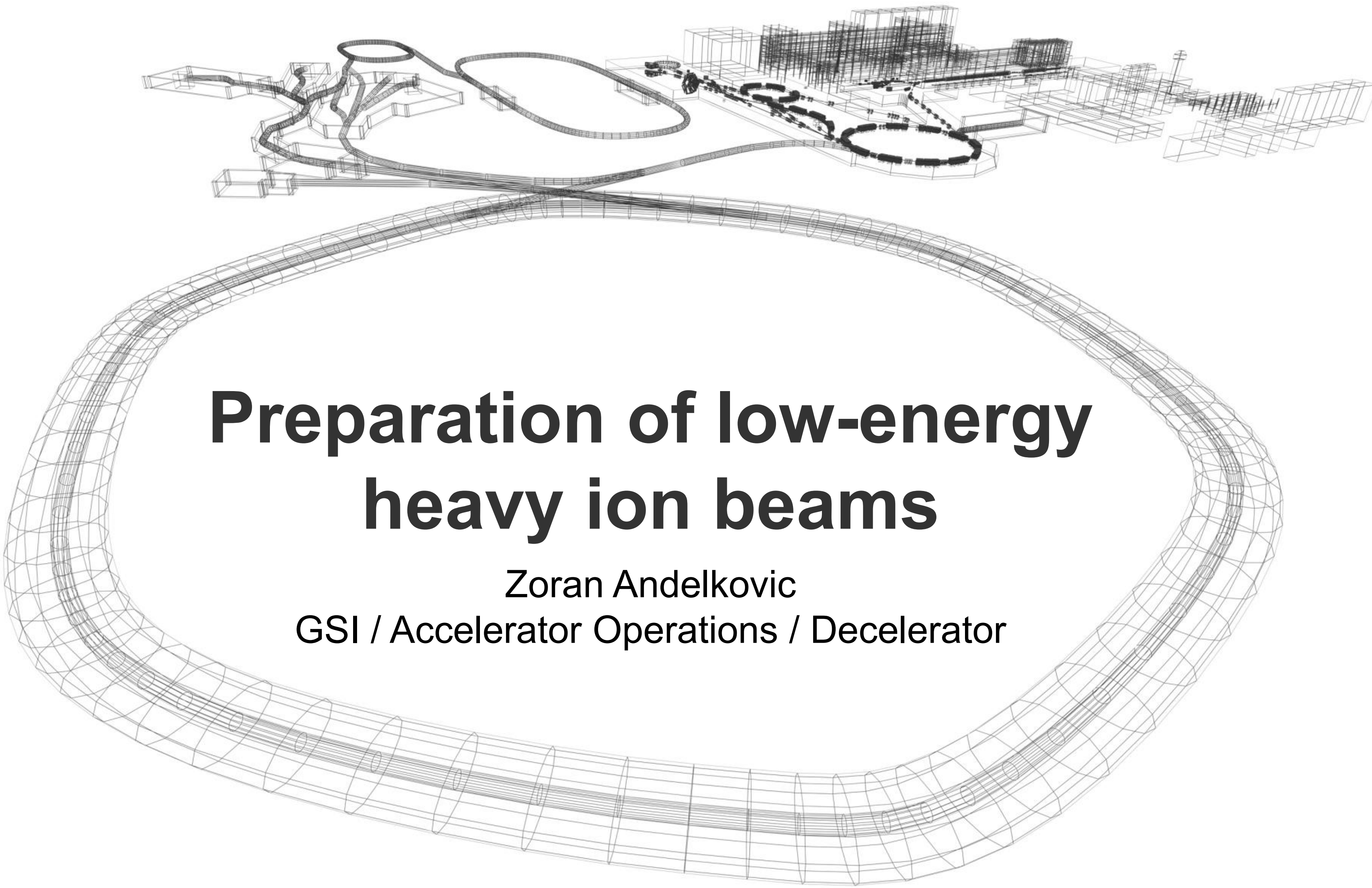
15th International Conference on Heavy Ion Accelerator Technology, June ‘22, Darmstadt

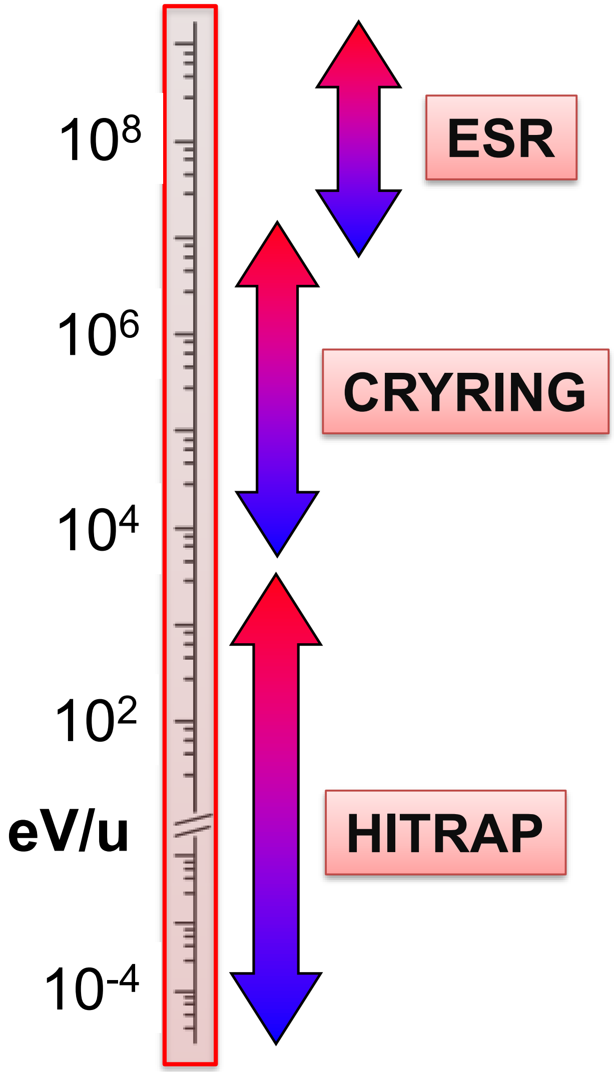


Preparation of low-energy heavy ion beams

Zoran Andelkovic

GSI / Accelerator Operations / Decelerator

Overview

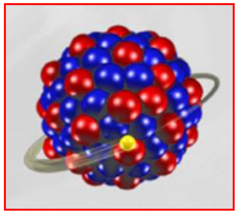


- What are “low energies”?
  - Energy down to 4 MeV/u
    - ESR (low) & CRYRING (mid)
  - Energy down to keV/u
    - CRYRING (low) & HITRAP (mid)
  - Energy below keV/u
    - Precision experiments
- Ion handling changes dramatically
  - device sensitivity changes
  - intensities are reduced
  - different time scales
- Different techniques & different goals

Why HCI at low energy?

e^- in Hydrogen

e^- in HCI



$$\Delta E_{\mathrm{HFS}} = \alpha g_I \frac{m_e}{m_p} \frac{F(F+1) - I(I+1) - j(j+1)}{2j(j+1)} m_e c^2$$

$$\times \frac{(Z\alpha)^3}{n^3(2l+1)} \mathscr{M} \left[A(Z\alpha)(1-\delta)(1-\varepsilon) + \left(\frac{\alpha}{\pi}\right) \Delta\mathscr{E}_{\mathrm{QED}} \right] .$$

Nuclear Mass Effect ($\mathscr{M}$) | Relativistic Effects ($A(Z\alpha)$) | Breit-Rosenthal Effect ($(1-\delta)$) | Bohr-Weisskopf Effect ($(1-\varepsilon)$) | QED Contribution ($\left(\frac{\alpha}{\pi}\right)\Delta\mathscr{E}_{\mathrm{QED}}$)

HFS spectroscopy in:	H	$^{209}Bi^{82+}$
transition energy ~ Z^3	$\lambda \approx 21$ cm	$\lambda \approx 243.9$ nm
state lifetime ~ $1/Z^9$	$\tau \approx 10^7$ a	$\tau \approx 400\ \mu s$

- needed relative accuracy $\Delta\lambda/\lambda < 10^{-6}$ only with low energy!
- QED validity test under extremely strong *both* **E** *and* **B** fields

Producing HCI @ MeV/u range

1

- GSI (a low-charge IS + an accelerator facility)

~ 10 keV/u

LCI source → accel. → stripper target

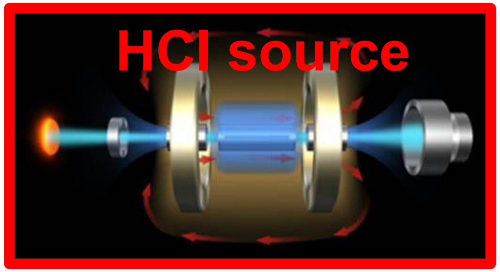
~ 400 MeV/u

→ decele-ration

~ 4 MeV/u

2

- ECRIS (a high charge IS + a small accelerator)



~ 10 keV/u

→ accelerator

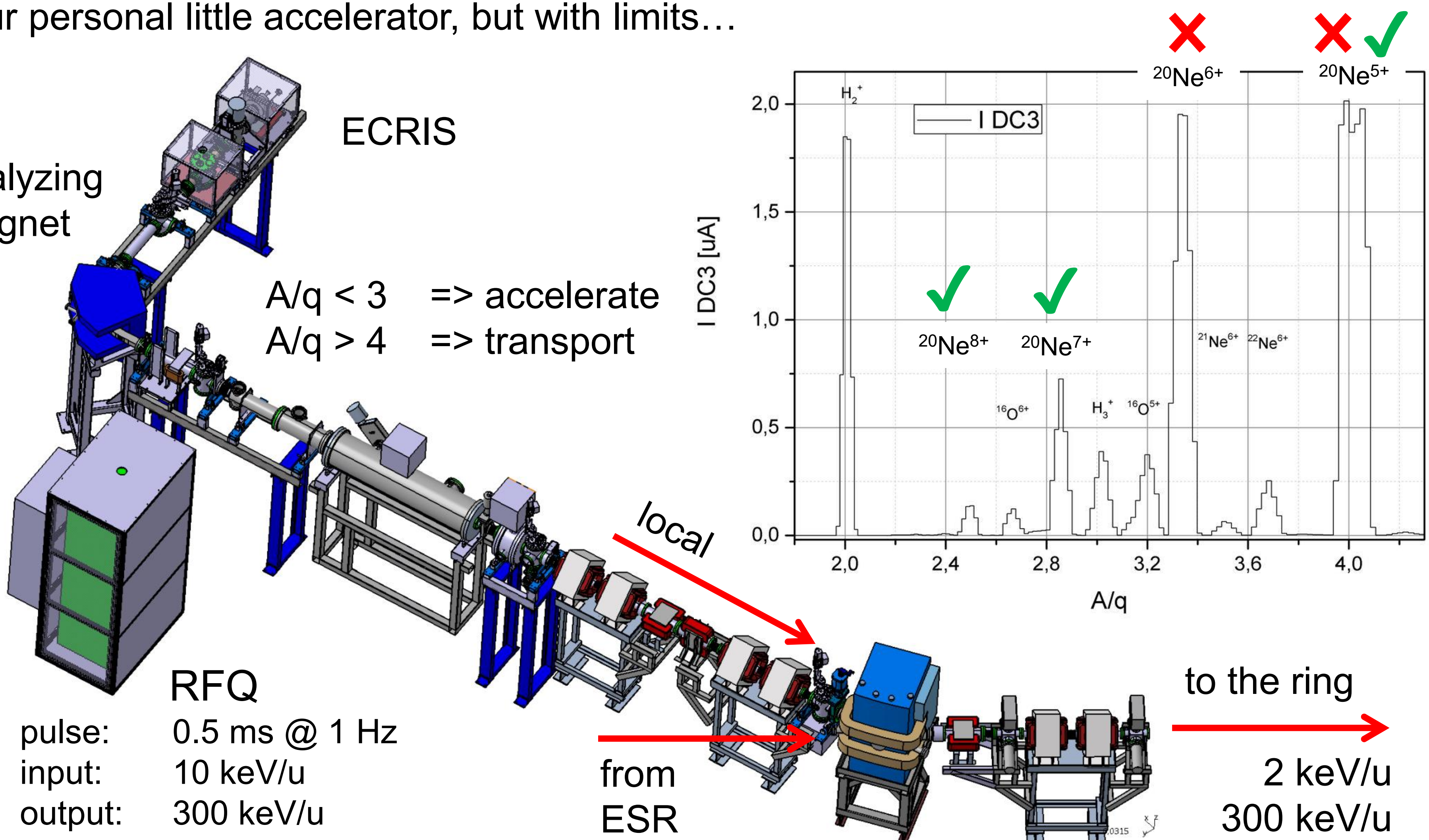
~ 300 keV/u

→ low-E storage ring

Local IS + RFQ: production limits

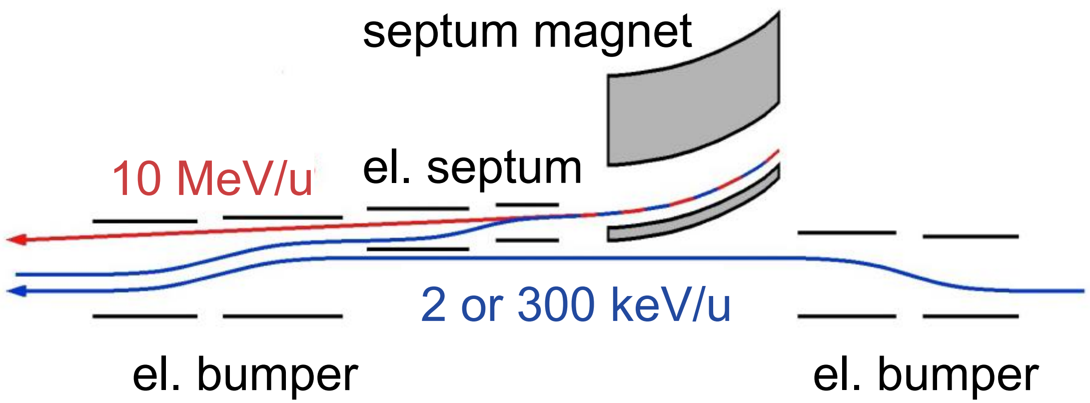
your personal little accelerator, but with limits…

A/q < 3 => accelerate
A/q > 4 => transport

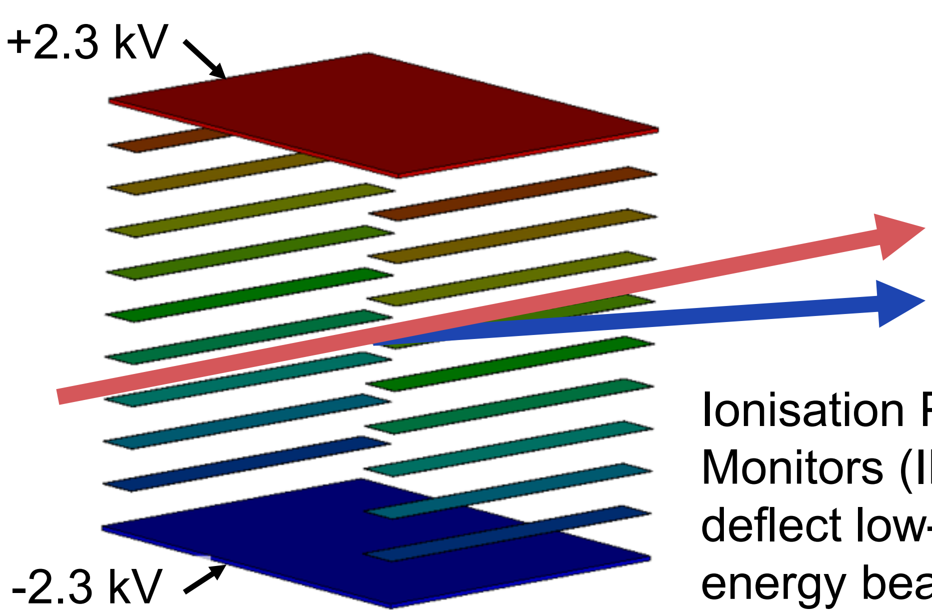


pulse: 0.5 ms @ 1 Hz
input: 10 keV/u
output: 300 keV/u
dp/p: ±1.0% (0.5%)

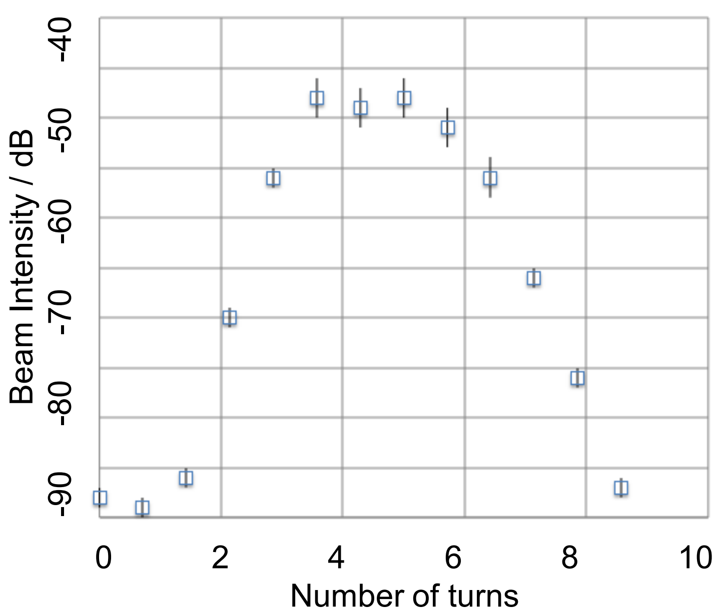
Ion injection at low energy



Injection limits 2 / 300 keV/u	
Min. intensity	40 / 200 nA
Injection efficiency	20-50 %
Multiturn	1-5 turns
Detection limit	ca. 10^6 q
Max. intensity	10^7 / 10^8 q

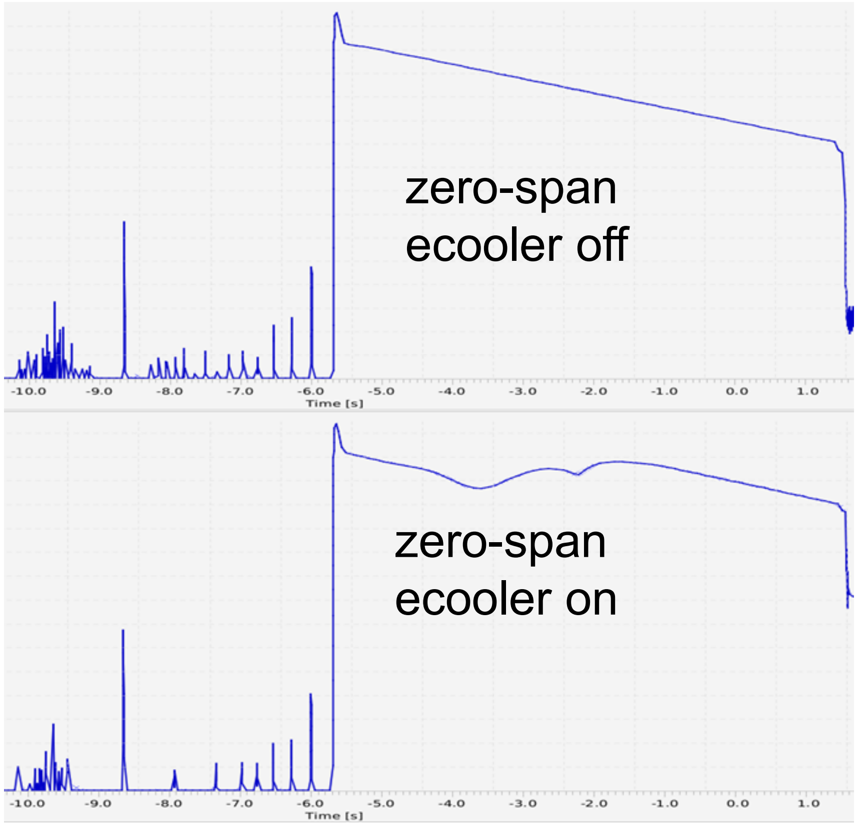


Ionisation Profile Monitors (IPM) deflect low-energy beams



Ion detection at low energy

	LCI @ 300 keV/u	HCI @ 4 MeV/u
current	0.3 μA	3 μA
velocity β	2% c	14% c
ecool	100 V	5495 V
lifetime	10 sec	10 sec
BPM.	✗ ✓	✓
Schottky	✗ ✓	✓
AC Transf.	✓	✓
DC Transf.	✗	✓
IPM	✗	✓



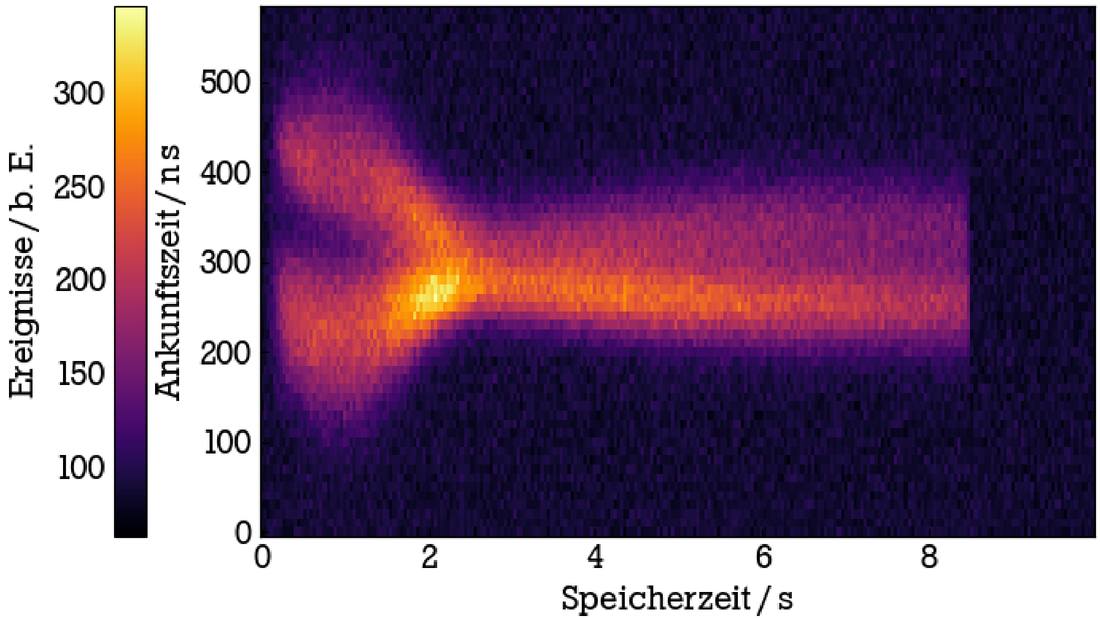
- lifetime dominated by: e^- capture for HCI; stipping for LCI → vacuum crittical
- measured pressure $5 \cdot 10^{-11}$ mbar (250°C baking + 10 ion pumps + 60 NEG pumps)

Ion storage at low energy

laser fluorescence as a function of electron cooling al low-E

→ No other diagnostic element offers sufficient sensitivity

- a unique combination of sensitivity (1 mm, 0.1 V) and energy range (0.17 MeV/u)
- dispersive effects of the electron cooler excite synchrotron oscillations of ions



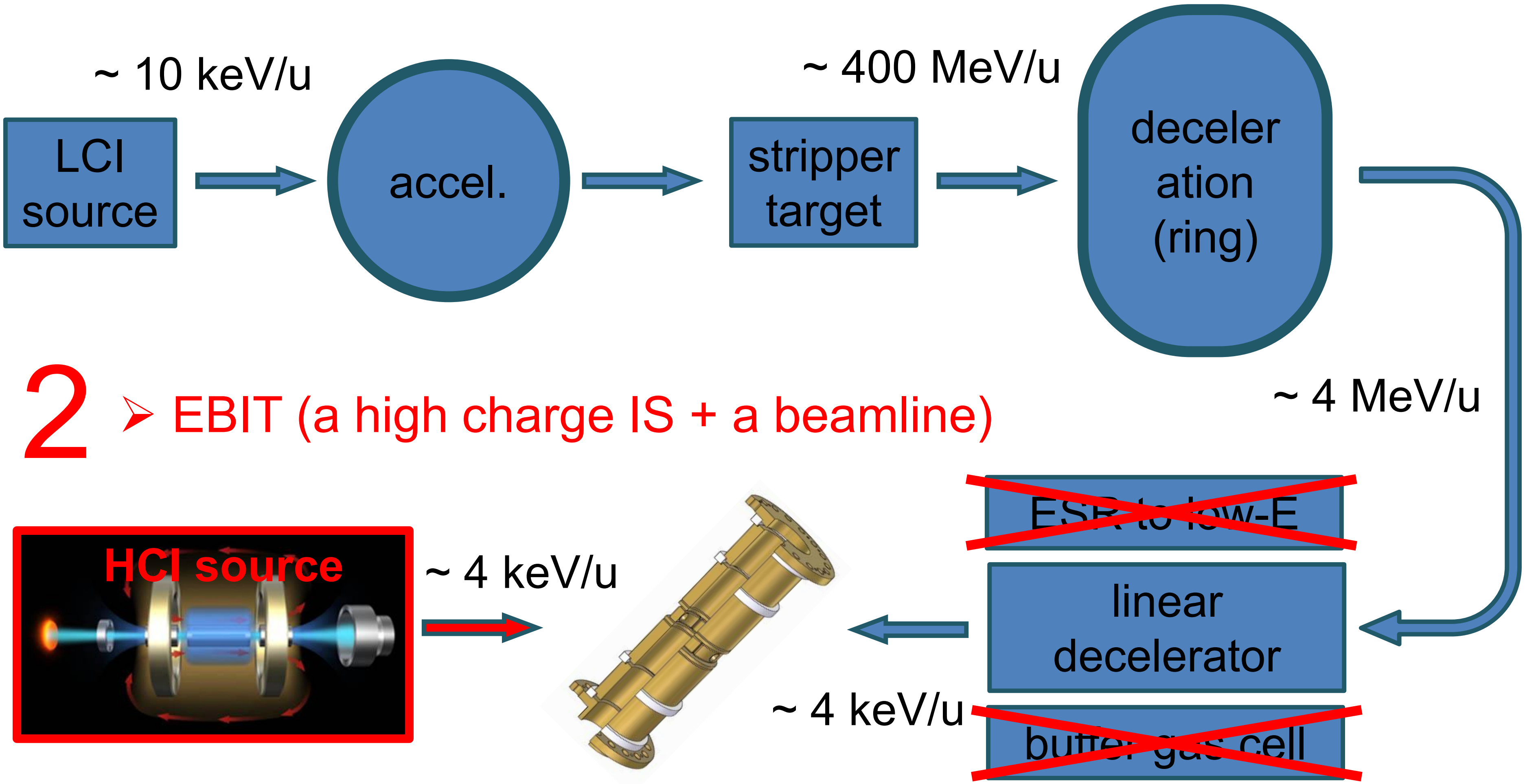
courtesy of K. Mohr, PhD Thesis, TU Darmstadt 2022

LCI in CRYRING	Energy	HCI in CRYRING	Energy
H_2^+, D^+, Li^+, C^+, $O^{2..5+}$, $Ne^{2..3+}$, $^{24}Mg^+$, $^{25}Mg^+$, Ar^+	1 keV/u (inj.) 170 keV (Mg^+) 20 MeV (D^+)	Ar^{18+}, Ag^{46+}, Au^{78+}, $Pb^{78..81+}$, U^{91+}	1 MeV/u … 15 MeV/u

Producing HCI @ keV/u range

1 ➢ GSI (a low-charge IS + an accelerator facility)

2 ➢ EBIT (a high charge IS + a beamline)



Linear decelerator

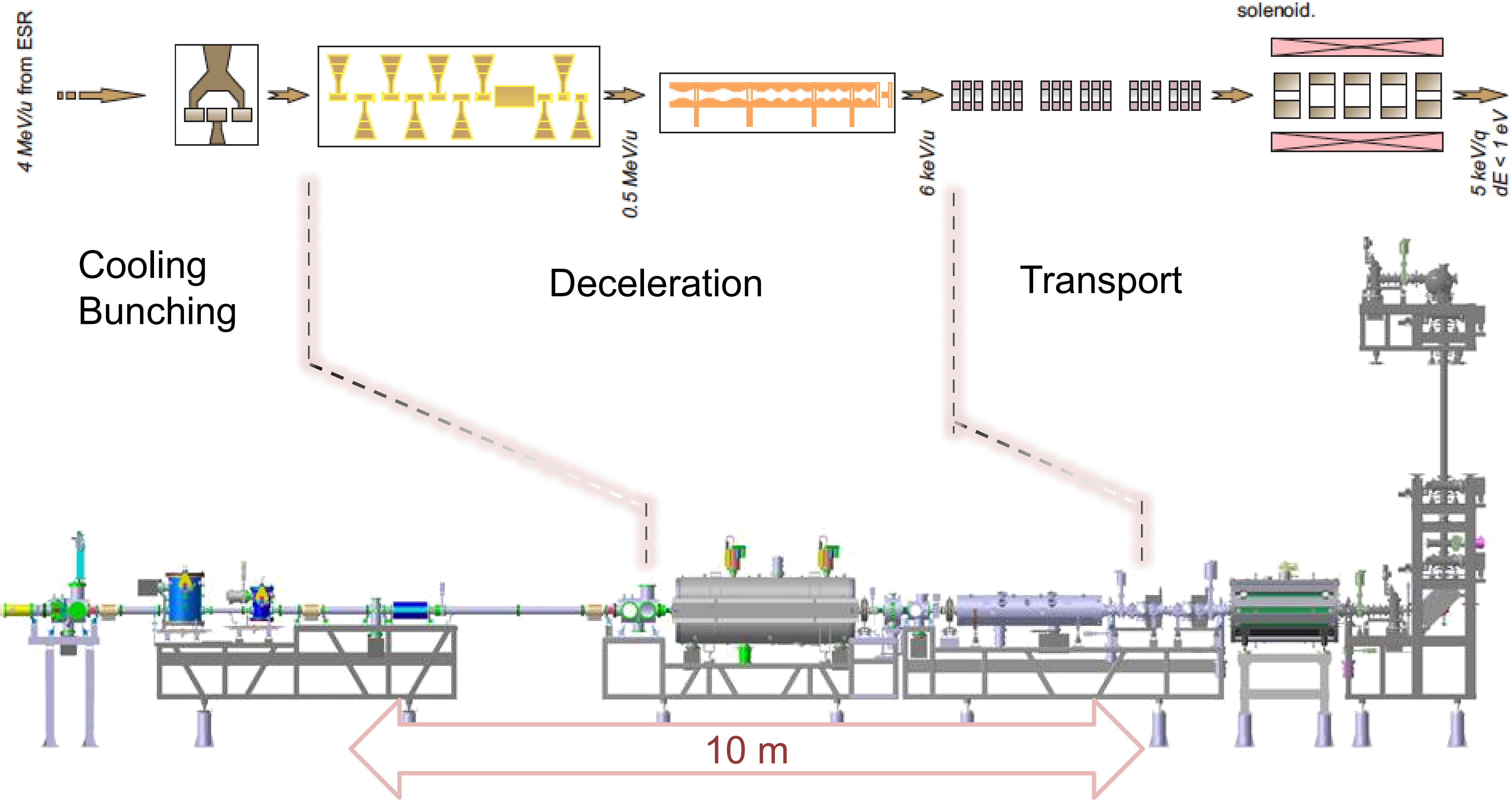
Double Drift Buncher running at 108.408 and 216.816 MHz

Interdigital H-type linac (*IH*) with integrated magnetic quadrupole triplet and steerer

Four-rod radiofrequency quadrupole linac (*RFQ*) with integrated debuncher

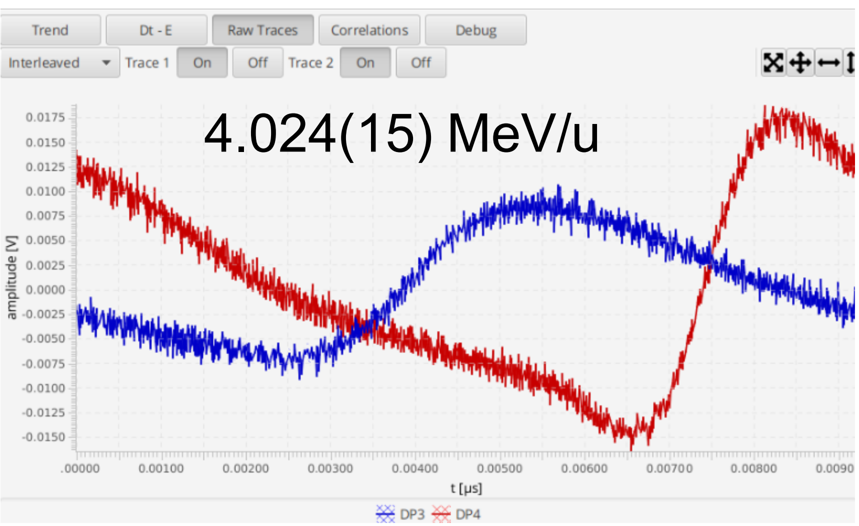
Low energy beam transport line (*LEBT*) based on electrostatic *einzel lenses* and with integrated differential pumping barriers

Cooler Penning trap (TRAP) in the 400 mm long homogeneous field of a 6 Tesla superconducting solenoid.



Requirements for ion deceleration

Deceleration parameters	
No. ions	1-5 μA, 10^6 part.
Bunch length	0.5 μs
Energy IH	4.024(5) MeV/u
Energy RFQ	0.495(5) MeV/u
Energy final	0.006(1) MeV/u



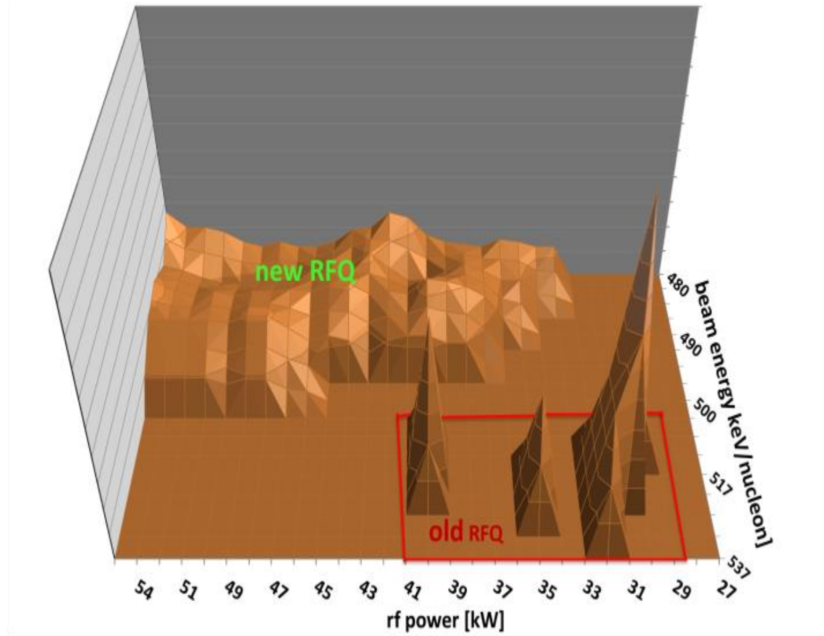
1. transport to IH
   - energy measurement
   - energy adjustment at ESR
2. deceleration in IH
   - beam alignment
   - optimize phase, amplitude
3. deceleration in RFQ
   - beam alignment
   - optimize phase, amplitude
4. transport in LEBT
   - energy separation
   - trap, cool and eject
5. towards experiments

ACC-DEC = ƆƎᗡ-ƆƆA ?

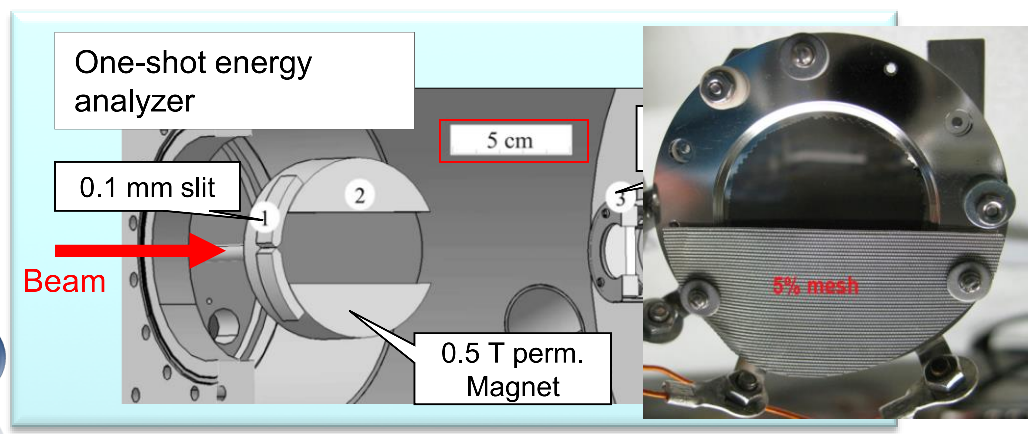
Why is a linear decelerator NOT simply a reversed accelerator?

- *the emittance grows*
- *narrow acceptance*
- *fast beams stay in*
- *low repetition rate*

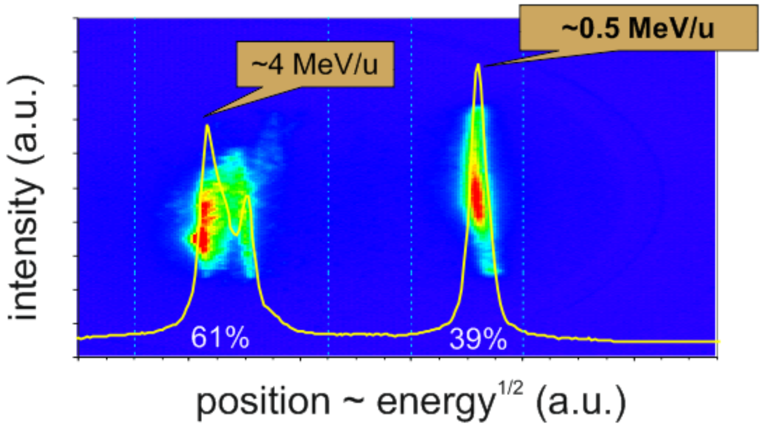
$$\iint \mathrm{d}x\mathrm{d}x' = \pi\epsilon \approx x\cdot x' \approx x\cdot\frac{p_x}{p_z}$$



16 On-Line Tests (3-7 days, 45 sec / shot) = 1 (one) hour of operation @ 50 Hz

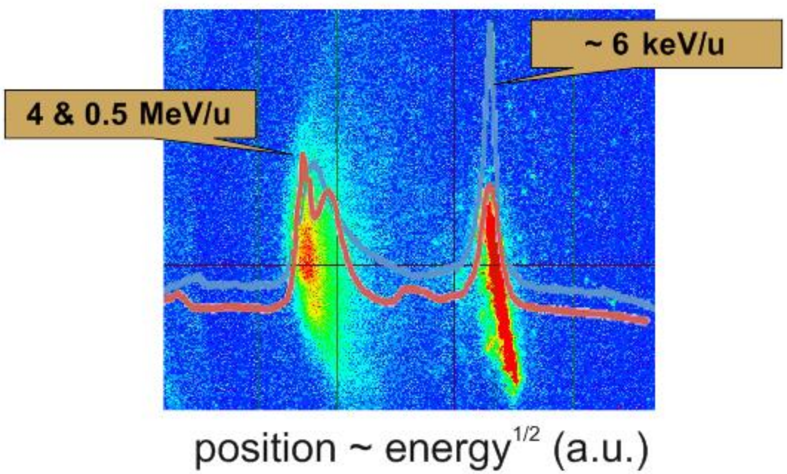


Commissioning of HITRAP



IH ↑

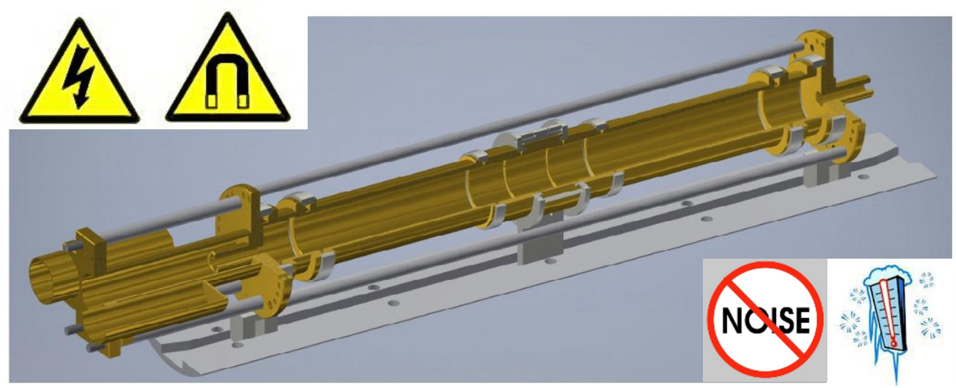
↓ RFQ



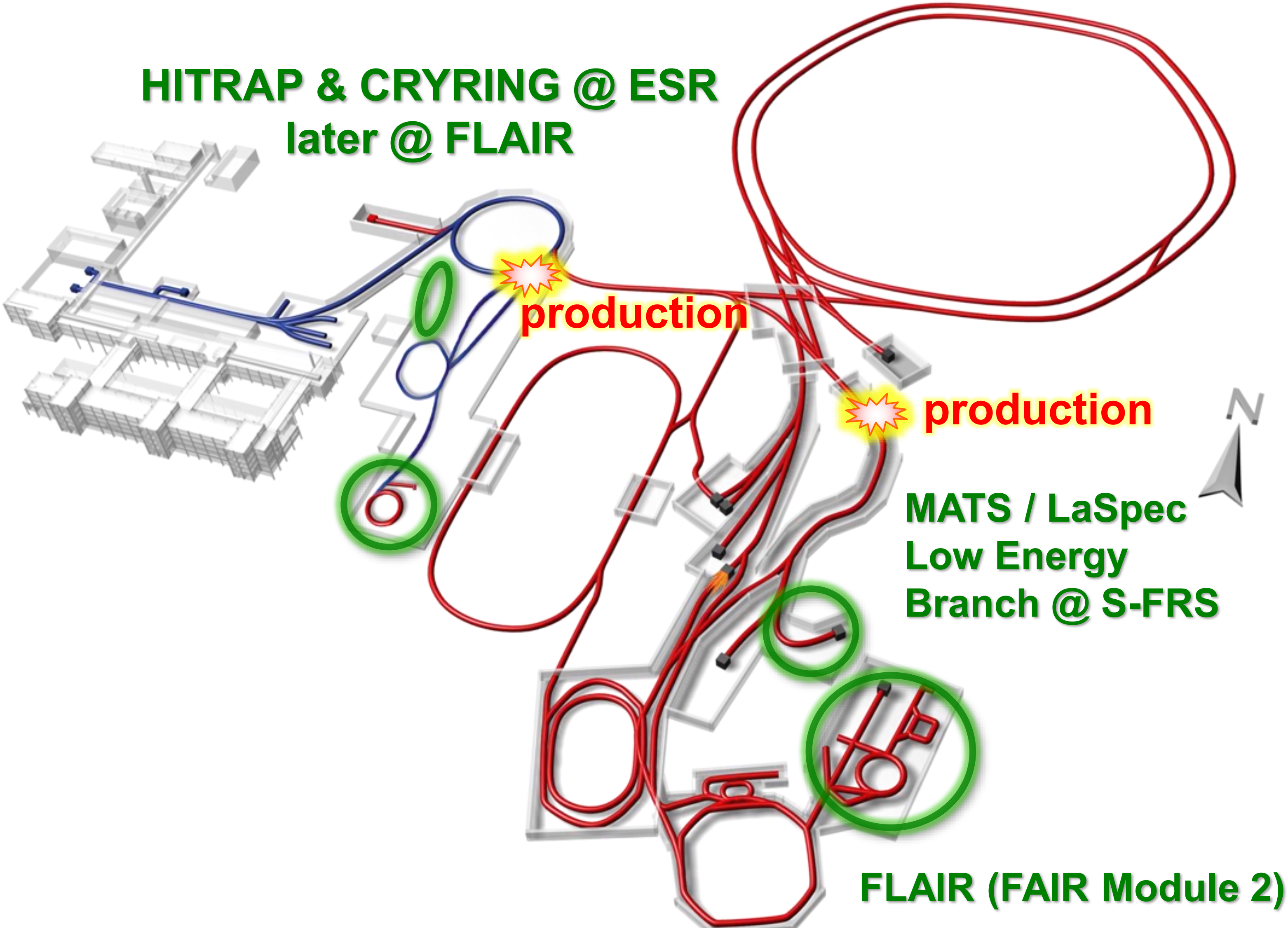
Decelerated beam characteristics	
Central energy	5-7 keV/u
1σ emittance	180 π mm mrad

ca. 20 m low-energy HCI transport beamline

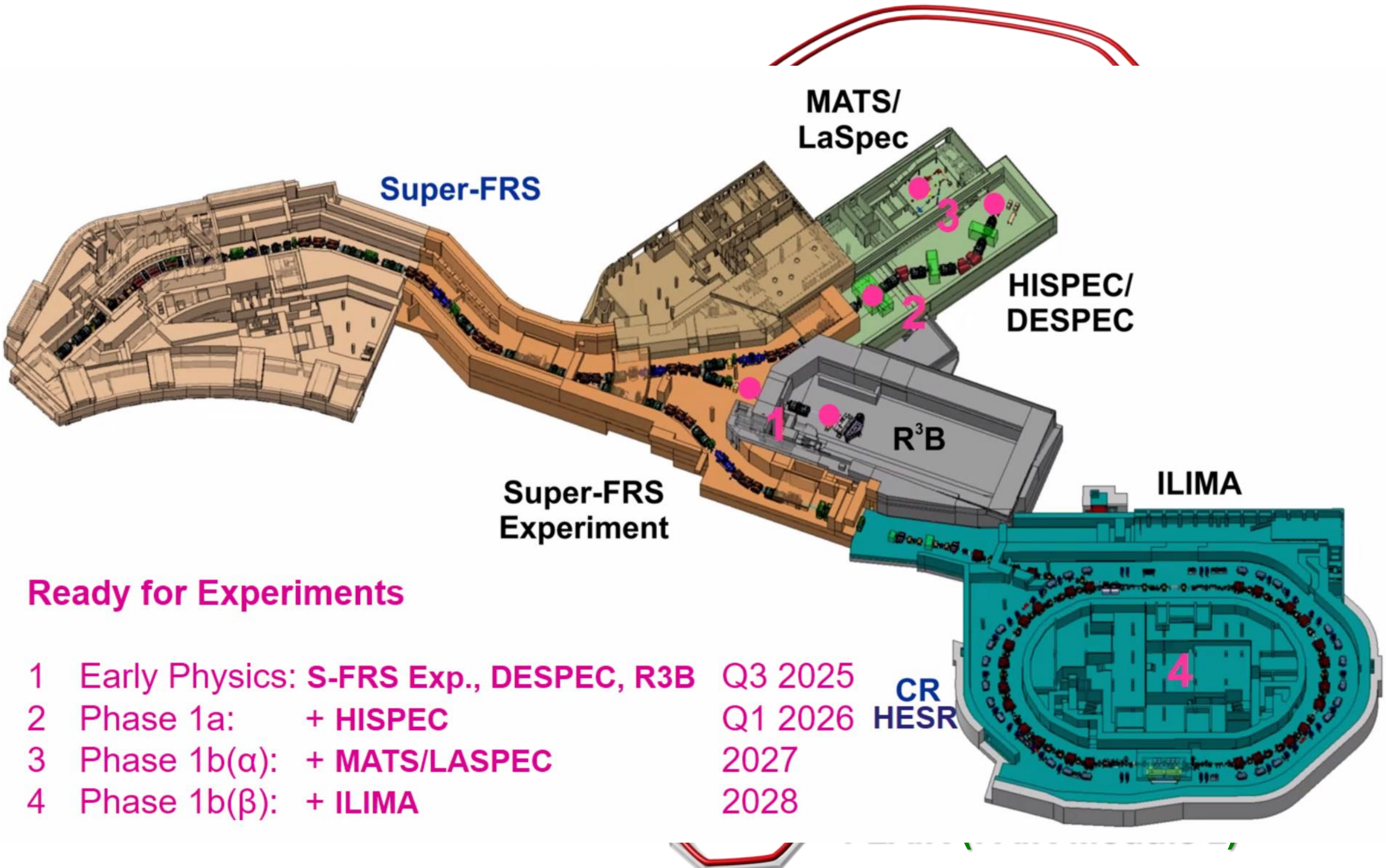
- energy and mass separation necessary
- focusing & diagnostic every meter
- 10^{-9} mbar (transport) - 10^{-12} mbar (trap)
- cooling for precision experiments



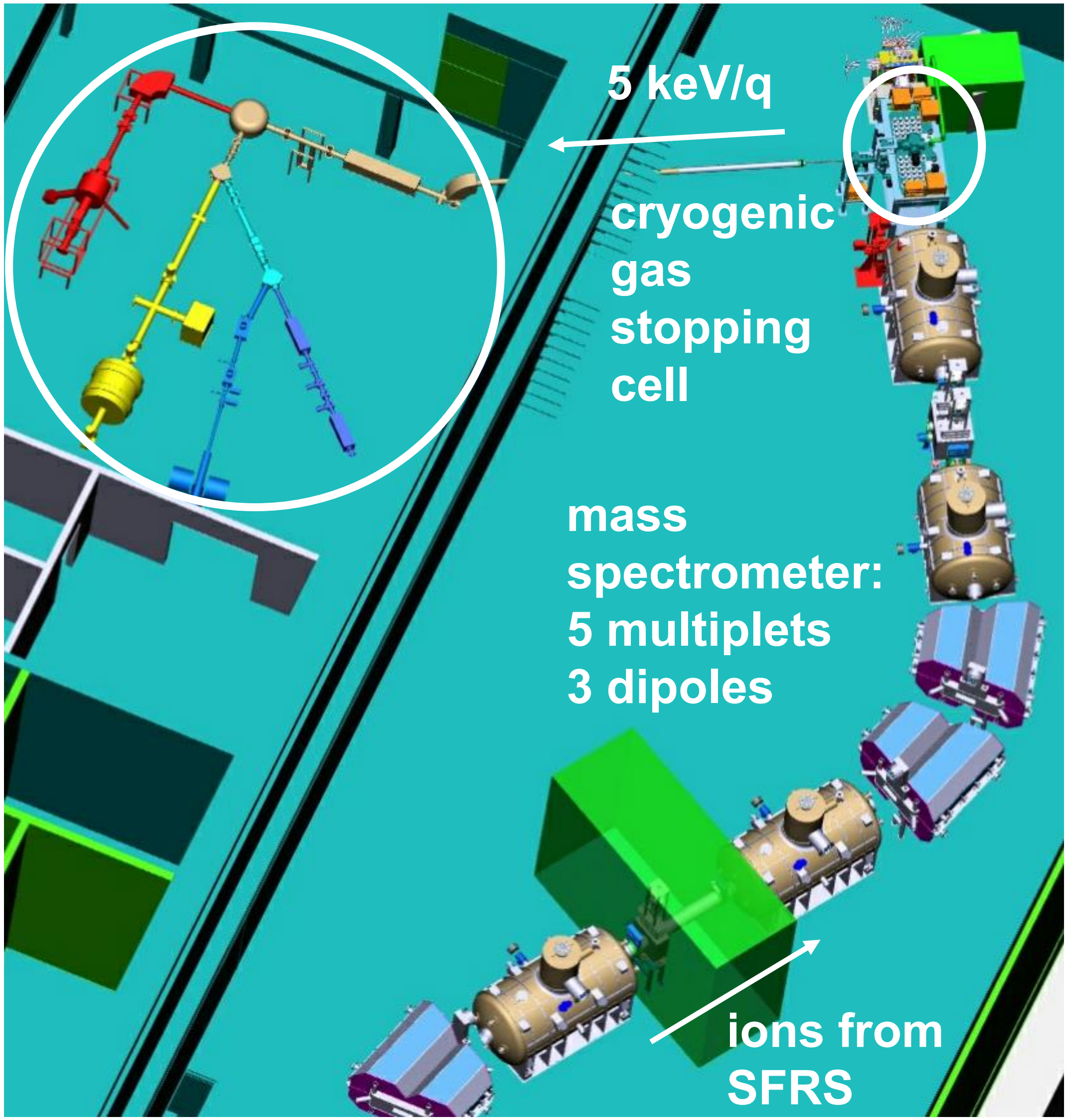
FAIR – low energy branch



FAIR – low energy branch



MATS-LaSpec @ FAIR



Investigation of r- and p-processes, e.g.

- Laser spectroscopy in the region Zr (Z=40) → Ag (Z=47)
- Mass spectrometry of yet unexplored, short lived isotopes