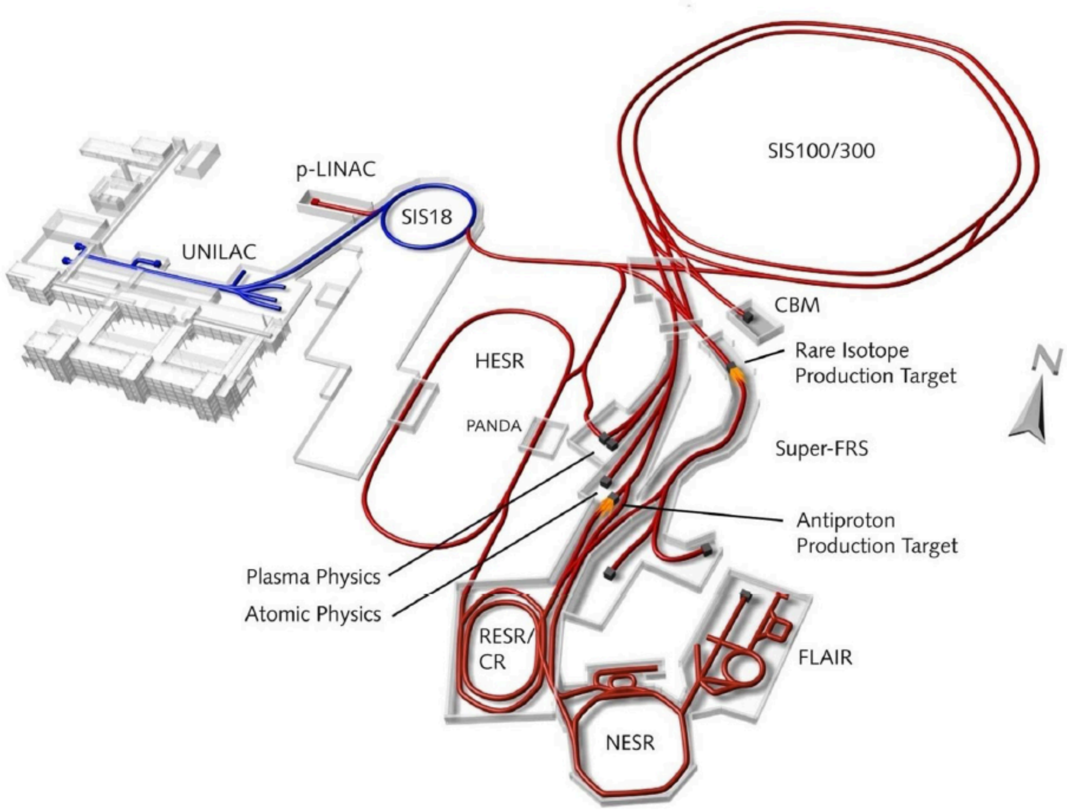
State of the Art of Hadron Storage Rings, GSI FAIR Challenges, Limitations and Prospects

G. Franchetti, GSI

EuCARD-2 XBEAM Strategy Workshop,
13-17 February 2017,
Colegio Mayor Rector Peset, Valencia, Spain

FAIR



Primary Beams

- 5×10^{11}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- 2×10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u (up to 90 GeV protons)

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

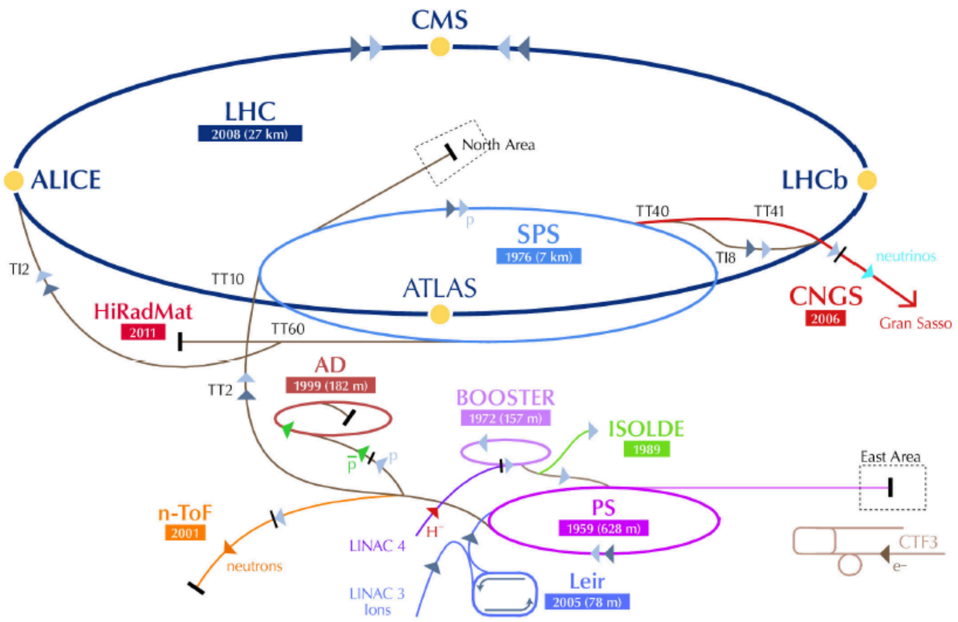
Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

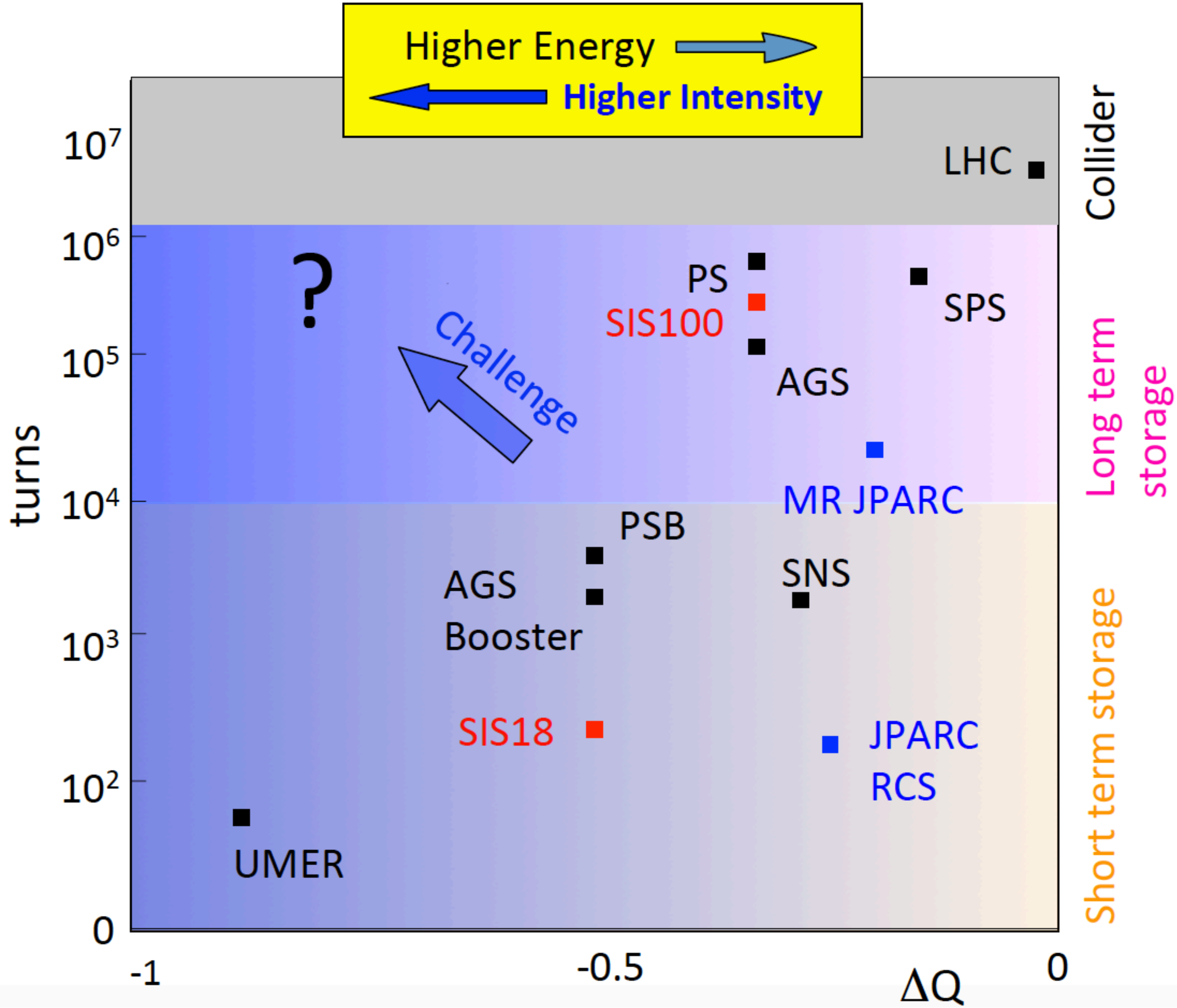
- Cooled beams
- Rapidly cycling superconducting magnets

J-PARC & LIU



Param. @ LHC collision	Nominal[1] 25 ns	Today * 50 ns	HL-LHC[1] 25 ns	HL-LHC[1] 50 ns
Int/bunch	1.15E11	~1.6E11	2.2E11	3.5E11
Bunches	2808	1374	2808	1404
Beam current [A]	0.58		1.12	0.89
ε_n[μm]	3.75	~ 2.4	2.5	3.0
β*[m]	0.55	0.6	0.15	0.15
Peak Lumi [cm^{-2} s^{-1}]	1 10^{34}	7.74 10^{33}	9 10^{34}	9 10^{34}

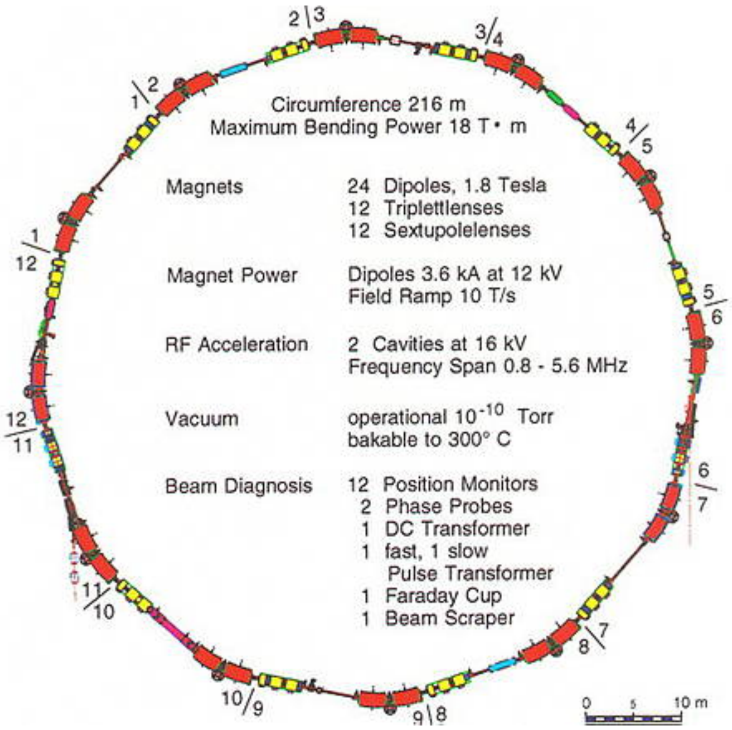
Trends



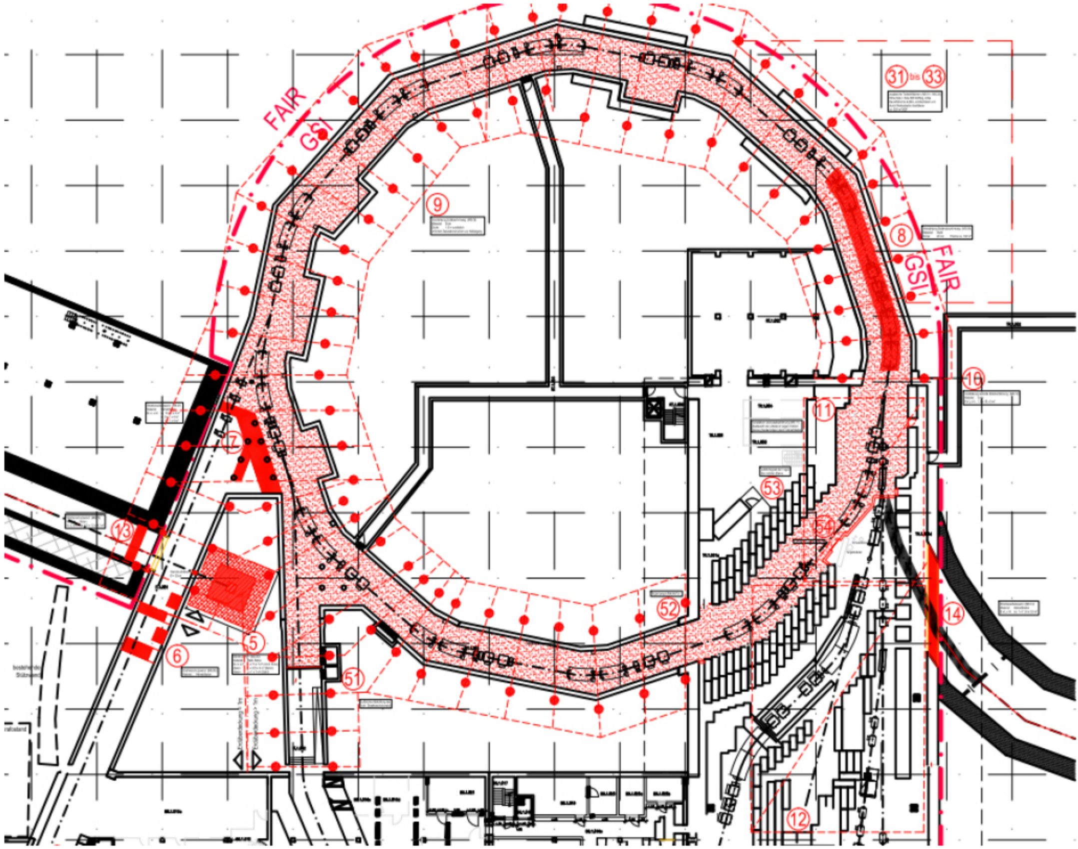
Higher Energy
Higher Intensity
LHC
Collider
PS
SIS100
AGS
SPS
?
Challenge
MR JPARC
Long term storage
PSB
AGS Booster
SNS
SIS18
JPARC RCS
UMER
Short term storage
turns
10^7
10^6
10^5
10^4
10^3
10^2
0
-1
-0.5
0
ΔQ


My office
New entrance gate
New restaurant + new offices
Additional Park lots

SIS18



Circumference 216 m
Maximum Bending Power 18 T • m
Magnets
24 Dipoles, 1.8 Tesla
12 Triplettlenses
12 Sextupolelenses
Magnet Power
Dipoles 3.6 kA at 12 kV
Field Ramp 10 T/s
RF Acceleration
2 Cavities at 16 kV
Frequency Span 0.8 - 5.6 MHz
Vacuum
operational 10^-10 Torr
bakable to 300° C
Beam Diagnosis
12 Position Monitors
2 Phase Probes
1 DC Transformer
1 fast, 1 slow
Pulse Transformer
1 Faraday Cup
1 Beam Scraper
0 5 10 m



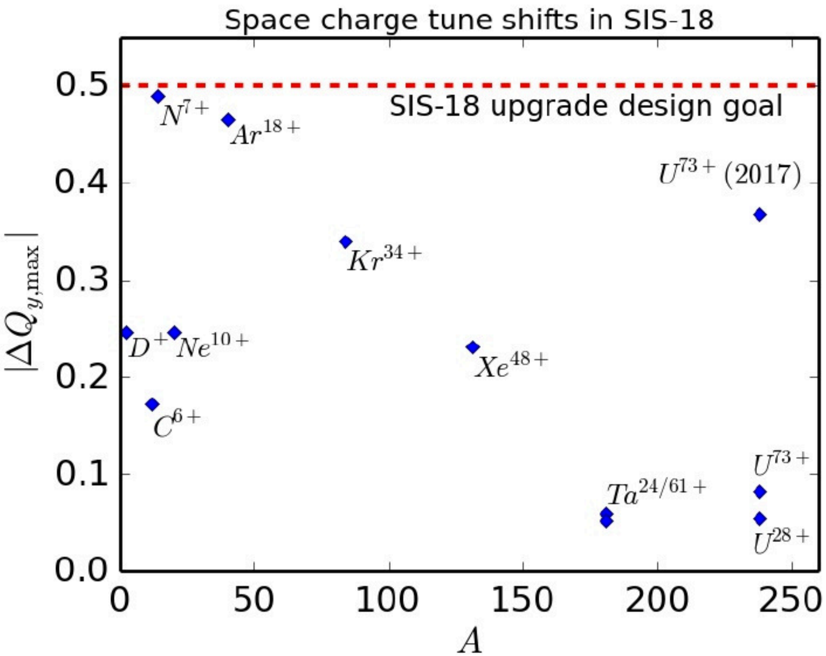
FAIR
GSI

UNILAC/SIS18 Beam parameter

	UNILAC today	FAIR	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Current (mA)	5/1	15	3
Emittance, 4σ (h, mm mrad)	**7/7**	**5**	**7**
Momentum spread (2σ)	**1E-3/1E-3**	**5E-4**	**5E-4**

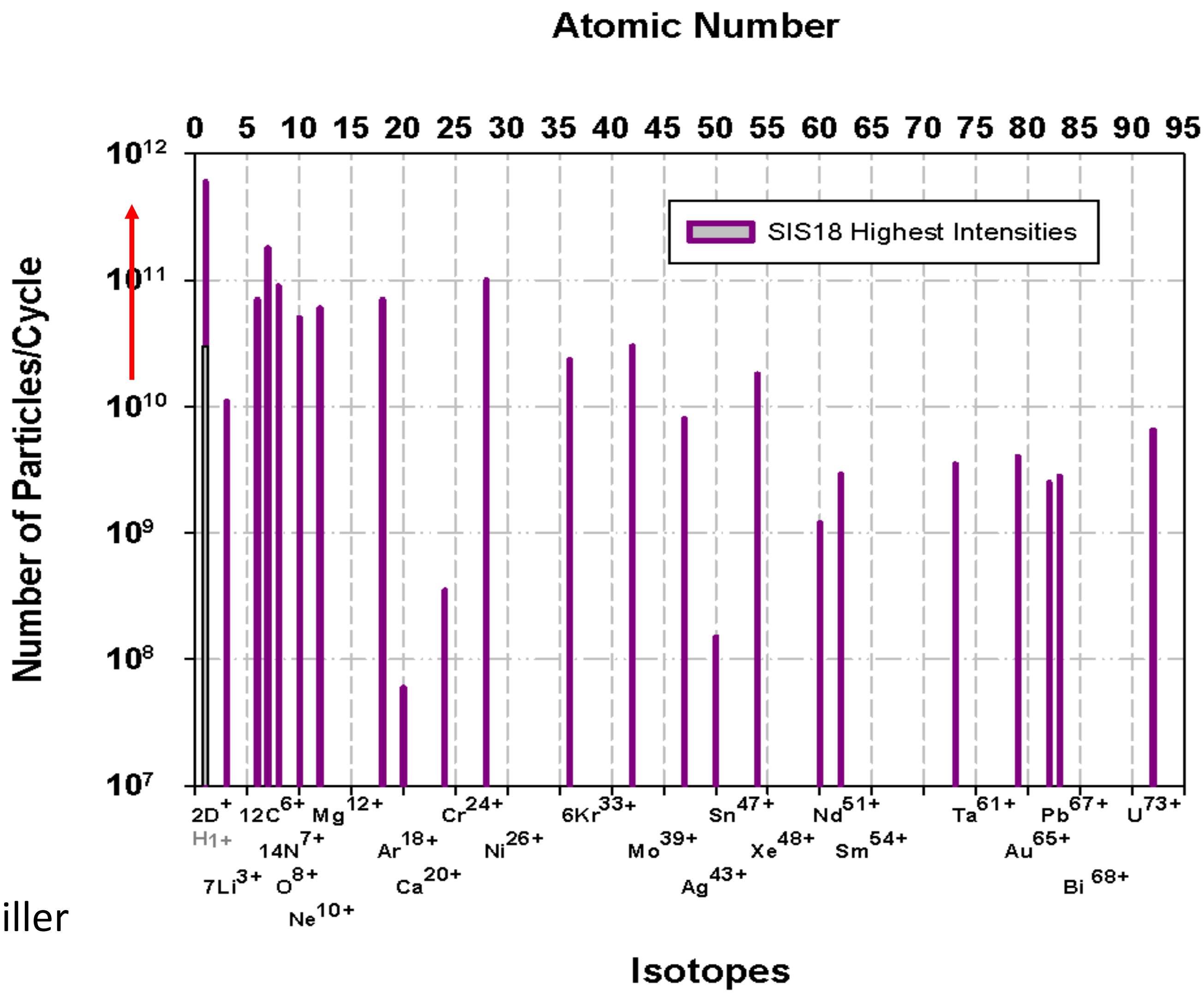
	SIS-18 today	FAIR design	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Reference energy GeV/u	0.2/1	0.2	1
Ions per cycle	**4E10/4E9**	**1.5E11**	**2E10**
cycle rate (Hz)	0.5 Hz	2.7 Hz	2 Hz
Long. dilution	**> 2**	**1.5**	**2**

Present SIS-18 intensities



$$\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

Space charge limit in SIS18



Spiller

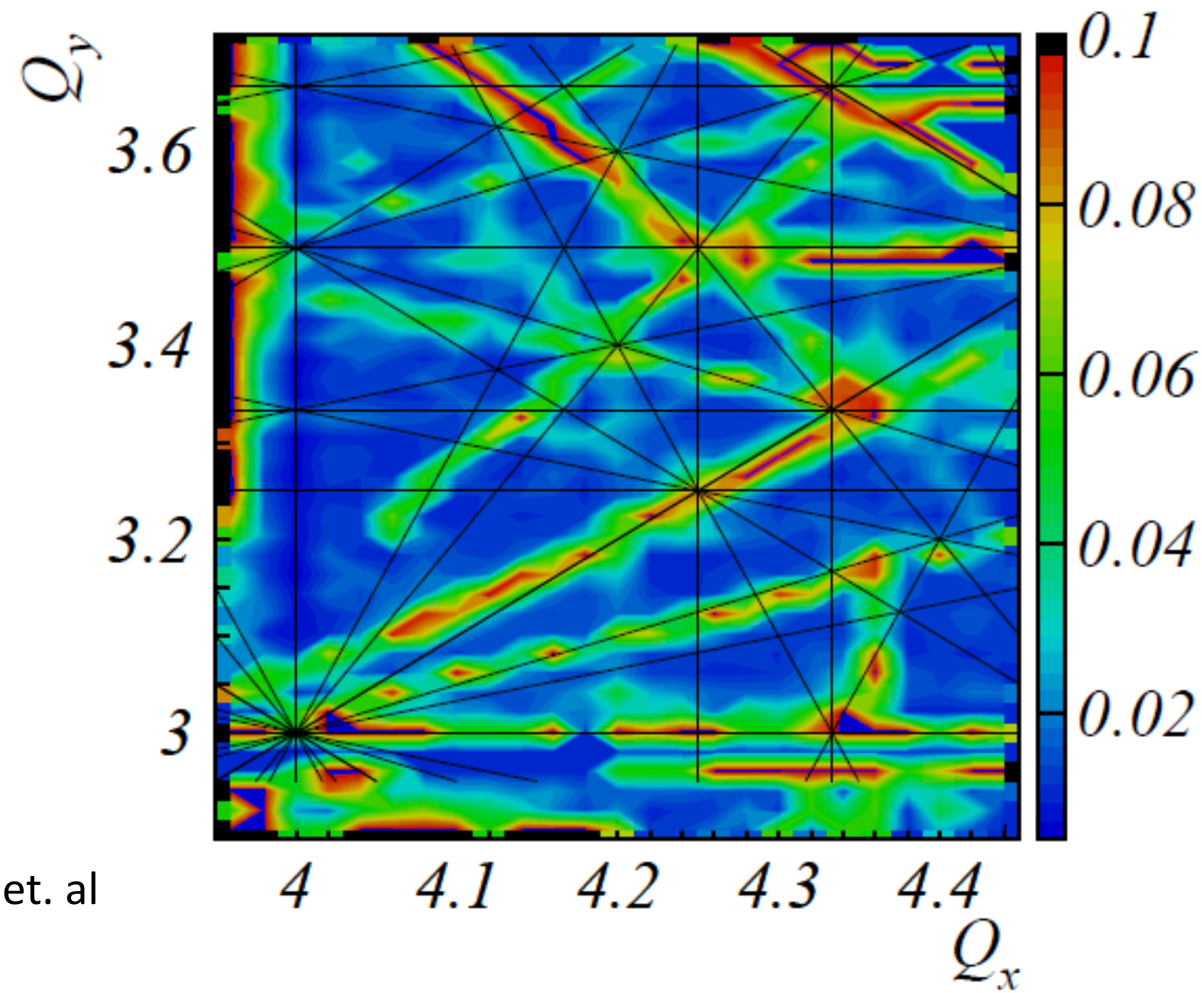
Ion sources at GSI: Status (O. Kester)

Element	Ion Beam	Ion Source	Duty Factor	Beam current in front of the RFQ	Particles in 100 µs pulse	Space-charge limit RFQ
CH_4	$^{12}CH_3^+ \rightarrow$ * p	MUCIS	2 Hz / 1 ms	3 mA $\rightarrow$ * 3 mA	$1.9 \cdot 10^{12}$	3.8 mA
N_2	$^{14}N_2^+$	CHORDIS	5 Hz / 1 ms	4 mA	$2.5 \cdot 10^{12}$	7 mA
Ar	$^{40}Ar^+$	MUCIS	5 Hz / 1 ms	20 mA	$1.2 \cdot 10^{13}$	10 mA
Ca	$^{40}Ca^{2+}$	PIG	50 Hz / 5 ms	100 µA	$3.1 \cdot 10^{10}$	5 mA
	$^{48}Ca^{10+}$	ECR	DC	100 µA	$6.3 \cdot 10^{9}$	-
Ni	$^{58}Ni^{2+}$	VARIS	1 Hz / 0.5 ms	5 mA	$1.6 \cdot 10^{12}$	7.3 mA
Kr	$^{86}Kr^{2+}$	MUCIS	5 Hz / 1 ms	7 mA	$2.2 \cdot 10^{12}$	10.8 mA
Ag	$^{107}Ag^{2+}$	VARIS	1 Hz / 1 ms	10 mA	$3.1 \cdot 10^{12}$	13.4 mA
Sn	$^{112}Sn^{15+}$	ECR	DC	25 µA	10^{9}	-
Xe	$^{124}Xe^{3+}$	MUCIS	5 Hz / 1 ms	4 mA	$8.3 \cdot 10^{11}$	10.3 mA
Au	$^{197}Au^{4+}$	VARIS	0.5 Hz / 0.5 ms	4.5 mA	$7 \cdot 10^{11}$	12.3 mA
Pb	$^{208}Pb^{4+}$	VARIS	0.5 Hz / 0.4 ms	5 mA	$7.8 \cdot 10^{11}$	13 mA
Bi	$^{209}Bi^{4+}$	VARIS	0.5 Hz / 0.5 ms	12 mA	$1.9 \cdot 10^{12}$	13.1 mA
U	$^{238}U^{4+}$	VARIS	1 Hz / 0.5 ms	12 mA	$1.9 \cdot 10^{12}$	15 mA

Example for proton

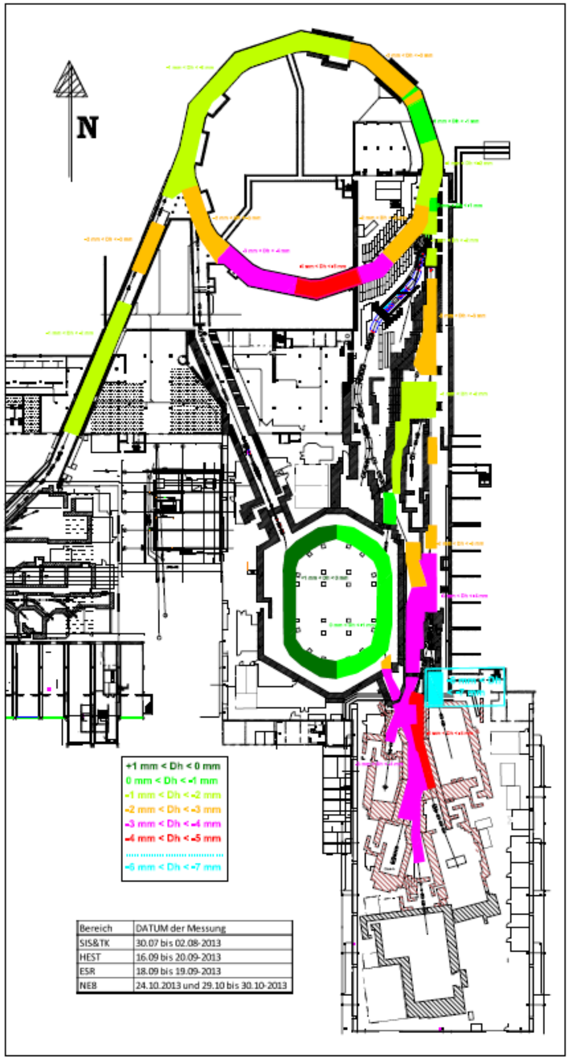
E [MeV]	70	11,4	11,4
I [mA] (UNILAC)	35	1	2
SIS18 output (particles/cycle)	5,0E+12	3,4E+11	6,8E+11
Space charge limit (N)	5,8E+12	8,6E+11	8,6E+11

SIS18 resonances

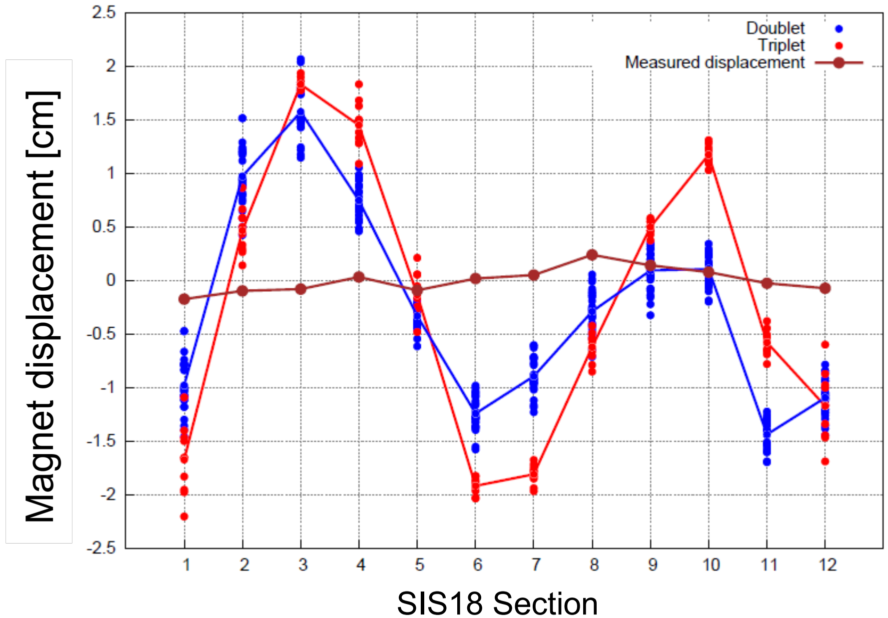


Franchetti, et. al

Misalignments do to ground motion



Major misalignment of SIS18 measured in 2013



Attempt for beam based alignment measurement.

G. Franchetti et.a.

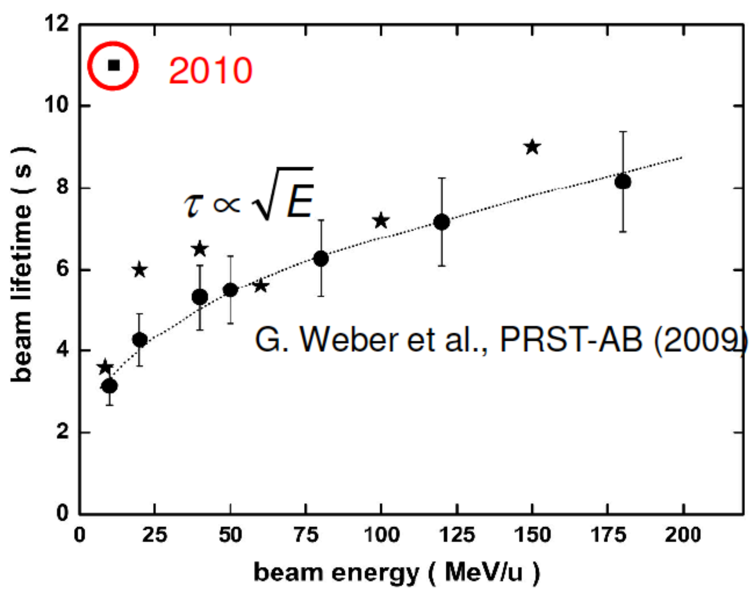
Dynamic pressure issues

Electron stripping: $U^{28+} + X \rightarrow U^{29+} + X + \epsilon$

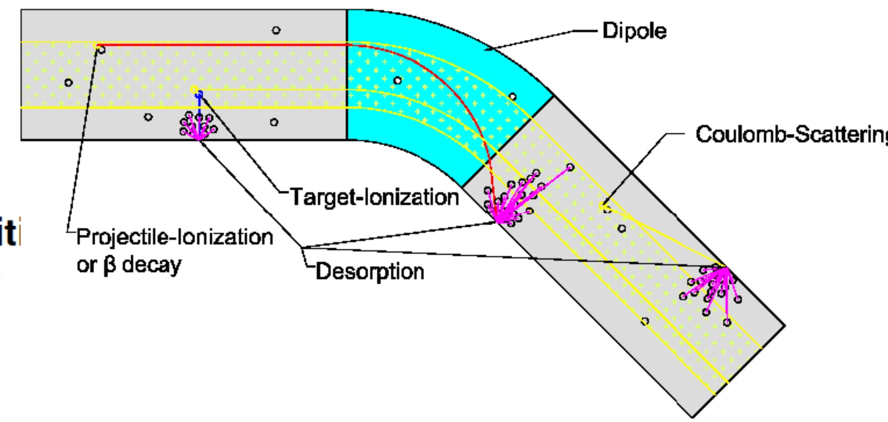
(Lifetime)$^{-1}$: $\tau^{-1}(P) = \beta_0 c \sigma_{loss} \dfrac{P}{k_B T}$

Born approximation: $\sigma_{loss} \propto E^{-1}$

Measured U^{28+} life time for **low intensiti**



High intensities

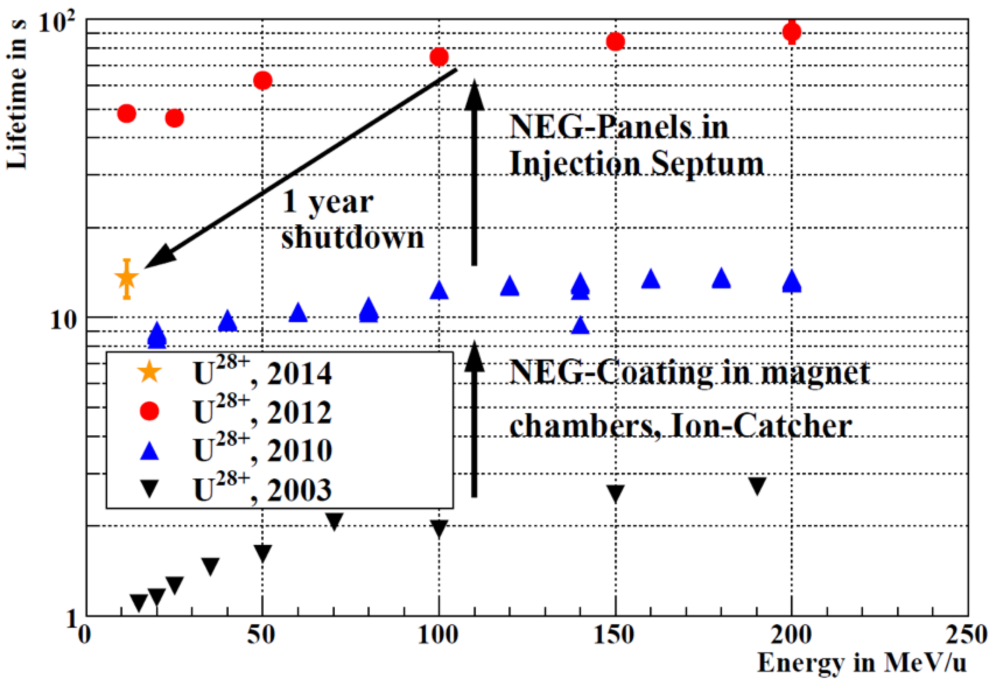


$$\eta = \frac{\#\ \text{desorbed molecules}}{\#\ \text{incident ions}} \propto \left(\frac{dE}{dx}\right)^n$$

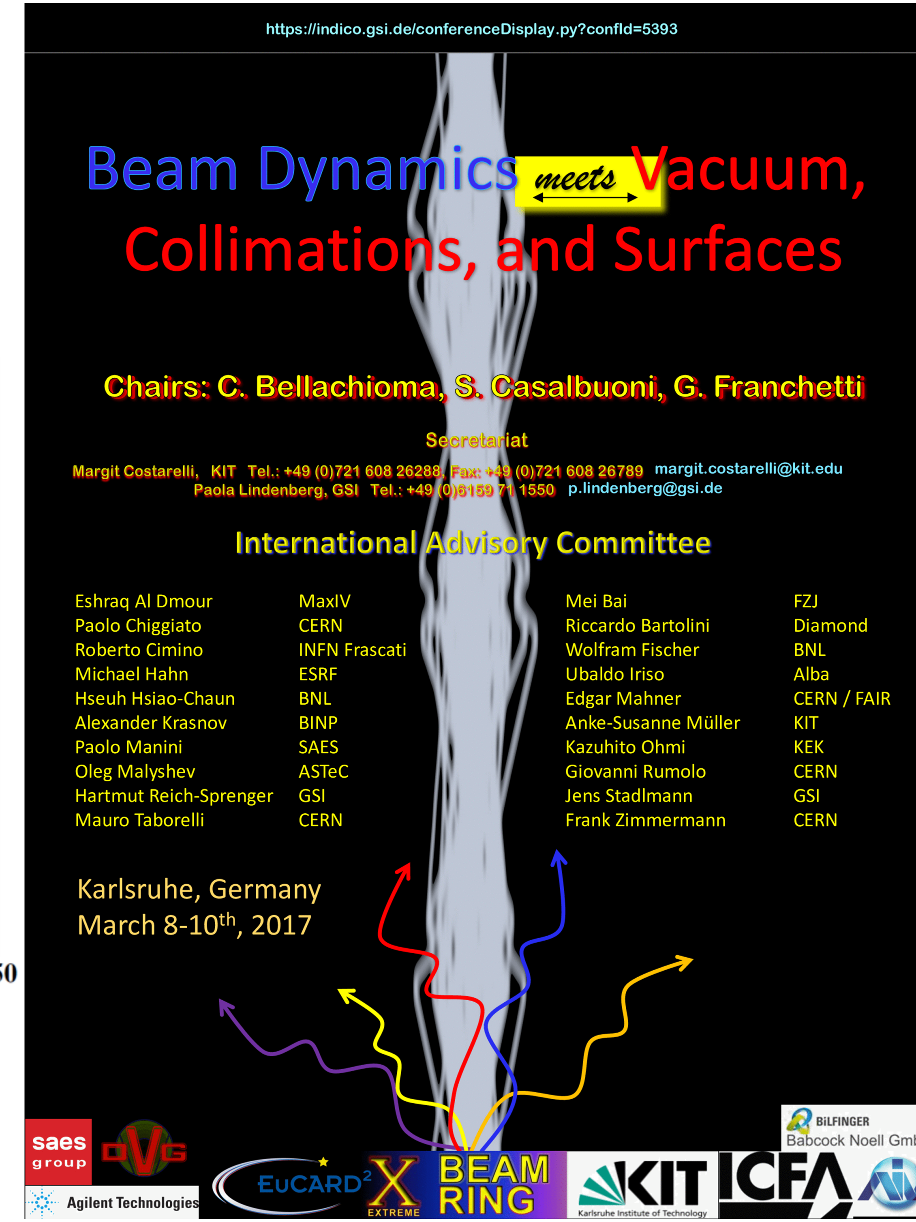
Stopping power: $\dfrac{dE}{dx} \propto \dfrac{Z^2}{A}$ H. Kollmus et al., J. Vac. Sci. (2009)

Dynamic pressure: $\dfrac{dP}{dt} = \tau_p^{-1}(P - P_0) + \alpha \eta_{loss} N P$

Lifetime of U28+ beams

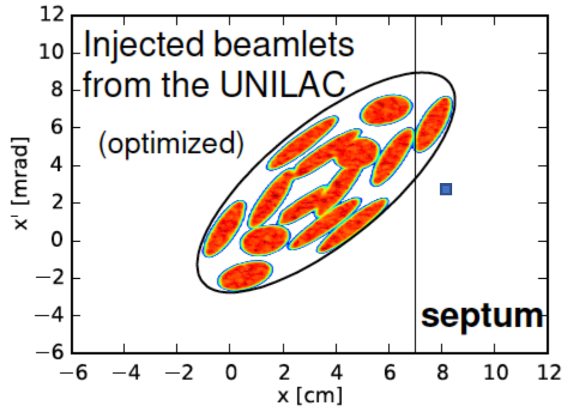


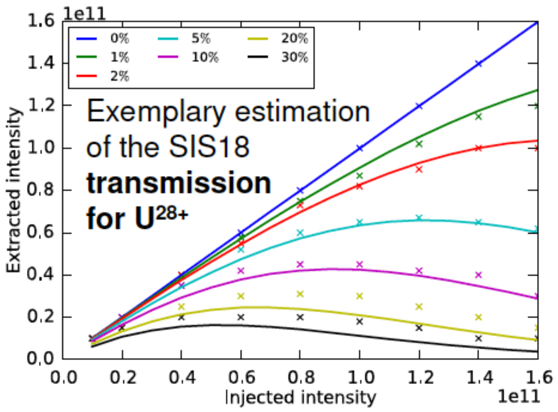
P. Spiller



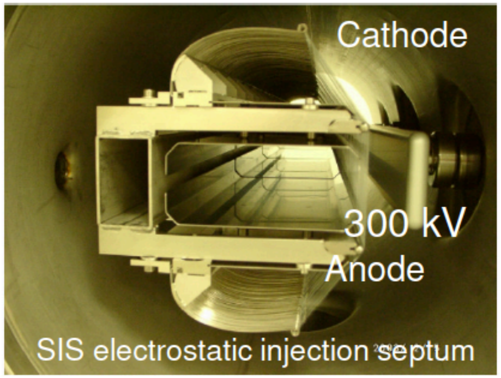
SIS18 multi-turn injection (MTI) efficiency

- The UNILAC->SIS18 multi-turn injection is one of the main “bottlenecks” for FAIR.
- **Design goal:** the UNILAC should provide the current and emittance (brilliance) to fill the (horizontal) SIS aperture to the space charge limit.
- Intermediate charge state heavy-ions: Losses well below 10 % to avoid vacuum + lifetime degradation.

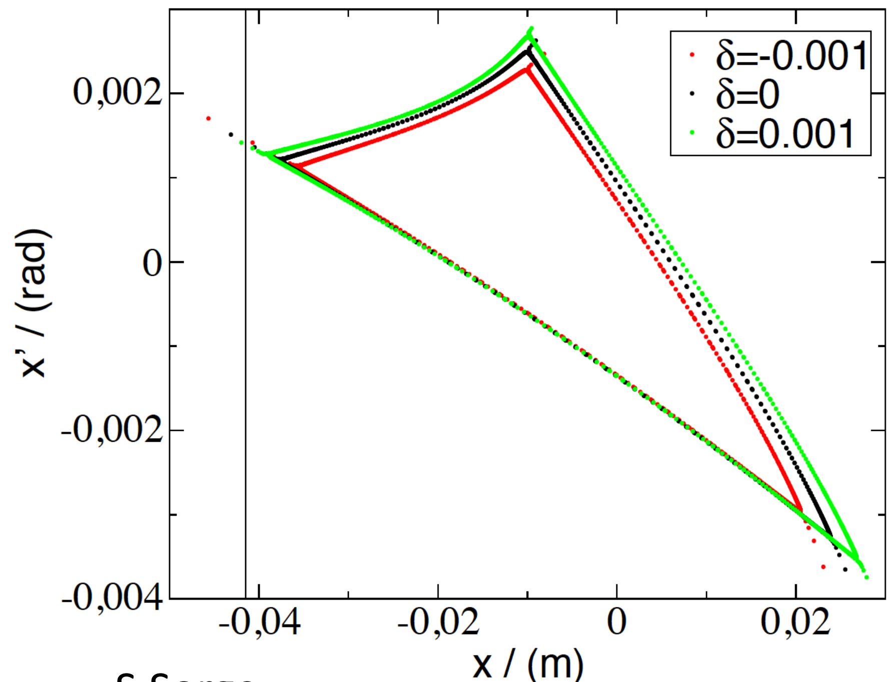




S. Appel



Slow extraction



S.Sorge

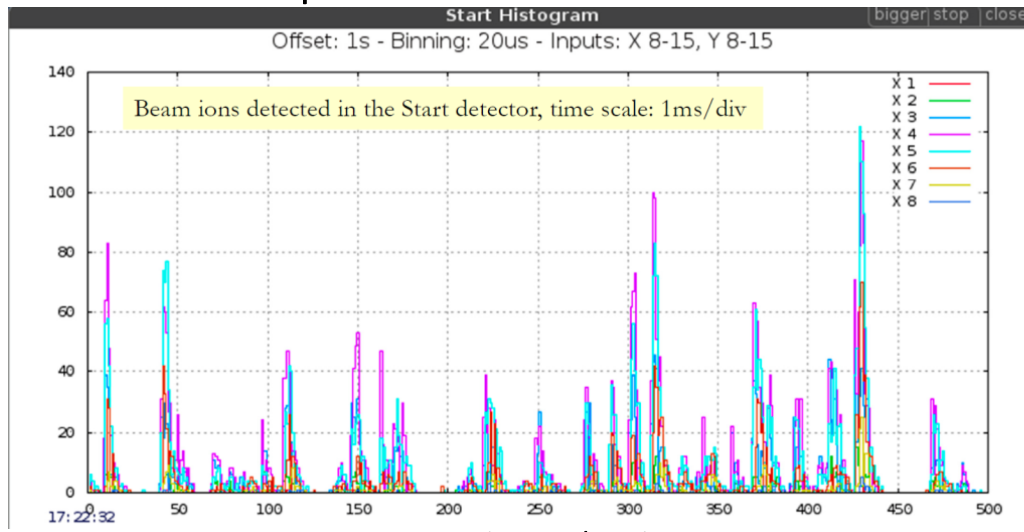
Issues:

1) Estimation of beam loss
2) Identification of factors and modeling of the spill structure

CBM@SIS100: Micro-spill structure

CBM@SIS100 reference
Au^{79+} 10^9 pps 10 sec 2-11 GeV/u
p 10^{11} pps 10 sec 5-29 GeV

micro-spill structure from SIS-18



time (1 ms / div)

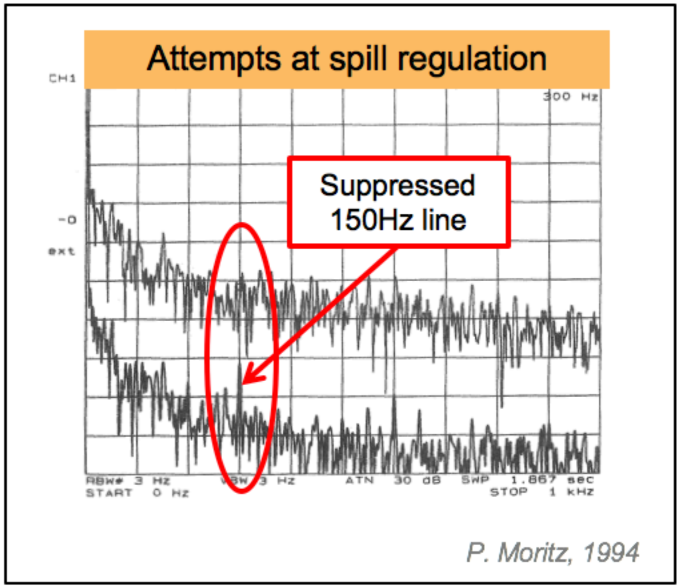
(J. Pietraszko, C. Sturm)

At present: Significant data quality loses because of micro-spill structure.

- reduced data quality and rate capability !
- load on detectors !
- **Not acceptable for CBM@SIS100 !**

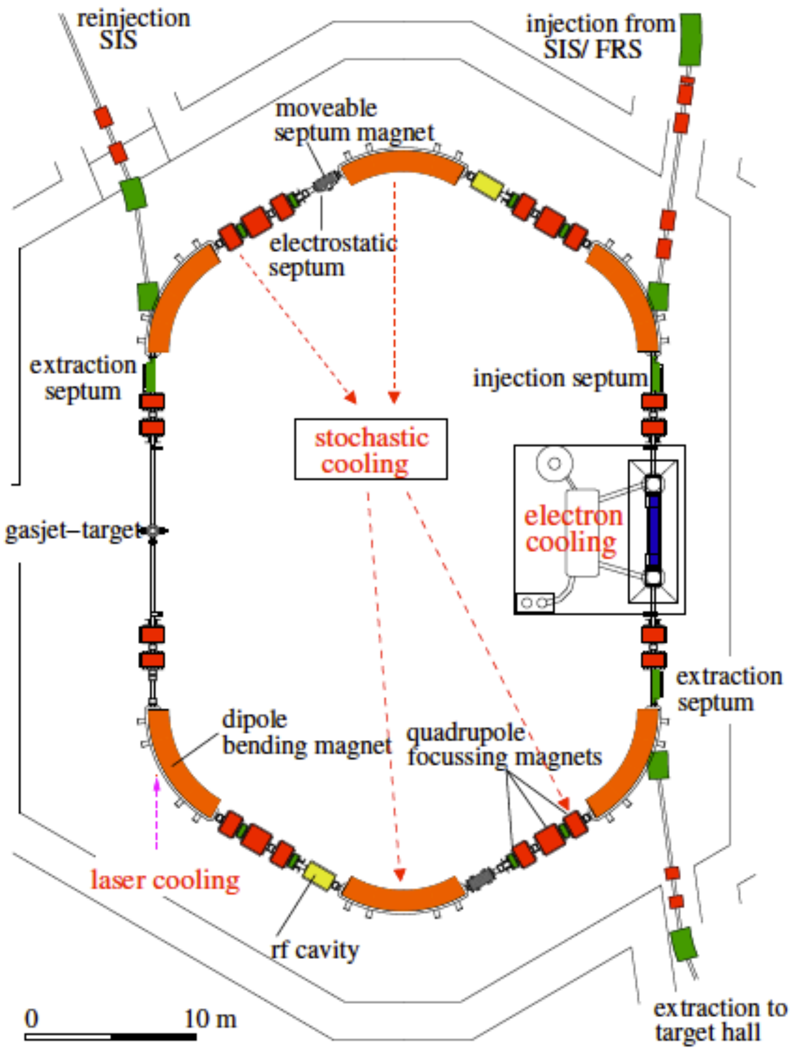
Ripple Mitigation: Spill Feedback

- 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)



D. Ondreka

ESR Operation



Fast injection (stable ions / RIBs)

Stochastic cooling (≥ 400 MeV/u)

Electron cooling (3 - 430 MeV/u)

Laser cooling (C^{3+} 120 MeV/u)

Internal gas jet target

Laser experiments

Acceleration/deceleration (down to 3 MeV/u)

Fast extraction (reinjection to SIS / HITRAP)

Slow (resonant) extraction

Ultraslow extraction (charge change)

Beam accumulation

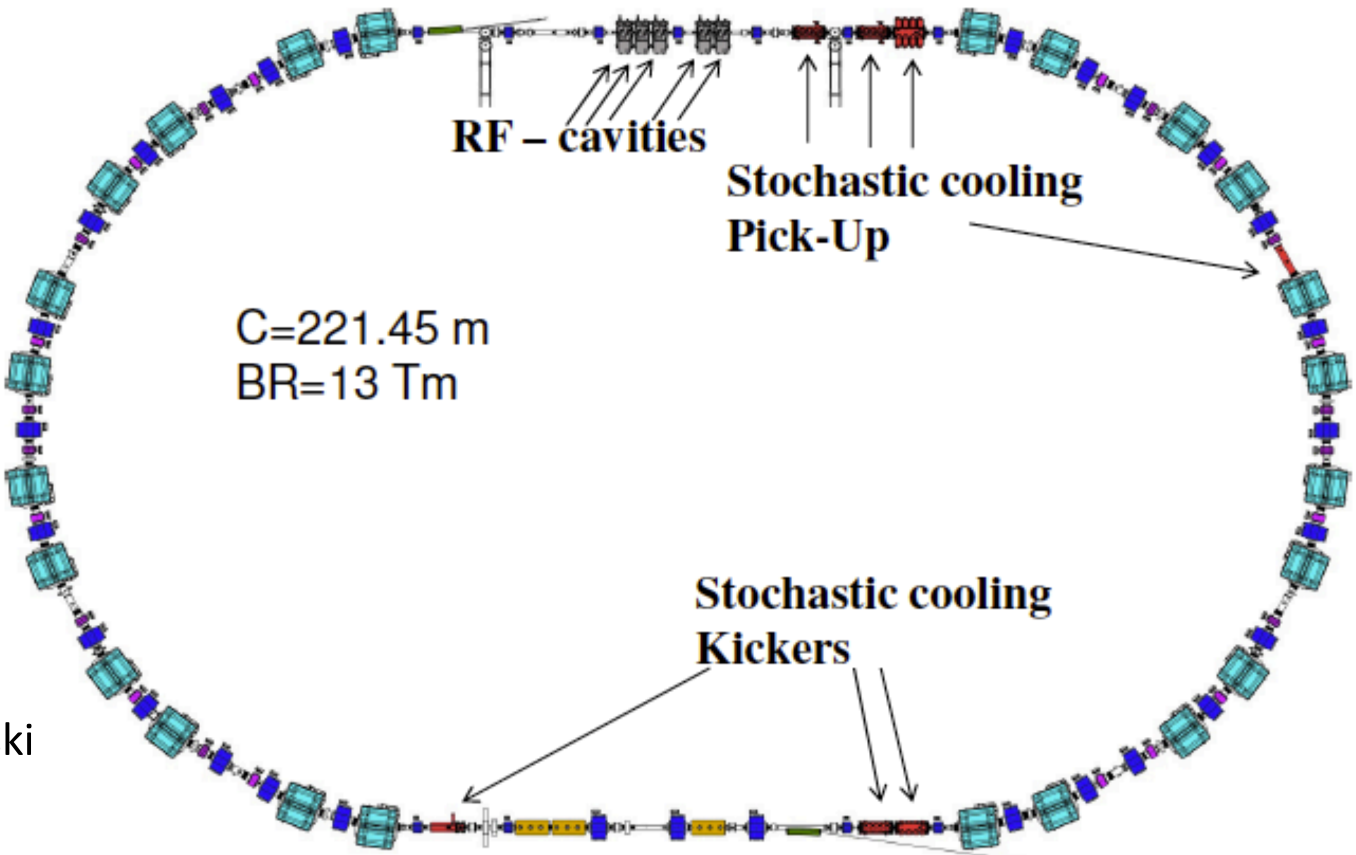
Multi charge state/multi component operation

Schottky mass spectrometry

Isochronous mode (TOF detector)

**All these modes work somehow,
but all are far from perfect or routine.**

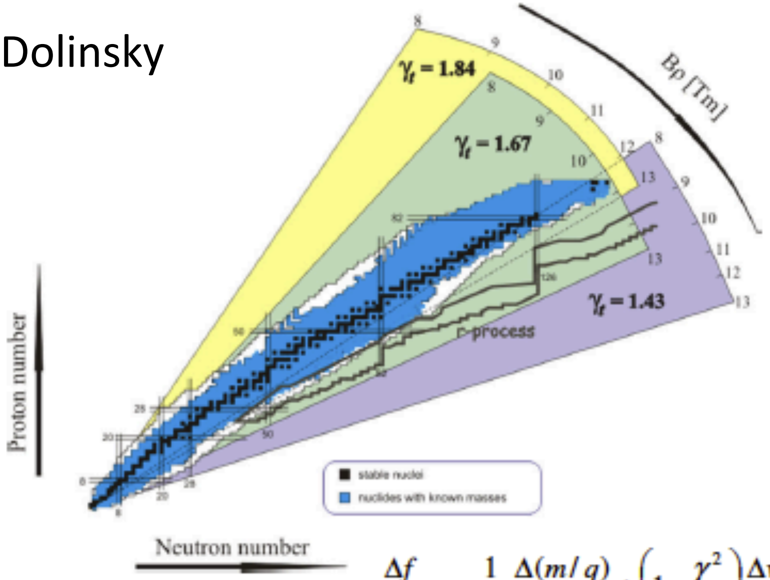
Layout of the CR



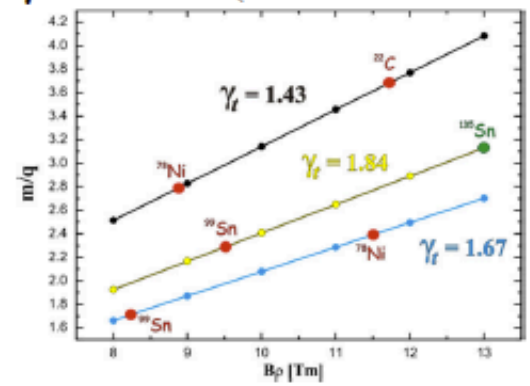
O. Dolinski

Mass measurements in CR

O. Dolinsky



1. $\gamma_t = \gamma = 1.84$ (E = 782.5 MeV/u)
2. $\gamma_t = \gamma = 1.67$ (E = 624.1 MeV/u)
3. $\gamma_t = \gamma = 1.43$ (E = 400.5 MeV/u)



$$\frac{\Delta f}{f} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta(m/q)}{m/q} + \left(1-\frac{\gamma^2}{\gamma_{tr}^2}\right)\frac{\Delta v}{v} + \left(\frac{\delta f}{f}\right)_{error}$$

Isochronous mode ($\gamma_{tr} = \gamma$) is required for fast mass measurements.
Methods: TOF, Schottky spectroscopy

RIBs from SFRS: 100 mm*mrad; $\Delta p/p = 1\%$; $t_b = 50$ ns

Isochronous condition at CR

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta(m/q)}{m/q} + \left(1-\frac{\gamma^2}{\gamma_{tr}^2}\right)\frac{\Delta v}{v} + \left(\frac{\delta f}{f}\right)_{error}$$

Ideal isochronicity can be guarantied only for one m/q ion applying correction scheme (sextupole, octupole, decapole correctors).

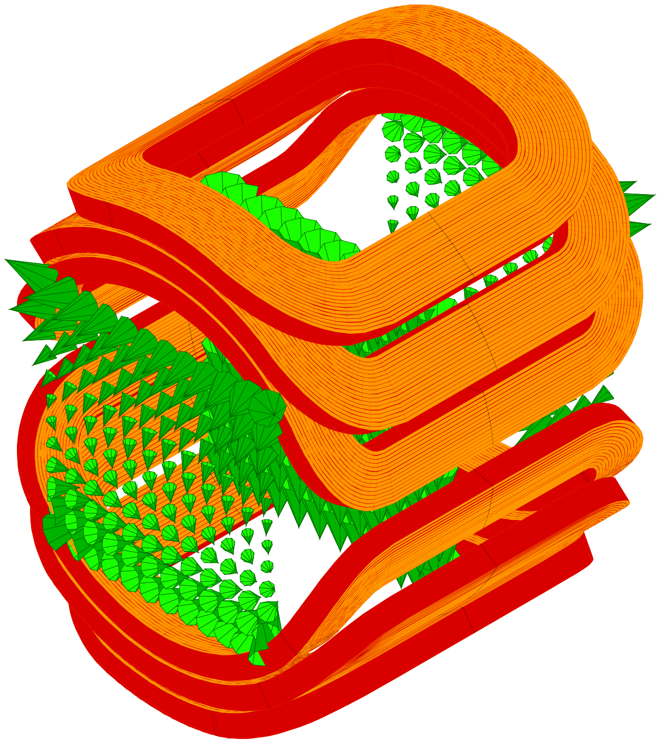
Frequency calibration by velocity measurement with two TOF detectors.

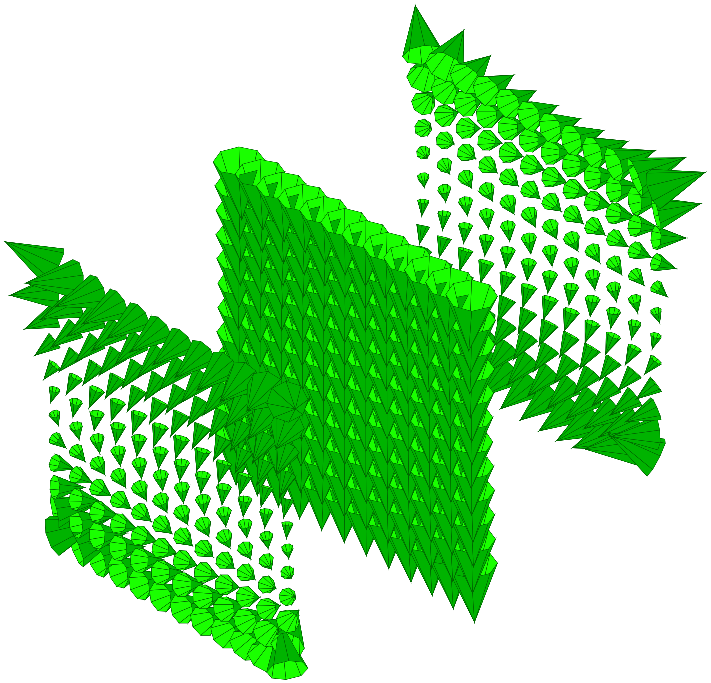
O. Dolinsky

Basic beam parameters

		Antiprotons SIS100 – pSep - CR –HESR		RIBs SIS100 – SFRS – CR - HESR		Mass measurements SIS100-SFRS-CR
		Injection into CR	Extraction to HESR	Injection into CR	Extraction to HESR	Injection into CR
Kinetic energy	MeV/u	3000	3000	740	740	400 - 790
Δp/p	%	6	0.2 ?	3	0.1	1
Emittance	mm*mrad	240	5	200	0.5	100
Bunch length	ns	50	400	50	500	50
Number of particles		2×10^8	10^8	10^8	10^8	$1 - 10^8$
Cooling time	s	10		1.5		-
Cycle time	s	10		1.5 - 5		1.5
Beam loss	%	30	20 ?	10	1	0

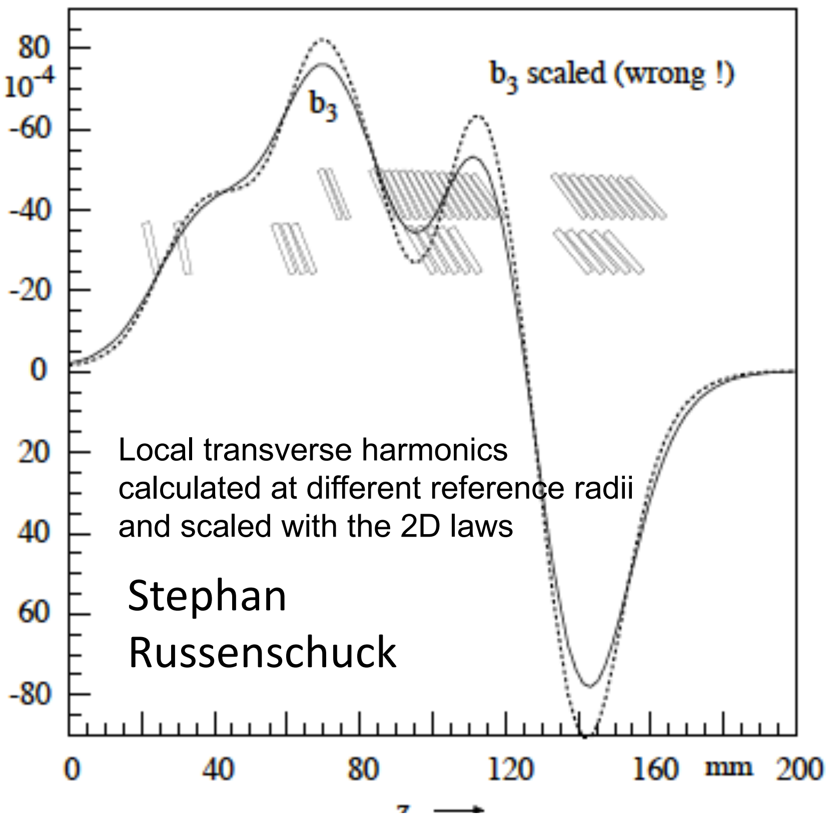
The issue of Magnetic field locality





Stephan Russenchuck

Integrated Harmonics



Local transverse harmonics calculated at different reference radii and scaled with the 2D laws

Stephan Russenschuck

$$b_n(r_1) = \left(\frac{r_1}{r_0}\right)^{n-N} b_n(r_0),$$

wrong

Beam Dynamics meets Magnets

1st XBEAM-XRING Workshop

2-4 December 2013
Darmstadt, Germany

Chair G. Franchetti
Workshop Secretary I. De Caluwe

International Advisory Committee

P. Fabbricatore	INFN	O. Boine-Frankenheim	TUD/GSI
E. Fischer	GSI	S. Machida	RAL
H.G. Khodzhibagiyan	JINR	K. Ohmi	KEK
S. Russenschuck	CERN	F. Schmidt	CERN
C. Spencer	SLAC	F. Zimmermann	CERN

TOPICS

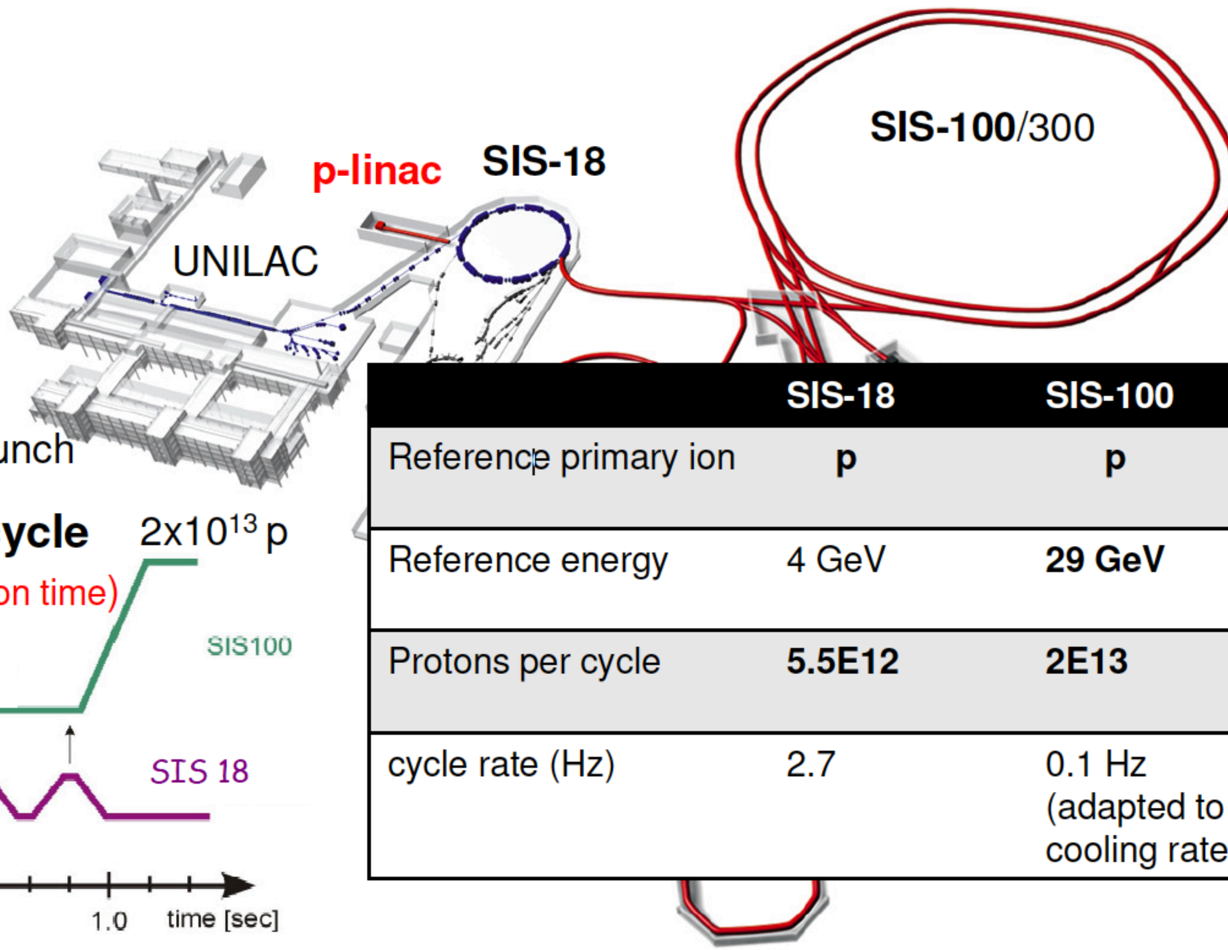
Magnet field mapping	Nonlinear dynamics
Multipole measurements	Emittance growth
Magnetic field in elliptical chambers	Beam loss
3D vs. 2D description	Space charge
Magnet design	Lattice modeling
Mathematical models	Tracking and multipoles

GSI FAIR · EuCARD² · XBEAM RING · HIC for FAIR · Technische Universität Darmstadt

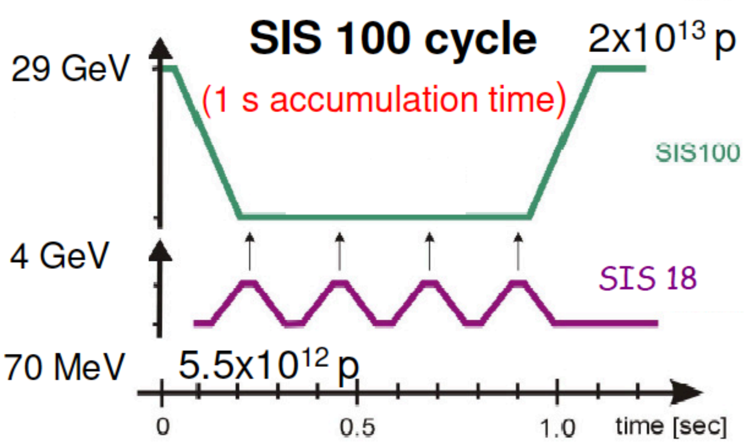
web page: https://indico.gsi.de/conferenceDisplay.py?confId=2352

Long term storage of high intensity beams

O. Boine-Frankenheim



SIS-100 extraction:
Single, short (50 ns) bunch



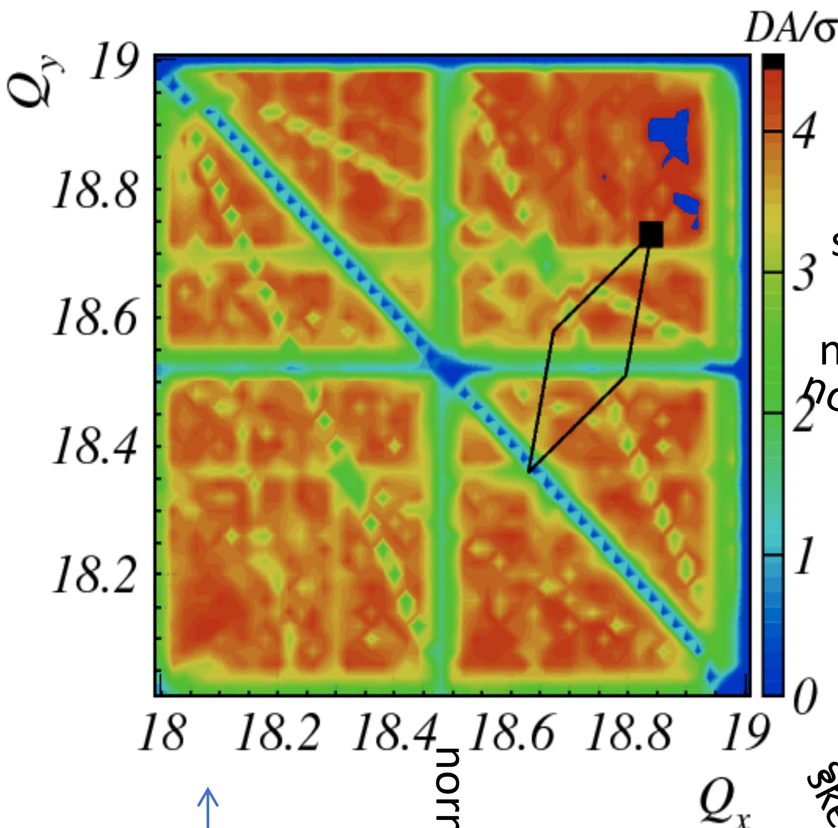
	SIS-18	SIS-100
Reference primary ion	**p**	**p**
Reference energy	4 GeV	**29 GeV**
Protons per cycle	**5.5E12**	**2E13**
cycle rate (Hz)	2.7	0.1 Hz (adapted to CR cooling rate)

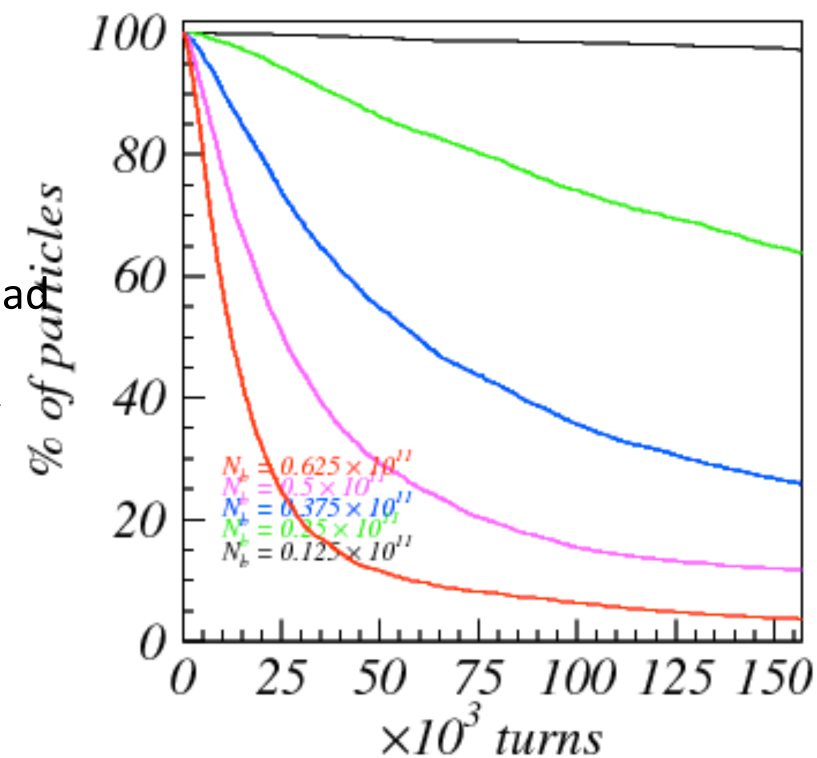
Optional: 8 injections and up to 4E13 protons ('space charge limit').

Space charge and resonances

Typical pattern of beam loss for a frozen beam tracking

Frozen model: means that the source of detuning with amplitude remains unaffected by the beam loss



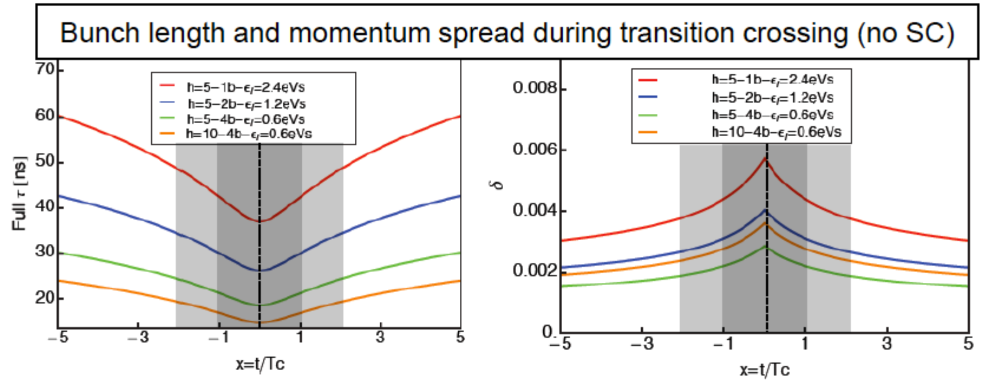


One error seed

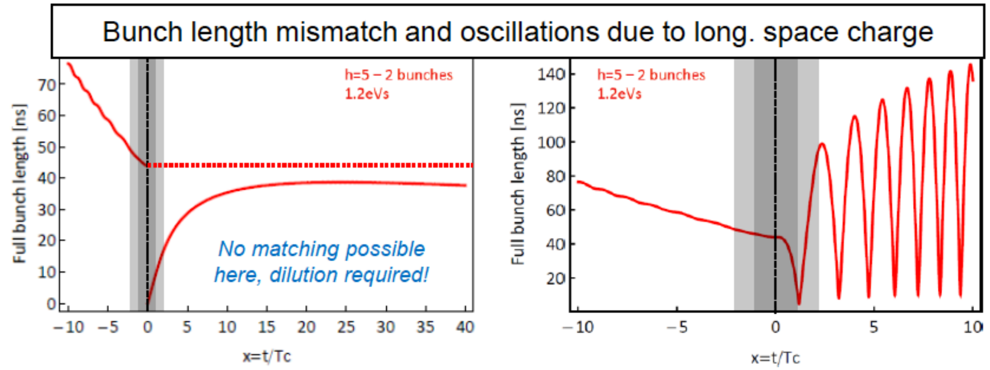
G. Franchetti, S. Sorge *Proc. of IPAC2011*, S. Sebastian, Spain. MOPS002

Transitions crossing in SIS100 (protons).

- Momentum acceptance
  - Bunch length shrinks sharply close to transition
  - Momentum spread peaks correspondingly
  - Momentum acceptance critical when dispersion is large
  - Potential cures:
    - Transition jump to escape peak
    - Optics with small dispersion



- Longitudinal space charge
  - Bunch lengthening below transition
  - Bunch shortening above transition
  - Bunch length mismatch after transition crossing
  - Effects quadrupole oscillations
  - May lead to significant blow-up if large and undamped
  - Potential cures:
    - Transition jump fine tuned to match bunch length
    - Dilution to reduce long. space charge
    - Damping of oscillations with feedback



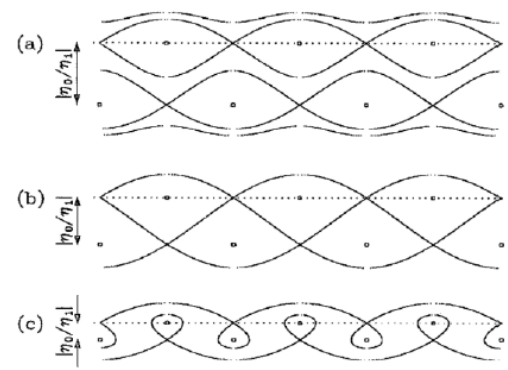
D. Ondreka

Transition Shift Scheme: Distorted Buckets Near Flattop

D. Ondreka

- Longitudinal dynamics near flattop
  - Phase slip becomes very small
  - Higher orders can't be neglected
  - Bucket dominated by new fixed point
    - Shorter bunches with higher momentum spread
    - Asymmetry in momentum distribution
  - Chromaticity correction to ΔQ = ±0.05 helps
    - Larger bucket due to reduction of η_1

$$\eta = \eta_0 + \eta_1\delta = \frac{1}{\gamma^2} - \frac{1}{{\gamma_t}^2} + \eta_1\delta$$

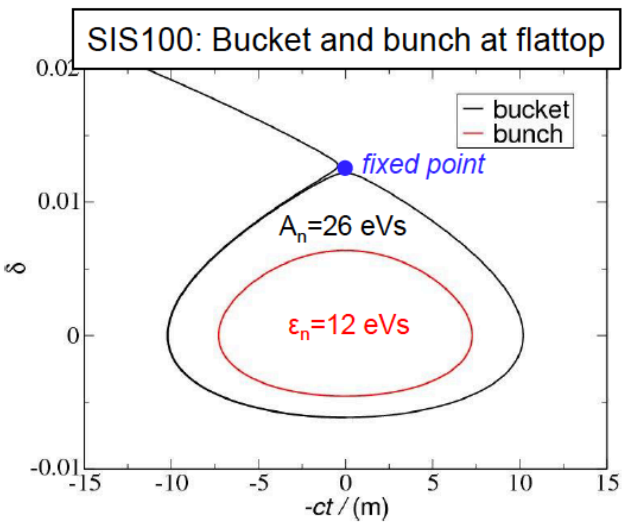


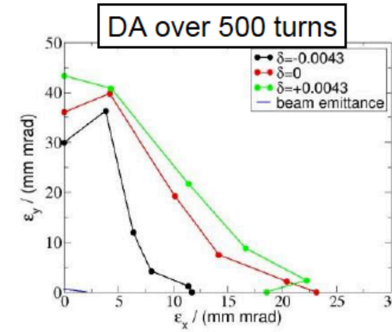
[*Ng, NIM A 404, 1998*]

$$\delta_{\mathrm{fp}} = \left|\frac{\eta_0}{\eta_1}\right|$$

- Implications
  - Without field errors no problems
  - Results with field errors ambiguous
    - Short-term (500 turn) dynamic aperture reasonable
    - Long-term tracking simulations (32000 turns) give losses of few per cent

- Limitation of present studies
  - Only stationary buckets, no beam loading
  - Origin of losses needs to be better understood
  - Further studies necessary





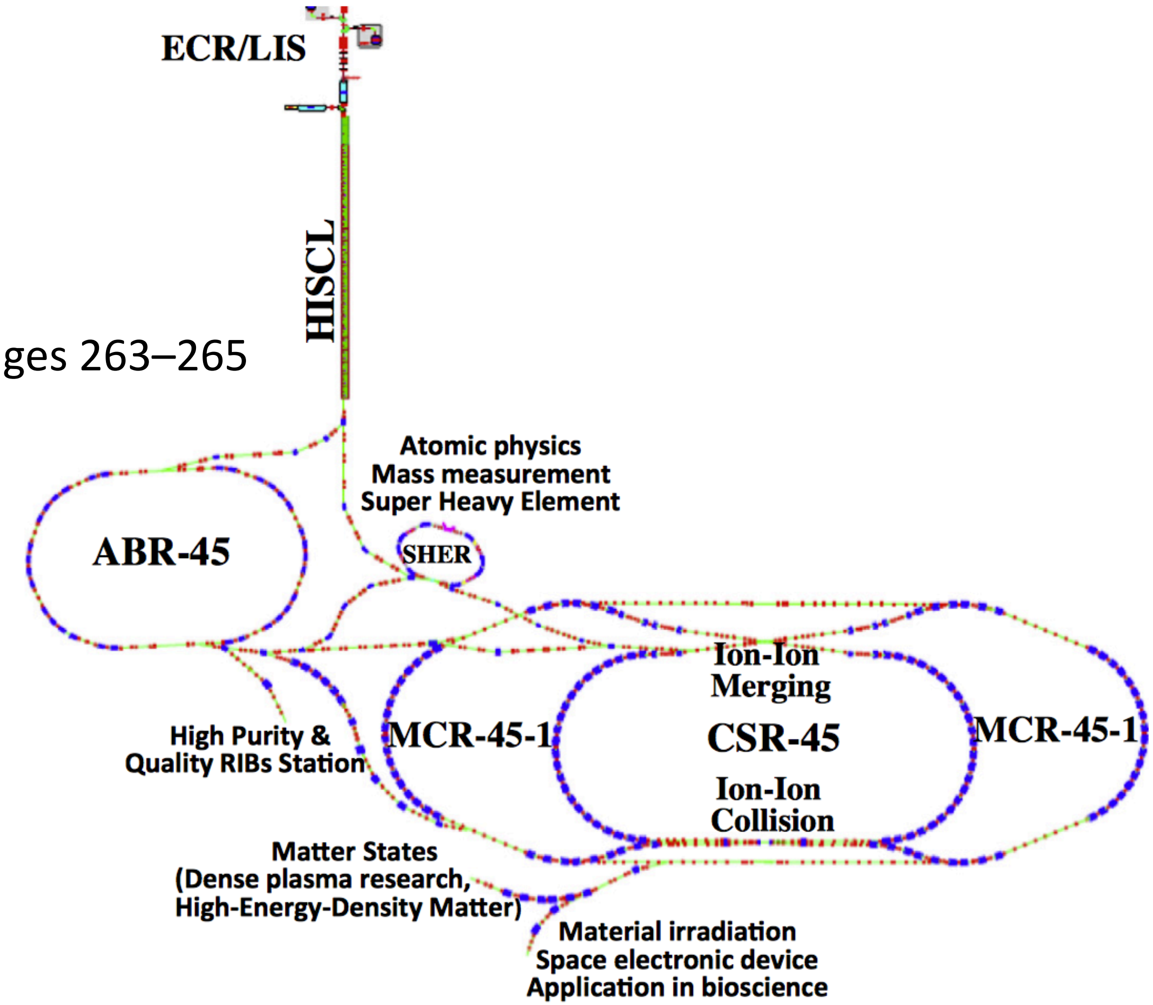
Simulation of losses over 32000 turns	
Field errors off	<0.1 %
Field errors on	2.0 %

[*Images and data courtesy of S. Sorge*]

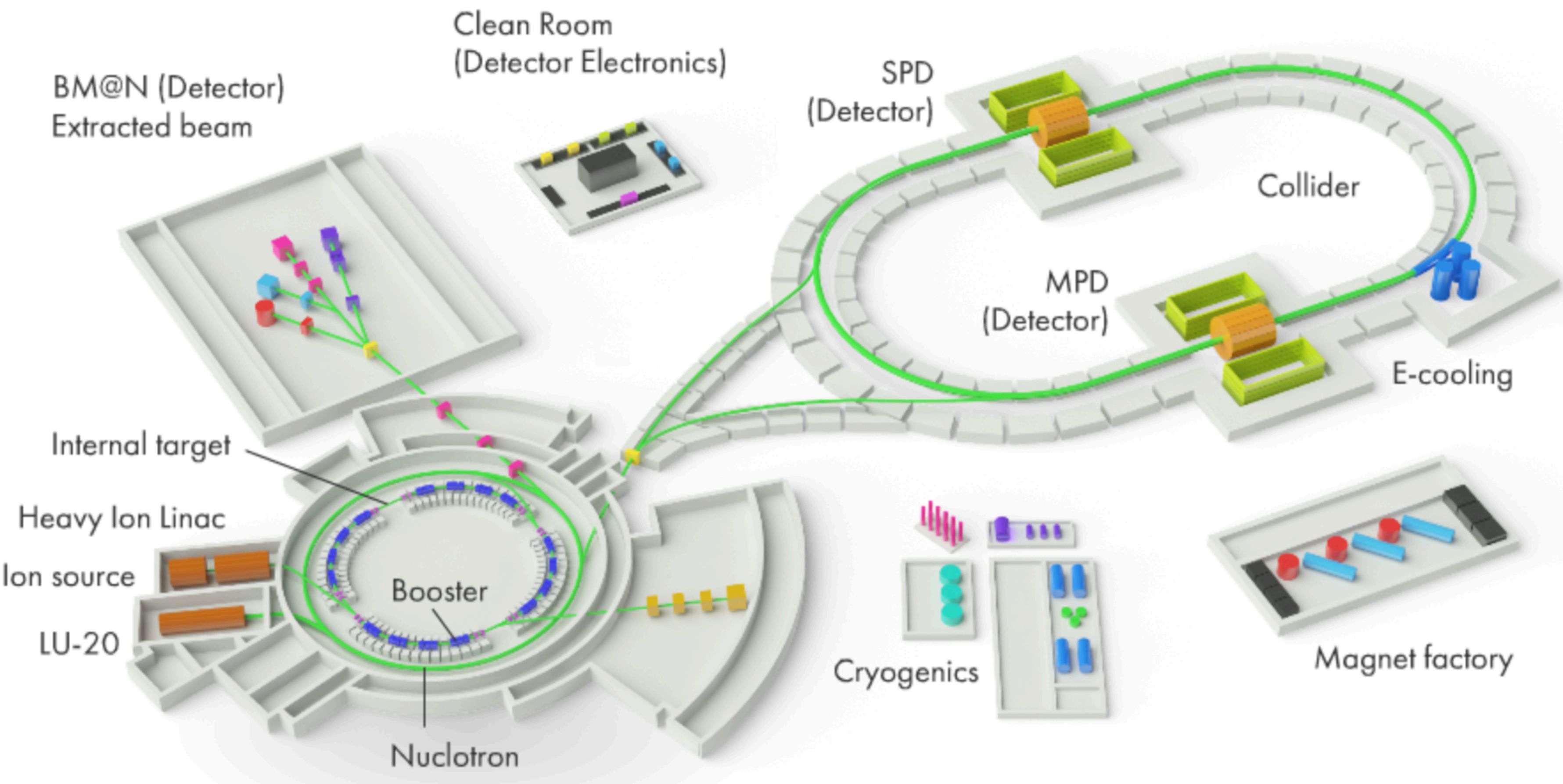
HIRFL (Heavy Ion Research Facility in Lanzhou)

J.C. Yang

NIM A, Volume 317, Part B, 15 December 2013, Pages 263–265



NICA Complex



HIRFL (Heavy Ion Research Facility in Lanzhou)

HIAF main design parameters of typical U^{34+} ion beam. ppp denotes particle per pulse.

Machine	Ion	Energy	Intensity
ECR source	U^{34+}	60 kV/q	0.02 pmA
LIS source	U^{34+}	60 kV/q	0.1 pmA
HISCL	U^{34+}	25 MeV/u	0.015–0.075 pmA
	U^{76+}	40 MeV/u	0.003–0.015 pmA
ABR-45	U^{34+}	1.2 GeV/u	$0.25–1.3 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.5–2.5 \times 10^{10}$ ppp
CSR-45	U^{34+}	1.2 GeV/u	$1.0–5.0 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
	U^{92+}	4.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
MCR-45-1(2)	U^{34+}	1.2 GeV/u	$1.0–5.0 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
	U^{92+}	4.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp

J.C. Yang, NIM B 317 (2013) 263–265

Beam Dynamics *meets* Magnets

Dec. 2013, Darmstadt

by PSI, Dec. 2014

Advanced Optics Control Workshop
215, CERN

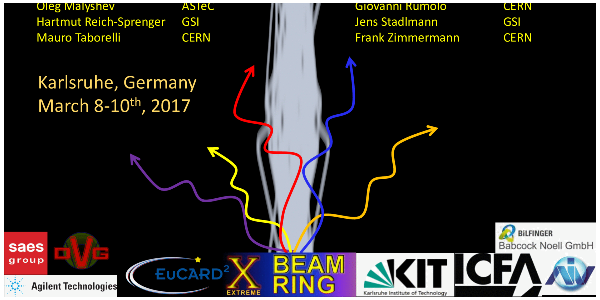
Mechanisms

Collaboration meeting 2014, CERN

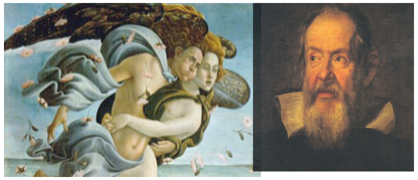
Space charge, Oxford 2015

Beam Dynamics

Beam Dynamics meets Vacuum, Collimation, and Surfaces



Beam dynamics *meets* Diagnostics



Challenges

Study the machine from beam-based measurements

1. Control system usable, and flexible for beam studies
2. Availability of diagnostics that is user-friendly, and which limits are clear
3. Development of theoretical / numerical tool

The Foundation of everything

The understanding of the machine linear optics

The pandora-box

The understanding of the machine nonlinear Dynamics

Challenges II

Taming Space Charge: For long term storage → resonance compensation

How about shaping the beam ? → towards flat beams?

Electron lenses are trendy, but do they work ?

Taming instabilities: Advances in feed-back systems technology

The difficulty of the 3D world: Modeling the 3D dynamics, requires a complete Understanding of the dynamics & computer science

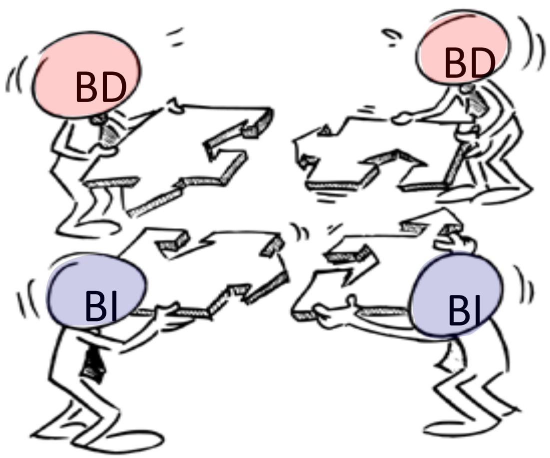
Reality and Myths: Genetic Algorithms are applicable beyond light sources experience?

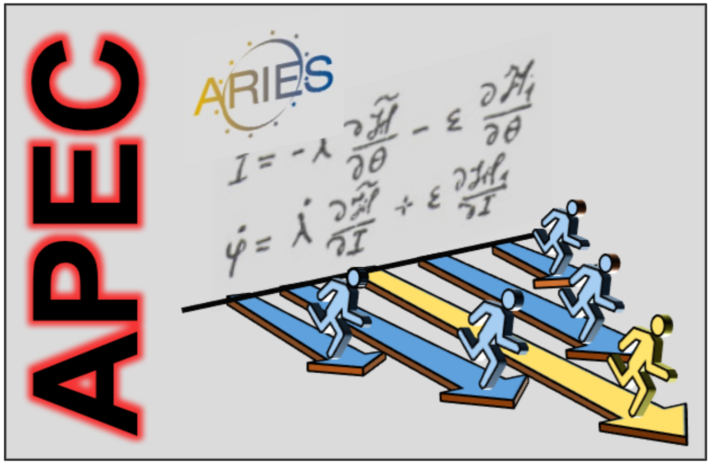
Advent of new concepts: Do we learn know how transfer from the IOTA Experience ?

Challenges III

The control issue and complexity: User friendly control system ?
Is the LSA the ultimate control system ?

Synergies across communities: BD & Magnets & Diagnostics & Vacuum & RF   X EXTREME BEAM RING




APEC
ARIES