Antiproton Production at FAIR

basic requirements:

HESR experiments:

stored antiprotons in the energy range 0.8 - 14 GeV

study of pbar-p interaction with internal hydrogen target

maximum luminosity $L = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$

with total cross section σ_{tot}= 70 mbarn

$\Rightarrow$ consumption rate $1.4 \times 10^{7}\ s^{-1}$

energy resolution 10^{-5} $\Rightarrow$ cooling in HESR

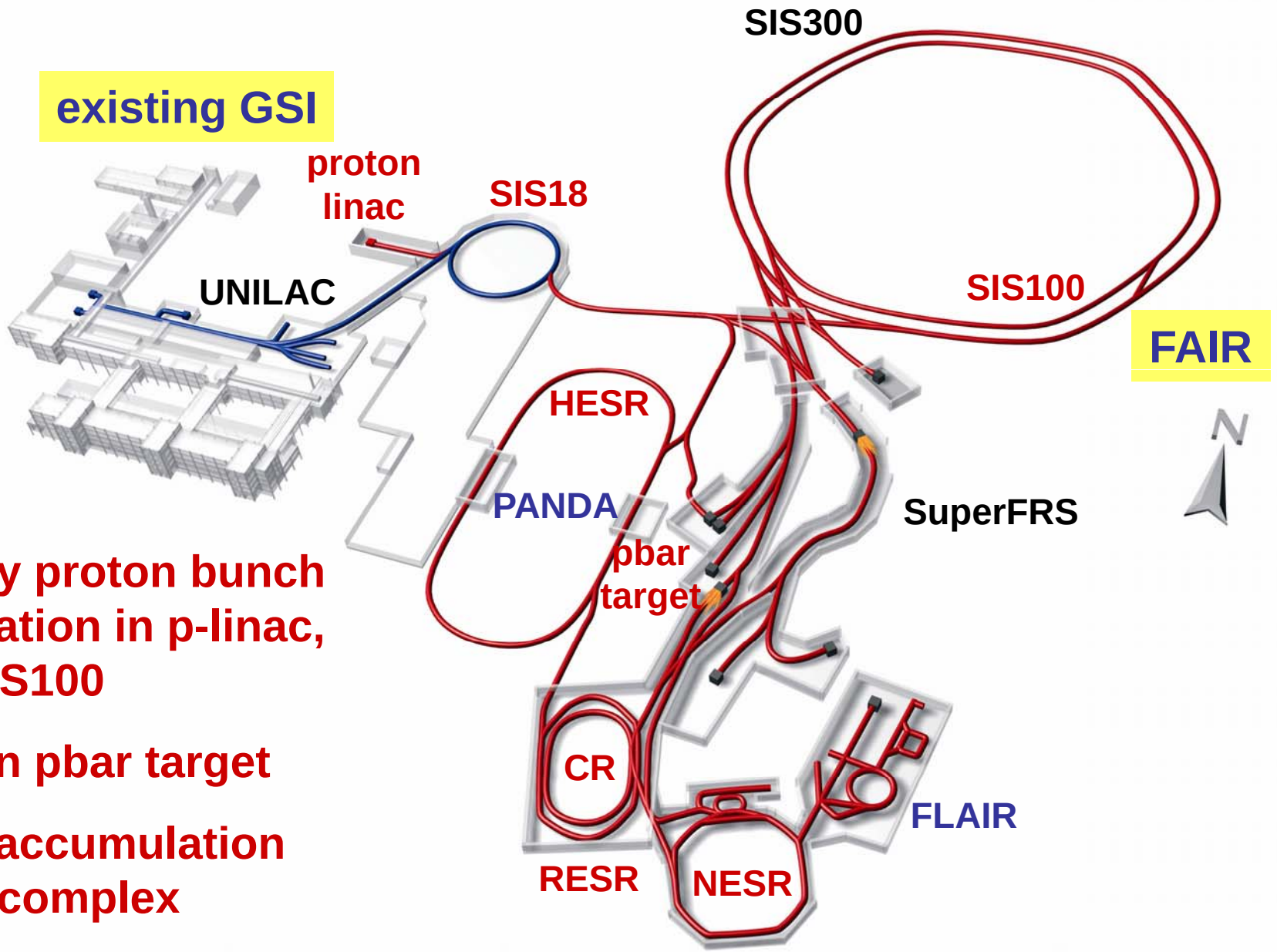
low energy antiprotons after NESR:

extracted (slow, fast) antiprotons down to 30 MeV

use fraction (10 - 20 %) of produced antiprotons

goal: **overall production rate 2 (1) × $10^{7}\ s^{-1}$**

The FAIR Accelerator Facility



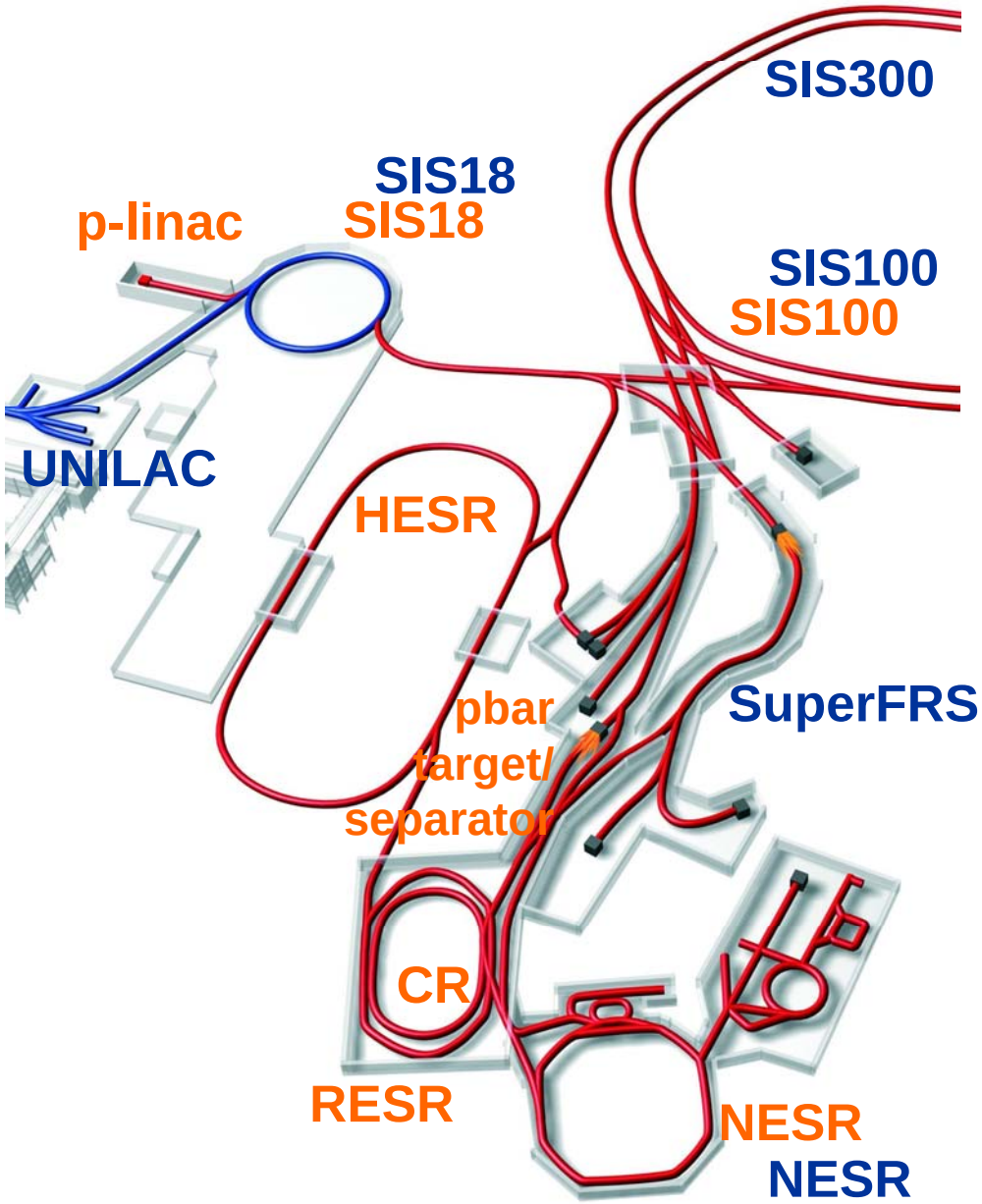
high intensity proton bunch after acceleration in p-linac, SIS18 and SIS100

conversion in pbar target

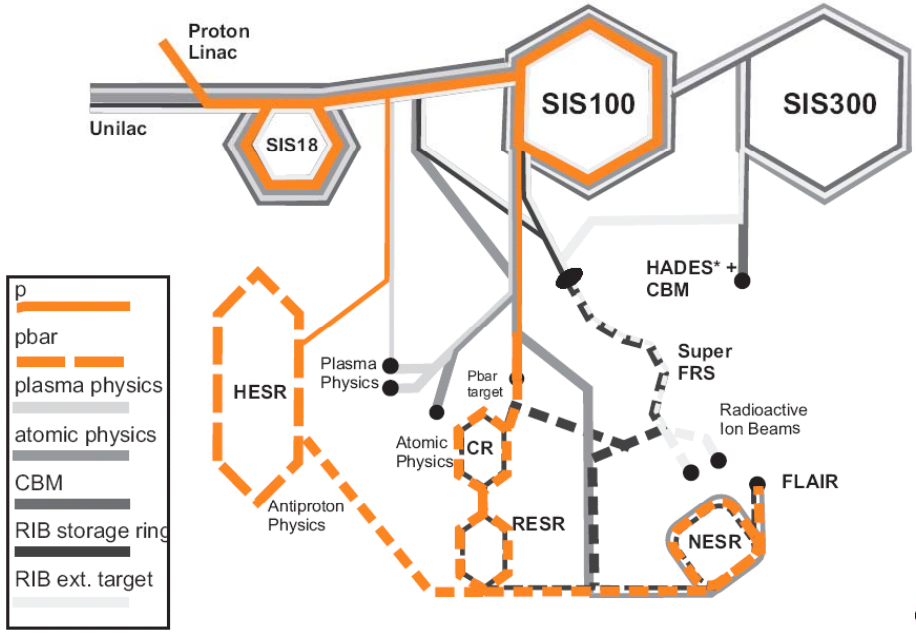
cooling and accumulation in CR/RESR complex

Experiments: PANDA in HESR, FLAIR after NESR

Antiproton Chain



- 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 RESR
- transfer at 3 GeV to users (HESR and NESR)
- storage of antiprotons in the HESR (0,8 - 14 GeV)
- 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
production rate	25 $\times10^{10}$/hr	0.7 $\times10^{10}$/hr	6 $\times10^{10}$/hr	3.5/7 $\times10^{10}$/hr
max. pbar stack	4×10^{12}	2.8×10^{11}	1.3×10^{12}	1×10^{11}

Proton Beam Parameters

	p-linac	SIS18	SIS100
output energy	70 MeV	4 GeV	29 GeV
output Bρ	1.23 Tm	16.2 Tm	100 Tm
momentum spread δp/p	1.0×10^{-3} (extr.)	1.0×10^{-3} (inj.)	1.2×10^{-4} (inj.)
horiz. emittance	6 μm (extr.)	150 μm (inj.)	13 μm (inj.)
vertic. emittance	6 μm (extr.)	50 μm (inj.)	4 μm (inj.)
tune shift at inj.		0.50	0.04
cycle time	40 μs (2.7 Hz)	0.37 s	2.3 s

(2σ-values)

requirement for antiproton production:

single bunch (shorter than 50 ns) of 29 GeV protons

Antiproton Beam Parameters

fixed energy 3 GeV	pbar Target / separator	CR	RESR
task	production	pre-cooling	accumulation
number of antiprotons (inj.)	4×10^8/cycle	2.8×10^8/cycle	2×10^8/cycle stack: 10^8-10^{11}
momentum spread $\delta p/p$	± 3 % (homogeneous)	1×10^{-3}	$\leq 5 \times 10^{-4}$
horiz. emittance	240 μm	5 μm	1 μm (after core cooling)
vertic. emittance	240 μm	5 μm	1 μm (after core cooling)
cycle time (after upgrade)	10 s (5 s)	10 s (5 s)	10 – 10000 s

(2σ-values)

RESR will provide a variable number of antiprotons to HESR and/or NESR

Potential Losses during Antiproton Accumulation

CR:

particles outside kicker flat top	≤ 5 %
bunch rotation and debunching	≤ 10 %
stochastic cooling (6D)	≤ 10 %
rebunching and transfer to RESR	≤ 5 %

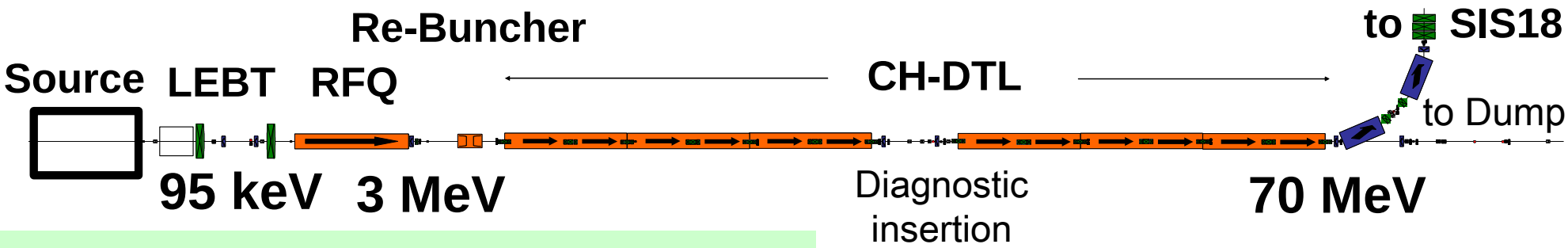
RESR:

stacking losses	≤ 20-50 % ?
(heating by injection kicker, diffusion by rf, rf acceleration, beam feedback)	
rebunching and extraction	≤ 10 %

The RESR should be able to accumulate 1×10^7 antiprotons/s reliably

Proton Linac

The new proton linac is needed to fill SIS18 with protons to the space charge limit

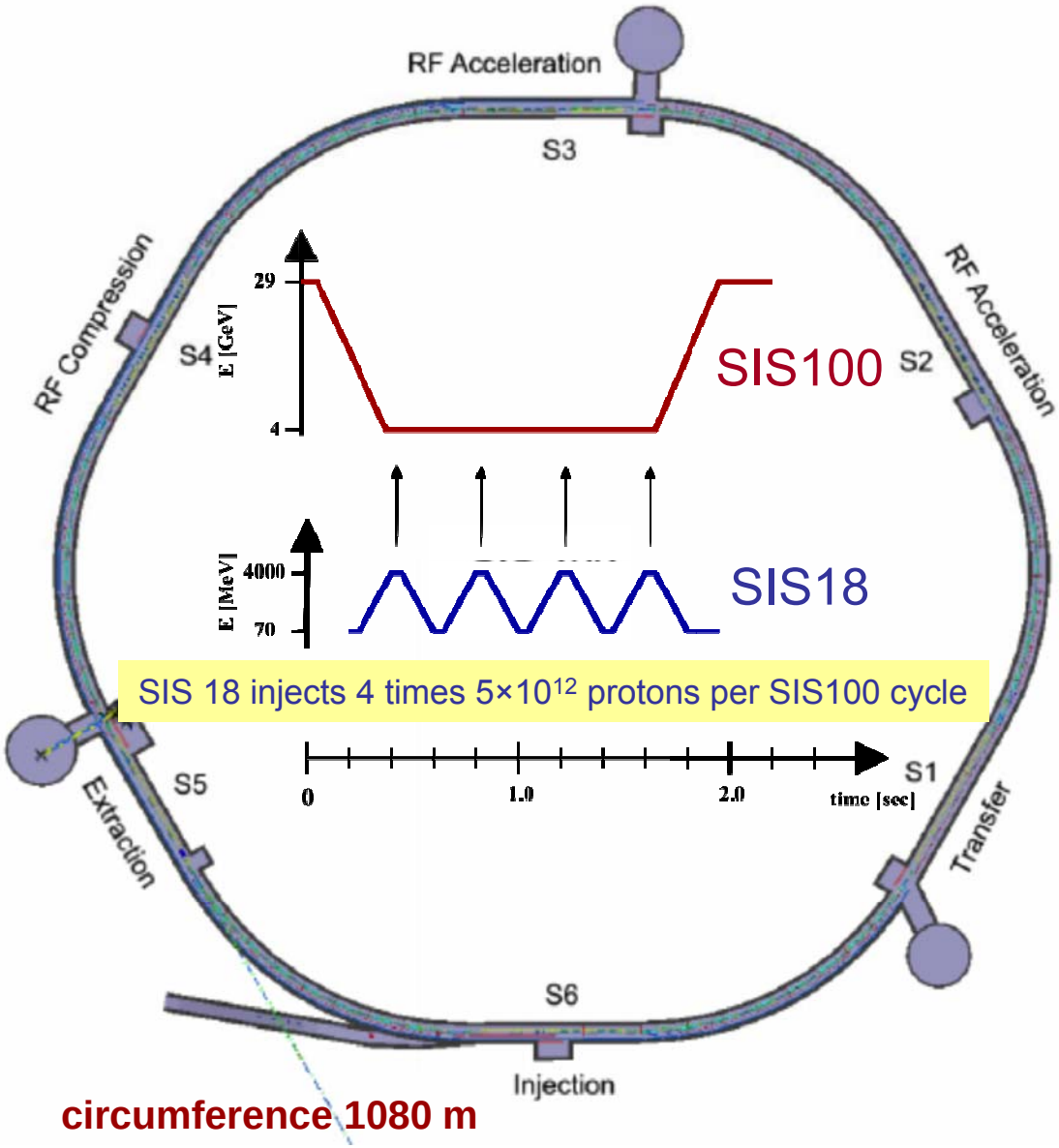


collaboration with: *University of Frankfurt*
CEA/Saclay, IN2P3, GANIL

- **ECR proton source & LEBT**
- **RFQ**
- **2 re-bunchers**
- **2 * 6 accelerating cavities**
- **5 MW of beam loading (peak), 720 W (ave.)**
- **11 MW of total rf-power (peak), 5 kW (ave.)**
- **2 dipoles, 46 quadrupoles, 7 steerers**
- **10 turbo pumps, 34 ion pumps, 9 sector valves**
- **41 beam diagnostic devices**

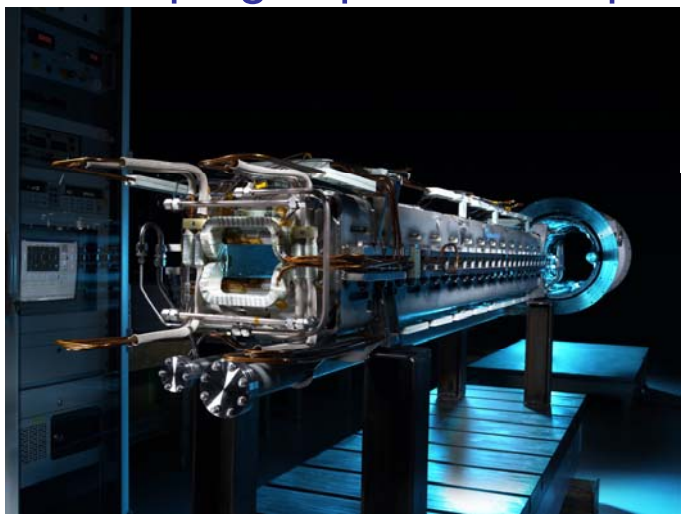
Energy	70 MeV
Current (oper.)	35 mA
Design current	*70 mA*
Beam pulse length	36 µs
Repetition rate	4 Hz
Rf-frequency	325.224 MHz
Norm. horiz. emit.	2.1 / *4.2* µm
Tot. mom. spread	≤ ± 10^{-3}
Linac length	≈ 35 m

SIS 100

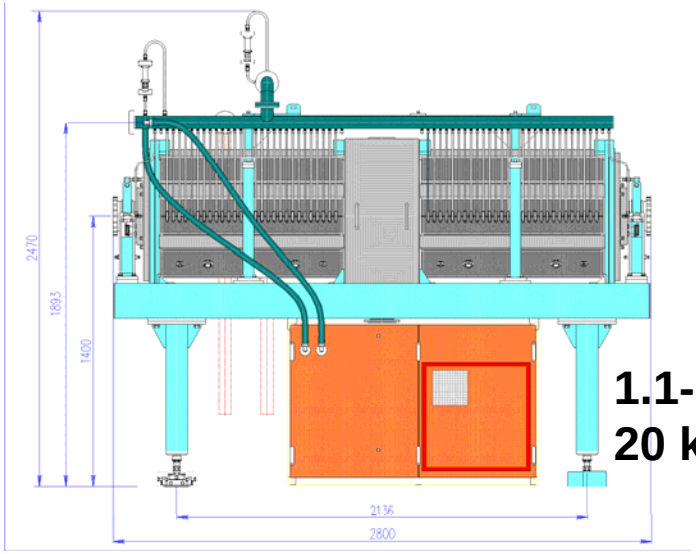


circumference 1080 m

fast ramping super-ferric dipole



4 T/s

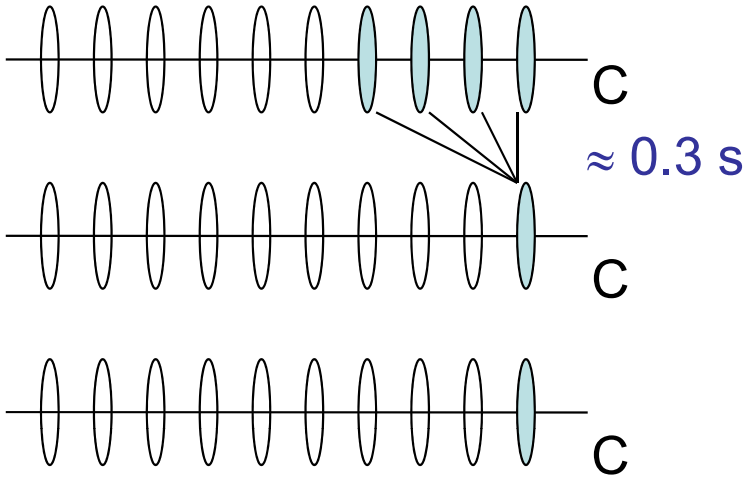


1.1-2.7 MHz
20 kV

acceleration cavity h=10

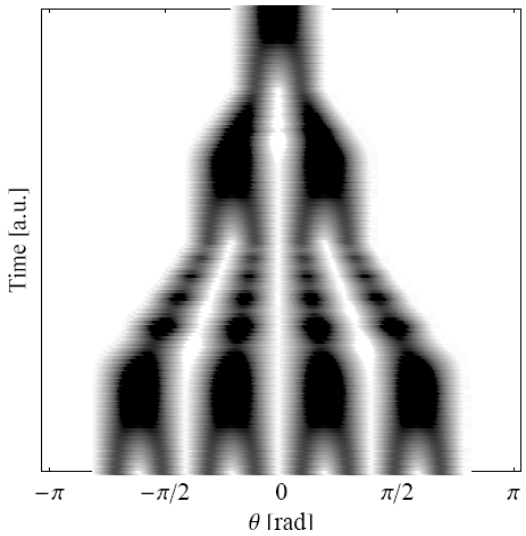
Rf Manipulations in SIS100

- **Stacking at 4 GeV**
  (4 bunches – 10 rf buckets)
- **Single bunch generation by batch compression**
  (1 bunch – 10 rf buckets)
- **Acceleration to 29 GeV and extraction**
  (1 bunch – 10 rf buckets)



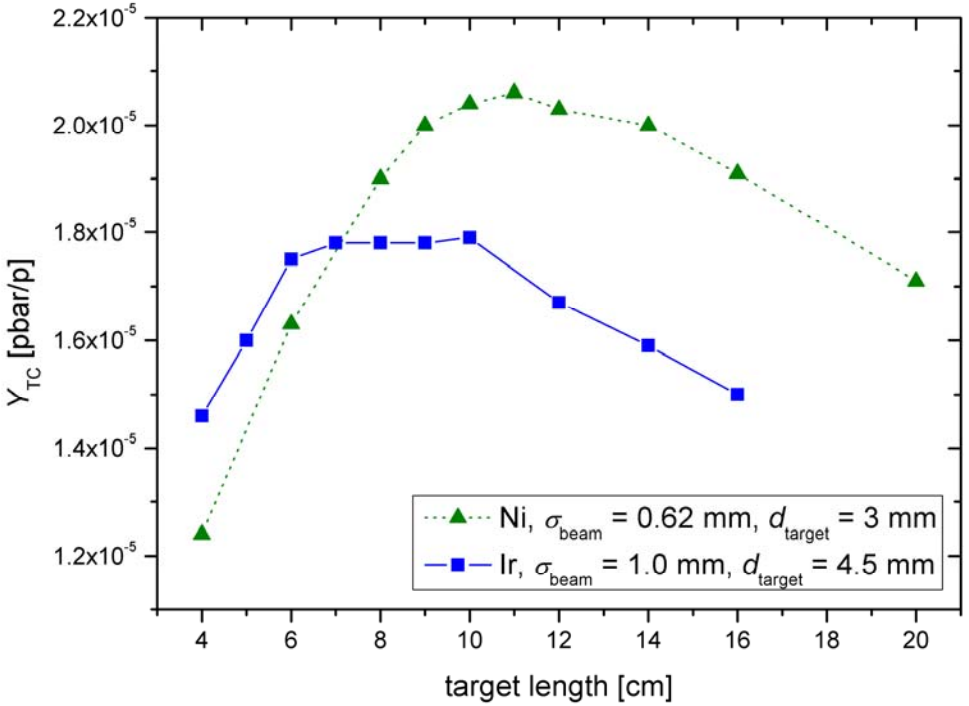
synchrotron frequency for rf manipulations at high gamma too low ⇒ takes too long

standard scheme for single bunch generation and compression not applicable

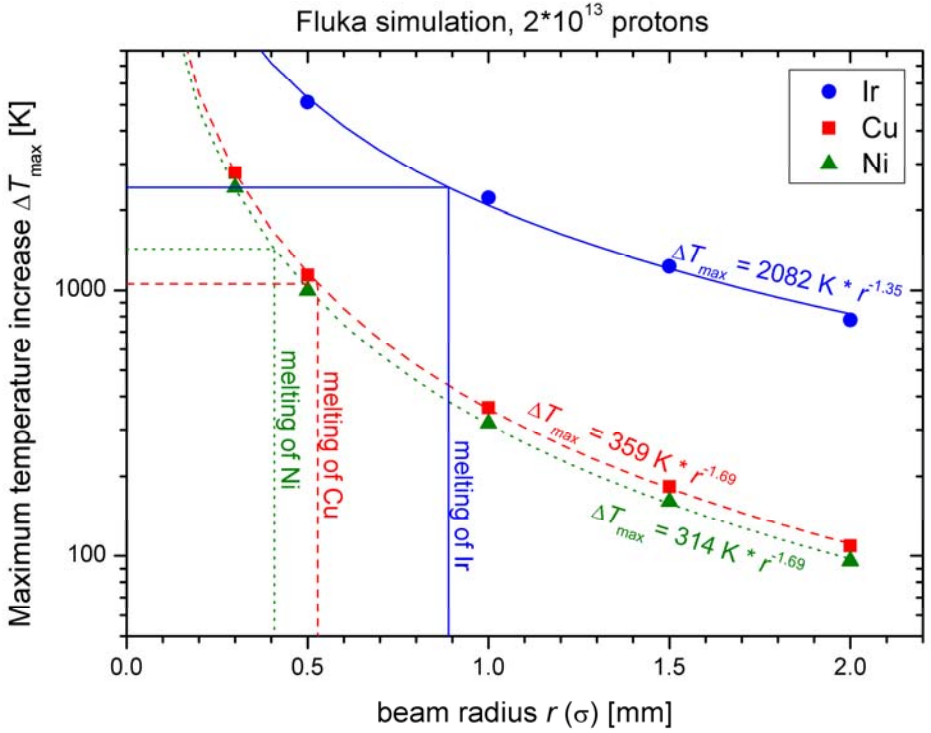


Antiproton Target - Choice of Material

production rate of antiprotons
primary beam 29 GeV protons

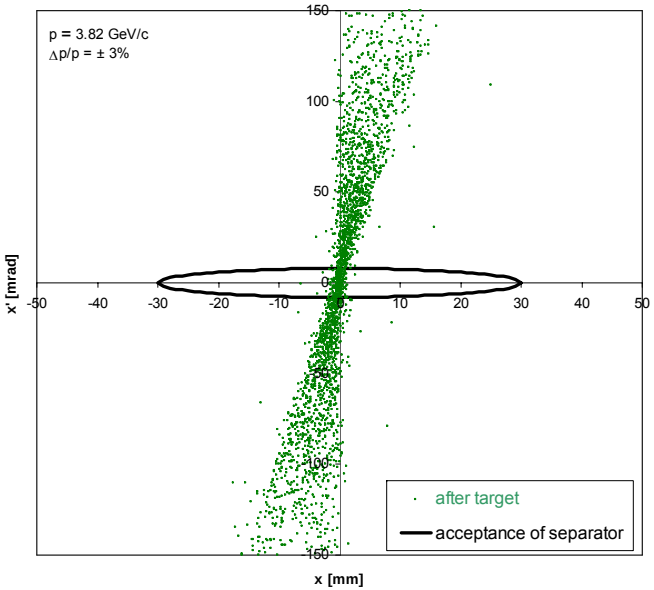


temperature of target

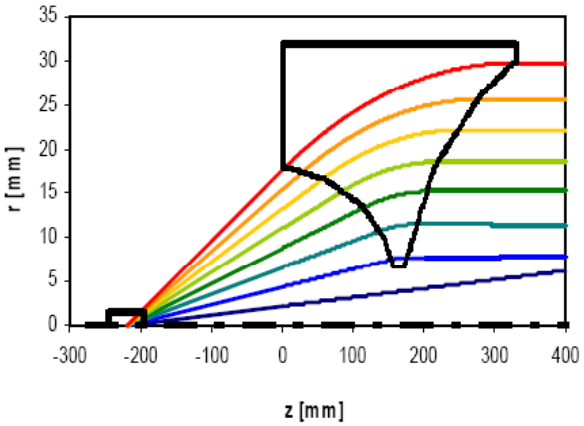


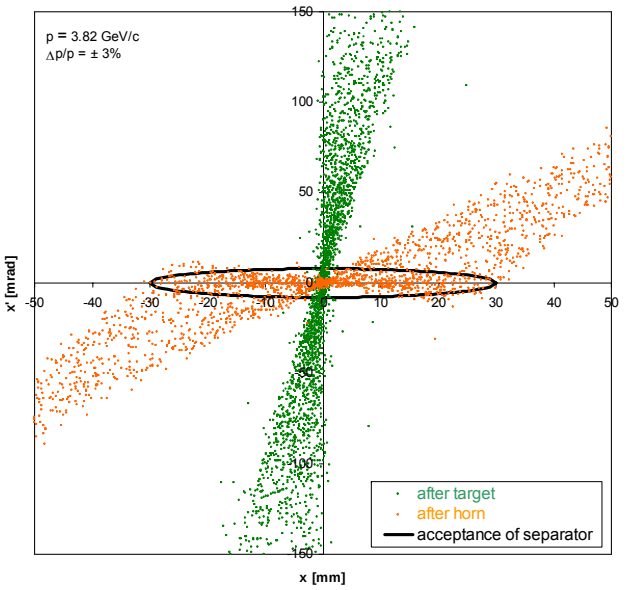
nickel is superior with respect to strong focusing and thermal heating

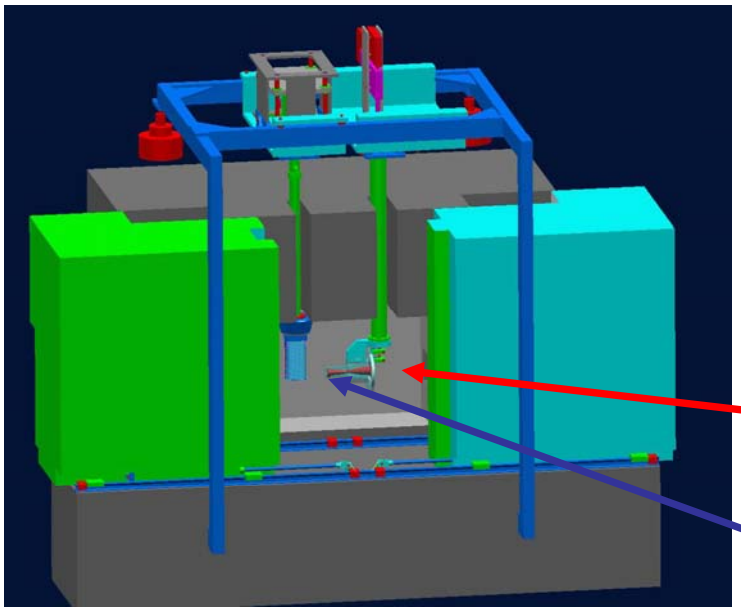
Focusing of Antiprotons by Magnetic Horn

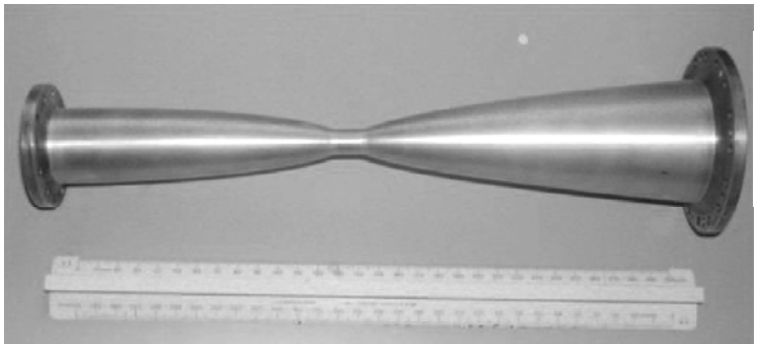


magnetic horn





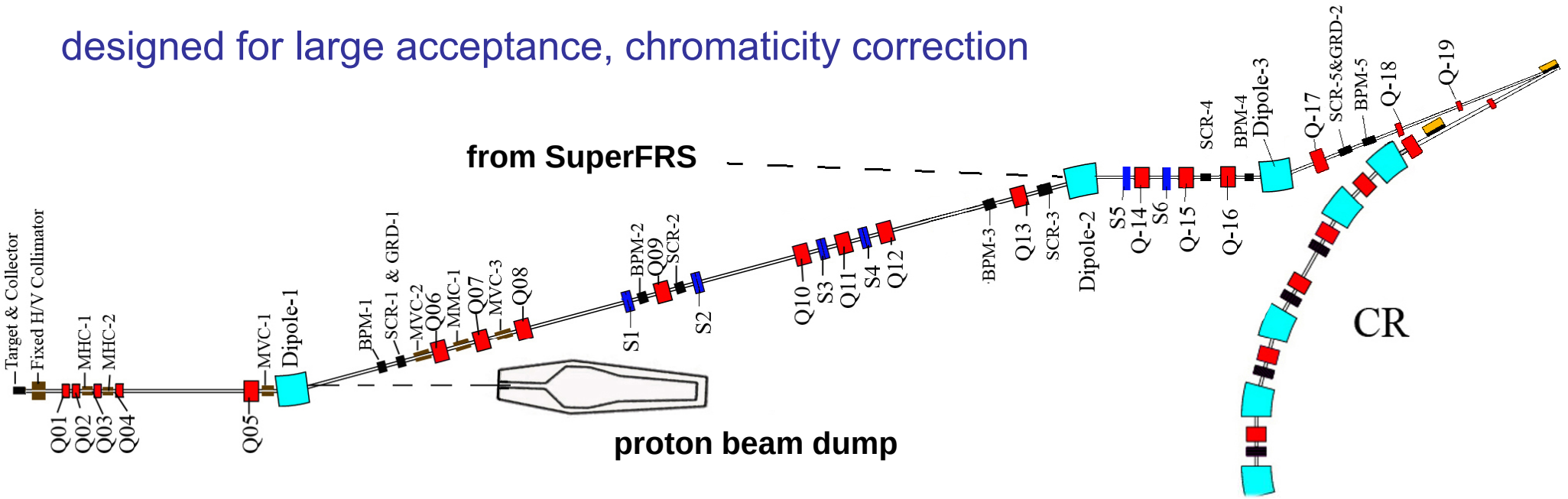




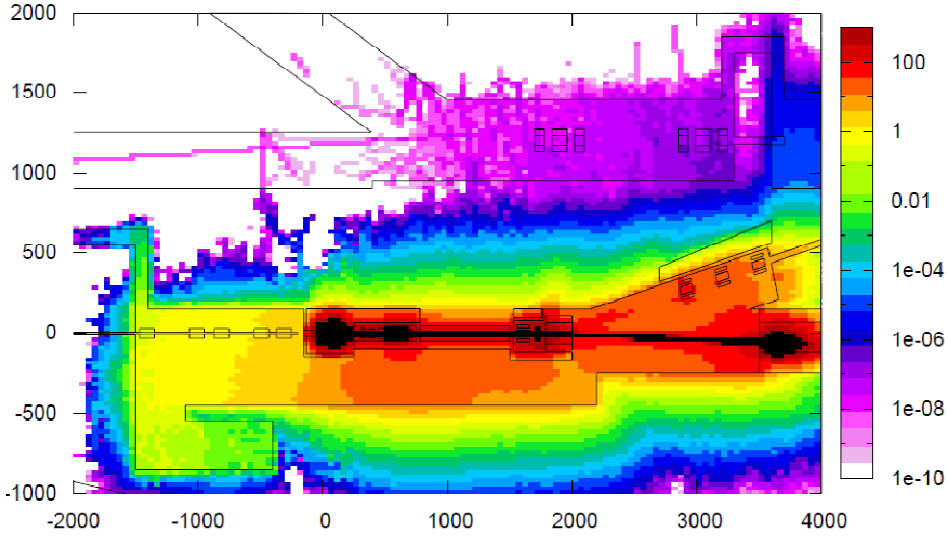
CERN ACOL Horn, I = 400 kA

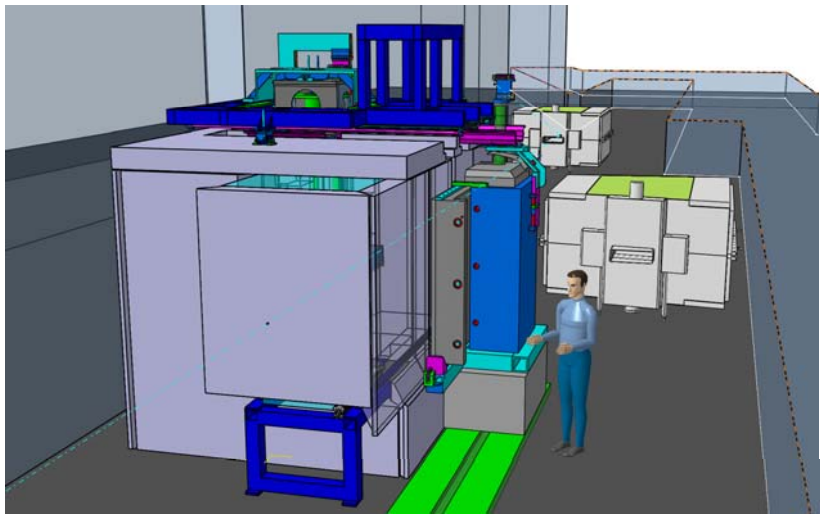
Antiproton Separator

designed for large acceptance, chromaticity correction



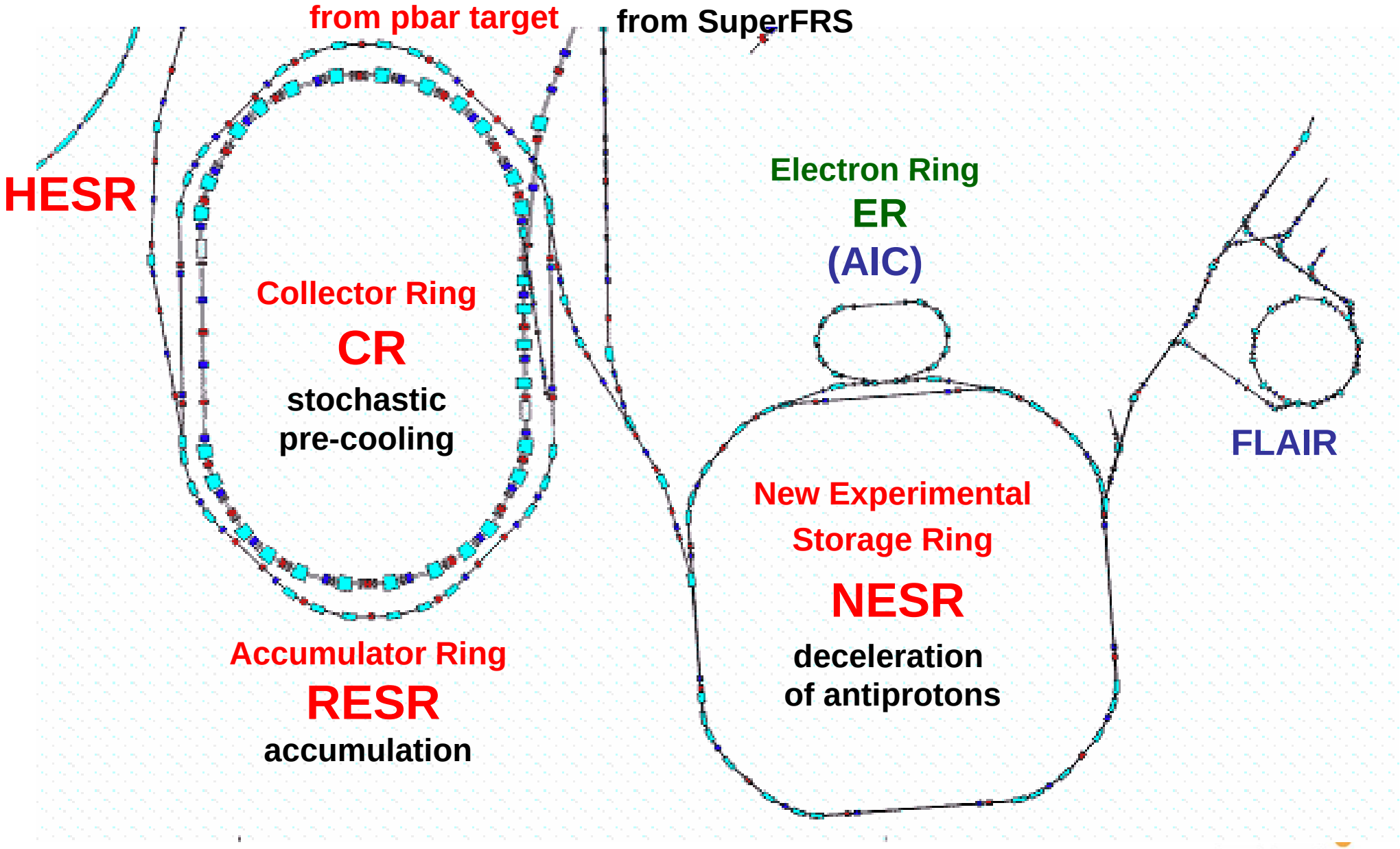
equivalent dose rate [Sv/h], 2 × 10^{13} p, 0.1 Hz



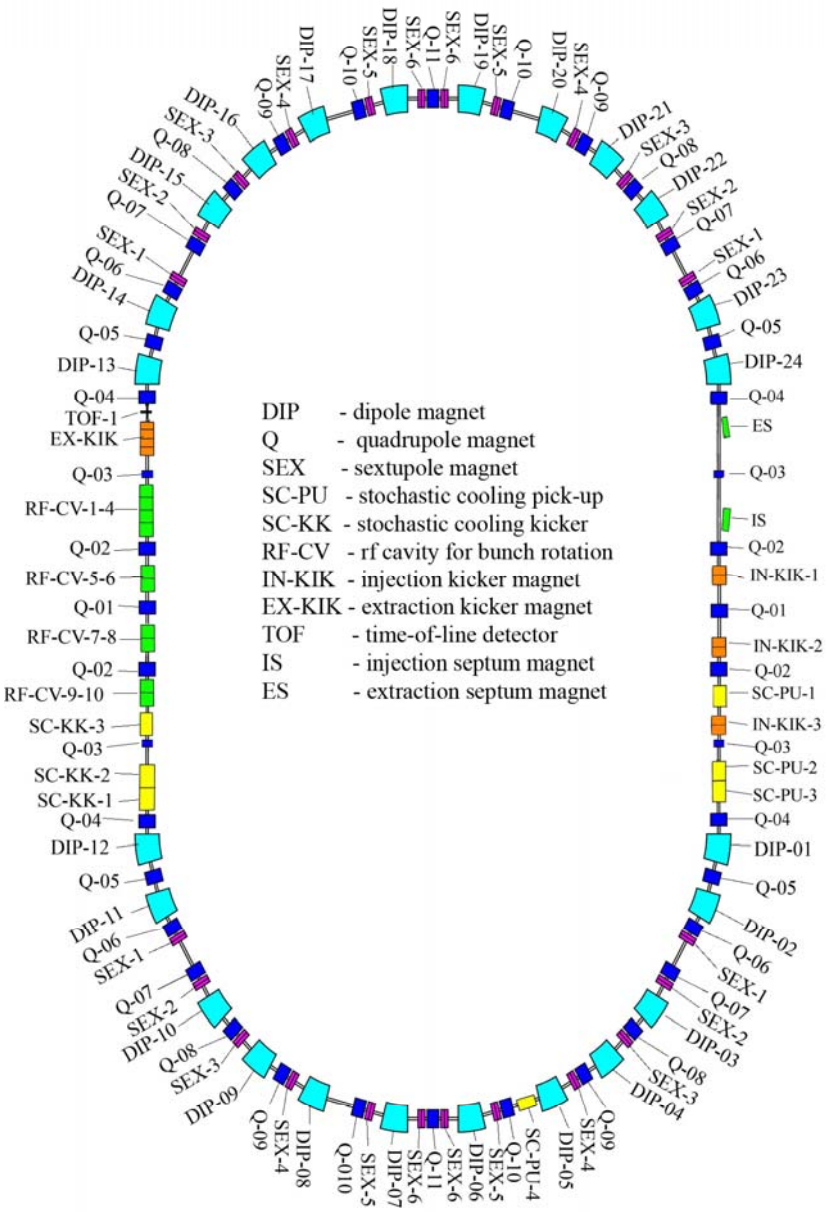


target handling

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) %

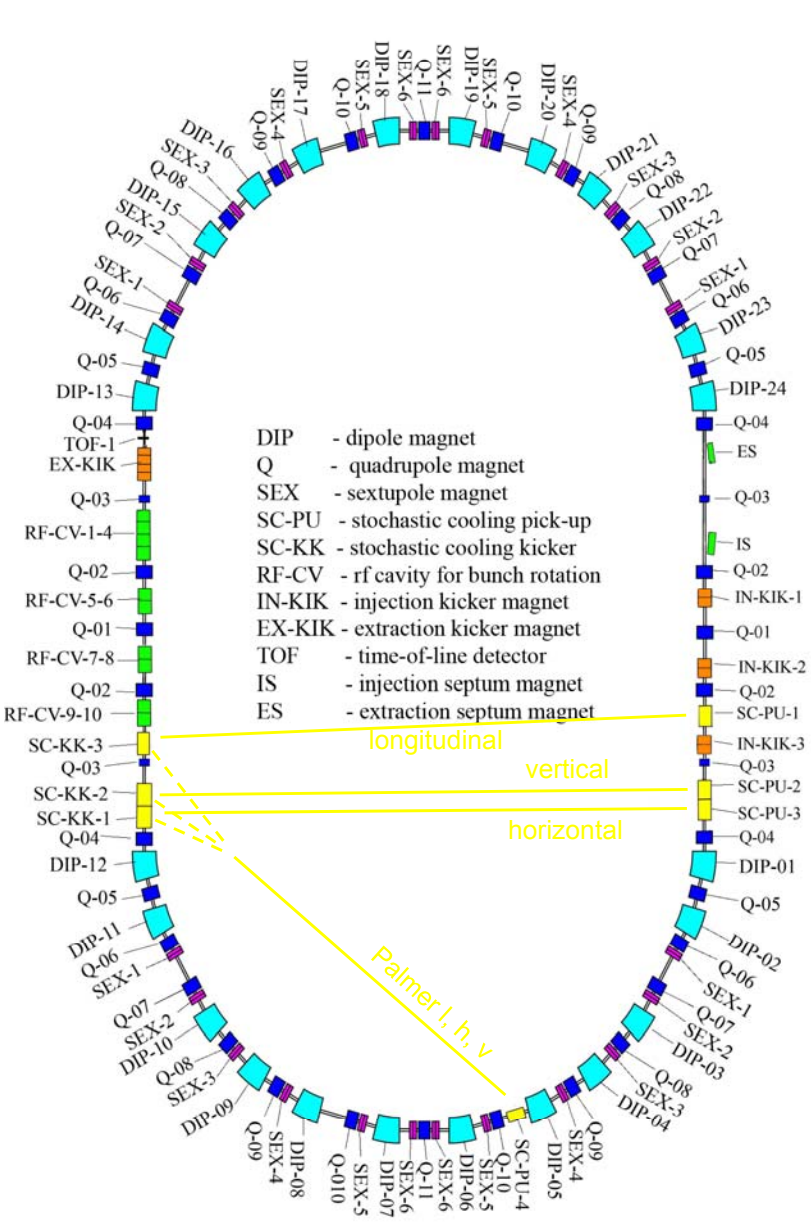
fast stochastic cooling (1-2 GHz) of antiprotons (10 s) and rare isotope beams (1.5 s)

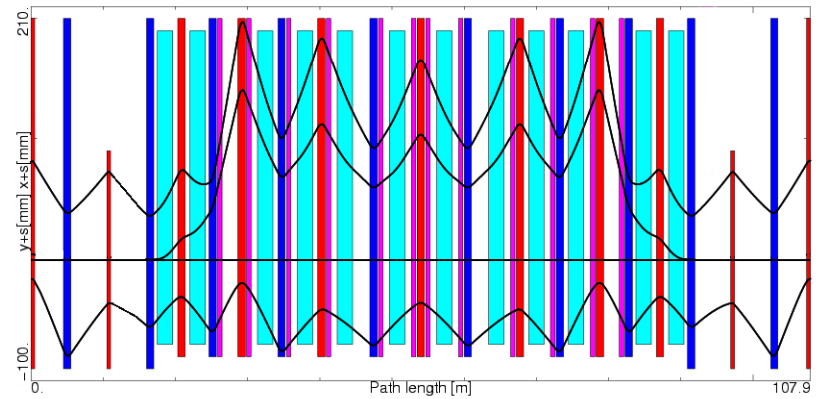
fast bunch rotation at h=1 with rf voltage 100/200 kV adiabatic debunching

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



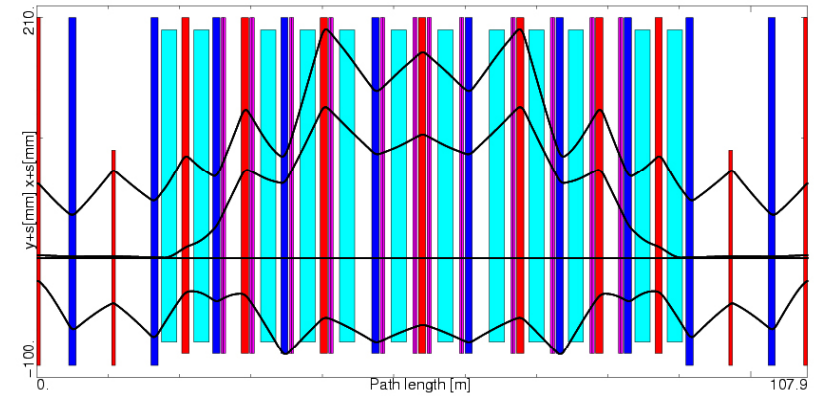


antiprotons

Q_x= 4.26, Q_y= 4.84

γ_t = 3.85

η = - 0.0107

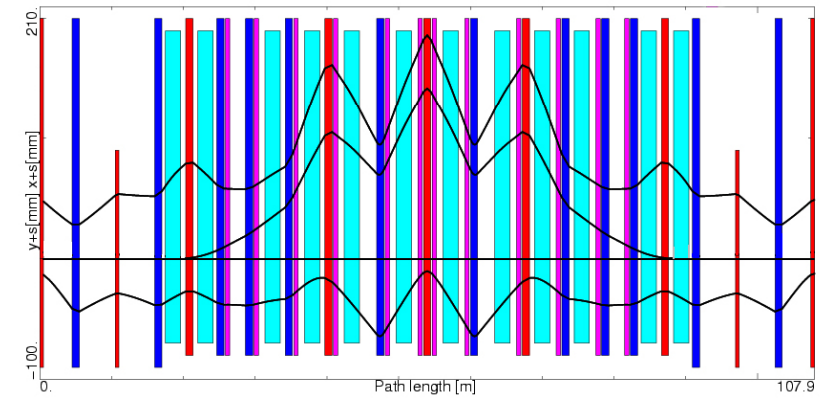


RIBs

Q_x= 3.19, Q_y= 3.71

γ_t = 2.82

η = + 0.186



isochronous

Q_x= 2.23, Q_y= 4.64

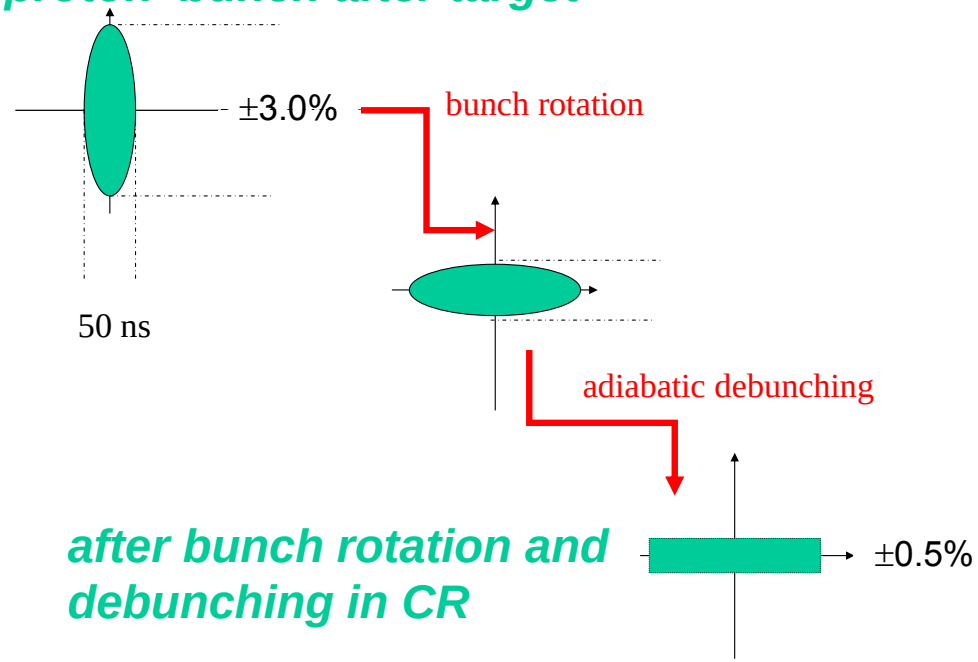
γ_t = 1.84

η = 0

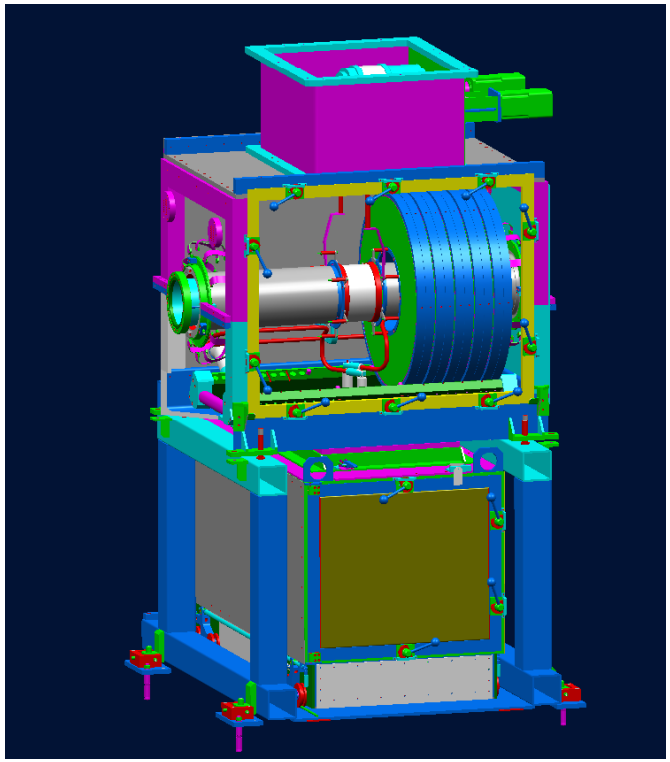
Fast Bunch Rotation in CR

Fast bunch rotation of bunch from SIS100
to provide optimum initial parameters
for stochastic cooling
total rf voltage 100 kV at h=1 reduces
the momentum spread (± 3.0 → ± 0.5 %)
after passage of production target

antiproton bunch after target



after bunch rotation and debunching in CR

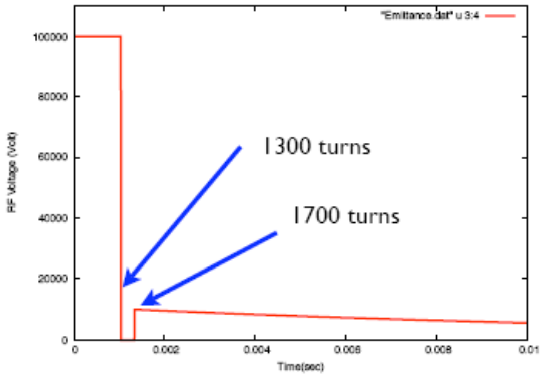


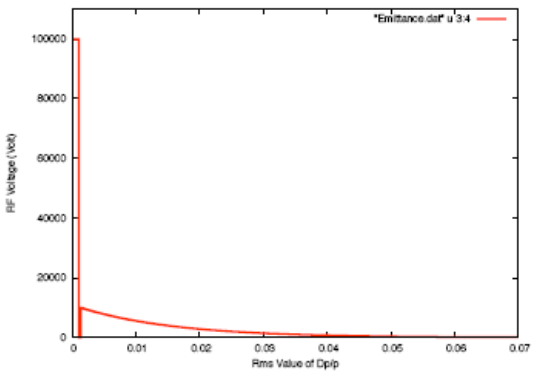
bunch rotation cavity
filled with magnetic alloy
(*SIS18 bunch compressor*)

length 1 m
voltage 20 kV (40 kV)
frequency 1.38 (1.18) MHz
rotation time ~ 1 ms (0.1 ms)

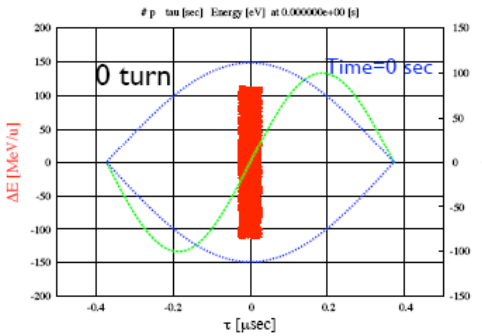
Simulation of Bunch Rotation in CR

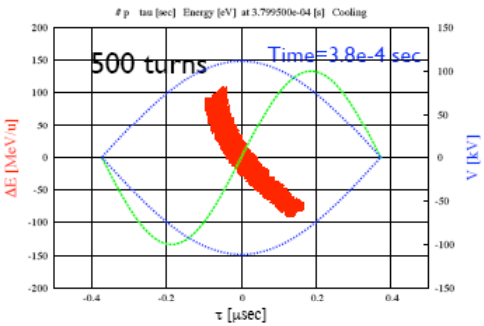
rf voltage

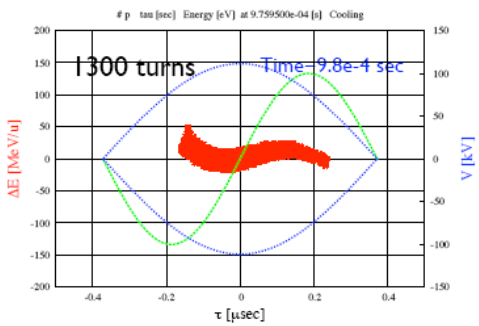




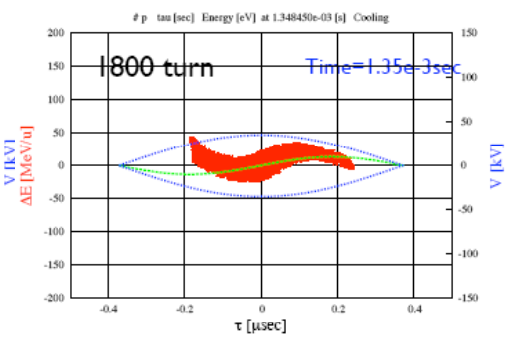
bunch rotation

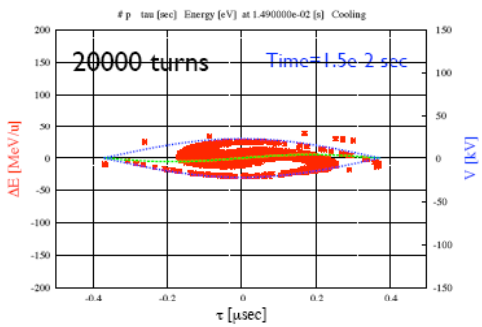


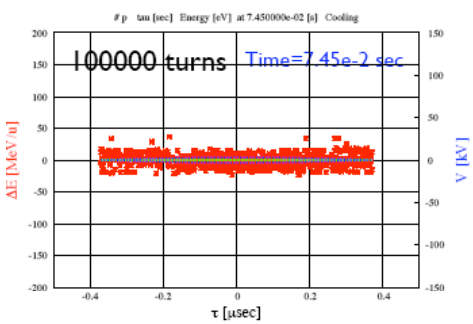




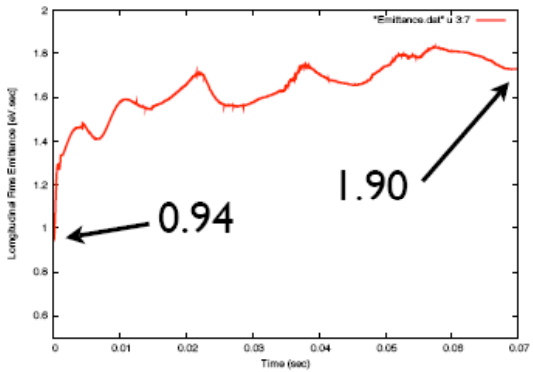
debunching



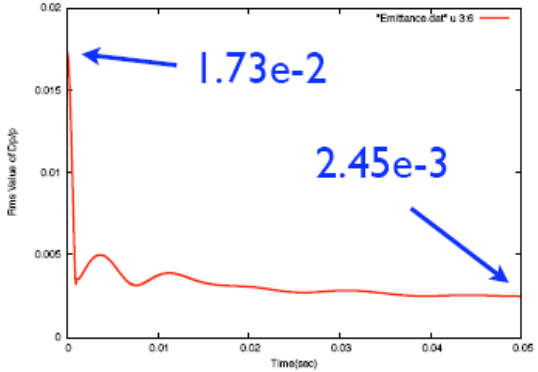




longit. emittance

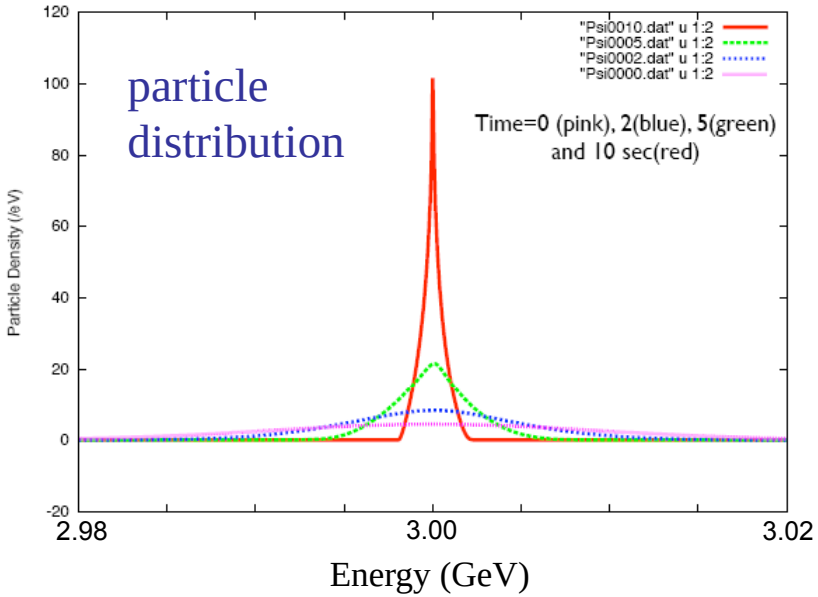


momentum spread



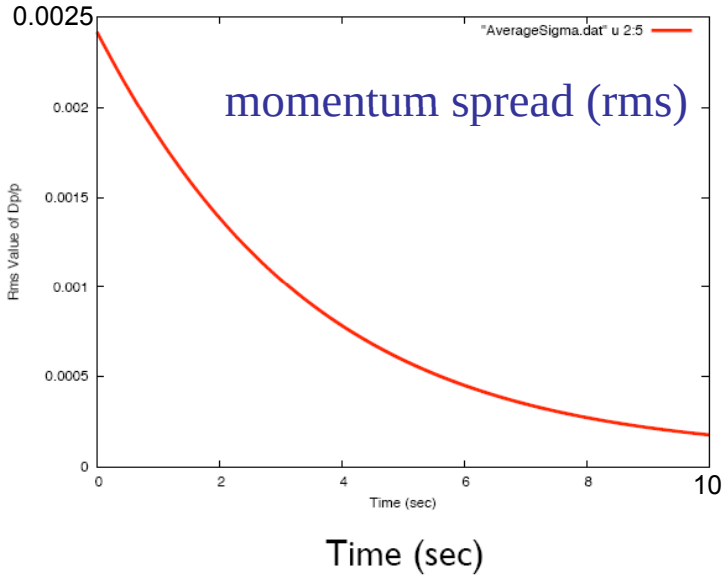
(rms-values)

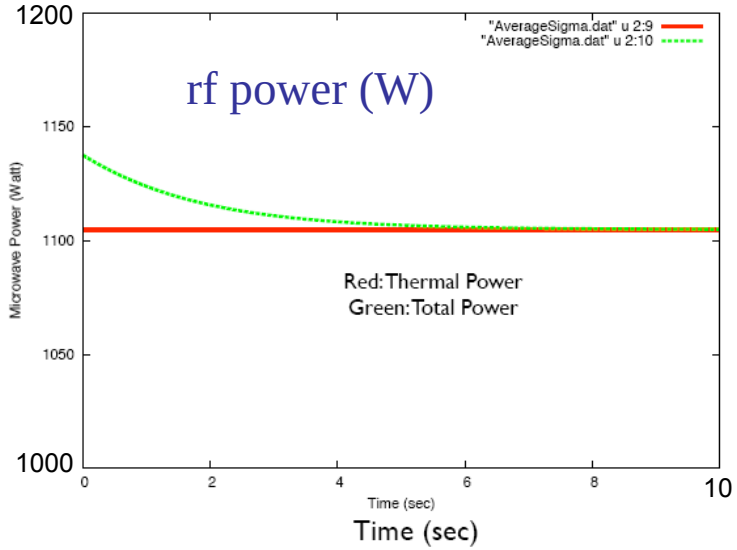
Simulation of Stochastic Cooling in CR



longitudinal stochastic cooling system

- **band 1 – 2 GHz**
- **temperature 40 K**
- **notch filter cooling**
- **gain 150 db**
- **power 1.2 kW**
- **electrode impedance 100 Ω**





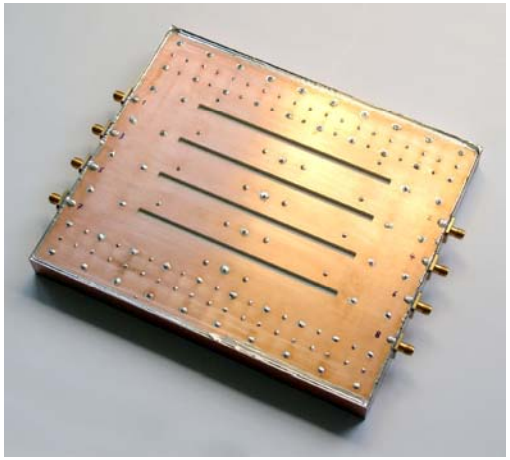
CR Stochastic Cooling Electrodes

Fast Stochastic Pre-cooling

system band width 1-2 GHz

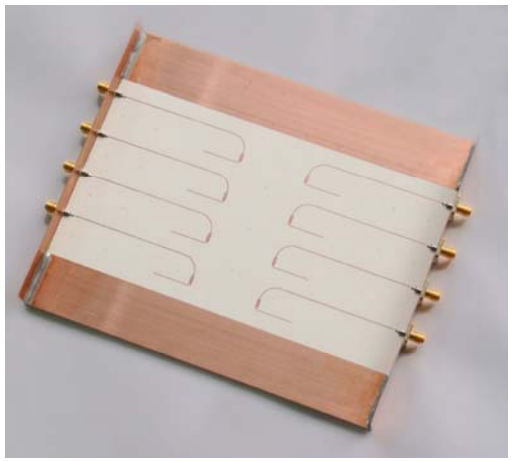
matched to velocities β = 0.83 - 0.97

rf power ~ 1-2 kW per system



electrode prototype (slotline type)

front side



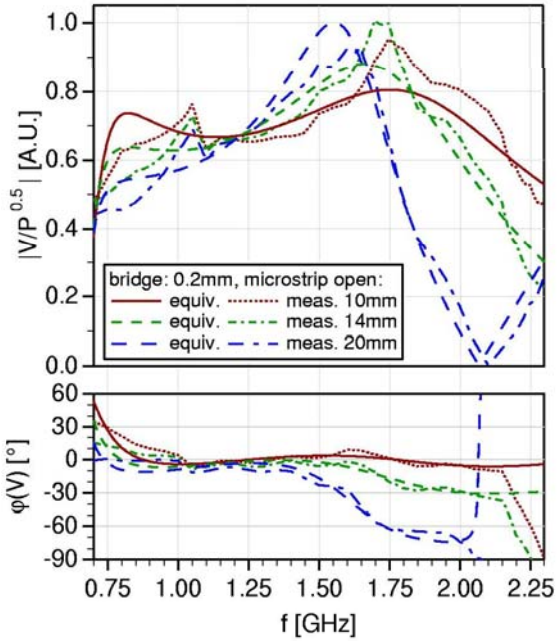
back side

flatness of

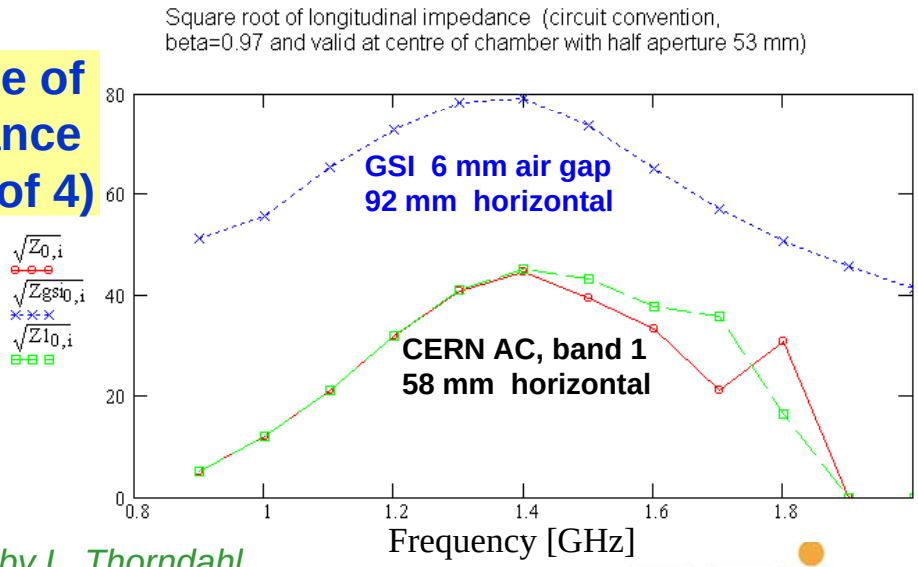
voltage

and

phase



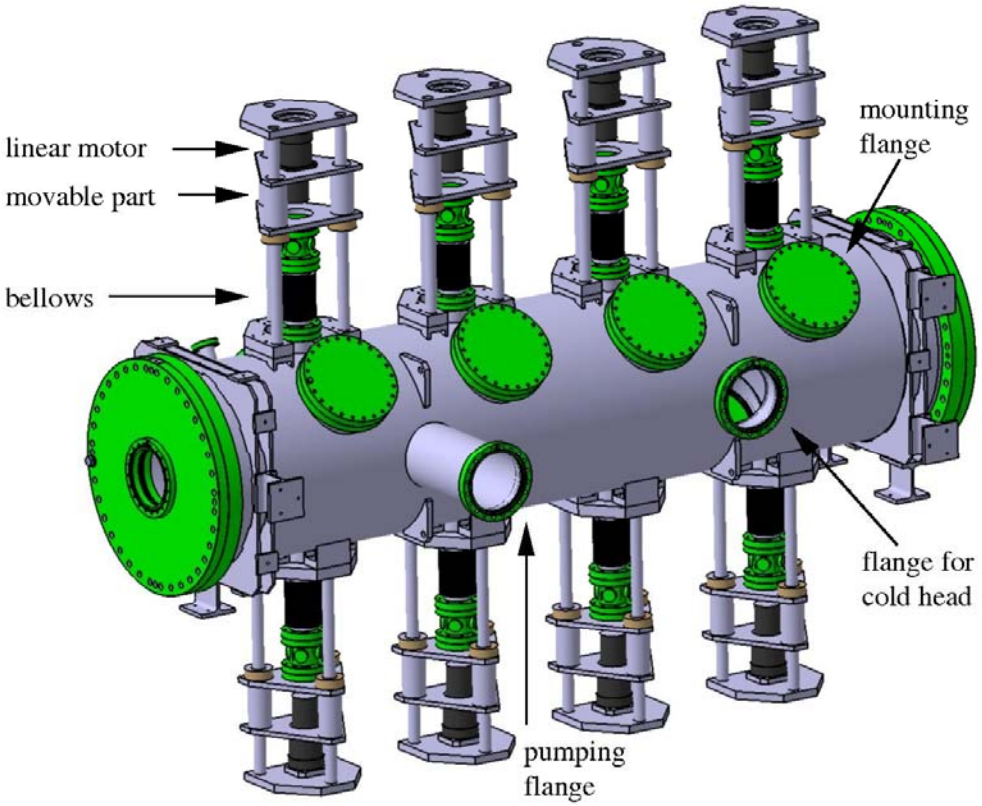
increase of impedance (factor of 4)



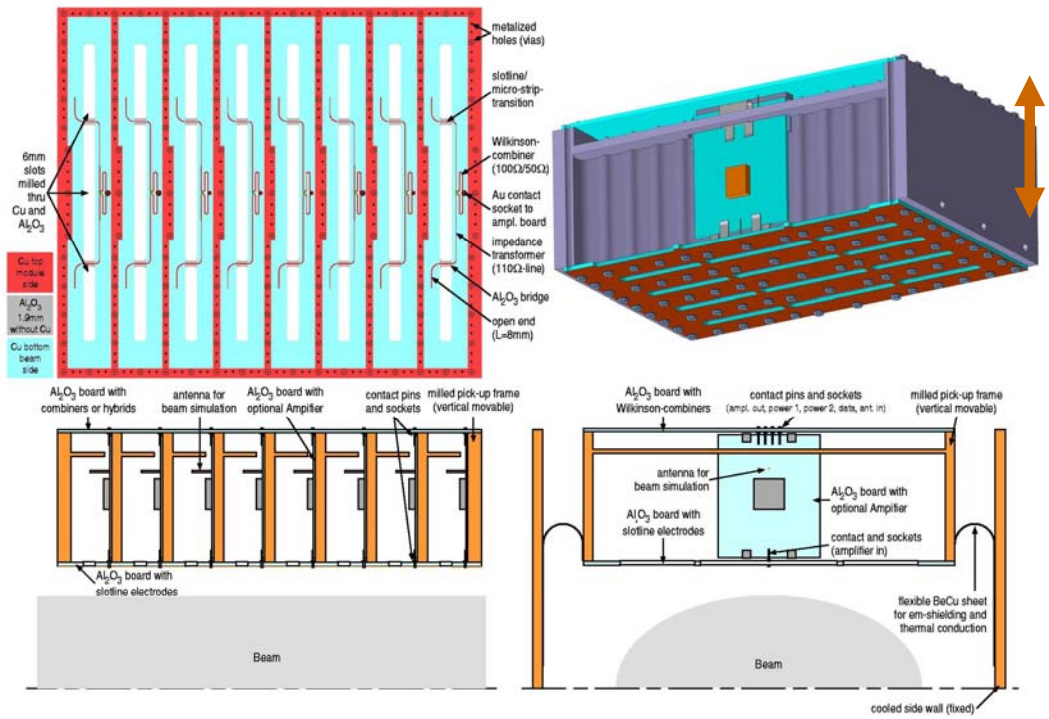
analysis by L. Thorndahl

CR Stochastic Cooling

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



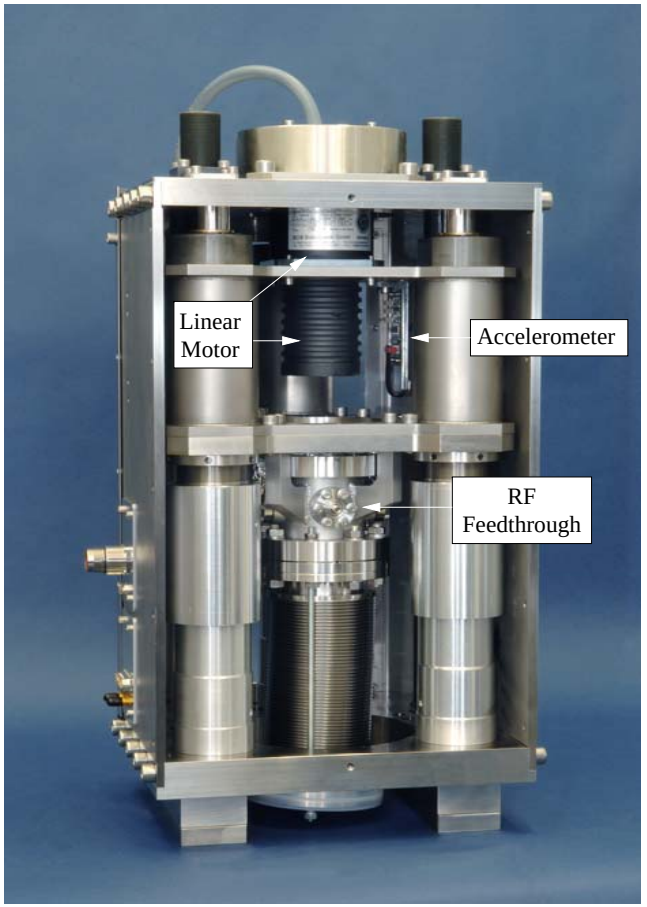
electrodes (and pre-amplifiers) installed in the vacuum tank
cooled to 20 K



CR Stochastic Cooling Prototypes

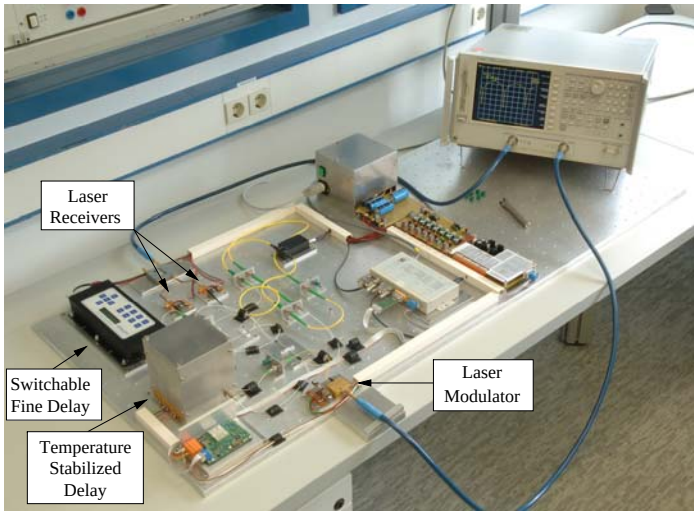


vacuum tank for moving cold electrodes



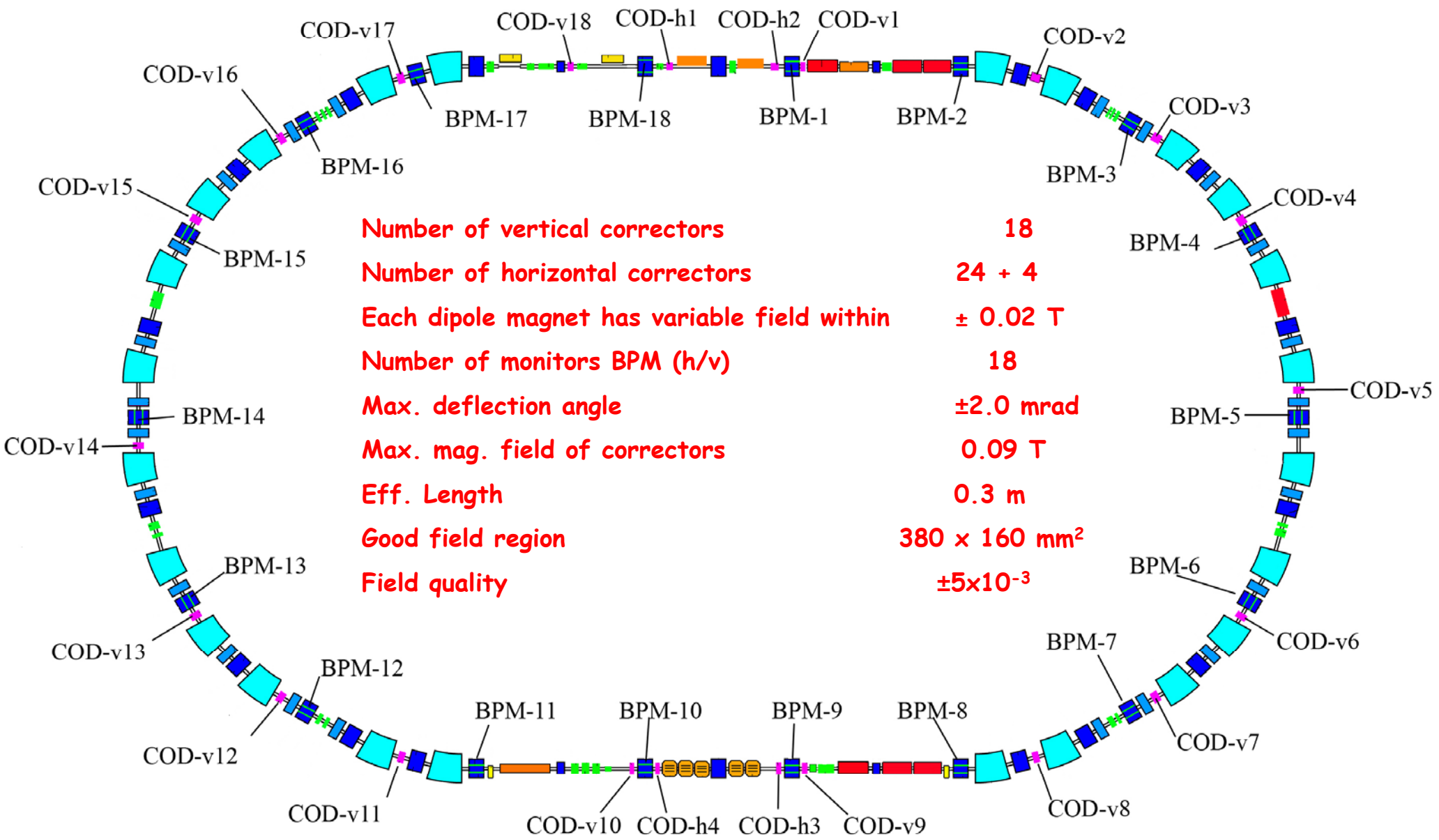
programmable linear actuator

optical delay line



Prototype development supported by EUFP6 design study

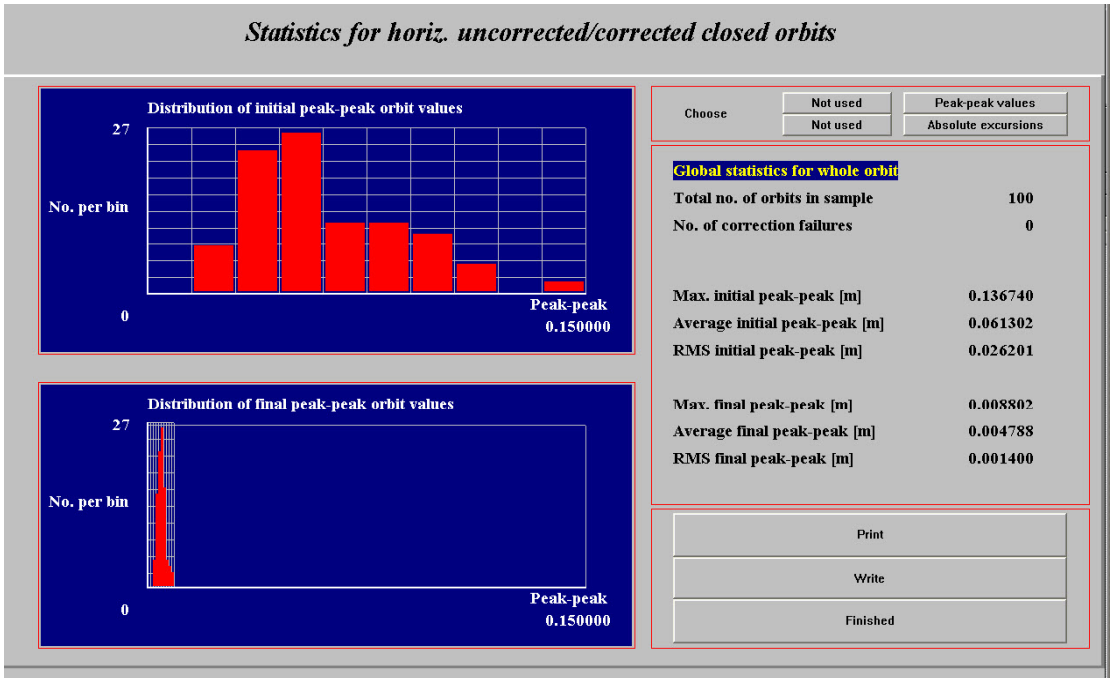
Closed orbit correction



Number of vertical correctors	18
Number of horizontal correctors	24 + 4
Each dipole magnet has variable field within	± 0.02 T
Number of monitors BPM (h/v)	18
Max. deflection angle	±2.0 mrad
Max. mag. field of correctors	0.09 T
Eff. Length	0.3 m
Good field region	380 x 160 mm^2
Field quality	$\pm 5 \times 10^{-3}$

Closed orbit correction

antiproton operation mode



alignments errors used in tracking studies (1σ)

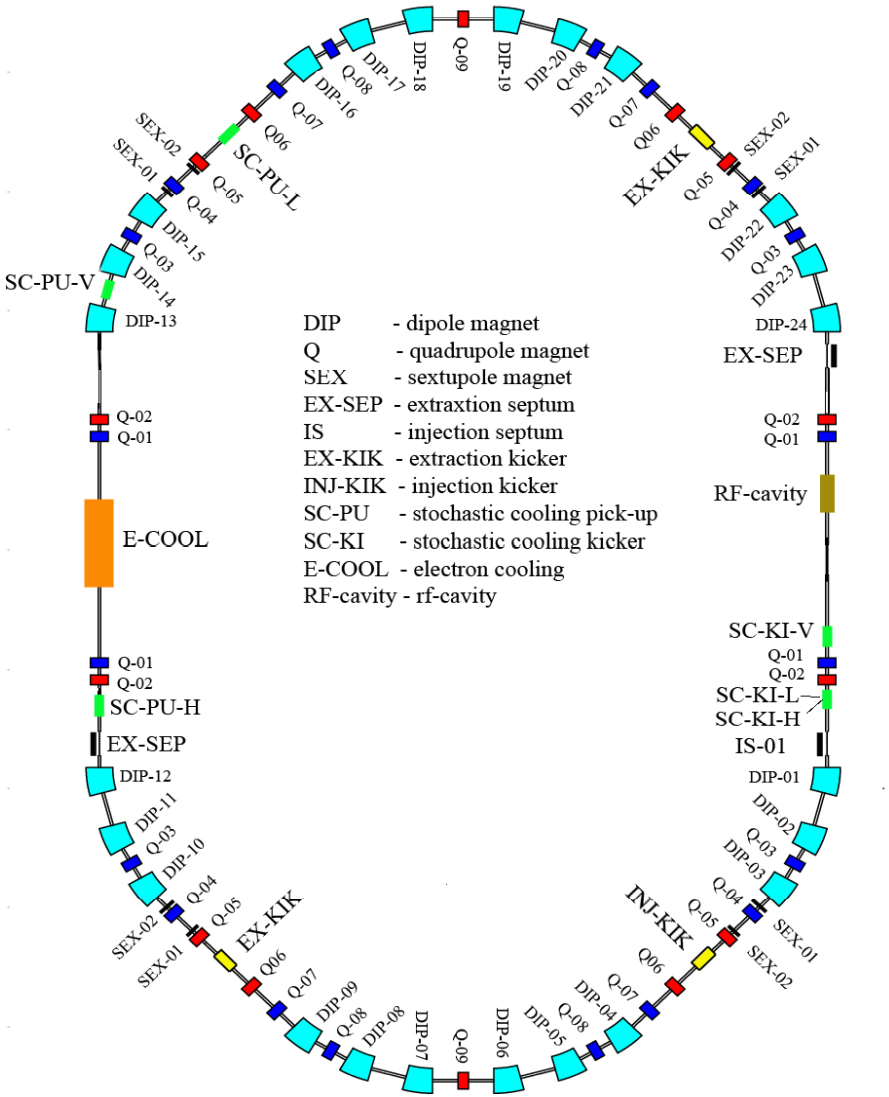
Element	ΔX [mm]	ΔY [mm]	ΔZ [mm]	Roll [mrad]
Dipole	0.2	0.2	0.5	0.5
Quadrupole	0.2	0.2	0.3	0.5
Sextupole	0.2	0.2	0.3	0.5

Closed orbit excursions

	Before correction		After correction	
	hor	ver	hor	ver
ΔC_{max} [mm]	30	46	1.8	4.0
$\Delta C_{average}$ [mm]	12	18	1.2	2.3

proper orbit control will be crucial for optimum stochastic cooling

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

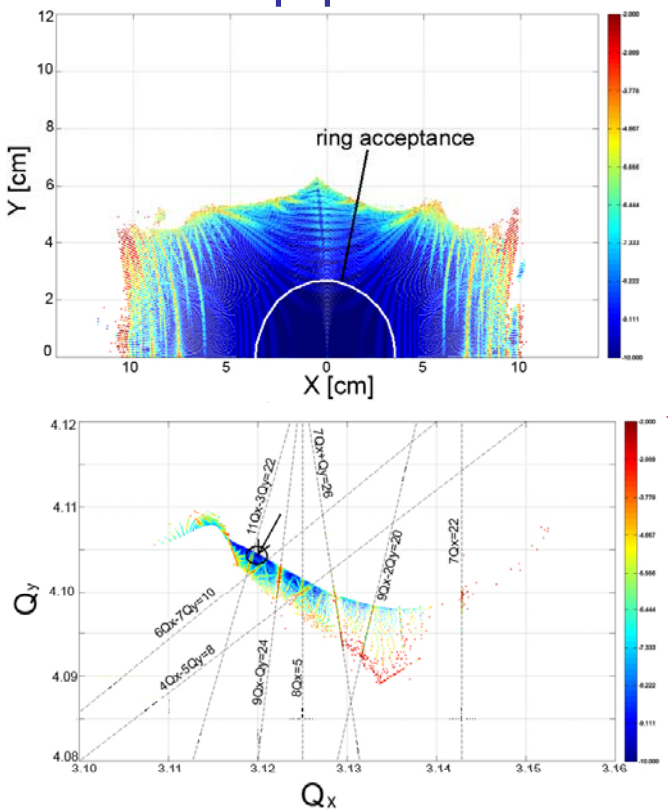
RESR Dynamic Aperture Calculations

Q_x = 3.11, Q_y =4.12

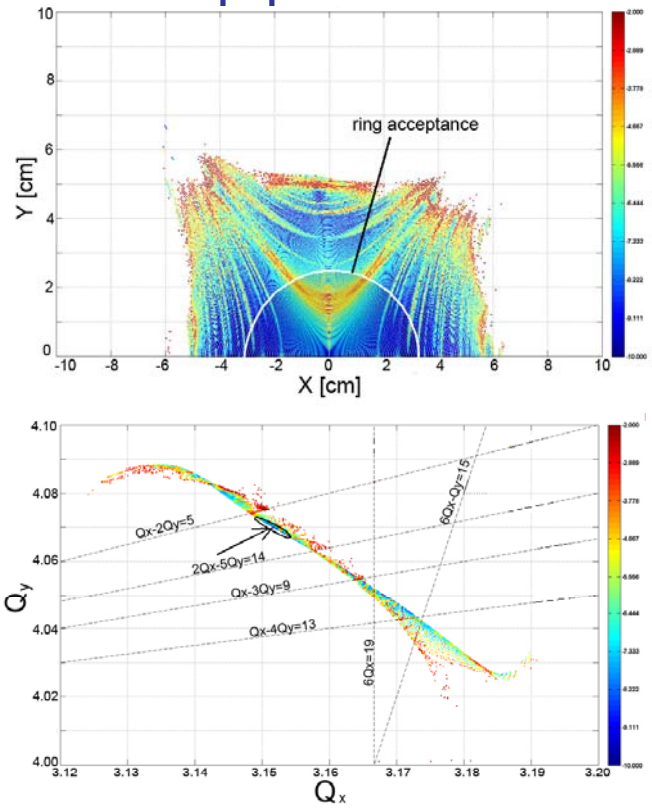
field errors

Harmonic order	2	3	4	5	6	7	8	9	10
Dipole	0	0.12	0	-0.016	0.0	0.017	0	-0.001	0
Quadrupole	0	4.0	2.8	3.0	14.0	1.8	2.5	1.0	2.0
Sextupole	0	0	0	0	0	0	0	6.0	0

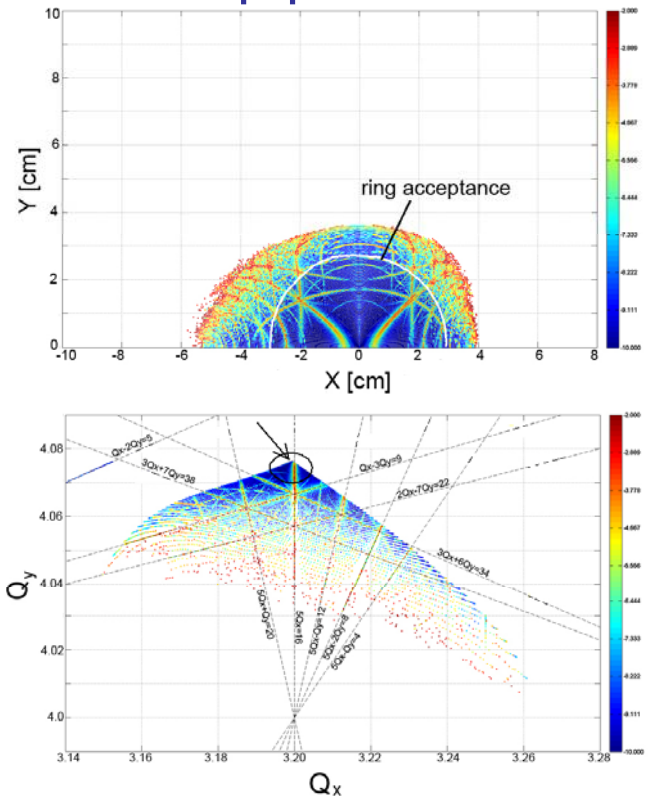
Δp/p = 0



Δp/p = -1 %



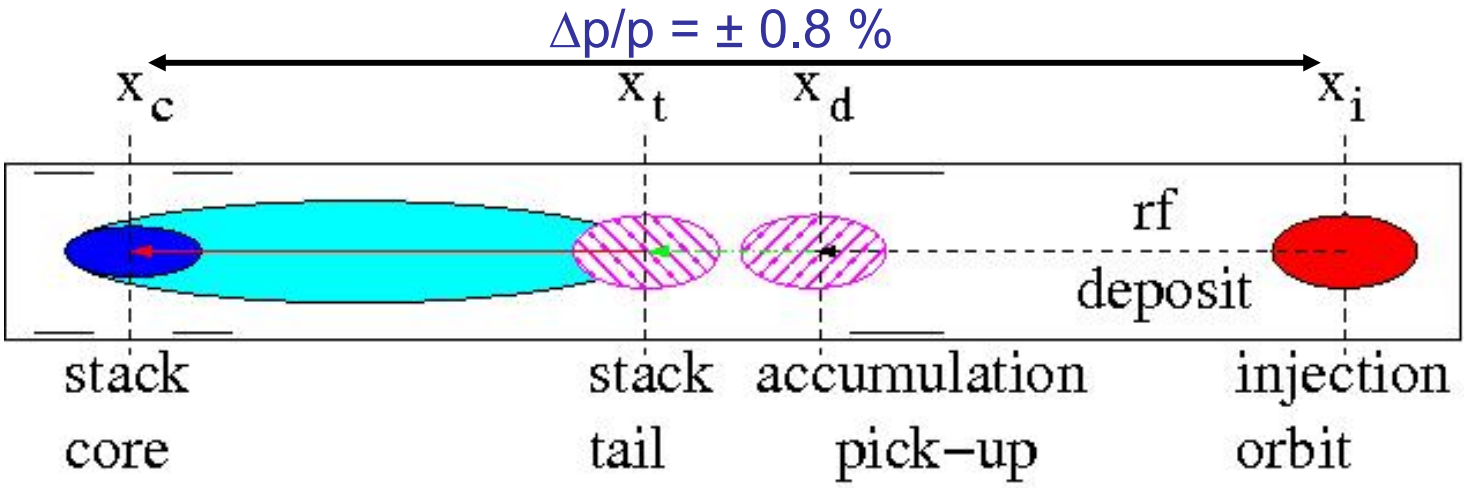
Δp/p = + 1 %



Frequency Map Analysis

calculated with PTC code (MAD)

Antiproton Accumulation in RESR

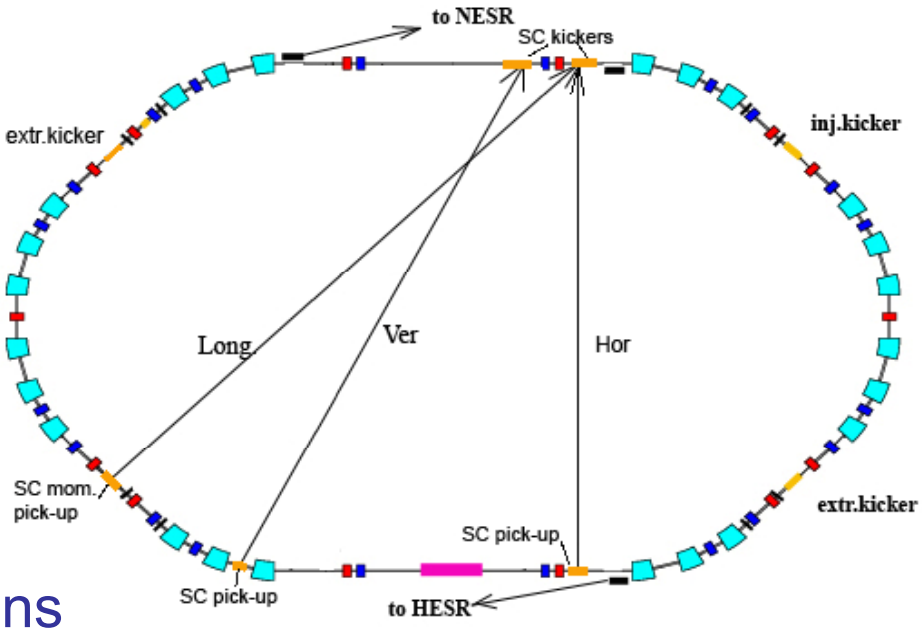


core cooling 2-4 GHz

longitudinal
horizontal
vertical

tail cooling 1-2 GHz

longitudinal



injection of 1×10^{8} antiprotons every 10 s

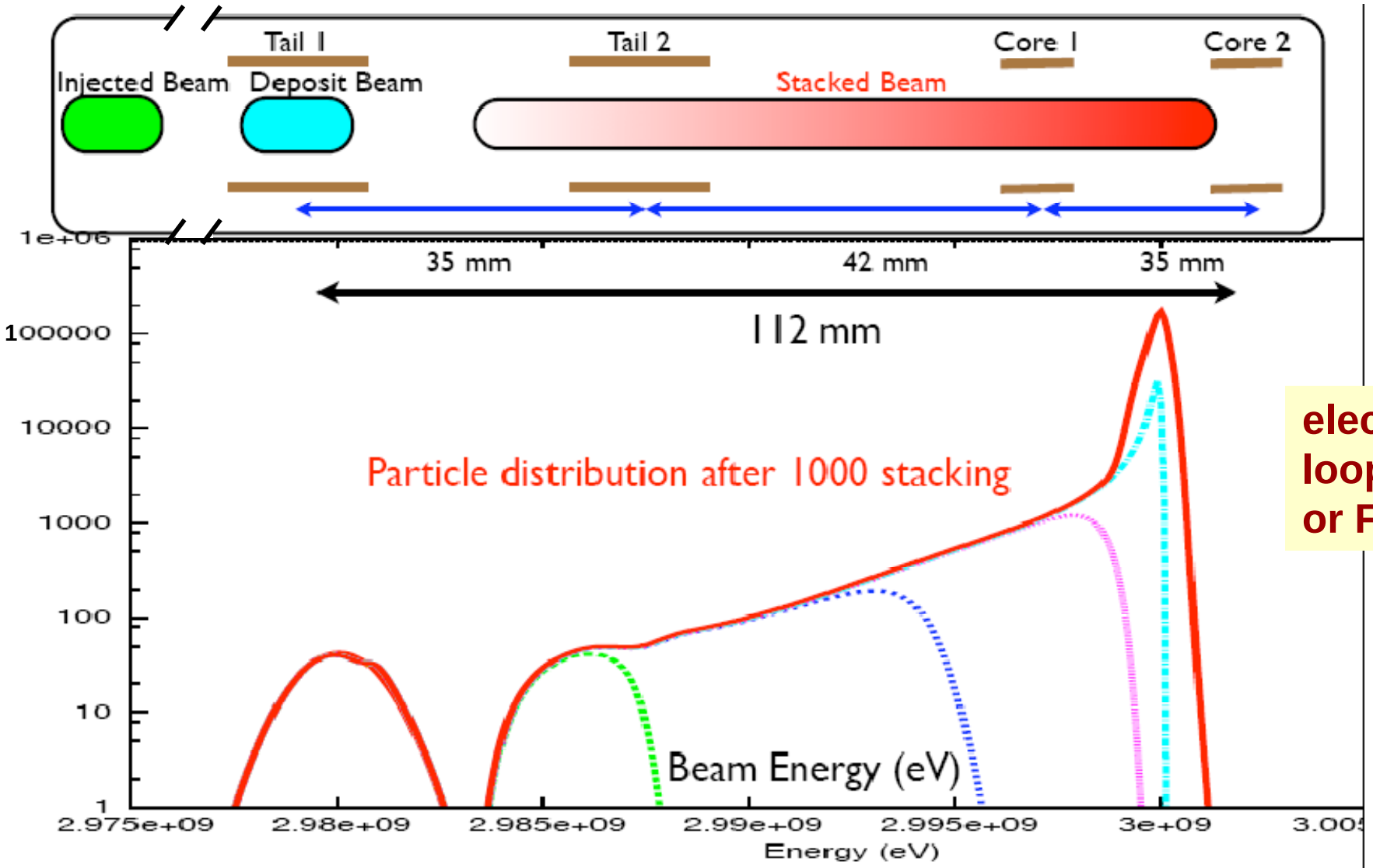
pre-cooling in CR provides
$\delta p/p = 1\times10^{-3}$, $\varepsilon_{x,y}$= 5 mm mrad

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

pre-cooling after injection considered as an option

Accumulation System for RESR

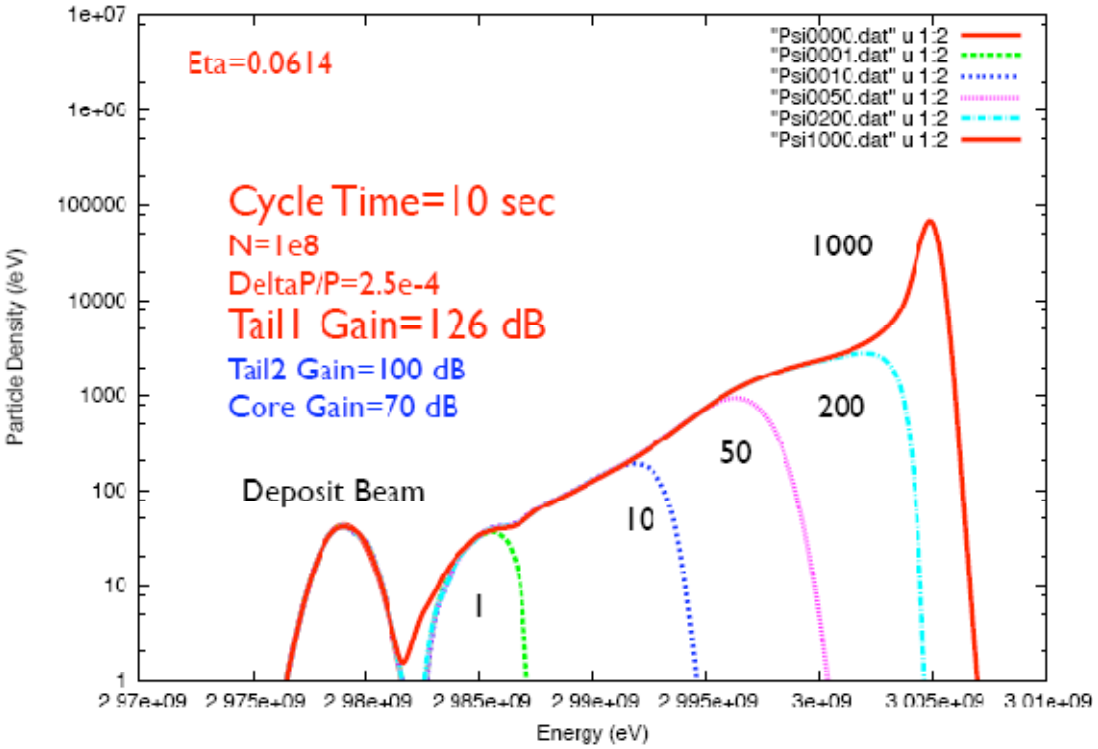
Longitudinal stochastic cooling system: tail and core cooling



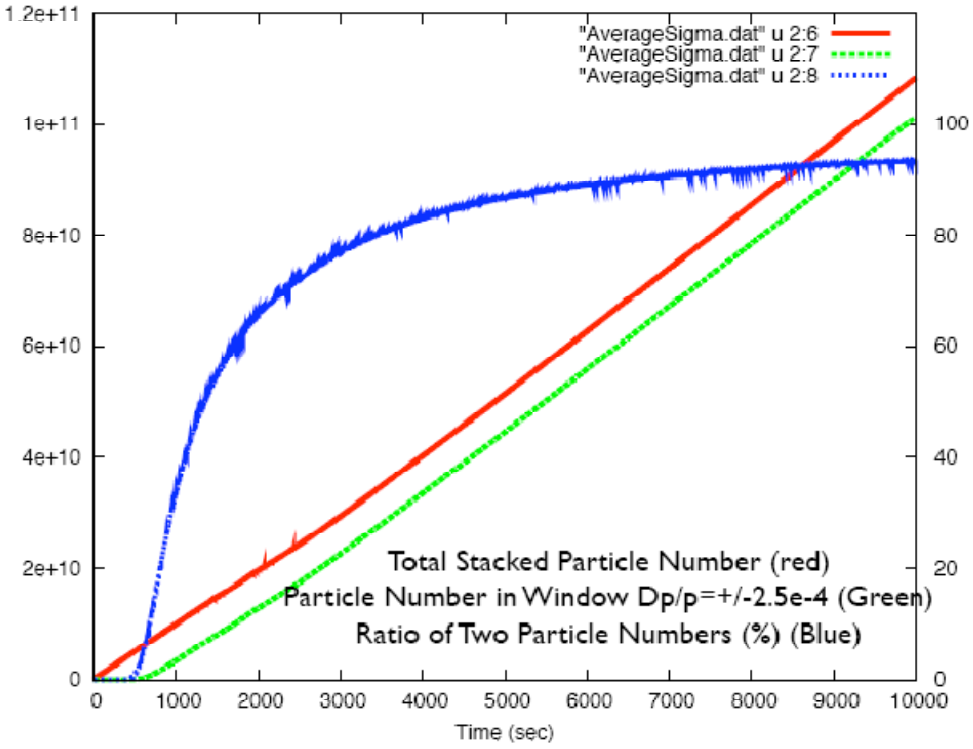
electrodes: loop couplers or Faltin-type

Distribution of Antiproton Stack

longitudinal distribution



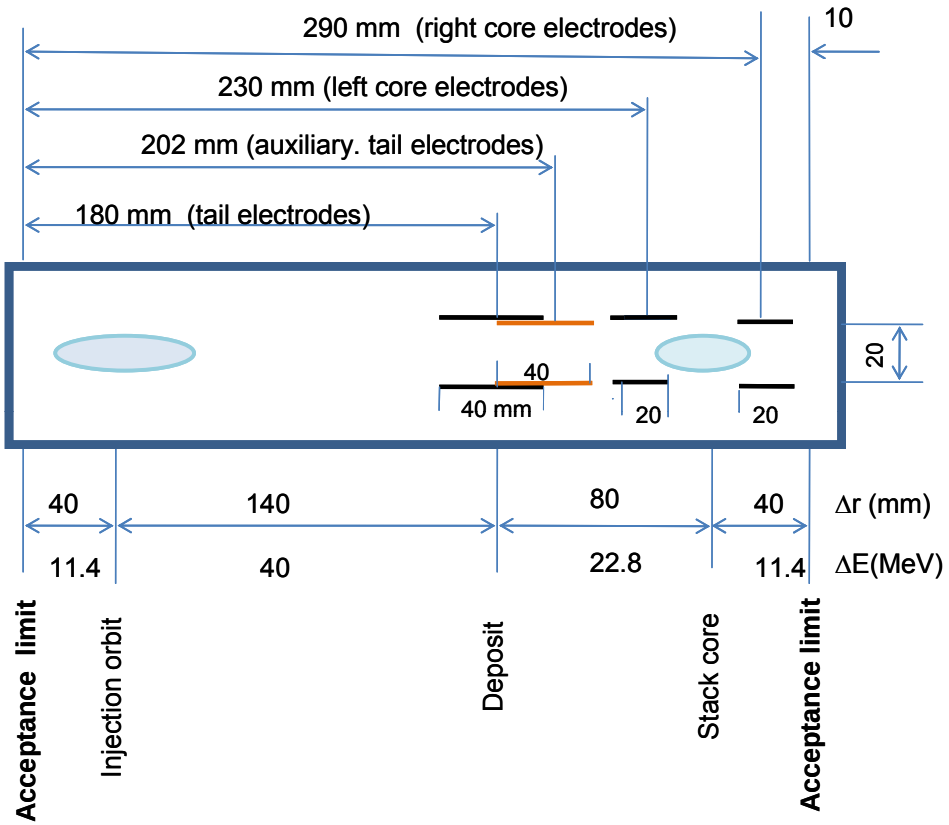
stacking efficiency



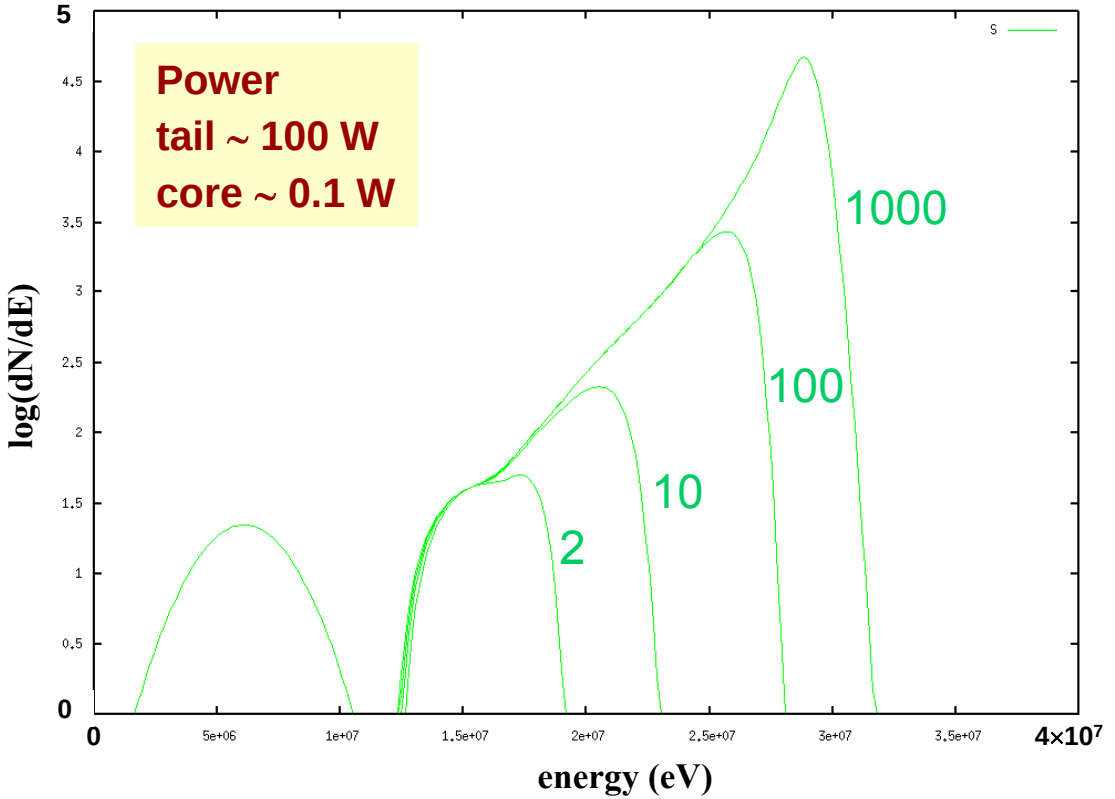
an adjustable antiproton number will be captured from the core for extraction

`Alternative` Accumulation System

pick-up geometry



10^8 antiprotons injected every 10 s

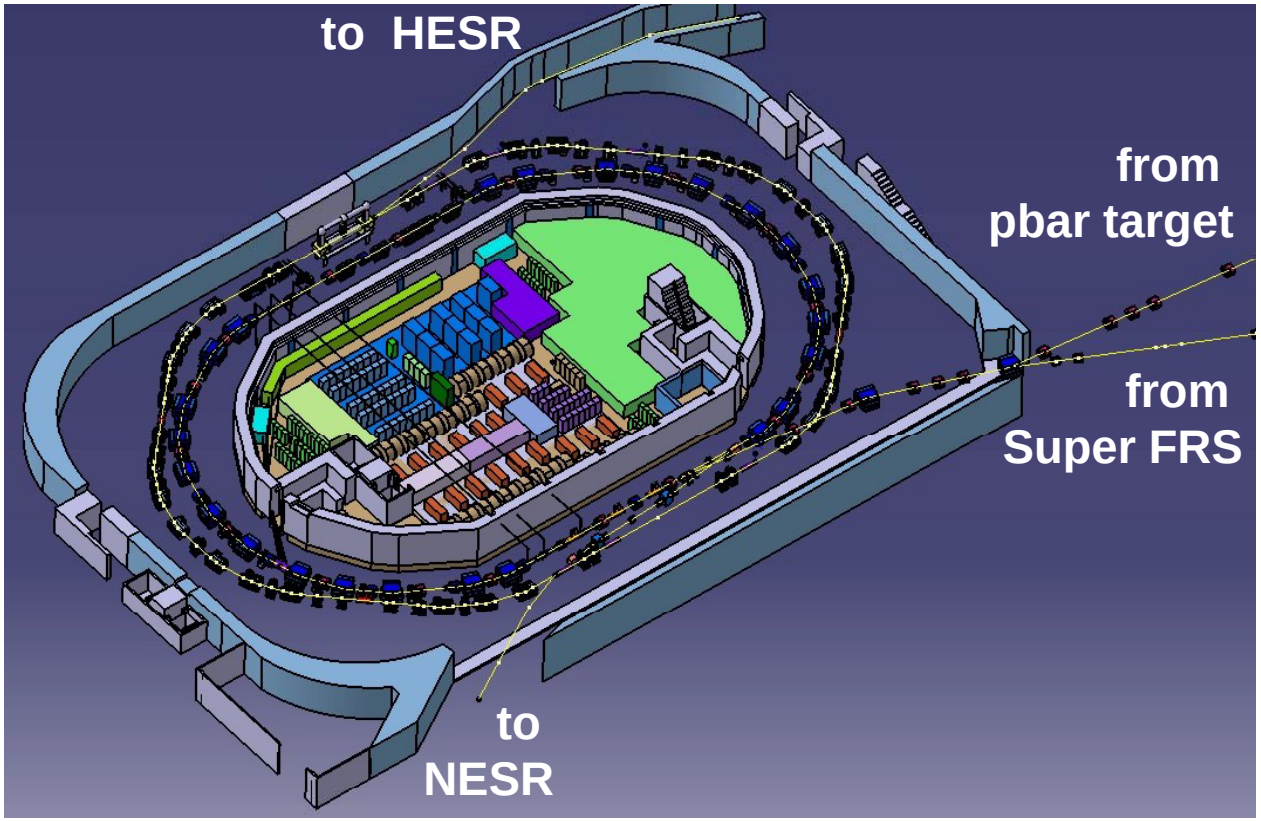


64 pick-up and 16 kicker electrodes for core and tail cooling system

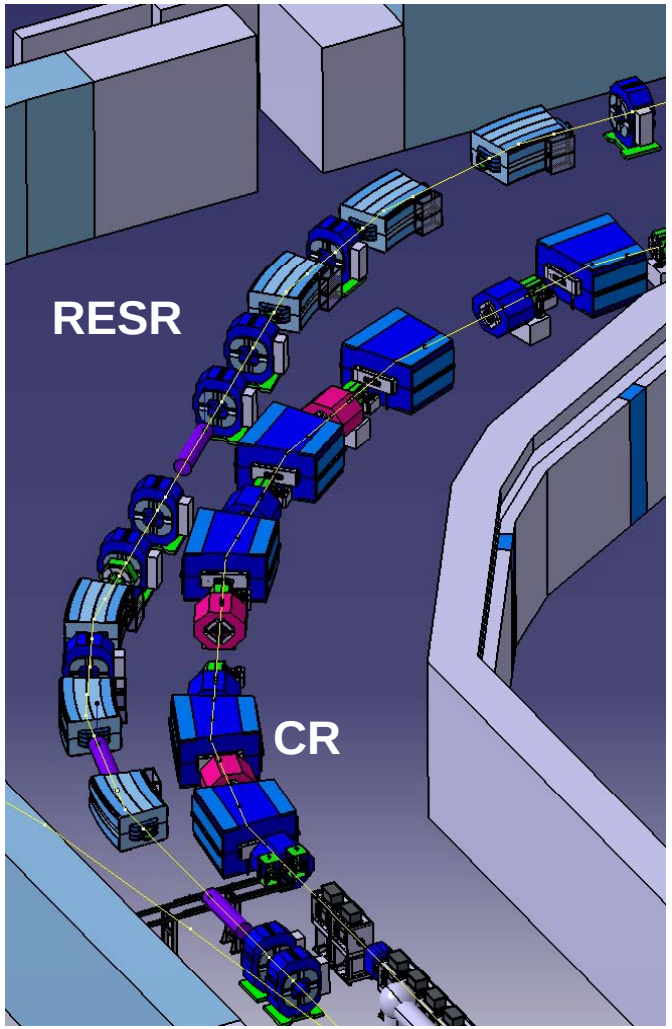
D. Möhl, L Thorndahl (CERN)

Civil Construction of CR/RESR-Complex

Technical building



Ring Tunnel



RESR Antiproton Accumulation



- ring lattice is designed for longitudinal antiproton accumulation
- flexibility in the tuning of the ring optics
- basic cooling system design is available
- proposal to use electrodes of Faltin type
- details need to be optimized
- cooling/accumulation time of 10 s is reasonable
- no serious limitation by beam feedback or IBS (up to 10^{11})
- some reserve for unexpected trouble or more ambitious accumulation

a factor of two higher antiproton intensities could be handled

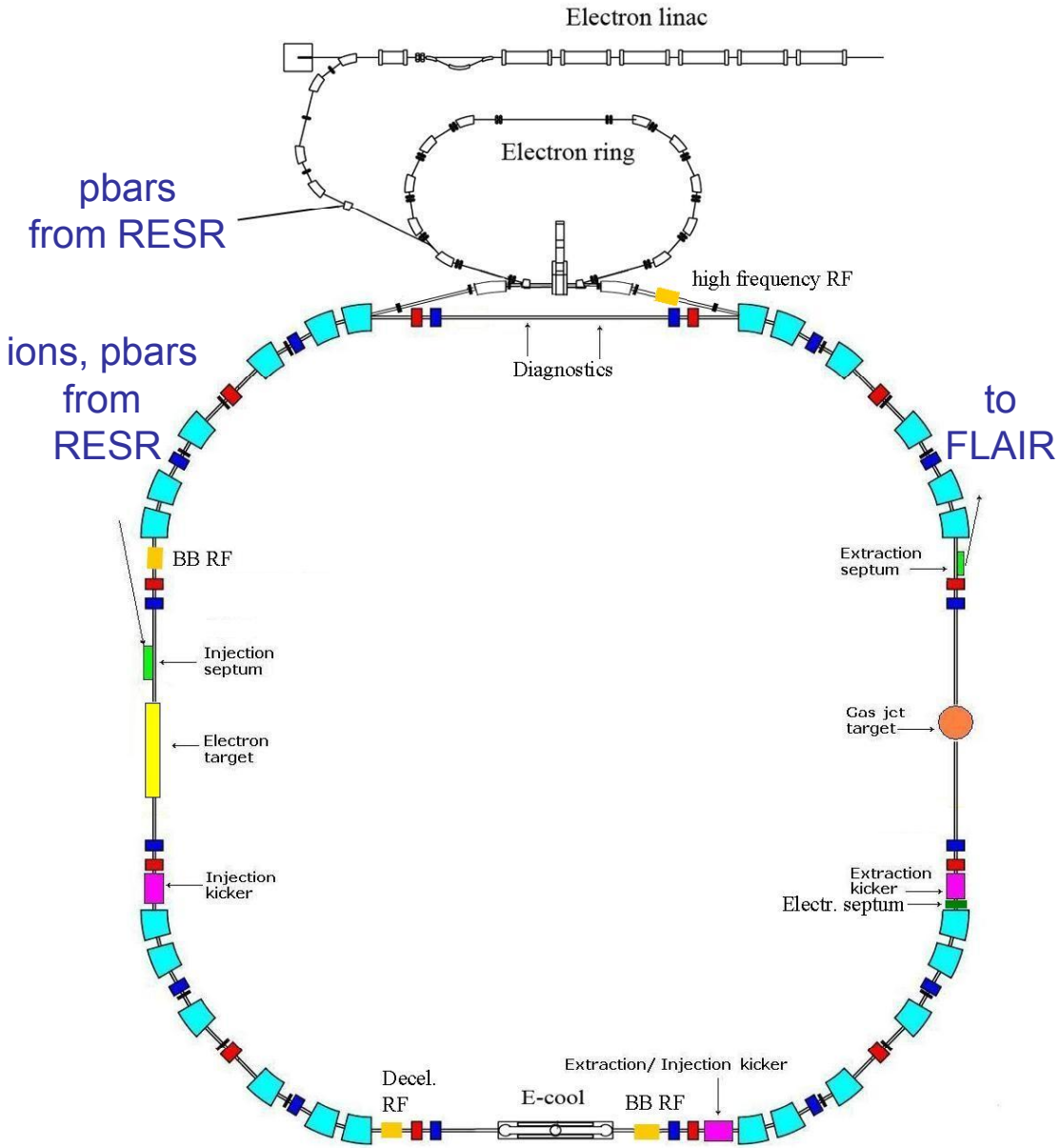
upgrades are possible (CR cooling 2 - 4 GHz, RESR pre-cooling system)

Critical Aspects of pbar Production

primary proton intensity:	linac current SIS18 operation at space charge limit transfer SIS18 → SIS100 single bunch generation with bunch length ≤ 50 ns
target:	focusing thermal load
pbar beamline/separator:	ion optical matching large acceptance collimation
collector ring CR:	injection (transverse matching, kicker timing) ring acceptance bunch rotation and debunching, rebunching cooling time and beam quality after cooling
accumulator ring RESR:	injection (transverse matching, kicker timing) stacking (rf capture and acceleration) cooling time/accumulation time and efficiency, beam quality beam feedback, IBS → high intensity limit

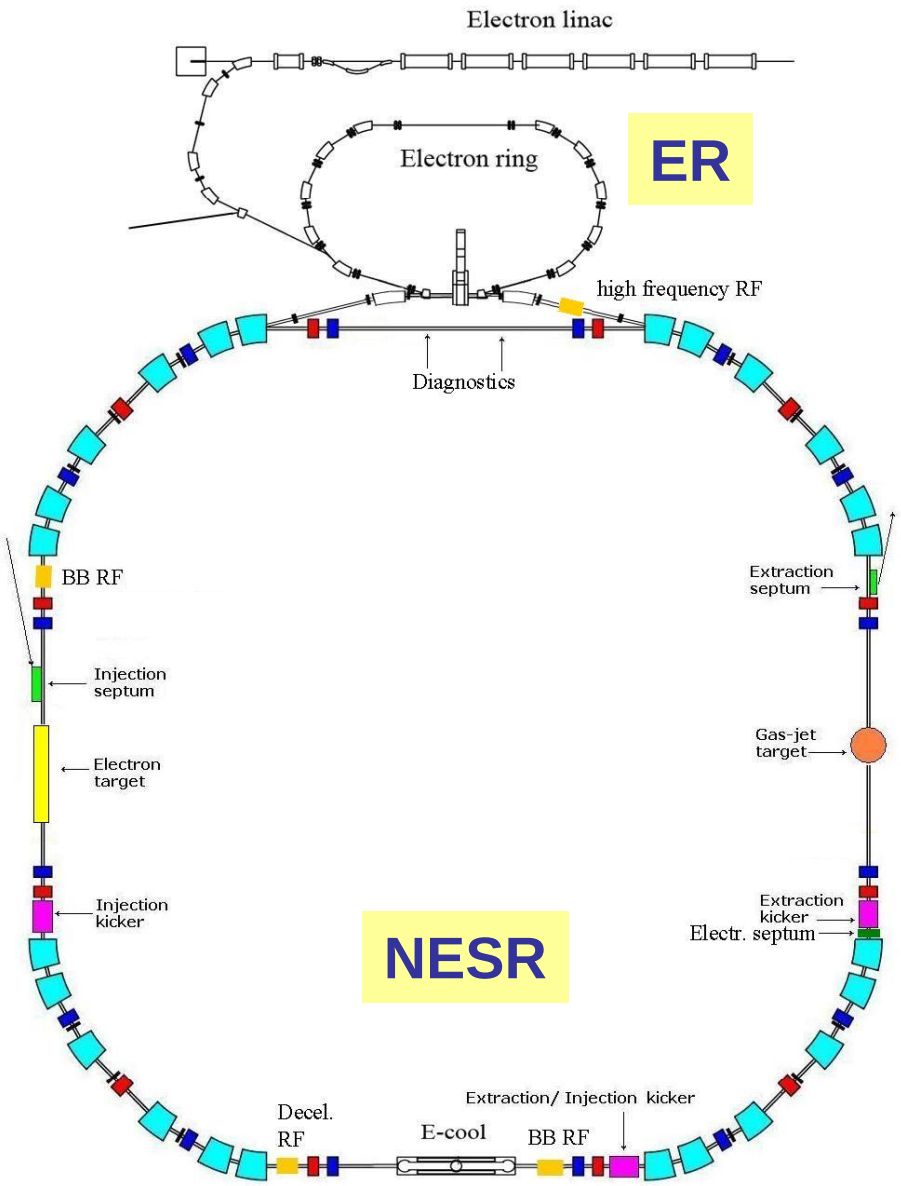
general: reliability, availability, radiation damage, additional preparation beam time
machines are not designed for exclusive antiproton operation (polarity changes)

The New Experimental Storage Ring



Circumference [m]	222.8
Straight section length [m]	18
Horizontal acceptance [mm mrad]	150
Vertical acceptance [mm mrad]	40
Momentum acceptance [%]	± 1.5
Max. momentum deviation [%]	± 2.5
Horizontal tune	4.2
Vertical tune	1.87
Transition energy	4.59
Maximum dispersion [m]	6.8
Horizontal chromaticity	5.9

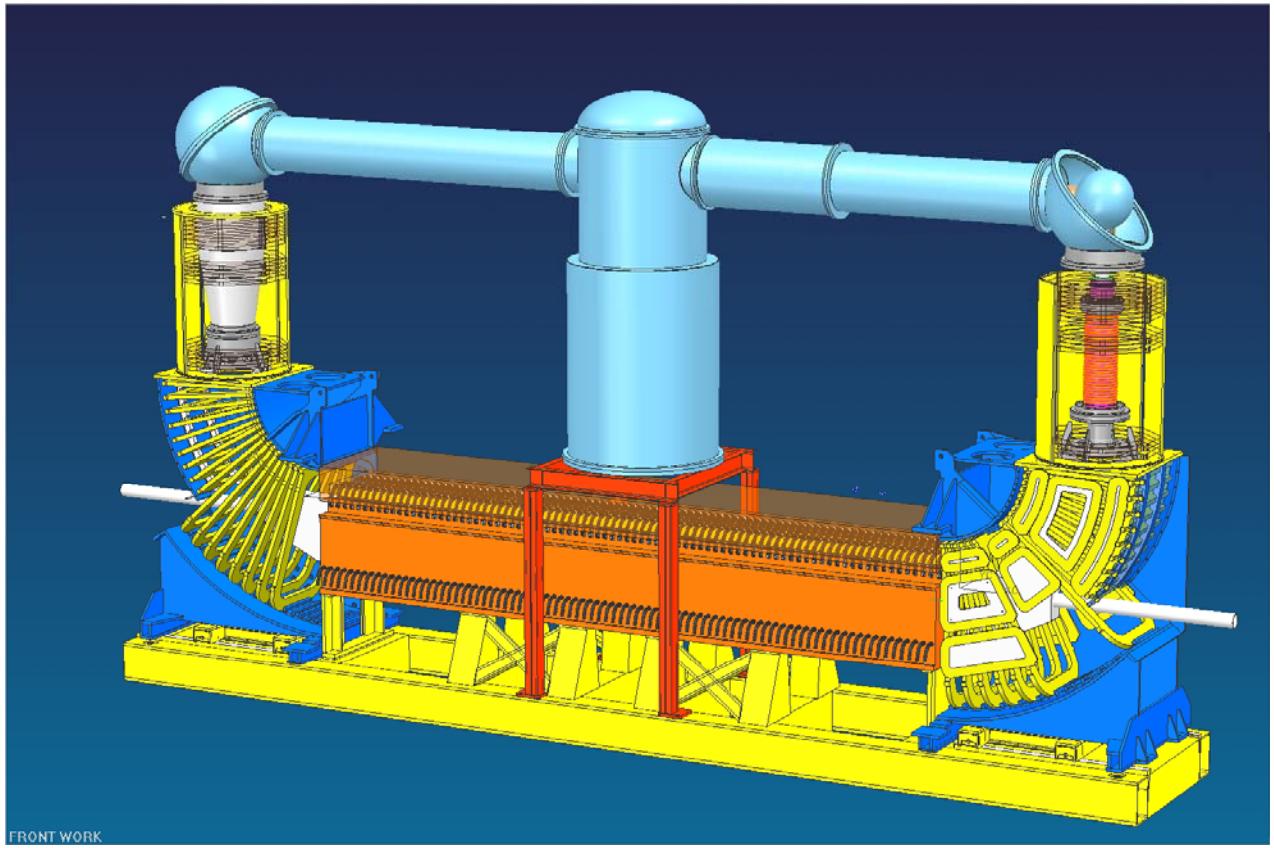
Operation of the NESR with Antiprotons



- Injection at 3 GeV from RESR
- Deceleration to intermediate energy
- Electron cooling below 800 MeV
- Deceleration to minimum energy 30 MeV
- Fast extraction
- Slow (resonance) extraction below 4 Tm
- Antiproton-ion (ER-NESR) collisions

NESR Electron Cooler

design by BINP, Novosibirsk



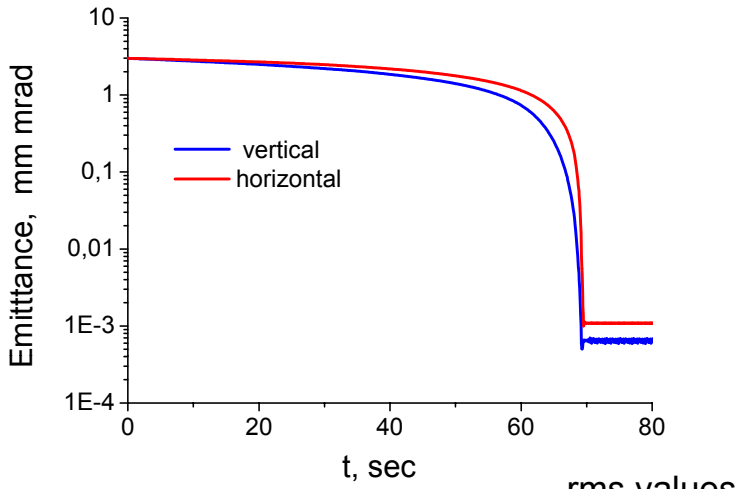
Cooler Parameters

energy	2 - 450 keV
max. current	2 A
beam radius	2.5-14 mm
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	2×10^{-5}
vacuum	$\leq 10^{-11}$ mbar

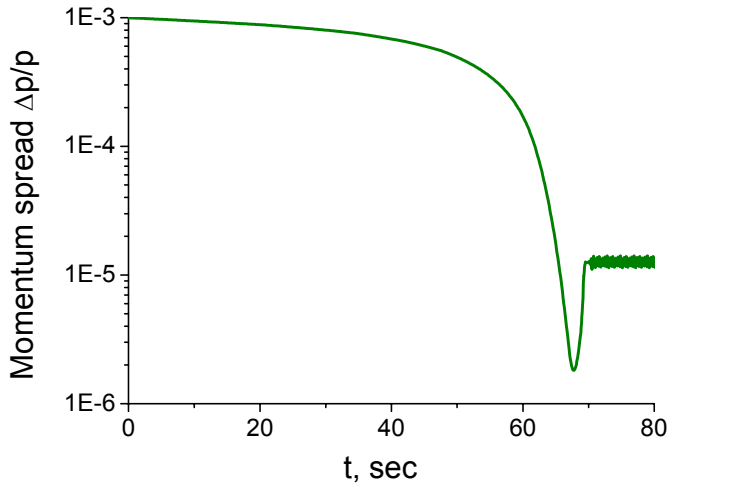
- high voltage up to 500 kV
- magnetic field quality
- fast ramping, up to 250 kV/s (RIBs)

Electron Cooling in the NESR

Simulation with BETACOOL
E_i = 800 MeV (E_e = 435 keV)
I_e= 2 A, r_e= 1 cm, B = 0.2 T

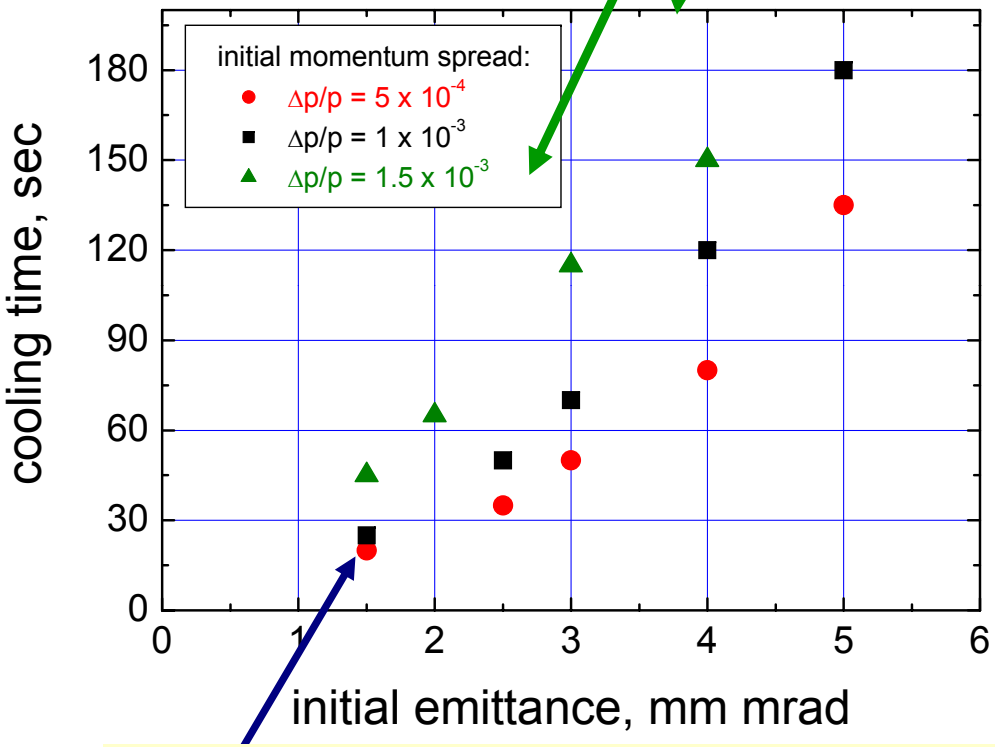


rms values



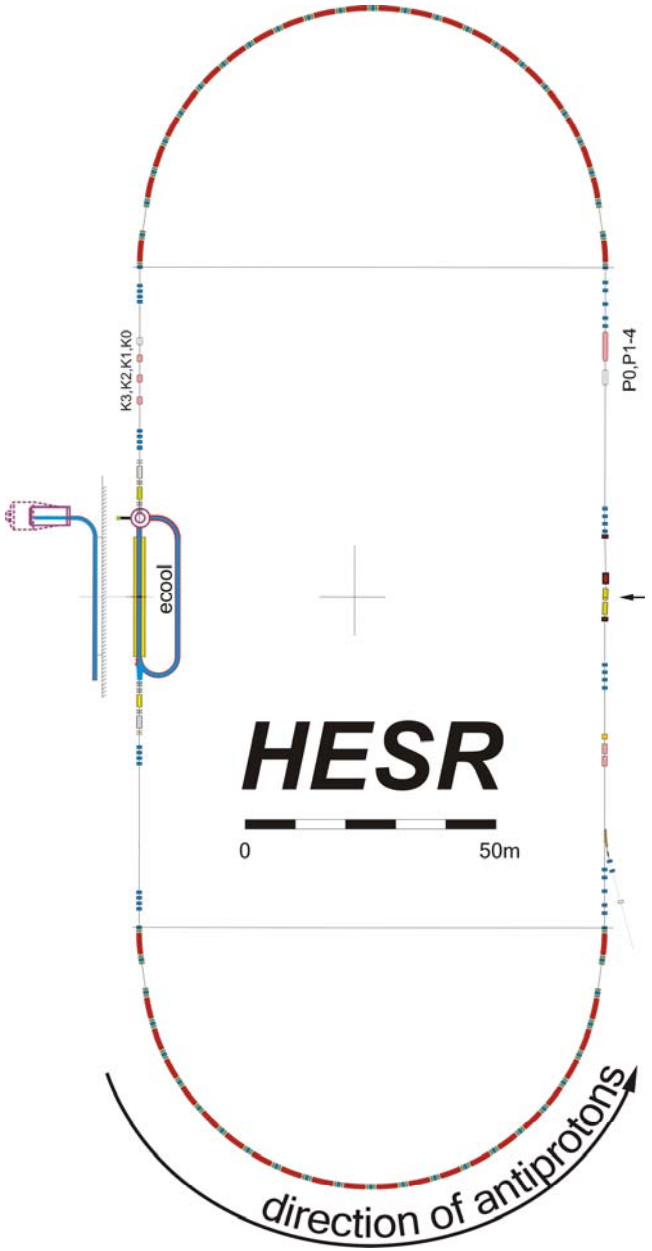
Cooling time dependence on initial beam quality

1σ (CR) $\Rightarrow \tau_{total} \sim 140$ s



$\tau_{total} \sim 20$ s $\Rightarrow$ $\varepsilon \leq 1.5$ μm, $\delta p/p \leq 1 \times 10^{-3}$ requires transverse cooling in the RESR

High Energy Storage Ring HESR



HESR Consortium: FZJ, GSI, TSL (Sweden), Georgia, Poland, Romania

- **circumference 574 m**
- **momentum (energy) range**
- **1.5 to 15 GeV/c (0.8-14.1 GeV)**
- **injection of (anti-)protons from RESR at 3.8 GeV/c**
- **Maximum dipole field: 1.7 T**
- **dipole field at injection: 0.4 T**
- **dipole field ramp: 0.025 T/s**
- **acceleration rate 0.2 (GeV/c)/s**
- **internal experiment PANDA: dipole field ramp: 0.015 T/s internal hydrogen target**

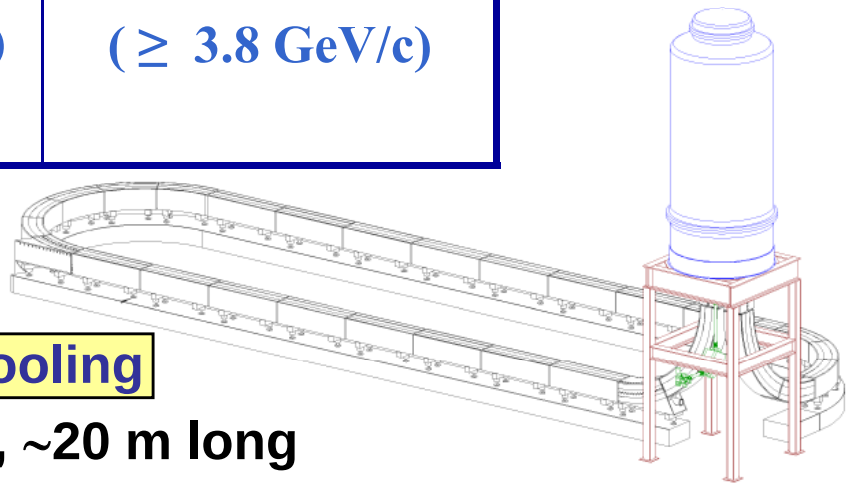
Cooling in the HESR

Effective target thickness (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
Antiproton number	10^{10}	10^{11}
Peak luminosity	2×10^{31} cm^{-2}s^{-1}	2×10^{32} cm^{-2}s^{-1}
Momentum spread	$\Delta p/p \leq 4\times10^{-5}$	$\Delta p/p = 1\times10^{-4}$
Beam cooling	Electron ($\leq$ 8.9 GeV/c)	Stochastic ($\geq$ 3.8 GeV/c)



stochastic cooling

printed loop coupler, 2-4 GHz



electron cooling

5 MeV, 1 A, ~20 m long