Long Term
Beam Dynamics Simulation
with the BETACOOL Code

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http://betacool.jinr.ru

Physical motivation

Accelerator design, beam stability, non linear effects, particle tracking, dynamics aperture and vacuum, etc. investigations can be provided using: **MADX**, **OPERA**, **COSY**, **UAL, OPTIMA, ESME** ….

General goal of the **BETACOOL** program is
to simulate long term processes
(in comparison with the ion revolution period)
leading to variation of the ion distribution function
in 6 dimensional phase space.

Competitive programs:

MOCAC (MOnte-CArlo Code) – ITEP, Moscow, P. Zenkevich, A. Bolshakov
SIMCOOL (SIMulation of COOLing) – BINP, Novosibirsk, V.Parkhomchuk, V.Reva
PTarget (Pellet Target) – GSI, Darmsdadt, A.Dolinsky
CodeK2 (Katayma & Kikuchi) – Tokyo University, T.Katayama, T,Kikuchi

Numerical algorithms in BETACOOL

- **RMS Dynamics**
  no any particles are used and the evolution of RMS parameters (emittances, particle number) are simulated
- **Model Beam**
  ion beam is presented by array of model particles and each effect calculates a kick of the ion momentum components and changes the particle number
- **Tracking**
  ion beam is presented by array of real particles and Coulomb scattering is calculated by the Molecular Dynamics technique
- **3D Phase Diagram**
  A few of 3D projection of 6D phase space volume of ion beam. Results of beam dynamics simulation for different algorithms on the same diagram

Physical Effects involved in BETACOOL

- **Electron cooling**
  a few models of the friction force (magnetized, non magnetized) and the electron beam (bunched, hollow, arbitrary distribution)
- **Intrabeam scattering**
  different Gaussian models (Martini, Bjorken, Wei), simulation for arbitrary distribution
- **Internal target and scattering on rest gas**
  different target types (gas cell, pellet), combination of short and long time processes, detector limits (effective luminosity)
- **Collider regime**
  a few model of luminosity calculation, hour glass effect
- **Other effects**
  Stochastic cooling, Laser cooling, Particle losses, etc.

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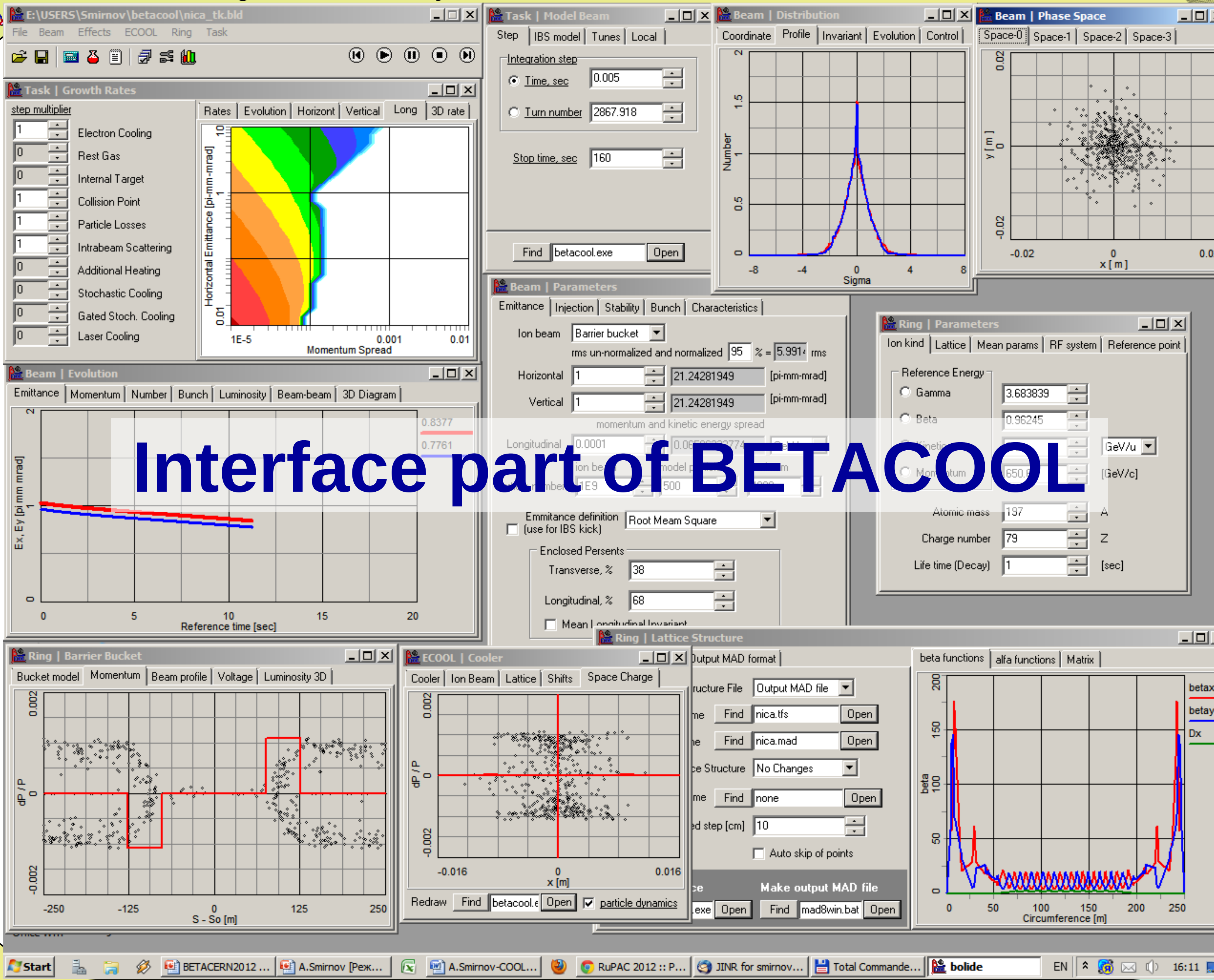


Interface part of BETACOOL

Nowadays

Benchmarking of IBS and electron cooling models:
CELSIUS (TSL), ESR (GSI), RHIC (BNL), Recycler (FNAL), Erlangen University, TechX (Colorado), S-LSR (Kyoto Univ.)

Luminosity preservation in colliders:
MUSES (RIKEN), RHIC-II (BNL), PAX (FAIR), NICA (JINR)

Simulations of experiments with internal target:
PANDA@HESR (FAIR), WASA@COSY (FZJ), ESR (GSI)

Beam ordering (crystalline beams) investigations:
S-LSR (Kyoto University), COSY (FZJ), NAP-M (BINP), ESR (GSI)

Simulations of cooling-stacking process:
LEIR (CERN), HIRFL-CSR (Lanzhou), NICA Booster (JINR)

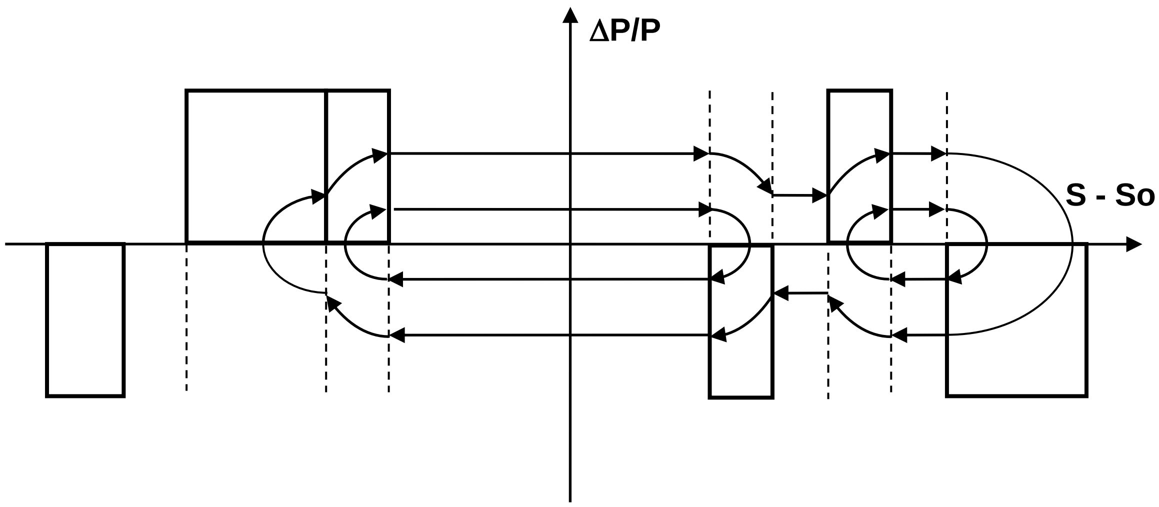
Low energy electron cooling:
TSR and USR (MPI), ELENA (CERN)

Barrier Bucket model in BETACOOL code

equations of the synchrotron motion

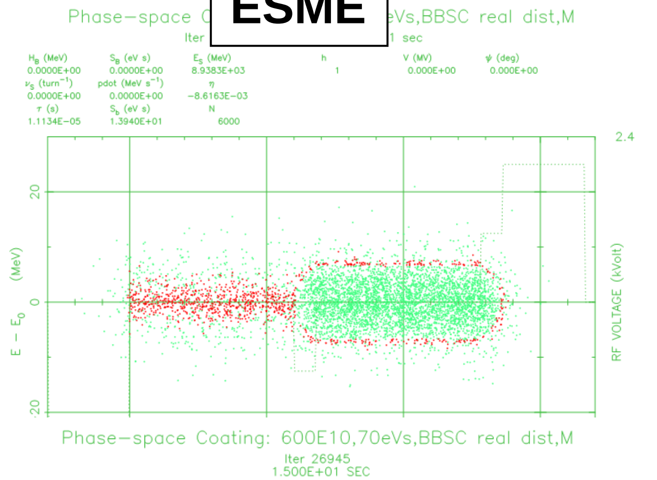
$$\begin{cases} \dfrac{d(s-s_0)}{dt} = |\eta|\beta c\delta \\ \dfrac{d\delta}{dt} = -\dfrac{ZeV(t)}{Cp_0} \end{cases}$$

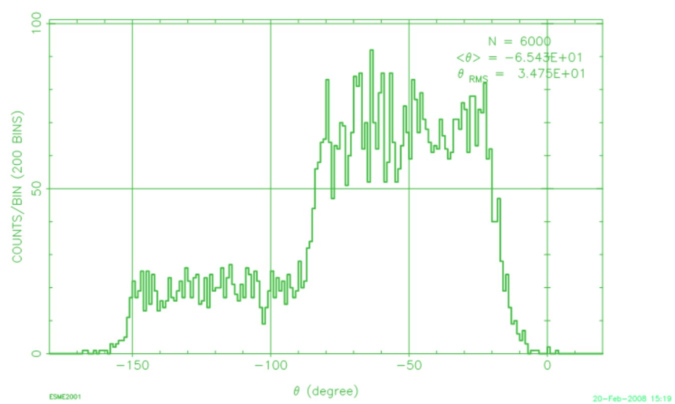
where βc is the ion velocity, η is the ring off-momentum factor, *Ze* – particle charge, *V(t)* – the dependence of RF voltage on the time, *C* – ring circumference, p_0 – momentum.



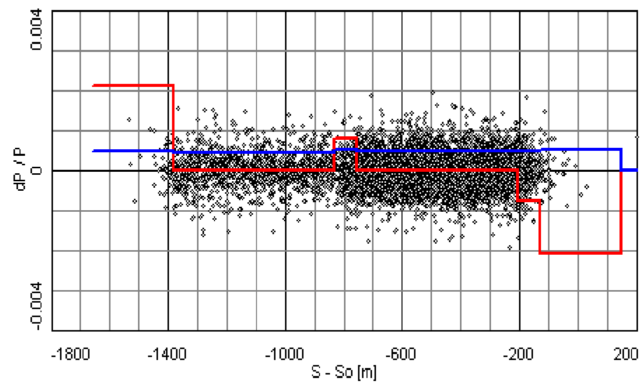
Comparison of ESME and BETACOOL simulation of longitudinal dynamics with barrier bucket

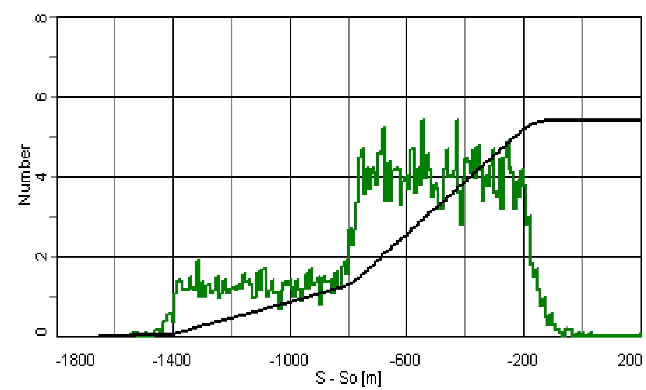
ESME



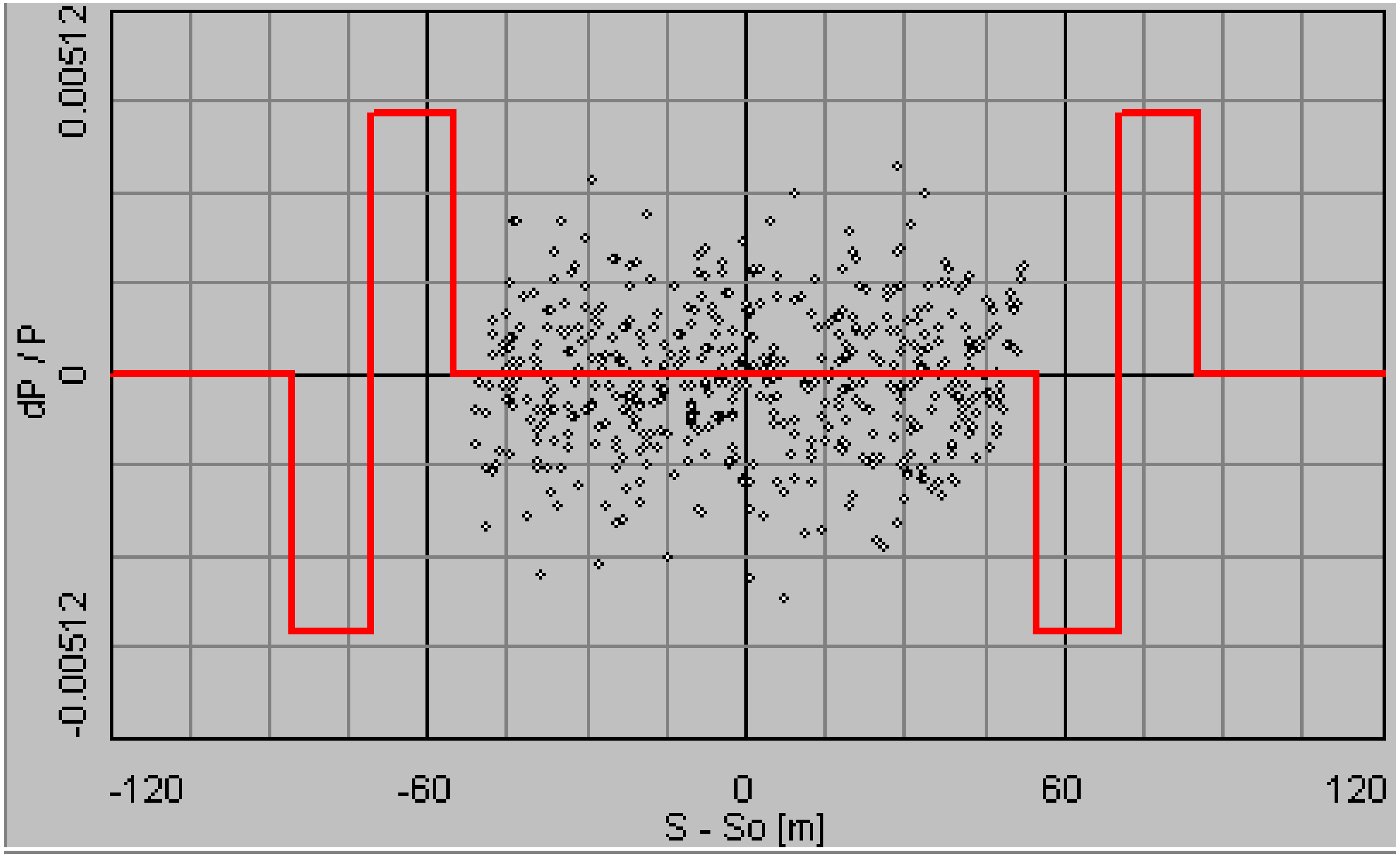


BETACOOL

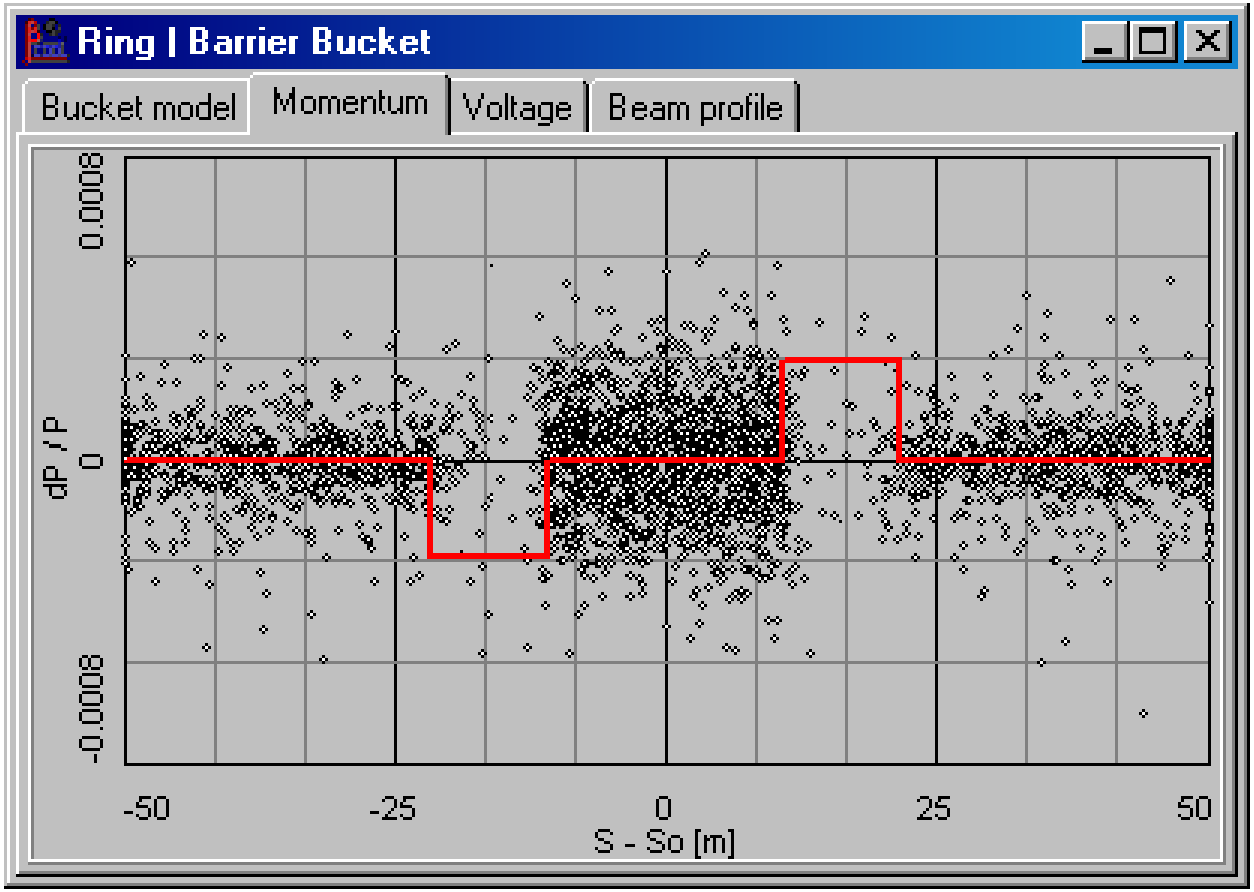




Particle accumulation with moving Barrier Bucket



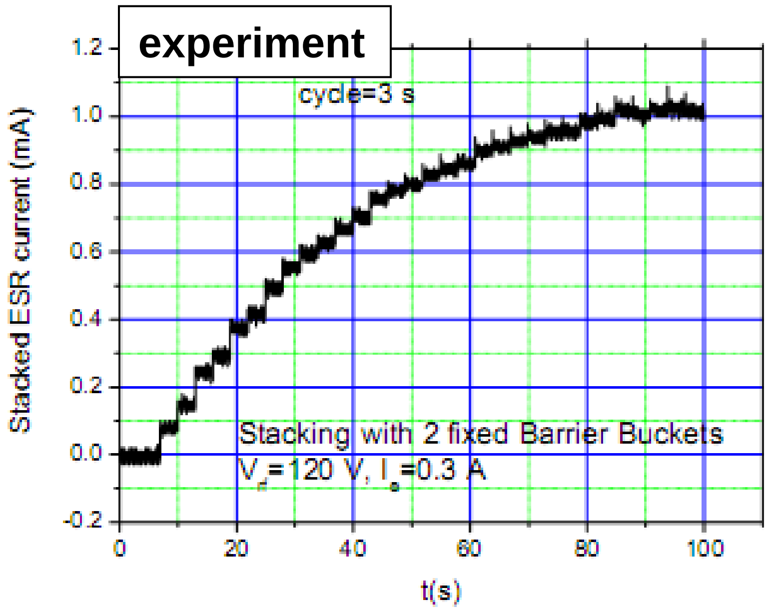
Particle accumulation with stationary Barrier Bucket and Electron Cooling

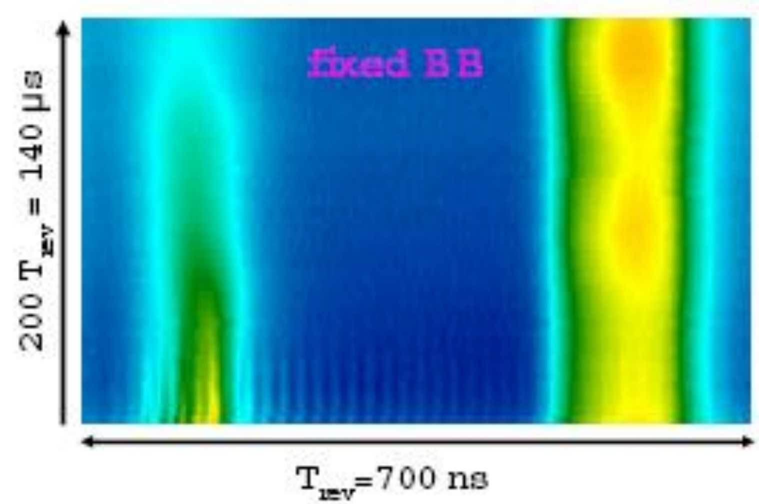


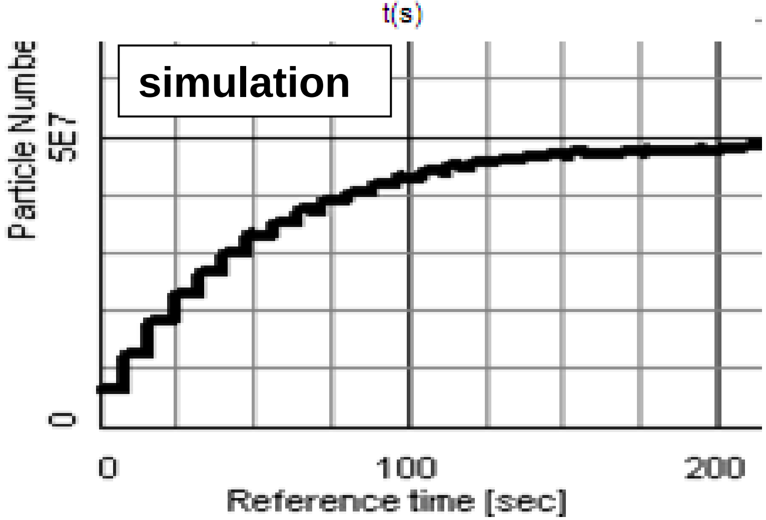
Particle accumulation with stationary barrier bucket at ESR

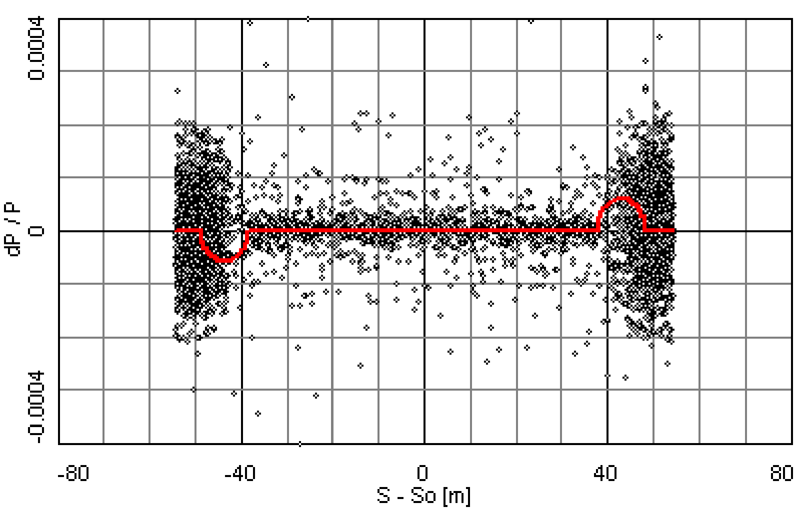
Ion kind	$^{124}Xe^{54+}$
Particle number	10^7 / injection
Energy	154,4 MeV/u
Circumference	108.5 m
Initial momentum spread	5×10^{-4}
Initial hor./vert. emittance	0,7 mm mrad
RF voltage	120 V
Electron cooler length	1.8 m
Electron beam radius	2.5 cm
Effective electron temperature	10^{-3} eV
Cooler magnetic field	0.08 T
Beta functions in cooler hor./vert.	16 / 7 m

Particle accumulation with fixed BB and electron cooling (experiments at ESR)





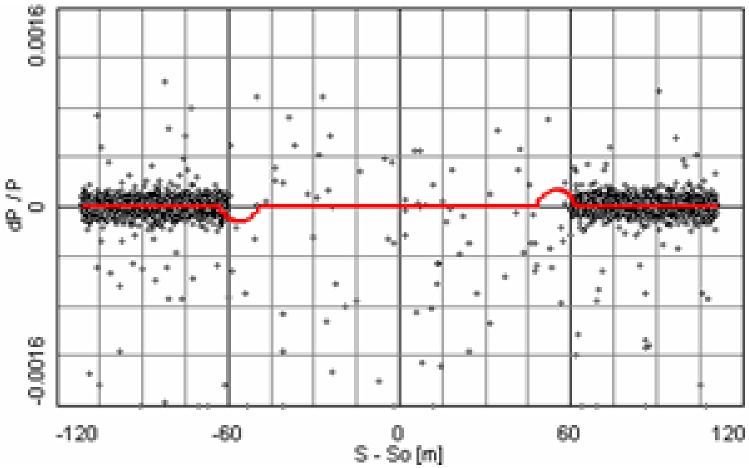


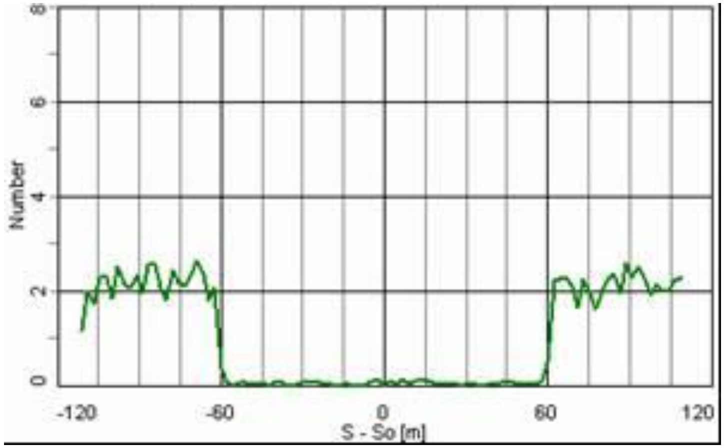


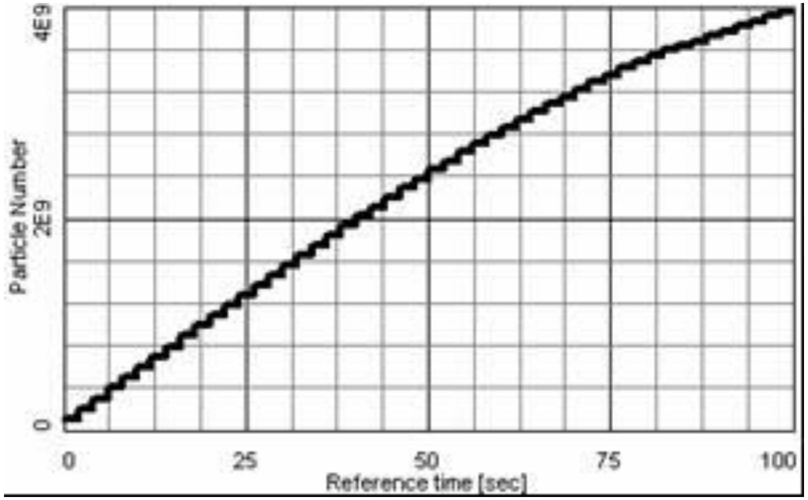
Simulation for NESR (FAIR) parameters

Ion kind	$^{132}Sn^{50+}$
Particle number	$1{,}0\times10^{8}$ / injection
Energy	740 MeV/u
Circumference	222,8 m
Initial momentum spread	$6{,}5\times10^{-4}$
Initial hor./vert. emittance	0,125 mm mrad
RF voltage	2000 V
Interval between injection	2 – 2.5 sec
Electron cooler length	5 m
Electron beam current	1 A
Electron beam radius	0.5 cm
Effective electron temperature	10^{-3} eV
Cooler magnetic field	0.2 T
Beta functions in cooler hor./vert.	10 / 22 m

Particle accumulation in longitudinal phase space with barrier bucket and electron cooling (NESR, FAIR)



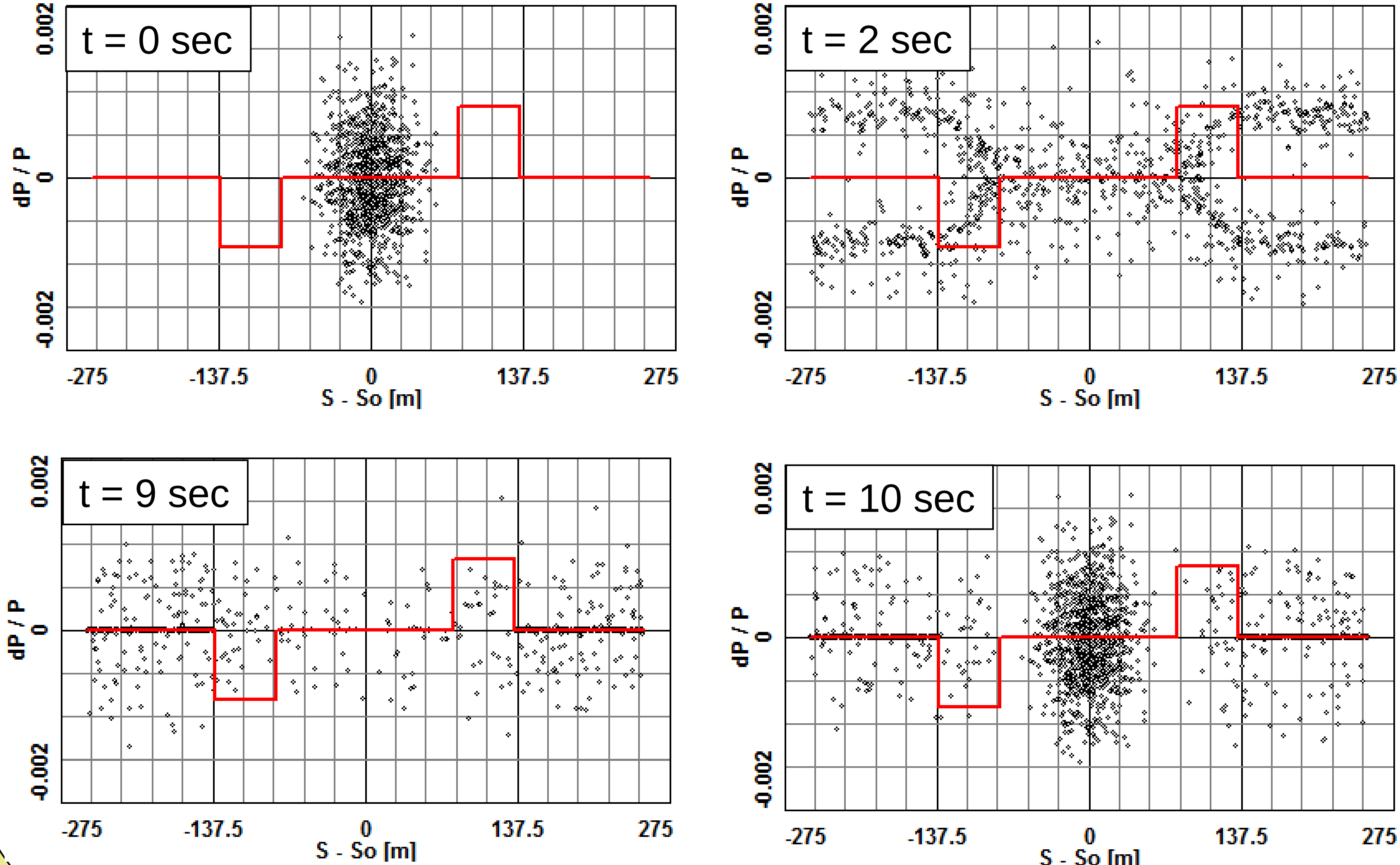




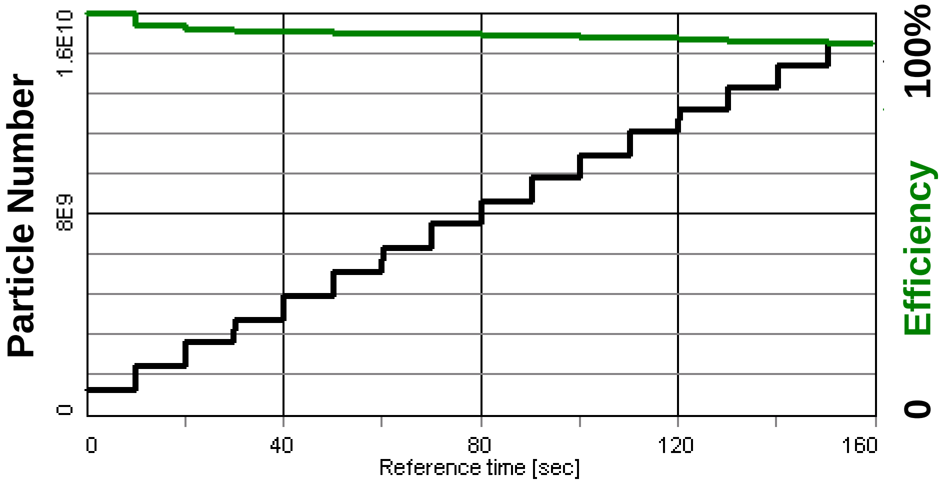
Particle Accumulation at NICA Collider

Ion ring			
Ion energy, GeV/u	1.5	2.5	4.5
Particle number per injection cycle		10^9	
Initial emittance (h/v), π mm mrad		1.1/0.9	
Initial momentum spread		5×10^{-4}	
Barrier bucket voltage, kV		2	
Electron cooling			
Cooler length, m		6	
Electron current, A		1	
Electron beam radius, cm		1	
Magnetic field, kG		1	
Beta function at cooling section, m		16	
Longitudinal cooling time, sec	3	12	80
Accumulation efficiency, %	92	66	34

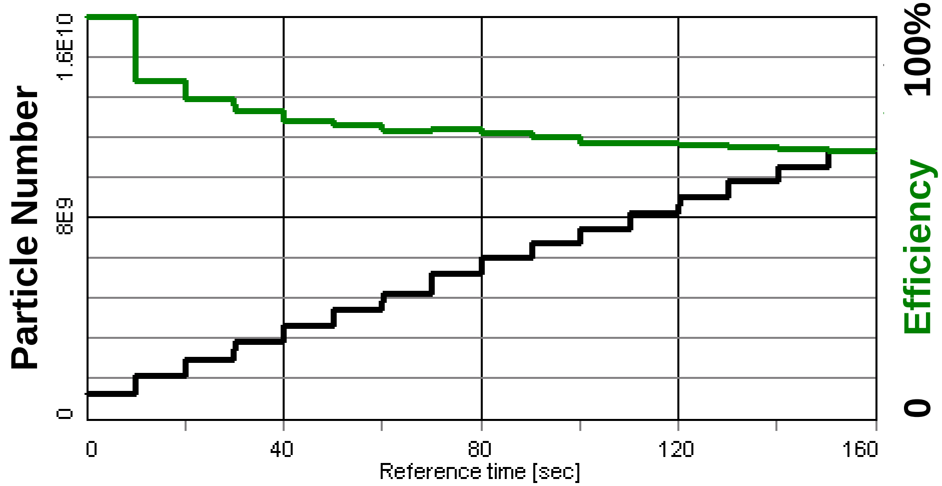
Beam dynamics during one injection cycle
E = 1.5 GeV/u



Efficiency of ion accumulation with stationary barrier buckets

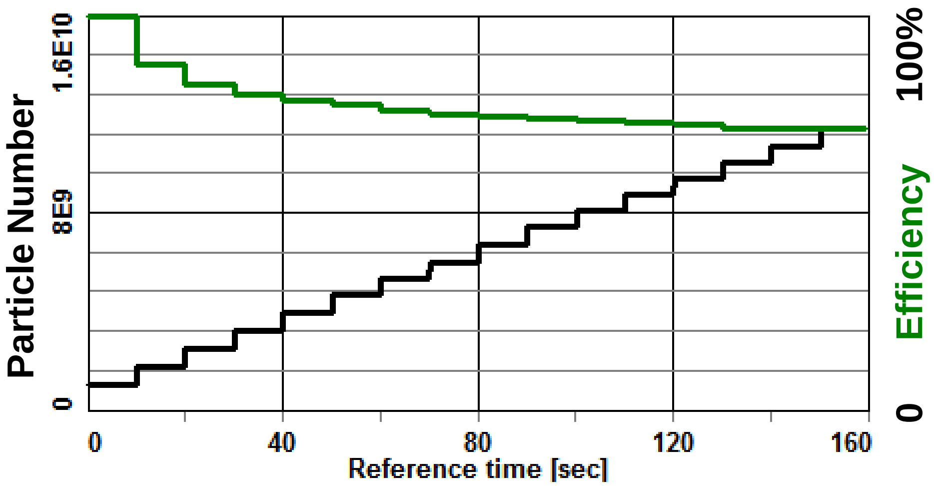


E = 1.5 GeV/u

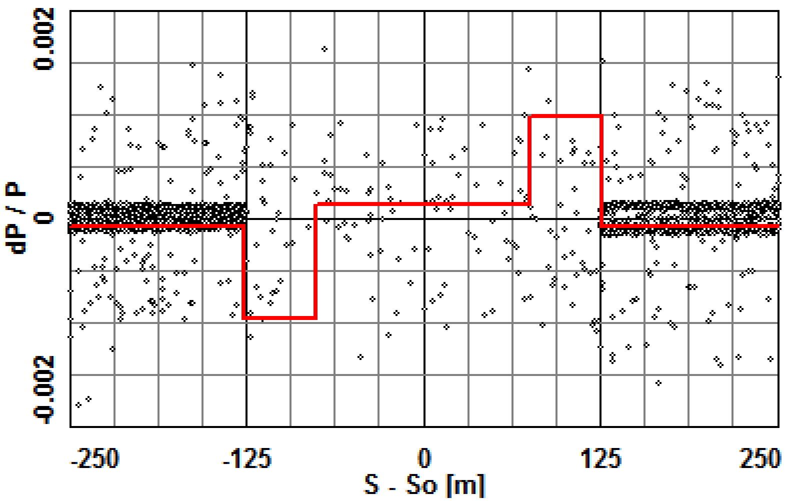


E = 2.5 GeV/u

Accumulation with electron energy shift (dp/p=1e-4) and nonzero voltage at the injection point (10 V)



E = 2.5 GeV/u

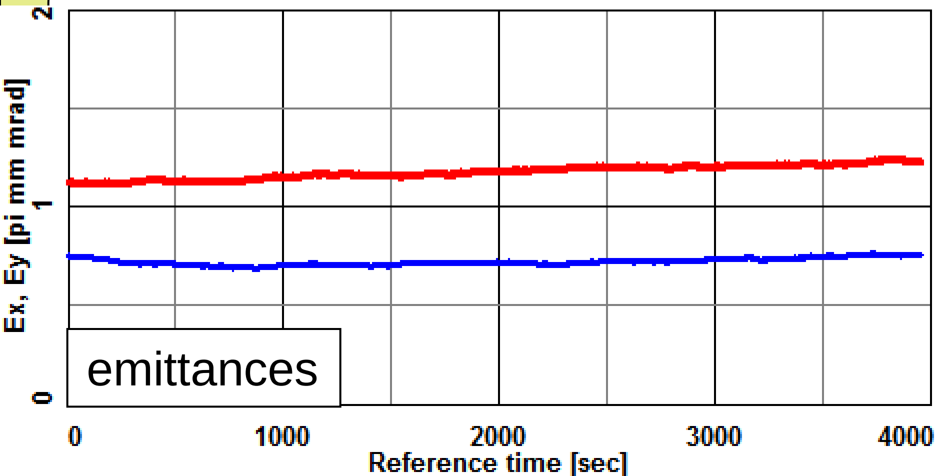


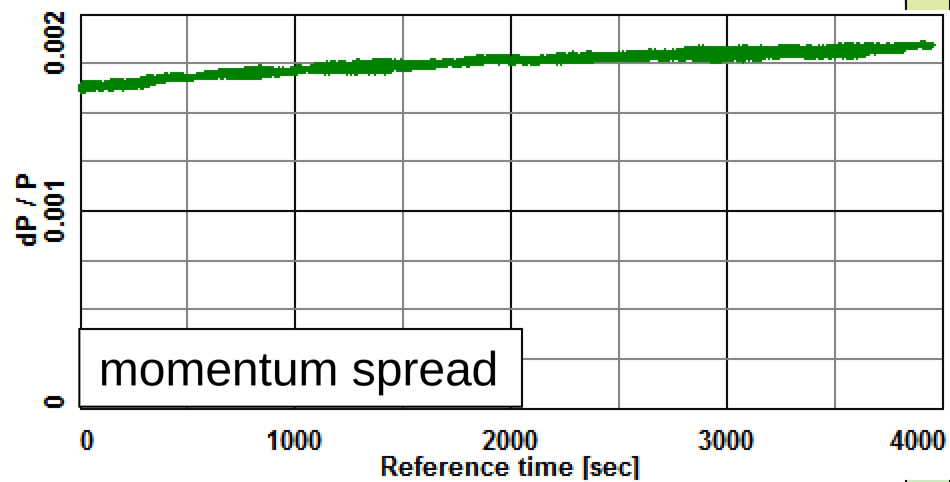
t = 160 sec

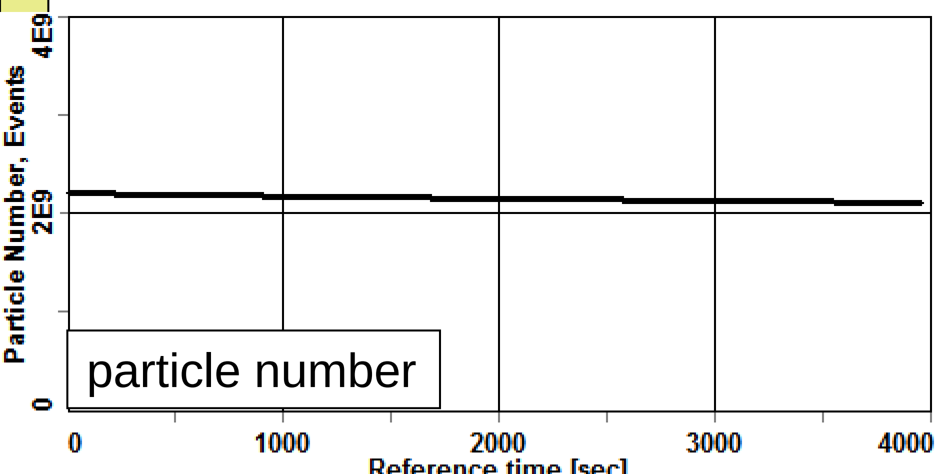
NICA Collider parameters

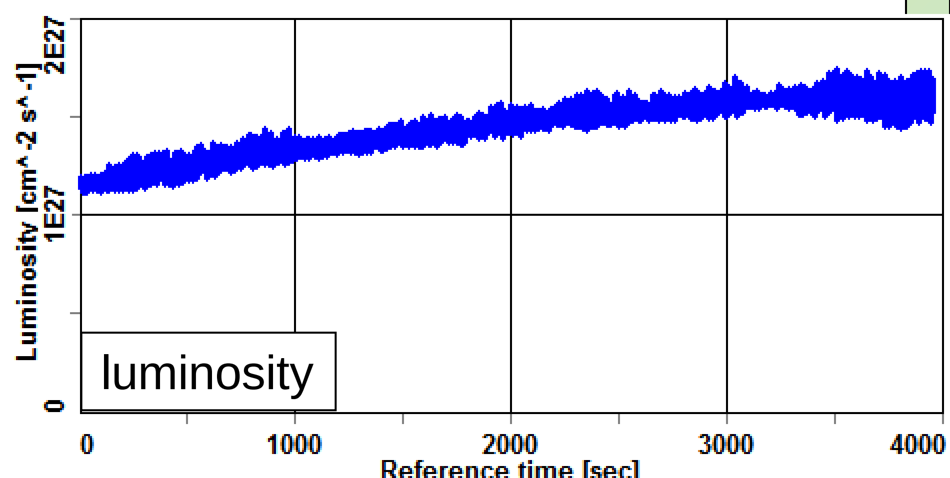
Ring circumference, m	503,04		
Bunch number	23		
Bunch length, m	0.6		
Beta-function at interaction point, m	0.35		
Transverse acceptance, π mm mrad	40		
Longitudinal acceptance	±0.010		
Gamma transition	7.091		
Ion energy, GeV/u	1.0	3.0	4.5
Particle number per bunch	$2.7\cdot10^{8}$	$2.4\cdot10^{9}$	$2.2\cdot10^{9}$
Momentum spread, 10^{-3}	0.62	1.25	1.65
Transverse emittances (hor/ver), non-normalized, π·mm·mrad	1.1/ 1.01	1.1/ 0.89	1.1/ 0.76
Average luminosity, 10^{27} cm^{-2}sec^{-1}	$1.1\cdot10^{25}$	$1\cdot10^{27}$	$1\cdot10^{27}$
Intrabeam scattering rates, sec	186	702	2540

Beam dynamics in collider mode with hollow electron beam, E=4.5 GeV/u

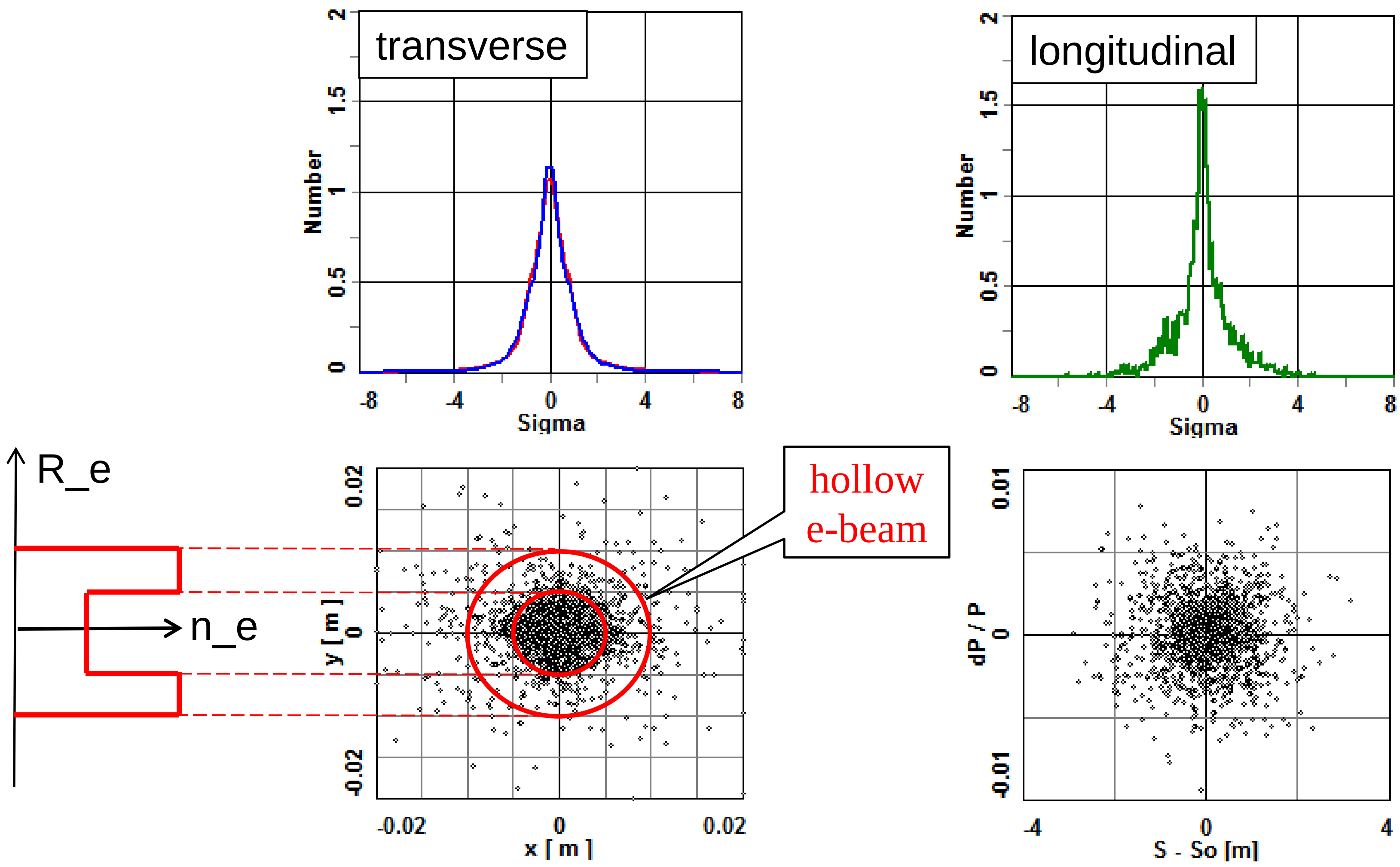








Beam profiles after 4000 sec



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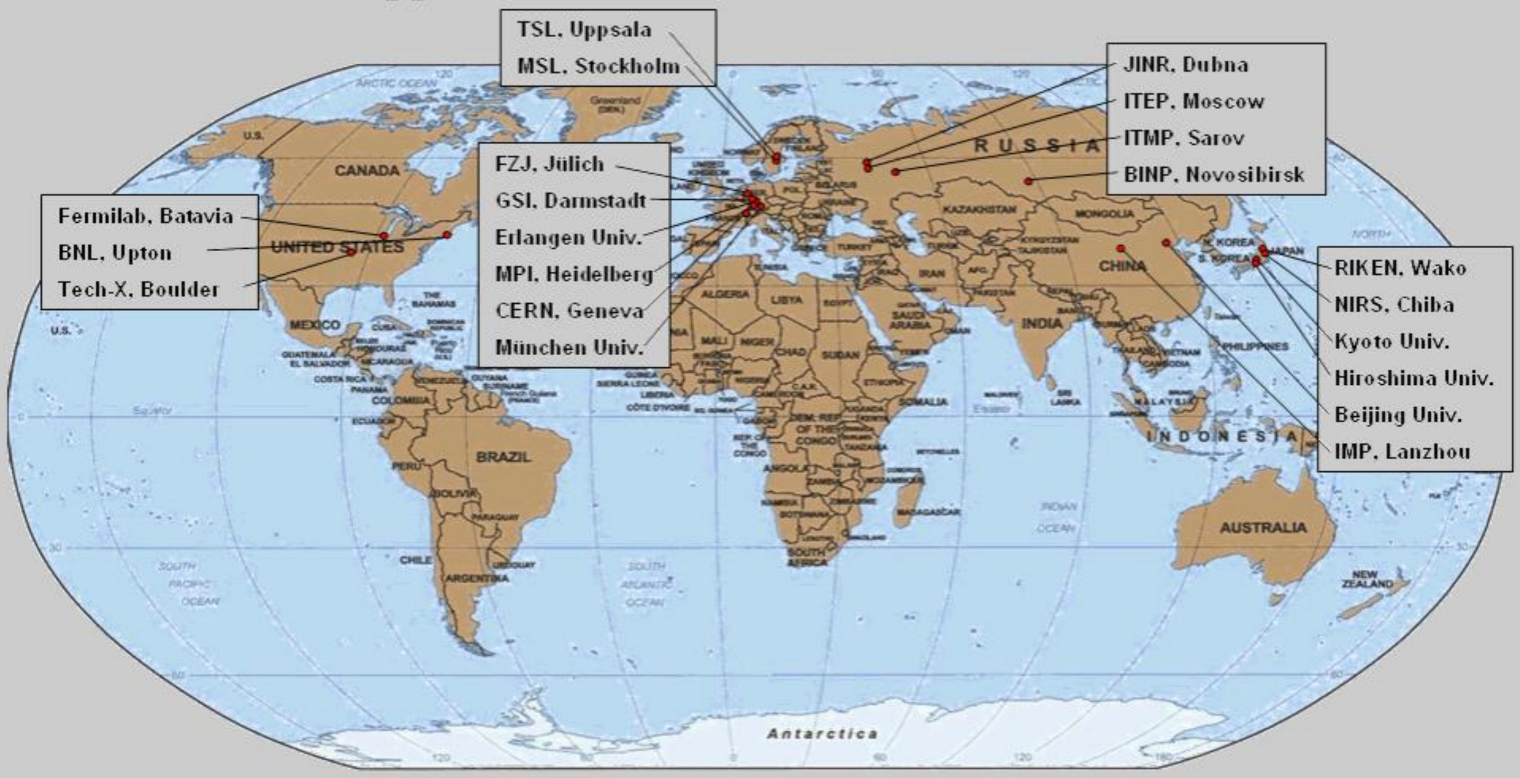
Application of BETACOOL over the world



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