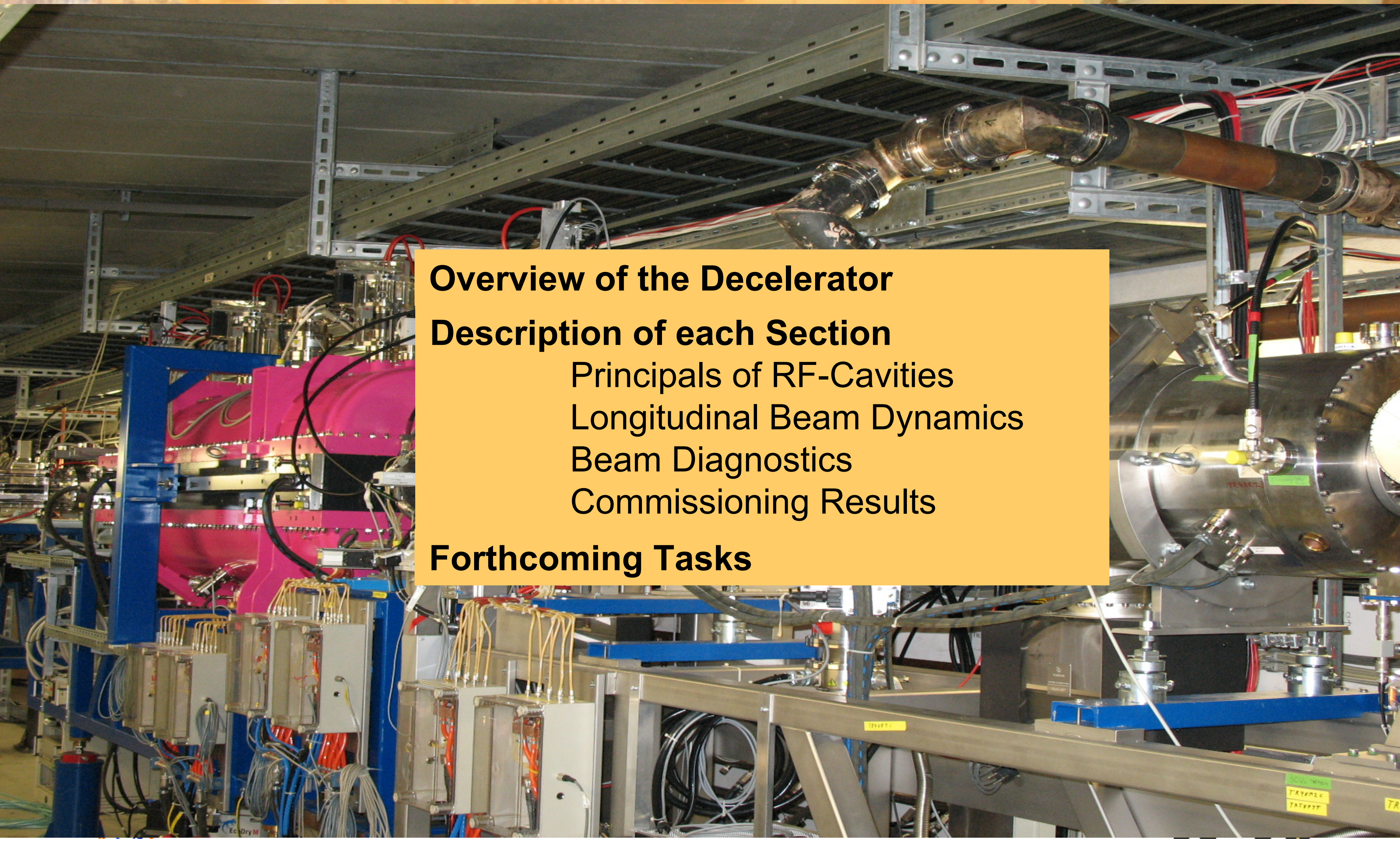
The HITRAP Linear Decelerator - Concept and Commissioning Results



Overview of the Decelerator

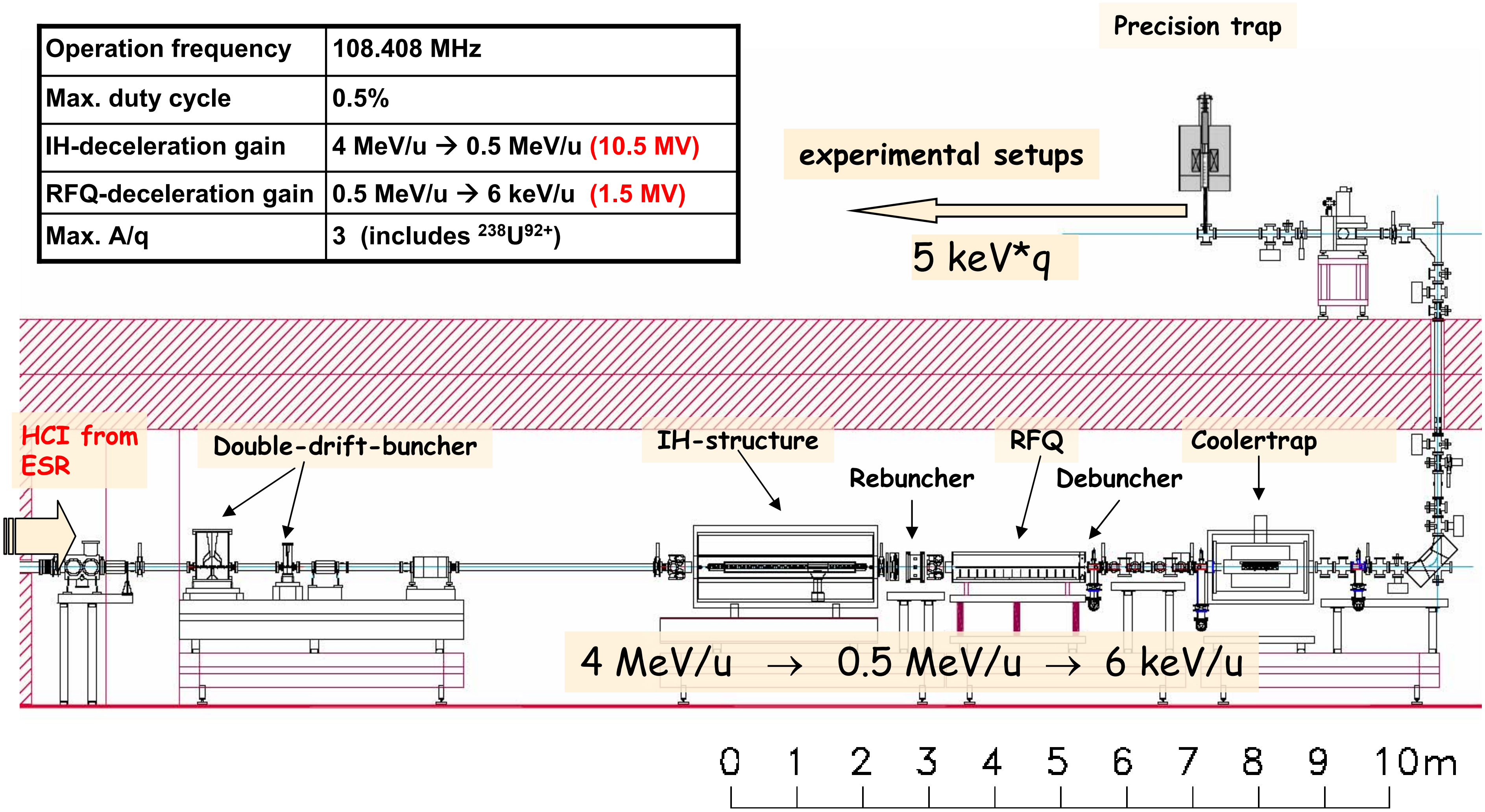
Description of each Section

- Principals of RF-Cavities
- Longitudinal Beam Dynamics
- Beam Diagnostics
- Commissioning Results

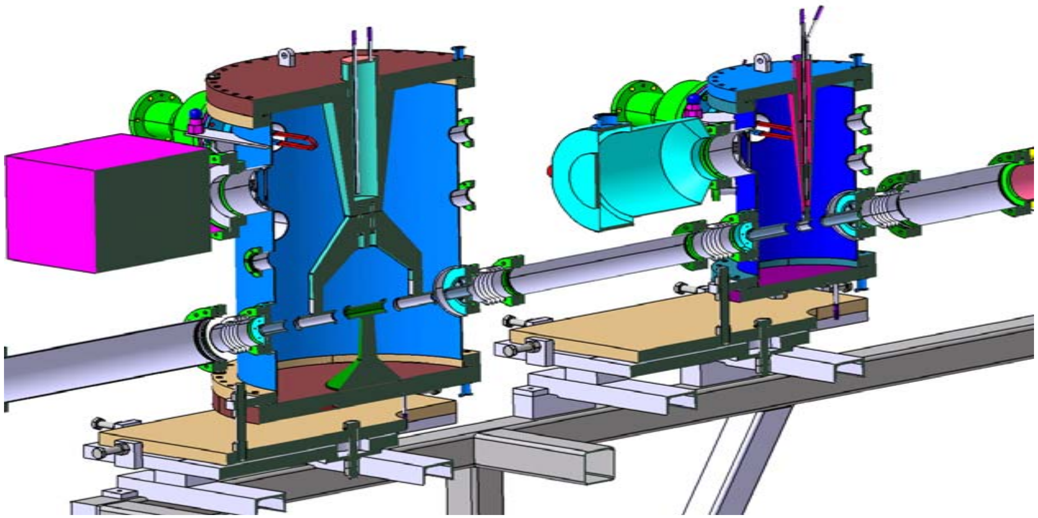
Forthcoming Tasks

Schematic View of the Decelerator

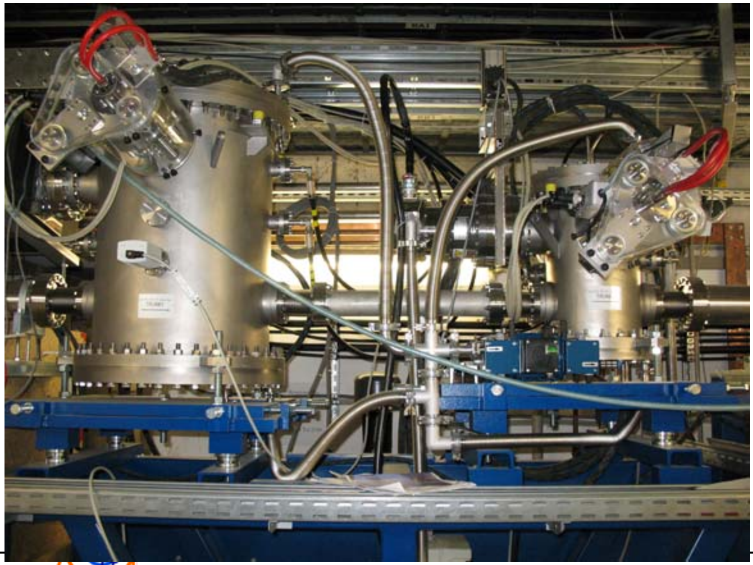
Operation frequency	108.408 MHz
Max. duty cycle	0.5%
IH-deceleration gain	4 MeV/u → 0.5 MeV/u (10.5 MV)
RFQ-deceleration gain	0.5 MeV/u → 6 keV/u (1.5 MV)
Max. A/q	3 (includes $^{238}U^{92+}$)

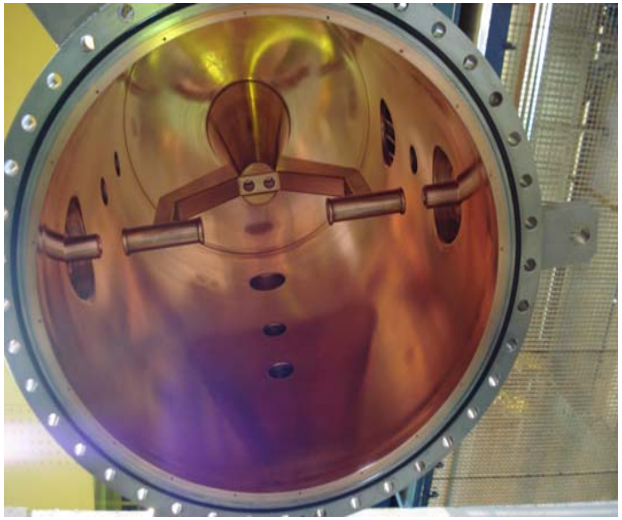


108 and 216 MHz Double Drift λ/4 Buncher

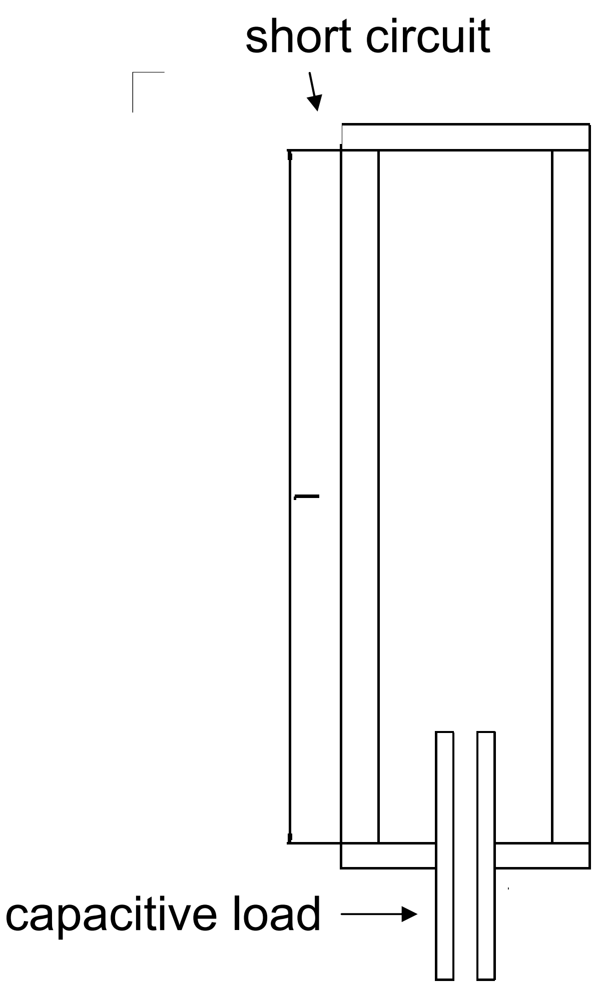


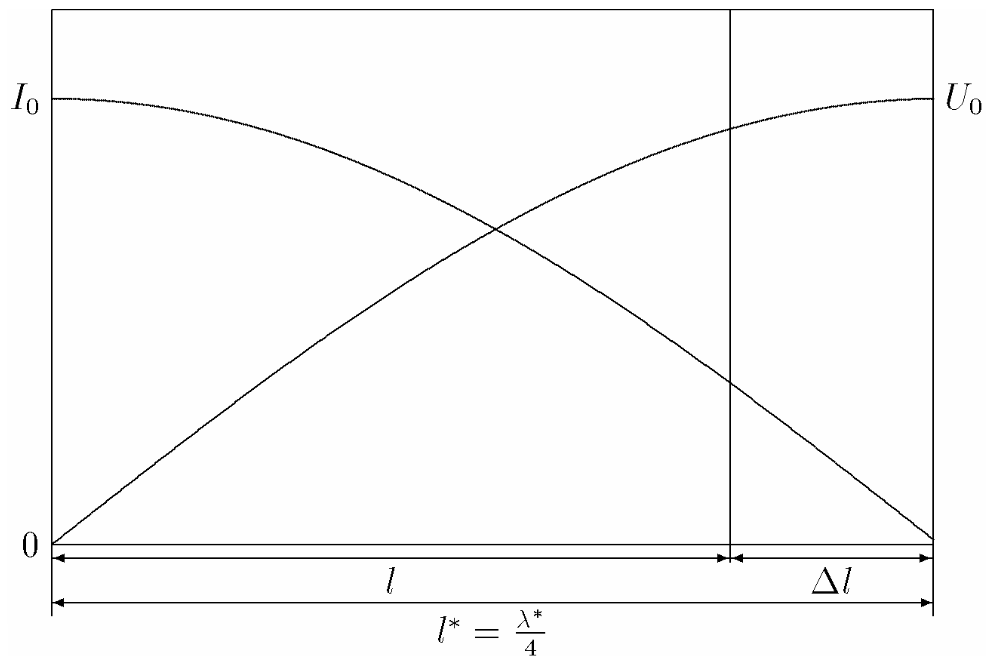
DDB	4-gap-Buncher	2-gap-Buncher
f_0	108.4 MHz	216.8 MHz
V_0	250 kV	65 kV
Q_0	13,700	6,700
Z_{eff}	120 MV/m	36.2 MV/m
P_{rf}	1.52 kW	1.33 kW



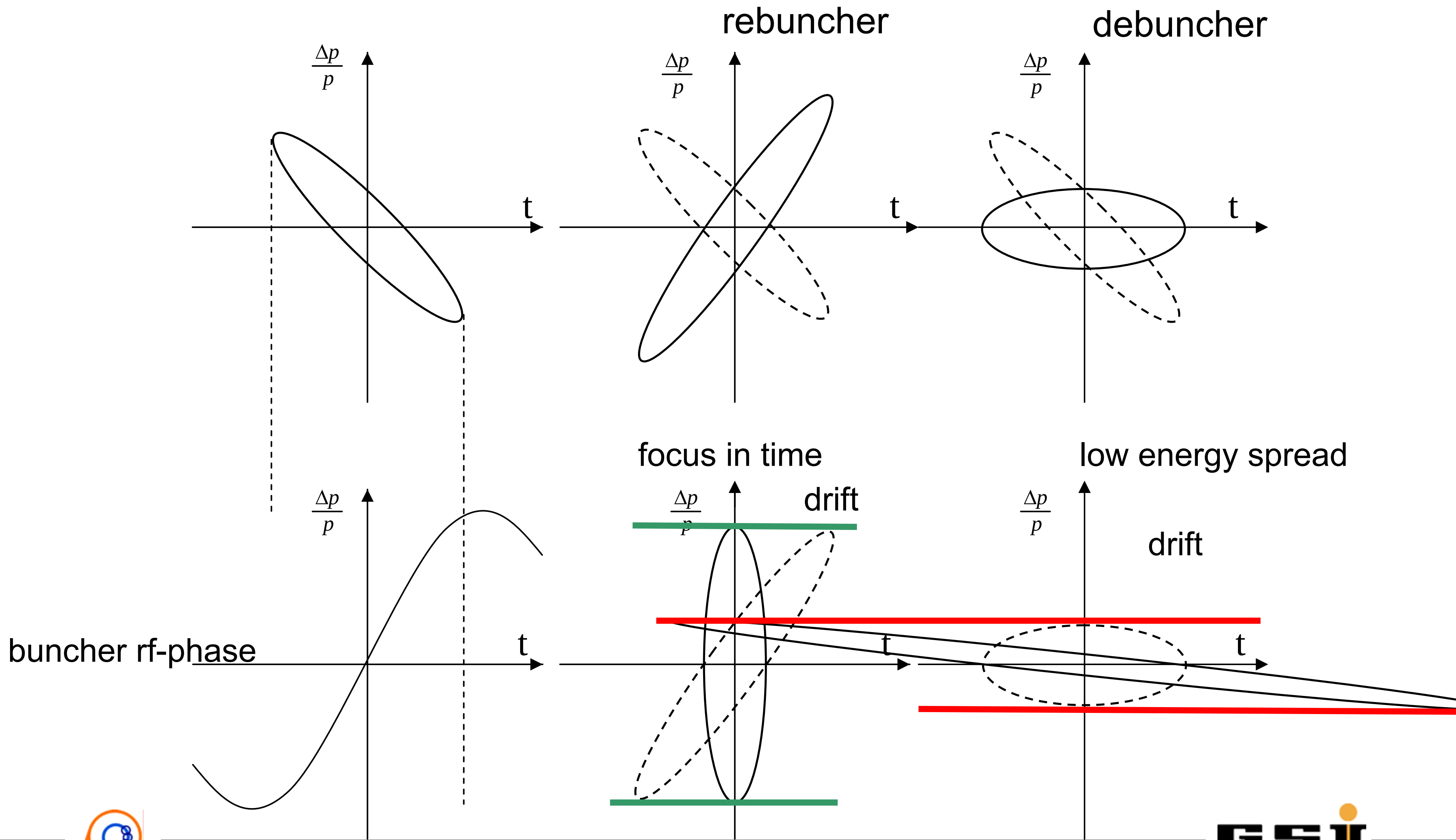


λ/4 Waveguide with Capacitive Load

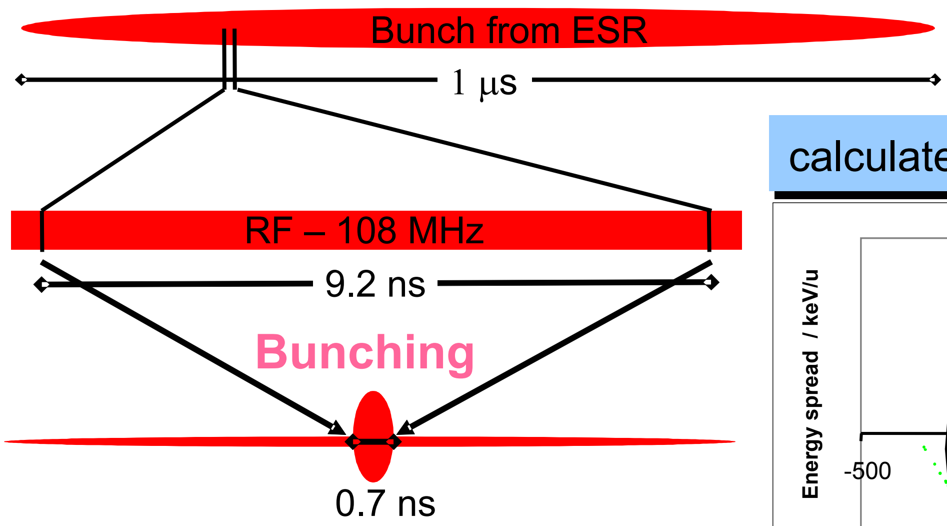




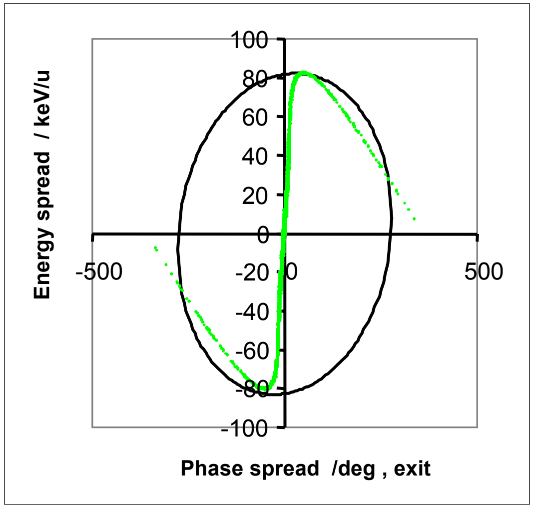
Longitudinal Beam Matching

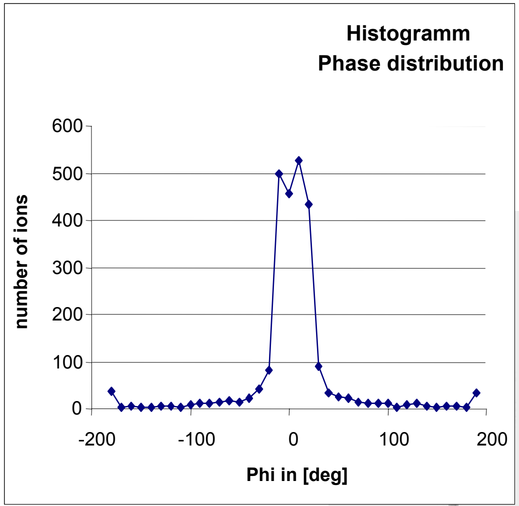


Bunching of the ESR beam



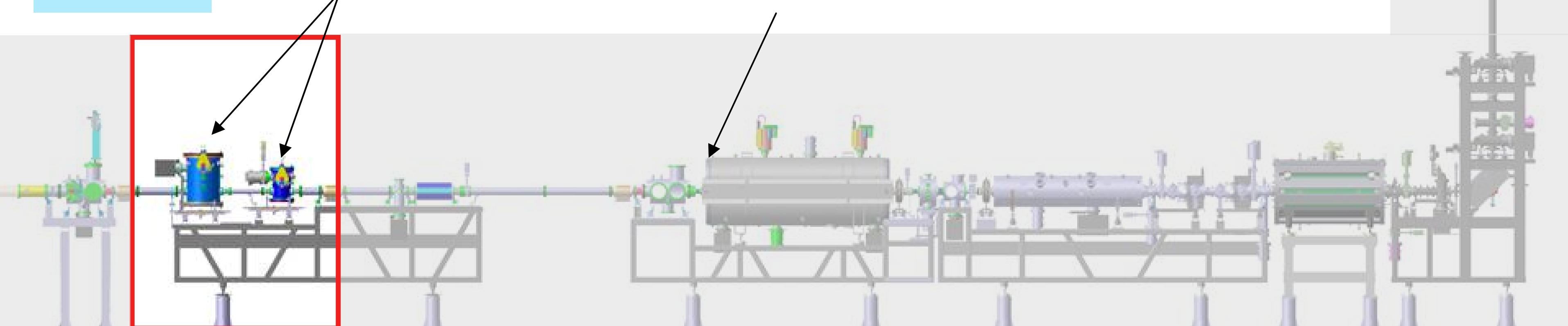
calculated particle distribution at entrance IH-structure





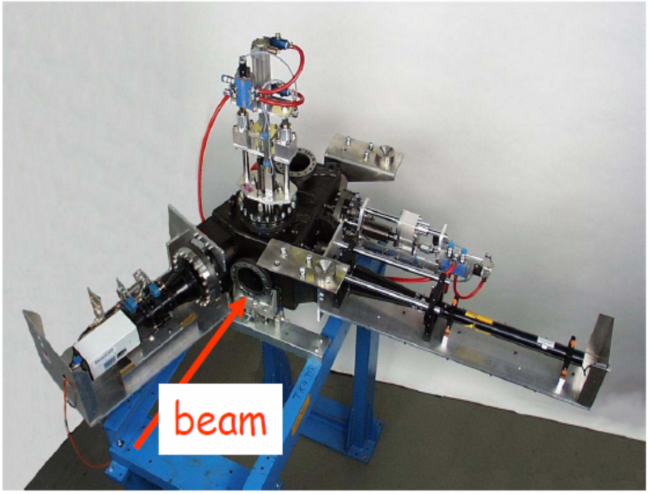
4 MeV/u

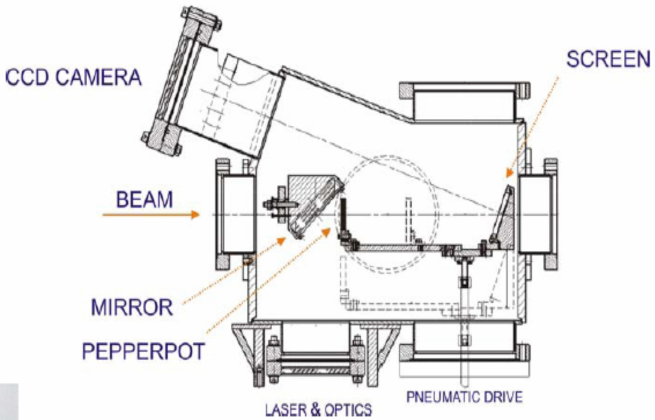
saw tooth voltage

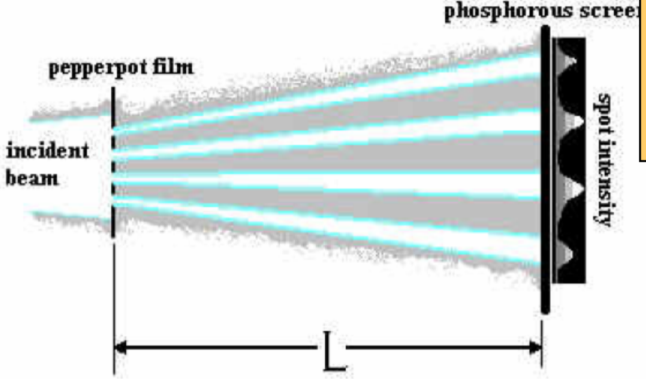


Beam Diagnostics Devices

- matrix of 15x15 holes
- diameter 100µm
- spacing 1.6mm
- drift length 150mm
- 10-bit cooled CCD
- $\delta\phi$ 0.3mrad

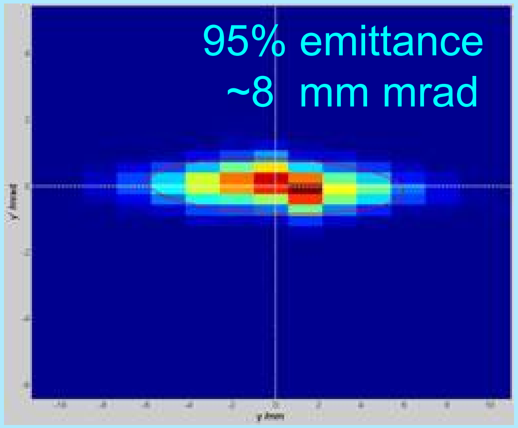




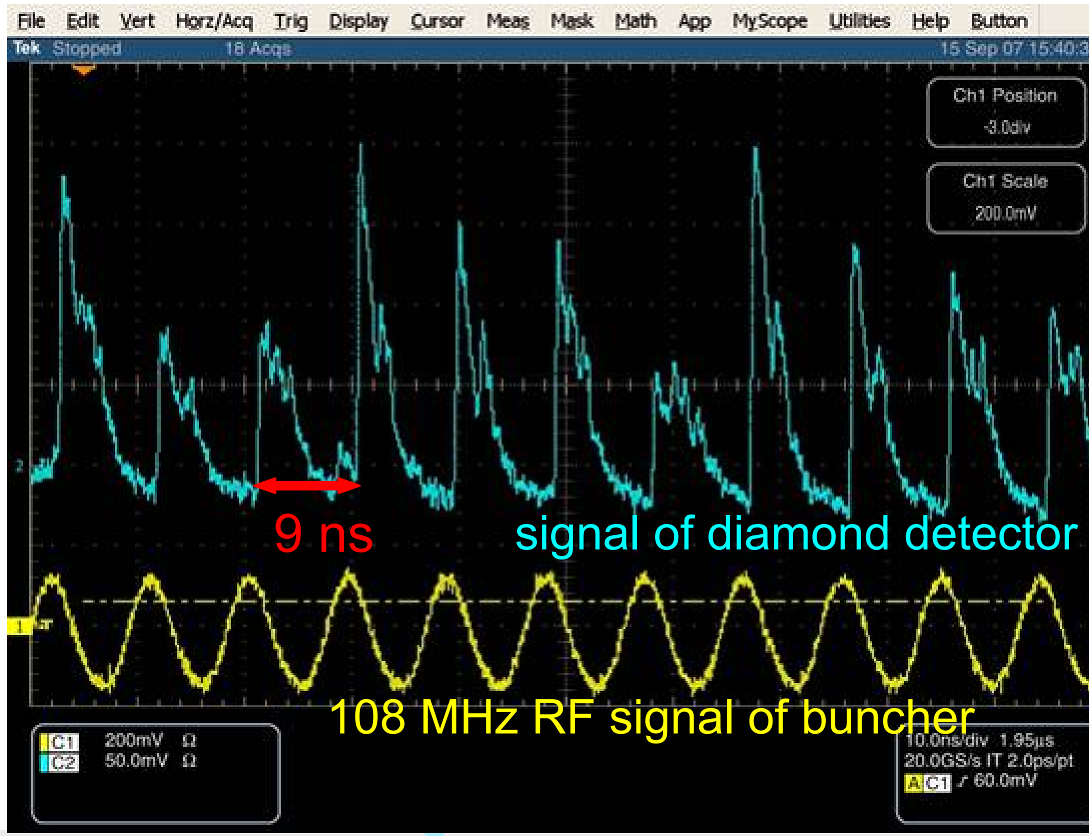


- Scintillation screens based on YAG single crystals
- Capacitive phase probes
- Wire grids
- Faraday cups
- Diamond detector for energy and position
- Emittance meter
- MCP/Dipole magnet for energy detetction

Commissioning of DDB with Ne^{10+} Beam
August 2007

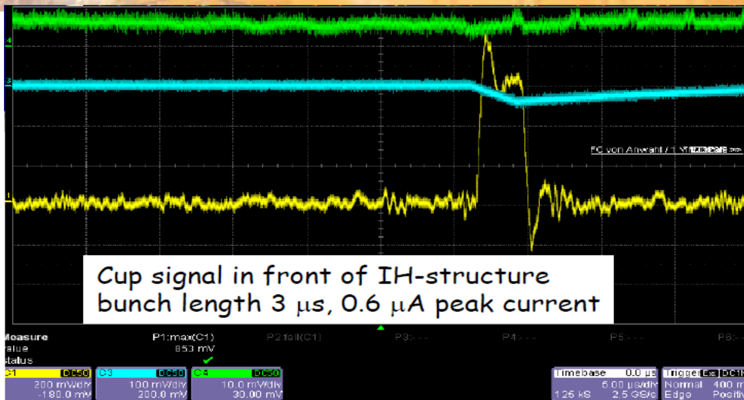


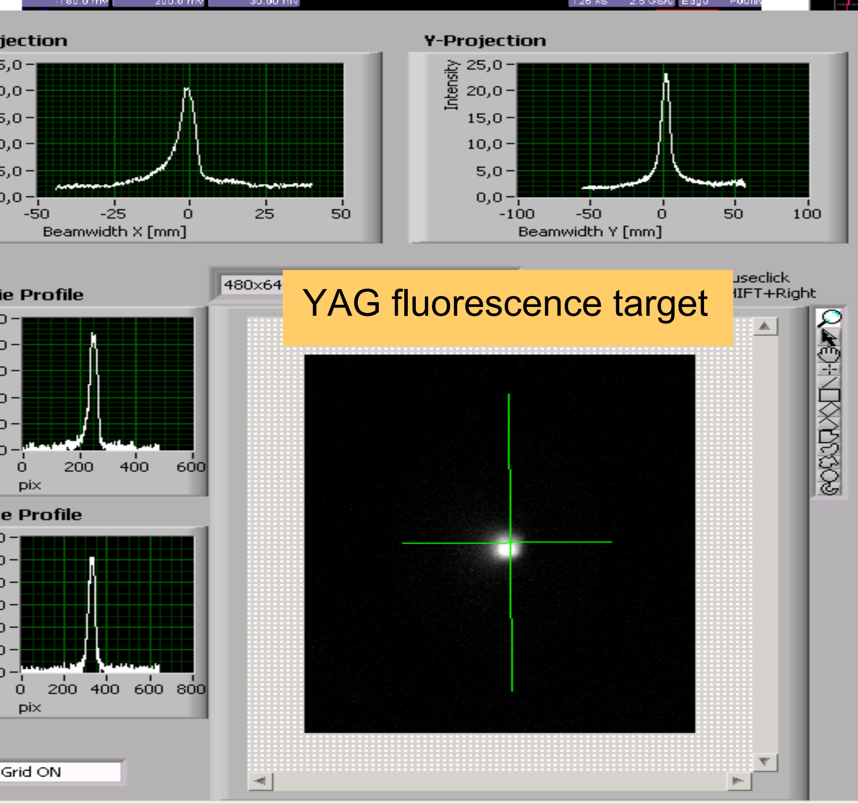
pepper pot emittance meter
Ne^{10+}, not cooled in ESR

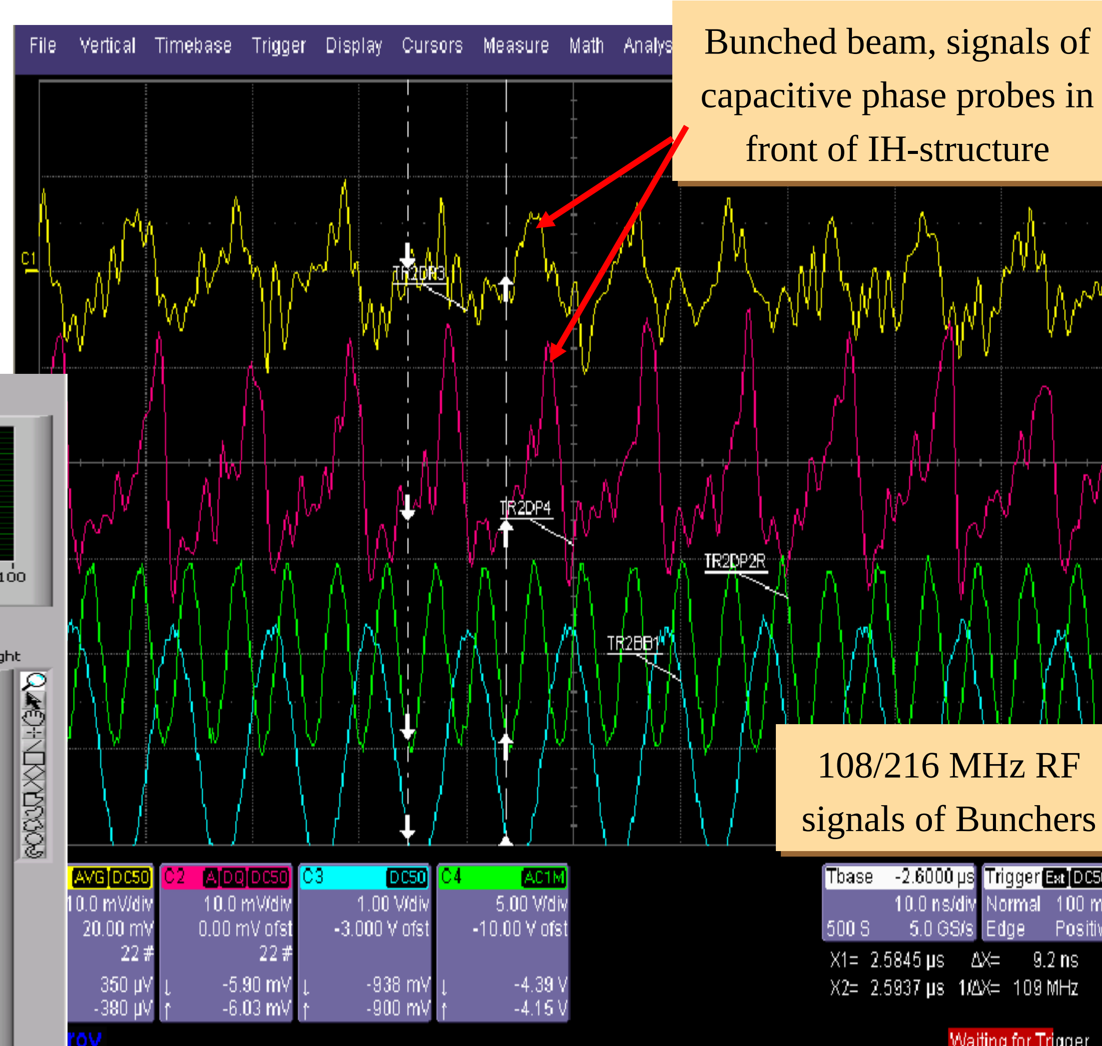


4 MeV/u

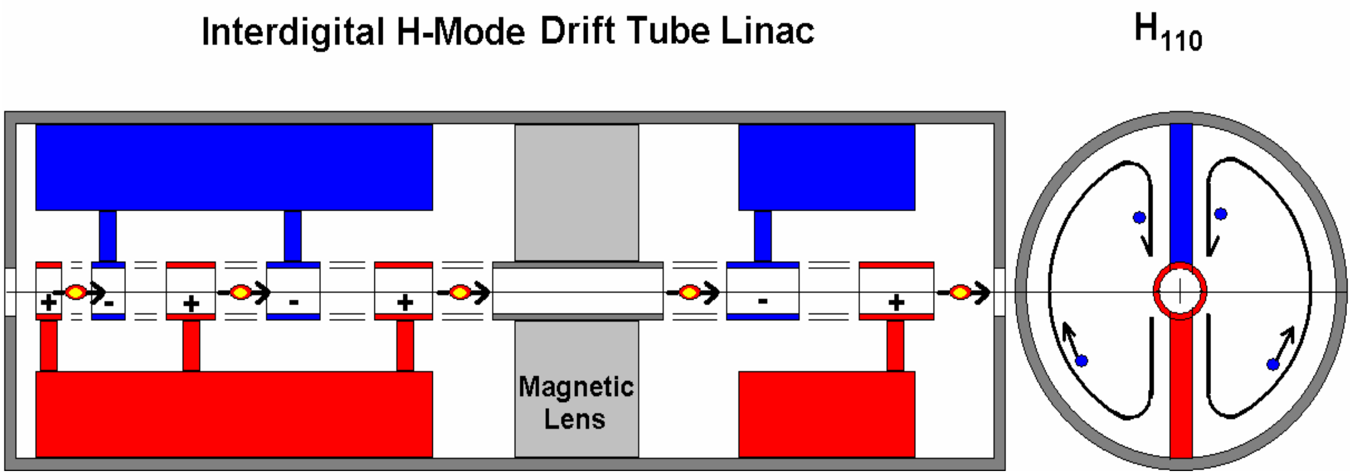
Commissioning of DDB with Ne^{10+} Beam August 2007



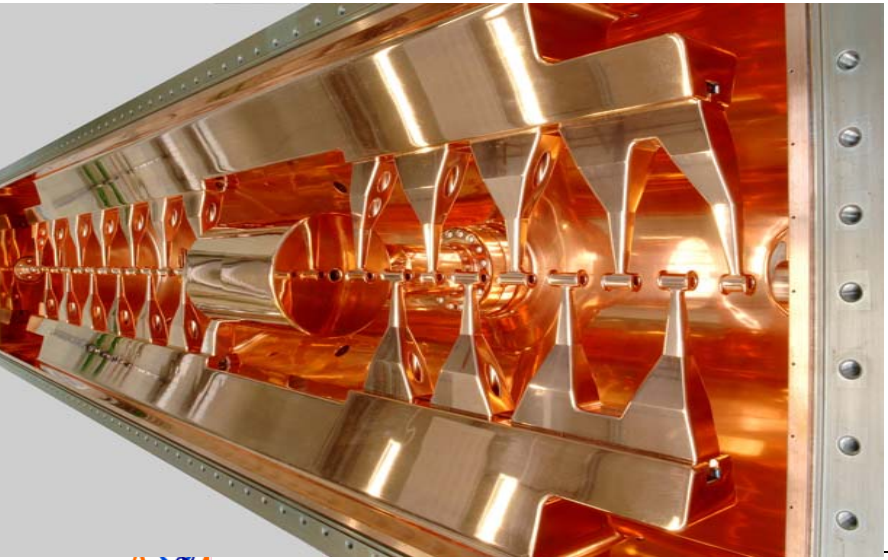




IH- 108 MHz Drift Tube Decelerator

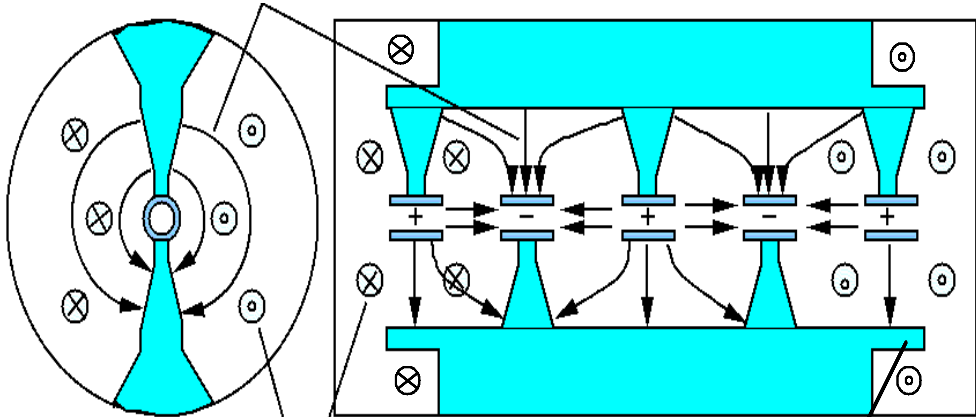


f_0	108,4 MHz
Q_0	25.750
Z_{eff}	285 MΩ/m
E_{eff}	4 MV/m
L_{tank}	2,64 m
P_{rf}	174 kW
gaps	25

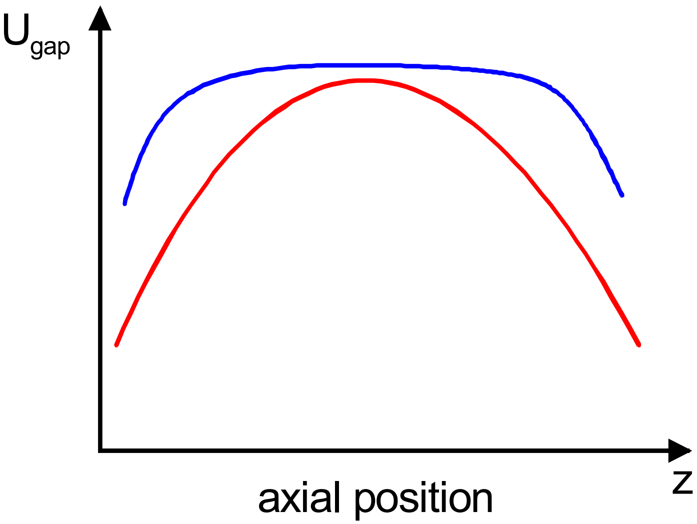


Principle of Interdigital H-type structures

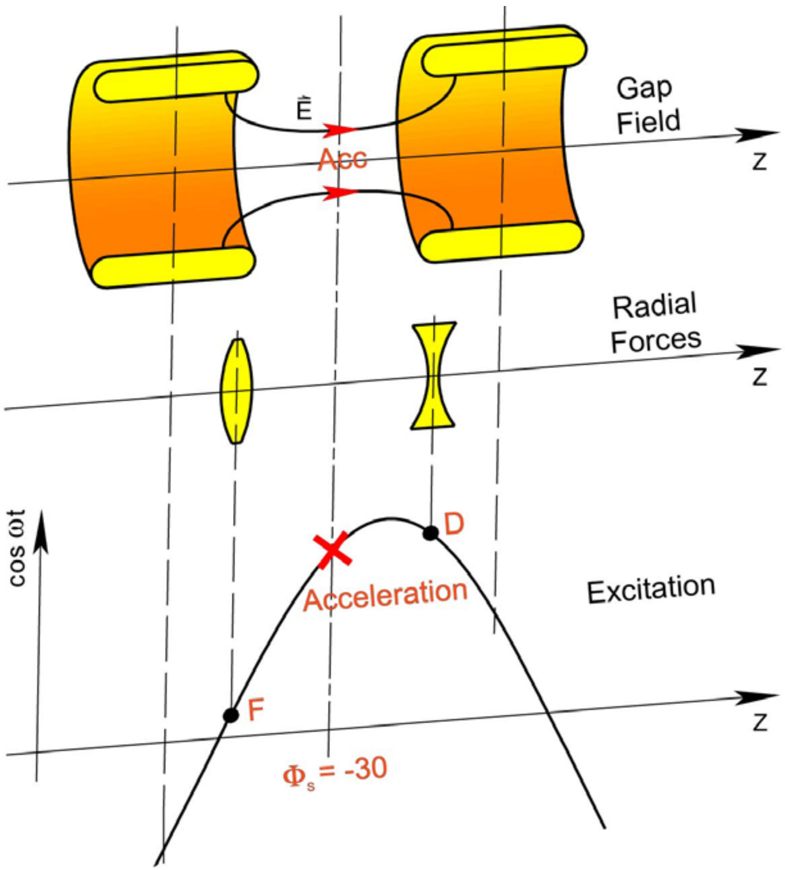
IH-structure with drift tube structure and magnetic flux inducers

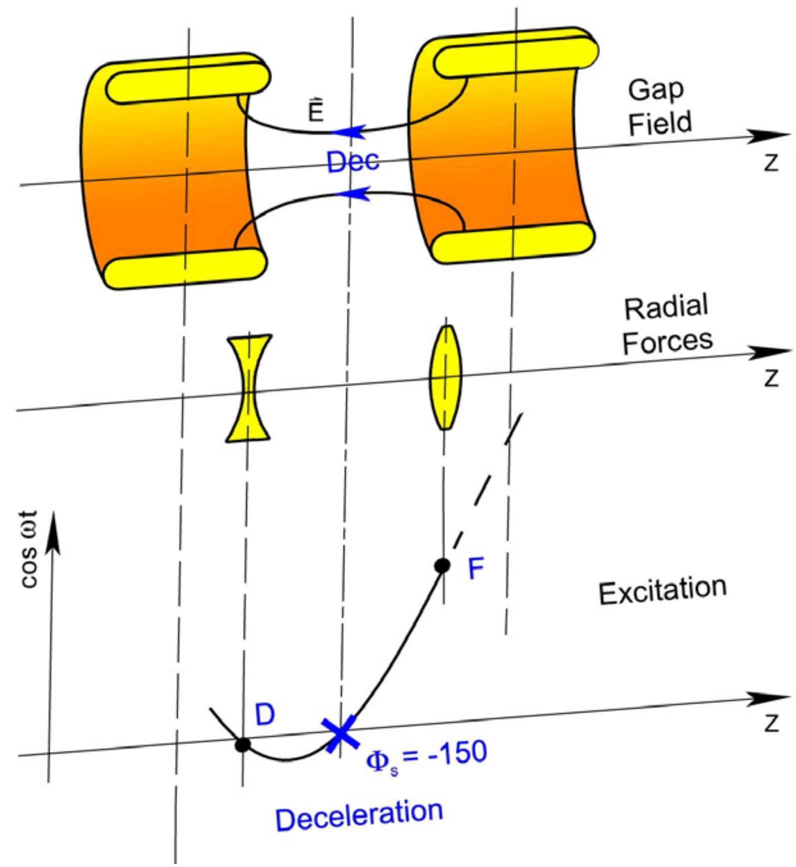


distribution of the gap voltage without magnetix flux inducers (red) and with flux inducer with optimized undercuts (blue)



Beam Dynamics Basics



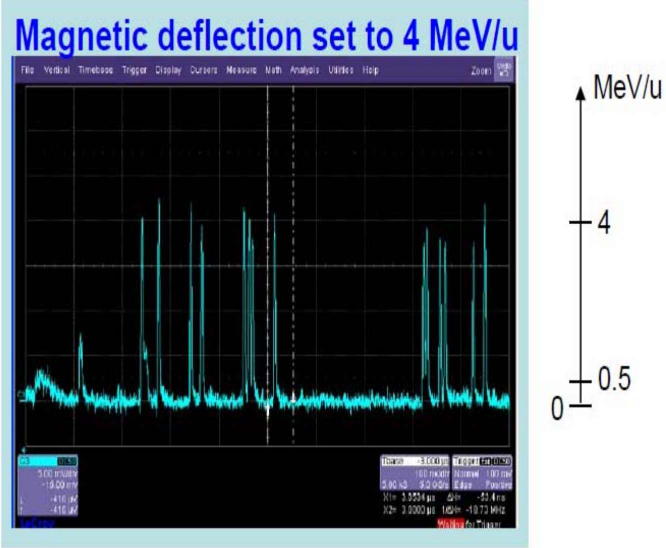


Commissioning of the IH-tank with $^{197}Au^{65+}$ Beam

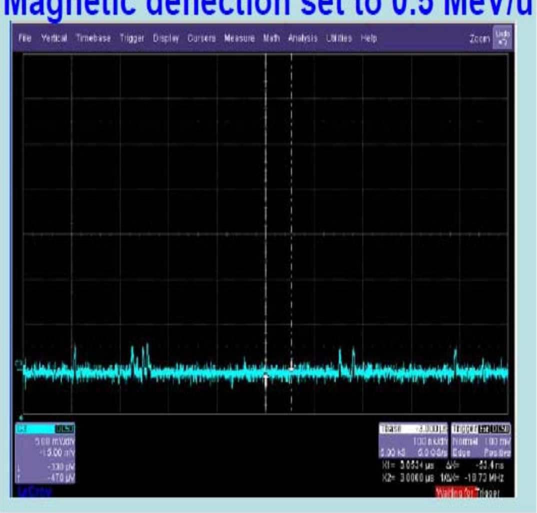
- IH commissioning: deceleration from 4 MeV/u to 0.5 MeV/u
- Energy signal on single crystal diamond detector:

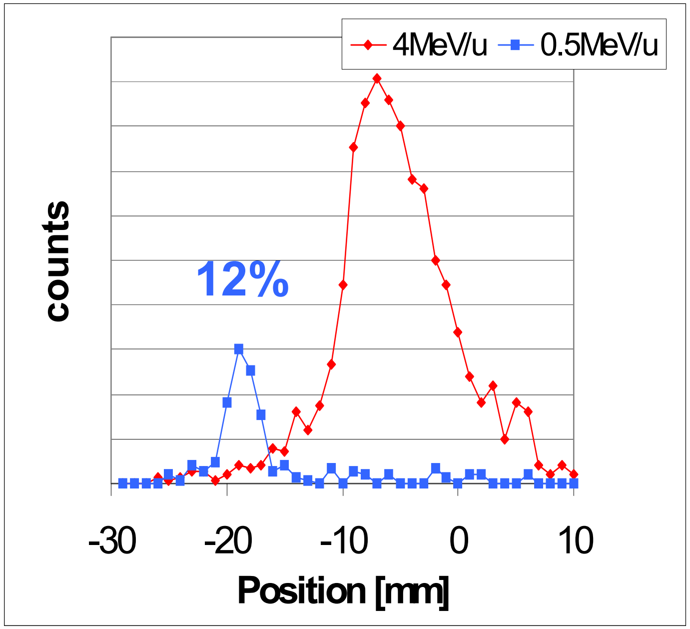
beam energy profile on diamond detector

Magnetic deflection set to 4 MeV/u

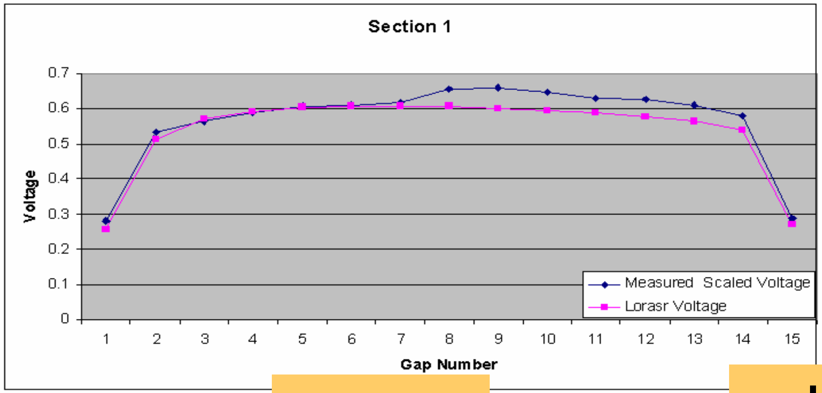


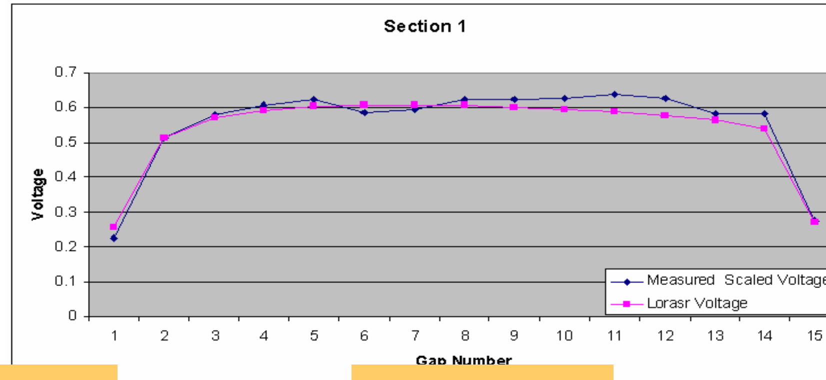
Magnetic deflection set to 0.5 MeV/u





Retuning of the IH- Gap Voltage Distribution

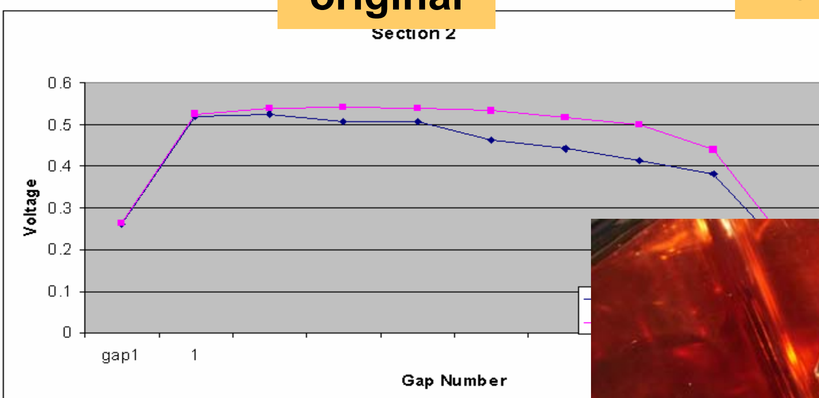


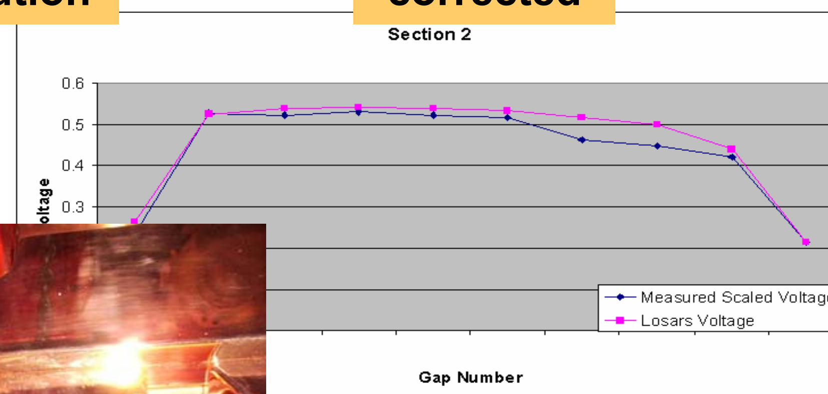


original

voltage distribution

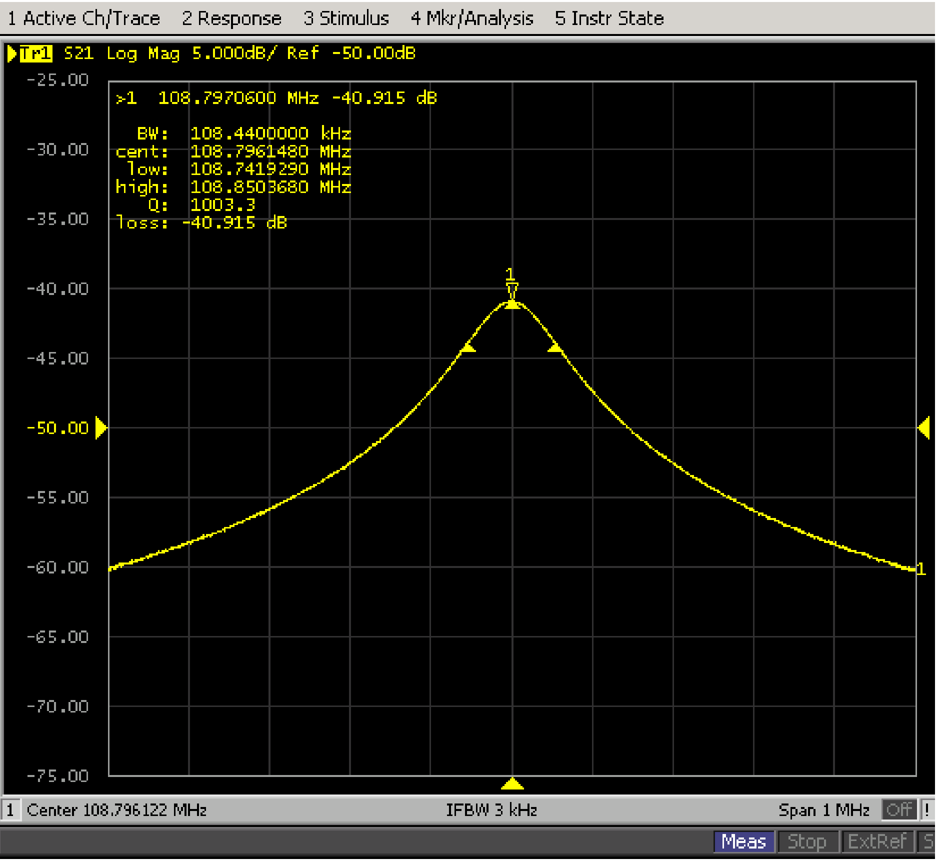
corrected

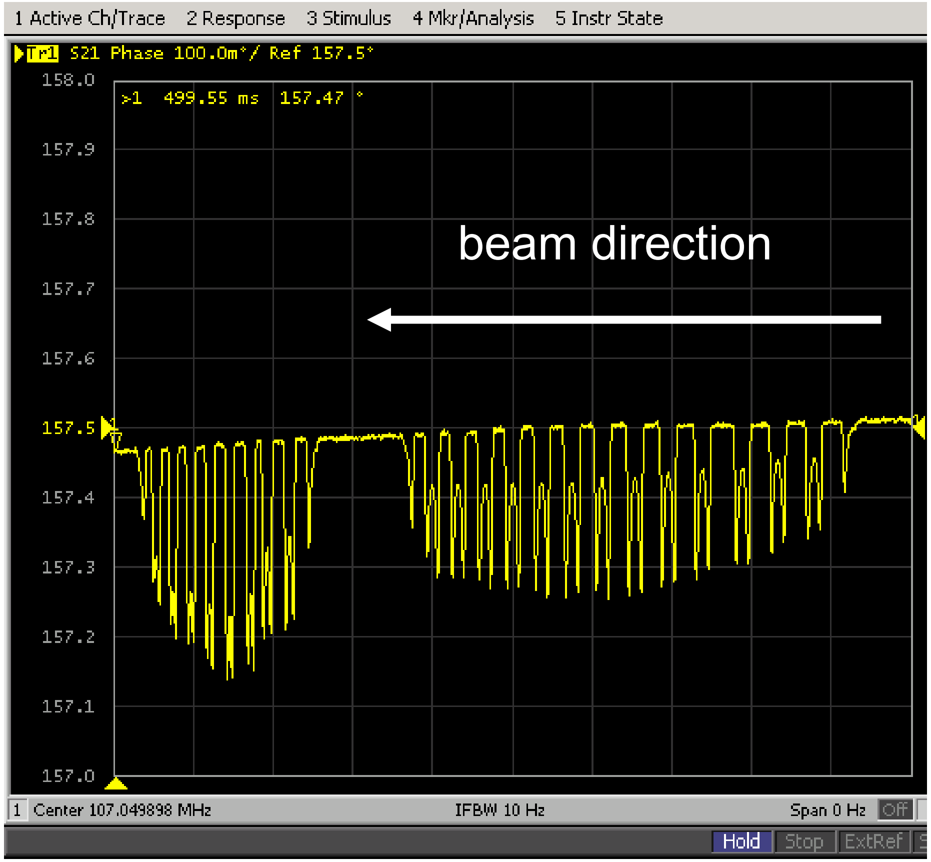




additional capacitive tuner at the low energy end

Bead Pull RF-Measurements at the IH-structure

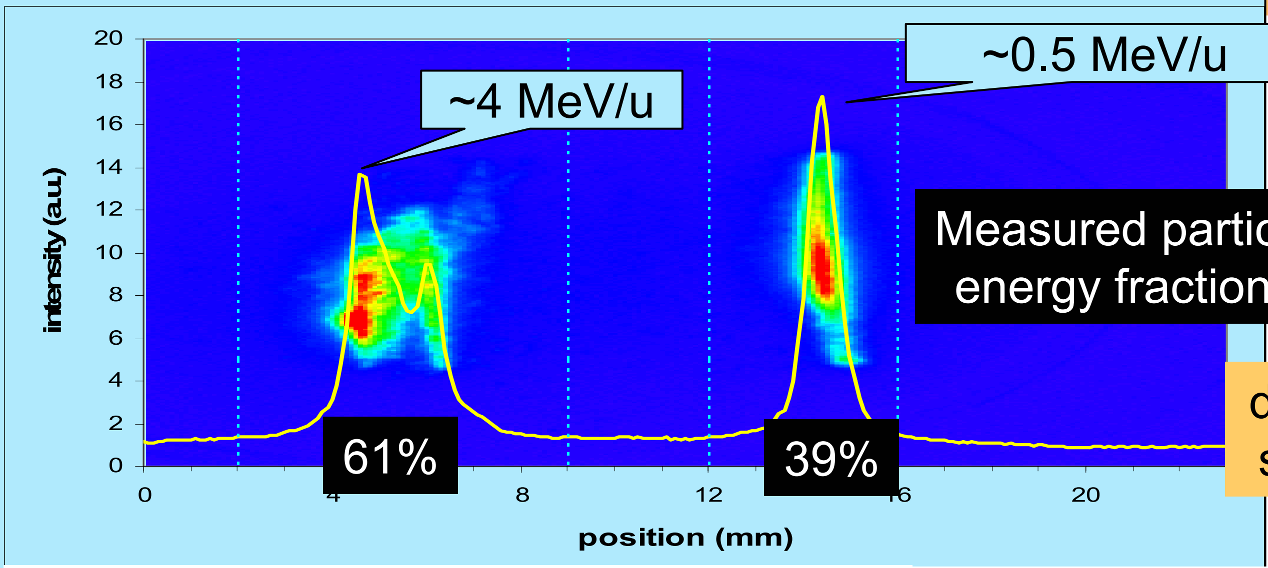




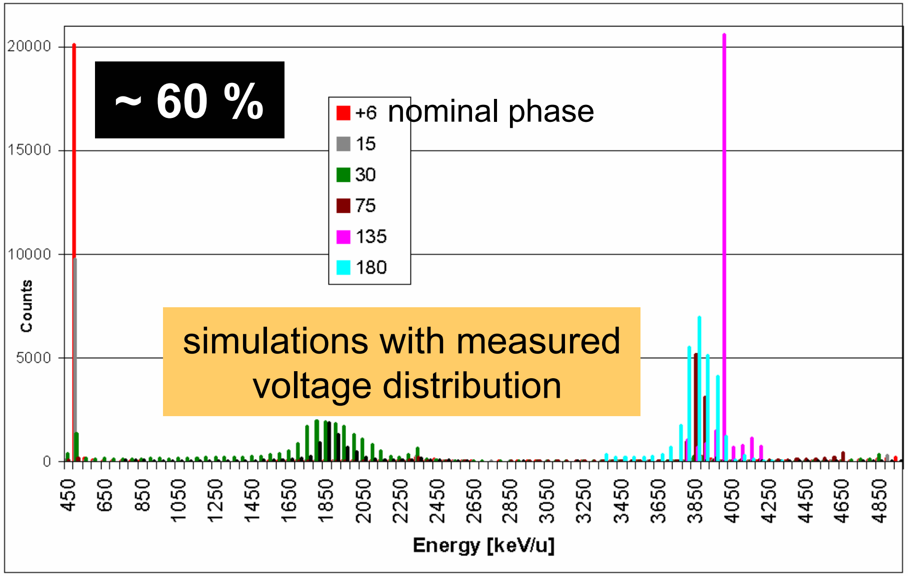
Resonance profile with center frequency at 108.44 MHz

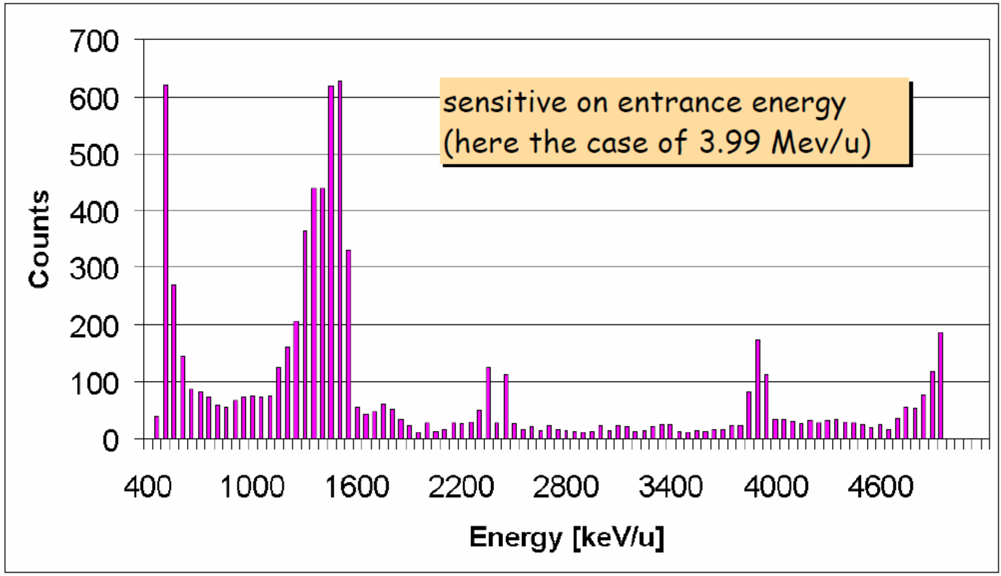
Electric field (E^2) distribution

Energy Spectrum of $^{86}Kr^{33+}$ (March 2010)

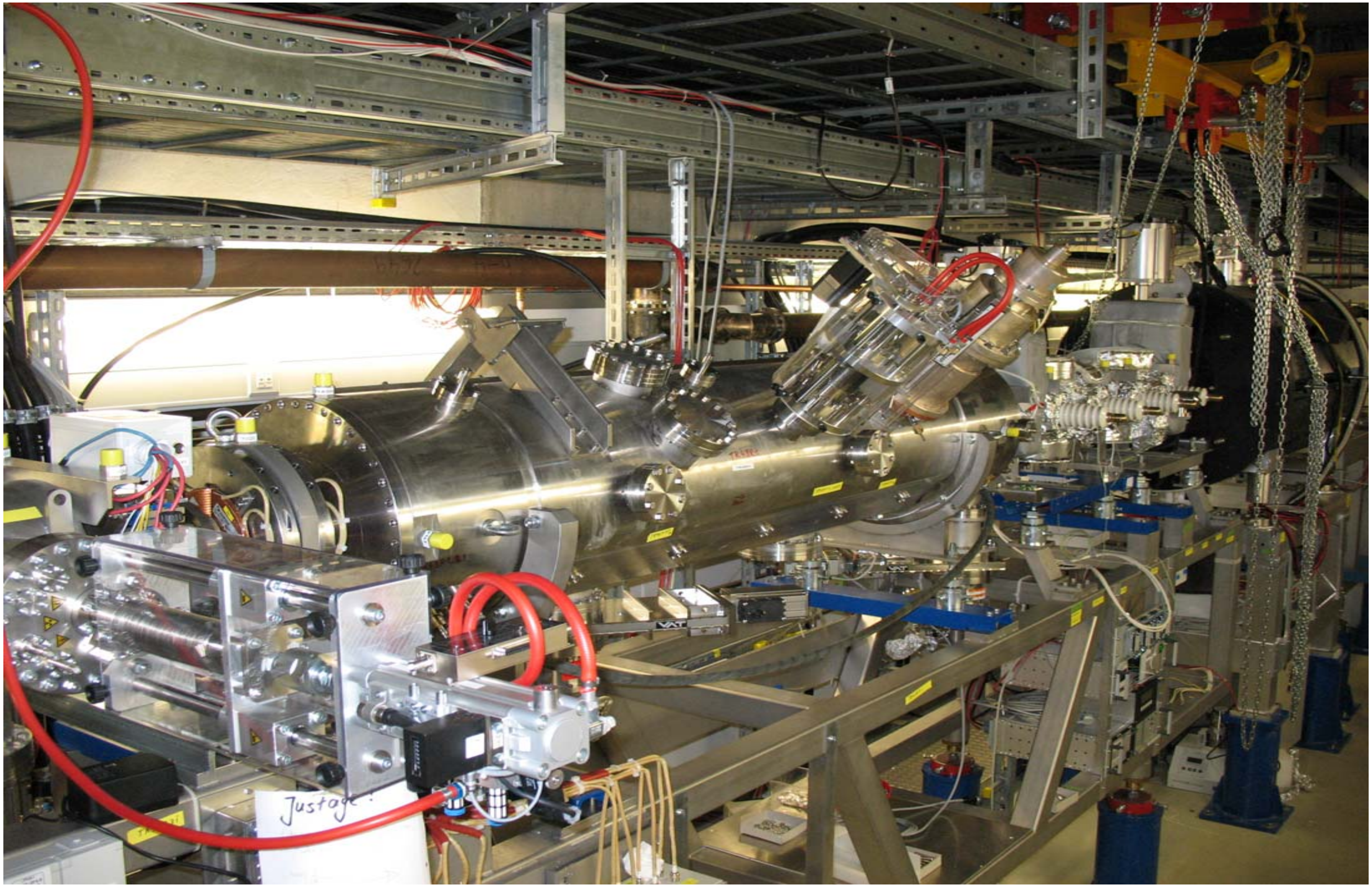


diagnostic device comprising: slit, permanent magnet, MCP





RFQ Decelerator



Rebuncher and RFQ-Tank with Integrated Debuncher

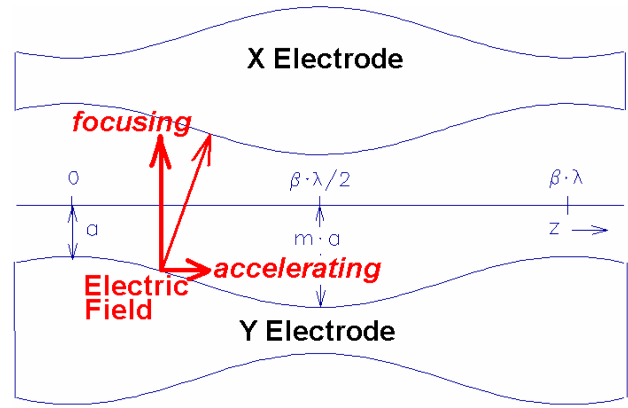
spiral type rebuncher

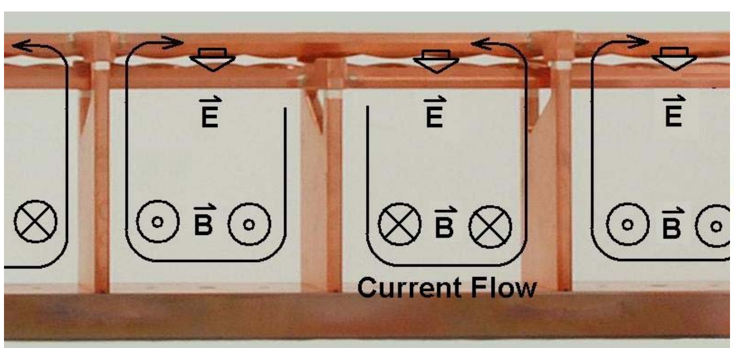
	RFQ
f_0	108.4 MHz
r_0	4 mm
length	1.9 m
cells	143
Z_{eff}	120 kV/m
V_{rod}	75 kV

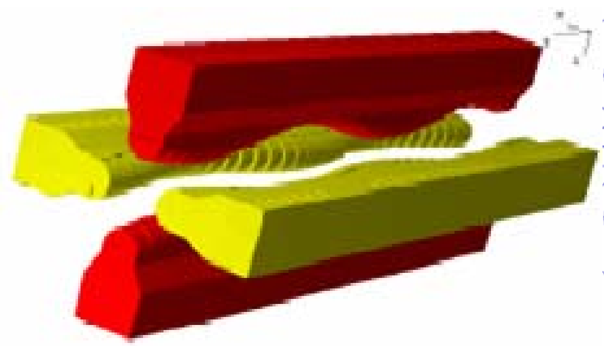
spiral type debuncher

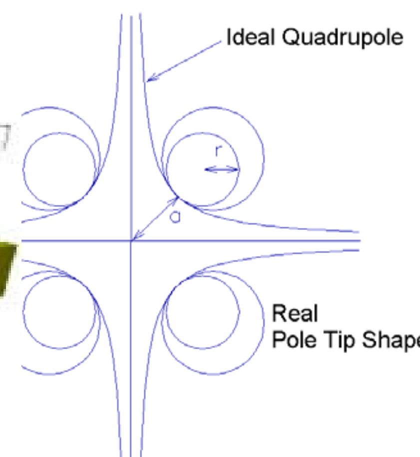
4-rod RFQ

Electric and Magnetic Fields of an RFQ

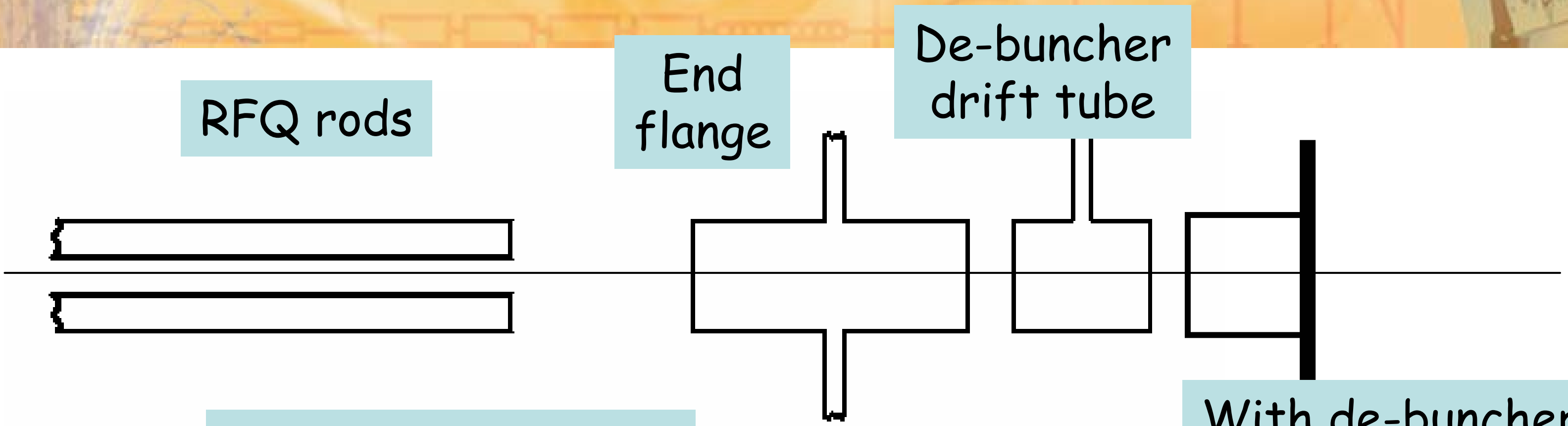


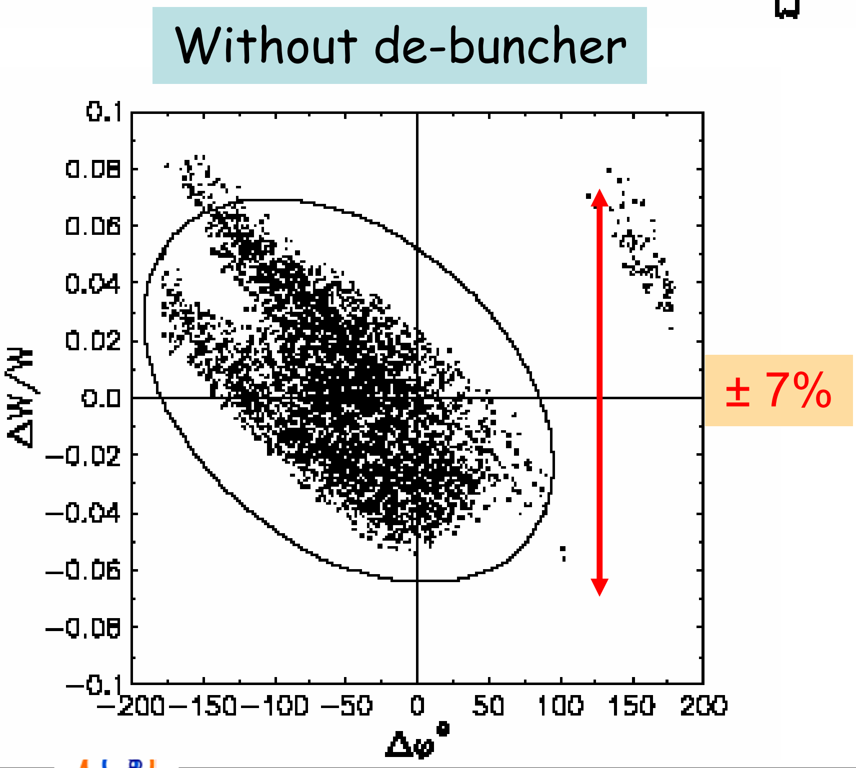


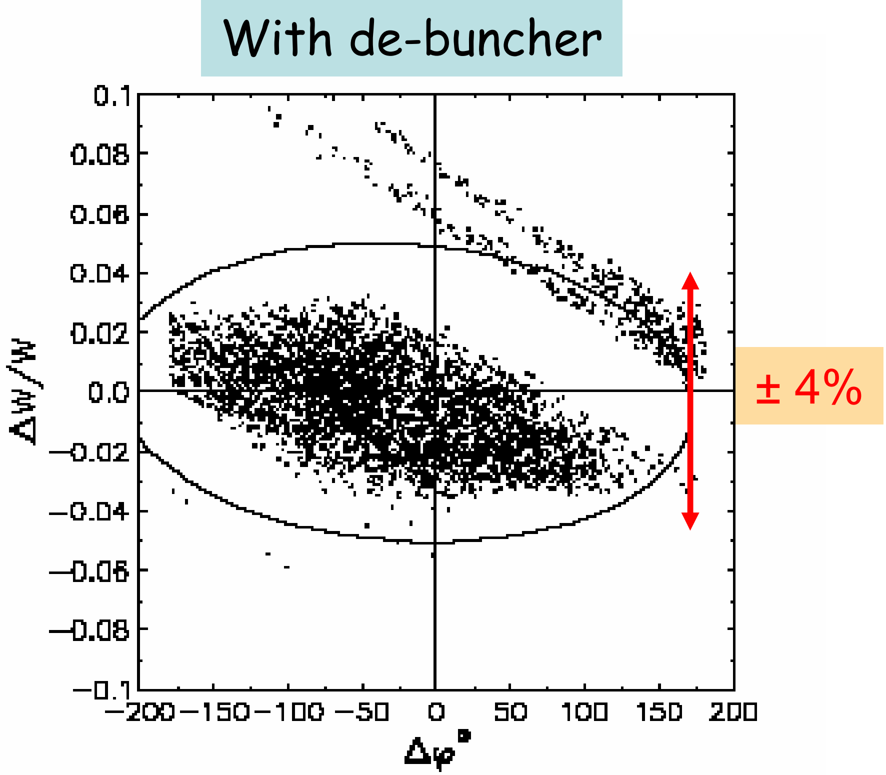




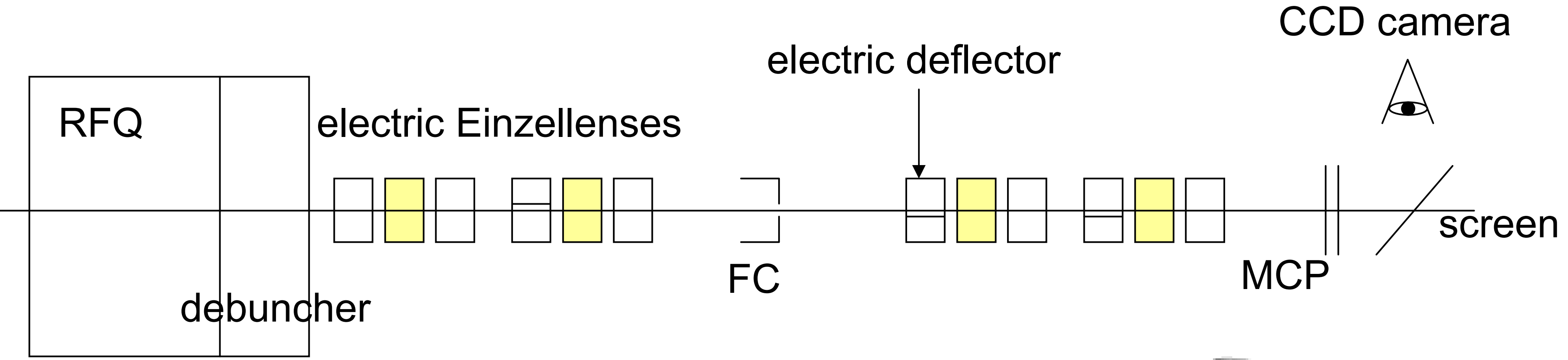
Reduction of Energy Spread





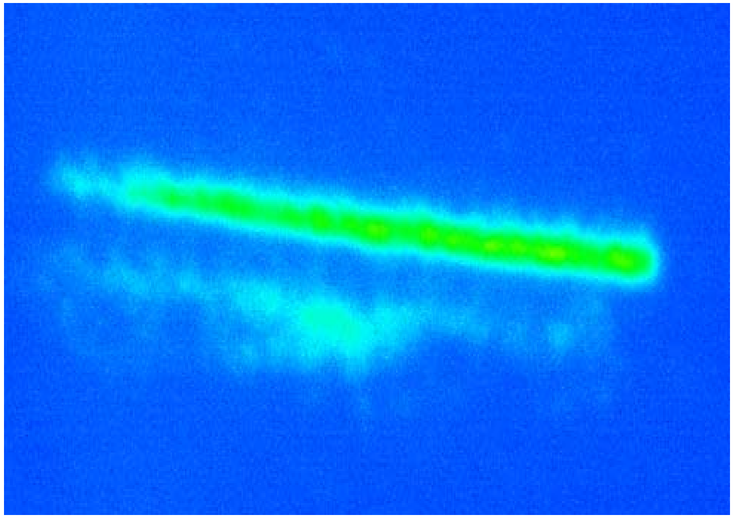


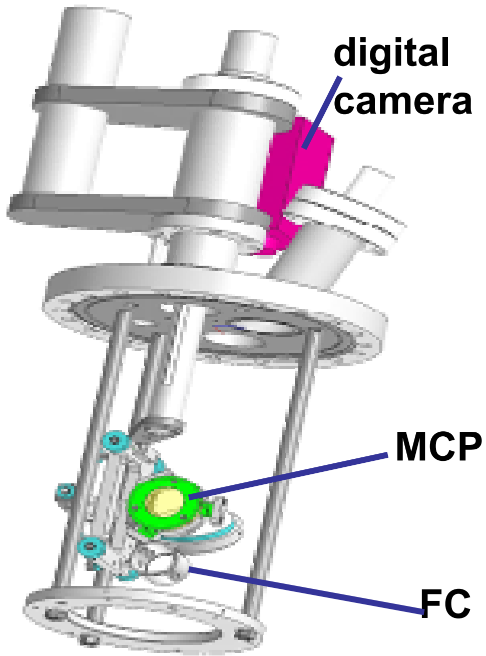
First Beam through the RFQ-Tank
($^{86}Kr^{33+}$, March 2010)



two simultaneous spots for different settings of RFQ phase and amplitude

no visible change due to different settings of electrostatic elements





→ positive aperture test

Space Charge Forces Negligible?

Extracted from Kapchinsky theory for periodic channels:

phase advance:

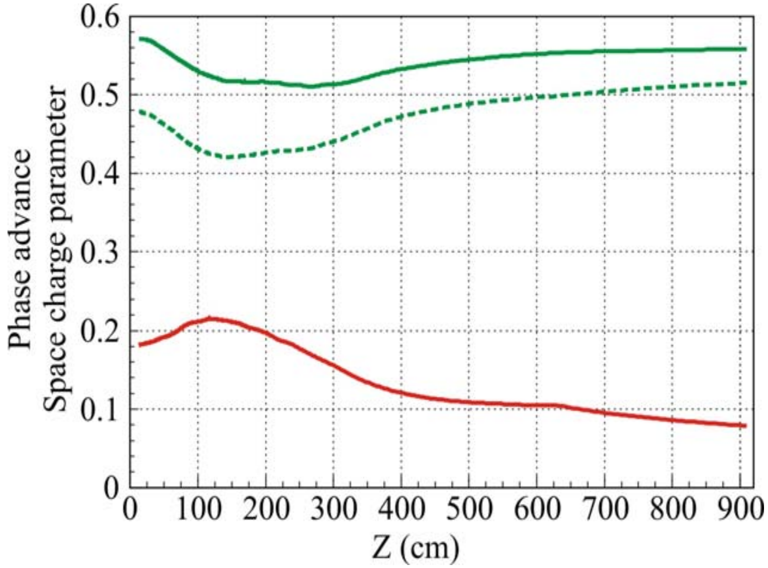
$$\sigma = \sigma_0 \left(\sqrt{1+h^2} - h \right)$$

acceptance:

$$V_k = V_{k0} \left(\sqrt{1+h^2} - h \right)$$

beam radius:

$$R = R_0 \left(\sqrt{h + \sqrt{1+h^2}} \right)$$



High Current Injector	HITRAP
U4+	U92+
2.2 keV/u	6 keV/u
25 mA	25 µA
β = 0.00217	β = 0.0036
Vp = 0.5 mm*mrad (norm)	Vp = 0.2 mm*mrad (norm)
$h \approx 0.22$	$h \approx 0.002$

Status and Forthcoming Tasks

Status:

- Beams of different ion species were decelerated from 4 MeV/u to 500 keV/u
- Beam quality and intensity meet the expectations of the TDR.
- Nevertheless, potential for improvements is given (longitudinally + transversally)

To do:

- Beam experiments for definition of the working points (phase and amplitude) of RFQ, rebuncher, debuncher :

  needs additional installation of a Wienfilter behind IH-tank and energy analysis by a MCP/dipole device behind the RFQ
- Increase of the diameter of the diaphragma in front of the DDB to enable improved transverse beam optics and hence particle transmission
- Finally, developing of a scalable data compilation comprising all values of 26 magnetic, 12 rf set up parameters, and the electrostatic lenses

HITRAP Projekt Collaboration

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and the HITRAP collaboration

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[5]J. W. Goethe-Universität Frankfurt am Main

HITRAP

GSI

Beam Parameters Along the Decelerator

	DDB	IH-structure	Re-buncher	RFQ+de-buncher
E entrance [MeV/u]	4	4	0.5	0.5
E exit [MeV/u]	4	0.5	0.5	0.006
β exit	0.093	0.033	0.033	0.0036
$\varepsilon_{xx'}$ ($_{yy'}$) normalized (entrance) [mm mrad]	0.2	0.21	0.3	0.34
phase spread [°] entrance	240 (accepted)	20	75	45
energy spread [%] entrance	0.01	3.5	5	5
$\varepsilon_{xx'}$ ($_{yy'}$) normalized (exit) [mm mrad]	0.21	0.3	0.34	0.36
phase spread [°] exit		20	70	300
energy spread [%] exit	3.5	6	5	8
Expected transmission [%]	98	70	95	85

Kapchinsky Theory for Periodic Channels

Assuming low beam current and smooth approximation, a local normalized acceptance V_k for each RFQ cell can be calculated from the Floquet functions, which are the solution of the Mathieu-Hill equation for the particle motion.

$$V_k = \nu_f \frac{a^2}{\lambda} \qquad \nu_f = \frac{1}{\rho^2}$$

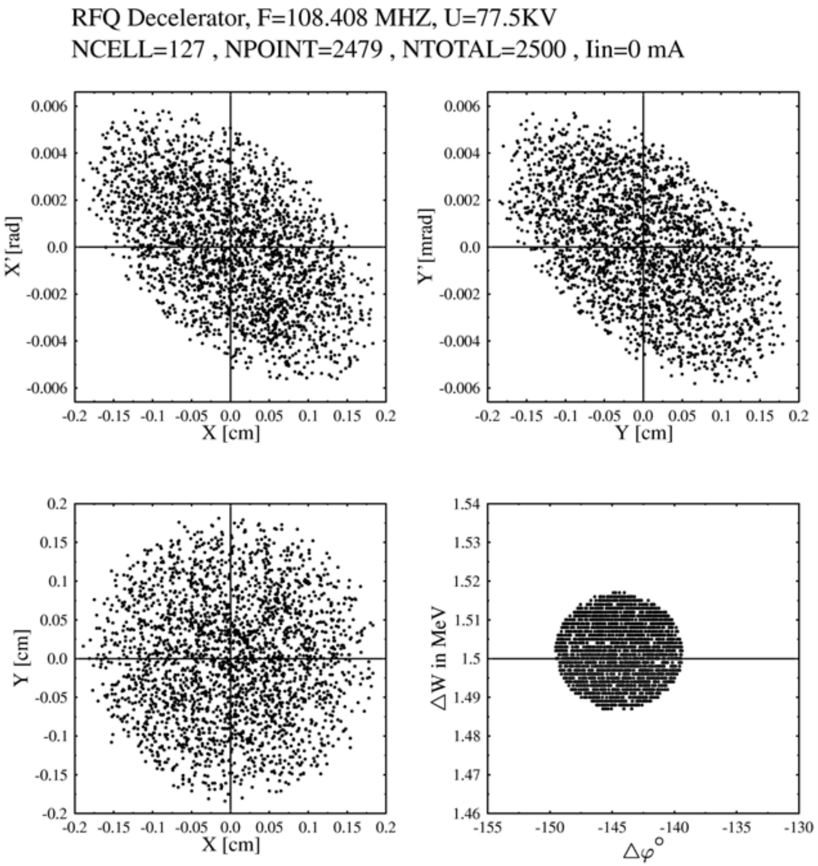
where ρ is a module of the Floquet function, a - aperture (radius) of the cell, λ - wave length of the operating frequency; ν_f can be treated as a minimum of the phase advance σ on the focusing period.

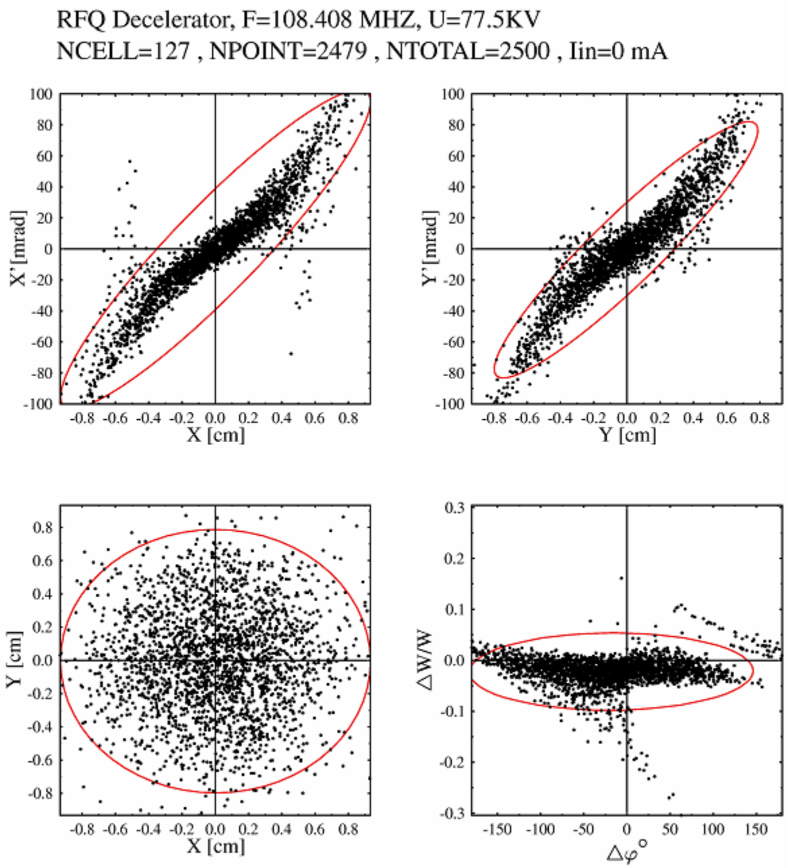
In presence of the beam current, a tune depression of σ and ν_f can be calculated using Coulomb parameter h, which combines parameters of the beam and accelerating channel:

$$h = j \cdot \frac{B\lambda}{\sigma_0 \beta I_0} \qquad j = \frac{I}{V_p}$$

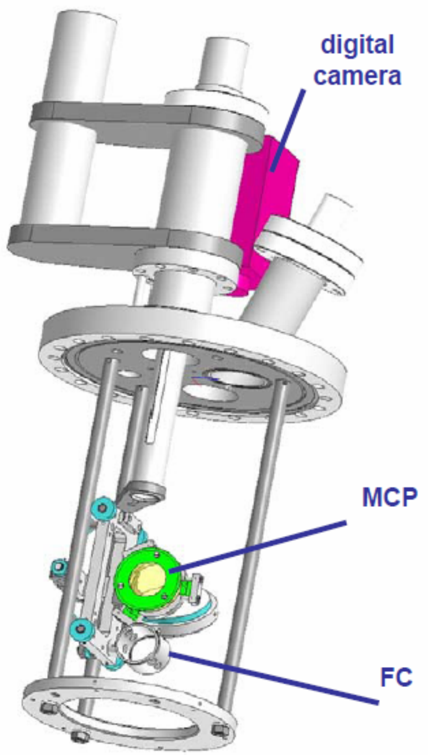
j - beam brilliance, I - beam current, V_p - normalized beam emittance, B - ratio of the peak current to the pulse current, $I_0=3.13\cdot10^7\cdot A/Z$ - characteristic current, A, Z - mass and charge numbers, σ_0 - phase advance for "zero" current, β - relative velocity of particle.

RFQ Input and Output Emittances

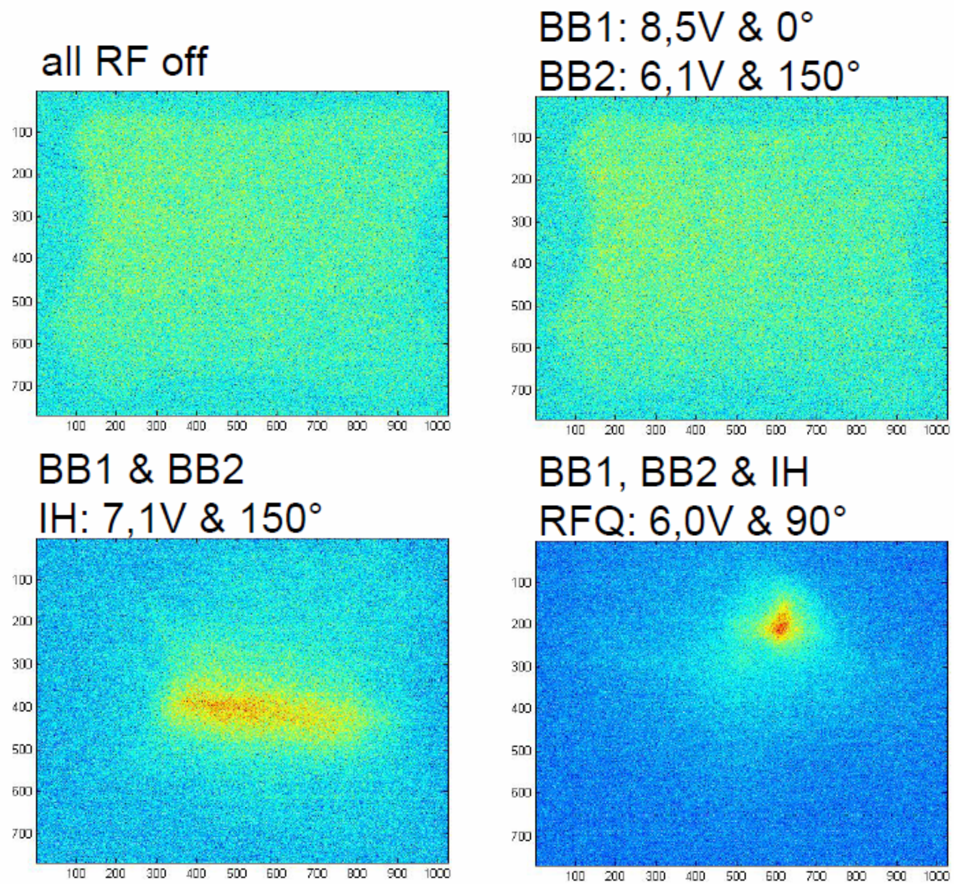




First Beam through the RFQ-Tank ($^{86}Kr^{33+}$)



low energy, low intensity
MCP-based imaging detector

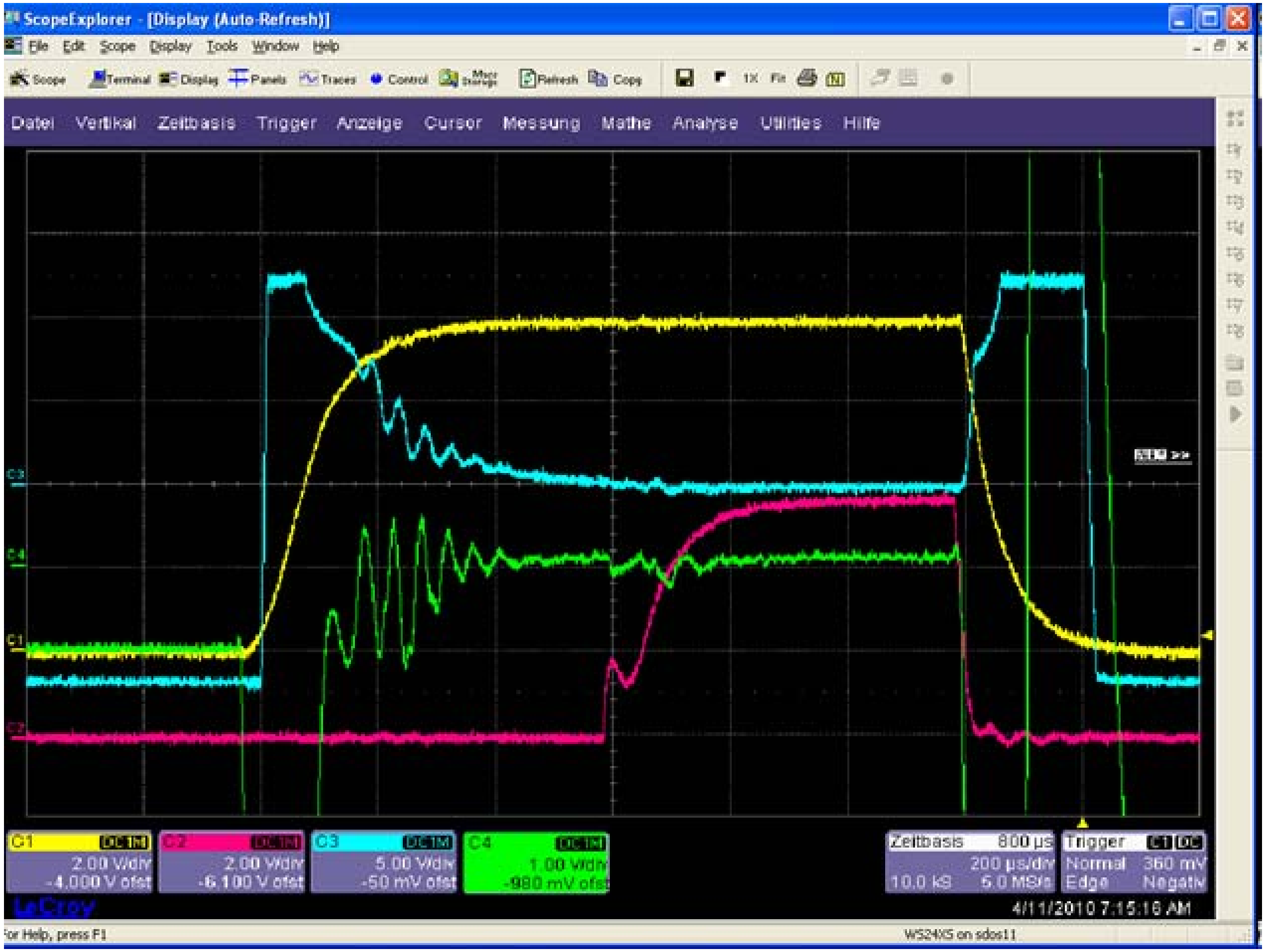


Phase Probes

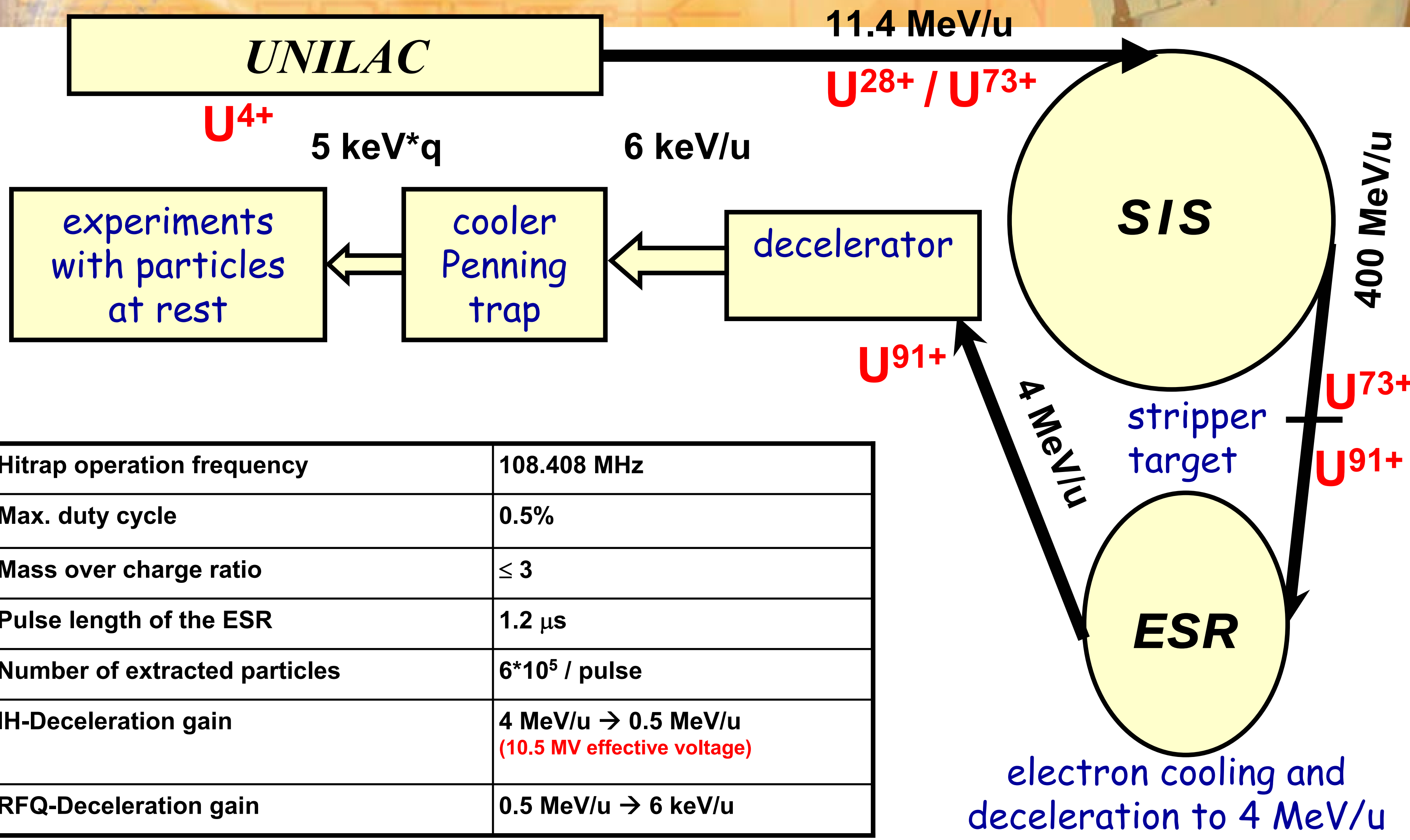
- green trace – BB2 signal
- blue trace – BB1 signal
- yellow trace – DP4
- red trace – DP3

IH RF- problems

- green trace – IH amplitude error signal
- blue trace – IH phase error signal
- yellow trace – IH RF envelope
- red trace – RFQ RF envelope



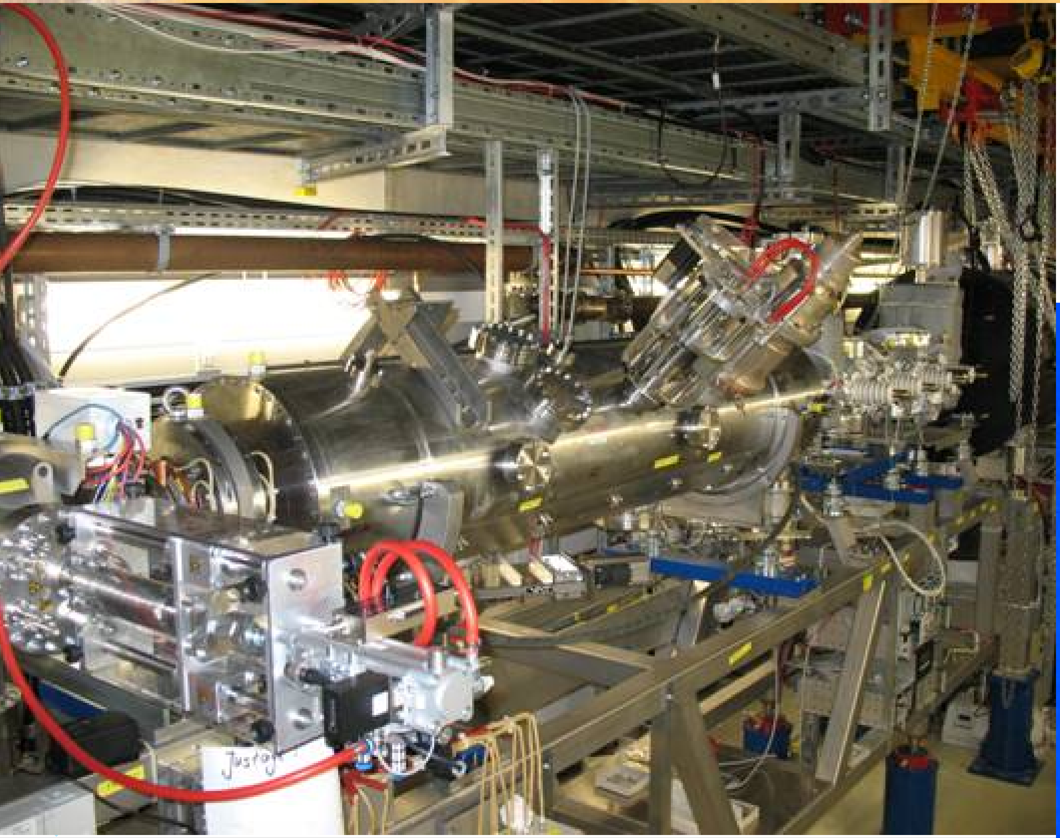
Production of Highly-charged Ions



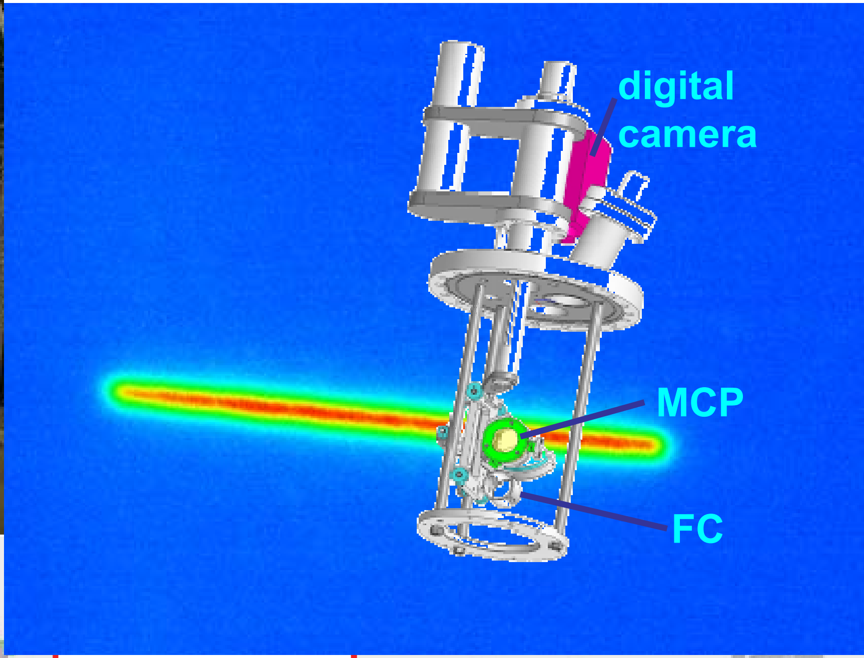
Hitrap operation frequency	**108.408 MHz**
Max. duty cycle	**0.5%**
Mass over charge ratio	**$\leq$ 3**
Pulse length of the ESR	**1.2 μs**
Number of extracted particles	**$6*10^5$ / pulse**
IH-Deceleration gain	**4 MeV/u → 0.5 MeV/u** **(10.5 MV effective voltage)**
RFQ-Deceleration gain	**0.5 MeV/u → 6 keV/u**

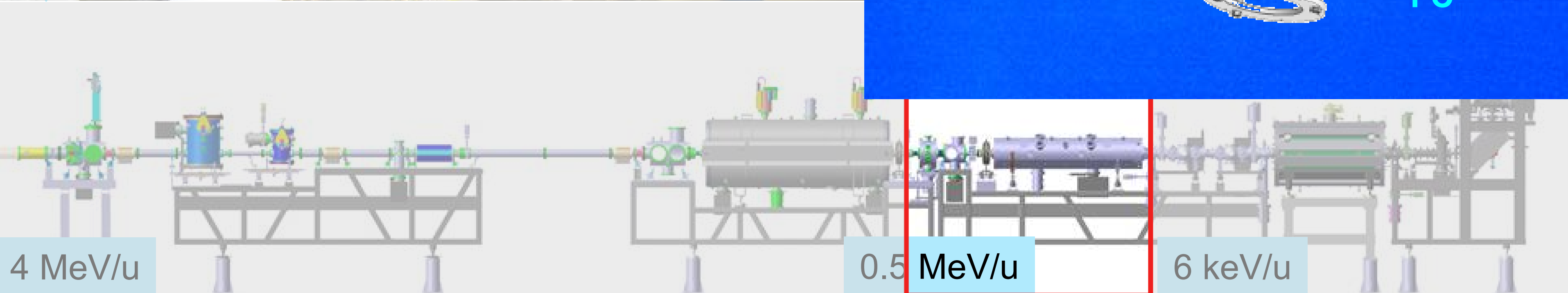
L. Dahl, Workshop HITRAP-ESR-2010, Eisenach 28.06.2010

HITRAP – ReBuncher & RFQ

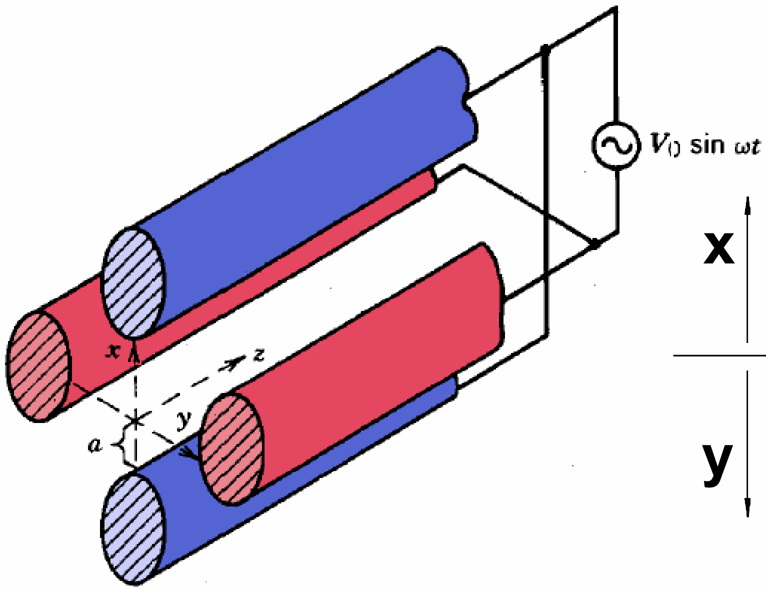


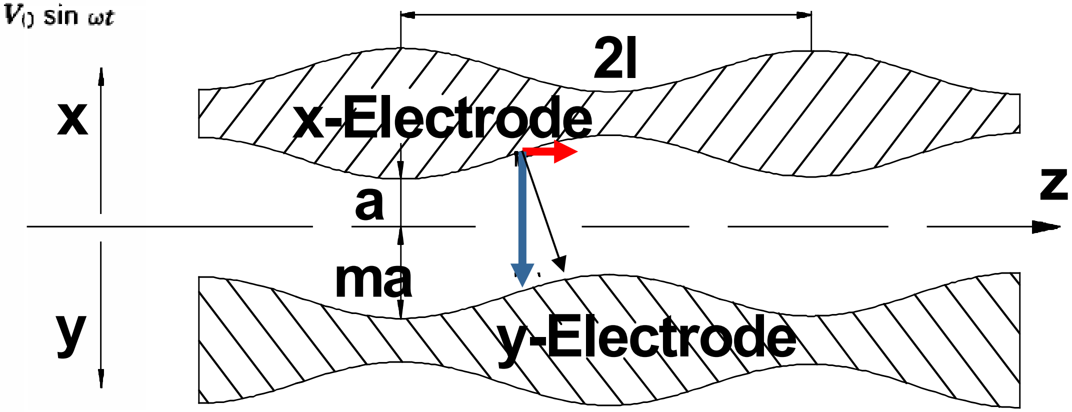
- deceleration from 0.5 MeV/u to 6 keV/u
- Installed, first beam through

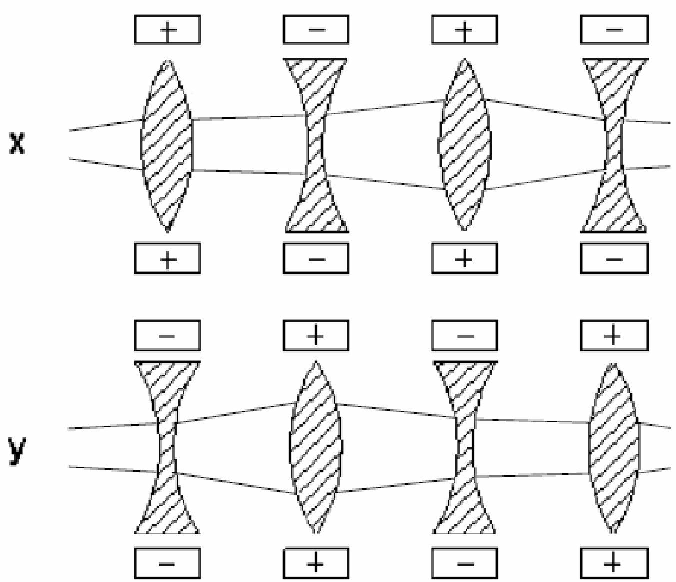


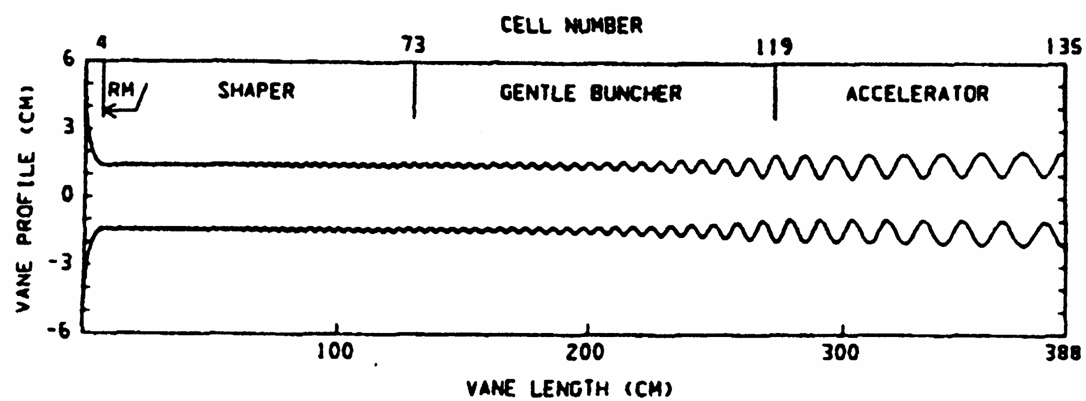


Radio Frequency Quadrupole

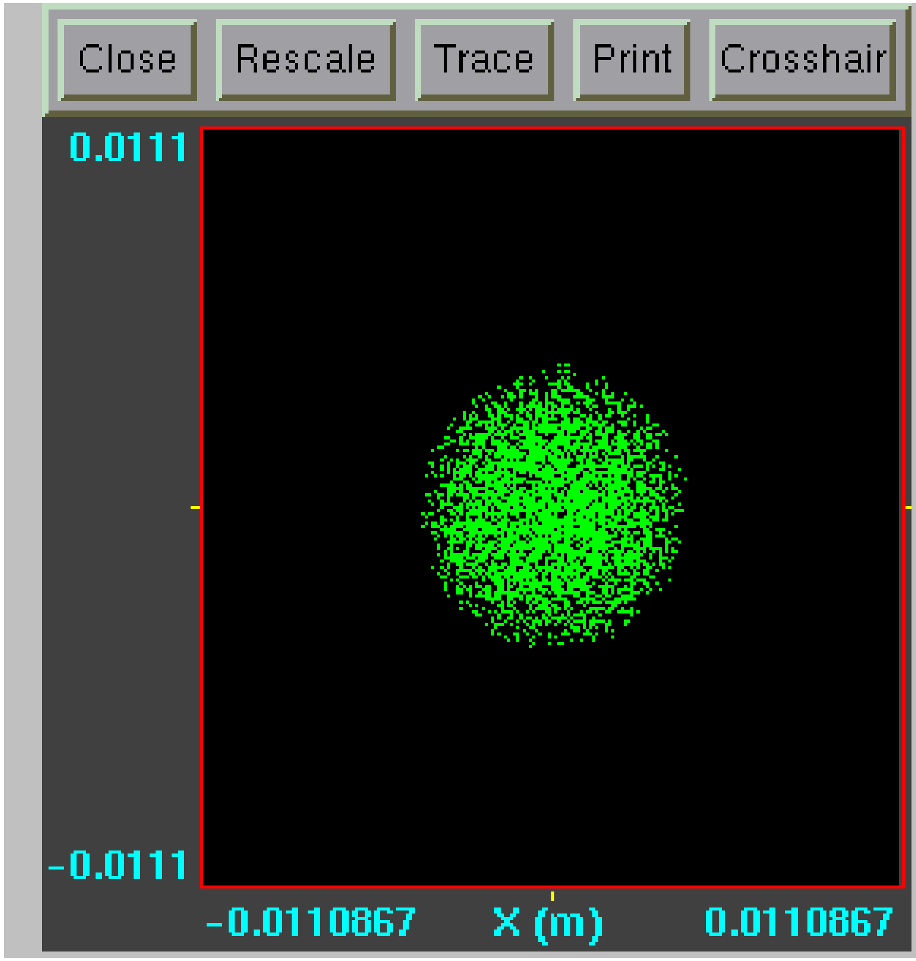


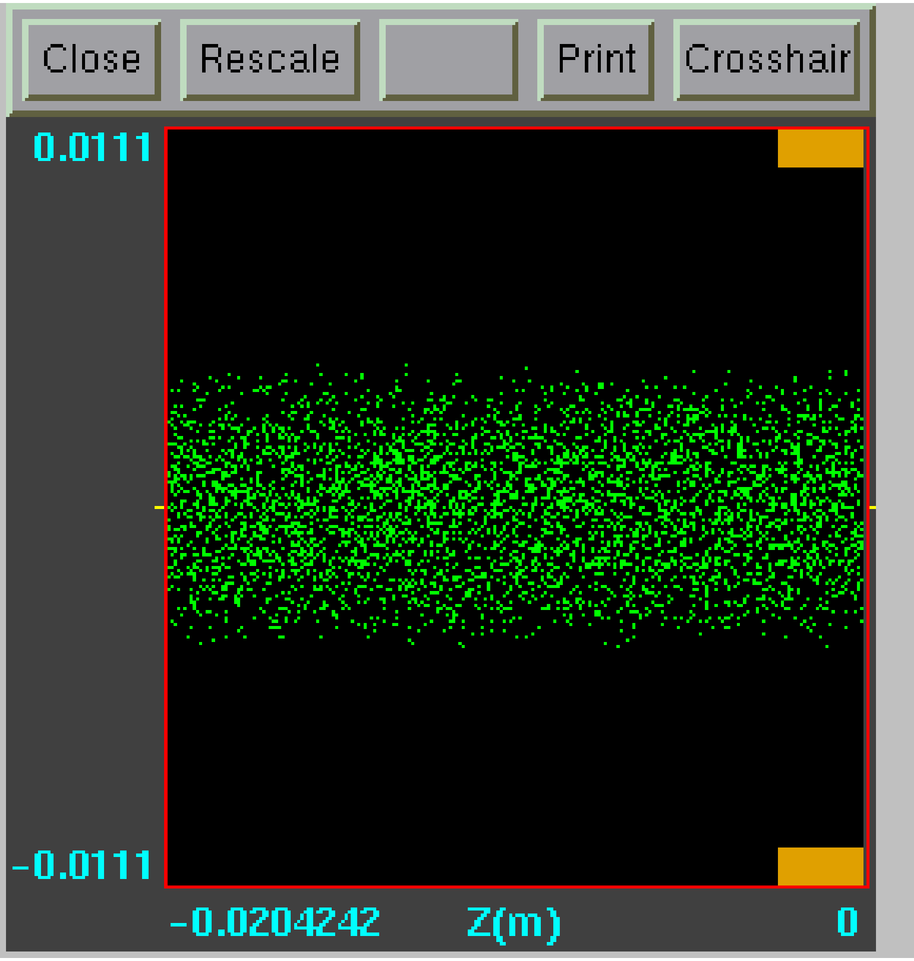






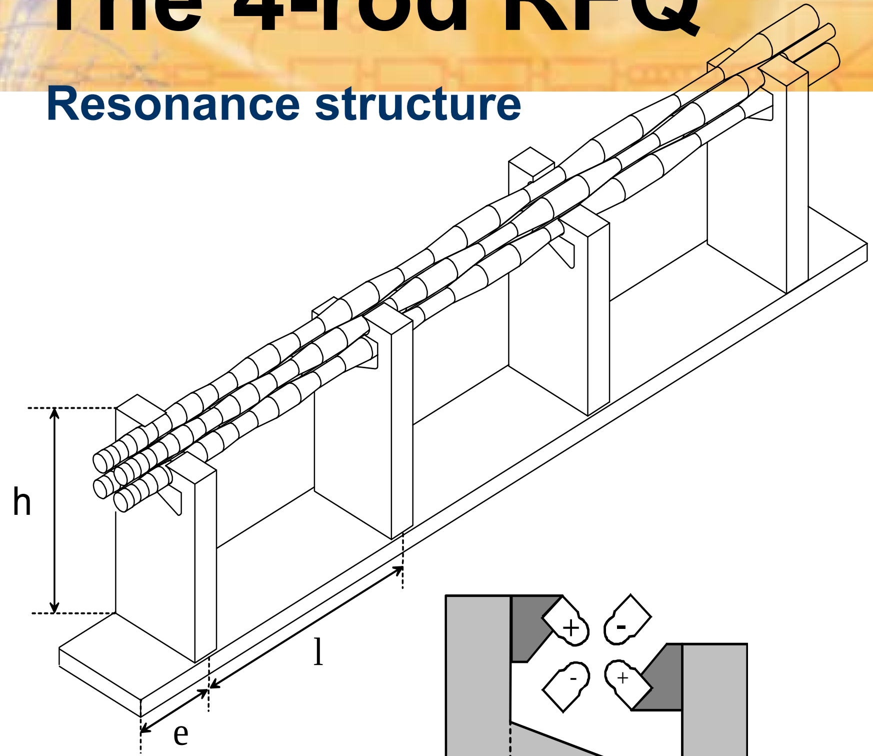
RFQ beam gymnastics

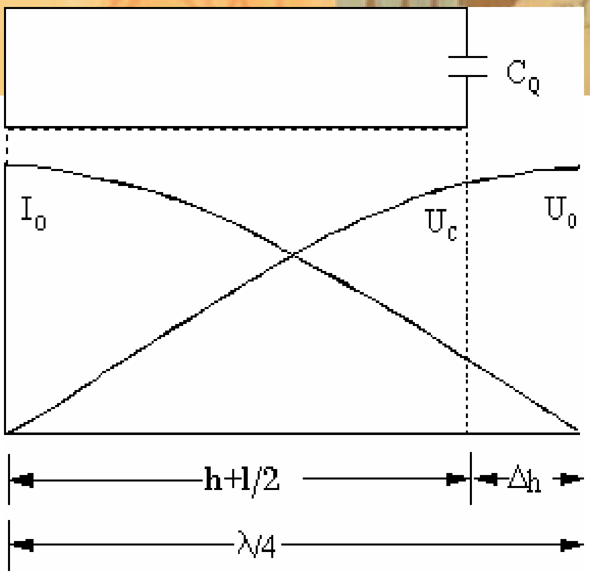


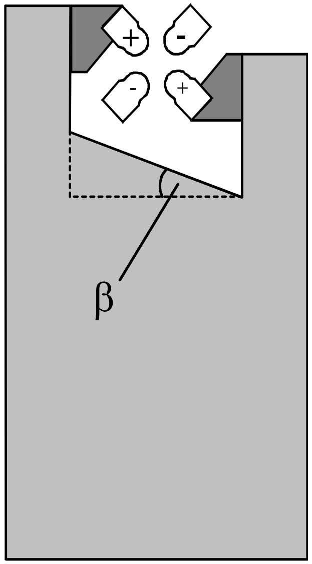


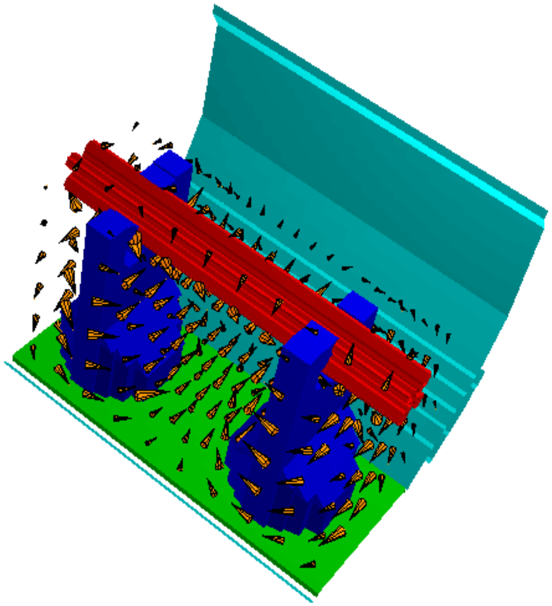
The 4-rod RFQ

Resonance structure

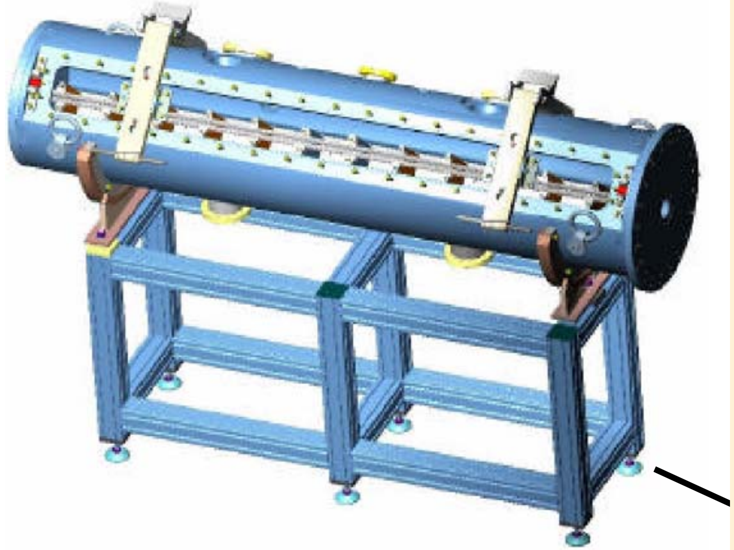




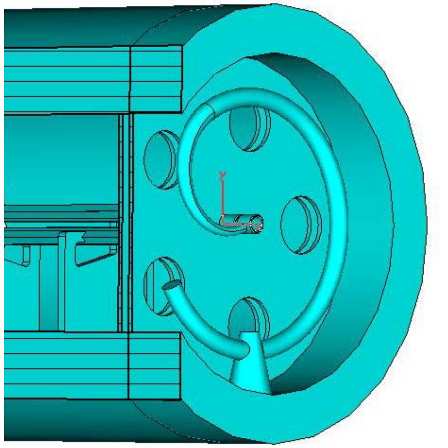


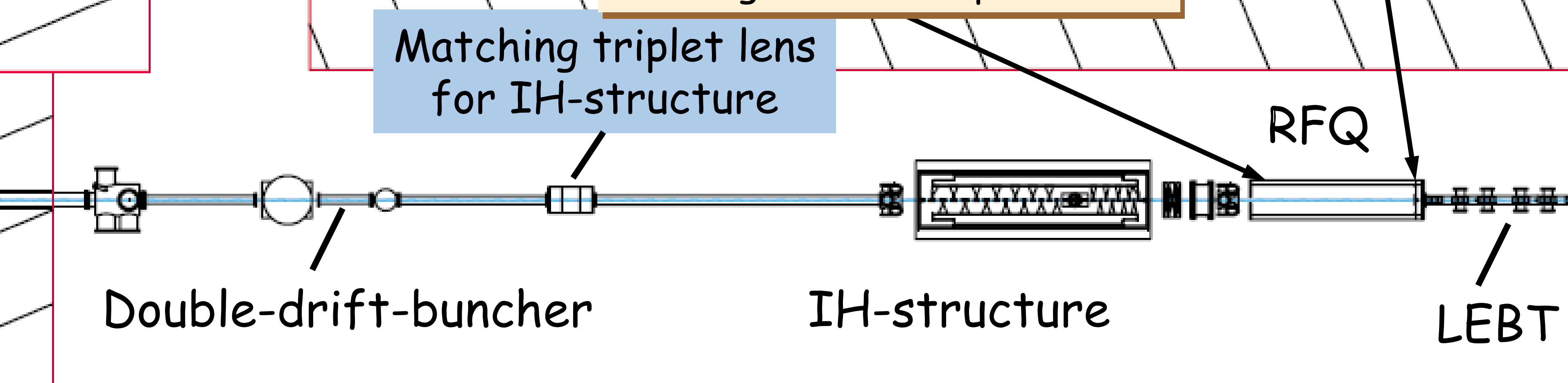


HITRAP decelerator cavities

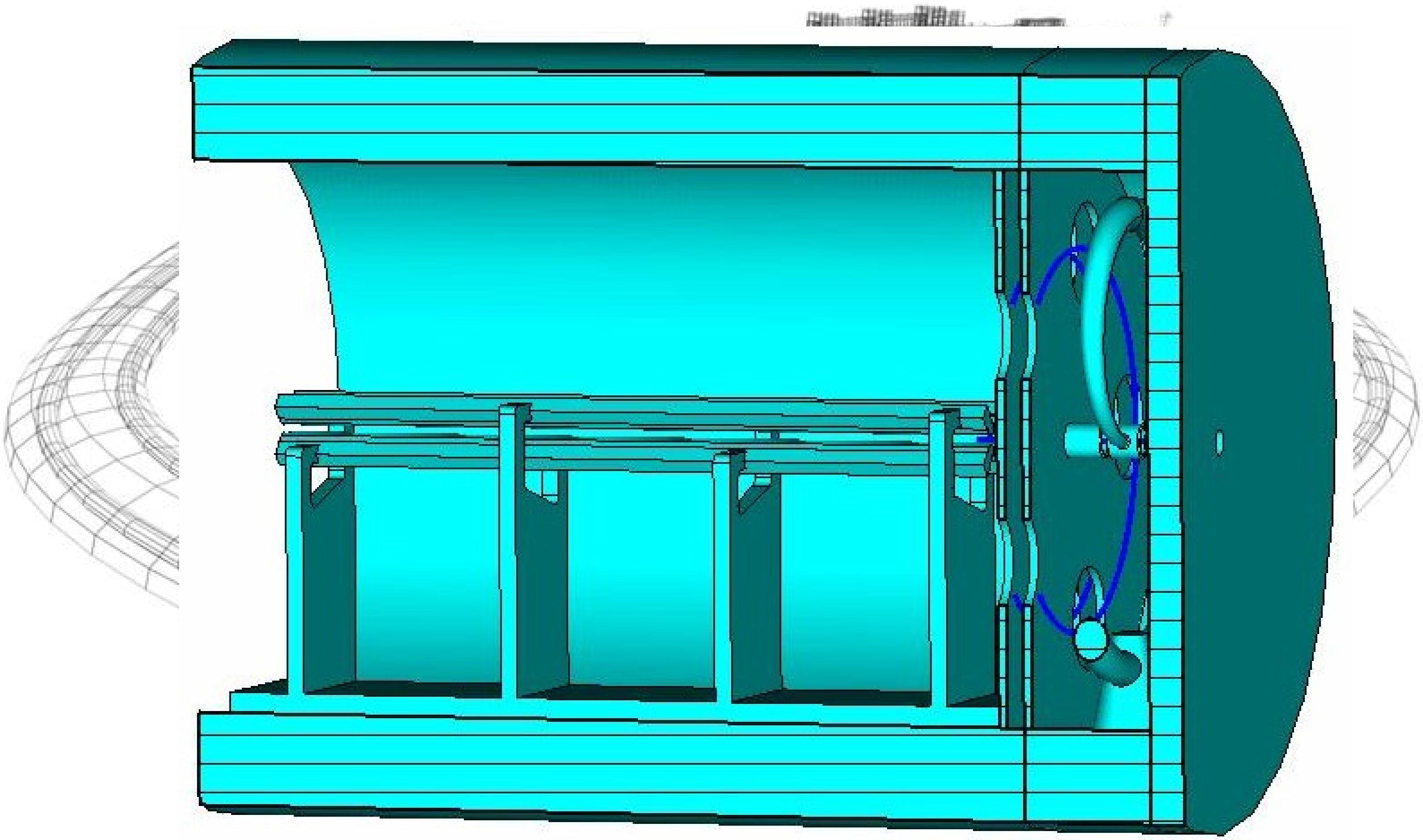


- Beam dynamics calculations have been carried out
- Cavity design with MWS of RFQ an de-buncher has been performed
- RFQ-tank is already manufactured
- De-buncher cavity is being built at IAP Frankfurt
- Both cavities are fed by an existing 180 kW amplifier



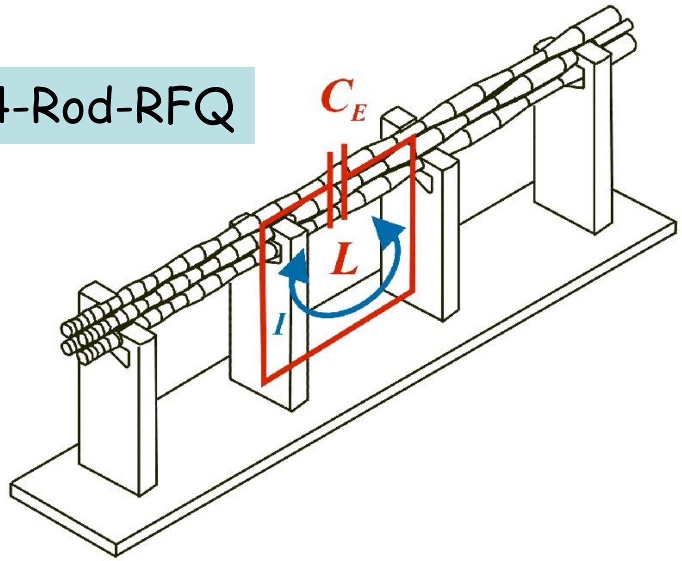


RFQ – Decelerator with integrated Debuncher

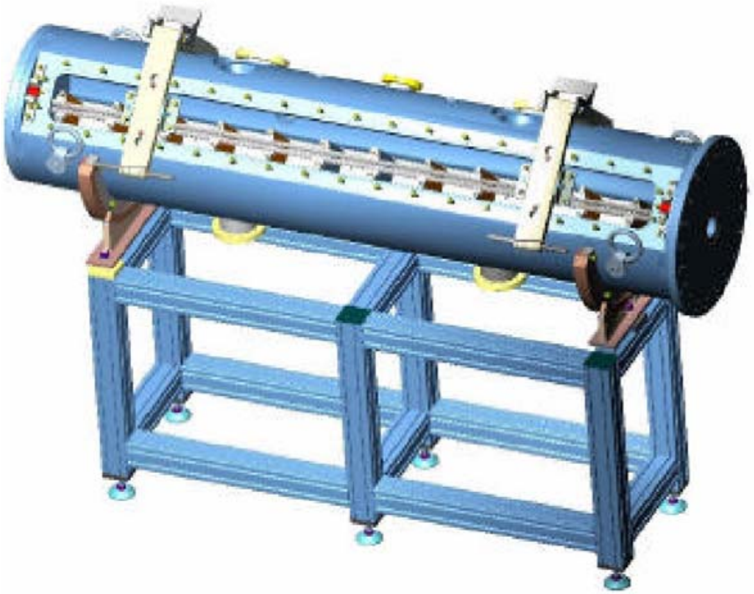


Radio Frequency Quadrupol (RFQ)

4-Rod-RFQ



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



- Rod design completed
- beam dynamics calculations of de-buncher is completed
- tank is delivered

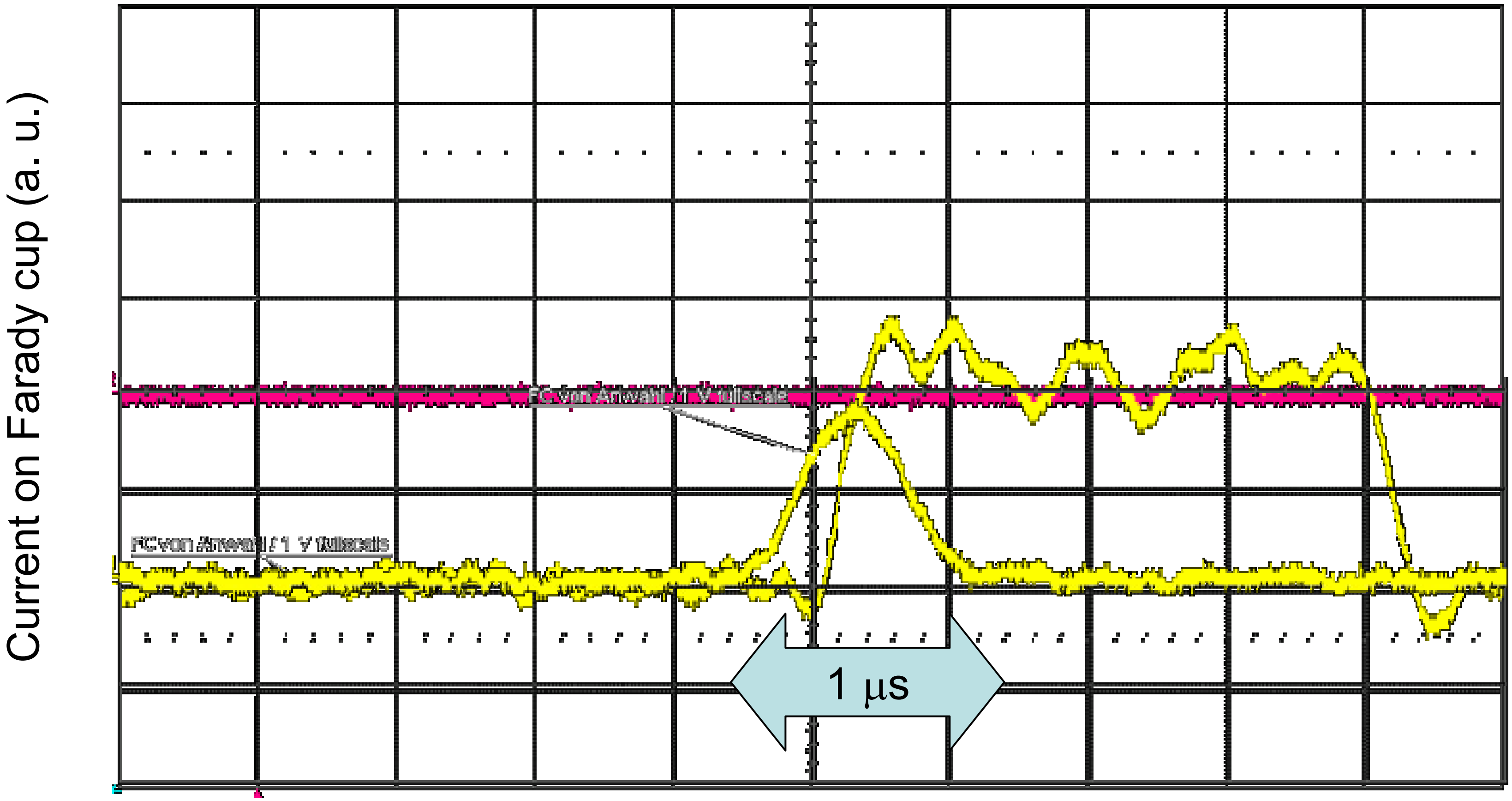
Parameters of the Cavities

DDB	4-gap-Buncher	2-gap-Buncher
f_0	108.4 MHz	216.8 MHz
V_0	250 kV	65 kV
Q_0	13,700	6,700
Z_{eff}	120 MV/m	36.2 MV/m
P_{rf}	1.52 kW	1.33 kW

	IH
f_0	108.4 MHz
Q_0	25,750
Z_{eff}	285.084 MV/m
E_{eff}	1,3 A/q * MV/m
length	2.64 m
P_{rf}	174 kW
V_{rod}	75 kV
gaps	25

	RFQ
f_0	108.4 MHz
r_0	4 mm
length	1.9 m
cells	143
Z_{eff}	120 kV/m
V_{rod}	75 kV

ESR – Rebunching at 4 MeV/u



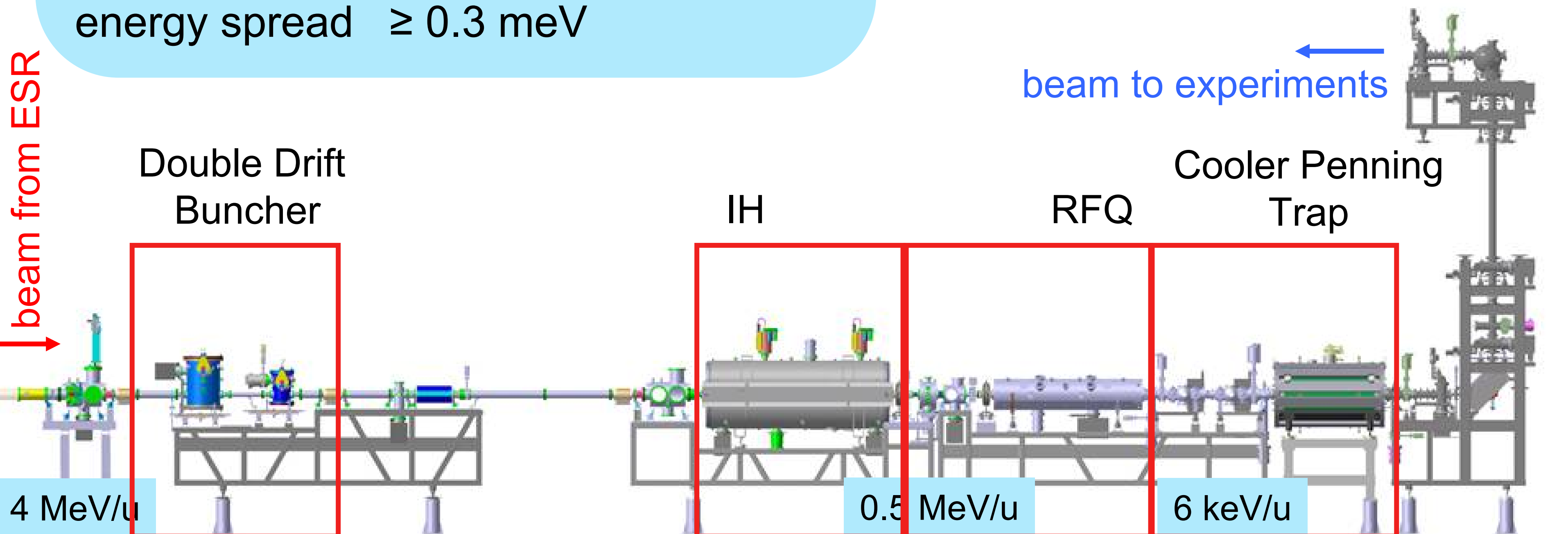
HITRAP – Linear Decelerator

Beam that will be available to users:

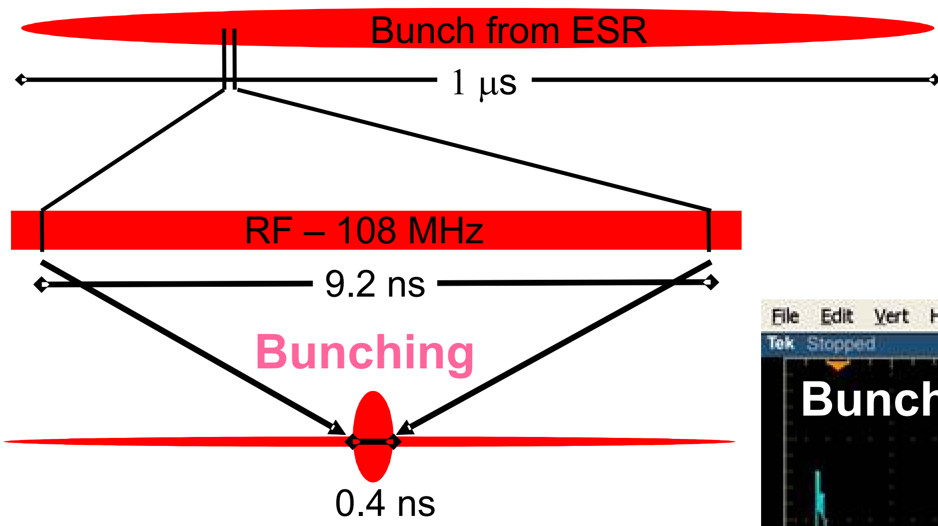
type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

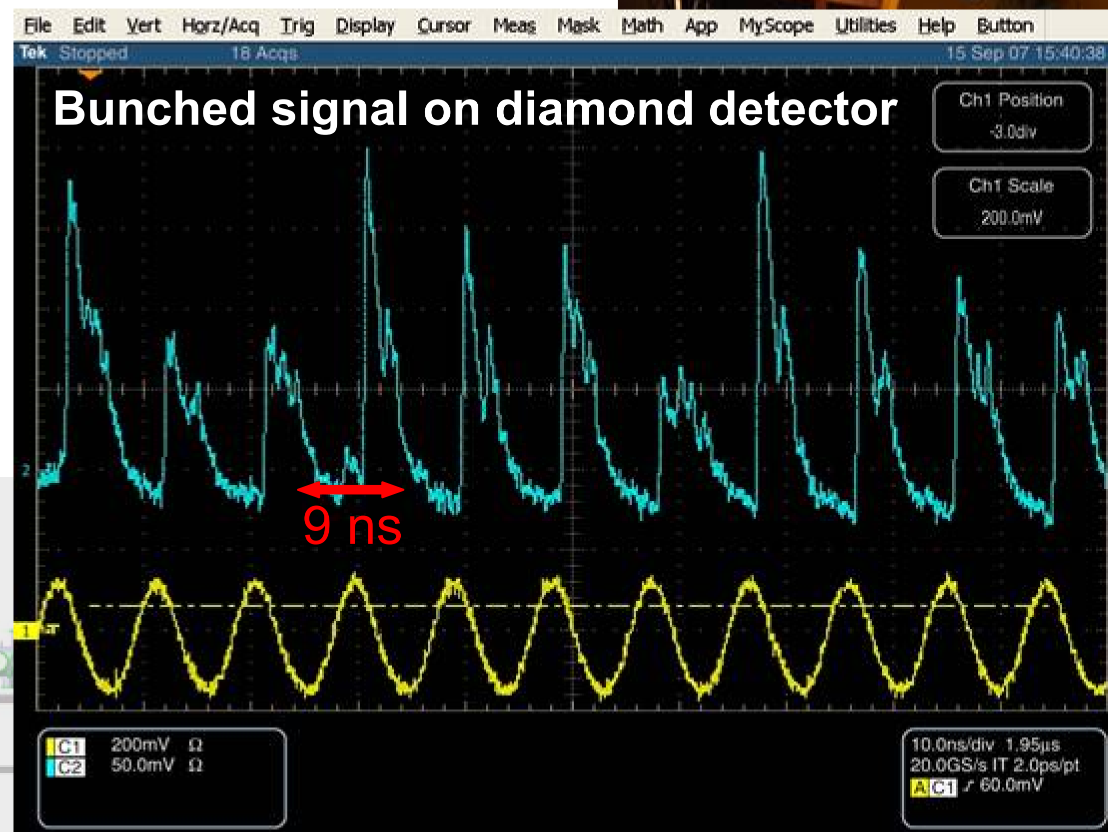
Instrumentation for beam diagnostics

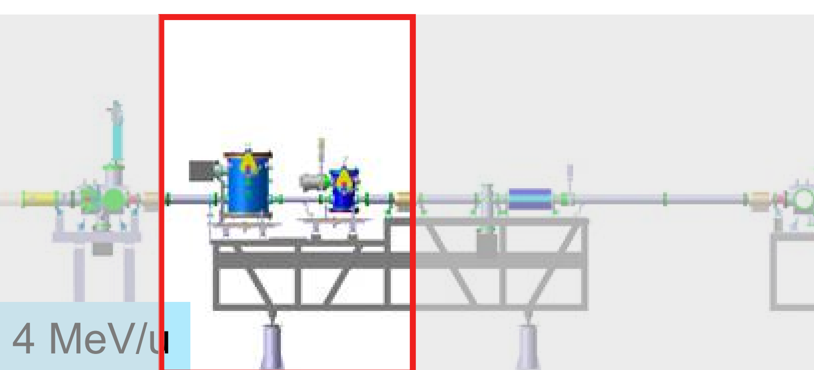
- Scintillation screens based on YAG single crystals
- Capacitive phase probes
- Wire grids
- Faraday cups
- **Diamond detector** for energy and position



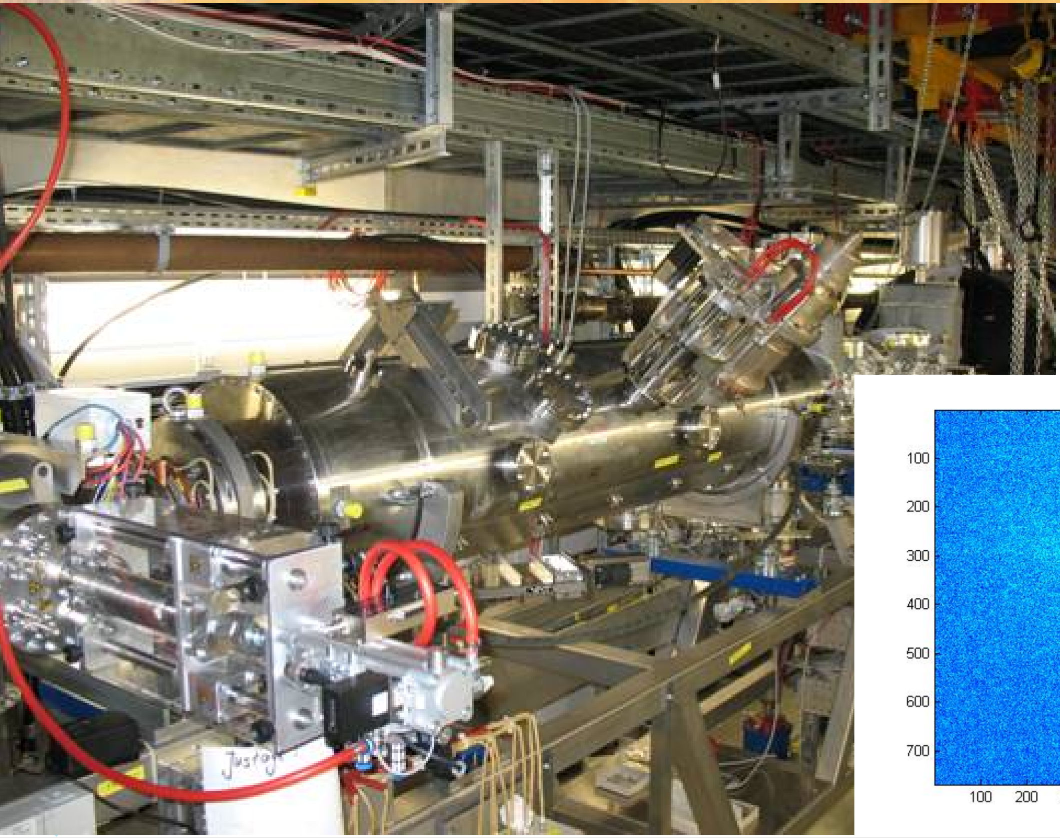
HITRAP – Double Drift Buncher



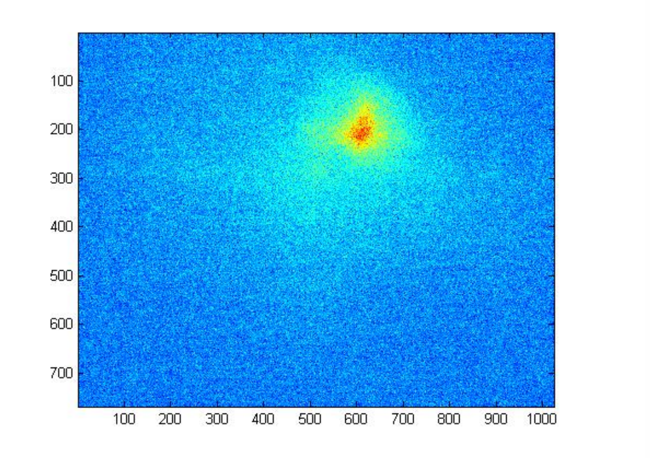


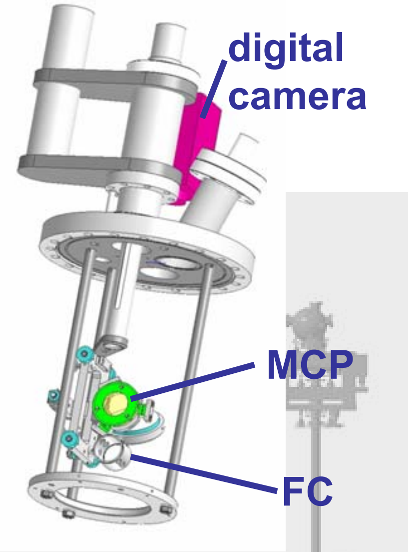


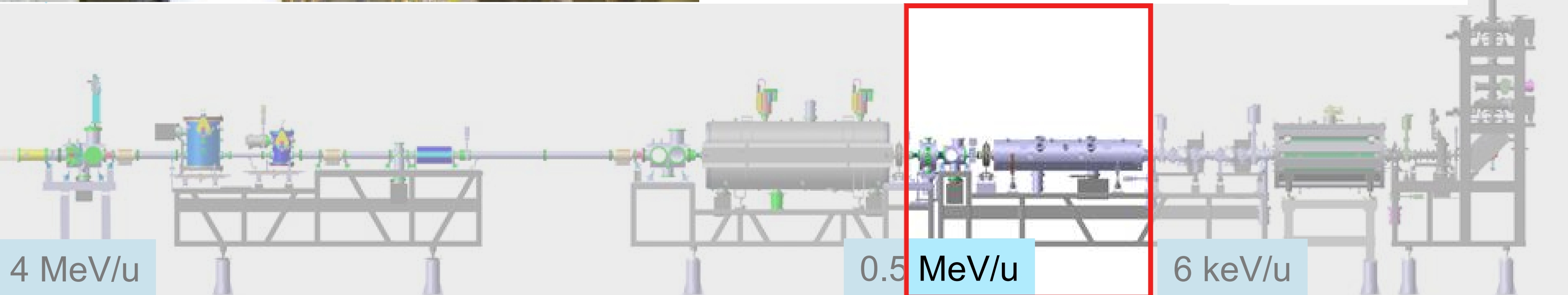
HITRAP – ReBuncher & RFQ



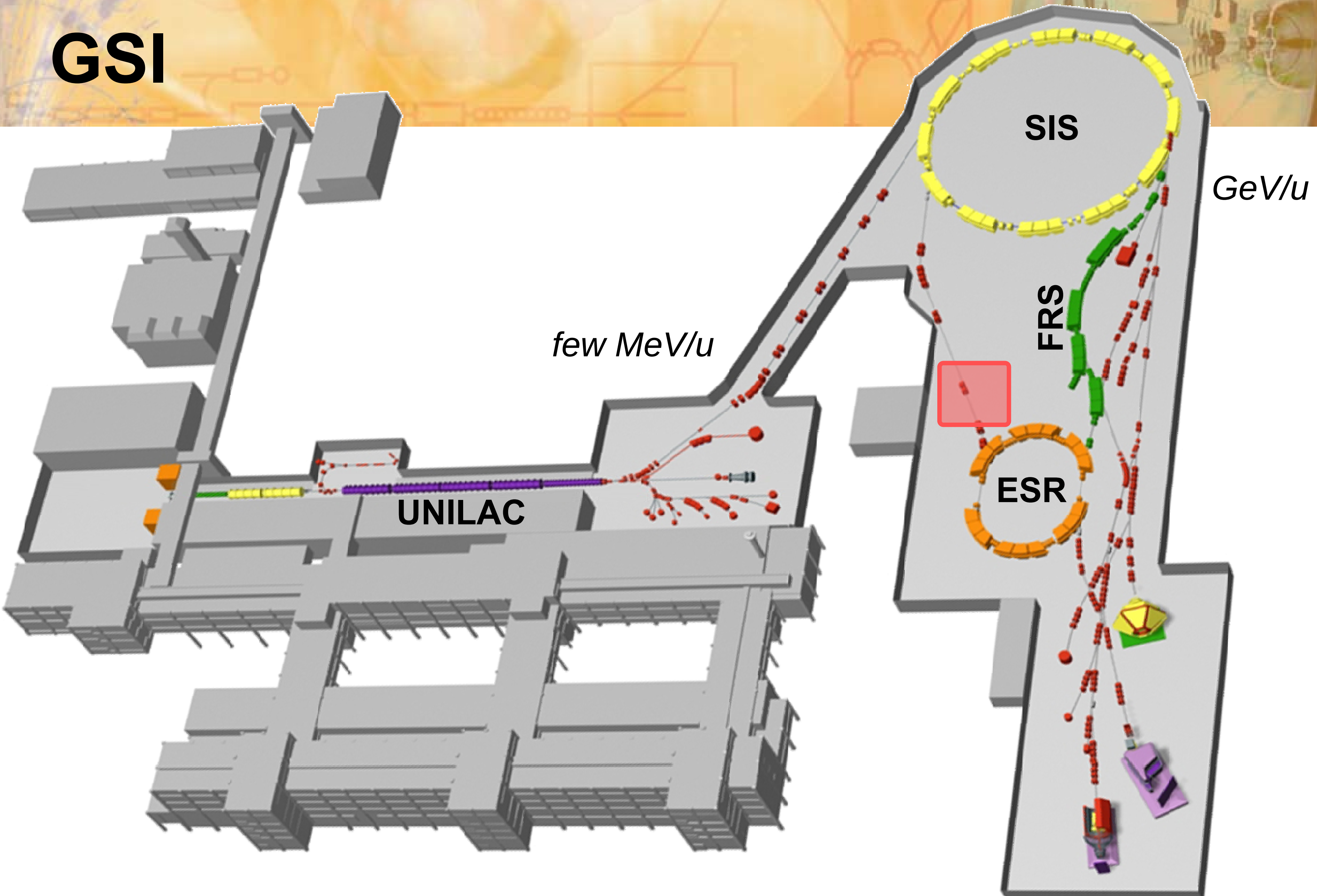
- deceleration from 0.5 MeV/u to 6 keV/u
- installed



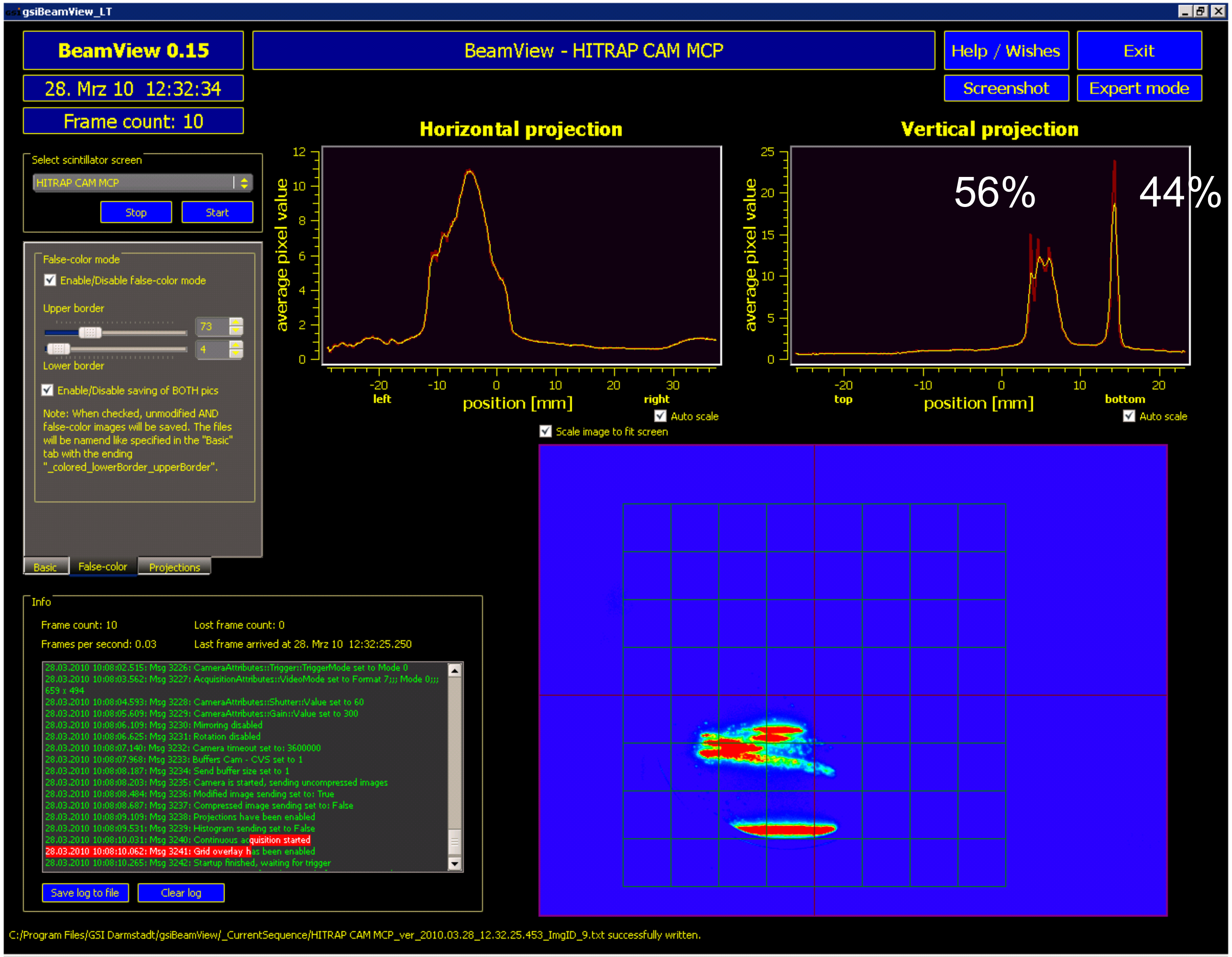




GSI

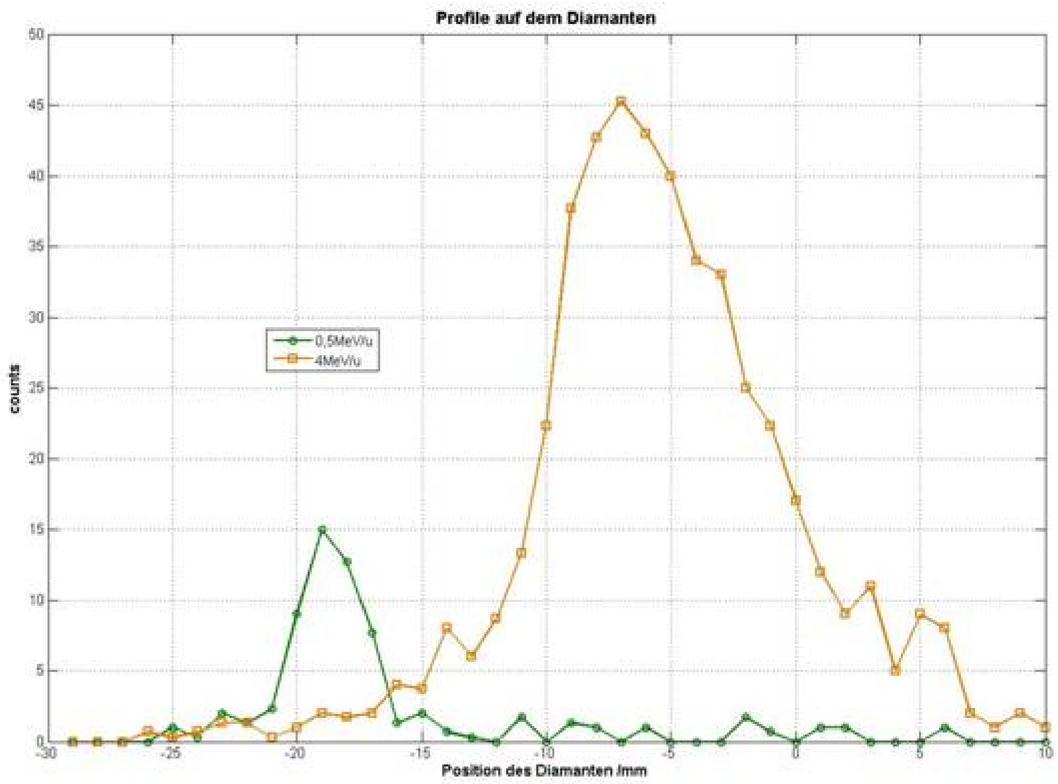


Best Spectrum 2010



Remember 2009

beam profile separation of 0.5 and 4 MeV/u beam on diamond



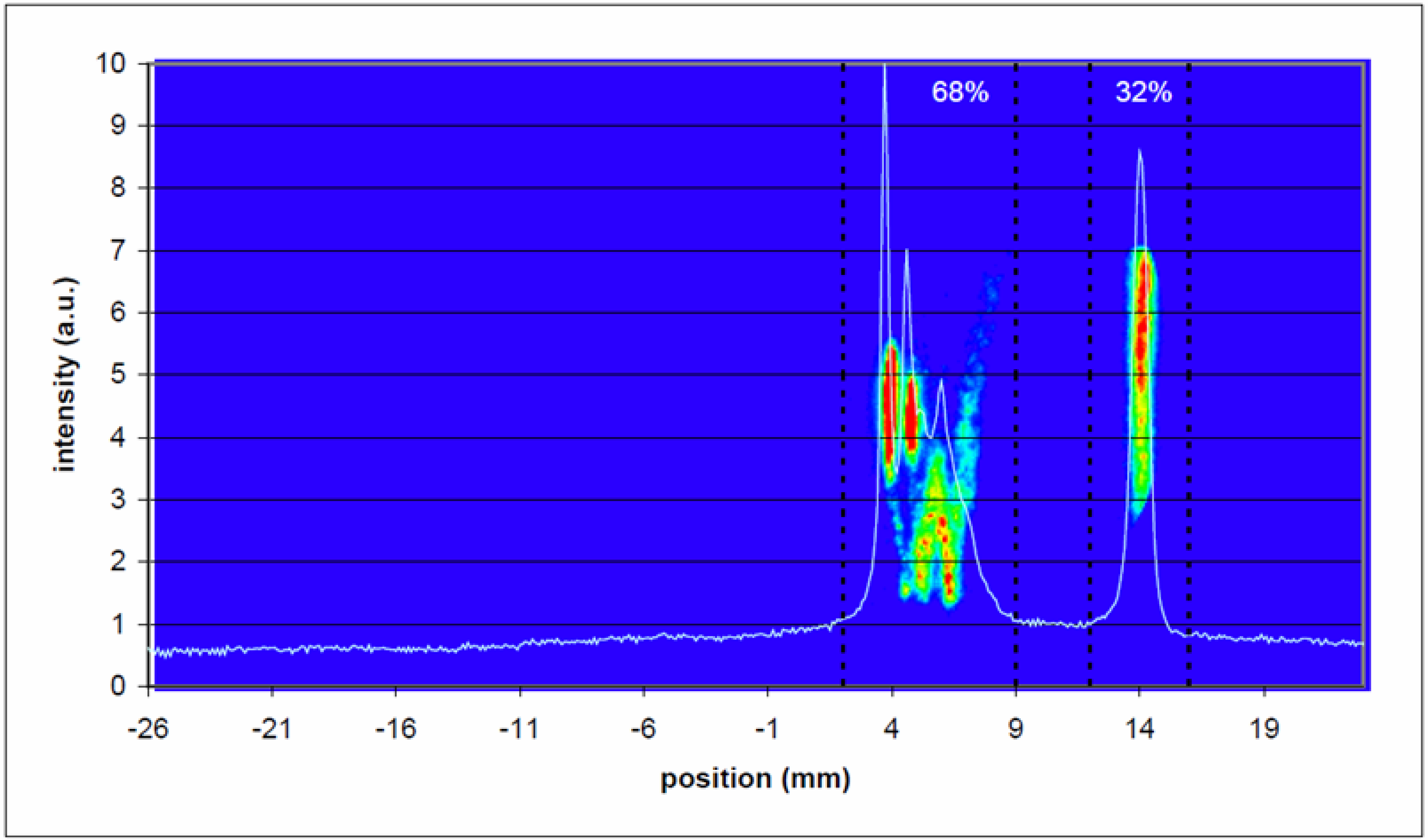
ratio between decelerated and non-decelerated ions

1:7.22

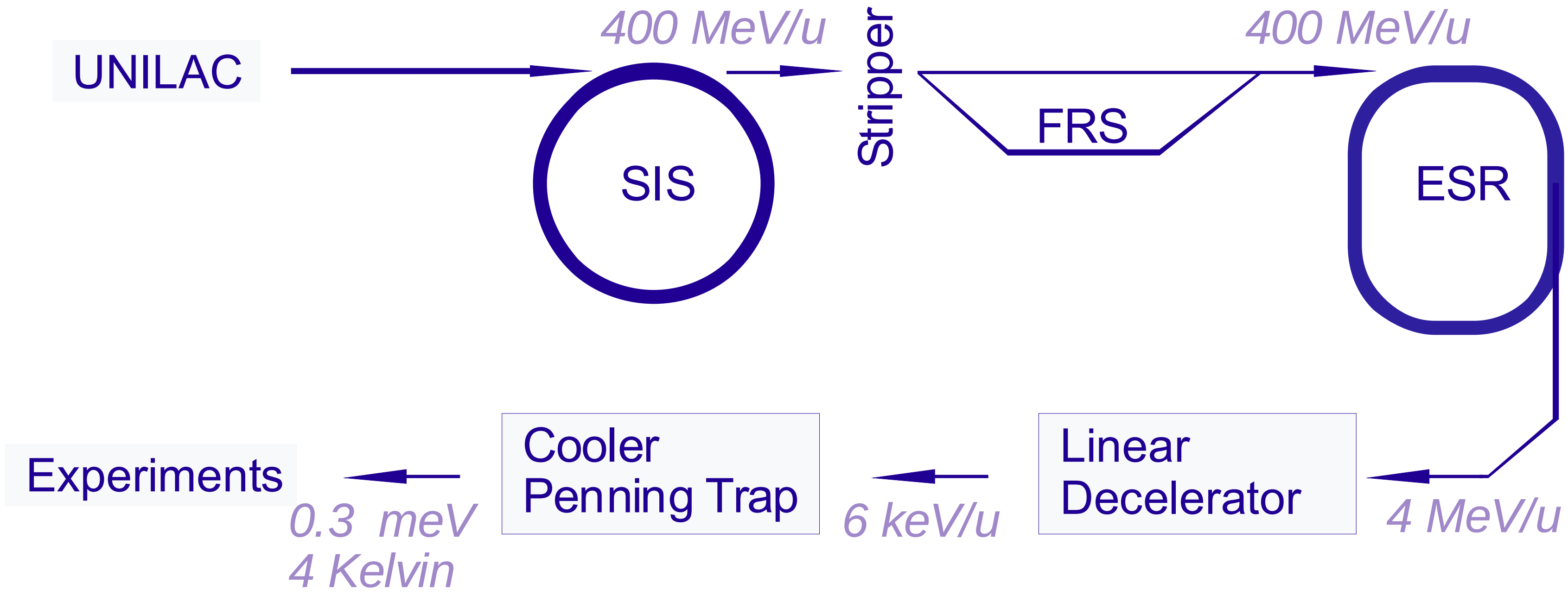
=

12% of ions @ 500keV/u (seen 1-dimensional)

Energy Measurement by MCP in 2010



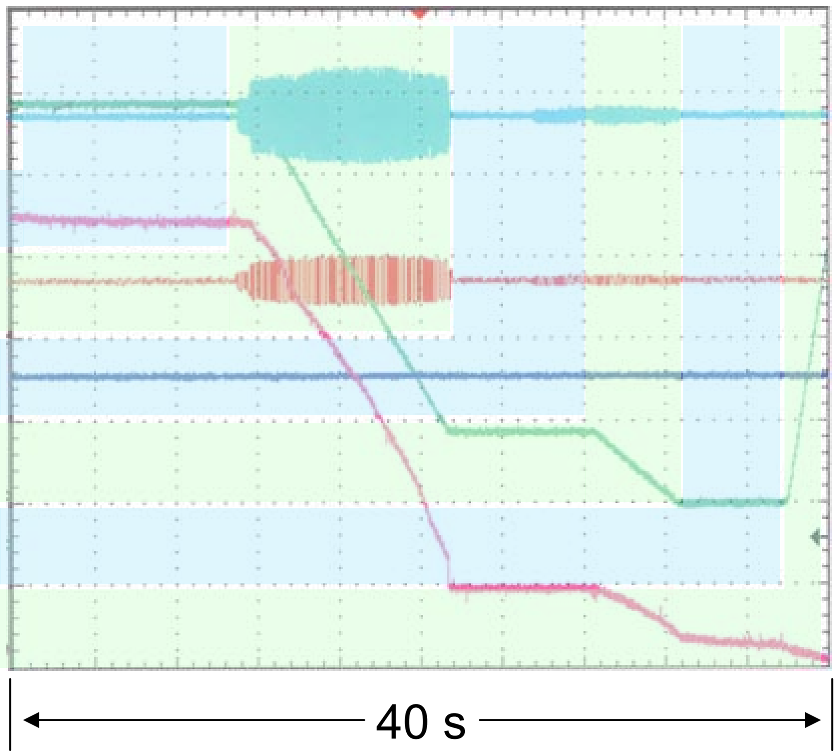
HITRAP



- g-factor of the bound electron
- hyperfine spectroscopy with laser light
- collision studies HCI – atoms
- high-precision mass measurements
- HCI - surface interactions
- hollow atom spectroscopy

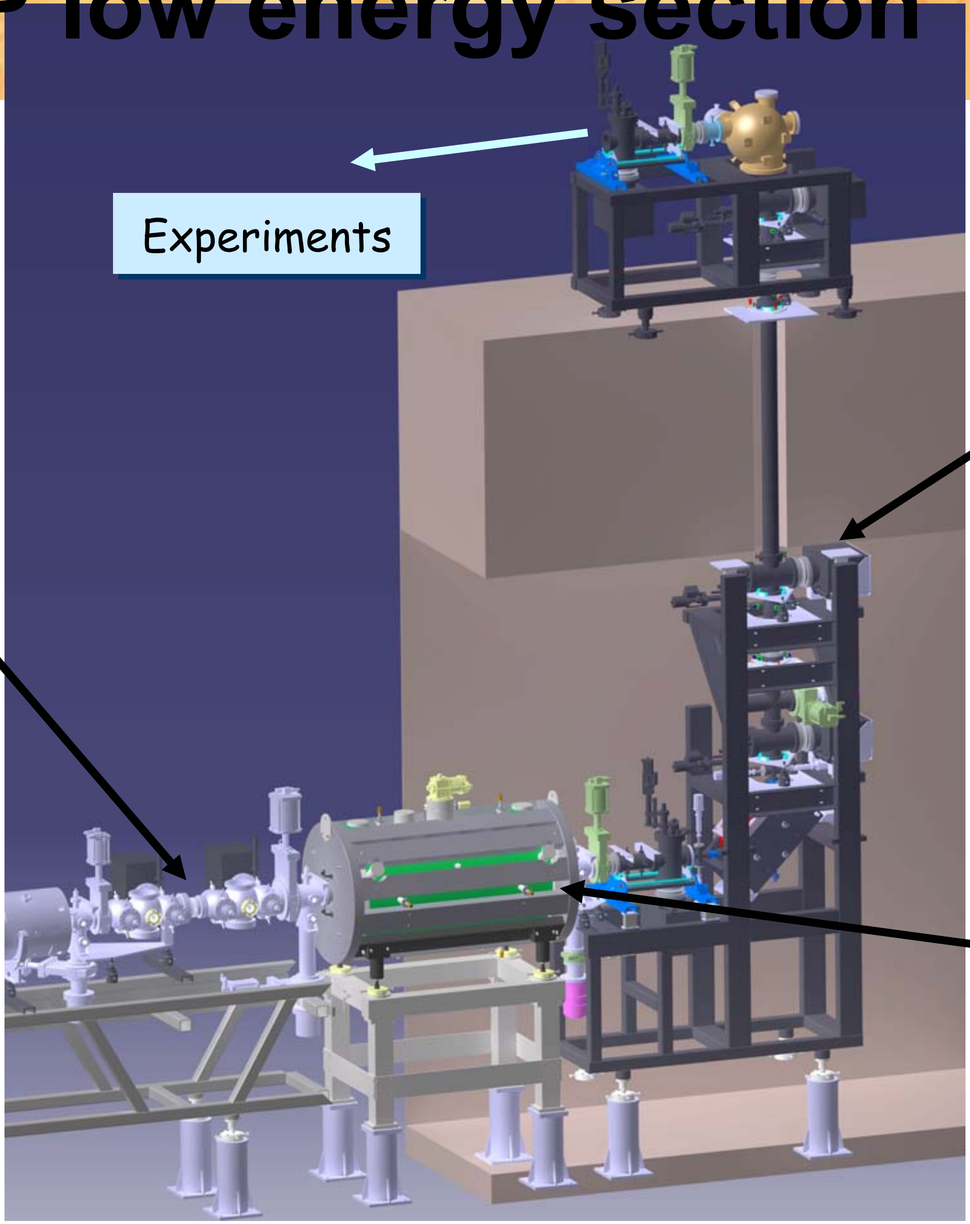
ESR – From 400 to 4 MeV/u

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

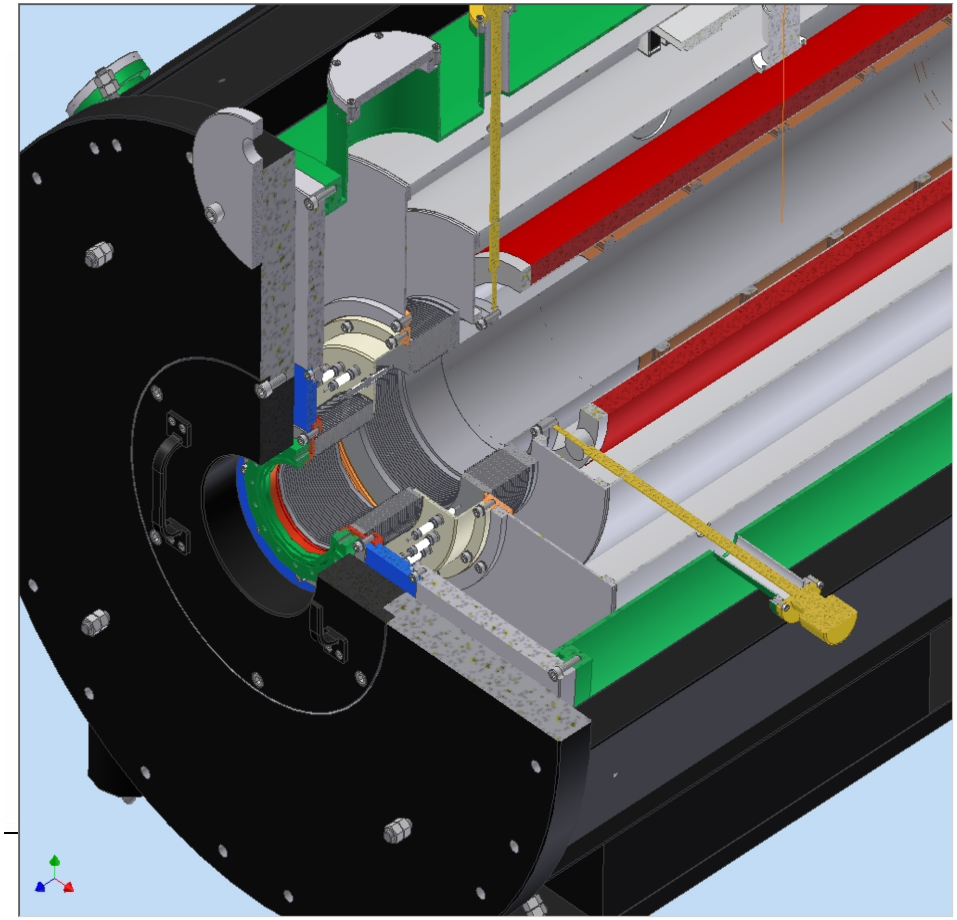


- stochastic cooling at injection energy implemented
- electron current for final cooling at 4 MeV/u increased

HITRAP low energy section

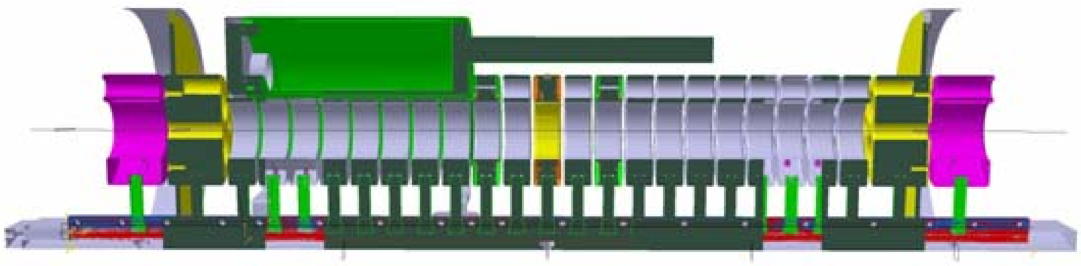


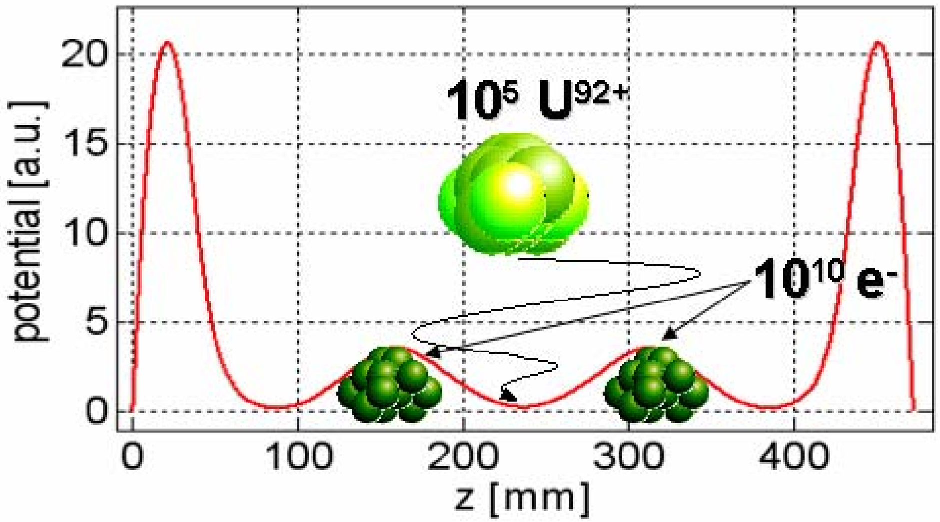
The HITRAP cooler trap magnet



- SC magnet, B = 6 T
- Inner structure kept on 4 K

The HITRAP cooler trap





21+4 electrodes
potential shaping =>
nested traps for 10^5 ions,
10^{10} e^-

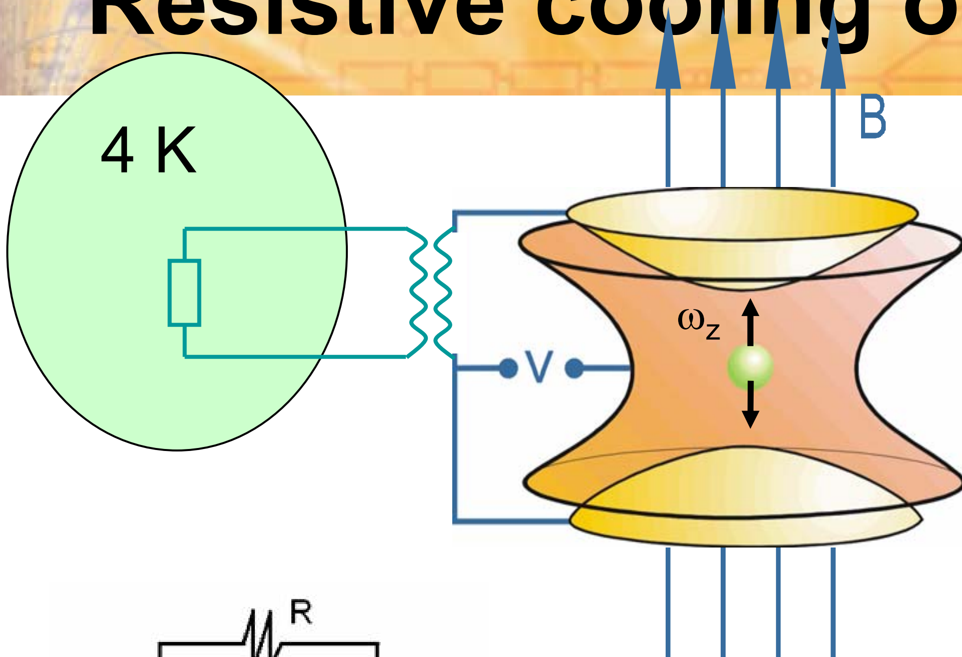
e- cooling to 10 eV
resistive cooling to 4 K

thermal contact with the cold magnet environment
vacuum better than 10^{-13} mbar

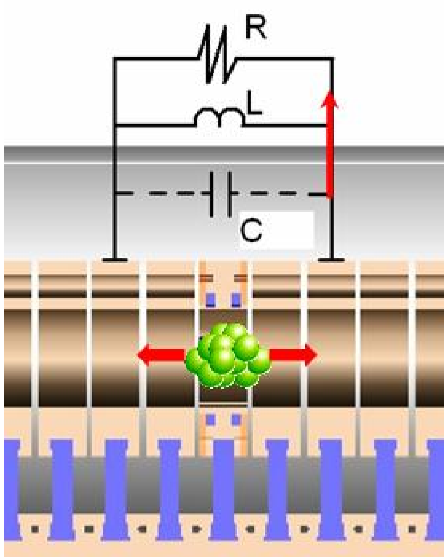
Questions

- space charge and frequency shifts
- cooling times
- survival probability

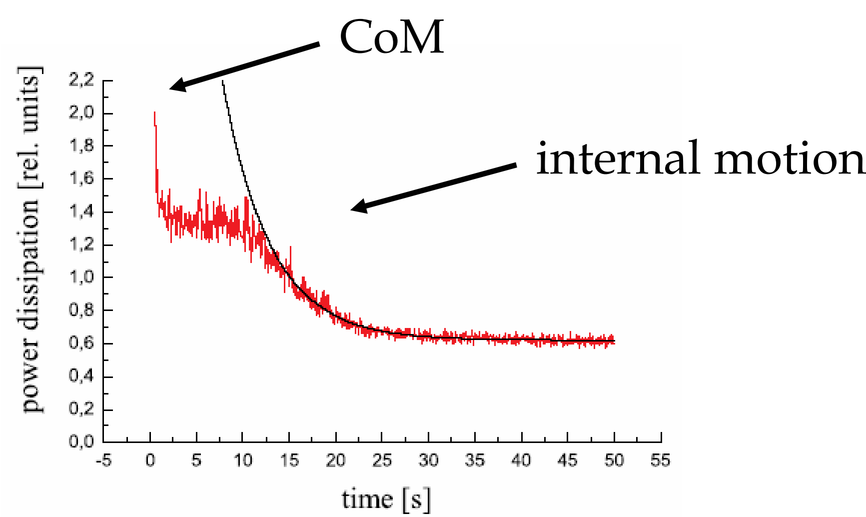
Resistive cooling of an ion cloud



cooling of Center of Mass!
"invisible" internal modes

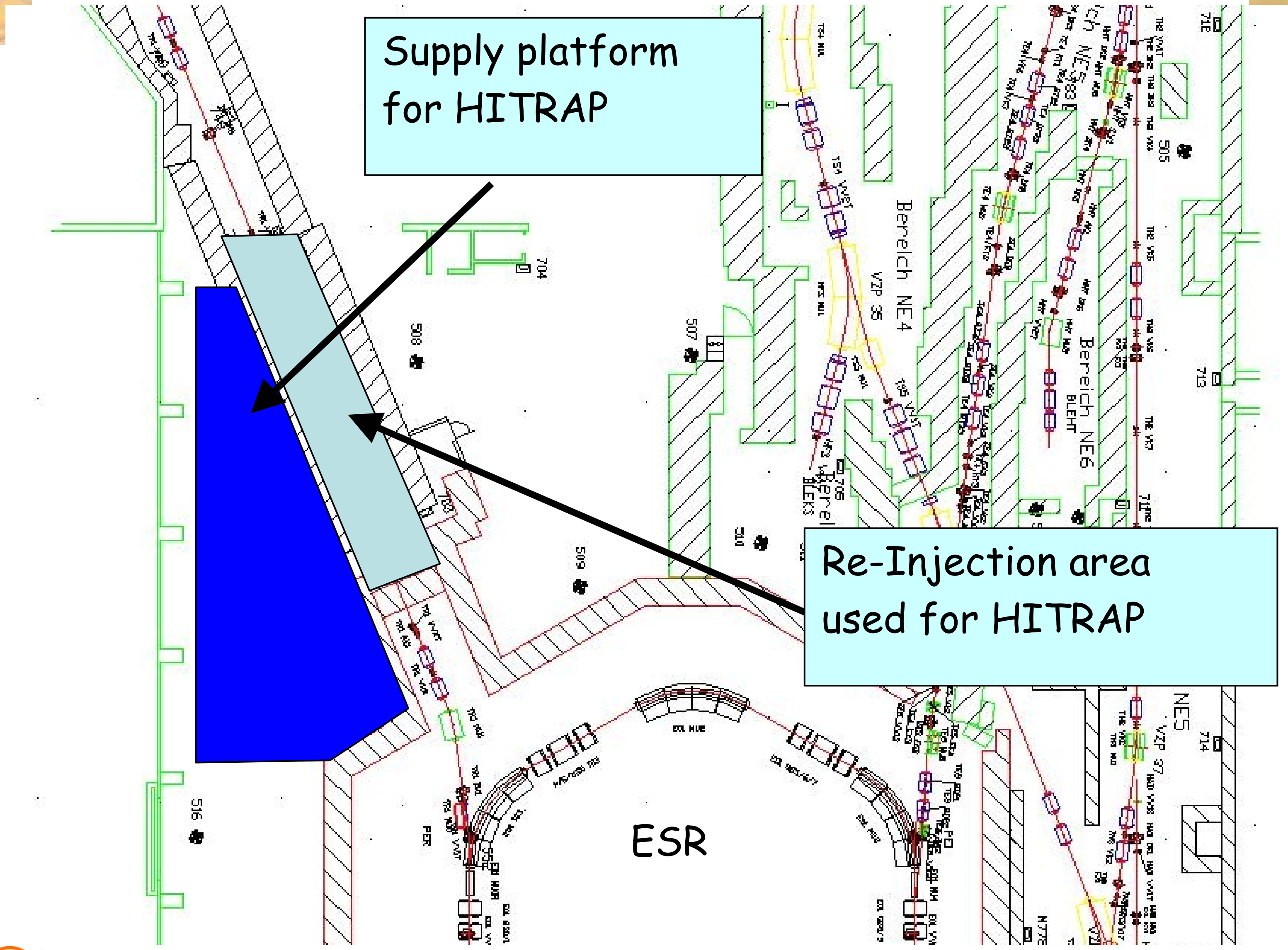


Cooling of the axial motion of an ion cloud (30 $^{12}C^{5+}$)*

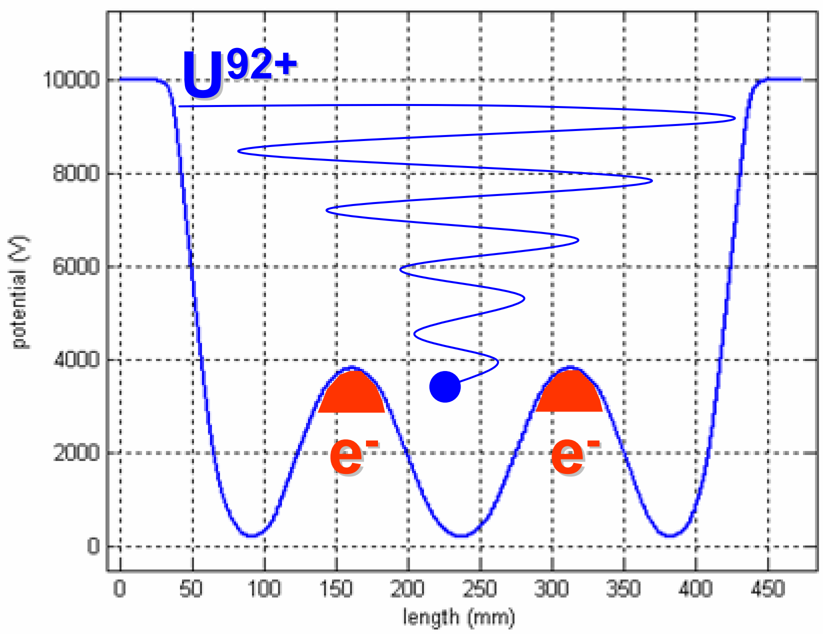


* = ***H. Häffner et al.,*** *Eur. Phys. J. D* ***22****, 163 (2003)*

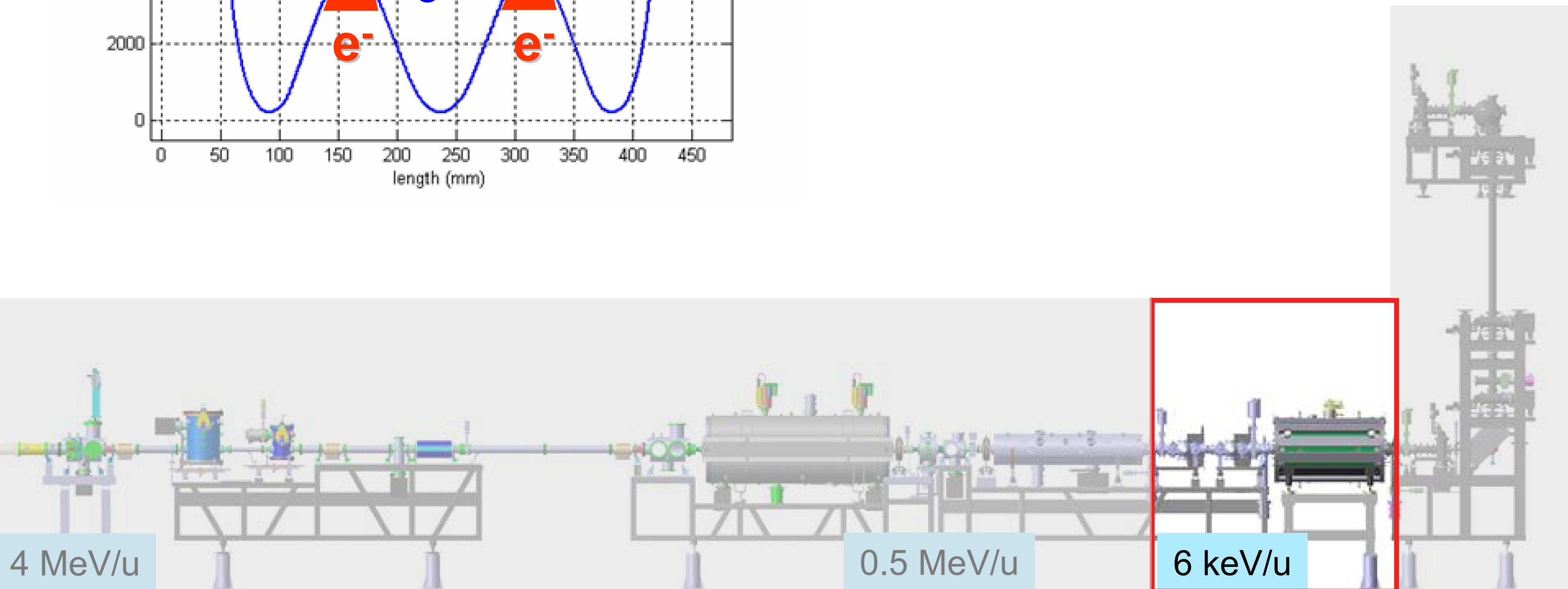
HITRAP in the re-injection channel



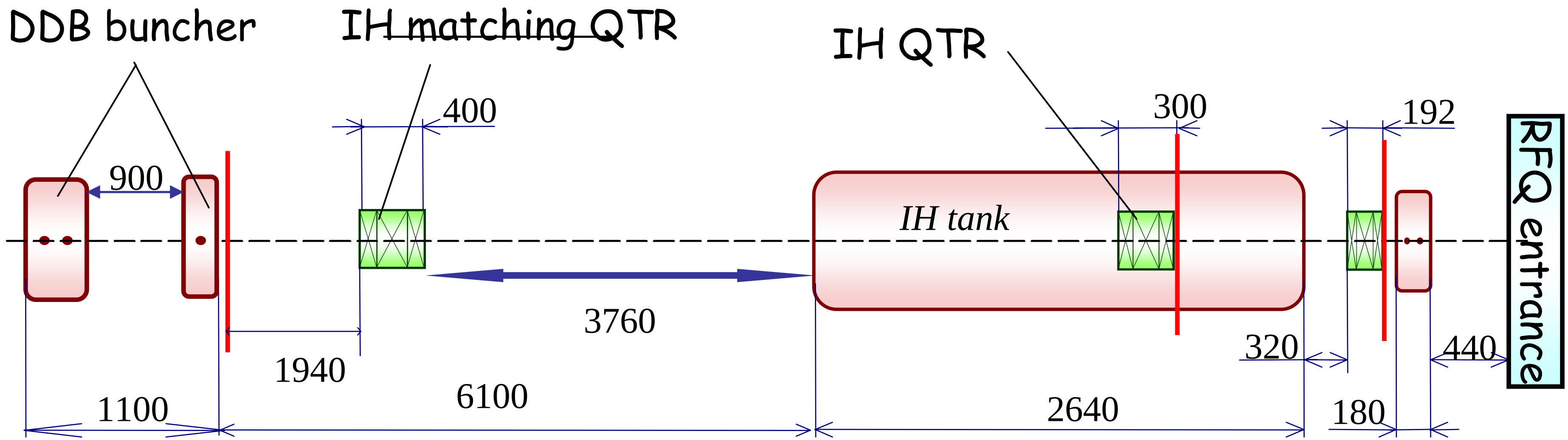
HITRAP – LEBT & Cooler Trap

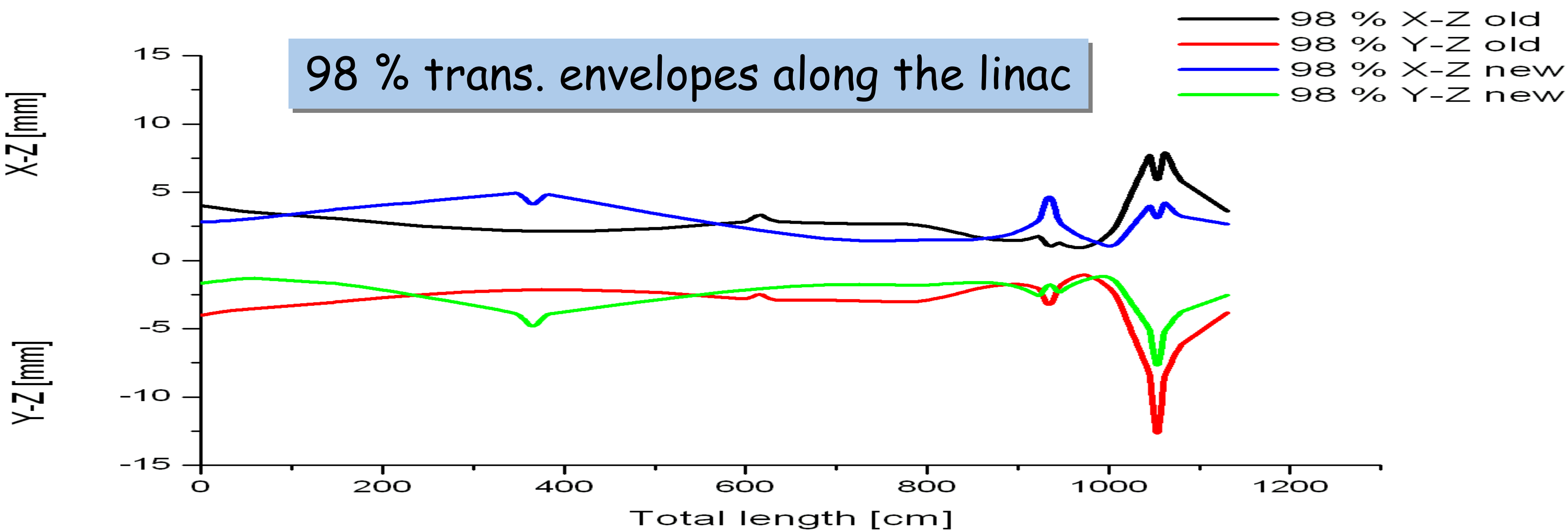


- catch the ions in flight
- cool them with combined electron and resistive cooling to ~ 4 Kelvin

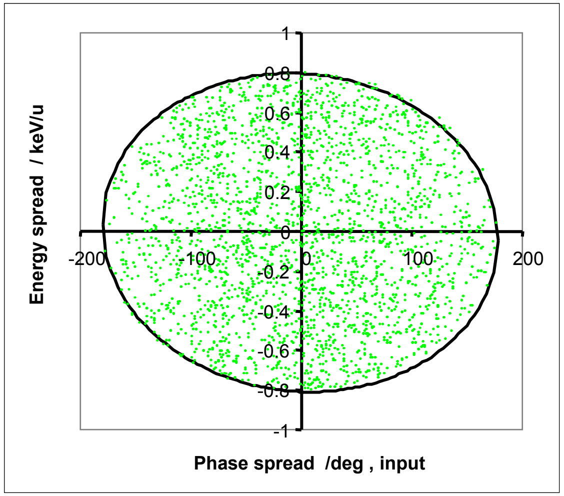


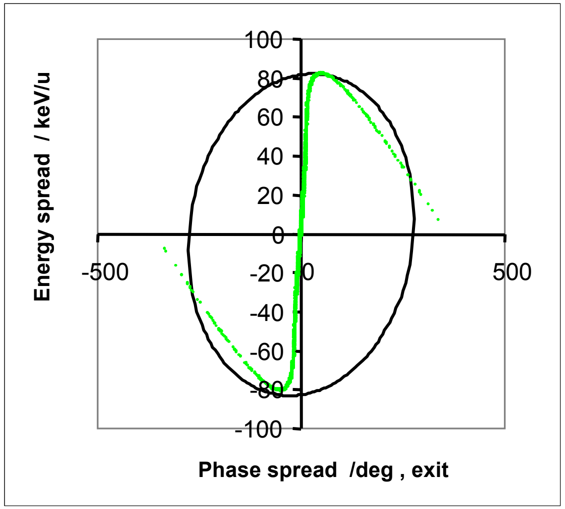
Beam dynamics: DDB to the RFQ





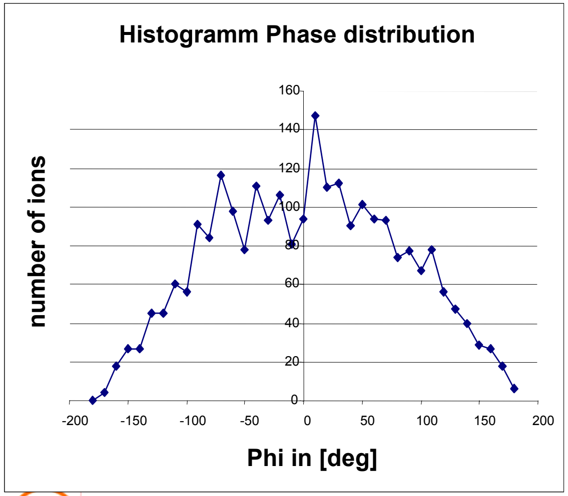
Bunching of the ESR beam

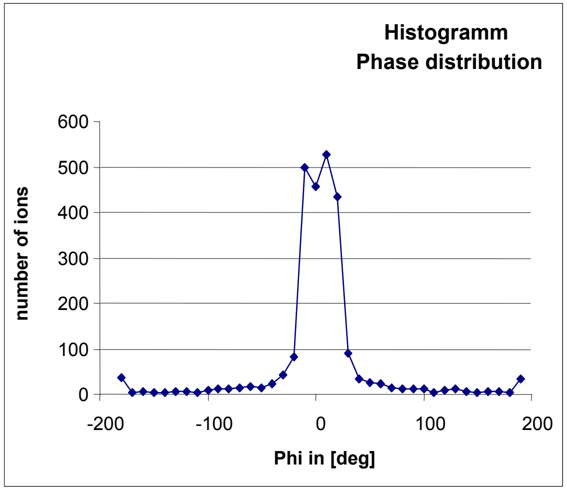




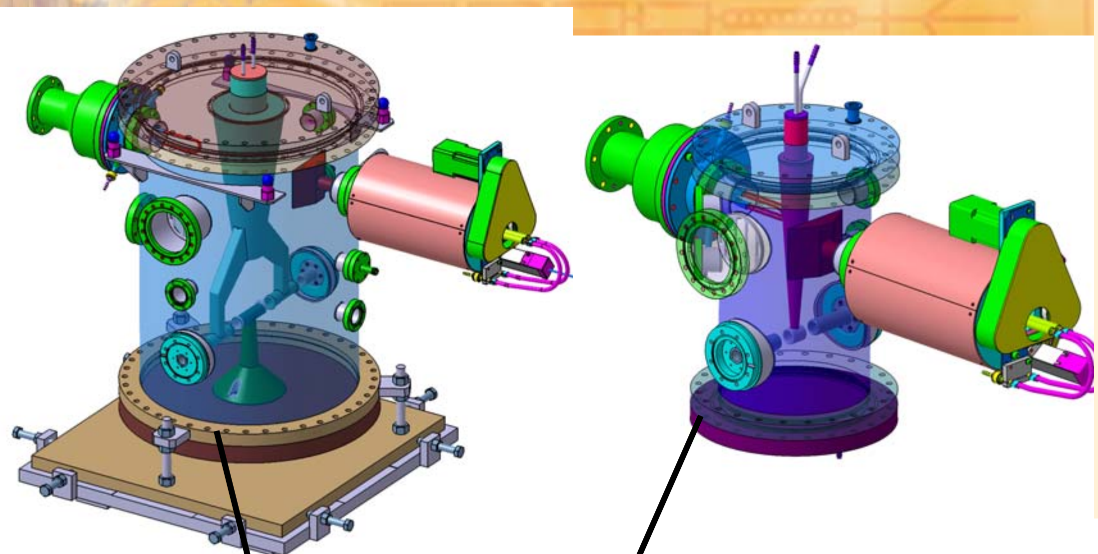
entrance DDB

entrance IH-structure

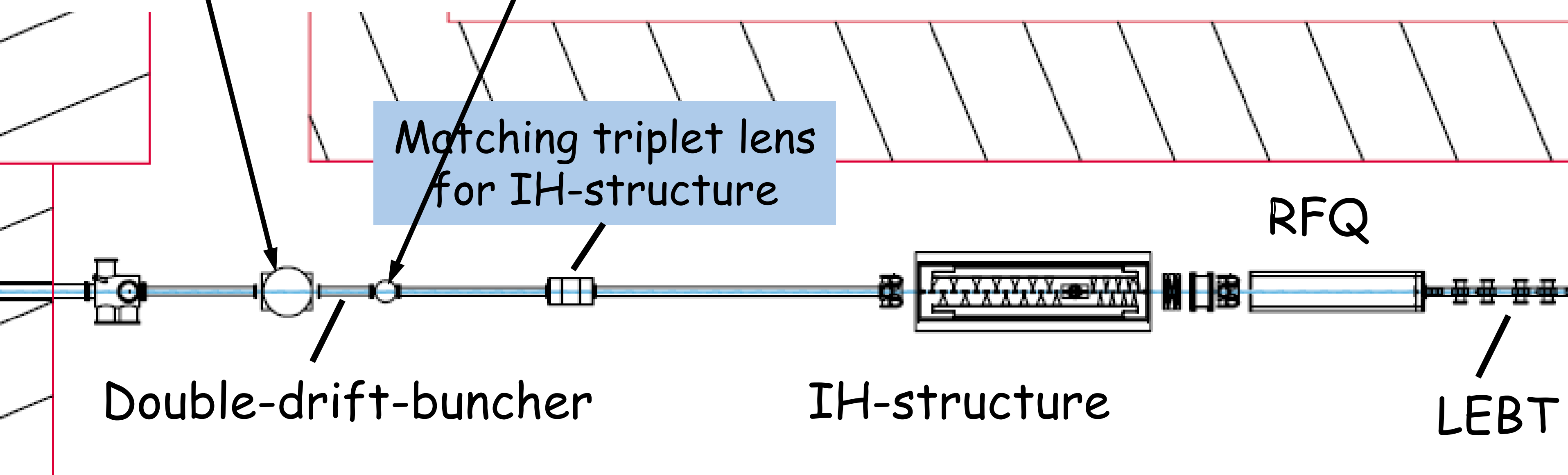




HITRAP buncher cavities



- Beam dynamics calculations have been carried out
- Cavity design with MWS has been done
- Both cavities, 4 gap 108 MHz and 2 gap 216 MHz are delivered
- 2 kW Solid state rf-amplifiers are already delivered

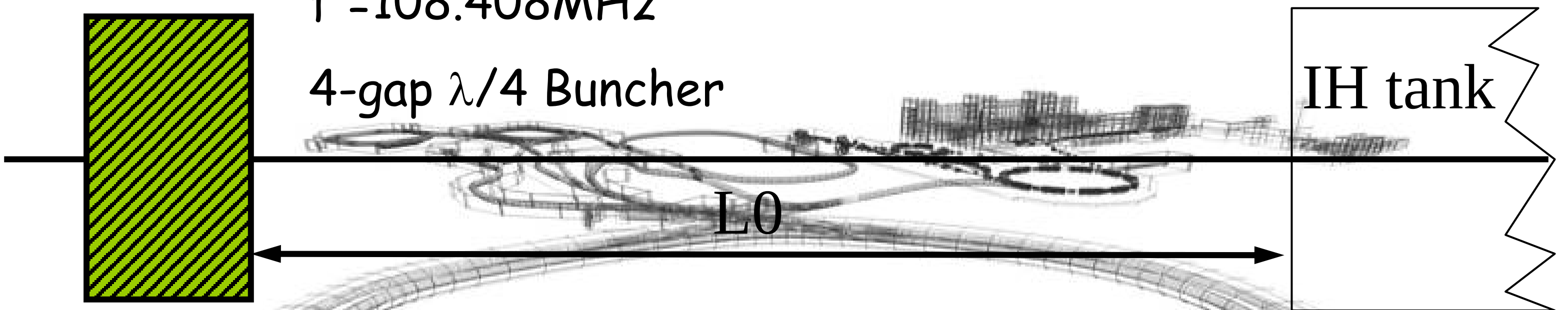


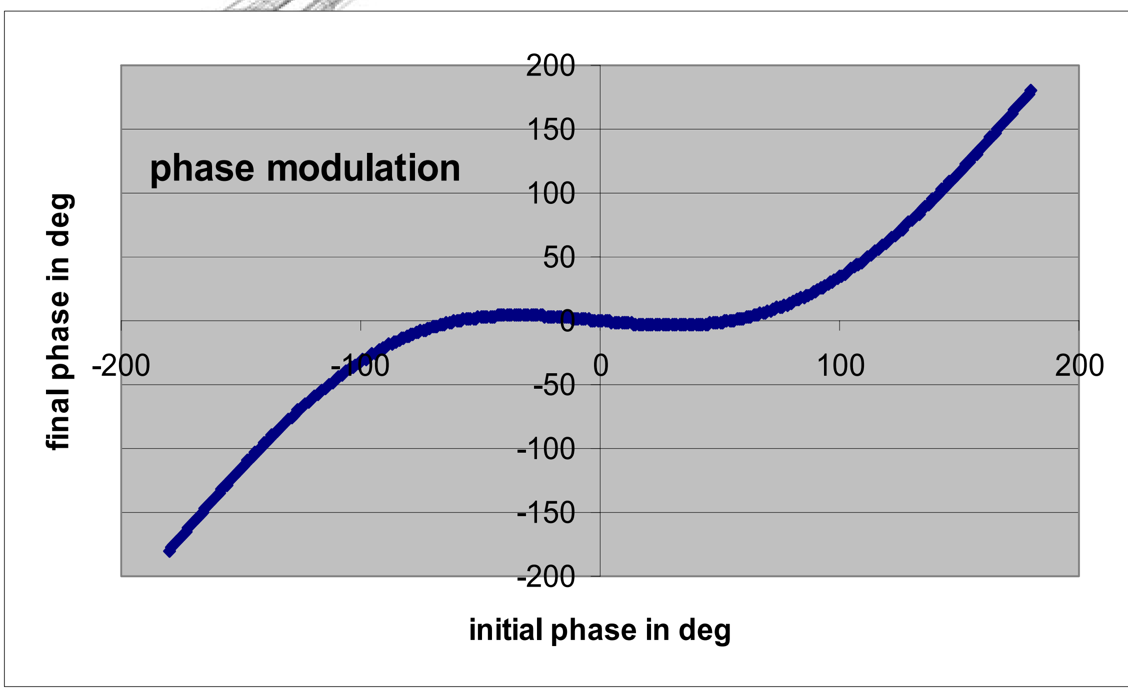
Harmonic buncher

phase acceptance $\pm 5^{o}$

f =108.408MHz

4-gap $\lambda/4$ Buncher





Bunching efficiency < 37%

L0 = 4 m

Double Drift buncher (DDB)

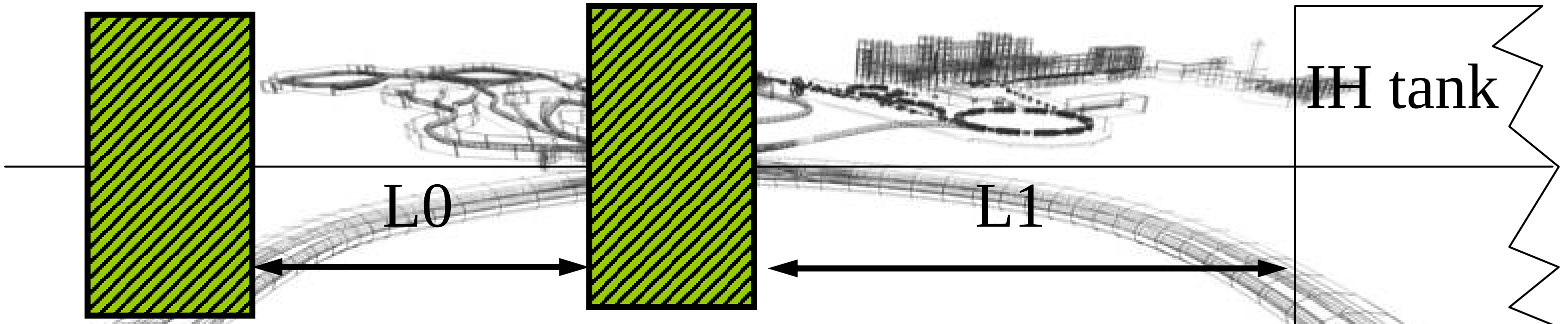
f =108.408MHz

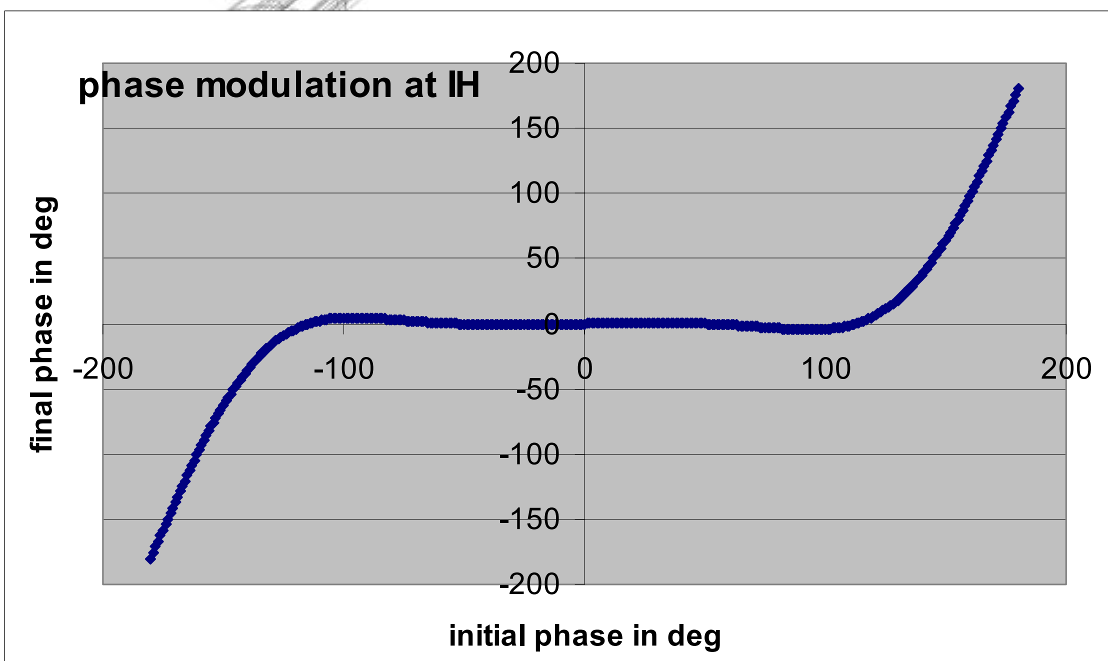
4-gap λ/4 Buncher

f =216.816MHz

2-gap λ/4 Buncher

phase acceptance $\pm 5^{o}$

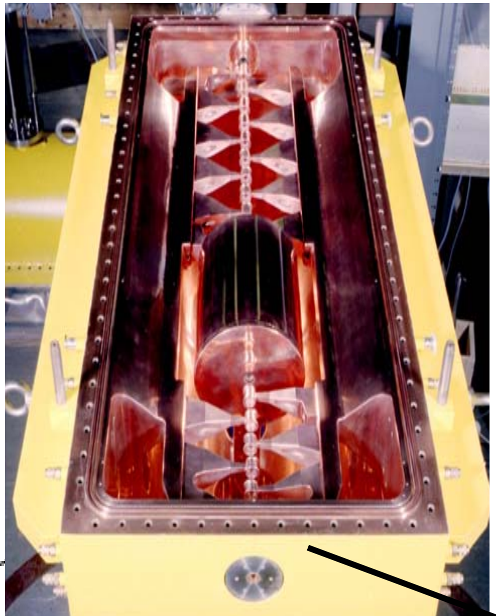


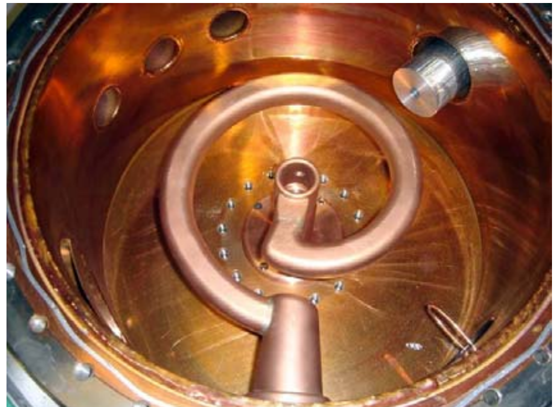


Bunching efficiency < 67%

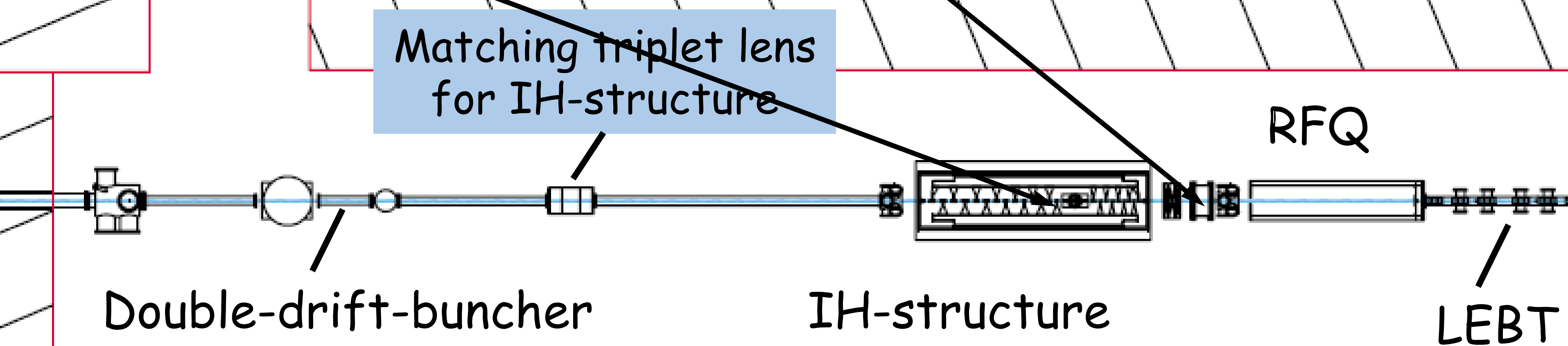
L0 = 0.9 m
L1 = 5.8 m

HITRAP decelerator cavities





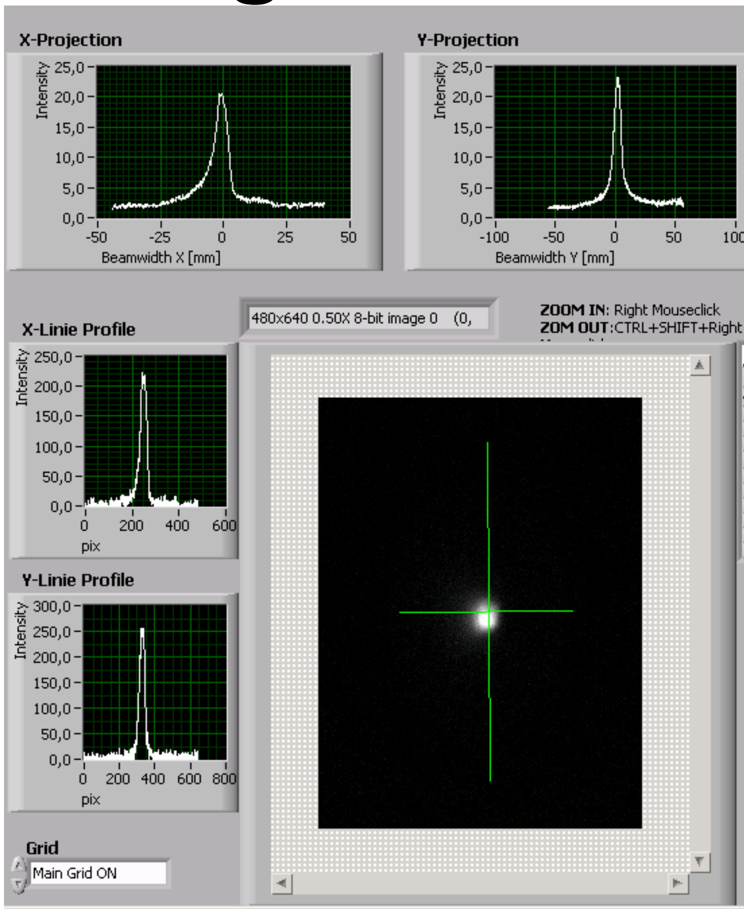
- Beam dynamics calculations have been carried out
- Cavity design with MWS has been done
- Existing re-buncher cavity has been modified in Frankfurt University
- IH-structure is in manufacturing
- 2 kW solid state amplifier already delivered for Rebuncher
- 180 kW-amplifier from GSI equipment is ready for IH-structure

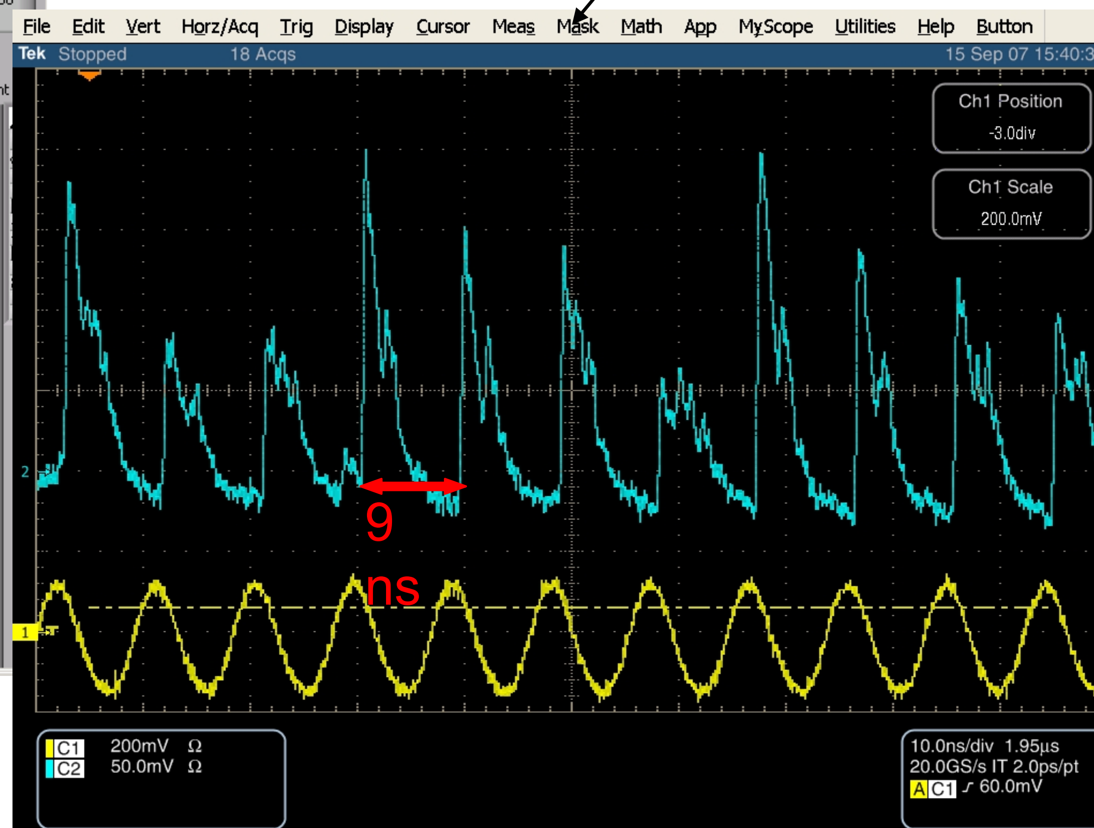


Commissioning beamtime – August 2007

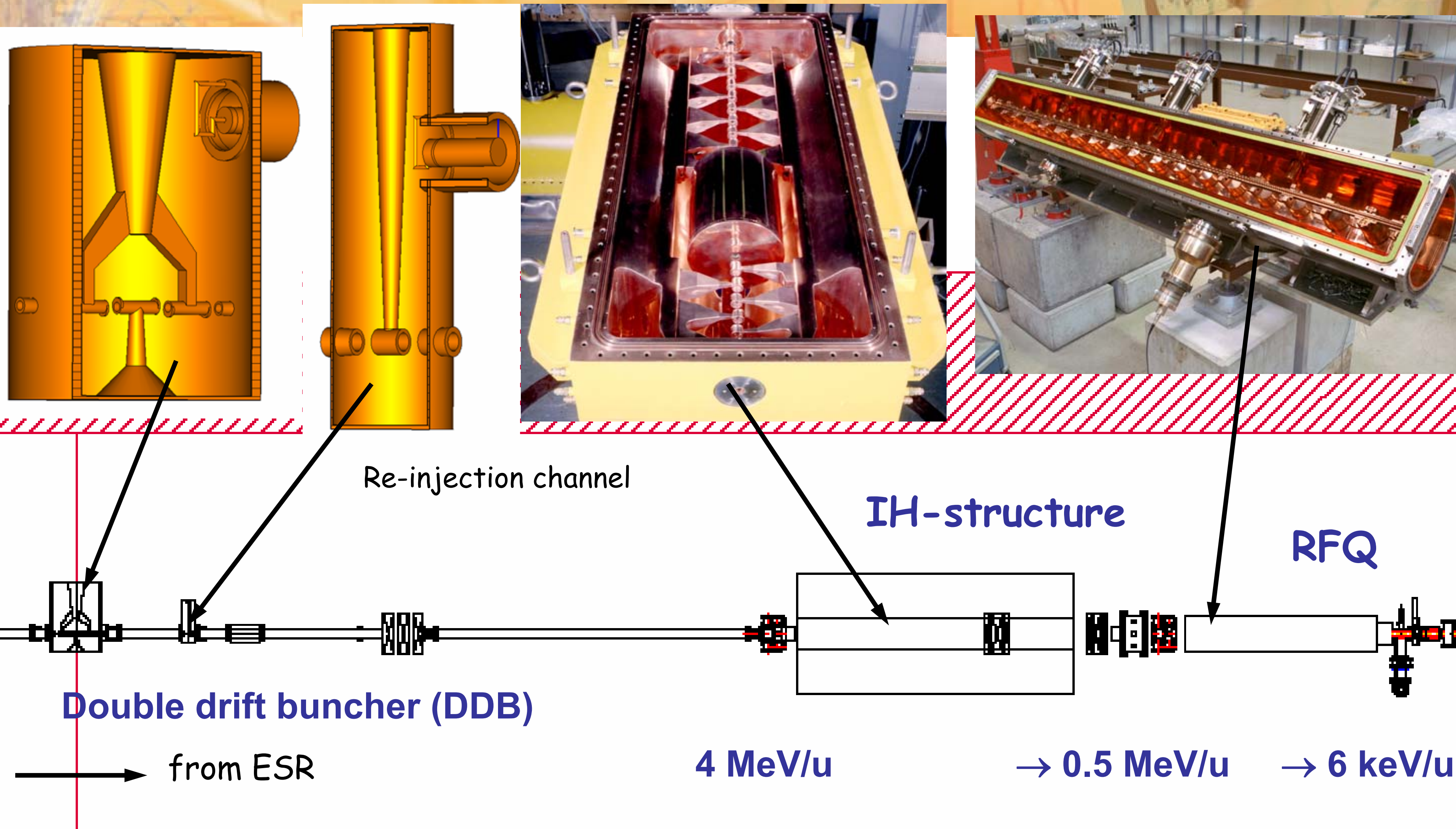
YAG fluorescence target: beam is focused!

Diamond detector: beam is bunched!

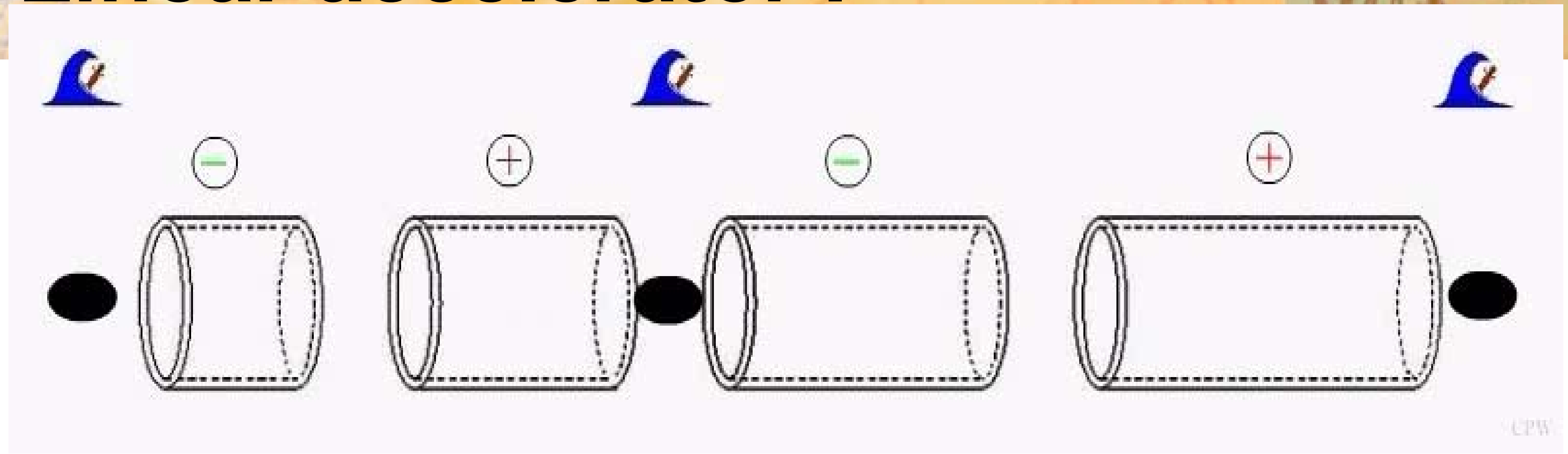


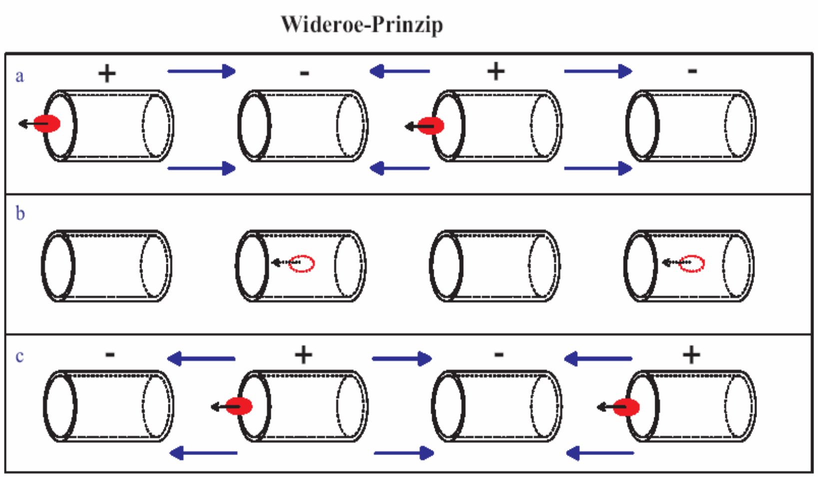


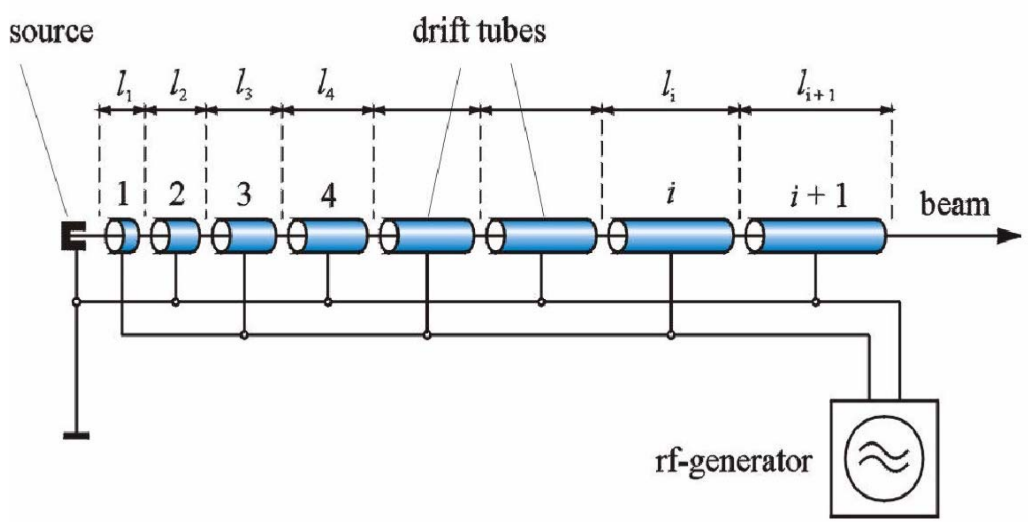
The HITRAP LINAC



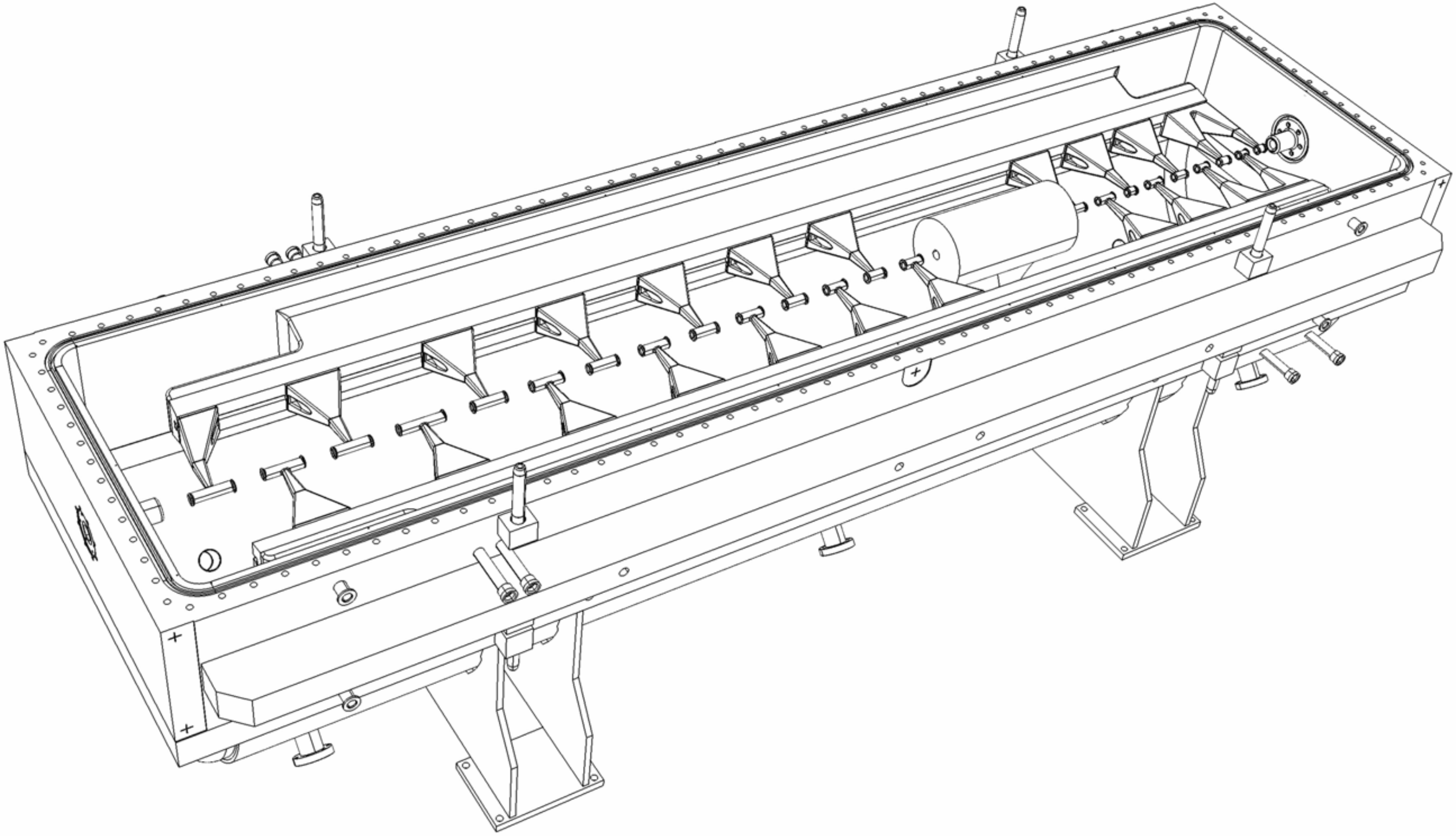
Linear accelerator I



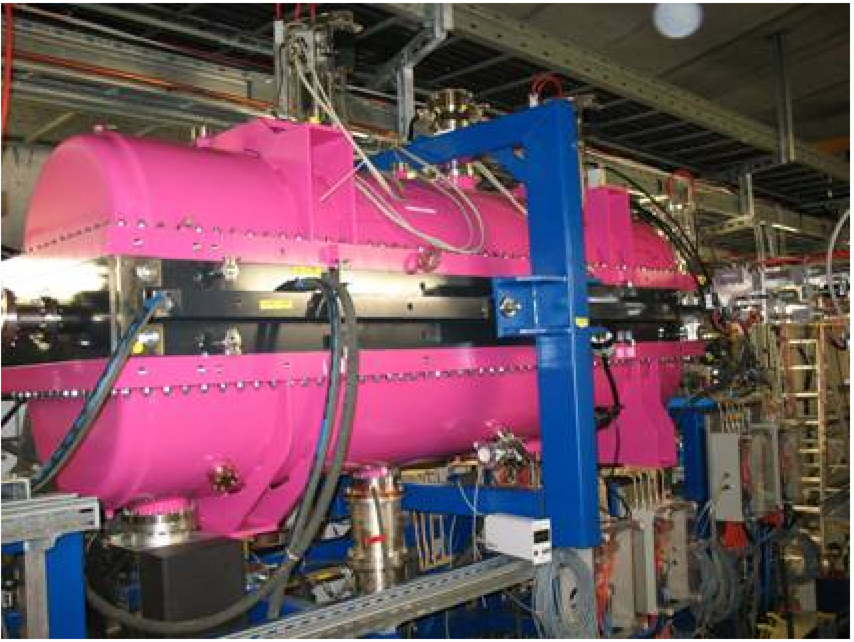


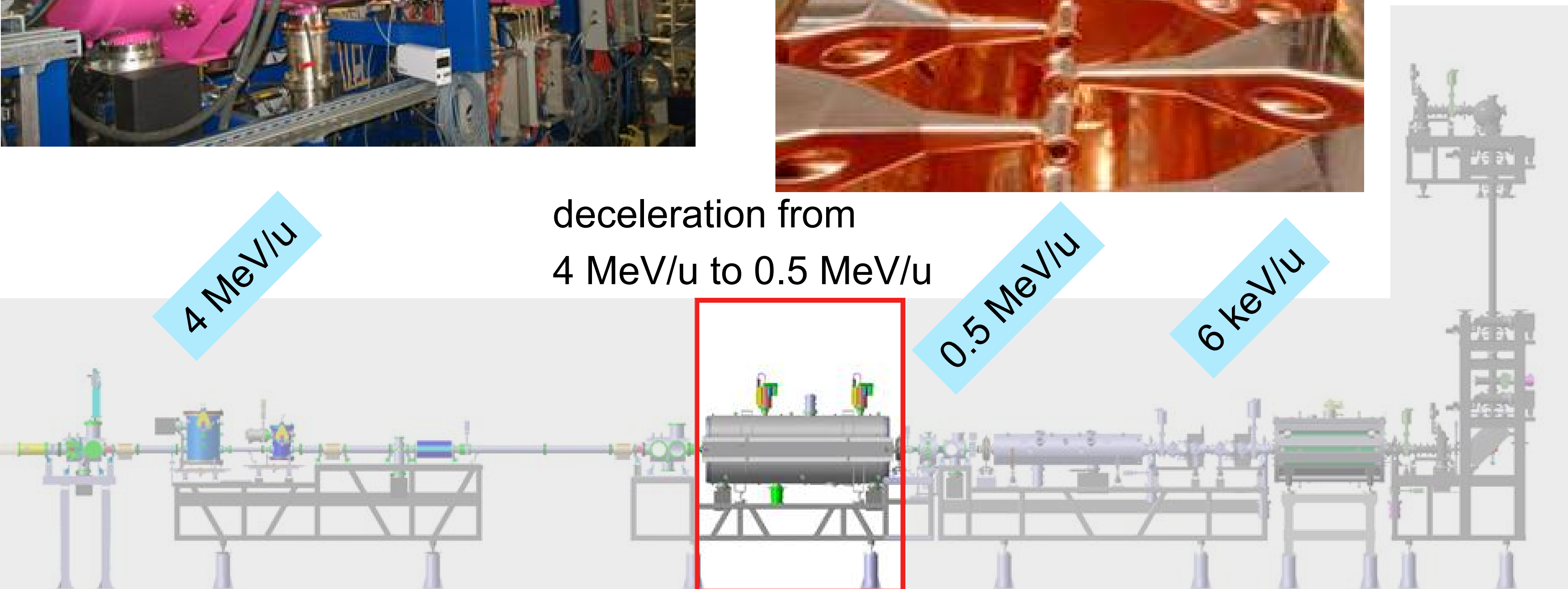


IH – Decelerator



HITRAP – IH-Type Structure

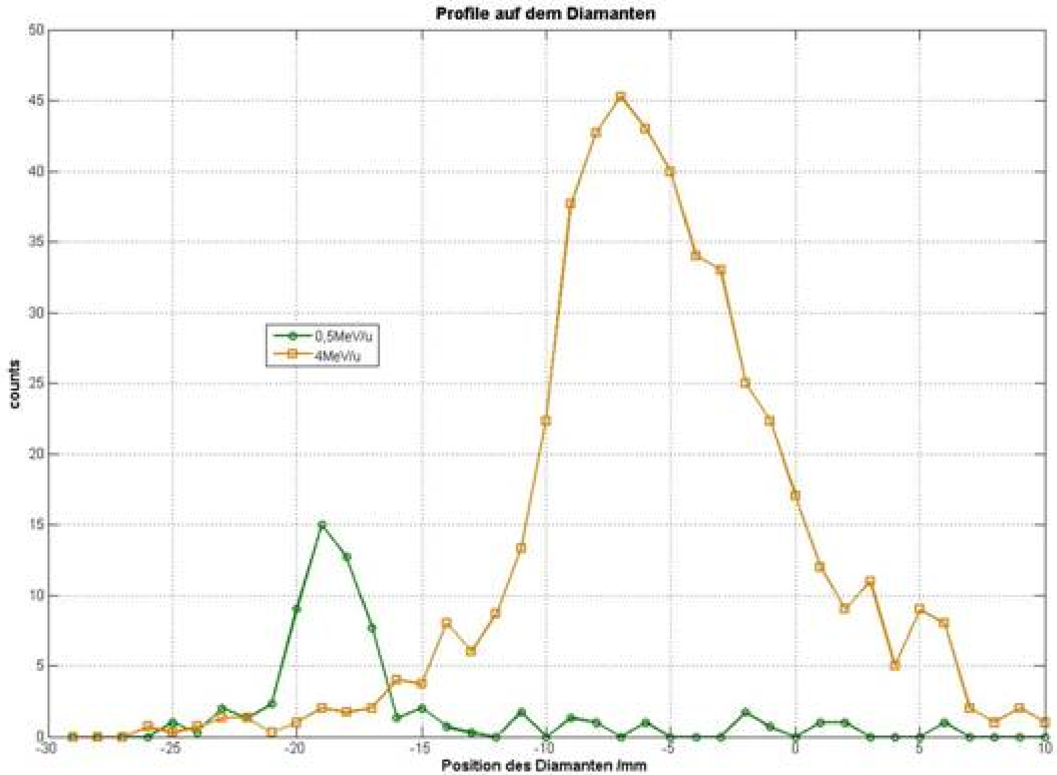




deceleration from
4 MeV/u to 0.5 MeV/u

Remember 2009

beam profile separation of 0.5 and 4 MeV/u beam on diamond



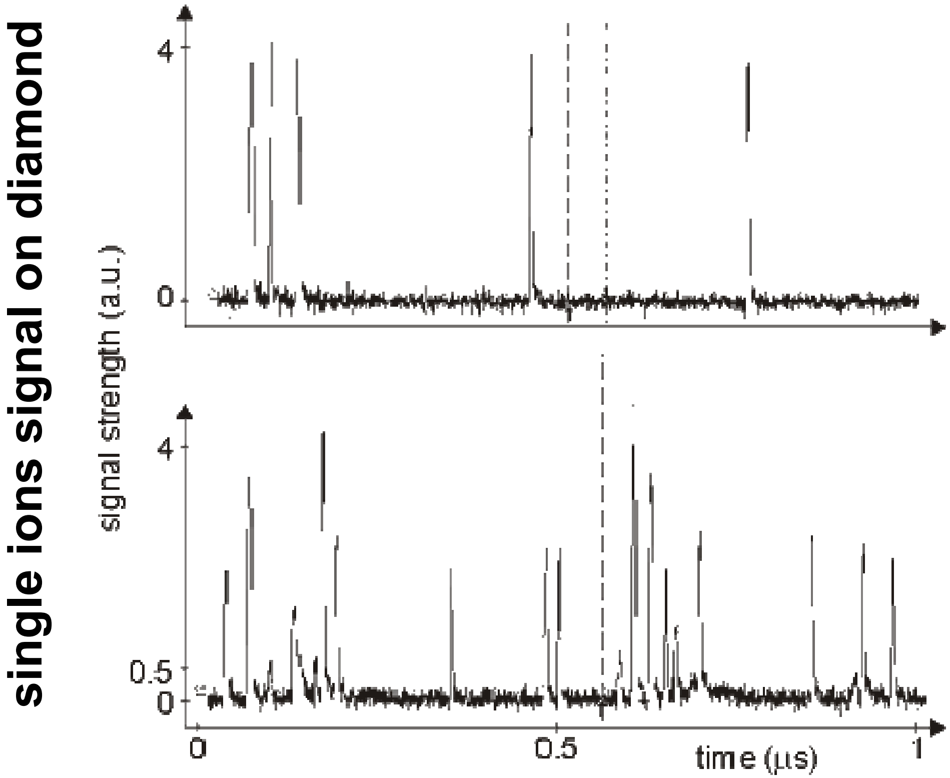
ratio between decelerated and non-decelerated ions

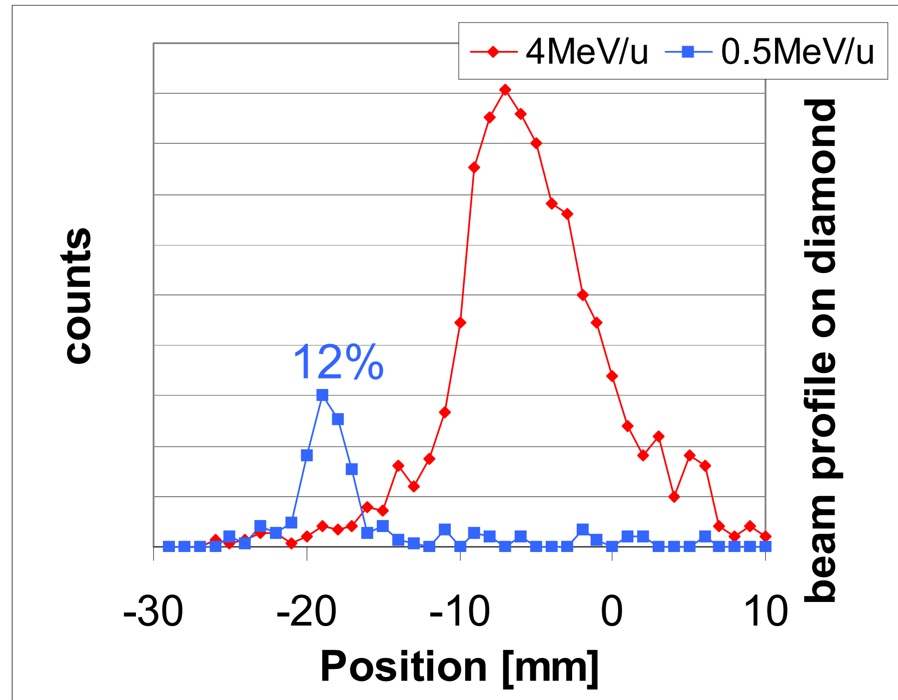
1:7.22

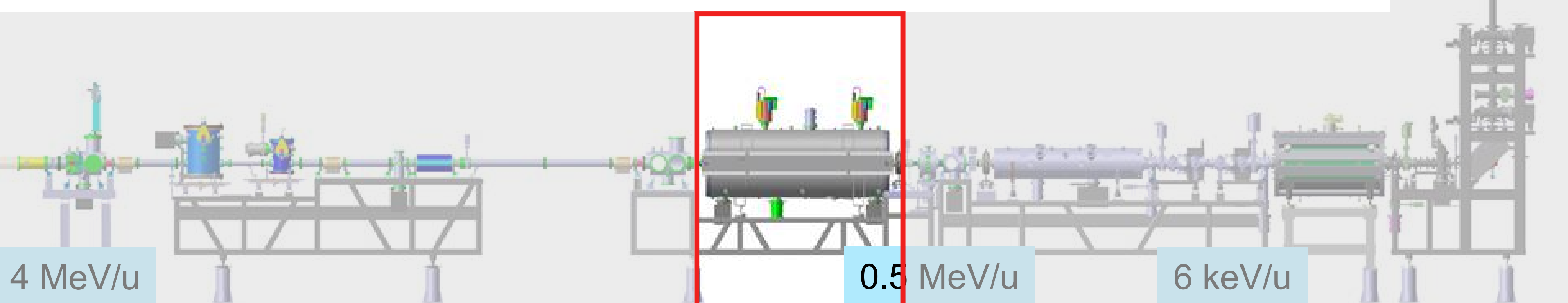
=

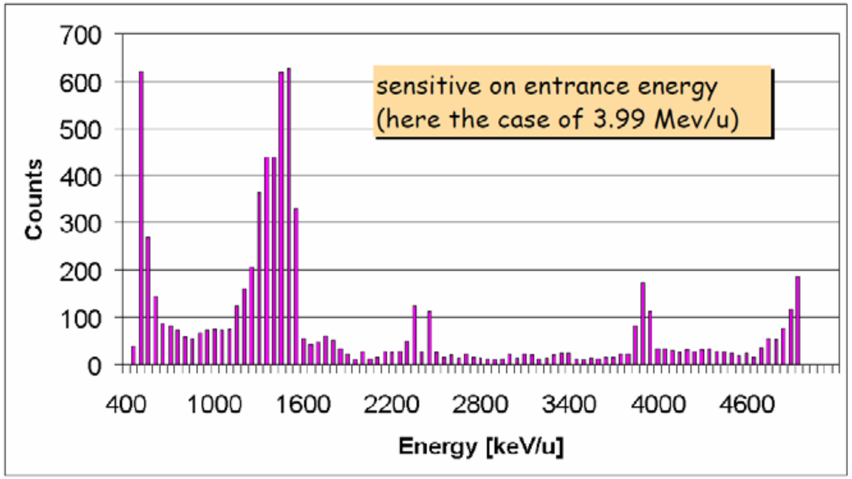
12% of ions @ 500keV/u (seen 1-dimensional)

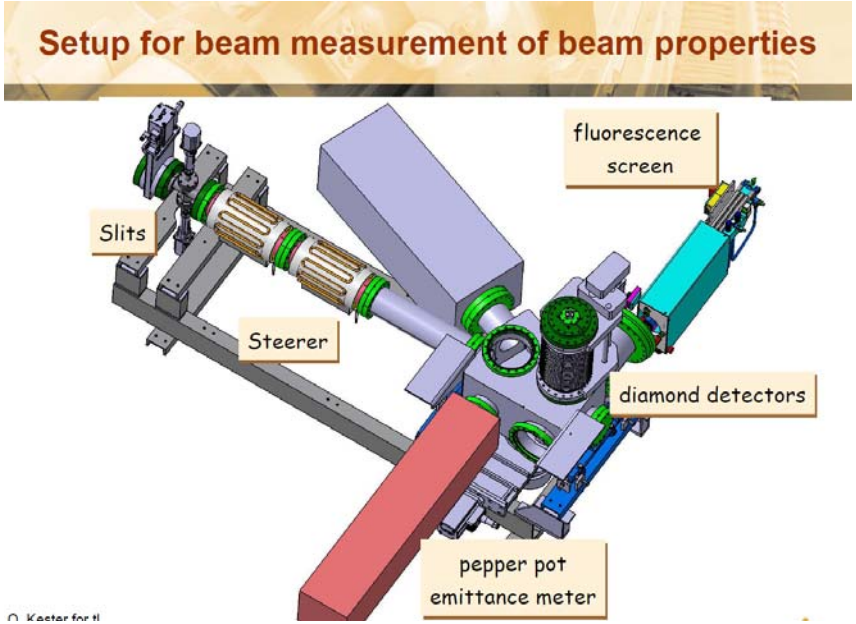
Commissioning of the IH-tank with .... Beam



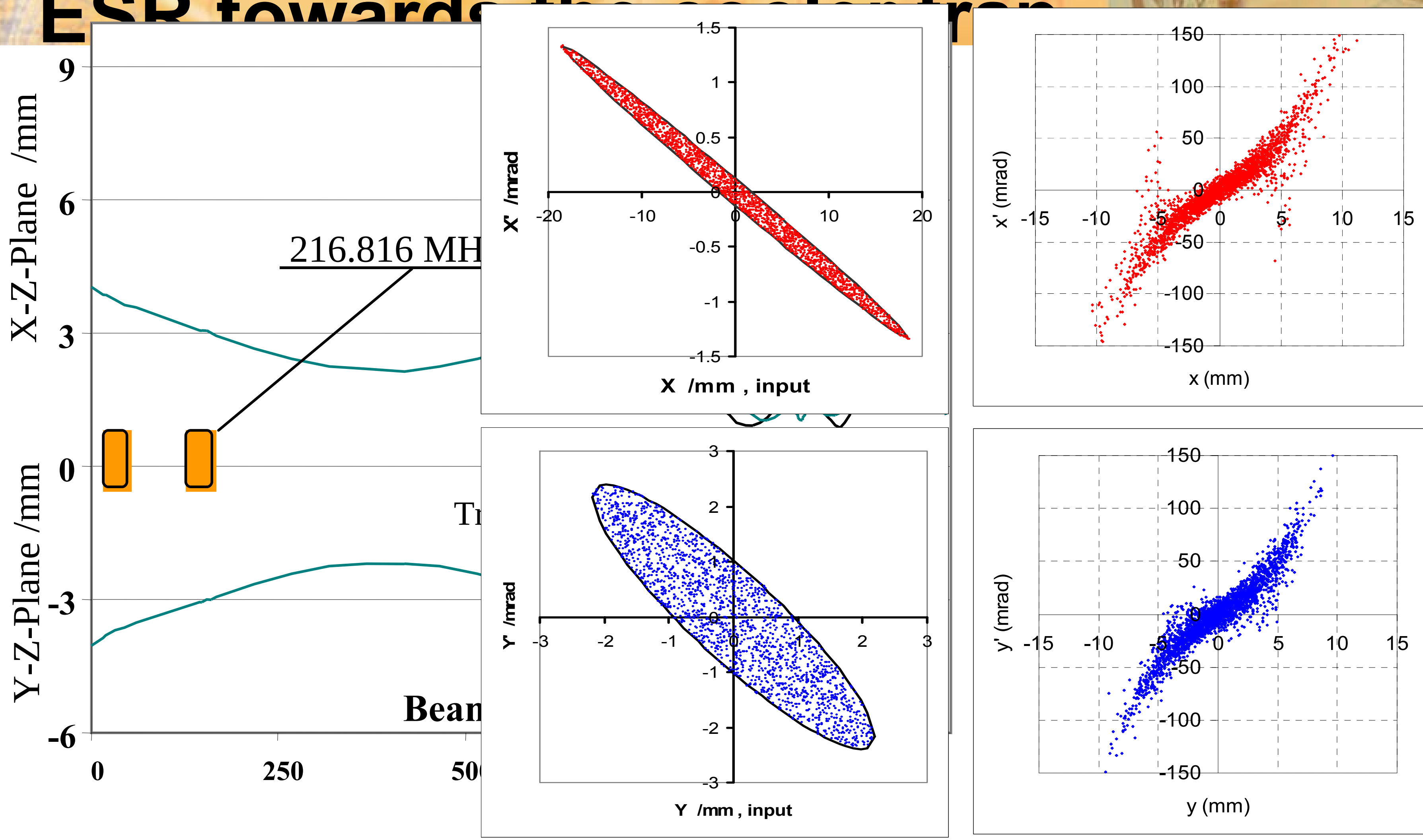





Counts
Energy [keV/u]
700
600
500
400
300
200
100
0
400
1000
1600
2200
2800
3400
4000
4600
sensitive on entrance energy
(here the case of 3.99 Mev/u)


Setup for beam measurement of beam properties
fluorescence screen
Slits
Steerer
diamond detectors
pepper pot emittance meter

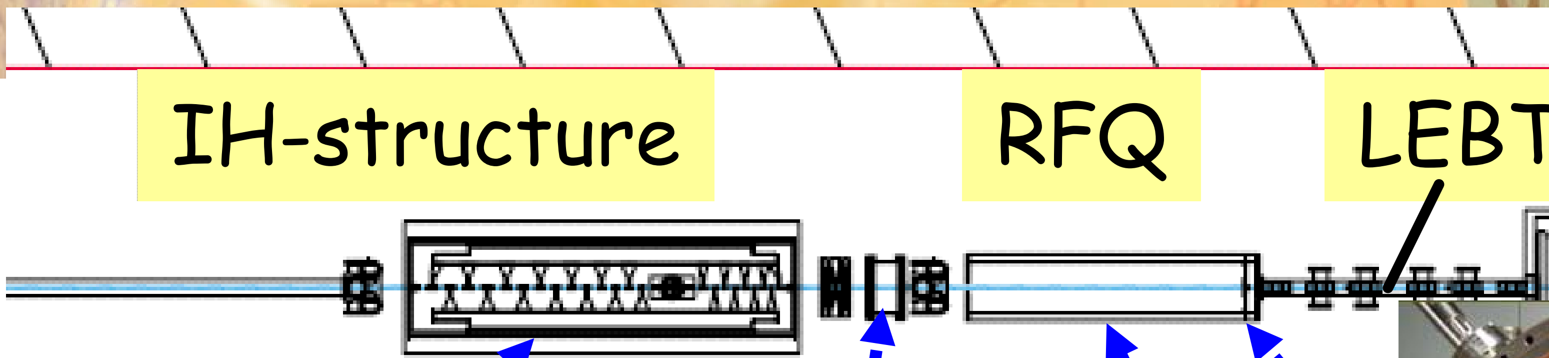
Beam dynamics design II: From ESR towards the



Exit ESR ε_t = 2 mm mrad

Exit RFQ ε_t = 140 mm mrad

RFQ-Decelerator with Integrated Debuncher



Re-Buncher (matching section)

De-buncher

RFQ

Beam dynamics

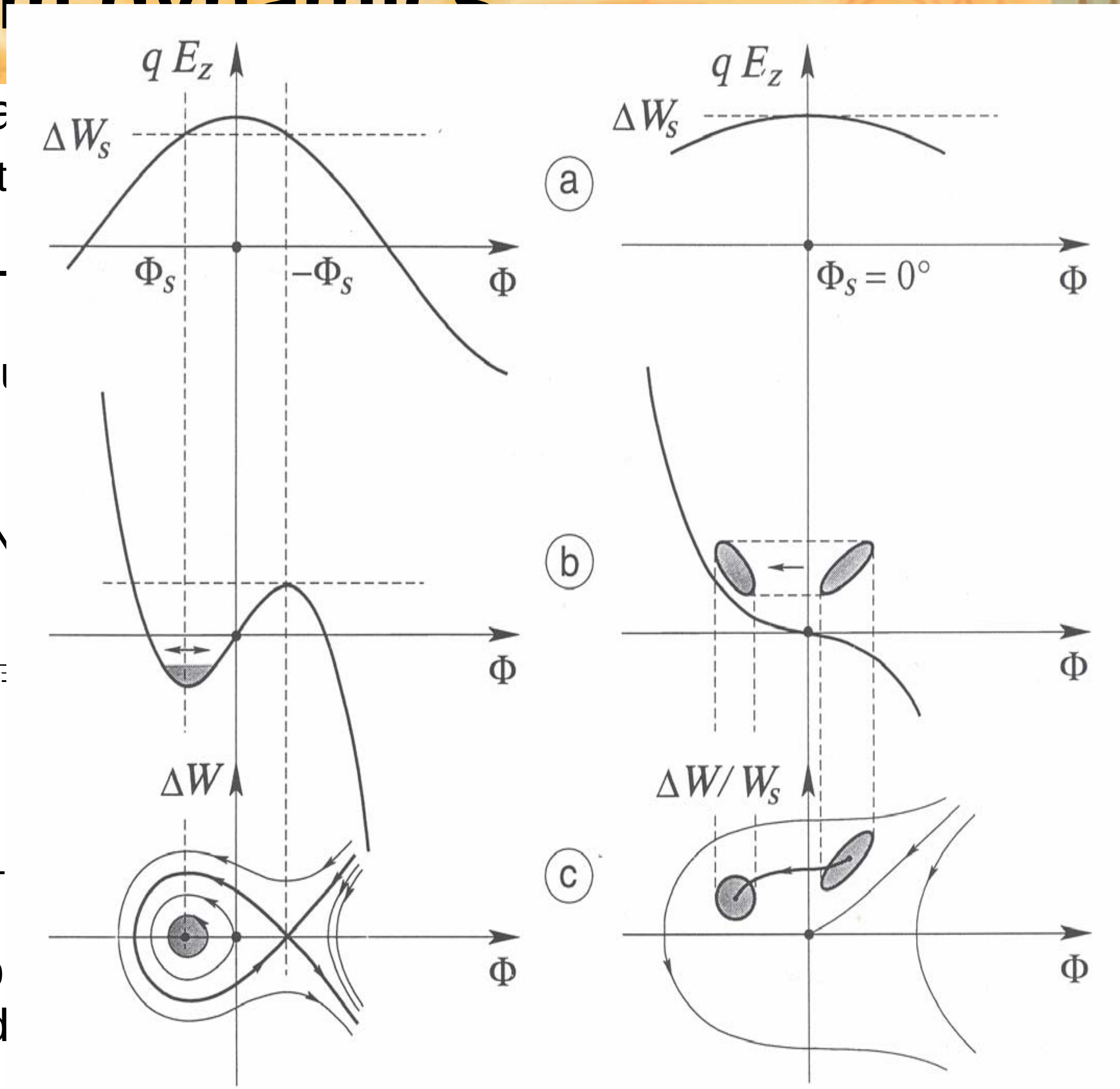
- Nega…
  drift…

  Foc… …n

- KON…

  L… …Lens

  sep… …cusing
  and…



H-mode (type) structures