The linear Decelerator Facility HITRAP

A Status Report

W. Barth, D. Beck, T. Beier, M. Bevcic, E. Berdermann, M. Block, A. Bräuning-Demian, H. Brand, K. Brantjes, E. Bodewits, G. Clemente, L. Dahl, C. Dimopoulou, C. Dorn, S. Eliseev, S. Fedotova, R. Fischer, P. Forck, F. Herfurth, R. Hoekstra, M. Kaiser, O. Kester, H.-J. Kluge, S. Koszudowski, N. Kotovski, C. Kozhuharov, C. Krantz, R. Lotz, M. Maier, F. Nolden, W. Nörtershäuser, F. Peldzinski, J. Pfister, W. Quint, D. Racano, U. Ratzinger, A. Sauer, A. Schempp, M. Shaaban, A. Sokolov, M. Steck, K. Stiebing, T. Stöhlker, W. Vinzenz, M. Vogel, G. Vorobjev, C. Will, D. Winters, A. Wolf, O. Zurkan
and the HITRAP collaboration

GSI — *Darmstadt*
Goethe-Universität, Johann Wolfgang, Frankfurt am Main, Institut für Angewandte Physik — *Frankfurt*
Max-Planck-Institut für Kernphysik — *Heidelberg*
universität mainz — *Mainz*
KVI — *Groningen*

Outline

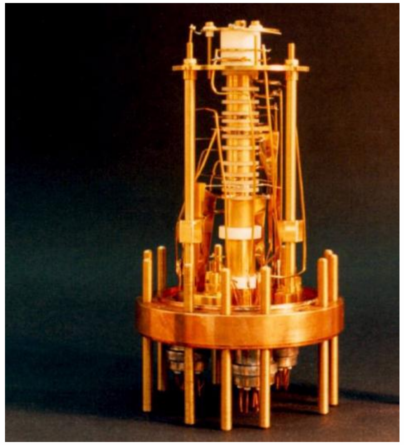
- Planned Experiments
- HITRAP overview
- Developments at the ESR
- The HITRAP facility
  - DDB
  - IH
  - RFQ
  - Trap
  - EBIT

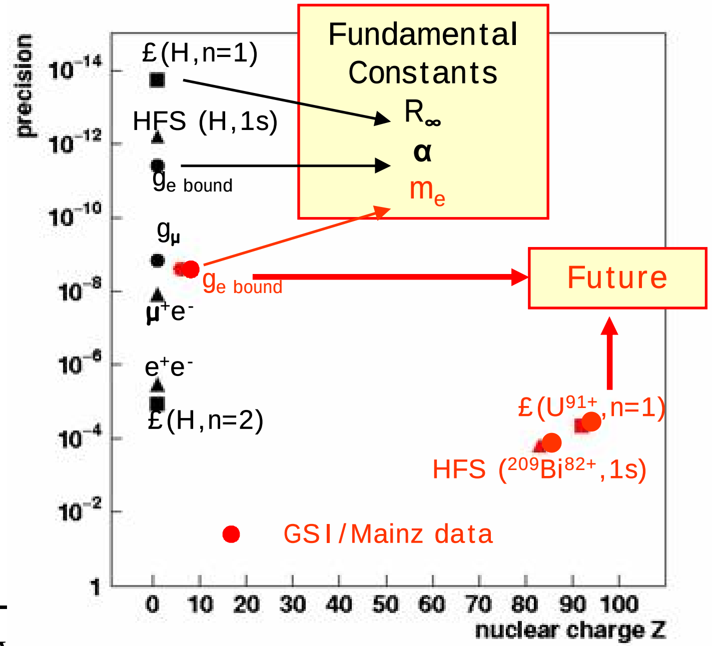
Precision Experiments on Single Highly-Charged Ions

Test of quantum electrodynamics in extreme fields
- g-factor of the bound electron
- Electron correlations and relativistic effects

Determination of fundamental constants
- Mass of the electron m_e
- Future: fine-structure constant α

Ultra-precise mass measurements
- Determination of atomic and nuclear binding energies





Spectroscopy, Reactions and Surface Studies with HCI

Laser spectroscopy of H-like ions:

- Nuclear properties (Bohr-Weisskopf effect)
- Atomic and nuclear polarization by optical pumping

X-ray spectroscopy with HCI:

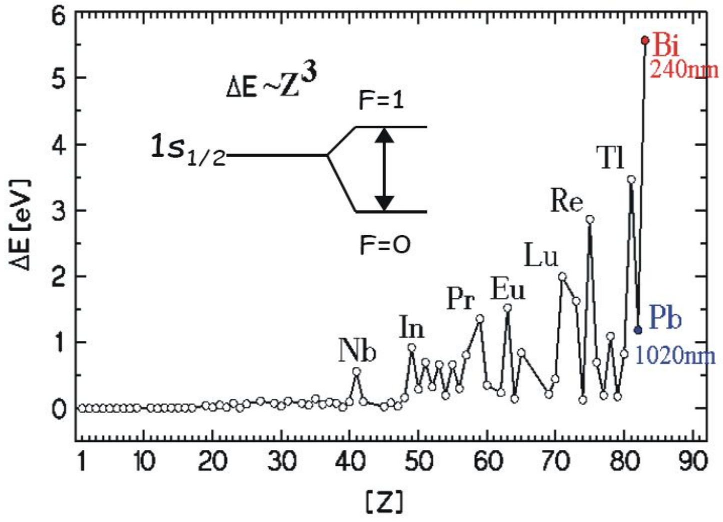
- Precision measurements of binding energies
- Isotope shift: nuclear charge radii

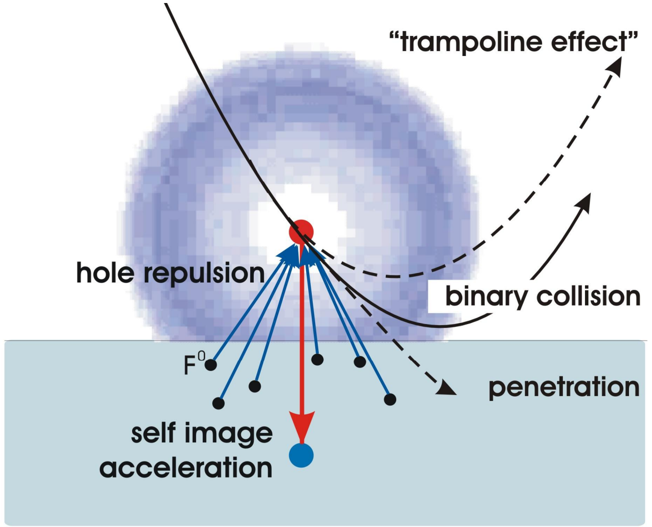
Reaction microscope:

- Studies of reaction kinematics of slow HCI

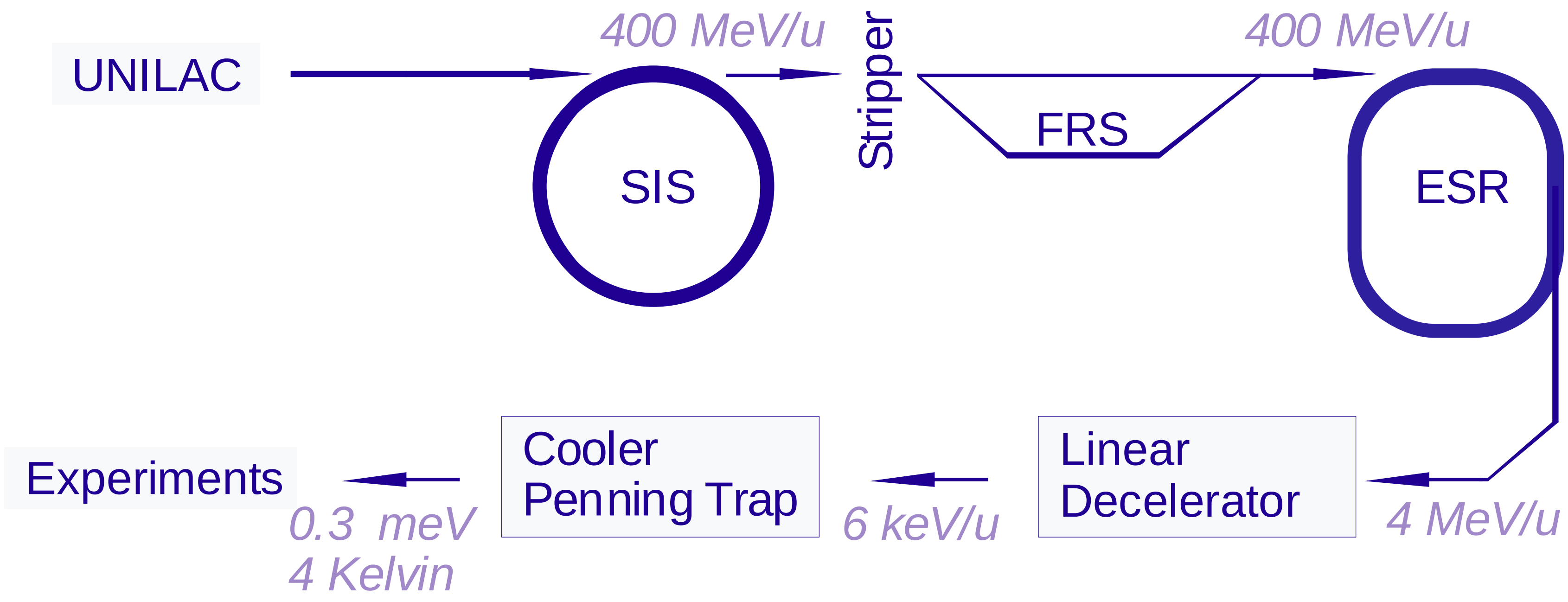
Interaction of slow HCI up to U^{92+} with surfaces:

- Strongly inverted systems ('hollow atoms')



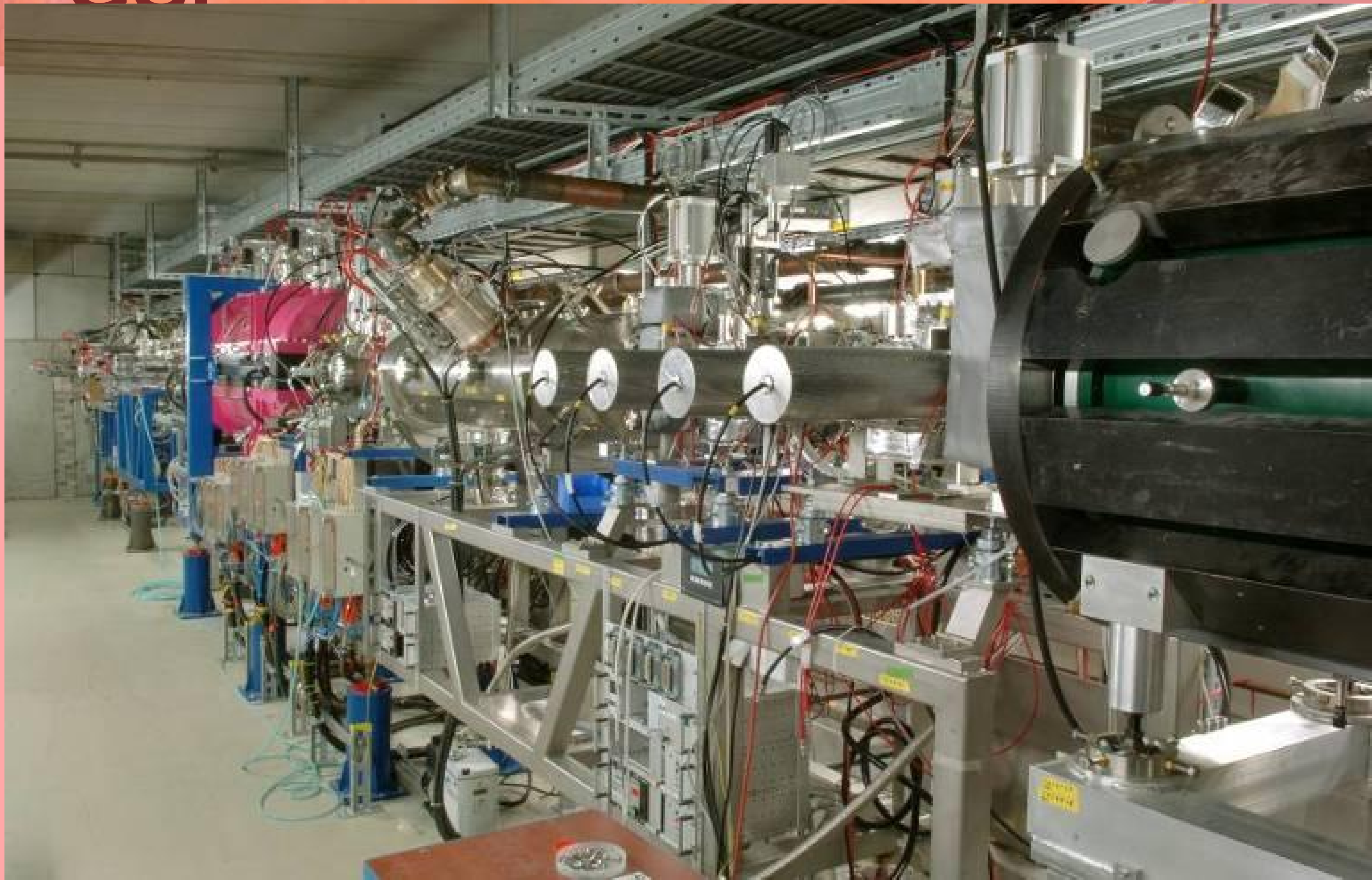


HITRAP @ GSI


UNILAC
400 MeV/u
SIS
Stripper
FRS
400 MeV/u
ESR
Experiments
0.3 meV
4 Kelvin
Cooler
Penning Trap
6 keV/u
Linear
Decelerator
4 MeV/u

HITRAP

GSI

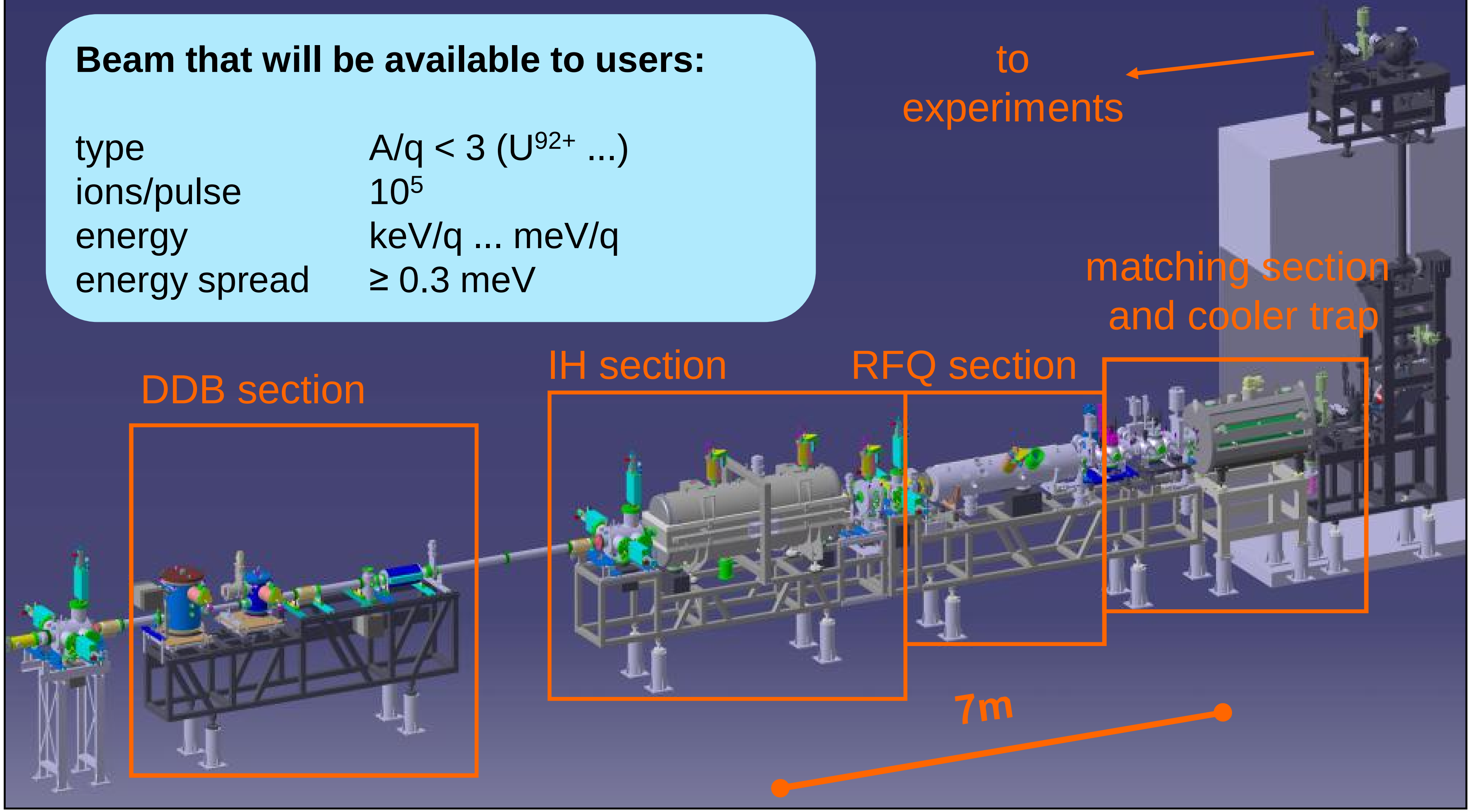


GeV/u

HITRAP – Linear Decelerator

Beam that will be available to users:

type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV



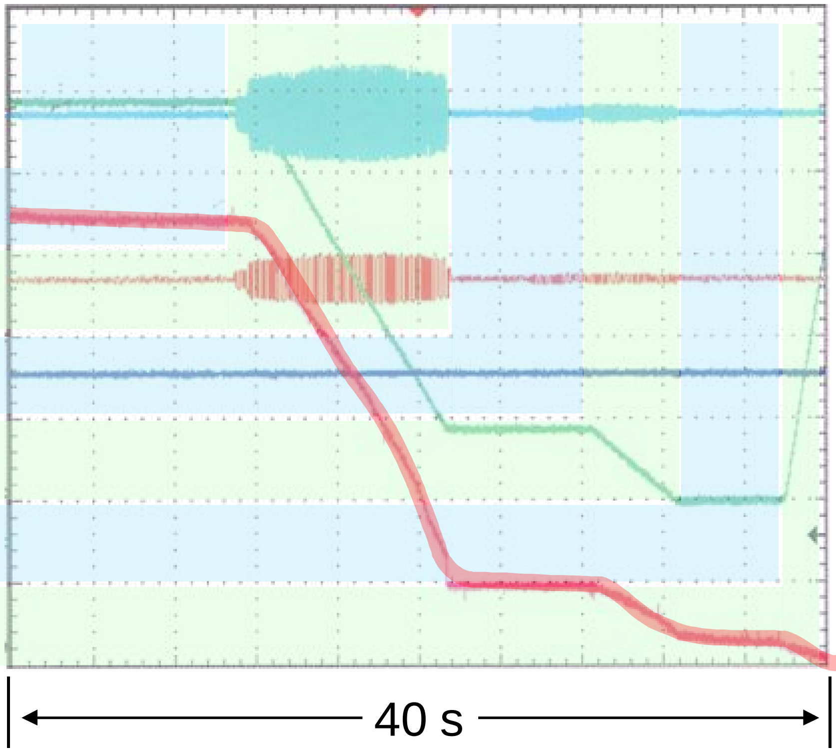
Some of the Challenges

- Never done before!
- 1 ion pulse with only 10^6 ions every 30 to 60 seconds
- “Normal” Linac diagnostics not well suited
- Unexpected behavior of decelerating accelerator

ESR – From 400 to 4 MeV/u

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

time (s)	**ESR cycle during recent experiment**
5..20	injection, **stoch. cooling**
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets

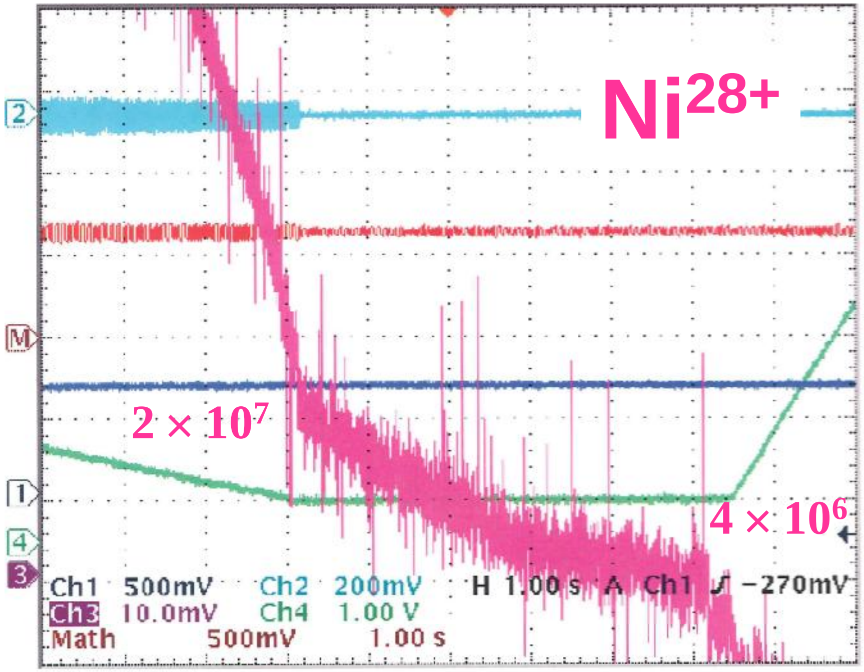


signal:
RF amplitude
magn.dipole field
ion current

ESR – From 400 to 4 MeV/u – critical points

Intensity limited at/due to

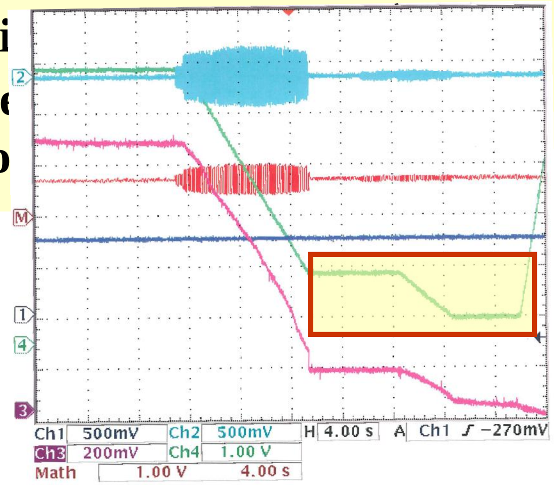
- **End of ramp**
- **Storage and cooling at low energy**



beam half life $T_{1/2}$ (vacuum dominated):
30 MeV/u: ≈ 480 s ⟺ 4 MeV/u: ≈ 2 s

Cycle time limited due to

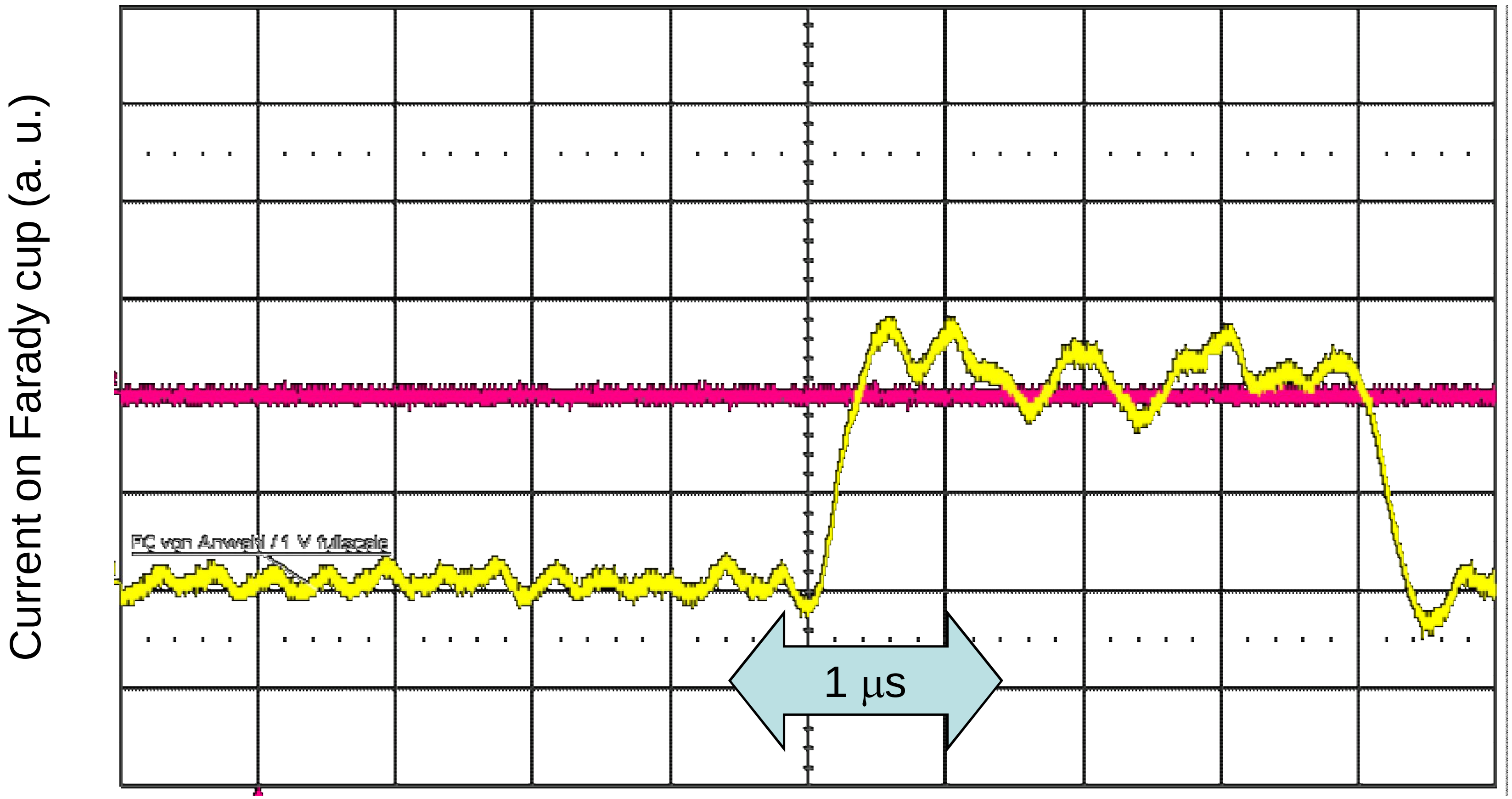
- **Flexibili**
- **Machine (man po**



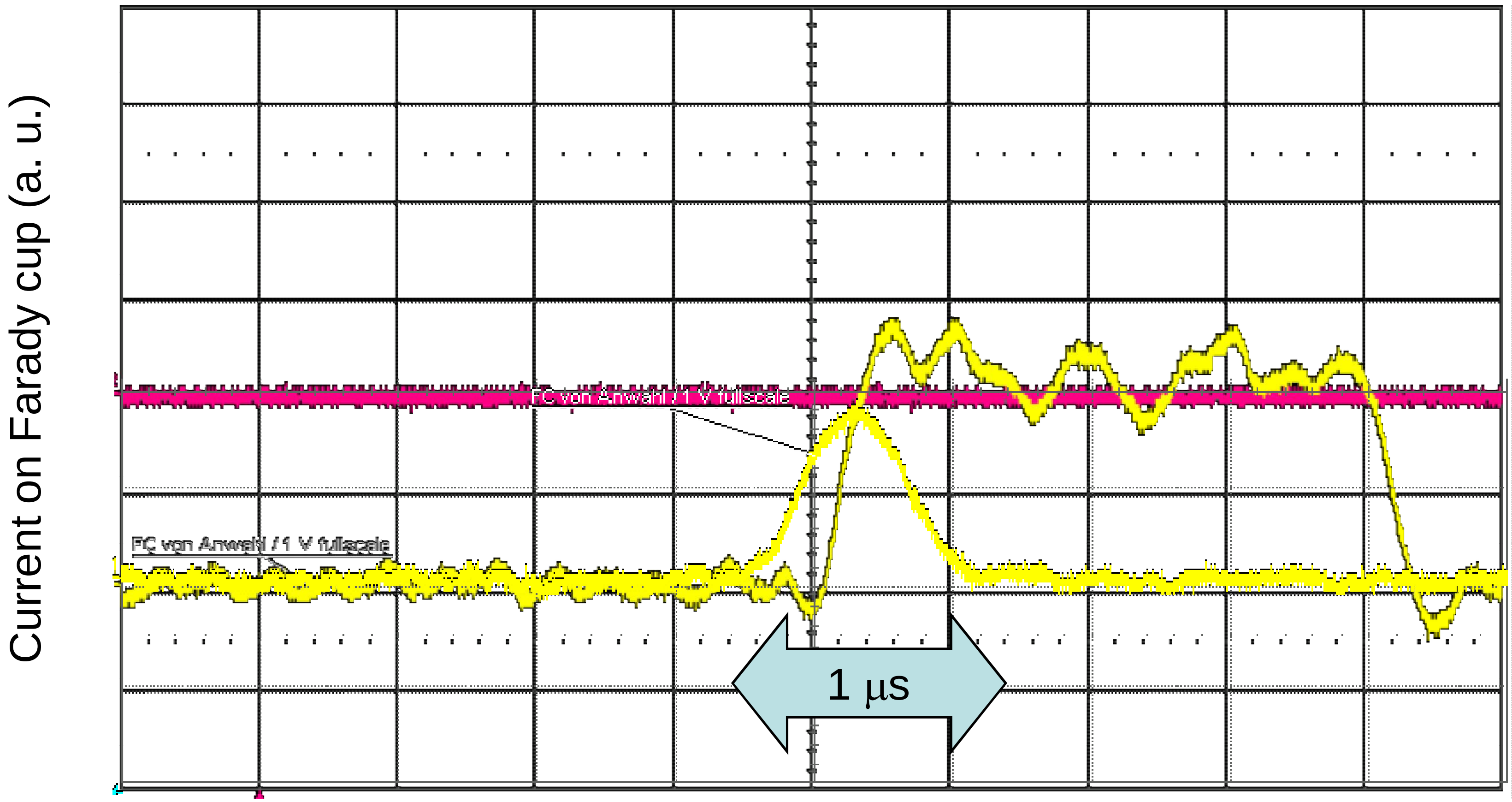
Cycle time reduction for commissioning

- **Transport 4 MeV/u beam without acceleration/decleration is not feasible**
- **30 MeV/u SIS extraction gives a factor 2**

ESR – Rebunching at 4 MeV/u



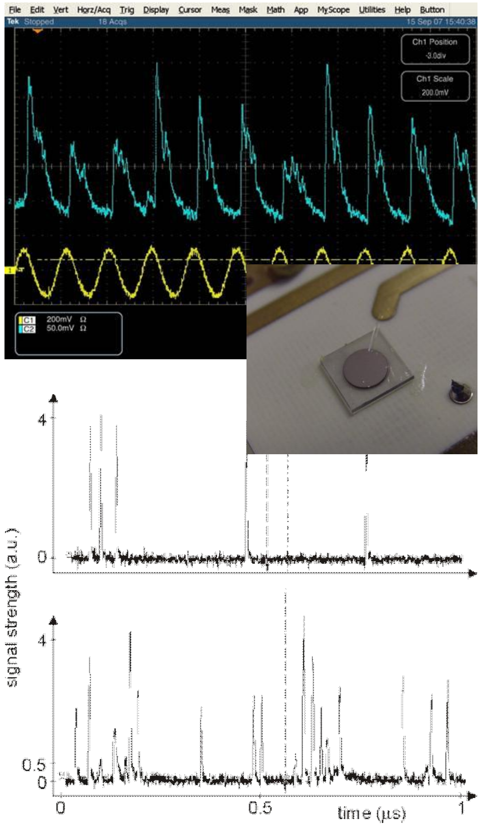
ESR – Rebunching at 4 MeV/u



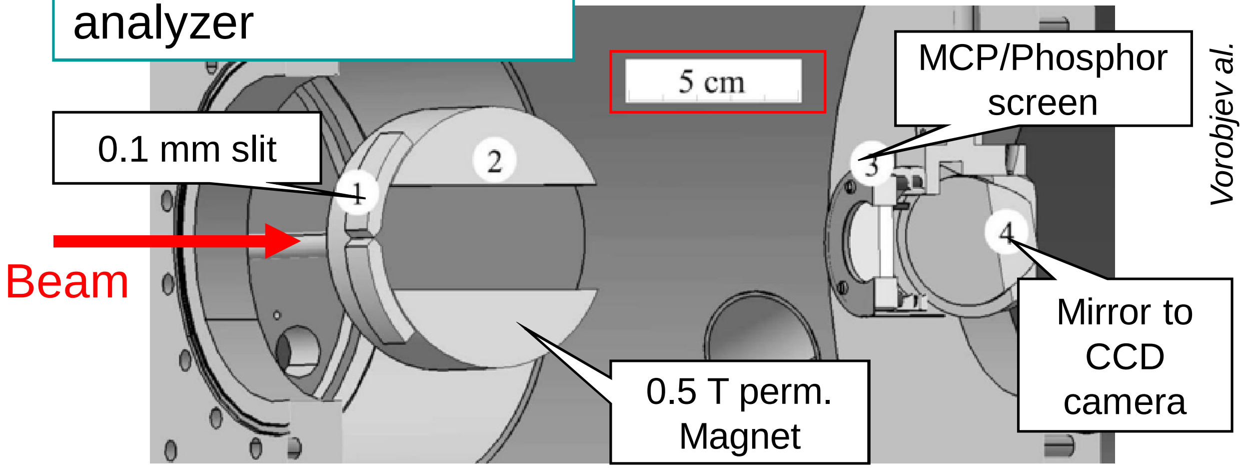
Newly developed Detectors

Diamond Detector

Berdermann et al.



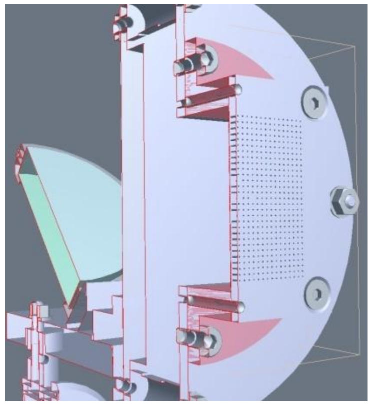
One-shot energy analyzer



Vorobjev al.

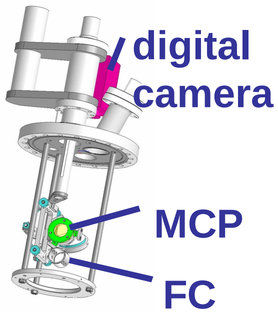
Sensitive single-shot emittance meter

Pfister et al.



MCP – Screen – camera combination

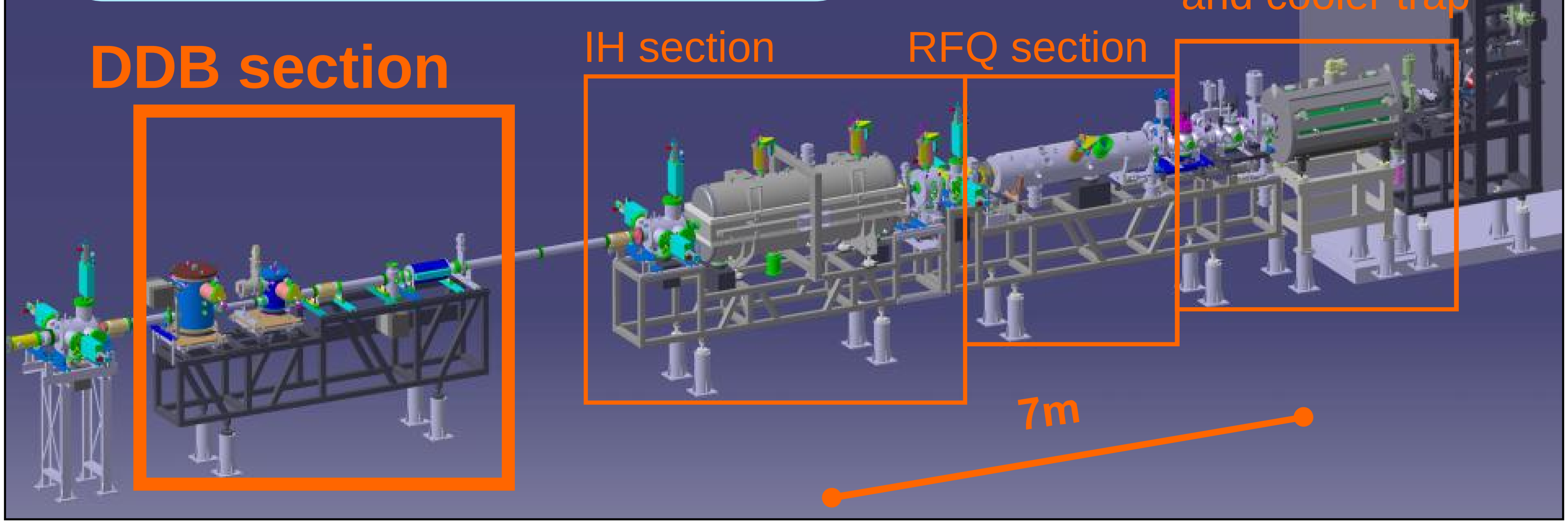
Hoekstra al.



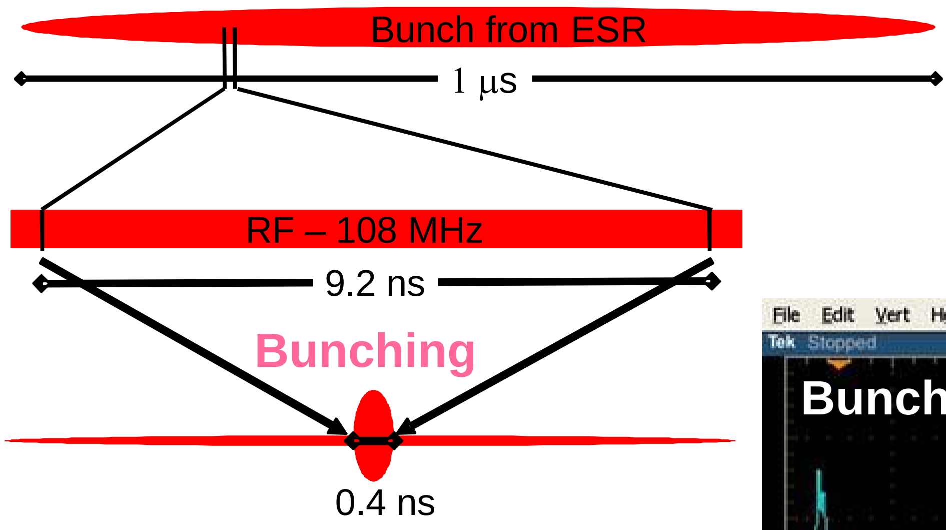
HITRAP – Linear Decelerator

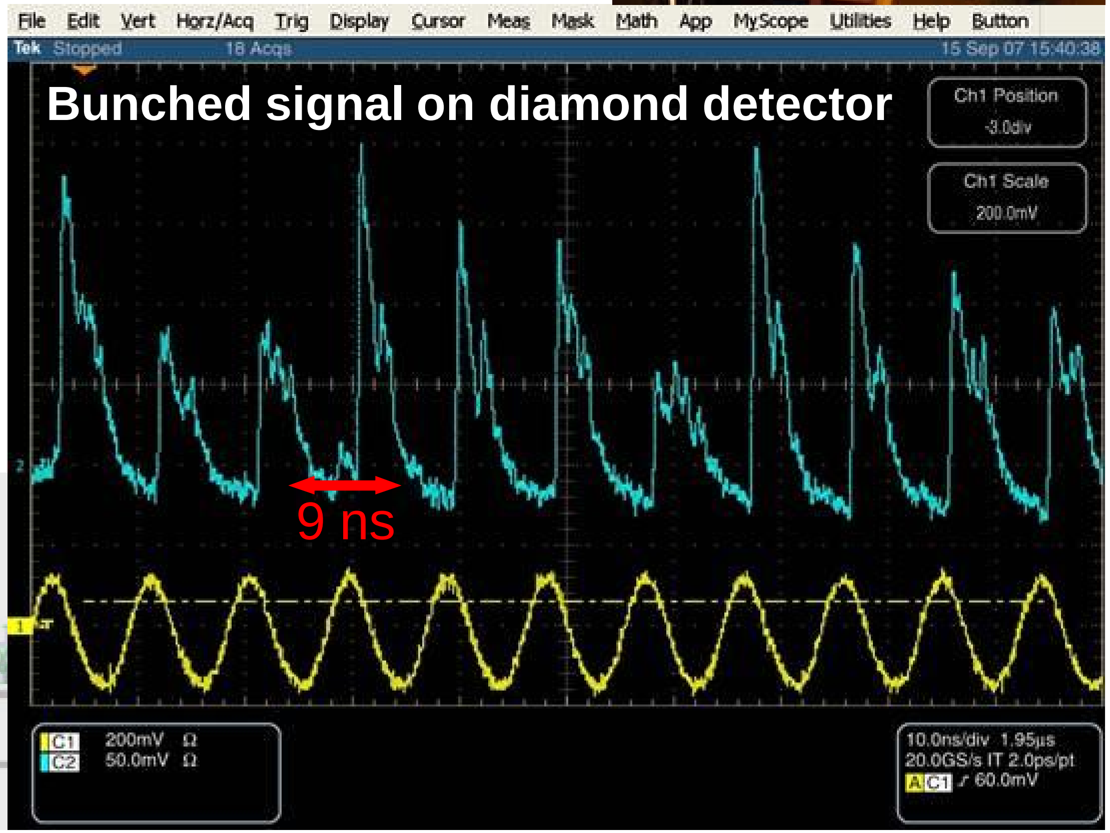
Beam that will be available to users:

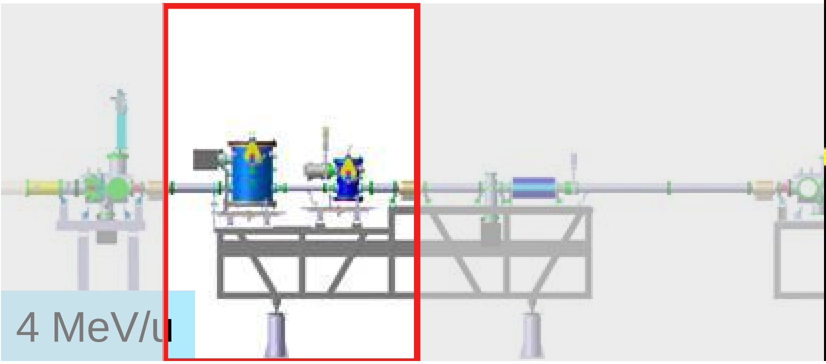
type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV



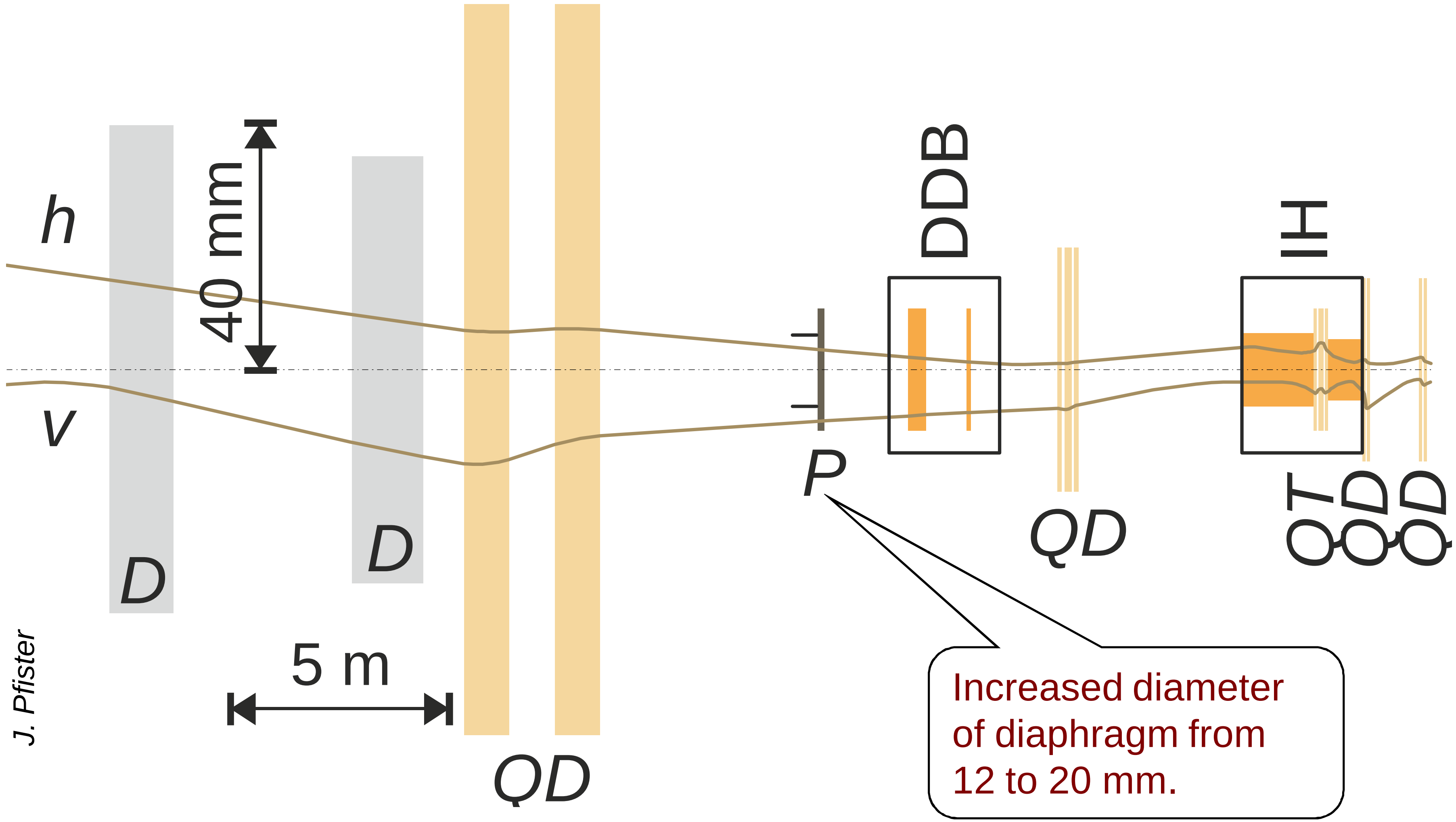
HITRAP – Double Drift Buncher







Simulations of transversal Optics



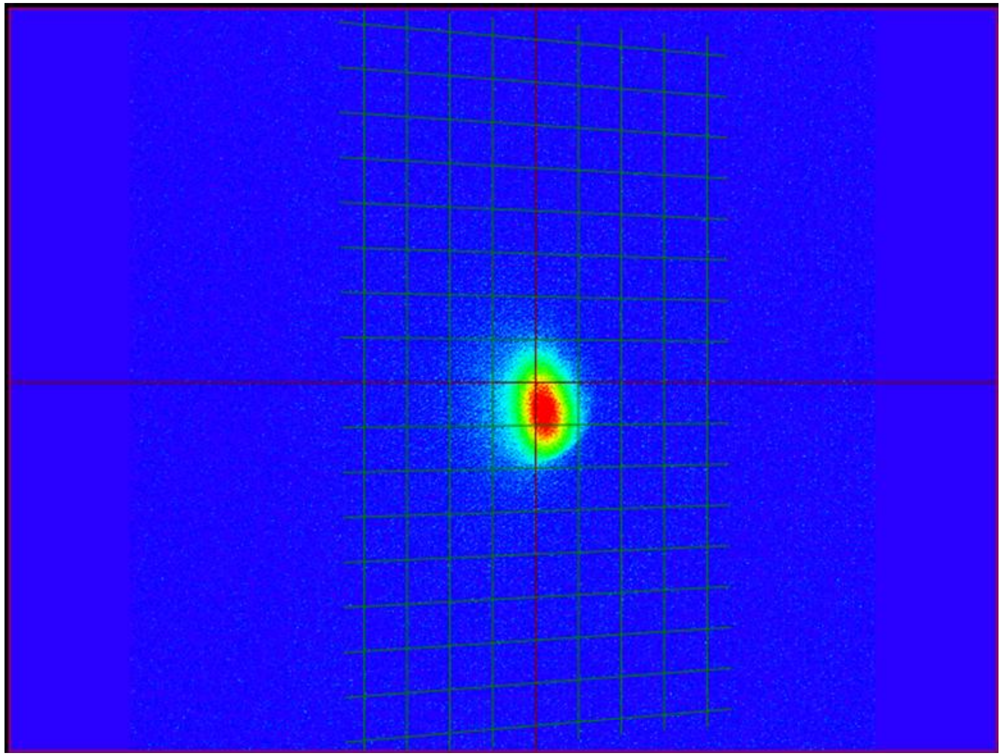
Increased diameter of diaphragm from 12 to 20 mm.

New transverse Settings

J. Pfister

Name	84Kr33+ (simulation) with bigger diaphragm B' [T/m]	84Kr33+ best setting with small diaphragm (April 2010) B' [T/m]
TR1 QD11	0,175	0,189
TR1 QD12	0,121	0,118
TR2 QT21	2,573	9,062
TR2 QT22	4,326	9,398
TR2 QT23	3,841	7,123
TR3 QT31	50,028	27,202
TR3 QT32	46,091	40,705
TR3 QT33	50,330	60,705
TR3 QD41	53,731	58,170
TR3 QD42	52,603	56,924
TR3 QD51	50,926	28,194
TR3 QD52	51,462	31,129

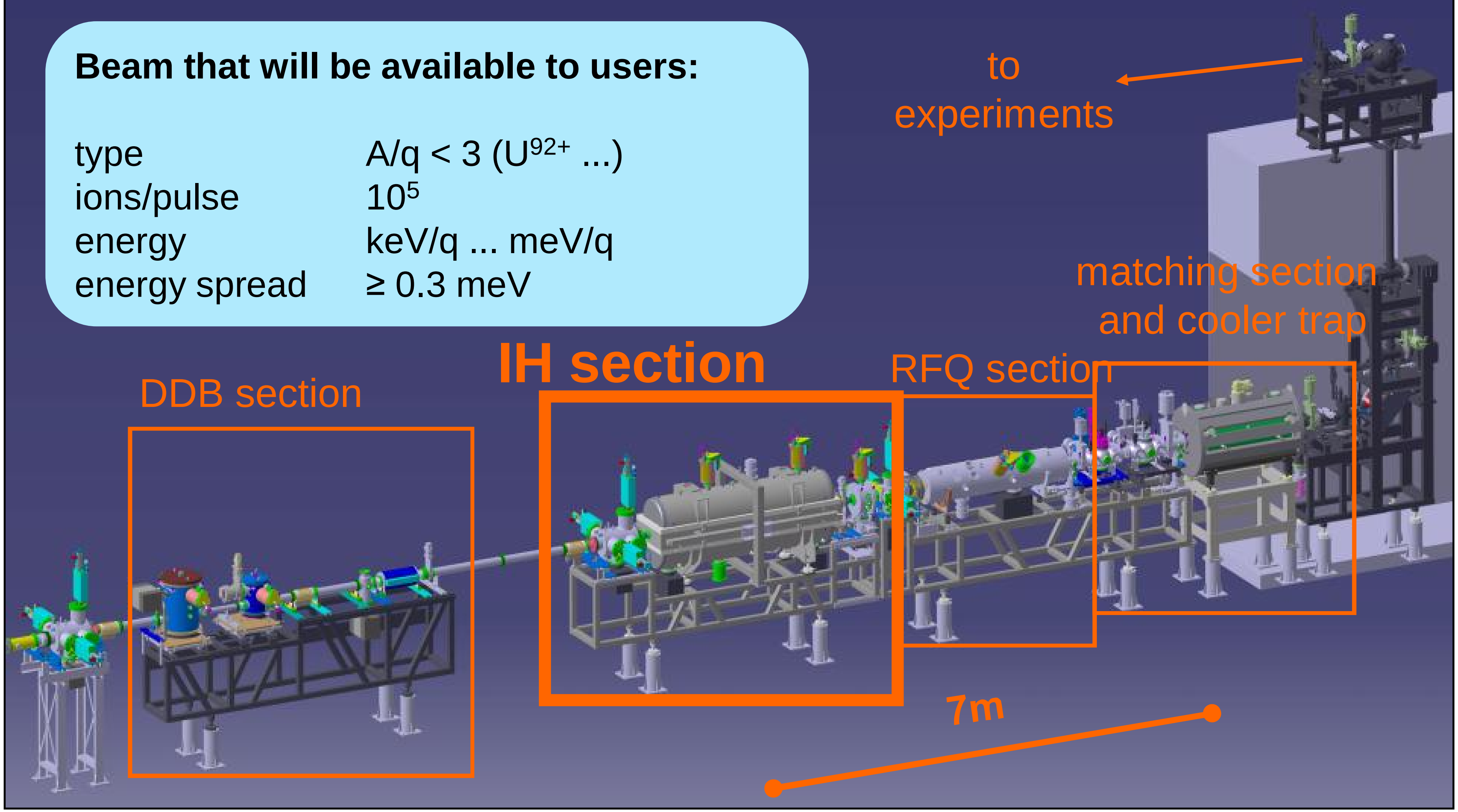
Beam on DF3



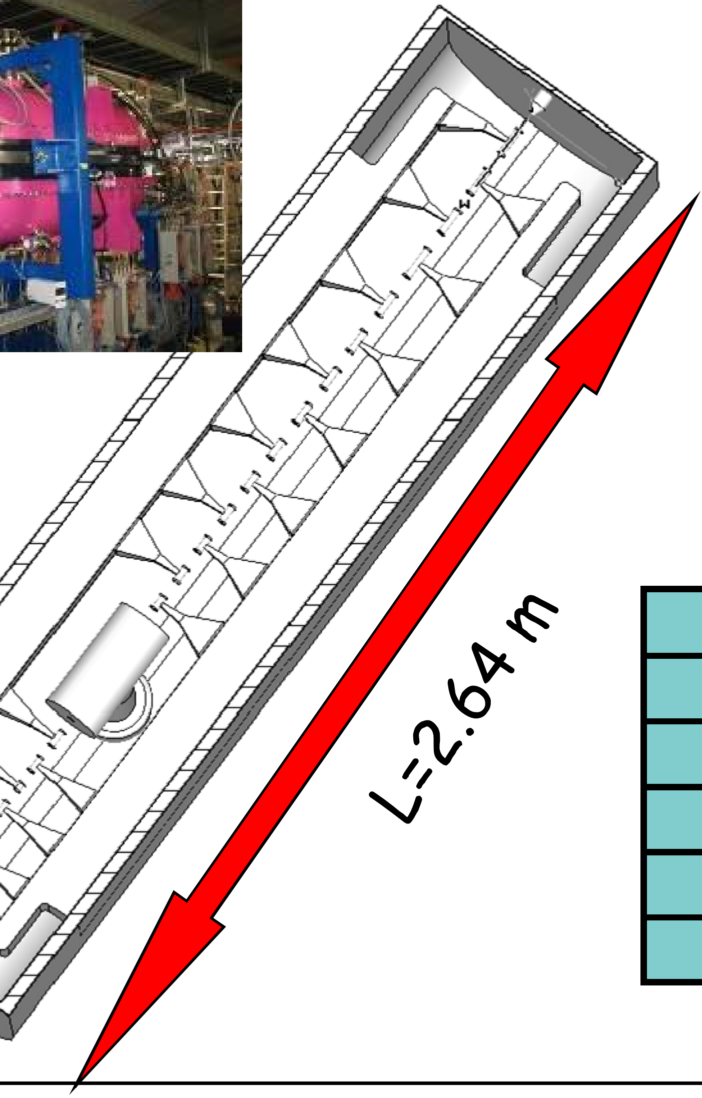
HITRAP – Linear Decelerator

Beam that will be available to users:

type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

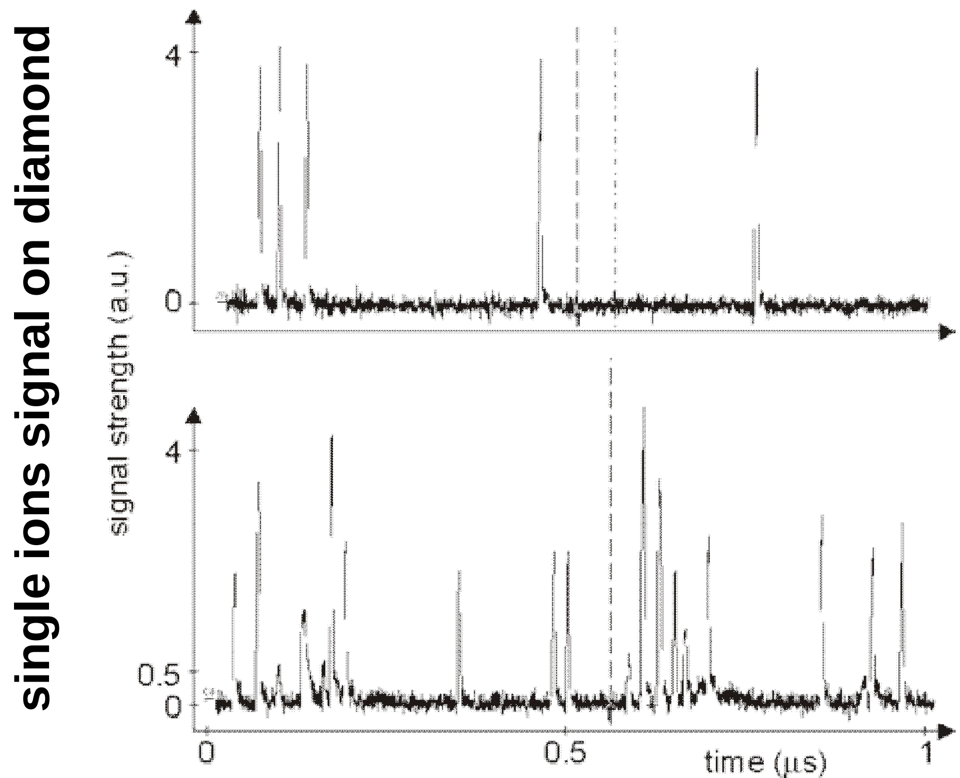


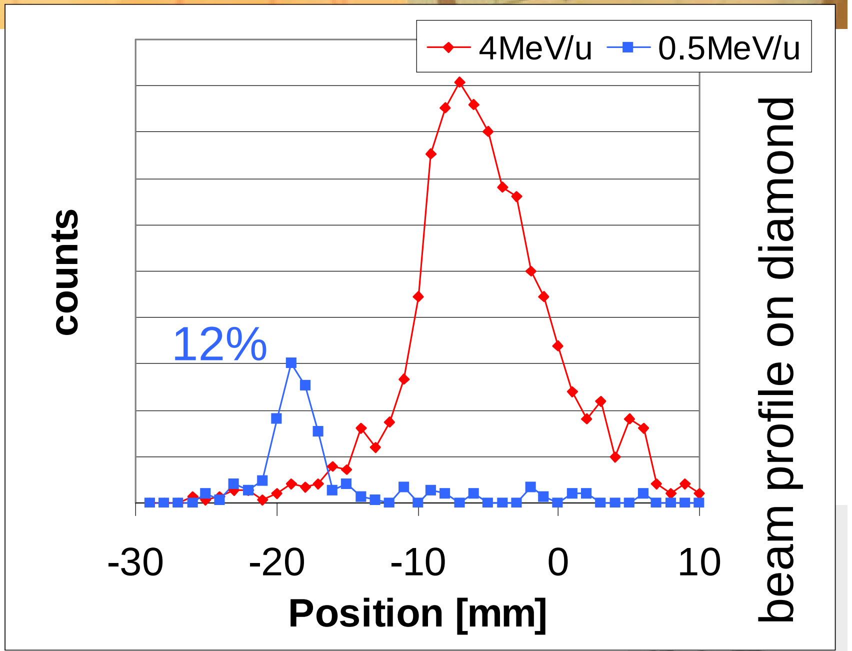
The HITRAP IH Structure

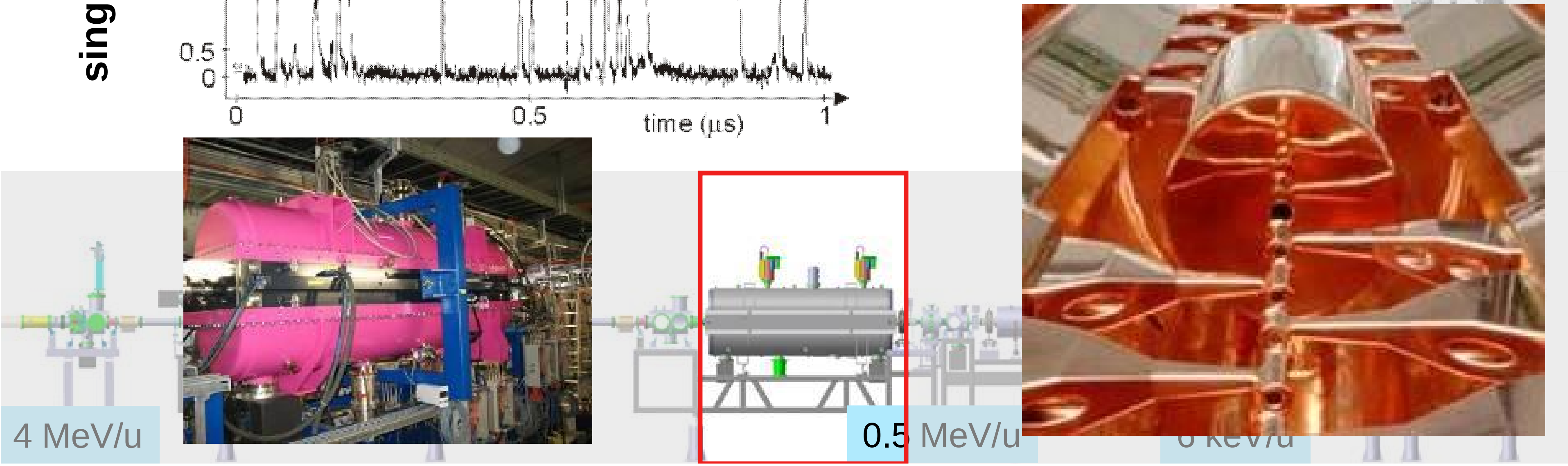


f_{rf}	108	MHz
Q_0	25800	
Z_{eff}	220	MΩ/m
E_{eff}	1.3	A/q*MV/m
Length	2.6	m
P_{rf}^1	170	kW

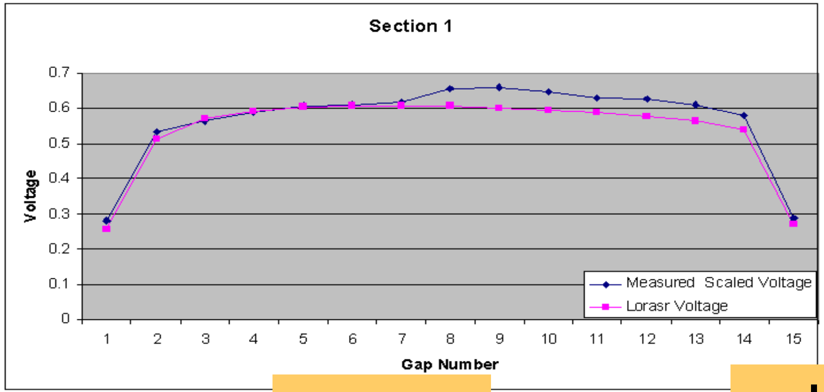
HITRAP – IH Structure

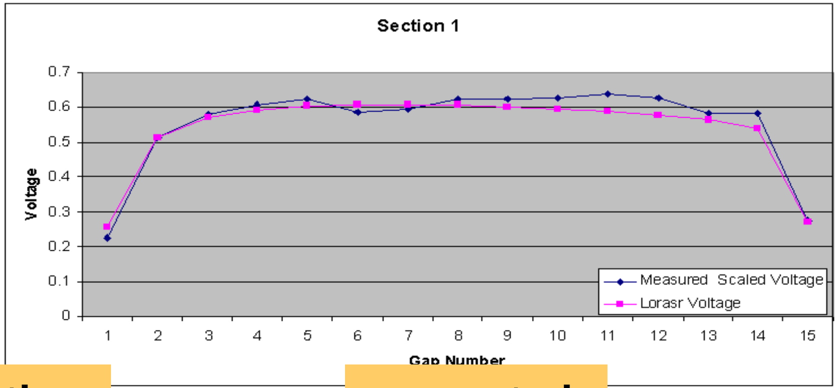




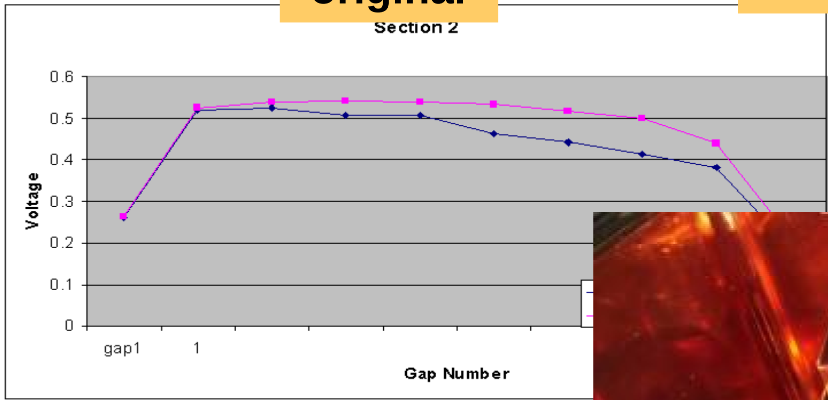


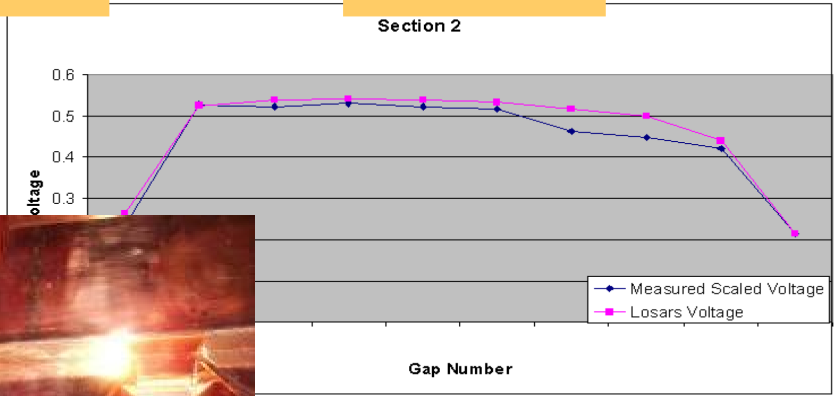
Retuning IH Gap voltage distribution





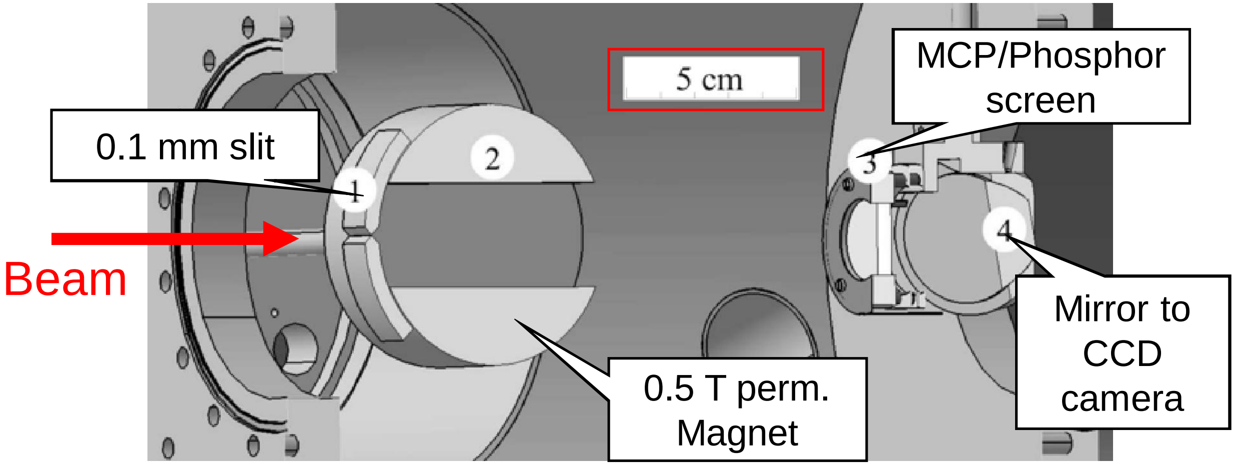
original **voltage distribution** **corrected**





additional tuner at the low energy end

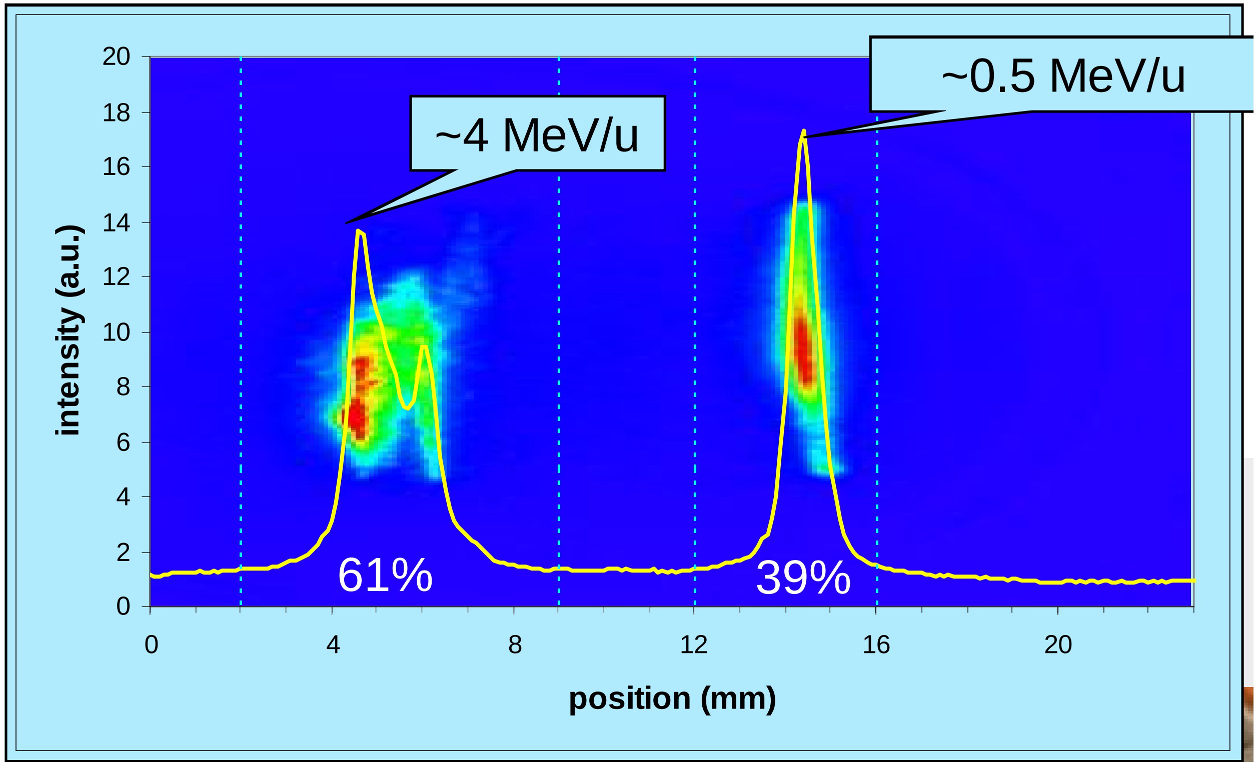
Principle of our Energy Analyzers

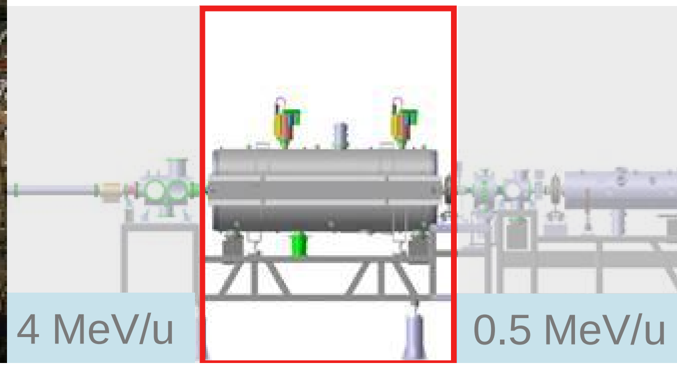


HITRAP – IH Structure

Energy spectrum IH

- Fraction of decelerated particles close to theory (55%)



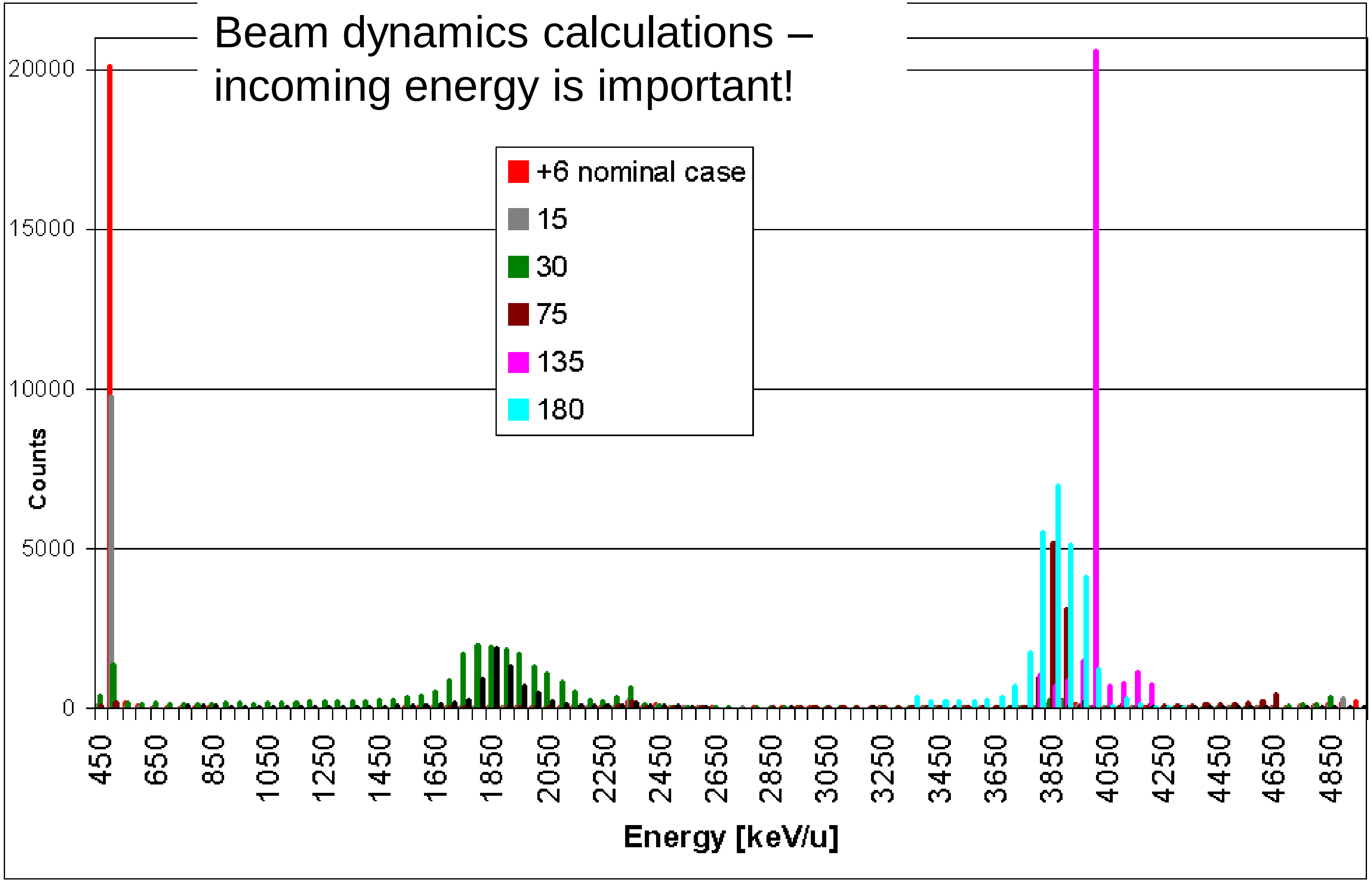


Energy spectrum after IH

- Fraction of decelerated particles close to theory (55%)

IH Structure – Energy Spectrum

Beam dynamics calculations – incoming energy is important!

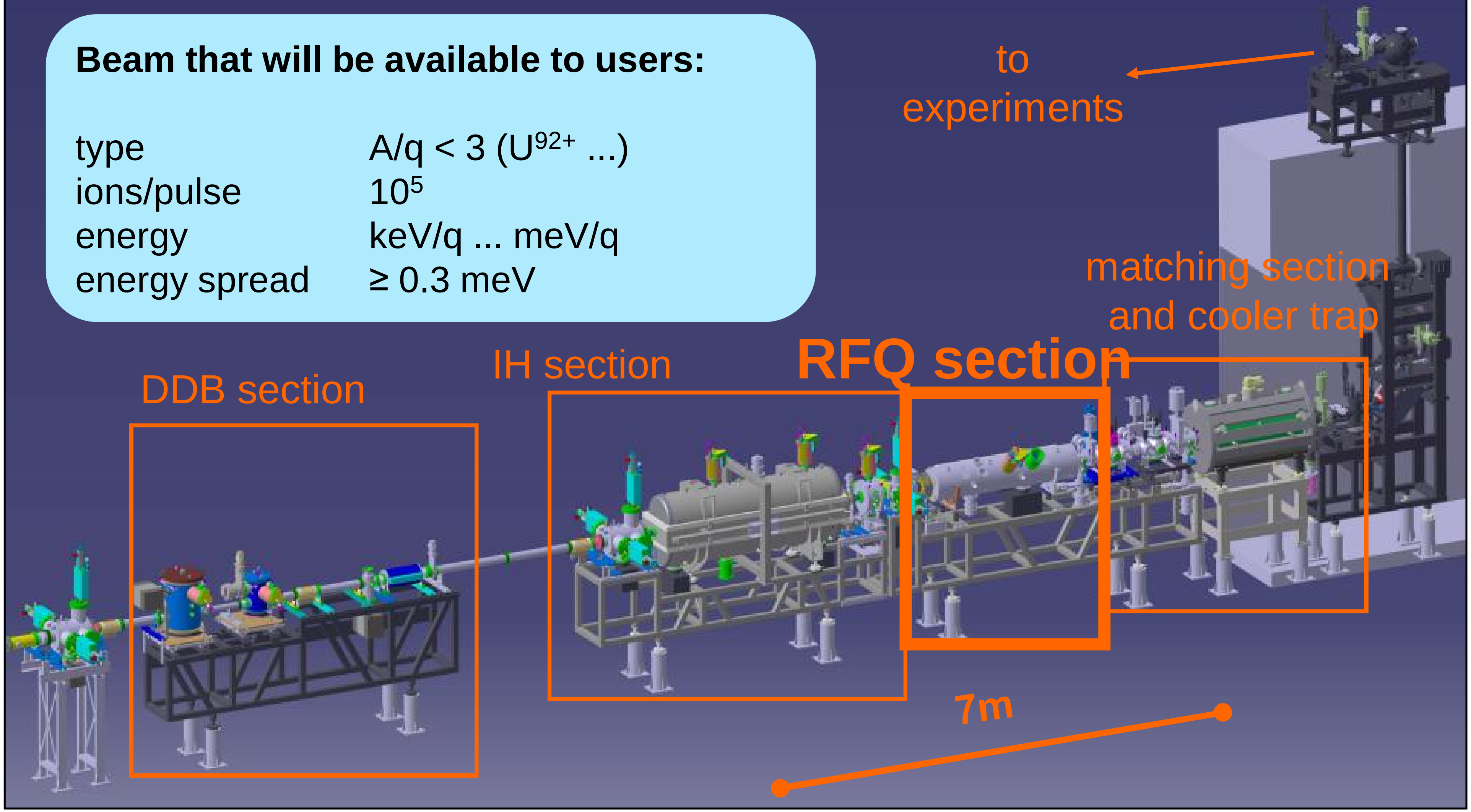


G. Clemente

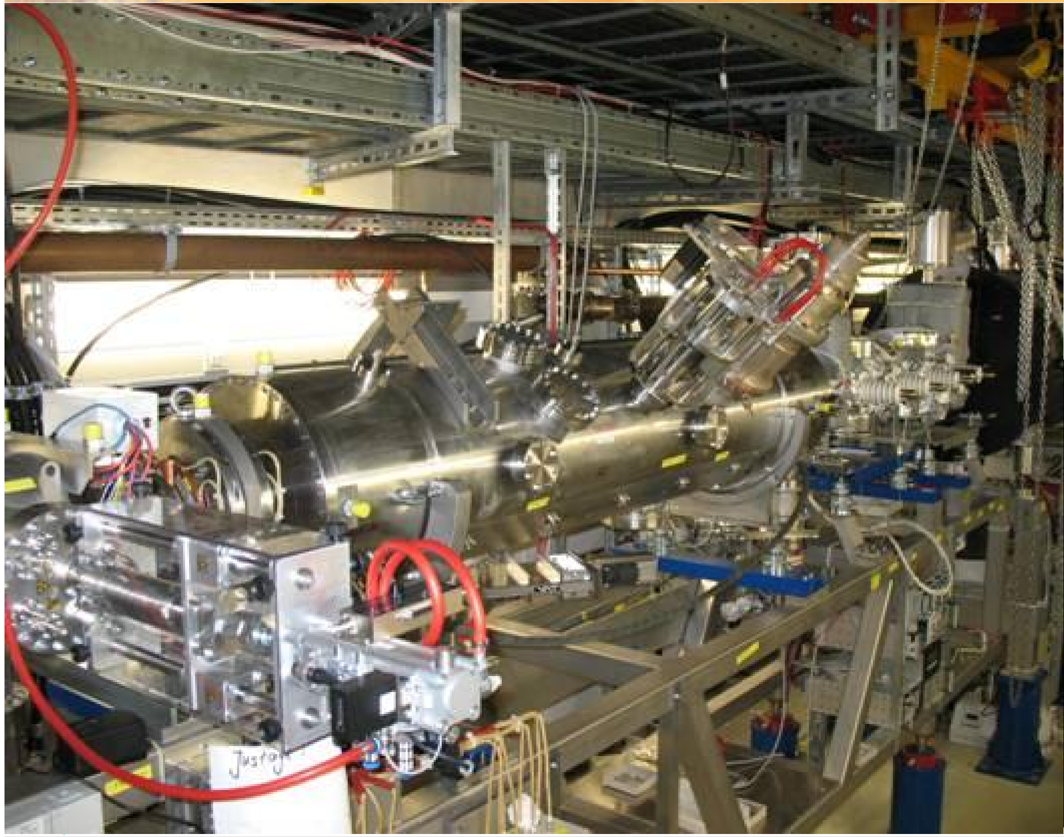
HITRAP – Linear Decelerator

Beam that will be available to users:

type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

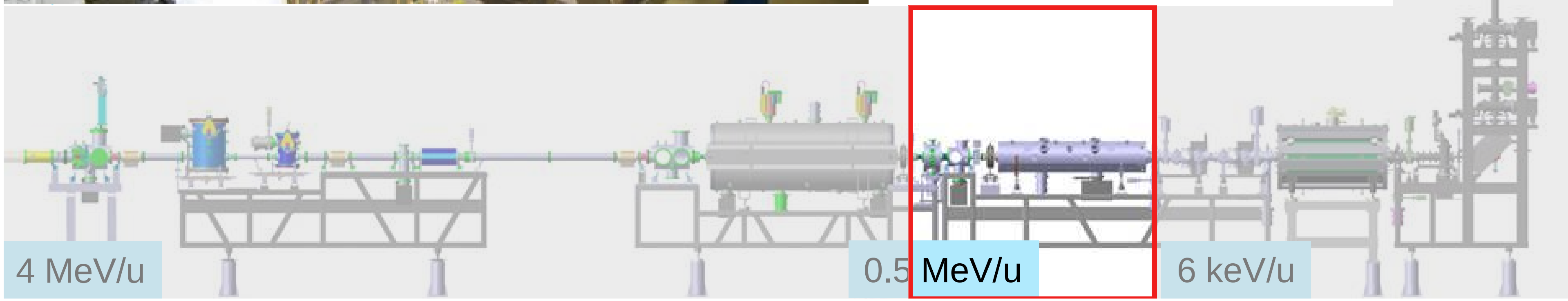


HITRAP – ReBuncher & RFQ



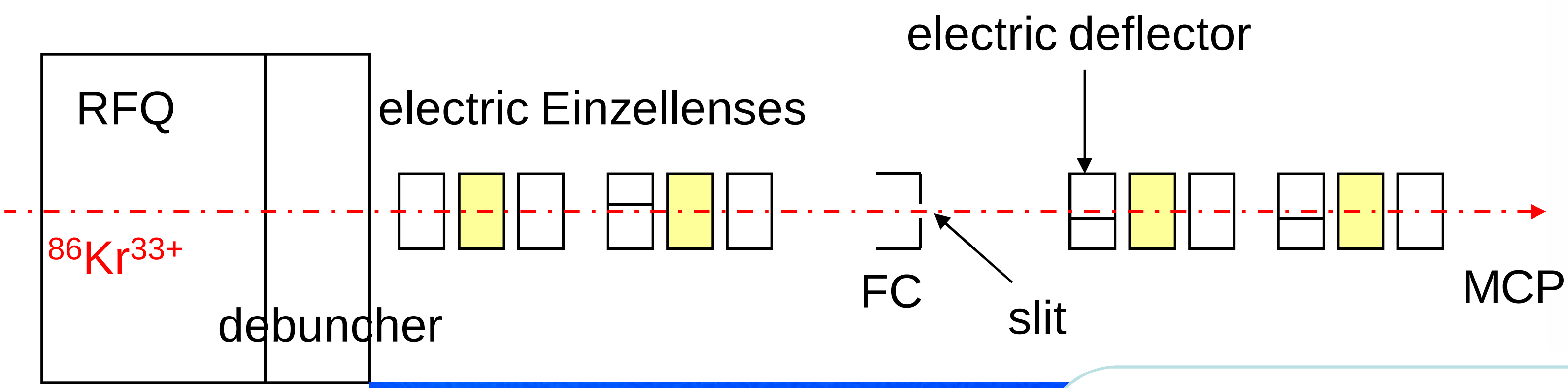
- deceleration from 0.5 MeV/u to 6 keV/u
- installed

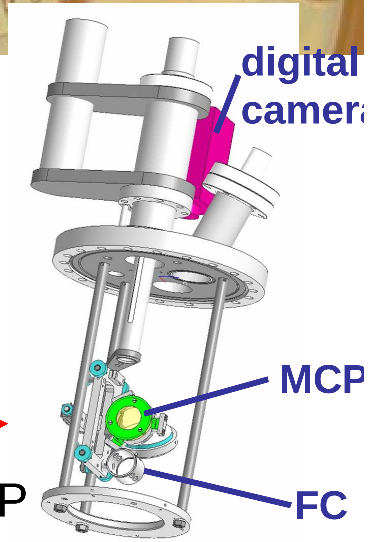
r_0	4 mm
Length	1.9 m
cells	143
stem distance	136 mm
stem width	120 mm
Z	120 kΩm
V_{rod}	70 kV



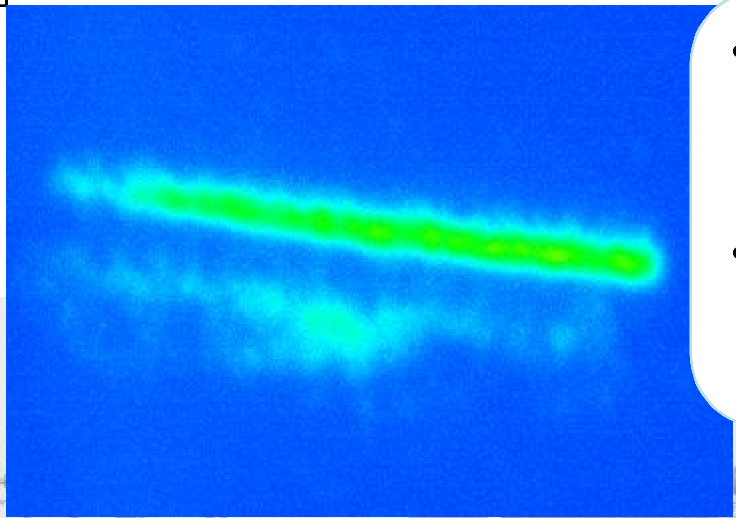
HITRAP – ReBuncher & RFQ

March 2010

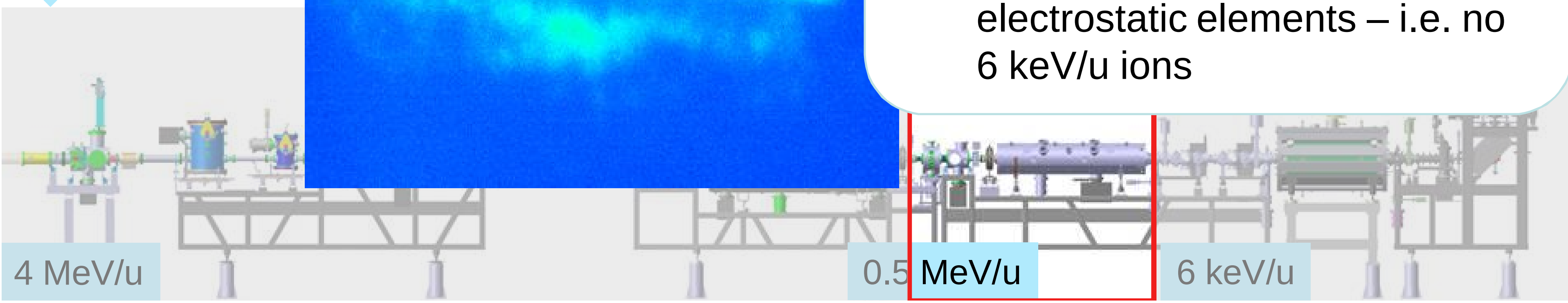




4 MeV/u

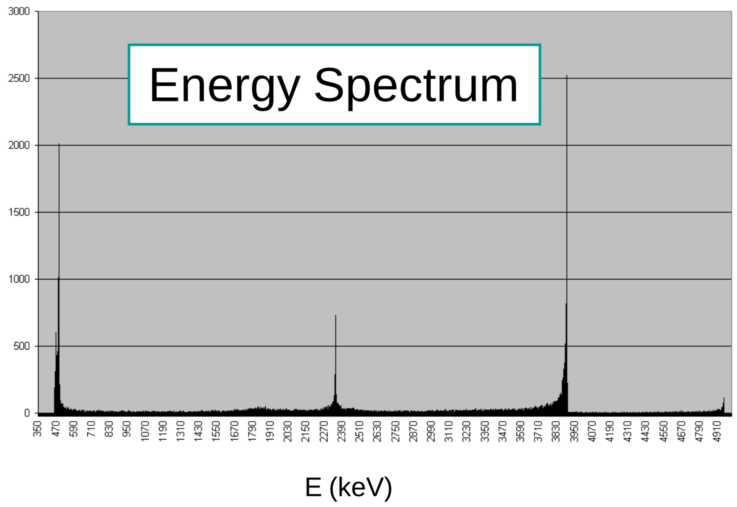


- two simultaneous spots for some settings of RFQ phase and amplitude
- no visible effect when changing electrostatic elements – i.e. no 6 keV/u ions

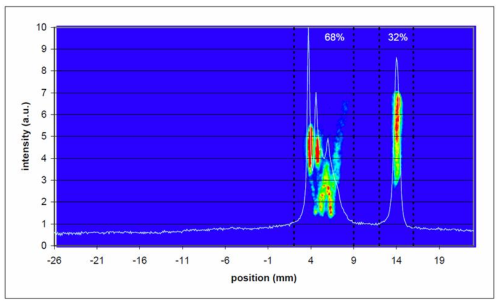


Longitudinal Simulations

IH Structure

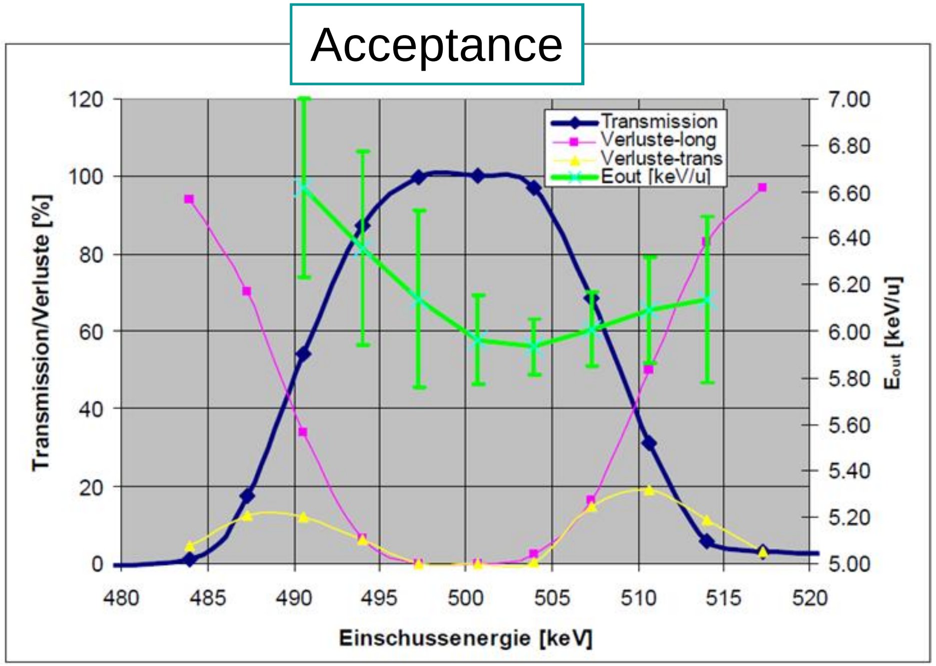


G. Clemente



RFQ Structure

M. Maier



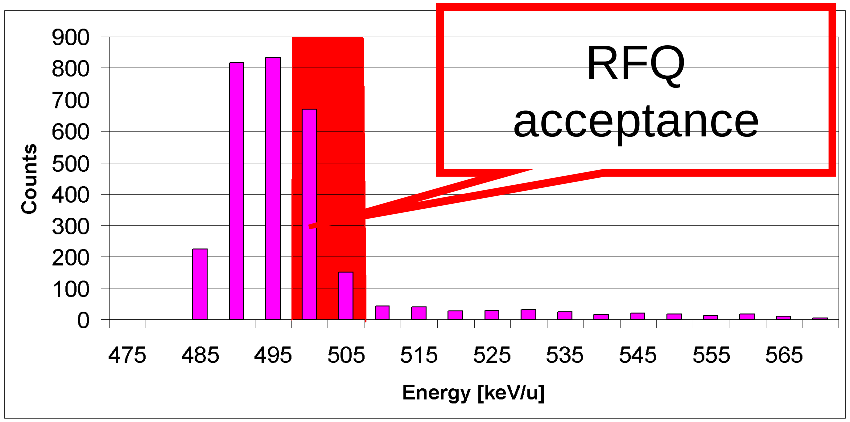
Accepted energy does not fit to the energy delivered by the IH

What did We try to do?

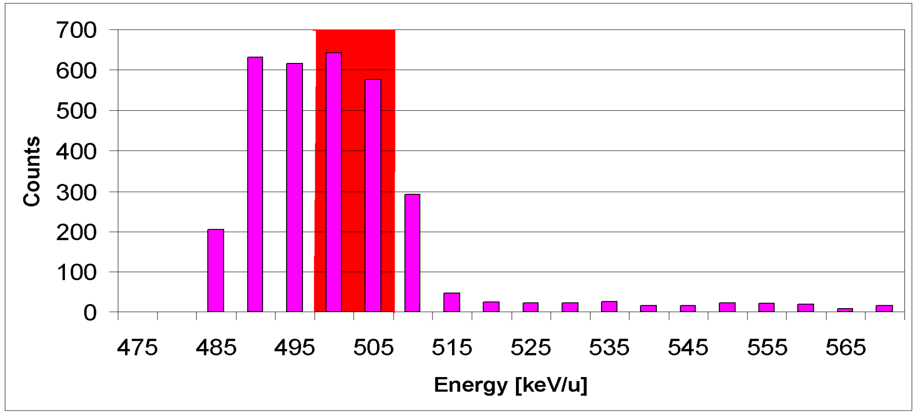
Tuning energy spectrum of IH output

Calc. by G. Clemente

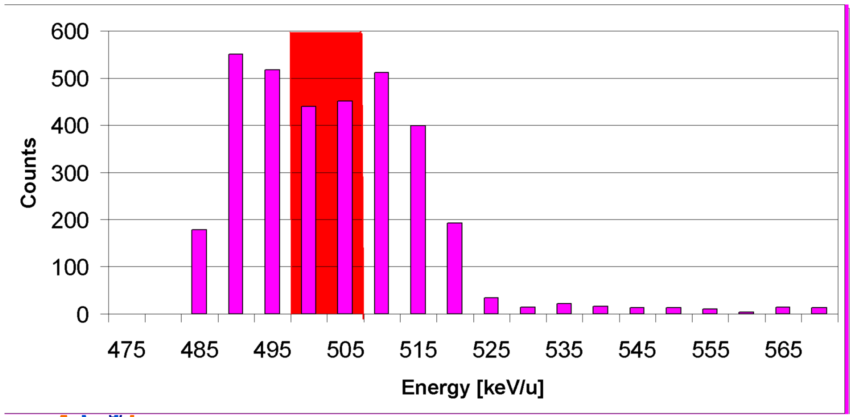
-2 % in Voltage



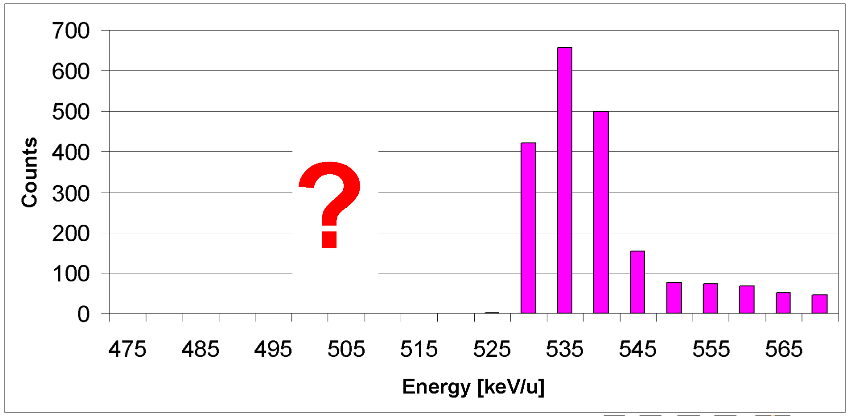
-2 % in Voltage of IH and shift of 1° of the IH phase



-2 % in Voltage of IH and shift of 2° of the IH phase

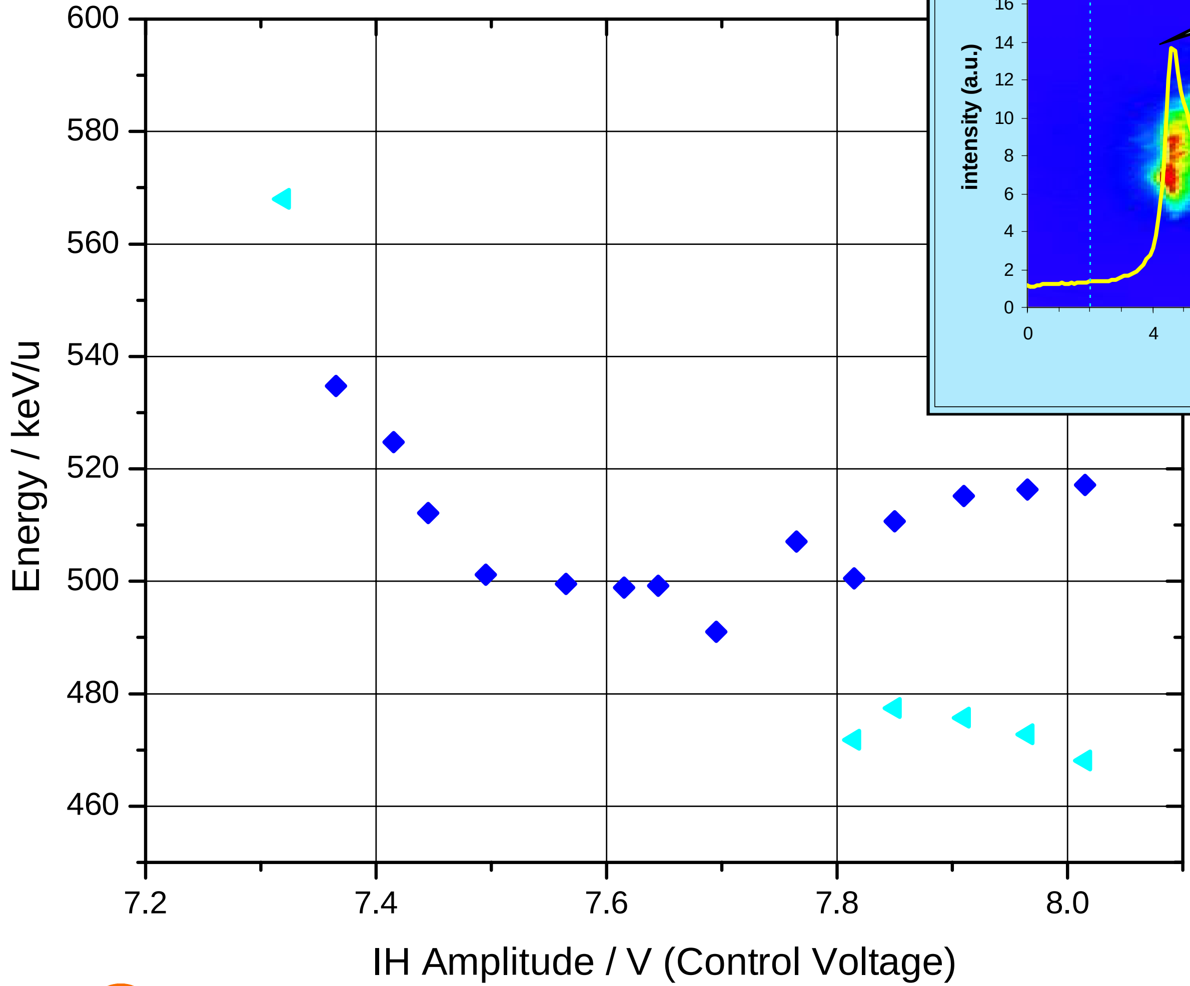


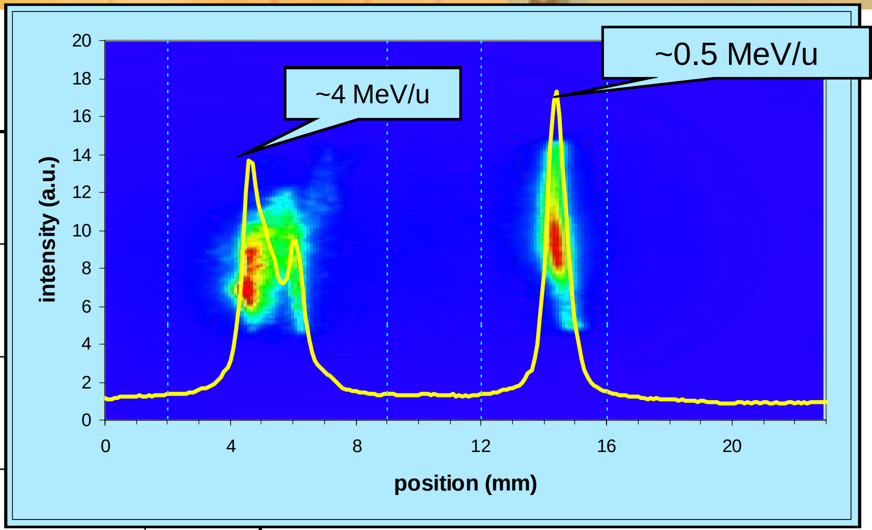
-3 % in Voltage: No overlap with acceptance



IH settings during RFQ Tests

Position of low energy peak vs. IH Power

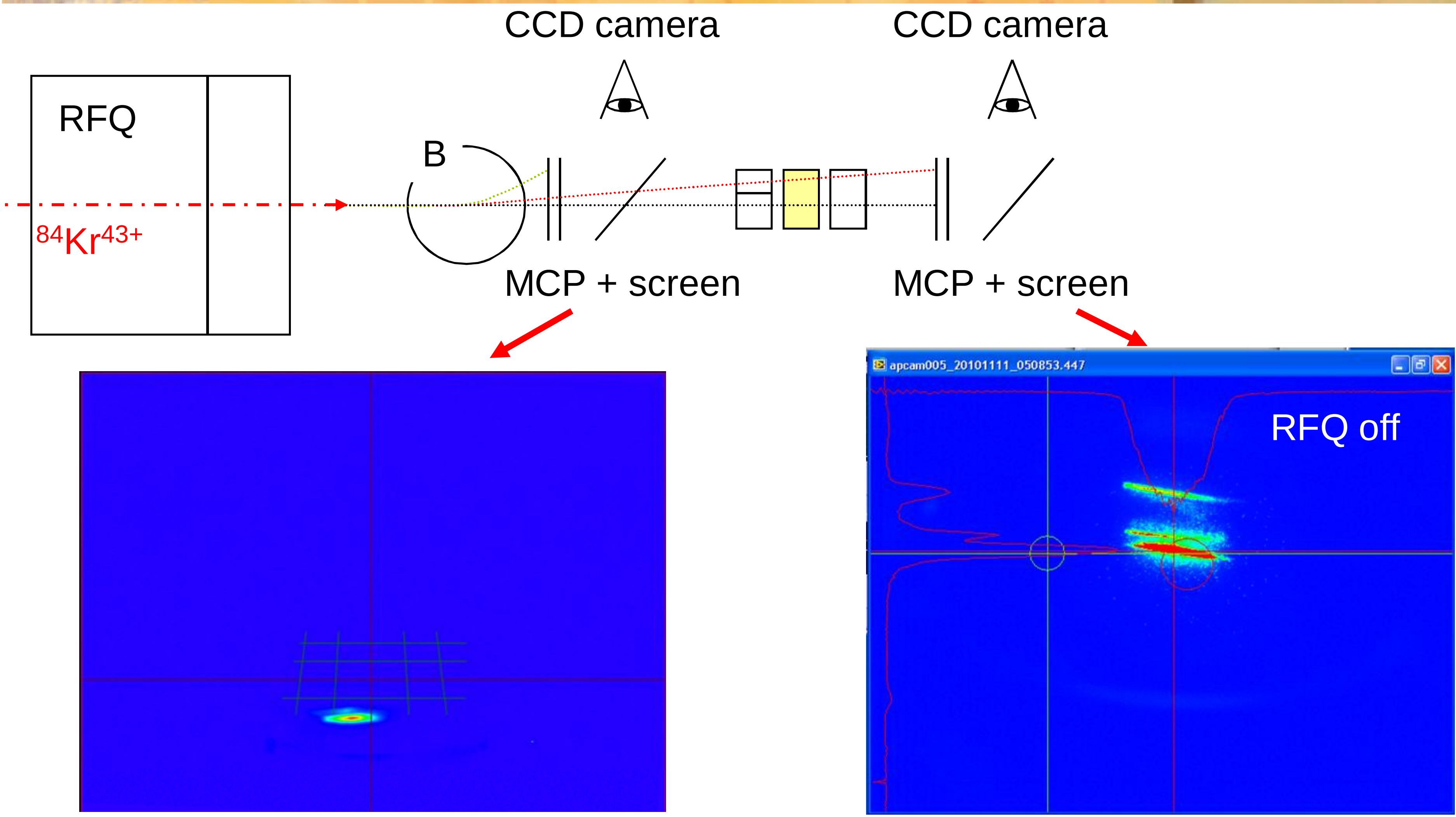




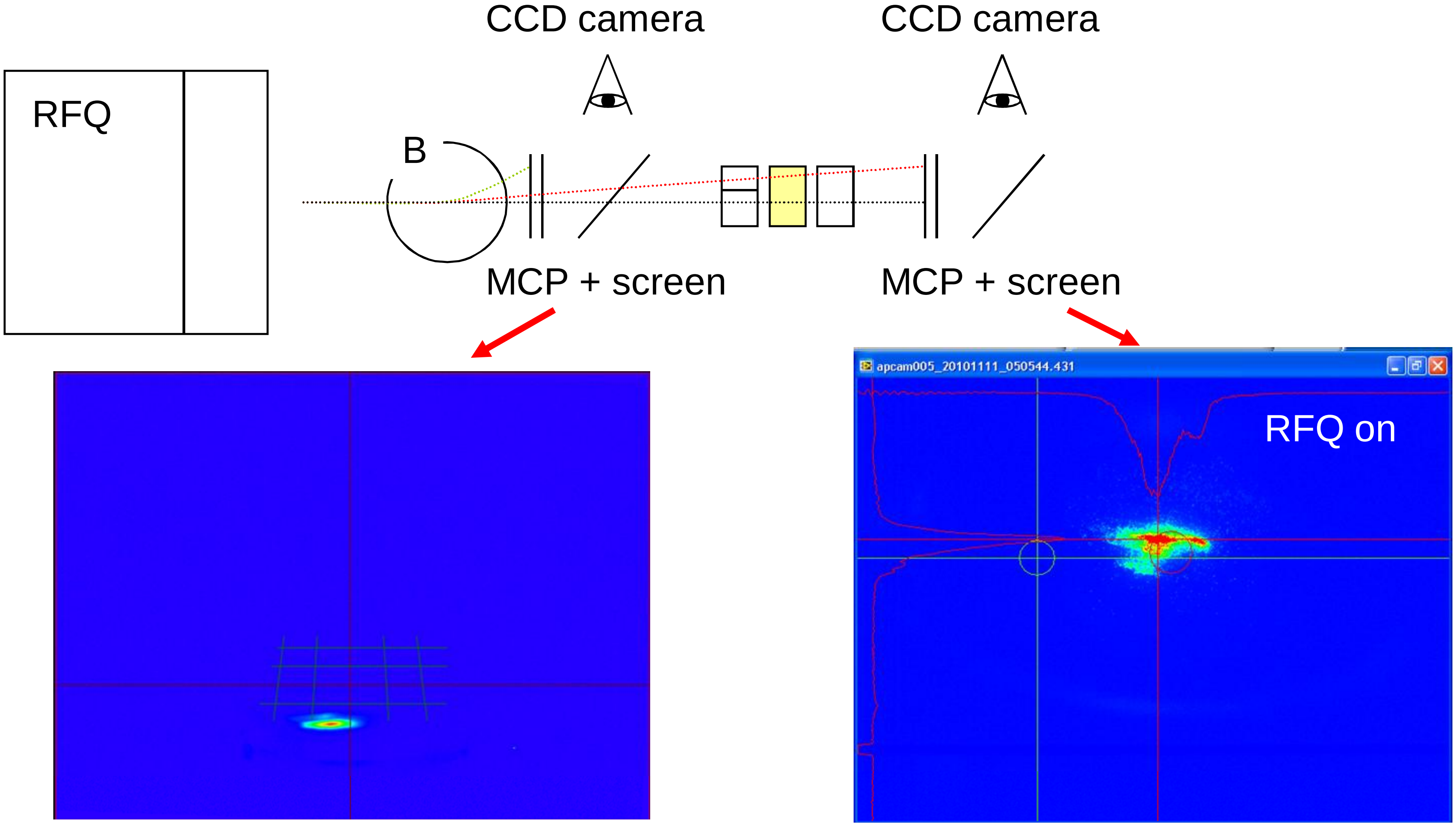
Scanned Power Range:
125 … 165 kW

Theo. Value for $^{84}Kr^{34+}$
144 kW (7.55V)

New Energy Analyzer – RFQ (Nov.10)



New Energy Analyzer – RFQ (Nov.10)



Commissioning Summary to Date

Two weeks/year; Beam intensity ~10^6 ions, once/minute

2007: ESR Extraction tests / Double Drift buncher comm.

2008: DDB / IH test, first deceleration in IH seen

2009: IH retuning, RFQ mounted, Emittance measurements

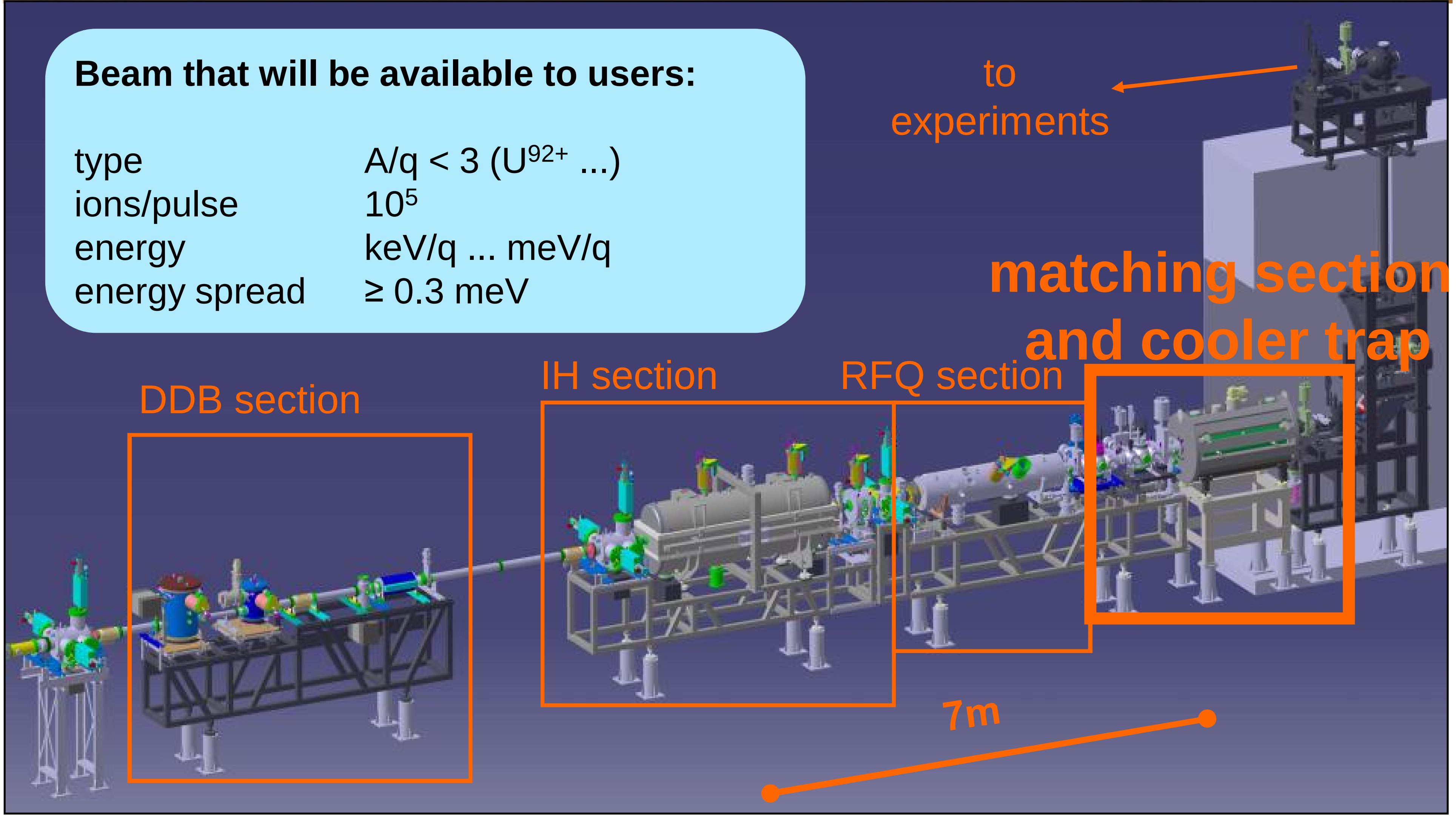
2010: ESR rebunching at 4 MeV/u, 30 MeV/u mode installed,
~40% decelerated to 500 keV/u

2010: RFQ commissioning run in November

HITRAP – Linear Decelerator

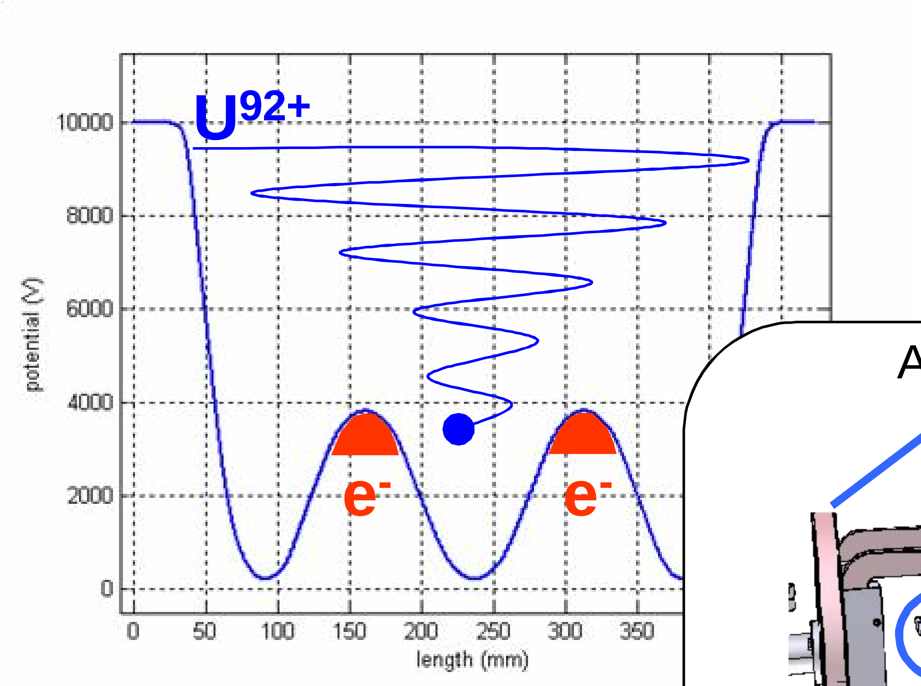
Beam that will be available to users:

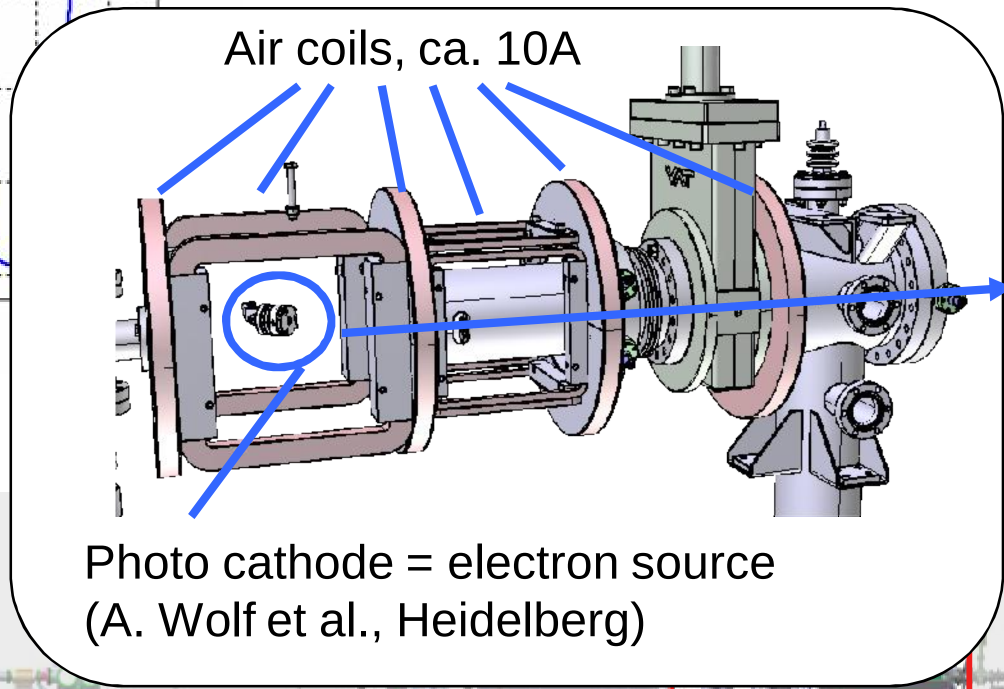
type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

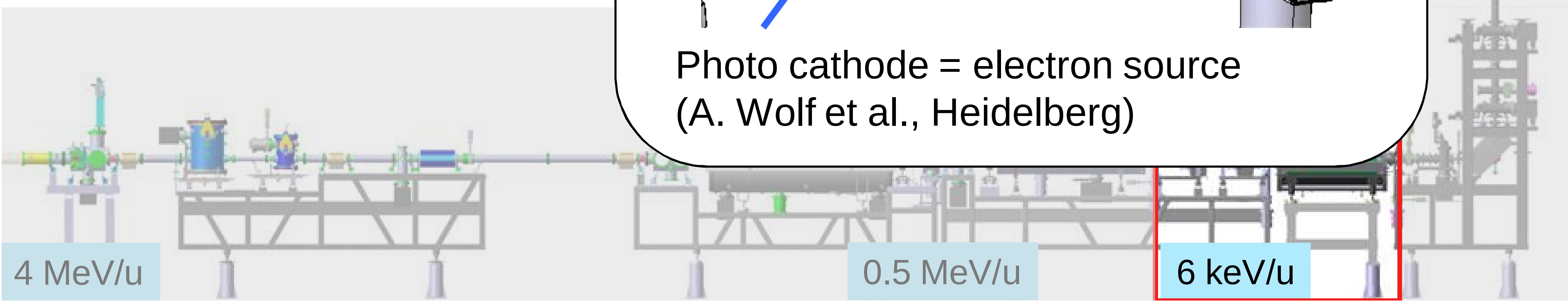


HITRAP – LEBT & Cooler Trap

- catch the ions in flight
- cool them with combined electron and resistive cooling to ~ 4 Kelvin

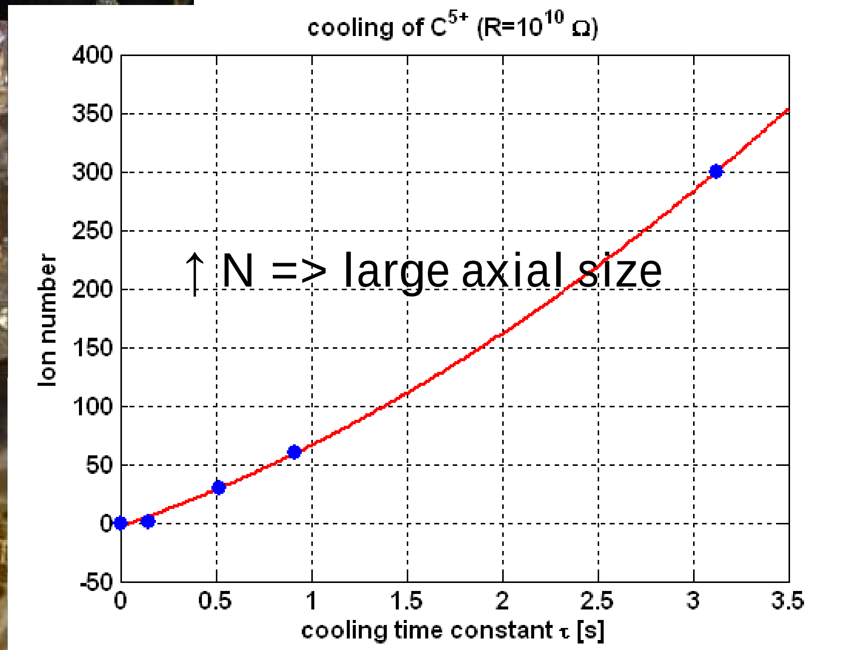


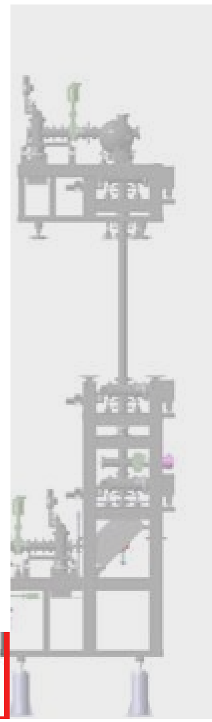




HITRAP – LEBT & Cooler Trap

- trap installed in magnet – offline injection tests ongoing
- Extensive calculations done – resistive cooling possible but slower than expected



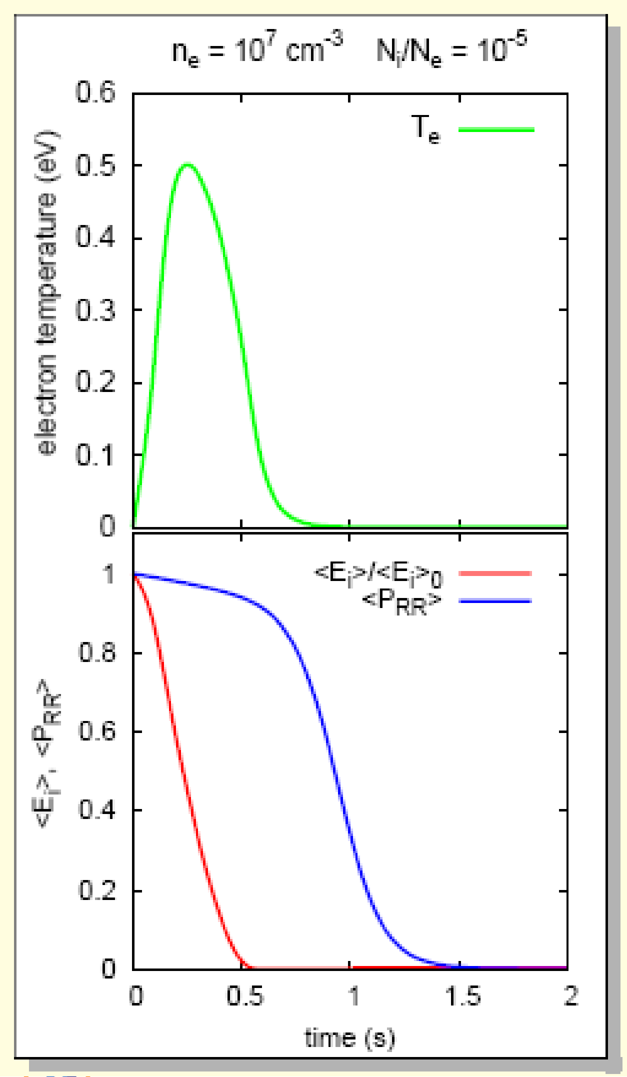


4 MeV/u

0.5 MeV/u

6 keV/u

Electron cooling*



- in Coulomb collisions, ions transfer energy to e^-
- electrons are rapidly cooled by synchrotron radiation to 4.2 K

Approximations:

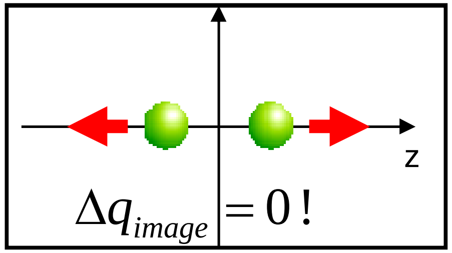
- instantaneous conversion $E_{ion} \rightarrow T_e$
- no ion-ion collision
- isotropic e^- distribution

Warning: radiative recombination!

Conclusions:
e^- cooling down to 10 eV possible within ~ 1 s and 10-20% ion losses

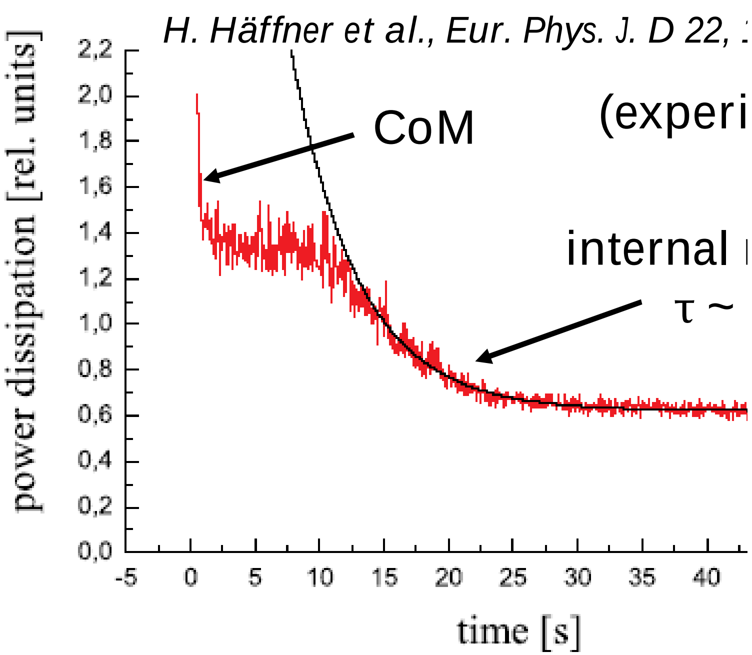
** = G. Zwicknagel, in „Non-neutral Plasma Physics VI“, eds. M. Drewsen, U. Uggerhoj, H. Knudsen, AIP Conference Proceedings, 862, 281 (2006)*

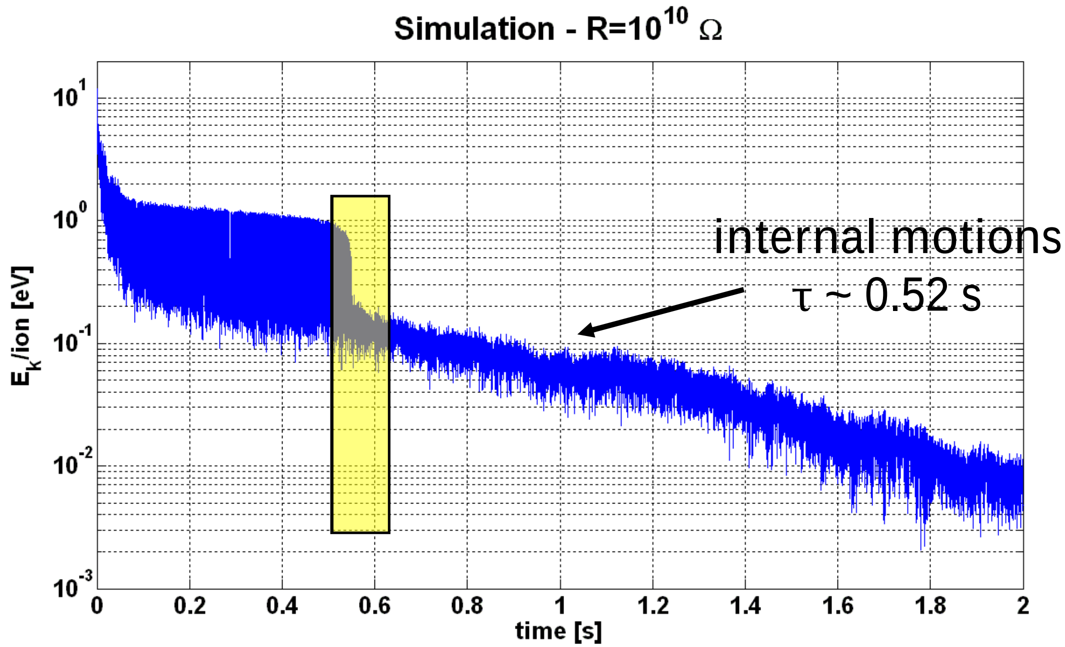
Resistive cooling of an ion cloud



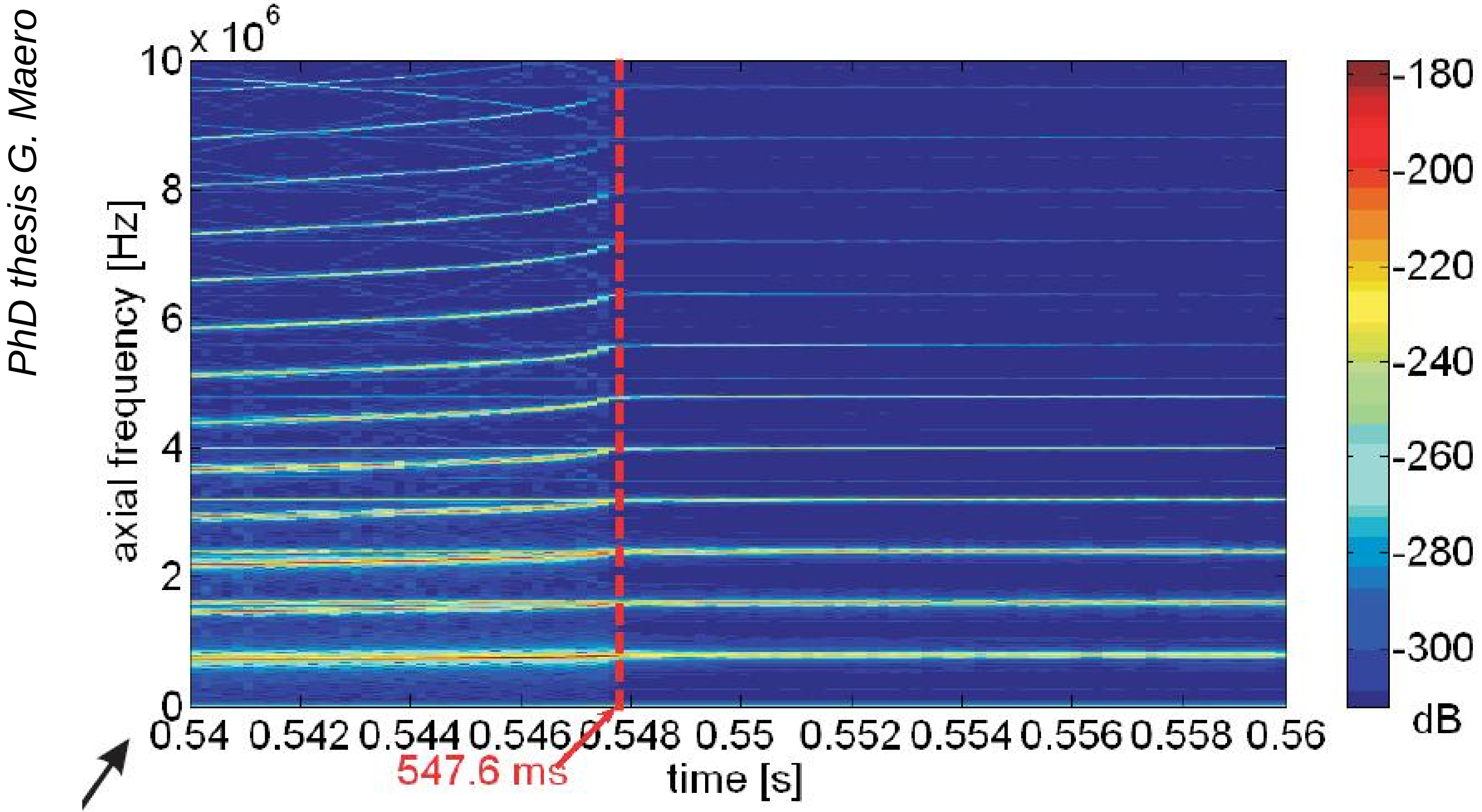
- cooling of Center of Mass motion N times faster
- “invisible” internal modes?

→ asymmetric coupling and nonlinear contributions to image charge



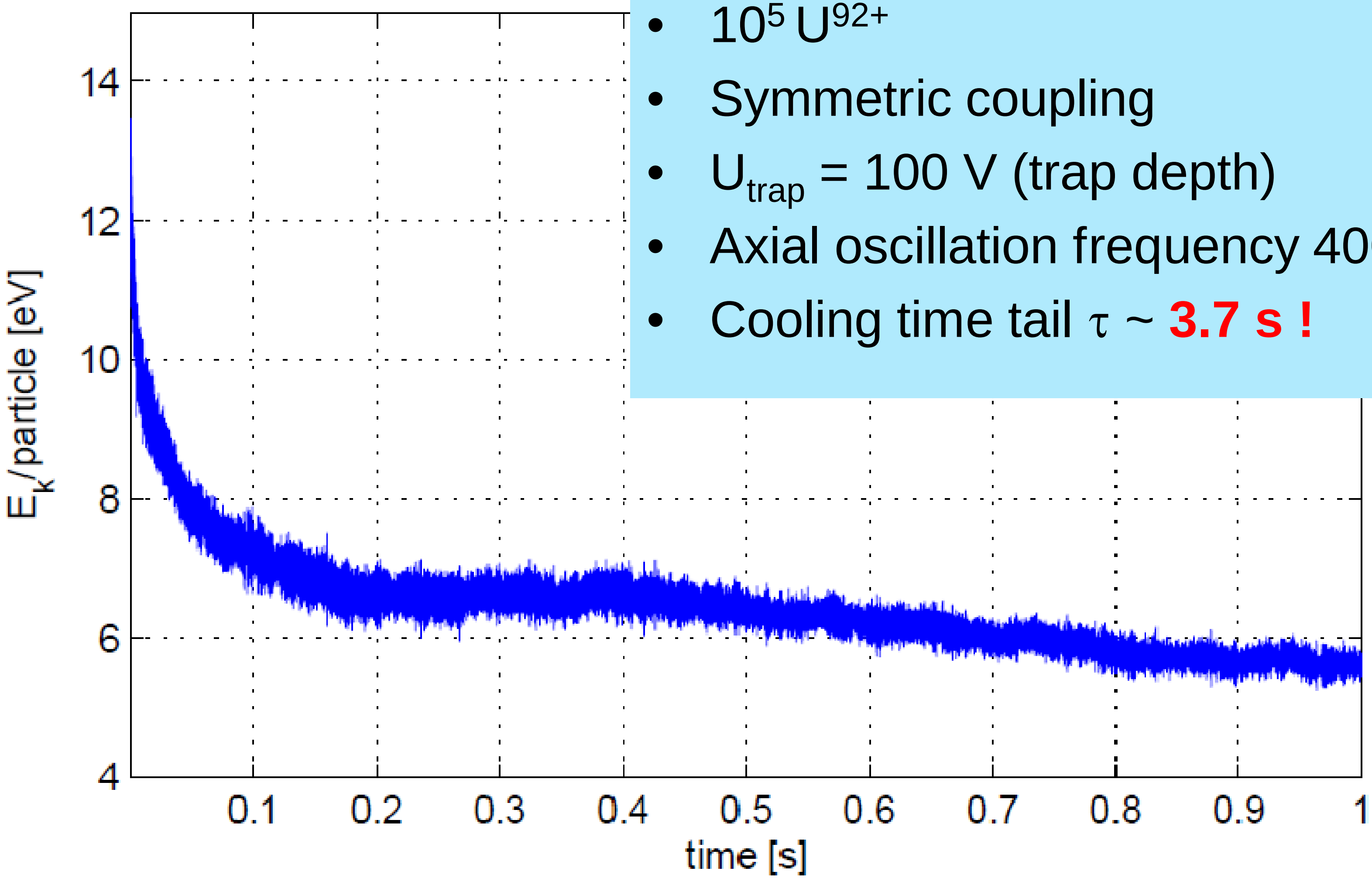


Spectrogram of 30 C^{5+} from our PIC code



U^{92+} in the HITRAP cooler Trap

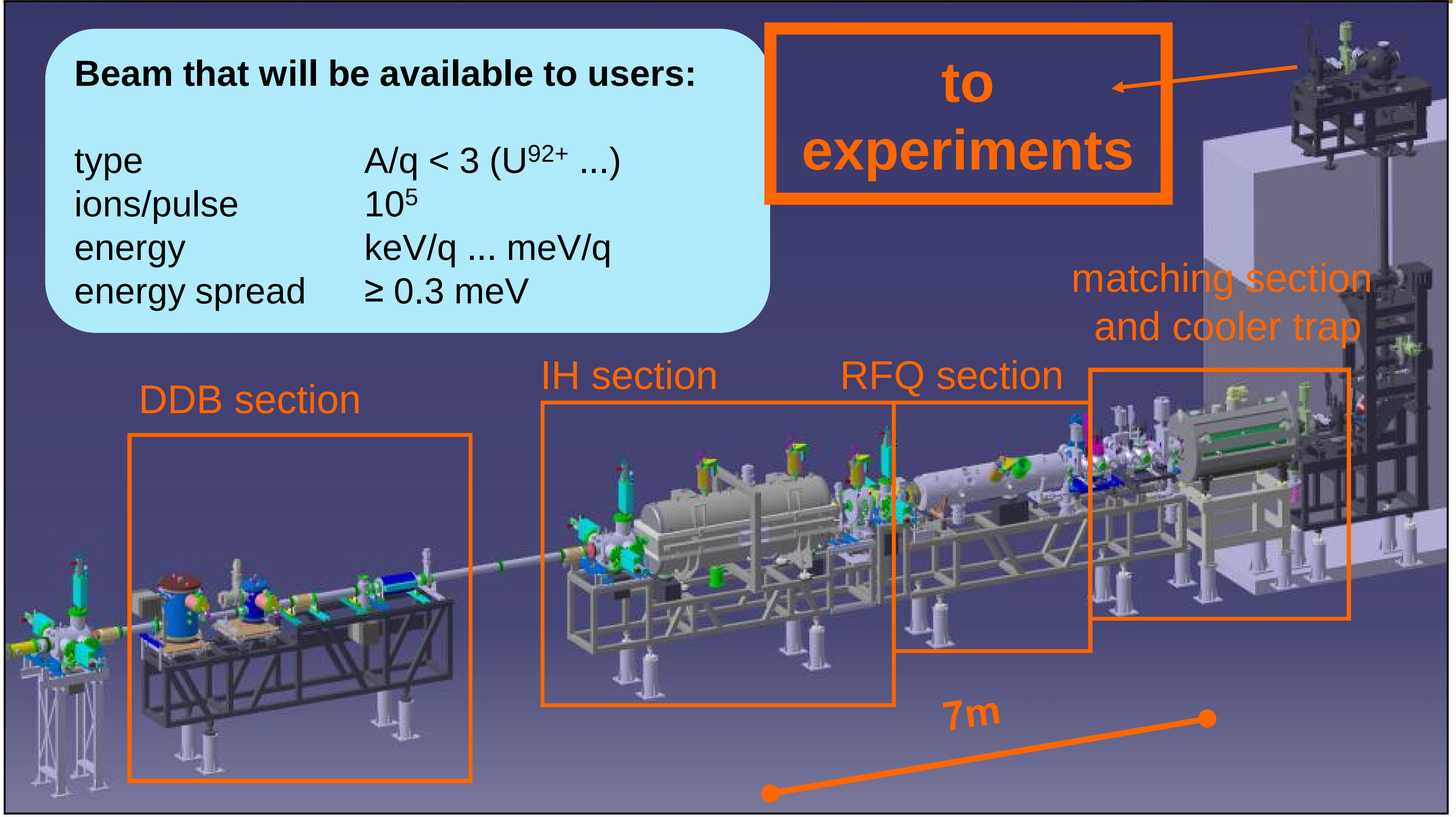
- 10^5 U^{92+}
- Symmetric coupling
- U_{trap} = 100 V (trap depth)
- Axial oscillation frequency 400 kHz
- Cooling time tail τ ~ **3.7 s !**



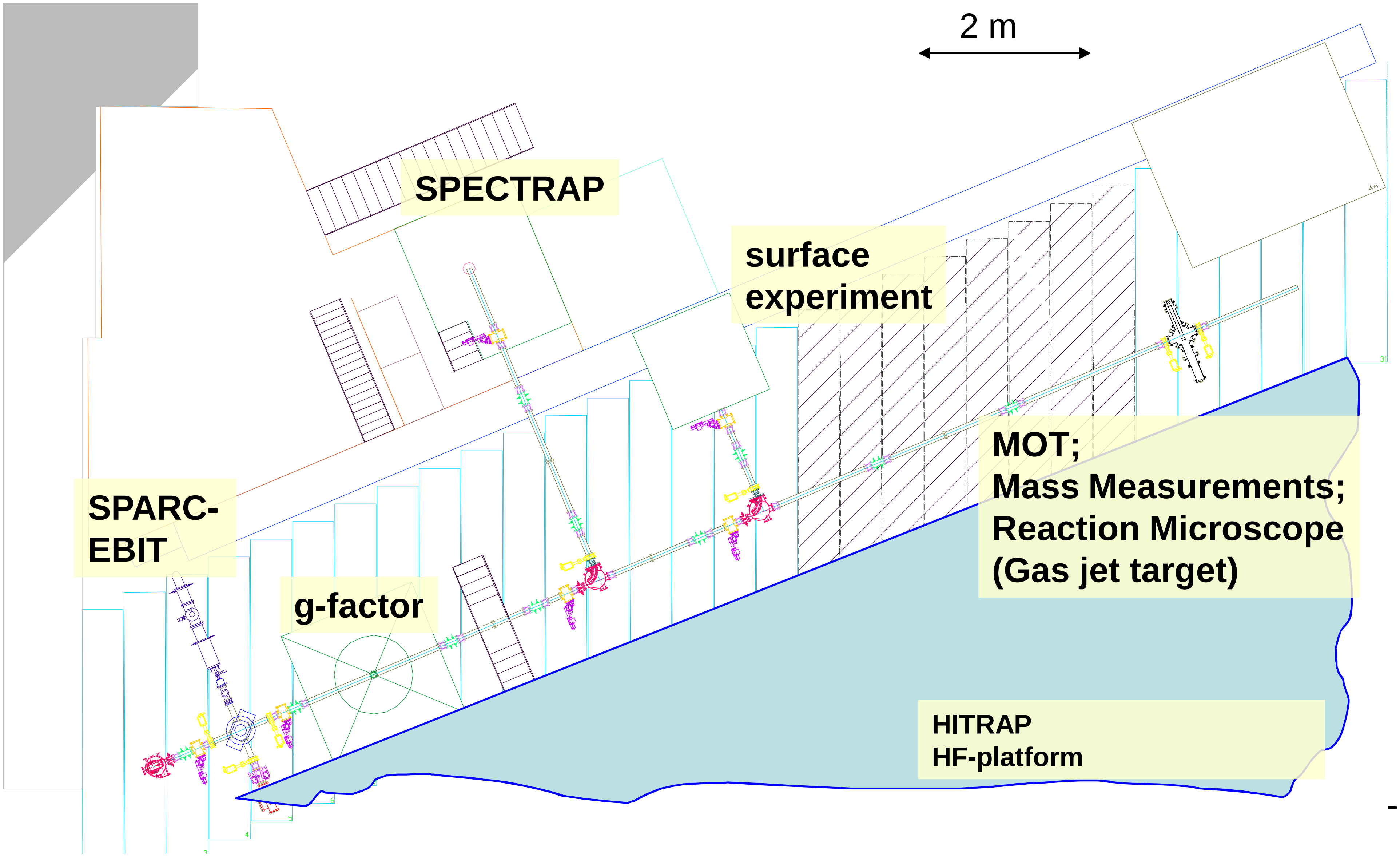
HITRAP – Linear Decelerator

Beam that will be available to users:

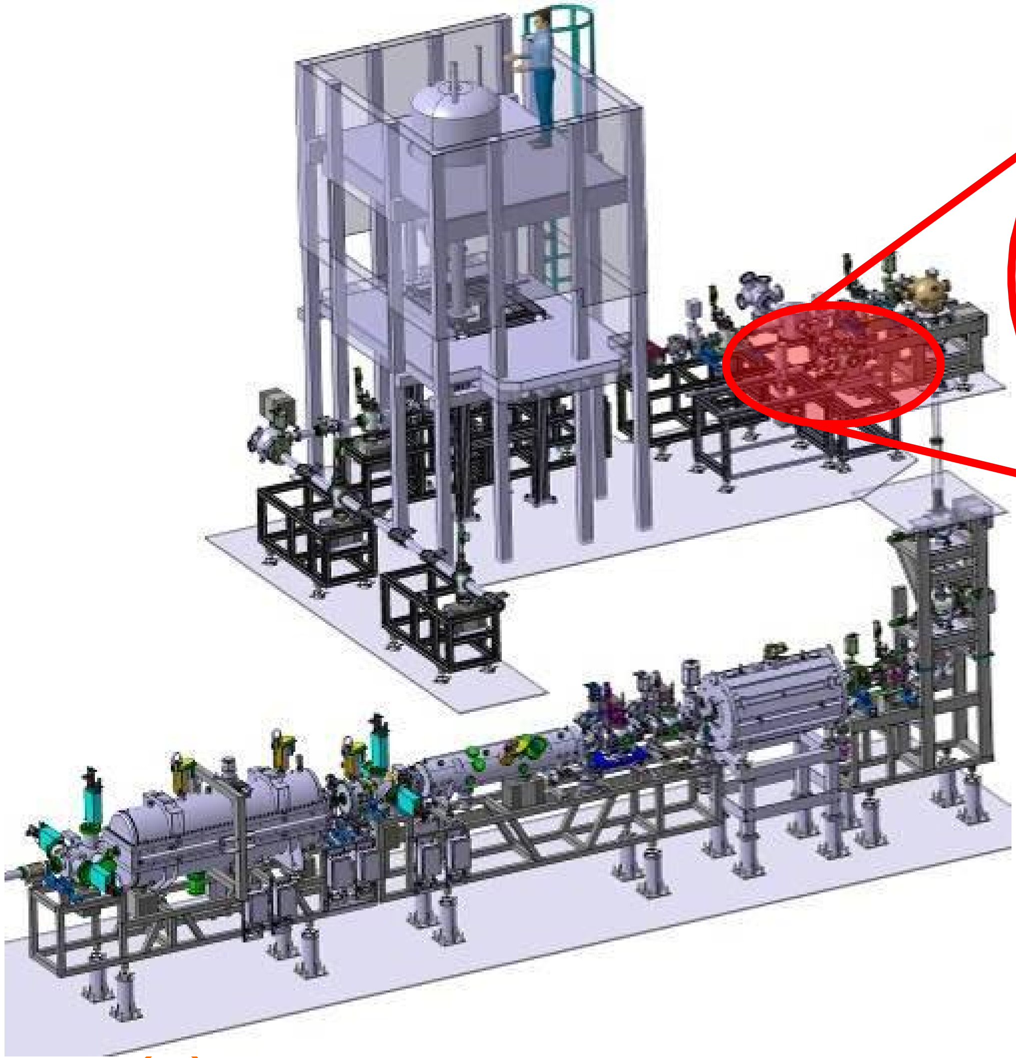
type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

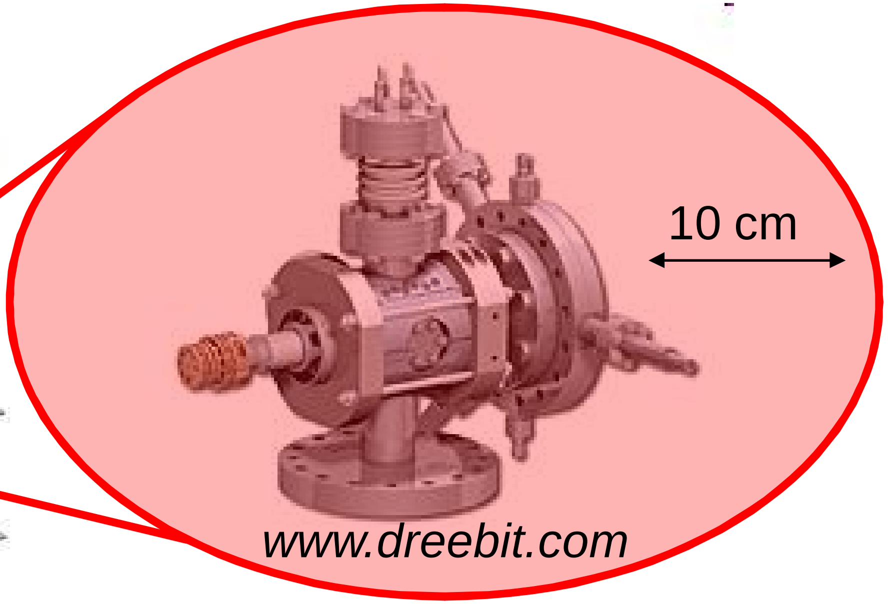


HITRAP Experimental Area



A small EBIT as Test Ion Source

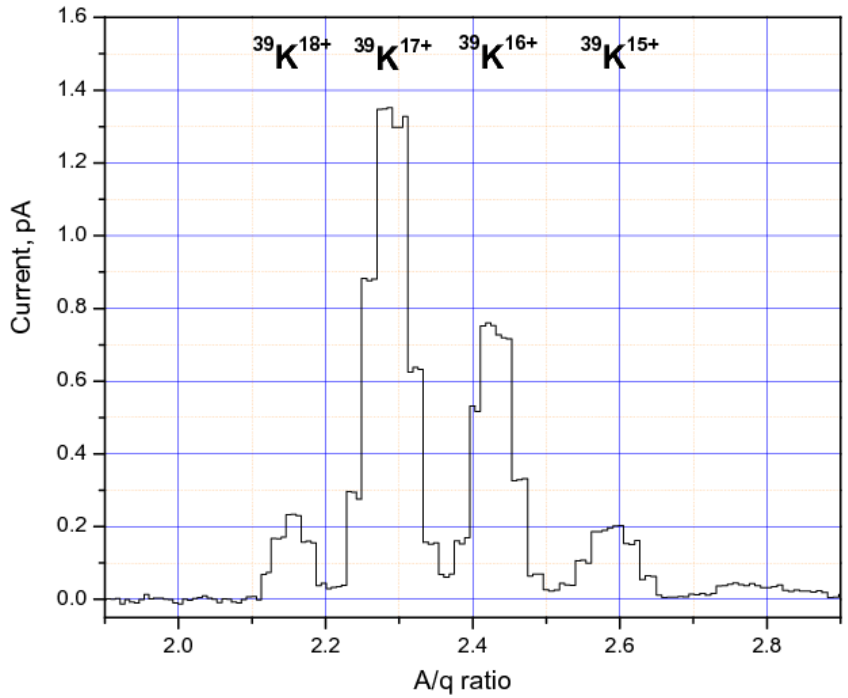


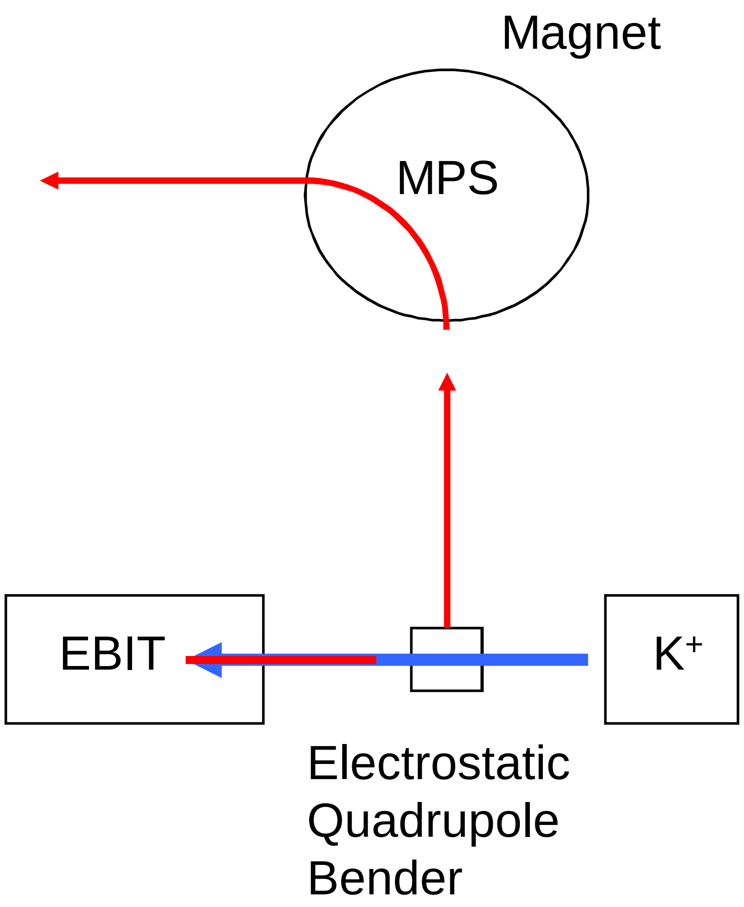


- Room temperature, permanent magnets (0.25 T)
- Electron current 25 mA (100 A/cm2)

Charge Breeding of Potassium

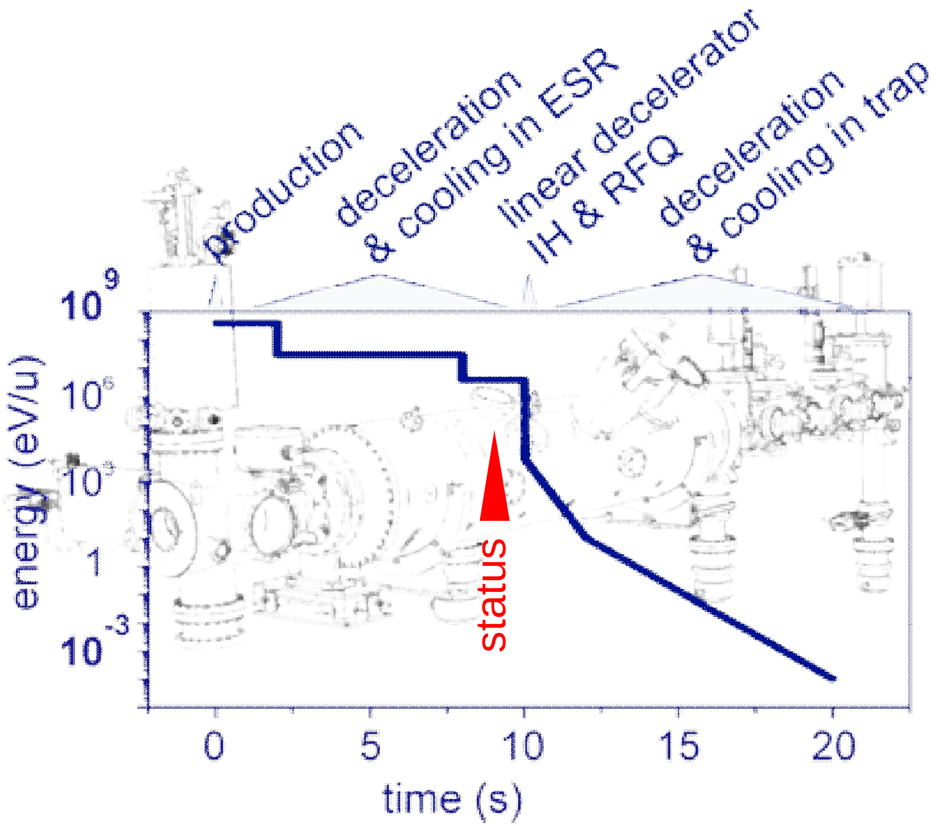
G. Vorobjev, A. Thorn, A. Sokolov et al.





Summary

- HITRAP will be the strongest source for heavy, highly-charged ions
- A linear decelerator has been constructed – key components are an IH, a RFQ and a Penning trap + ESR special operation
- First deceleration has been achieved – beam quality and intensity as expected
- A EBIT test ion source for intermediately charged ions is operational



Particle-In-Cell (PIC) with R-cooling

$$W = \frac{N_i(real)}{N_{sim}}$$

("superparticles")

- rz-symmetry
- charge smearing on a ring
- FFT method

Particle generation

$$\rho = \sum_{i=1}^{N_{sim}} q_i \cdot W$$

$$\nabla^2 \Phi = -\frac{\rho}{\varepsilon_0}$$

$$\{\vec{x}, \vec{v}, \vec{a}\}_i = f(\Phi, \vec{B}, \ldots)$$

$$\Delta V = f(q_{im})$$

correction voltage applied to the pick-up electrodes

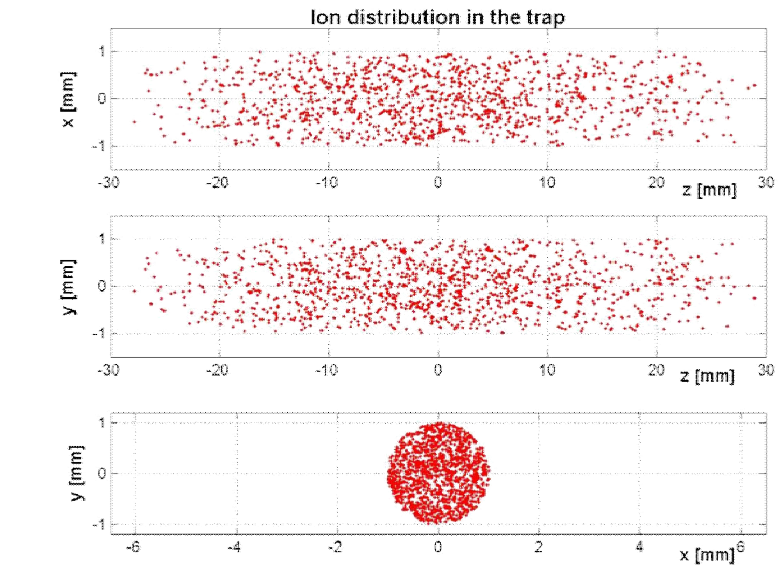
$$\Delta V = \mathbf{Re}\{Z\} i_{img}$$

- each superparticle treated as **real**
- full **3d** motion
- B field-independent algorithm*

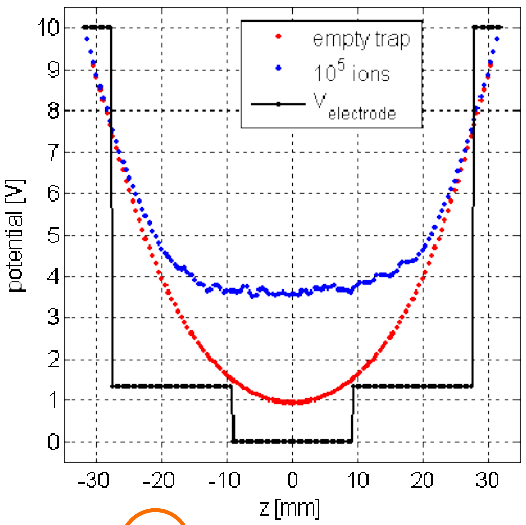
PhD thesis G. Maero

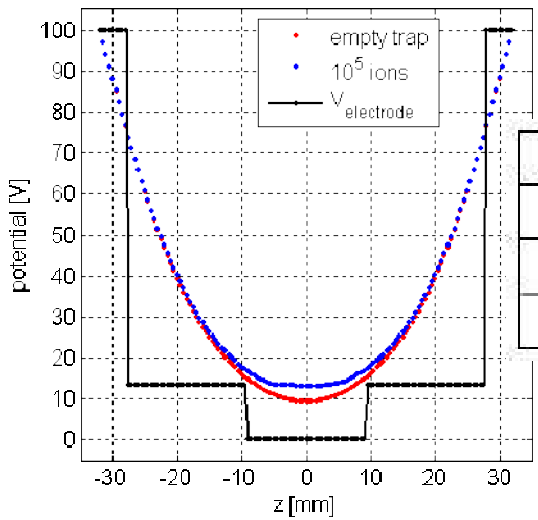
* = Q. Spreiter, M. Walter, Journal of Computational Physics 152, 102-119 (1999)

Space charge: potential flattening / frequency shifts



- 10^5 U^{92+} ~ 10^7 charges
- $n_B = \frac{\varepsilon_0 B}{2m} = 4 \cdot 10^8\ cm^{-3}$
- potential well is filled

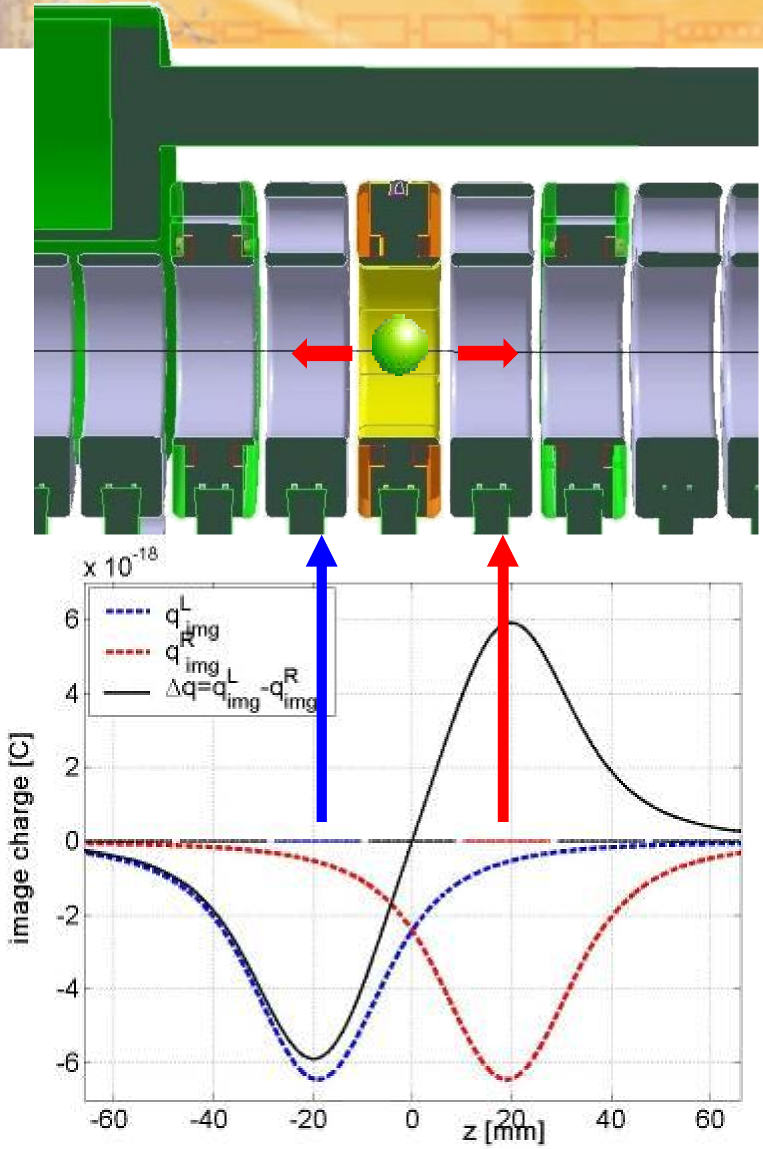


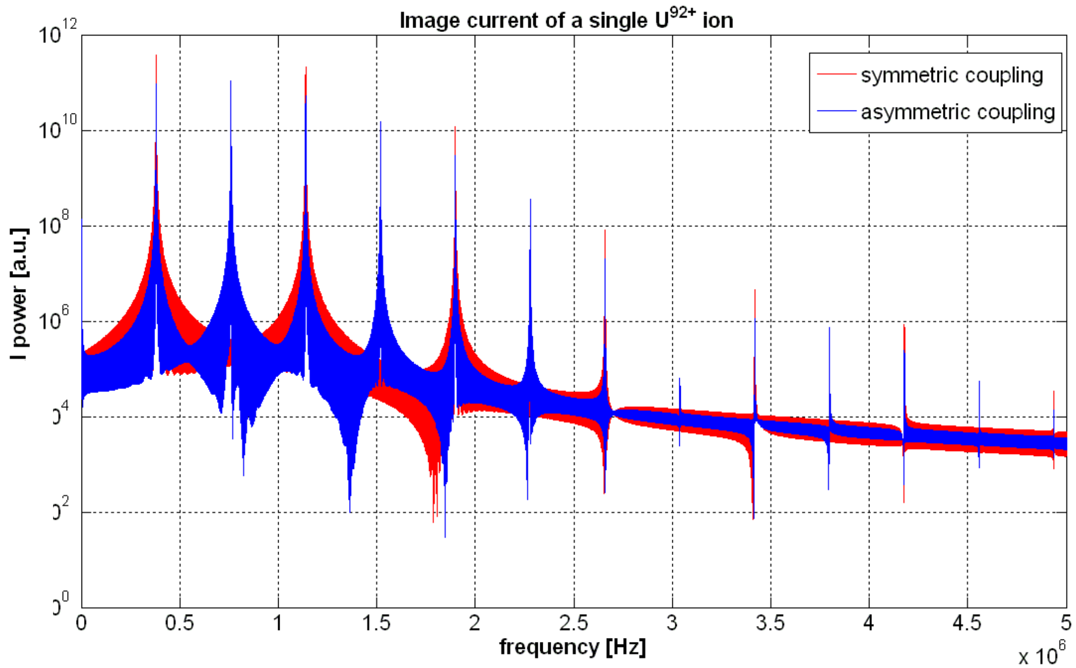


ω_z = 383.15 MHz

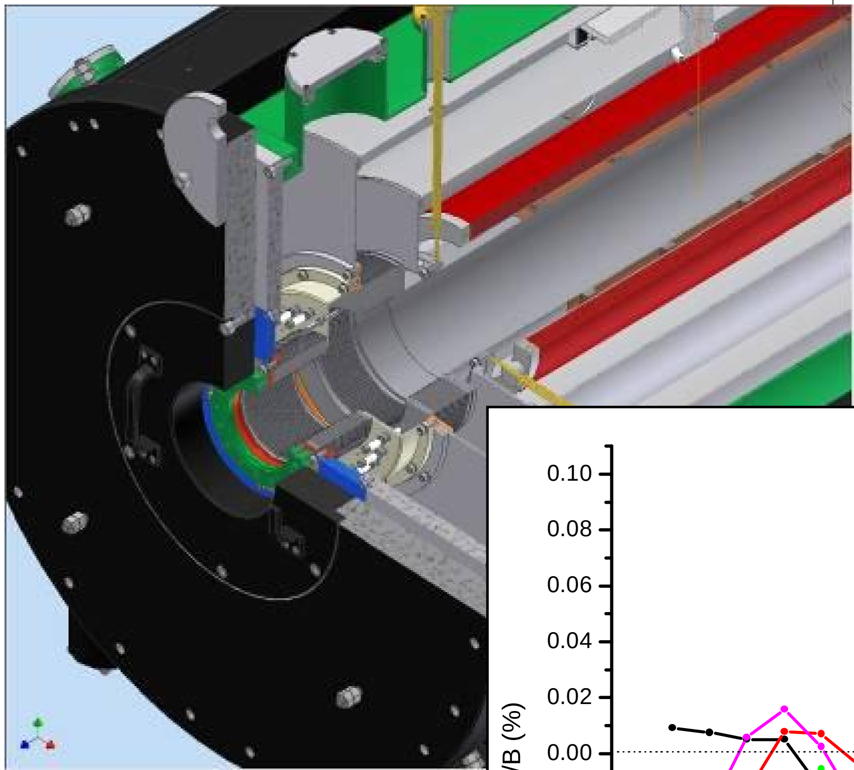
No. ions	$\overline{\omega}'$	$-\Delta\omega/\omega$
10^3	379.72 KHz	$8.95 \cdot 10^{-3}$
10^4	374.91 KHz	$2.15 \cdot 10^{-2}$
10^5	362.05 KHz	$5.51 \cdot 10^{-2}$

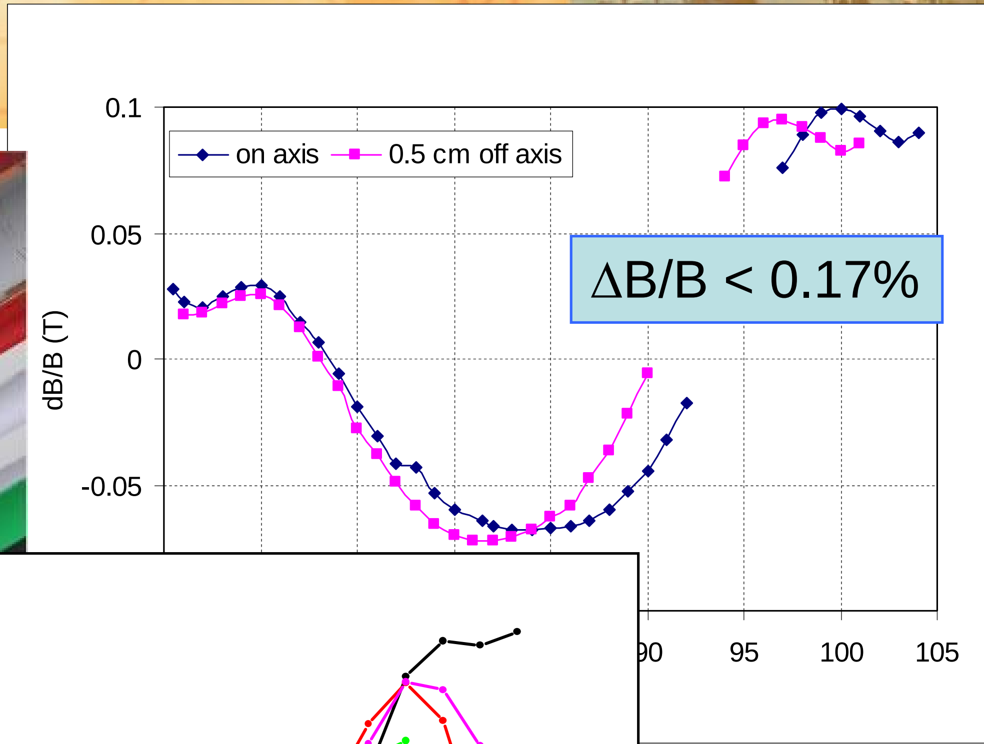
Image charge

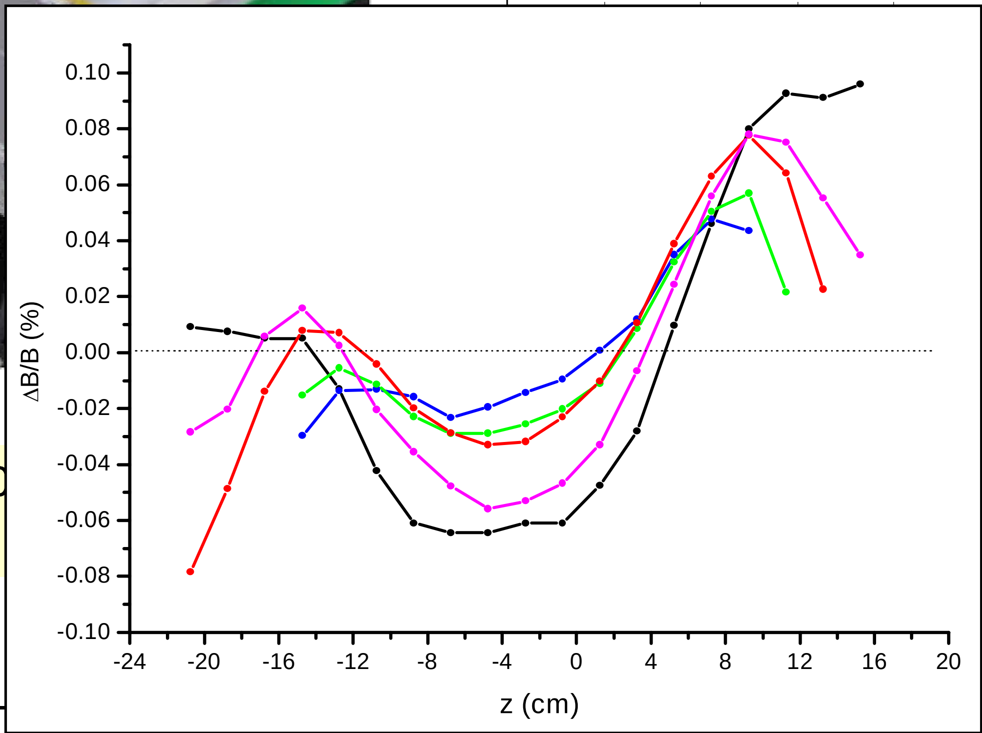




The Solenoid







- SC magnet, B = 6 T, 400
- Installed and tested