Electrostatic Storage Rings

at the Ultra-low Energy Range

(1 to 100 keV/A)

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ESR – is a ring using electrostatic bending and focusing elements

Abstract

Electrostatic storage rings have proven to be invaluable tools for atomic and molecular physics at the ultra-low energy range from **1 to 100 keV/A**. Due to the **mass independence** of the electrostastic rigidity, these machines are able to store a wide range of different particles, from **light ions** to **heavy singly charged bio-molecules**. **Reaction Microscope** incorporated into a ring lattice is considered to be a new powerful tool to study high precision effects by **multiple crossing** of incident beam of ions with **ultrasonic gas jet**. To enable operation of Reaction Microscope one should provide very short bunches in the 1-2 nanosecond regime in order to pave the way for kinematically complete measurements of the **collision dynamics** of fundamental few-body quantum systems on the level of **differential cross sections**. However, earlier measurements at some rings showed **strong limitations** depending on beam intensity, probably linked to **non-linear fields** that cannot be completely avoided in such machines. In this contribution, we discuss common features of electrostatic storage rings and analyse rings performance.

- **Predessor:**
- e-model of Brookhaven synchrotron made of electrostatic elements
- **THE BROOKHAVEN ELECTRON ANALOGUE**
- 1953 - 195**7**

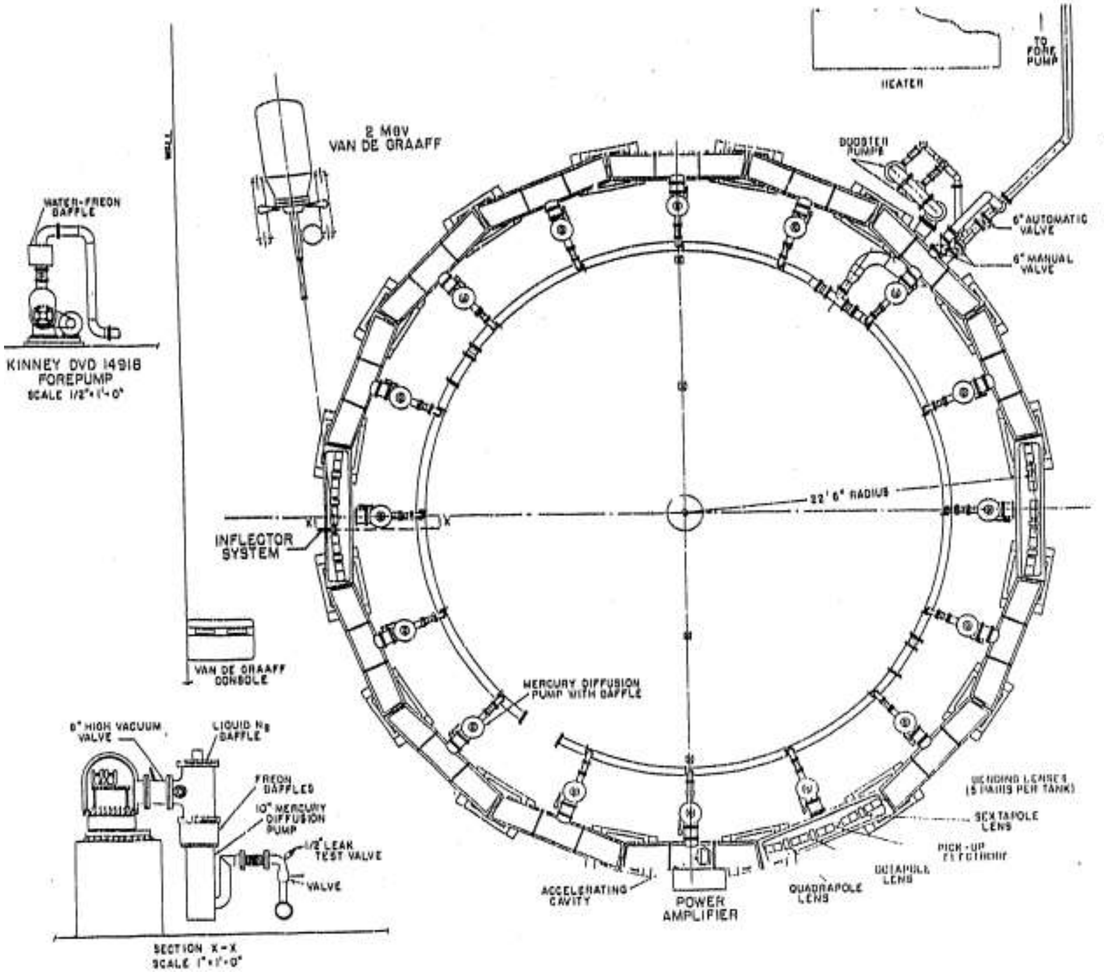


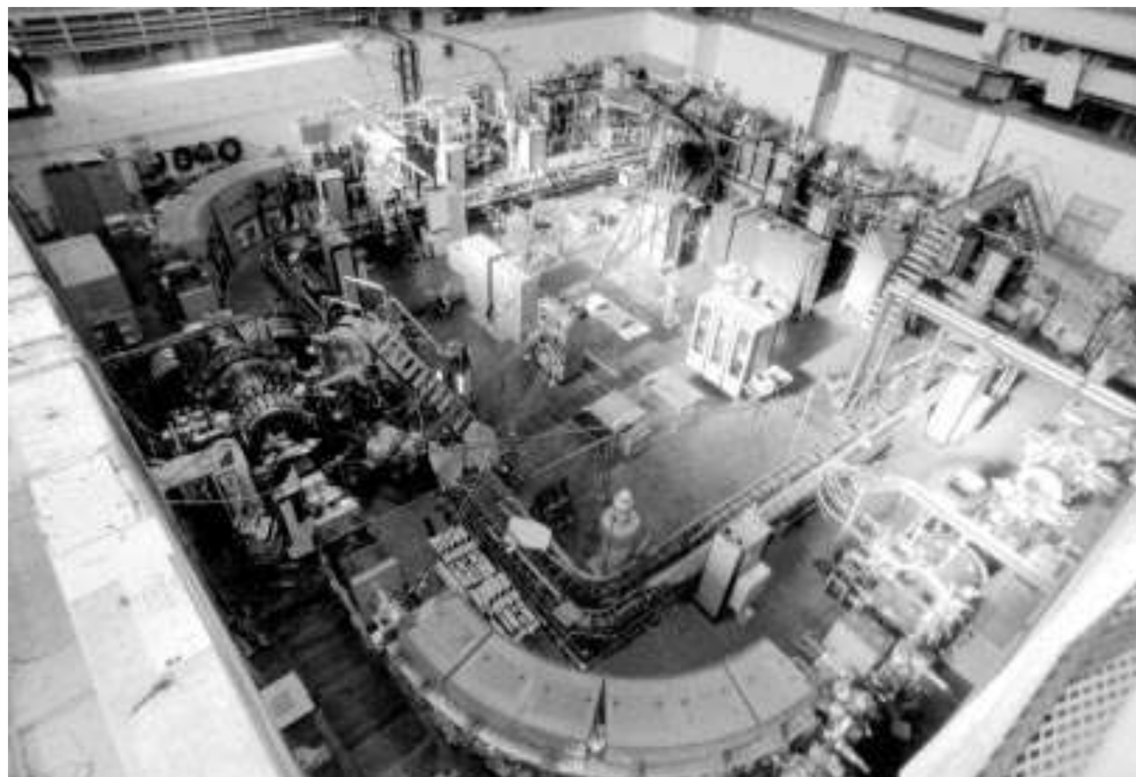
Fig. 22 Vacuum system layout.

Predecessors: **LEAR magnetic ring**
CERN Antiproton decelerator with e-cooling
1982 - 1996

„*LEAR was the first machine to use electron cooling as an integral part of its operation*” *(CERN statement)*

<u>Antirpotons</u> cooled and decelerated down to T=5 MeV (pc=100 MeV/c)

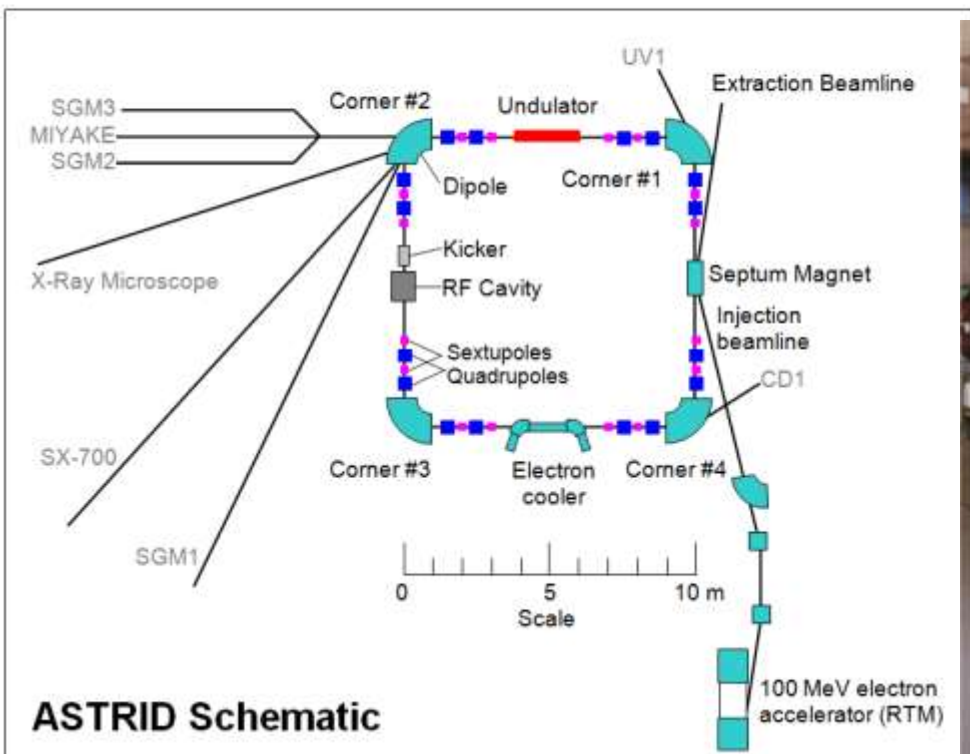
<u>Heavy ions</u> from LINAC stored and accelerated to E/A = 11÷400 MeV/A



Predecessor: **ASTRID** magnetic ring

(Aarhus, Danmark)

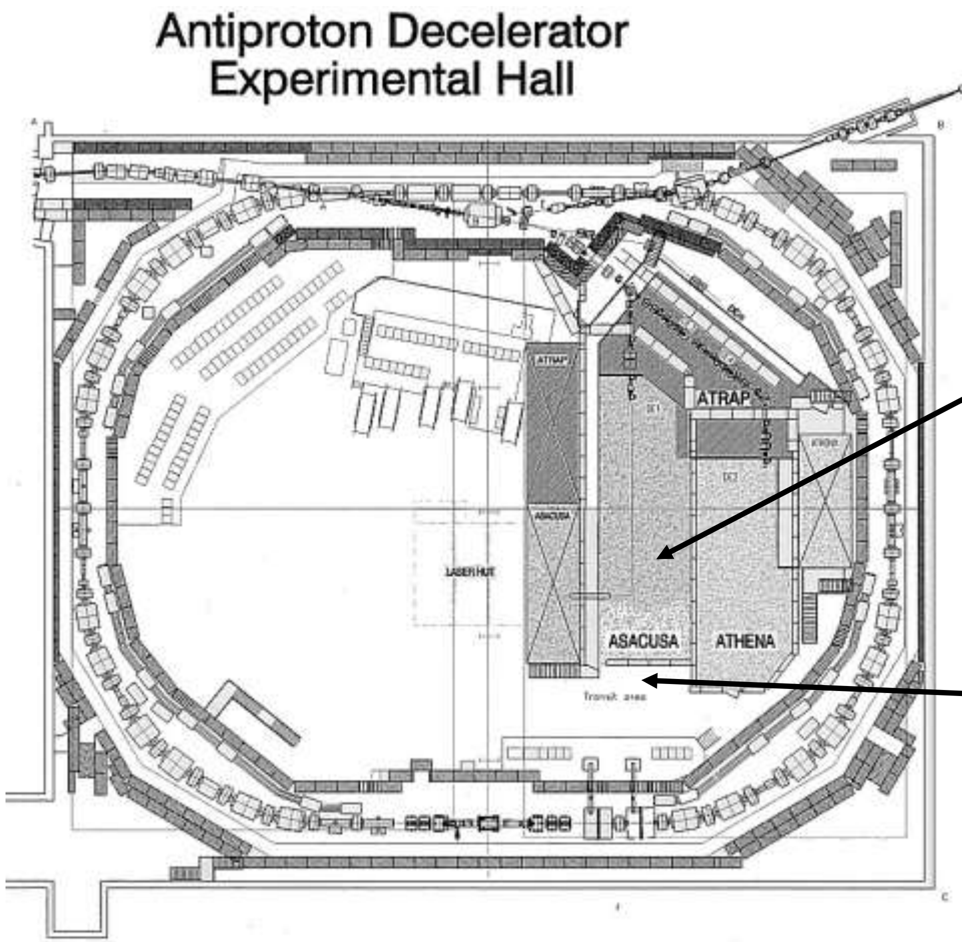
- **Ion mode – (A =1÷840)**
- **Injection energy = 5-150 keV**
- **He^- ions at 5 keV**
- **$^{12}C^-_{70}$ stored at 25 keV ($\beta = 2.5 \cdot 10^{-4}$)**
- **Laser Cooling Technique was developed**
- **Ring operates in electron storage mode (E=100÷580 MeV)**
- **Vacuum P=$2.5 \cdot 10^{-11}$ torr**



Operating ring: AD – Antiproton Decelerator (CERN)

After LEAR and AA were closed in 1999
the AC was transformed to AD (magnetic dipoles and quads)

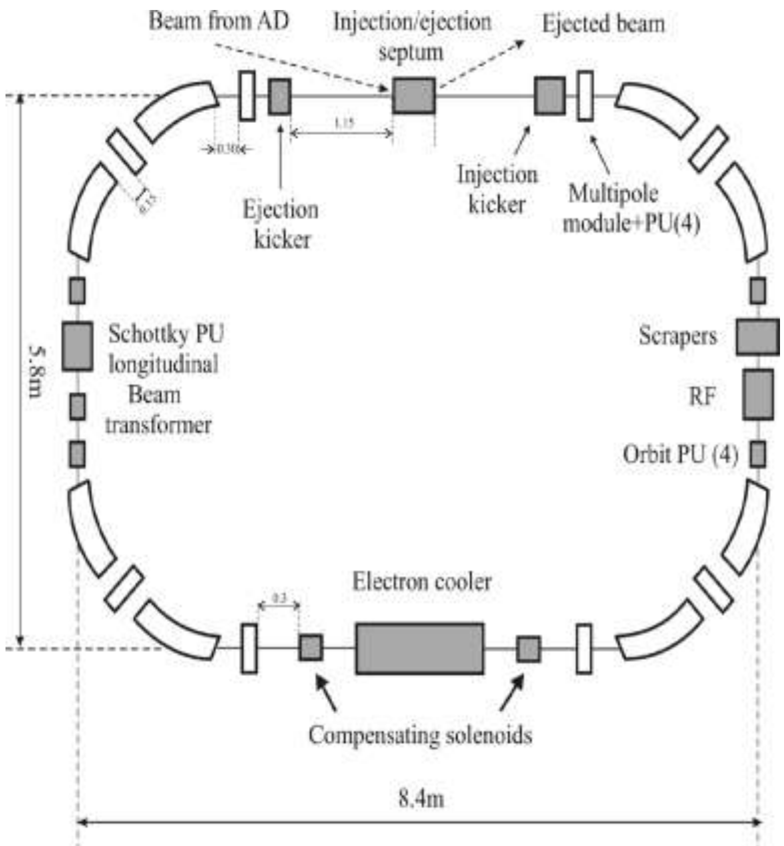
Pbar energy is reduced from **E = 2.75 GeV down to 5 MeV**
Operation cycle (stoch.cooling-decel-ecool-decel-ecool) ~70 sec



„ASACUSA“
RFQD
pbar energy reduced from 5.33 MeV down to 63 keV

Single passage MUSASHI trap

AD Future (approved) ELENA (dipole magnets and magnetic quads)



Energy, MeV	5.3 – 0.1
Circumference, m	25.6
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitation by space charge	$1\ 10^{7}$
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Expected cooling time at 100 keV, sec	1
Required vacuum* for Δε=0.5π mm mrad/s,Torr	$3\ 10^{-12}$

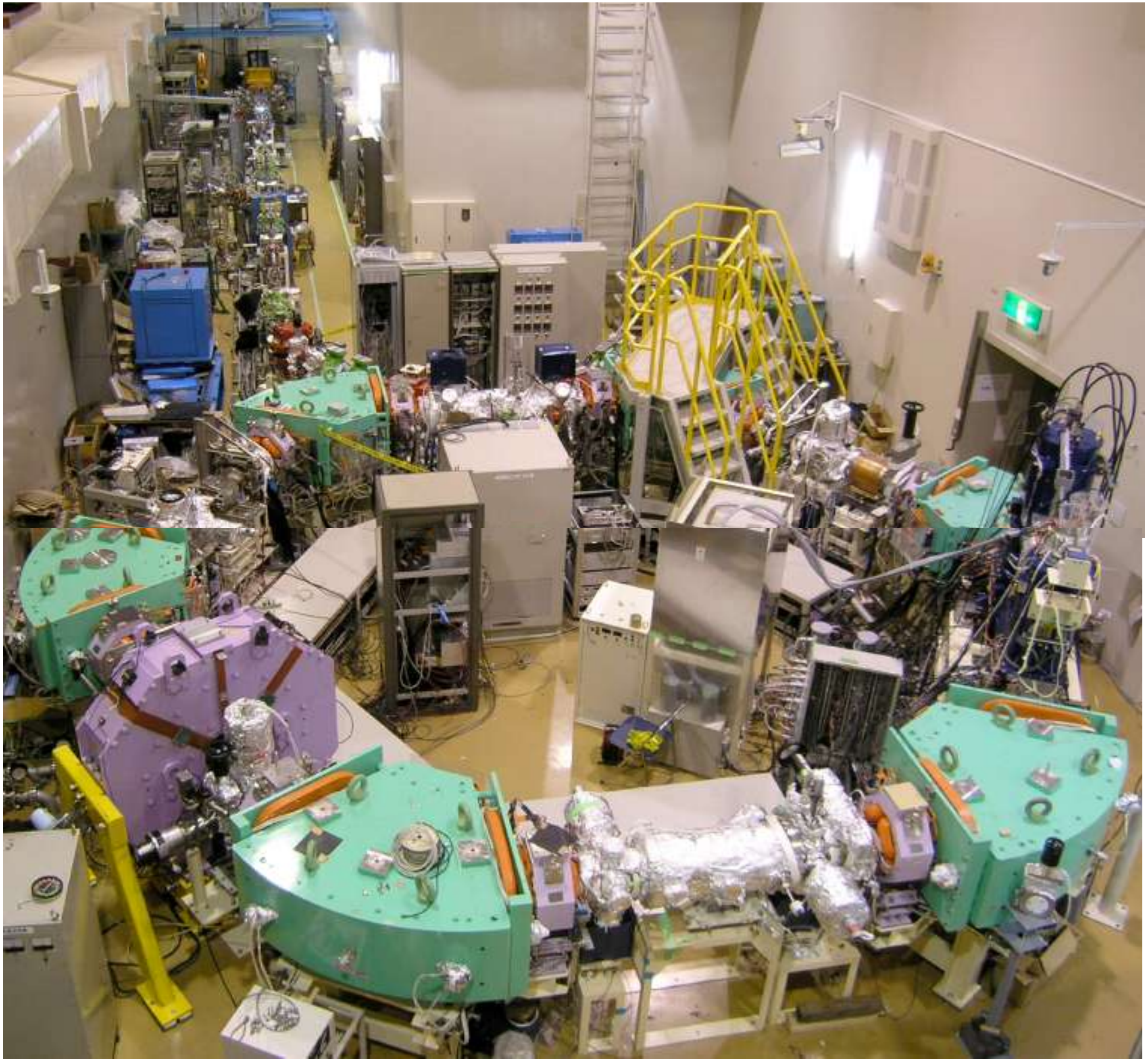
E= 5 MeV down to <u>100 keV</u>

Antimatter Physics Opportunities with ELENA at CERN-AD

S-LSR KYoto Japan Dispersion free ring magnets with ES Dispersion supperssors

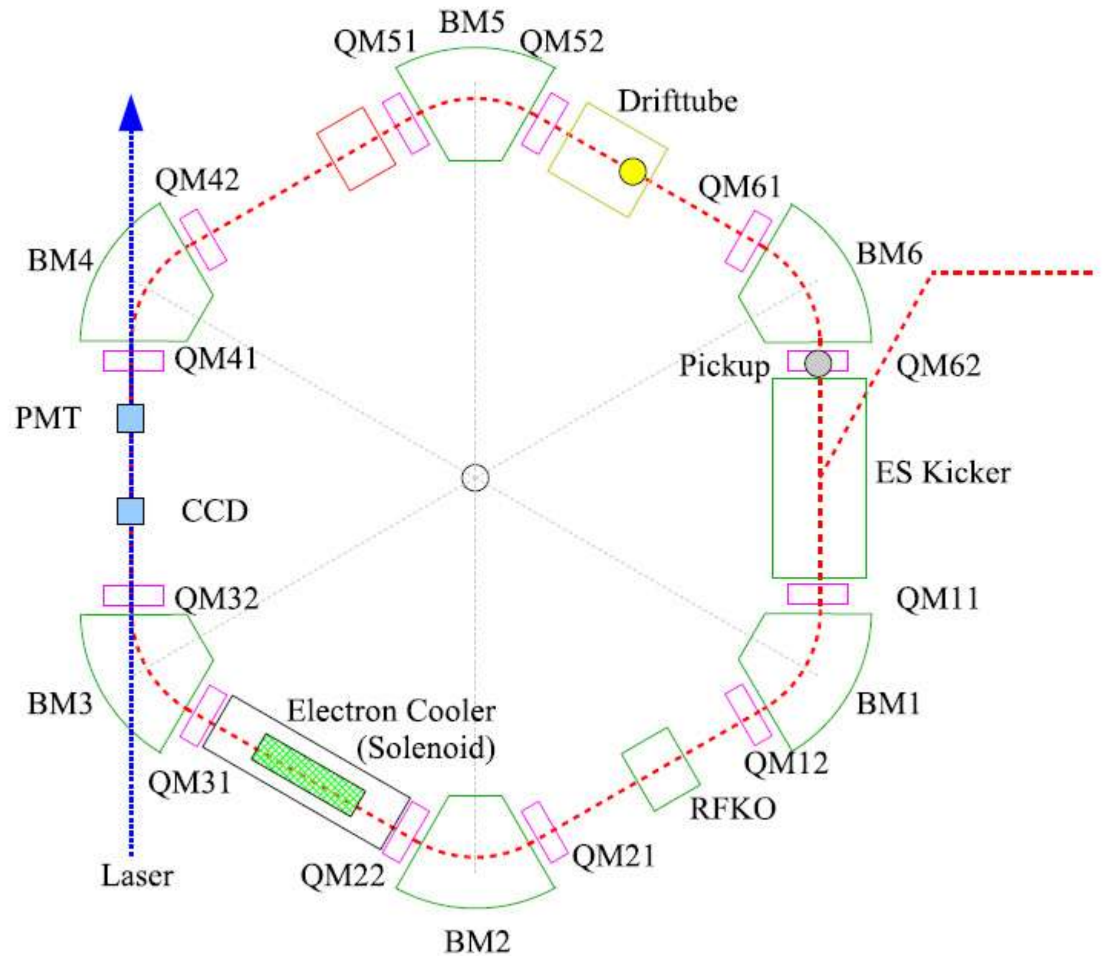
Not yet electrostatic but already combination of magnetic Dipoles with ES elements

(next slide)



S-LSR Dispersion free ring (magnetic bends with ES Dispersion suppressors)

S-LSR is a compact ion storage and cooler ring to inject beam of 7MeV proton and 40MeV Mg+ and slowed down to 30 keV for Mg^+



Why ES rings ?
To reduce energy as low as possible

- Electrostatic traps and rings allow operation with ion beams at ultra-low energies
- Ion traps store ions as long as possible, localize the stored particles in space
- ES Rings complimentary to Ion traps
- In ESR Ions circulate in one direction -- in traps no preferable direction of motion
- ES Rings – mass independent while magnetic rings mass dependent

Voltage applied to ES Deflector plates: $\mathbf{U_{\pm} = (1/q)\, E_{kin}\, (d/R)}$

q – ion chargem, E – kinetic energy, d - gap between plates R – curvature radius

- Mass range - from protons / antiprotons to heavy molecula ions and high charge state ions, positive and negative ions
- Energy range – down to few keV and even less
- ESR are used for storage, acceleration and deceleration

Why ES rings ?

- No remanent fields, no hysteresis like in magnetic rings
- Absense of magnetic fields which may induce transitions between the hyperfine levels of the circulating ions
- Fast acceleration / deceleration due to absence of eddy currents
- Multiturn circulation of ions for in-ring experiments (in contrary to RFQ-D whith single passage of ions over the target)
- Possibility to detect neutrals at the end of straight sections
- In combination with RM should provide powerfull tool for atomic physics
- Compact, Small dimensions, relatively chip (with respect to magnetic ring)

Ultra-low energy ES storage rings are used to study

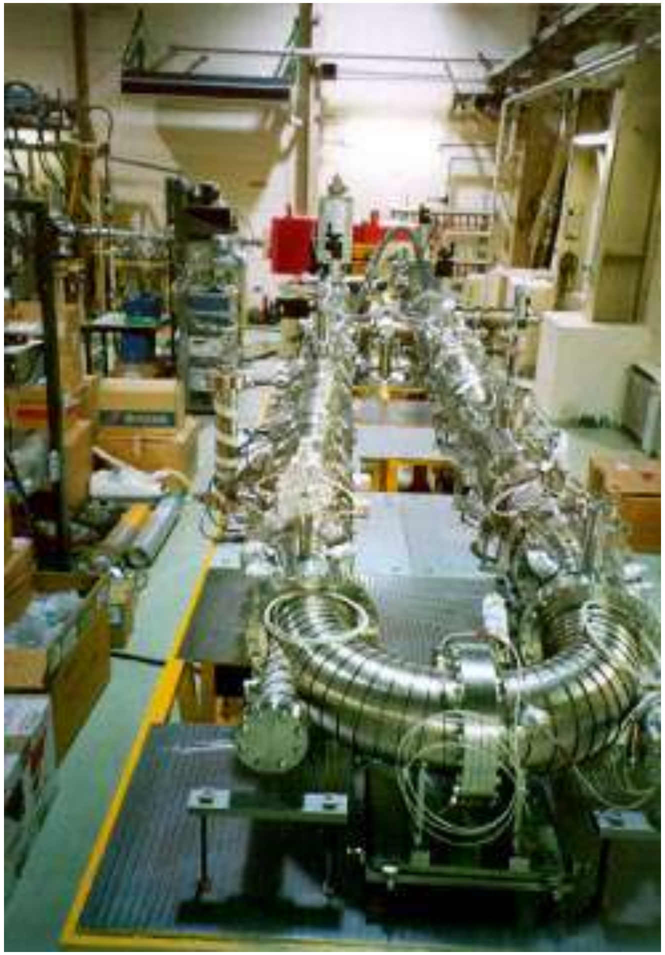
- Collision phenomena and plasma properties of astrophysical objects
- electron impact rotational and vibration excitation of cold molecular ions
- quantum reaction dynamics of cold molecular ions;
- gas-phase spectroscopy of bio-molecular ions
- ring cooled down to 2°K allow to store molecular ions in rotational ground state
- rotational effects in the process of dissociative recombination of molecular ions with low temperature electrons (<10 K)
- molecular dynamics - to achieve Coulomb cristallization for a fast strored beam and study phase transition to a cristalline beam

Ultra-low energy ES storage rings are used to study

- fundamental few body Coulomb problem for single as well as for multiple ionisation
- measurements of single and multiple ionization cross-sections (total and differential) of antiprotons colliding with atoms of supersonic gas jet
- ion-impact ionisation to benchmark theoretical predictions
- anti-hydrogen studies by merging antiprotons with positrons
- study of the lifetime of meta-stable atomic states
- investigations of the single component plasma

Ring	**ELISA [9,10]**	**ESR [11]**	**FRR [13]**	**DESIREE [14]**	**CSR [18,19,20]**	**USR [21,22,23]**	**AD-REC [24]**
Location	Aarhus Univ. Danmark	KEK Tsukuba Japan	Frankfurt Univ. Germ	Stockholm Univ. Sweden	MPI Heidelberg Germany	FAIR-GSI Darmstadt Germany	ASACUSA CERN Switz
Ions, molecul	A ≤ 100	A ≤ 100	A ≤100	A ≤ 100	A ≤ 1000	antiprotons	antiprotons
Energy, keV	(5–25)·Q	20·Q	50	(25-100)·Q	(300-20)·Q	300-20	3-30
Type	Racetrack	Race track	Race track	2 x Race tracks	quadratic	Achromat quadratic	Low beta racetrack
Symmetry	2	2	2	2 x 2	4	4	2
Perimeter, m	7.62	8.14	14.17	9.2 x 9.2	35.2	43	7.9
Revolution time, µs	3.5 (p) 93 (C_{80})	4 (p) 22 (N_2^+)	4.5 (p)	4–60	4–180	5.67–22	10–3
ES Deflectors	160°+10°	160°+10°	75°+15°	160°+10°	39°+6°	37°+8°	90°+90°
Defl.Rad, mm	250	250	250	250	2000+1000	2000+1000	400
Deceleration/ acceleration	Drift tube	Drift tube	--	--	Drift tube 10 V	Drift tube 10 V	Pulsed injector
e-cool, eV	NO	NO	NO	NO	10	10	NO
life time, s	10-30	12-20	--	--	10–100	~10	~20 ms
Operation modes	storage	Storage	D=0 at target	Colliding beams	Cooling storage	Short bunch Slow extr.	Low beta Low Disp.
Vac. mbar	10^{-11}	$5\cdot10^{-11}$	10^{-12}	10^{-12} (10°K)	10^{-15} (2°K)	10^{-11}	10^{-10}
Status	operate	operate	tested	Project	Manufact.	Design	Manufact.

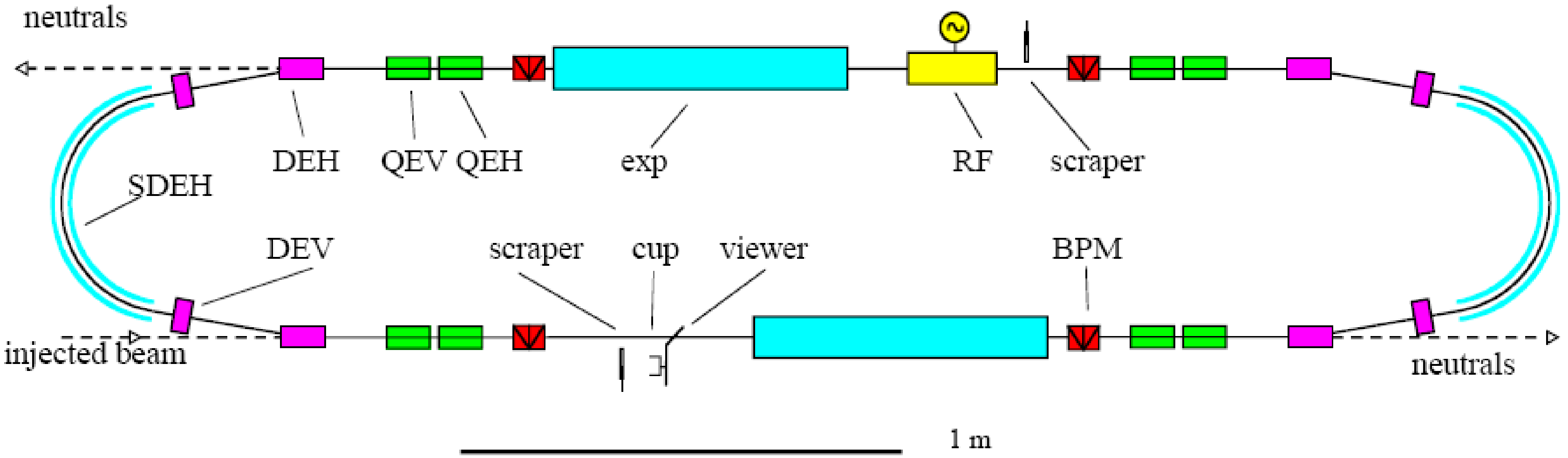
First: ELISA (Aarhus,Danmark)



Second: KEK (Tanabe) Japan

Third: Tokyo Metropolitan University

ELISA



Layout of **ELISA** storage ring.

Neutrals can be detected behind the 10° parallel plate deflectors - DEH.

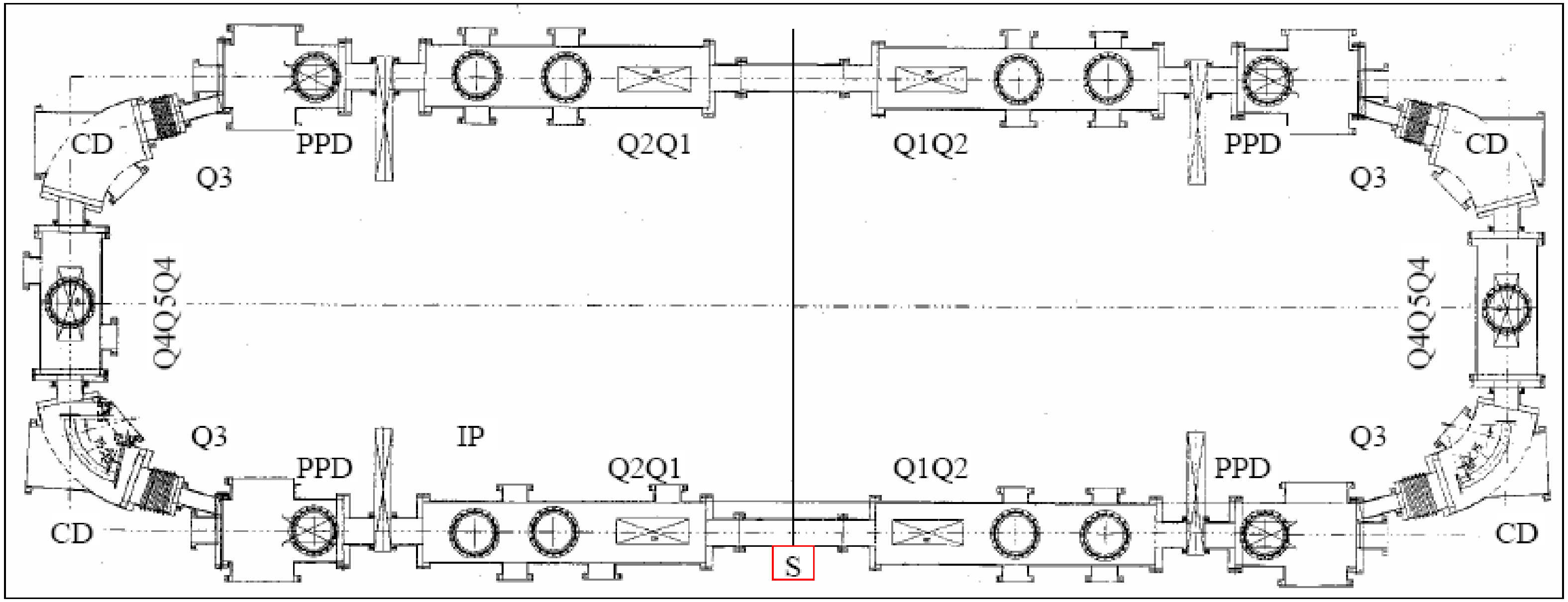
SDEH – 160° deflector of spherical shape (original set-up)

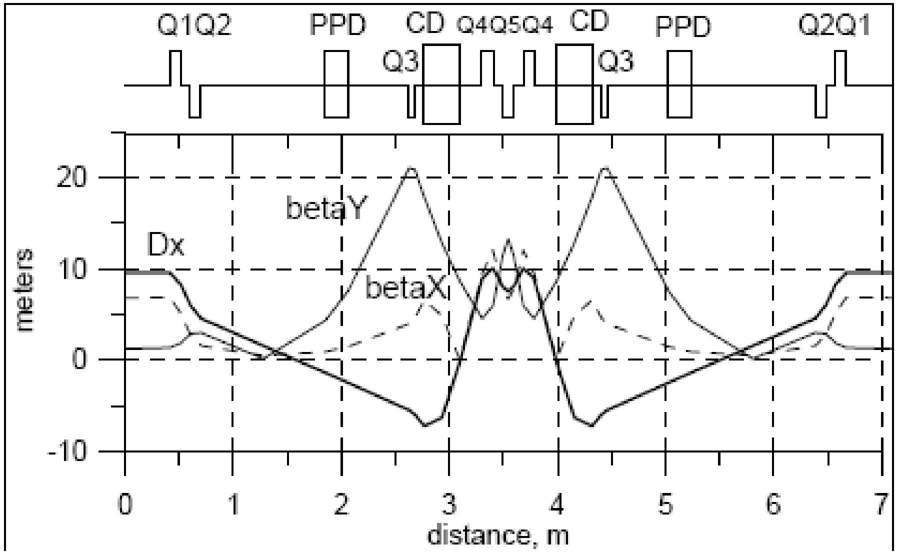
DEV – vertical steerers

QEV, QEH – ES quads (doublet)

RF – drift tube (U·sinφ = 10 V)

Frankfurt ring. Lattice designed by V.Aleksandrov and N.Kazarinov (JINR, Dubna)

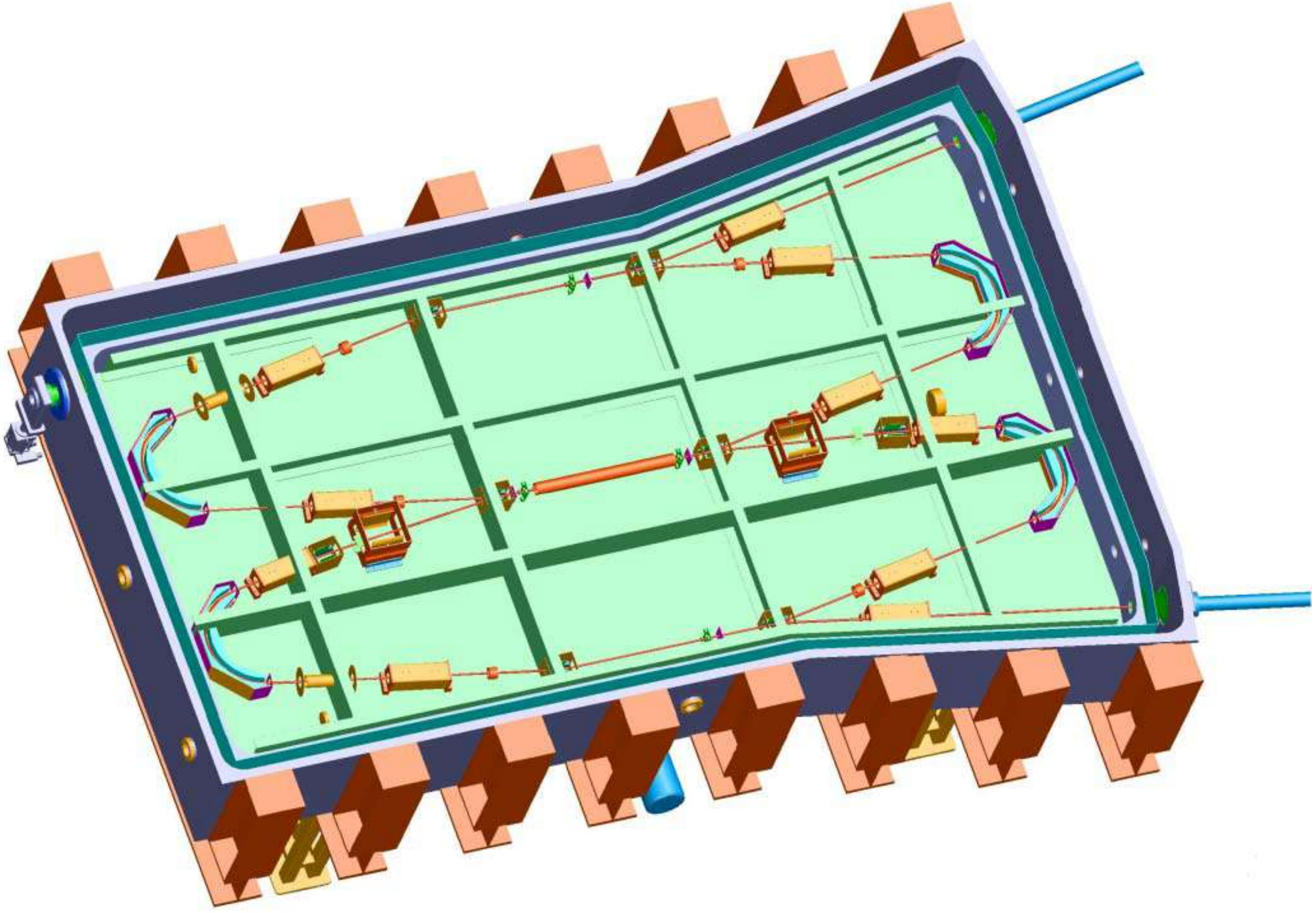




Dispersion crosses zero value at position of low beta-functions (IP)
Expected beam size at IP
3 x 4 cm^2

PPD -- 15° parallel plate deflector
CD -- 75° ESD of cylindrical shape
IP -- interactin point

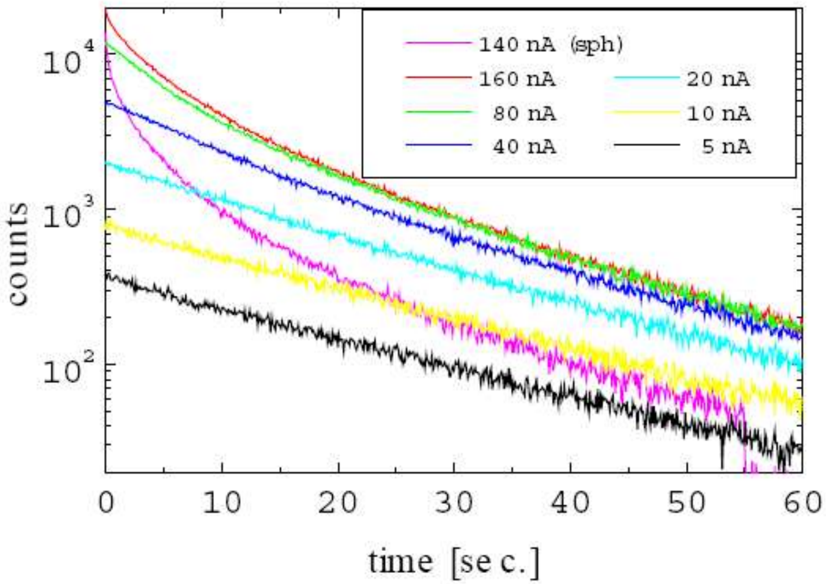
DESIREE double ES ring project (Stockholm, Sweeden)



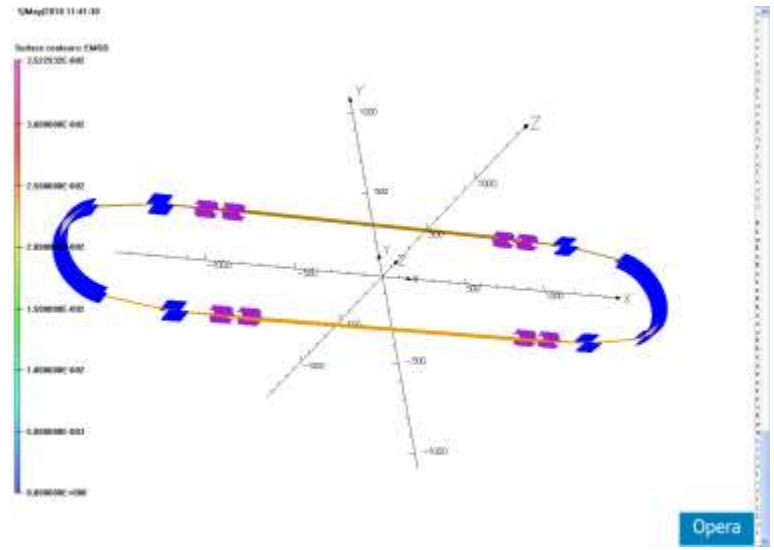
Two ESR of the same racetrack type as ELISA are overlapped,
to allow for ion-molecular head-on collision studies

NON-LINEAR EFFECTS IN ESR

Experimental data from ELISA ring

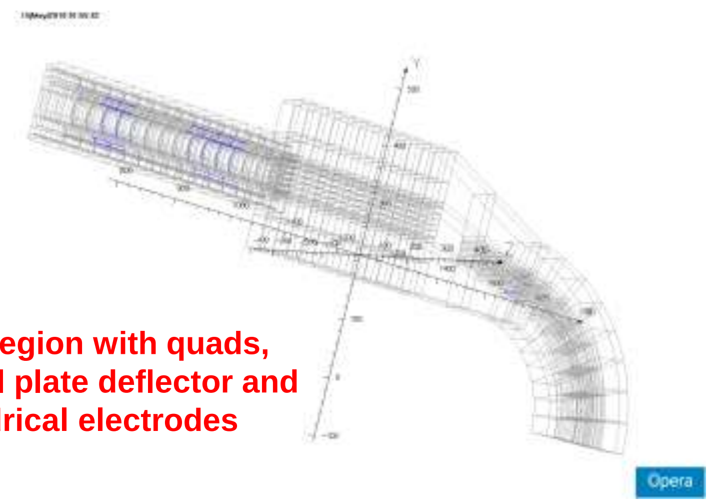


Model of ring used in OPERA3D



Dimensions and distances between elements similar to original ELISA design

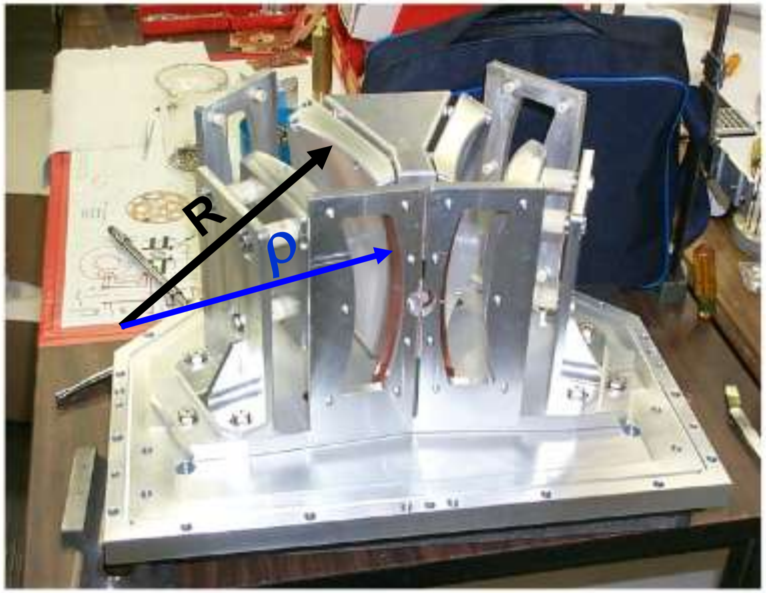
- **Decays of stored O– beams at 22 keV.**
- **Pink curve – ESD-SPH**
- **Others – ESD-CYL**
- **Beam losses grow with beam current increase**



Shown is region with quads, 10° parallel plate deflector and 154° cylindrical electrodes

Ring geometry was split in multiple sectors and parts to provide correct distribution of electric field

Basics ## Arbitrary shape of ESD



Electric field INDEX

$n_E = -(R/E_R)\, dE_R/dR \cong 1 + R/\rho$

$K_x = (3 - n_E - \beta^2) / R^2$

$K_y = (n_E - 1) / R^2$

ELFLD focusing condition $1 < n_E < 3$

sector magnet $0 < n_M < 1$

- Three-way electrostatic bend: left, right and straight through. Electrodes are spherical (concentric) giving focusing in both planes.
- In general electrodes are:
  - Concentric cylinders (*cylindrical bend*), or
  - Concentric spheres (*spherical bend*), or
  - Concentric toroids (*toroidal bend*).

$U\pm = (1/q)\, E_{kin}\, (d/R)$

ESD type	cylindrical	spherical	Hyperbolic	Anti-spherical
ρ	$\rho = \infty$	$\rho = R$	$\rho = -R/2$	$\rho = -R$
n_E	1	2	–1	0
k_X	$2/R^2$	$1/R^2$	$4/R^2$	$3/R^2$
k_Y	0	$1/R^2$	$-2/R^2$	$-1/R^2$
	focus in X drift in Y	Equal focus $f_x = f_y$	Focus X Defocus Y	Focus X Defocus Y

Equation of transverse motion in ESD with CYLINDRICAL shape electrodes

second order approximation

$$x'' + \frac{2}{R_{eq}^2} x - \frac{1}{R_{eq}^3} x^2 = 0$$

$$y'' = 0$$

Linear approximation

*X" + (2 / R**2) X = 0*

y" = 0

IN the Linear approximation Cylindrical deflector focuses beam in radial direction with DOUBLE strength wrt Sperichal electrode and it is DRIFT In axial direction

DIPOLE Magnet
Plane of bend

$$\frac{d^2x}{ds^2} + \left(\frac{1}{\rho_0^2} - k\right)x = \frac{1}{\rho_0}\frac{\Delta p}{p_0}$$

Equation of transverse motion in ESD with SPHERICAL shape electrodes

Second order approximation*

$$x'' + \frac{1}{R_{eq}^2} x - \frac{1}{R_{eq}^3} x^2 - \frac{3}{2 \cdot R_{eq}^3} y^2 = 0$$

$$y'' + \frac{1}{R_{eq}^2} y - \frac{3}{R_{eq}^3} xy = 0$$

Linear approximation

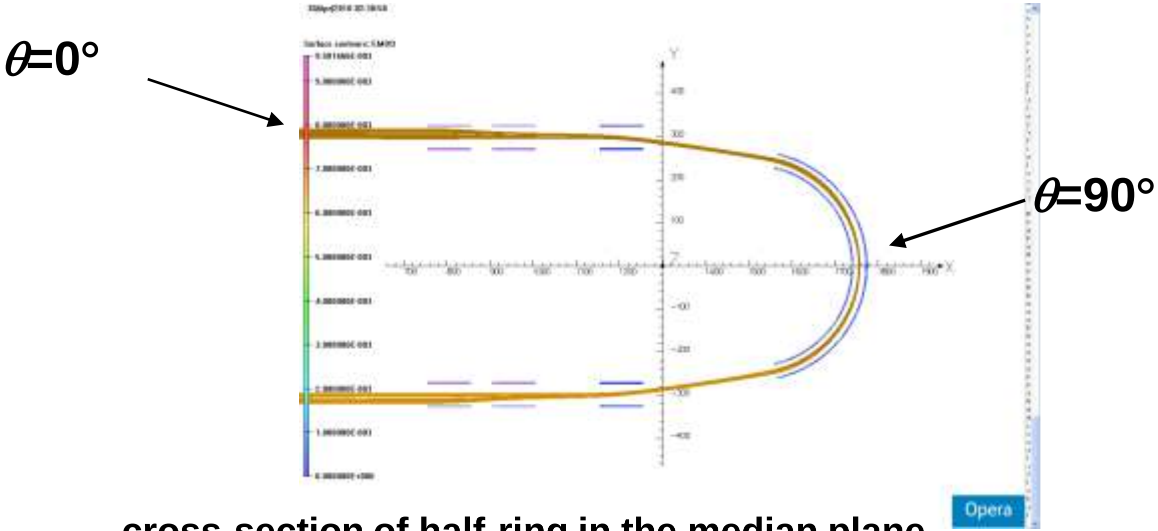
$$x'' + \frac{1}{R_{eq}^2} x = 0$$

$$y'' + \frac{1}{R_{eq}^2} y = 0$$

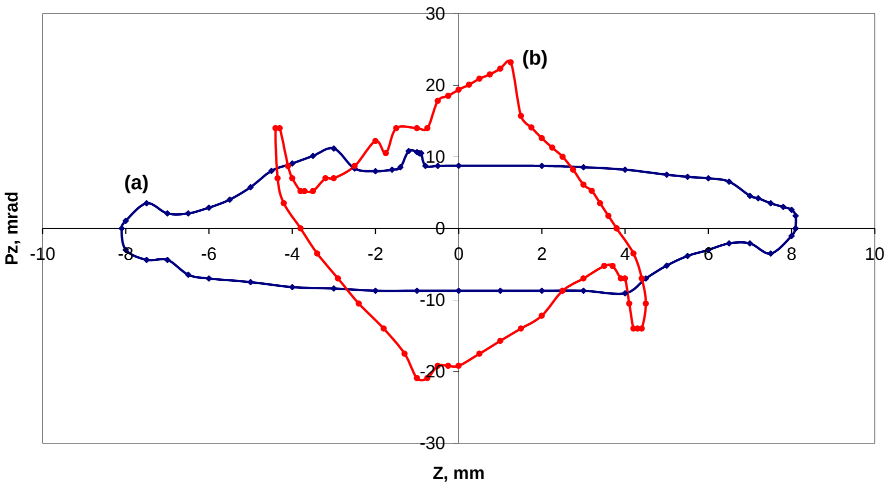
In the linear approximation spherical deflector focuses beam in both directions with the same force

* Yu.Senichev. "Beam Dynamics in Electrostatic Rings". Proc. Europ. Part. Accel. Conf., Vienna, Austria (2000).

NON-LINEAR EFFECTS IN ESR

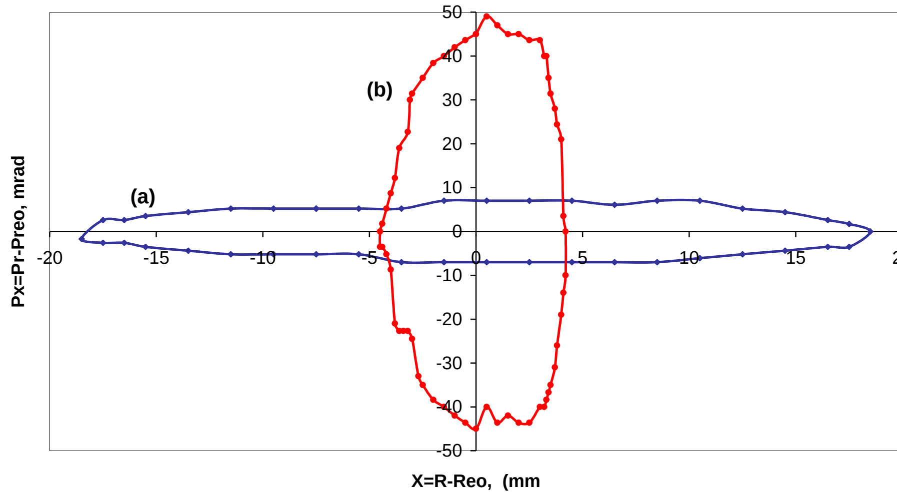


cross-section of half-ring in the median plane



Vertical acceptance of ring with 160° ESD-CYL.

a) middle of long straight section, θ=0°,
b) Middle of deflector, azimuth θ=90°.



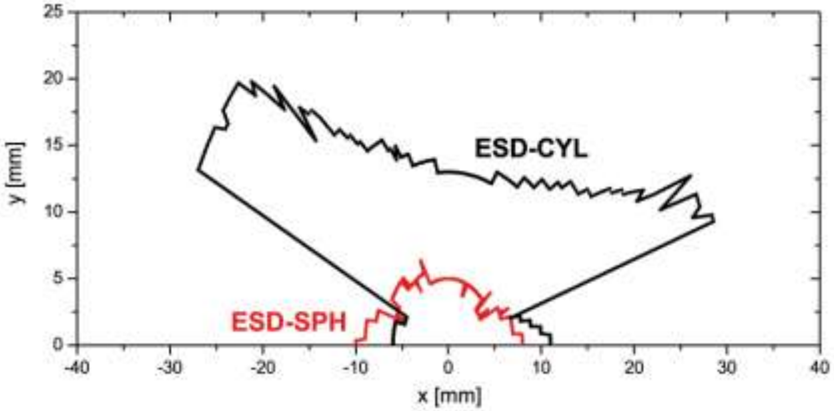
Radial acceptance of ring with 160° ESD_CYL.

a) middle of long straight section, θ=0°,
b) middle of deflector, azimuth θ=90°.

NON-LINEAR EFFECTS IN ESR

- Strong non-linear effects clearly visible in the axial phase space
- In vertical direction size of stable beam is reduced from $\Delta z = \pm 8$ mm at $\theta = 0°$ to
- $\Delta z = \pm 3$ mm inside deflector
- Ring acceptance in vertical plane might be estimated as $Ax \sim 30\pi$mm·mr i.e. five times less than in radial direction.
- It is despite the fact that radial gap between electrodes is narrow (±15 mm) while in vertical direction electrodes are extended over ±50 mm
- Coupling between radial and axial phase spaces is a possible reason of beam losses in the ring.
- with increase of beam current from ion source (in our example - in 30 times) beam emittance is growing and transmission in the ring is reduced i.e. beam losses grow
- for the Deflectors of SPHERICAL shape sextupole component of ELFLD distribution is 3.5 times more then for ESD-CYL
- ring acceptances with ESD-SPH much less and nonlinear effects more visible
- Most important non-linear harmonic is sextupole one (next slide)

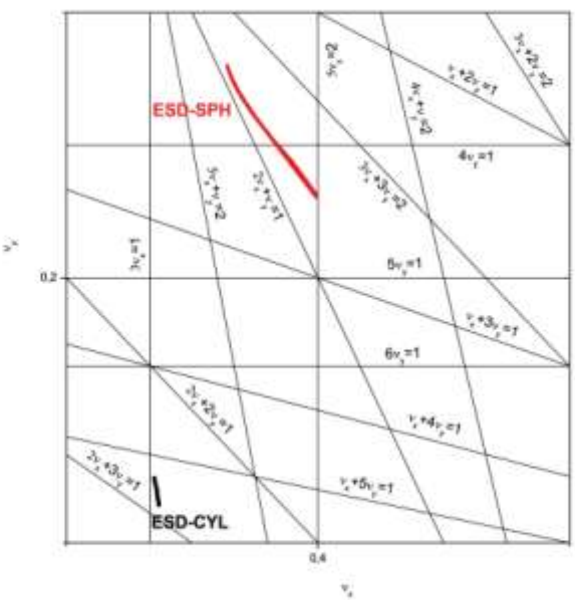
NON-LINEAR EFFECTS IN ESR (MAD-X nonlinear study)



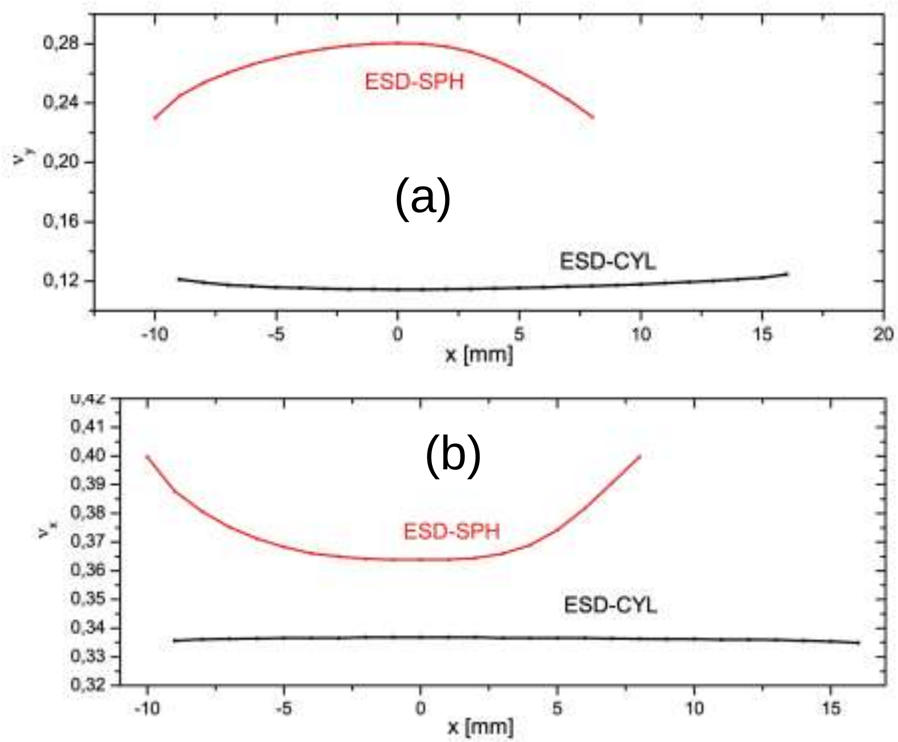
Dynamic aperture of ES ring with cylinder and spherical deflectors

Fourier analysis of ELFLD in OPERA-3D
Integral field harmonics of the cylindrical and spherical deflector at R = 14mm. Data are normalized to the main dipole component

n	ESD-CYL	ESD-SPH
1 Dipole	1.00	1.00
2 Quadr	5.63E-2	1.09E-1
3 Sext	1.67E-03	6.11E-03
4 Octupole	4.31E-05	1.30E-03
5	2.73E-05	1.31E-04
6	1.89E-05	1.03E-04

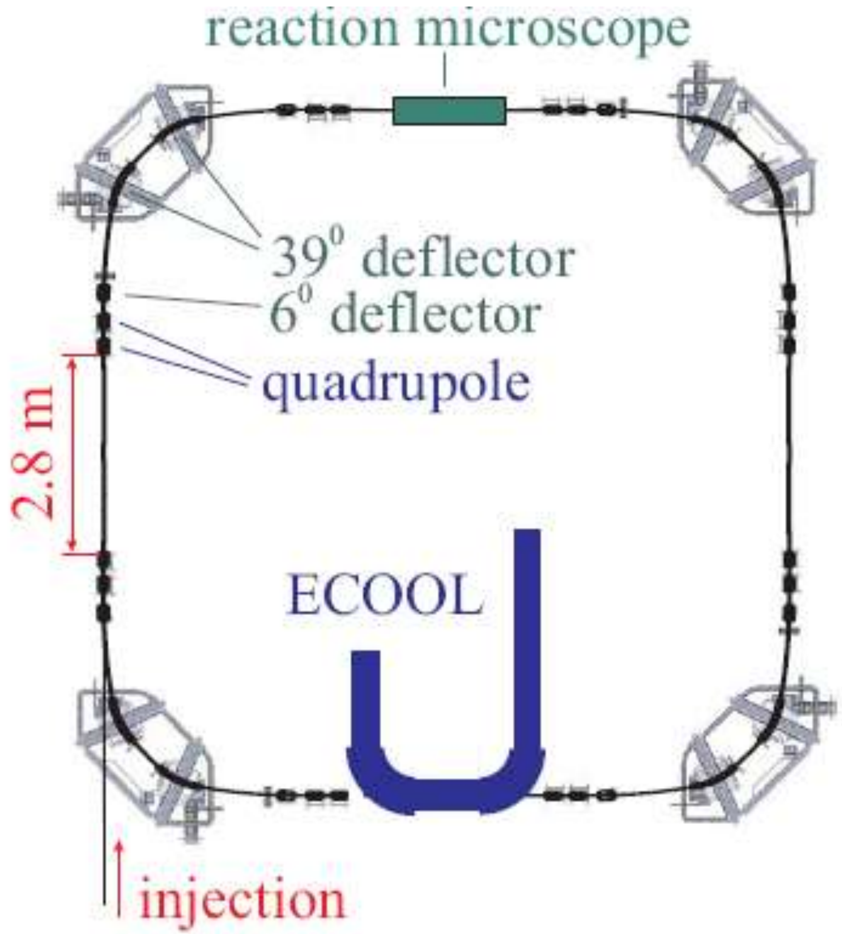


Amplitude-dependent tune shift for ESD-CYL and ESD-SPH

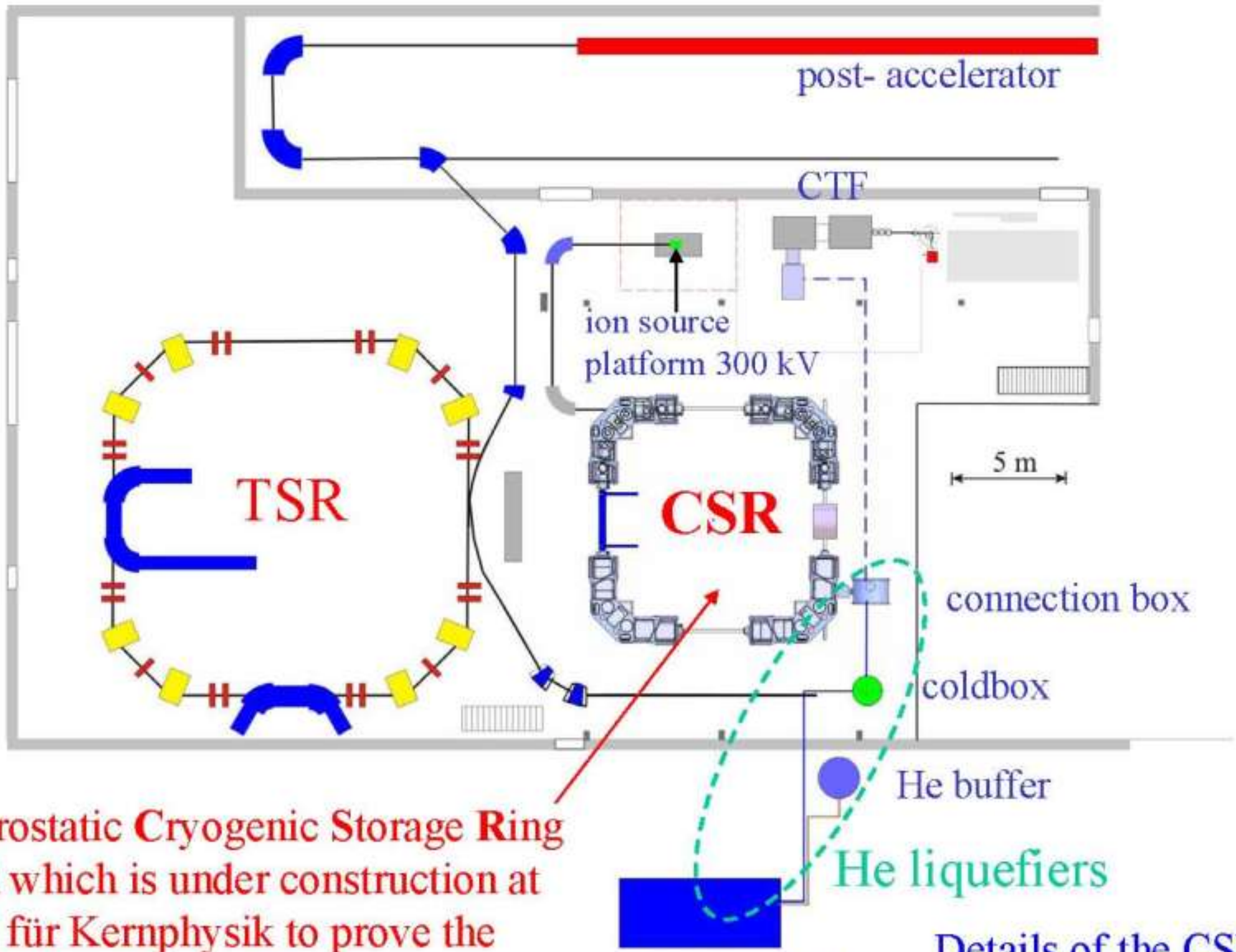


Amplitude dependent vertical (a) and horizontal (b) tune shifts for ESD-CYL and ESD-SPH

CRYOGENIC STORAGE RING (CSR)
at Max Planck institute of Nuclear Physics (Heidelberg, GERMANY)



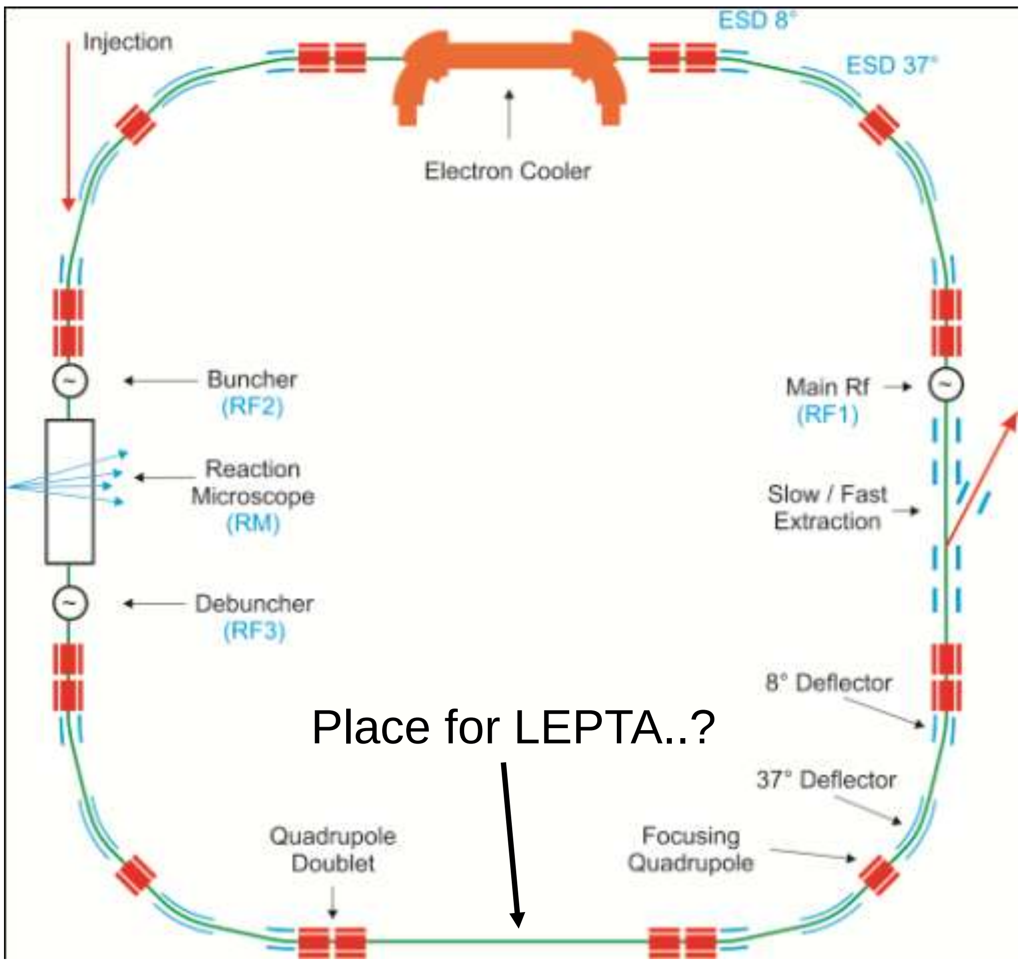
Layout of the CSR. The ring has a 4-fold symmetric lattice, each cell consists of two 39°, two 6° deflectors and two quadrupole doublets



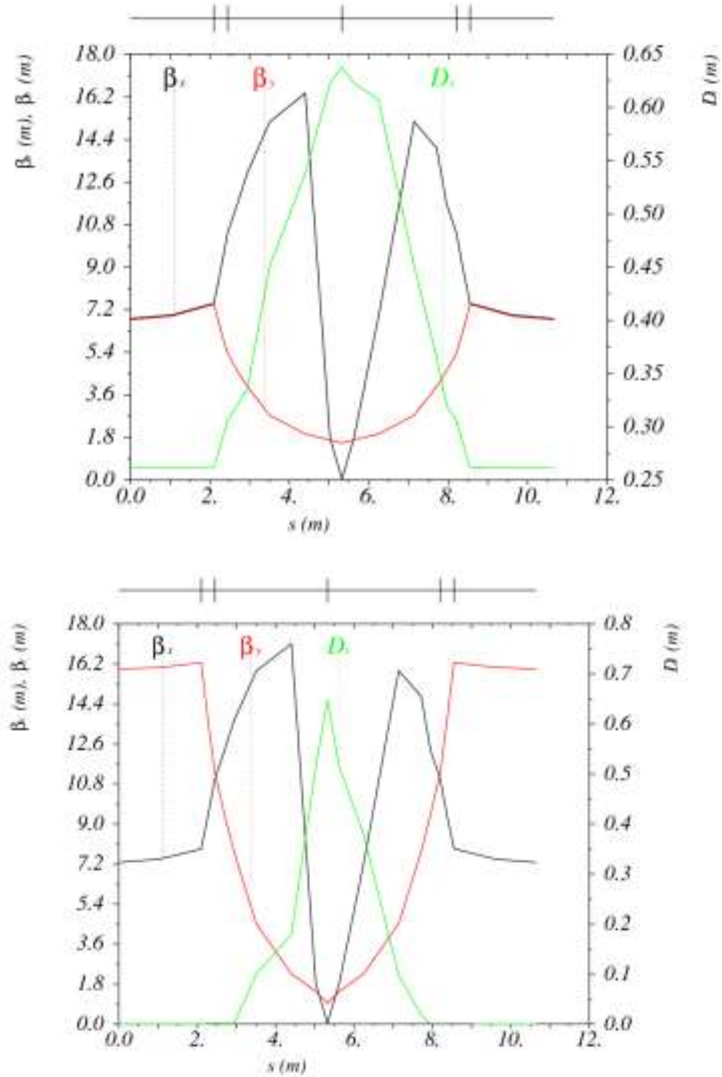
Cryogenic **S**torage **R**ing: an electrostatic ring, **CSR**, which is under construction at **MPI** für Kernphysik to prove the feasibility of the USR project

Details of the CSR project: talk given by R. v. Hahn

ULTRA-LOW ENERGY STORAGE RING (USR)
(FAIR-FLAIR-GSI, Darmstadt, Germany)

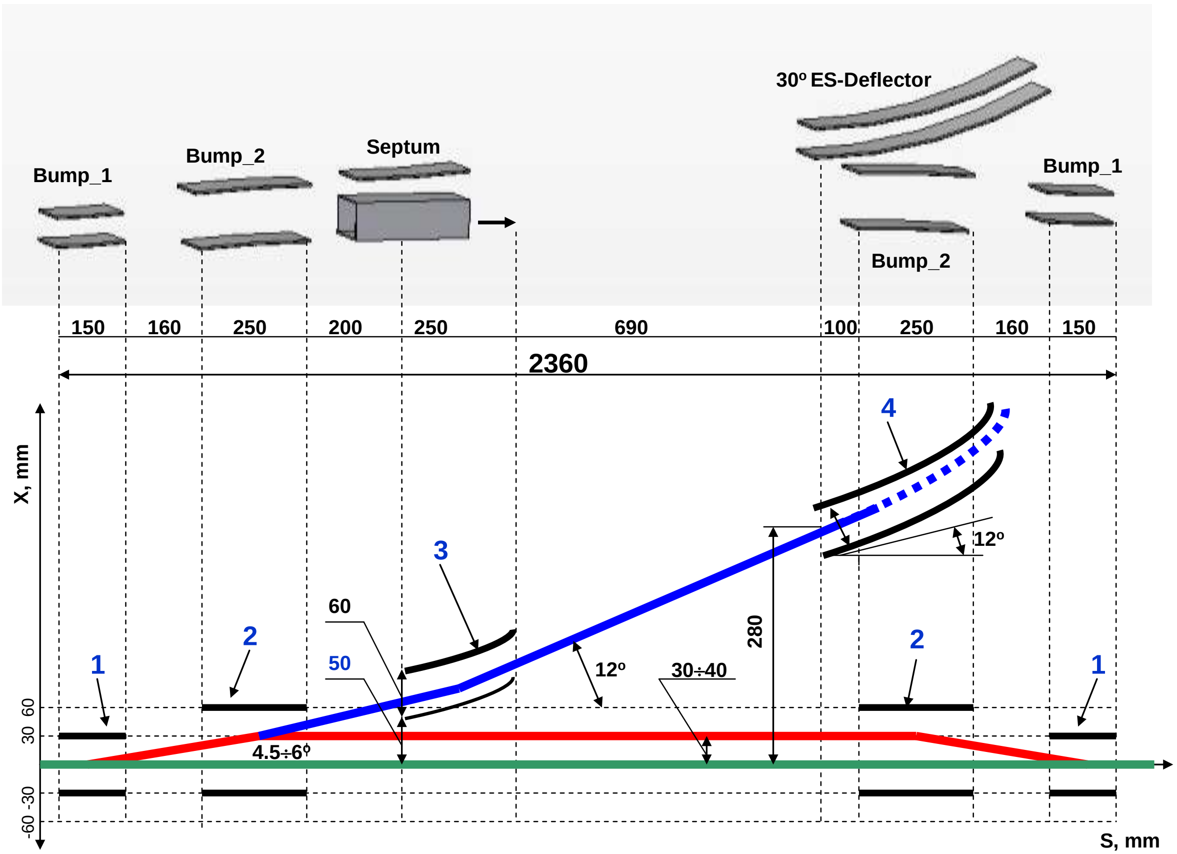


Layout of the ultra low energy storage ring USR



Beta function and dispersion in one ring quarter. (a) round beam mode (b) Achromat (short bunch operation)

ULTRA-LOW ENERGY STORAGE RING (USR)

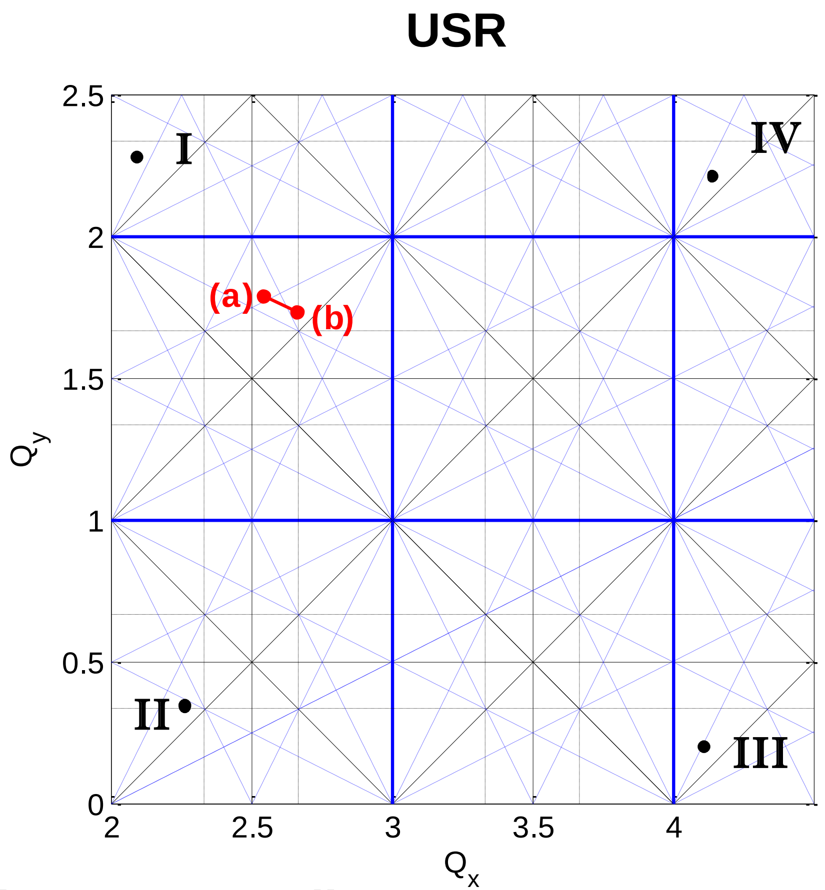


Location of elements in the combined SLOW/FAST extraction system.

1 and 2 - parallel plate bump electrodes;

3 – 6° electrostatic septum deflector of cylindrical shape;
entrance tilt angle with respect to the beam axis is variable from 0° to 6°;

4 - 30° electrostatic deflector.



The USR tune diagram.

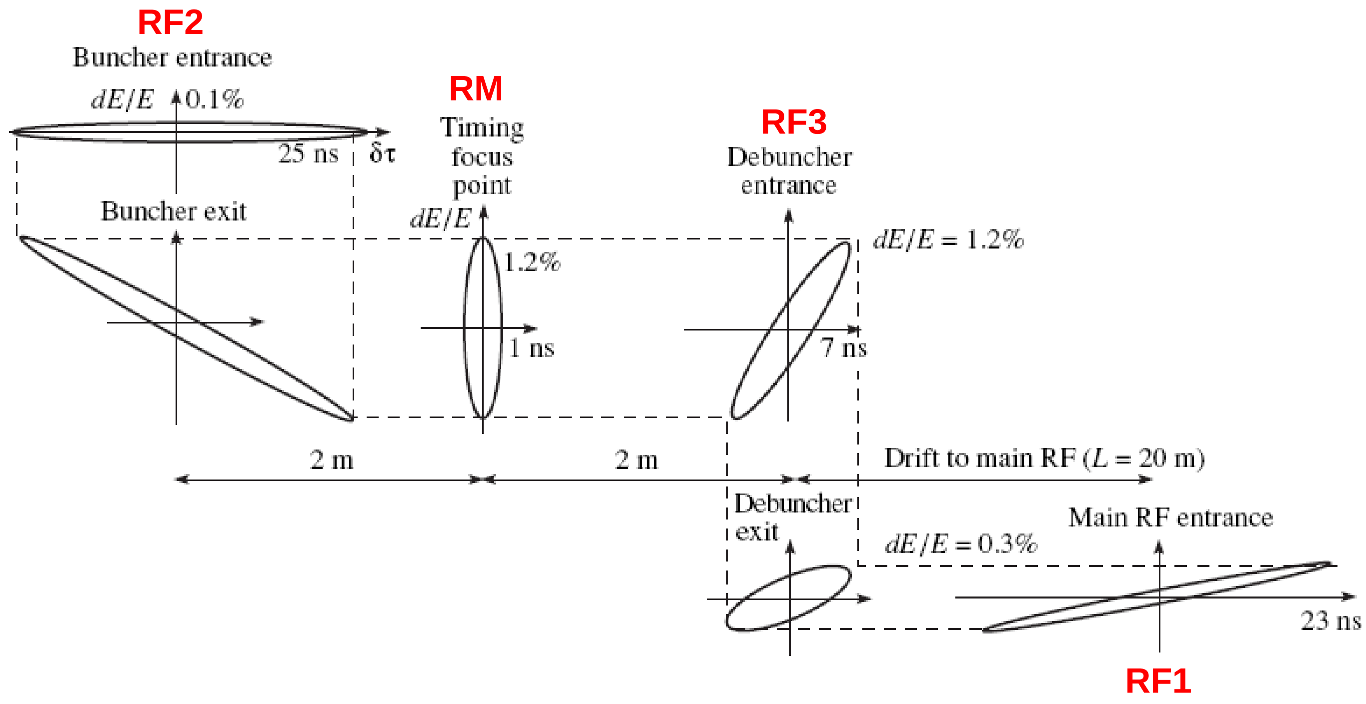
(a) The operation point of the stored beam ν_r=2.5443 and ν_z=1.7905;

(b) The excited resonance ν_r=2.6637 and ν_z=1.7315 during slow extraction

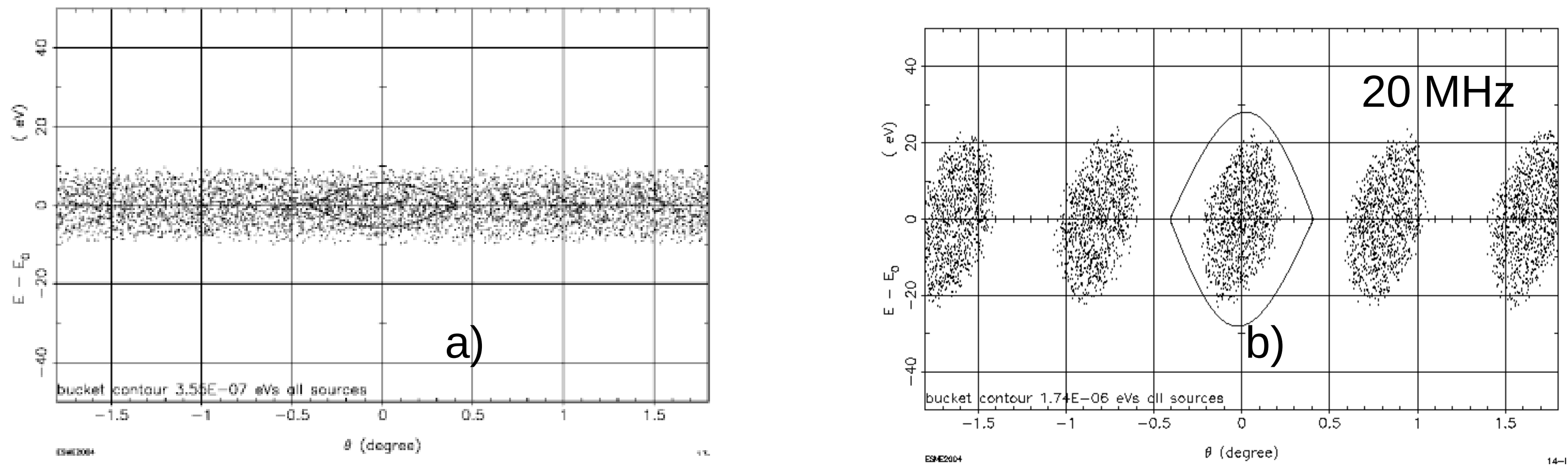
Also shown are the operation points of the original USR design.

USR
ultra-short bunch operation mode

Illustration of the beam compression - decompression scheme



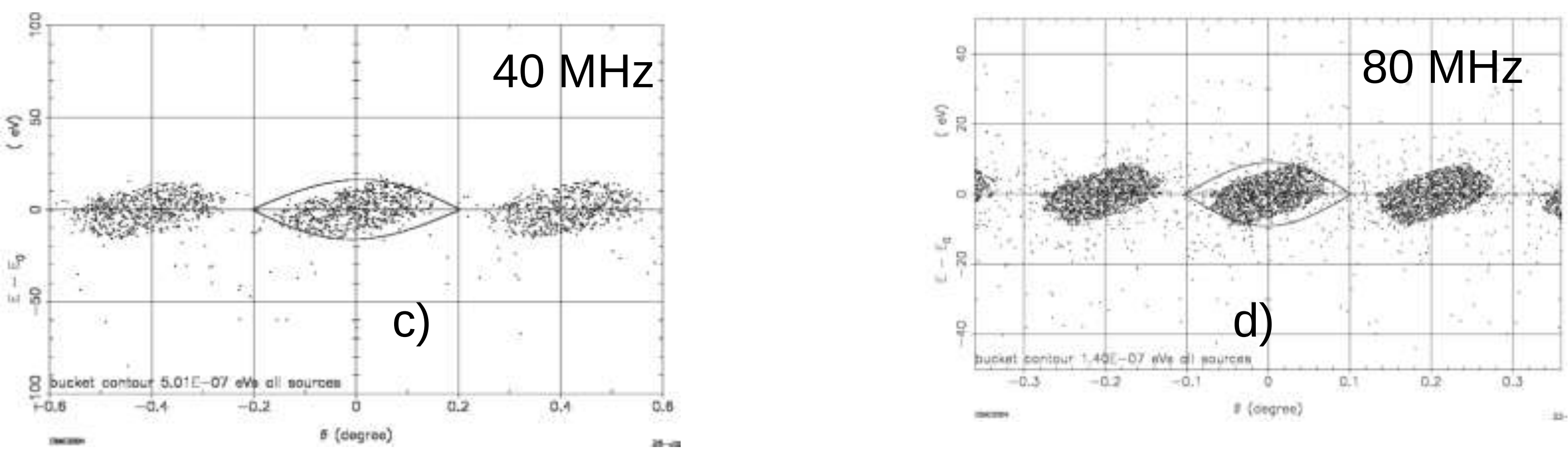
USR short bunch operation mode. High harmonic RF capture (ESME simulations)



Iso-adiabatic capture of the coasting beam by a 20 MHz RF cavity (h_{RF}=440, E = 20 keV)

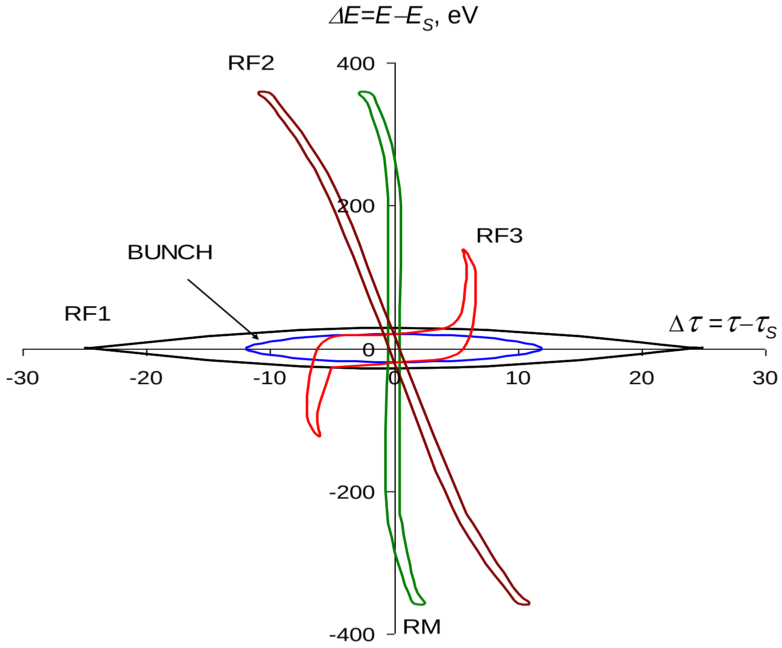
a) Initial beam distribution in longitudinal phase space ($\Delta\theta$, ΔE), ΔE=±10 eV coasting beam,

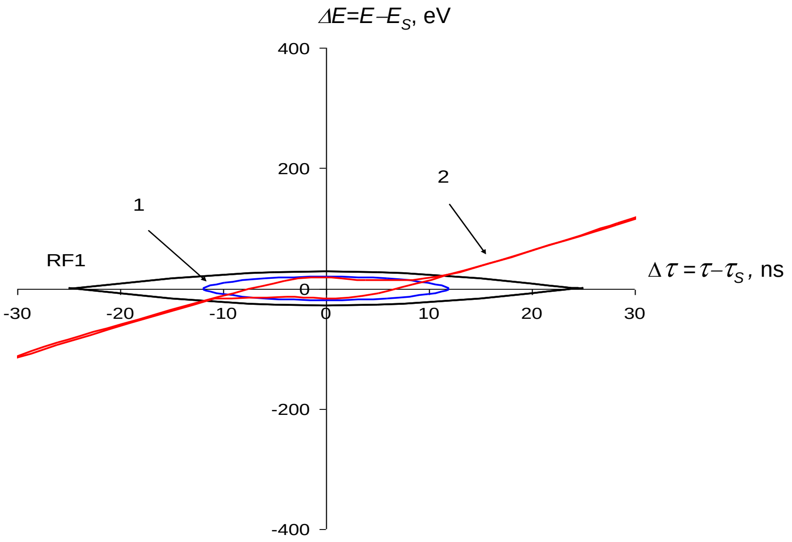
b) Beam distribution after RF capture; ΔE=±20 eV, final RF bucket is shown

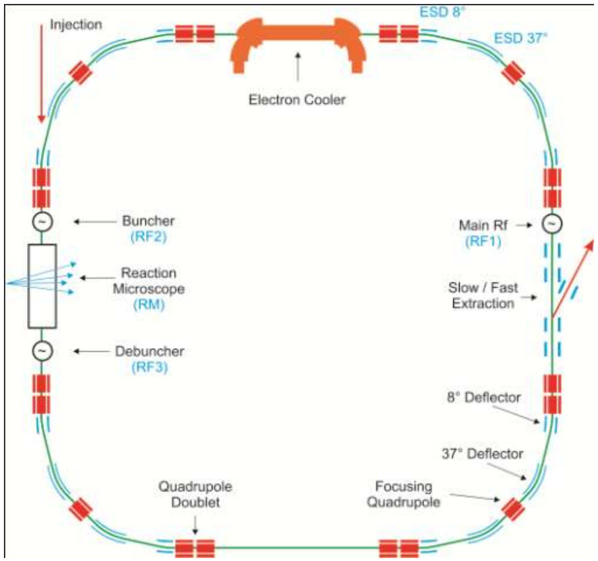


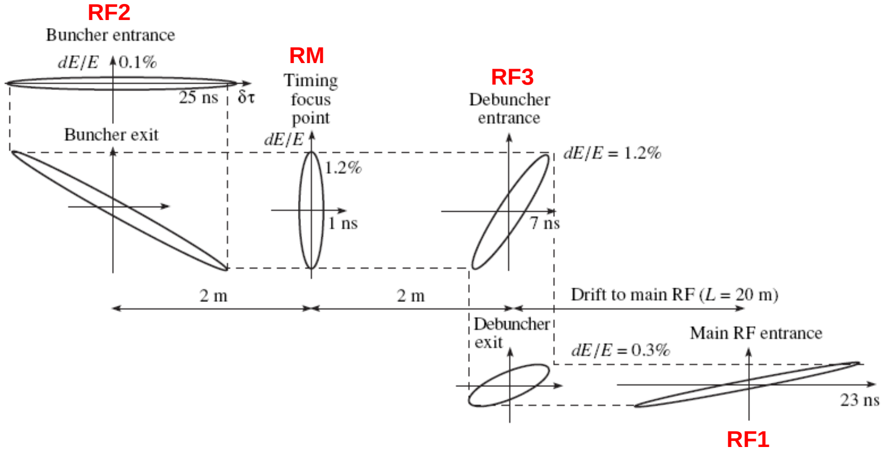
Losses during Iso-adiabatic capture of 20 keV coasting beam:
(c) by 40 MHz RF, (d) by 80 MHz RF

USR ultra-short bunch operation mode
Compression-decompression (MAD-X simulations)

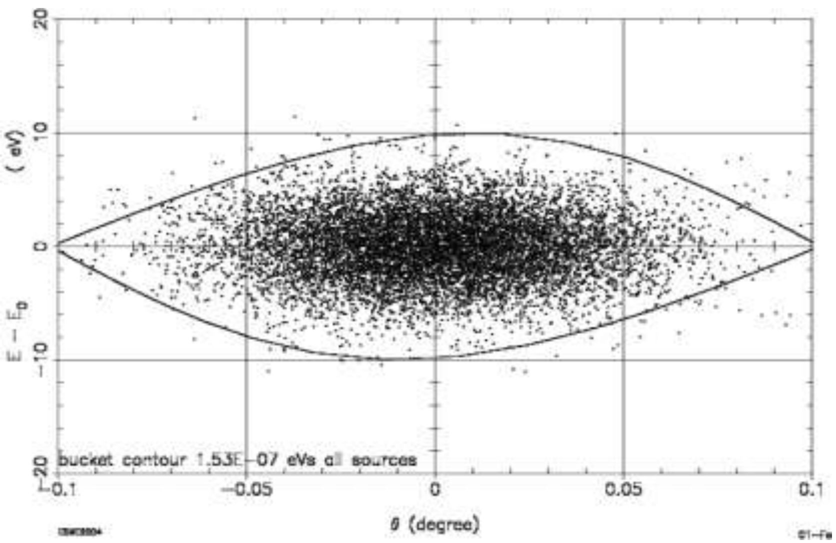


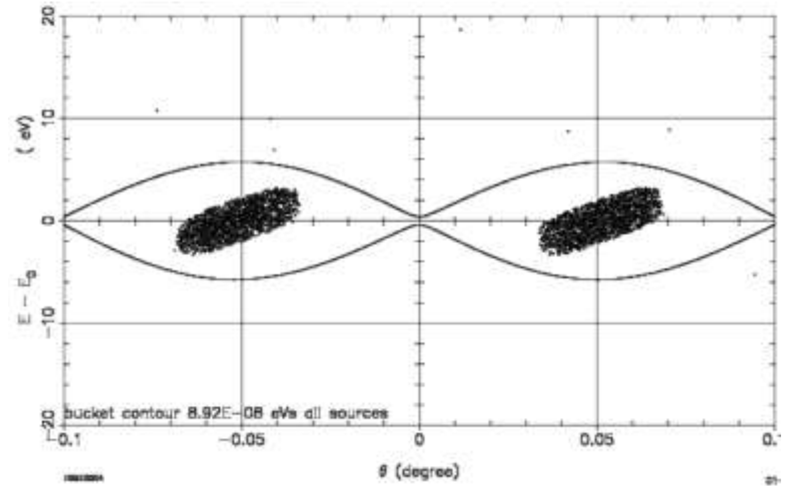


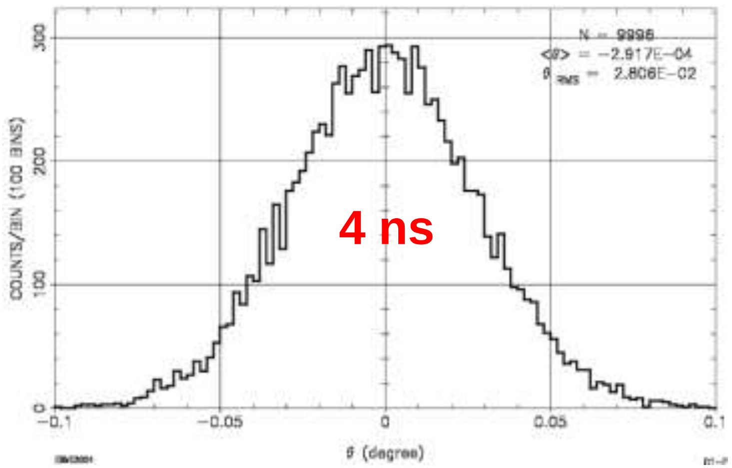


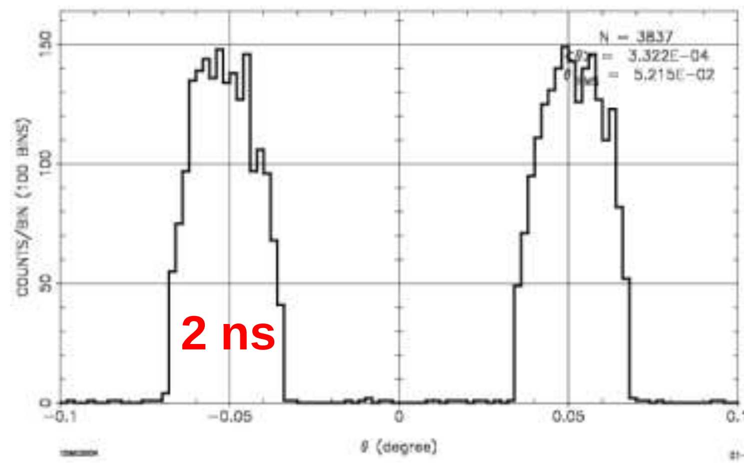


USR multiple split of high harmonic RF frequency (80 to 160 MHz)







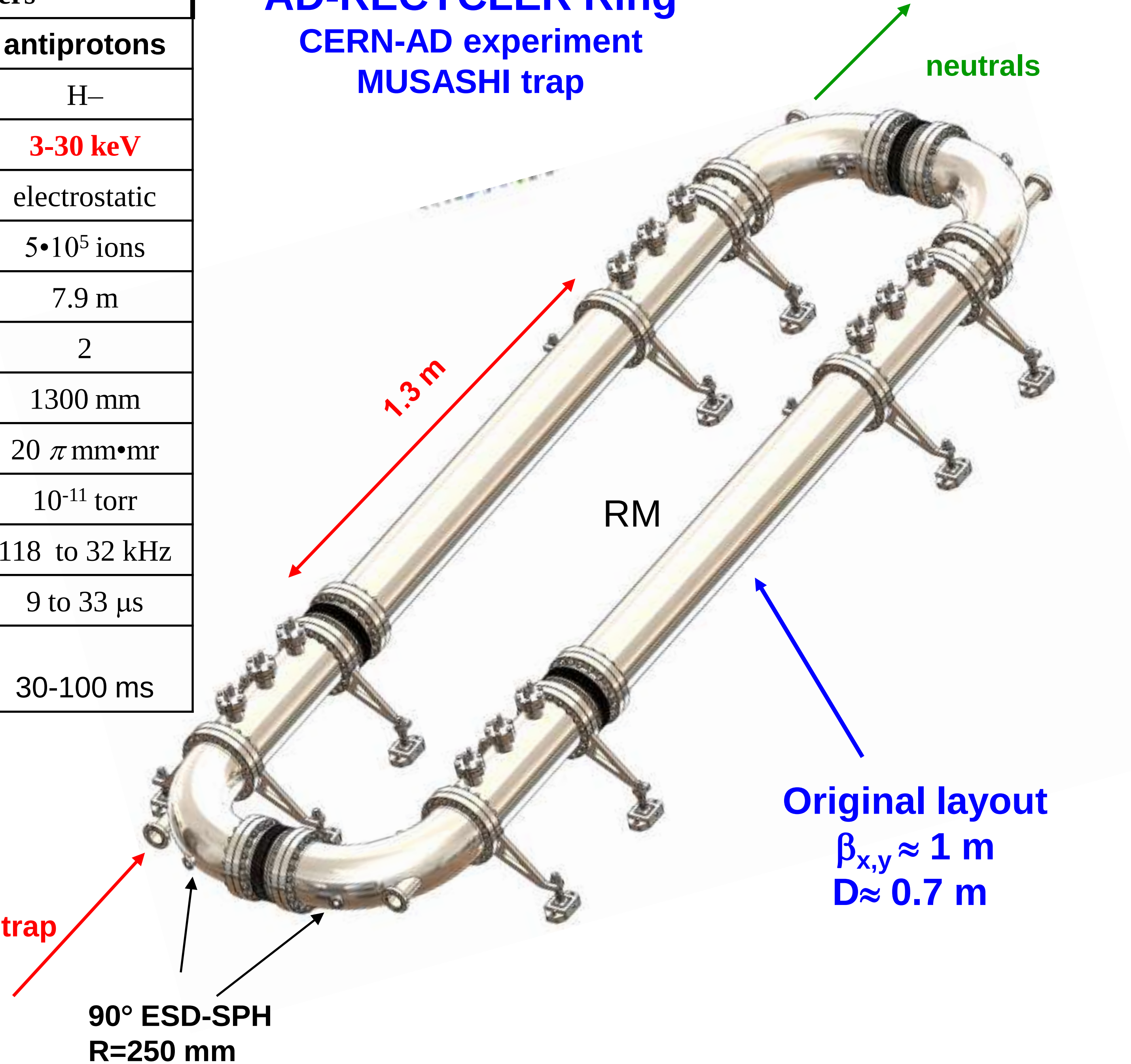


Iso-adiabatic split where the RF frequency is changed from 80 to 160 MHz (h_{RF}=1760 to h_{RF}=3520)

Ring parameters	
Ions	**antiprotons**
Test ions	H–
Energy Range	**3-30 keV**
Type	electrostatic
Beam intensity	$5 \cdot 10^5$ ions
Circumference	7.9 m
Straight sections	2
Straight section length	1300 mm
Ring Acceptance	20 π mm•mr
Vacuum	10^{-11} torr
Ion rotaton frequency	118 to 32 kHz
Ion rotation period	9 to 33 μs
Operation time ~3000 turns	30-100 ms

AD-RECYCLER Ring

CERN-AD experiment MUSASHI trap

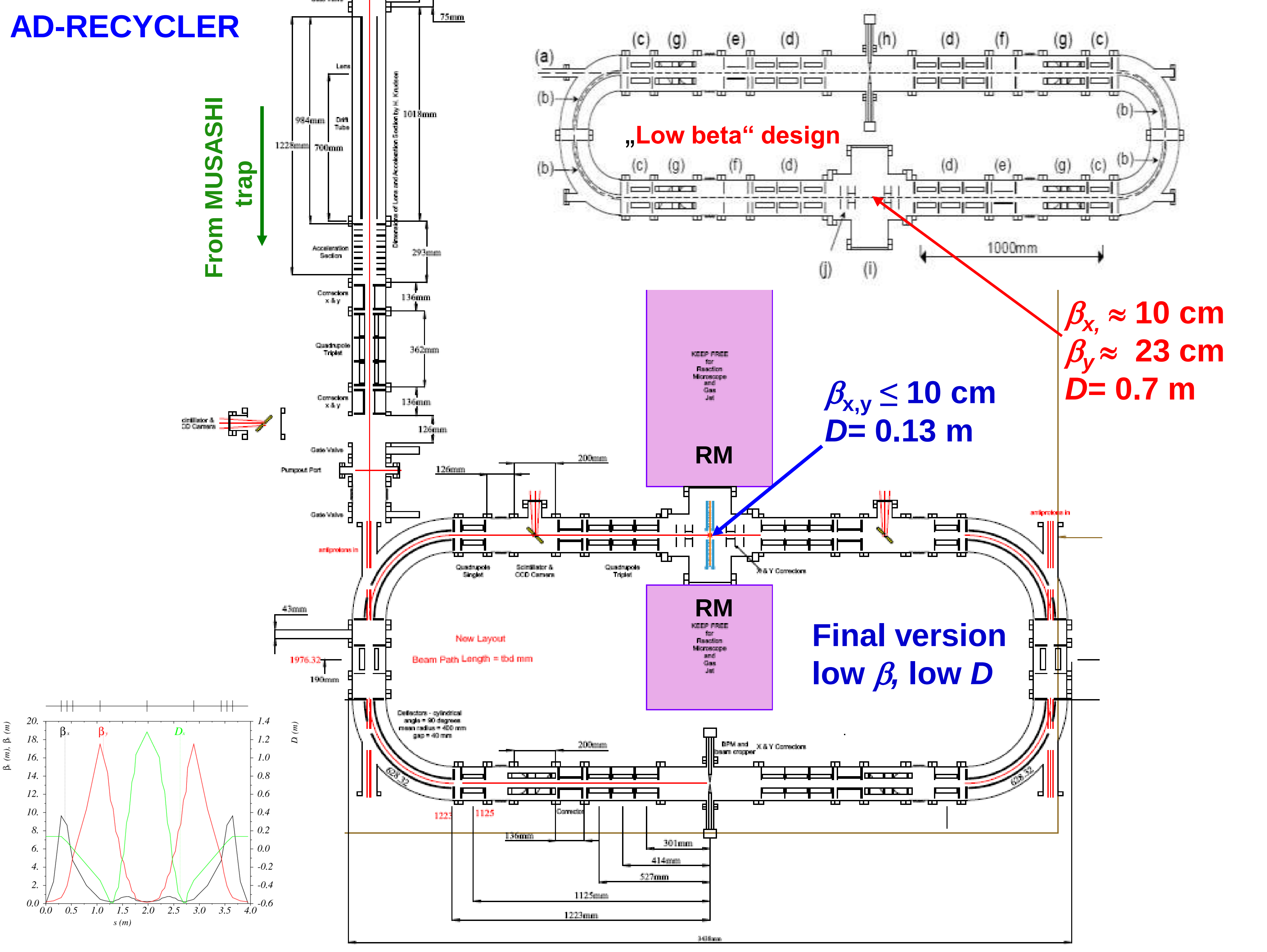


Original layout

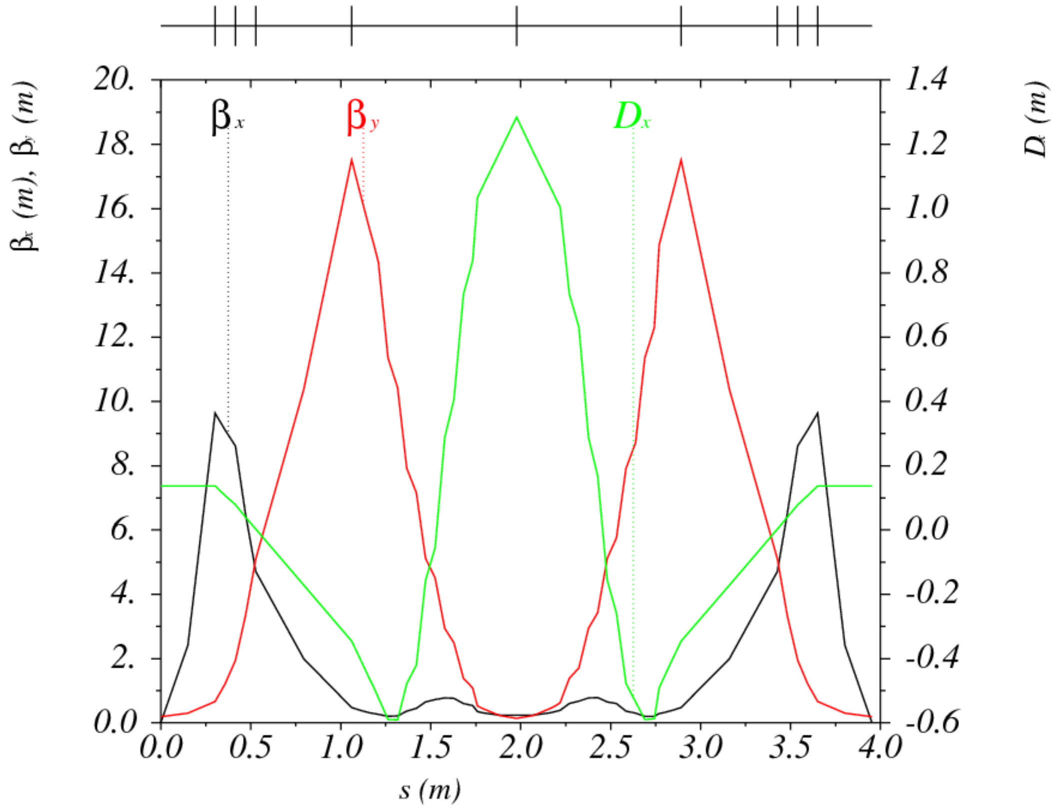
$\beta_{x,y} \approx 1$ m

$D \approx 0.7$ m

AD-RECYCLER


From MUSASHI trap
„Low beta“ design
1000mm
$\beta_{x,} \approx 10$ cm
$\beta_y \approx 23$ cm
D= 0.7 m
$\beta_{x,y} \leq 10$ cm
D= 0.13 m
RM
KEEP FREE for Reaction Microscope and Gas Jet
RM
KEEP FREE for Reaction Microscope and Gas Jet
Final version
low β, low D
New Layout
Beam Path Length = tbd mm
75mm
1018mm
984mm
1228mm
700mm
293mm
136mm
362mm
136mm
126mm
200mm
126mm
Acceleration Section
Correctors x & y
Quadrupole Triplet
Gate Valve
Pumpout Port
Quadrupole Singlet
Scintillator & CCD Camera
Quadrupole Triplet
X & Y Correctors
antiprotons in
43mm
190mm
Deflectors - cylindrical
BPM and beam cropper
200mm
136mm
301mm
414mm
527mm
1125mm
1223mm
β_x β_y D_x
β_x (m), β_y (m)
D (m)
s (m)

AD-REC Lattice



AD-REC low-β mode, MAD-X. Shown is one cell. In the middle of the straight section, the dispersion is D=15 cm and the beta-functions $\beta_{x,y} \approx 10$ cm.

ACKNOWLEDGMENTS

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