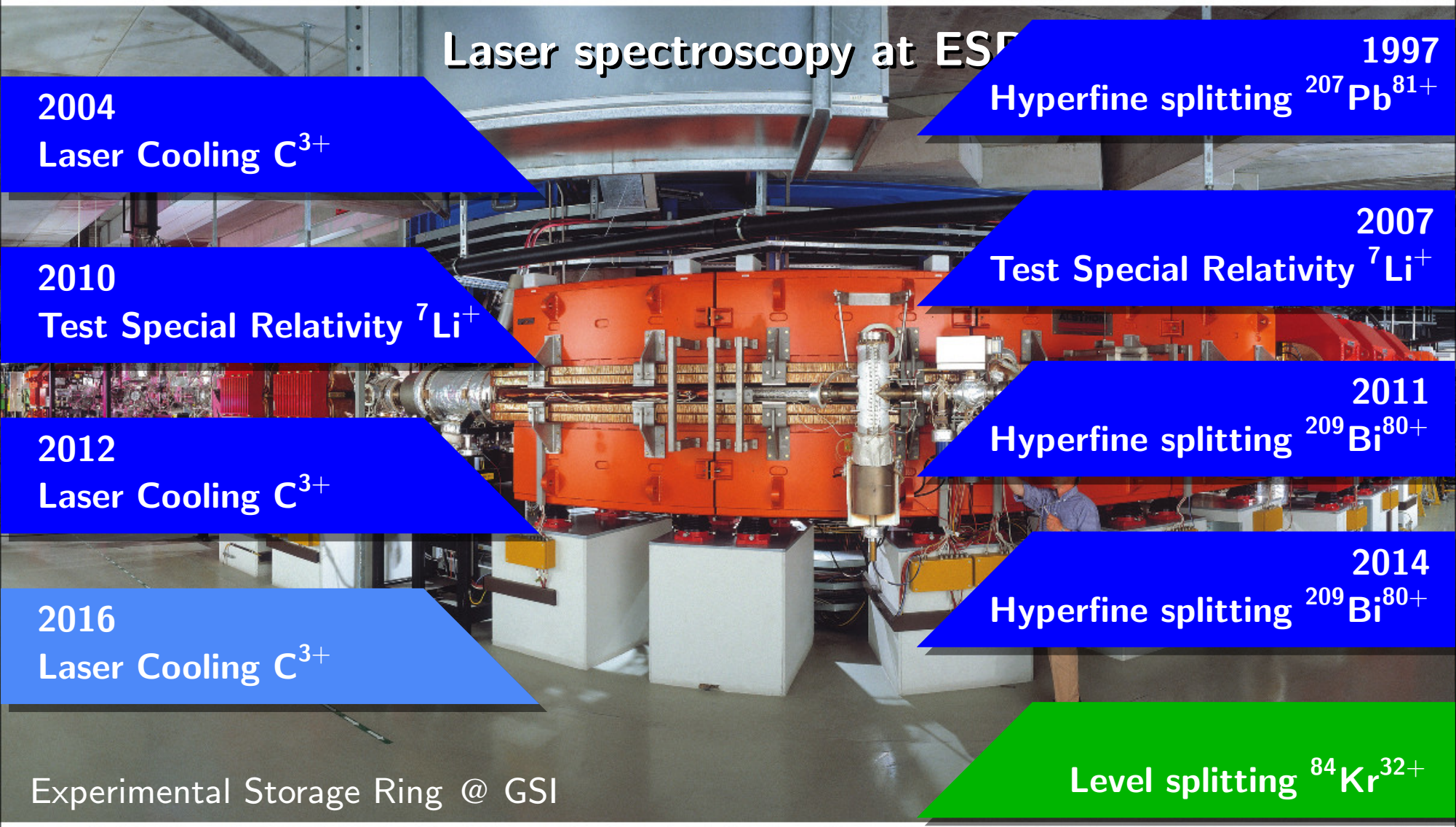
Exterior view

23 Years


Laser spectroscopy at ESR
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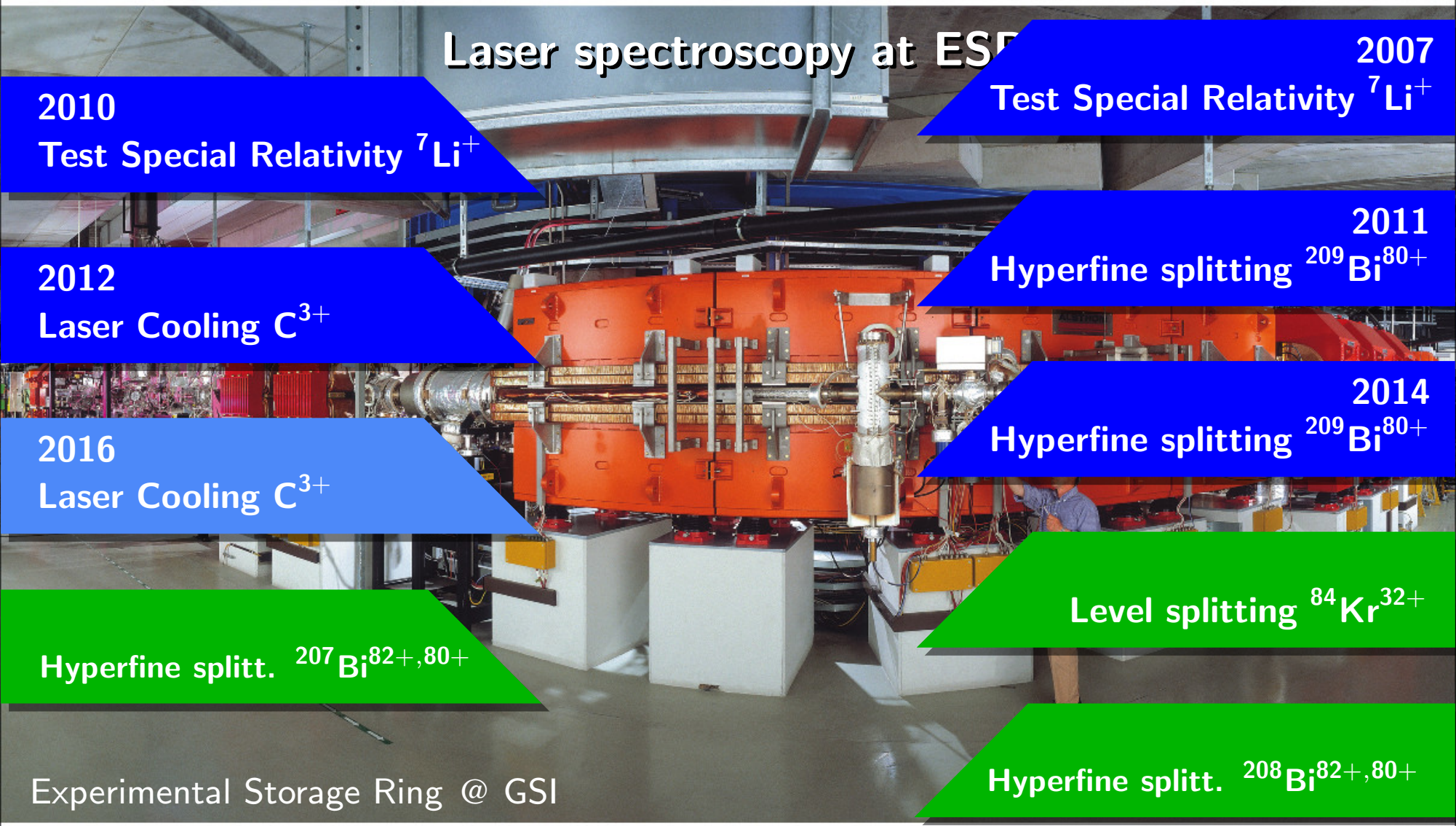
Laser Cooling C^{3+}
Level splitting $^{84}Kr^{32+}$
Experimental Storage Ring @ GSI

23 Years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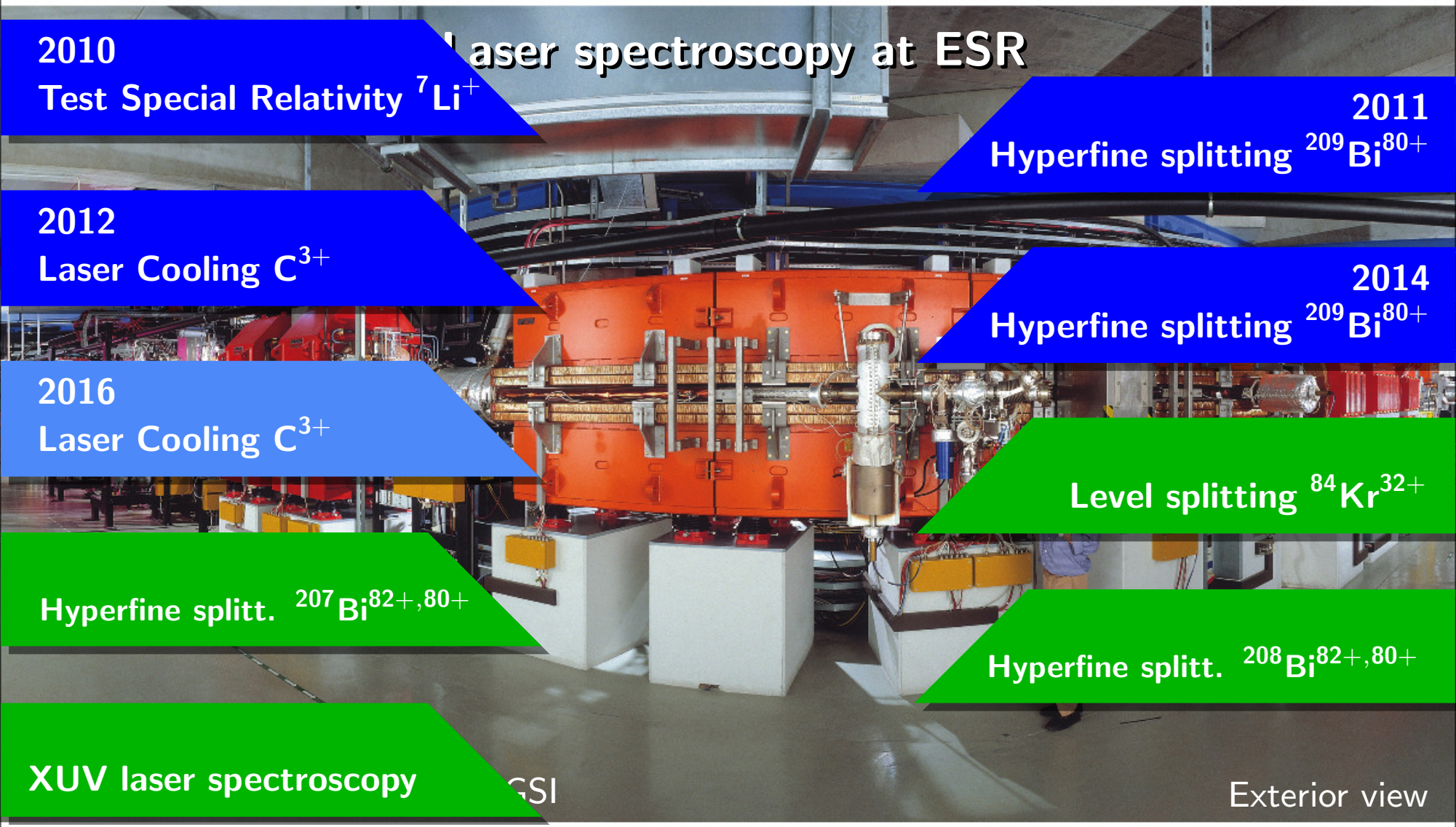
Experimental Storage Ring @ GSI

23 Years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XUV laser spectroscopy
GSI
Exterior view

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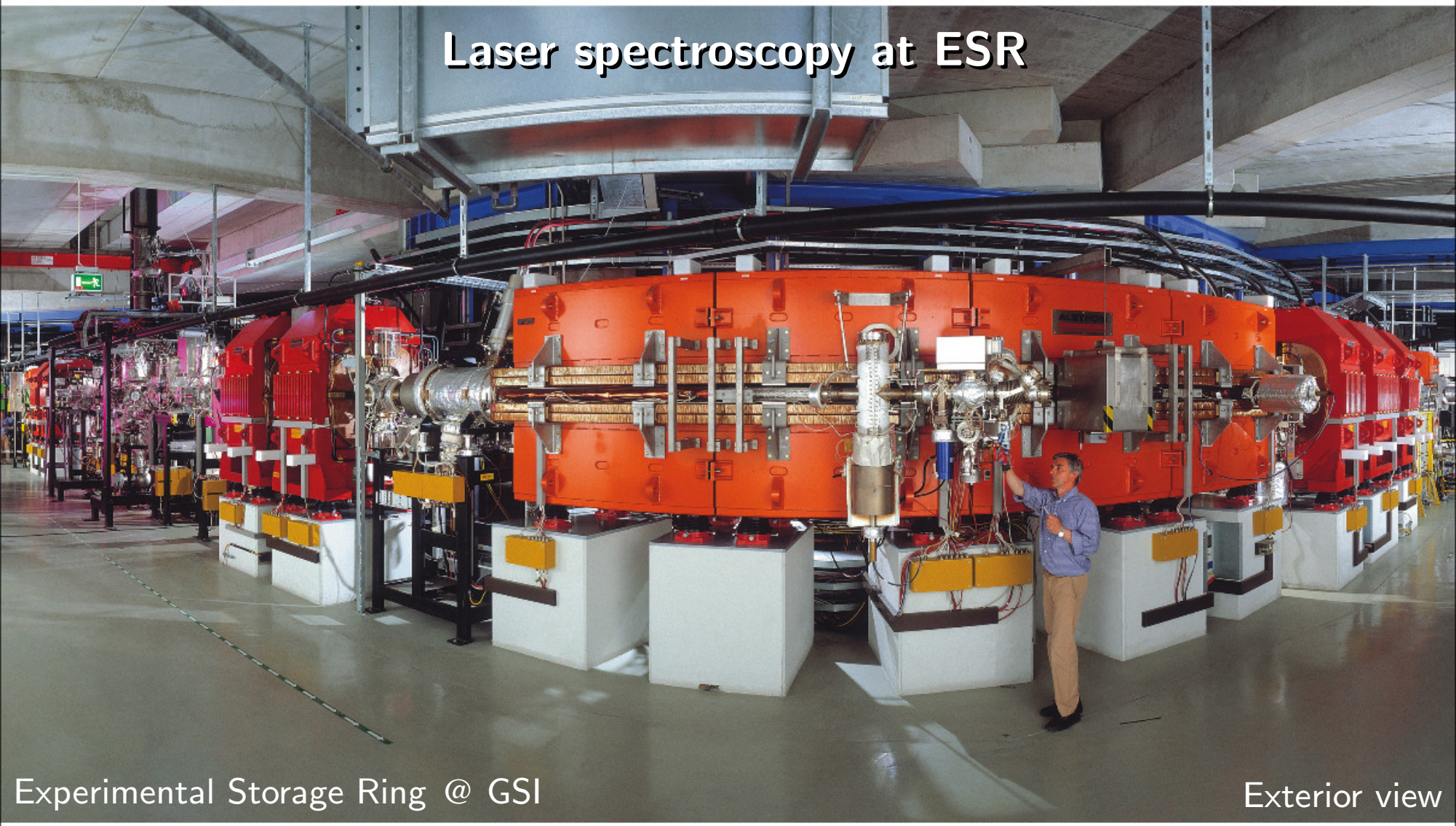
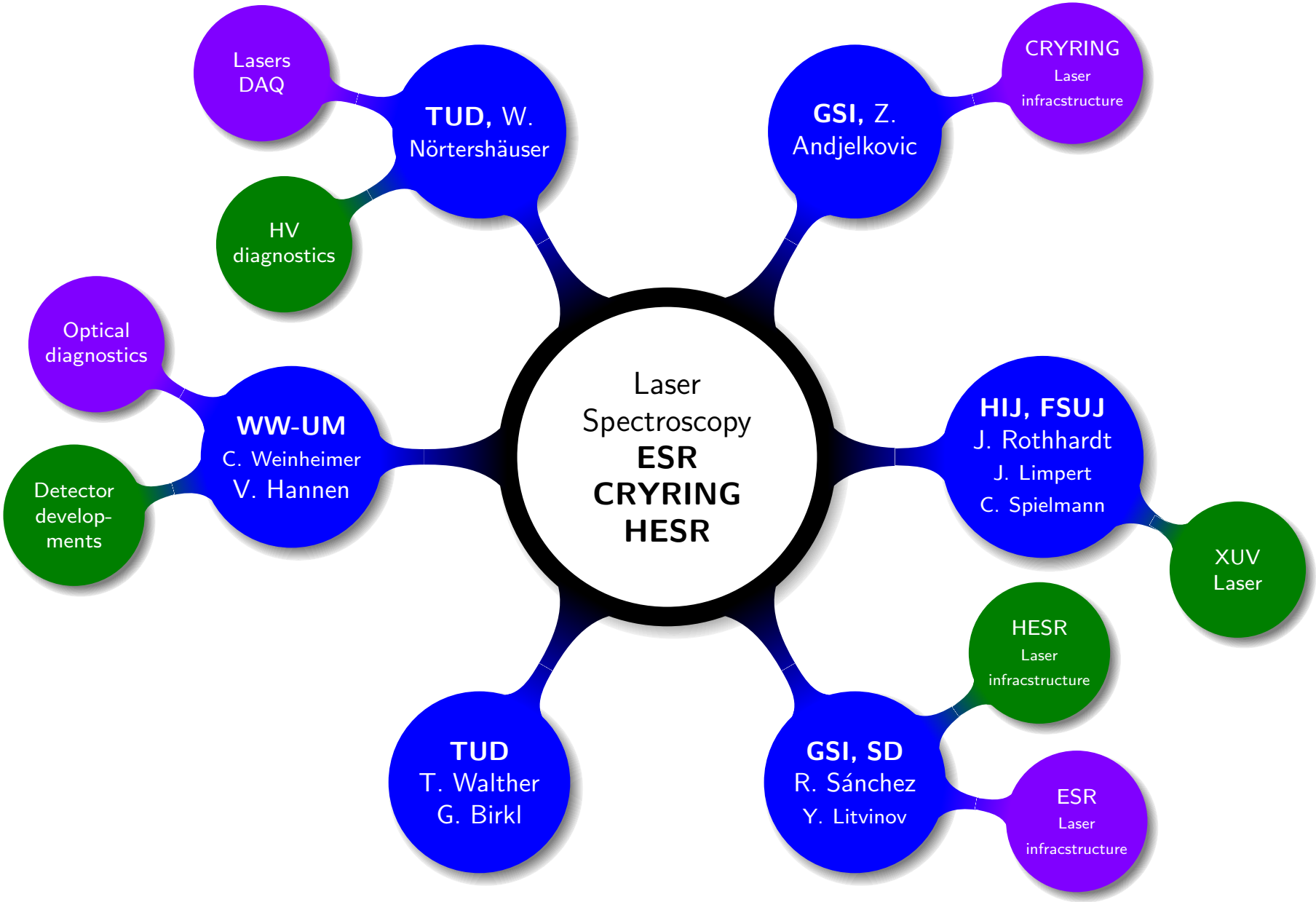

Laser spectroscopy at ESR
Experimental Storage Ring @ GSI
Exterior view

Topics

- Laser spectroscopy at storage rings, FAIR
  - *lithium-like systems*
  - *towards XUV laser spectroscopy*
  - *infrastructure HESR*

SPARC working group: Laser spectroscopy



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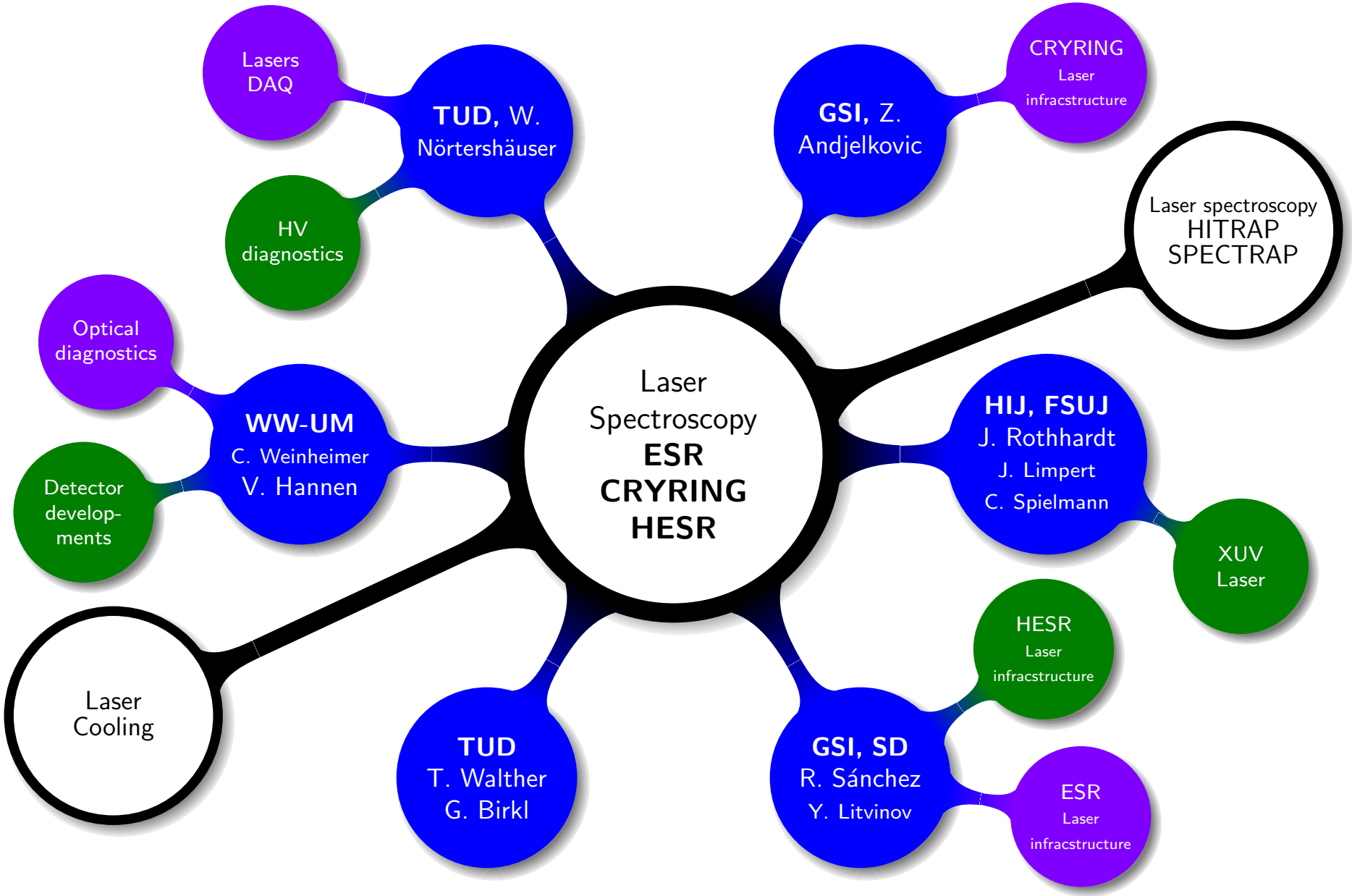


Laser spectroscopy: Publications

- **An improved value for the hyperfine splitting of hydrogen-like $^{209}Bi^{82+}$**
  Ullmann J *et al* 2015 *J. Phys. B* **48** 144022
- **Test of Time Dilation Using Stored Li^{+} Ions as Clocks at Relativistic Speed**
  Botermann B *et al* 2014 *Phys. Rev. Lett.* **113** 120405; Erratum **114** 239902
- **Observation of the hyperfine transition in lithium-like bismuth $^{209}Bi^{80+}$: Towards a test of QED in strong magnetic fields**
  Lochmann M *et al* 2014 *Phys. Rev. A* **90** 030501(R)
- **Detection system for forward emitted photons at the Experimental Storage Ring at GSI**
  Hannen V *et al* 2013 *J. Instr.* **8** P09018
- **APDs as single-photon detectors for visible and near-infrared wavelengths down to Hz rates**
  Jöhren R *et al* 2012 *J. Instrum.* **7** P02015

Submitted

- **Laser spectroscopy measurement of the 2s-hyperfine splitting in lithium-like bismuth**
  Sánchez R *et al* 2016 *New J. Phys.*

In preparation

- **Specific difference in bismuth troubles QED tests in strong B-fields**
  Ullmann J *et al* 2016
- **Lifetime of the upper hyperfine splitting state in $^{209}Bi^{80+}$**
  Vollbrecht J *et al* 2016

Laser spectroscopy: PhDs @ ESR

Next
Johannes Ullmann

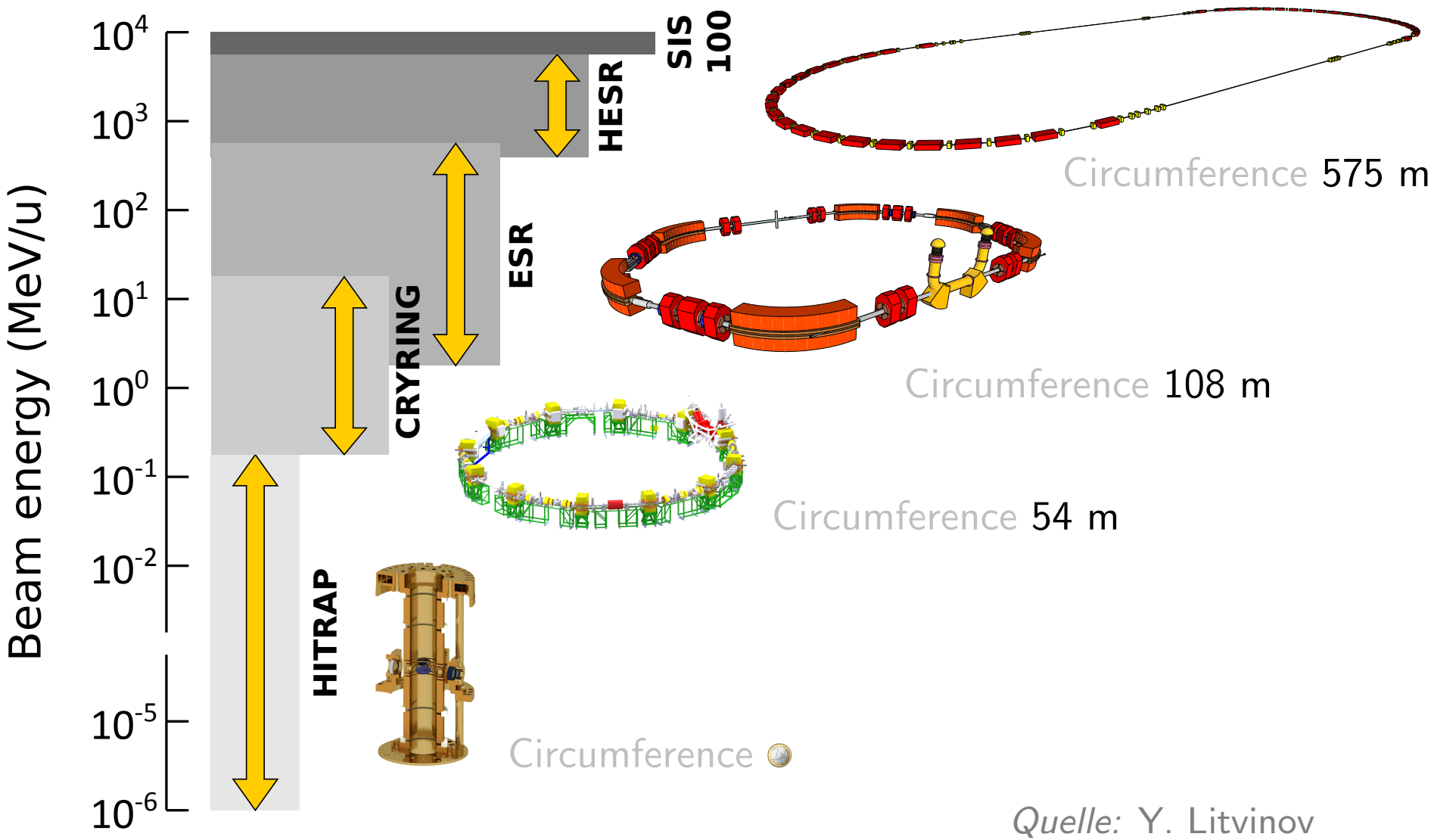
Would you like to join us? Apply! AG: W. Nörtershäuser, Ch. Weinheimer, Y. Litvinov

Activities, 2016

- **Mini workshop: XUV-Lasers at FAIR**
  Germany: Uni-Jena, GSI, Uni-Giessen, TU-Darmstadt. Romania: INFLPR
- **Beamtime: Laser cooling at ESR**
  Germany: GSI, TU-Darmstadt, HI-Dresden, Uni-Münster. China: IMP-Lanzhou
- **Installation of a HV-divider at ESR HV-Cage**
  TU-Darmstadt (J. Ullmann, W. Nörtershäuser), PTB Braunschweig
- **Planning of CRYRING laser laboratory - construction starts Fall 2016**
  GSI (Z. Andjelkovic, M. Lestinsky, W. Geithner, R. Sánchez)
- **Installation of the new detection system for XUV forward emitted photons at ESR**
  Uni-Münster (V. Hannen, D. Winzen, C. Egel, A. Buß), GSI (D. Winters, R. Sánchez)
- **Preliminary studies for the CRYRING optical detection region**
  Uni-Münster (V. Hannen, D. Thomas), GSI (Z. Andjelkovic, M. Lestinsky, R. Sánchez)
- **High-voltage diagnostics for the CRYRING electron-cooler**
  Uni-Münster (V. Hannen, D. Winzen)

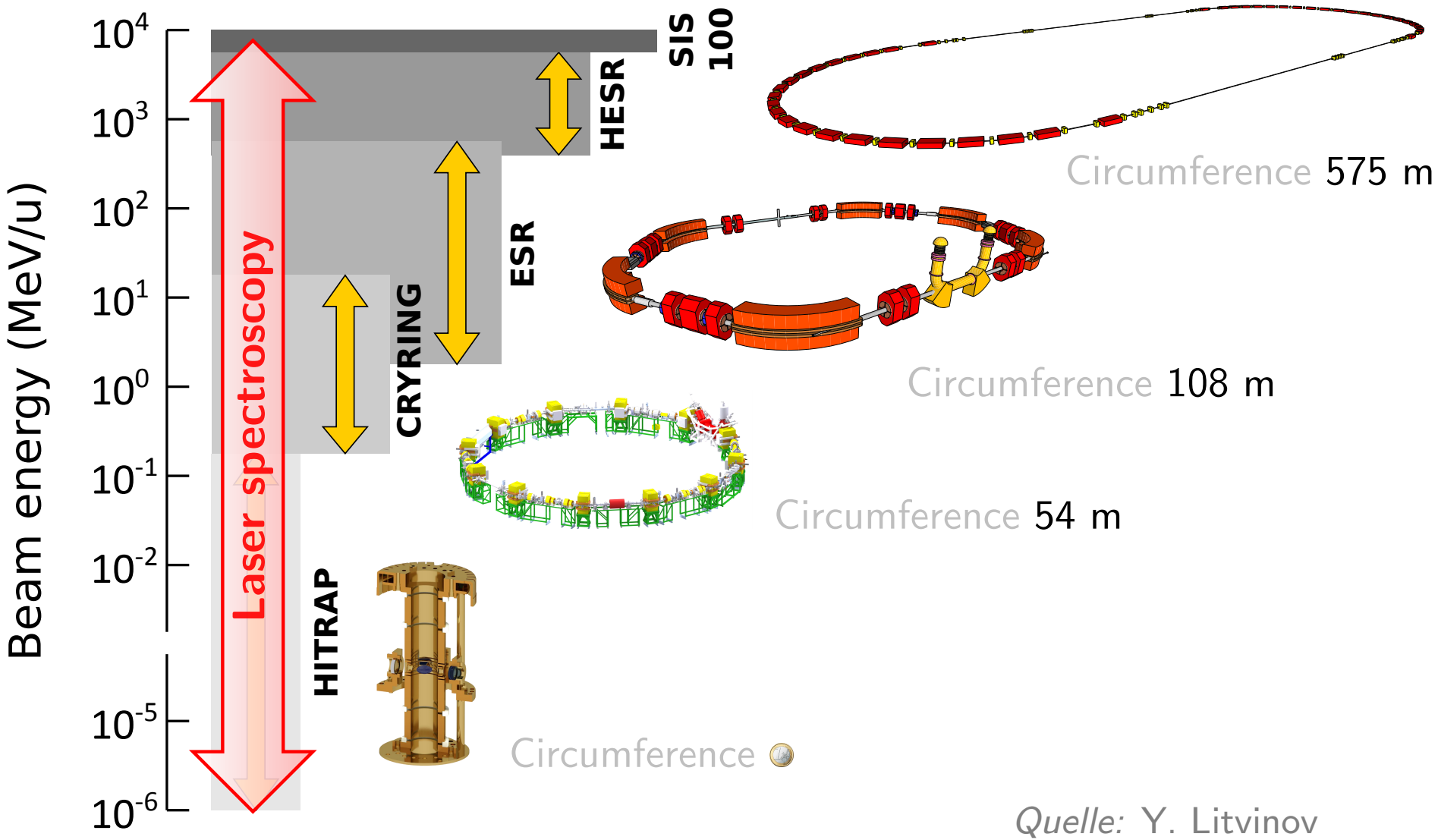
Laser spectroscopy at FAIR

Ion energy spectrum @ FAIR



Quelle: Y. Litvinov

Ion energy spectrum @ FAIR



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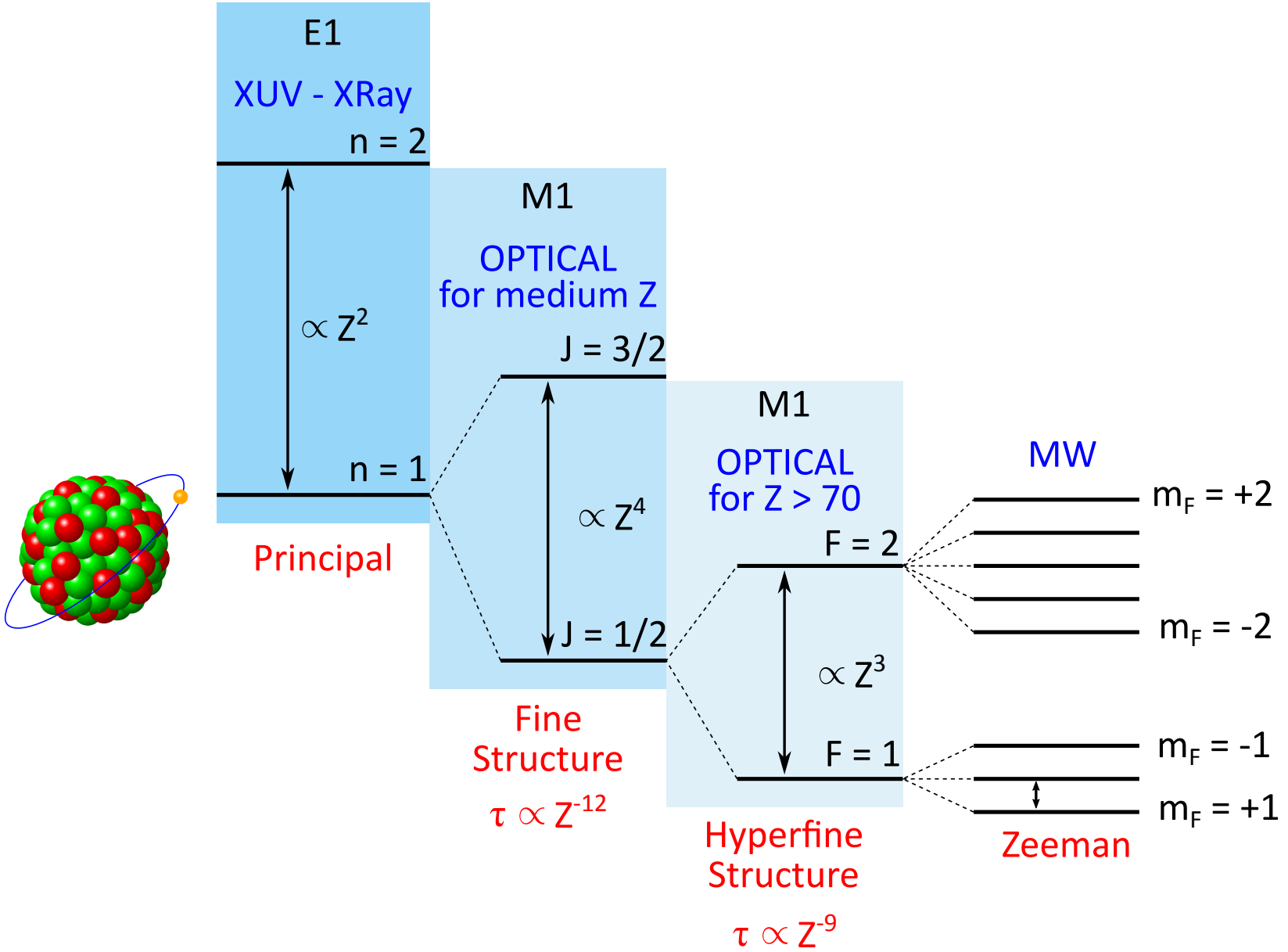
Electron Transitions in HCI



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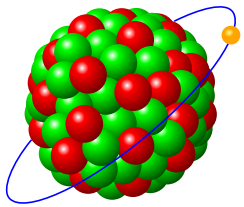

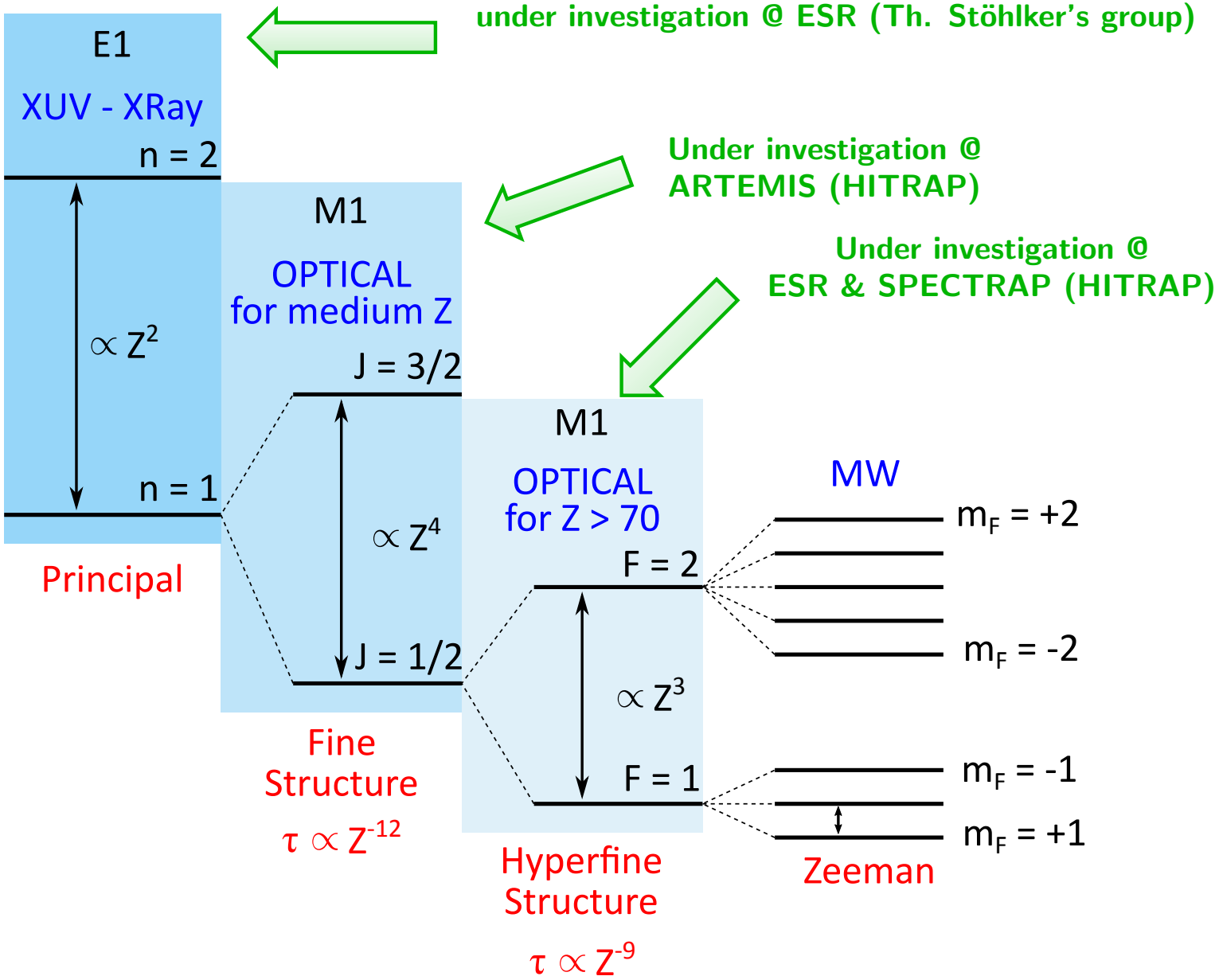

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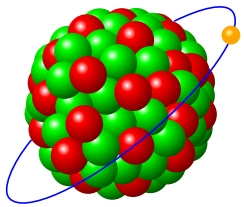
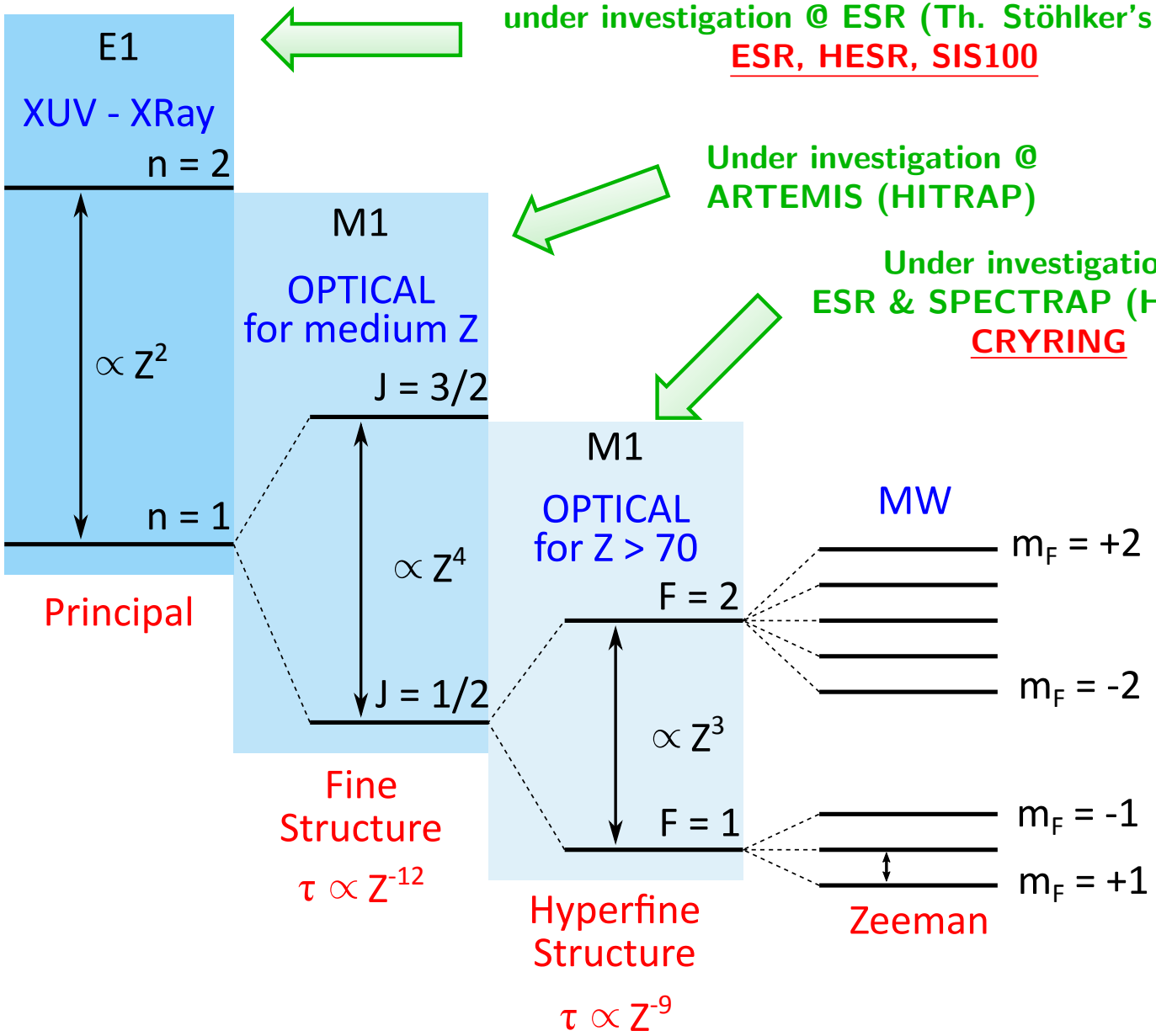
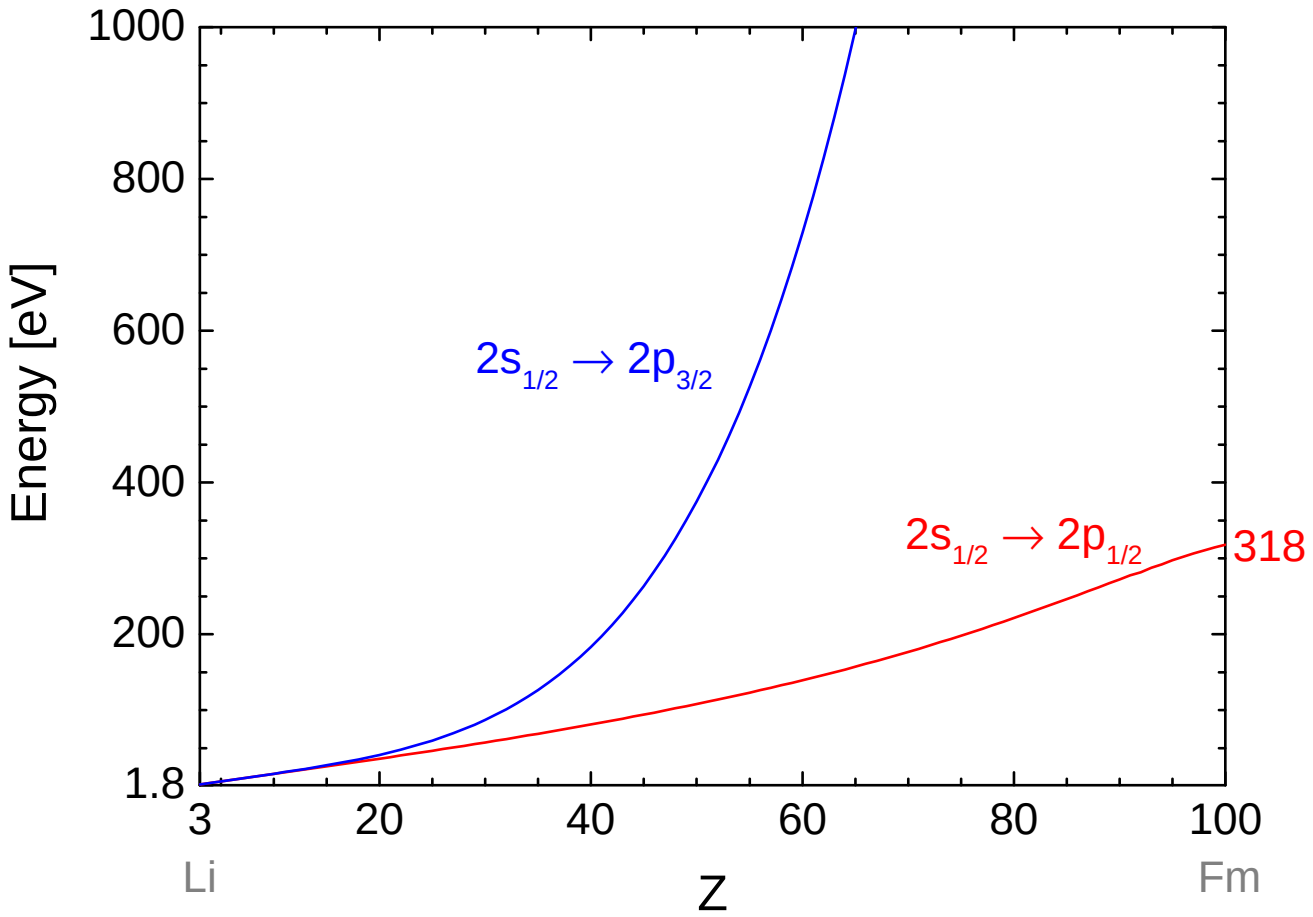
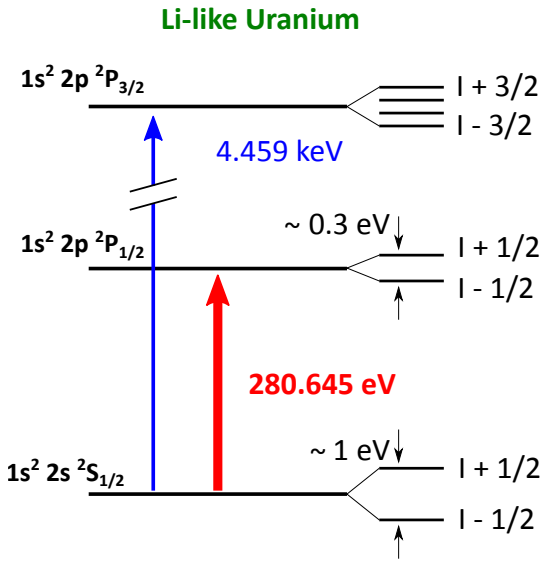




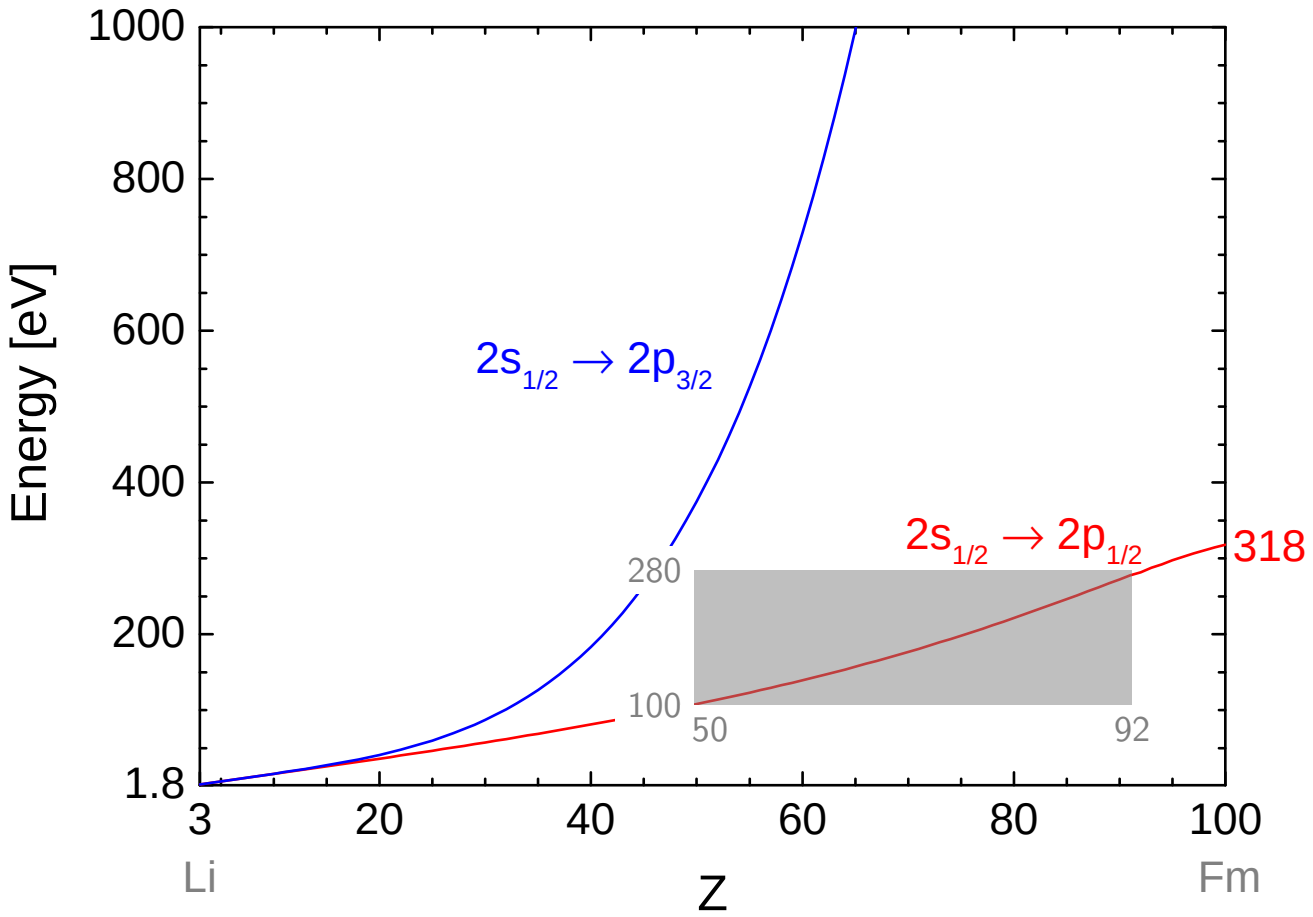
D1 and D2 transitions in Li-like ions

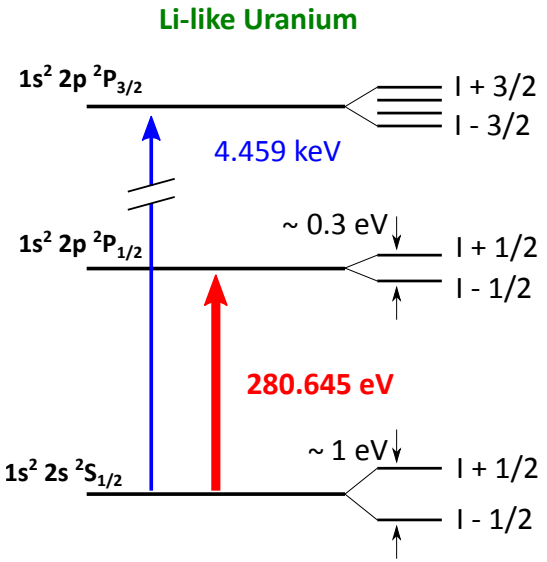




Quelle: Johnson W R, Liu Z W, Sapirstein 1996 *J. At. Data Nucl. Data Tables* **64** 279

D1 and D2 transitions in Li-like ions





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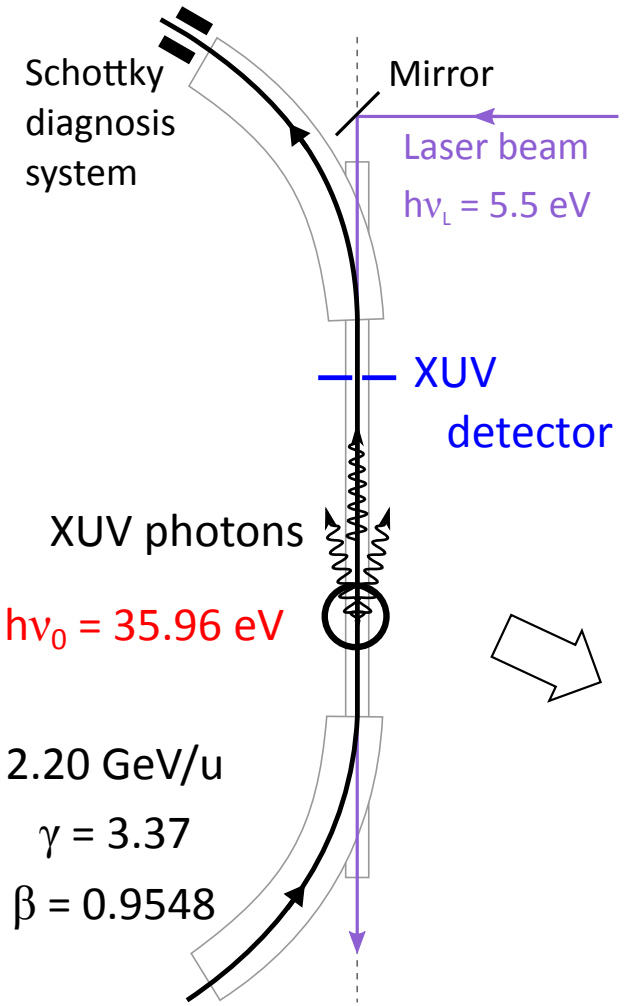
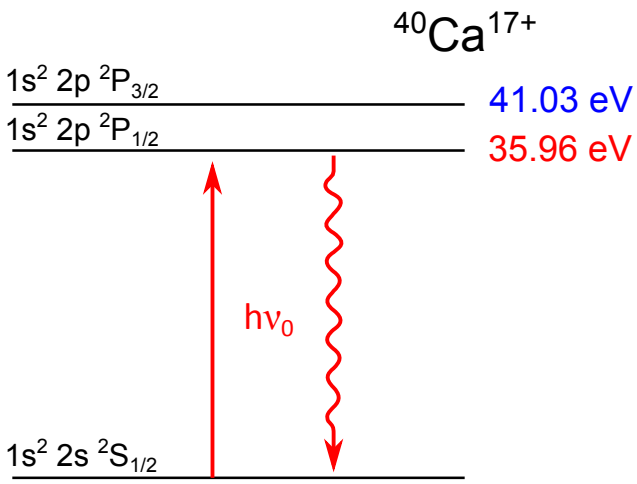
Gedankenexperiment: LS with 5.5 eV laser

Li-like calcium



$$h\nu_0 = \sqrt{\frac{1+\beta}{1-\beta}}\, h\nu_L$$

Ion rest frame



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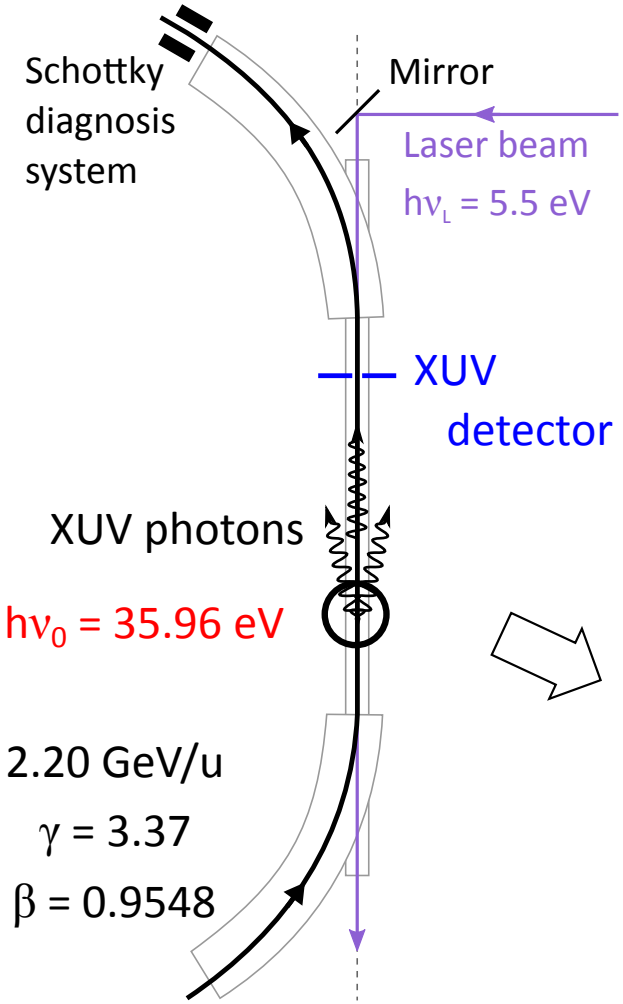

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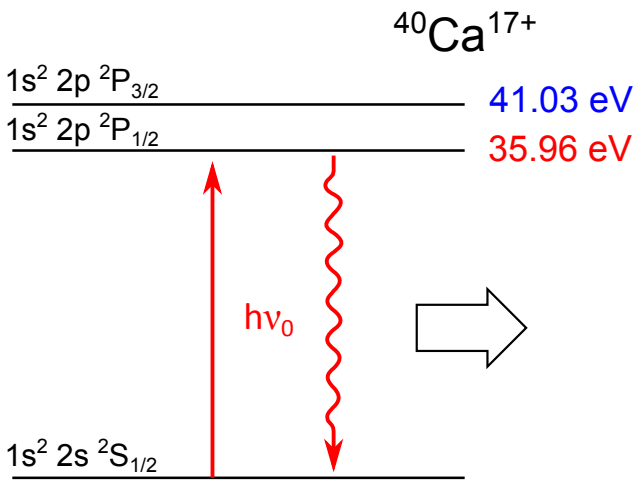
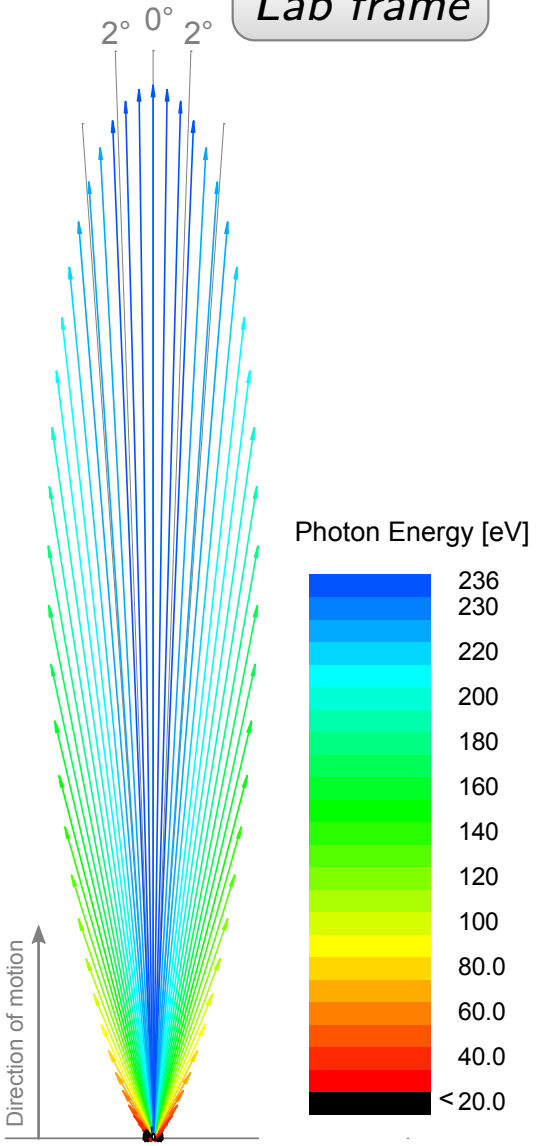
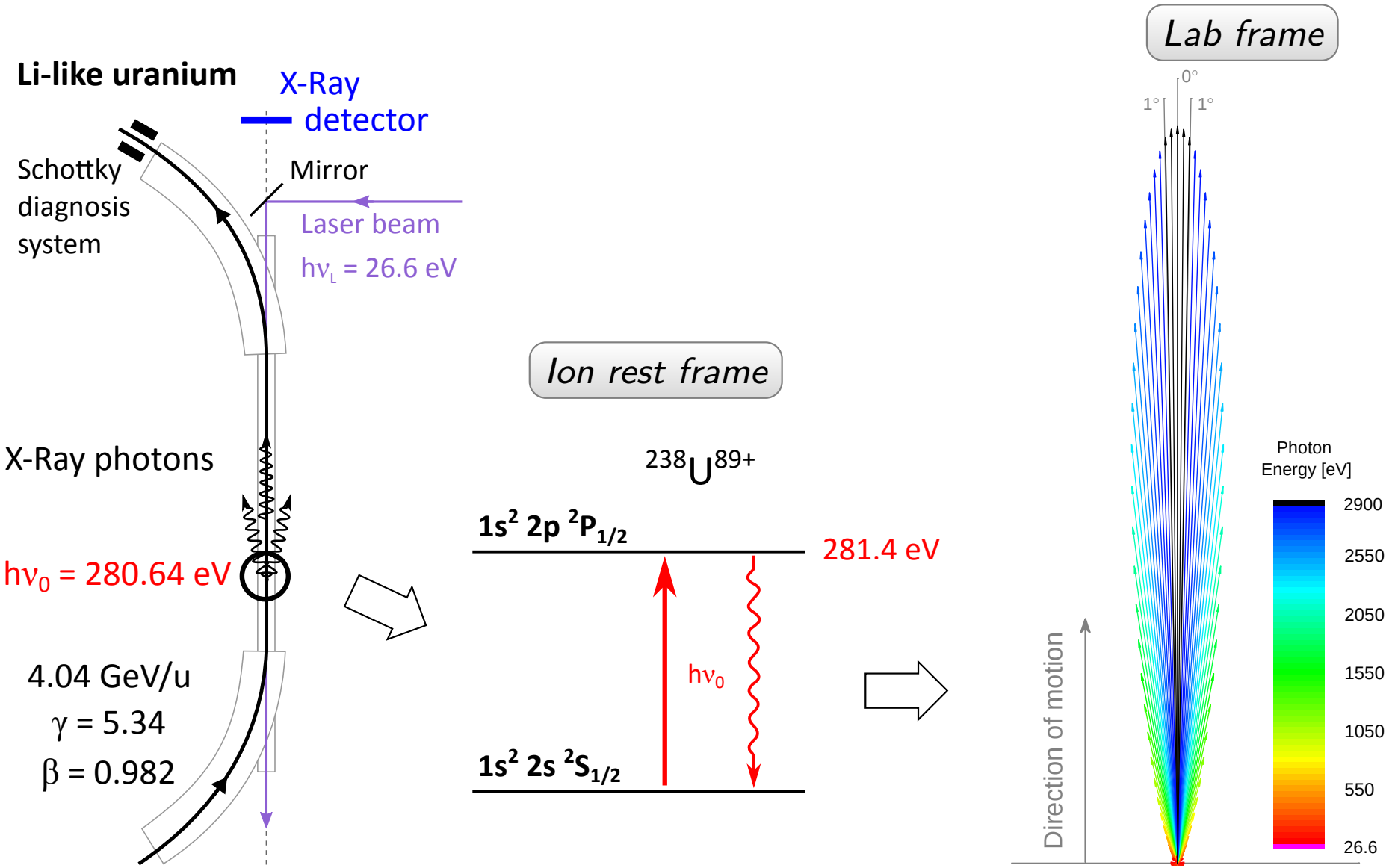


Lab frame

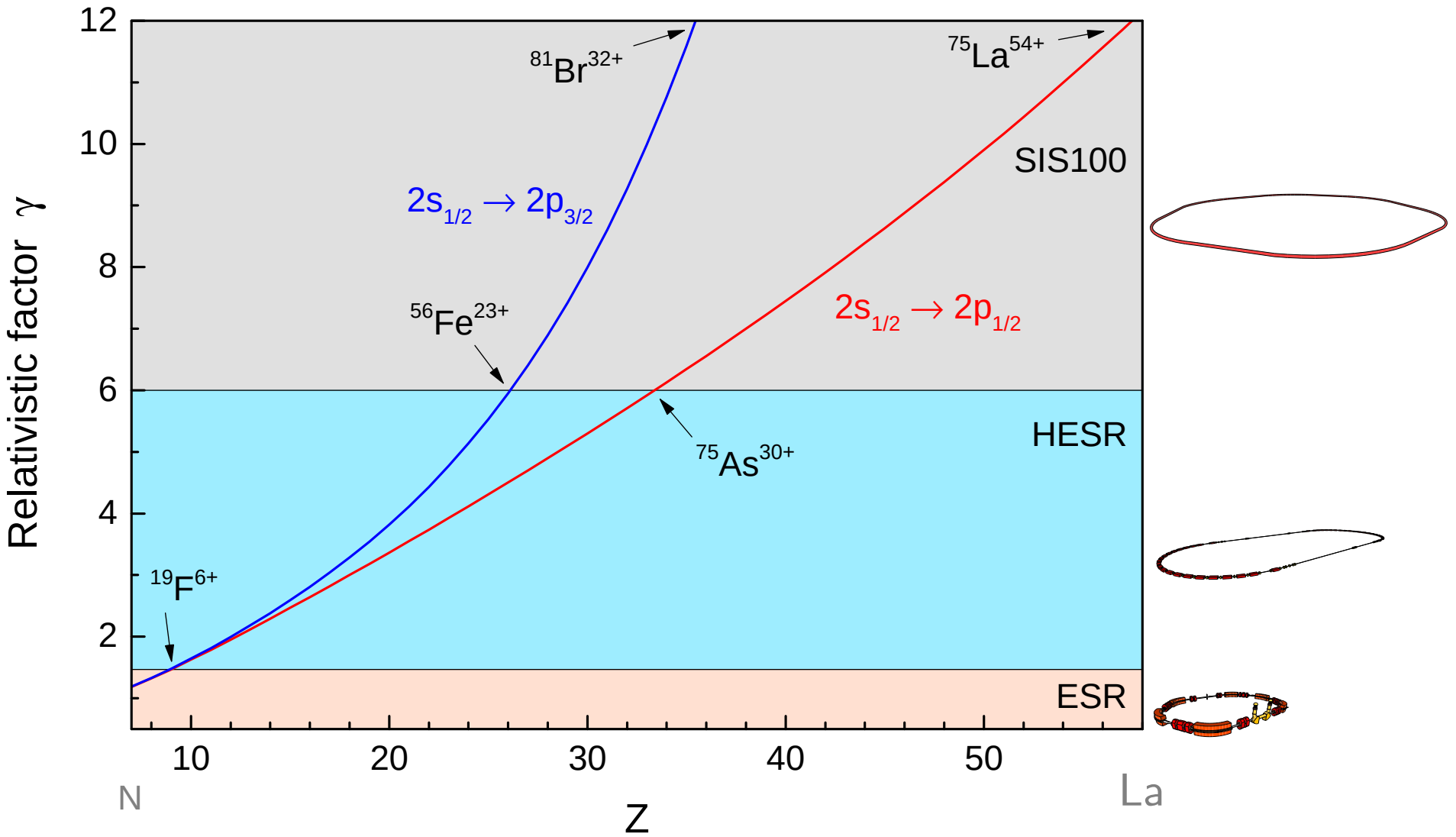


Gedankenexperiment: LS with 26.6 eV laser



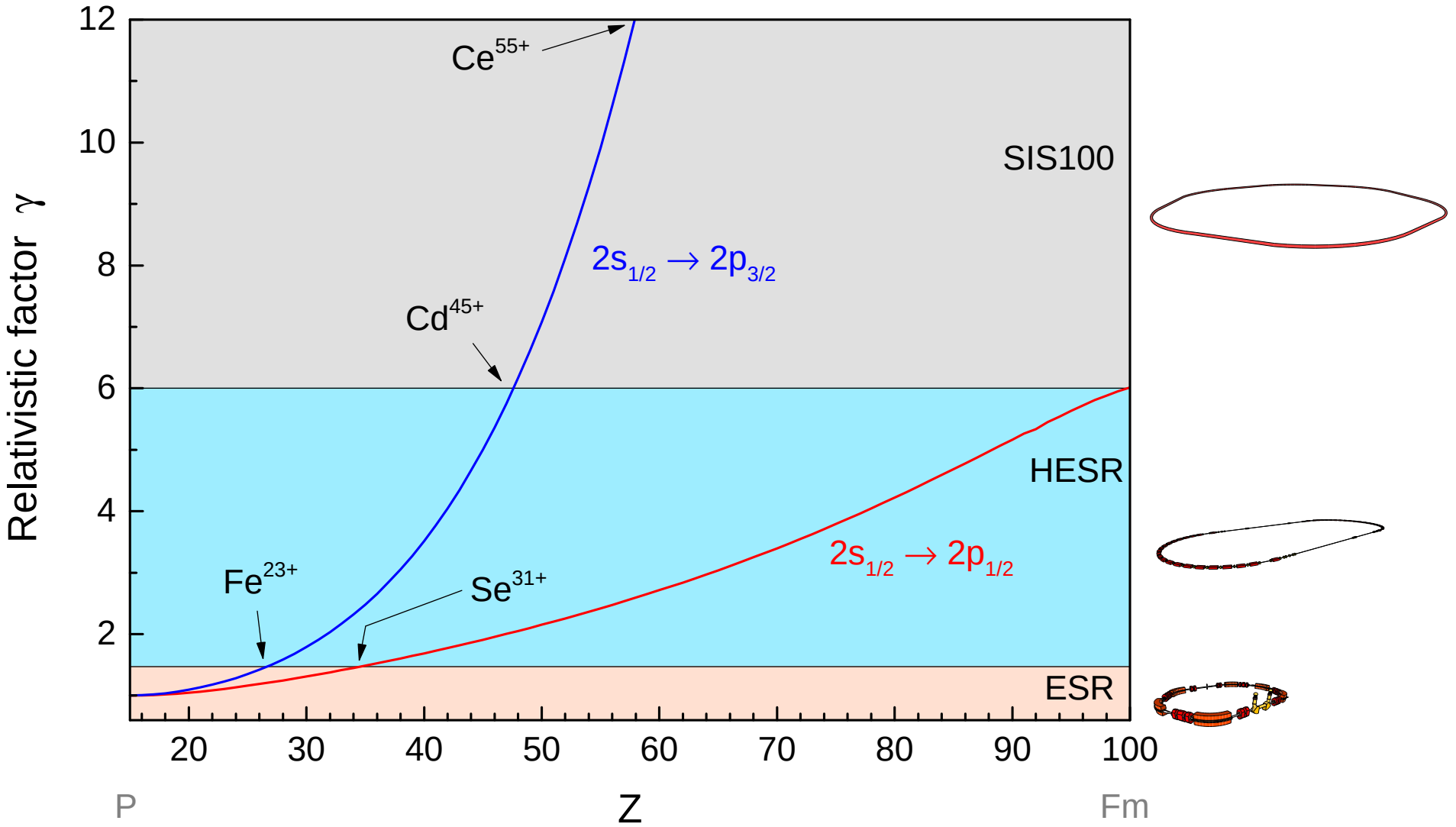
D1 and D2 transitions in Li-like ions

Laser wavelength fix at $\lambda_{Lab} = \mathbf{226.87}$ nm, $E_{photon} = \mathbf{5.5}$ eV



D1 and D2 transitions in Li-like ions

Laser wavelength fix at $E_{photon} = \mathbf{26.6}$ eV



Laser spectroscopy

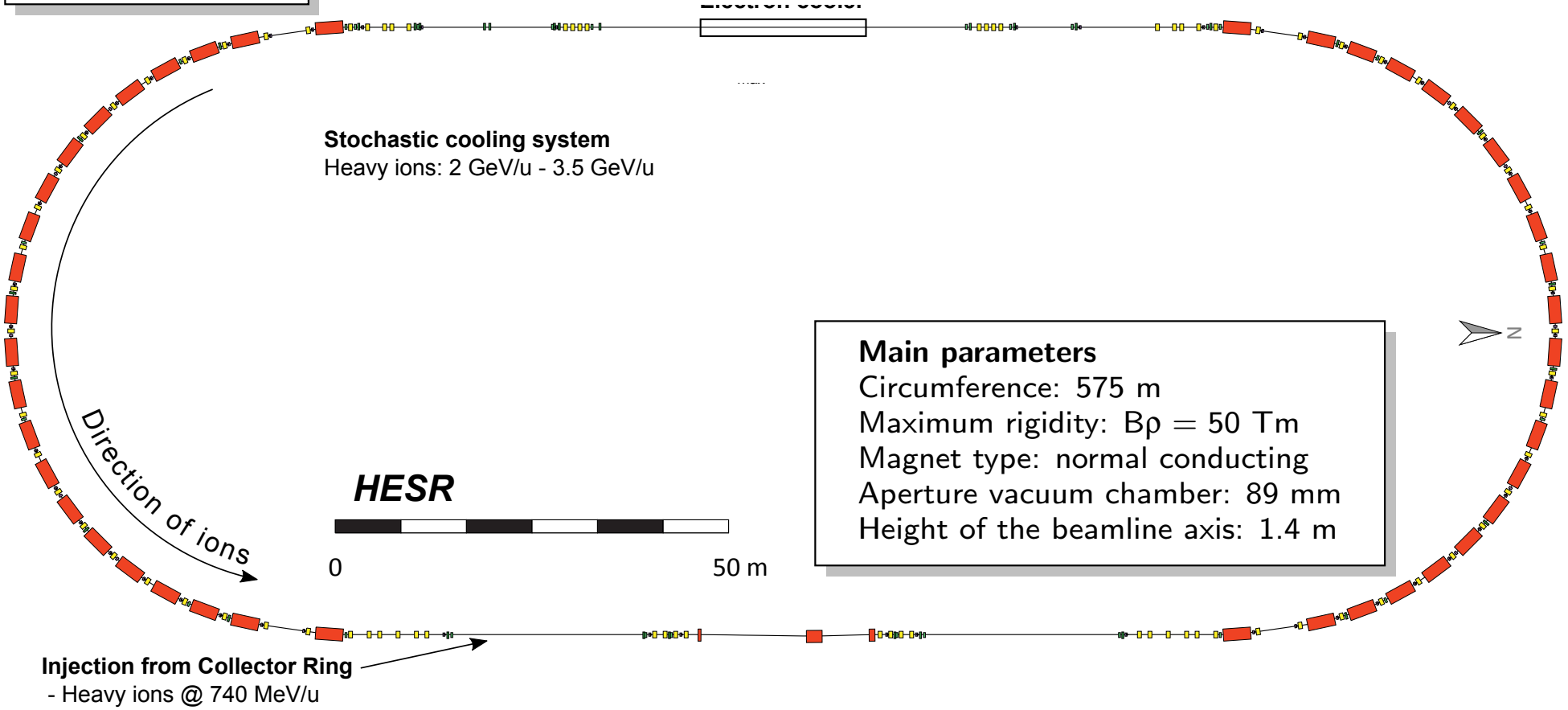
- **Absolute transition energy determination**
  - Requirement: relative accuracy better than 10^{-5}
- **Hyperfine spectroscopy on radioactive isotopes**
  - Required accuracy $\approx 10^{-4}$
  - Isotope shifts $\rightarrow$ difference in nuclear charge radii
  - Hyperfine spectra $\rightarrow$ nuclear magnetic moment and quadrupole moment
- **Application: Preparation of polarized Li-like ion beams**
  - This leads to nuclear polarization
  - First evidence: Laser spectroscopy on Li^+ at the ESR
  - Proporsal: Polarization studies at CRYRING using single charged ions
- **Appication: Laser cooling studies**

Infrastructure

for laser experiments @ HESR

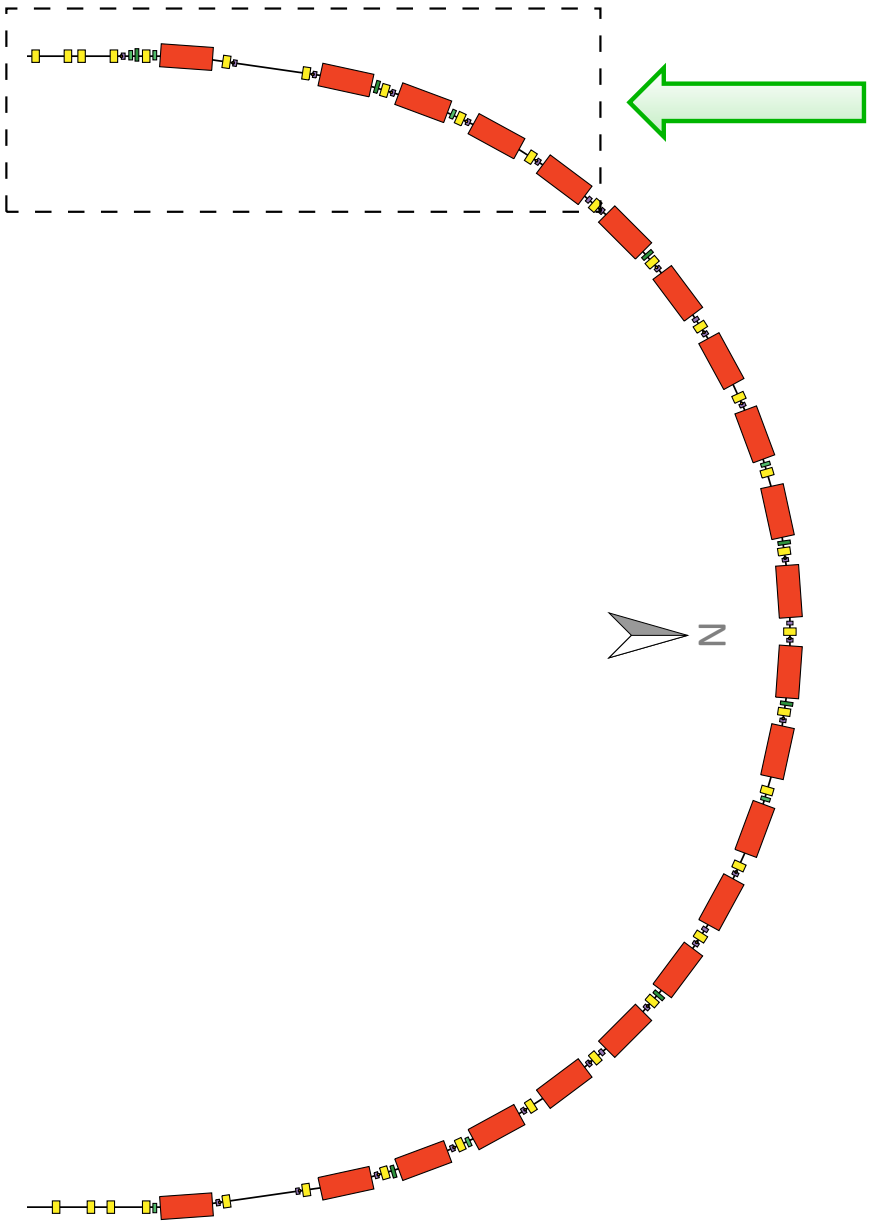
High Energy Storage Ring

Verantwortung:
Institut für Kernphysik
Forschungszentrum Jülich



Main parameters
Circumference: 575 m
Maximum rigidity: $B\rho = 50$ Tm
Magnet type: normal conducting
Aperture vacuum chamber: 89 mm
Height of the beamline axis: 1.4 m

SPARC @ HESR



NW location of SPARC setup
(TDR SPARC@HESR)

SPARC @ HESR

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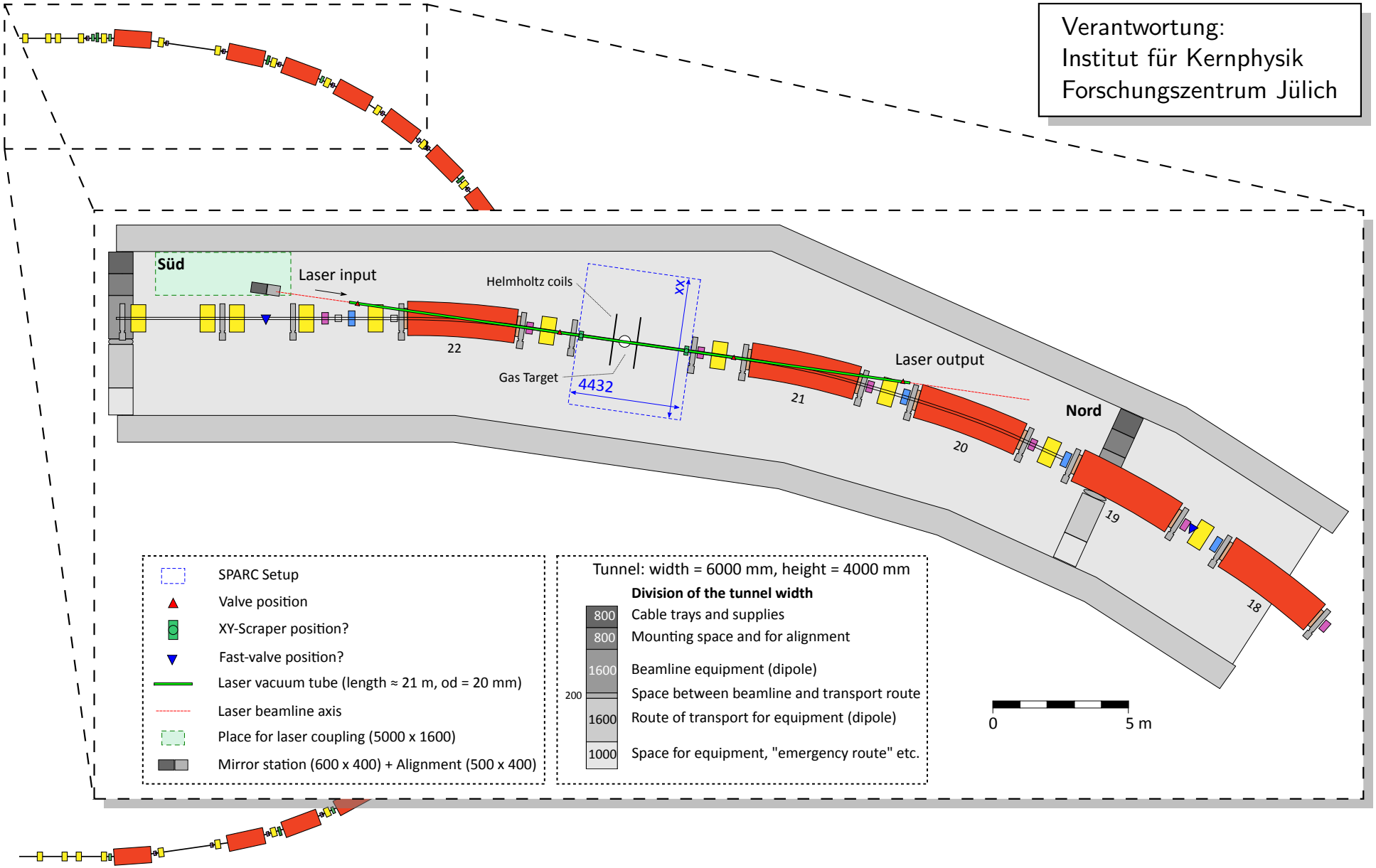

SPARC @ HESR

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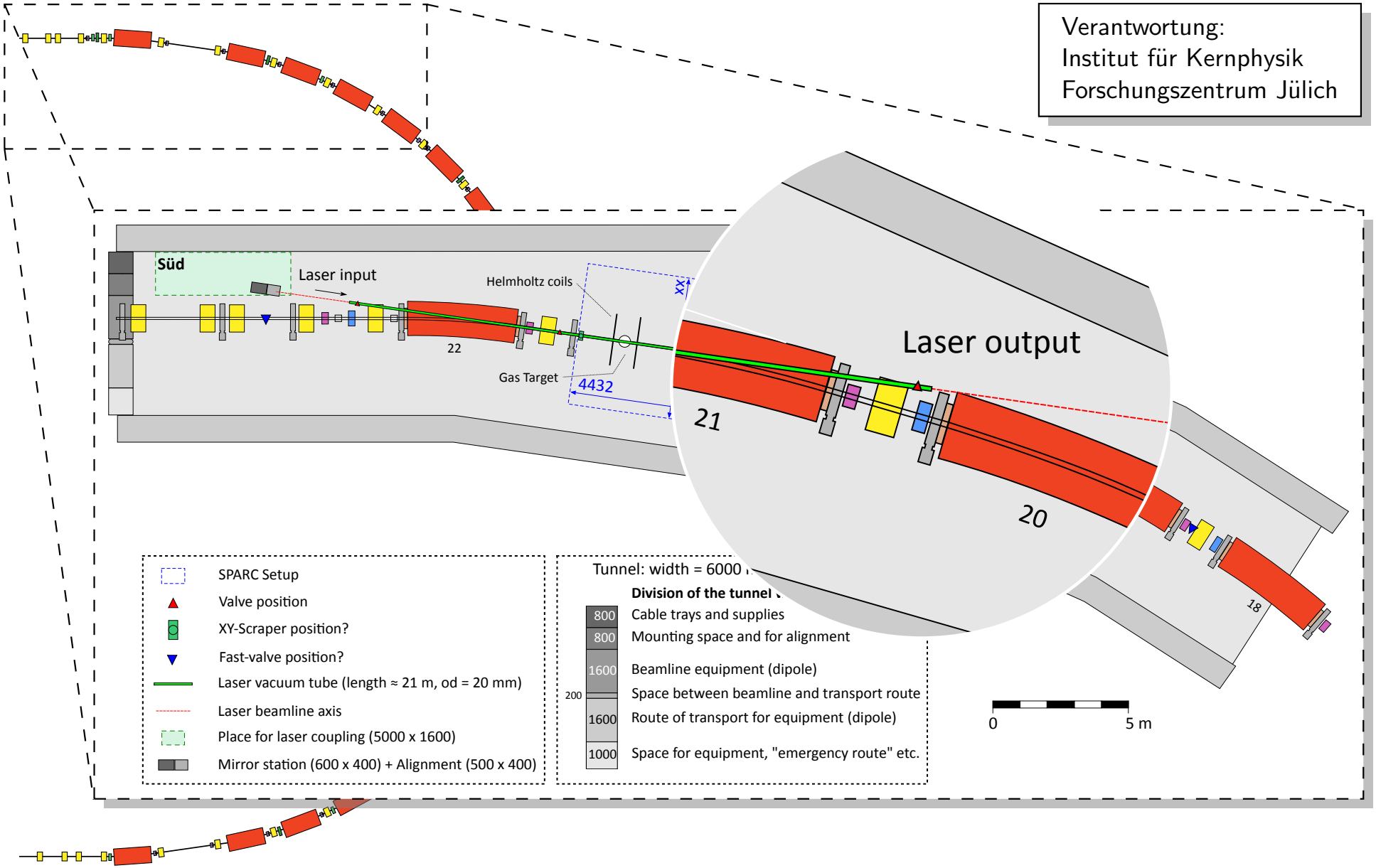

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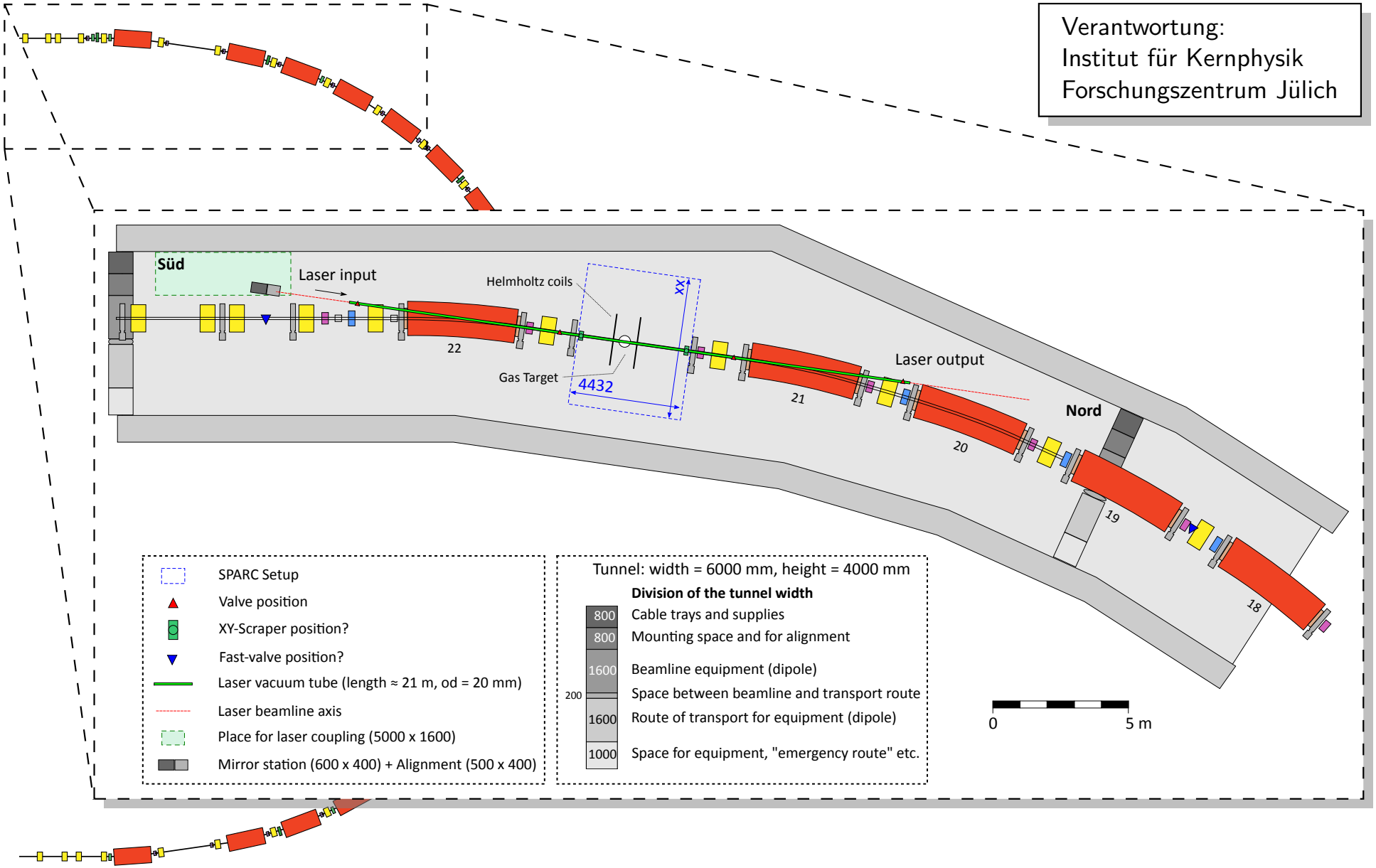
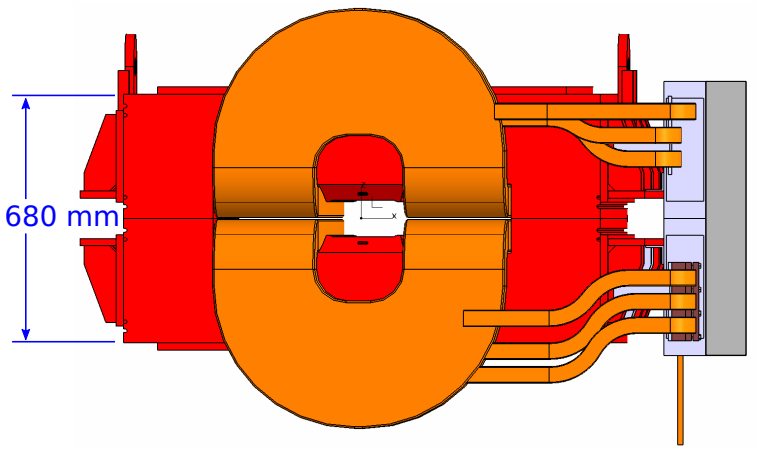
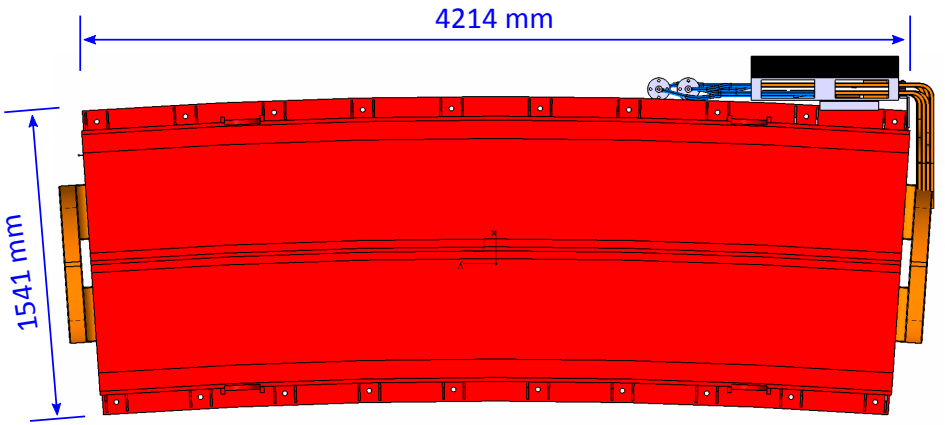
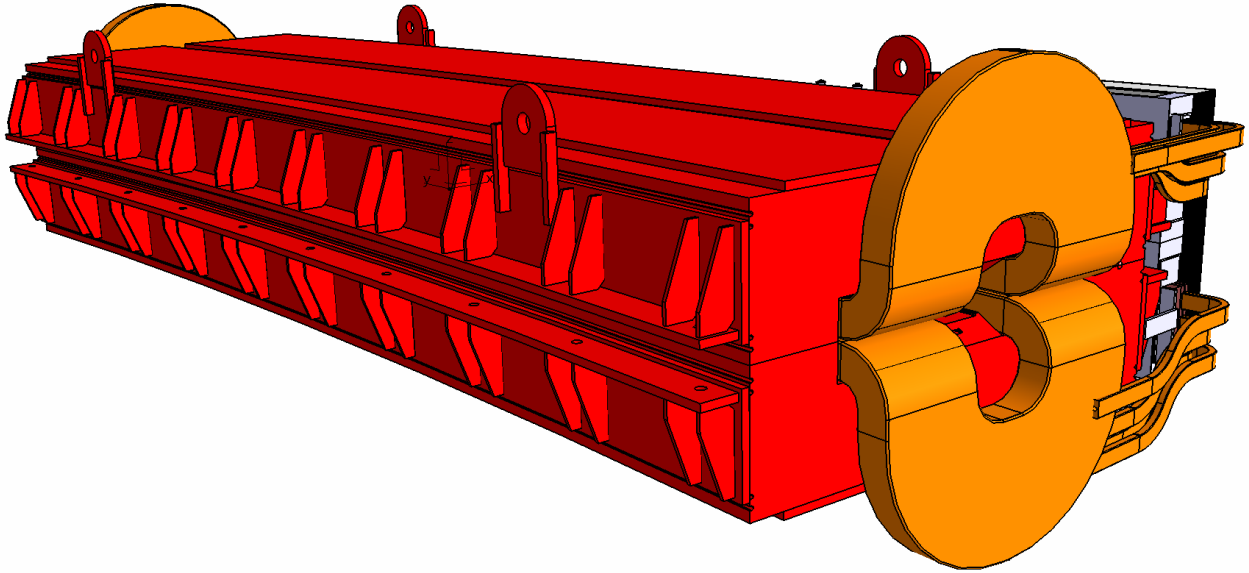


HESR Dipole Magnet







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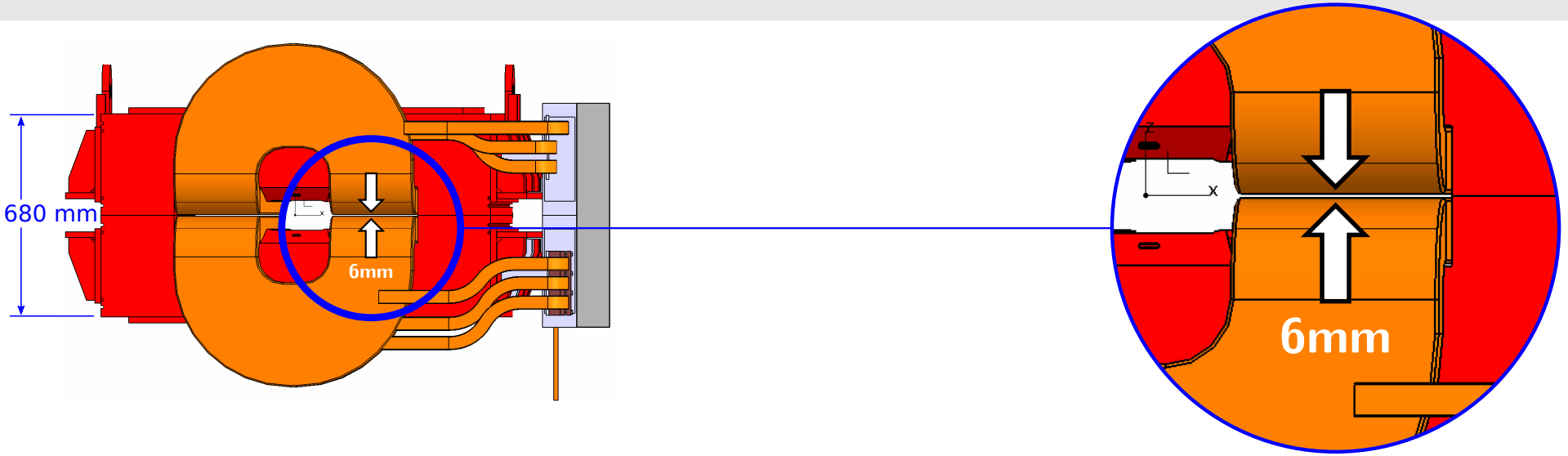
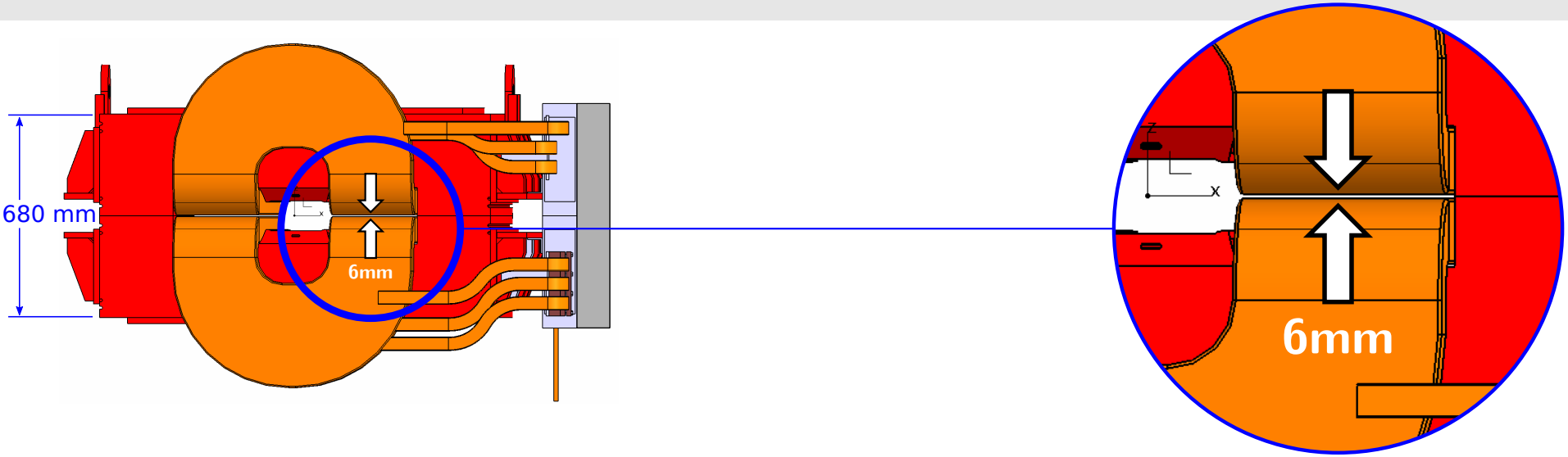
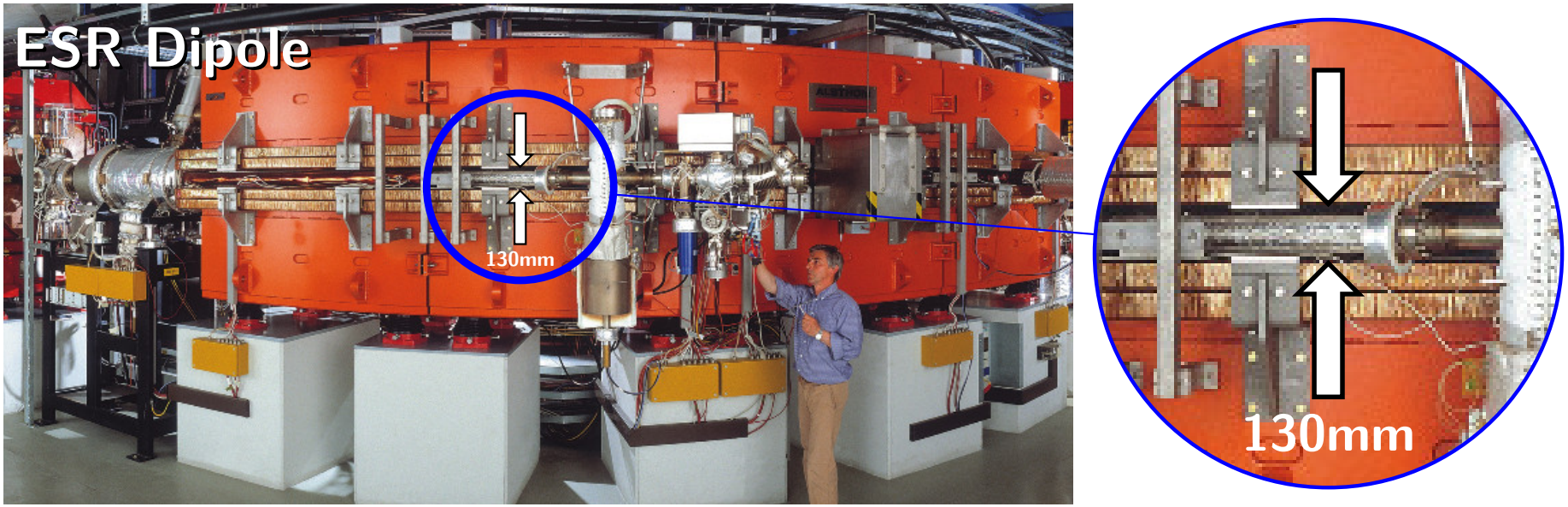
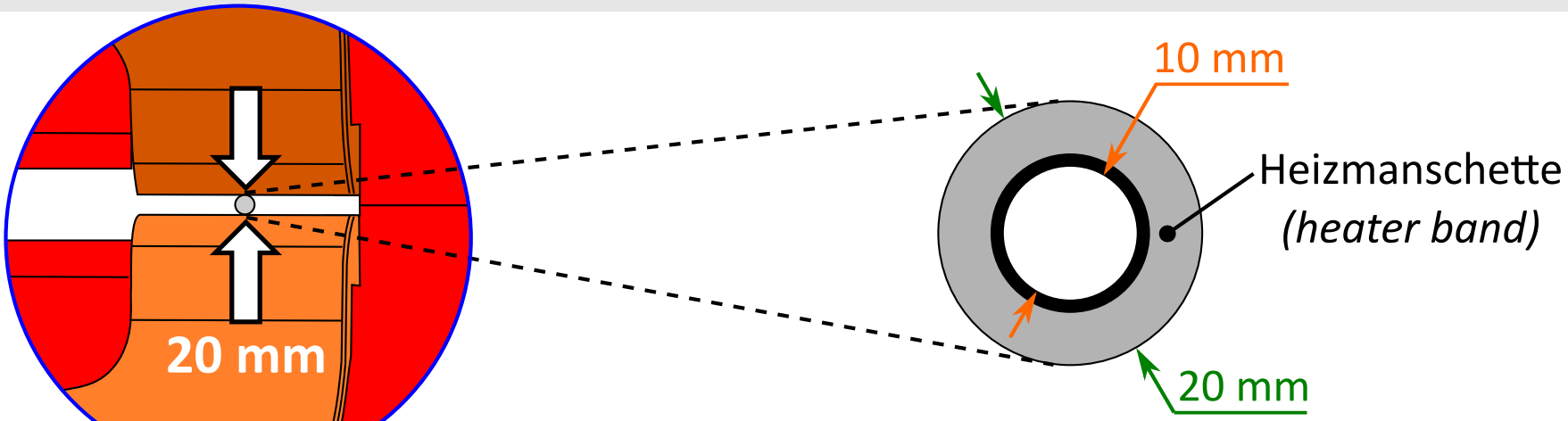


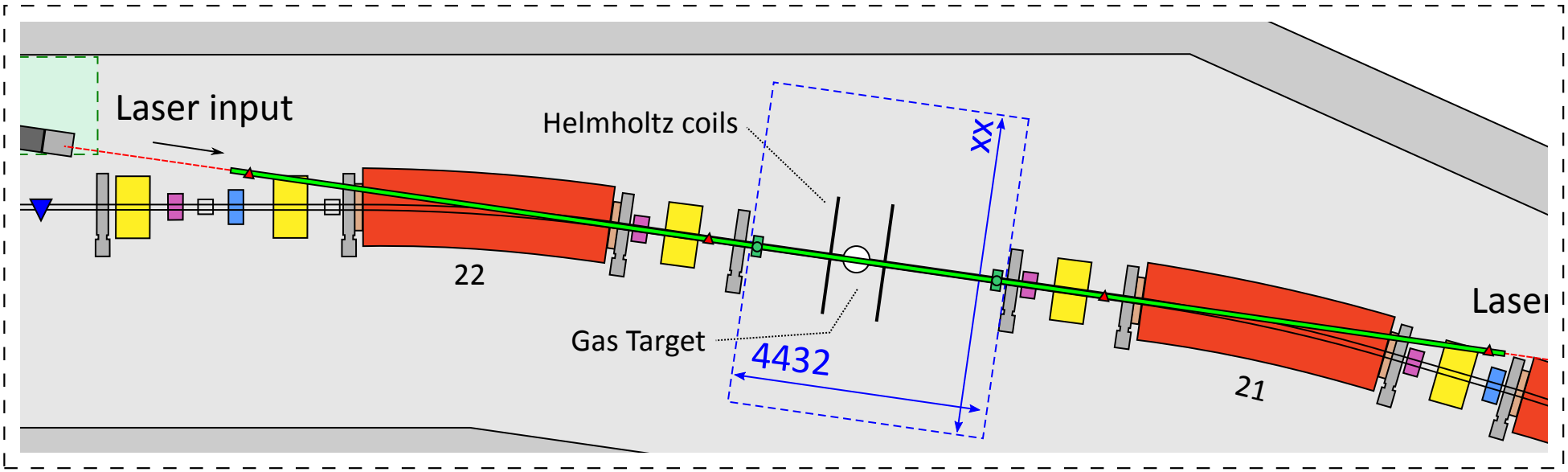
HESR Dipole Magnet





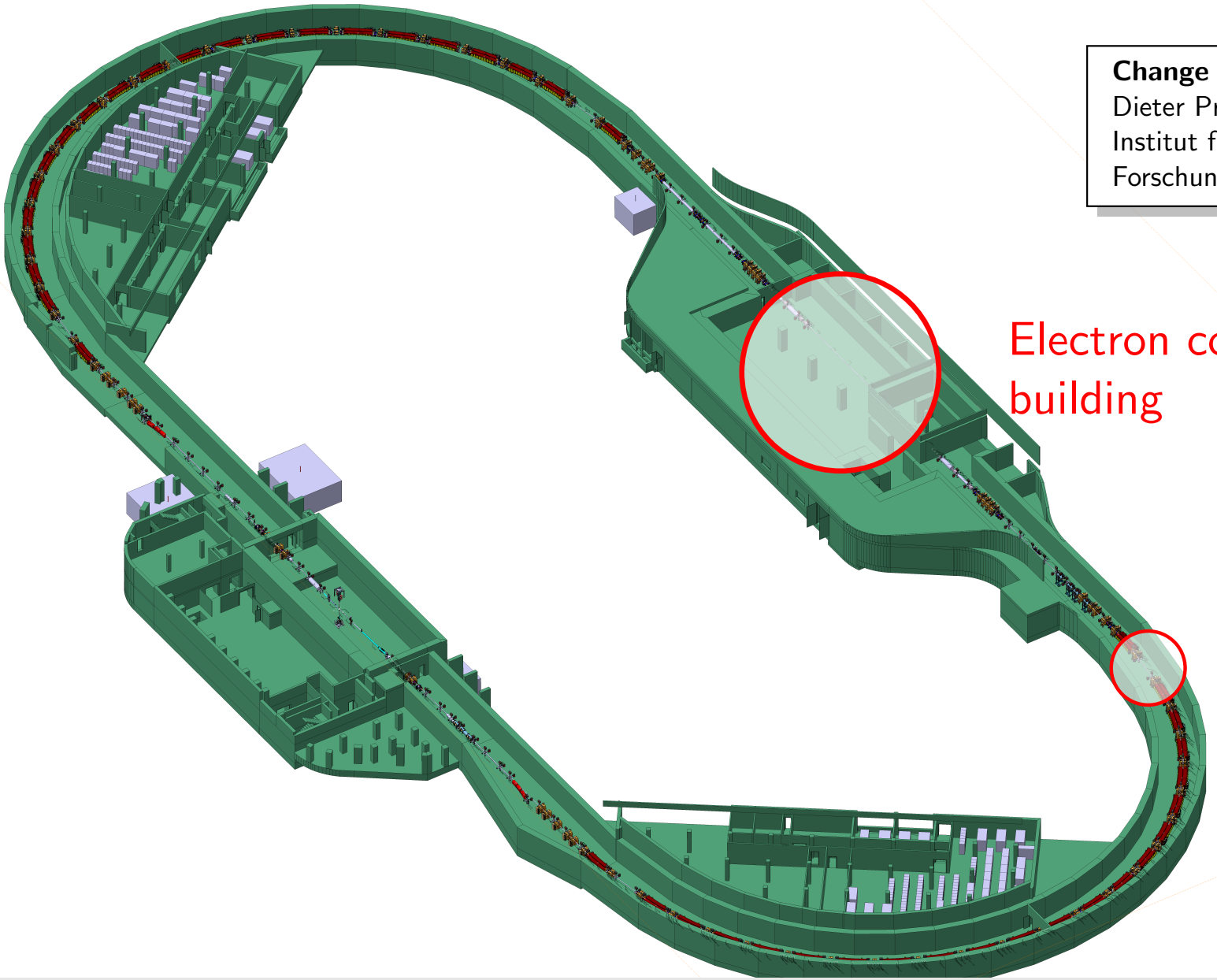
HESR Dipole Magnet



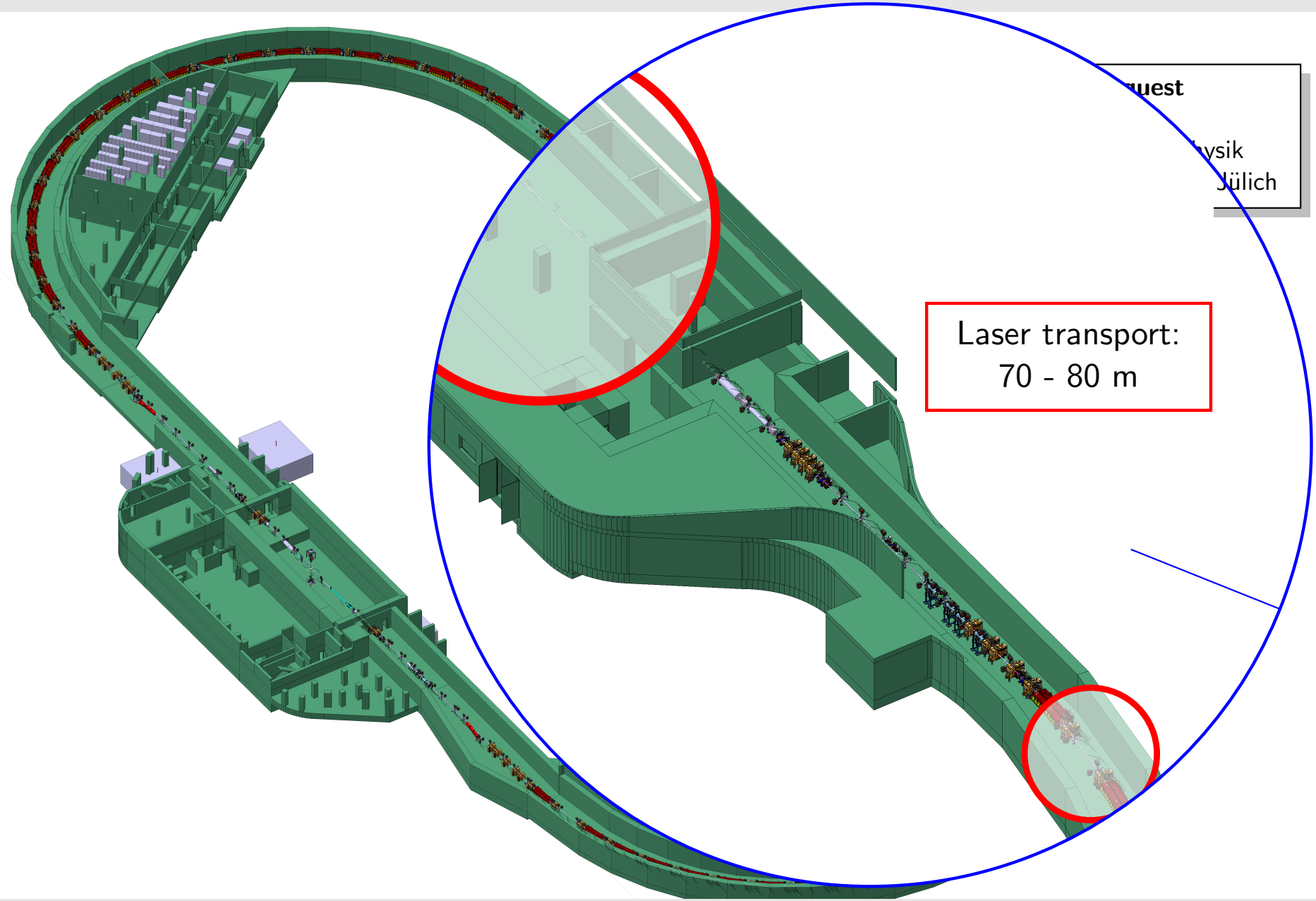


Laserlab @ HESR

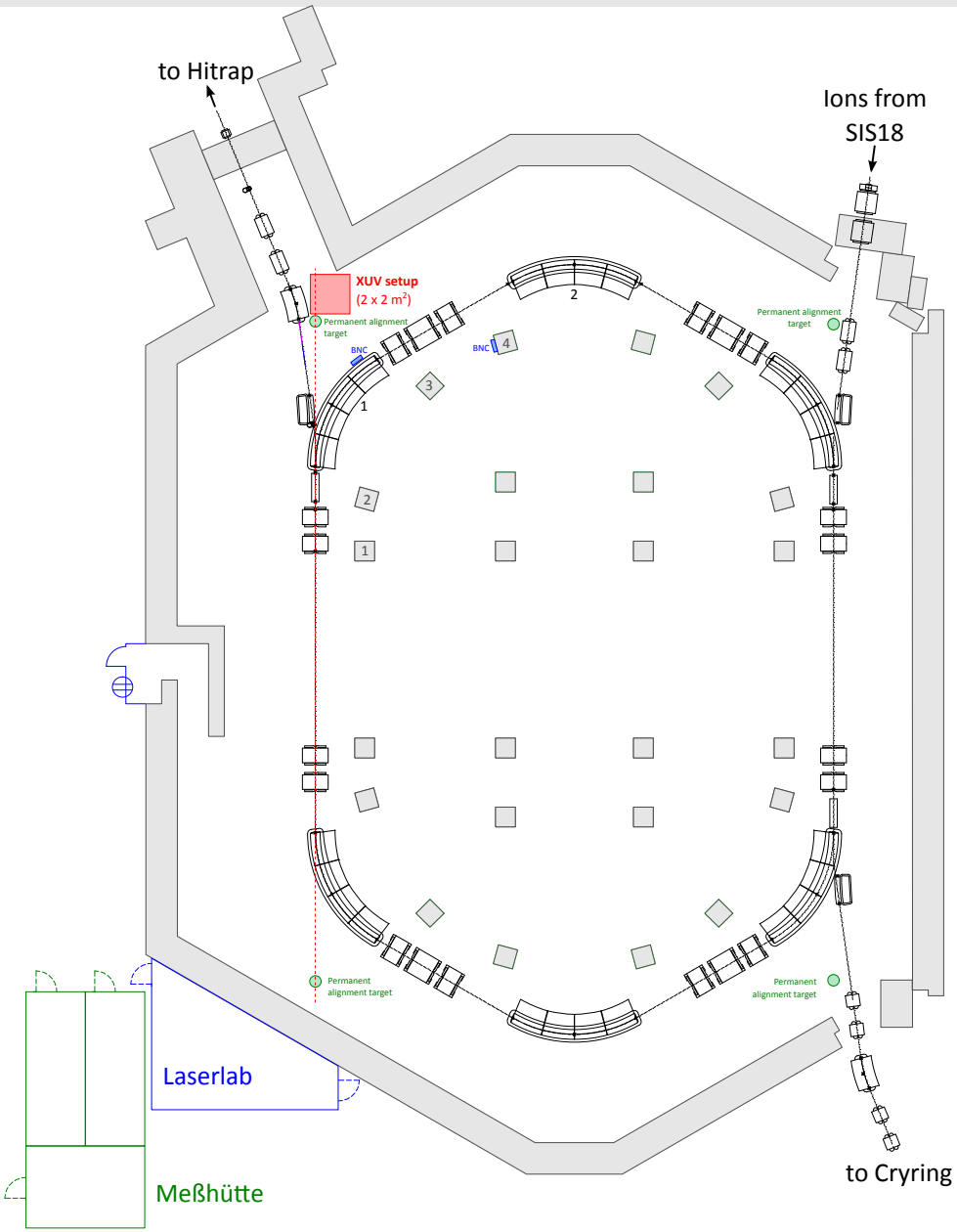
Change request
Dieter Prasuhn
Institut für Kernphysik
Forschungszentrum Jülich



Laserlab @ HESR



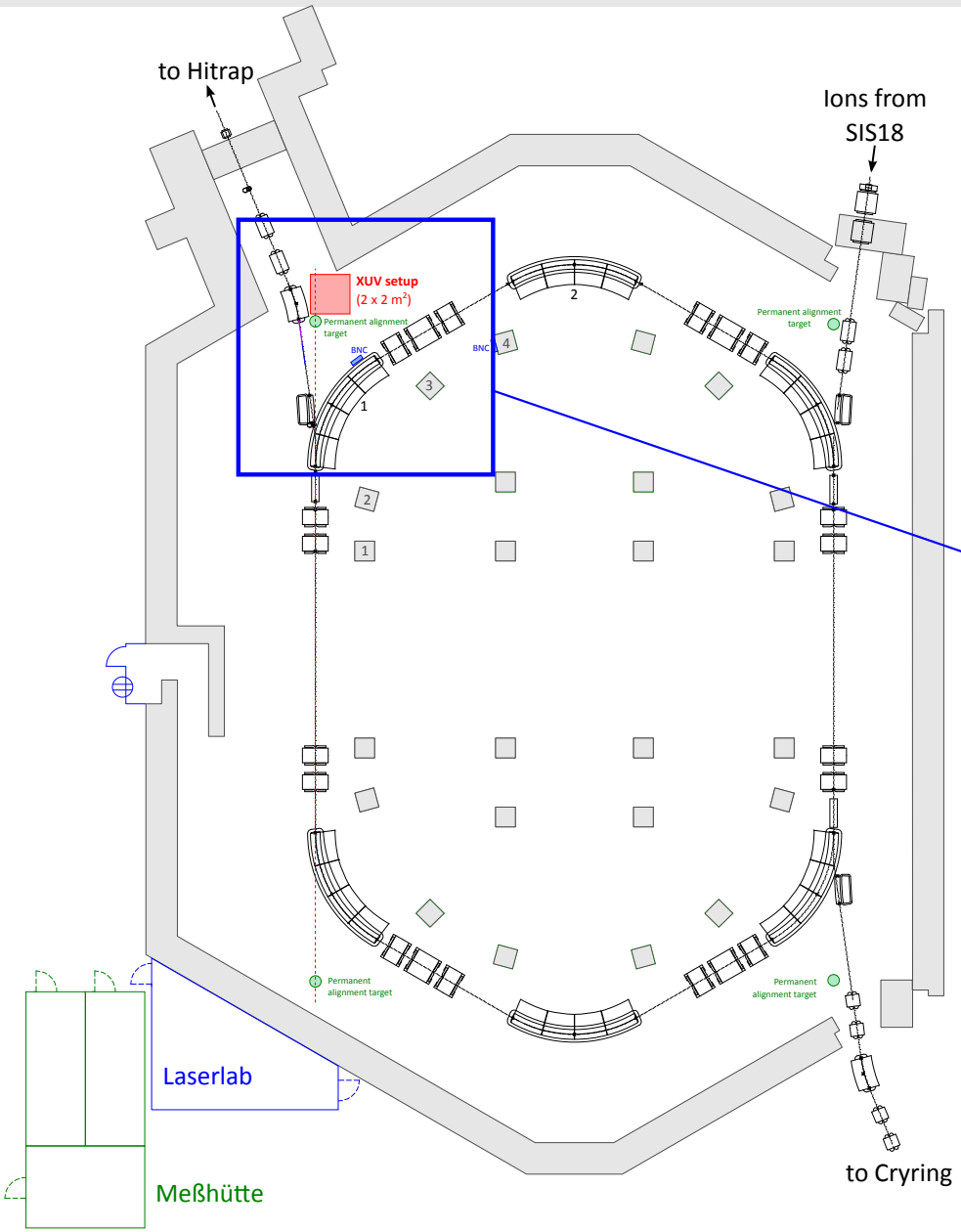
XUV Laser spectroscopy @ ESR

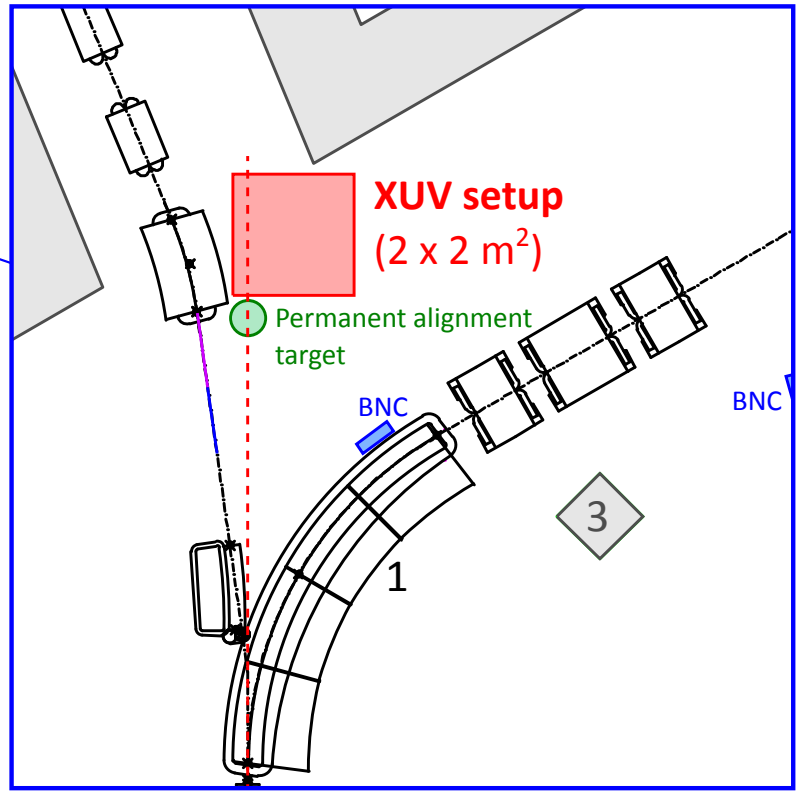


2014
Jan Rothhardt
HI-Jena
BMBF Antrag?

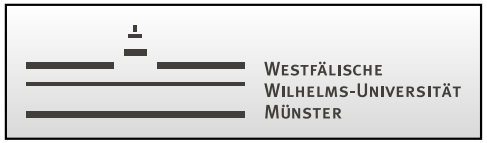
XUV Laser spectroscopy @ ESR

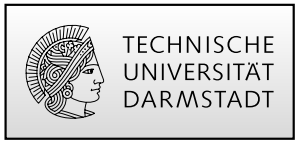
2014
Jan Rothhardt
HI-Jena
BMBF Antrag?

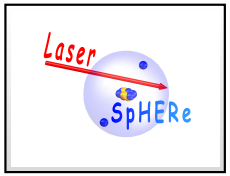


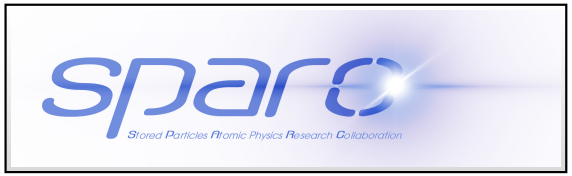


To be continued ...









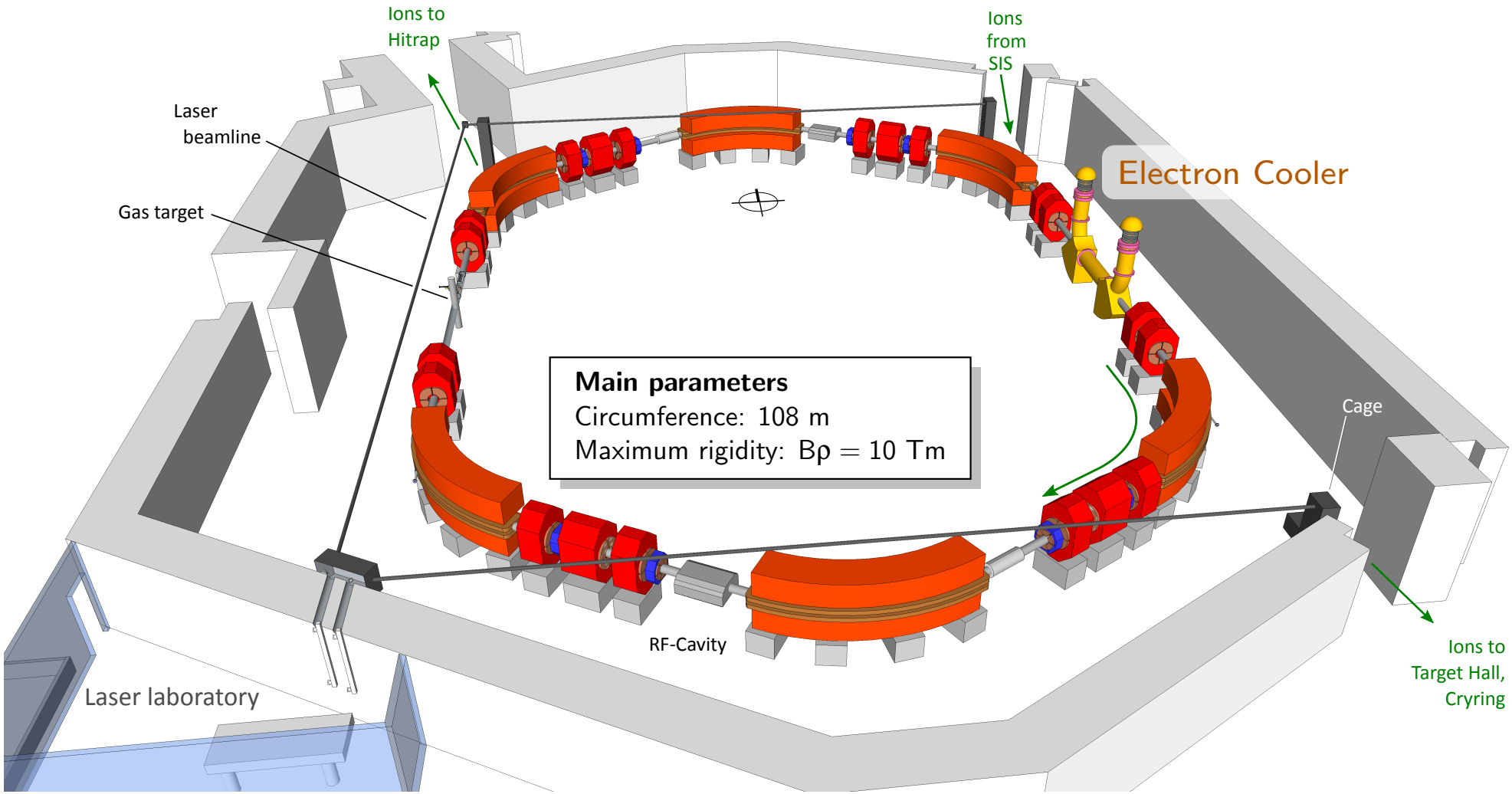
Thank you!

Supported by:

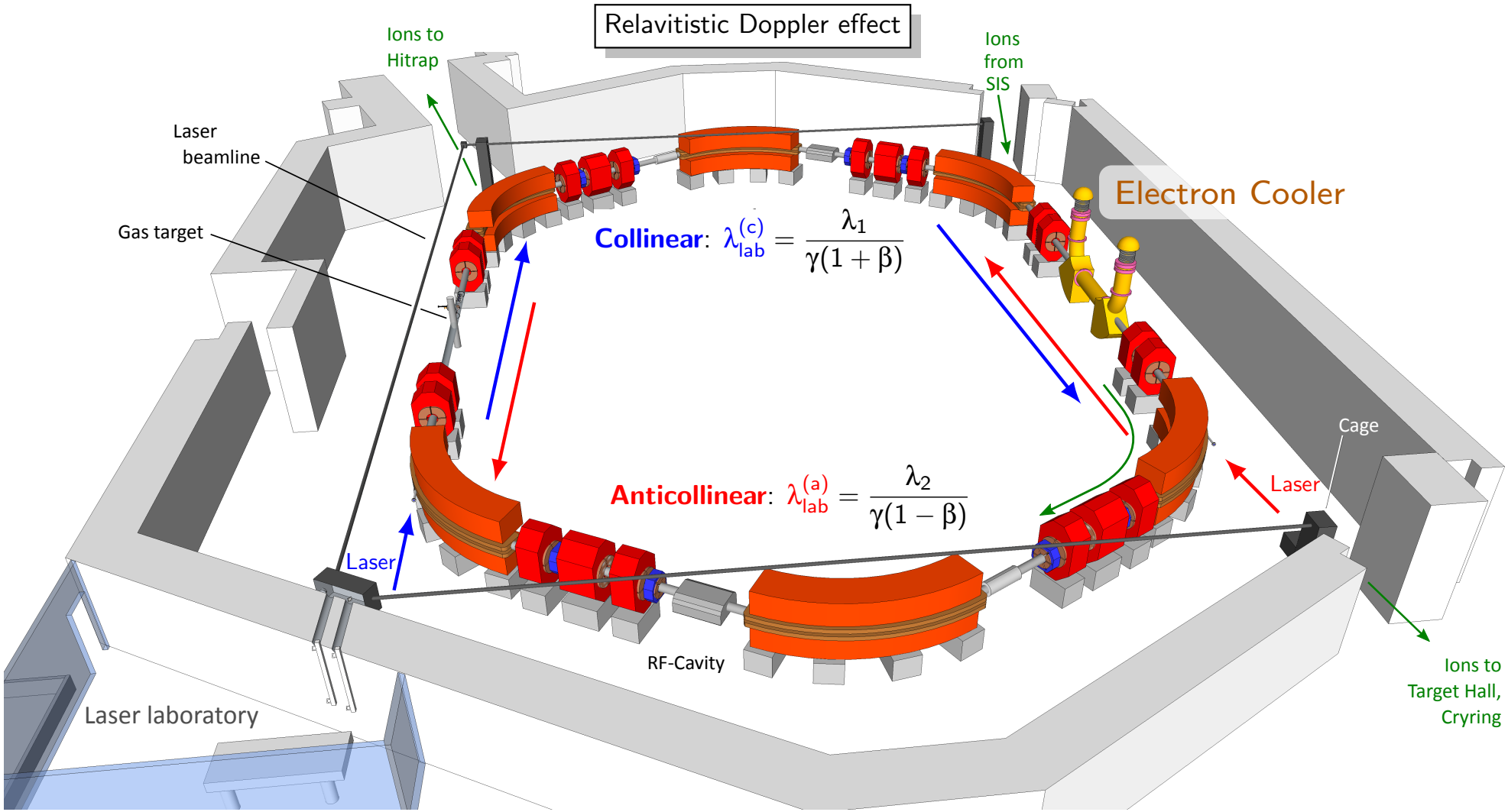
Overview

23 Years laser esr	**Sparc WG** laser	**Publications** laser	**PhDs** laser esr	**Activities** 2016
FAIR energy spectrum	**HCI** transitions	**Li-like** xuv-xray	**D1, D2** li-like ion	
Gedanken experiment	**Spectroscopy** 5.5 eV laser	**Spectroscopy** 26.6 eV laser	**Laser** spectrosopy	
HESR parameters	**NW Arc** sparc	**SPARC** setup	**Dipole** magnet	**Laser** laboratory
XUV esr	**XUV** detector	**ESR** lasers	**Rest** frame	**Libelle** 2011

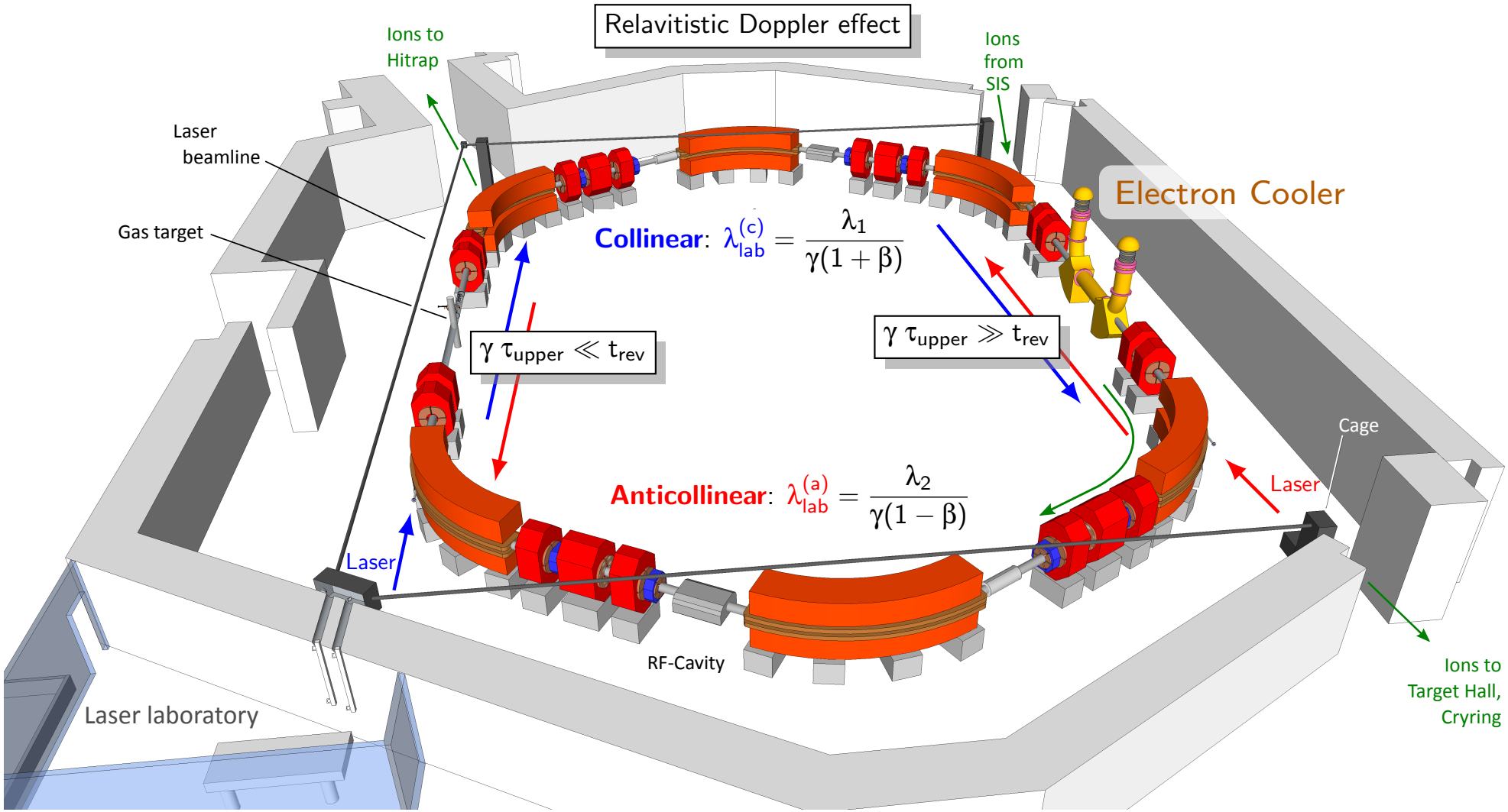
Lasers @ ESR


Ions to
Hitrap
Ions
from
SIS
Laser
beamline
Gas target
Electron Cooler
Main parameters
Circumference: 108 m
Maximum rigidity: Bρ = 10 Tm
Cage
RF-Cavity
Ions to
Target Hall,
Cryring
Laser laboratory

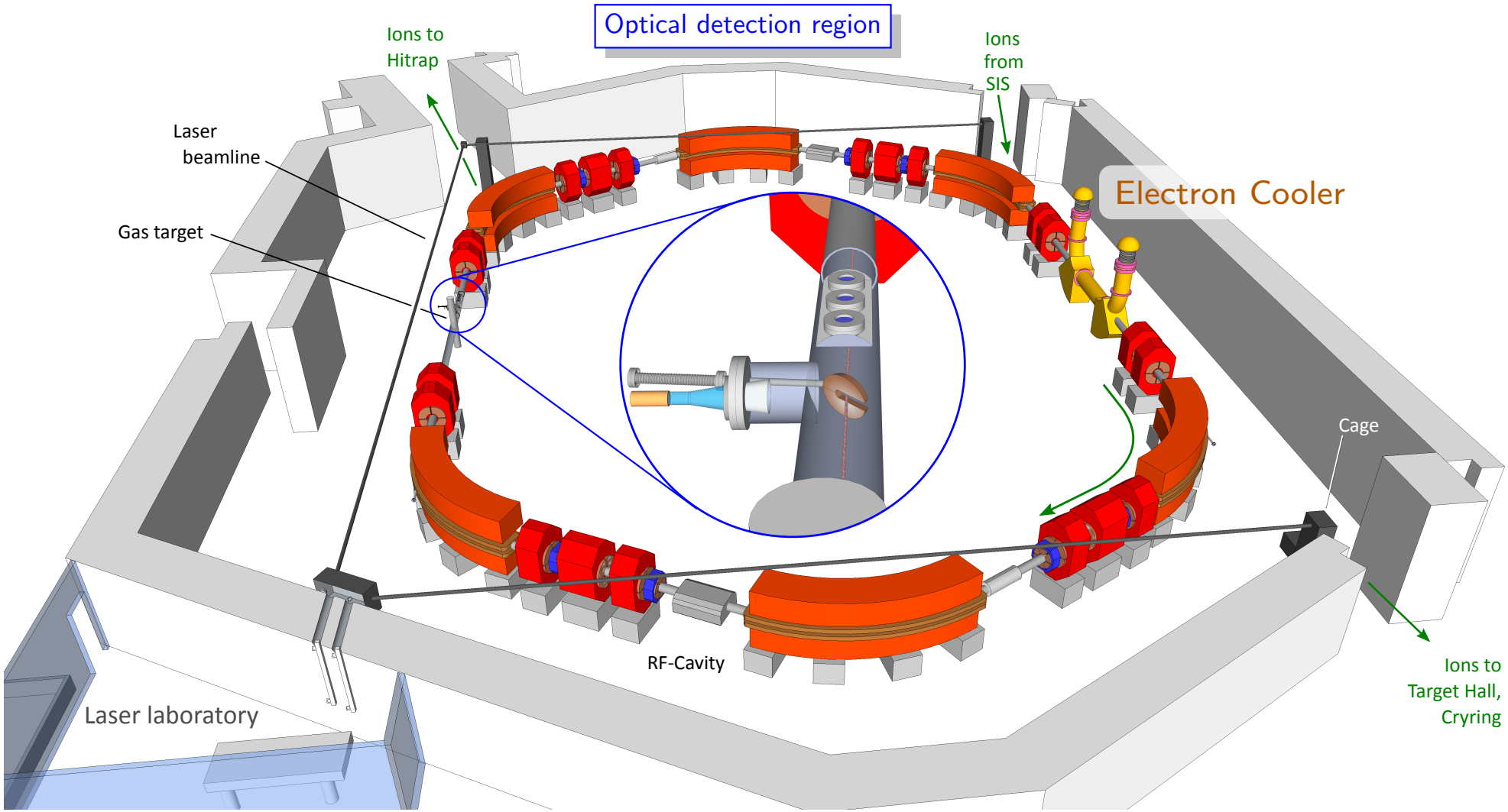
Lasers @ ESR


Relativistic Doppler effect
Ions to Hitrap
Ions from SIS
Laser beamline
Gas target
Electron Cooler
Collinear: $\lambda_{lab}^{(c)} = \frac{\lambda_1}{\gamma(1+\beta)}$
Anticollinear: $\lambda_{lab}^{(a)} = \frac{\lambda_2}{\gamma(1-\beta)}$
Cage
Laser
Laser
RF-Cavity
Laser laboratory
Ions to Target Hall, Cryring

Lasers @ ESR


Relativistic Doppler effect
Ions to Hitrap
Ions from SIS
Laser beamline
Gas target
Electron Cooler
Collinear: $\lambda_{lab}^{(c)} = \frac{\lambda_1}{\gamma(1+\beta)}$
$\gamma\,\tau_{upper} \ll t_{rev}$
$\gamma\,\tau_{upper} \gg t_{rev}$
Cage
Laser
Anticollinear: $\lambda_{lab}^{(a)} = \frac{\lambda_2}{\gamma(1-\beta)}$
Laser
RF-Cavity
Ions to Target Hall, Cryring
Laser laboratory

Lasers @ ESR

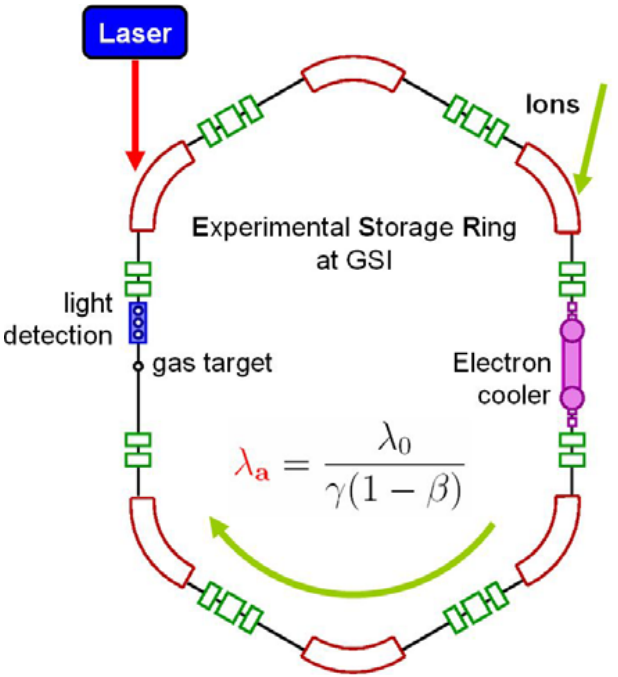

Optical detection region
Ions to Hitrap
Ions from SIS
Laser beamline
Gas target
Electron Cooler
Cage
RF-Cavity
Laser laboratory
Ions to Target Hall, Cryring

Laser spectroscopy on the $^3P_0 - {}^3P_1$ level splitting in Be-like krypton

IOP Publishing Physica Scripta
Phys. Scr. **T144** (2011) 014013 (3pp) doi:10.1088/0031-8949/2011/T144/014013

Laser spectroscopy of the $(1s^2 2s2p)$ $^3P_0$–$^3P_1$ level splitting in Be-like krypton

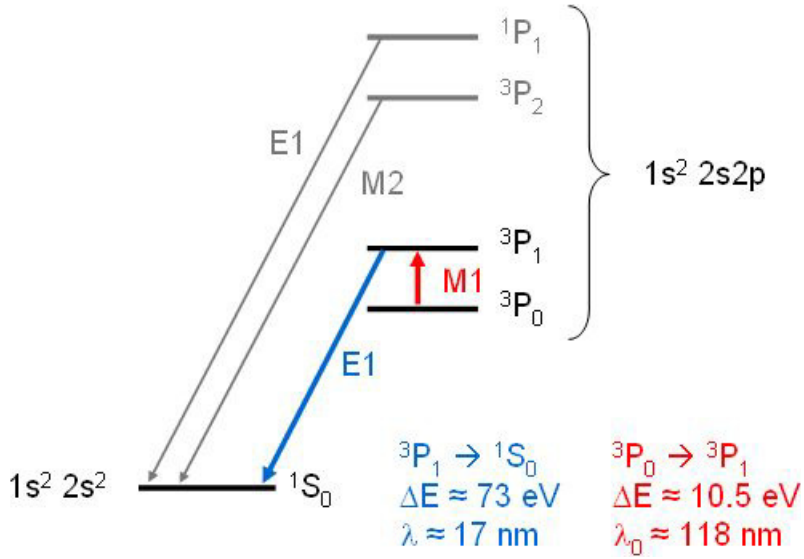
D F A Winters[1,2], Th Kühl[1,3], D H Schneider[4], P Indelicato[5], R Reuschl[6], R Schuch[7], E Lindroth[7] and Th Stöhlker[1,2,8]



Be-like $^{84}Kr^{32+}$
$E_{beam} \approx 360$ MeV/u
$(\beta \approx 0.69, \gamma \approx 1.38)$
$f_{rev} \approx 1.92$ MHz

Frequency-doubled
Dye-laser
$\lambda_a \approx 276$ nm (4.5 eV)

$^3P_0 \rightarrow {}^3P_1$
$\Delta E \approx 10.5$ eV
$\lambda_0 \approx 118$ nm



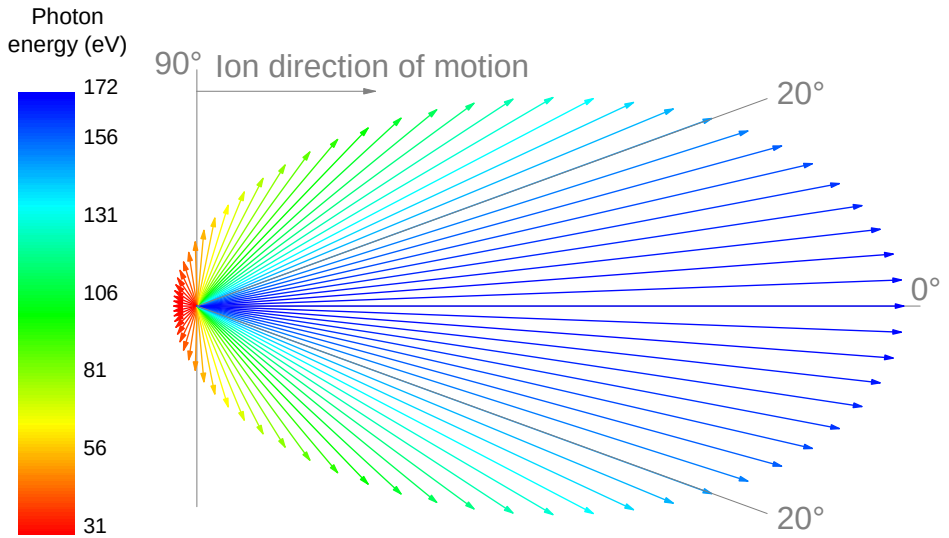
- $^{84}Kr^{32+}$ can be produced at UNILAC
- 10^8 ions (10% in $^3P_0$)
- $^3P_0$ has long lifetime (Be-like Pb, 116 d)

$^3P_0 - {}^3P_1$ { unaffected by QED corrections; test of electron correlation effects

Fluorescence in laboratory frame

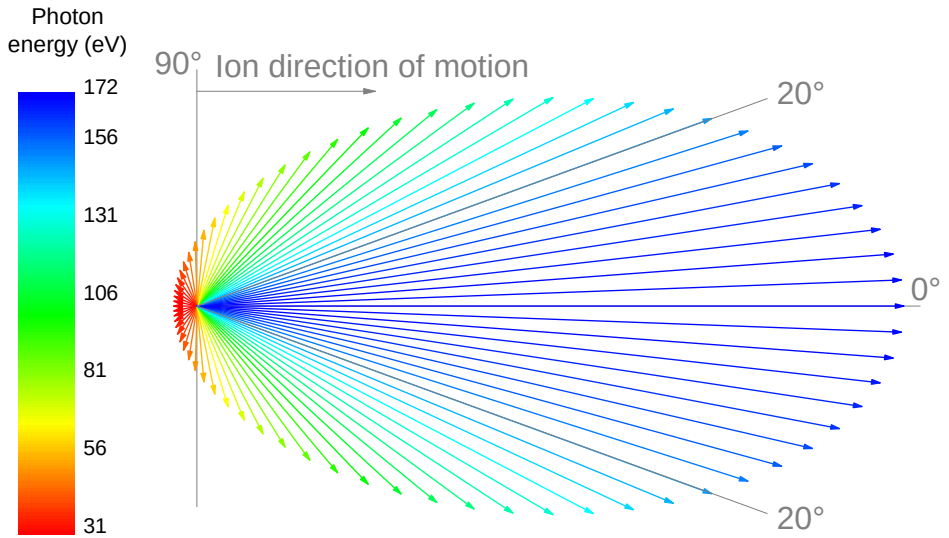
Searchlight cone

Rest frame photon energy: 73 eV

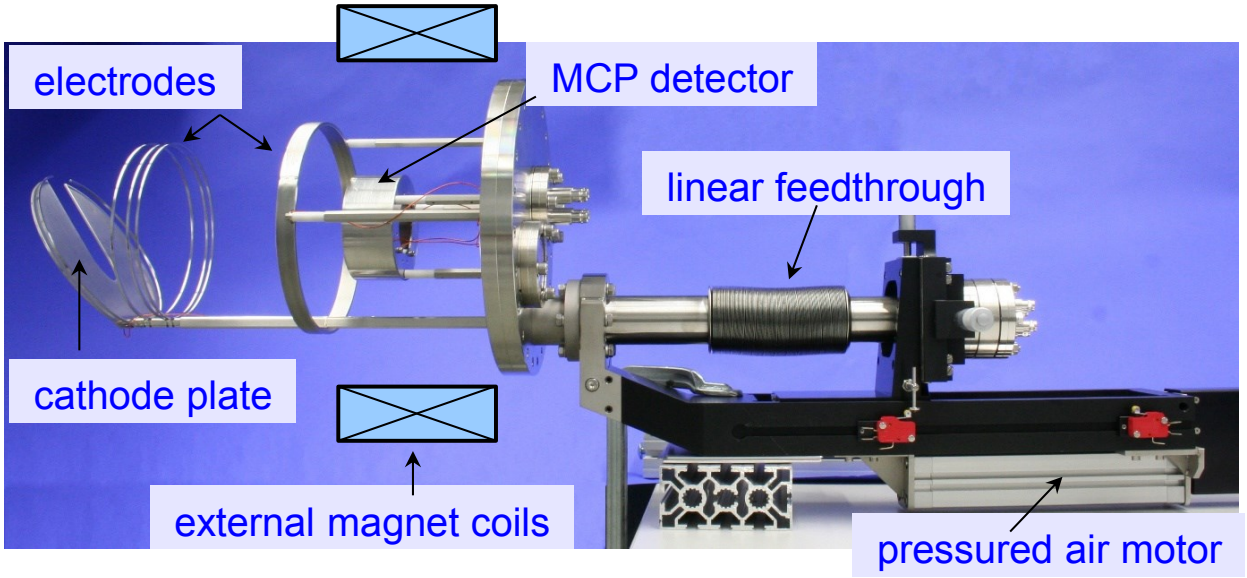


Fluorescence in laboratory frame

Searchlight cone
Rest frame photon energy: 73 eV



XUV Detector
IKP, WW-Universität Münster
Volker Hannen
Jonas Vollbrecht
Daniel Winzen
Christian Weinheimer



Expected count rate in resonance: 10 events (for 10^{-5} detection efficiency)

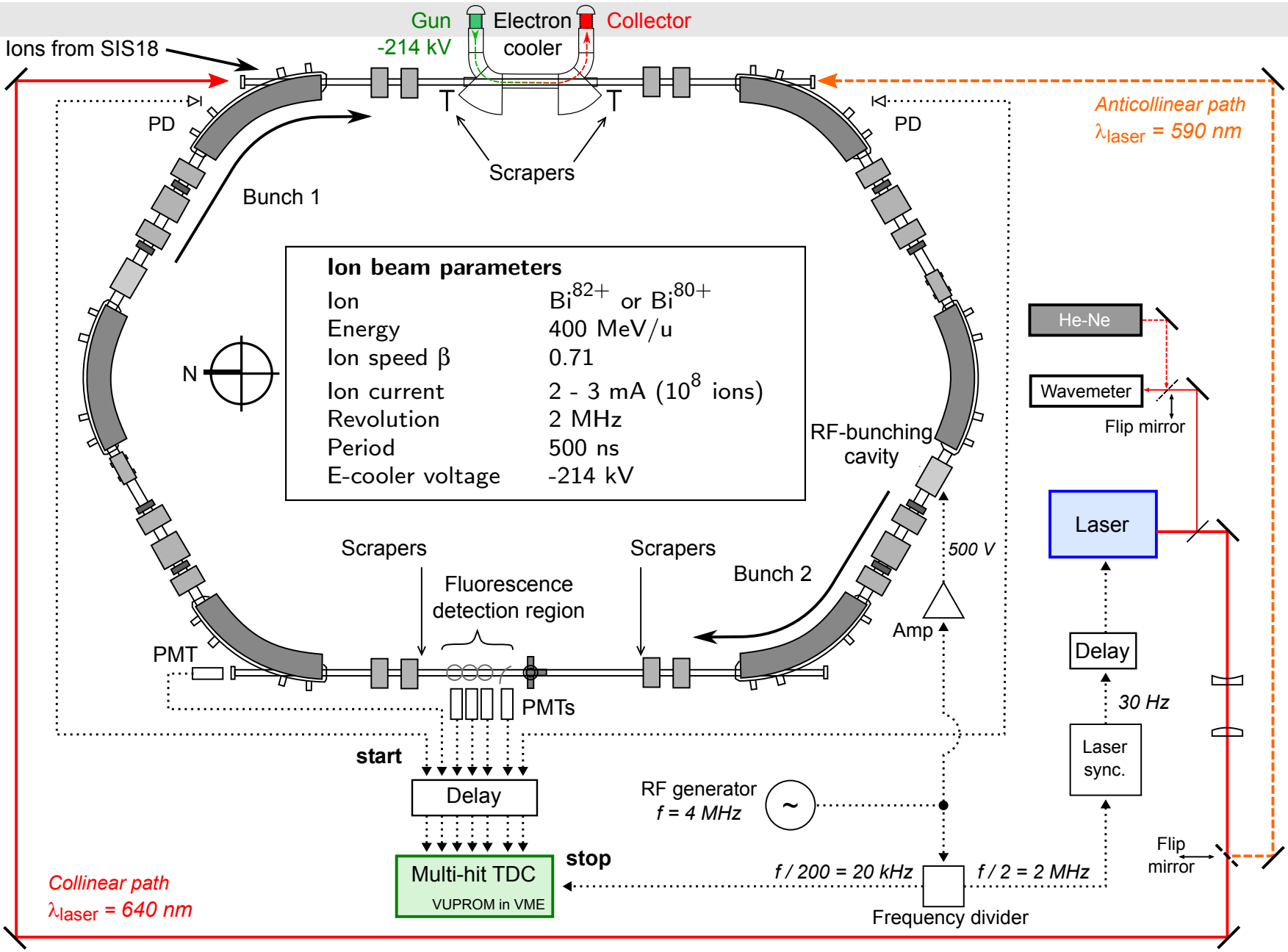
Ion rest frame transition frequency

$$h\nu_0 = \sqrt{h\nu_L \cdot h\nu_X}$$

$$\beta = \frac{h\nu_X/h\nu_L - 1}{h\nu_X/h\nu_L + 1}, \qquad \gamma = \frac{1}{2}\frac{h\nu_X/h\nu_L + 1}{\sqrt{h\nu_X/h\nu_L}} \cong \frac{1}{2}\sqrt{\frac{h\nu_X}{h\nu_L}}$$

$$\frac{\Delta h\nu_0}{h\nu_0} = \frac{1}{2}\sqrt{\left(\frac{\Delta h\nu_L}{h\nu_L}\right)^2 + \left(\frac{\Delta h\nu_X}{h\nu_X}\right)^2}$$

New Trial - 2011



New Trial - 2011