FAIR Accelerators

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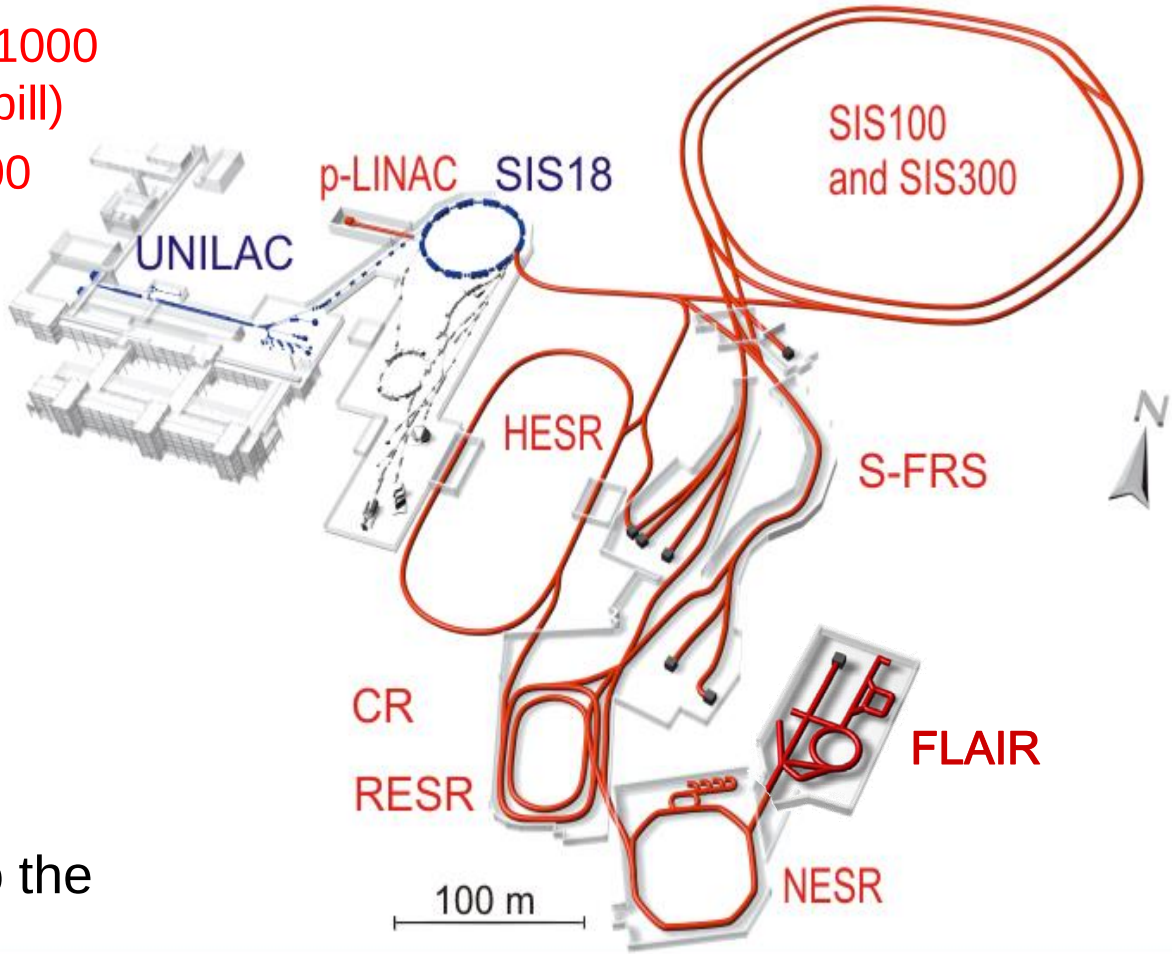
Outline

- (very) short FAIR introduction
- FAIR injectors
  - SIS18 upgrade
  - recent UNILAC improvements
  - FAIR phase 0
- FAIR accelerators
  - overview
  - procurement status
- Conclusion
- Extra slides (protons@fair and spill structure)

The Facility for Antiproton and Ion Research (FAIR)

- Beam intensity increase:
  - Primary beams: x 100 – x 1000 (5*10^{11} uranium ions per spill)
  - Secondary beams: x 10.000
- Beams:
  - Anti protons
  - Protons to uranium, RIBs
- Beam quality:
  - Cooled anti proton beams
  - Cooled, intense RIBs
- Beam pulse structure:

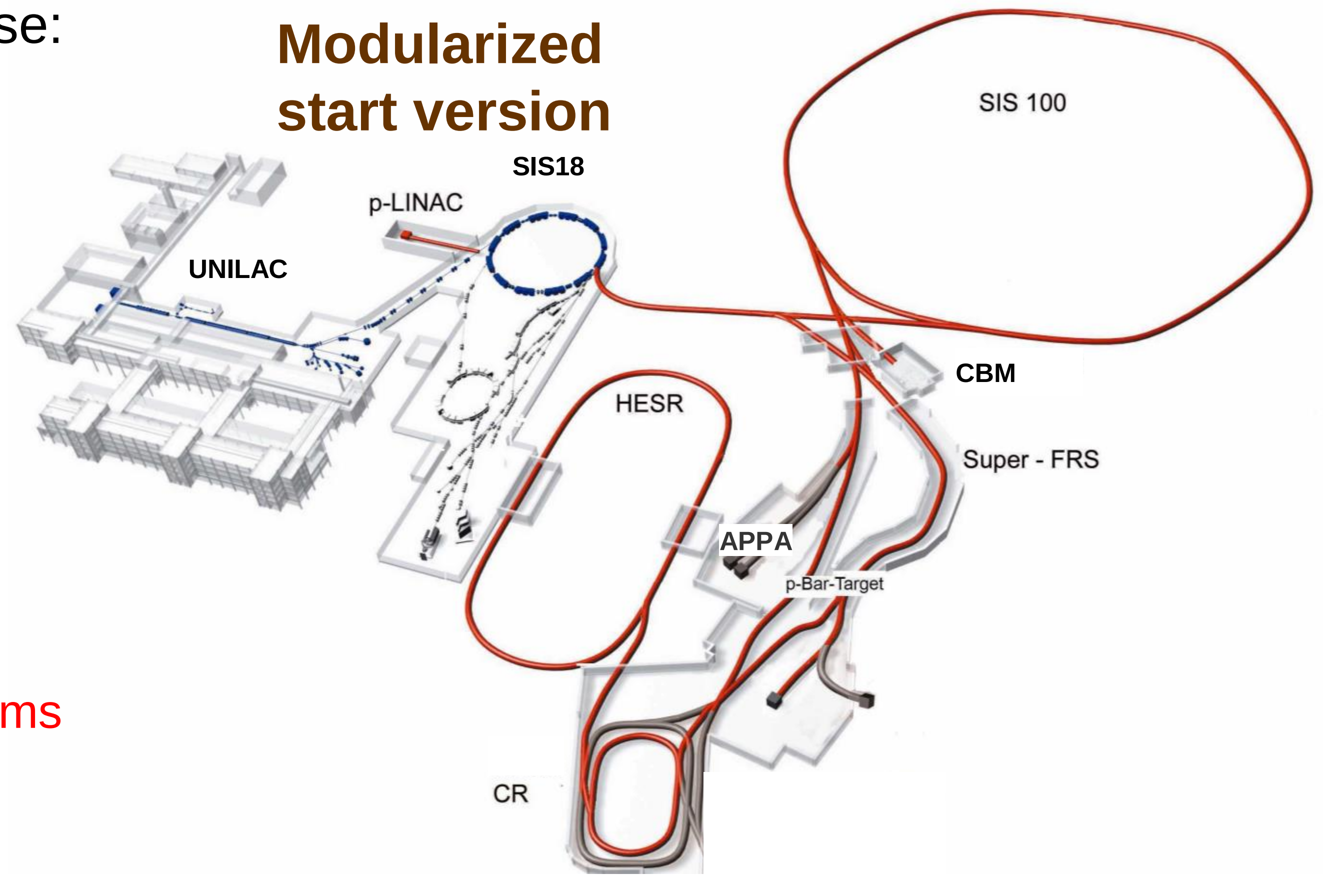
  extreme short pulses to
  quasi continuous
- 1.5 GeV/u ^{238}U beams to the S-FRS for instance



Requirements to the FAIR accelerators

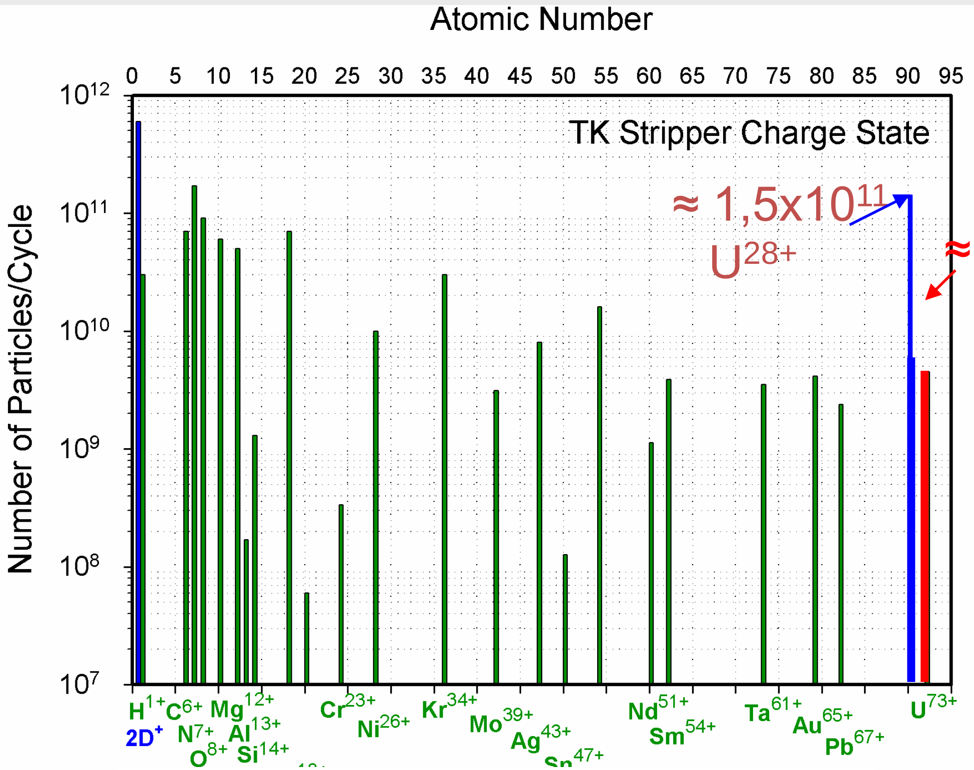
- Beam intensity increase:
  - Primary beams: x 100 – x 1000
  - Secondary beams: x 10.000
- Beams:
  - Anti protons
  - Protons to uranium
  - RIBs
- Beam quality:
  - Cooled anti proton beams
  - Cooled, intense RIBs
- Beam pulse structure:
  extreme short pulses to quasi continuous

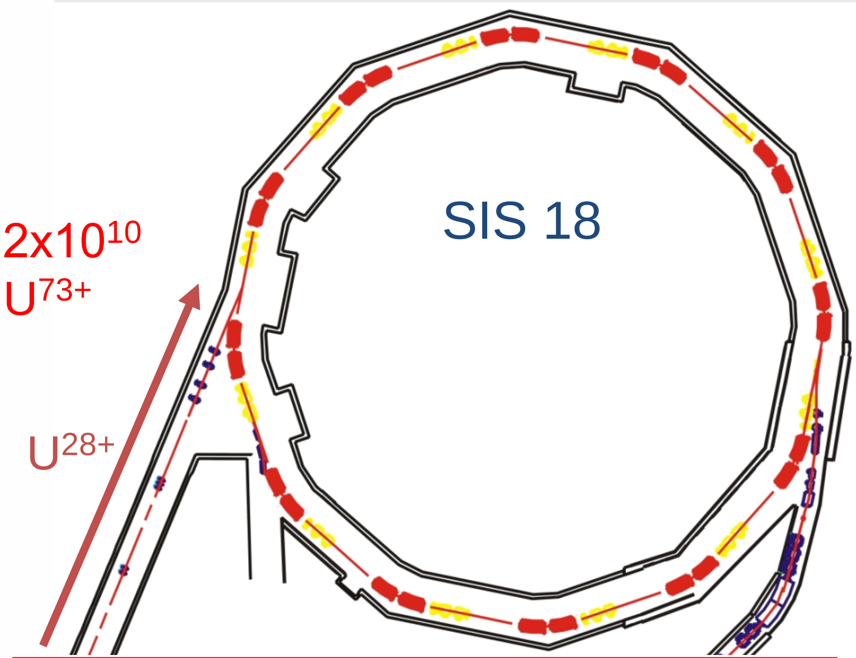
Modularized start version

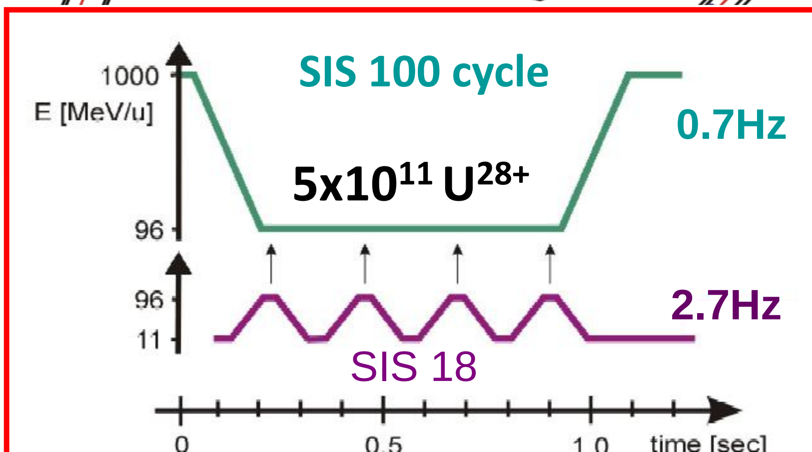


- Design ion beam: U^{28+} with 2.7 GeV/u, $5x10^{11}$ Ions/Cycle
- Protons up to 29 GeV
- Heavy ion beams up to about 11 GeV/u

SIS 18 as Injector for SIS 100







Choice of U^{28+} as design ion:

+ Lower space charge

  → higher intensity $N_{max} \sim A/Q^2$

+ No stripping losses

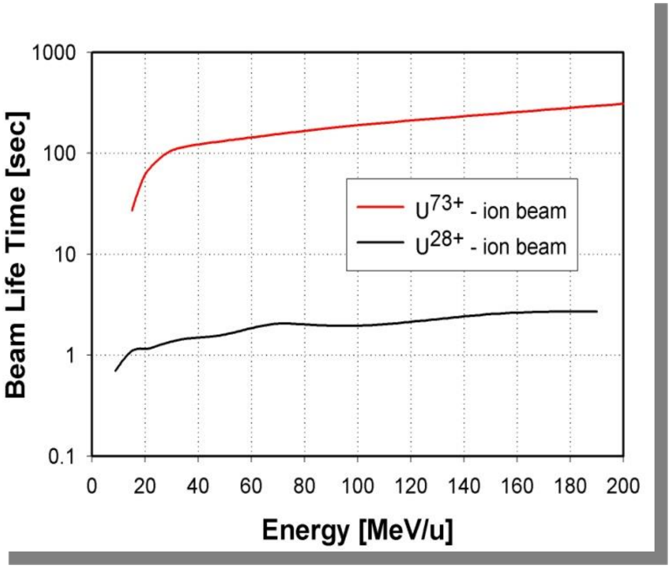
- Lower beam lifetime

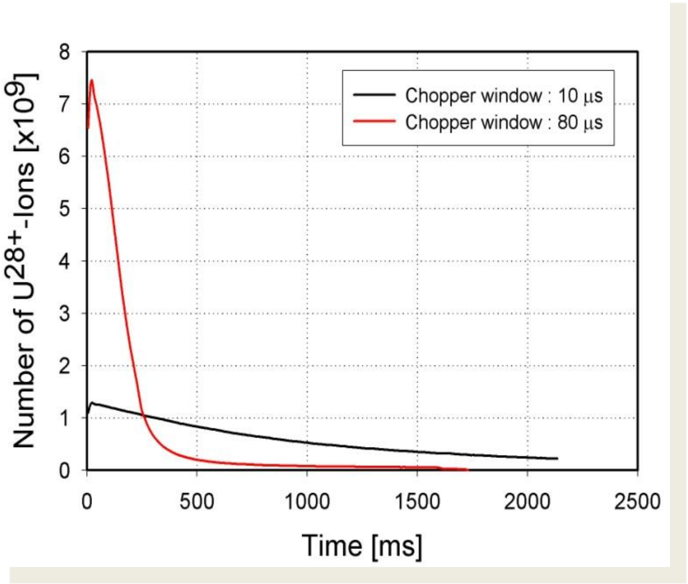
FAIR Requirements for SIS18

	Today	FAIR Booster	Today	FAIR Booster
Reference Ion	U^{73+}	U^{28+}	P	P
Maximum Energy	1 GeV/u	0.2 GeV/u	4 GeV	4 GeV
Maximum Intensity	$4x10^{9}$	$1.5x10^{11}$	$2x10^{11}$	$2.5x10^{12}$
Repetition Rate	0.3 - 1 Hz	2.7 Hz	0.3 – 1 Hz	2.7 Hz

Main challenge: Intermediate charge state heavy ions, dynamic vacuum and ionization beam loss

Life Time and Beam Loss:
dynamic vacuum effects limit ion intensities

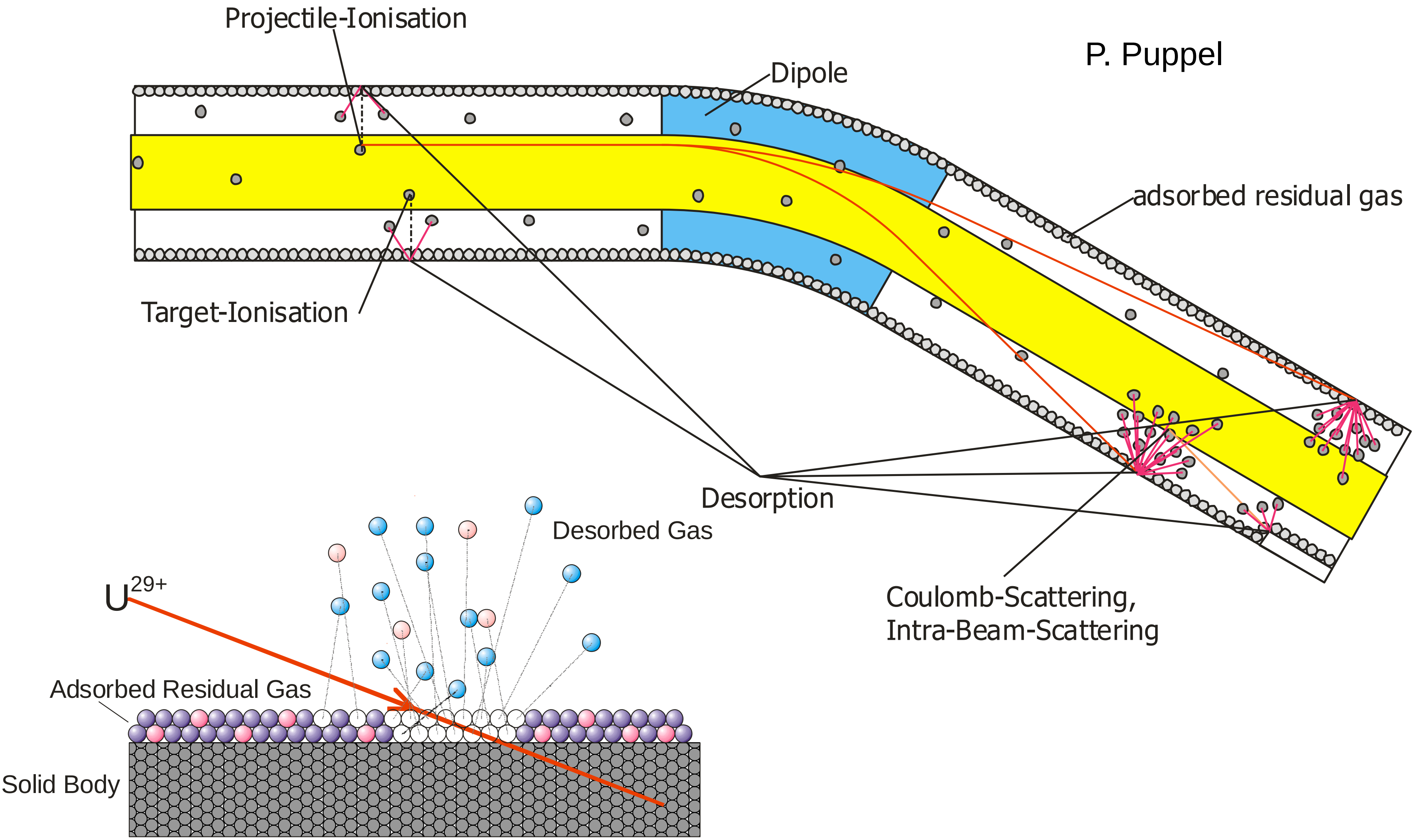




- **Life time of U^{28+} is significantly lower than of U^{73+}**
- **Life time of U^{28+} depends strongly on the residual gas pressure and composition**

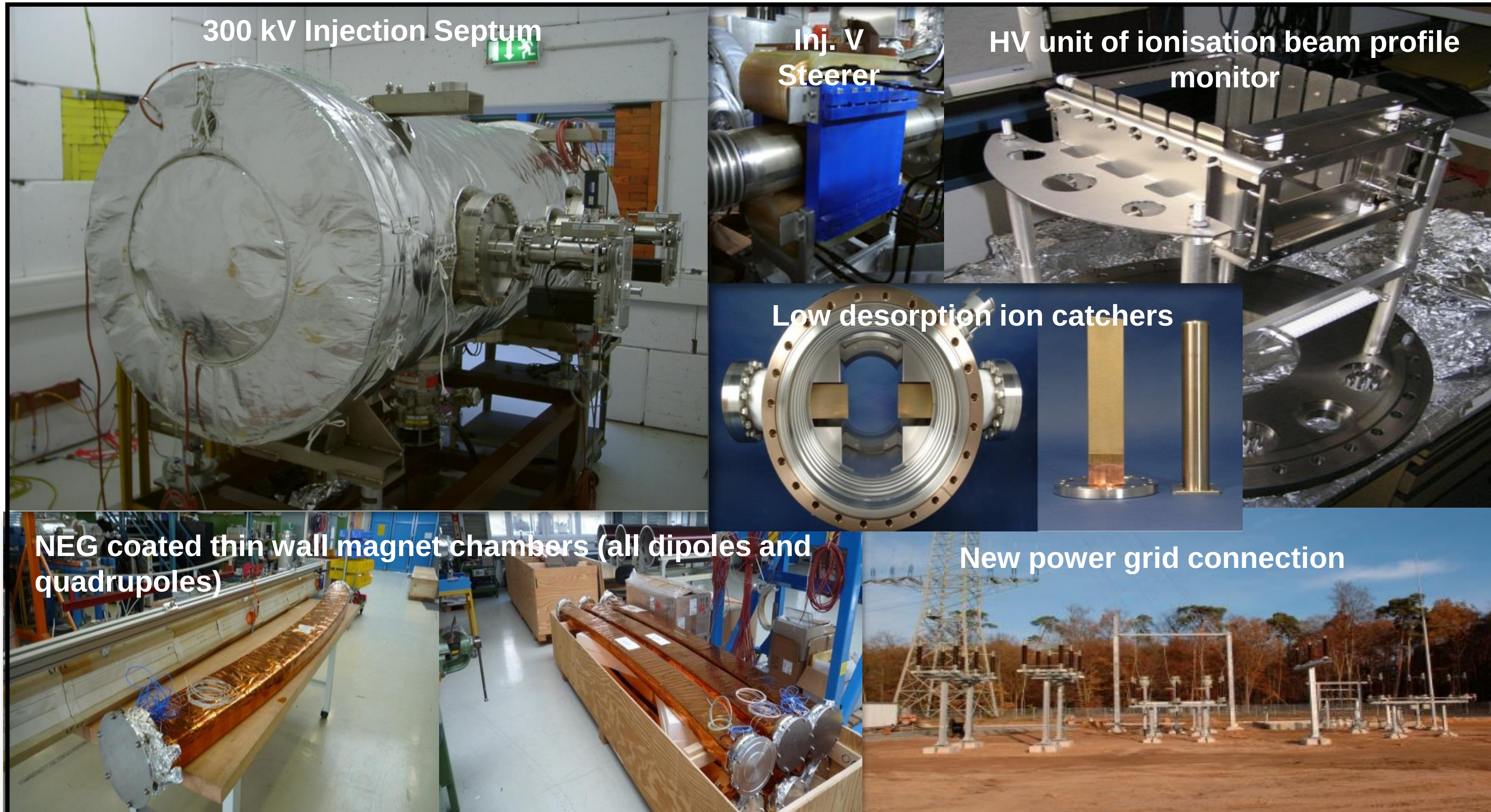
- **Ion induced gas desorption ($\eta \approx$ 10 000) increases the local pressure**
- **Beam loss increases with intensity (dynamics vacuum, vacuum instability)**

Dynamic Vacuum effect and collimation



SIS18 Upgrade Program 2005 - 2013

Dedicated to intermediate charge state heavy ion operation and FAIR booster operation

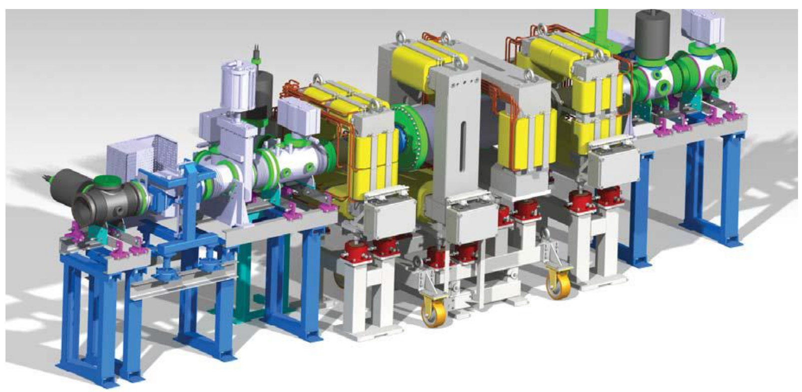


SIS18 Upgrade Program 2013 - 2017

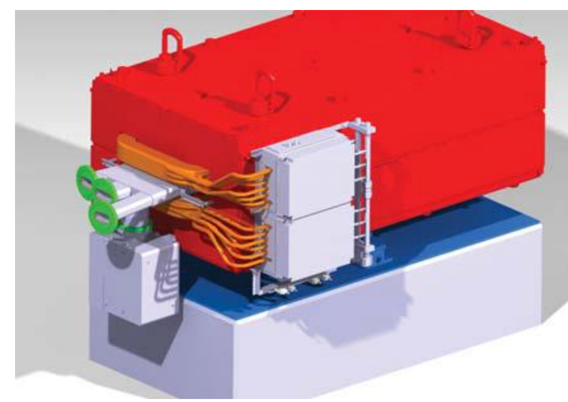
Dedicated to intermediate charge state heavy ion operation and FAIR booster operation

Three new MA acceleration cavities installed (50 kV, h=2)

Replacement of main dipole power converter completed (10 T/s, 50 MW)



SIS18/SIS100 IPM magnet system ordered



Bipolar dipole magnet for the link to tunnel 101

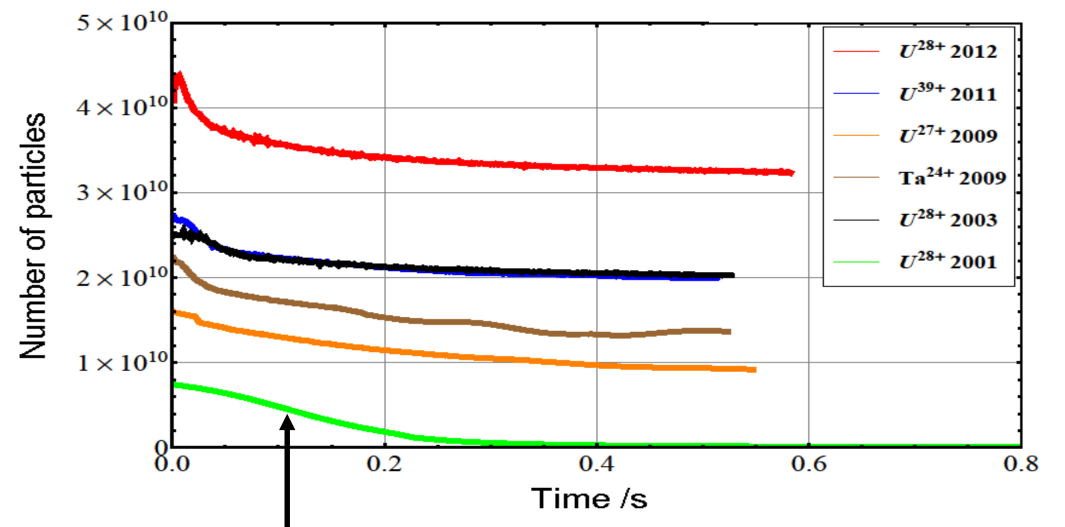
The originally defined SIS18upgrade program will be completed in 2018.

Status U^{28+} -Beam Intensity

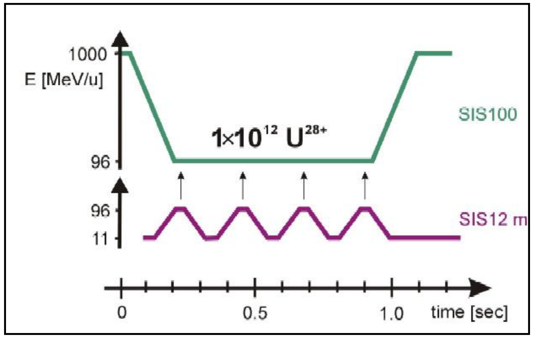
World record intensity for intermediate charge state heavy ions in heavy ion booster.

The feasibility of high intensity beams of intermediate charge state heavy ions has been demonstrated.

World record



2001 FAIR conceptual design report (FAIR proposal)



Stacking in SIS100 (4x)

SIS100 commissioning:

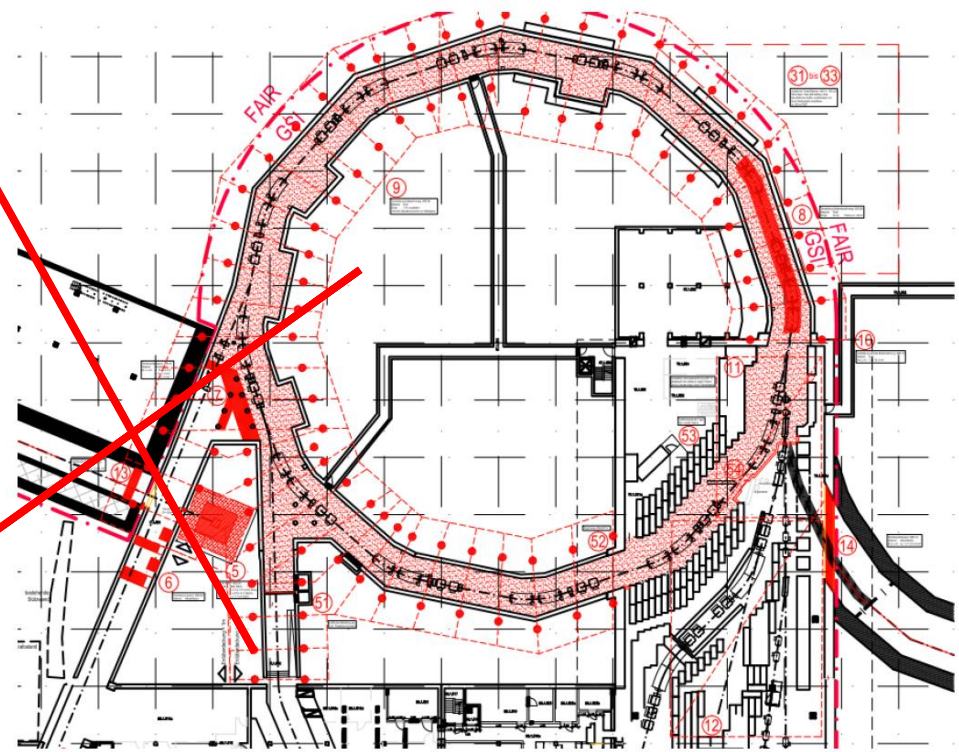
An intensity of U^{28+} of 1-2 x10^{11} per cycle is already possible today.

Further upgrade measures are required for reaching the goal for the most heavy ions (e.g. Uranium with 1.5x10^{11} per cycle at a (high) repetition rate of 2.7 Hz.)

SIS18 Civil Construction 2016/2017

Link existing facility –
civil construction comprises:

-the shielding enhancement by means of a
    table construction on top of the existing
    tunnel
-other radiation protection measures
    e.g. steel plates below extraction system
-under pressure generation in the tunnel
    (treatment possibly activated air)
-link to FAIR via new tunnel "101"



-Consequences from Heuer review:
1. all measures for the connection of the p-Linac are removed and postponed
2. a staged (two stage) upgrade of the shielding in the TR hall:
    a) operation between 2017- 2021 (FAIR phase 0)
    b) FAIR operation 2021 -> "11@2022" (11 main Experiments in 2022)
    (at the beginning with limited p and U-intensities)

Staged Beam Intensity Increase

Case a) Experiment Operation 2018 – 2021 (FAIR Phase 0)

Basis:

Operation with TK stripper (highly charged ions)
Routine operation with high ramp rates (1.3 T/s > 10 T/s)
No high repetition modes (limit 1 Hz) (or with restricted intensity per cycle)
Operation with two Rf harmonics (enhanced space charge limit)
Improved slow extraction efficiency
Enhance gas pressure in post stripper

Case b) Booster Operation 2021... (FAIR Module 1 – First FAIR Experiments)

Basis:

Operation without TK stripper (intermediate charge states)
Routine operation with high ramp rates (10 T/s)
Maximum repetition rate (2.7 Hz)
Betrieb ohne TK Stripper (niedrig geladene Ionen)
Routinebetrieb mit hohen Rampraten (10 T/s)
Operation with two Rf harmonics
Improved slow extraction efficiency
Enhanced gas pressure in post stripper

Staged Beam Intensity Increase

Protons		SIS operation today	SIS operation after upgrade (2017-2021)	SIS operation booster mode >2021
Reference Ion		p	p	p
Maximum Energy		4,7 GeV	4,7 GeV	4,7 GeV
Linac Current		1 emA	3 emA	70 emA (**)
Maximum Intensity per Cycle		$2{\cdot}10^{11}$	$1{\cdot}10^{12}$	$6{\cdot}10^{12}$
Magnet Cycle	Fast Extraction	2,8 s 0,36 Hz	0,45 s 0,1 Hz (*)	0,45 s 2,2 Hz
	Slow Extraction (5 s Spill)	7,8 s 0,13 Hz	5,45 s 0,09 Hz	-
Maximum Intensity per Second	Fast Extraction	$7{,}2{\cdot}10^{10}$ /s	$1{\cdot}10^{11}$/s	$5{\cdot}10^{12}$/s (***)
Maximum Intensity per Second	Slow Extraction	$2{,}6{\cdot}10^{10}$ /s	$9{\cdot}10^{10}$ /s	-
Slow extr. efficiency (**)		50 %	75 %	-

(*) Limitiert. maximal possible 2.2 Hz – no user for high rep. rate and fast extraction known
(**) from p-Linac at 70 MeV
(***) Determined by SIS100 cycle

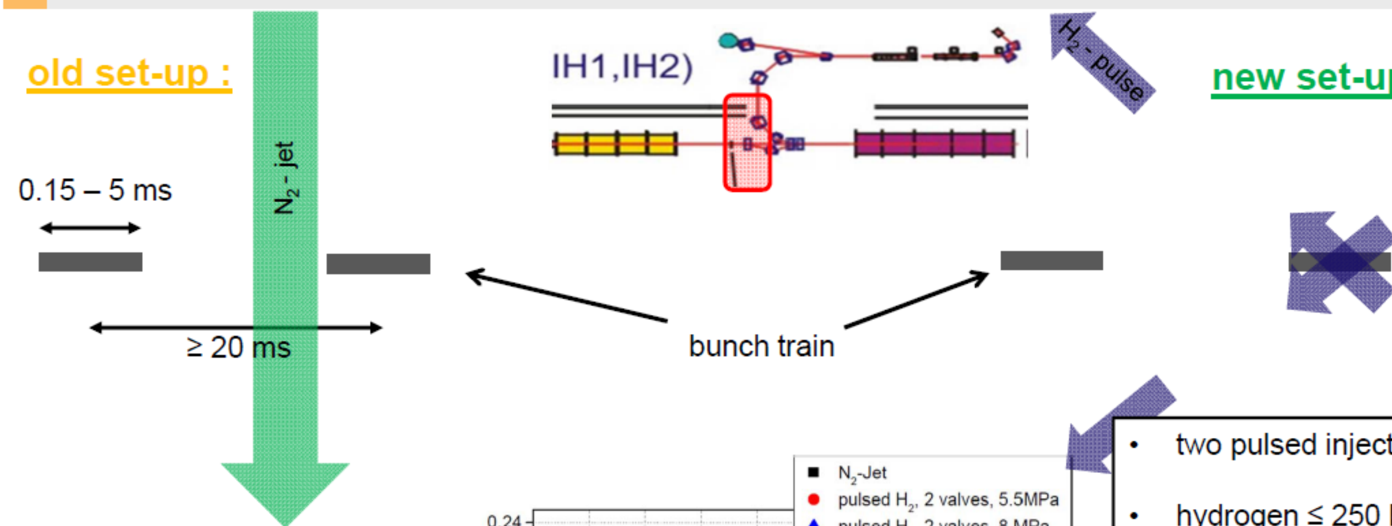
Staged Beam Intensity Increase

Uranium		SIS operation today	SIS operation after upgrade (2017-2021)	SIS operation booster mode >2021
Reference Ion		U^{73+}	U^{73+}	U^{28+}
Maximum Energy		1 GeV/u	1 GeV/u	0,2 GeV/u
UNILAC Current		1 emA	3 emA	15 emA
Maximum Intensity per Cycle		$4 \cdot 10^{9}$	$1{,}5 \cdot 10^{10}$	$1{,}5 \cdot 10^{11}$
Magnet Cycle	Fast Extraction	2,2 s 0,46 Hz	0,37 s 1 Hz (*)	0,37 s 2,7 Hz
	Slow Extraction (5 s Spill)	7,2 s 0,14 Hz	5,37 s 0,19 Hz	-
Maximum Intensity per Second	Fast Extraction	$1{,}8 \cdot 10^{9}$ /s	$1{,}5 \cdot 10^{10}$ /s	$3 \cdot 10^{11}$ /s (**)
Maximum Intensity per Second	Slow Extraction	$5{,}6 \cdot 10^{8}$ /s	$2{,}8 \cdot 10^{9}$ /s	-
Slow extr. efficiency		50 %	75%	

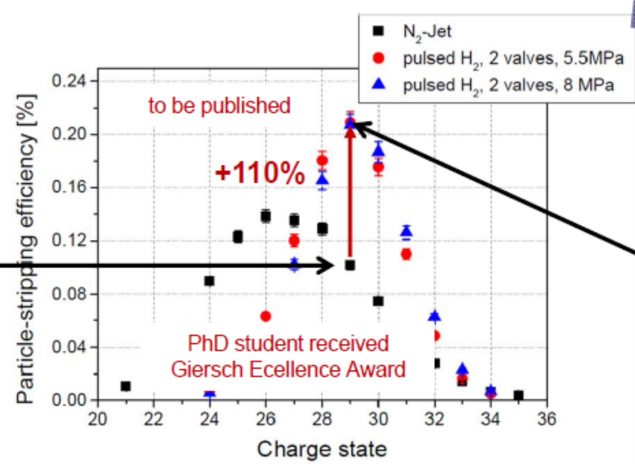
(*) Limitiert, maximal möglich: 2.7 Hz
(**) Determined by cycle time SIS100

PROGRESS UNILAC Intensities

High Pressure Pulsed Gaseous Stripper Cell



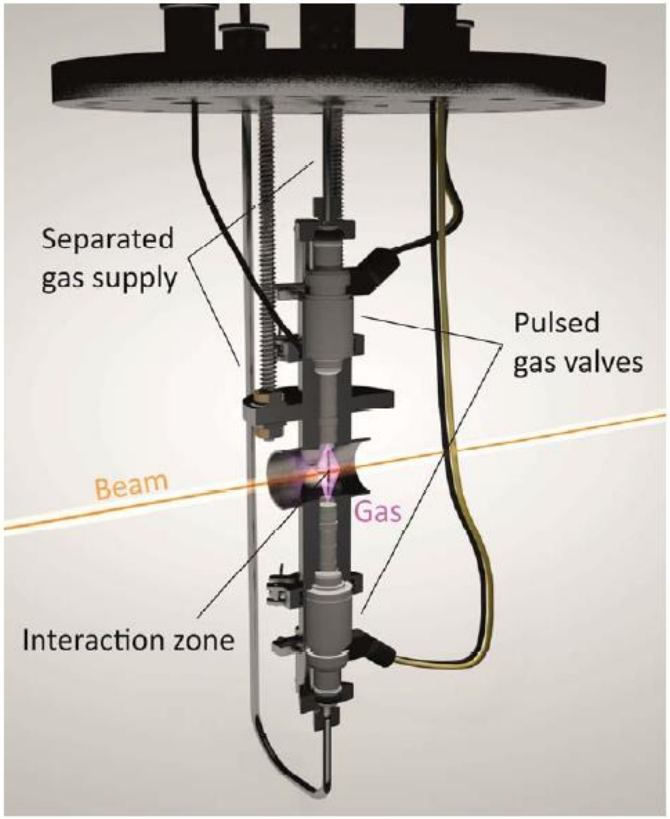
- one single continuous jet
- nitrogen 4 bar
- stripper parameters are constant

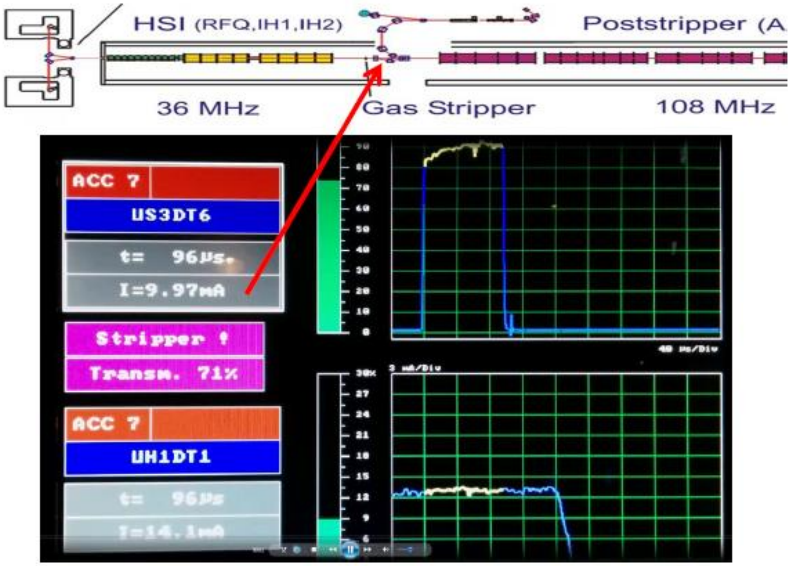


- two pulsed injections
- hydrogen ≤ 250 bar
- higher density @ beam, but lower avarage gas load at pumps
- variable pressure, duration, and rep.rate
- pulse-to-pulse variation of stripper parameters

PROGRESS UNILAC Intensities

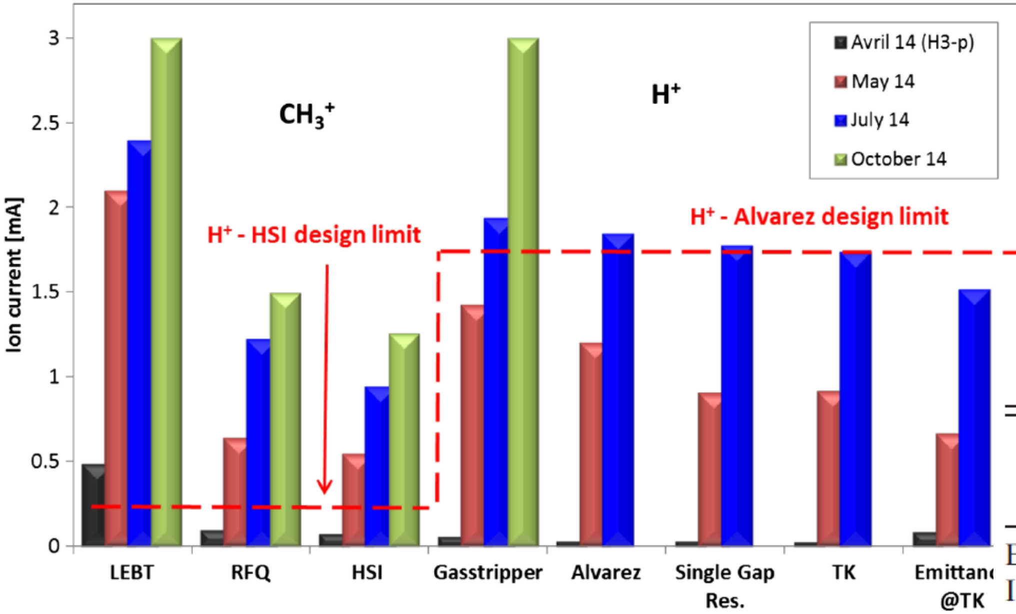
High Pressure Pulsed H_2 Stripper Cell





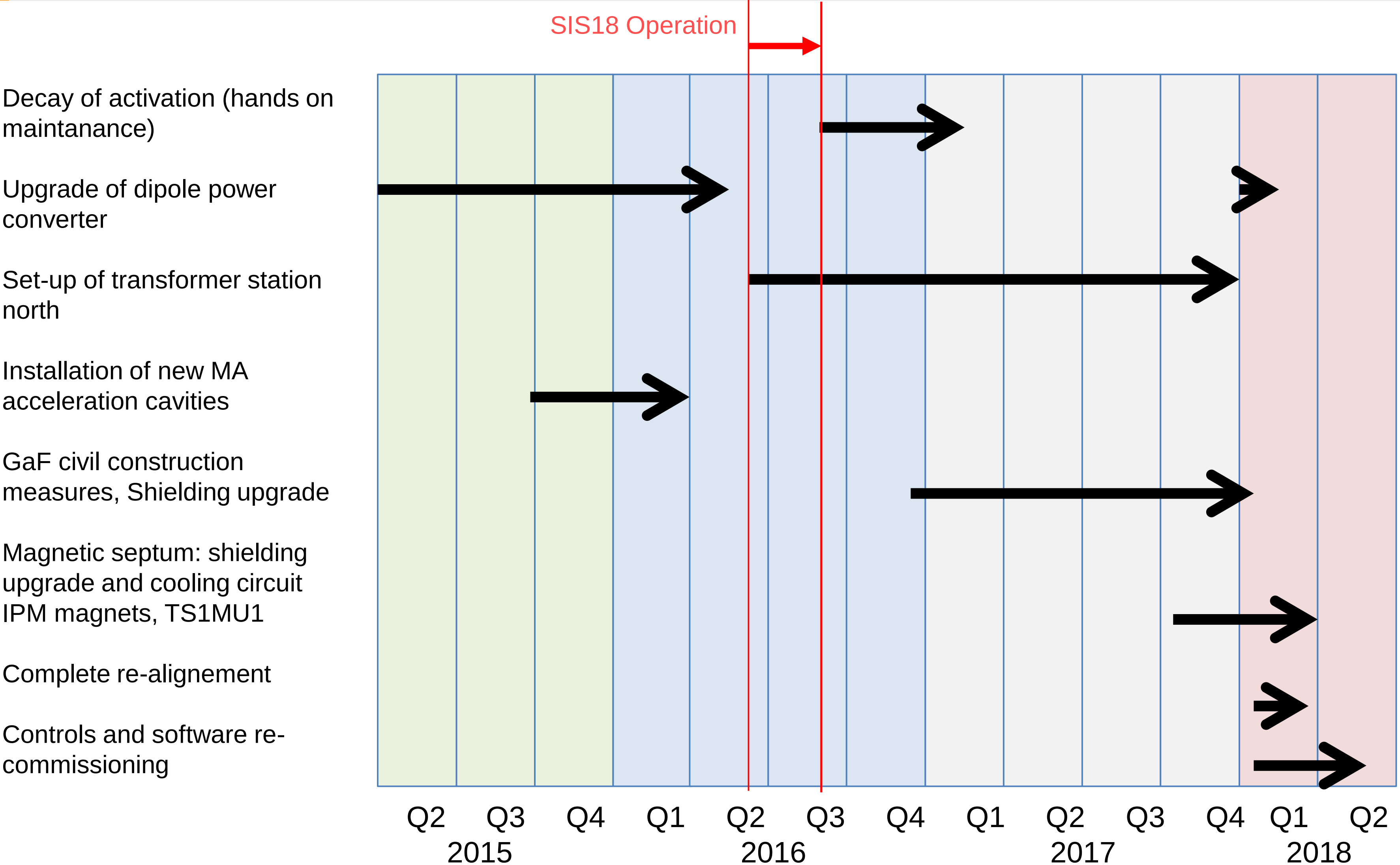
- 9.5(5) mA of U^{29+} achieved behind stripper
- 2016: injecting this beam into SIS18
- temporary stripper set-up to be integrated into routine operation until 2018

PROGRESS UNILAC p Intensities



	p-LINAC	UNILAC		
	Design	**Measurement**		Extrapolation
E [MeV]	70	**11.4**	**20**	20
I [mA]	35	**2**	**2**	3
$E_{x\ phys}$ 4 rms [mm mrad]	7	**7**	**3**	3
$E_{y\ phys}$ 4 rms [mm mrad]	8	**8**	**3**	3
SIS18 MTI output (N)	5.8×10^{12}	8.2×10^{11}	9.7×10^{11}	1.5×10^{12}
Space charge limit (N)	5.8×10^{12}	8.7×10^{11}	1.5×10^{12}	1.5×10^{12}
SIS100 output	1.8×10^{13}	2.4×10^{12}	2.9×10^{12}	4.5×10^{12}
SIS100 output (relative)	100%	13.0%	16.0%	25.0%

SIS18 Schedule – Status Q2 2016



Recommissioning of the existing facility in 2018 and Operation in Phase 0

SIS18 and ESR need to be „recommissioned“ in 2018

- The complete control system is been modernized now (LSA Framework).
- New FAIR timing system will be used (BUTIS, White Rabbit).
- Many old front end electronics are being replaced.

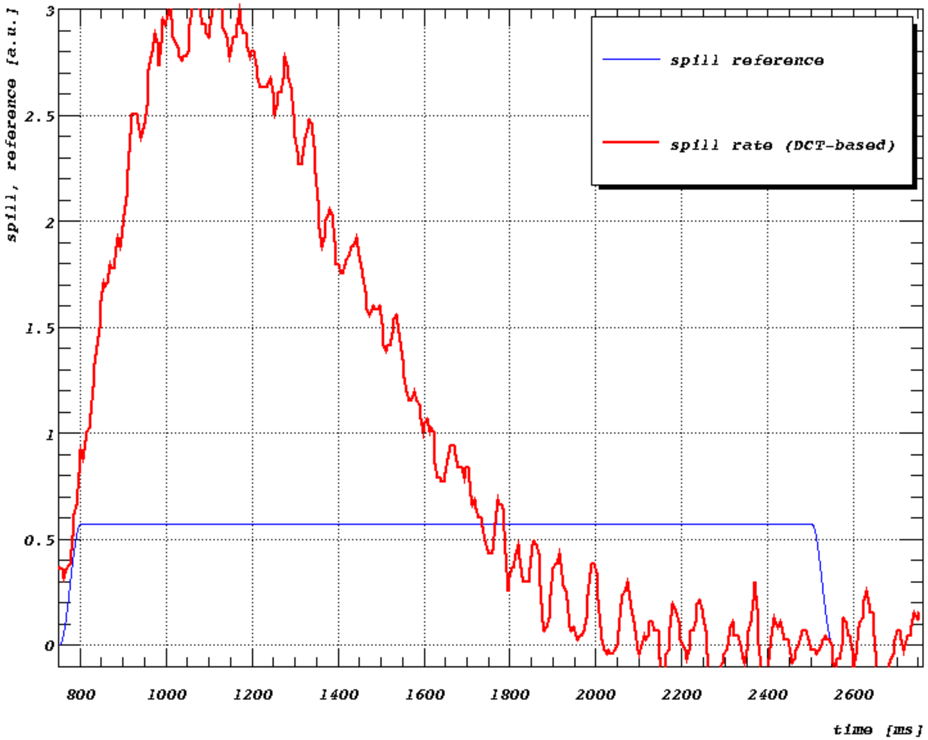
Good news:

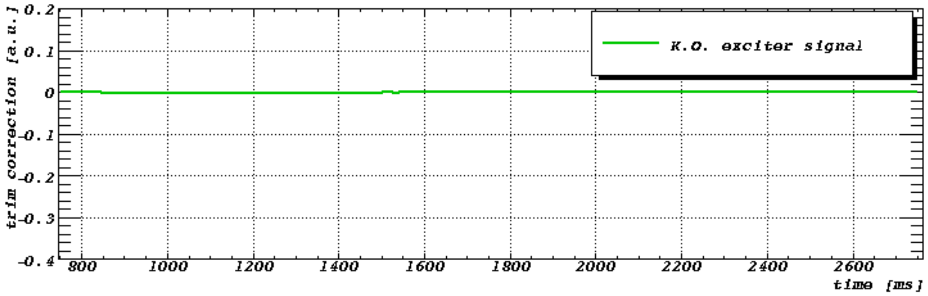
- The new data supply has been already tested in various machine experiements and works very well.
- Many modern devices already use new frontends today
- The Cryring was successfully tested (only basic operation) some weeks ago with new software and FAIR timing system.

What can we already do with the new FAIR control system?

- Fun with LSA:
slow extraction profile „optimized“ with a feed forward algorithm during 2016 machine experiments.

(R. Steinhagen, D. Ondreka, B. Schlei, H. Liebermann et. Al.)





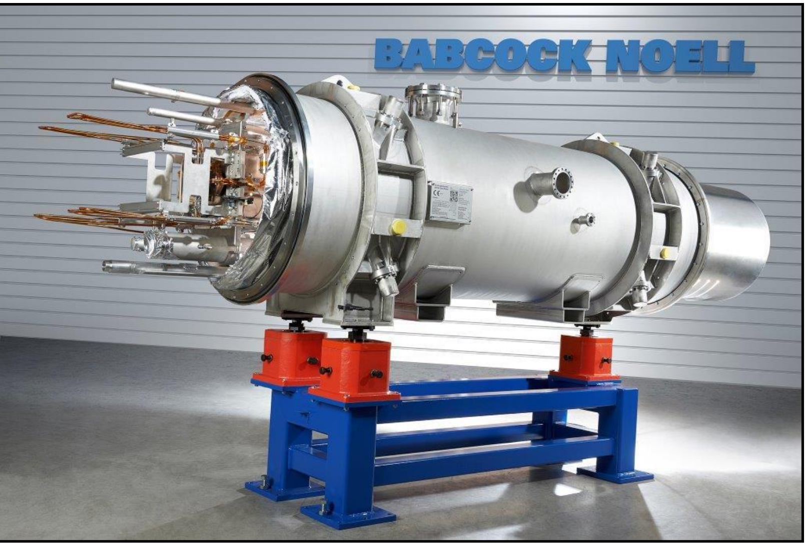
Status of FAIR accelerators and procurement

All prepared! What about FAIR now?

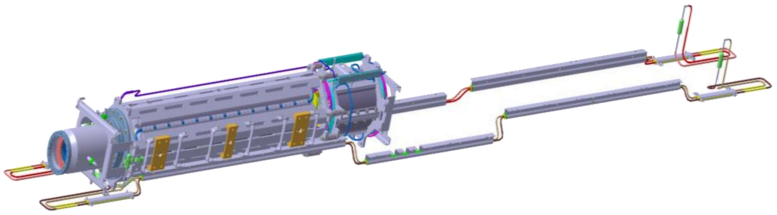
- As Klaus Peters already reported yesterday experiments are well set up for FAIR phase 0 and full operation (and he was bold enough to show a schedule) .
- The international partners agreed to the baseline project.
- A full schedule will be prepared till end of 2016 aiming for 11@2022.
- First applications for building permits are submitted now.
- Link existing facility (SIS18 to SIS100) building permit granted. Internal pre-work has started and project will start end of the year.

Overview of accelerator procurement ->

Procurement Highlights SIS100



SIS100 s.c. dipol magnet:
Release of series production in July 2016



SIS100 s.c. quadrupole units production started at JINR

First SIS100 bunch compressor cavity delivered

First cryogenic bypass line ready for shipment

All main magnets, all main Rf and all injection devices under contract. 50 % of M3 and M4 milestones achieved. 65 % of SIS100 value under contract.

Laser Cooling @SIS100

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

TECHNISCHE UNIVERSITÄT DARMSTADT

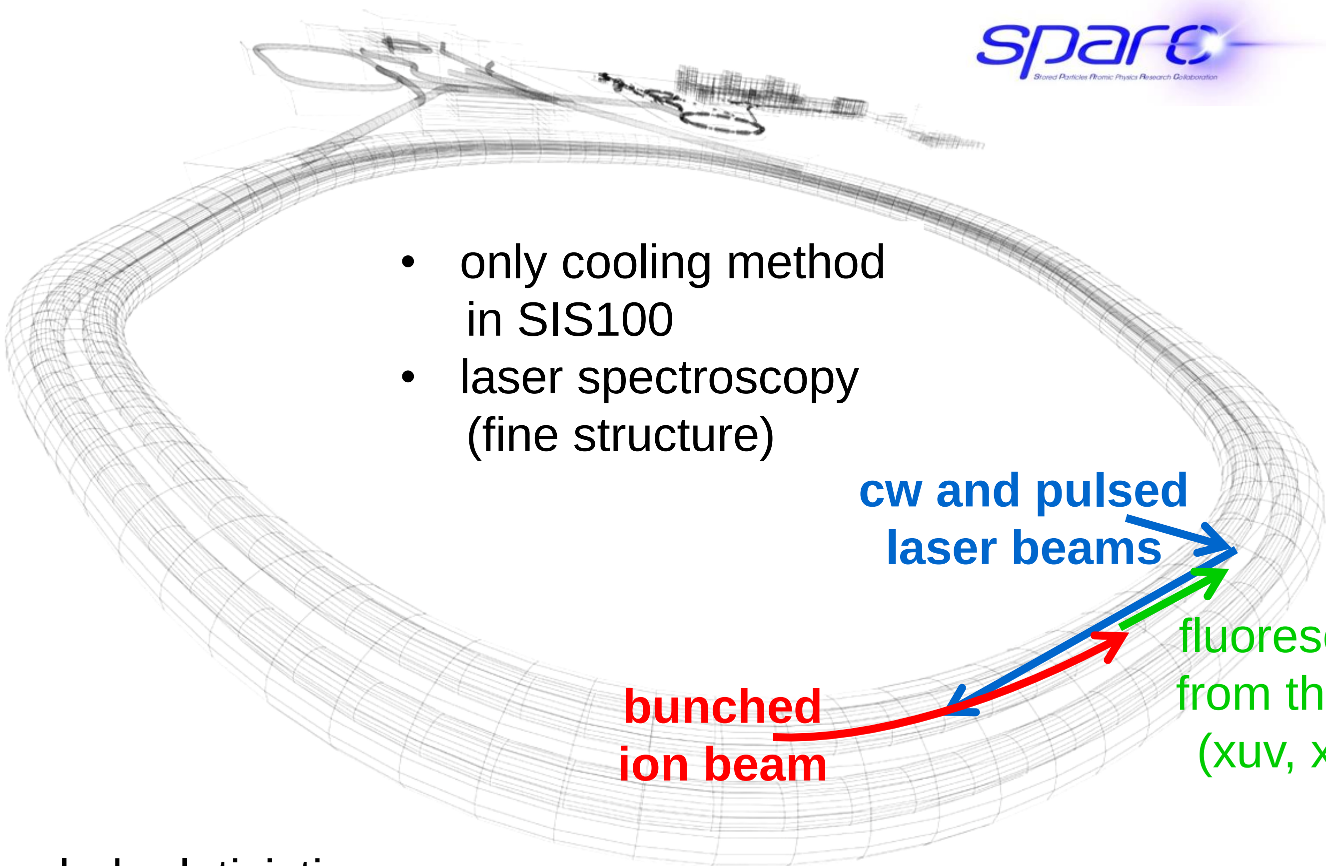
Westfälische Wilhelms-Universität Münster

sparc

Funding:
BMBF
POFIII ARD

HELMHOLTZ ASSOCIATION
Helmholtz Institute Jena

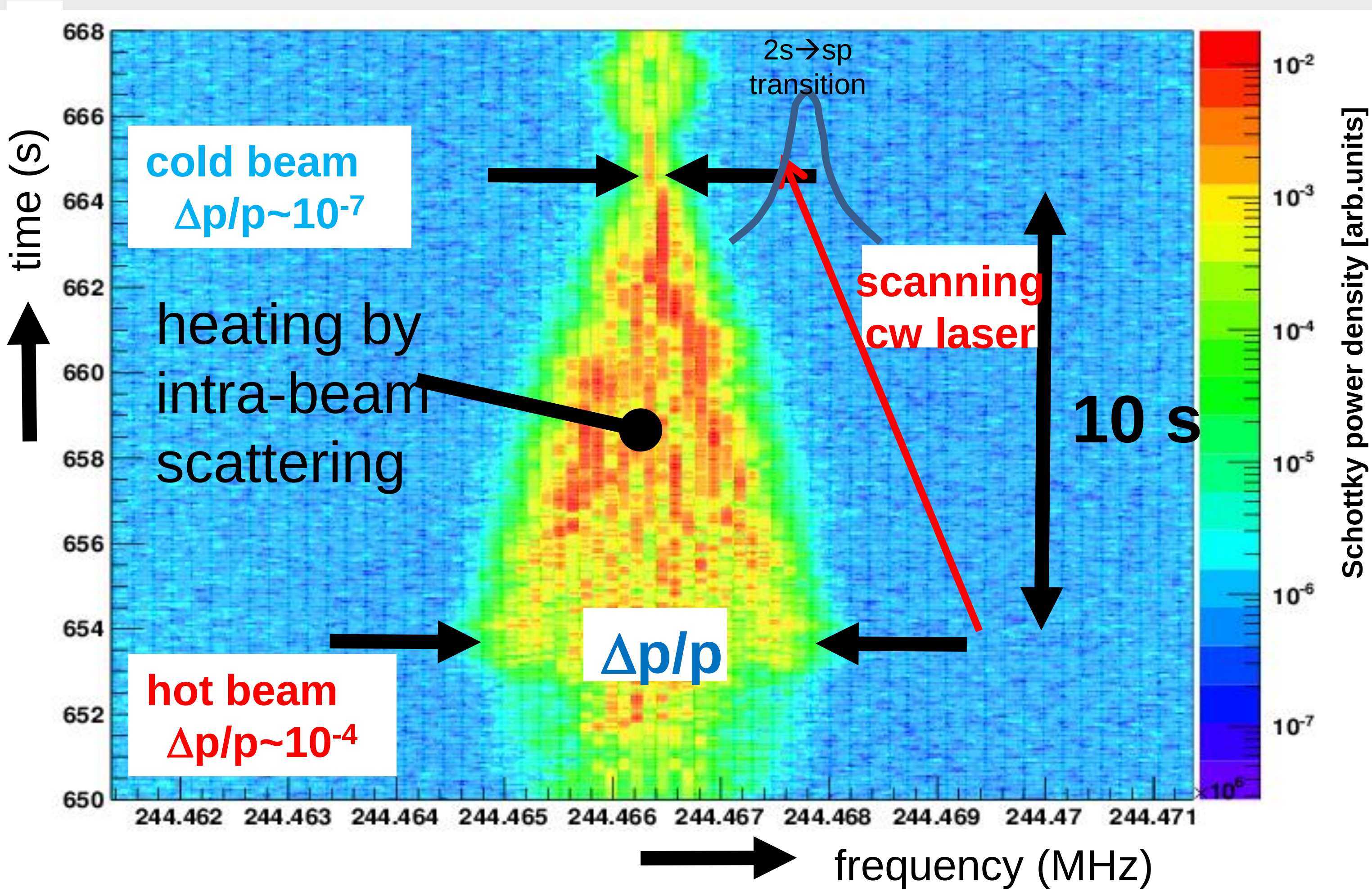
- only cooling method in SIS100
- laser spectroscopy (fine structure)



- laser-cooled relativistic heavy ion beams
- Z_{ion}= 10 – 60 (3 – 19 electrons)
- γ up to 13 (huge Doppler-shift)

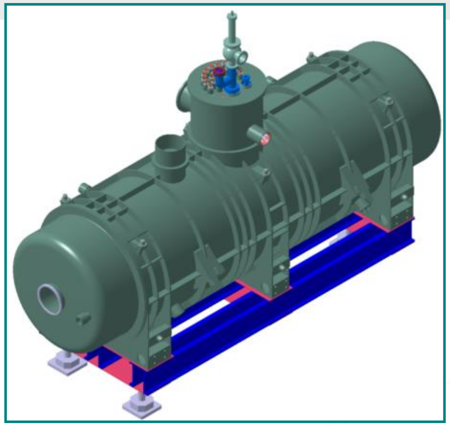
- extraction of very cold and very short ultra-relativistic ion bunches

C^{3+} ions stored in the ESR, 122 MeV/u, scanning the laser frequency



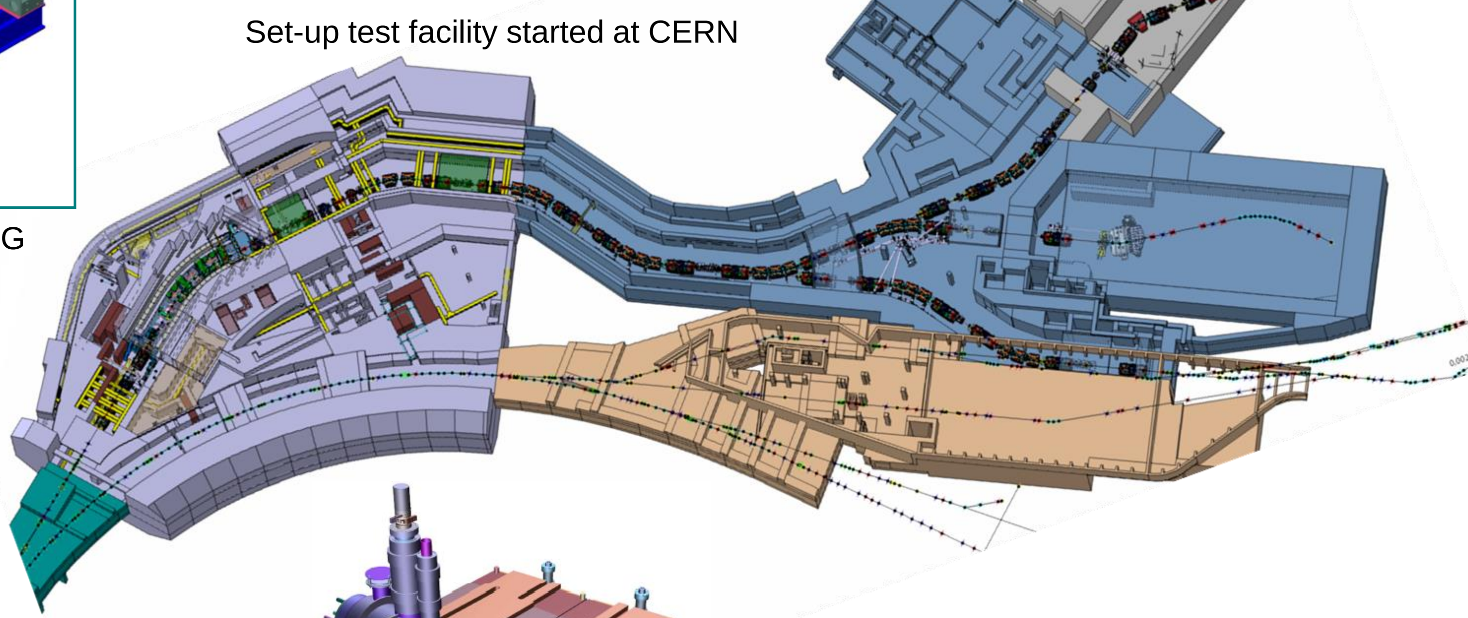
In general, within a few seconds, the scanning laser can effectively cool all the ions in the bunch. If the laser scans faster, or if a pulsed laser is used, this greatly improves!

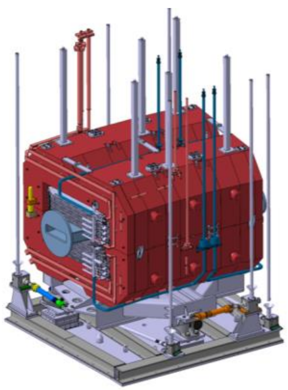
Super FRS



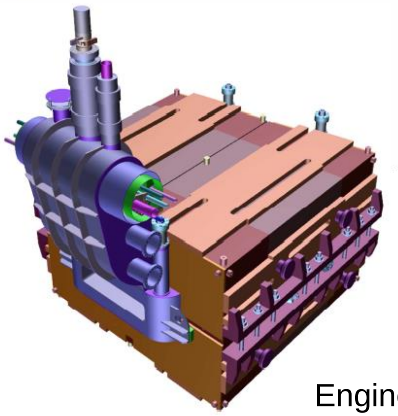
S.c multiplett awarded to ASG

Set-up test facility started at CERN





Radiation hard dipole.
Prototype und testing.
Tendering on short term.



Engineering design completed by
CEA, Tendering on short term

p Linac status

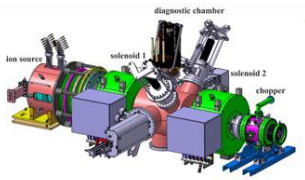
After the „Heuer review“, excecution of project has been limited to the so far started activities.

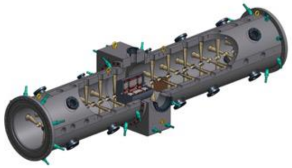
Modulator:
Lease Modulator from CERN is at GSI
Prototype Modulator needs to be tendered

Klystron:
1st already at GSI
Last Klystron in late 2016

Quadrupole Magnets:
Already ordered
Delivery until 2018

CH cavities:
Design is almost ready
Waiting for tendering
2 Years until first cavity is delivered





4-Vane RFQ:
Could have been build by INFN Legnaro
3 Years for production
IAP, Frankfurt is building a Ladder RFQ

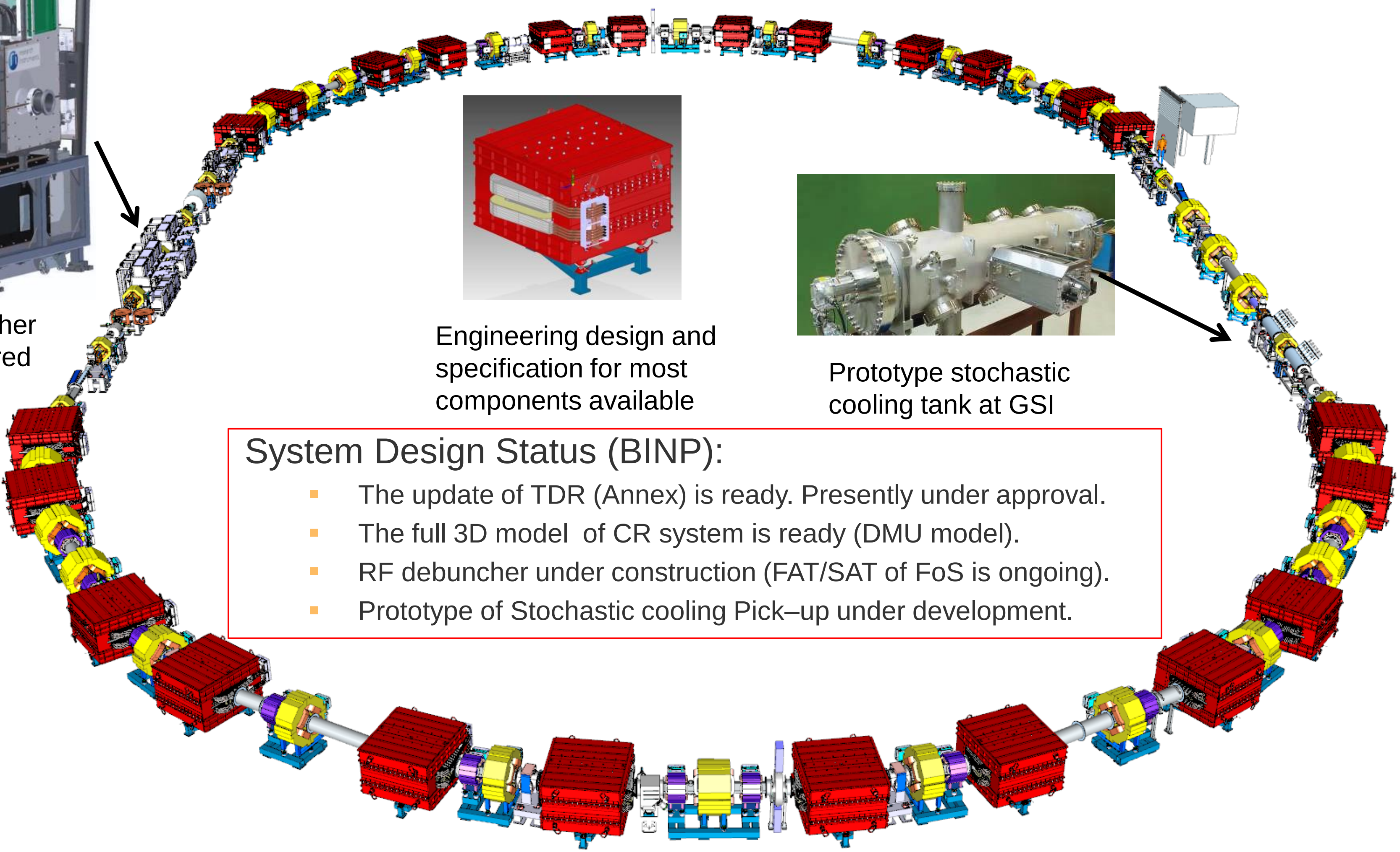
Dipole magnets:
Already at GSI

Source and LEBT:
Beam tests in 2016
Delivery to GSI until 2017

Buncher cavities:
Design is ready.
Waiting for tendering

CR Storage Ring

FOS debuncher cavity delivered



Engineering design and specification for most components available

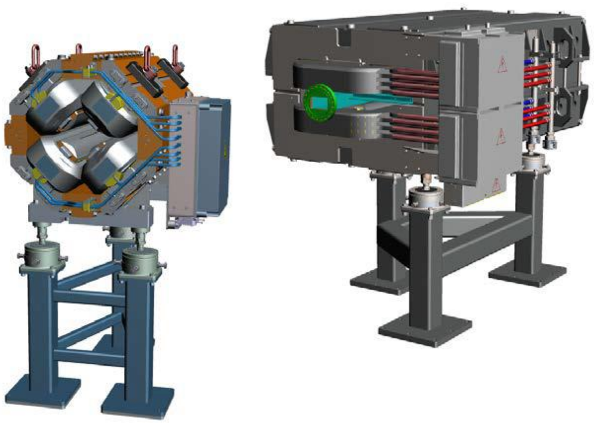
Prototype stochastic cooling tank at GSI

System Design Status (BINP):

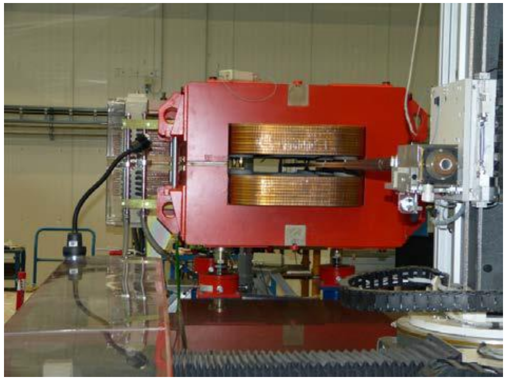
- The update of TDR (Annex) is ready. Presently under approval.
- The full 3D model of CR system is ready (DMU model).
- RF debuncher under construction (FAT/SAT of FoS is ongoing).
- Prototype of Stochastic cooling Pick–up under development.

HEBT (High Energy Beam Transport)

Almost all HEBT magnets are contracted (EFREMOV/BINP)

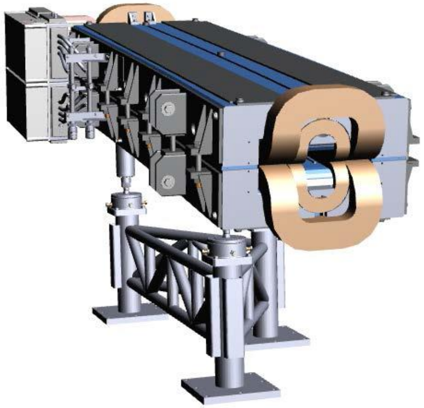


BINP has delivered several 3 models (contract signed Oct.15)



First FOS magnet under testing at GSI

Second FOS magnet ready for assembly



Preparation for series production started at EFREMOV

Contracts over 196 power converter closed with BOSE/ECIL India (first deliveries expected in Q2 2017). Indian inkind standard diagnostics chambers in preparation.

HESR

Large amount of dipole and quadrupole delivered to FZJ

Four magnets delivered to GSI after integration of UHV chamber

All dipole chambers delivered and shipped to GSI for NEG coating

27 quadrupole PCs delivered to FZJ

Conclusions

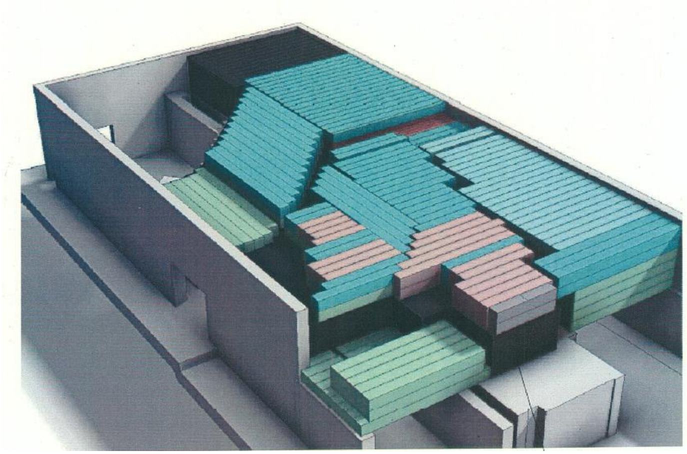
- Planed upgrade of SIS18 will be finished till 2018. Further steps will follow to reach full FAIR performance.
- Many UNILAC improvements. Alvarez upgrade design not fixed yet -> planned end of 2016.
- Procurements are progressing well for SIS100, HEBT, HESR
- Procurements for Super-FRS started. Major procurements start on short term.
- CR technical design report and engineering layout completed.
  - FOS devices or prototypes for German in-kind components to CR built.
- P-Linac and pbar target limited to the continuation of started activities but recent UNILAC improvements can somewhat compensate for the delay.

Thank you for your attention and all the colleagues for their passion and work put into the FAIR project. (and for the stolen slides)

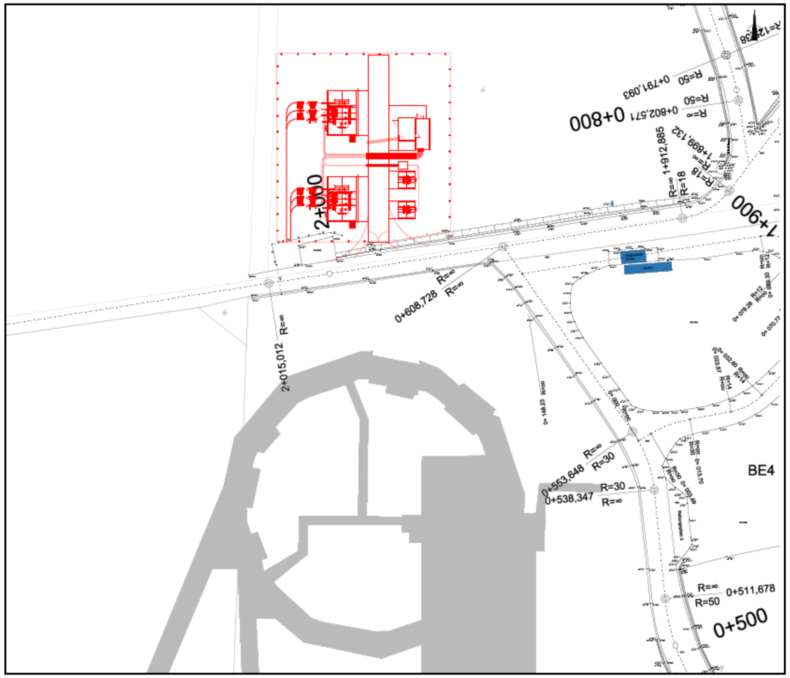
Special thanks to poor Tim who keept asking for his dad all weekend.

Extra Slides

Link Existing Facility – Transformer Station North



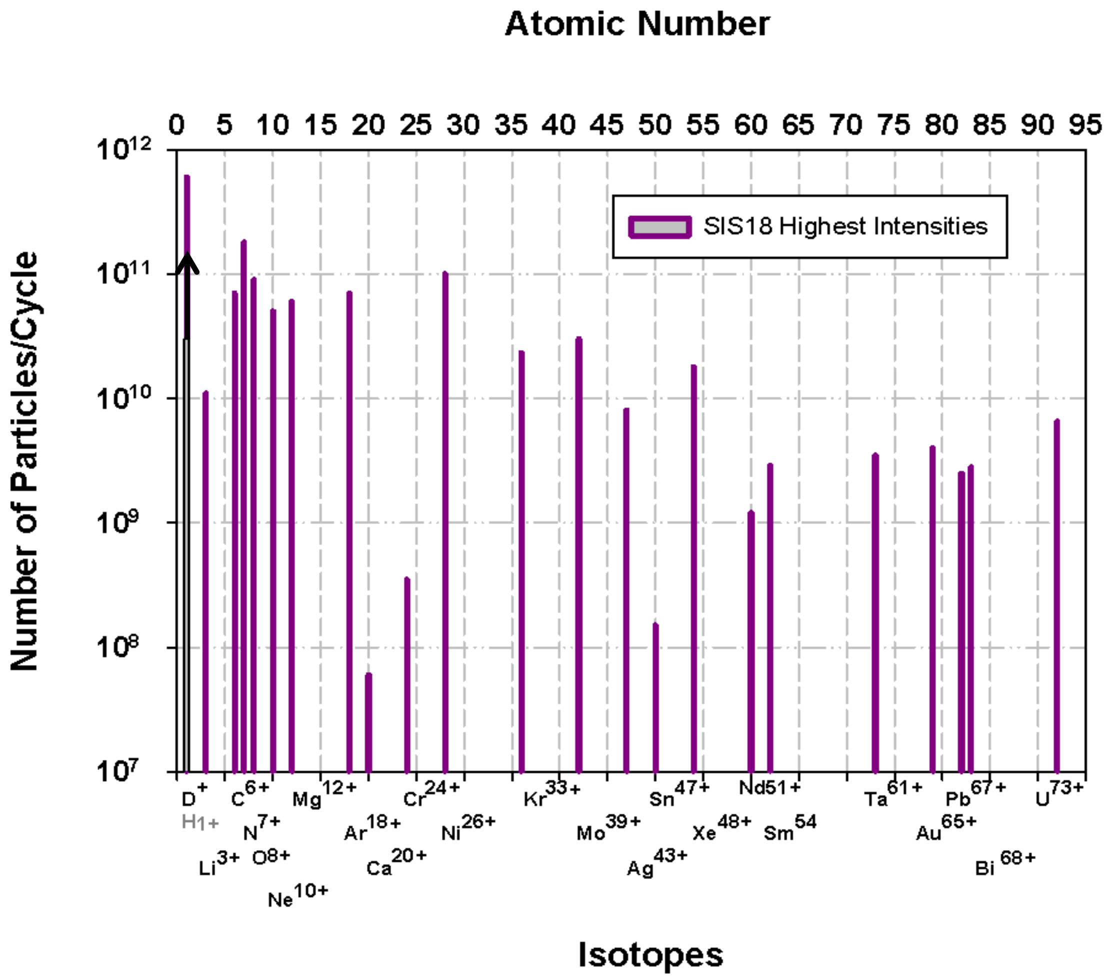
Shielding upgrade postponed until start of booster operation > Limited SIS18 repetition rate (1 Hz) at highests intensities in FAIR phase 0



New transformer station north

About 50 MW pulse power in booster mode. Fast ramping with 10 T/s enabled by new transformer station in 2018. Fast ramping helps to overcome ionization beam loss.

SIS18 Peak Intensities



- The space charge limit is reached for many light ions.
- The space charge limit is missed by a factor of ten for the most heavy ions.

The goal is to reach the space charge limit for all ions !
For FAIR: Transition to intermediate charge states (no TK stripper) > Enhanced space charge limit

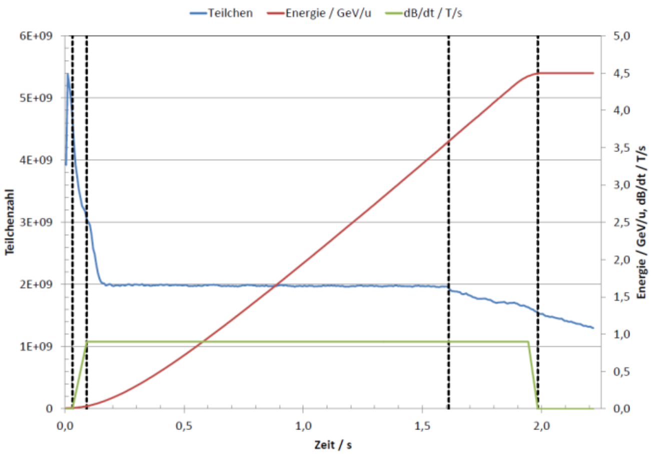
Protons @ FAIR

- Slowly extracted protons for HADES and CBM
- HADES @ SIS18
  - 4.5 – 4.7 GeV/u
  - 10^8 p/cycle
  - 10s extraction
- CBM @ SIS100
  - 2 – 29 GeV/u
  - 10^{12} p/cycle
  - 10s extraction

SIS18: Protons at High Gamma

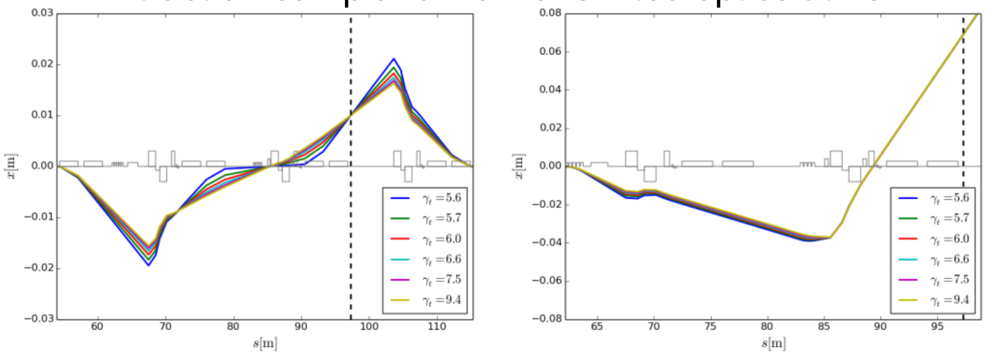
- Protons for PRIOR (2014)
  - Protons up to 4.5 GeV/u (18Tm)
  - Reduced ramp rate to minimize losses at end of ramp (~ 1T/s)
  - High sensitivity to radial position
  - Max. 10^{11} particles/cycle
  - No losses during acceleration and extraction up to 4 GeV/u
- MD in 2016 with LSA
  - Original aim: slow extraction at max. rigidity
  - Not feasible due to severe technical problems
  - Improved optical model successfully tested with fast extraction

Protons @ 4.5 GeV/u (May 2014)



Courtesy C. Omet

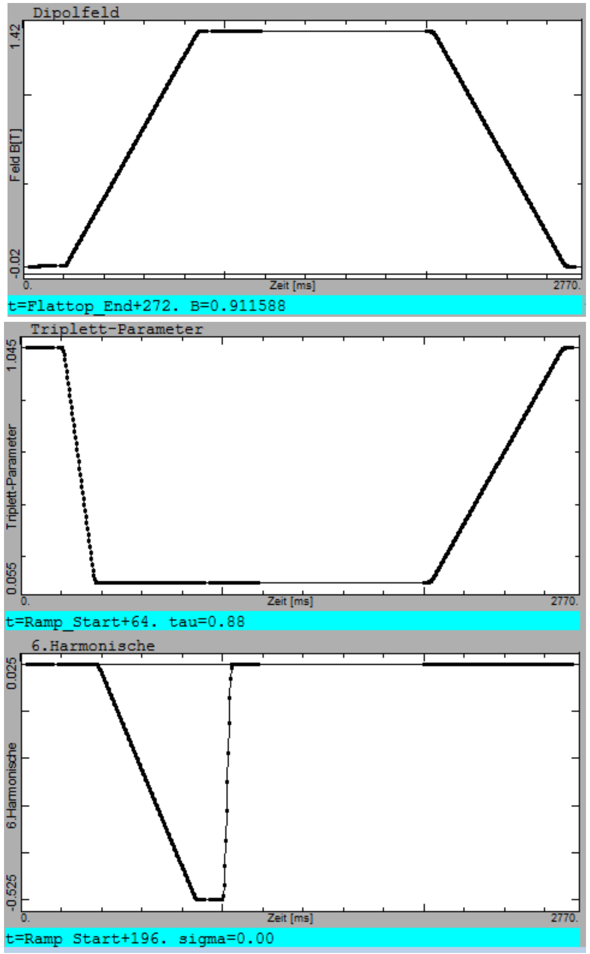
Extraction bump and kick for shifted optics at 18Tm



SIS18: Slow Extraction at High Gamma

- Optics with shifted γ_t not designed for slow extraction
- Protons with max. energy rarely requested from experiments
- Past scheme (Franczak, 2001):
  - Acceleration with γ_t shift during ramp
  - De-bunching of the beam on flattop
  - Restoration of normal extr. optic
  - Slow extraction of coasting beam
- Little operational experience at GSI
- Routinely done at COSY (FZ Jülich)
- Probably limited in intensity due to instabilities close to transition
- Should be feasible for intensities requested by HADES

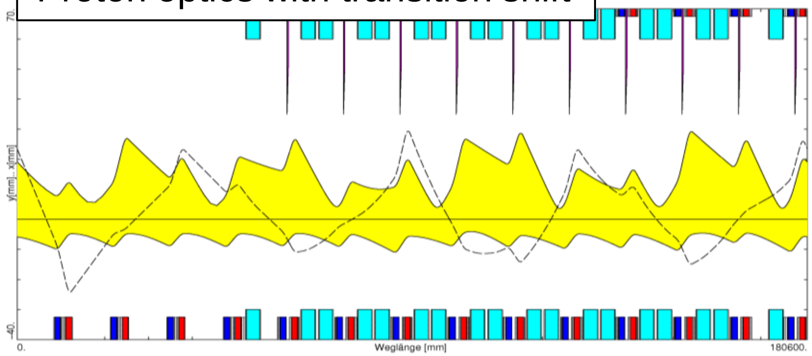
SISMODI parametrization of shift



SIS100: Protons for p-bar Chain

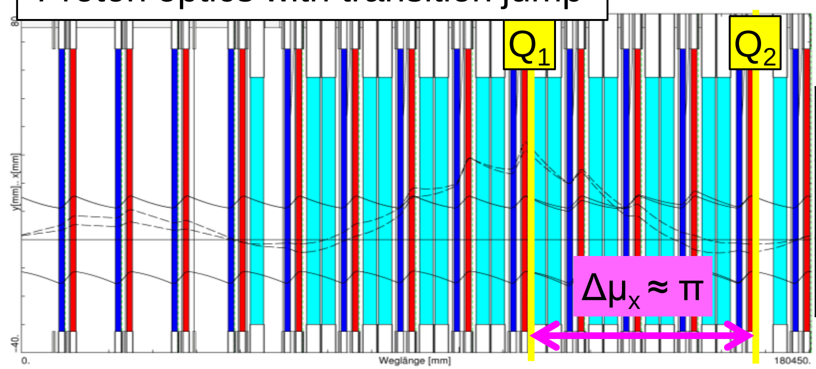
- Transition shift
  - Asymmetry in QF to change γ_t
  - Irregular optic with large hor. beta function and oscillating dispersion
  - Large Q_h for intrinsically high γ_t
- Transition jump
  - Small Q_h for intrinsically low γ_t
  - π-doublet for transition jump
  - Large difference in dispersion at both jump quadrupoles required
- Both optics designed exclusively for fast extraction of single high intensity bunch at max. energy

Proton optics with transition shift



Q_h	21.8
Q_v	17.7
γ_t	45

Proton optics with transition jump



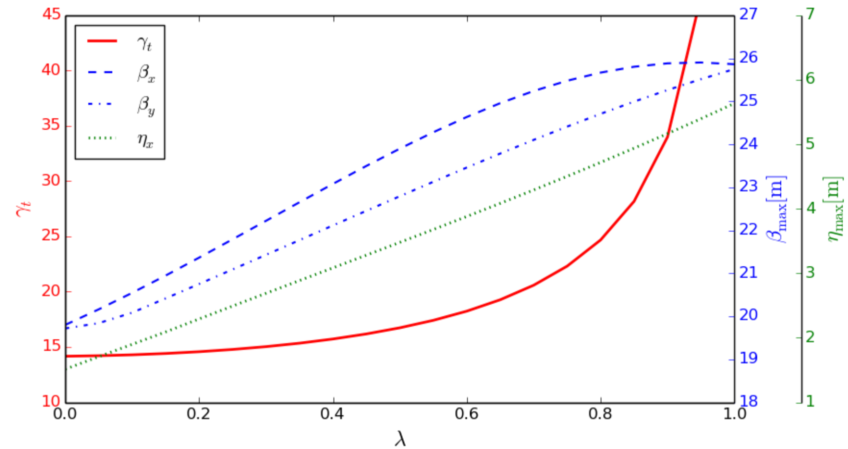
Q_h	10.4
Q_v	10.3
γ_t	8.9

$$\Delta\gamma_t \sim k\left(D_1{}^2 - D_2{}^2\right) + O(k^2)$$

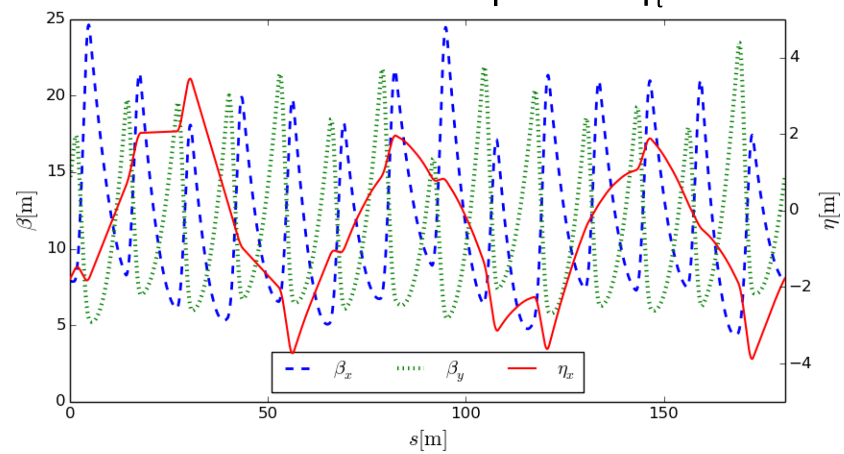
SIS100: Crossing with Optic for Ions

- Proton intensity for CBM relaxed
  - 10^{12}/cycle vs. $2 \cdot 10^{13}$ for p-bar
  - No single bunch required
- Crossing γ_t with slow extraction optic for ions seems feasible
  - Moderate long. blow-up expected
  - RF parameters can be optimized to minimize blow-up
  - Beam physics group studies
- Transition shift for ions
  - γ_t can be shifted splitting F quads
  - Useful for speeding up crossing or shift/de-bunch/restore scheme
- Potential dead band at transition

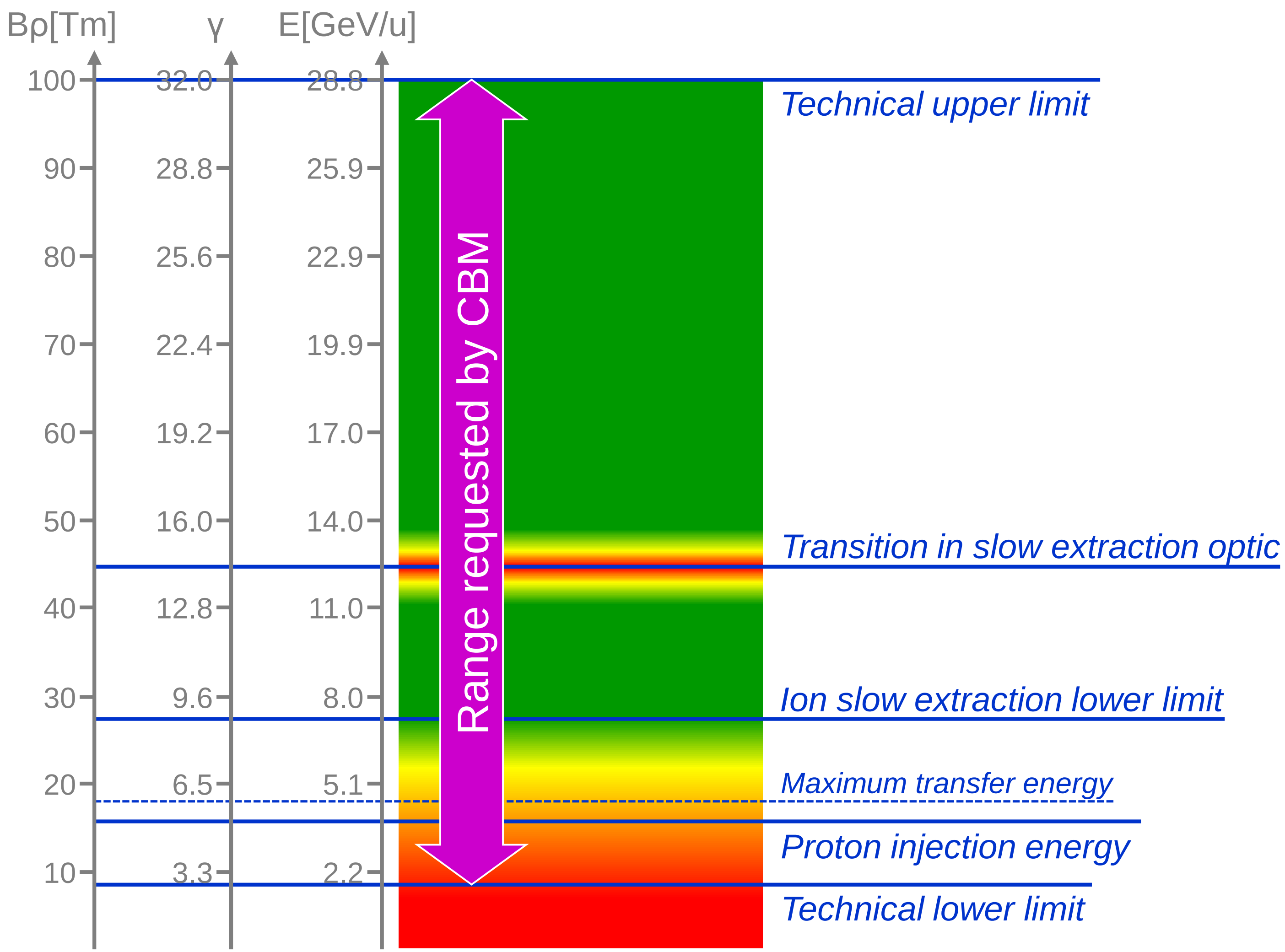
Properties of shifted slow extraction optics



Shifted slow extraction optic with γ_t=18.2



SIS100: Proton Energy Range



Proton Summary

- HADES requirements for SIS18 can be granted
  - No collective effects due to very low intensity requirements
  - 10^8/12s, 24/7, 14 days => 10^{13} protons
  - Electro-static septum not critical if operation with 10^{11} N works

- CBM requirements for SIS100 more critical
  - Use of slow extraction optic mandatory
  - Crossing transition seems feasible with slow extraction optic
  - Requested energy range can’t be fully served
    - 6 ... 11 GeV/u and 14 ... 29 GeV/u appear to be safe
    - Energies below 5 GeV/u will probably not work at all
    - Difficulties expected around transition for 11 ... 14 GeV/u

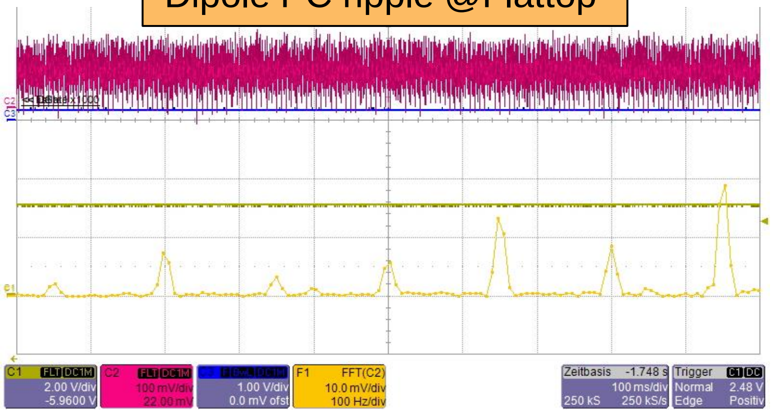
FAIR

Power Converter Ripple

GSI

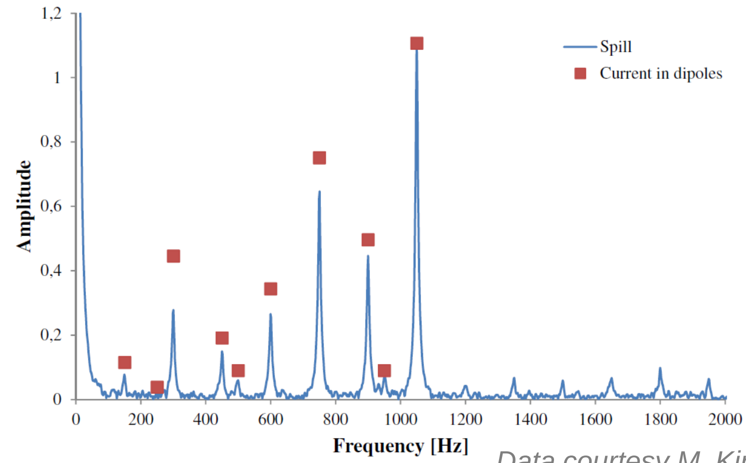
- Measurements on dipole and quadrupole power converters
  - Ripple on flattop
  - No simultaneous measurement with spill
- Frequency spectrum shows peaks at multiples of 150Hz
- Simulations of spill ripple
  - Good correspondence of spill spectrum with PC spectrum, BUT:
  - PC ripple seems too small to explain observed spill ripple

Dipole PC ripple @Flattop



Data courtesy H. Welker/M. Kirk

Simulated spill ripple with Hardt condition

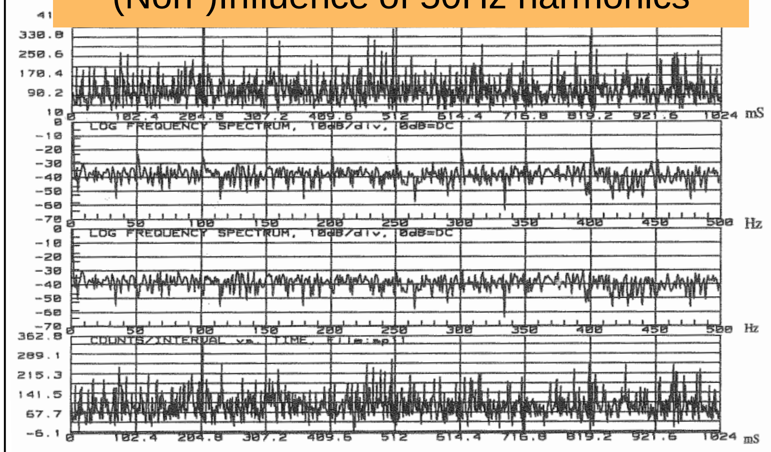


Data courtesy M. Kirk

Spill Ripple Measurements

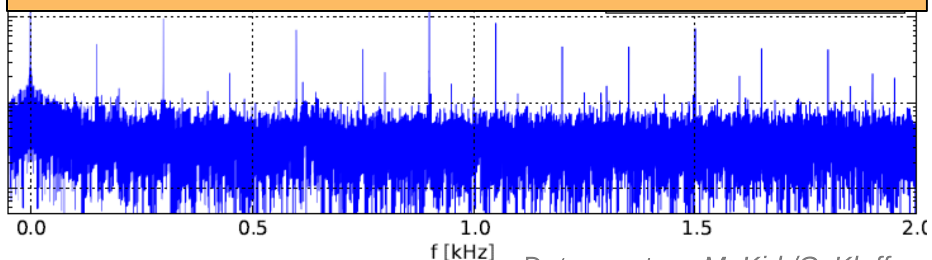
- Some reports from early 1990's available
- Data from more recent machine experiments
- Results obtained so far
  - Multiples of power grid frequency visible in the spill spectrum
  - Spill structure not dominated by these lines
- Conclusions
  - We do not understand the origin of spill ripples in SIS18
  - New ideas necessary

(Non-)Influence of 50Hz harmonics



P. Moritz, 1994

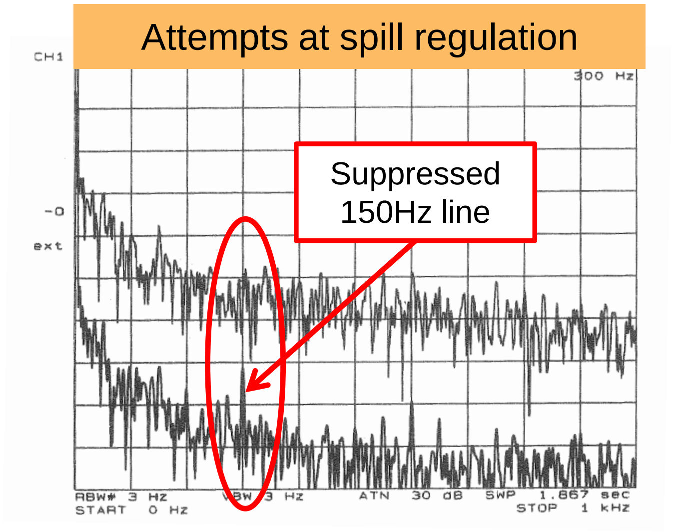
KO@HADES: Lines at harmonics of 150Hz



Data courtesy M. Kirk/C. Kleffner

Ripple Mitigation: Spill Feedback

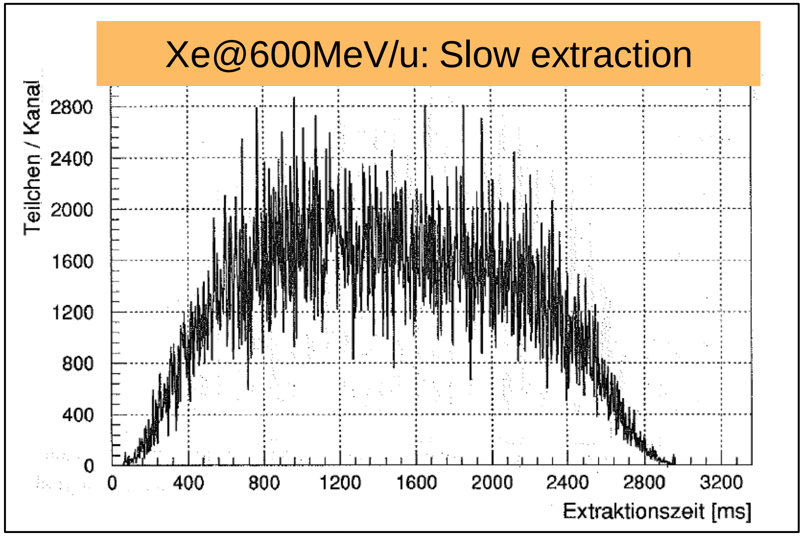
- First attempts in 1994
  - Artificial ripple on PCs to measure beam transfer function during SE
  - Group delay of 50us measured
  - Promising attempts at spill regulation, but not continued
- Realization with KO extraction relatively simple
  - Might be testable short-term using analog feedback
  - For FAIR real-time digital intensity signal should be provided by experiments (covered by FC2WG)

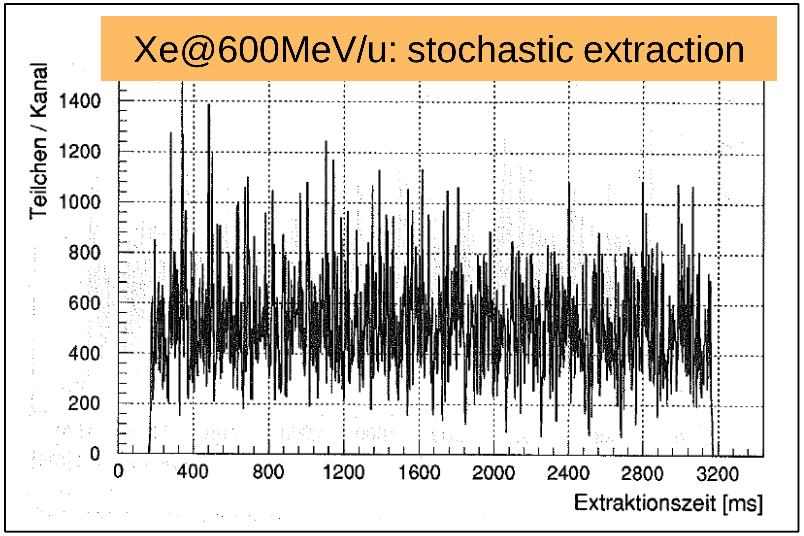


P. Moritz, 1994

Ripple Mitigation: Stochastic Extraction

- Beam driven into resonance by longitudinal excitation
  - Idea: higher dQ/dt for particles at stability limit
  - Supposed to be less sensitive to PC ripples by design
- Experimentally tested at SIS18 in the early 1990's
  - Long shaping time
  - No improvement of micro structure over slow extraction
  - Never made operational at SIS18
  - Maybe room for improvements



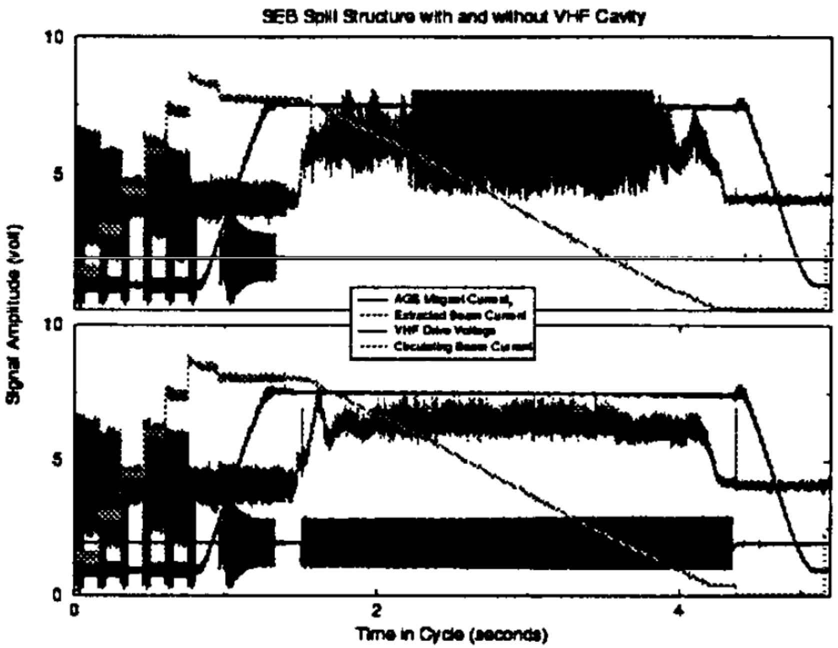


J. Pinkow, PhD Thesis, 1994

Ripple Mitigation: High Frequency Cavity

- Spill smoothing by extracting controlled bursts at high frequency
  - Empty bucket channeling
  - Creation of mini-bunches
- Bunched extraction at SIS18
  - 5 MHz maximum
  - Used for therapy
  - Some experiments at FRS seem to profit (AGATA)
- Higher frequencies require new RF cavity (e.g. >50MHz)
  - Theoretical studies for SIS18 necessary
  - Substantial R&D for HW required

Improved spill at AGS with channeling



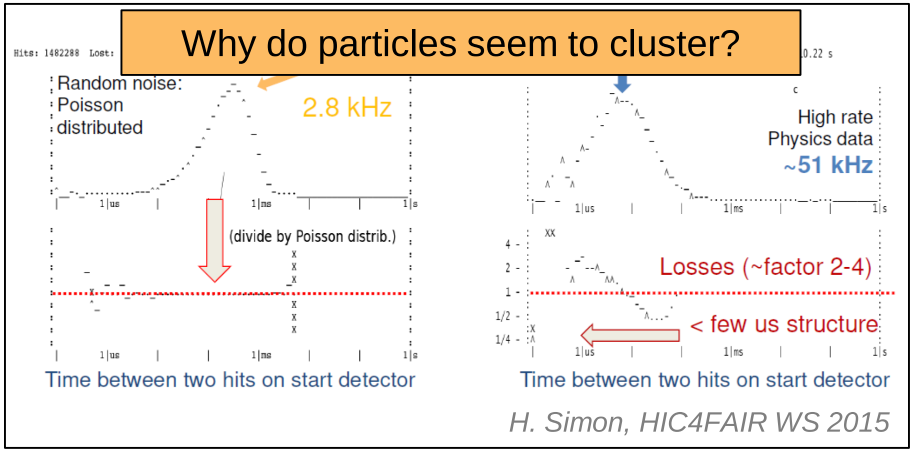
Next Steps

- Common effort to clarify origin of spill ripples
  - Simultaneous measurement of power converter and spill ripple
  - Comparison of quad driven and KO extraction
  - Influence of chromaticity and resonance strength on ripple sensitivity
  - Inclusion of experimental detectors for spill analysis

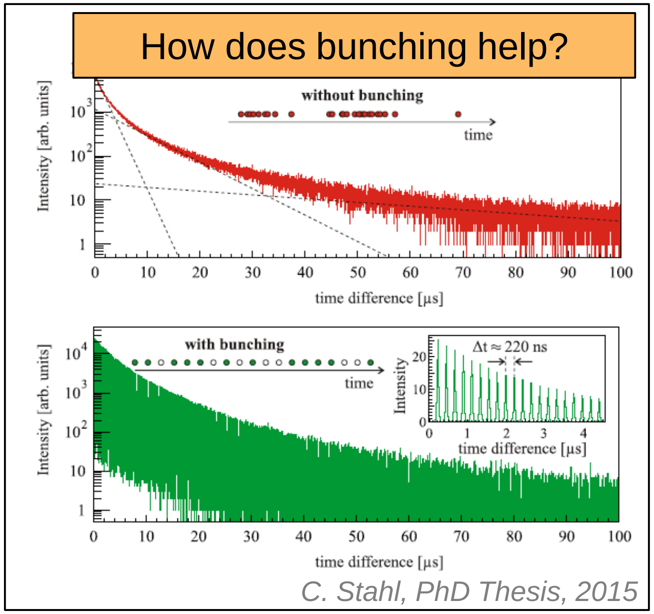
Machine Experiments 2016
Simultaneous ripple measurements
Comparison of extraction methods
Influence of chromaticity and res. strength
Spill feedback using KO?

Long Term Strategy

- Major problem pile-up
  - Deviations from random distribution not understood
- Studies on origin of particle clustering
  - Very difficult to observe in the ring
  - Theoretical models required
    - Identification of possible mechanisms
    - Predictions for observables
  - Experiments to verify or refute certain mechanisms
- R&D for technical measures
  - (Digital) Spill feedback
  - High frequency cavity
- Extensive machine development program done 2016. Data still under analysis



H. Simon, HIC4FAIR WS 2015



C. Stahl, PhD Thesis, 2015