Fermilab

Induction Linac Based Ring Cooler

Valeri Lebedev & Sergei Nagaitsev
Fermilab

EIC Hadron Cooling Workshop
Fermilab
October 7-8, 2019

U.S. DEPARTMENT OF ENERGY

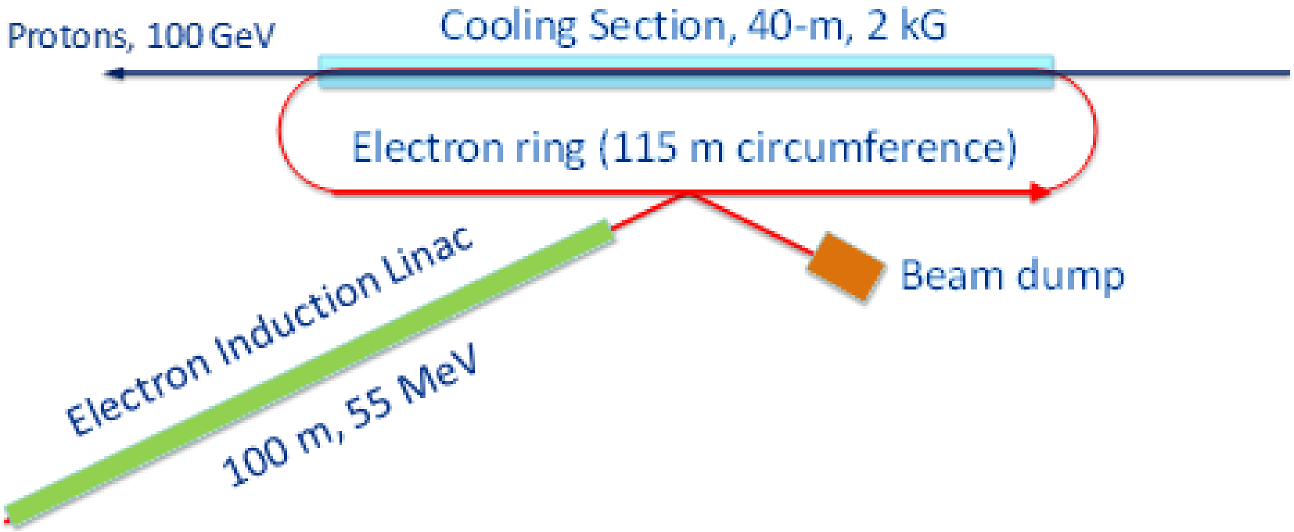
Fermilab

Outline

- Objectives and basic choices
- Main parameters
- Optics of the cooling ring &
  - Sensitivity to errors
  - Chromatic correction
- IBS and Touschek scattering
- Cooling force and cooling rates
- Injection/Extraction
- Conclusions

Objectives and Basic Choices

- Achievement of high energy efficiency = Energy recovery
    - Ring based cooling ~10,000 turns
    - Energy recovery linac 1% looks quite optimistic
  - ♦ Potentially, gain of 1-2 orders of magnitude
    - DC beam requires an order of magnitude larger number of particles



- Weakly-magnetized cooling is preferred due to large temperature in proton beam

$$F(\mathbf{v}) = -\frac{4\pi n e^4}{n}\int \frac{\mathbf{v}-\mathbf{v}'}{\left|\mathbf{v}-\mathbf{v}'\right|^3} d\mathrm{v}^3 \Rightarrow F_{\max} \propto \frac{1}{\sigma_p{}^2+\sigma_e{}^2}$$

  - ♦ Electron temp. with the same rms velocity: $T_{eff} = m_e c^2 \beta\gamma\varepsilon_n / \beta_x \approx 1.4\,\mathrm{eV}$ for pc = 100 GeV, ε_n = 1 μm, β_x = 40 m
  - ♦ Magnetization helps only for small amplitude particles – not good!!!

Basic Choices

- Small ⊥ temperature of e-beam is not required
  - ⇨ thermionic cathode with moderate current density + large compression in the gun to create small e-beam size in the cooling section
  - ⇨ Longitudinal magnetic field to keep constant e-beam size in the cooler (beam focusing => ⊥ beam stability)
    - Magnetic field at the cathode to compensate rotation appearing at the solenoid entrance
- DC beam to avoid problems with wakes and CSR in the ring
  - ⇨ Long pulse electron gun (~0.5 μs) and induction linac
- Beam current in the ring is limited to ~100 A by IBS and instabilities
- For 100 A beam the instabilities are a serious issue
  - The beam is stabilized by wide band dampers (~200 MHz) in each of 3 planes
  - No RF to minimize the ring impedances
    - ⇨ No abort gap
    - ⇨ Beam loss at extraction (however at the acceptable level)
  - Additional low energy electron beam to introduce non-linearity for ⊥ beam stabilization

Main Parameters of the Cooler

Proton beam energy	100 GeV
Proton ring circumference (used for cooling rate computation only)	~3,000 m
Normalized rms proton beam emittance	1 μm
Proton beam rms momentum spread	$<3\cdot10^{-3}$
Proton beam rms angular spread in cooling section	**15 μrad**
β-functions of proton beam in the cooling section center	40 m
Electron beam energy	54.48 MeV
Electron ring circumference	114.2 m
Cooling length section	40 m
Electron beam current	100 A
Longitudinal magnetic field in the cooling section, B_{cs}	1.848 kG
Electron beam rms momentum spread, initial/final	$(1.0/1.7)\cdot10^{-3}$
Initial rms electron angles in cooling section	**27 μrad**
Initial rms electron beam size in the cooling section, r_{cs}	2.04 mm
e-beam rms norm. mode emittances at the cycle beginning, $\varepsilon_1/\varepsilon_2$, μm	**453 / 0.081!!!**
Number of cooling turns in the electron storage ring	13,000
Longitudinal cooling time (emittance)	~1 hour
Transverse cooling time (emittance)	~2 hour

Electron Gun

Details will be presented in V. Yakovlev talk

- Large compression in electron gun
- Rms normalized emittance is set by the cathode temperature (0.11 eV) and its radius (2.5 cm)

$$\varepsilon_n = \frac{r_c}{2}\sqrt{\frac{T_c}{m_e c^2}} \approx 6\,\mu\text{m}$$

- Magnetic field at the cathode (~ 12 Gs) is chosen to match magnetic fluxes coming through beam cross-section

$$r_{cath}{}^2 B_{cath} = r_{cs}{}^2 B_{cs}$$

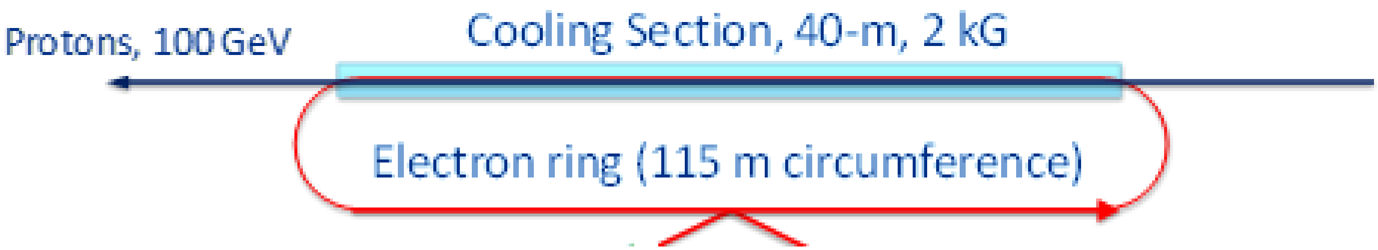
- Magnetic field makes emittances of normal modes different

$$\varepsilon_{1n,2n} = \frac{\varepsilon_n}{\sqrt{1+\Phi^2\beta_0{}^2} \pm \Phi\beta_0}, \quad \Phi = \frac{eB_{cs}}{2\gamma\beta m_e c^2}, \quad \beta_0 = \frac{r_{cs}{}^2}{\varepsilon_n / \beta\gamma}$$

  - Mode with larger emittance determines the rms beam size
  - Mode with smaller emittance determines the angular spread

Beam Optics in Cooling Ring

- Major ideas
  - Race track with two long straights



  - Long cooling solenoid makes optics completely coupled in the cooling straight
  - Coupling in straights reduces IBS and space charge tune shift ⇨coupling in the second (technical) straight
    - The same Derbenev's adapters are used in both straights
  - Optics is uncoupled in arcs to reduce $(d\varepsilon/dt)_{IBS}$ for the mode with smaller emittance

$$d\varepsilon / dt \propto D^2 / \beta$$

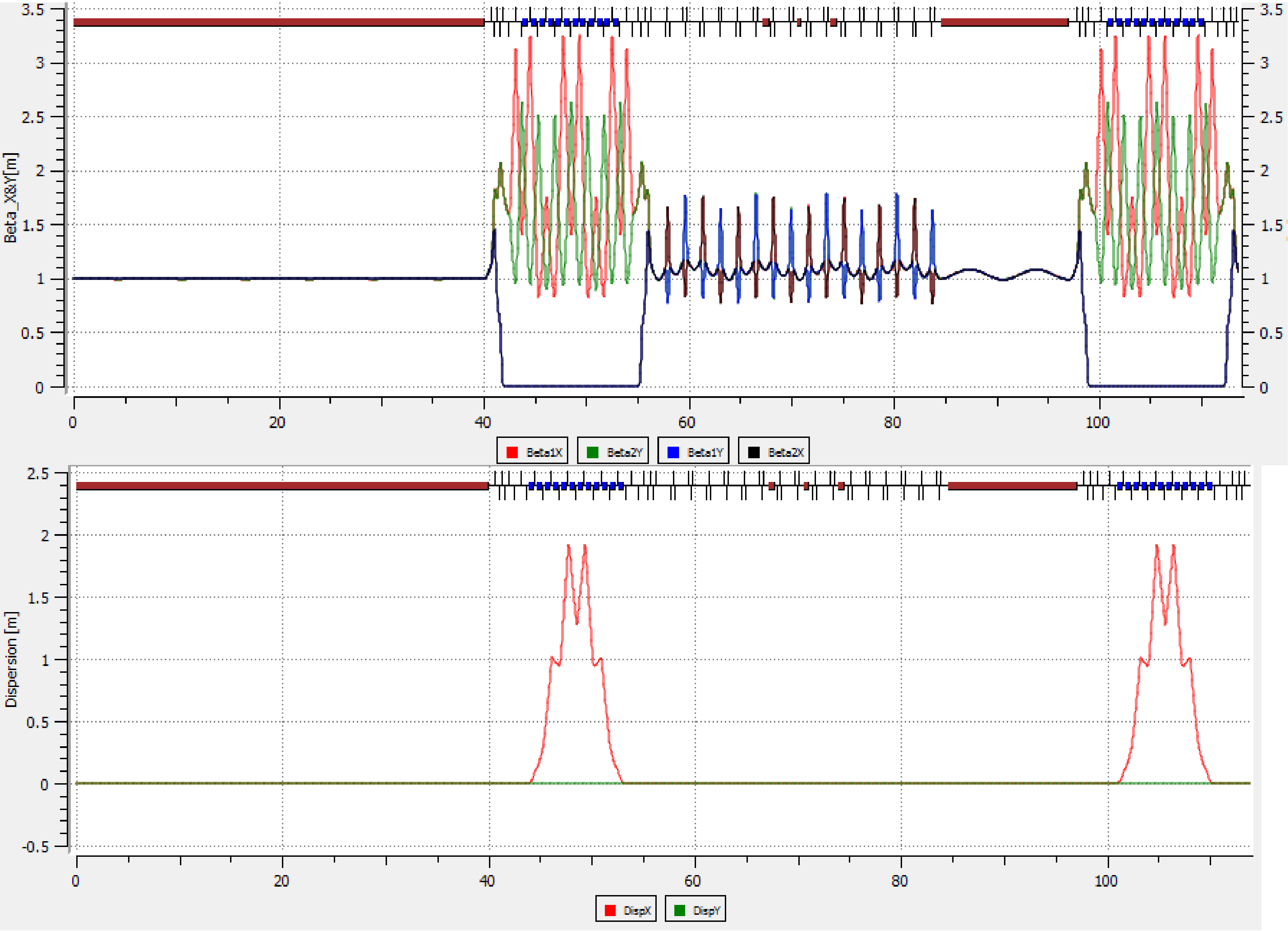
  - Tunes are chosen to minimize problems with space charge i.e. no coupling resonance => no emittance exchange

Beam Optics: Major Parameters

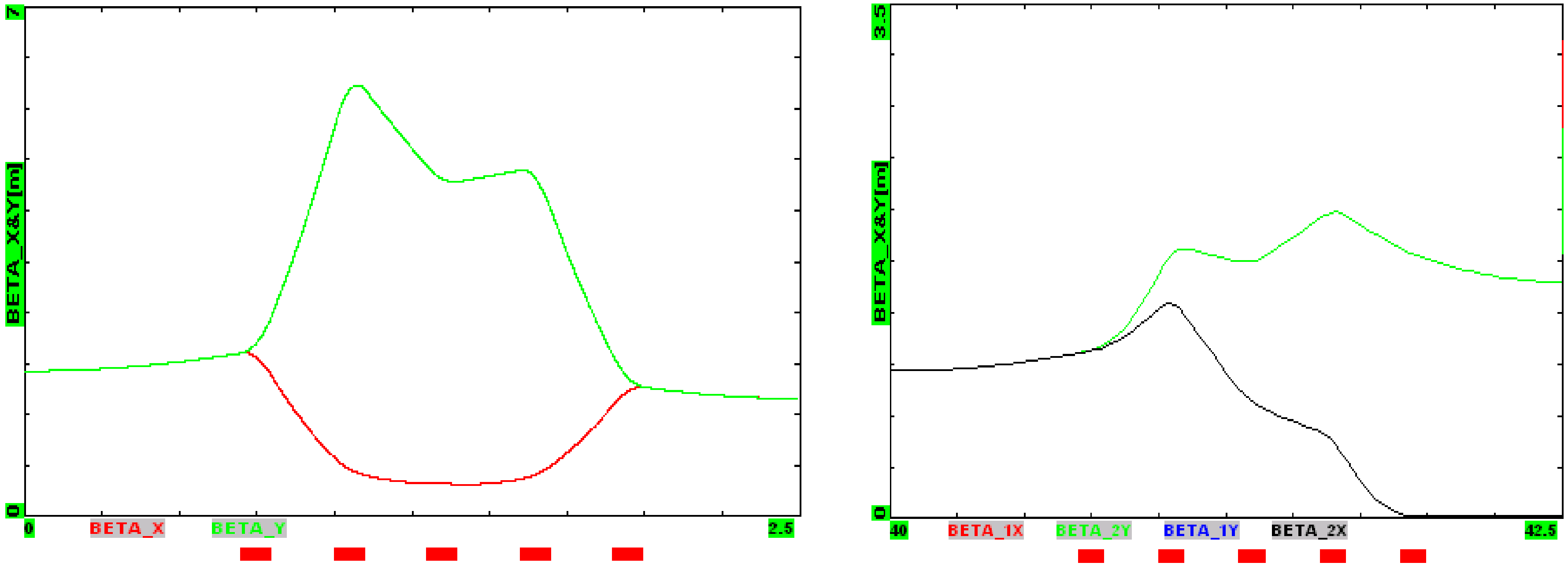
Betatron tunes, ν_1/ ν_2	13.8764 / 5.8548
Natural chromaticities	-14.09/ -5.53
Corrected chromaticities	-6.99 / -8.05
Slip-factor, α	0.04437
Damping parameters, $g_x / g_y / g_s$	0.57693 / 1 / 2.42307
Equilibrium rms horizontal emittance set by SR	2.9 nm
Equilibrium rms momentum spread set by SR	$3.1 \cdot 10^{-5}$
Amplitude damping decrements per turn, $\lambda_x / \lambda_y / \lambda_s$, $[10^{-9}]$	2.24 / 3.88 / 9.41
Energy loss due to SR	0.42 eV/turn
Transverse acceptance	150 μm
Longitudinal acceptance (maximum momentum spread)	±0.011

- OptiM is used for optics calculations
  - It correctly accounts x-y coupling
  - Results are presented in the extended Mais-Ripken representation
- SR plays negligible role
  - Total deceleration in the course of 13,000 turns is $\Delta p/p \approx 10^{-4}$

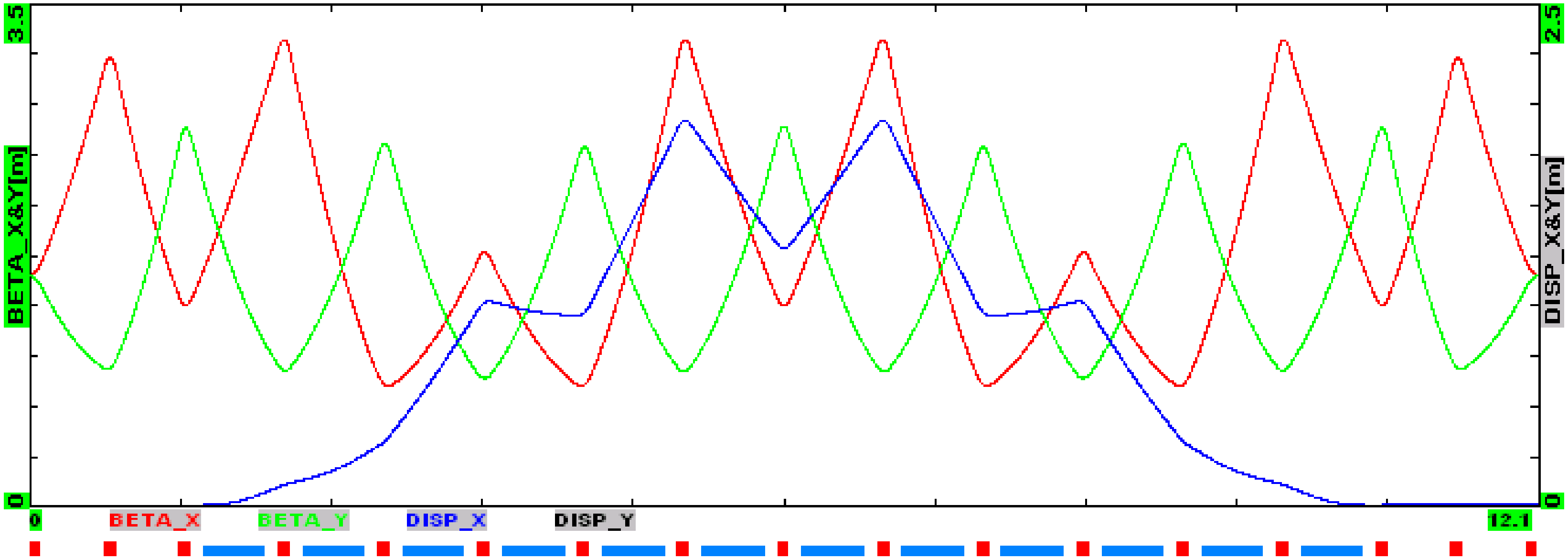
Beam Optics in Cooling Ring: 4D Twiss Parameters



Beam Optics: Adapters and Arcs



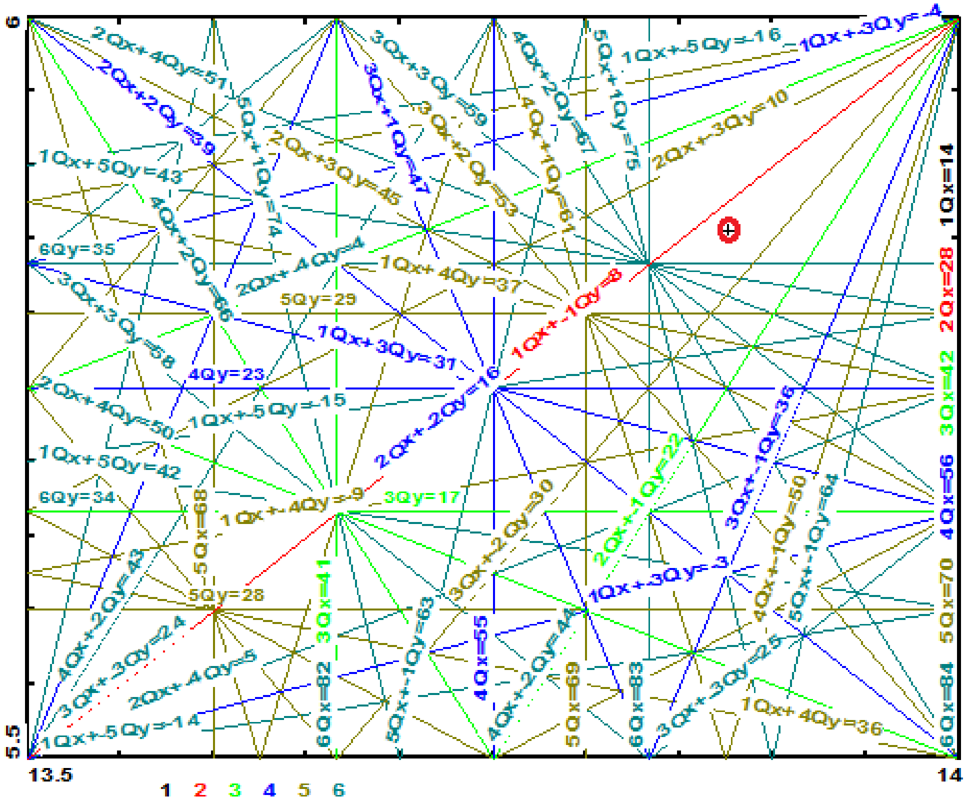
The vertex-to-flat adapter (left - no quad rotation, right – quads @45°)

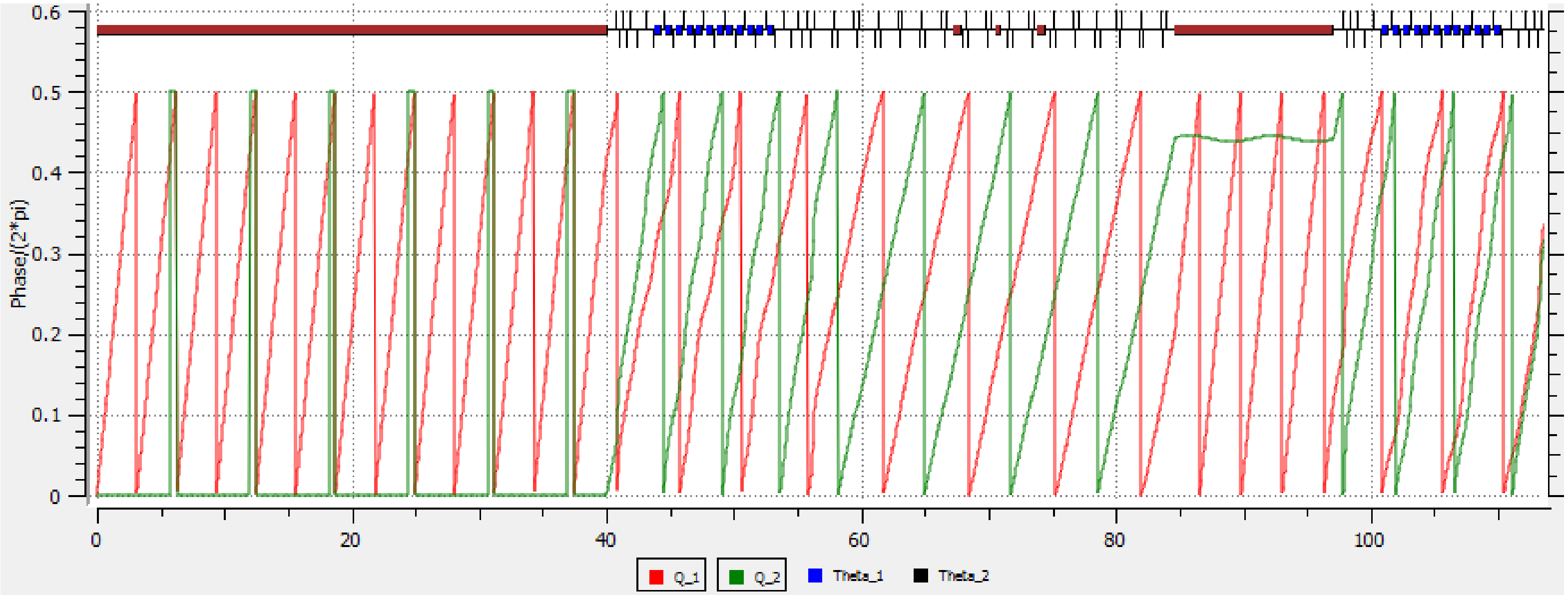


Uncoupled optics in arcs

Beam Optics: Tunes and Tune Correction

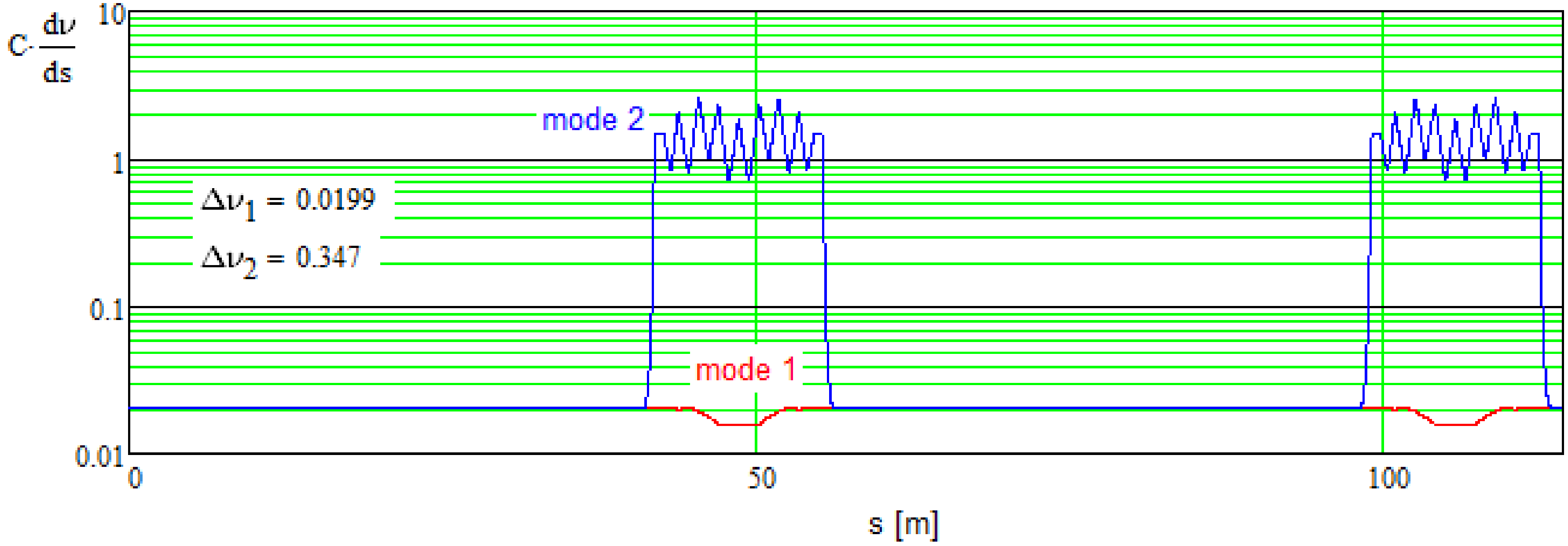
- Tune shift for the smaller emittance mode (vertical in arcs) much larger than for another one
    - Tune is chousen below coupling resonance
- Tune advance for mode 2 is zero in the cooling solenoid
- Tune correction may be performed by cooling solenoid field and quads in arcs and technical straight





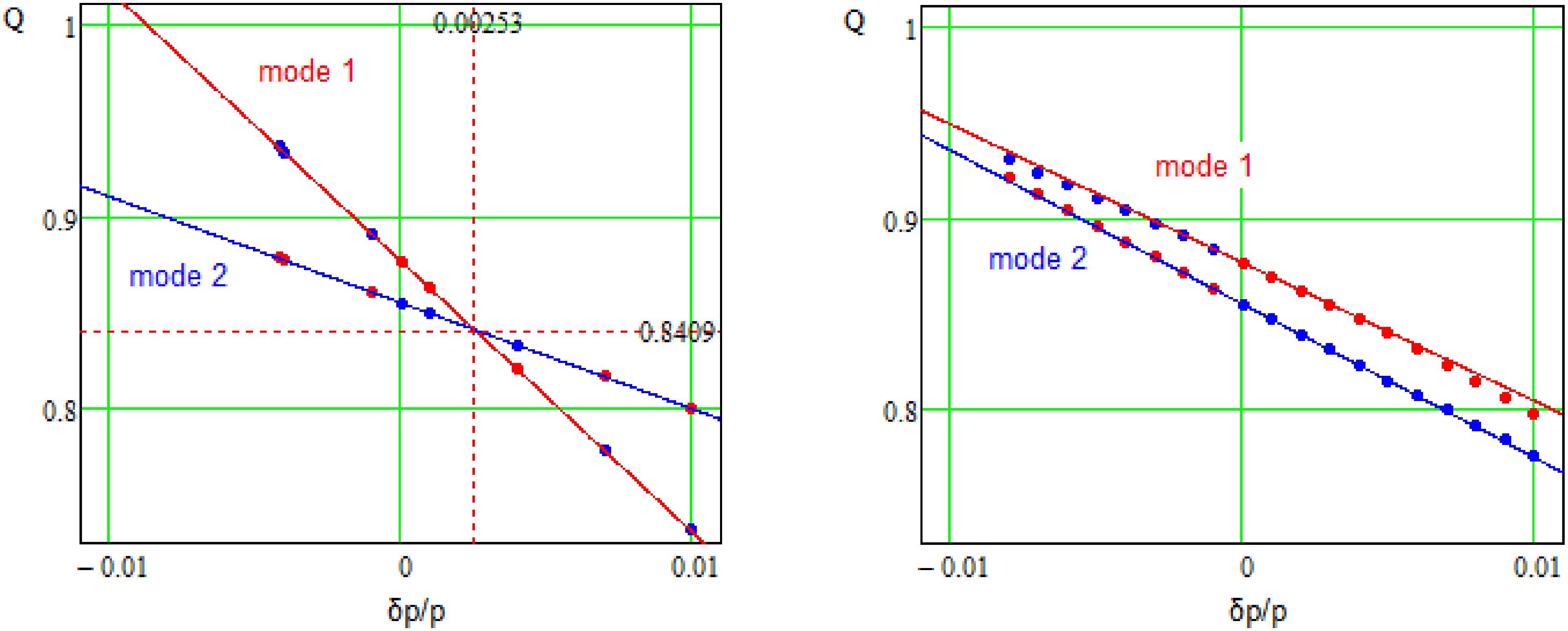
Beam Space Charge Tune Shifts

- Coupling is correctly accounted
- Mode 2 has 17 times larger tune shift due to small vertical size in arcs
- Usage of rotational modes in starts minimizes their contribution to the tune shifts



- Basing on Booster experience we believe that the beam lifetime should not be a problem for 13,000 turns
- However, emittance exchange may represent a problem
  - Simulations initiated

Chromaticity Correction



- Chromaticity has to be corrected to avoid tunes crossing which would result in an emittance exchange
  - Tunes are changed by 0.06 at maximum momentum deviation of 0.85%
  - Relative variations of beta-functions in the solenoid are within required ±10% in the entire momentum acceptance of the ring of ±0.85%
- One family of sextupole is used
  - Major part of sextupole field is built-in into focusing quads of the arcs

Optics Chromaticity and Sensitivity to Errors

- Requirements to optics accuracy are set by loss of cooling rates

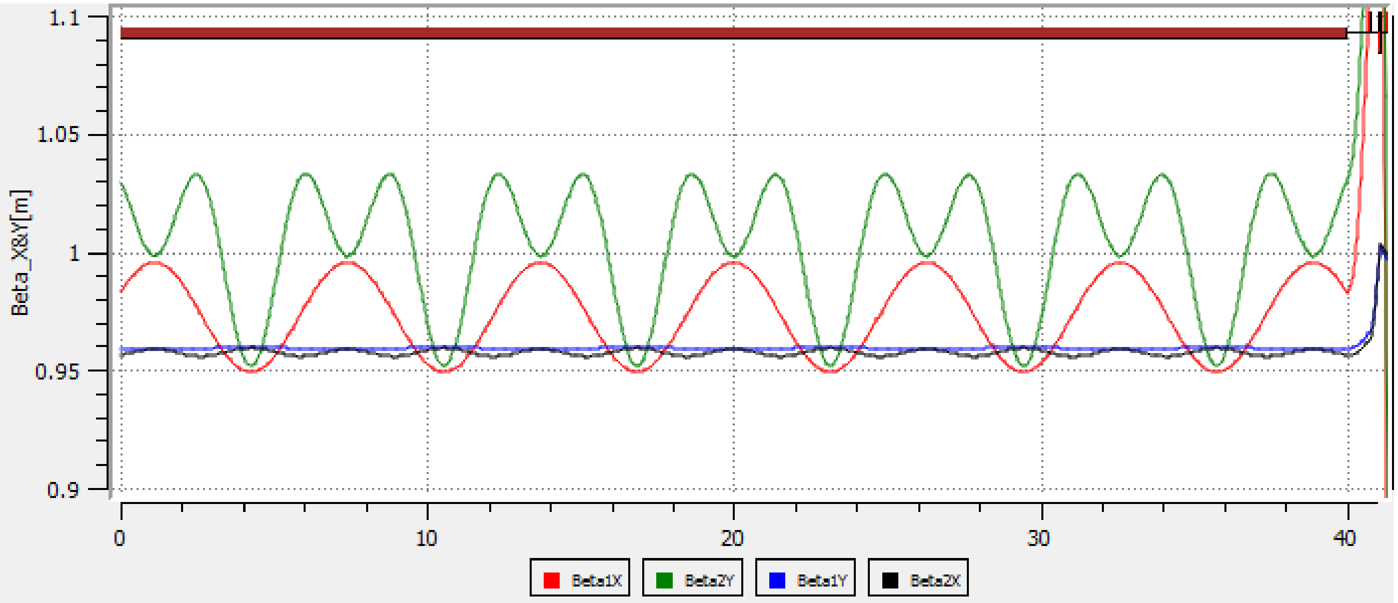
$$\theta_{\perp eff}{}^2 \approx \frac{\varepsilon_2}{\beta_0\left(1+\frac{\delta\beta_{2x}}{2\beta_0}+\frac{\delta\beta_{2y}}{2\beta_0}-\frac{\delta\nu_2{}^2}{2}\right)},$$

$$\sigma_{\perp eff}{}^2 \approx \varepsilon_1\beta_0\left(1+\frac{\delta\beta_{1x}}{2\beta_0}+\frac{\delta\beta_{1y}}{2\beta_0}-\frac{\delta\nu_1{}^2}{2}\right),$$

$$\varepsilon_2 << \varepsilon_1$$

$$\mathbf{v}_1=\begin{bmatrix}\sqrt{\beta_{1x}}\\ -\frac{i(1-u)+\alpha_{1x}}{\sqrt{\beta_{1x}}}\\ \sqrt{\beta_{1y}}\,\mathrm{e}^{i\nu_1}\\ -\frac{iu+\alpha_{1y}}{\sqrt{\beta_{1y}}}\mathrm{e}^{i\nu_1}\end{bmatrix},\quad \mathbf{v}_2=\begin{bmatrix}\sqrt{\beta_{2x}}\,\mathrm{e}^{i\nu_2}\\ -\frac{iu+\alpha_{2x}}{\sqrt{\beta_{2x}}}\mathrm{e}^{i\nu_2}\\ \sqrt{\beta_{2y}}\\ -\frac{i(1-u)+\alpha_{2y}}{\sqrt{\beta_{2y}}}\end{bmatrix}.$$

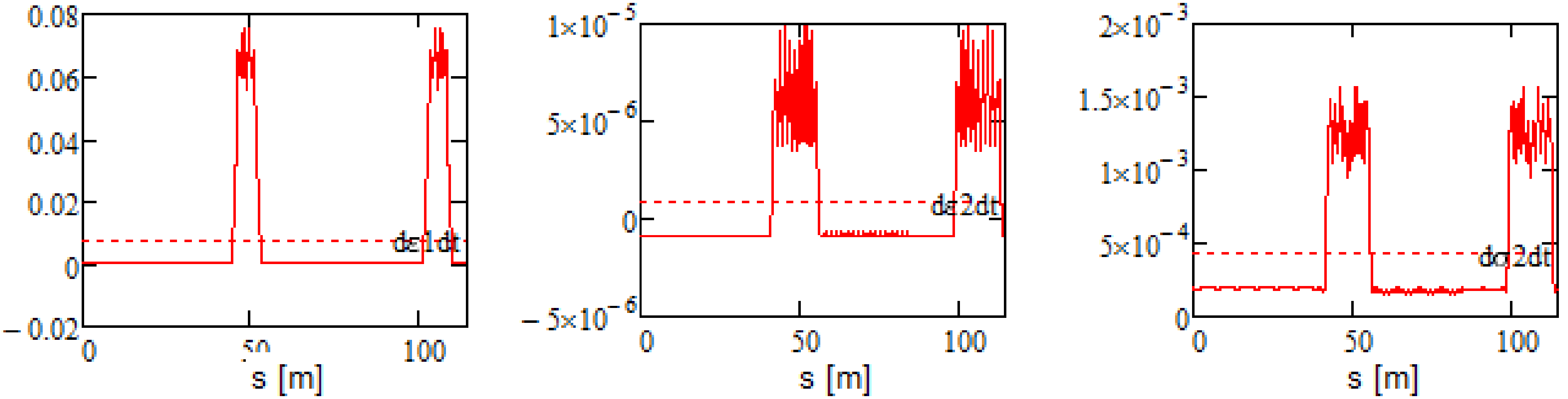
- Requirement that beam cross-section and temp. are within ±10% yields that the beta-functions should be within ±10% and $|\delta\nu_1|$ & $|\delta\nu_2| < 0.45$
- Focusing accuracy and stability of separate elements are within typical requirements of about $2\cdot10^{-4}$



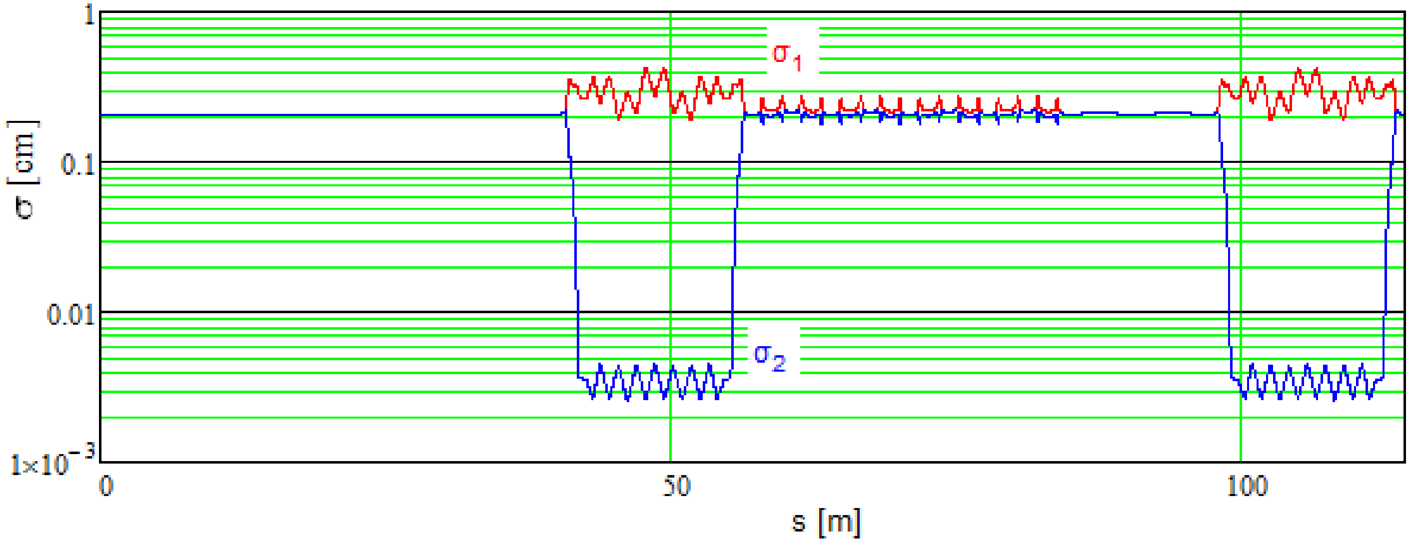
β-func. in solenoid for Δp/p=1% in absence of chromaticity correction

Multiple Intrabeam Scattering

- IBS is the main mechanism driving growth of beam emittances
- Theoretical model accounts x-y coupling

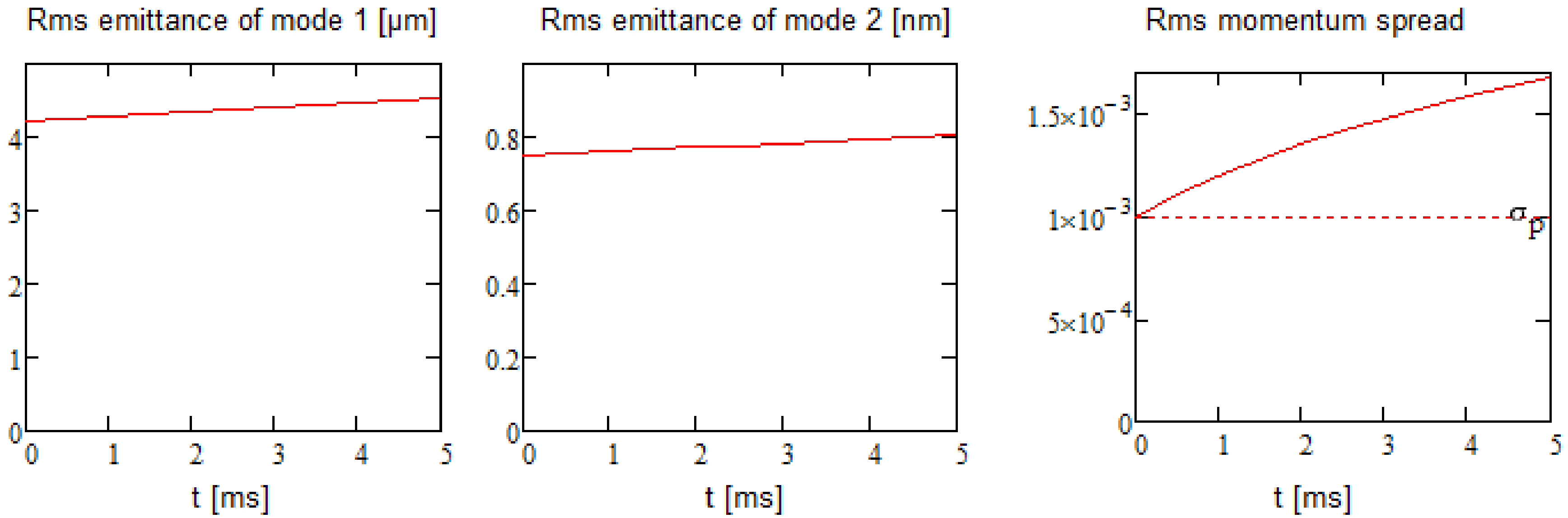


Local contributions to the emittance growth for entire ring; left-to-right: mode 1, mode 2, Δp/p

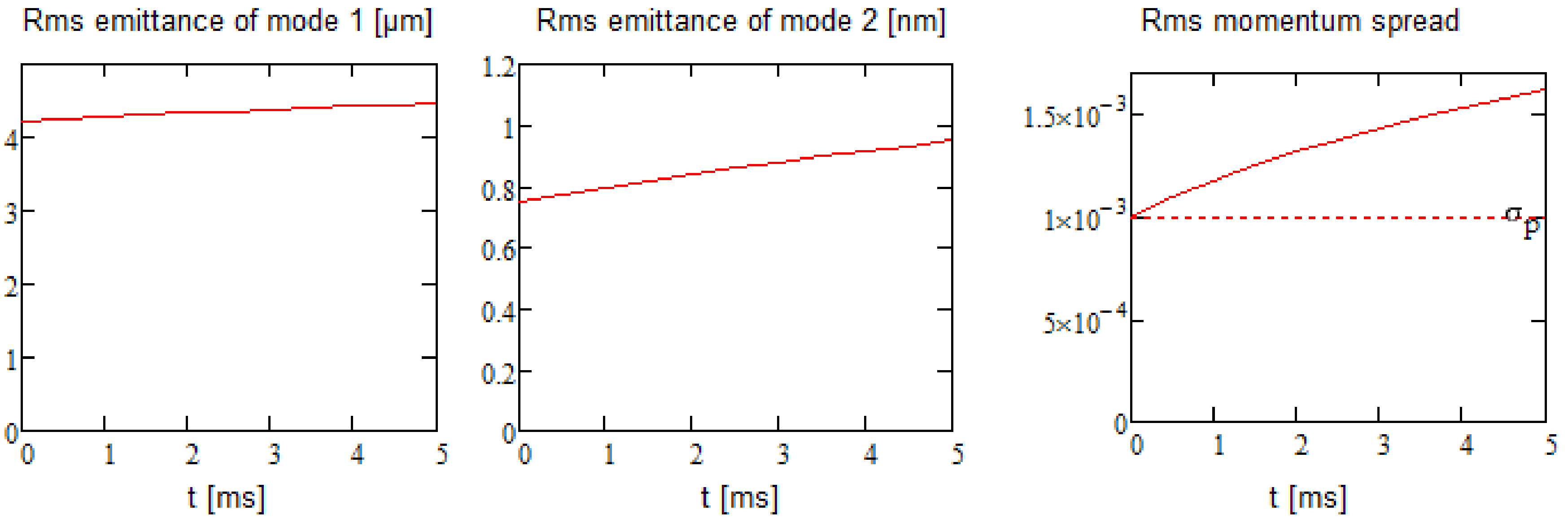


- Contribution of arcs strongly dominates

Multiple Intrabeam Scattering (2)



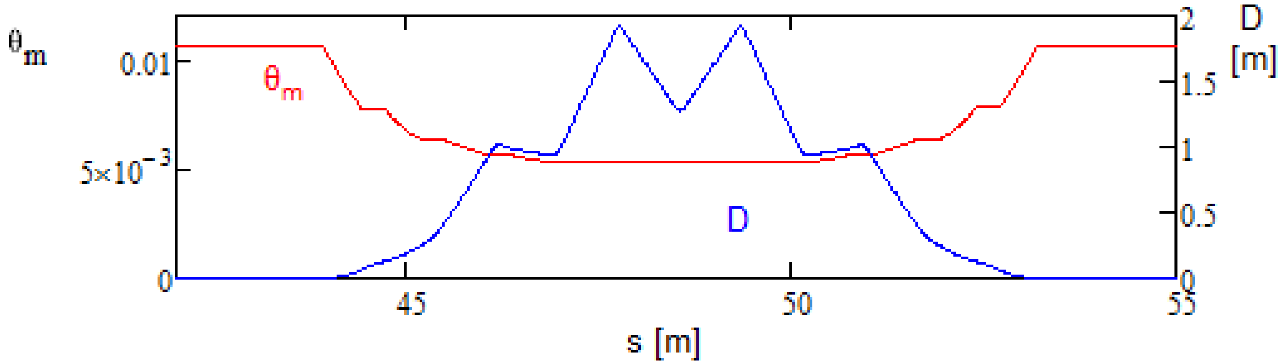
Dependencies of rms mode emittances and momentum spread on time for 100 A electron beam.

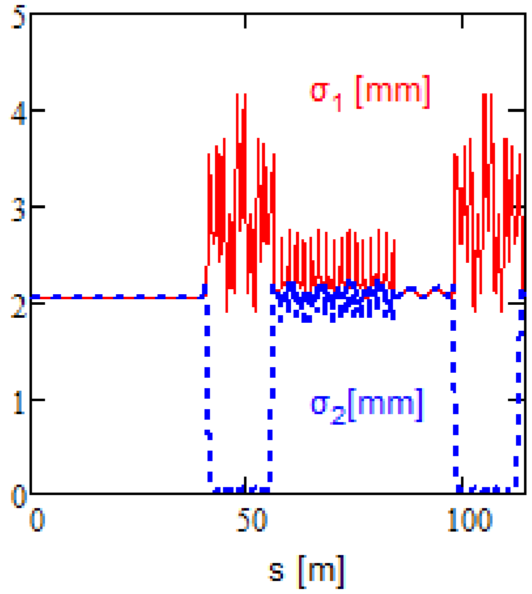


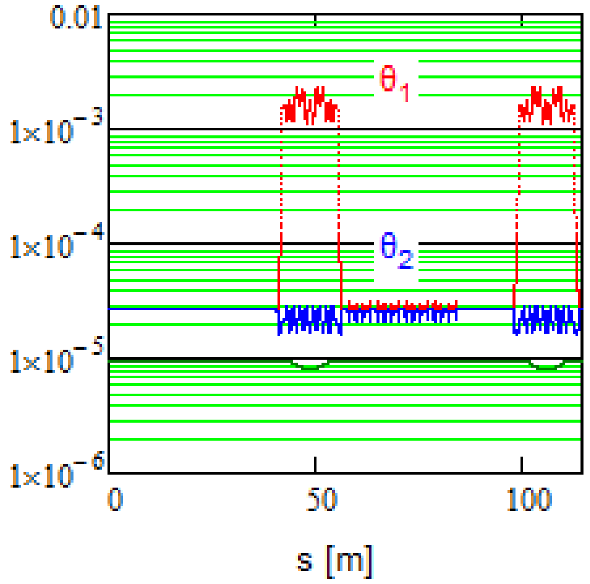
Dependencies of rms mode emittances and momentum spread on time for perturbed optics: one quad in high dispersion is rotated by 0.1 deg (Coupling resulted in an increase of mode 2 growth)

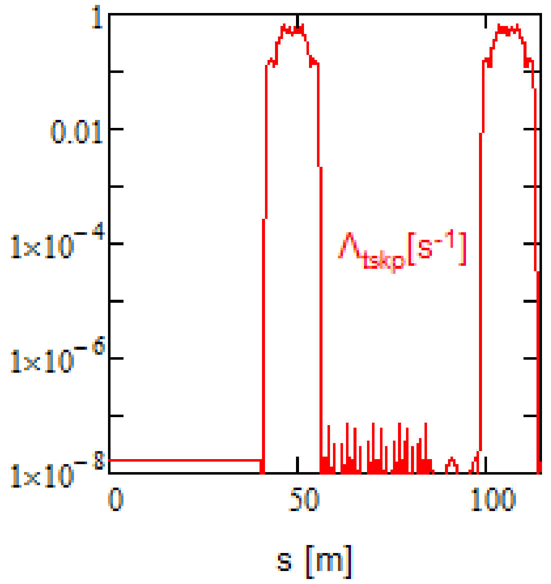
Touschek Scattering

- x-y coupling is accounted
- Longitudinal acceptance is determined by aperture at maximum D
- Scattering at high dispersion area results in a reduction of maximum momentum for these particles due to excitation of betatron motion
- Touschek lifetime - 13s
  - Corresponding power is 160 W
  - most loss is in arcs
    - considerable radiation









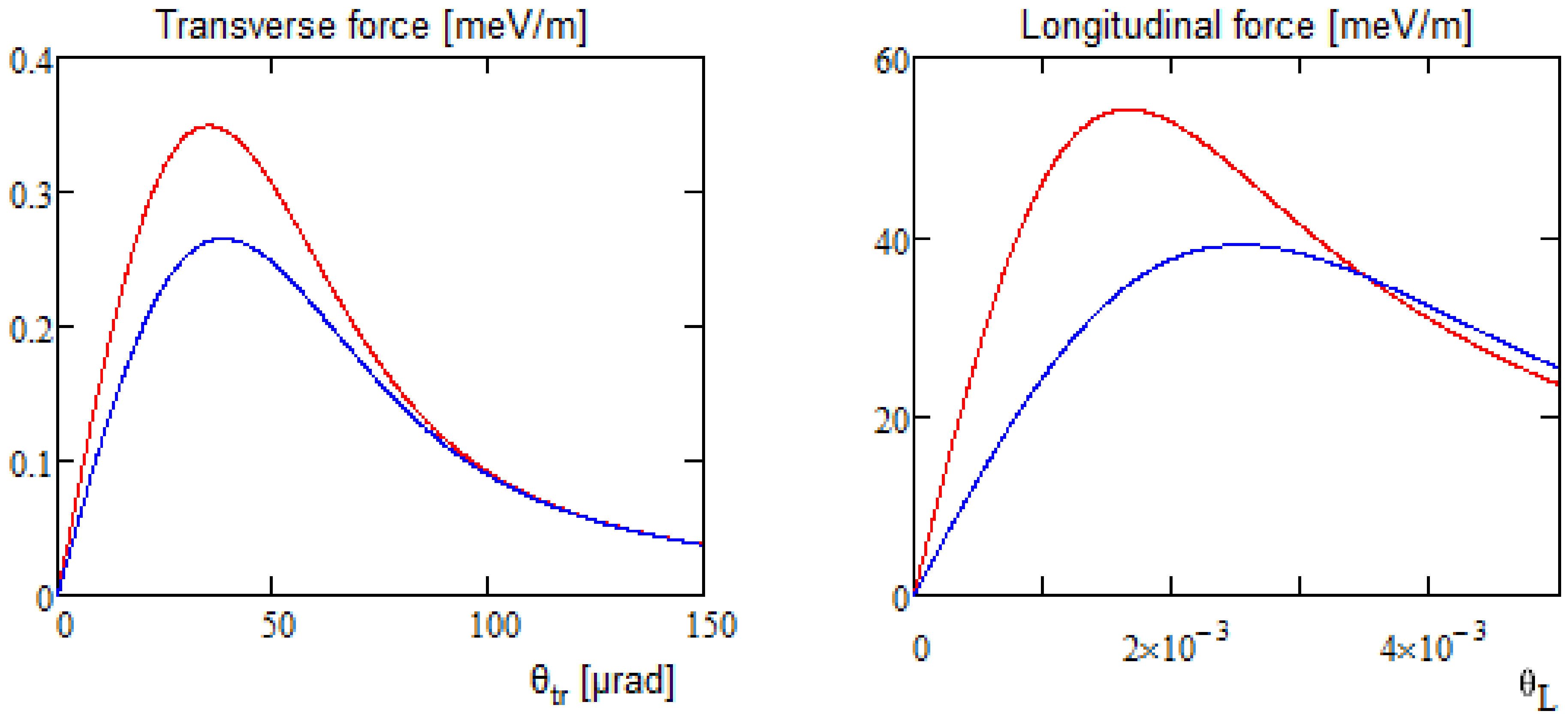
Cooling Beam Parameters

Electron beam parameters in the beam frame

Electron density, n_{ebf}	$1.5\cdot10^{9}$
Transverse electron temperature at the cooling start (ε_{2n}=81 nm)	4.5 eV
Longitudinal electron temperature at the cooling start ($\sigma_p=10^{-3}$)	0.5 eV
Larmor radius	27 μm
Debye radius	410 μm
Average distance between electrons, $n_{ebf}^{-1/3}$	8.8 μm
Rms transverse velocity at the cooling cycle start	$8.8\cdot10^{7}$ cm/s
Rms longitudinal velocity at the cooling cycle start	$3\cdot10^{7}$ cm/s
Larmor frequency, $\omega_p = eB / m_e c$	$3.2\cdot10^{10}$ s^{-1}
Plasma frequency, $\omega_p = \sqrt{4\pi n_{ebf} e^2 / m_e}$	$2.2\cdot10^{9}$ s^{-1}
Length of Larmor period in the lab frame, $2\pi\beta\gamma c/\omega_L$	6.24 m
Length of plasma period in the lab frame, $2\pi\beta\gamma c/\omega_p$	93.6 m

- Weakly magnetized beam
  - ⊥ and || rms velocities are different by 3 times only
- Cooling length is about half of plasma period

Cooling Force

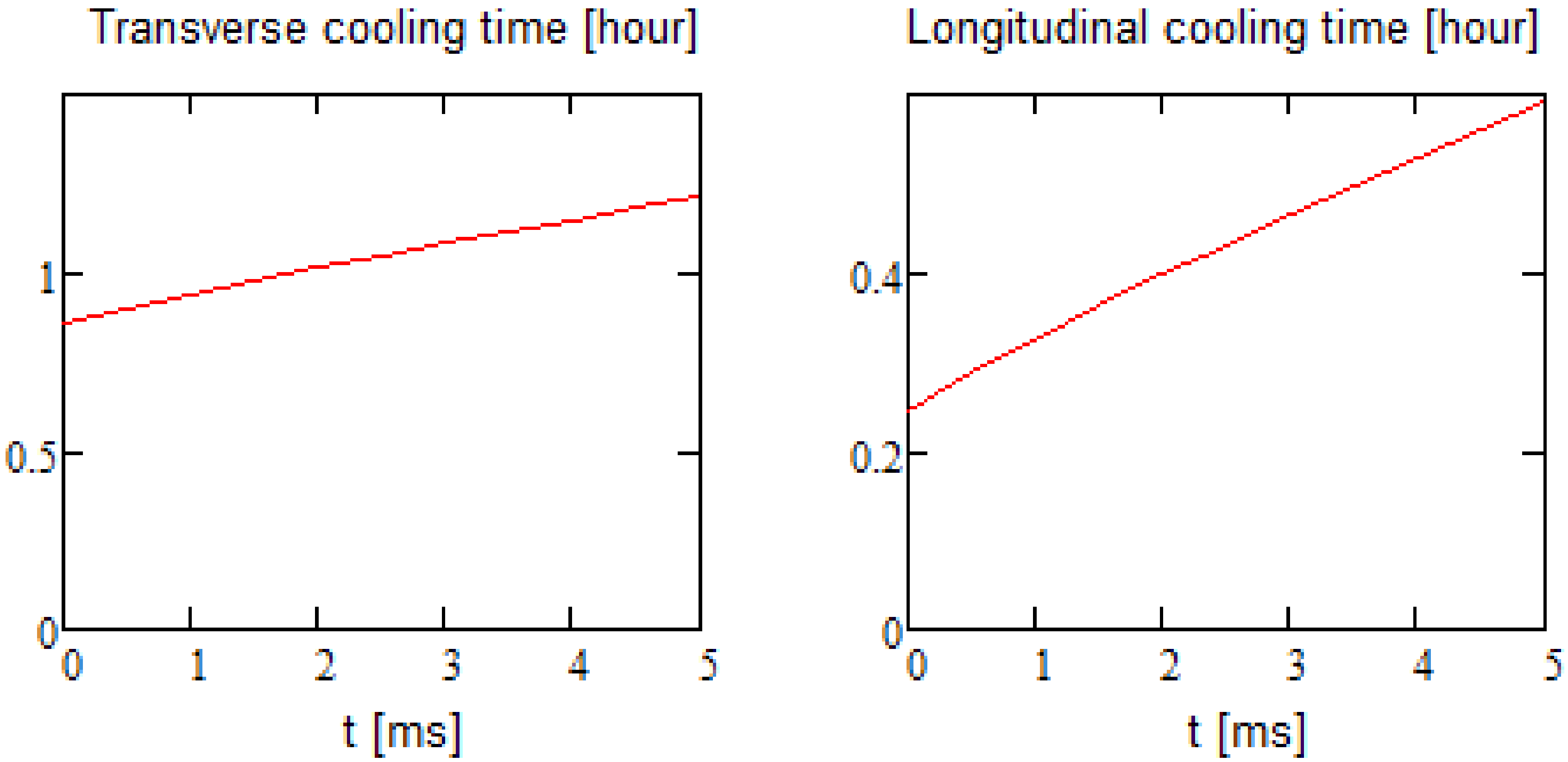


Dependencies of transverse (left) and longitudinal (right) cooling forces at the cooling cycle beginning (red curve, 0 ms) and at the cooling cycle end (blue curve, 5 ms).

$$F_{\parallel}(\mathrm{v}_z)=\frac{4\pi n'_e e^4 L_c}{m_e}\left(\frac{4\mathrm{v}_z}{\sqrt{\pi}}\int_0^\infty \exp\left(-\frac{\mathrm{v}_z{}^2 t^2}{1+2\sigma_{\mathrm{v}z}{}^2 t^2}\right)\frac{t^2\,dt}{\left(1+2\sigma_{\mathrm{v}\perp}{}^2 t^2\right)\left(1+2\sigma_{\mathrm{v}z}{}^2 t^2\right)^{3/2}}\right),$$

$$\mathbf{F}_{\perp}(\mathbf{v}_\perp)=\frac{4\pi n'_e e^4 L_c}{m_e}\left(\frac{4\mathbf{v}_\perp}{\sqrt{\pi}}\int_0^\infty \exp\left(-\frac{\mathrm{v}_\perp{}^2 t^2}{1+2\sigma_{\mathrm{v}\perp}{}^2 t^2}\right)\frac{t^2\,dt}{\left(1+2\sigma_{\mathrm{v}\perp}{}^2 t^2\right)^2\sqrt{1+2\sigma_{\mathrm{v}z}{}^2 t^2}}\right),$$

Cooling Rates



Dependencies of the transverse (left) and longitudinal (right) emittance cooling times on time within one cooling cycle for the case when the proton beam emittance and momentum spread in the proton beam are much smaller than for the electron beam.

$$\lambda_z \approx \frac{2\sqrt{2\pi} n_e r_e r_p L_c}{\gamma^4 \beta^4 \left(\Theta_\perp + 1.083\Theta_\parallel / \gamma\right)^{3/2} \sqrt{\Theta_\perp \Theta_\parallel}} L_{cs} f_0 \ ,$$

$$\lambda_\perp \approx \frac{\pi\sqrt{\pi} n_e r_e r_p L_c}{\sqrt{2}\gamma^5 \beta^4 \Theta_\perp^{\ 2} \left(\Theta_\perp + \sqrt{2}\Theta_\parallel / \gamma\right)} L_{cs} f_0 \ ,$$

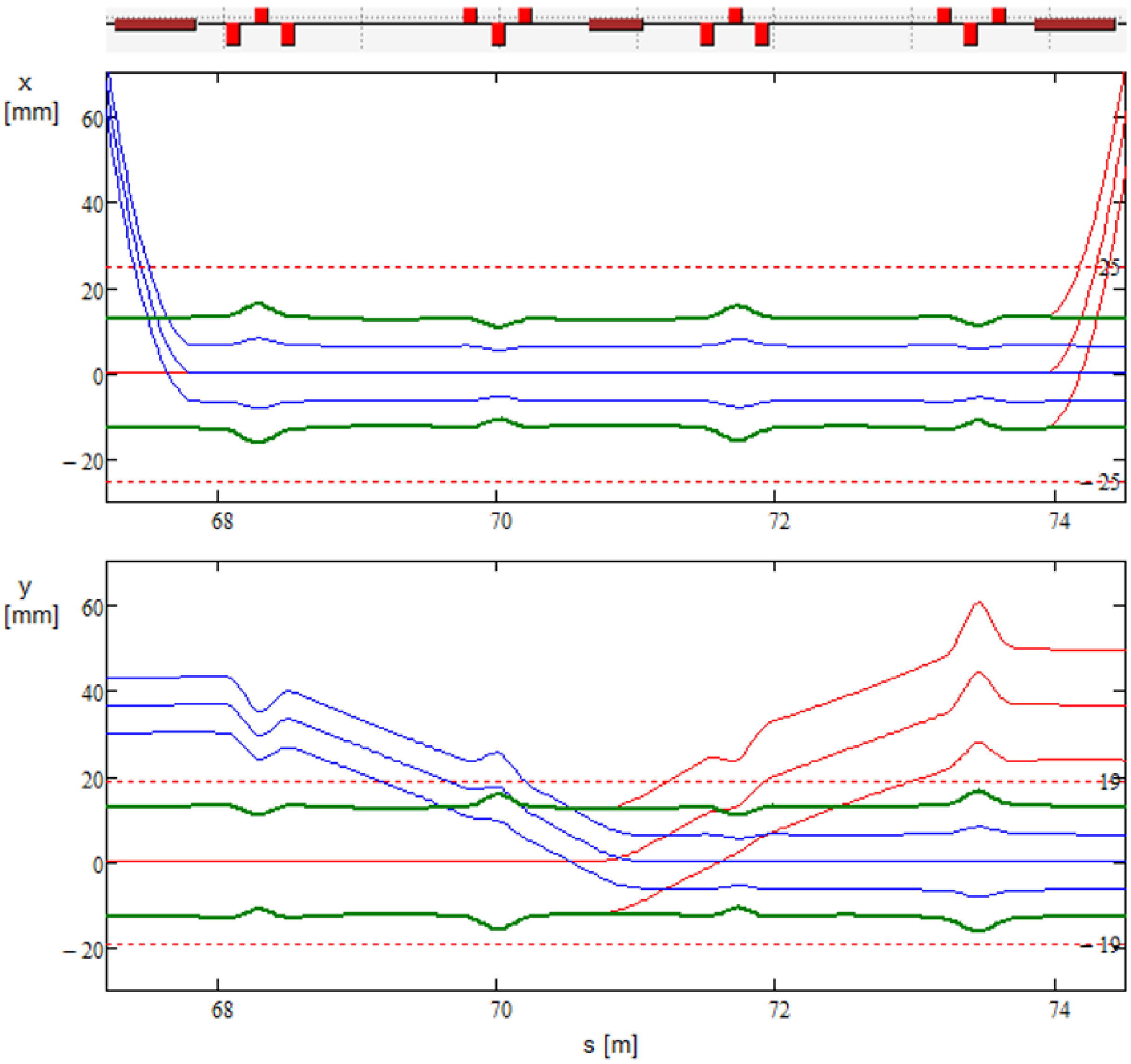
$$\Theta_\parallel = \sqrt{\sigma_{pe}^{\ 2} + \sigma_{pp}^{\ 2}} \ , \quad \frac{\Theta_\parallel}{\gamma\Theta_\perp} \le 2 \ .$$

$$\Theta_\perp = \sqrt{\theta_e^{\ 2} + \theta_p^{\ 2}} \ ,$$

Injection and Extraction

- To reduce impedances the same kicker and kicker pulse are used for both inject. & extract.
- Effective rise/fall time is 4 ns
  - Kicker filling time is 2 ns (L=60 cm)
  - Rise and fall times for pulse generator – 2 ns
    - Present state of the art
  - 1% beam loss at extraction (2 kW)
- Low impedance for the beam

  ⇨Large kicker current
- Vertical kick
- Horizontal Lambertson septum



Parameters of the Injection/Extraction System

Kicker bending angle	17.7 mrad
Kicker length	60 cm
Kicker gap (distance between plates)	38 mm
Kicker voltage	±15.4 kV
Beam displacement at the extraction septum entrance (exit for injection)	36.5 mm
Kicker pulse duration, FWHM	385 ns
Injected beam duration	376 ns
Kicker characteristic impedance (per plate)	25 Ω
Kicker current (per plate)	615 A
Septum bending angle	200 mrad
Septum length	60 cm
Septum magnetic field	612 G

Conclusions

- We are working on development of ~55 MeV ring-based electron cooling
  - Reactive beam power – 5.5 GW
  - Actual beam power – 0.4 MW (goes to the beam dump)
  - Beam power lost in the ring <2 kW (Touschek & extraction)
- So far, we did not find showstoppers
- Emittance exchange may present the problem
  - Simulations are initiated
- More work is required on the beam stability
  - Preliminary estimates are encouraging