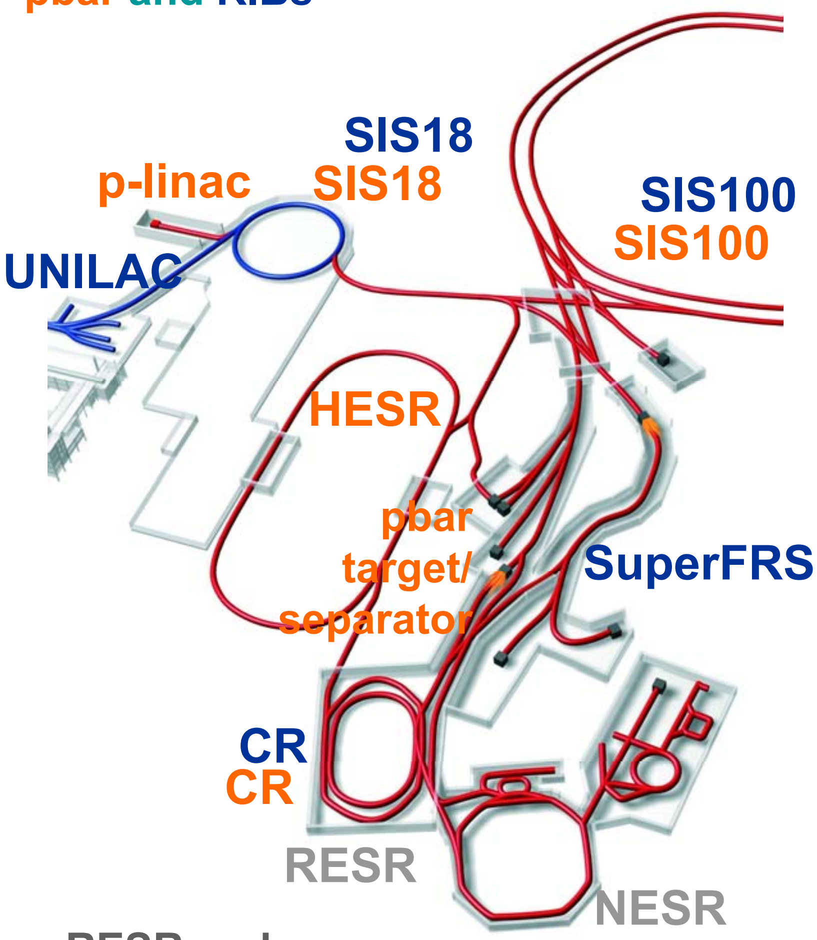
Antiproton Chain (Modularised Start Version)



RESR and NESR will be added

- acceleration in linac to 70 MeV
- multiturn injection into SIS18, acceleration to 4 GeV
- transfer of 4 SIS pulses to SIS100
- acceleration to 29 GeV and extraction of single bunch
- antiproton target and separator for 3 GeV antiprotons
- collection and pre-cooling in the Collector Ring CR
- accumulation of up to 10^{11} antiprotons in the RESR
- transfer at 3 GeV to users (HESR, NESR)
- accumulation and storage of antiprotons in the HESR
- deceleration in the NESR to 300-30 MeV

FNAL / CERN / FAIR pbar Sources

FAIR is not a dedicated antiproton facility, but the antiproton mode is competitive

	FNAL	CERN-AA	CERN-AAC	FAIR
proton energy	120 GeV	25 GeV	25 GeV	29 GeV
proton intensity	8×10^{12} / 2.2s	1.2×10^{13} / 2.4s	1.4×10^{13} / 4.8s	2×10^{13} / 10s
target	inconel	copper	iridium	nickel
pbar energy	8 GeV	2.7 GeV	2.7 GeV	3 GeV
ring sizes (m)	3320/505/474	628/157	628/157/187	1080/216/240
max. pbar stack	4×10^{12}	2.8×10^{11}	1.3×10^{12}	1×10^{11}
production rate	25×10^{10}/hr	0.7×10^{10}/hr	6×10^{10}/hr	$3.5/7\times10^{10}$/hr

gain AA → AAC:
factor of 9

cost ⇒ performance reduction ???

Vacuum Issues in Antiproton Storage Rings

CR: antiprotons are stored for 10 s,
design intensity ⇒ no instability problems
vacuum specifications are determined by ions

RESR: at low intensity (≤ 10^{11}) multiple scattering dominates beam lifetime (compared to nuclear and single scattering)

$$\frac{\partial \epsilon_{ms}}{\partial t} = 8\pi \beta_{\perp} n_{gas} ln(\frac{280}{\alpha}) r_e^2 \frac{(m_e c^2)^2}{\beta c p^2}$$

For 3 GeV pbar and 1×10^{-10} mbar N_2 ⇒ **$\partial\varepsilon/\partial t$ = 0.1 mm mrad / h**

can be easily compensated by cooling

according to CERN experience no serious trapping or instability problems have to be expected for 1×10^{11} antiprotons

clearing electrodes will be considered during vacuum system design

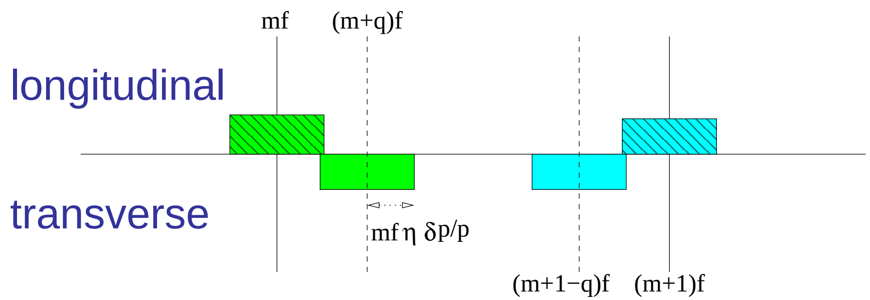
beam shaking electrodes are available
(broad band kickers for BTF measurements)

Synchronicity of S.C. Electrode Movement

see report by F. Nolden

Main effect of asynchronous motion of electrode pairs: transverse heating

Only effective, if transverse Schottky sidebands overlap with longitudinal Schottky signal



overlap condition

$$\frac{\delta p}{p} \geq \frac{q_x}{2m\eta}, \qquad q_x < 0.5$$

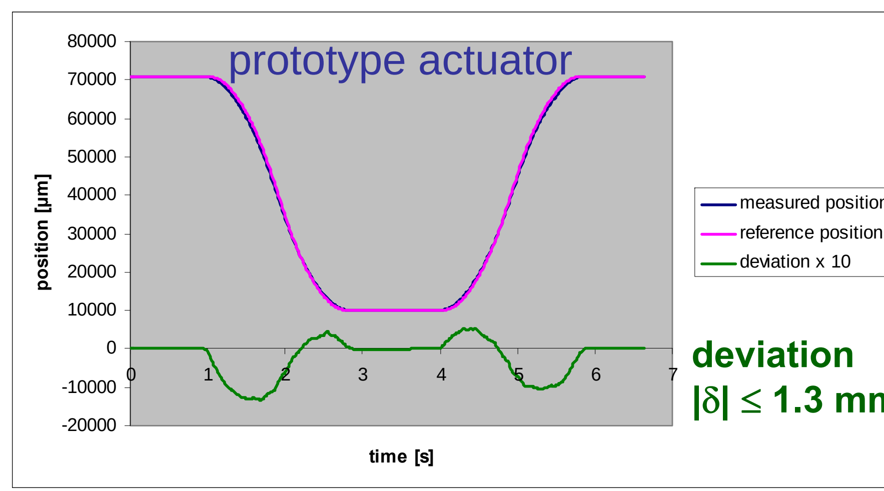
$$\frac{\delta p}{p} \geq \frac{1-q_x}{2m\eta}, \qquad q_x > 0.5$$

Overlap at upper band limit (2 GHz)

for antiprotons $\delta p/p \geq 8.7\times10^{-3}$

for RIBs $\delta p/p \geq 3.6 \times 10^{-4}$

$\Rightarrow$ no heating for antiprotons

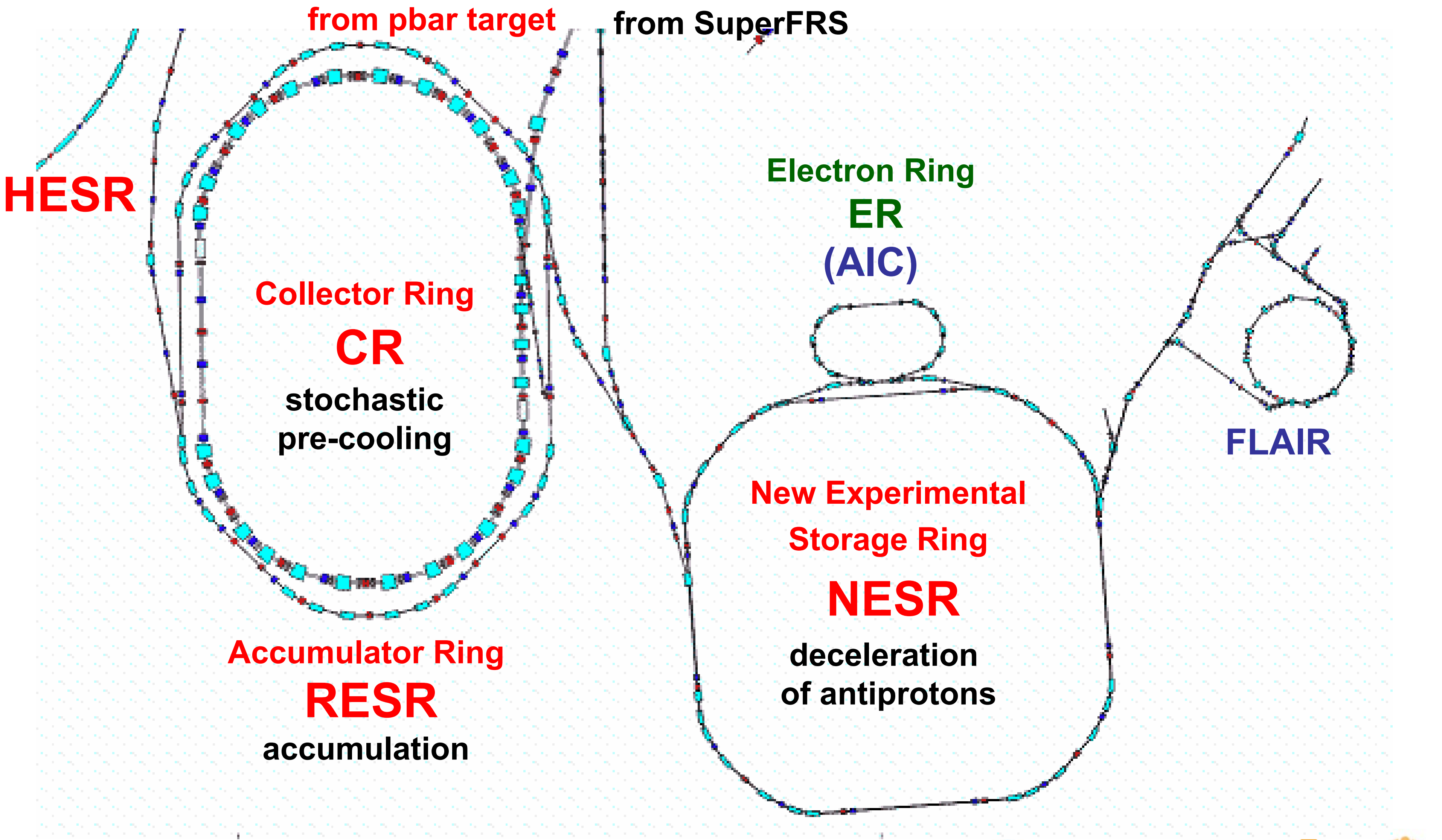


For RIBs: ratio of Schottky noise power longitudinal/transverse $C_L/C_H = 4\delta^2/\beta_x\varepsilon_x$

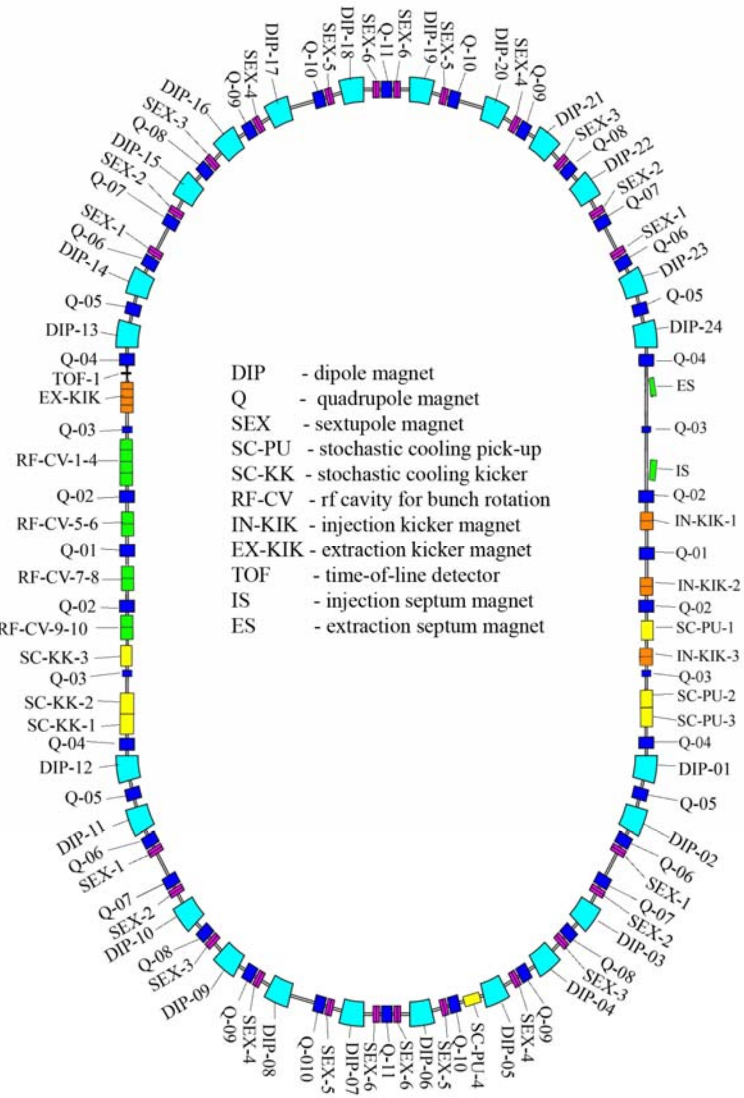
$C_L/C_H < 1/4 \Rightarrow$ $|\delta| < 5$ mm

coincides with ESR experience of required orbit accuracy

The FAIR 13 Tm Storage Rings



The Collector Ring CR



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

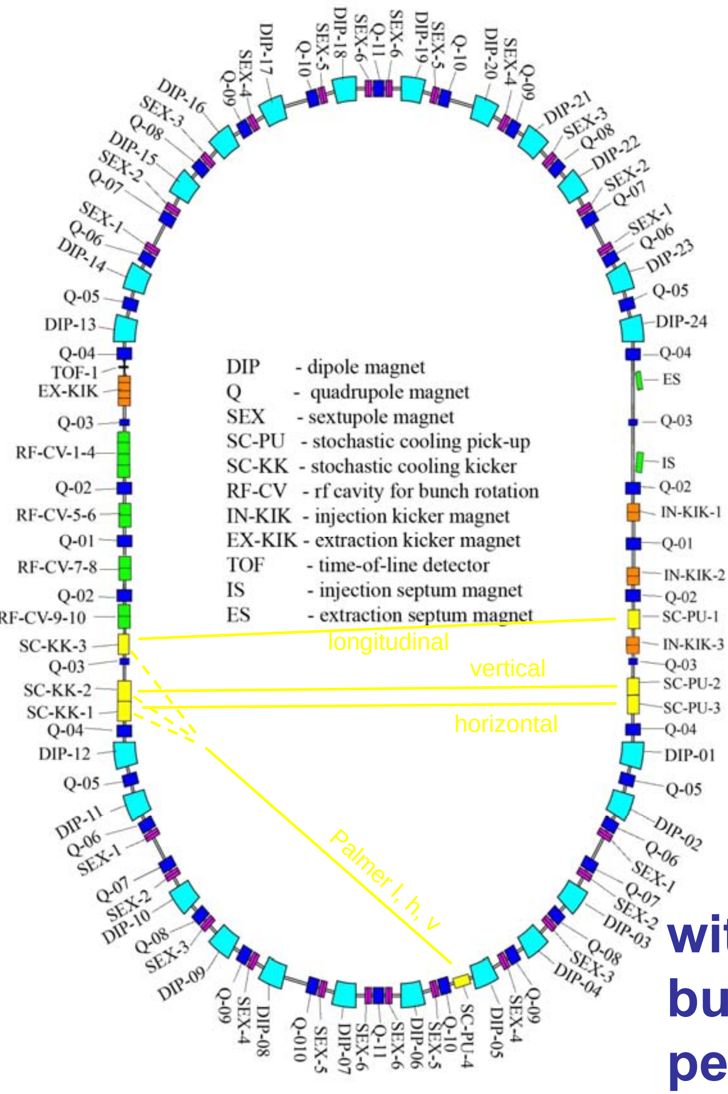
fast stochastic cooling (1-2 GHz)
of antiprotons (10 s) and
rare isotope beams (1.5 s)

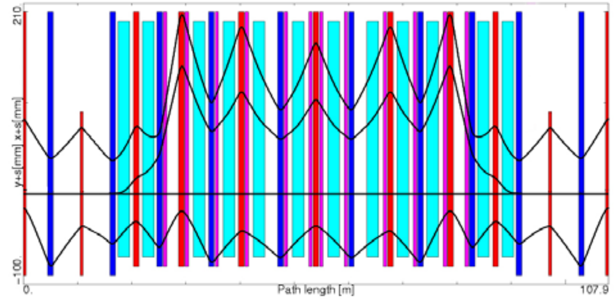
fast bunch rotation at h=1
with rf voltage 100/200 kV
adiabatic debunching

optimized ring lattice (slip factor)
for proper mixing
large acceptance magnet system

upgrade of rf voltage by a factor of 2
and additional cooling system 2-4 GHz
should reduce the cooling time (factor 2)

Optical Modes of the CR



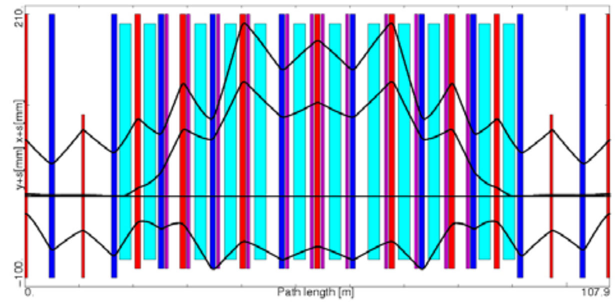


antiprotons

$Q_x = 4.26$, $Q_y = 4.84$

$\gamma_t = 3.85$

$\eta = -0.0107$

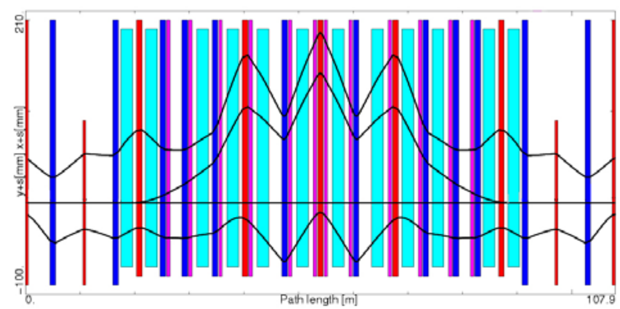


RIBs (cooling)

$Q_x = 3.19$, $Q_y = 3.71$

$\gamma_t = 2.82$

$\eta = +0.186$



isochronous

$Q_x = 2.23$, $Q_y = 4.64$

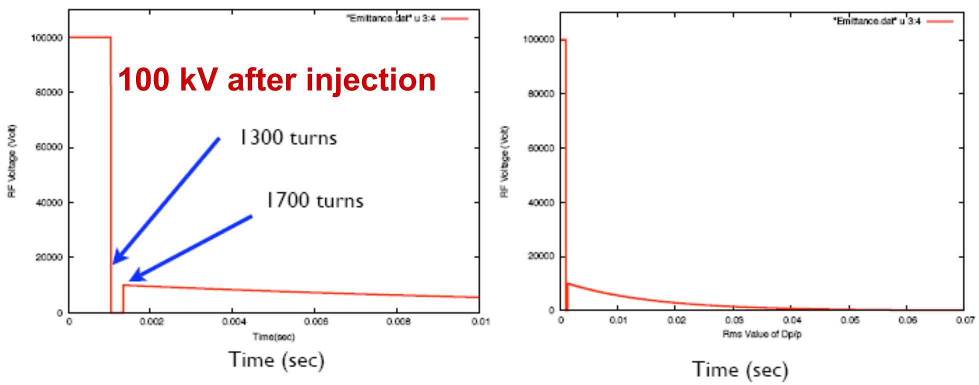
$\gamma_t = 1.84$

$\eta = 0$

without NESR: no user of cooled RIBs from CR
but: Isochronous Mass Spectrometry can be performed with RIBs from SuperFRS

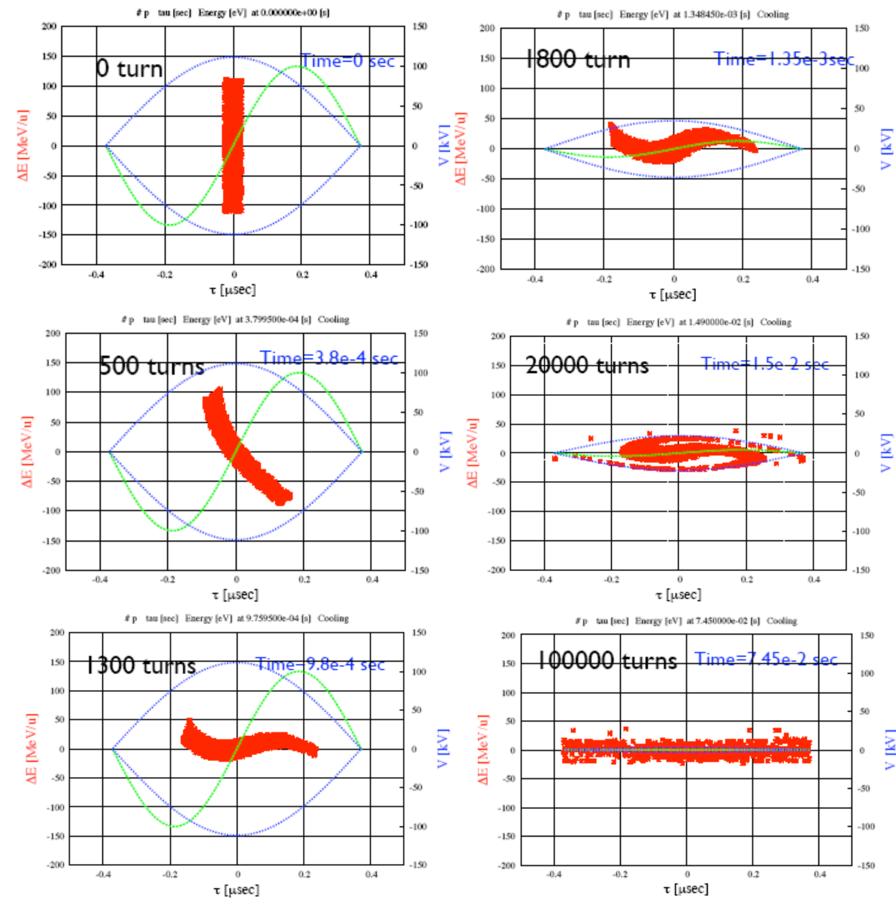
Simulation of Bunch Rotation in CR

rf voltage

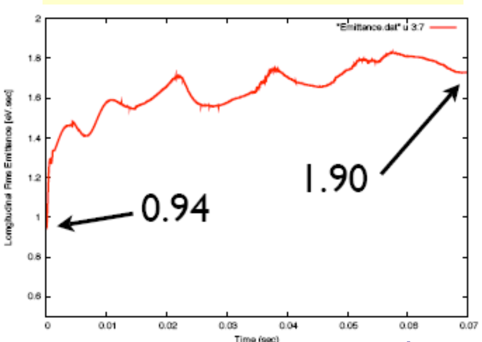


bunch rotation

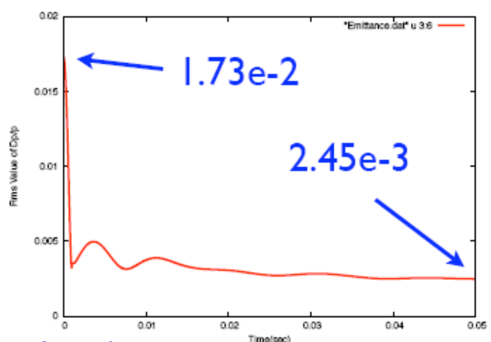
debunching



longit. emittance



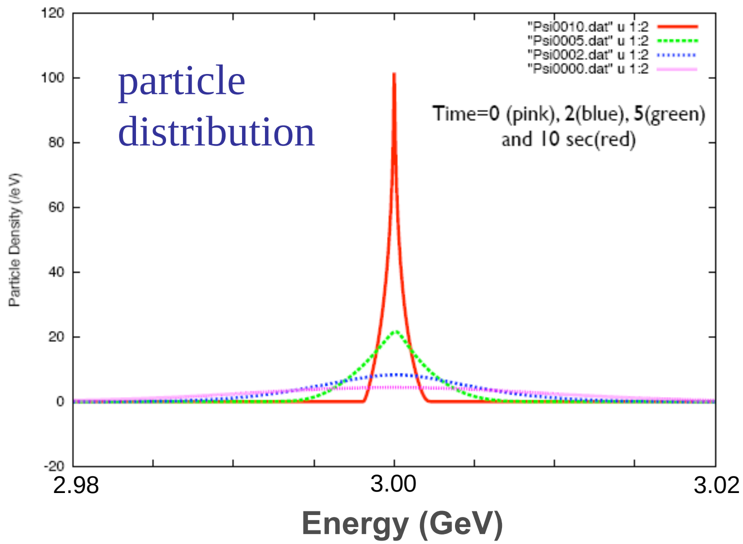
momentum spread



(rms-values)

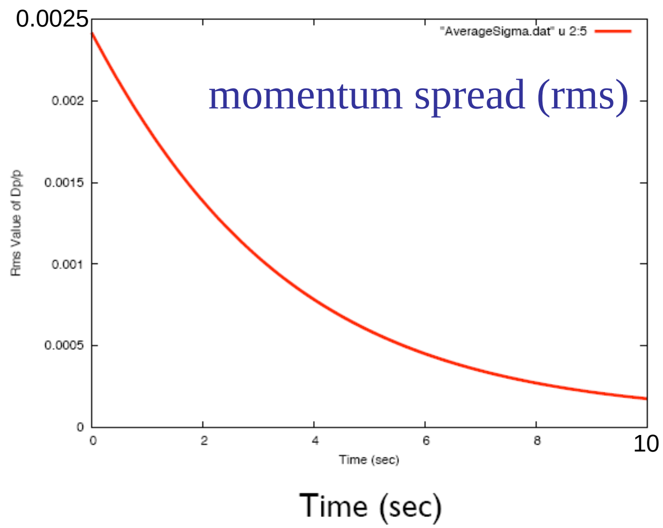
bunch rotation after injection of the short bunch (for both pbars and RIBs) reduces the momentum spread ⇒ reduction of cooling time

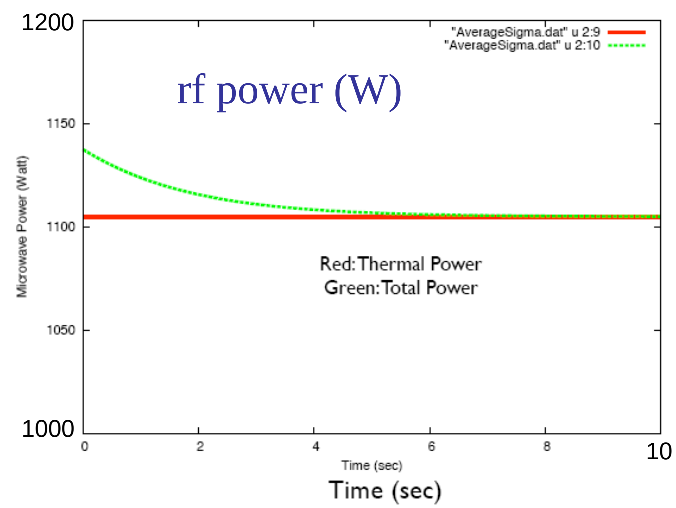
Simulation of Stochastic Cooling in CR



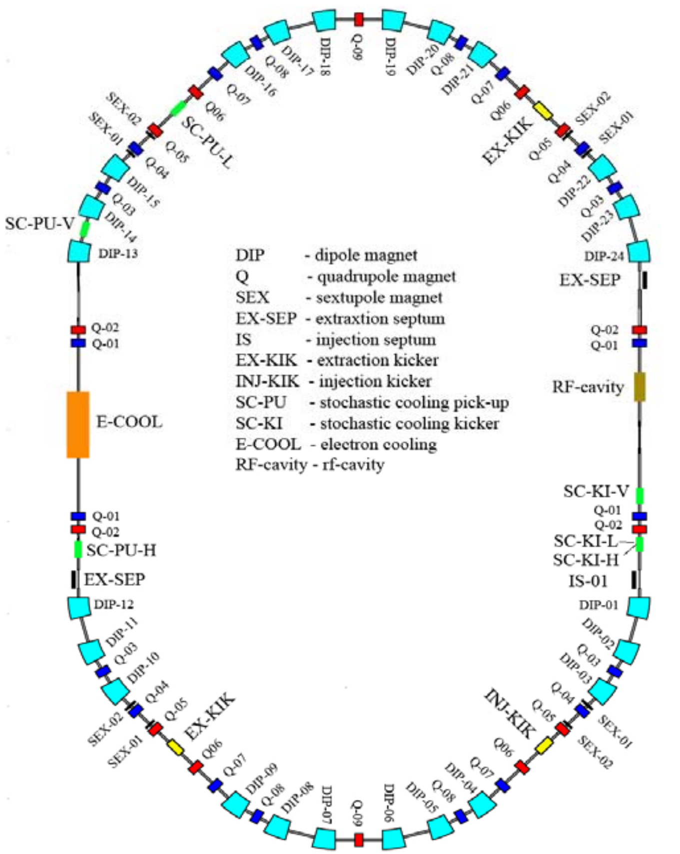
longitudinal stochastic cooling system

- **band 1 – 2 GHz**
- **temperature 40 K**
- **notch filter cooling**
- **gain 150 db**
- **power 1.2 kW (installed 5 - 10 kW)**
- **electrode impedance 100 Ω**
- **plunging electrodes**





The Accumulator Ring RESR



circumference	240 m
magnetic bending power	13 Tm
tunes Q_x/Q_y	2.57/4.45
momentum acceptance	±1.0 %
transverse accept. h/v	25 mm mrad
transition energy	2.5 - 6.4

accumulation of antiprotons by a combination of rf and stochastic cooling

max. accumulation rate 3.5 (7)×10^{10}/h

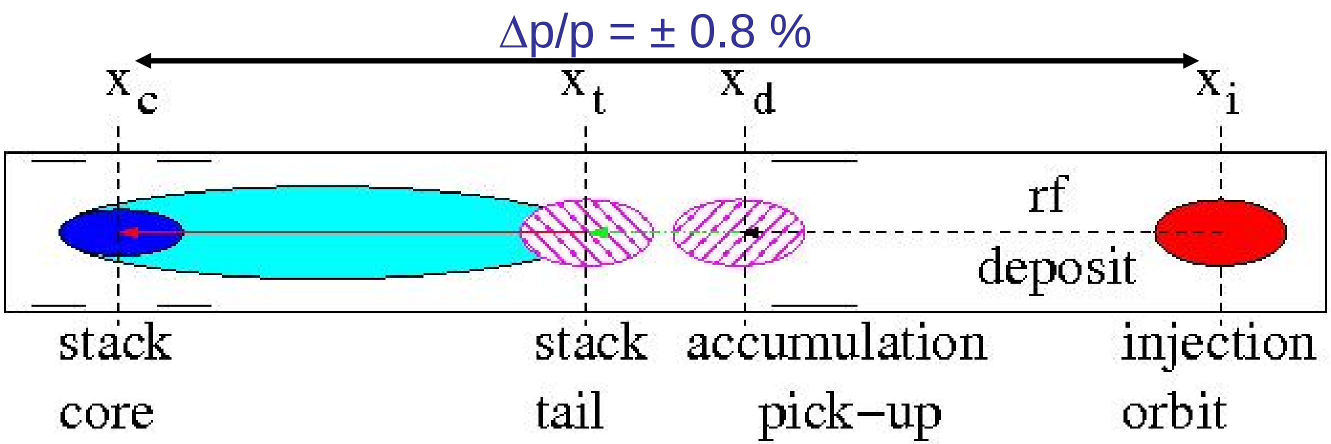
max. stack intensity ~ 1 × 10^{11}

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

vacuum (bakeable):
p ≤ 1×10^{-10} mbar

maximum intensity: 1×10^{11}
cooled beam emittance moderate
ε_x=ε_y=5 mm mrad (AA: 2 mm mrad)

Antiproton Accumulation in RESR

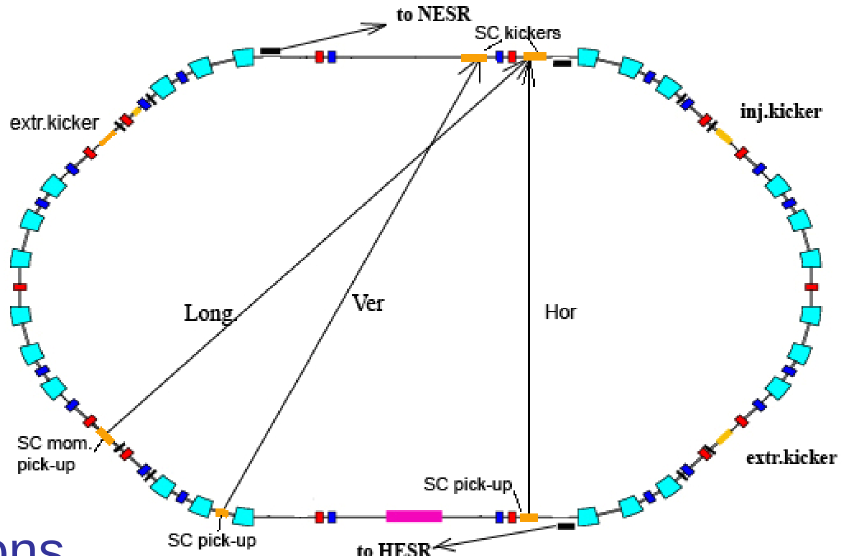


core cooling 2-4 GHz

longitudinal
horizontal
vertical

tail cooling 1-2 GHz

longitudinal



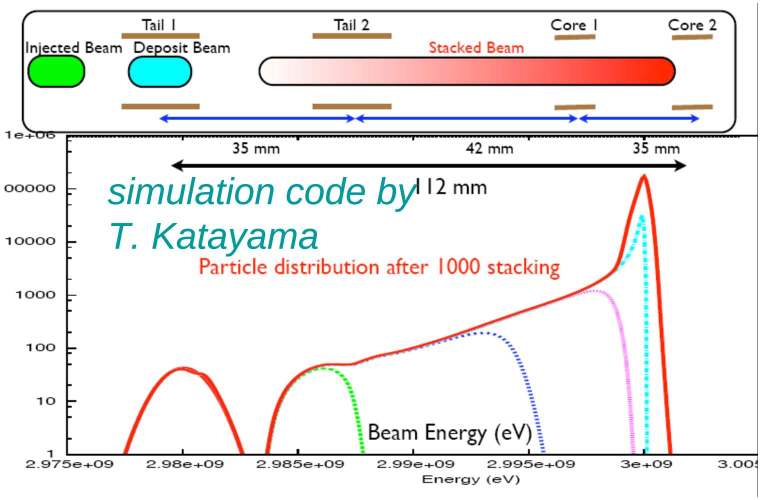
injection of 1×10^8 antiprotons every 10 s

pre-cooling in CR provides
$\delta p/p = 1\times10^{-3}$, $\varepsilon_{x,y}$= 5 mm mrad

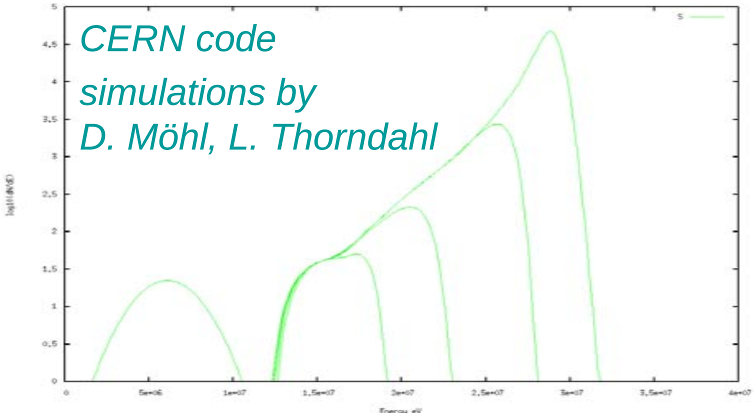
maximum stack intensity: 1×10^{11} antiprotons

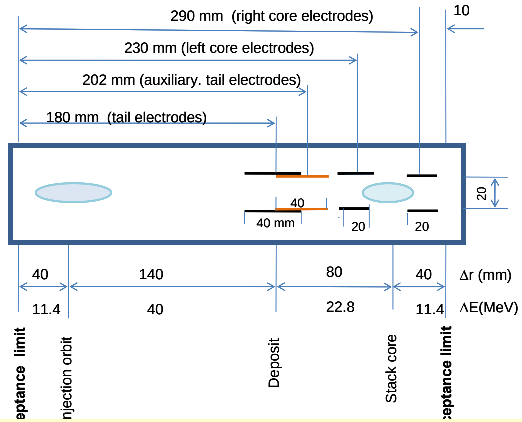
pre-cooling after injection considered as an option

RESR Stochastic Accumulation System



system was simulated with two independent programs





basic electrode geometry is fixed
space for electrodes is available

system parameters

cooling circuit	tail1	tails	core
frequency	1-2 GHz	1-2 GHz	2-4 GHz
pick-ups/kicker	64/16	25/16	64/16
length pu/kicker	1.45/1.16m	0.58/1.16	0.73/0.58
power	100-1000 W	0.06-1.2 W	0.2 W
gain	130-140 dB	84-106 dB	90 dB

optimized for cycle time 10 s and maximum intensity 1×10^{11} antiprotons

Problems of a Combined Ring

Studies following a recommendation in the last MAC summary and forced by political and financial constraints for the modularized FAIR Start Version

- **bunch rotation difficult, heating of the accumulated stack**
- **interference between stack and injected beam because of small separation of injection and stack orbit**
- **stochastic cooling system must be developed from scratch (separate systems for pre-cooling and accumulation)**
- **upgrade for full FAIR project must be possible**
- **operation with RIBs (pre-cooling, isochronous mode)**

Bunch Rotation in Combined Ring

Bunch rotation voltage will strongly interfere with the circulating stack

⇒ Heating of stack

energy 3 GeV

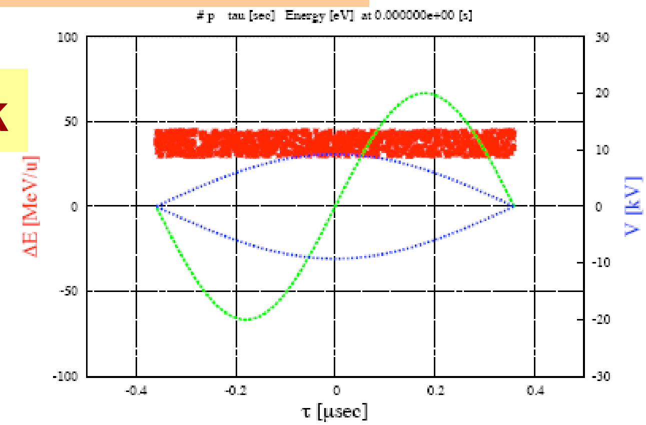
ring slip factor η=0.05

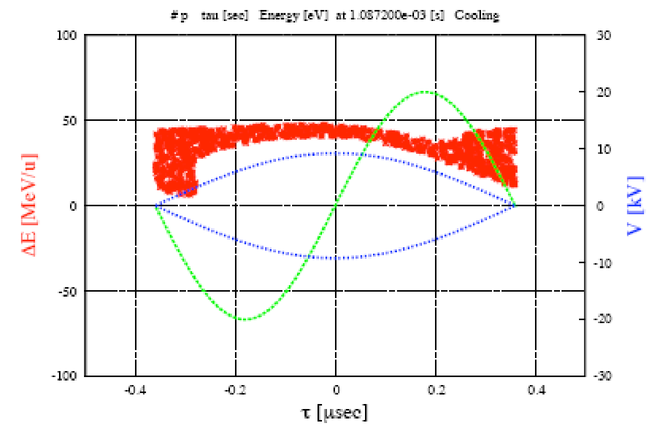
ring circumference 216 m

incoming bunch
- **spread $\Delta p/p = \pm 0.75$ %**
- **length ±25 ns**

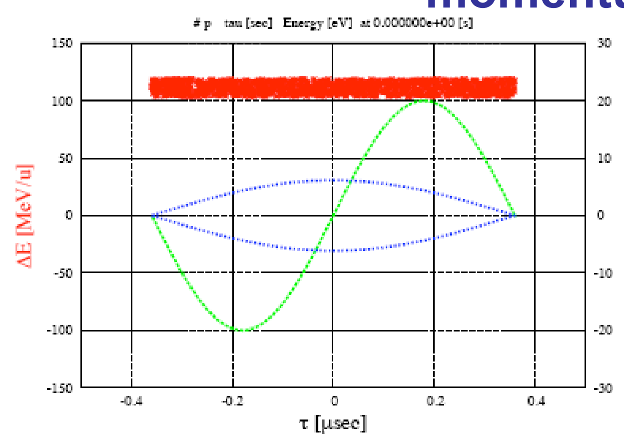
rf amplitude 20 kV

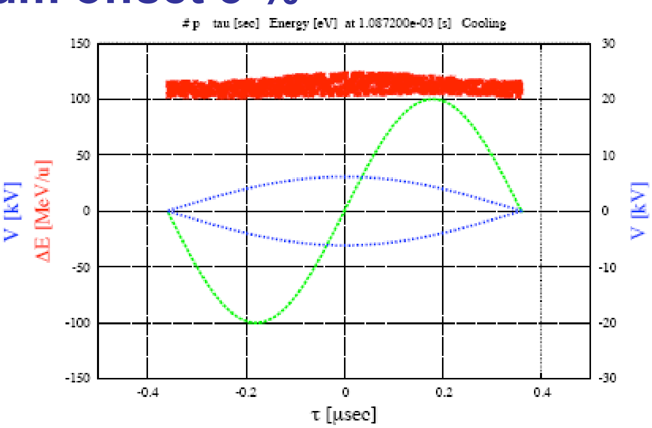
momentum offset 1 %





momentum offset 3 %

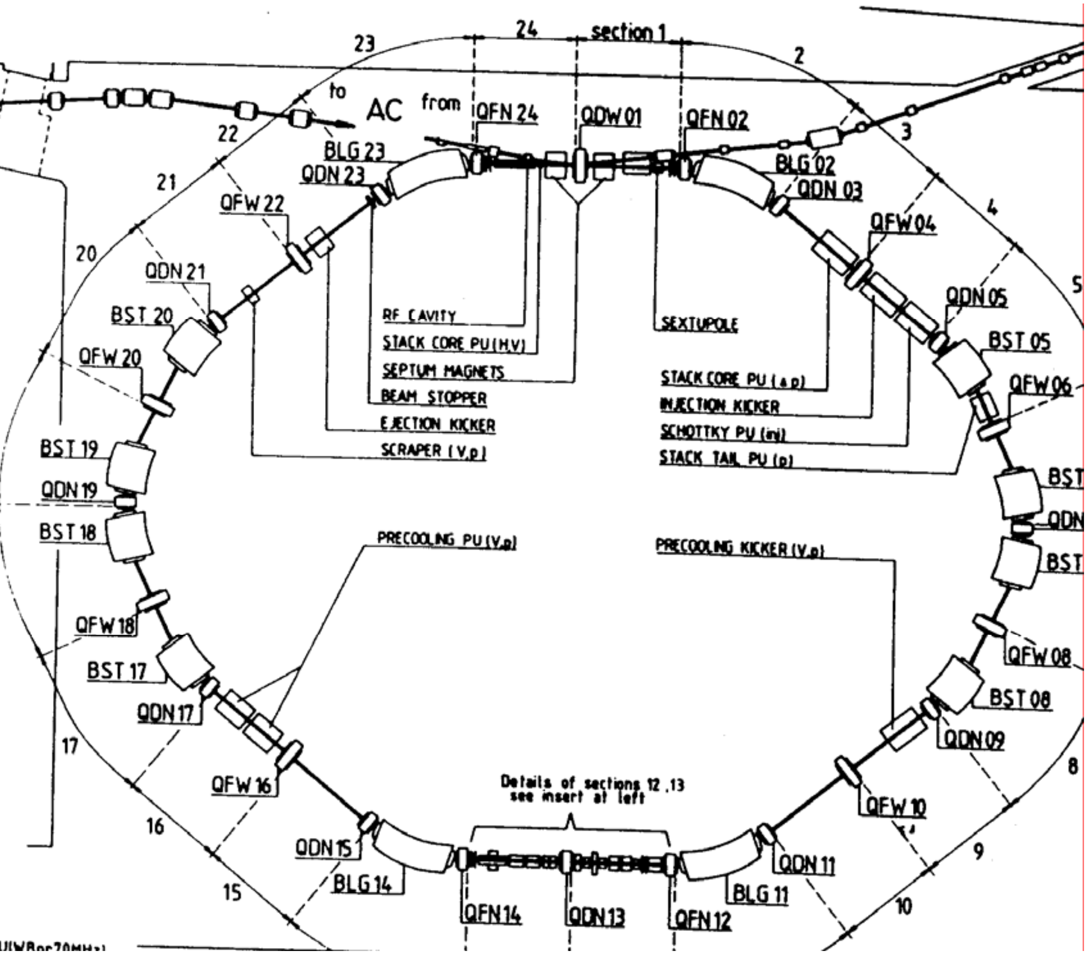




initially | **after 1500 revolutions**

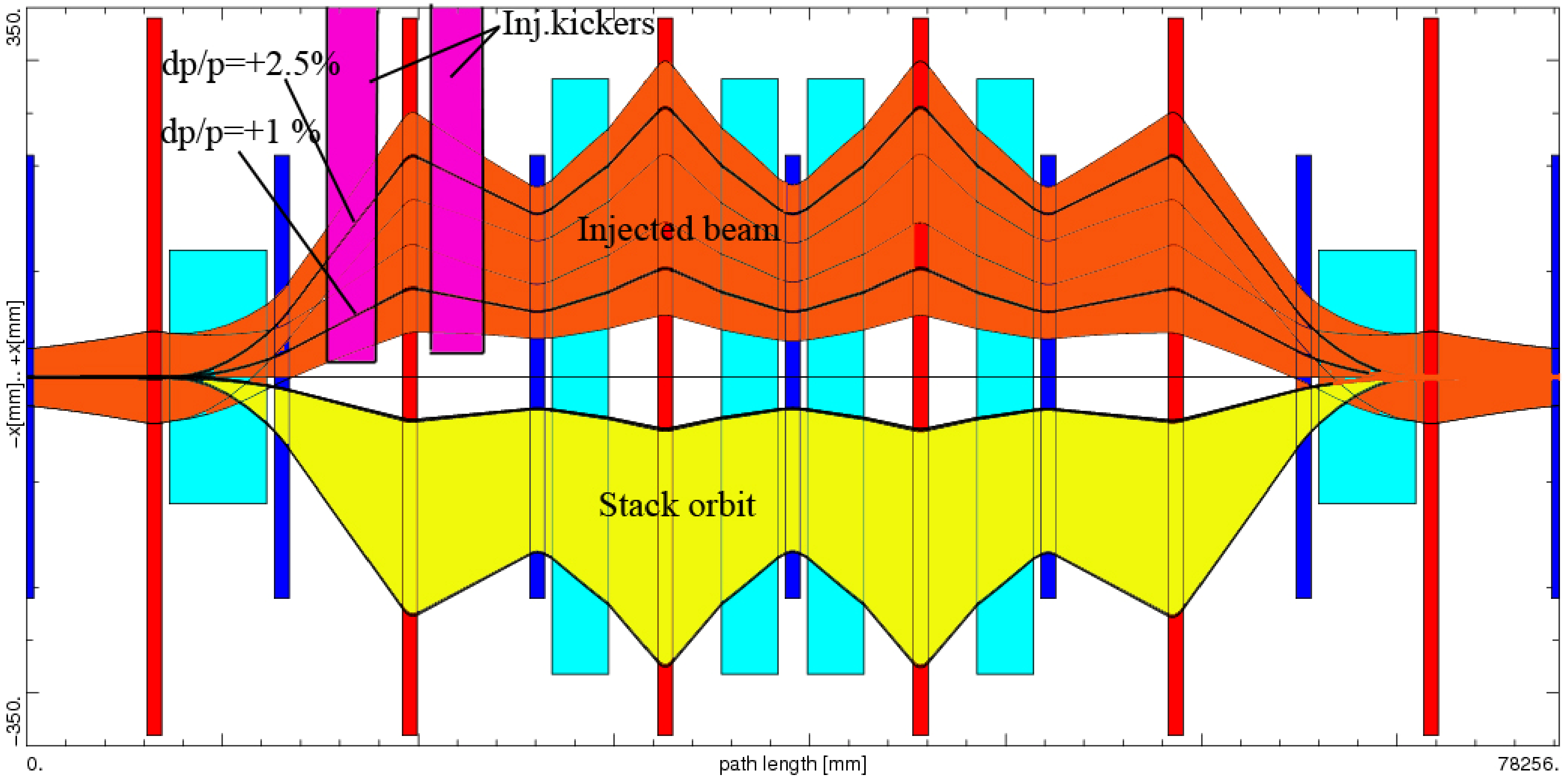
Antiproton Accumulator (AA) layout

Model for a machine which combines pre-cooling and accumulation



Circumference	156.5 m
Max Rigidity	12 Tm
Rev. frequency	1.85 MHz
Rev. period	540 ns
Q_x	2.26
Q_y	2.26
Transition energy γ_t	2.4
Slip factor η	-0.106
Momentum acceptance	6%
Transverse acceptance	100 mm mrad

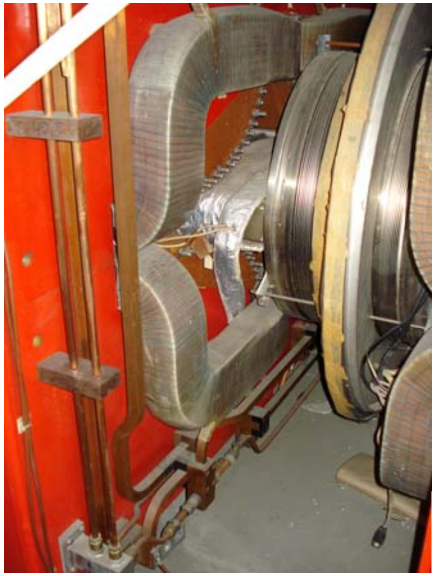
Beam dimensions in AA



acceptance for injected antiproton beam (about half of the acceptance) : transverse $\varepsilon_x = \varepsilon_y$ = 100 mm mrad, momentum spread = 1.5 %

the other half is reserved for stacking a high intensity antiproton beam

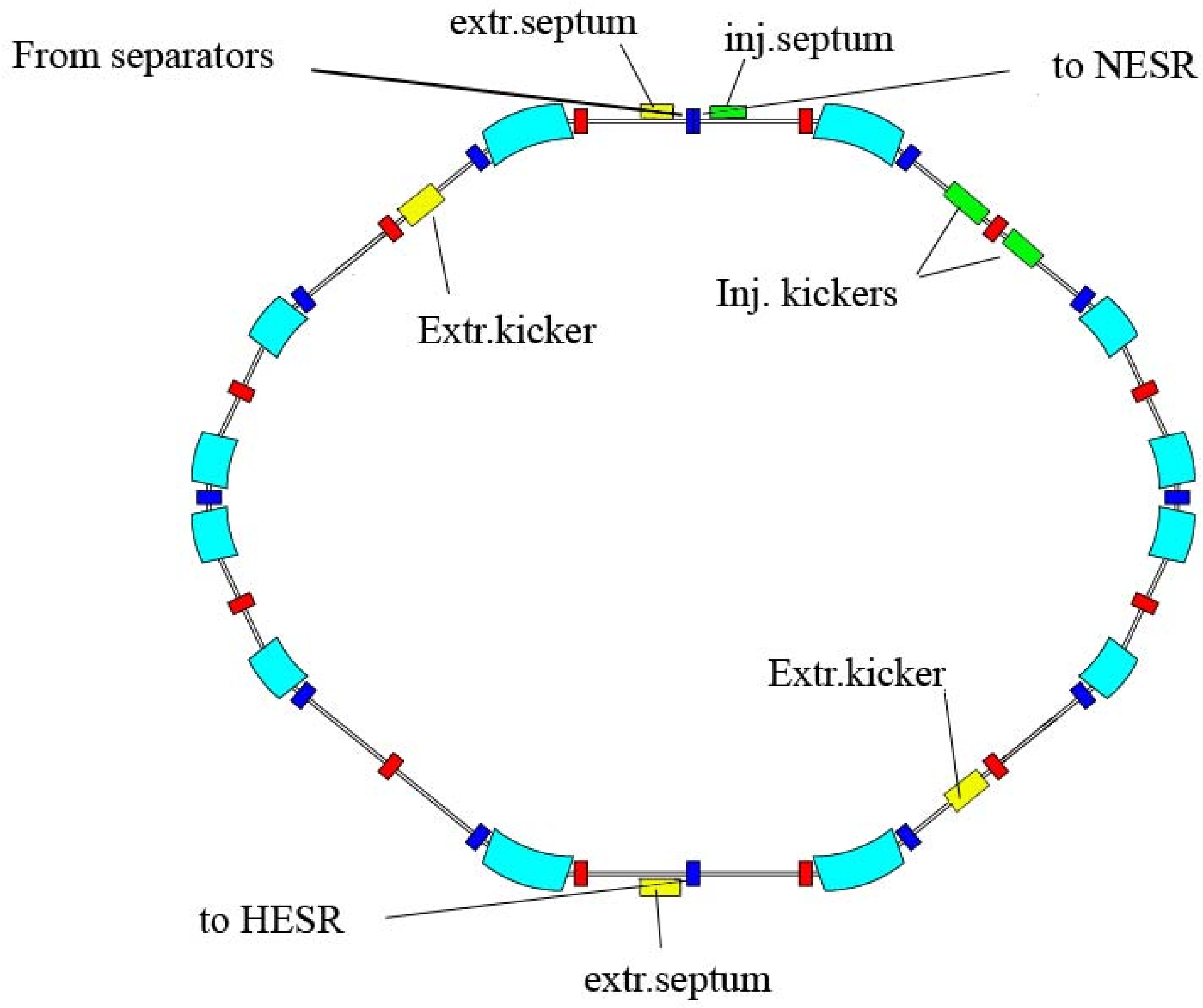
AA Components from KEK



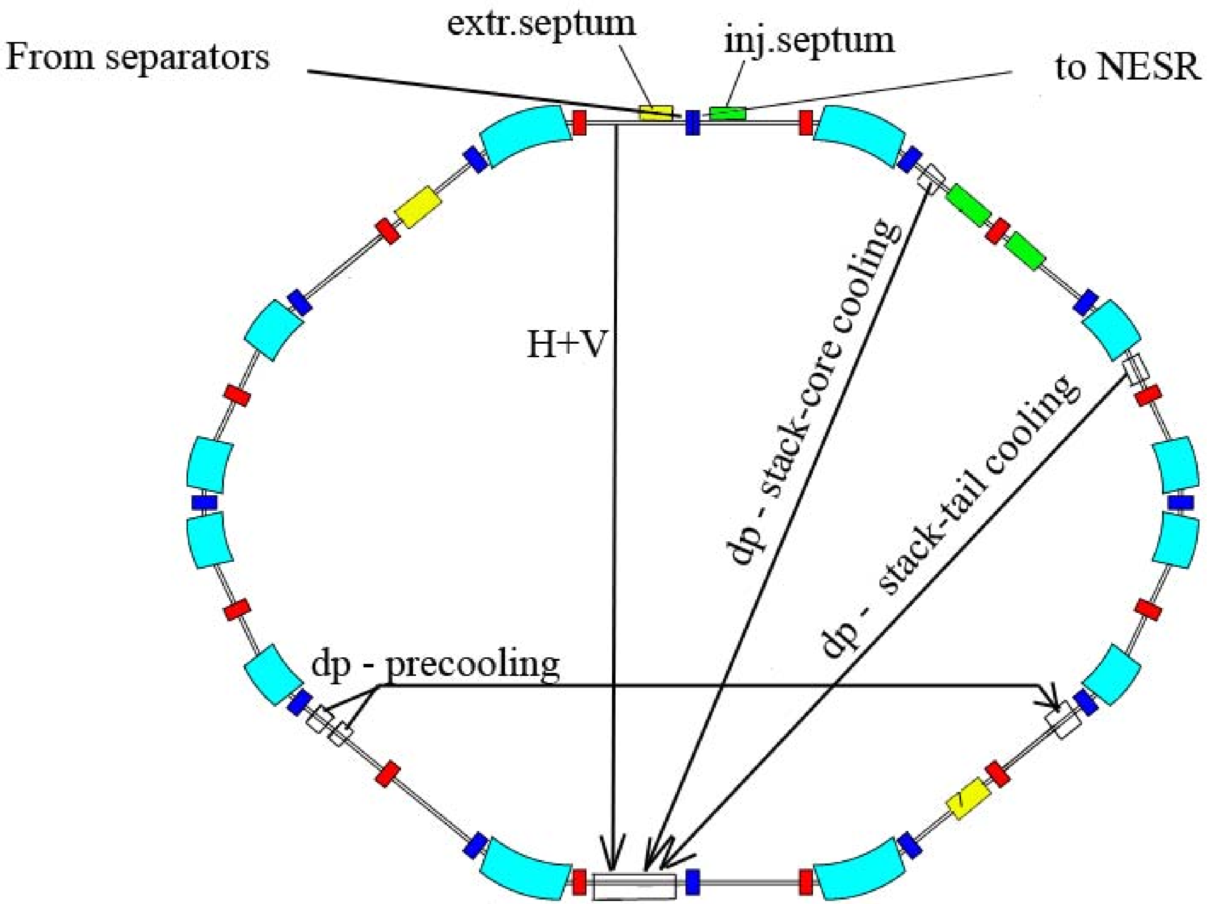
The AA magnets were considered to be used for FAIR,

presently stored at KEK are:
all dipole magnets,
all quadrupole magnets
in addition:
some magnet vacuum chambers
some kicker components

Injection / extraction in AA



Stochastic Cooling System of AA



pre-cooling
on injection orbit
0.8 – 2.4 GHz

Stack-tail cooling
0.15 – 0.5 / 0.9 – 1.65 GHz

Stack-core cooling
dp : 1 – 2 / 1 – 4 GHz
Hor : 2 – 8 GHz
Ver: 2 – 8 GHz

no space for extraction components

CR with AA arcs (CAR=CR+AA)

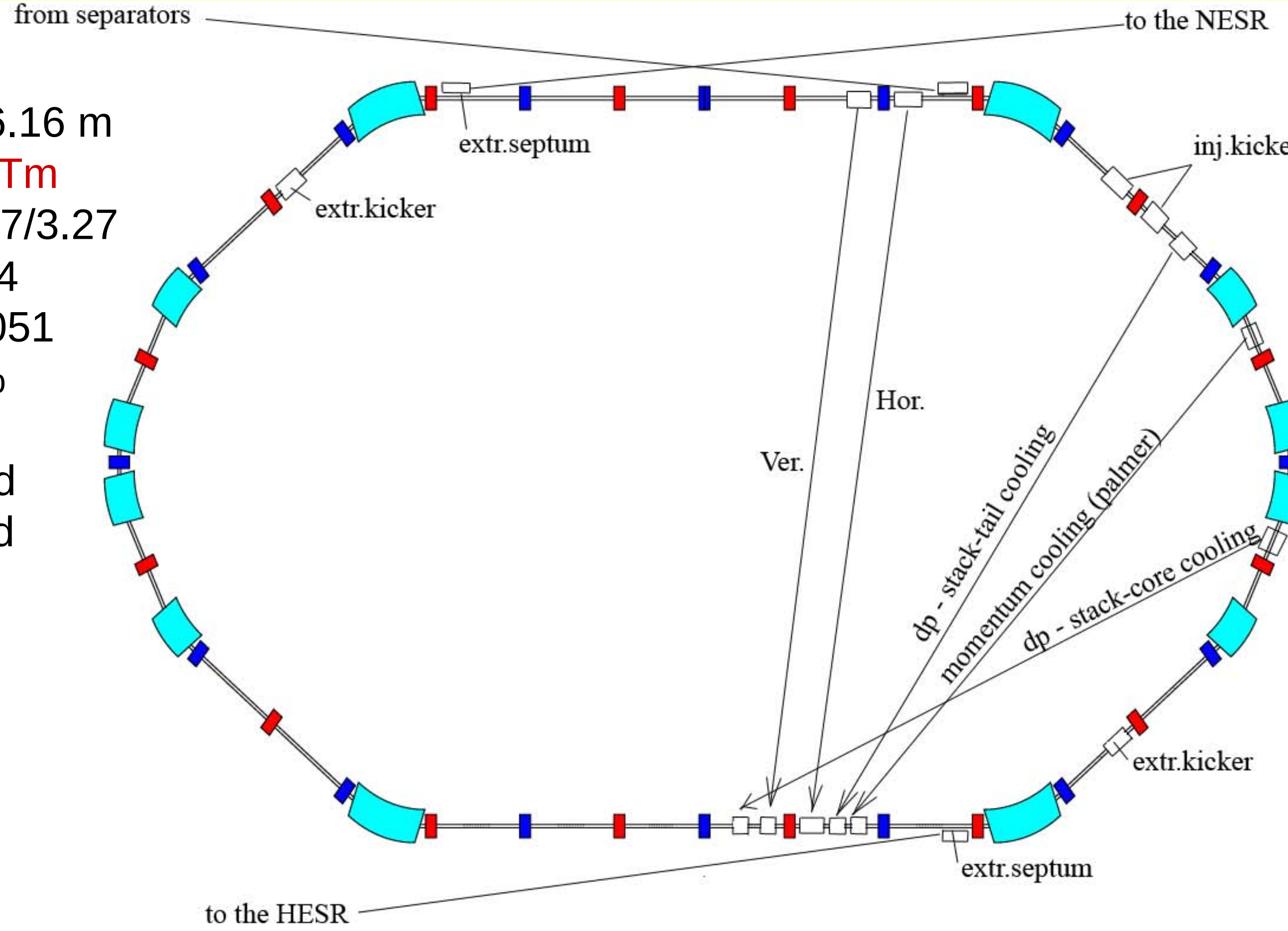
8 new quadrupole magnets are needed to have 2 long straight sections

Circumference	206.16 m
Max Rigidity	12 Tm
Q_x/Q_y	3.27/3.27
Transition energy γ_t	2.94
Momentm slip factor	-0.051
Momentum acceptance	6%

Transverse acceptance:

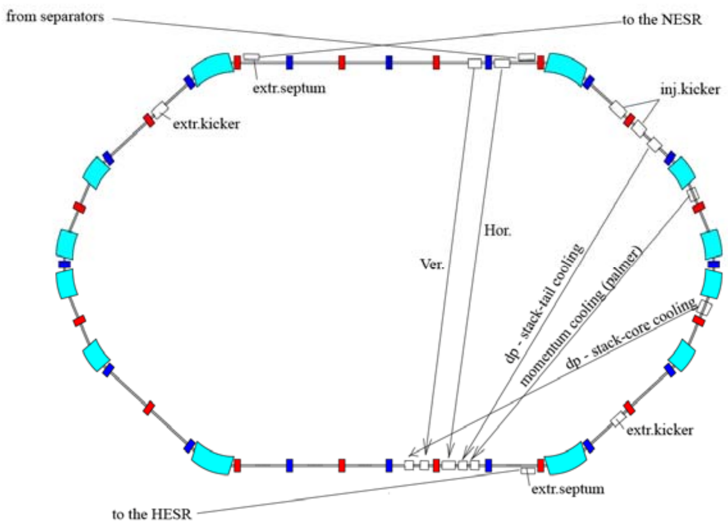
Horizontal: 240 mm mrad

Vertical: 200 mm mrad

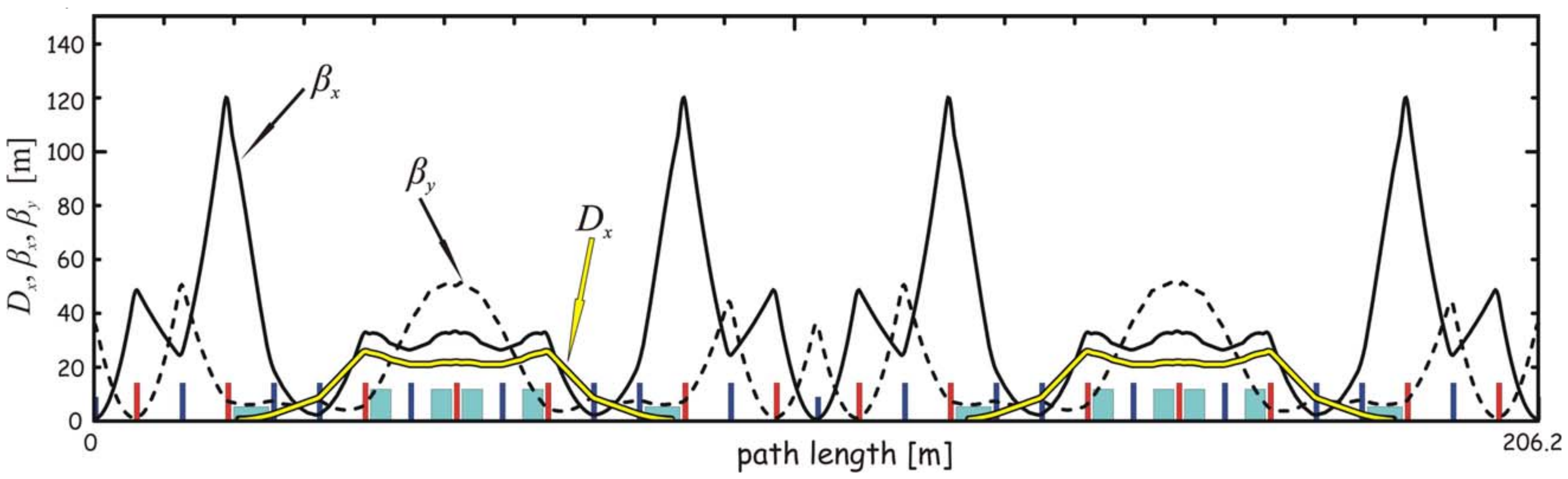


extraction to HESR

Isochronous Mode in CAR



- in linear optics isochronous mode is feasible
- large dispersion (over 20 m) allows the use of sextupoles of moderate strength
- big uncertainty:
  - field quality of AA magnets
  - higher order field contributions
  - field level dependence



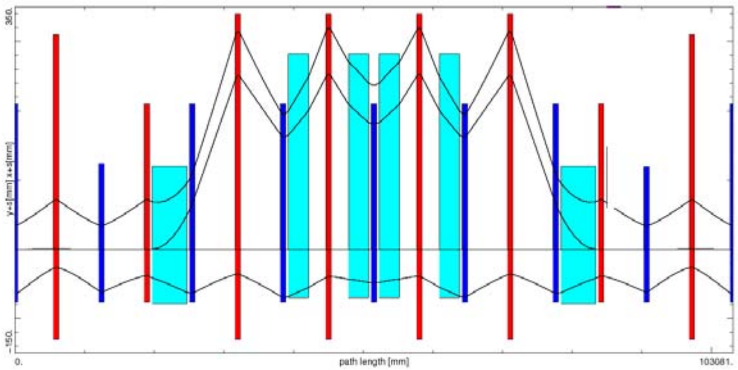
Specific AA problems for Use in FAIR

reduced magnetic rigidity
- reduced antiproton production rate
- reduced energy for RIB operation

magnetic system was designed and optimized for fixed magnetic rigidity
- issue of field quality at variable bending power
- higher order corrections for isochronous mode
- (no field data available ⇒ field measurements as basis for corrections)

long term reliability

extension of FAIR facility to full size



CAR in collector ring mode

Acceptances: A_x= 240 mm mrad
A_y= 200 mm mrad
$\Delta p/p$= ±3 %

Options for Antiproton Production 'without RESR'

1) CR as combined ring
   ⇒ add accumulation in CR

2) RESR as combined ring
   ⇒ increase acceptance and add stochastic pre-cooling

3) Accumulation of CR beam in HESR
   ⇒ provide accumulation in HESR

4) Use of AA components for CAR
   ⇒ design combined ring including AA existing magnets

5) New AA-Type ring
   ⇒ design new ring (from scratch)

RESR as Combined Ring

- small acceptance for injected beam

  horizontal and vertical acceptance: 25 mm mrad

  momentum acceptance $\Delta p/p \leq \pm 0.5$ %

  $\Rightarrow$ acceptance reduction (compared to CR): factor 60

- pre-cooling system on injection orbit must be installed from the beginning

- redesign of injection, height difference to pbar separator

- pre-cooling of RIBs, not yet studied

- isochronous mode difficult, not yet studied

CR as Combined Ring

even with reduced acceptance and without bunch rotation
(strong intensity reduction)
accumulation in the present CR seems to be impossible

longitudinal accumulation:
no space in straight section with dispersion
(for the installation of the accumulation system)

barrier bucket accumulation:
cooling time increases due to larger momentum spread
cooling time will also increase during accumulation
(cooling time proportional to stored antiproton number, if $N \geq 10^{10}$)
feedback, instabilities
fast rise and fall time is difficult for full aperture kicker

stochastic stacking system will obstruct rare isotope beams,
both in cooling and isochronous mode

Accumulation of CR beam in HESR

everything stays as planned (CR design is very advanced)

RESR can be added later

questions and problems:

no extraction from CR to HESR on the western straight

beam lifetime in HESR

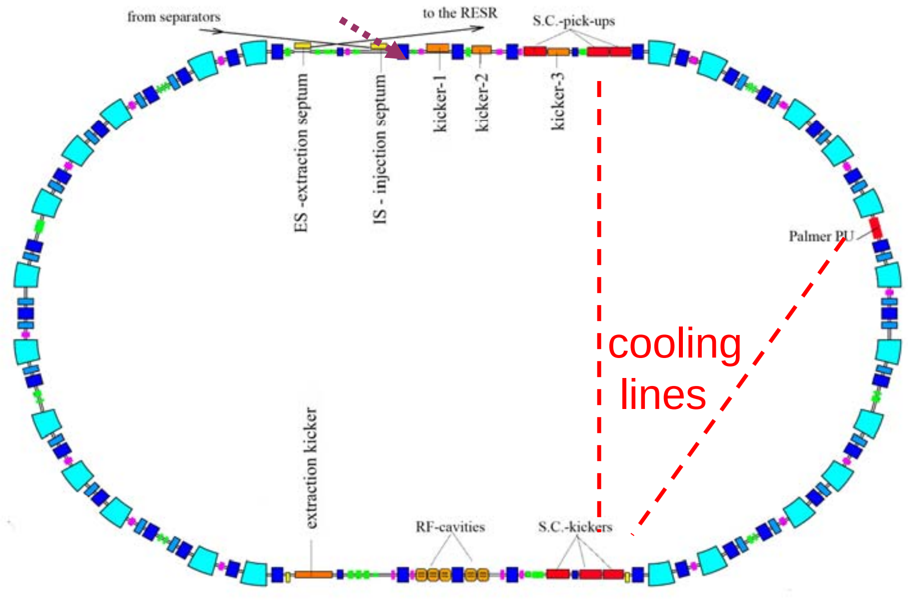
reduced duty cycle (luminosity) of HESR

reduction of beam emittance from CR and of pre-cooling time in CR would improve performance and increase luminosity

Modification of CR Extraction

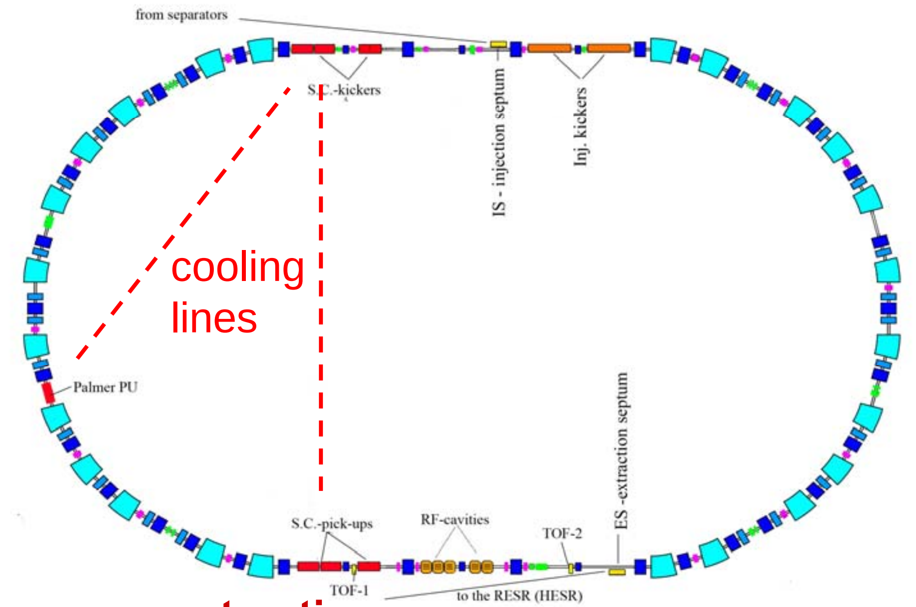
CR version 66

extraction to RESR from eastern straight



CR version 67

extraction to HESR from western straight



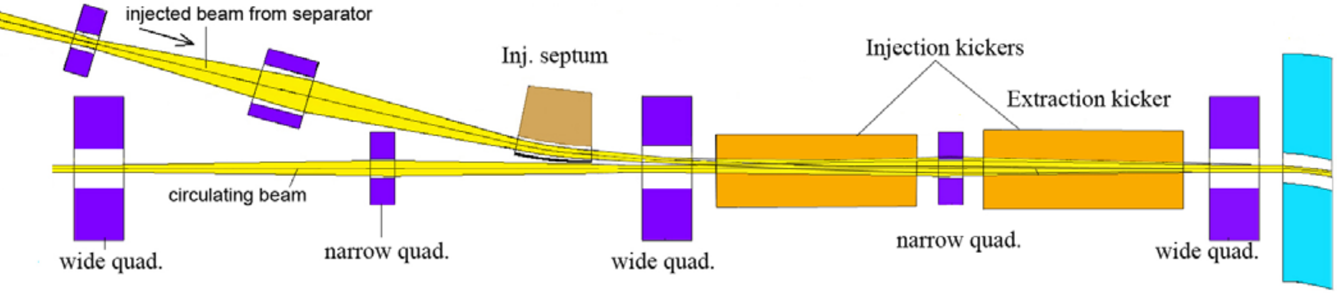
ring circumference and basic magnetic structure remain unchanged

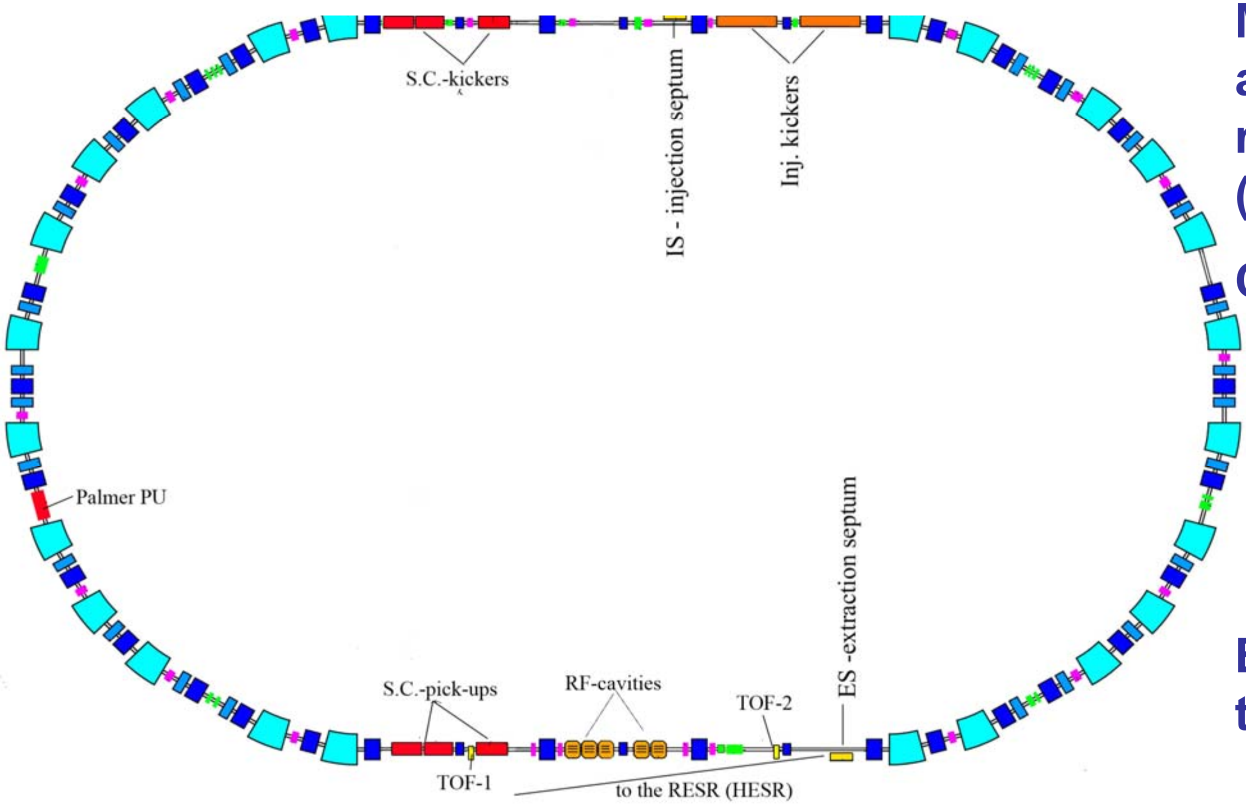
rearrangement of injection/extraction kickers, stochastic cooling system, rf cavities

combined (bipolar) injection/extraction kicker

later: also RESR must be rotated (mainly for injection)

Optimization of Injection Section





Minor changes of the arcs and some modifications of ring magnets (quadrupoles, septum)

Change of injection point provides space for stochastic cooling kicker, but requires bipolar kicker modules for antiproton operation

Extraction can be used for transfer to HESR or RESR

Next Steps towards CR Version67

- final ion optical design
  injection /extraction, optimum lattice for cooling
- technical design of CR components
  allocation and rearrangement of components
- optimize beam parameters for HESR accumulation
- redesign of RESR (common tunnel and technical building)
  injection, technical design

barrier bucket accumulation with stochastic cooling will be tested in the ESR (proof of principle, code benchmarking)

ESR test scheduled in July

Expected Reduction of Luminosity

assumption: 2×10^{13} protons in 50 ns bunch from SIS100 (rep. rate 10 [5] s)
no modification of target and separator
compared to RESR accumulation of 1×10^{11} antiprotons after 10000 s (3.6×10^{10}/hr)

HESR: **luminosity reduced by factor 5-10** **intensity up to 10^{10} ?**
same production cycle, but intensity limited and duty cycle reduced
reduction of production time 2-3, reduction of measuring time 2
finally: RESR will be added

CAR: **luminosity reduced by factor 15-30** **intensity up to 10^{11}**
reduced acceptance ⇒ reduced Intensity by a factor of 12-23 (simulation)
no bunch rotation, lower $B\rho$ (12 Tm)
finally: new pre-cooling or accumulator ring

RESR: **luminosity reduced by factor ≥ 60 (30)** **intensity up to 10^{11}**
reduced acceptance ⇒ reduced intensity by a factor of 60
no bunch rotation, isochronous mode unclear
finally: CR will be added

new AA: **luminosity reduced by factor ≥ 5** **intensity up to 10^{11}**
maybe a factor of 2-3 better than CAR
finally: CR will be added