FORMATION OF PROTON BEAMS IN NICA COLLIDER

E. Syresin on behalf of team

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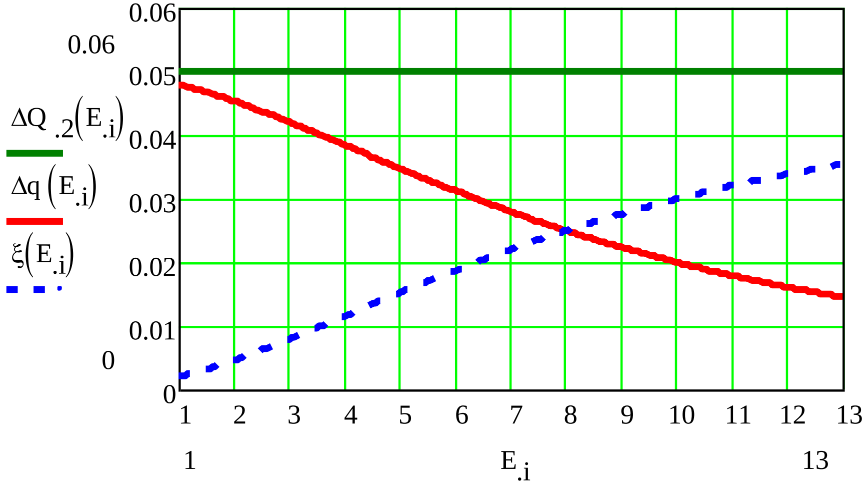
Luminosity at energy of experiments

Formation of polarized proton beams

Proton-Proton Mode: 2 IP, but (!) Luminosity for 1 IP



SPD only!

Luminosity for 1 IP

and

N_p is proton number

per bunch

$\Delta Q_{1\,=\,0.05}$

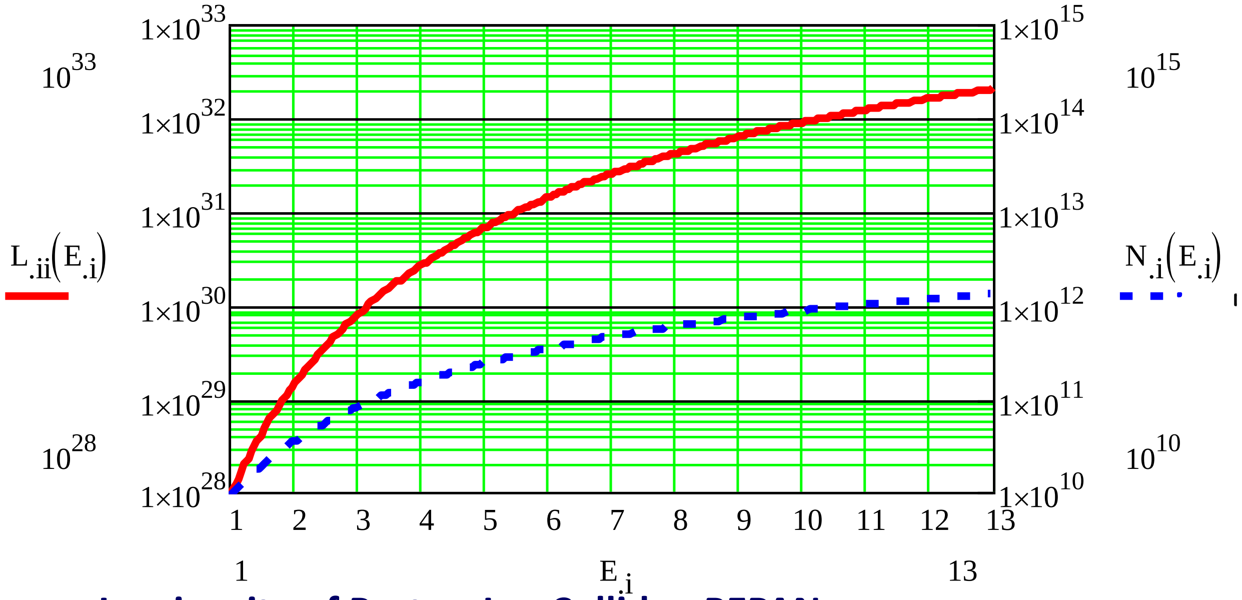
$\Delta Q_2 = \Delta q + \xi = 0.05$

$\varepsilon = 1.1\ \pi$*mm*mrad

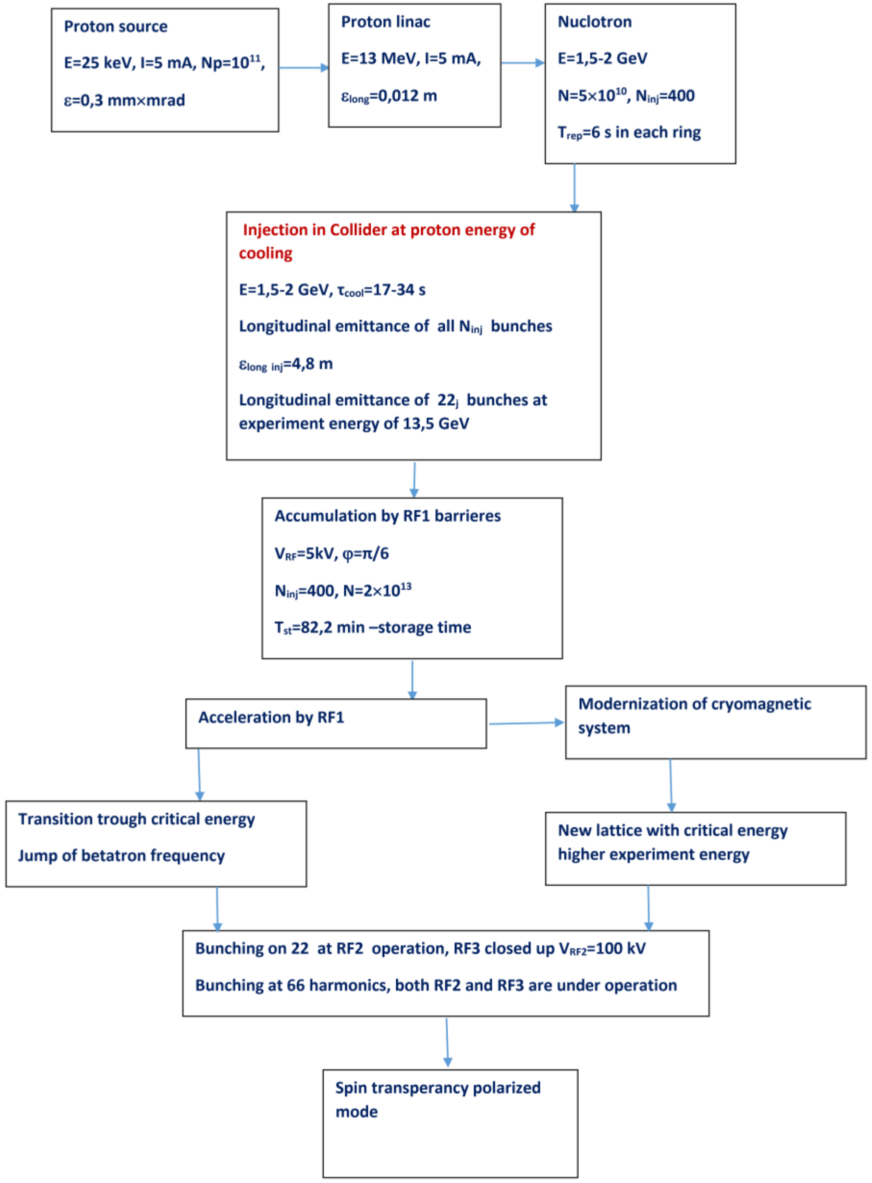
PROJECT LUMINOSITY $L=10^{32}cm^{-2}s^{-1}$

Bunch intensity $N_b=10^{12}$

Proton intensity in ring $N=2.2\times10^{13}$

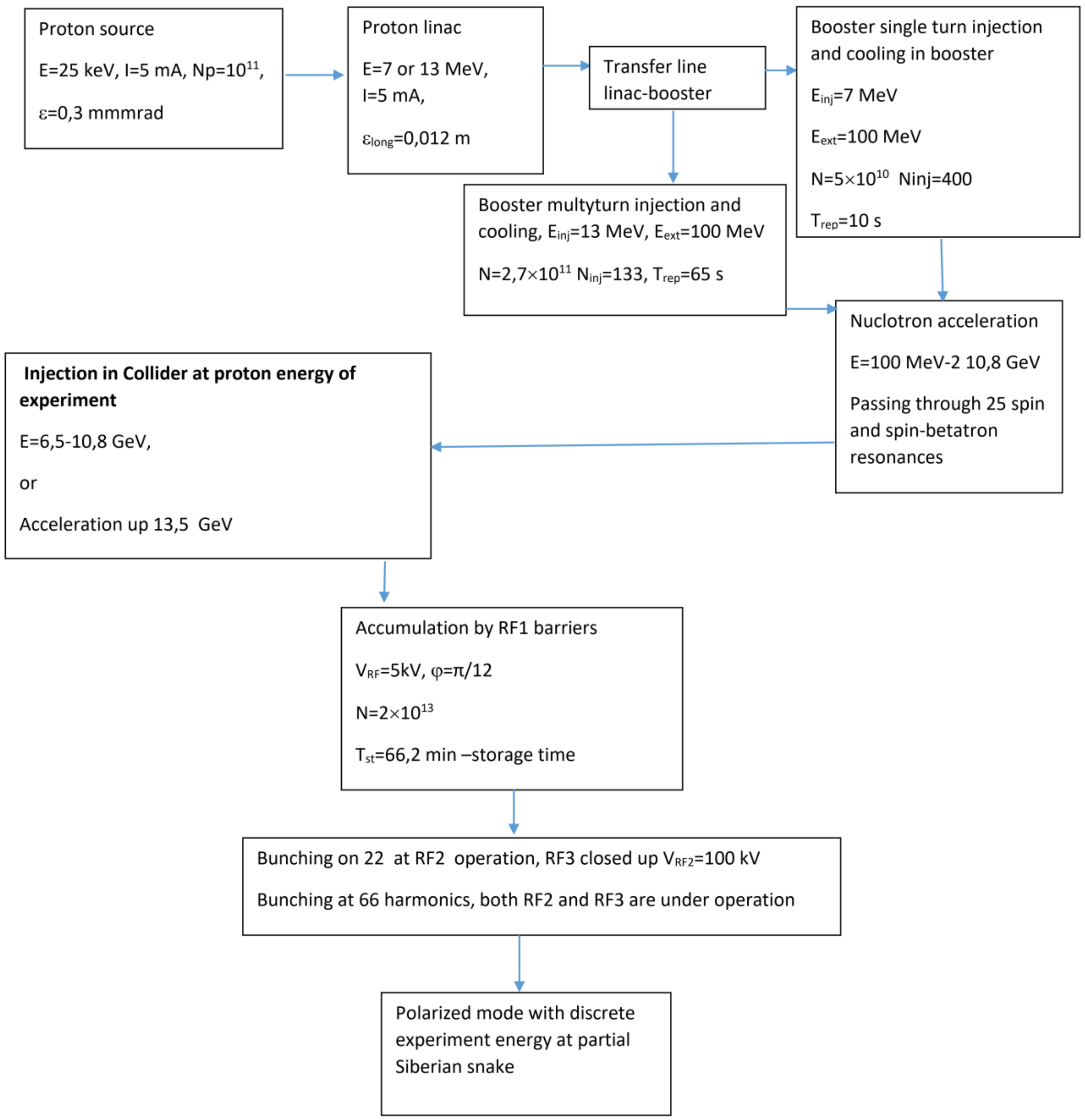


Injection in Collider at proton energy of cooling

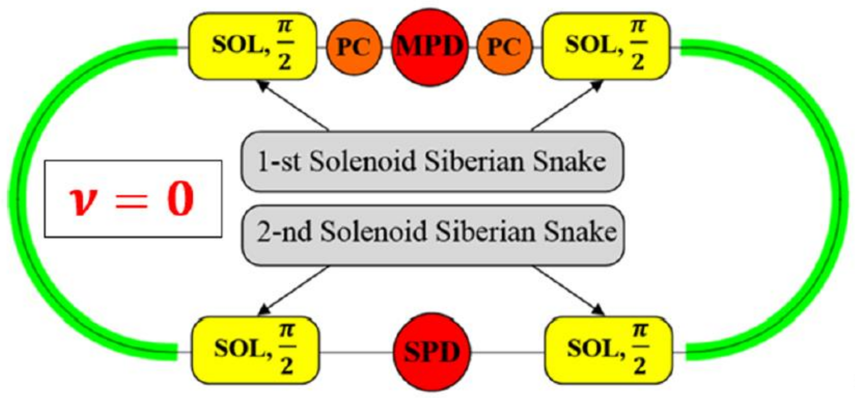


TWO SCHEMES OF PROTON BEAM FORMATION

Scheme with proton injection in collider at energy of experiment



Formation of polarized proton beams at initial stage of project



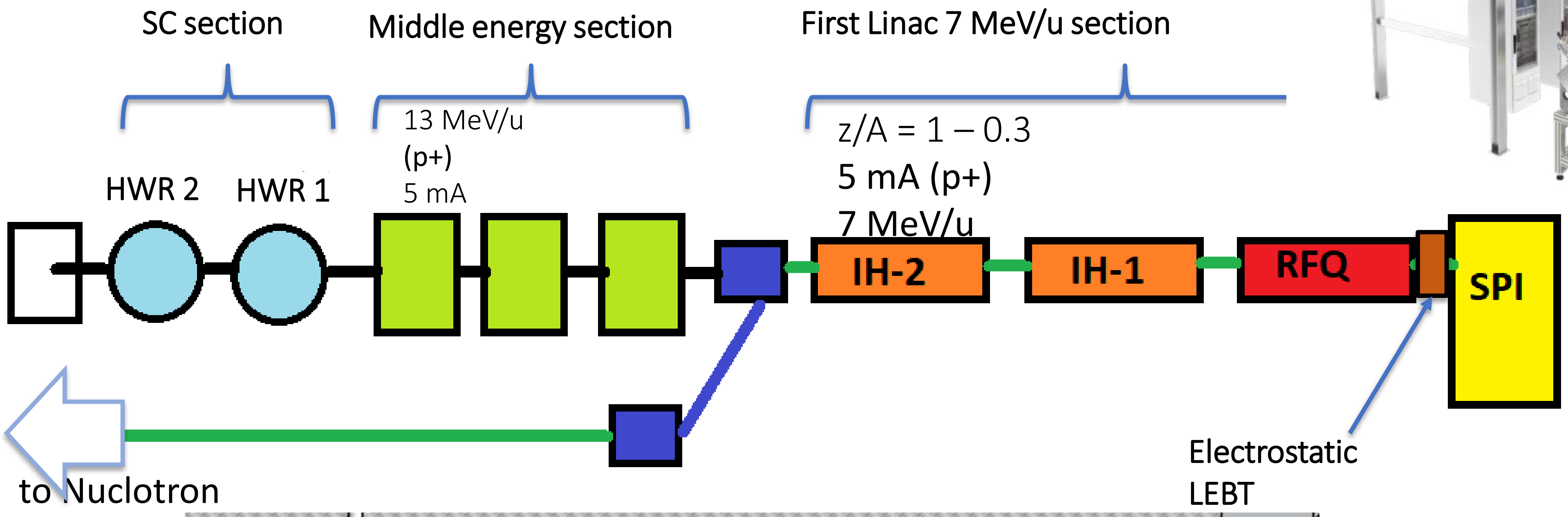
Polarized mode at initial part of NICA

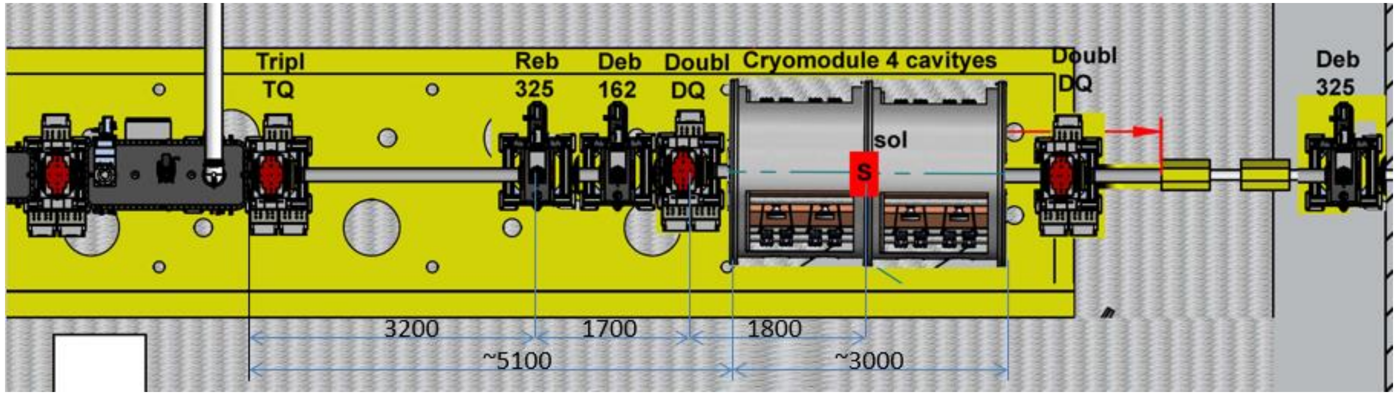
4 solenoids with magnetic field of 6 T and length of 1 м are planned to installed in each Collider ring (24 T*m)

At low proton energy E<3,2 GeV is planed spin transparency mode

At energy of 12.5 GeV>E>3,2 GeV will be realized polarized mode with partial Siberian snake. Longitudinal polarization in detector at discret proton energy with gap of0,523 GeV.

Light-ion Linac layout





PROTON INJECTION FROM NUCLOTRON TO COLLIDER

Proton bunch intensity at Nuclotron injection in collider

$N=5\times10^{10}$

Proton repetition frequency at Nuclotron injection in two collider rings at kinetic energy 1,5-2 GeV (B=0.4-1T, dB/dt=0.8T/s, t=1 sec- time between end of one cycle and start of new cycle)

$f=0.3$ Hz

Number of injection cyles in each ring

$N_{inj}=400$

Normalized rms longitudinal emittance

$\gamma\beta\sigma_s\,\sigma_p=1{,}2\times10^{-2}$ m

Normalized rms longitudinal emittance at N_{inj} =400 injections

$\varepsilon_{inj}=N_{inj}\gamma_{inj}\beta_{inj}\sigma_s\sigma_p=4.8$ m.

Normalized rms emittance at experiment energy

$\varepsilon_{exp}=n_b\gamma_{exp}\beta_{exp}\sigma_s\sigma_p=0.26$ m

Proton intensity in collider ring

$N=2\times10^{13}$

Rms momentum spread after debuncher $\sigma_p=10^{-3}$.
Injection rms bunch length in Nuclotron with circumference $C_N=253$ м, $\sigma_s=C_N/2\times3^{1/2}=74.4$ м.

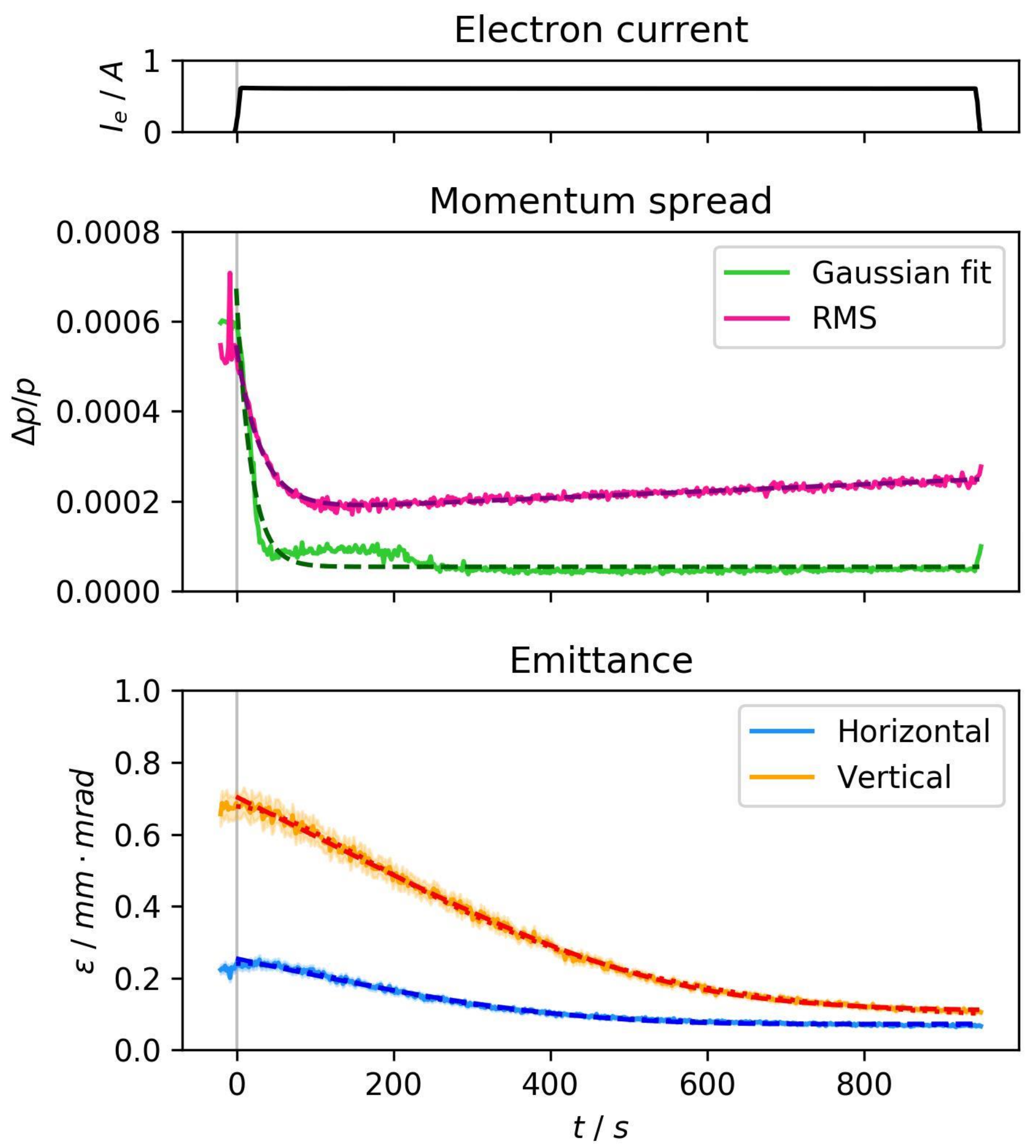
Normalized rms transverse emittance

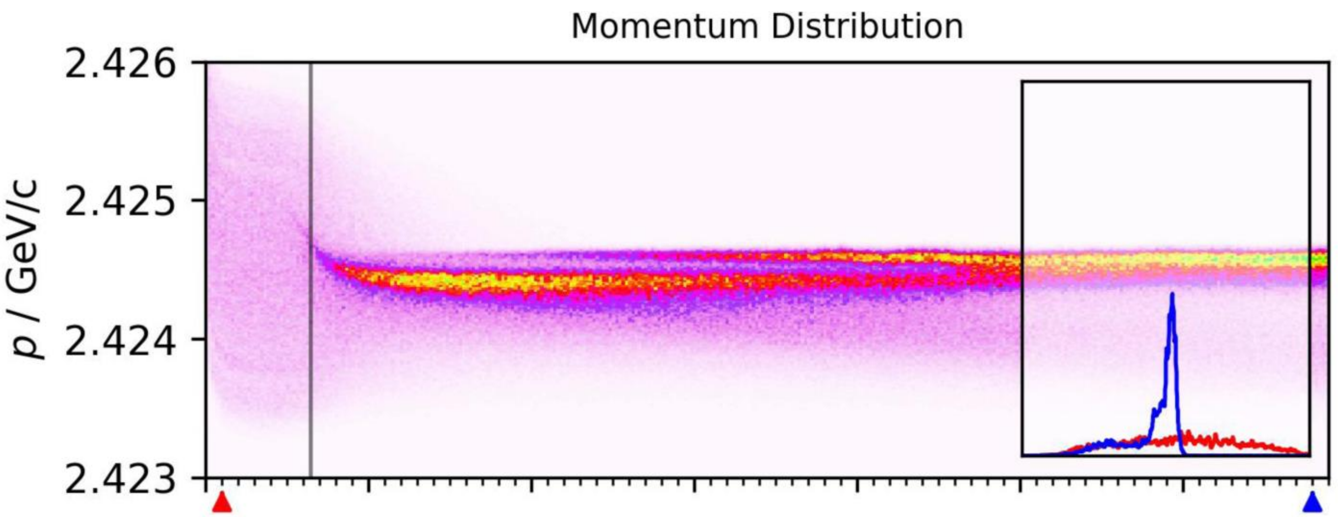
$\gamma\beta\varepsilon=4\ \pi\times$mm$\times$mrad

Strong longitudinal electron cooling is required to reduce longitudinal injection emittance

ELECTRON COOLING OF PROTON BEAMS AT COSY

Electron cooling of 1.6E9 protons until equilibrium





COSY experiment

γ=2.78, E_k=1.66 GeV, E_e=907 MeV, I=0,62 A

Longitudinal cooling time

τ_{cool}=18,6 s

Transverse cooling time

τ_{cool-h}=132 s

τ_{cool-v}=182 s

FORMATION OF HIGH DENSITY COOLED PROTON BEAM AT LOW ENERGY

Proton intensity in collider ring

$$N=2\times10^{13}$$

At

$$\gamma=3$$

Laslet tune shift

$$\Delta Q=0,05$$

Stored stack, occupied half of Collider ring, has rms emittance

$$\varepsilon=r_p N/(2\pi\Delta Q\gamma^3\beta^2)=4,8\ \pi\times mm\times mrad$$

After acceleration up to proton kinetic energy 12 GeV rms emittance is reduced to

$$\varepsilon= 1.1\ \pi\times mm\times mrad$$

Application of electron cooling with transverse cooling time about τ_{cool}=100 s by one order shorter than storage ion time T_{inj}= 2500-4000 s permits to form dense proton beam with small emittance and large betatron tune shift of ΔQ=0,05.

RF1 BARRIER PARAMETRS

Maximal voltage – 5 kV

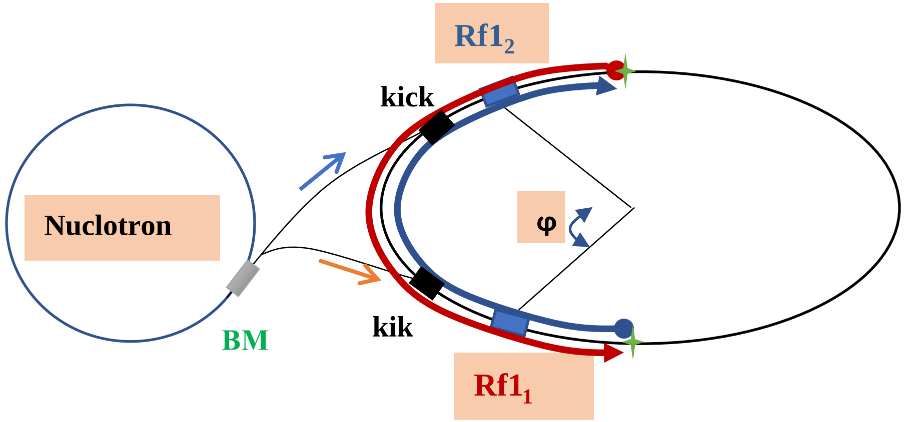
Four rectangular barriers per turn with phase length- π/12

Stack phase zone– π (Nuclotron perimeter 251.5 м).

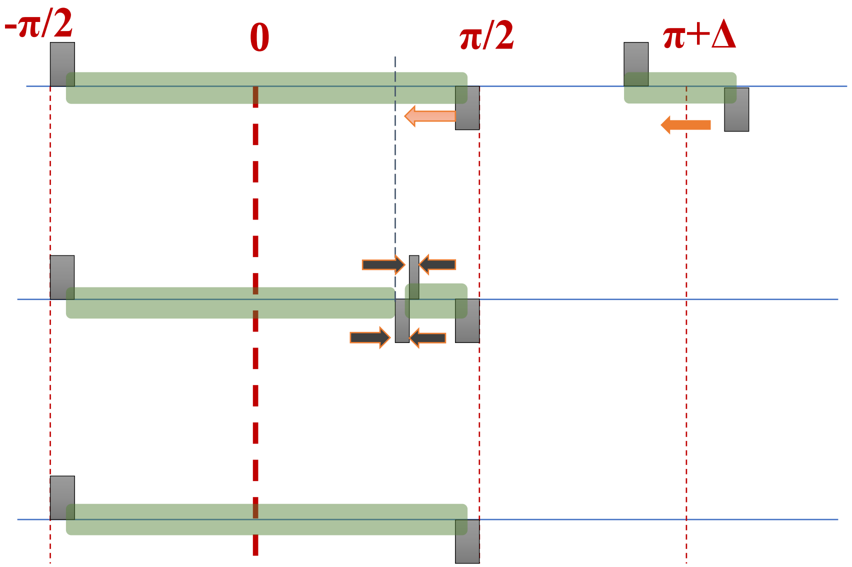
Kicker fronts – 2 x 200 ns = 0.54π

Kicker plato -200 ns=0.27 π

Injection zone = kicker frons + kicker plato=0.54 π=204 m



Synchronization of stack formation in two
Collider rings permits to avoid parasitic stack collisions



At acceleration stack occupies half of ring

PROTON STACK SPACE CHARGE EFFECTS AT RF1 BARRIER BUCKET STORAGE

RF1 voltage at heavy ion operation U=5 kV,

Phase width $\varphi=\pi/12$

Current of Au^{79} ions I=0,4 A, $N_i=5.2\times10^{10}$, Z=79

$W_{sp}/W_{RF}=1,2I/\gamma^2\beta$

Space charge effects of Au^{79} ions gives a reduction of 5,5% of RF1 barrier bucket capacity

Current of protons I=1.87 A, $N_p=2\times10^{13}$

Space charge effects of protons by 4.5 times larger than Au^{79}ions

Space charge effects of Au^{79} gives a reduction of 26% of RF1 barrier bucket capacity $V\times\Delta\varphi$

Height of separatrix $\sigma_{p\text{-}s}=1.25\times10^{-3}$.

Critical rms momentum spread at development of longitudinal instability $\sigma_{p\text{-}th}=6\times10^{-4}$

Losses at high proton intensity, increase of phase width

$\varphi=\pi/6$

Storage of intensive proton beam

$L_b=L_{bar}+2\Delta L_{bar}=30{,}3$ м injection length

At barrier width $\varphi=\pi/6$ storage stack has size C/3=167 m

With out cooling longitudinal stack spice is fulfilled through $n_{inj}=C/3L_b\cong 5$ injection cycles

$$dL_{st}/dt=-L_{st}/2\tau_{cool}+L_{s0}\times D(\sigma_p)/2\sigma_p^{2}+L_b/2\tau_{rep},$$

$\tau_{rep}<\tau_{cool}$

Goal: Cooling time is factor by 3-5 times larger than injection repletion time

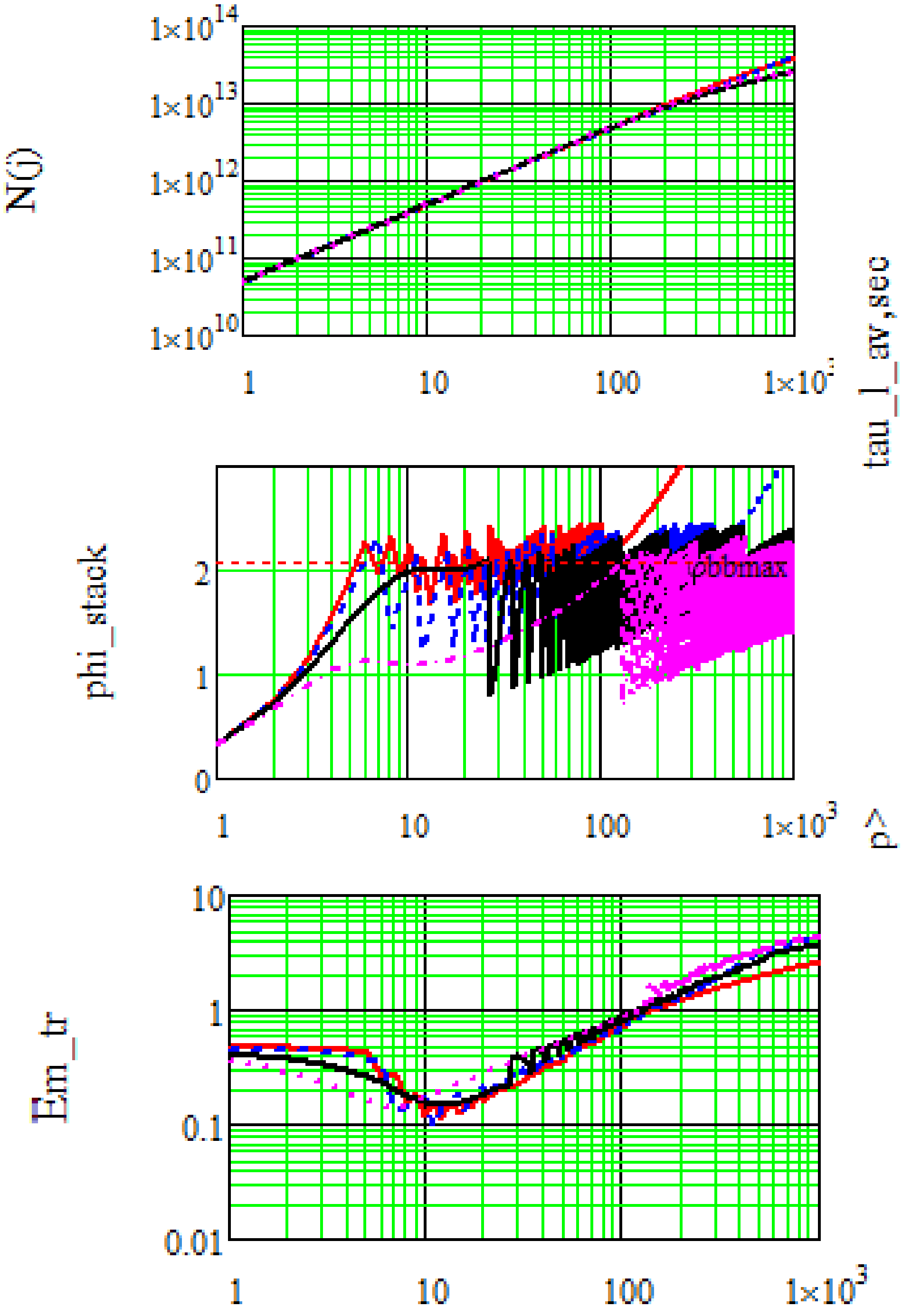
Numerical simulation of proton storage

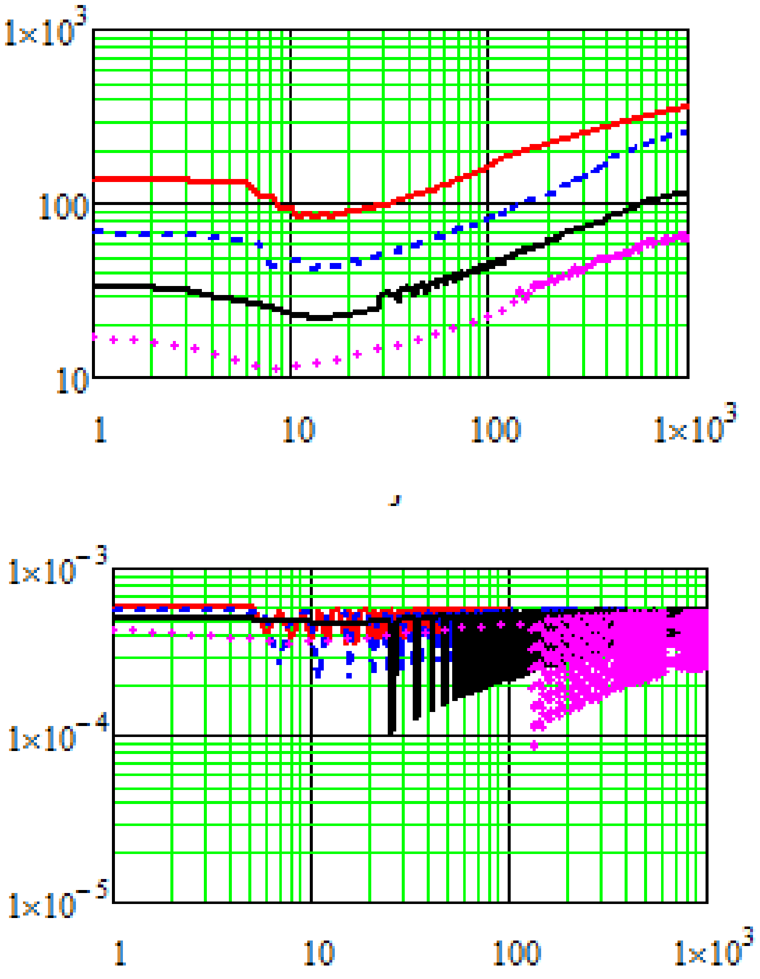
T_{inj}, c	m	N_{inj}	N_{inj}-$_{long}$	T_{st}, min	τ_{cool}, c	$\Delta\varphi_{st}$, rad	N_{max}
Periodical injection							
6	0	26	0	2.6	21.9	2.1	1.2×10^{12}
6	0	114	0	11.4	10.9	2.1	5.6×10^{12}
6	0	327	0	32.7	5.5	2.1	1.6×10^{13}
12	0	98	0	19.6	21.9	2.1	4.8×10^{12}
12	0	245	0	49	10.9	2.1	1.2×10^{13}
12	0	401	0	80.2	5.5	2.1	2×10^{13}
Injection with additional stack deep cooling							
6	5	477	247	146.5	34	2.1	2×10^{13}
6	5	478	86	82.2	17	1.74	2×10^{13}
12	5	490	113	188.4	34	1.9	2×10^{13}
12	5	414	6	87.6	17	1.46	2×10^{13}
6	10	651	217	260.4	34	1.85	2×10^{13}
6	10	532	72	118.8	17	1.2	2×10^{13}
12	10	561	97	286.8	34	2.31	2×10^{13}
12	10	417	6	94.2	17	1.36	2×10^{13}

1.Project intensity can be obtained at cooling time $\tau_{cool}=\tau_{rep}/2$ during 80 min injection

2.Project intensity can be obtained at $\tau_{cool}=3\tau_{rep}$ with additional deep stack cooling during 80 min injection

Storage of intense proton beams

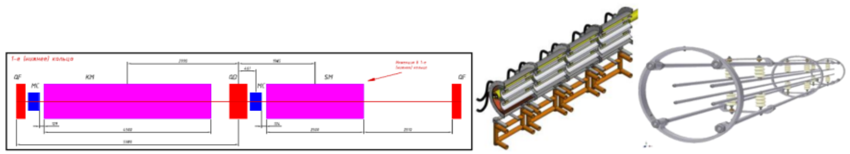




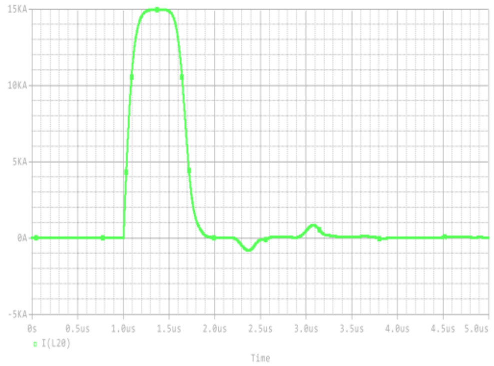
Dependences of a)proton intensity, b) longitudinal cooling time, c) stack phase width, d), rms proton momentum spread e) rms transverse emittance on number of injections   at different initial longitudinal cooling time.

Parasitic post pulses of collider injection kicker

COLLIDER INJECTION SYSTEM



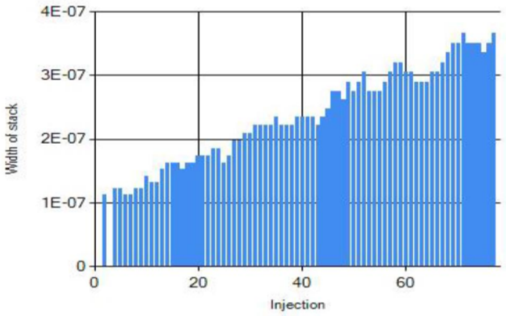
Scheme and design of Collider injection system



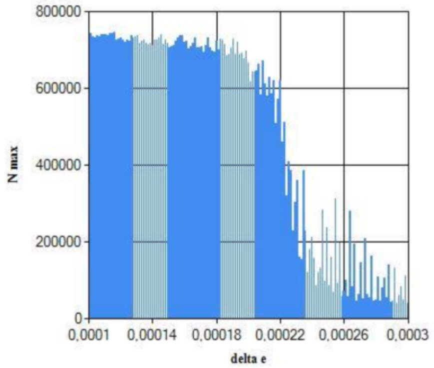
The kicker pulse with parasitic post pulses

Parameter	Value
Aceptance, $\pi\times$mm$\times$mrad	40
Relativistic factor, γ	4.26
Rms emittance, ε, $\pi\times$mm$\times$mrad	0.4
Kicker	
Acceptance angle, θ_c, mrad	1.5
Magnetic field, kG	1.3
Length, m	3.9
Ion deflection angle, mrad	12
Kicker parasitic post- pulses	
Magnetic field, G	23
Deflection angle, $\Delta\theta$, mrad	0.18
Percentage of ions affected by post- pulses, η, %	40

SIMULATION OF ION STORAGE



The dependence of the FWHM square angle spread on the number of injections



Dependence of the number of stored ions on the kicker post-pulses deflection angle at the electron temperature Te=10 eV.

The critical kicker post-pulses deflection angle corresponds to $\Delta\theta=1.8\times10^{-4}$, at which the intensity of stored ions is equal to the project value 6.6×10^{10}. The magnetic field amplitude of parasitic post-pulses B_p=23.4 Gs corresponds to 1.8% of the main magnetic field of the kicker pulse.

The intensity of stored ions fast decreases with increasing kicker post-pulses deflection angle when the rms stack ion angle spread θ is comparable with the critical angle θ_{cr}

INDUCTION ACCELERATION BY RF1 BARRIERS
TRANSITION THROUGH CRITICAL ENERGY

Induction acceleration of stack ions fulfilled half of ring by RF1 voltage U=300 V.

Required time for proton acceleration

$$\tau_{ac}=T_{rev}(\gamma_{exp}-\gamma_{inj})\ mc^2/eU=50\ s.$$

Momentum spread and beam emittance at proton acceleration are reduced as

$$\Delta p/p\propto 1/\gamma,\ \varepsilon\propto 1/\gamma.$$

parameter	value
Betetron tune shift, Δq_{sp}	0.05
variation of factor $\Delta\gamma_{tr}$	0.09
rate $d\gamma_{tr}/dt$ (c^{-1})	8,5
Transition time through critical energy, t_0 (ms)	10,5
rms momentum spread $\sigma_{p\text{-}tr}$	$3,3\times10^{-3}$
Impedance Z_{imp}(Ohm)	20
Pipe radius (m)	0.05
Number of harmonic cut n_{cut}	1602
Integral of inciment s_+/n	$6,3\times10^{-3}$

Maximum rate $d\gamma_{tr}/dt$ is restricted by rate of lense gradient $dG/dt=14,3$ T/(m×s) or its current rate $dI/dt=6,4$ kA/s.

At proton energy close to critical $\gamma=\gamma_{tr}=7,089$, the RF barriers switch off. Protons pass through the critical energy without RF barriers. When proton energy becomes larger critical energy RF1 barriers turn on again with opposite polarities.

At energy close to critical momentum compaction factor is equal to $\eta\cong 2\Delta\gamma/\gamma^3\cong 3\times10^{-4}$ at $\Delta\gamma=0.05$.

To accelerate protons to this energy the required time is of 0.25 s.

Quadrupole power supply that creates current difference between F and D lenses will be used for fast variation of dispersion to provide a jump of critical gamma on a value $\Delta\gamma_{cr}=-0.09$ during $T_{jump}=10,5$ ms

$$\Delta\gamma_{cr}=1.8\times\Delta Q,\ \Delta Q\cong 0.05 \text{ at } \Delta\gamma_{cr}=0.09,$$

$$\alpha=1/\gamma_{cr}^2=\int D_x/\rho ds/C,\ \Delta\alpha==-\Delta Kl/G\times(D_x^2-D_y^2)=5.8\times10^{-4}$$

$\Delta Kl=0.075$
$\Delta Q=\beta\Delta Kl/4\pi=0.05$
ΔK produced by 24 lenses in one arc at $\Delta I=67$ A. $T_{jump}=10.5$ ms, $L_Q=2.25$ mGn, V=14.5 V

Продольная неустойчивость при прохождении критической энергии

Пороговый ток продольной неустойчивости

$$I=4mc^2\beta^2\gamma\eta\sigma_{p-th}{}^2/eZ$$

$$N_{th}=I_{th}\times L_{s-tr}/ec\propto\varepsilon_{st-tr}\times\sigma_{p-tr}$$

$$\sigma_{p-tr}=(\Delta p/p)/3=3.3\times10^{-3}$$

$\sigma_p\times10^{-3}$	2,1	2,8	3,25
σ_{p-sep}/σ_p	3,85	2,9	2,5
σ_s(м)	0.87	1.08	1.21
σ_{s-sep}/σ_s	8,7	7,05	6,3
ε_{exp}(м)	0,54	0,9	1,17
H_0	0.4	0,6	0,8
H_{max}/H_0	5	3,3	2,5
df/dH (H_{max}/H_o)	0.013	0.051	0.093

ε_{exp}=0,9 m, $\sigma_p=2,8\times10^{-3}$ и σ_s=1,08 m.

Threshold proton intensity

$$N_{st}=2,6\times10^{13}$$

Increment γ_{ins} is proportional to number of harmonic $\gamma_{ins}\propto n\times Z_{imp}(n)^{1/2}$ and empidance

Maximum number of harmonic is equal to $n_{cut}=C/2\pi b=1602$, where b=50 mm

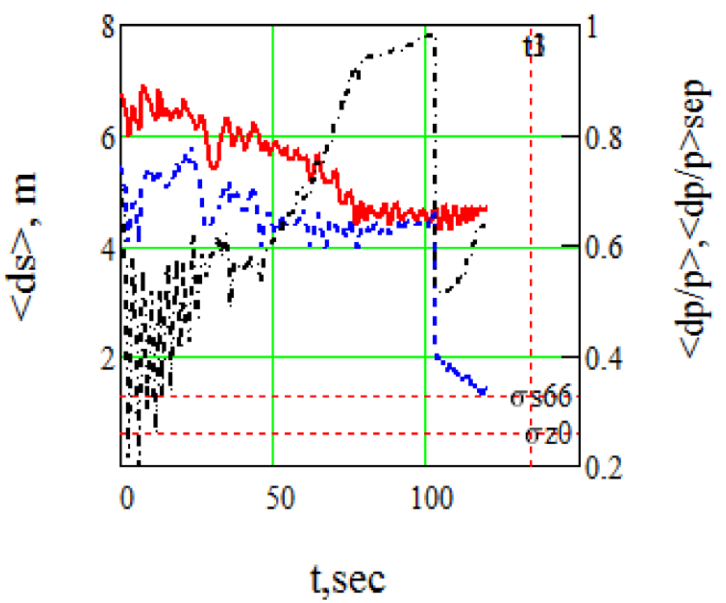
Integral fromincrement corresponds to:

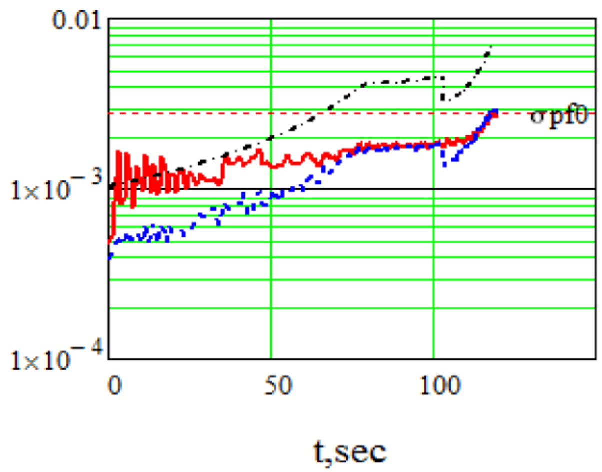
$$s_+/n=\int\gamma_{ins}dt=0.1\omega_0 t_0\eta_{tr}\sigma_{p-tr}=6,3\times10^{-3}$$

At development of instability longitudinal emittance increases less than 10%.

Bunching of intense proton beam)

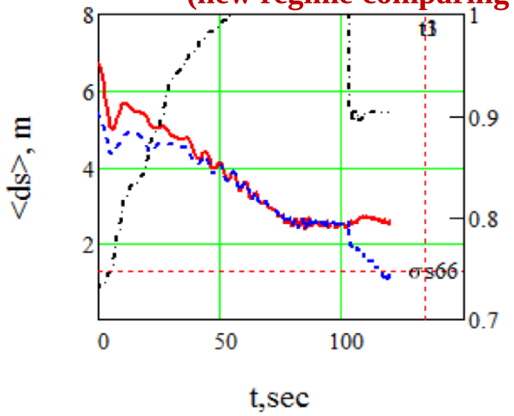
RF3 regime	Rms length in central ceparatrix	Rms momentum spread	Percentage of protonc in cental ceparatrix
RF2 bunching with short circuit of RF3 cavities at an increase of RF2 voltage. Further bunching by RF3 cavities	1.05 m	2.76×10^{-3}	91%
RF2 bunching at increase RF2 voltage and an input of RF3 voltage produced by proton beam space charge	**1.37 m**	**2.74×10^{-3}**	**63%**

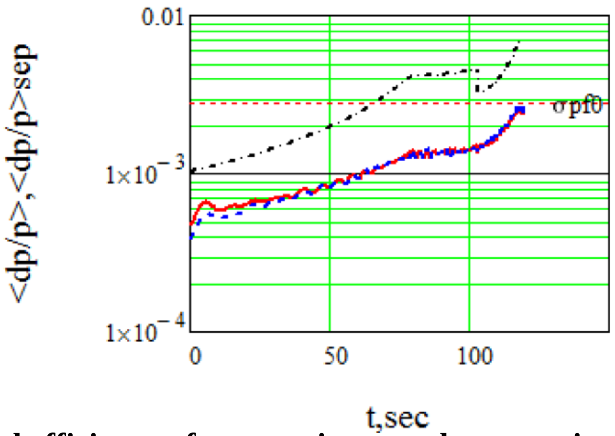




At proton intensity 2×10^{13} the avarege circulated proton beam corresponds to 1,5 A (for gold ions it is 0,4 A), RF3 voltage from proton beam space charge is equal to 57 kV. The proton beam bunch length after RF2 bunching is very high 4м, at longitudinal length of RF3 separatrix 7,6 м. About 37% are captured in side separatrix at regime with out short circuit RF3 cavity, that became to parasitic collisions.

Bunching of RF2 with short circuit of RF3 cavities (new regime comparing with ion mode)





a)Dependence of rms bunch length and efficiency of capture in central separatrix on time.

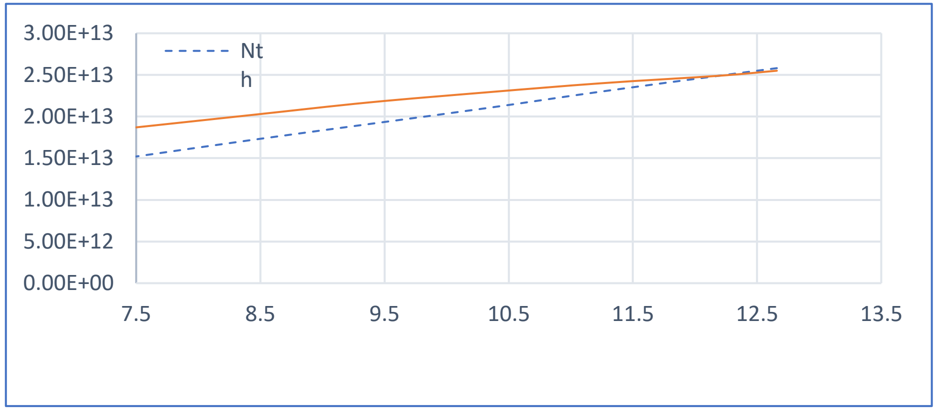
b). Dependence of rms momentum spread and separatrix heigt on time.

When short circuit of RF3 cavities is finished same transition effects may be produce an influence on parameters of bunching beam. These effects are unpredictable during computer simulations and can be tested only by experimentally.

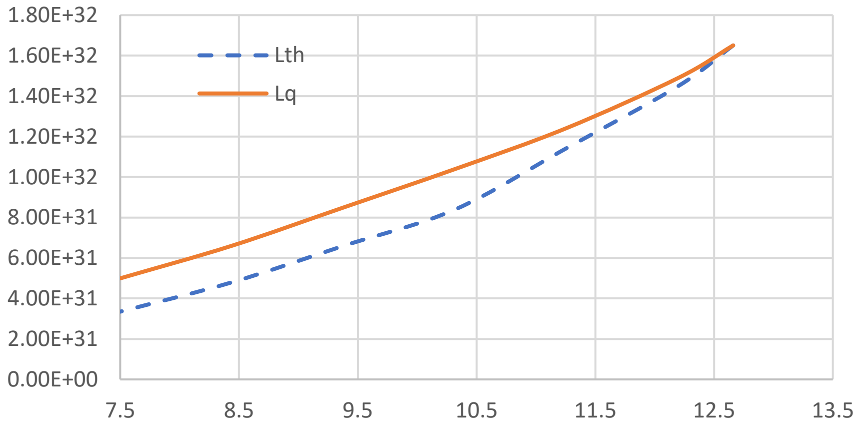
Luminosity at energy of experiment

$N \propto \beta_{exp}\gamma_{exp}\sigma_{s\text{-}exp}\sigma_{p\text{-}exp}$ Number of protons defined by longitudinal instability

$N=(\pi\varepsilon_n n_b \Delta Q\times\beta_{exp}/r_p)/[1+C/(4\times(2\pi)^{1/2}\sigma_{s\text{-}exp}\times\gamma_{exp}^2)$ Number of protons defined by space-charge effects.



Dependence of proton intensity on relativistic factor γ



Dependence of luminosity on relativistic factor γ , corresponding to energy of experiment.

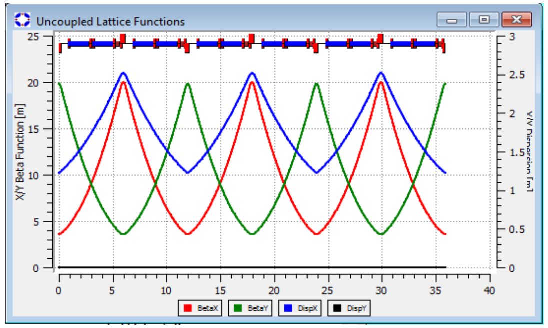
Optical structure with high critical energy (Y. Senichev)

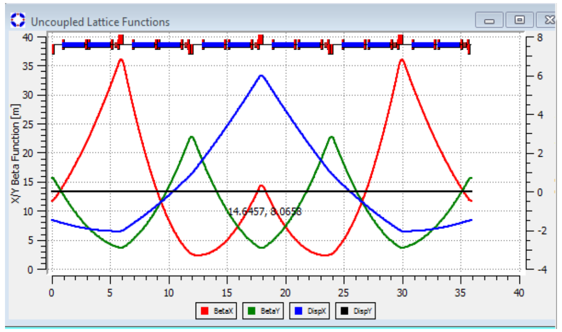
Increase of critical energy $\gamma_{tr} > \gamma_{exp\text{-}max} = 14{,}4$ is planned by method of resonance modulation of dispersion function at arc super periodic

Modulation $\Delta G(s)$ of quadrupole gradient $G(s)$ on length of superperiod $[K(s)+\varepsilon k(s)]$, leads to

$$d^2D/ds^2+[K(s)+\varepsilon k(s)]D=0,$$

$$K(s)=eG(s)/p,\quad k(s)=e\Delta G(s)/p,\quad p=\gamma A m_p c.$$





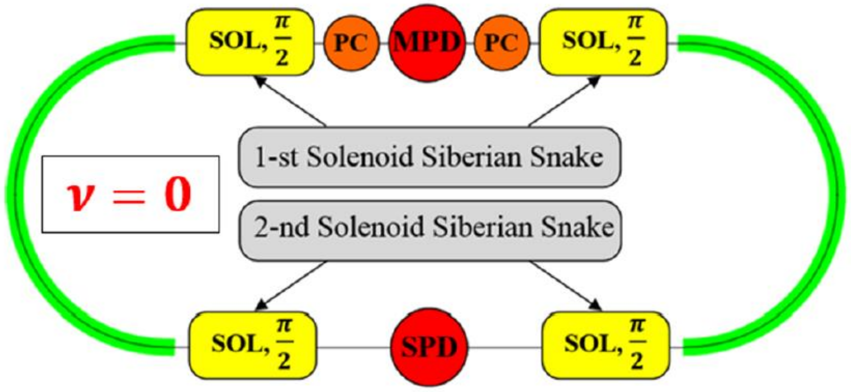
Twiss parameters for super periodic optic

Optical structure	γ_{tr} arc	γ_{tr} ring	D	F2	F1	$\beta_{x\text{-}max}$ arc	$\beta_{y\text{-}max}$ arc	$D_{x\text{-}max}$ arc	ν_x,ν_y arc
Regular structure	4.7	7.09	-2.24	2.29	2.29	20 m	20 m	2.7 m	3 и 3
Superperiodic structure	12.2	18.6	-2.24	2.04	3.0	36	23	6.1	3 и 3

To provide supersymmetric structure with modulation of dispersion function the currents in lenses F1 and lenses F2 are differed from nominal values for ion mode structure on 1,1 kA and 3 kA, correspondently.

Realization of new optical structure required disassembling of present arc cry-magnetic structure, installation of new current leads at 3 kA and new current traces in cryostats.

FORMATION OF PROTON POLARIZED BEAMS



Spin transparency mode, which involves two Sibirian snakes and pair of control solenoids

Spin transparency mode, any polarization – integral of field 100 T*m

At magnetic field of 6 T about 20 m of free space in collider ring is required (in future it is possible less than 50 T*m)

Partial Siberian snake, vertical, longitudinal at resonance ν_0=k

-integral 6-12 Тл×м

Longitudinal polarization at discreet energy with step 0,523 GeV.

System	Spin frequency	Direction of polarization in SPD/MPD
With out snake	$\nu_0 \neq k$	vertical
Partial snake	ν_0=k	longitudinal
Spin transparency mode	ν_0=k	any
One snake (MPD)	ν_0=1/2	longitudinal
Spin transparancy mode	ν_0=0	any

Polarized proton beams in Nuclotron

At Nuclotron proton acceleration there are 25 spin resonances ν_0=n and 6 spin-betatron resonances $\nu_0 \pm q$=k at betatron tunes $q_{x,y}$ =7,4

Creation of new Nuclotron cry-magnetic system is planned in 2024-2030 years. Construction of new lattice with installation of Sibirian snakes

Thanks for your attention