Antiprotons at FAIR

Two directions of experiments with antiprotons

High energy stored antiprotons

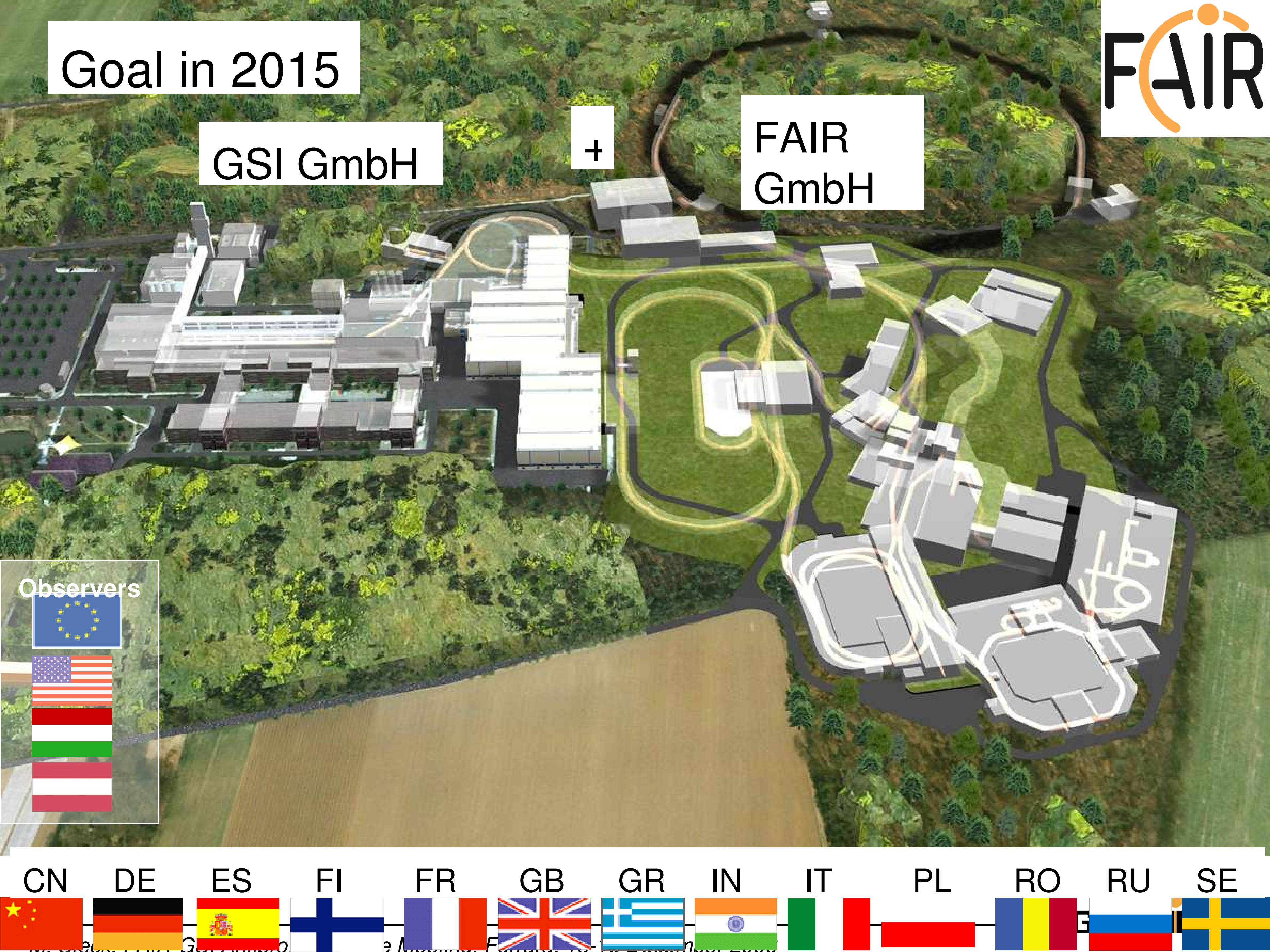
Cooled stored antiprotons in the HESR in the energy range 0.8-14.5 GeV

Decelerated antiprotons

Antiprotons decelerated to 30 MeV in the NESR with further deceleration to lowest energies

common limitation:
total production rate of 2×10^7 antiprotons/s limited by cooling time and/or production target

AIC is a RIB experiment, it cannot be operated in parallel to other antiproton experiments


Goal in 2015
GSI GmbH
+
FAIR GmbH
FAIR
Observers
CN
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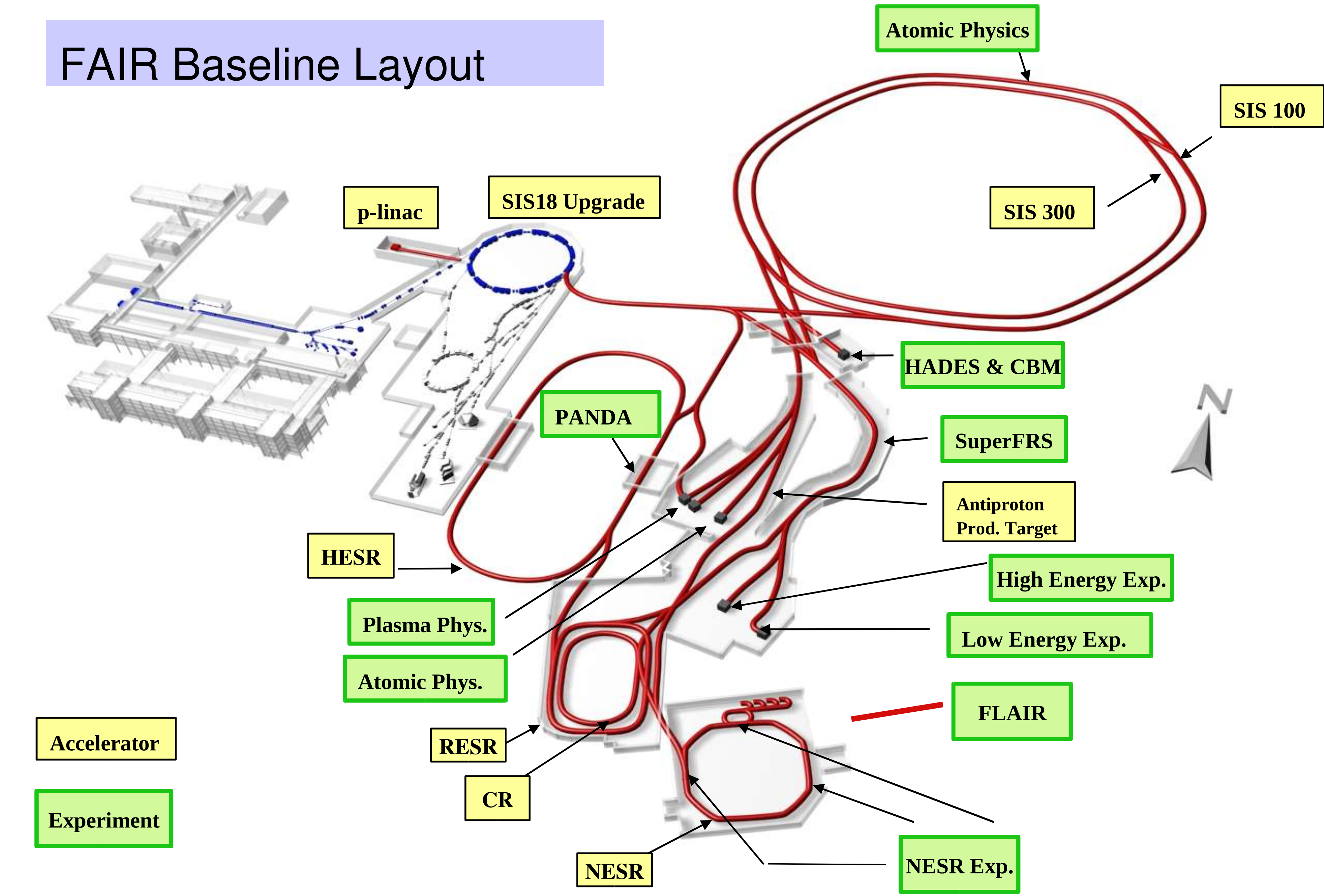
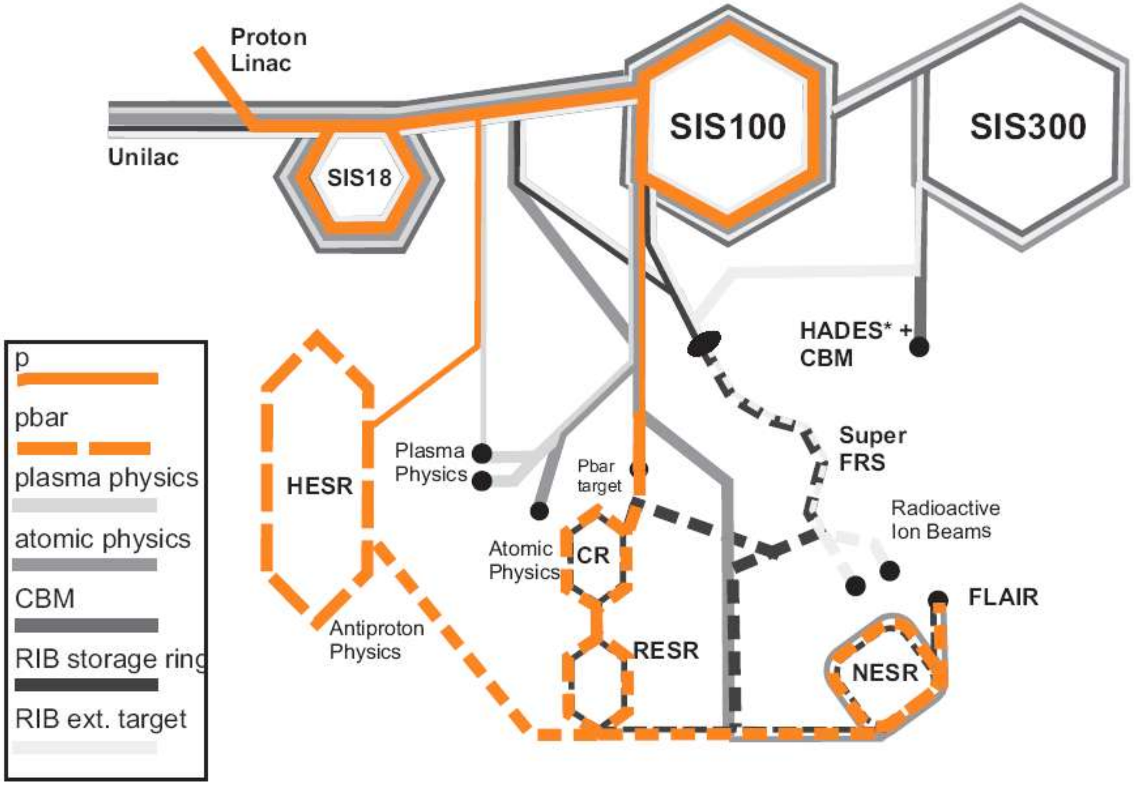
FAIR Baseline Layout



Accelerator Chain for Cooled Antiprotons



<=1000 x :

4 (8) x :
Injection of protons into SIS18
Acceleration to 2 GeV
Injection into SIS100

Acceleration to 29 GeV
Impact on target → hot pbars
Stoch. pbar cooling in CR
Injection into in RESR

↓

Injection into HESR
Acceleration/Deceleration to 14.5/0.8 GeV

or

Deceleration in NESR to 30 MeV
Extraction to low energy pbar experiments

Multi-Turn Injection into SIS18 requires:

$$B_n := \frac{I}{(\beta\gamma)\epsilon_{tot}} = 63.6 \frac{\text{mA}}{\mu\text{m}} \cdot \frac{(\beta\gamma)^2}{\eta_{MTI}}$$

η_{MTI} := MTI filling factor → 60%

Storage Rings – Antiproton Operation (Concept of 2003)

SIS 100: acceleration of 2.8×10^{13} protons and bunching to a 25 ns pulse

E = 29 GeV
$\delta p/p = \pm 0.7$ %, $\varepsilon_{x,y} = 4 \times 10^{-6}$ m

pbar target: production of 1.0×10^{8} pbars/ 5 s

E = 3 GeV, N = 1×10^{8}/cycle
$\delta p/p = \pm 3.0$ %, $\varepsilon_{x,y} = 240 \times 10^{-6}$ m

CR: bunch rotation and fast stochastic cooling with total cooling time 5 s

E = 3 GeV, N = 1×10^{8}/cycle
$\delta p/p = \pm 1 \times 10^{-3}$, $\varepsilon_{x,y} = 5.0 \times 10^{-6}$ m

RESR: accumulation of pbars by stochastic cooling, deceleration of pbars

E = 0.8 - 3 GeV, N = 10^{8} - 10^{11}
$\delta p/p = 5 \times 10^{-4}$, $\varepsilon_{x,y} = 1 \times 10^{-6}$ m

SIS 100: acceleration to final energy

E = 0.8 – 14.5 GeV

HESR: internal experiments with cooled pbars

E = 0.8 – 14.5 GeV

NESR: deceleration to 30 MeV

FLAIR

E = 30 – 0.3 MeV

Storage Rings – Antiproton Operation Concept of FBTR

SIS 100: acceleration of 4×10^{13} protons and bunching to a 25 ns pulse

↓

pbar target: production of 1.0×10^{8} pbars/10 s

↓

CR: bunch rotation and fast stochastic cooling with total cooling time 10 s

↓

RESR: accumulation of pbars by stochastic cooling, deceleration of pbars

~~SIS 100: acceleration to final energy~~

HESR: internal experiments with cooled pbars

injection at 3 GeV, accel/decel to 0.8 – 14.5 GeV

NESR: deceleration to 30 MeV

FLAIR

E = 30 – 0.3 MeV

remarks:

use barrier bucket injection of up to 4 x 10^{13} protons (needs to be confirmed)

target must withstand higher intensity

cooling of higher antiproton intensity in CR seems to be ok

future options:

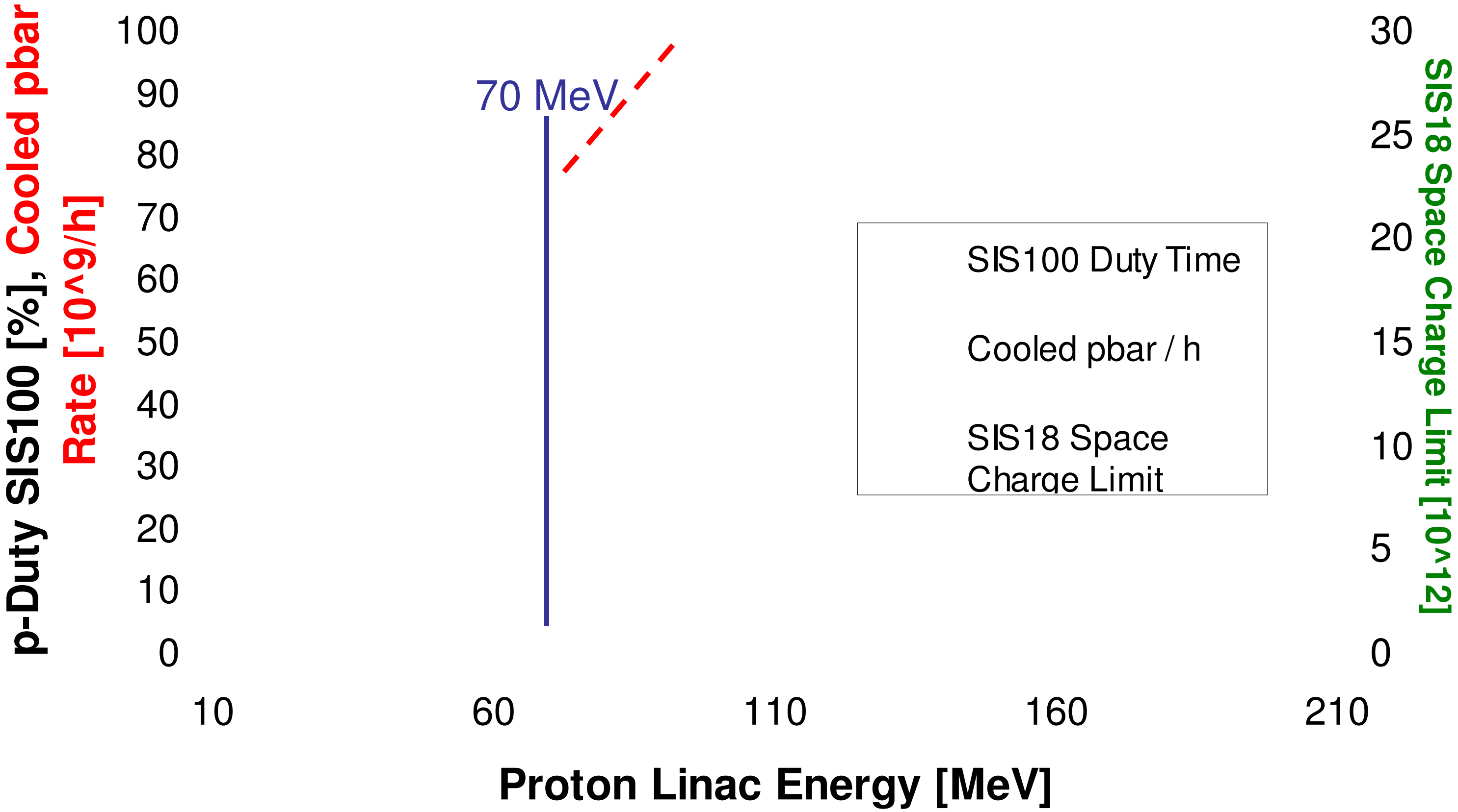
add cavities (bunch rotation) and increase cooling bandwidth (1- 4 GHz)

⇒ reduce cooling time to 5 s (intensity limitation)

increase injection energy after linac from 70 to 100 MeV

Parameters for Proton Linac

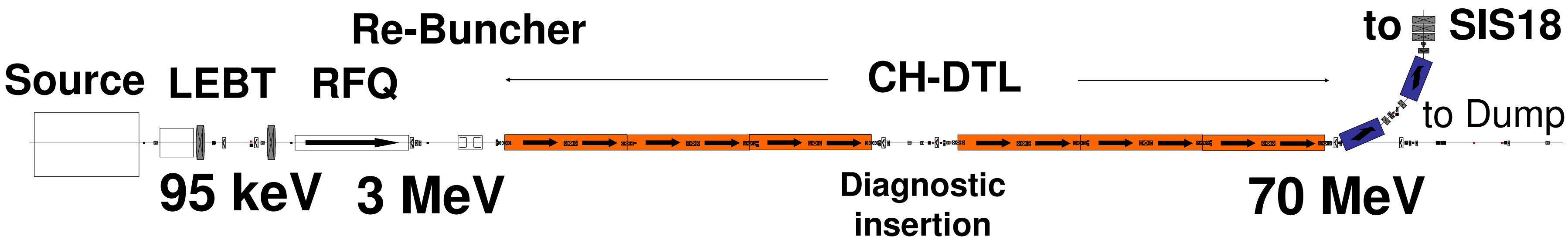
final rate of cooled pbar depends on injector energy:



$$B_n := 63.6 \frac{\text{mA}}{\mu\text{m}} \cdot \frac{(\beta\gamma)^2}{\eta_{MTI}}$$ → **16.5 mA / µm** →

- **I = 70 mA**
- **$\beta\gamma\epsilon_x$ = 4.2 µm**

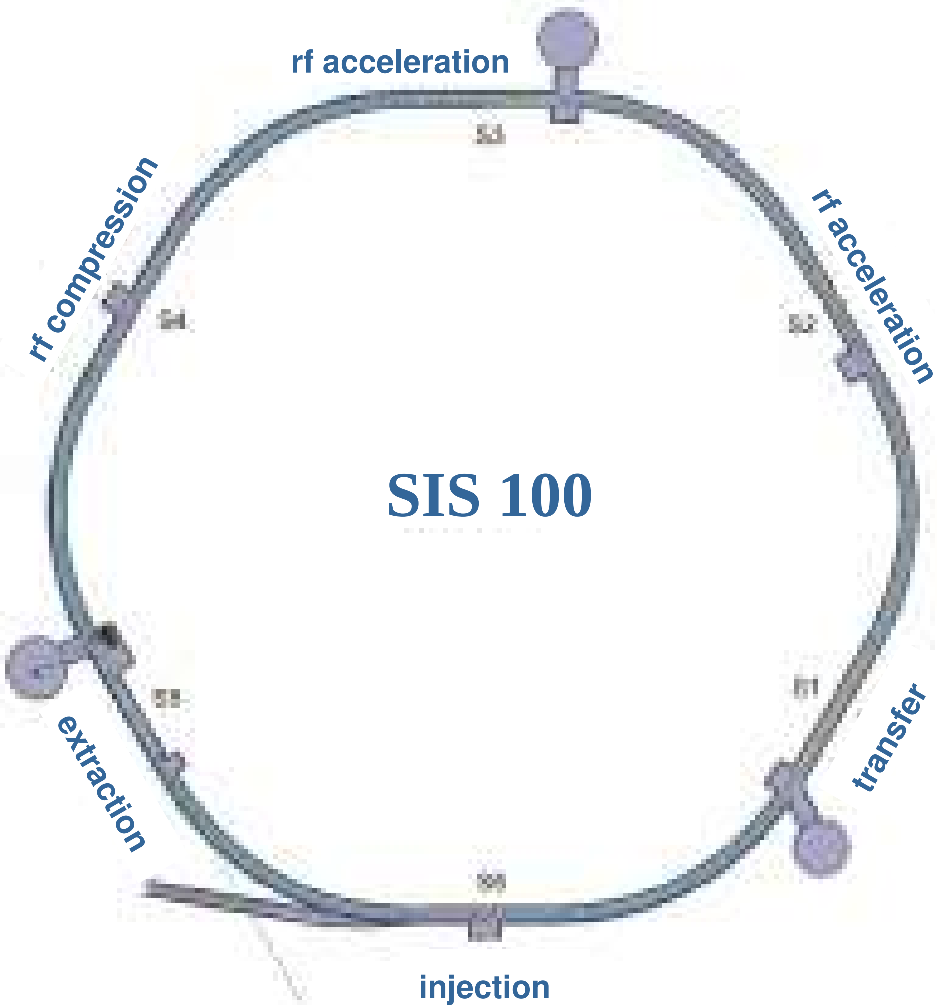
The Proton Linac



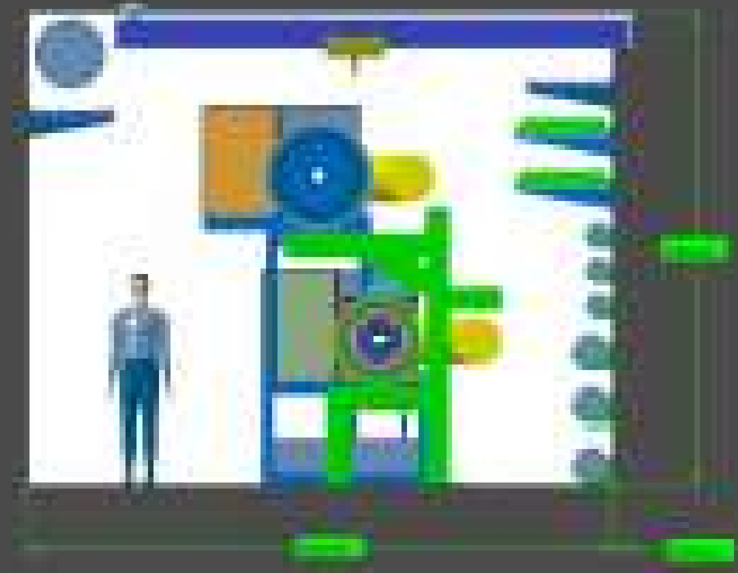
- Proton source & LEBT
- RFQ
- 2 re-bunchers
- 2*6 rf-coupled Crossed bar H-cavities
- 5.1 MW of beam loading (peak), 710 W (average)
- 11 MW of total rf-power (peak), 1600 W (average)
- 2 dipoles, 45 quadrupoles, 7 steerers
- 10 turbo pumps, 34 ion pumps, 9 sector valves
- 41 beam diagnostic devices

Beam energy	70 MeV
Beam current (op.)	35 mA
Beam current	70 mA
(des.)	36 µs
Beam pulse length	4 Hz
Repetition rate	325.224 MHz
Rf-frequency	4.2 µm
Tot. hor emit	$\leq \pm 10^{-3}$
(norm.)	≈ 35 m
Tot. mom. spread	
Linac length	

Fast Ramping Synchrotron SIS100



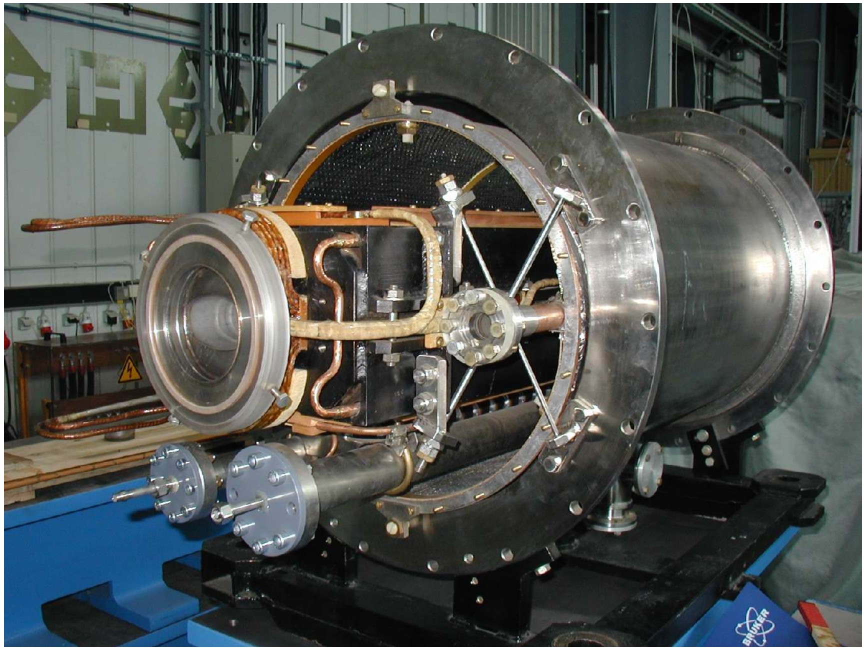
SIS 100/300 tunnel



SIS100

maximum magnetic rigidity	100 Tm
maximum proton energy	29 GeV
ring circumference	1084 m
ramp rate	4 T/s (up to 2 T)

SIS100 Superconducting Magnet R&D

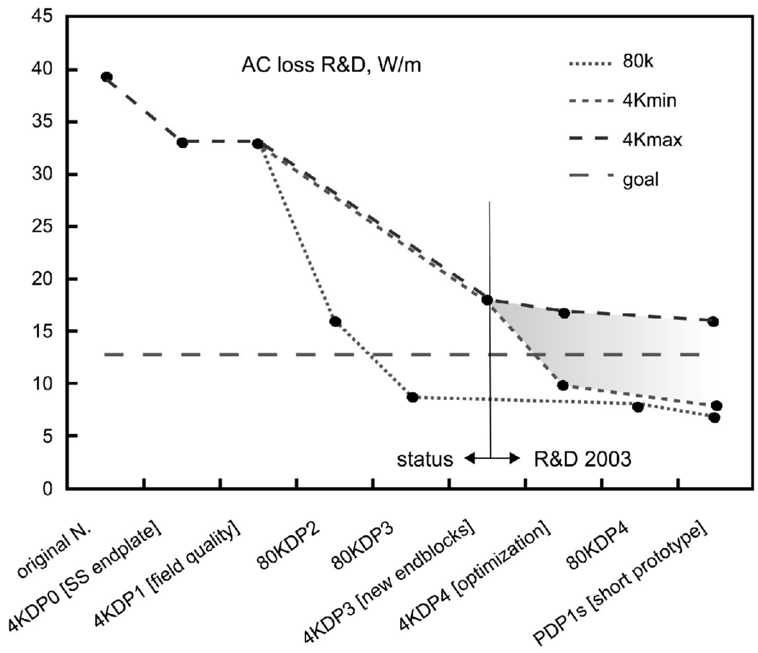


Nuclotron Dipole

- **B_{max} = 2 T – dB/dt = 4T/s**
- **Window frame magnet with s.c. coil**
- **Main task :**
  Reduction of AC losses during ramping
  improved iron yoke design (40 > 13 W/m)

in collaboration with JINR Dubna

significant R&D progress achieved on dynamic losses and field quality



RF Systems for SIS100

- **Dual Harmonic Acceleration Systems SIS100**
  20 ferrite loaded cavities - $V_{a,tot}$ =400 kV
  frequency range : 1.15 – 2.67 MHz, h=10
  (8 ferrite loaded cavities - $V_{a,tot}$ =150 kV
  frequency range : 2.3 – 5.35 MHz, h=20)

  alternative solution: MA loaded cavities

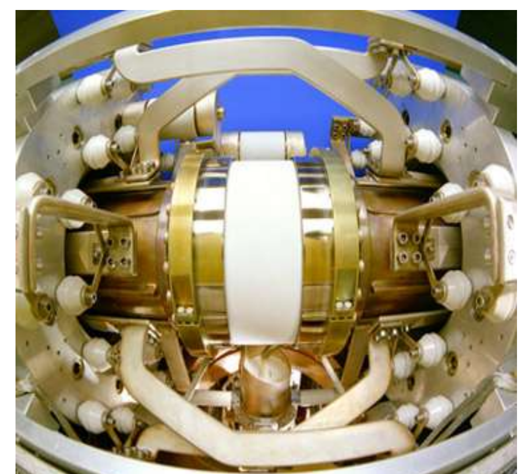
- **Compression Systems SIS100**
  25 MA loaded cavities - $V_{c,tot}$ = 1 MV
  frequency range : 465 kHz (±70) (h= 2)

- **Barrier Bucket Systems SIS100 (precompression and stacking)**
  broad band MA loaded cavities - V_b = 2 x 15 kV

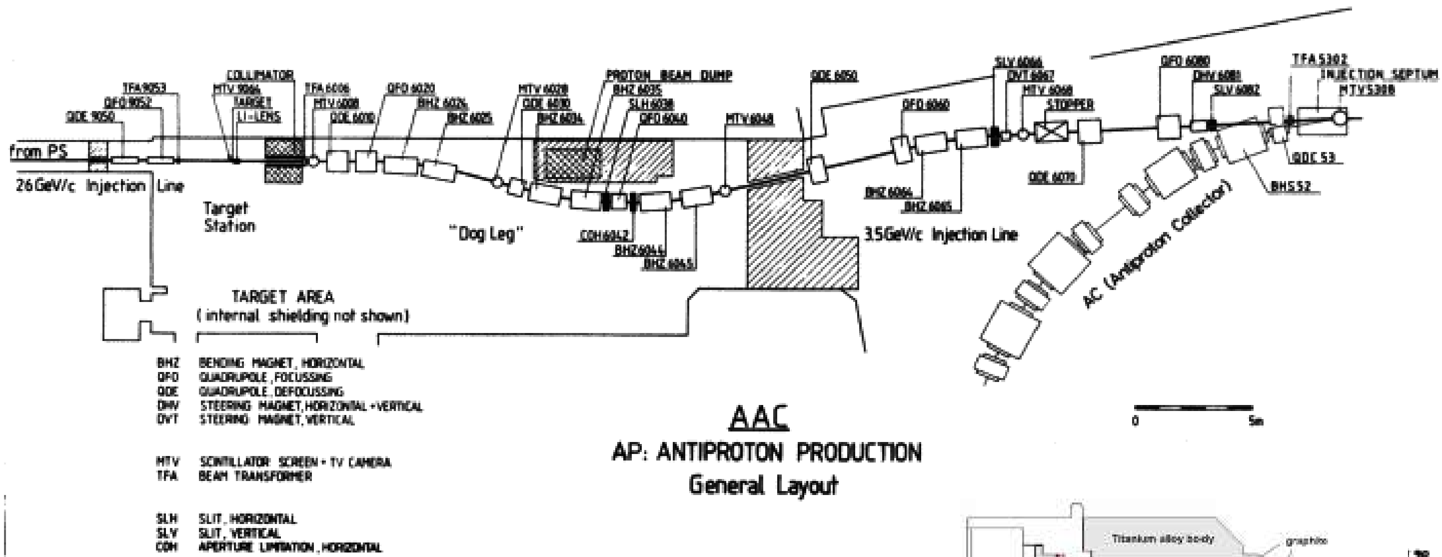
total length of RF-Systems ~ 90 (115) m
(~ 10 % of ring circumference)

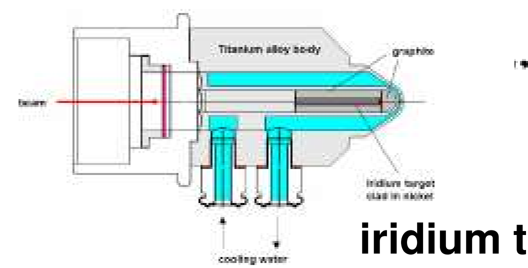
- **Dual Harmonic Acceleration Systems SIS300**
  6 ferrite-loaded cavities - V_{tot} = 80 kV (h=10)
  frequency Range: 2.67 – 2.76 MHz

SIS18



Antiproton Production Area





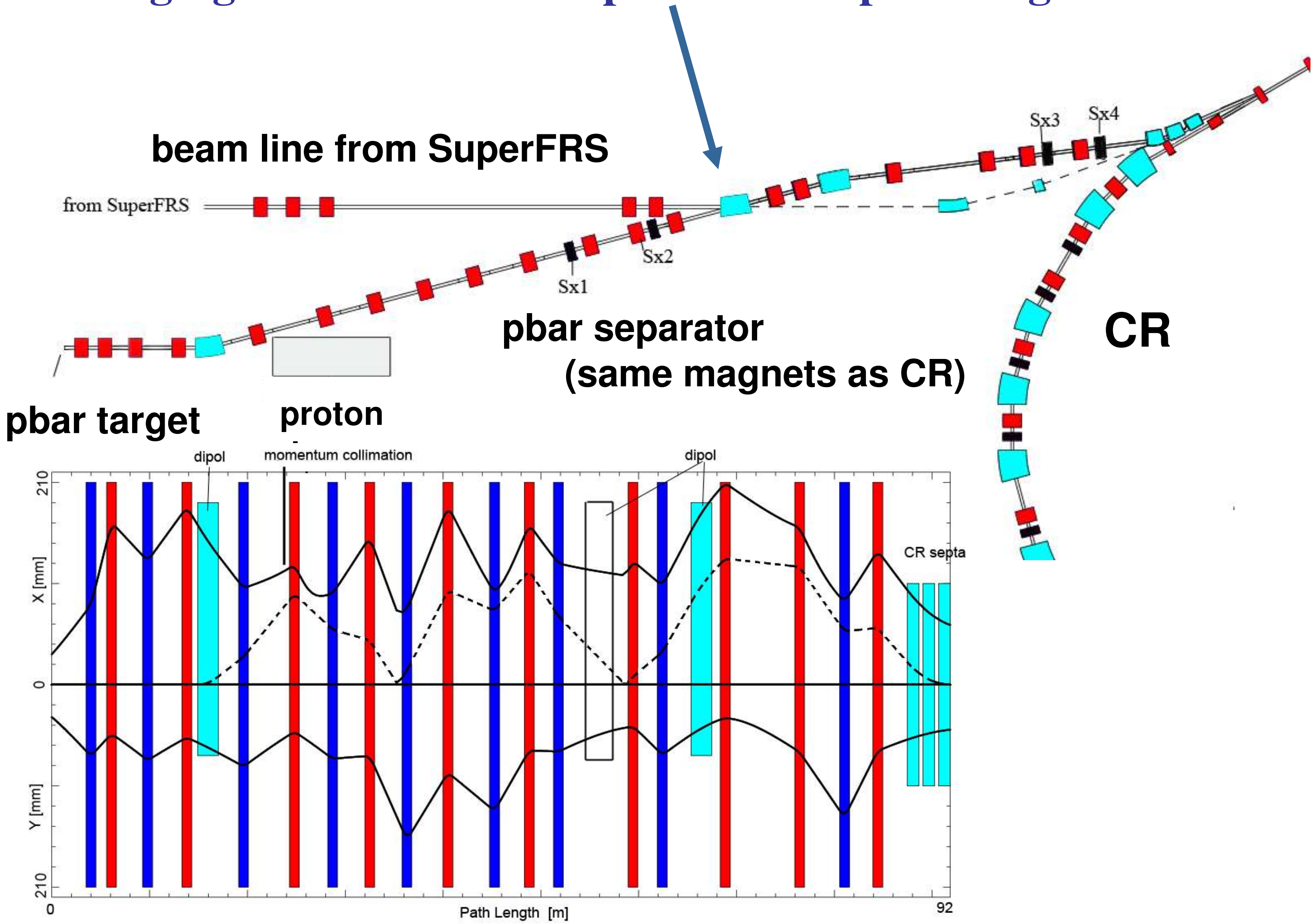
concept of FBTR is based on CERN antiproton target

iridium target embedded in graphite

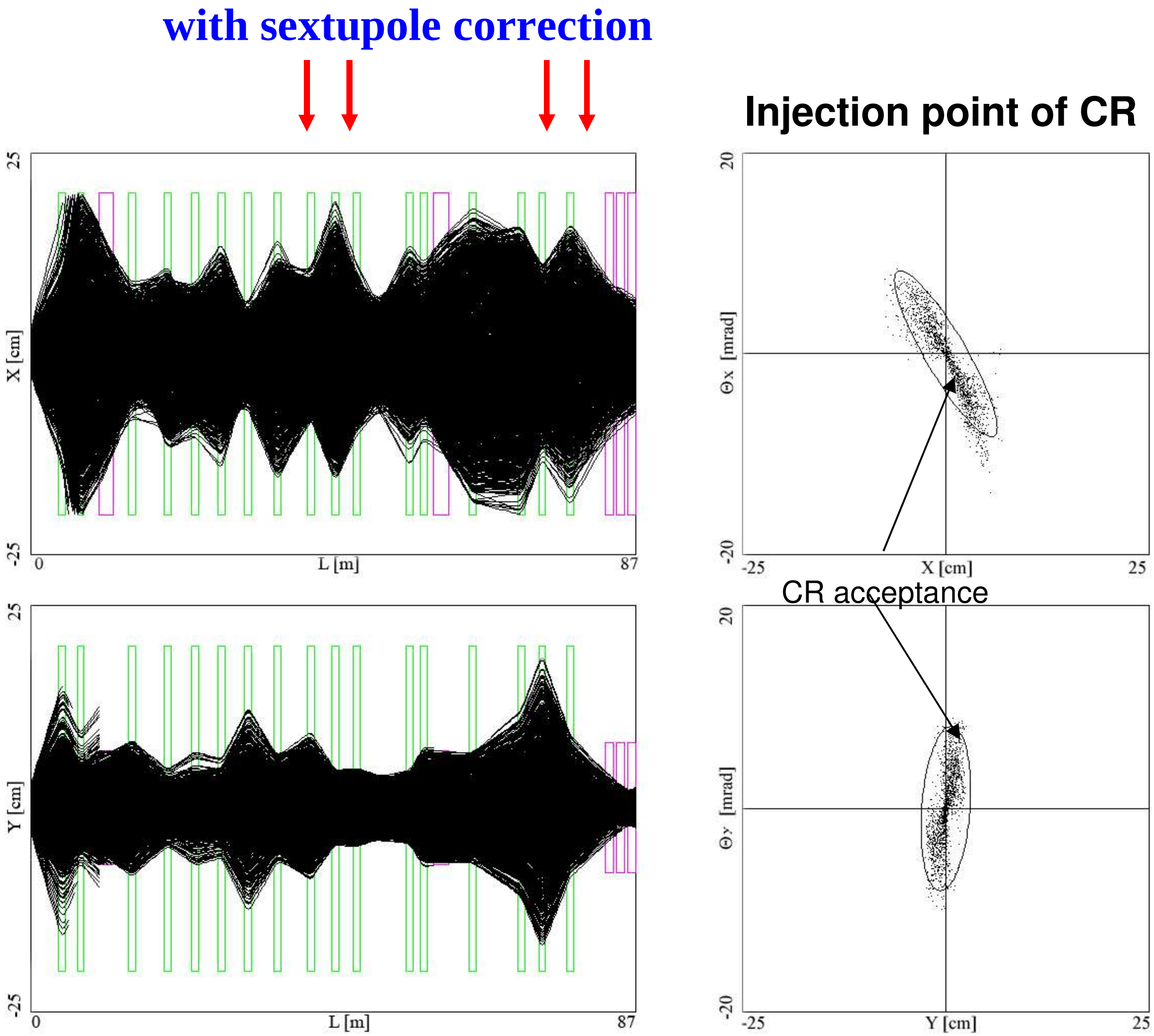
similar proton energy and intensity as CERN, different from FNAL antiproton production scheme

Antiproton Separator

merging of beams from SuperFRS and pbar target



Tracking from target to CR with quadrupole non-linearity



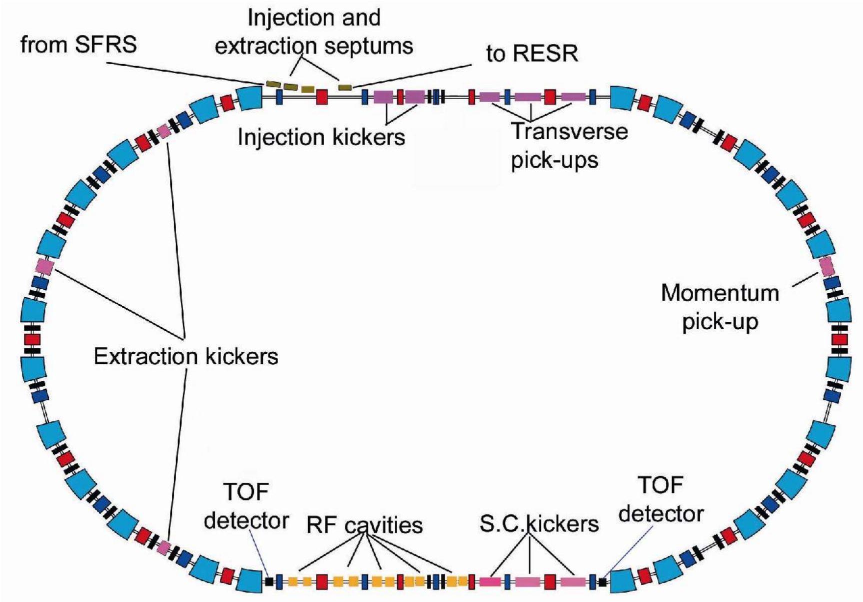
input from MARS code (P. Shatunov)

Total: 19 % losses

6 % due to chromatic effect

13 % due to aperture restriction

The Collector Ring CR



- **fast stochastic cooling of antiprotons and rare isotope beams**

  fast bunch rotation
  with rf voltage 200(400)kV
  adiabatic debunching

  stochastic pre-cooling system 1-2 (1-4) GHz

  optimized ring lattice for proper mixing
  large acceptance superconducting dipoles

circumference	**212 m**
magnetic bending power	**13 Tm**

	RIB	pbar	isochronous (RIB)
energy	740 MeV/u	3.0 GeV	≤ 790 MeV/u
tunes Q_x/Q_y	3.17/3.18	4.42/4.24	2.55/3.17
mom. accept.	± 1.5 %	± 3.0 %	± 0.7 %
transv. accept.	200×10^{-6} m	240×10^{-6} m	$70/50\times10^{-6}$ m
transition energy	2.9	3.54	≥ 1.84

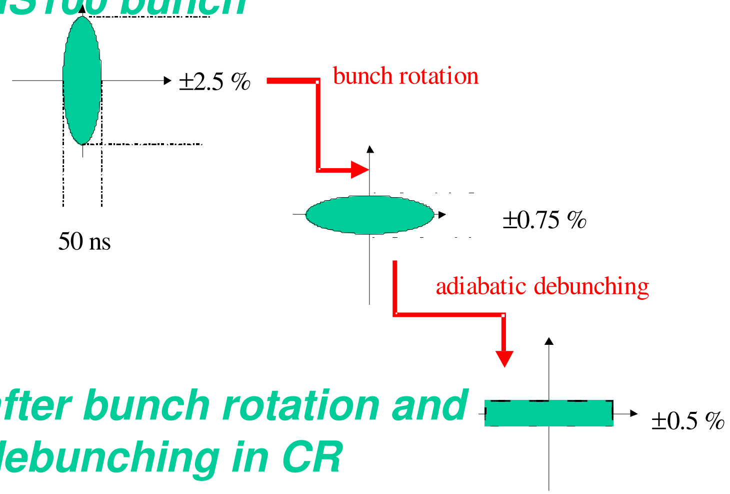
isochronous mass measurements of rare isotope beams

Techniques for Fast Cooling in CR

Fast bunch rotation of SIS100 bunch

rf voltage 200 (400) kV at h=1
after passage of production target
to reduce momentum spread (2.5 → 0.5 %)

SIS100 bunch



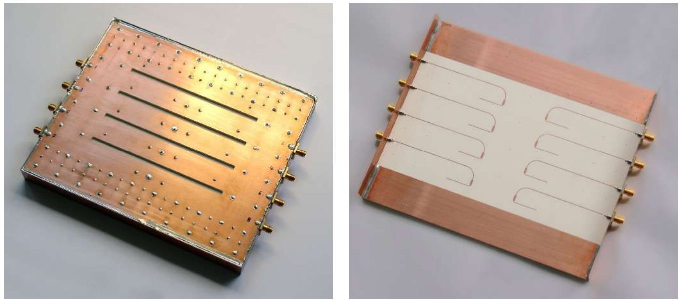
after bunch rotation and debunching in CR

providing optimum initial parameters for stochastic cooling

Fast stochastic pre-cooling

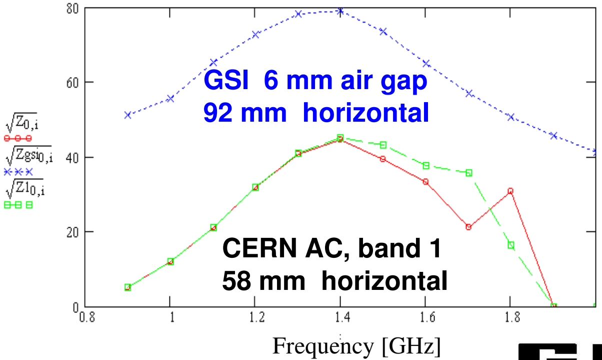
system band width 1-2 (1-4) GHz
matched to velocities β = 0.83 - 0.97
rf power ~ 1-2 kW per system

electrode prototype



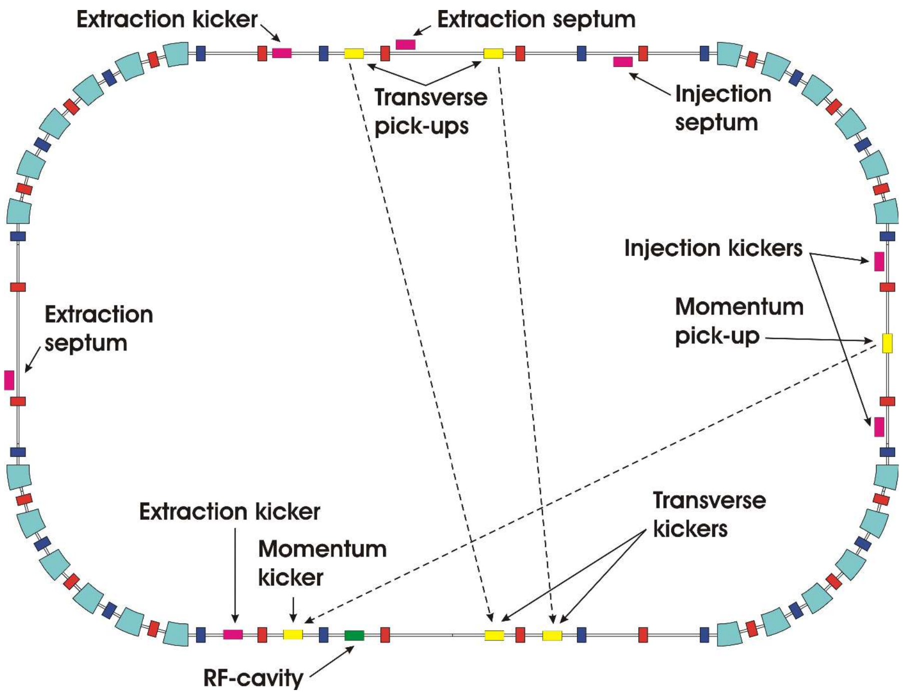
front and back side

Increase of impedance (factor of 4)



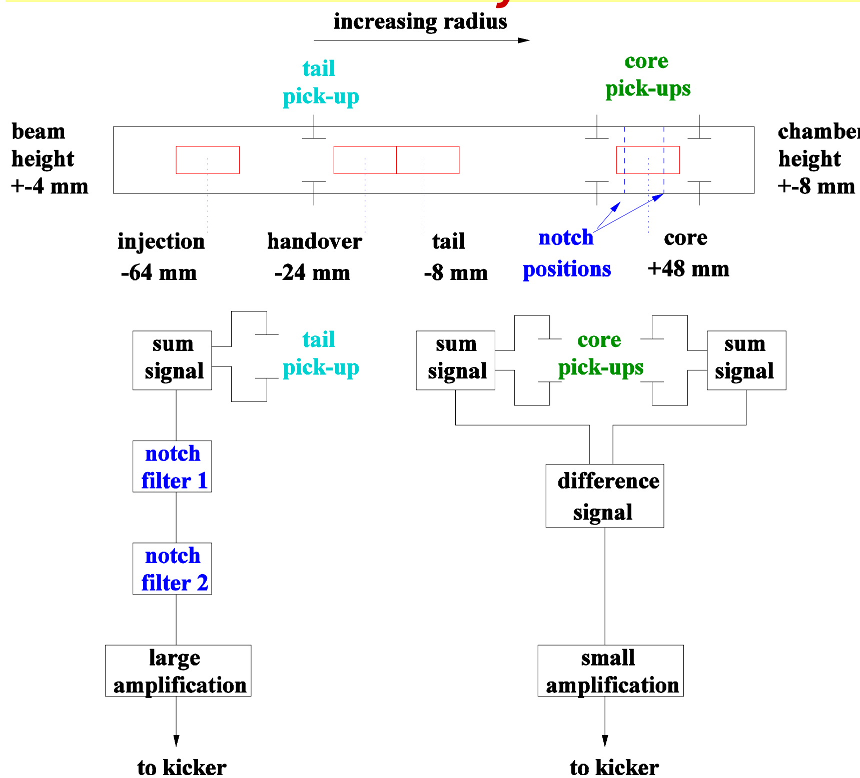
analysis by L. Thorndahl

The Antiproton Accumulator Ring RESR



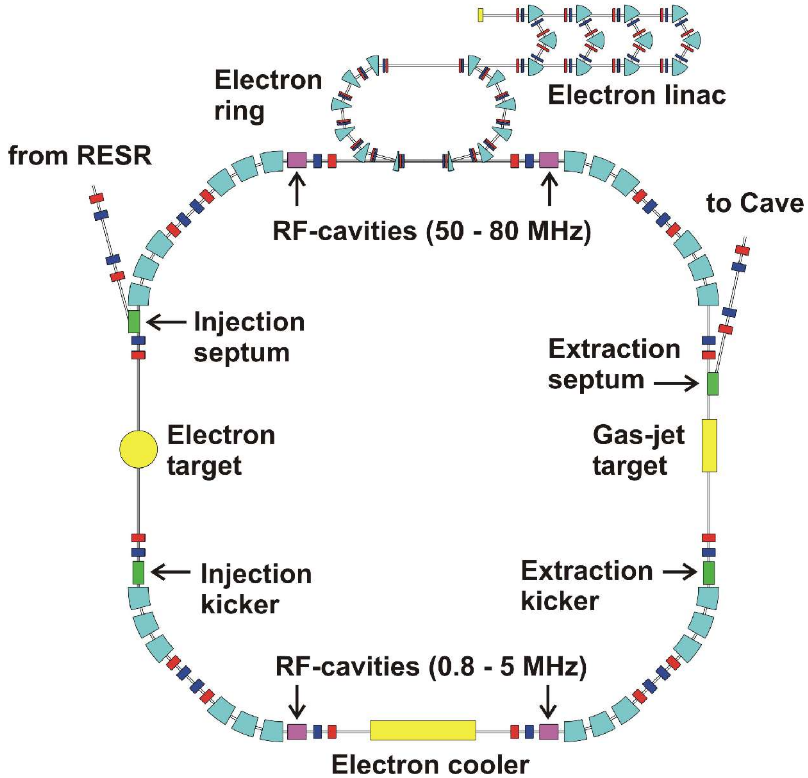
circumference	245.5 m
magnetic bending power	13 Tm
tunes Q_x/Q_y	3.8/3.3
momentum acceptance	±1.0 %
transverse accept. h/v	$80/35 \times 10^{-6}$ m
transition energy	3.62

- **accumulation of antiprotons by stochastic cooling**
  - *max. accumulation rate* 7×10^{10}/h
  - *max. stack intensity* $\sim 1 \times 10^{11}$



Additional modes: fast deceleration of RIBs and antiprotons for AIC

Antiproton Deceleration in NESR



circumference	222.11 m
magnetic bending power	13 Tm
tunes Q_x/Q_y	3.4 / 3.2
momentum acceptance	±1.75 %
transverse accep. h/v	$160/100\times10^{-6}$ m
length of straight section	18 m

Ions

storage and cooling of ion beams in the energy range 740 → 4 MeV/u

maximum deceleration rate 1 T/s

experiments with internal target

luminosity up to 10^{29} $cm^{-2}s^{-1}$

RIB accumulation by electron cooling

collider mode

1) **with electrons** *luminosity up to 10^{28} $cm^{-2}s^{-1}$*
2) **with antiprotons** *luminosity up to $10^{23} cm^{-2}s^{-1}$*

electron target

Antiprotons for FLAIR

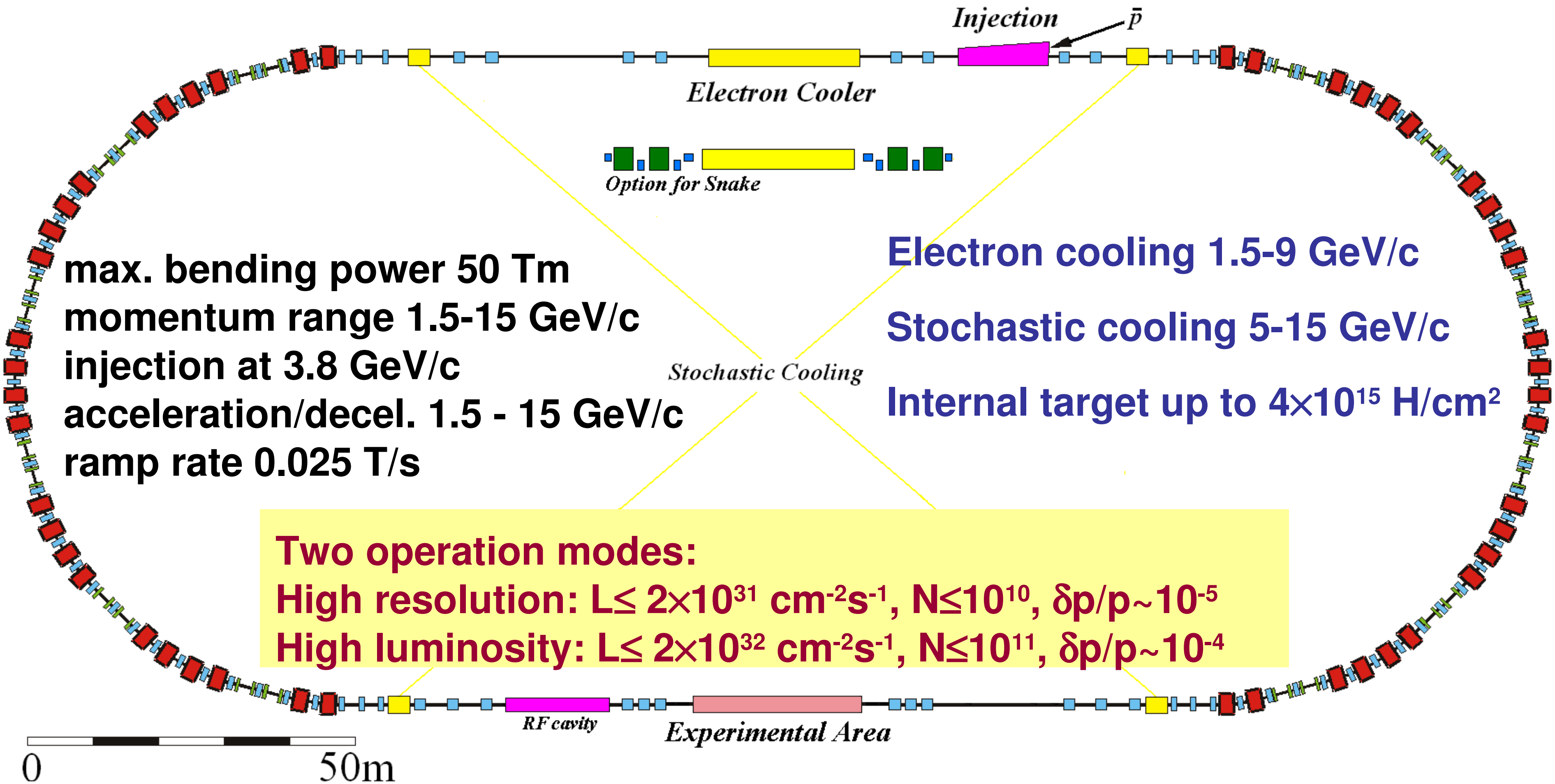
deceleration 3000 → 800 → 30 MeV

electron cooling at 800 MeV

electron cooling limits cycle time

The High Energy Storage Ring HESR

designed by a consortium between FZ Jülich, TSL Uppsala, GSI



max. bending power 50 Tm
momentum range 1.5-15 GeV/c
injection at 3.8 GeV/c
acceleration/decel. 1.5 - 15 GeV/c
ramp rate 0.025 T/s

Electron cooling 1.5-9 GeV/c

Stochastic cooling 5-15 GeV/c

Internal target up to 4×10^{15} H/cm^2

Two operation modes:
High resolution: $L\leq 2\times10^{31}$ cm^{-2}s^{-1}, $N\leq10^{10}$, $\delta p/p\sim10^{-5}$
High luminosity: $L\leq 2\times10^{32}$ cm^{-2}s^{-1}, $N\leq10^{11}$, $\delta p/p\sim10^{-4}$

straight sections of 132 m length
ring circumference 574 m.

	Protons			Antiprotons			
	p-Linac	SIS18	SIS100	p-target	CR	RESR	HESR
Output energy [GeV]	0.070	2.00	29.00	3.00	3.00	3.00	8.00
Output $B\rho$ [Tm]	1.2	9.3	100.1	12.8	12.8	12.8	29.7
output no.of bunches		1	1	1	1	1	1
stacking/convers. factor		15	8*	5.0E-06	1	600	1
relative loss/ring		0.1	0.1		0.1	0.1	100
Inj. SC tune shift (y)		0.55	0.27				
bunch area [eV s]	3.0E-06	4.2E-01	1.7E+01				
dp/p (dc)	1.0E-03	1.0E-03	1.1E-03	3.0E-02	1.0E-03	5.0E-04	1.0E-04
Dilutionfactor (long.)		3.5	3.5				
Output bunch length [ns]			25	25			
ϵ_x (norm.) [mm mrad]	2.8	59	65	989	21	4	
ϵ_y (norm.) [mm mrad]	2.8	20	22	989	21	4	
ϵ_x (phys.) [mm mrad]		150	22	240	5	1	
ϵ_y (phys.) [mm mrad]		50	7	240	5	1	
Dilutionfactor (transv.)		1.1	1.1				
Cooling down time [s]					10.00	10.00	10.00
Accumulation time [s]		0.016	1.75		0.00	6000.00	6000.00
Rep. time [s]		0.25	2.66	2.66	10.00	6000.00	6000.00
Output current [A]	0.035						
output no. of particles per cycle		5.8E+12	4.2E+13	2.1E+08	1.9E+08	1.0E+11	1.0E+11
Particles/s		2.3E+13	1.6E+13	7.9E+07	1.9E+07	1.7E+07	1.7E+07
Luminosity [$cm^{-2}s^{-1}$]							1.7E+32

*For barrier bucket injection.