The FAIR Storage Ring Complex

to deliver intense high-quality secondary beams for experiments

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on behalf of GSI Storage Rings Division

& collaborators

FAIR

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Motivation: Interaction of secondary ion beams (pbars, rare isotopes, heavy HCI) with matter

- high intensity dense quasi-monoenergetic beams
- dense localised targets
- optimal beam-target overlap in space & time

- good ion beam lifetime → UHV
- variation & control of beam energy (spread)

- Well-defined charge states, heavy HCI, rare isotopes, antiprotons, exotic beams

→ high energy accelerator complex

The FAIR Accelerator Complex

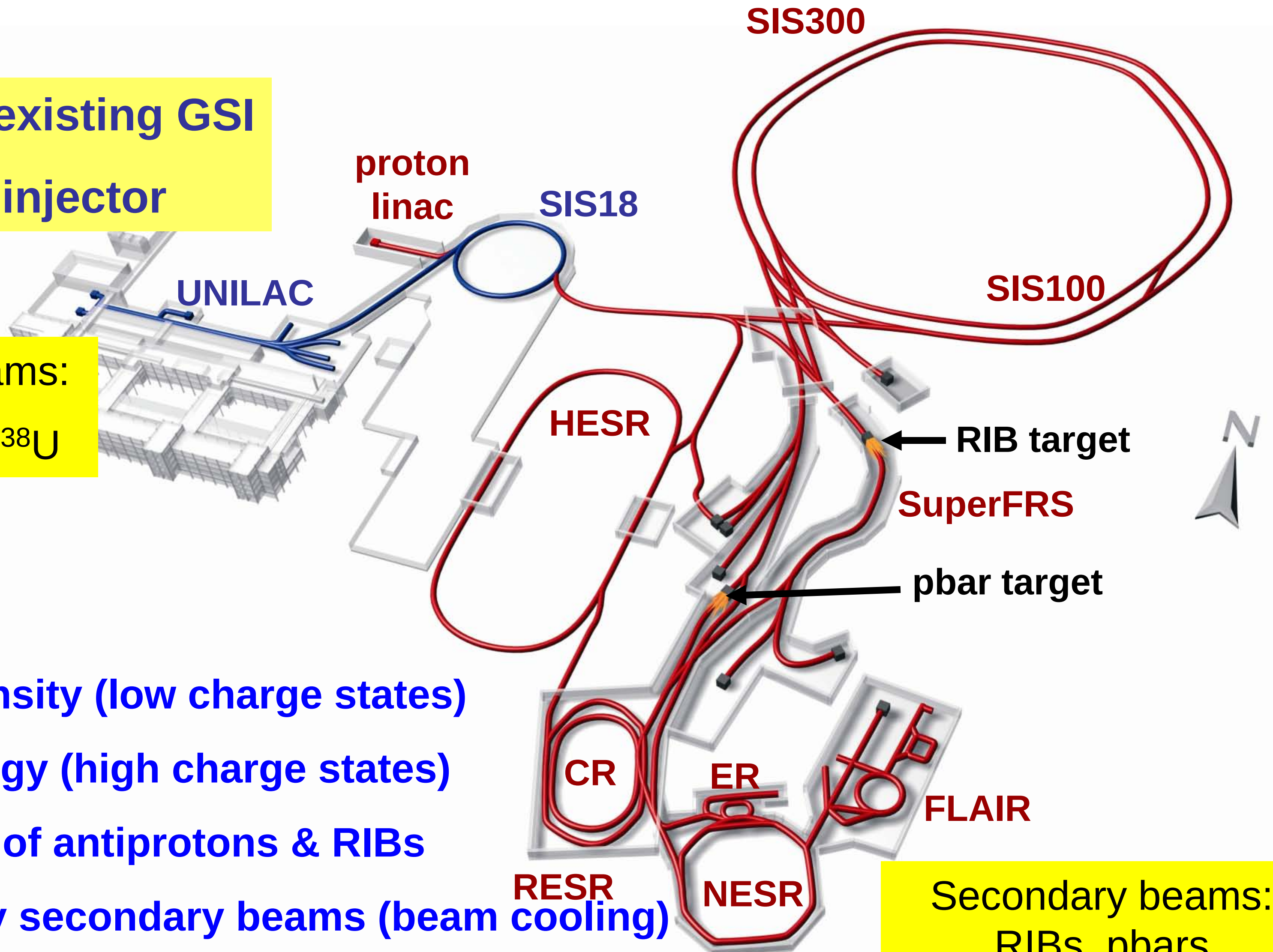
Great Variety of Experimental Requirements & Possibilities

upgraded existing GSI

= FAIR injector

Primary beams:

protons to ^{238}U



Secondary beams:
RIBs, pbars

goals:

higher intensity (low charge states)

higher energy (high charge states)

production of antiprotons & RIBs

high quality secondary beams (beam cooling)

increase intensity of secondary beams (accumulation)

Intensities of Primary Beams

	Heavy Ions			Protons
	SIS18 today	**upgraded SIS18 as SIS100 injector**	**SIS100**	**SIS100**
Reference ion	U^{28+} / U^{73+}	U^{28+}	U^{28+}	protons
Max. energy	0.2 / 1 GeV/u	0.2 GeV/u	**2.7 GeV/u**	**29 GeV**
Max. intensity	**$5x10^9$ / $3x10^9$**	**$1.5x10^{11}$ ($2x10^{10}$achieved)** → x 4	**$5x10^{11}$**	**$2x10^{13}$**
Repetition rate	0.3 Hz	2.7 Hz (not yet available)	0.7 Hz	0.1 (0.2) Hz
Bunch length	> 100 ns	-	**60 ns**	**< 50 ns**

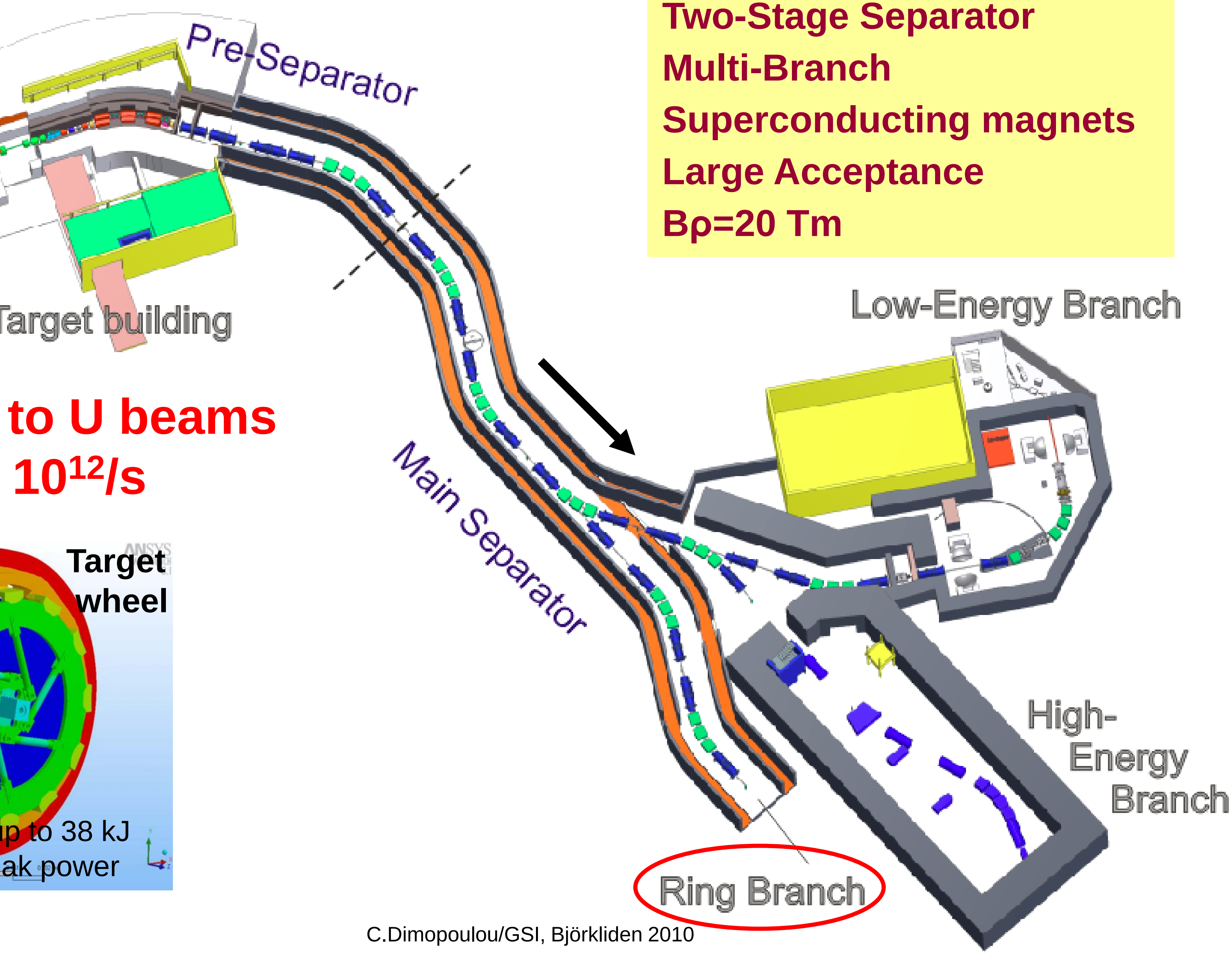
goal: fill SIS18 up to the space charge limit

Technical Challenges:

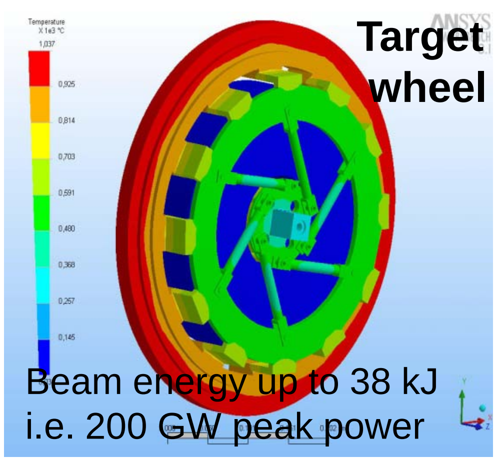
- control of intense beams: dynamic vacuum, space charge effects, instabilities
- fast ramping superconducting magnets,complex RF manipulations
- parallel operation of several beams

The Rare Ion Beam Separator Super FRS

Two-Stage Separator
Multi-Branch
Superconducting magnets
Large Acceptance
Bρ=20 Tm

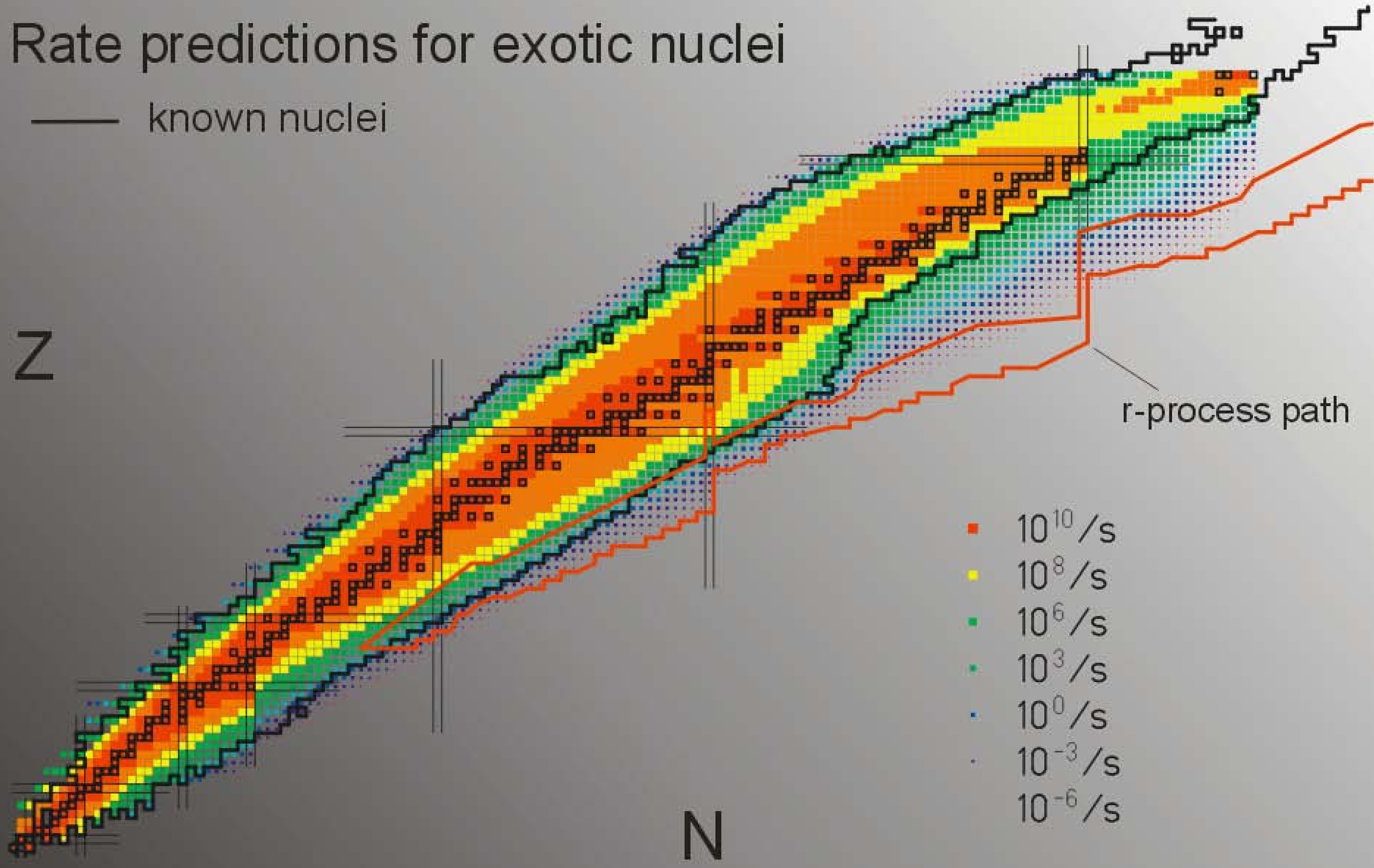


Primary p to U beams with up to 10^{12}/s



C.Dimopoulou/GSI, Björkliden 2010

Rate predictions for exotic nuclei

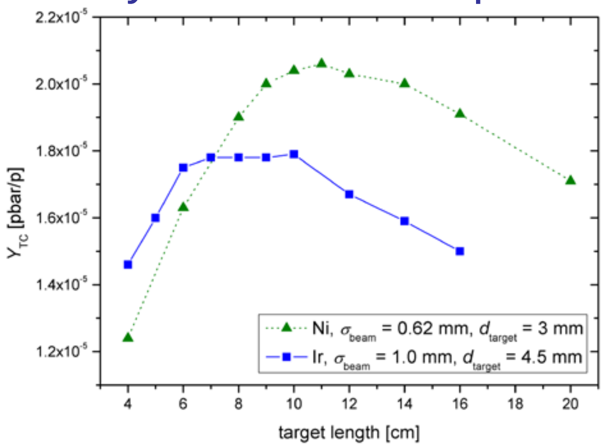


Rate after target for 10^{12}/s primary ions

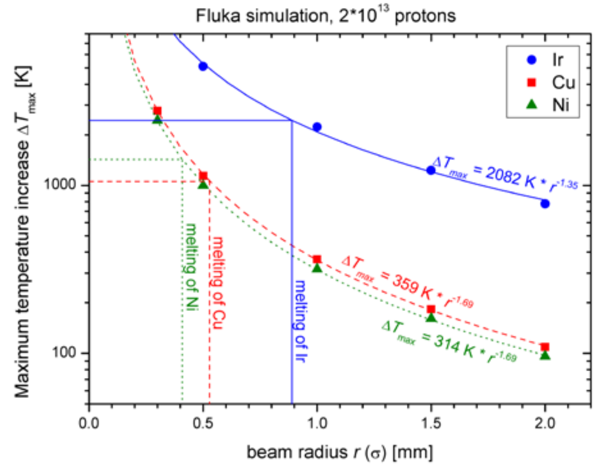
K.H. Schmidt et al.

The Antiproton Target and Separator

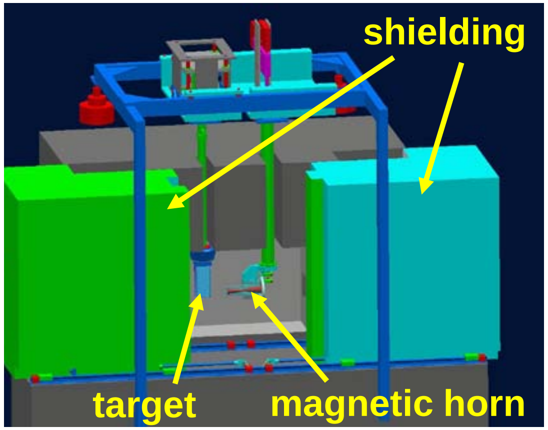
production rate of antiprotons
primary beam 29 GeV protons



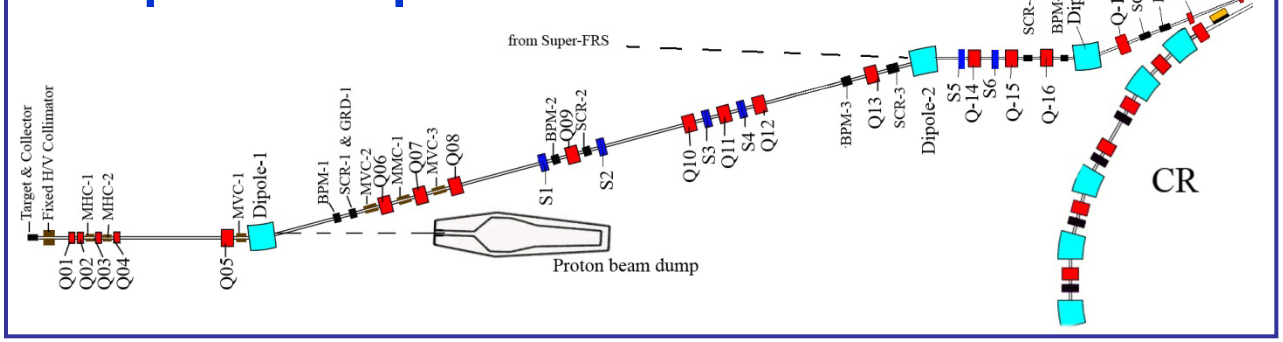
temperature of target
⇒ choice of nickel

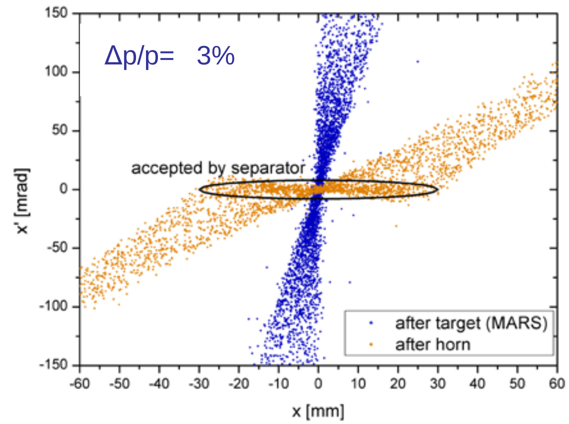


target station
shielding and handling



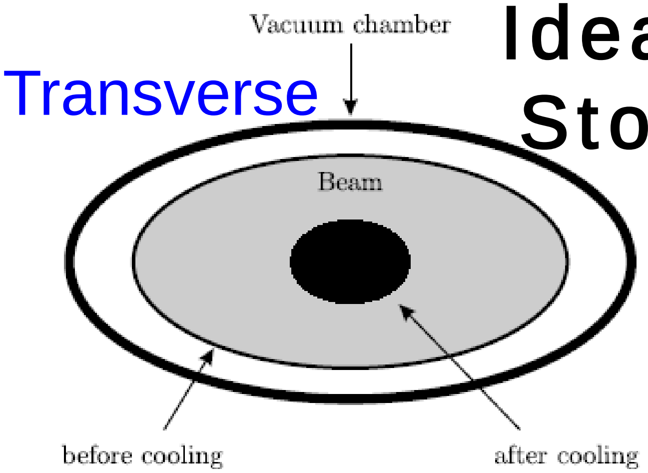
Antiproton Separator





according to tracking calculations about 70 % of the produced antiprotons with Δp/p≤ 3% will be stored in the CR

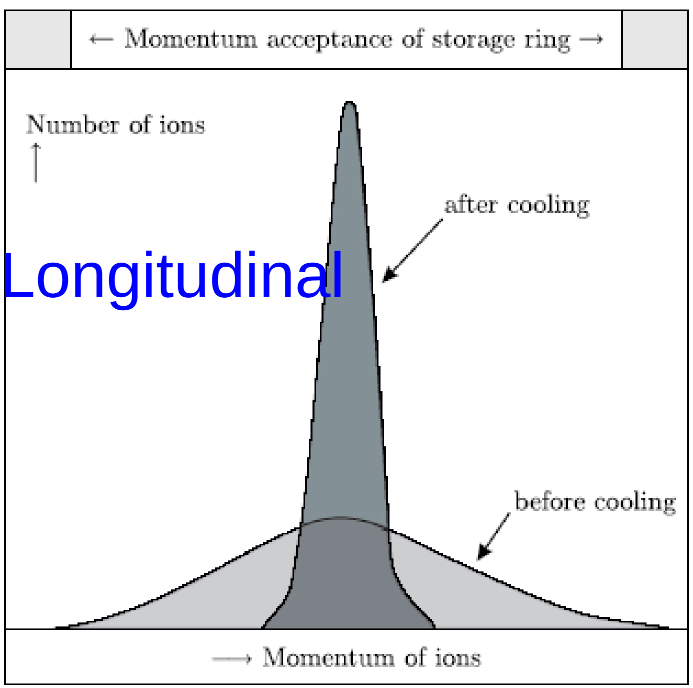
Ideal tool for secondary beams : Storage ring with beam cooling



Secondary beams emerge from targets at low abundancies & occupy a very large phase space (sizes, angles, energy spread)

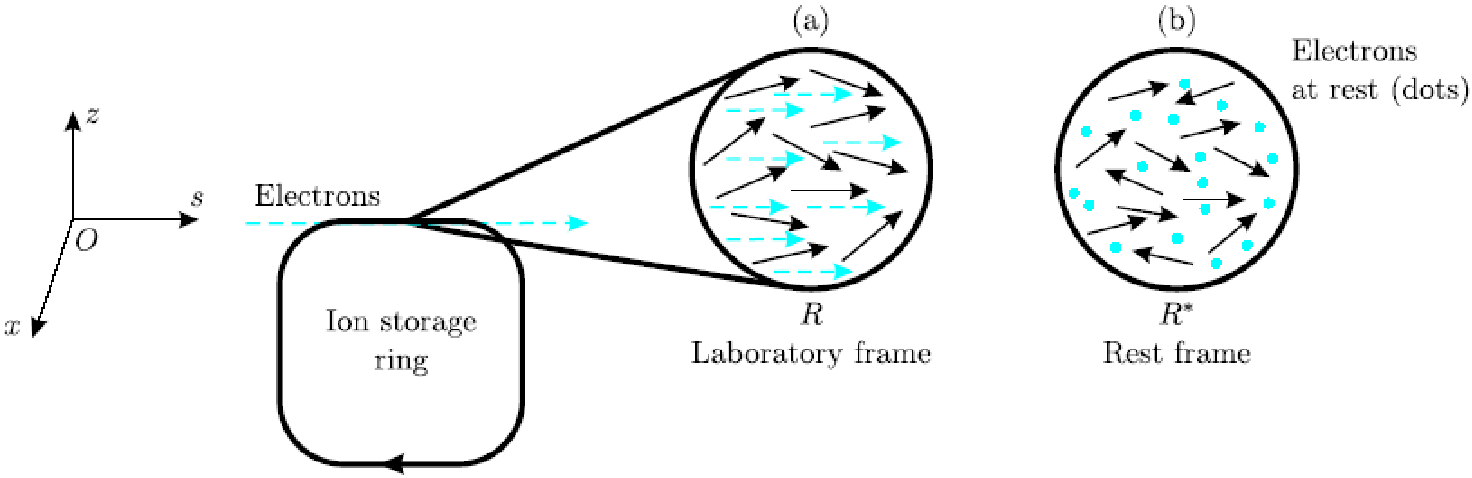
BEAM COOLING TECHNIQUES

- ➢Increase phase space density
- ➢ Accumulation of low-abundant ion species
- ➢Compensate diffusion (phase space growth) during deceleration
- ➢ Counteract beam heating effects i.e. in an internal target

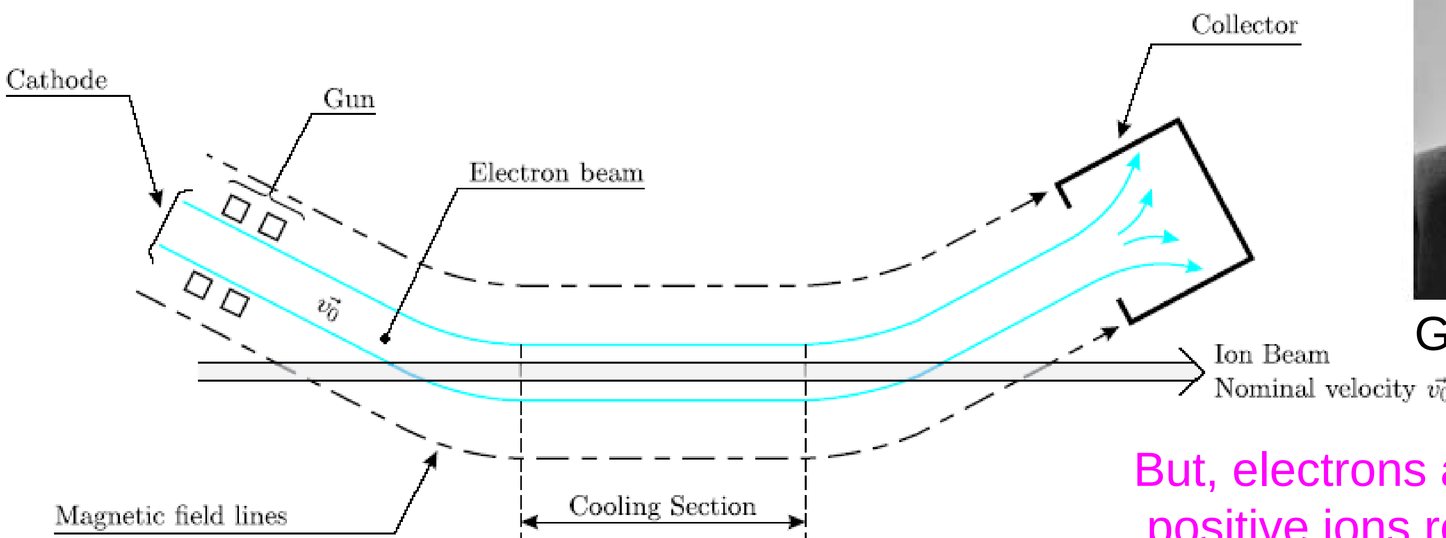


→ high-quality beams for high-luminosity, precision experiments !

Electron cooling: Principle

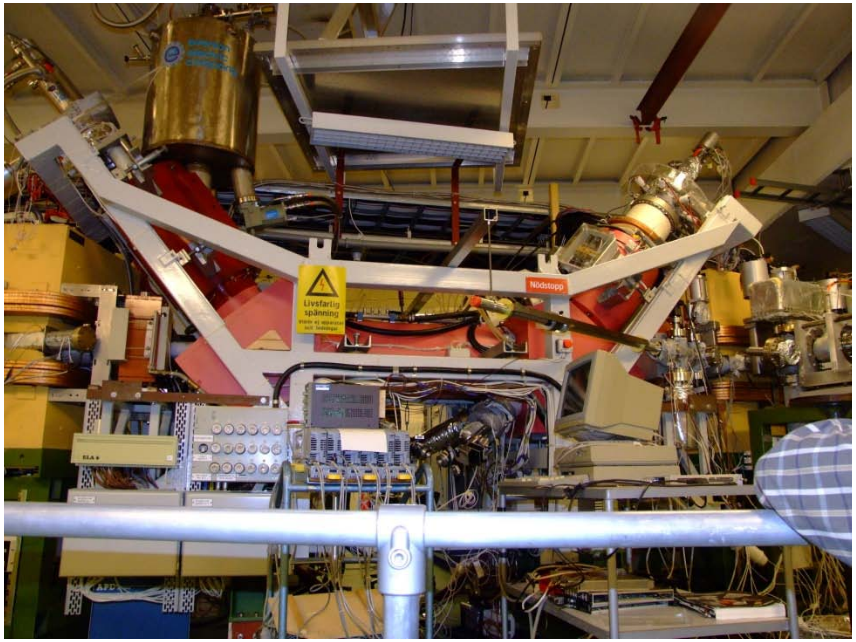


G.Budker,1966



But, electrons and
positive ions recombine !?

Electron cooling: Practice

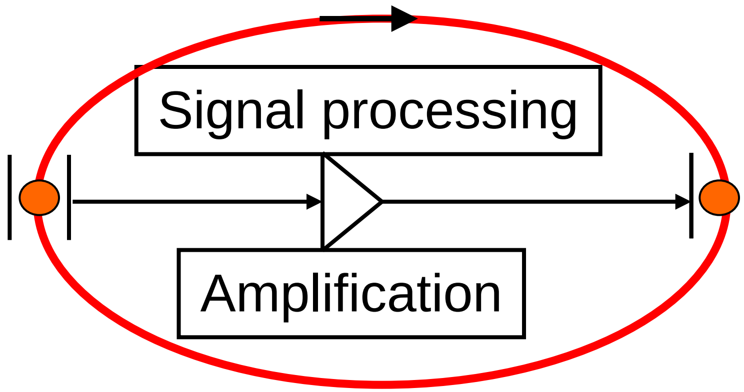


CRYRING, Stockholm, 2003

CELSIUS, Uppsala, 2008 (last photo ☹)

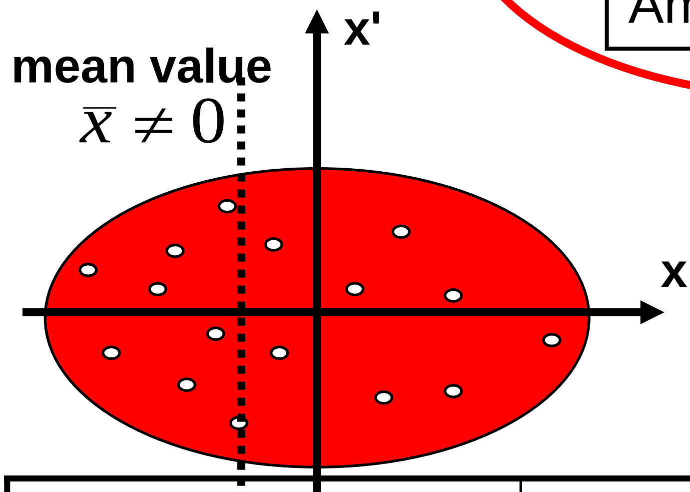
Stochastic cooling: Principle

Measure fluctuations in beam with high time resolution (pick-up)



Correction (kicker)

~ feedback system

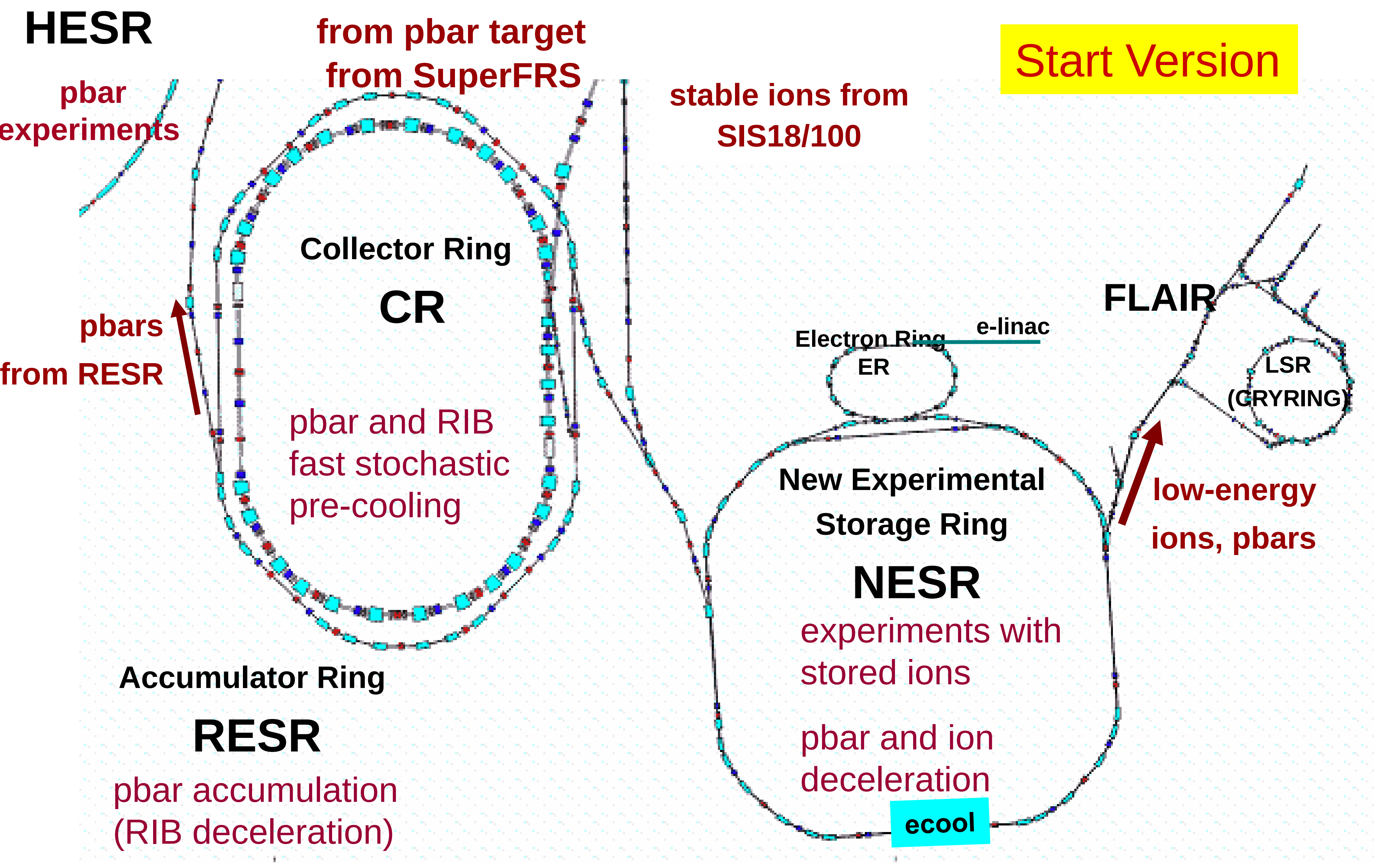


large electronic bandwidth of all subsystems (~ GHz)
low-noise pick-ups and preamps (also cryogenic)
high microwave power (~ kW)

S. van der Meer,1972
Nobel prize, 1984
(shared with C. Rubbia)

Beam Cooling	**Stochastic**	**Electron**
Ion species	all	ions
Favoured beam velocity	high	low/medium ($\beta_0\gamma_0 \leq 1$)
Beam intensity	low	any
Cooling time	N $\cdot 10^{-8}$ s, N $\geq 10^{8}$	$1\text{-}10^{-2}$ s
Favoured beam temperature	high	low

The FAIR Storage Rings



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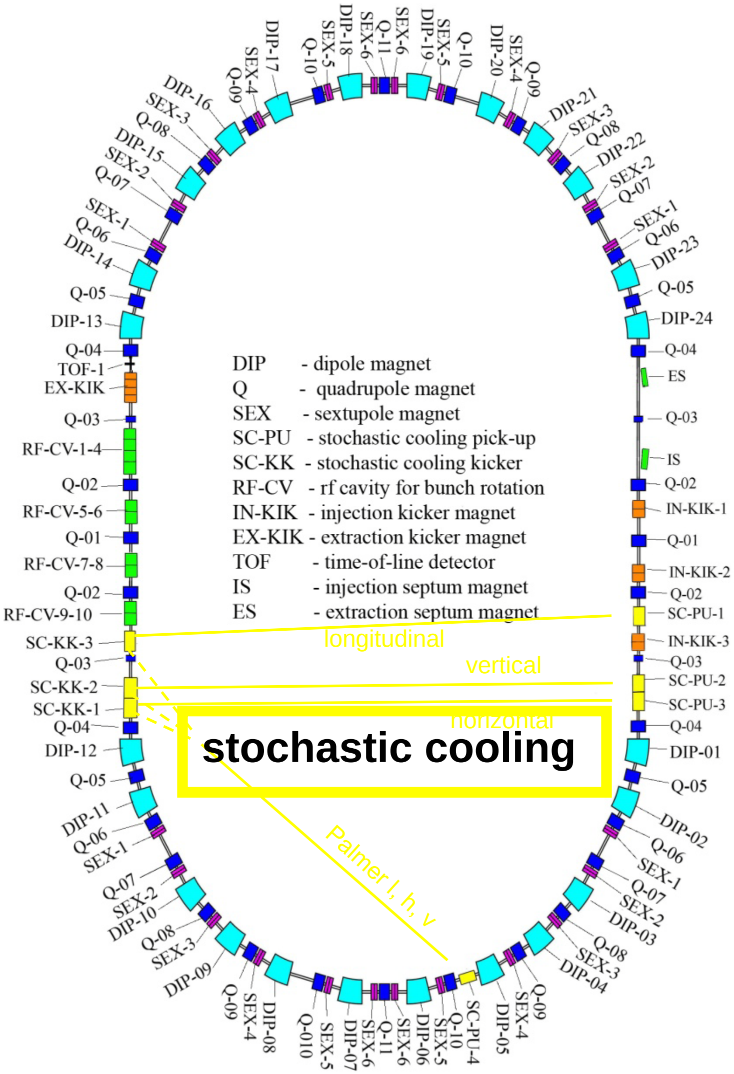
The Collector Ring CR



circumference 216 m
magnetic bending power 13 Tm
large acceptance $\varepsilon_{x,y}$ = 240 (200) mm mrad
$\Delta p/p = \pm$ 3.0 (1.5) %

fast stochastic cooling (1-2 GHz)
of antiprotons (10 s) and
rare isotope beams (1.5 s)

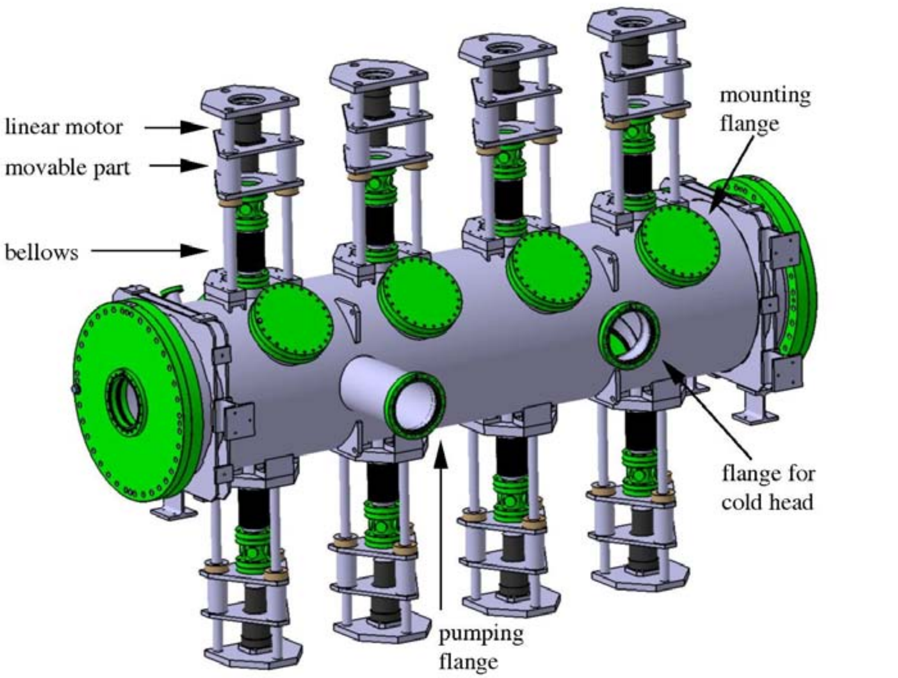
fast bunch rotation at h=1
with rf voltage 200 kV
adiabatic debunching
optimized ring lattice for proper mixing
large acceptance magnet system

NUSTAR-ILIMA Experiments:
isochronous mass measurements of RIBs

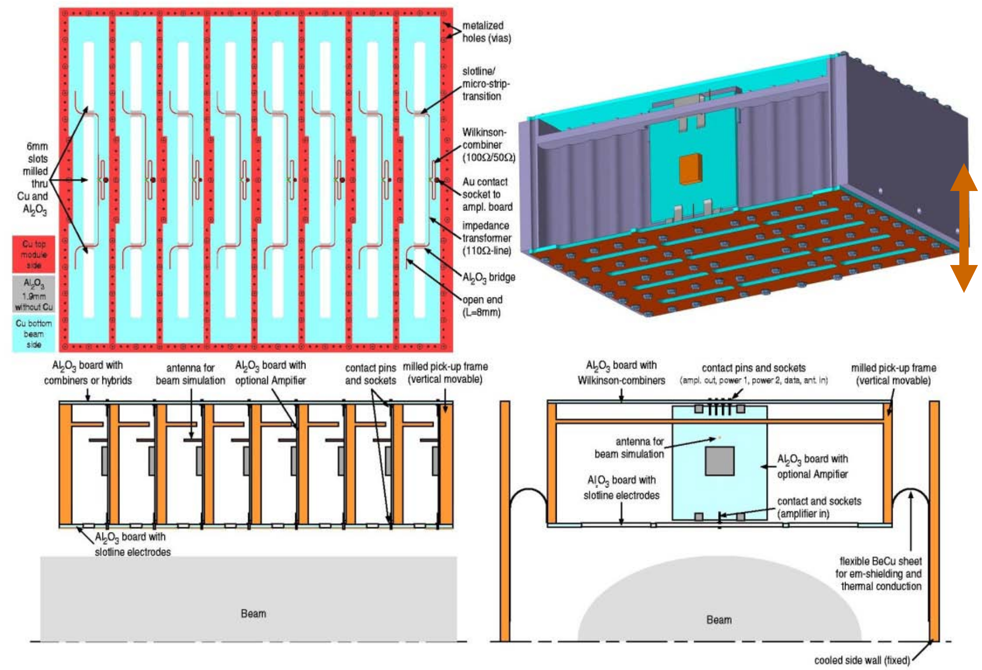
option: upgrade of rf system to 400 kV
and stochastic cooling to 1-4 GHz,
→ cooling times reduced by factor 2

CR Stochastic Cooling (Practice)

Fast Stochastic Pre-cooling: matched to velocities β = 0.83 - 0.97
system band width 1-2 GHz
rf power ~ 1-2 kW per system

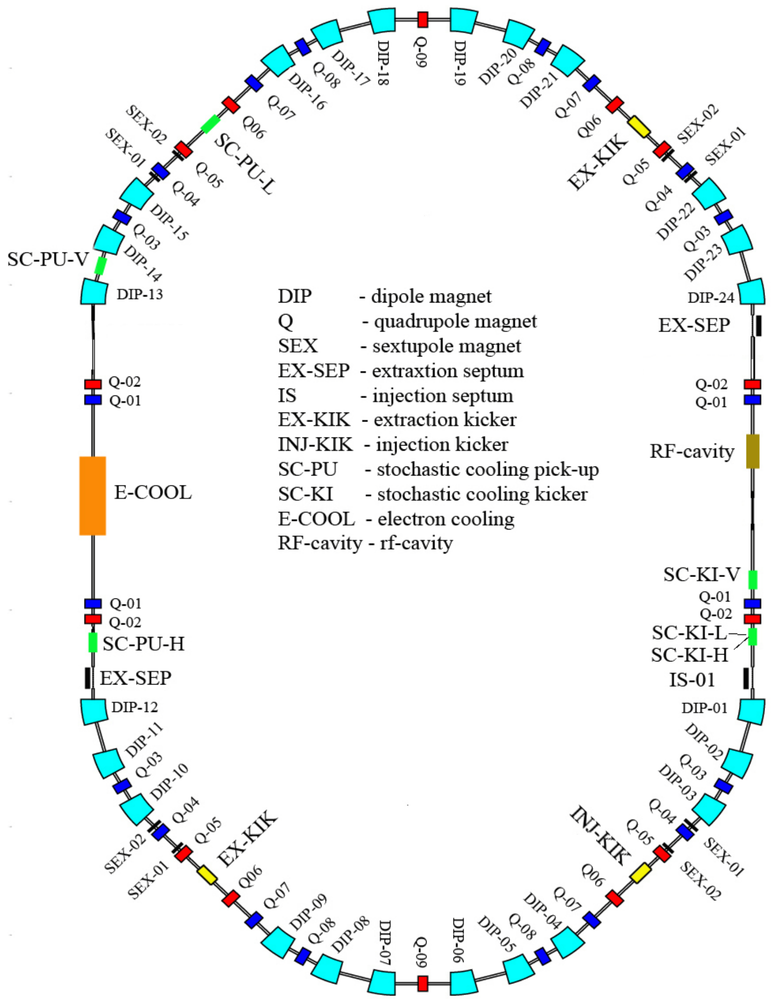


vacuum tank with actuators for electrode movement including cold heads (20 K) and cooled pre-amplifiers (option)



Installed in the vacuum tank: electrodes (and pre-amplifiers) can be cooled to 20 K

The Antiproton Accumulator Ring RESR



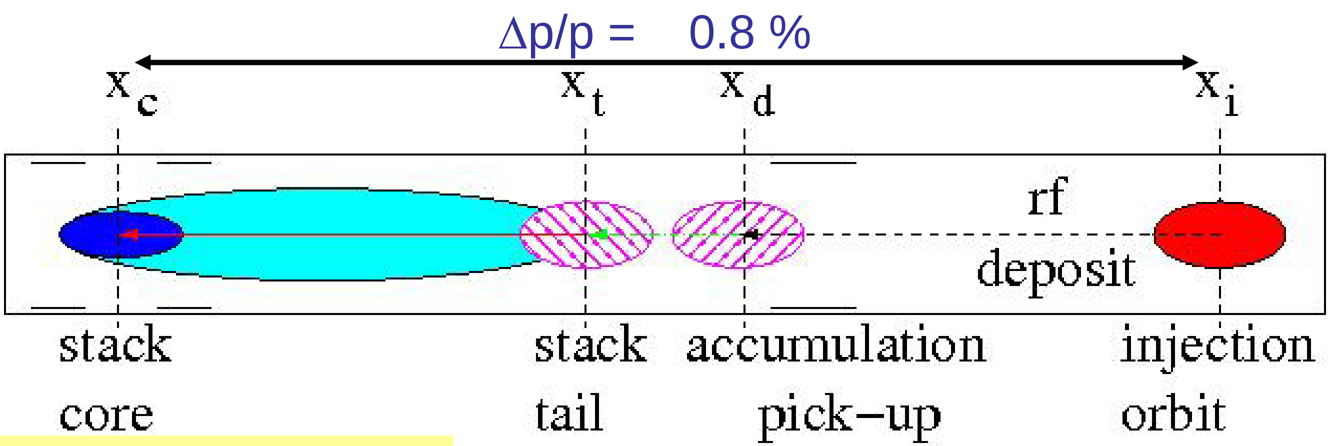
circumference	240 m
magnetic bending power	13 Tm
tunes Q_x/Q_y	3.12/4.11
momentum acceptance	±1.0 %
transverse accept. h/v	25×10^{-6} m
transition energy	3.3-6.4

accumulation of antiprotons by a combination of RF and stochastic cooling

max. accumulation rate 3.5 (7)×10^{10}/h
max. stack intensity ~ 1 10^{11}

additional mode:
fast deceleration of RIBs (antiprotons)
to a minimum energy of 100 MeV/u
for injection into NESR (ER)
for collider mode experiments

Antiproton Accumulation in RESR
RF Manipulation & Stochastic Cooling



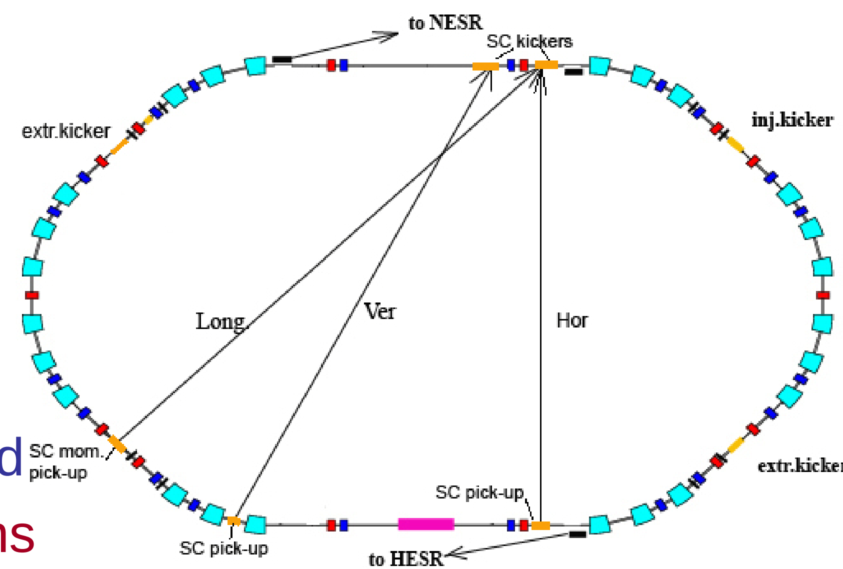
in collaboration with
D. Möhl, L Thorndahl (CERN)
T. Katayama

core cooling 2-4 GHz

long.,hor., vert.

tail cooling 1-2 GHz

long.



injection of 1 10^8 antiprotons every 10 s

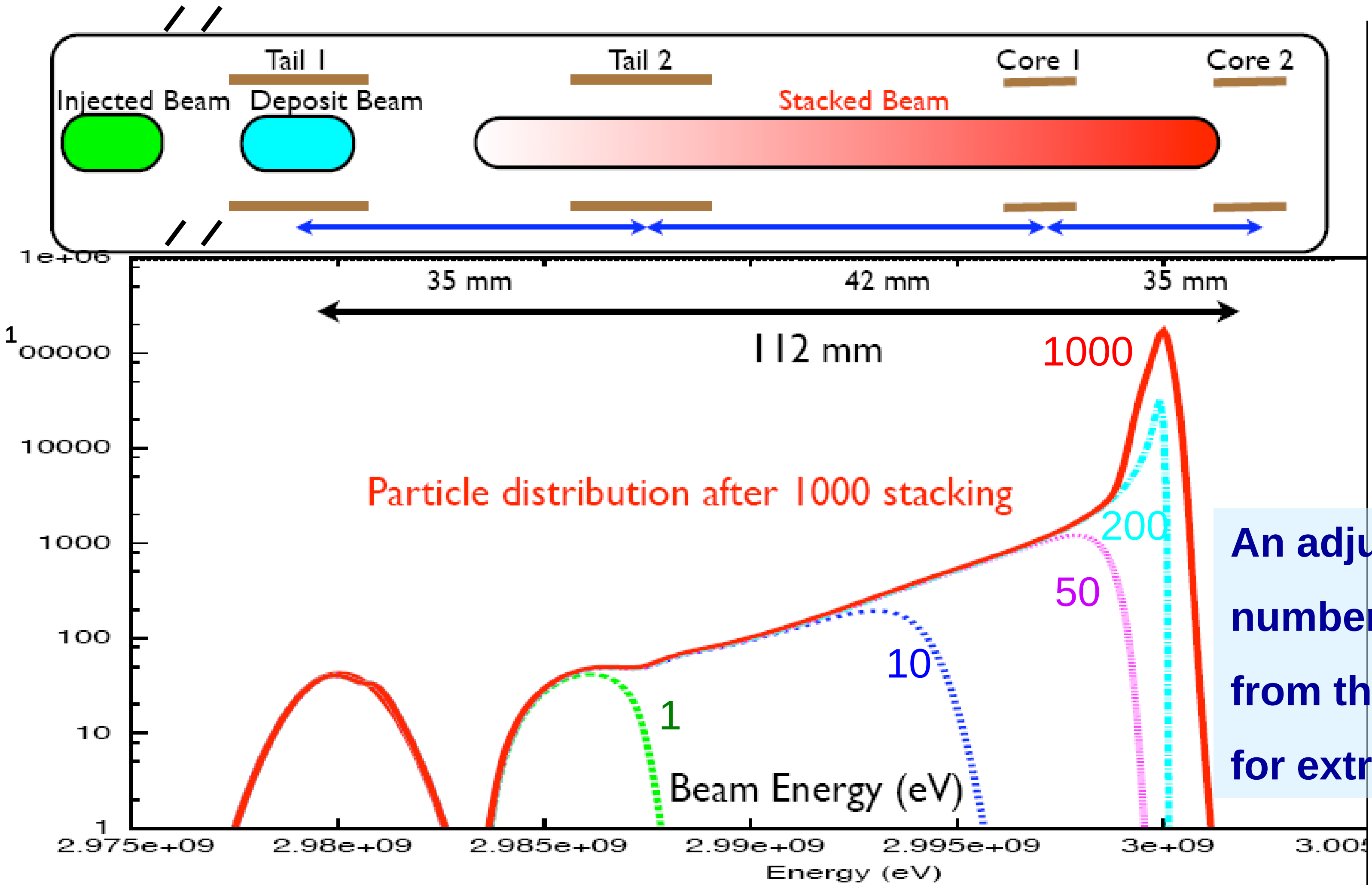
pre-cooled in CR: $\delta p/p = 10^{-3}$, $\varepsilon_{x,y} = 5$ mm mrad

maximum stack intensity~ 1 10^{11} antiprotons

max. accumulation rate: 3.5×10^{10}/ h

Accumulation System for RESR

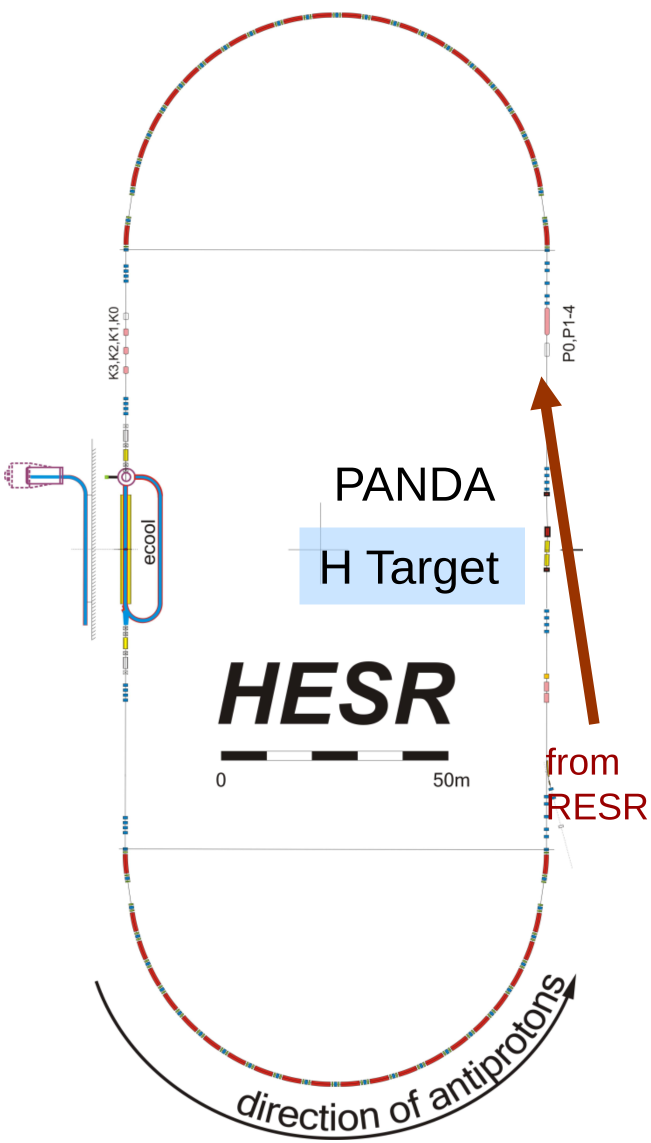
Longitudinal stochastic cooling system: tail and core cooling



An adjustable pbar number captured from the core for extraction

The High Energy Storage Ring HESR

HESR Consortium:
FZJ, GSI, (TSL)



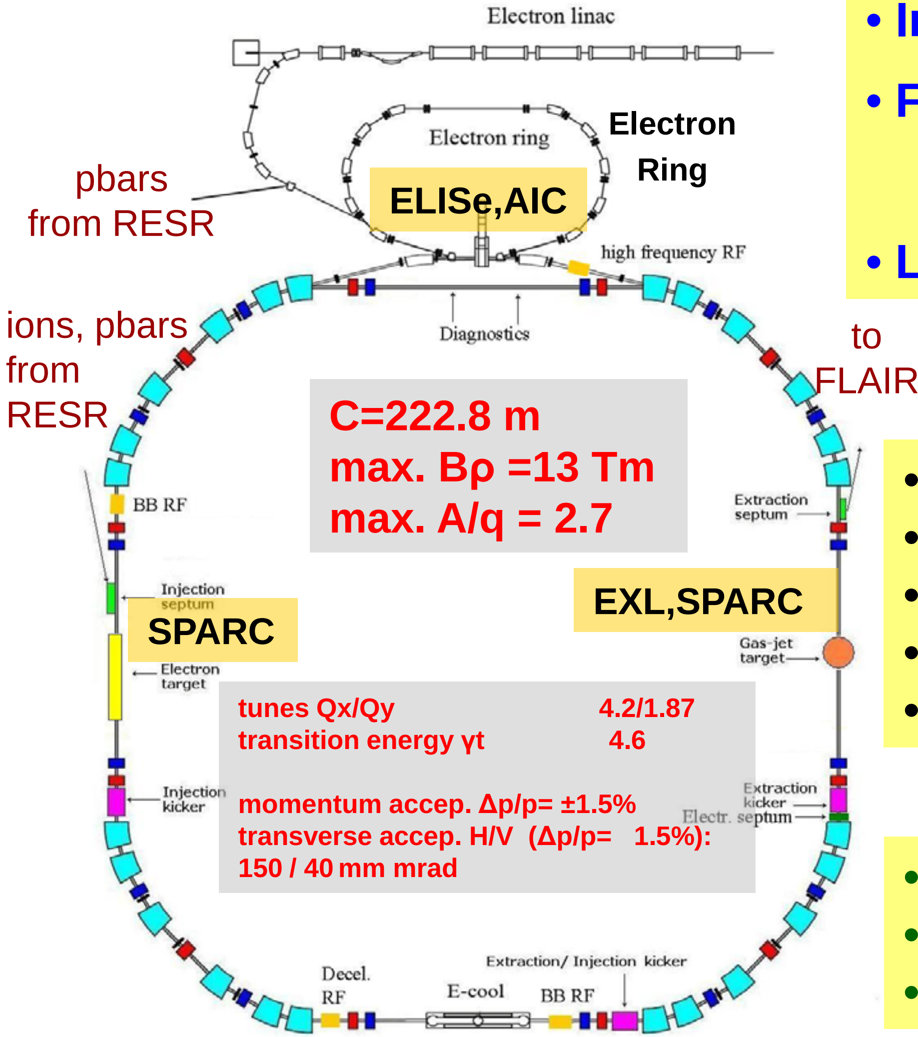
circumference 574 m
magnetic bending power 50 Tm
momentum (energy) range 1.5-15 GeV/c (0.8-14.1 GeV)
injection of (anti-)protons at 3.8 GeV/c (3 GeV)

Effective target thickness (H-pellets):	**4×10^{15} cm^{-2}**
Beam radius at target (rms):	**0.3 mm**

Mode	**High resolution**	**High luminosity**
Momentum range	**1.5 - 8.9 GeV/c**	**1.5 – 15 GeV/c**
Pbar number	**10^{10}**	**10^{11}**
Peak luminosity	**2×10^{31} cm^{-2}s^{-1}**	**2×10^{32} cm^{-2}s^{-1}**
Momentum spread	**$\Delta p/p \leq 4\cdot10^{-5}$**	**$\Delta p/p = 1\cdot10^{-4}$**
Beam cooling	**Electron ($\leq$ 8.9 GeV/c)**	**Stochastic ($\geq$ 3.8 GeV/c)**

The New Experimental Storage Ring NESR

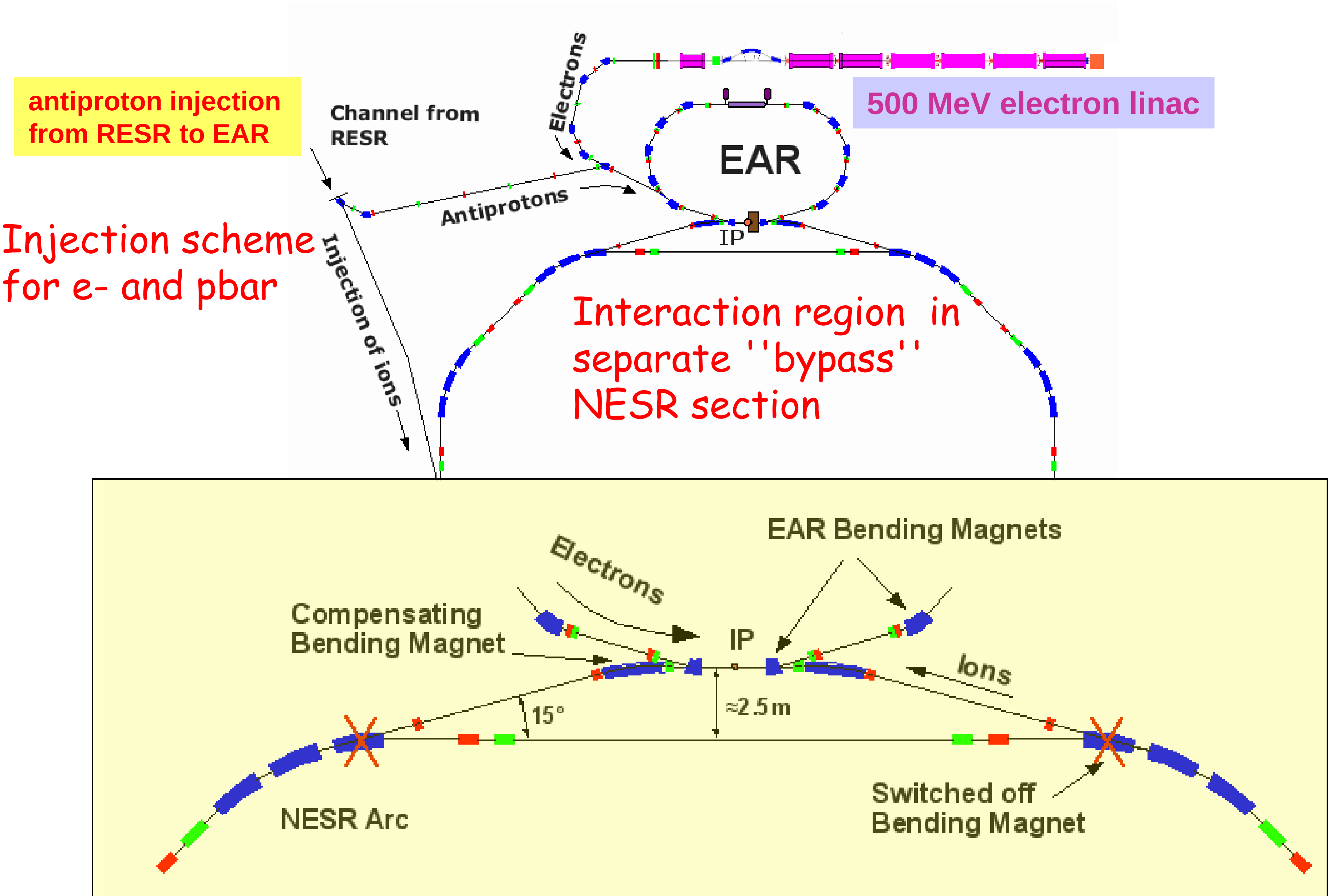
- Storage & electron cooling of ions & pbars
- Injection:ions at 740 MeV/u, pbars at 3 GeV
- Fast deceleration of ions to 4 MeV/u
  and antiprotons to 30 MeV
- Longitudinal accumulation of RIBs



- Internal target experiments
- Electron target (2nd electron cooler)
- Laser interactions (cooling,spectroscopy)
- Electron-Ion collisions (bypass mode)
- Antiproton-ion collisions (bypass mode)

- Fast extraction (1 turn)
- Slow (resonance) extraction
- Ultra-slow (charge-exchange) extraction

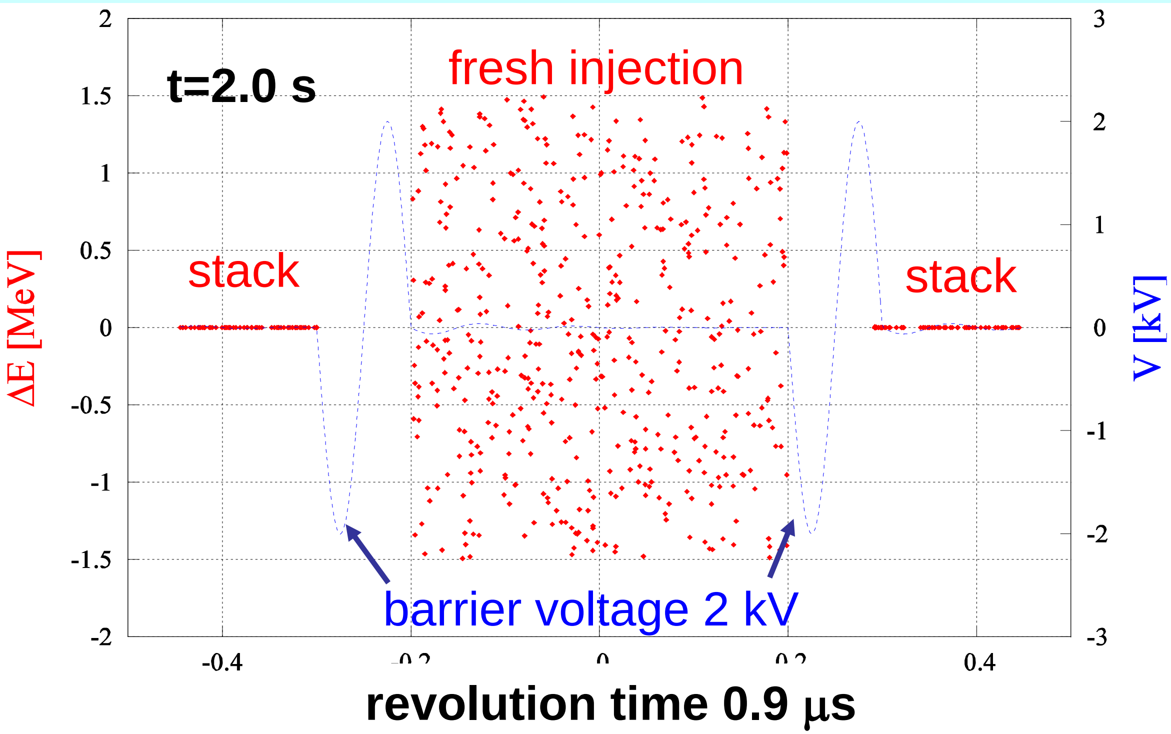
Design aspects from BINP:
The bypass collision section for ELISe & AIC



Longitudinal Accumulation of RIBs in NESR
RF Manipulation & Electron Cooling

Basic idea: confine with RF stored beam to a fraction of the circumference, inject into gap & apply strong electron cooling to merge the two beam components

⇒ fast increase of intensity (for low intensity RIBs)



$^{132}Sn^{50+}$

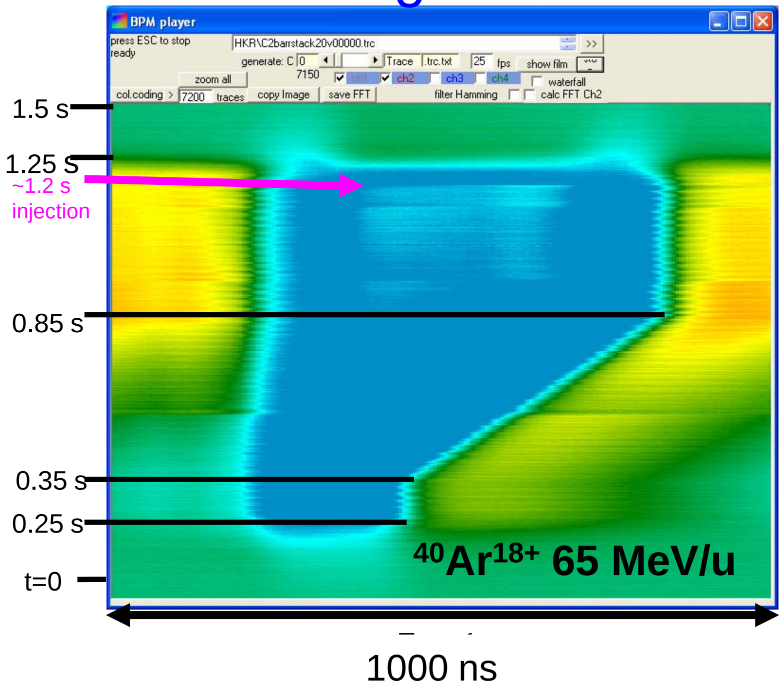
E_k = 740 MeV/u

Longitudinal stacking with Barrier Buckets
(simulations by T. Katayama, Dubna Group BETACOOL)

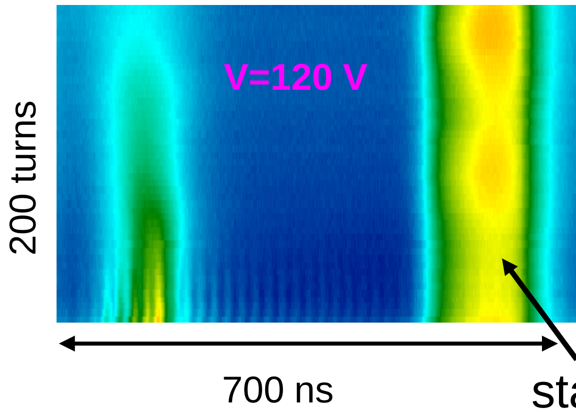
Goal: Fast increase of the intensity of RIBs for internal experiments e.g. ELISe

Proof of Principle in the ESR

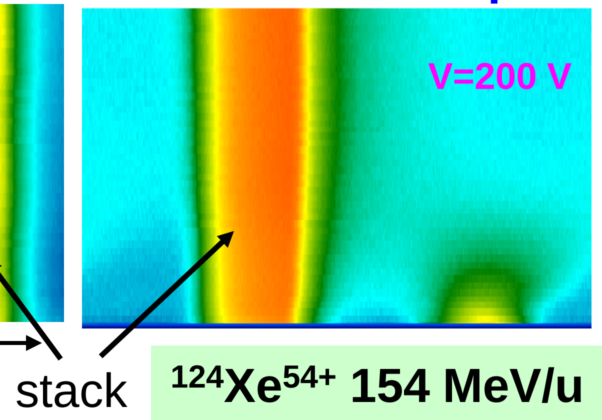
moving barriers

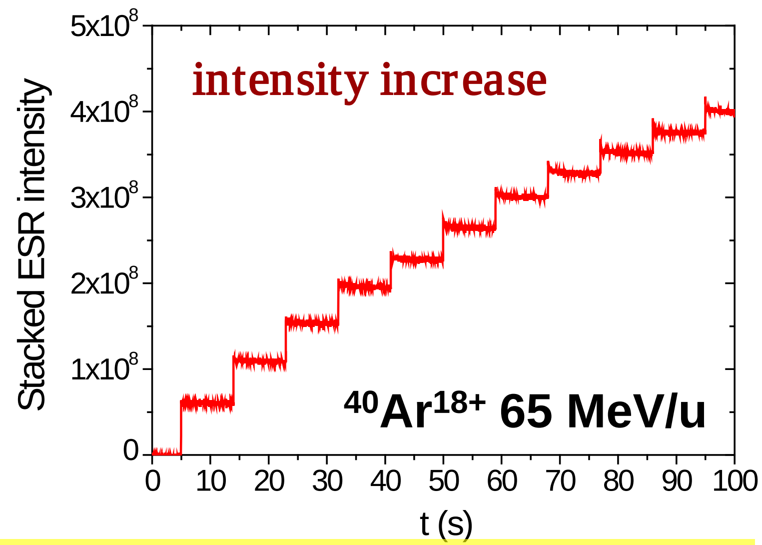


fixed barriers



h=1 unstable fixed point





all three schemes worked well:

cooling times close to expectations

efficient accumulation

high quality timing and kicker pulses required

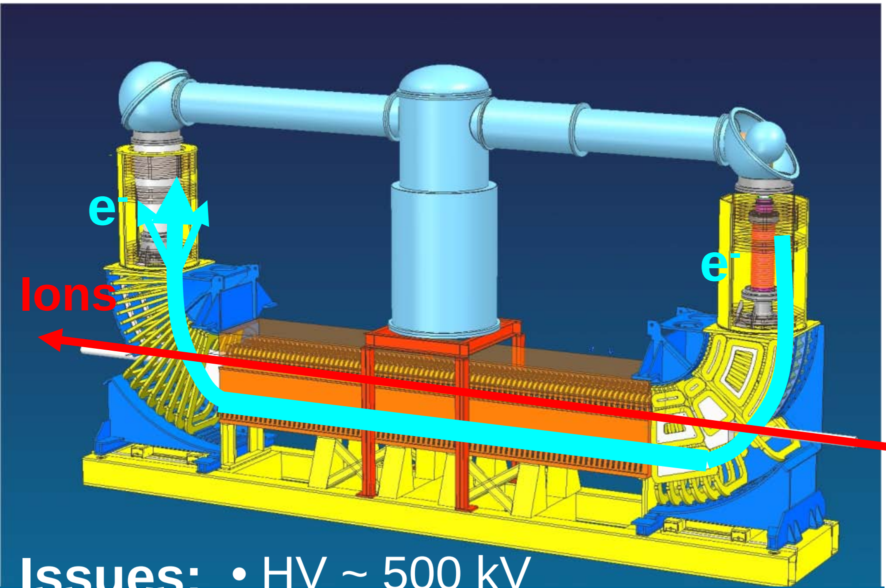
Intensity limits: RF voltage and instabilities

Benchmarked simulation tools

NESR: aim at 2s stacking cycle time with the foreseen RF and e-cooling systems

Electron Cooling in the NESR

design by BINP, Novosibirsk



Issues:
- HV ~ 500 kV
- fast ramping, ~250 kV/s
- magnetic field quality

Cooler Parameters

energy	2 - 450 keV
max. current	2 A
cathode radius	1 cm
beam radius	0.5-1.4 cm
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	$\leq 2\ 10^{-5}$
adiabatic expansion option	
cool. section length	5 m
max. power in collector	15 kW
vacuum	$\leq 10^{-11}$ mbar

In the cooling section: 2 main competing processes

Cooling rate

$$\frac{1}{\tau_{cool}} \propto \frac{q^2}{A} \cdot \frac{n_e L_c}{\beta^3 \gamma^5 \theta_{rel}^3}$$

Equilibrium

$$\frac{1}{\tau_{cool}} = \frac{1}{\tau_{IBS}}$$

IBS heating rate

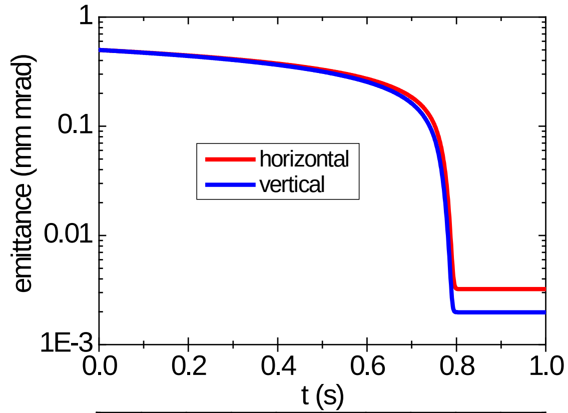
$$\frac{1}{\tau_{IBS}} \propto \frac{q^4}{A^2} \cdot \frac{N_i}{\beta^3 \gamma^4 \varepsilon_H \varepsilon_V (\Delta p/p)}$$

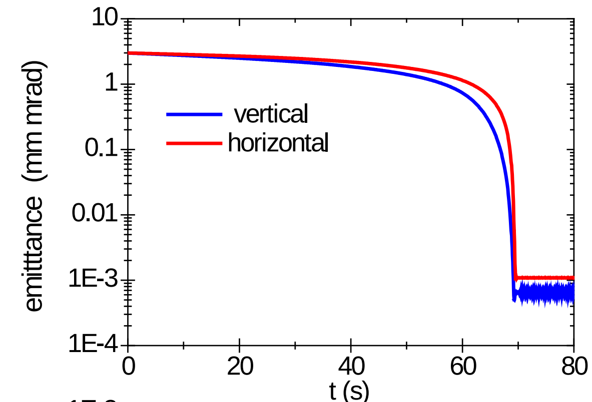
Electron Cooling in the NESR

Injected beam quality defines operation parameters of the cooler !

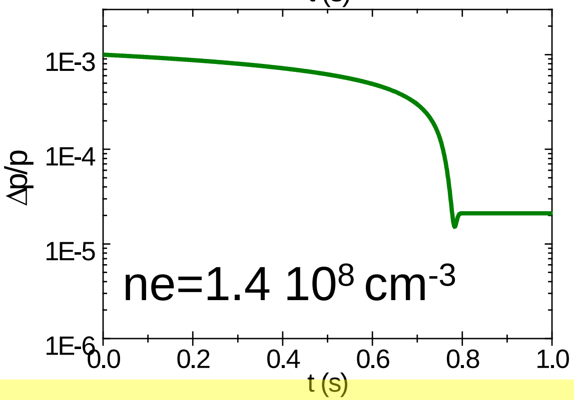
$^{132}Sn^{50+}$ 740 MeV/u 10^8 ions
Ie=1 A re=0.75 cm B=0.2 T

Antiprotons 800 MeV 10^8 ions
Ie=**2 A !** re=1 cm B=0.2 T

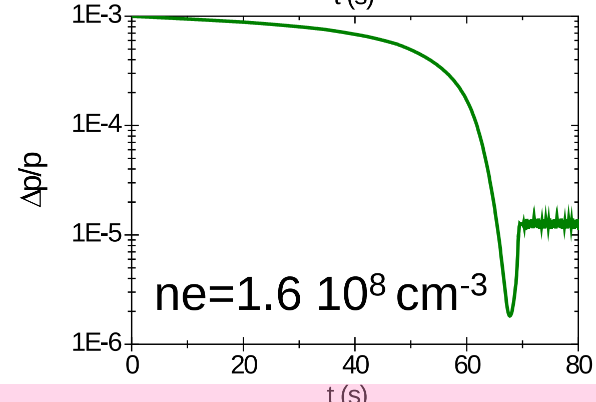




BETACOOL Simulations
Parkhomchuk ecool model ;
Martini IBS model



→ Beam parameters for the users!



Initial beam parameters expected after stochastic pre-cooling in the CR
t_{cool} < 1 s → full profit of SIS100 1.5 s cycle!

Initial beam parameters depend on stoch. pre-cooling in the CR & RESR
t_{cool} ~ 1-2 min !

Beam parameters for experimentalists

Beam size at location of detector/experiment:

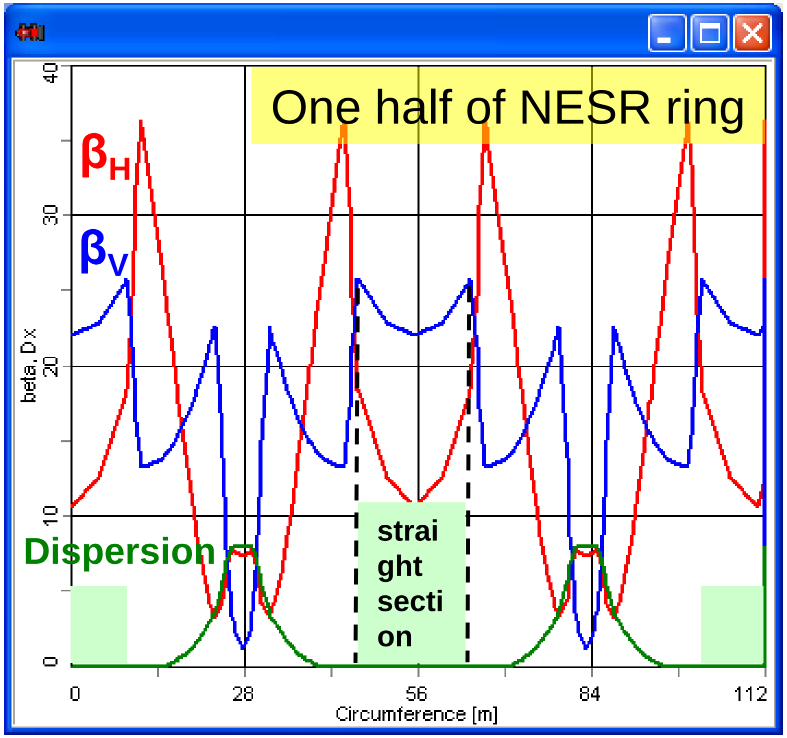
$$2\sigma_H = \sqrt{\beta_H \varepsilon_H} + D\frac{\Delta p}{p} \qquad 2\sigma_V = \sqrt{\beta_V \varepsilon_V}$$

Rev. frequency ↔ Momentum ↔ Kinetic energy spread:

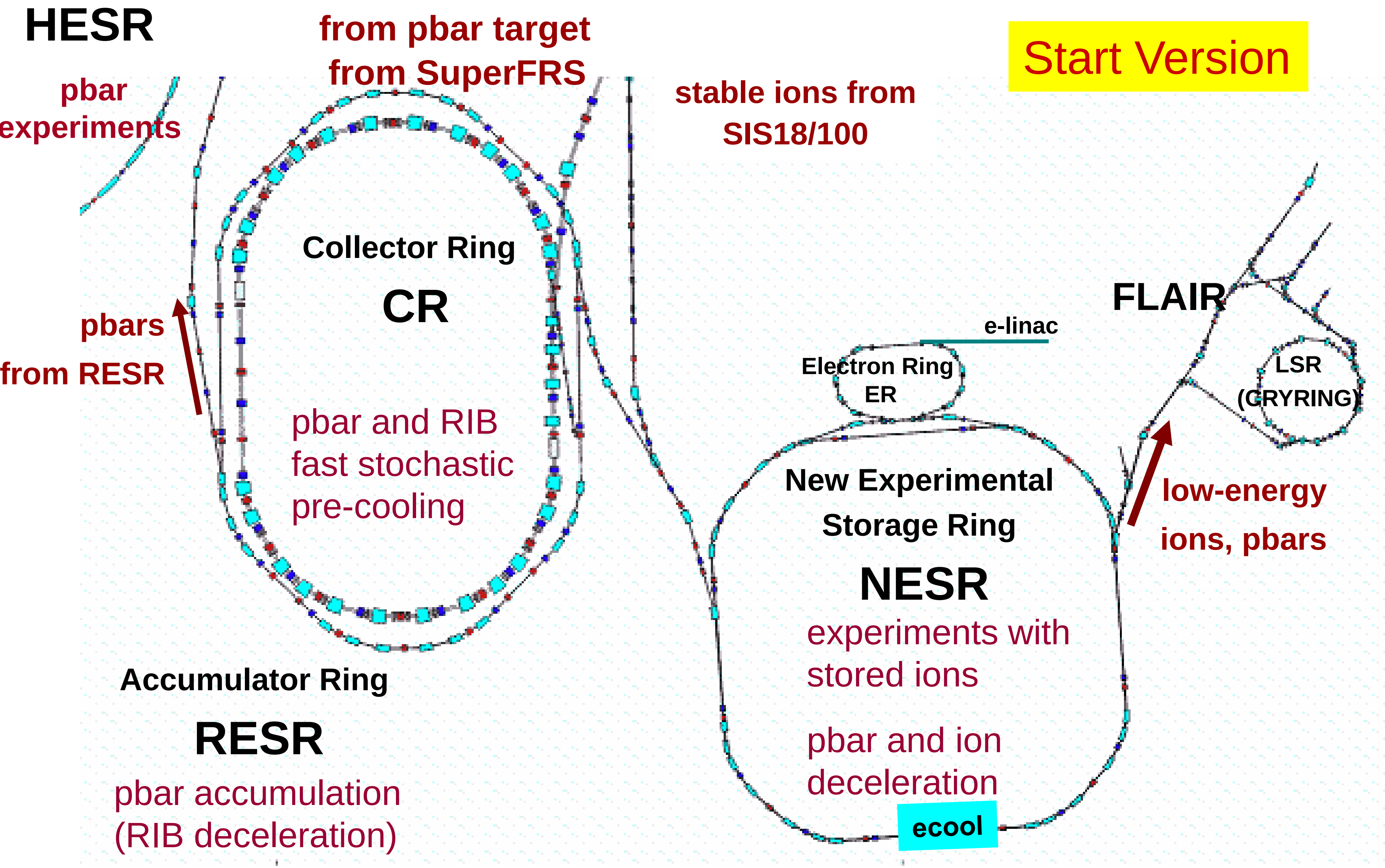
$$\frac{\Delta f}{f_0} = \eta \frac{\Delta p}{p_0} = \eta \frac{\gamma_0}{\gamma_0 + 1} \frac{\Delta E_K}{E_{K0}},$$

$$\eta = \frac{1}{\gamma_0^2} - \frac{1}{\gamma_t^2} \qquad \frac{1}{\gamma_t^2} = \frac{1}{C} \oint \frac{D(s)}{\rho} ds$$

$$f_0 = \frac{v_0}{C} \qquad \gamma_0 : \text{Lorentz factor}$$

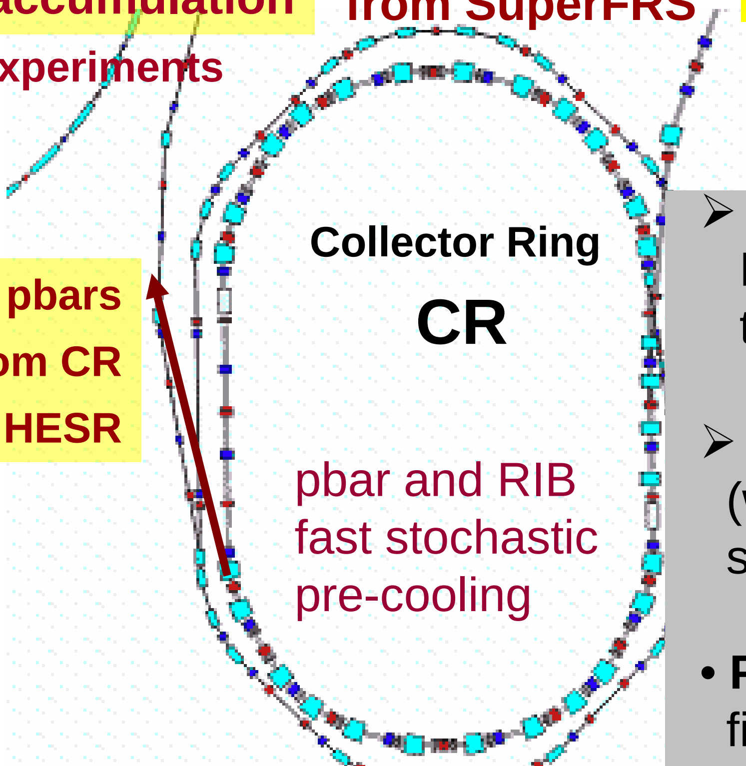


The FAIR Storage Rings



C.Dimopoulou/GSI, Björkliden 2010

The FAIR Storage Rings



Modularised Start Version (0-3)

Technically feasible, upgradeable concept

- **CR design (very advanced)** remains;
  Rearrangement of components & topology
  to **extract from CR to the HESR**

- Longitudinal **pbar accumulation in the HESR**
  (with barrier bucket RF and stochastic cooling);
  simulations and tests in the ESR underway!

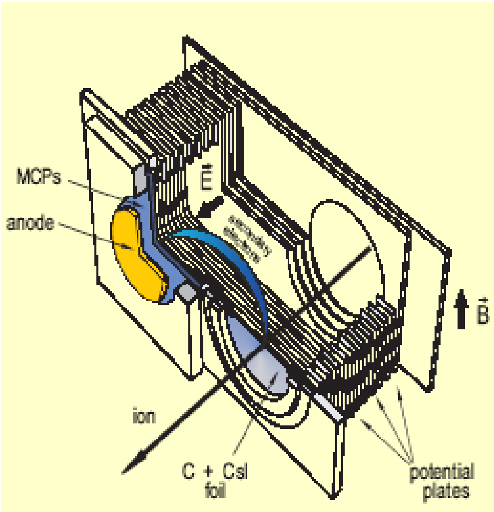
• **PANDA** at reduced intensity & duty cycle,
  first measurements at high-resolution mode
• **NUSTAR/ILIMA** in the CR

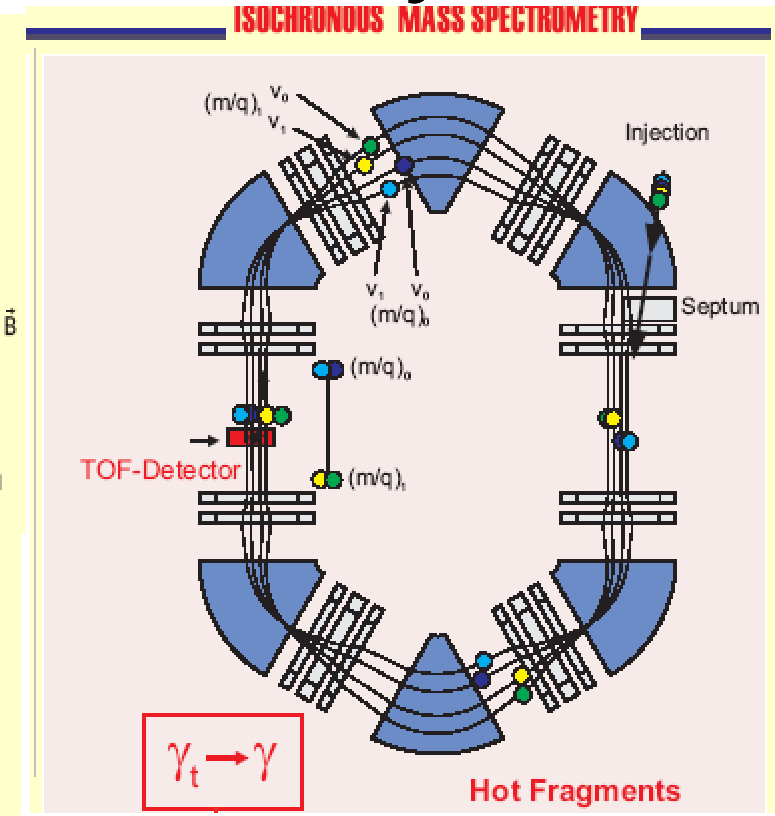
Later: Modules 4,5,6 → PHYSICS !

•NUSTAR & APPA physics program in NESR & ER
•NESR decelerates beams for FLAIR
•RESR increases pbar rate for high-luminosity at PANDA

Isochronous Mass Spectrometry in CR

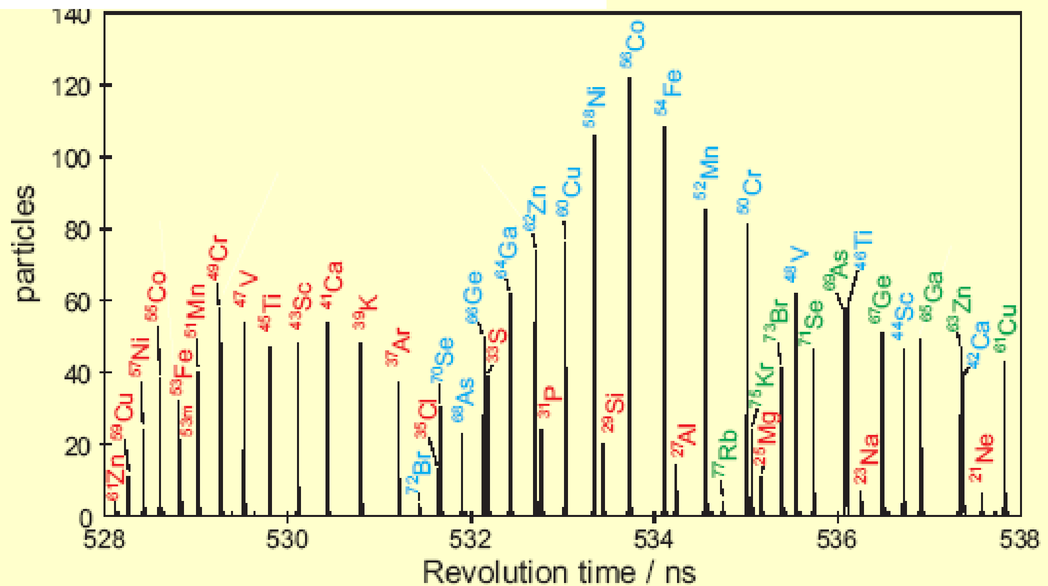
Masses and half-lives of unknown short-lived nuclei





$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \left(1-\frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$

Isochronous (IMS) : $\gamma = \gamma_t$;



resolving power 4 x 10^5

accuracy ≥ 100 keV

sensitivity 1 ion

$T_{1/2}$ > 10 µs

50 new masses

Conclusions & Outlook

- Storage ring complex: versatile operation with RIBs & pbars, pertinent technical systems, ''entangled'' with experiments
- Storage ring concept & design well advanced,
  civil construction planning underway

- Operation modes for in-ring experiments and extraction: investigated and feasible
- Beam parameters available for users

- FAIR: not a dedicated but a competitive facility with high and low energy antiprotons
- Within FAIR Modules 0-3: viable pbar chain (CR+HESR)