Long term beam dynamics in an ultra-low energy storage rings
(BETACOOL and non-linear studies)

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OUTLINE

1. Introduction

2. Benchmark on ELISA ring

    - beam degradation
    - beam profile
    - growth of momentum spread

3. Operation with internal target

4. Ring operation with e-cool and target

    - benchmark on TSR fotocathode
    - predictions for USR operationclusion

- 5. CONCLUSIONS

Abstract

Electrostatic storage rings operate at very <u>low energies in the keV</u> range and have proven to be invaluable tools for <u>atomic</u> and <u>molecular physics</u> experiments.

However, earlier measurements showed <u>strong limitations in beam intensity</u>, a fast <u>reduction</u> in the stored <u>ion current</u>, as well as significantly <u>reduced</u> beam <u>life time</u> at higher beam intensities and as a function of the ion optical elements used in the respective storage ring.

In this contribution, the results from studies with the computer code BETACOOL into the <u>long term beam dynamics</u> in such storage rings, based on the examples of ELISA ring are presented. Detailed investigations into the ion kinetics under consideration of the effects from electron cooling and multiple scattering of the beam on a <u>supersonic gas jet internal target</u> have been carried out.

The life time, equilibrium momentum spread and equilibrium lateral spread during <u>collisions with this internal gas jet target were estimated</u>. Based on these simulations, conditions for stable ring operation are presented.

Existing and future ES storage Rings at UltraLow Energy Range

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, molecule	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**	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.

“Exploring Sub-Femtosecond Correlated Dynamics with an Ultra-low Energy Electrostatic Storage Ring”

C.P. Welsch*, M. Grieser, A. Dorn, R. Moshammer, J. Ullrich,

AIP Conf. Proc. 796 (2005) p. 266-271

”An ultra-low-energy storage ring at FLAIR”

C.P. Welsch*, M. Grieser, J. Ullrich, A.Wolf

NIM A 546 (2005) 405–417

Abstract

- Whereas the three-body **Coulomb problem** for single excitation and ionization was claimed to be solved in a mathematically correct way for electron impact on hydrogen and helium, **ion-impact ionization** still represents a major **challenge** for theory.

- Troubling **discrepancies** have been observed in **fully differential cross sections (FDCS)** for helium single ionization by fast ion impact and even experimental **total cross sections** are in striking **disagreement** with the predictions of all state-of-the-art theories for low-energy antiproton collisions.

- Therefore, within the future Facility for Low-energy Antiproton and Ion Research (FLAIR), it has been proposed to **combine** state-of-the-art **many-particle imaging methods** with a novel **electrostatic storage ring** for slow antiprotons in order to

- **realize** single and multiple ionization cross section **measurements** for antiprotons colliding with atoms, molecules and clusters. Total, as well as any differential cross sections up to FDCS including ionization excitation reactions are envisaged to become available, serving as **benchmark** data for theory.

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Conclusion

- Despites its principal simplicity and central importance for atomic processes in particular, as well as for the understanding of **correlated few-particle quantum dynamics** in general, a full theoretical description of the **kinematics in singly and doubly ionizing antiproton collisions** in the time regime of few to **sub-femtoseconds** is still far from being available

- Ultra-low energy antiprotons in the energy range between 20 keV and 300 keV delivered by a novel **electrostatic storage ring** with its integrated an in-ring **reaction microscope** (supersonic gas jet) will provide an unsurpassed tool to investigate the importance of **correlation** effects on these timescales with unprecedented precision and completeness. They will serve as important **benchmark** data to test strong field theories in the presence of correlation

Physics with ES storage rings

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. 37 (2004) R57–R88 PII: S0953-4075(04)63251-2

TOPICAL REVIEW

Physics with electrostatic rings and traps

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Journal of Physics: Conference Series 4 (2005) 296–299
Sixth International Conference on Dissociative Recombination

Physics with colder molecular ions: The Heidelberg Cryogenic Storage Ring CSR

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- lifetime of meta-stable atomic states
- ion-impact ionisation to benchmark theoretical predictions
- 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 dissociative recombination of molecular ions with low temperature electrons
- molecular dynamics - Coulomb cristallization for a fast strored beam
- phase transition to a cristalline beam
- investigations of the single component plasma
- antihydrogen studies by mergins antiprotons with positrons (USR ?)

Why ES rings ?
To reduce energy as low as possible

- Electrostatic traps and rings allow operation with ion beams at **ultra-low energies (keV/A)**
- Ion traps store ions as **long** as possible, localize the stored particles in **space**
- ESR **complimentary** to Ion traps
- In ESR Ions circulate in **one direction** -- in traps no preferable direction of motion
- ESR -- for storage, acceleration and **deceleration**
- ESR – **mass independent**

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

magnetic field $\mathbf{(BR)^2 \sim (A/q)\, E_{kin}}$ - mass dependent

A –ion mass q – ion charge E – ion kinetic energy d - gap between plates R – curvature radius B - field

- ....
- ESR **Mass range** (1< A < 1000) - from protons / antiprotons to heavy molecula ions, clusters,high charge state ions, positive and negative ions

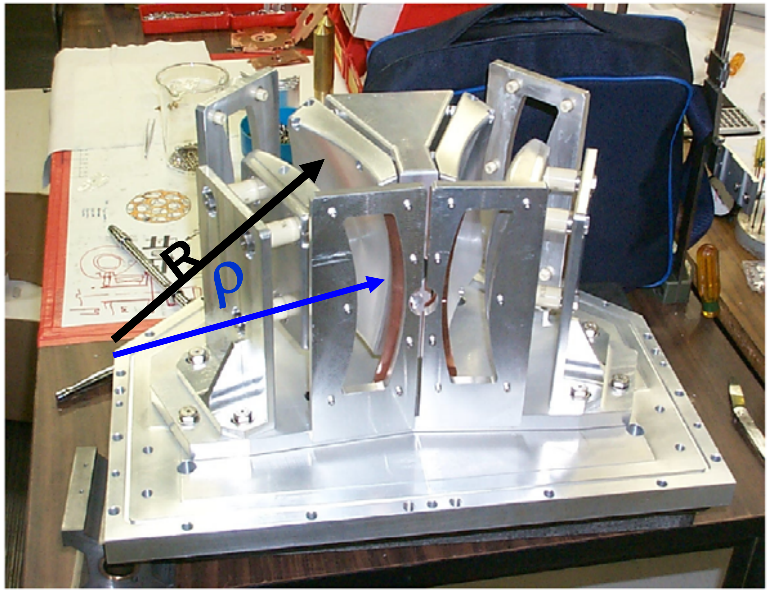
Why ES rings ?

- 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)

Basics

Arbitrary shape of ESD

JUAS08_03- P.J. Bryant - Lecture 3
Transverse motion & Electrostatic elements



- 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*).

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

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

$$0 < n_M < 1$$

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

Linear approximation

$$x'' + (2 / R_{eq}^2)\, x = 0$$
$$y'' = 0$$

ESD-CYL
Radial - double strength focusing
Vertical - drift

Second order *

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

$$y'' = 0$$

DIPOLE Magnet
Plane of bend

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

Equation of transverse motion in ESD with SPHERICAL shape electrodes

Linear approximation

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

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

ESD-SPH
Radial = Vertical = equal focusing

Second order *

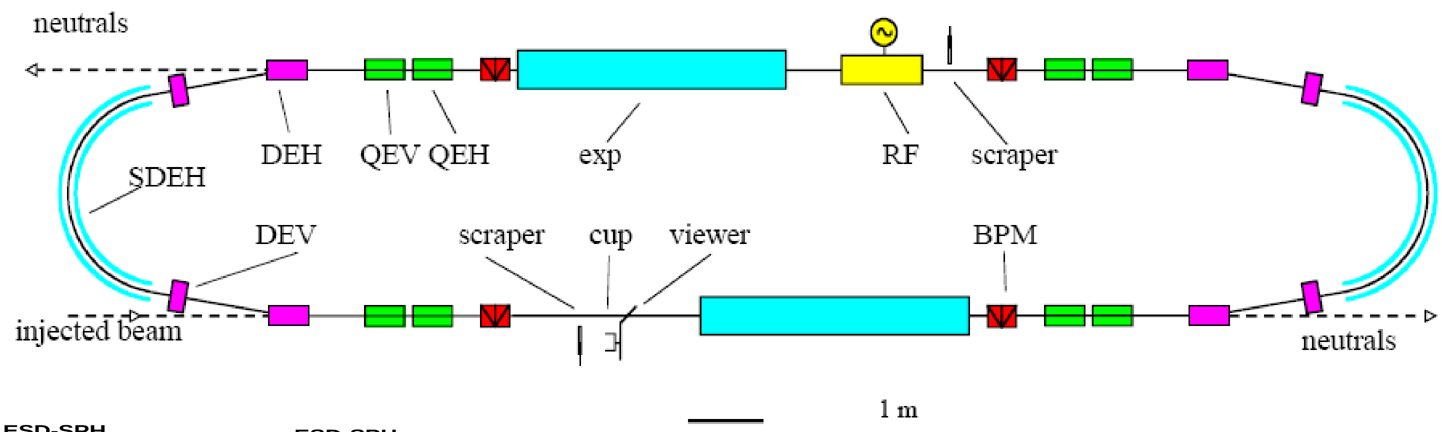
$$x'' + \frac{1}{R_{eq}^2} x - \frac{1}{R_{eq}^3} x^2 - \frac{3}{2 \cdot R_{eq}^3} y^2 = 0$$

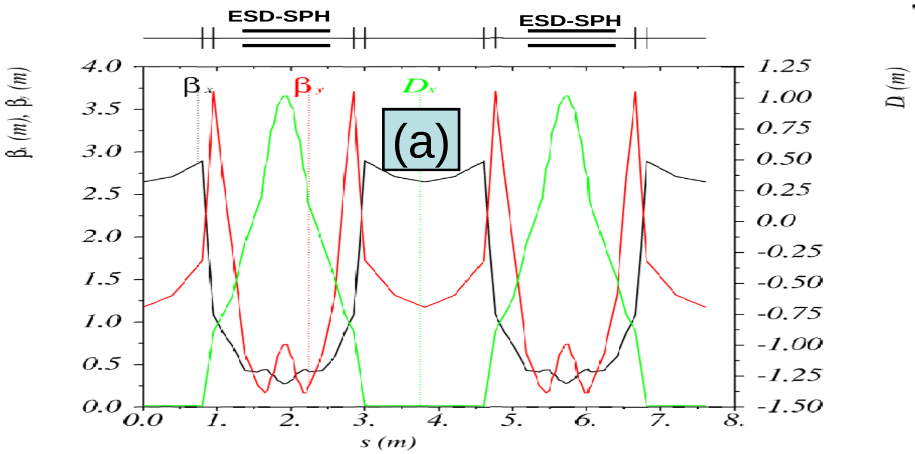
$$y'' + \frac{1}{R_{eq}^2} y - \frac{3}{R_{eq}^3} xy = 0$$

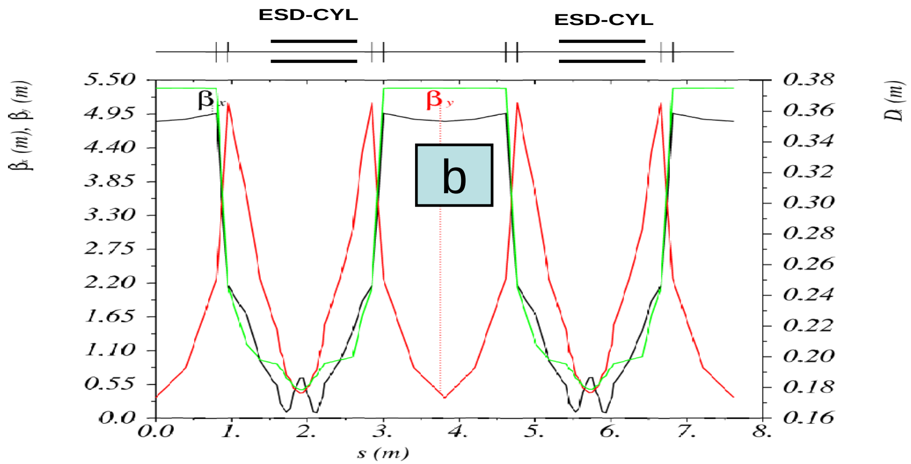
* Yu.Senichev. “Beam Dynamics in Electrostatic Rings”.
Proc. Europ. Part. Accel. Conf., Vienna, Austria (2000).

ELISA

Benchmark of ELISA experiment







ELISA ring lattice (MAD-X): a) spherical electrodes provides sharp focus β_y^{min} =0.07m; b) 160° electrodes of cylindrical shape, minimum value of beta-fuction β_x^{min} =0.13 m;

1. S.P. Moller. Design and First Operation of the Elec-trostatic Storage ring ELISA. *Proc.EPAC-1998*. p.73-77.

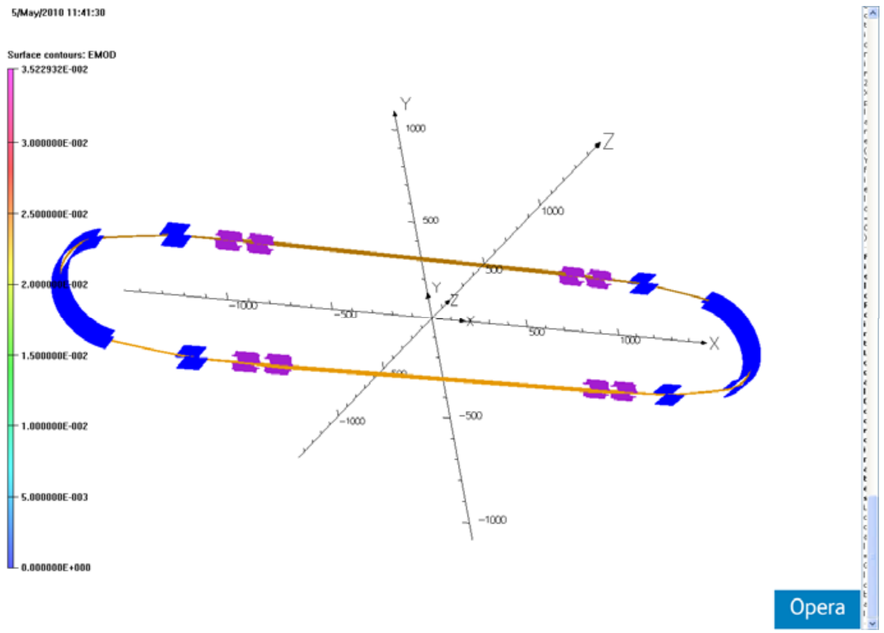
2. S.P. Moller. “Operational experience with the electrostatic Storage ring, ELISA”. *Proc. PAC-1999*. p.2295-2297.

3. S.P.Moller et al. Intensity Limitations of the Electrostatic Storagfe Ring ELISA. *Proc. EPAC-2000*. p.788-790.

ESR Beam dynamics - Advanced Studies

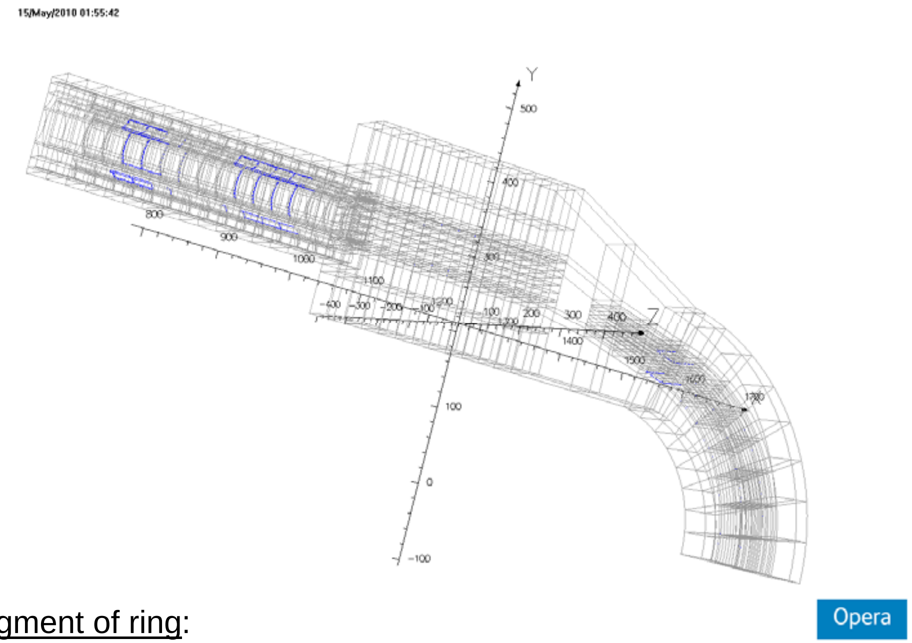
- **Non linear beam dynamics and long term beam kinetics**
- **Full 3D ring model**
- **Similar approach used for most new FAIR rings**
- **Benchmark on ELISA ring (Aarhus, Denmark)**

ELISA OPERA3D Model and orbit tracking



A.Papash et al. Proc. IPAC (2010)

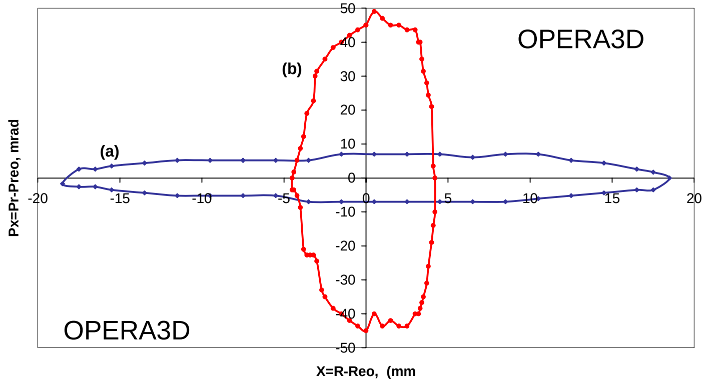
Ring geometry split in multiple sectors and parts to provide correct distribution of electric field



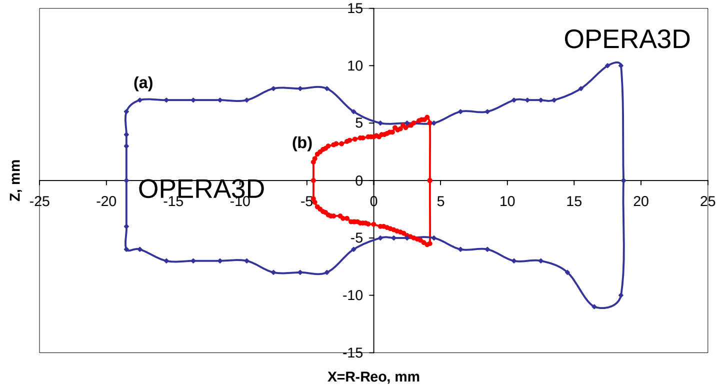
<u>Segment of ring</u>:
Bending section with quads, 10° parallel plate deflector and half of 154° cylindrical electrodes

Benchmark on ELISA – Nonlinear Studies

Horizontal Acceptance

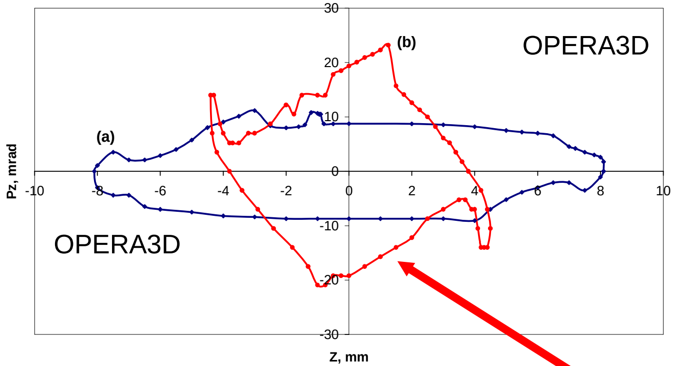


Ring Dynamic Aperture

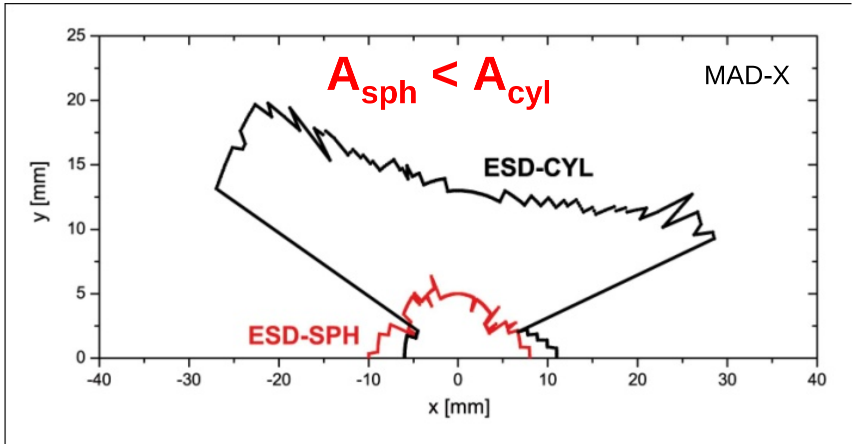


(a) middle of long straight section, azimuth θ=0°
(b) middle of ESD-160, azimuth θ=90°.

Vertical Acceptance



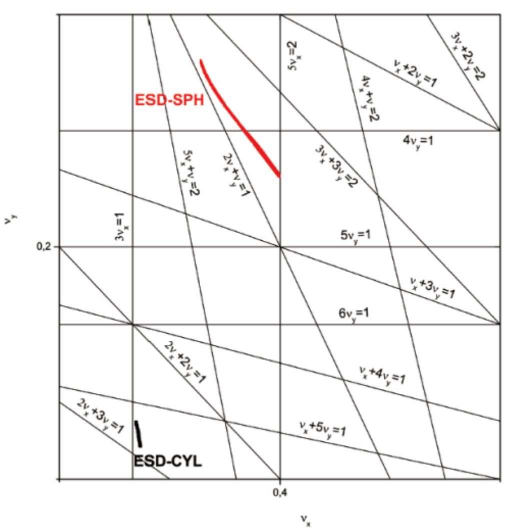
Proc. IPAC (2010)

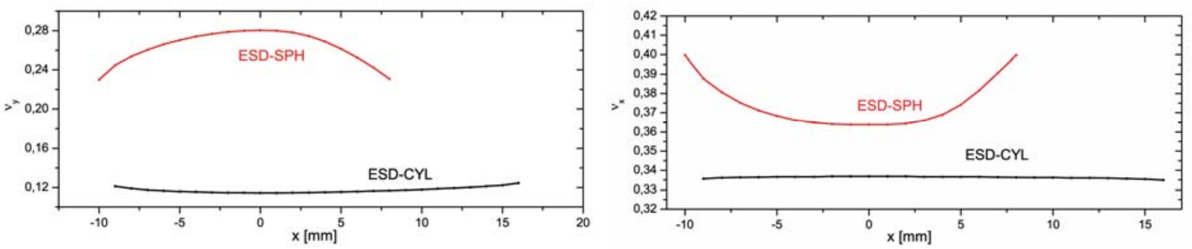


$A_z < 30\ \pi$ mm·mr

NON-LINEAR EFFECTS IN ESR

- **Strong non-linear effects <u>clearly visible</u> in the <u>axial</u> phase space**
- **in vertical direction size of stable beam is reduced from $\Delta z = \pm 8$ mm at θ=0° to**
- **$\Delta z = \pm 3$ mm inside deflector**
- **ring <u>acceptance</u> vertical $A_z \sim 30\pi$ mm·mr horizontal $A_x \sim 120\pi$ mm·mr**
-
- **important non-linear harmonic <u>sextupole</u> (next slide)**
- ELFLD sextupole **E_6 (SPH) > E_6 (CYL) <u>4 times</u>**
- **ring acceptances with ESD (SPH) essentially <u>less</u> and nonlinear effects more <u>visible</u> than for ESD (CYL)**





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

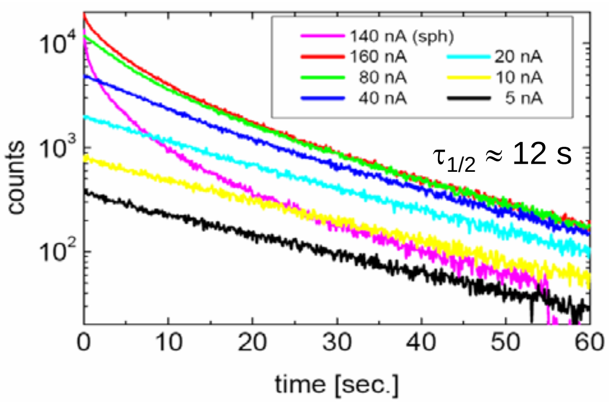
Benchmarking on ELISA Ring

Table 1: BETACOOL beam parameters of ELISA.

Ion	$\mathbf{O^{16}}$	$\mathbf{Mg^{24}}$
Charge	–1	+1
Ion energy, keV	22	18.4
Initial beam intensities	$5 \cdot 10^5 \div 1.6 \cdot 10^7$	$2.7 \cdot 10^7$
Ring circumference, m	7.616	7.616
Initial hor/vert ε, π mm mrad (σ)	1 / 1	0.7/0.35
Initial full ε, π mm mrad (3σ)	6 / 6	4 /2
Ring acceptance ESD-cyl, π mm mrad	10	10
Ring acceptance ESD-sph, π mm mrad	6	6
Initial RMS momentum spread, $\Delta p/p$	10^{-3}	10^{-4}
Equilibrium momentum spread, $\Delta p/p$	$4 \cdot 10^{-3}$	
Electron detachment life time of O^-, sec	26	--
Life time of O^- at 22 keV, sec	~ 12	

Beam Losses in ELISA

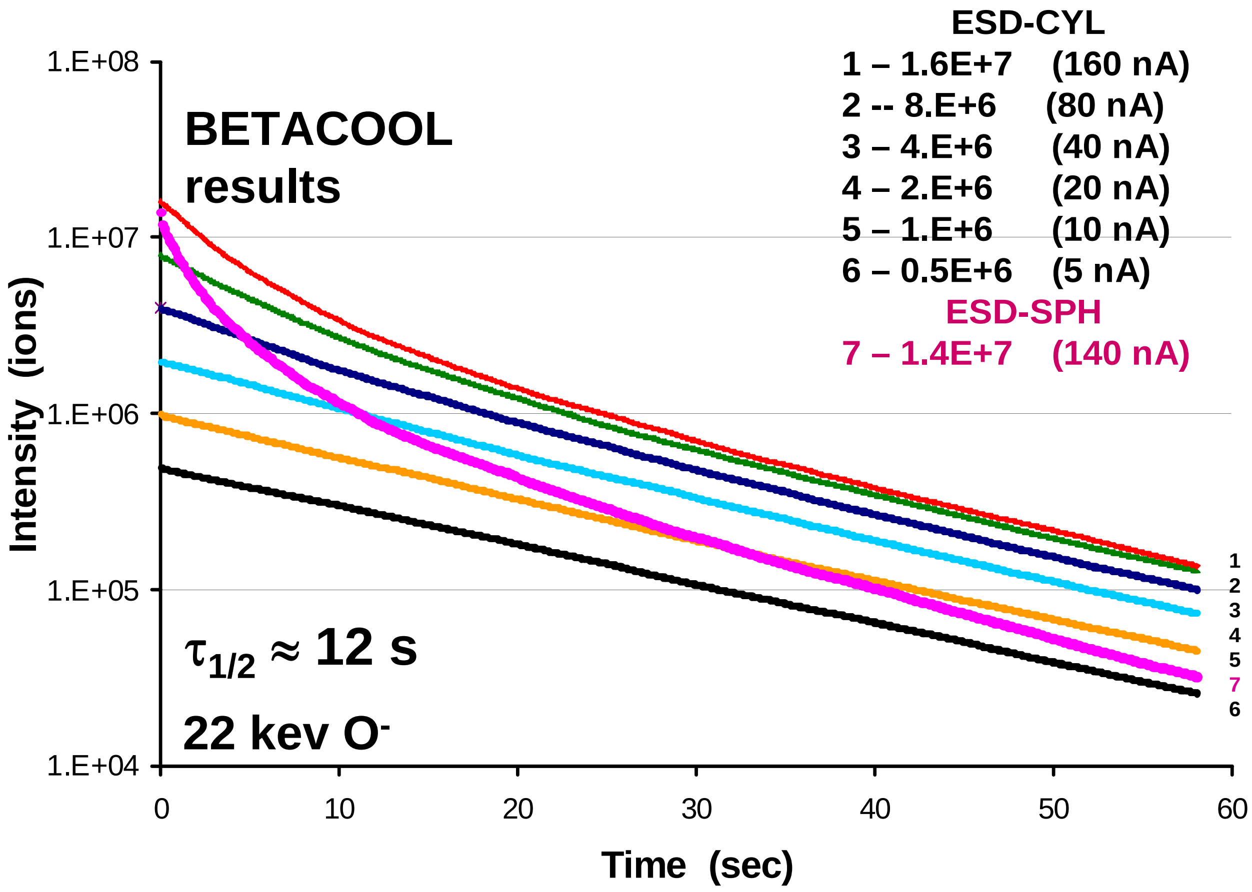
EXPERIMENT 22 kev O$^-$



S.P.Moeller, „Intensity Limitations of the Electrostatic Storage Ring ELISA“ Proc. EPAC (2000)

Losses in ELISA are caused by:

- **Multiple scattering on residual gas**
- **IBS at high intensites**
- **Electron detachment O$^-$ (τ= 25 s)**
- **Small ring acceptance**
- **ESD-CYL ≈ 15π mm·mrad**
- **ESD-SPH ≈ 8π mm.mrad**

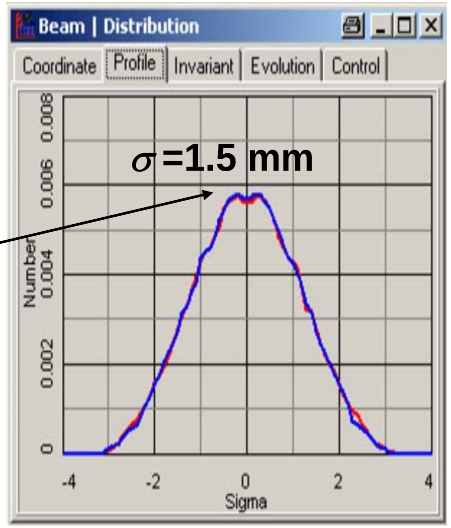


Benchmarking. ELISA beam profile corresponds to small Acceptance of the ring

Beam profile in ELISA ring

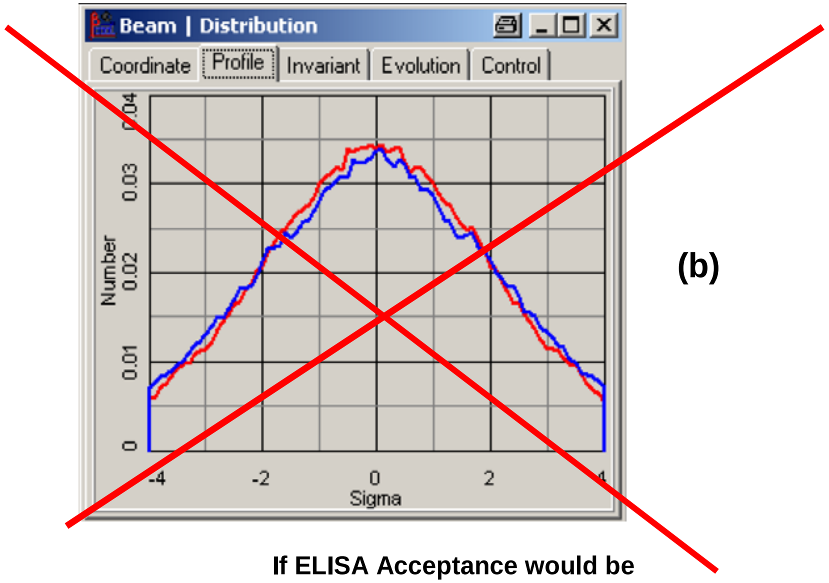
BETACOOL
Initial RMS emittance = 1π mm·mr
Ring Acceptance A= 10π mm·mr

BETACOOL



(a)

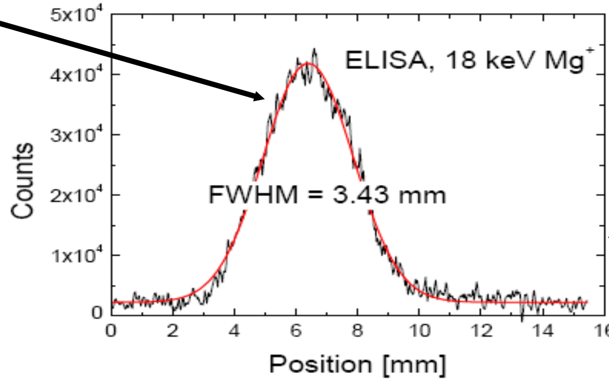
BETACOOL
Initial RMS emittance = 1π mm·mr
Ring Acceptance A= 50π mm·mr



(b)

Experiment

Experimental results



(c)

σ = SQRT($\beta\varepsilon_{rms}$)
A ≈ $(6\sigma)^2 / \beta$
σ =1.5 mm
β = 5 m
A ≈ 15 π mm·mr

Preliminary results,
to be published

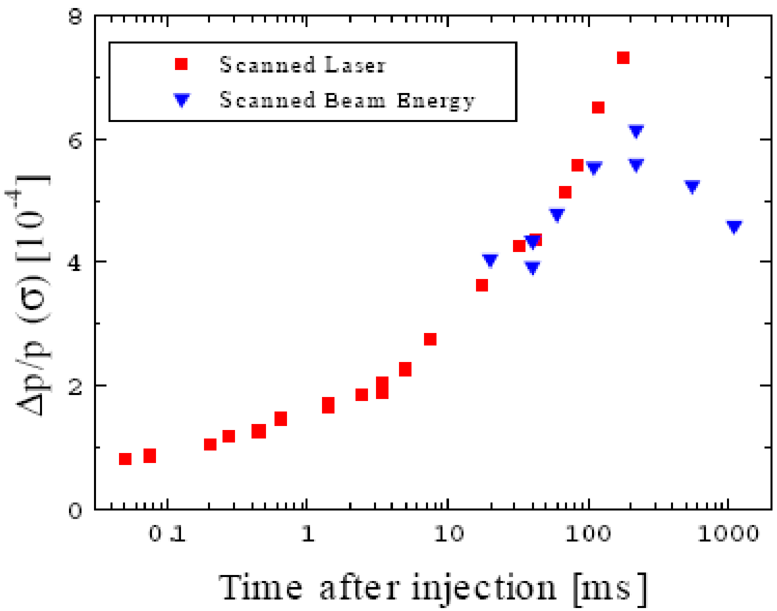
If ELISA Acceptance would be A= 50π mm·mr then beam profile should be as shown in fig. (b) i.e. few times wider than was measured in experiments (c)

Conclusion:
ELISA Acceptance do not exceed
A ≈ 15 π mm·mr
while geometric acceptance of ring is ~4 times more

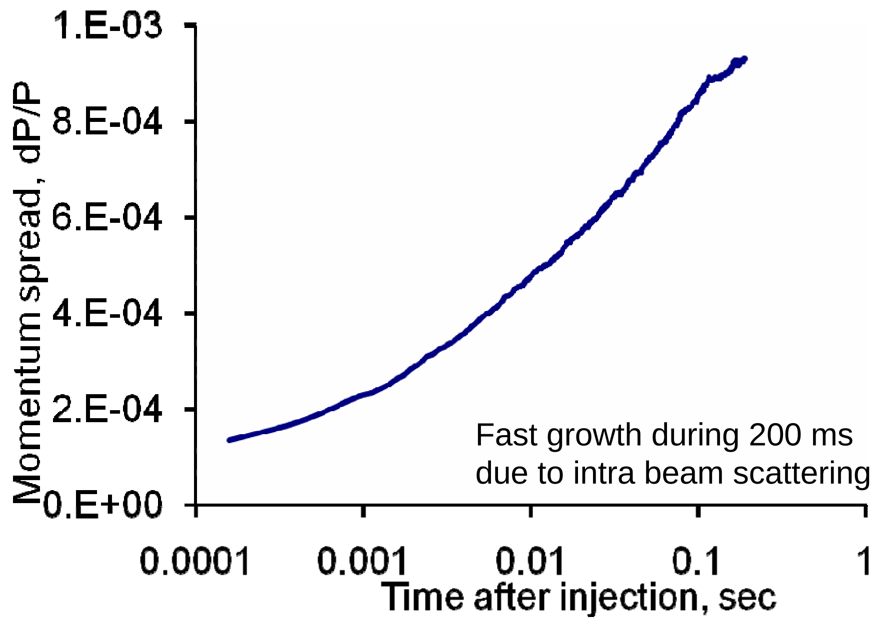
Benchmarking on ELISA ring

r.m.s. momentum spread of high intensity Mg+ beam as a function of time (a) experimental data; b) BETACOOL results

18.4 keV Mg^+ Experiment
N = 2.7·10^{+7} ions

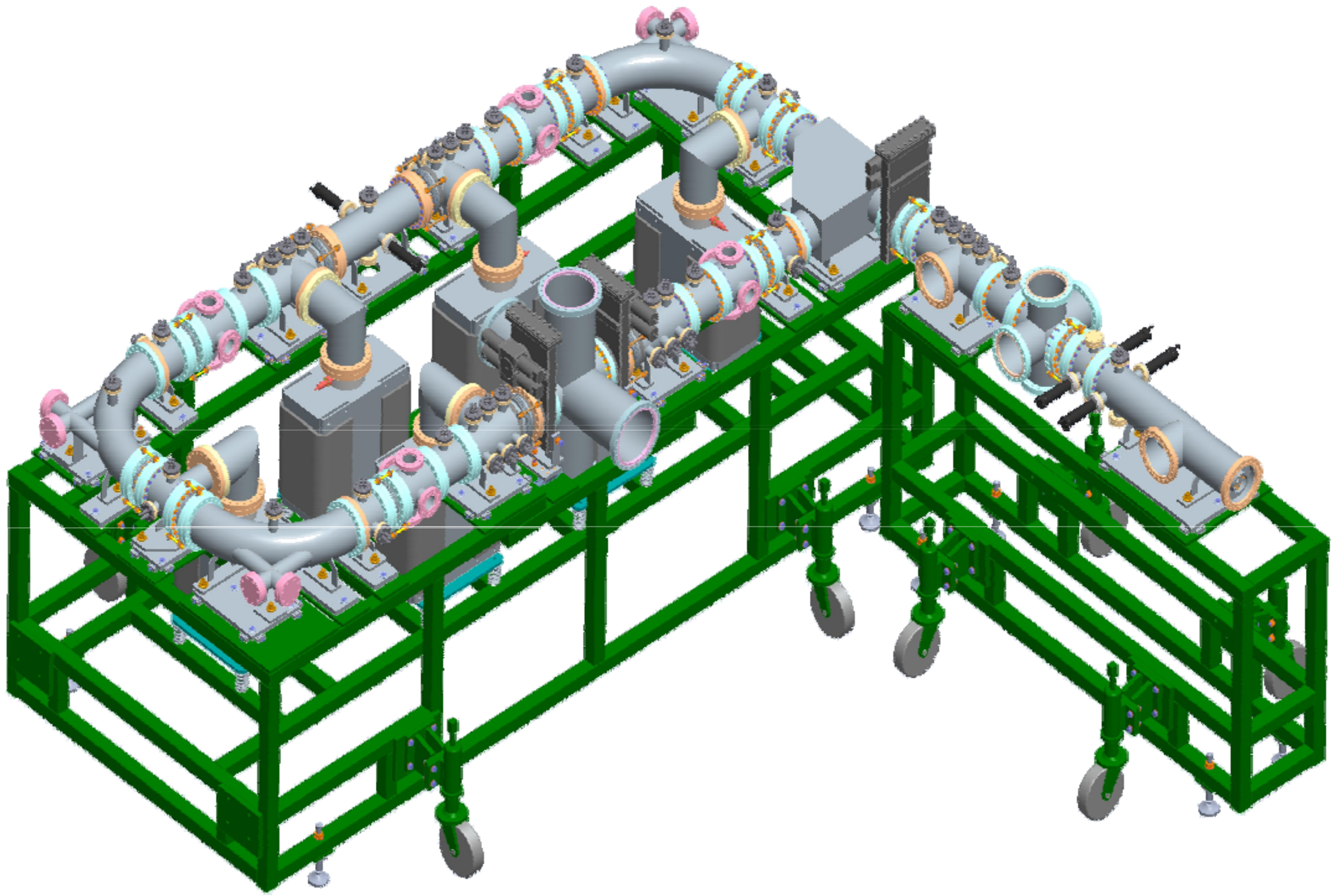


18.4 keV Mg^+ BETACOOL
N = 2.7·10^{+7} ions



Beam Momentum Spread fast growth due to IBS at high intensites

RECYCLER
Prototype
Internal target

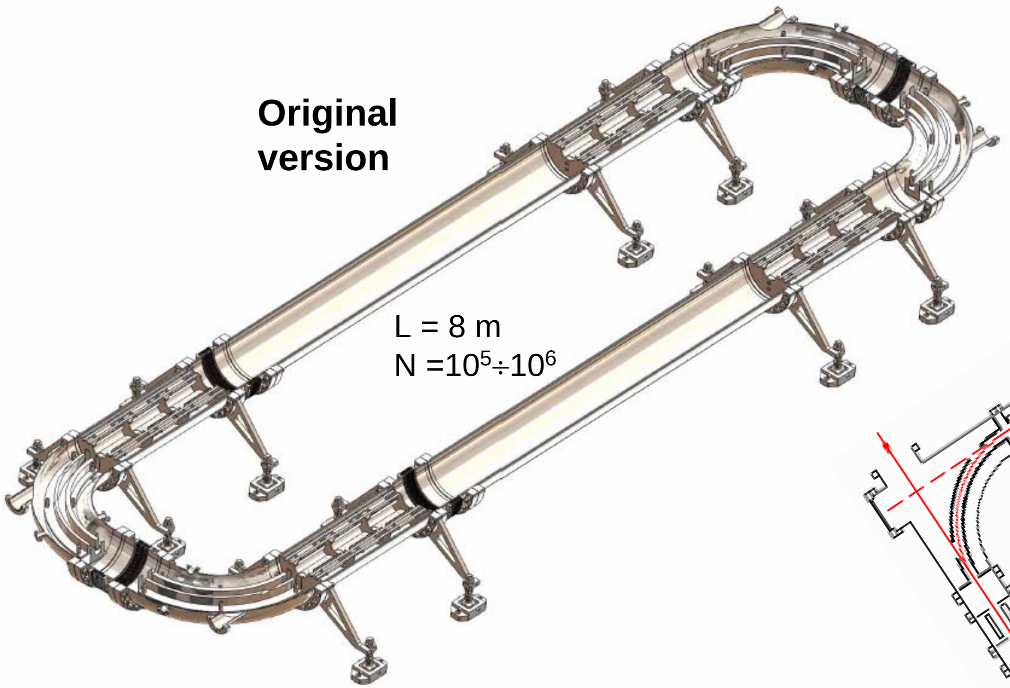


USR Prototype: Antiproton *Recycler*

- Proposed behind Musashi or ELENA
- Prototype for USR developments
- feasibility studies of operation with gas jet
- Possibility to measure partial differential antiproton cross sections

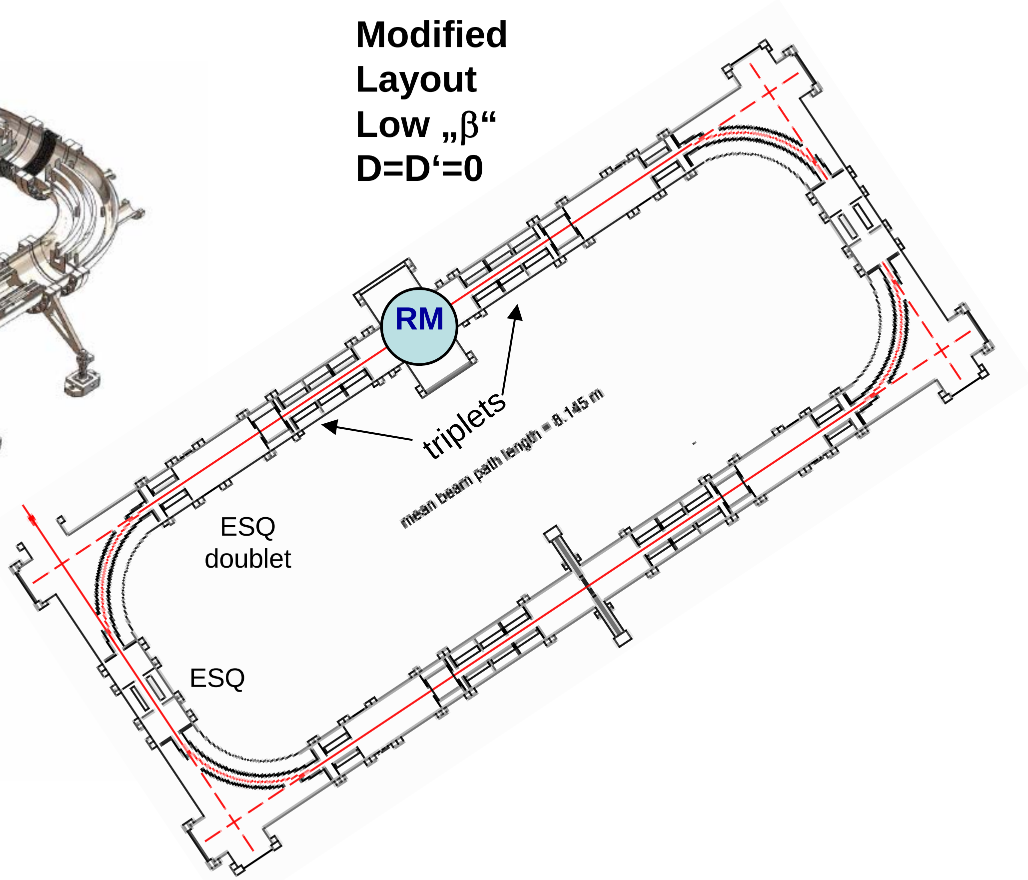
E=3-30 keV

Original version



TCP 2010 Conference

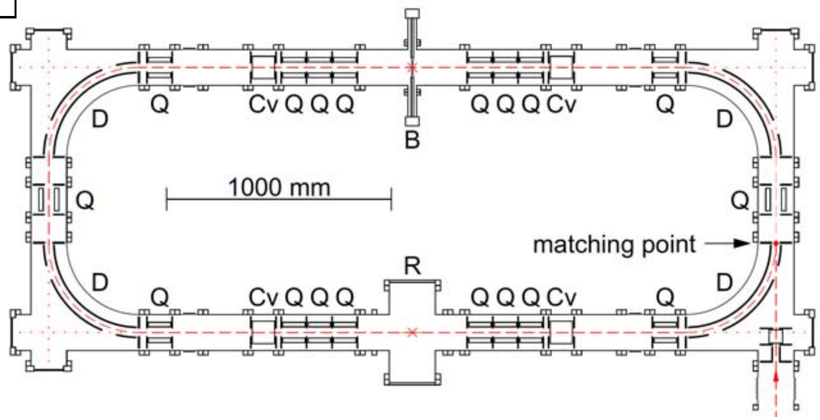
Modified Layout Low „β“ D=D‘=0



will be published

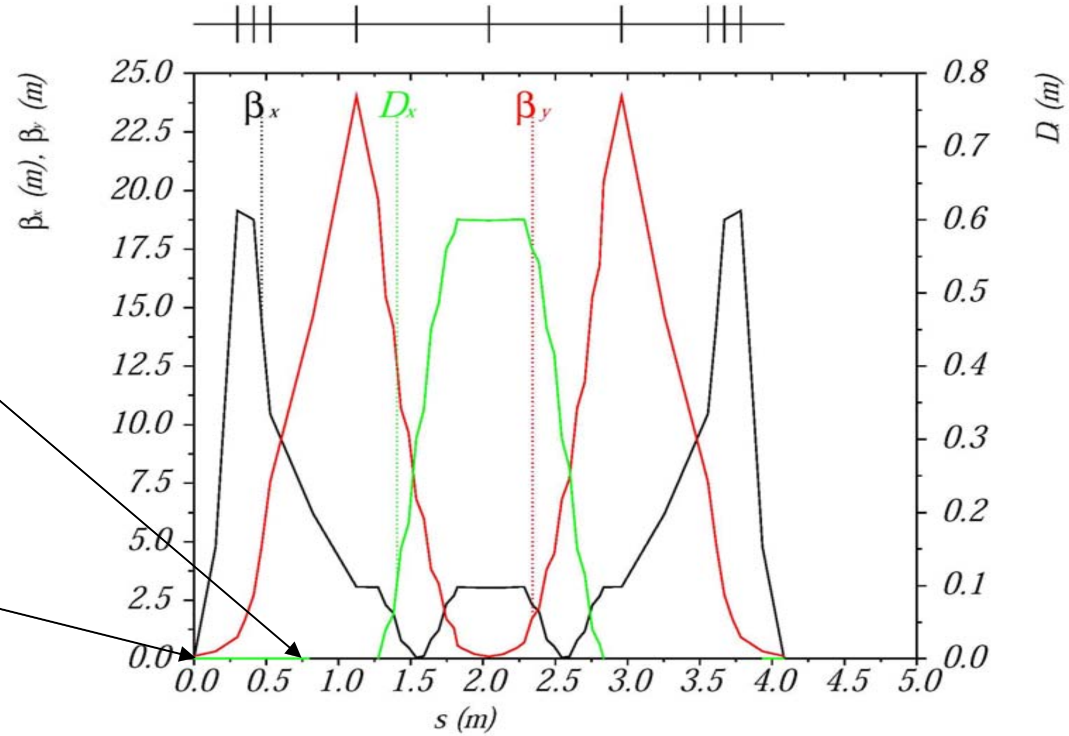
Table 2. BETACOOL parameters to study interaction of antiprotons with He supersonic jet target.

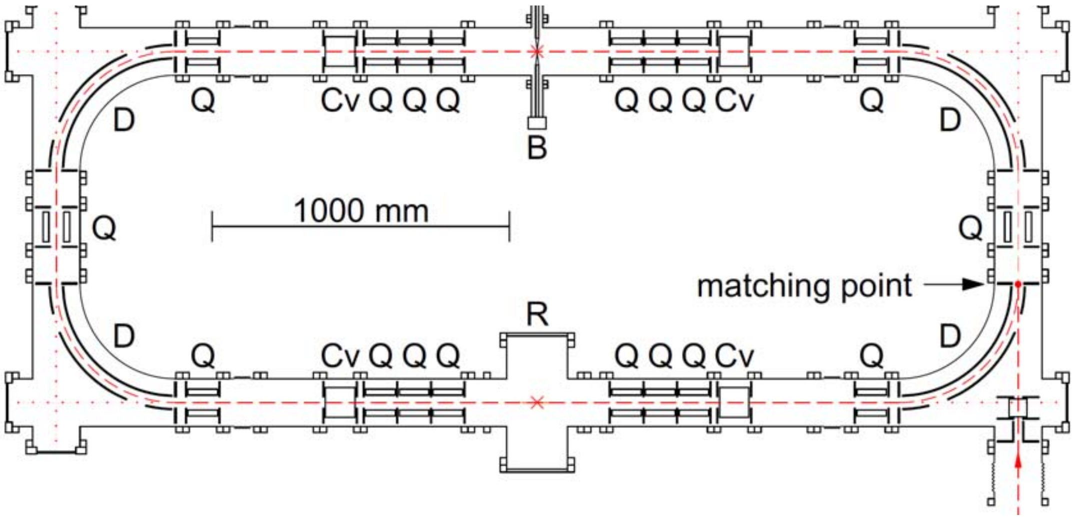
Antiproton energy range, keV		3 – 30
Ring circumference, m		8.165
Rotation period of pbars in the ring, μs		11 – 3.5
Initial intensity of antiprotons		5×10^{5}
Initial RMS emittance, pi mm mrad (σ)		2
Ring Acceptance, pi mm mrad		15
Initial momentum spread		10^{-3}
Vacuum pressure (hydrogen), Torr		10^{-11}
Helium target density, cm^{-3}		5×10^{11}
Target length (diameter), mm		1
Hor./Vert. beta functions at target, cm		2 / 11
Dispersion at target point, m		0
Ionization cross-section of antiprotons on He atoms, barn **[17]**	3keV 30keV	2×10^{7} 6×10^{7}
Integral of ionization events	3keV 30keV	$3.5\ 10^{3}$ 3.2×10^{5}
Beam life time, sec	3keV 30keV	0.09 0.82



Achromat
D=D'=0

Low β
$\beta_{X,Y}$< 20 cm



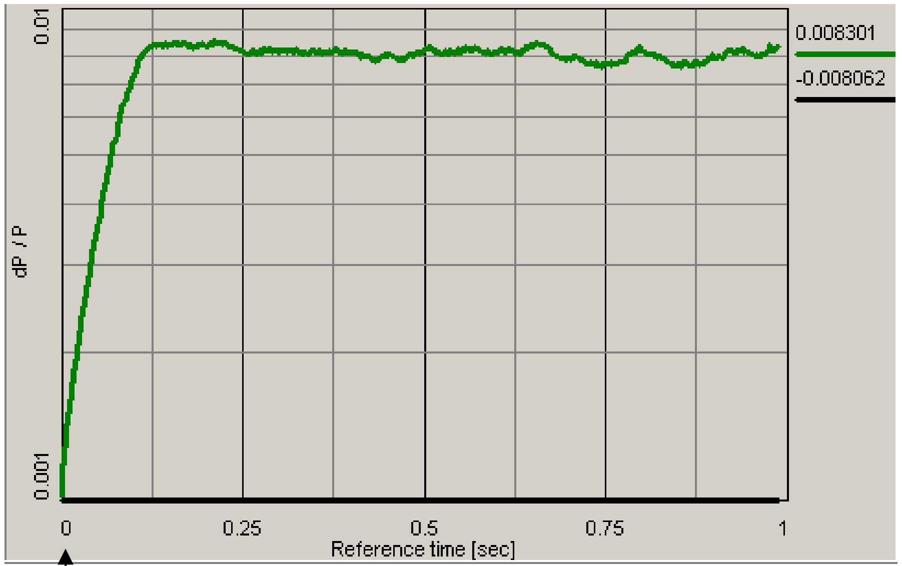


Prototyping: Antiproton *Recycler*
Momentum spread evolution

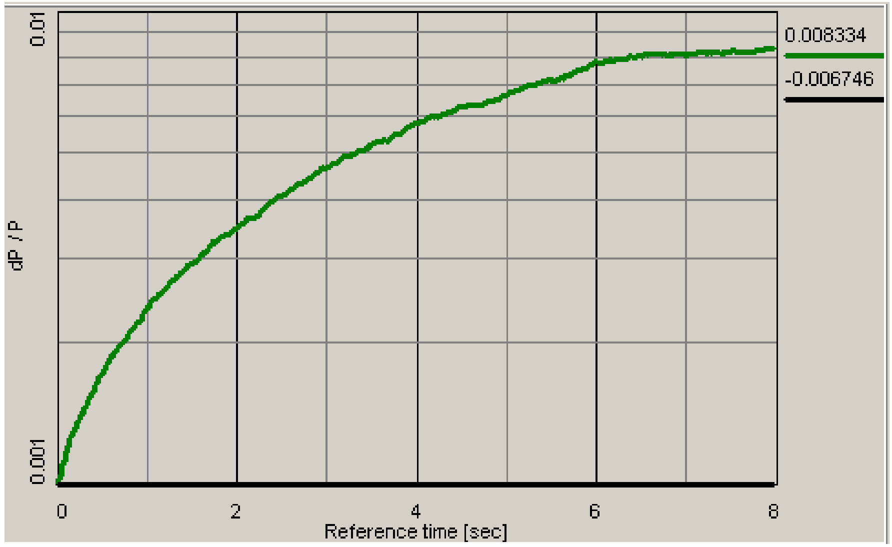
Circulating Antiprotons interact with He supersonic gas jet target

Target density $5{\cdot}10^{11}$ cm^{-3}, diameter 1 mm

3 keV



30 keV



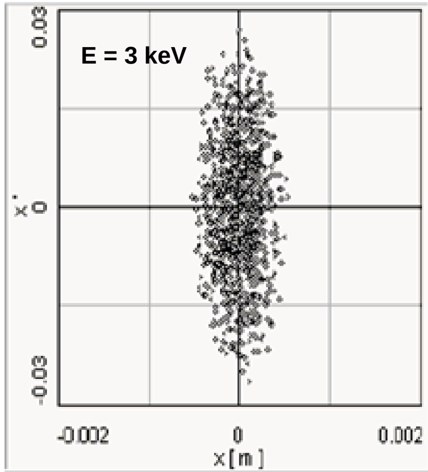
$dP/P_{rms}=10^{-3}$

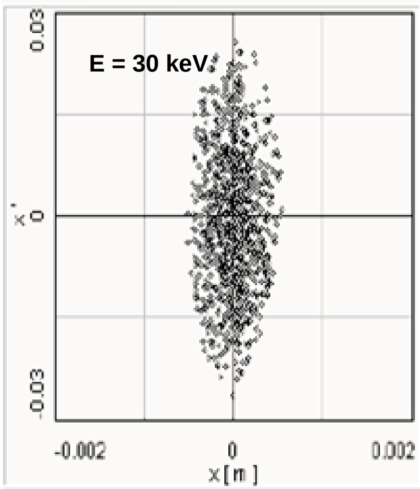
- Multiple scattering on residual gas and Target
- Ring acceptance ≈15π mm.mr

Papash, A. Smirnov et al. will be published

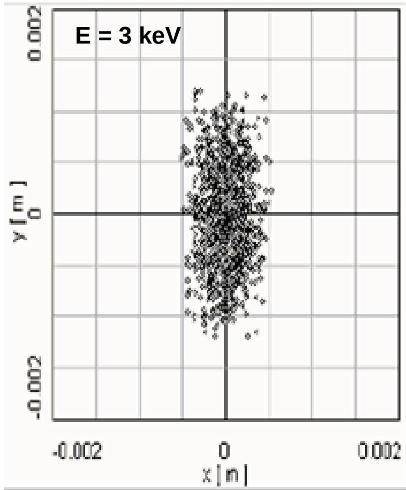
Prototyping: Antiproton *Recycler*
Equilibrium beam shape and evolution of beam emittance

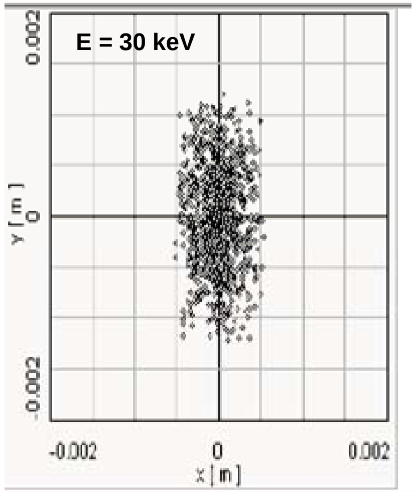
Beam phase ellipse at TGT location



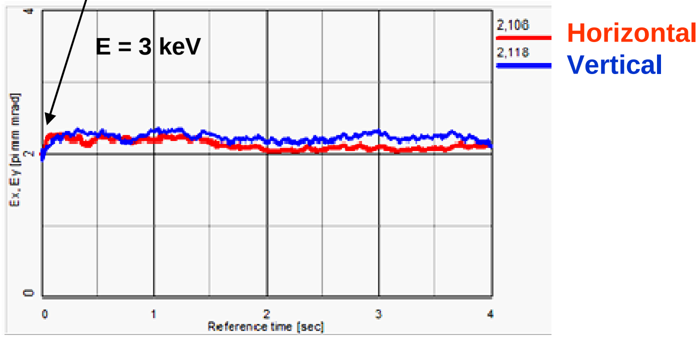


Beam spot at TGT location

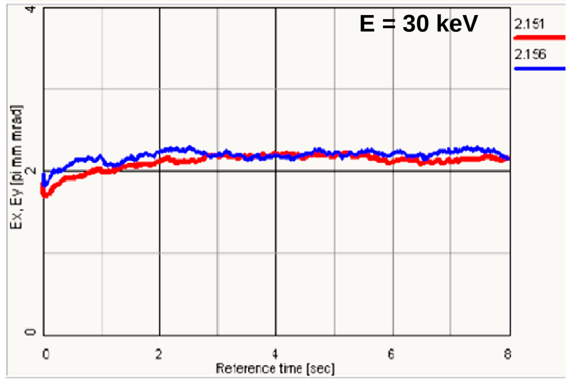




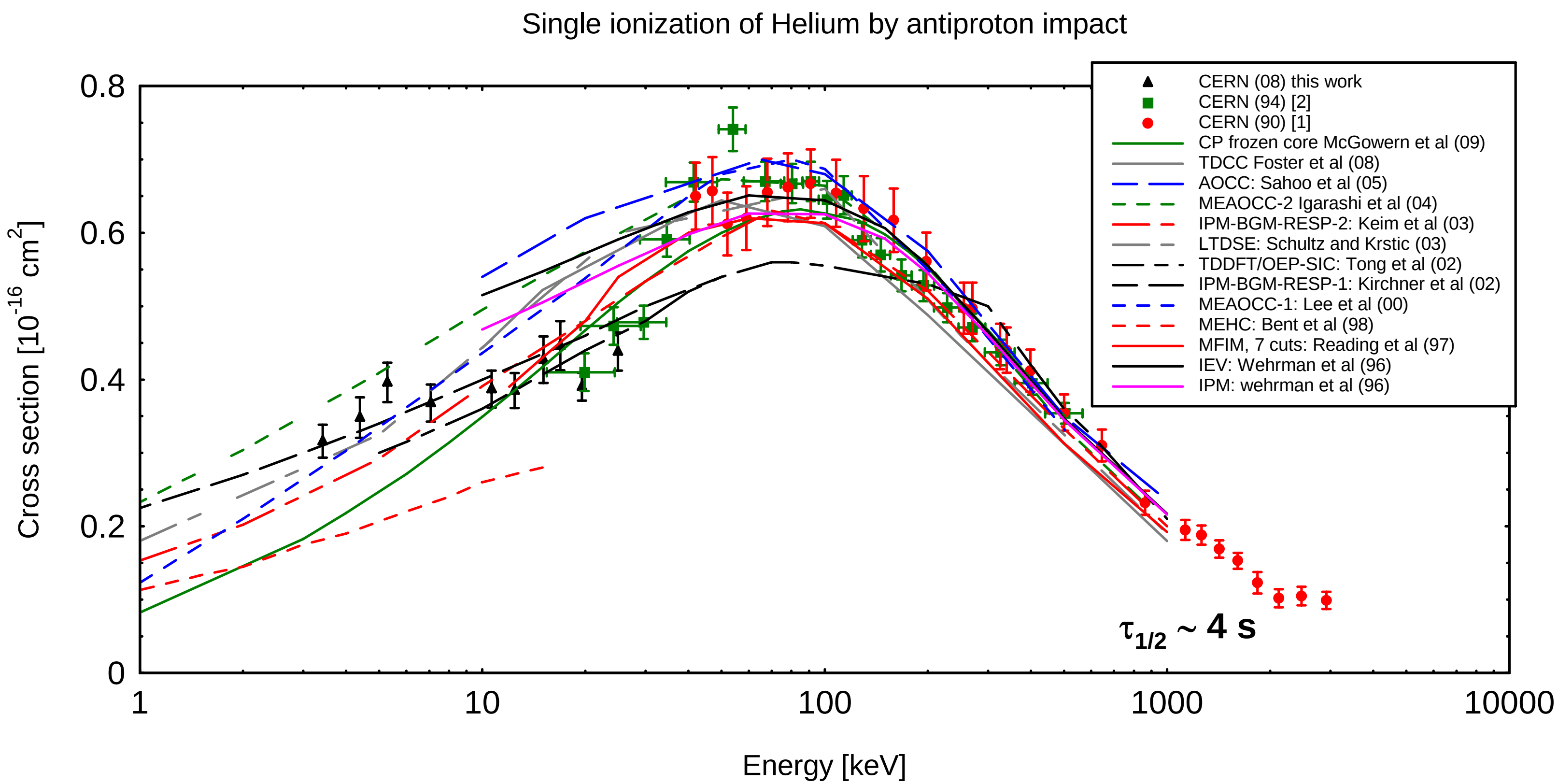
Beam emittance 2π mm·mr (rms) grows to Ring acceptance (15π mm·mr) and beam losses appears on ring aperture



At 30 keV the **Rate of emittance growth is less Beam emittance reach ring acceptance in ~2sec while at 3 keV beam grows to ring acceptance in 100 ms. But equilibrium value the same and equal to ring acceptance at any beam energy**



Papash, A. Smirnov et al.
will be published



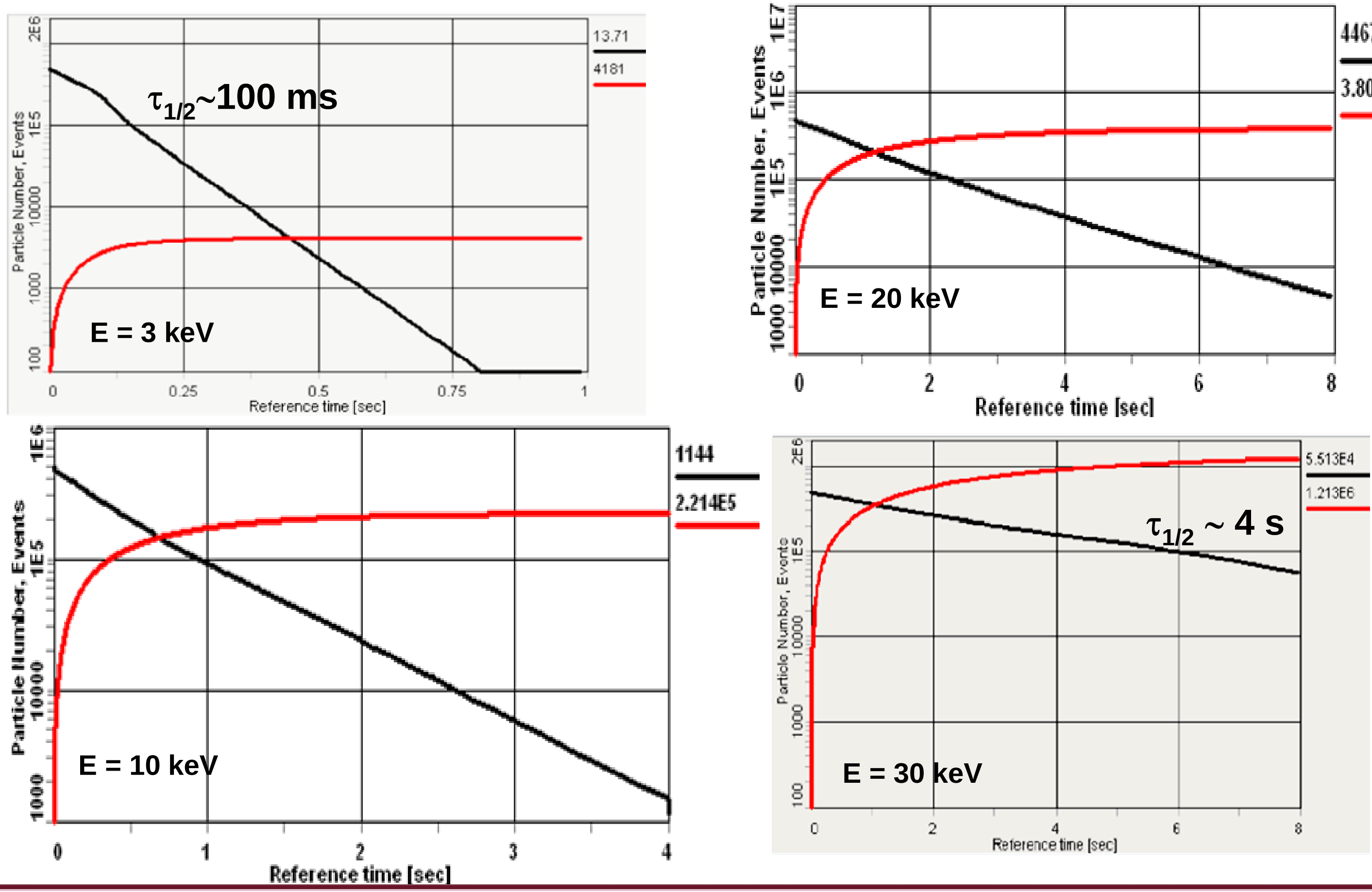
Single ionization of Helium by antiproton impact
Cross section [10^{-16} cm^2]
Energy [keV]
0.8
0.6
0.4
0.2
0
1
10
100
1000
10000
CERN (08) this work
CERN (94) [2]
CERN (90) [1]
CP frozen core McGowern et al (09)
TDCC Foster et al (08)
AOCC: Sahoo et al (05)
MEAOCC-2 Igarashi et al (04)
IPM-BGM-RESP-2: Keim et al (03)
LTDSE: Schultz and Krstic (03)
TDDFT/OEP-SIC: Tong et al (02)
IPM-BGM-RESP-1: Kirchner et al (02)
MEAOCC-1: Lee et al (00)
MEHC: Bent et al (98)
MFIM, 7 cuts: Reading et al (97)
IEV: Wehrman et al (96)
IPM: wehrman et al (96)
$\tau_{1/2}$ ~ 4 s

H.Knudsen

Prototyping: Antiproton *Recycler*
Long term Beam Dynamics

Ion losses and Count rate at different beam energies.
Gas jet target density is 5E+11 cm-3

Expected number of ionization events varies from ~4000 at 3 keV to ~1.2E+6 at 30 keV



Ions
Ionization events

Papash, A. Smirnov
will be published

Benchmarking the TSR experiment of the e-cooling with fotocathode to ultra-low emitance

TSR Fotocathode e-gun (experimental results)

Proceedings of COOL 2007, Bad Kreuznach, Germany

ELECTRON COOLING WITH PHOTOCATHODE ELECTRON BEAMS APPLIED TO SLOW IONS AT TSR AND CSR

D. A. Orlov#, H. Fadil, M. Grieser, C. Krantz, J. Hoffmann, O. Novotny, S. Novotny, A. Wolf
Max-Planck-Institut für Kernphysik, 69117, Heidelberg, Germany

beam size vs time

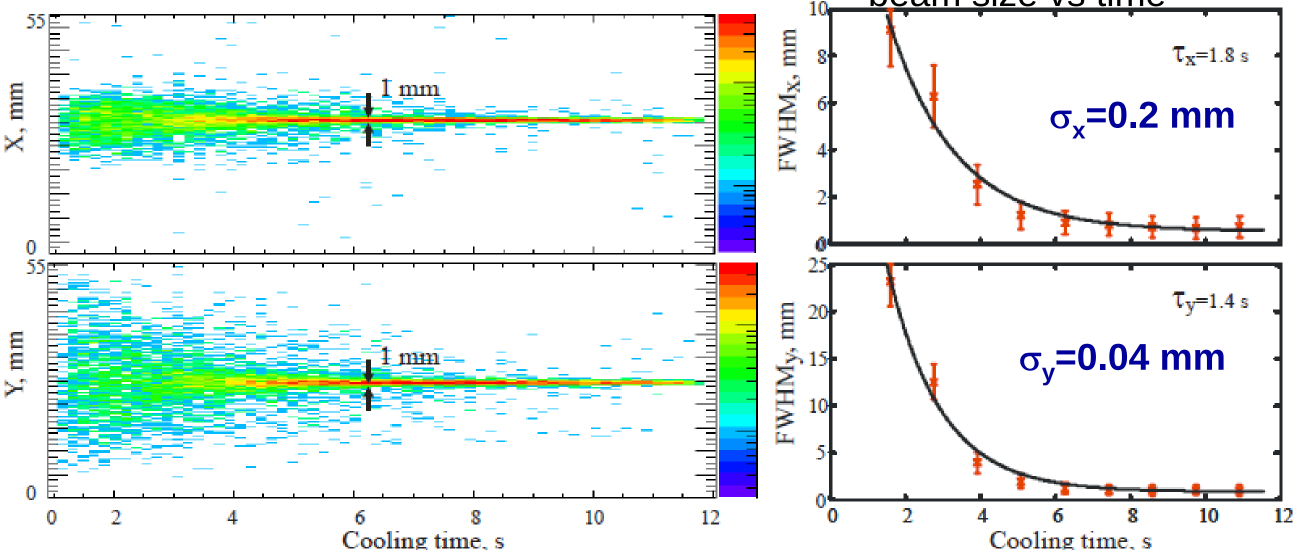


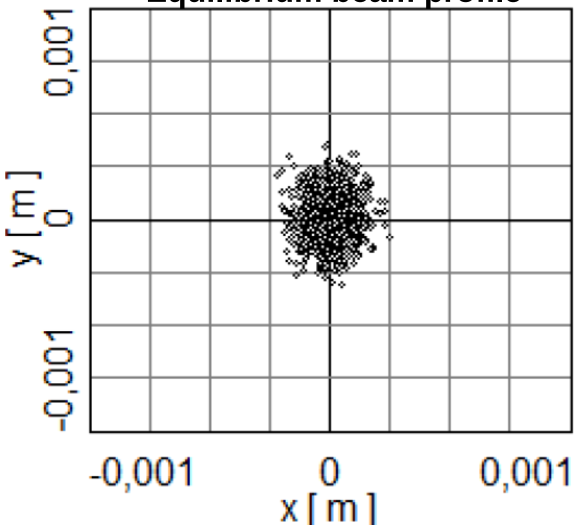
Figure 5: Transverse electron cooling of 97 keV/u CF^+. Centre-of-mass positions of the C and F neutral fragments vs time, recorded 12 m downstream of the electron target by the imaging detector and indicating rms divergence angles of about $3 \cdot 10^{-5}$.

longitudinal ion spread $\Delta P/P$ of about $5 \cdot 10^{-5}$

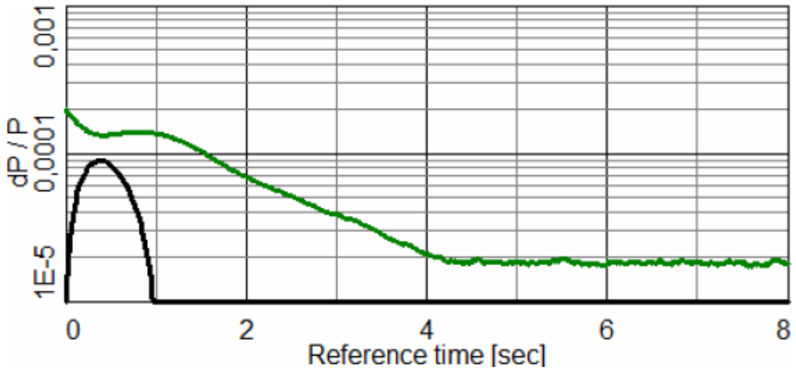
cooling time...about 1.5 s for the cold ion beam and 6 s for the hot ion beam (with a diameter of the injected ion beam about 2 times larger than that of the electron beam). After 6 s a

BETACOOL simulations of TSR ring with Fotocathode. CF+. 93 keV/A

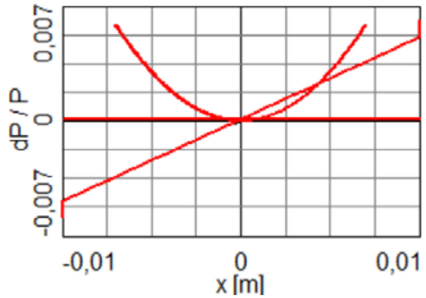
Equilibrium beam profile



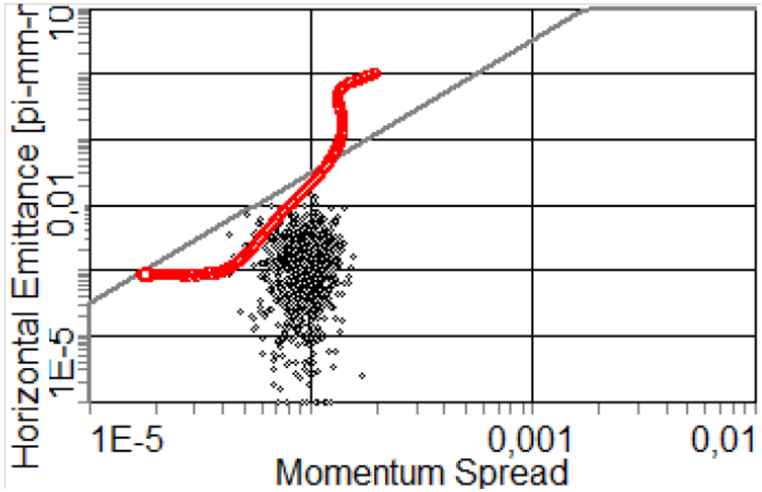
Momentum Spread evolution



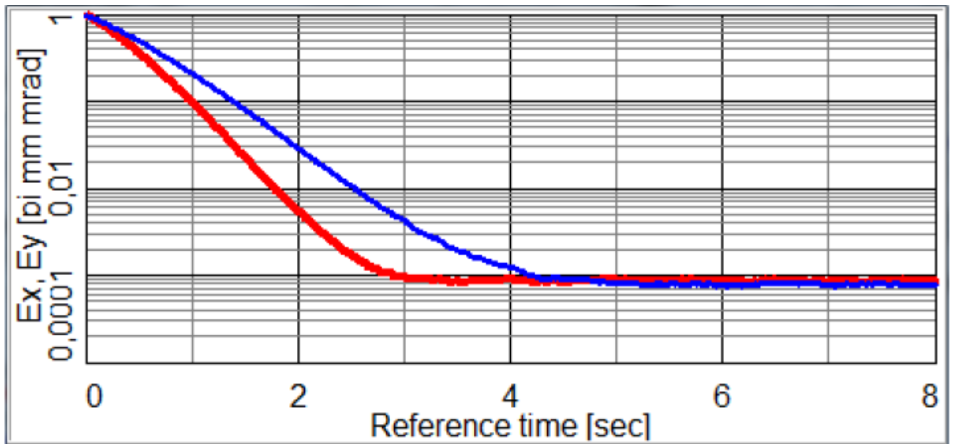
E-cooler space charge



3D evolution

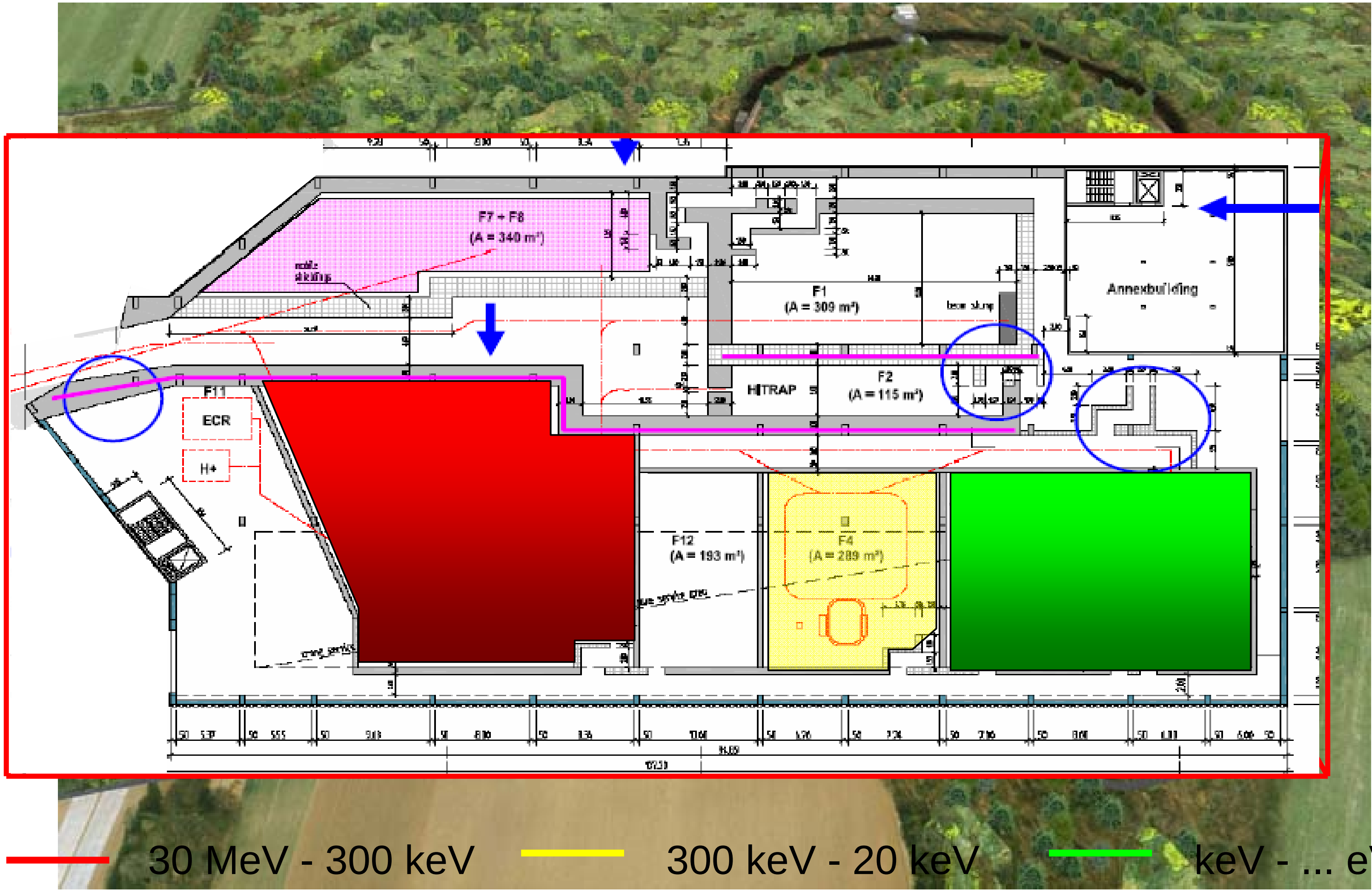


Evolution of r.m.s. Emittance



USR with e-cooling and internal target

FLAIR @ Facility for Antiproton and Ion Research



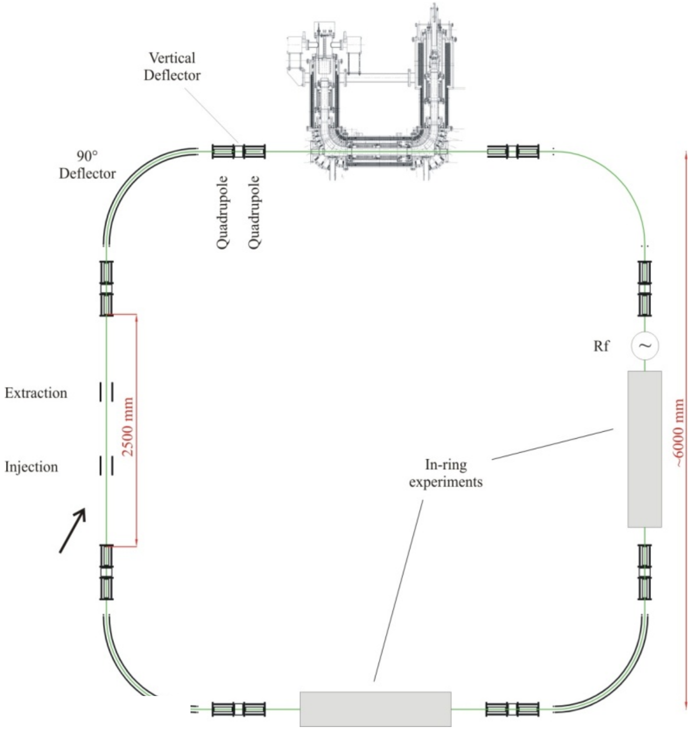
30 MeV - 300 keV

300 keV - 20 keV

keV - ... eV

2005 Layout

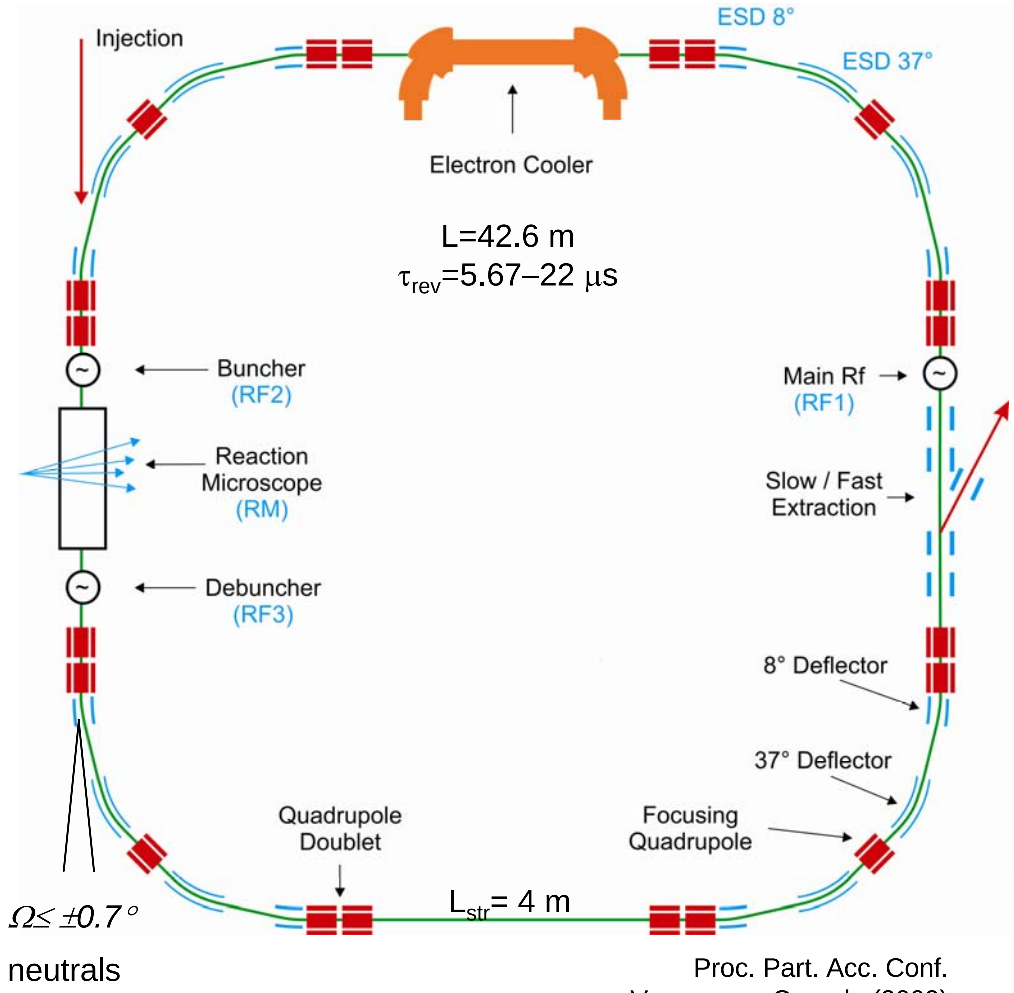
- four straight sections
- periodicity N = 4
- 90° ESD



Nucl. Instrum. Methods A **546**
405–417 (2005)

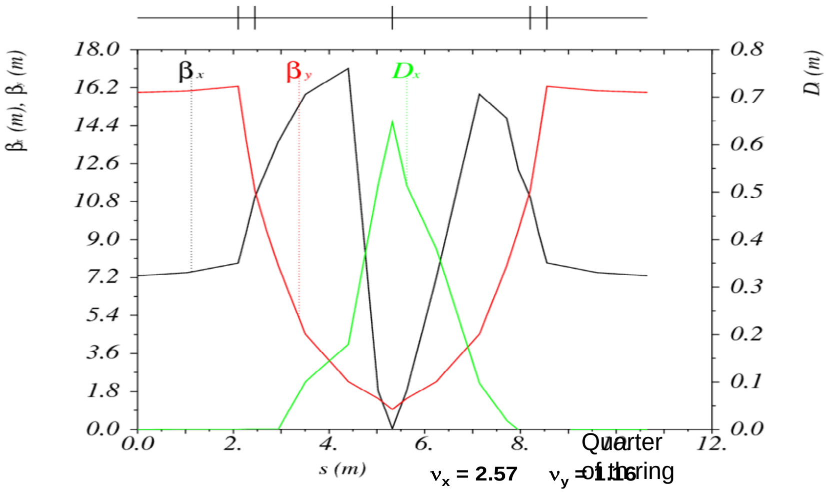
Revised Design

"Split-achromat" geometry

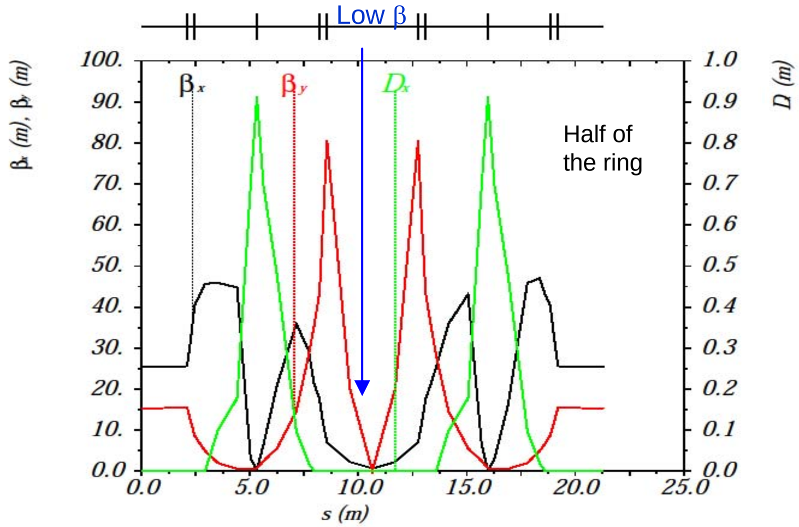


Proc. Part. Acc. Conf.
Vancouver, Canada (2009)

New USR Lattice



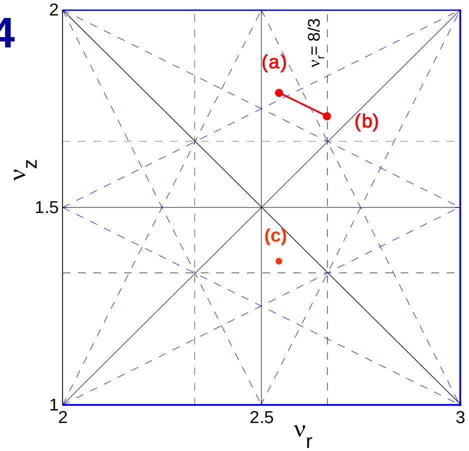
D=D'=0 8°+37° 37°+8° D=D'=0



- **Four fold symmetry, N=4**
- **Four achromat sections**
- **D=D`=0 in straights**

<u>Also possible</u>:

- **Variable dispersion**
- **Round beam**



- **Two fold symmetry, N=2**
- **Low-β mode**
- **D=D`=0 in straights**

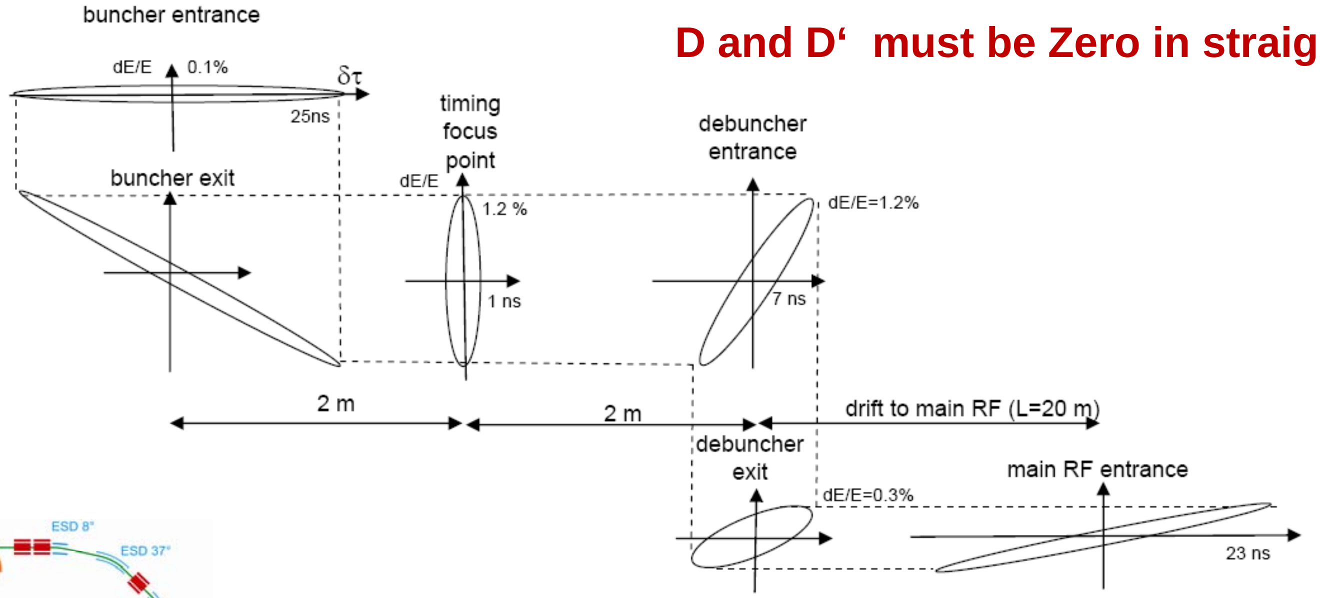
(a)"round beam" mode: ν_r =2.567, ν_z =1.7905;

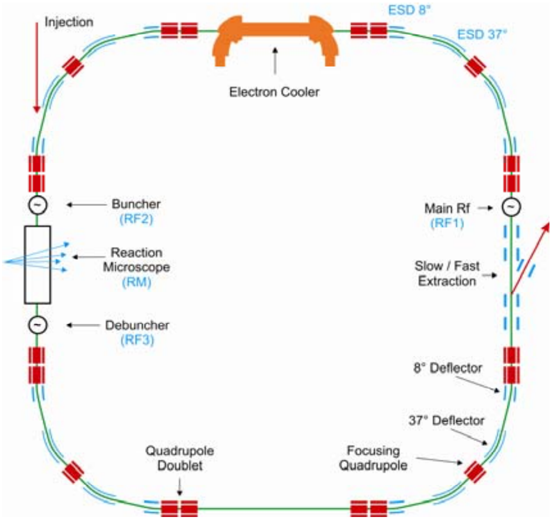
(b) slow extraction: ν_r =2.6637, ν_z =1.7315;

(c) achromatic lattice: ν_r =2.572, ν_z =1.374

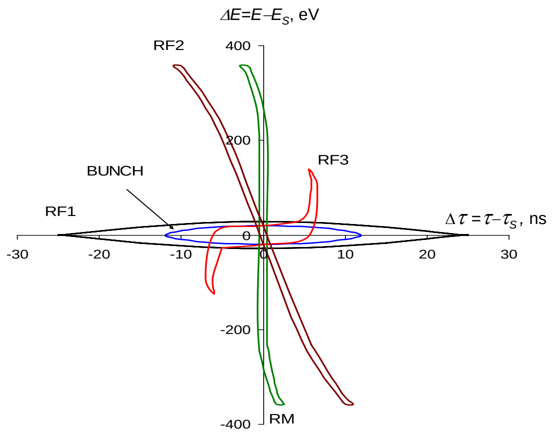
Beam Compression - Decompression Scheme in 4 m Long Straight Section

D and D' must be Zero in straight section

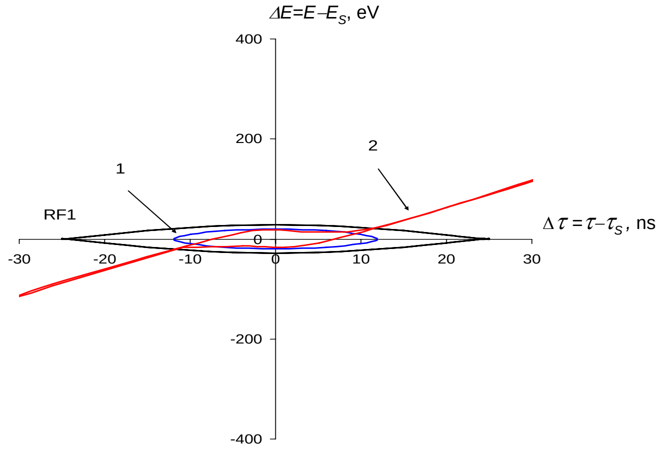




Part Phys. Nucl. Letters **3** (2009)



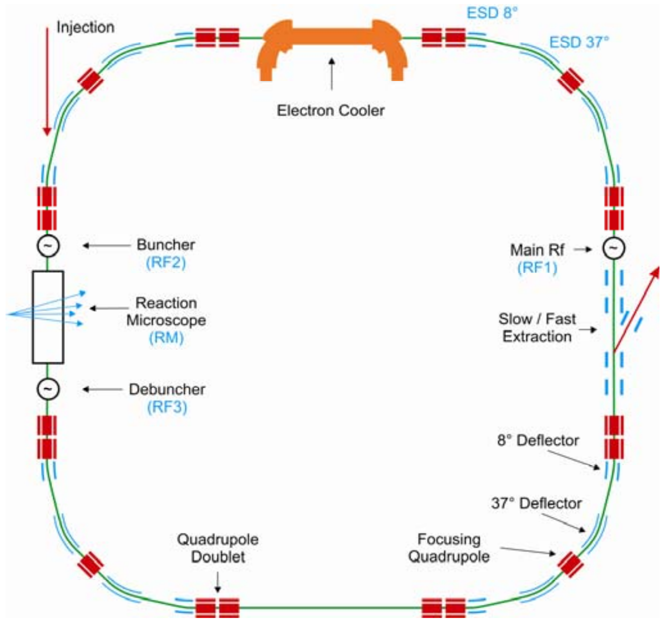
MAD-X



MAD-X

Table 2. Beam parameters for USR with internal target

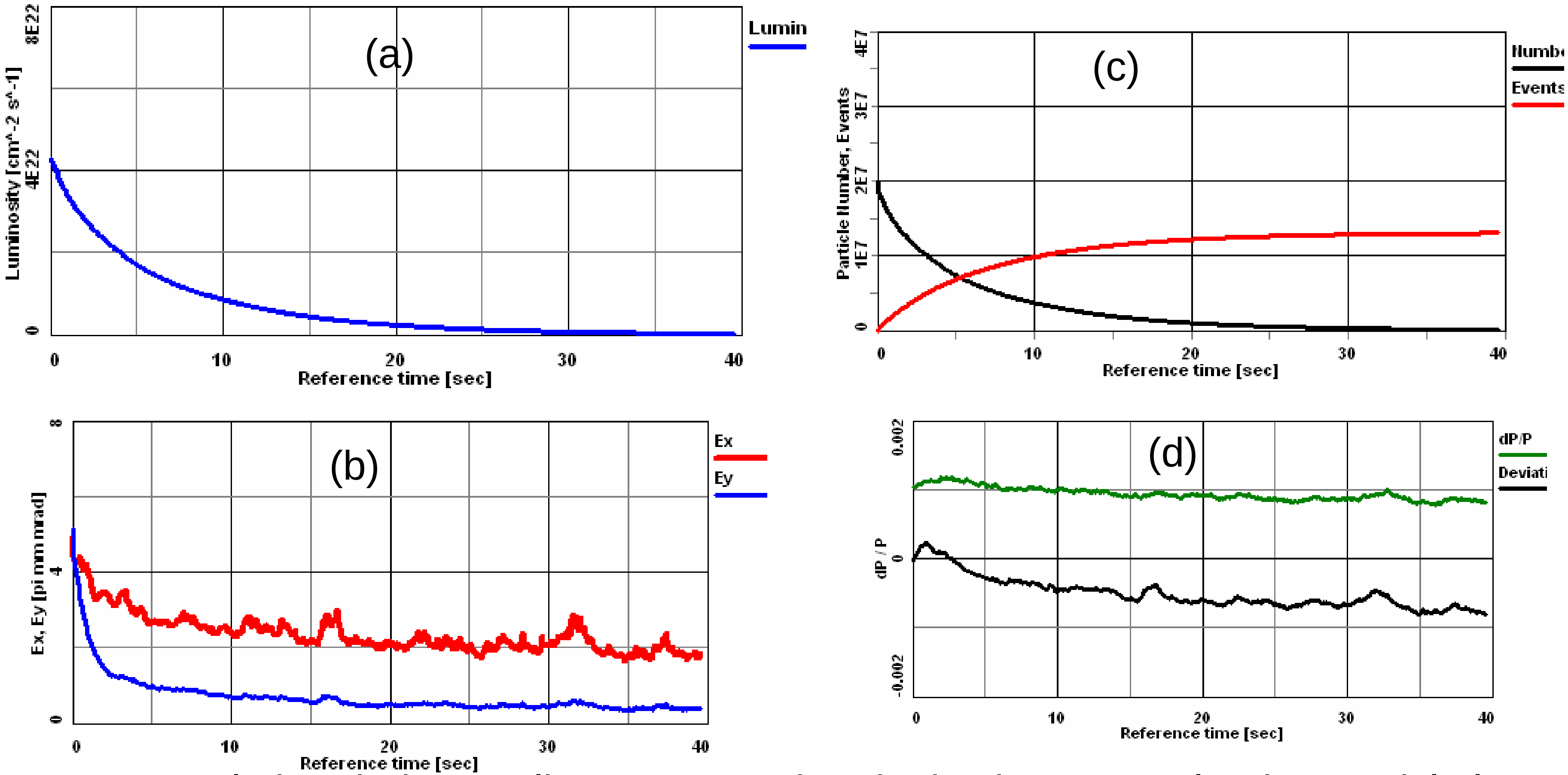
Ring circumference, m	42.598
Antiproton energy, keV	20
Vacuum pressure (hydrogen), Torr	10^{-11}
Number of achromatic straight sections	4
Length of achromatic straight sections, m	4
Particle number	2×10^{7}
Initial emittance, π mm·mrad	5
Acceptance, π mm·mrad	40
Initial momentum spread	10^{-3}
Helium target density, cm^{-3}	5×10^{11}
Target length, cm	0.1
Beta function at target (hor/ver), m	0.7 / 0.06
Dispersion at target point, m	0
Cross section of He ionization, barn	5×10^{7}
Length of electron cooler, m	2
Magnetic field at cooler, G	100
Beta functions at cooler (hor/ver), m	7.3 / 15.6
Dispersion at cooler, m	0
Electron beam radius, cm	2
Electron beam current, mA	0.1
Electron temperature (tran/long), eV	4 / 0.5
Electron energy shift (dp/p units)	-2×10^{-3}



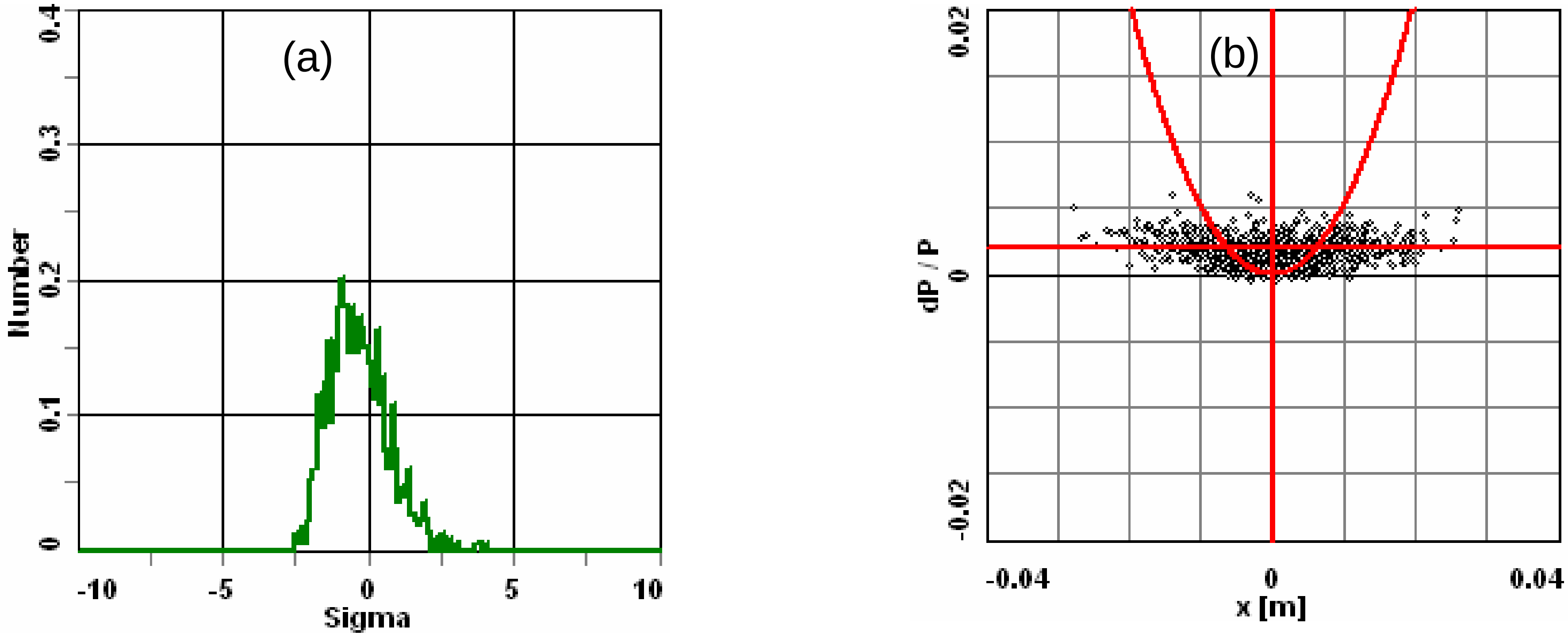
USR. Evolution of beam parameters

e-cool + multiple scattering +gas jet target

Initial beam $\varepsilon_{x,y}^{rms} = 5\pi$ mm·mrad $\Delta P/P = 10^{-3}$ (BETACOOL)



Beam evolution during cooling process when ionization events lead to particle losses:
a) luminosity, b) transverse emittances, red – horizontal, blue – vertical,
c) black – particle number, red – integral of ionization events,
d) green – momentum spread, black – momentum deviation.



. Beam distribution after 40 sec of cooling process.

a) longitudinal profile,

b) particle distribution at cooler section and space charge parabola of the electron beam.

SUMMARY

It was shown how the beam behaviour in keV electrostatic storage rings can be described, what processes lead to beam degradation and how the electron cooling will counteract the beam scattering on target. Experimental data from ELISA served as a benchmark and was reproduced with very good agreement in BETACOOL. The results from these studies were used to estimate the event rates of envisaged future collision studies between low energy antiprotons and gas targets in an Ultra-low energy Storage Ring.