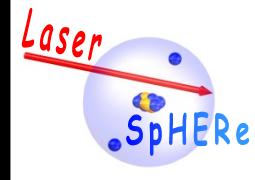
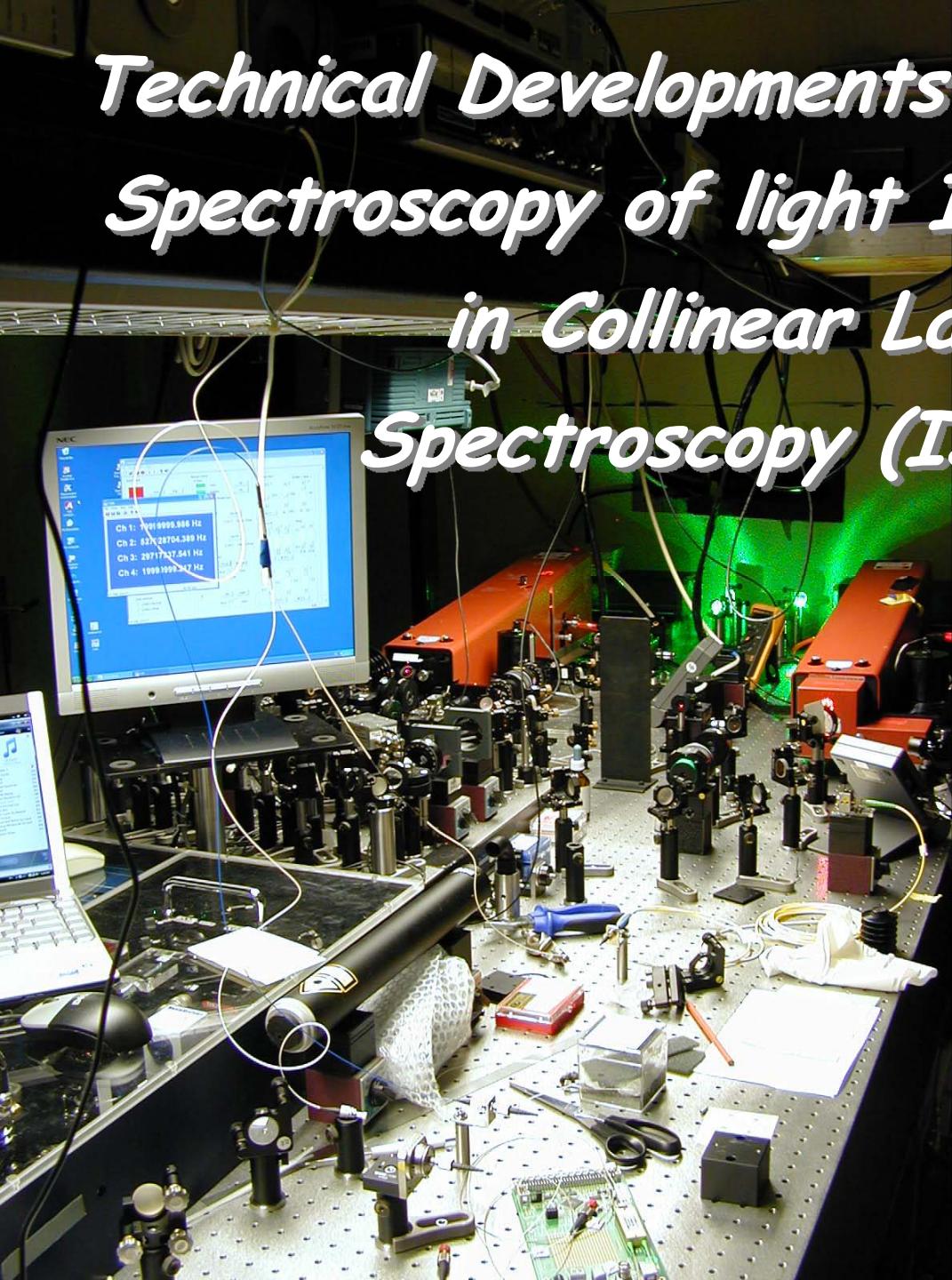
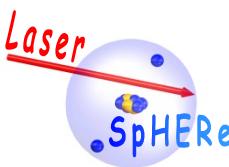


# *Technical Developments for Precision Spectroscopy of light Isotopes (Be) in Collinear Laser Spectroscopy (IS449)*



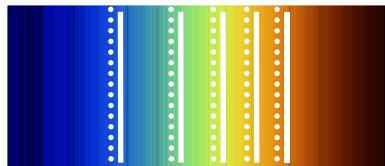
Ch. Geppert, W. Nörtershäuser,  
M. L. Bissell, M. Kowalska, J. Krämer,  
A. Krieger, R. Neugart, R. Sanchez,  
F. Schmidt-Kaler, D. Tiedemann,  
Ch. Weinheimer, D. T. Yordanov,  
C. Zimmermann, M. Zakova,

GSI, Germany  
Uni. Mainz, Germany  
MPI für Kernphysik, Germany  
Katholieke Universiteit Leuven, Belgium  
Uni. Tübingen, Germany  
CERN, Physics Department, Switzerland  
Uni. Münster, Germany  
Uni. Ulm, Germany



# Isotope Shift

Isotop 1



Isotop 2

= Frequency difference in an electronic transition between two isotopes

$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS}$$

Mass Effect, nuclear motion

$$\frac{2\pi Z}{3} \Delta|\psi(0)|^2 \delta\langle r^2 \rangle$$

Field Shift  
finite size of the nucleus

# Isotope Shift Measurement

...but calculations show: field shift coefficient for  $\text{Be}^+ \sim 16 \text{ MHz/fm}^2$   
 → accuracy of ~2 MHz sufficient for testing  $r_c$  on ~ 1 % level

## Method 1

laser spectroscopy on  
single ions in a two-stage  
**Paul trap**

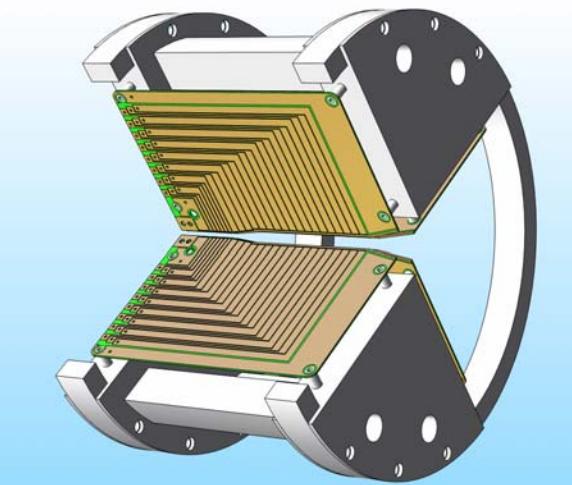
- + high accuracy ~200 kHz
- + laser system has been developed
- ! requires **long time** for trap and beam line development

## IS449

## Addendum to IS449

## Method 2

collinear laser spectros-  
copy on fast ion beam

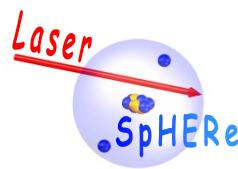


- + identical laser system

- + existing beam line **COLLAPS**

- ! requires improvement in **accuracy** on spectroscopy of light isotopes

# $^{11}\text{Be}$ - Technique: Frequency-Comb based Collinear Laser Spectroscopy

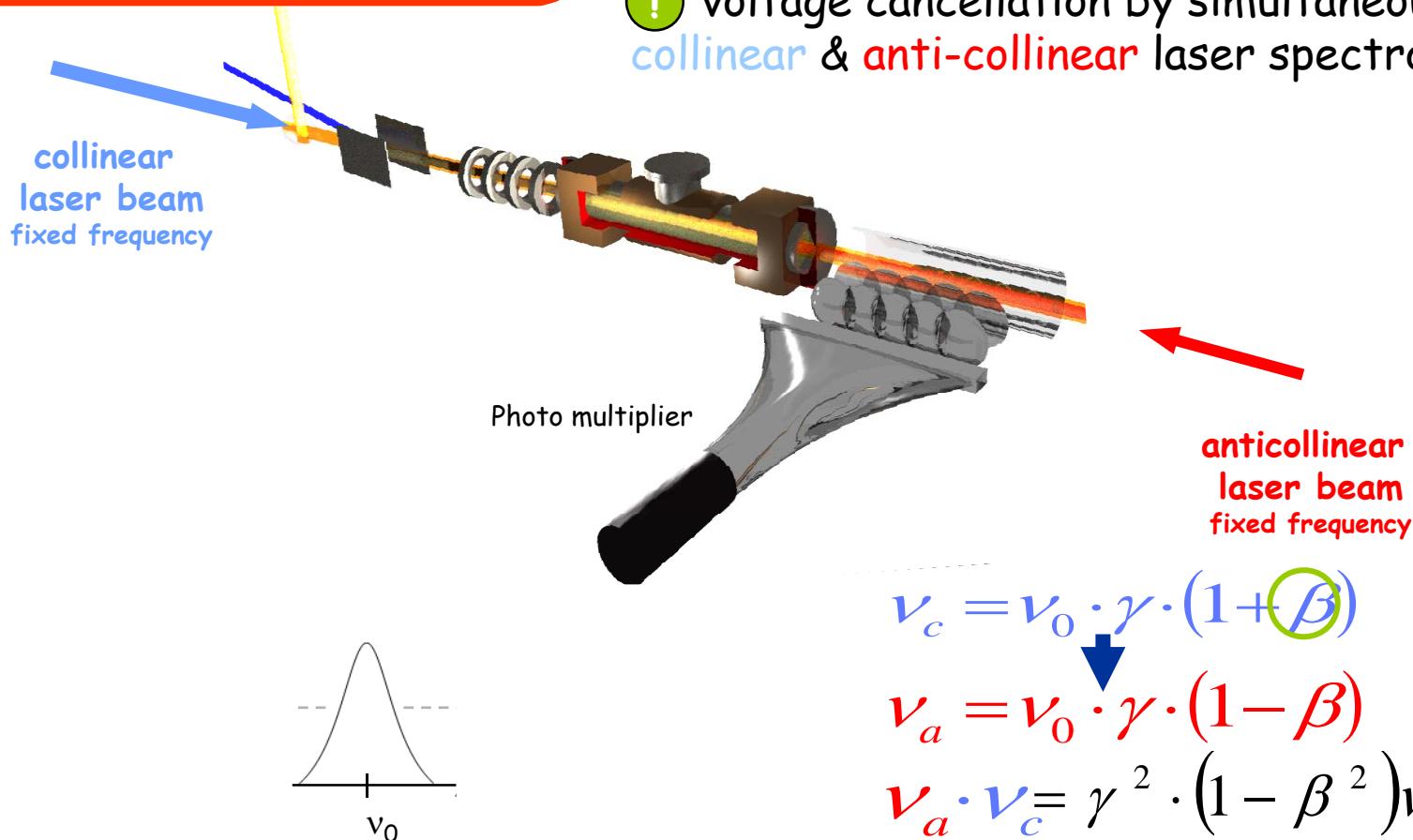


## working principle

- fixed laser frequency
- Doppler-tuning of ion velocity

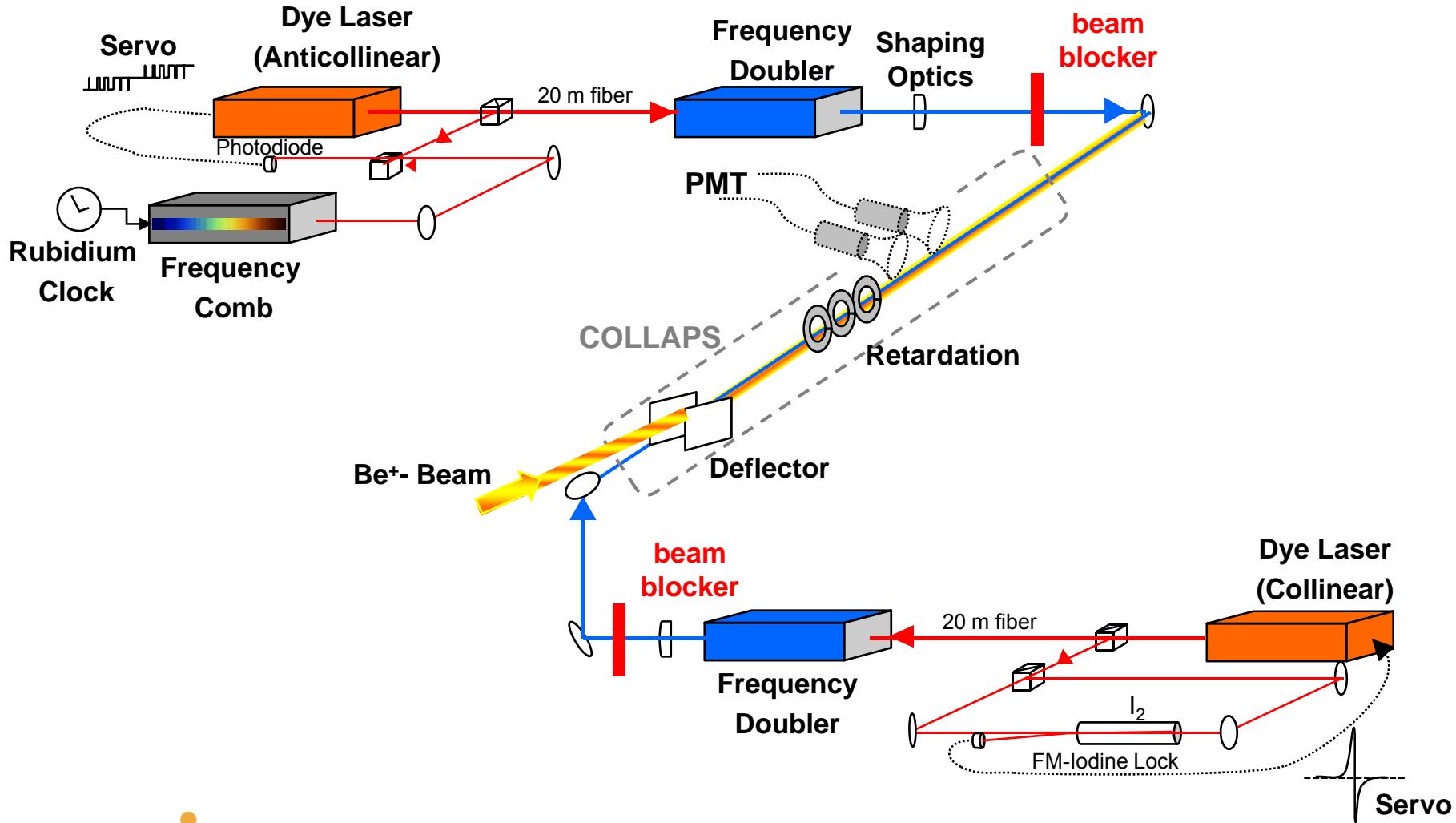
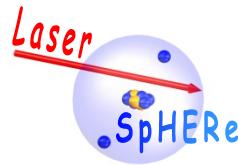
! large Doppler-coefficient for  $^{11}\text{Be}$ :  
30 MHz/Volt  $\rightarrow$  required **voltage** precision  
better than 0.1 V on  $\sim$ 60 kV  $\rightarrow$   $\sim$  1 ppm

! voltage cancellation by simultaneous  
**collinear & anti-collinear** laser spectroscopy

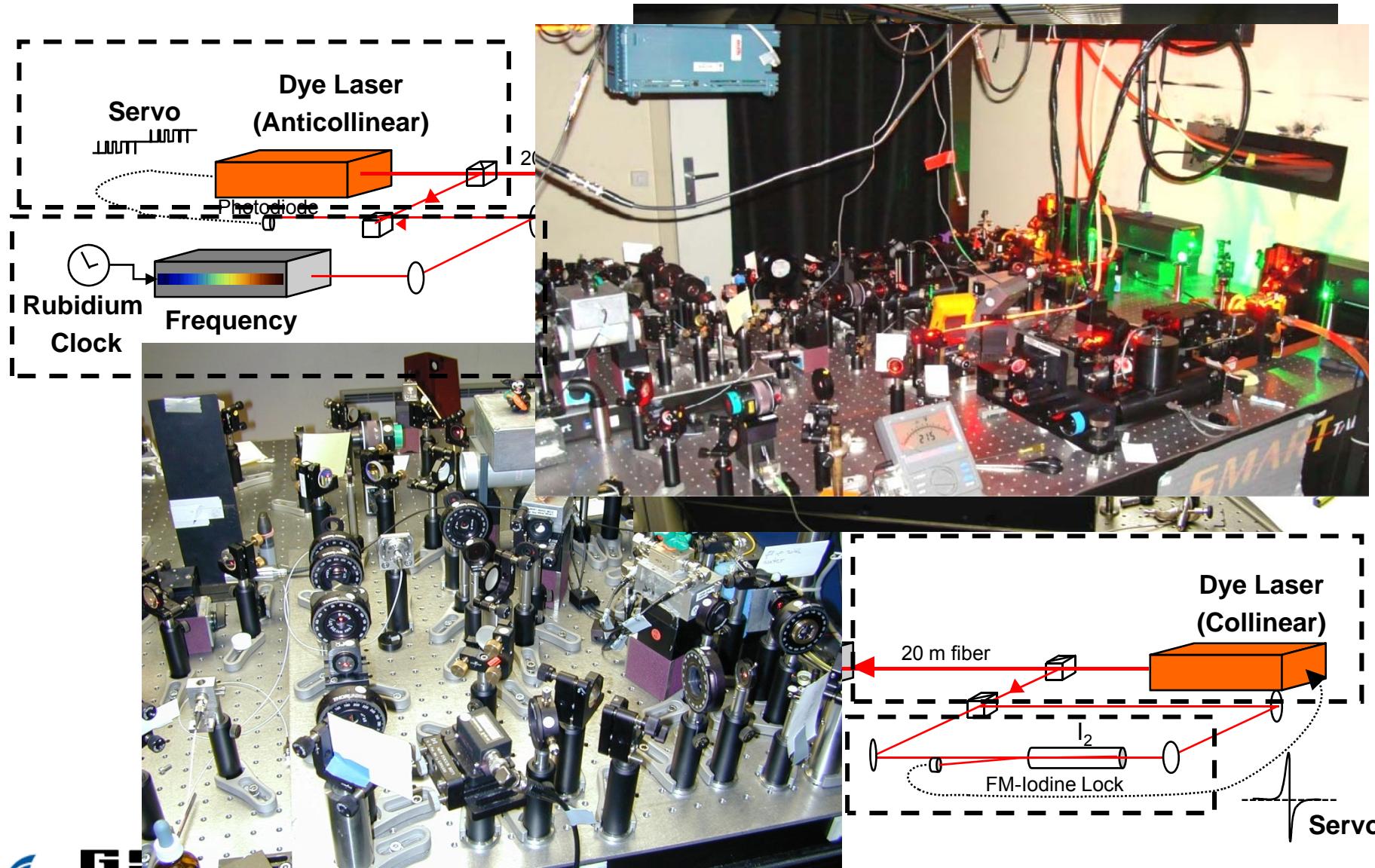
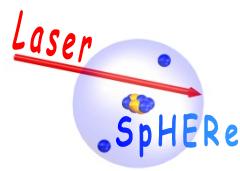


$$\nu_c = \nu_0 \cdot \gamma \cdot (1 + \beta)$$
$$\nu_a = \nu_0 \cdot \gamma \cdot (1 - \beta)$$
$$\nu_a \cdot \nu_c = \gamma^2 \cdot (1 - \beta^2) \nu_0^2 = \nu_0^2$$

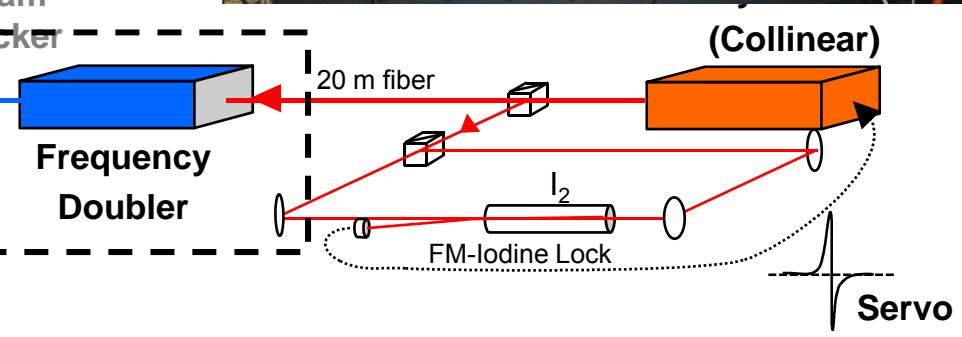
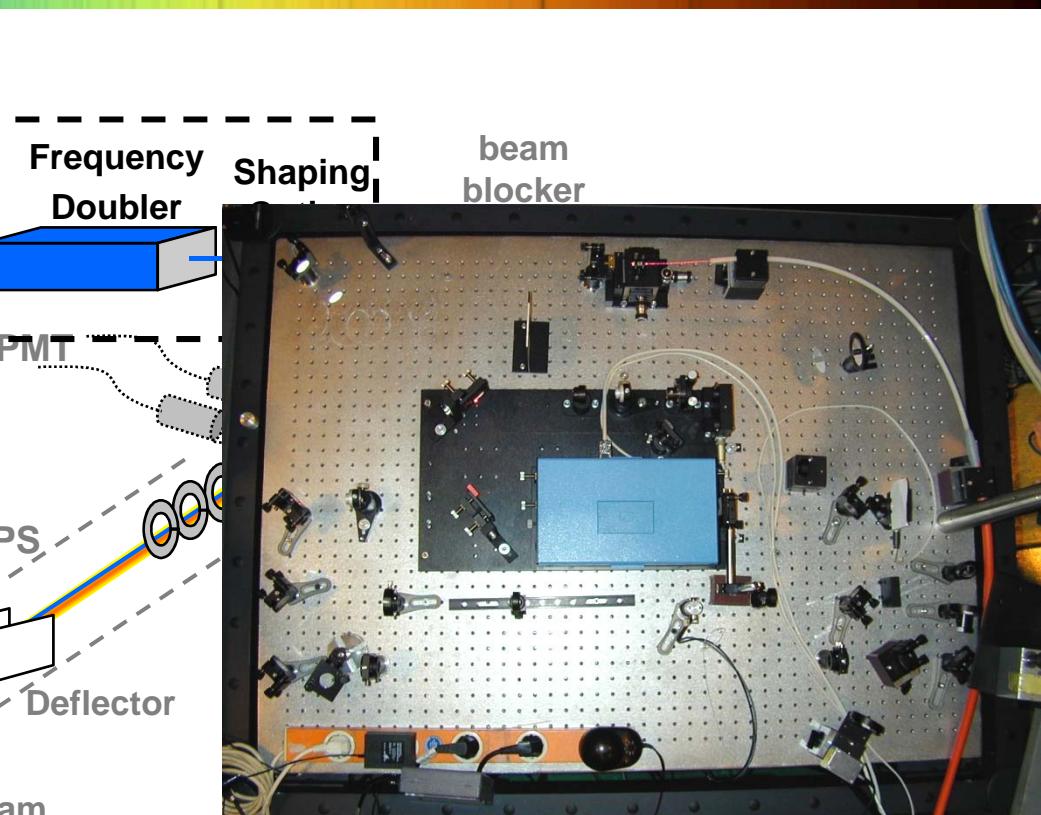
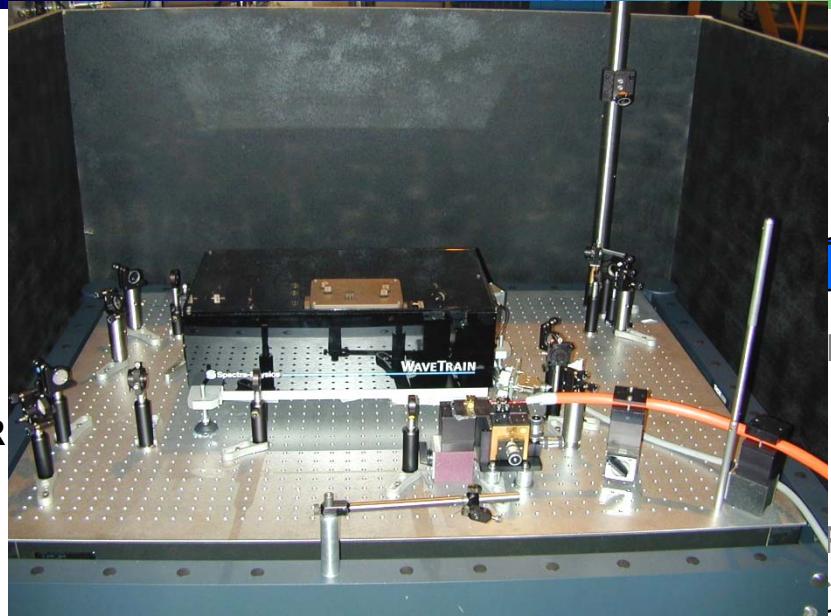
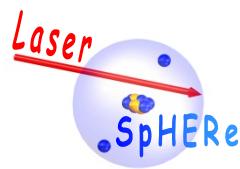
# Laser Spectroscopy Setup



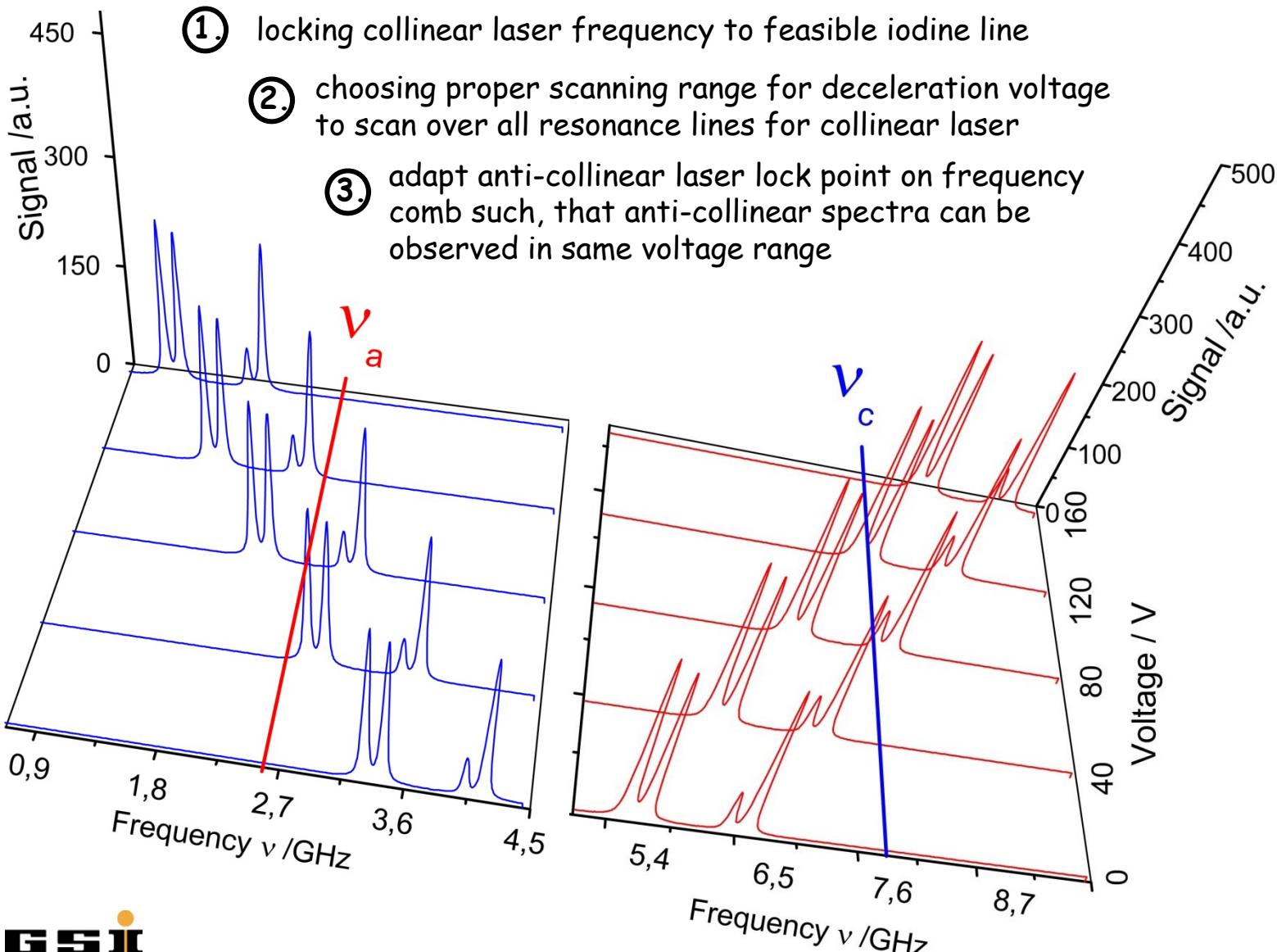
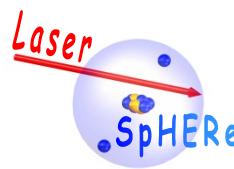
# Laser Spectroscopy Setup



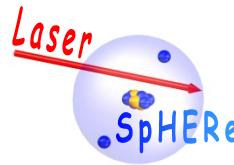
# Laser Spectroscopy Setup



# Scanning Procedure



# Off-line Results



## systematic effects testing :

Misalignment of collinear laser relative to the ion beam  $\leq 500$  kHz

Power dependence of spectroscopy lasers no effect

Variation of the offset voltage between optical detection region and deceleration electrodes no effect

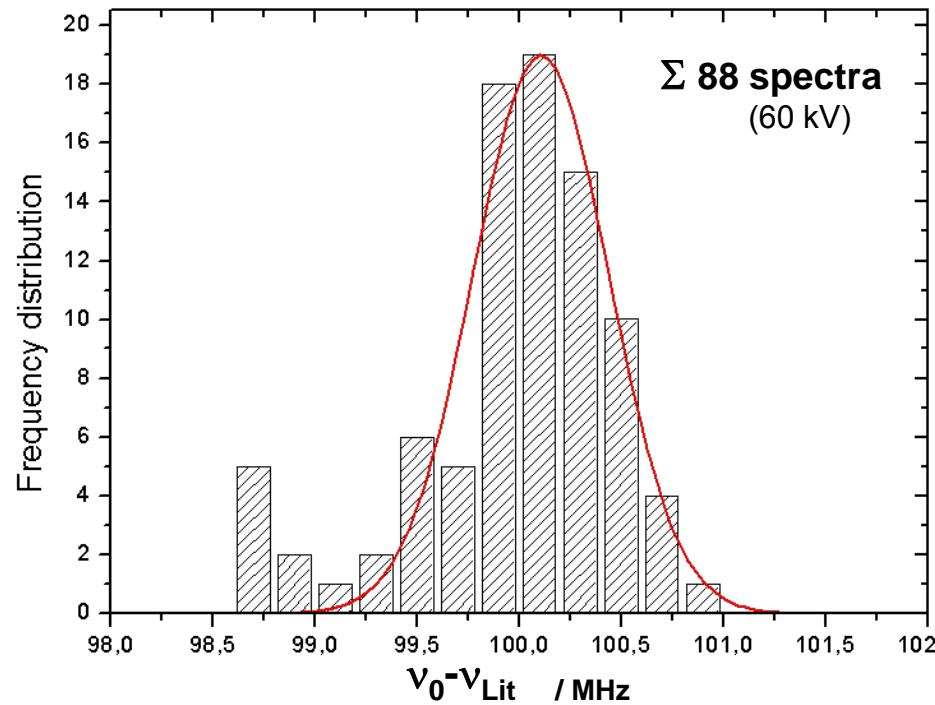
Measurements at different acceleration voltages of 30 and 60 kV no effect

Measurement of the absolute transition frequency at different iodine lines no effect

Iodine Line #	Frequency (cm <sup>-1</sup> )	Intensity (arb. units)	Rotat.	Vibr.	HF	Lock Frequency GHz
1	16.004,550544	2,13E-06	R( 62)	( 8- 3)	a 1	959608,7014
2	16.005,174912	1,20E-06	R( 70)	(10- 4)	a 1	959646,1375
3	16.005,596425	1,24E-06	P( 64)	(10- 4)	a 1	959671,4108
4	16.006,740634	2,16E-06	R( 60)	( 8- 3)	a 1	959740,0158
5	16.008,855569	2,19E-06	R( 58)	( 8- 3)	a 1	959866,8242
6	16.010,895381	2,21E-06	R( 56)	( 8- 3)	a 1	959899,1282
7	16.012,860102	2,22E-06	R( 54)	( 8- 3)	a 1	960106,9299
8	16.014,749763	2,23E-06	R( 52)	( 8- 3)	a 1	960220,2311
	16.018,304026	2,23E-06	R( 48)	( 8- 3)	a 1	960433,3394
9	16.019,968683	2,22E-06	R( 46)	( 8- 3)	a 1	960533,1497
10	16.021,558394	2,20E-06	R( 44)	( 8- 3)	a 1	960628,4664
11	16.023,073183	2,17E-06	R( 42)	( 8- 3)	a 1	960719,2908
12	16.024,513075	2,13E-06	R( 40)	( 8- 3)	a 1	960805,8246
13	16.025,878093	2,09E-06	R( 38)	( 8- 3)	a 1	960887,4690

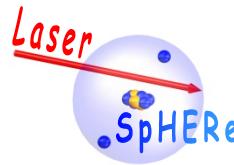
$v_{\text{Lit}}$  taken from: D. J. Wineland, J. J. Bollinger, and W. M. Itano, Phys. Rev. Lett. **50**, 628 (1983).

## <sup>9</sup>Be absolute frequency distribution



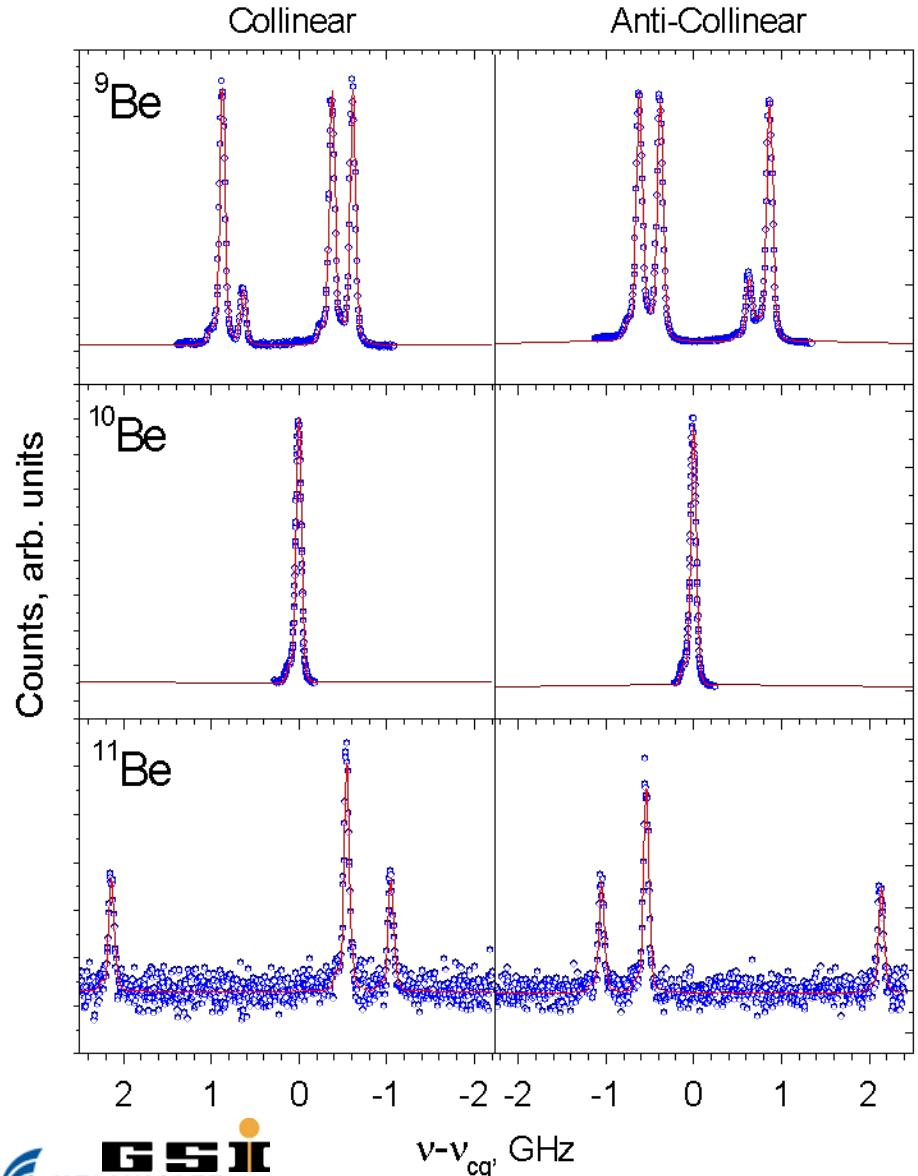
- ① off-line test shows feasibility of method
- ② <sup>9</sup>Be absolute frequency deviation from literature  
 $\rightarrow v_0 - v_{\text{Lit}} = 99.8 \pm 0.9 \text{ MHz}$

# On-Line Results



Collinear

Anti-Collinear



isotope	absolute frequency $\nu_0$ GHz	$\Delta\nu_0$ MHz
<i>Be</i>		
7	957150,31667	0,52
9	957199,55348	0,61
10	957216,87726	0,54
11	957231,11844	0,60

$\Delta\nu_0$  includes:

statistical standard deviation

laser-ion beam misalignment

*preliminary*

(~ 500 kHz)

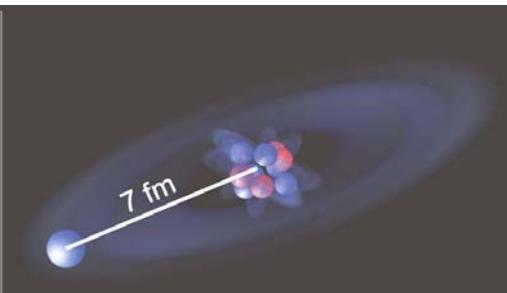
additional contributions:

rubidium clock uncertainty

~ 400 kHz

ion recoil correction

~ 100 kHz



**W. Nörtershäuser et al.**  
accepted for PRL

# Outlook Be-Laser Spectroscopy

## Current status:

Isotope shift of  $^{7,9,10,11}\text{Be}$  determined with  $\sim 1\text{MHz}$  precision  
 measurement of charge radii with  $\sim 1\%$  uncertainty

Addendum IS 449 completed

## Option:

Re-measuring isotope shift of  $^{7,9,10,11}\text{Be}$  determined with  
 $\sim 200\text{ kHz}$  precision in linear Paul trap

continue with original  
 proposal IS 449

depending on agreement with competitor's results

## Future:

① Isotope shift measurement of  $^{12}\text{Be}$  using COLLAPS $\otimes$ ISCOOL

new proposal 2009 (?)

but...: test of required precision in off-line Ga-beam time .....  $\rightarrow$  in  $1\frac{1}{2}$  weeks from now  
 : test of ISCOOL performance on very light isotopes .....  $\rightarrow$  ???  
 (buffer gas? transmission?)

② Isotope shift measurement of  $^{14}\text{Be}$  (2- or 4-neutron Halo?)

find adequate technique (yield ISOLDE:  $4\text{ s}^{-1}$ ,  $t_{\frac{1}{2}}=4\text{ ms}$ )

# ISOLDE high voltage calibration

## Situation:

Two high voltage power supplies for GPS and HRS with internal voltage divider measurement available:

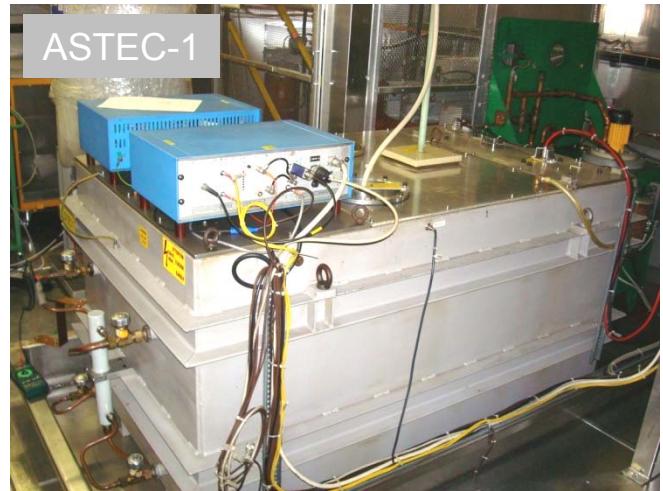
ASTEC-1 and ASCTEC-2  
specified relative precision  $10^{-4} = 6 \text{ V} @ 60 \text{ kV}$



HV potential determines the ion beam energy  
→ crucial for classical collinear laser spectroscopy

## Motivation for Voltage Calibration

- ① inconsistencies of ion energies observed at COLLAPS in between two runs in the past
- ② alternative approach for precision voltage determination instead of rather complicated collinear/anti-collinear laser spectroscopy



# High Precision Voltage Divider

access to high precision voltage divider build for voltage measurement in the sub-ppm regime

Collaboration with the group of Prof. Weinheimer at University Münster and the KATRIN collaboration

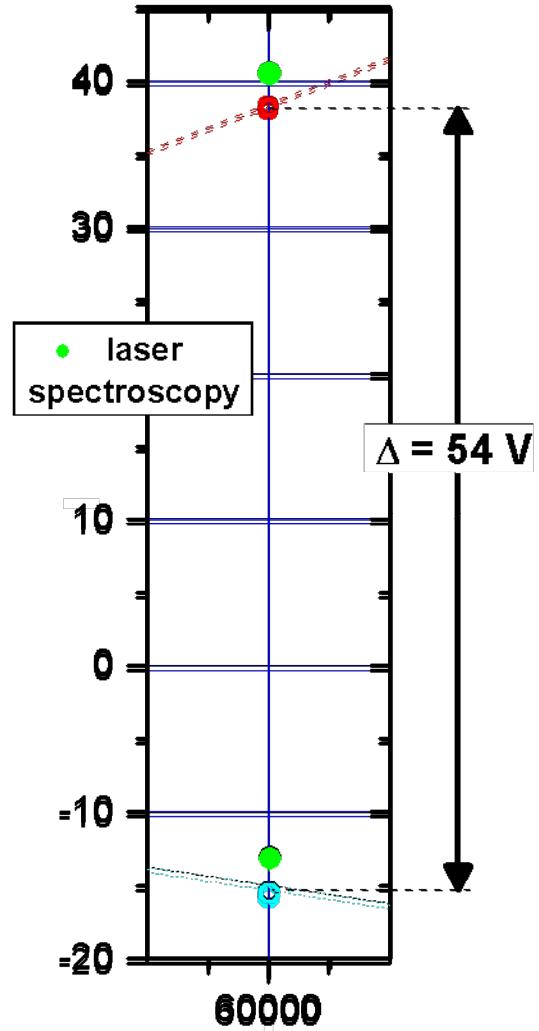
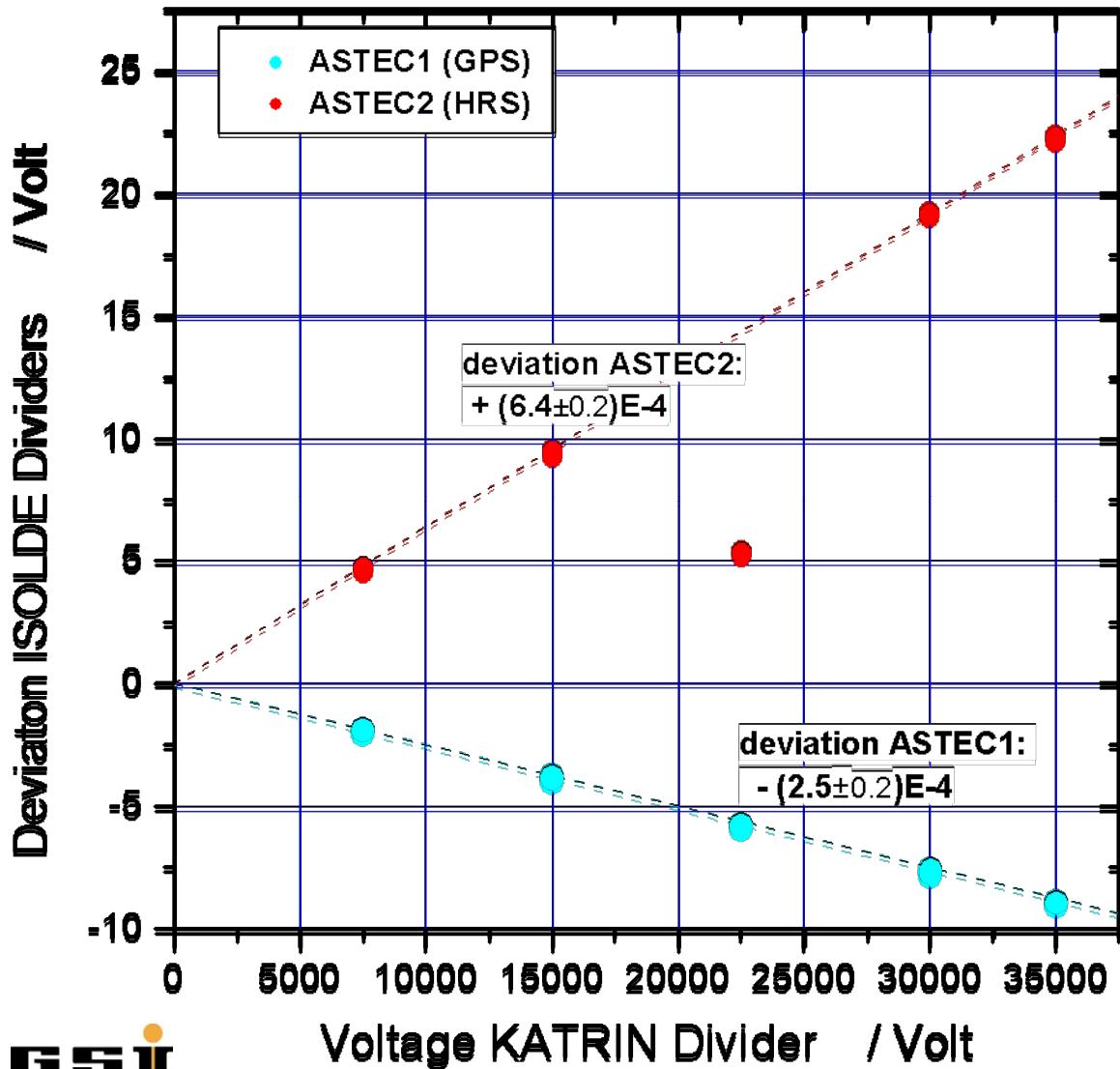
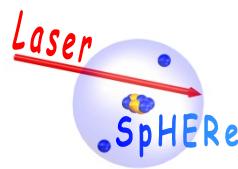


## Parameter

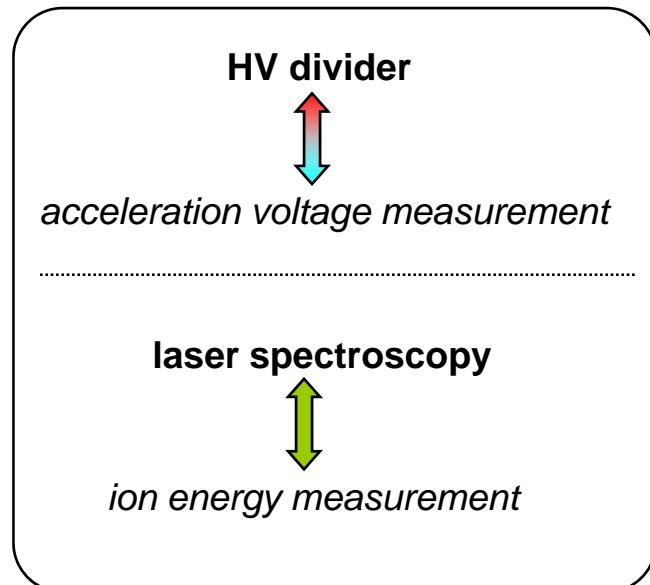
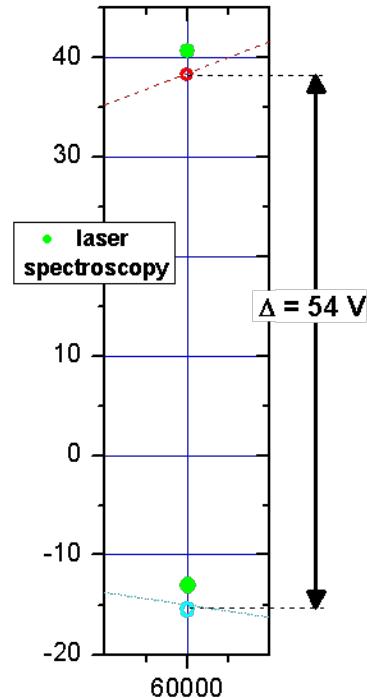
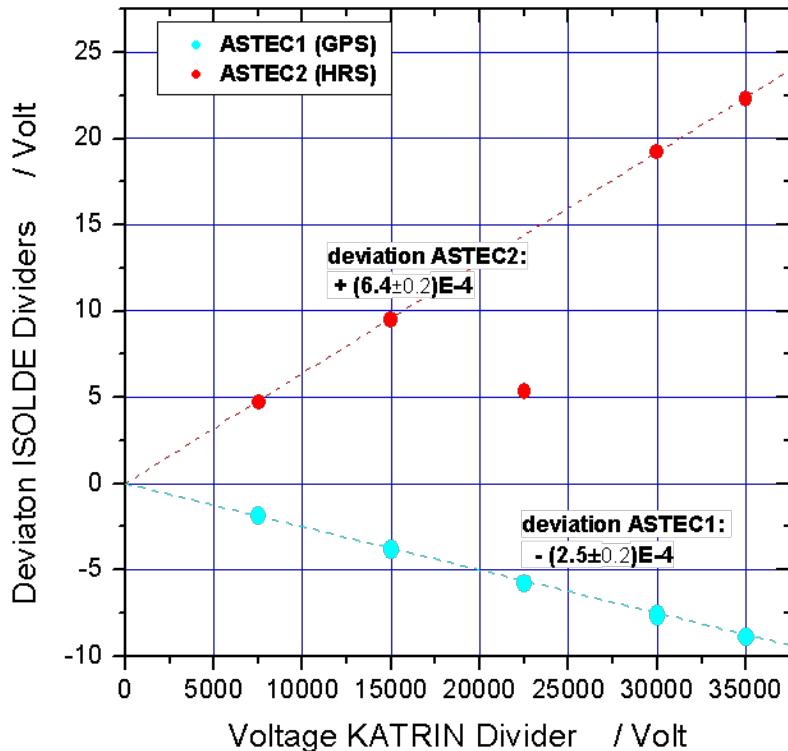
scaling factor	1972,48016(61)
relative. standard deviation	0,32 ppm
temperature dependence	-0,81(6)ppm/K
voltage dependence	0,032(6)ppm/kV
voltage regime	-8 kV to -32 kV
heating time (ppm regime)	~ 2 minutes
heating time (sub-ppm regime)	~ 3 hours
reproducibility (1 month)	~0,3 ppm
long time stability	0,604ppm/month

<http://www.uni-muenster.de/Physik.KP/AGWeinheimer/>

# Voltage Calibration ASTEC-1 & 2



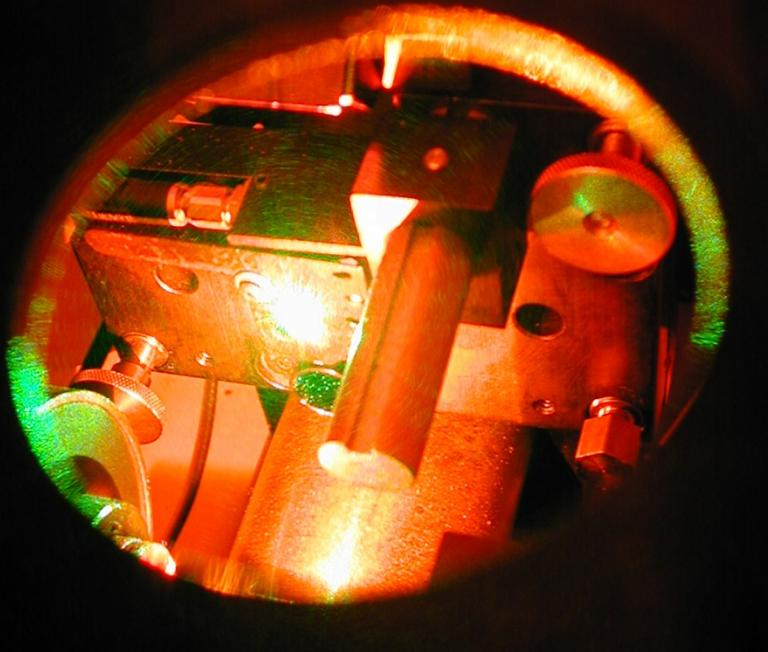
# Voltage Calibration ASTEC 1 & 2



## Observations and Results:

- total deviation in the order of  $10^{-3}$  = one order worse than specified
- low ripple (few mV at a ~ 5-10 s time base)
- small discrepancy (< 3 eV) between ion energy and HV platform potential

→ provide (temporary) calibration of ASTEC 1 & 2



# Thanks...

to the **RILIS** team and the  
impressive performance of their new  
solid-state pump laser system

strong support from coordinator  
and **ISOLDE technical crew**  
(operators, vacuum support, Jan  
Schipper for HV measurements, .....

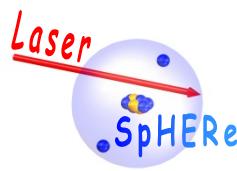
Element	A number	Half life	SC or PSB*	Yield at ISOLDE (ions/ $\mu$ C)	Target material
Be	7	53.12 d 7	PSB	2.0E+12	C
Be	7	53.12 d 7	PSB	1.4E+10	UC <sub>x</sub>
Be	10	1.51E+6 y 6	PSB	2.0E+12	C
Be	10	1.51E+6 y 6	PSB	4.9E+08	Ta
Be	10	1.51E+6 y 6	PSB	6.0E+09	UC <sub>x</sub>
Be	11	13.81 s 8	PSB	3.4E+06	Ta
Be	11	13.81 s 8	PSB	7.0E+06	UC <sub>x</sub>
Be	12	23.6 ms 9	PSB	7.0E+03	Ta
Be	12	23.6 ms 9	PSB	1.5E+03	UC <sub>x</sub>
Be	14	4.35 ms 17	PSB	6.1E+00	Ta
Be	14	4.35 ms 17	PSB	4.0E+00	UC <sub>x</sub>
Be	11 - g	13.81 s 8	SC	1.5E+05	Ta
Be	11 - g	13.81 s 8	SC	3.3E+03	Ta
Be	11 - g	13.81 s 8	SC	5.0E+04	Ta
Be	11 - g	13.81 s 8	SC	5.4E+04	Ta

Isotope	Yield
$^{11}\text{Be}$	$5.7 \times 10^7$ ions/pulse

thank you for your attention

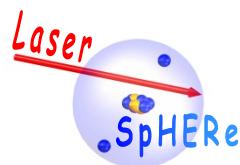
the Be<sup>+</sup> laser crew



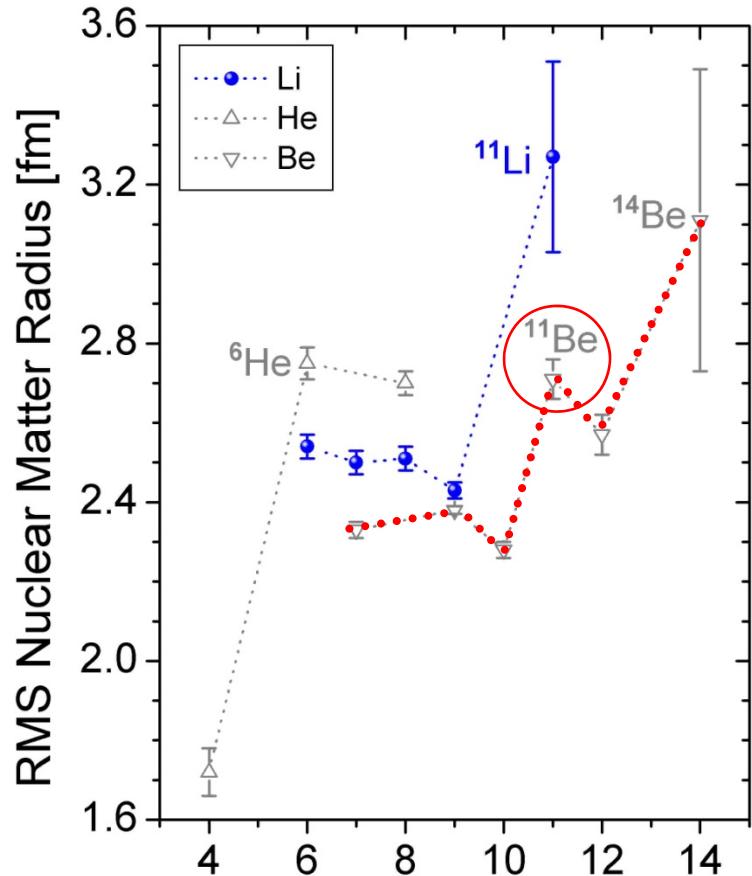


# End

# Radii of Halo Isotopes



Charge radius measurements of light ( $Z < 18$ ) radioactive isotopes:



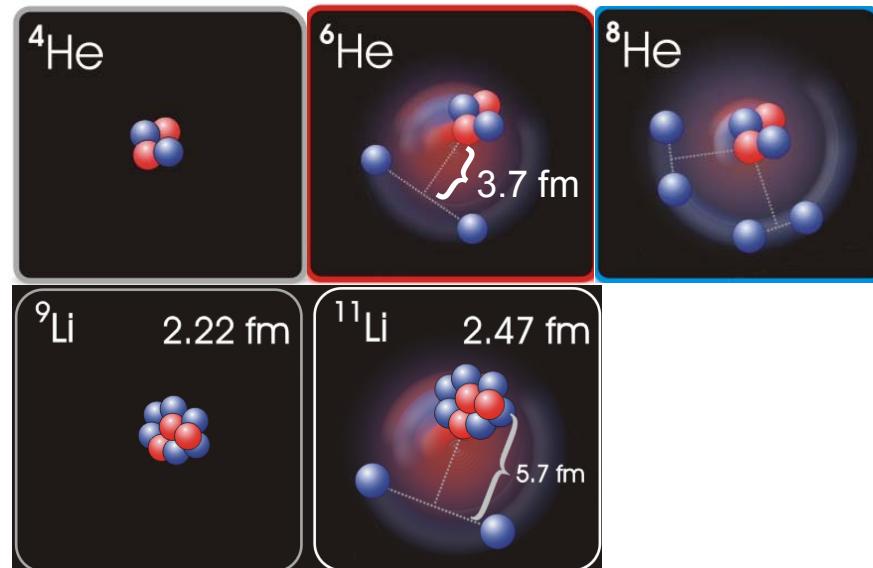
## Chronology:

2003 :  $^{6,7,8,9}\text{Li}$  at **GSI** G. Ewald et al., PRL 93, 113002

2004:  $^6\text{He}$  at **ANL**, L.-B. Wang et al. PRL 93, 142501

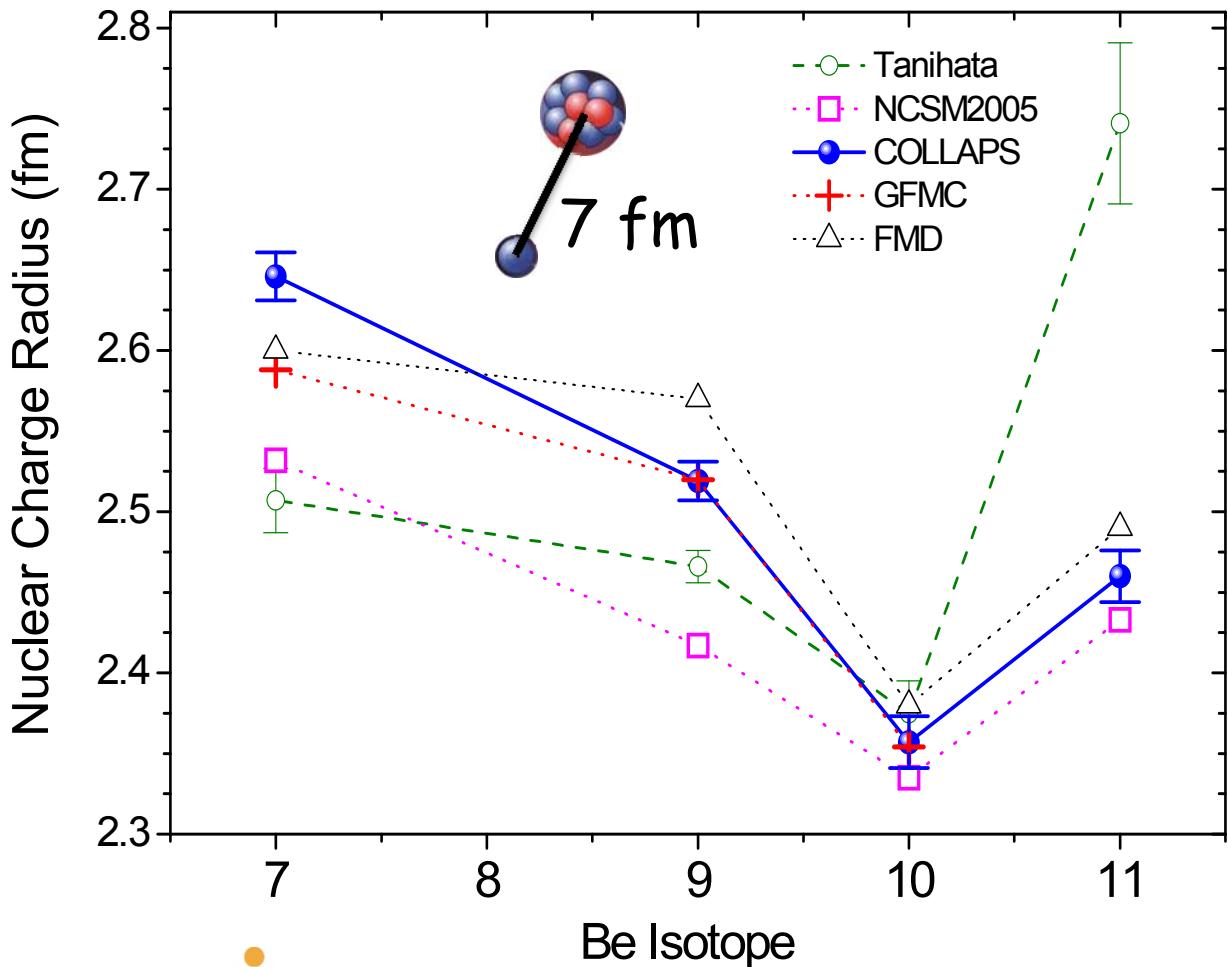
2004:  $^{11}\text{Li}$  at **TRIUMF**, R. Sanchez et al., PRL 96, 033002

2007:  $^8\text{He}$  at **GANIL**, P. Müller et al. PRL 99, 252501



# Beryllium: Nuclear Charge Radii

Electron Scattering:  $r_c(^9\text{Be}) = 2.519(12) \text{ fm}$ , J.A. Jansen et al., Nucl.Phys.A **188**, 337 (1972).  
 Muonic Atoms:  $r_c(^9\text{Be}) = 2.39(17) \text{ fm}$ , L.A. Schaller, Nucl.Phys.A **343**, 333 (1980).



## References:

NCSM2005: No Core Shell Model  
 P. Navratil, PRC 73, 065801 (2006) ( $^7\text{Be}$ )  
 C. Forssen, Phys. Rev. C71 (2005) ( $^{9,11}\text{Be}$ )  
 P. Navratil, priv. comm. (2008) ( $^{10}\text{Be}$ )

Tanihata: Interaction Cross Sections with Glauber model  
 I. Tanihata, Phys. Lett B 206, 592 (1988)

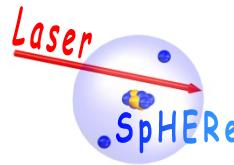
SVMC: Stochastic Variational Multicenter Method  
 Suzuki, J Phys.G 24, 1491 (1998)

GFMC: Greens Function Monte Carlo AV18/IL2  
 S. Pieper, Annu.Rev.Nucl.Part.Sci. 51, 53 (2001)  
 S. Pieper, PRC 66, 044310 (2002)

FMD: Fermionic Molecular Dynamic  
 R. Torabi, GSI, priv. comm. (2008)

Thanks to R.Torabi, Th. Neff,  
 H. Feldmeier and P. Navratil for  
 providing unpublished data !

# Scan Overview



D1-Linie						
Isotop	7Be	9Be	10Be	11Be	12Be	
Resolution	low	high	low	high	low	high
J2-Linie						
7			104	2287		
8			600	3636		
9	~600	850	600			
10	630	250				
11	0	0				
12	0	0				
14	0					
15	0					

D2-Linie						
Isotop	7Be	9Be	10Be	11Be	12Be	
Resolution	low	high	low	high	low	high
J2-Linie						
7					0	
8				145	495	
9			200	300	300	
10			100	217	356	
11	201	187	470			
12	300	300	0			
14	0					
15	0					

low resolution: 401 steps for odd isotopes, 201 steps for 10Be  
 high resolution: 801 steps for odd isotopes, 401 steps for 10Be

# Level Schemes for Beryllium

