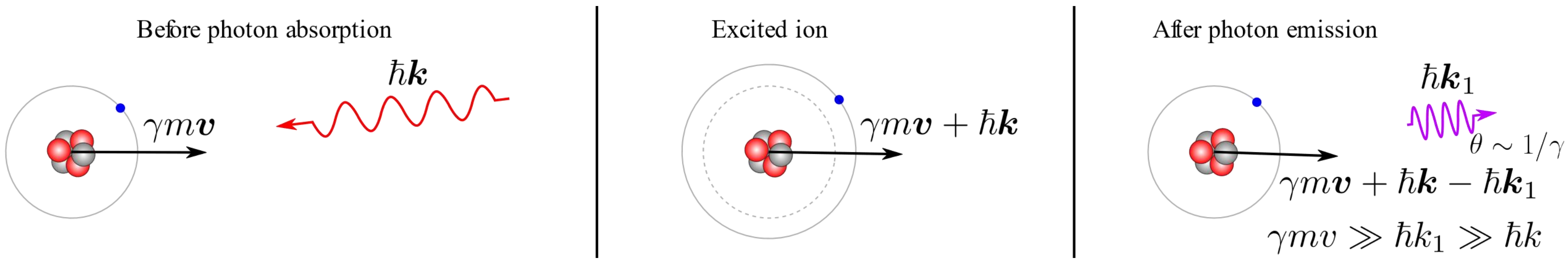
Beam stability and cooling aspects for the partially stripped ions in the storage rings (LHC/SPS)

Alexey Petrenko (CERN, Budker INP)

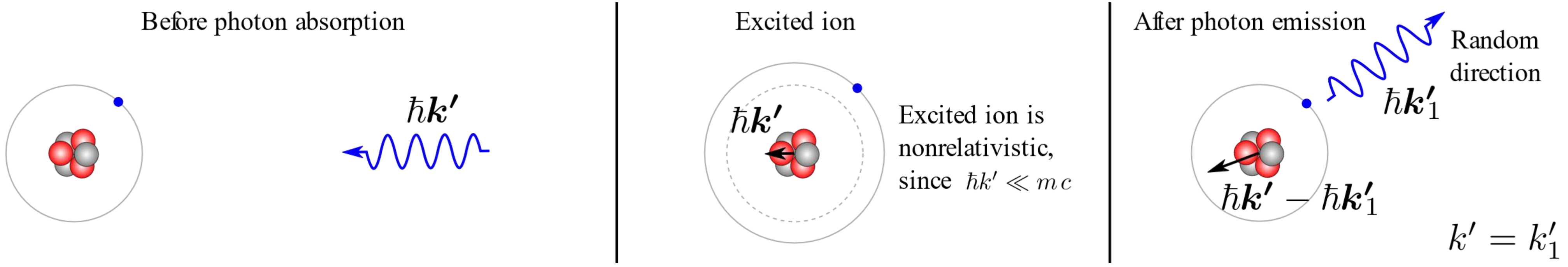
Photon Beams Workshop, 28.11.2017, Padua

Laser-ion interaction kinematics

In the lab frame:



In the ion’s frame:



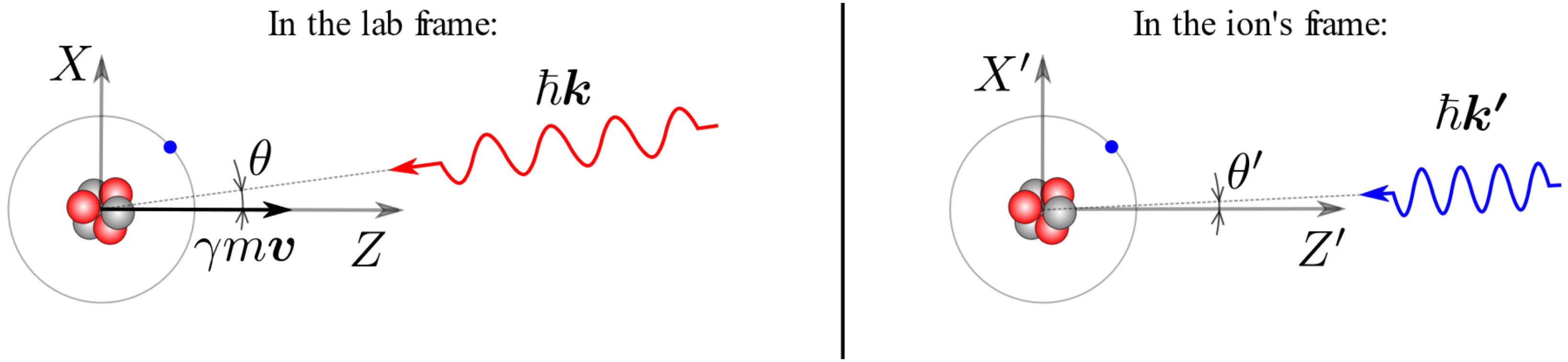
Excited ion is nonrelativistic, since $\hbar k' \ll mc$

Longitudinal cooling: because energy loss grows with ion energy:

Transverse cooling: because all components of ion momentum are lost due to the photon scattering but only the longitudinal component is restored in the RF resonator.

Heating: because angle of photon emission in the ion’s frame is random.
We would like to find an equilibrium between the cooling and heating processes.

Photon absorption



4-vector Lorentz transformation:

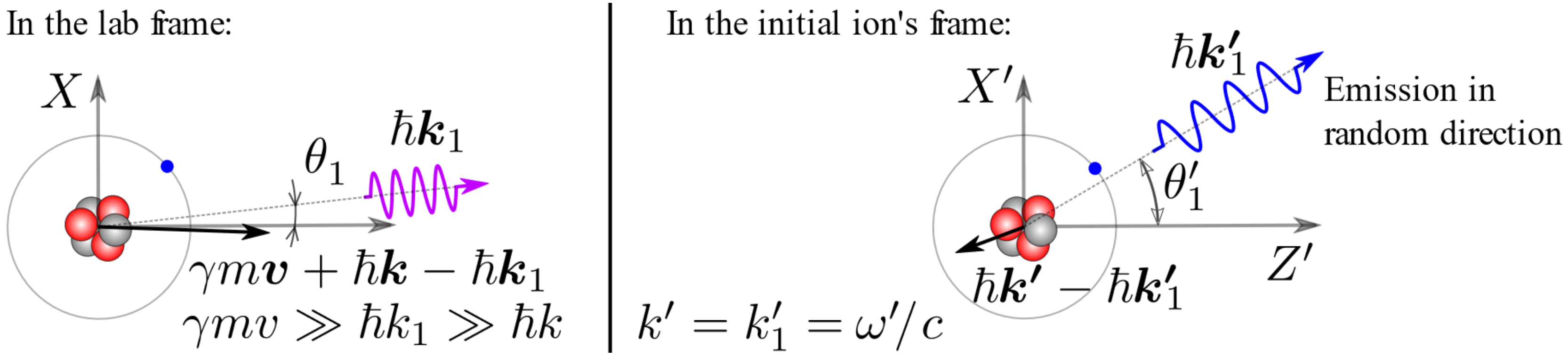
$$\begin{pmatrix} E'/c \\ p'_x \\ p'_y \\ p'_z \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

Assuming that $k_x = -k\sin\theta$, $k_y = 0$, $k_z = -k\cos\theta$, and $k = \omega/c$ we can find the incoming photon parameters in the ion's frame of reference:

$$\omega' = (1+\beta\cos\theta)\gamma\omega \approx \left(1+\beta-\beta\frac{\theta^2}{2}\right)\gamma\omega \approx 2\gamma\omega.$$

Incoming angular spread in the beam of $\theta \sim 1$ mrad will be translated to a frequency error of only $\sim 10^{-6}$ in the ion's frame of reference. Frequency mismatch is dominated by the energy spread in the ion beam (typically $\sim 10^{-4}$).

Photon emission



Photon emission will occur in a random direction. For simplicity let's assume that the photon was emitted in the same plane (X', Z') at a random angle θ'_1, i.e. $k'_{1x} = k' \sin\theta'_1$, $k'_{1z} = k' \cos\theta'_1$. Then inverse Lorentz transformation gives us the emitted photon parameters in the lab frame:

$$\begin{pmatrix} 1 \\ \sin\theta_1 \\ 0 \\ \cos\theta_1 \end{pmatrix} \frac{\omega_1}{c} = \begin{pmatrix} \gamma & 0 & 0 & \beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} 1 \\ \sin\theta'_1 \\ 0 \\ \cos\theta'_1 \end{pmatrix} \frac{\omega'}{c}.$$

Hence the scatterd photon has the frequency $\omega_1 = \gamma(1 + \beta\cos\theta'_1)\omega' \approx 2\gamma^2(1 + \beta\cos\theta'_1)\omega$.

$$\omega_1 \sin\theta_1 = \omega' \sin\theta'_1 \;\Rightarrow\; \sin\theta_1 = \frac{\sin\theta'_1}{\gamma(1 + \beta\cos\theta'_1)}.$$

The LHC example:

Lead ion with one electron:

Ion charge $Z = 81$, mass A = 208, $\gamma = 2928$, $p_z = 567$ TeV/c,

$\hbar\omega' = 69$ keV (Lyman-alpha line), laser $\hbar\omega = 12$ eV, emitted gamma $\hbar\omega_{1,\mathrm{max}} = 402$ MeV, typical angle of emission $\theta_1 \sim 1/\gamma \sim 0.3$ mrad.

Typical transverse kick due to gamma emission:

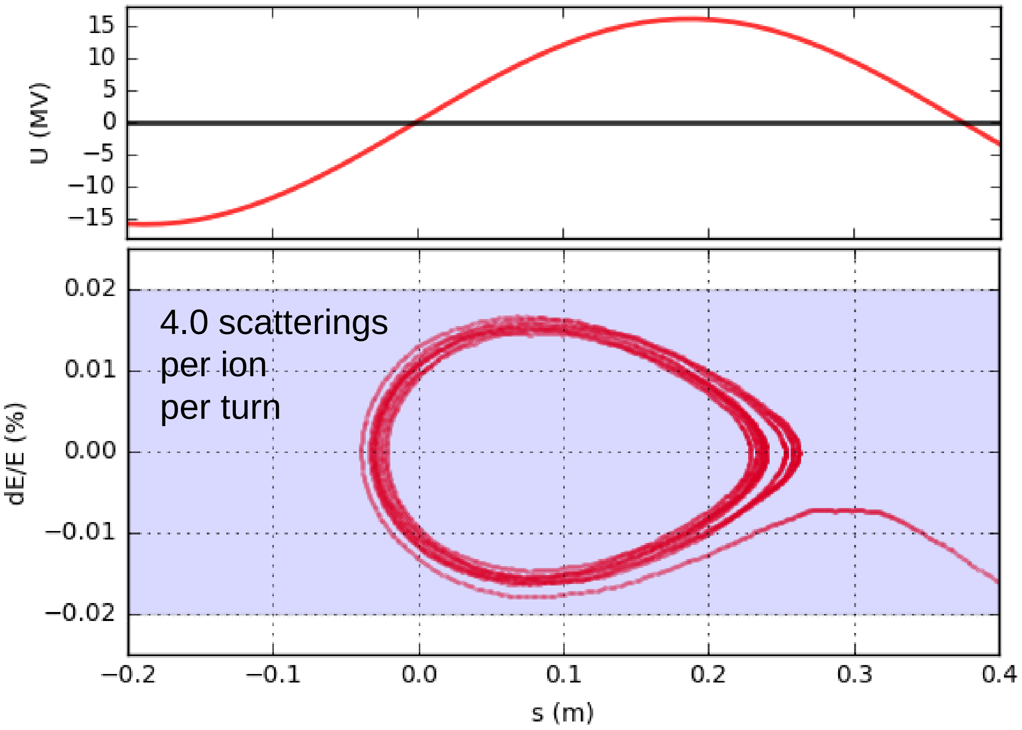
$p_x/p_z \sim \hbar\omega'/p_z c \sim 69$ keV/567 TeV $\sim 10^{-7}$ mrad.

Typical transverse beam parameters at the LHC interaction point for example:
Transverse beam size = 0.026 mm, angular spread = 0.026 mrad (10^5 times higher).

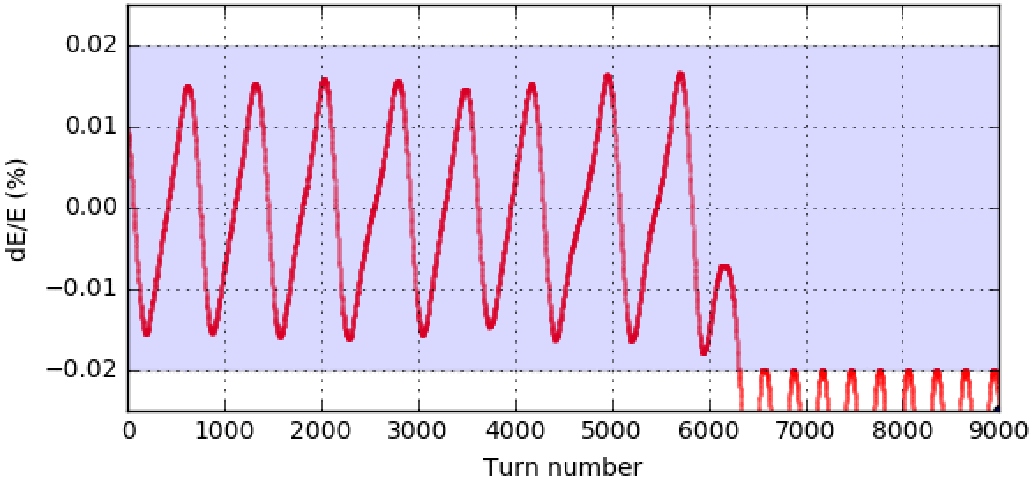
Typical energy spread in the beam is $\Delta p/p \sim 10^{-4}$, while the average δp_z due to the photon emission is 200 MeV/c => $\delta p_z / p_z = 200$ MeV / 567 TeV $= 3.5 \cdot 10^{-7}$ => $\Delta p/\delta p \approx 300$, even with one scattering per turn the longitudinal effects will be significant in 100s of turns.

First of all we should consider the influence of photon emissions on the synchrotron oscillations.

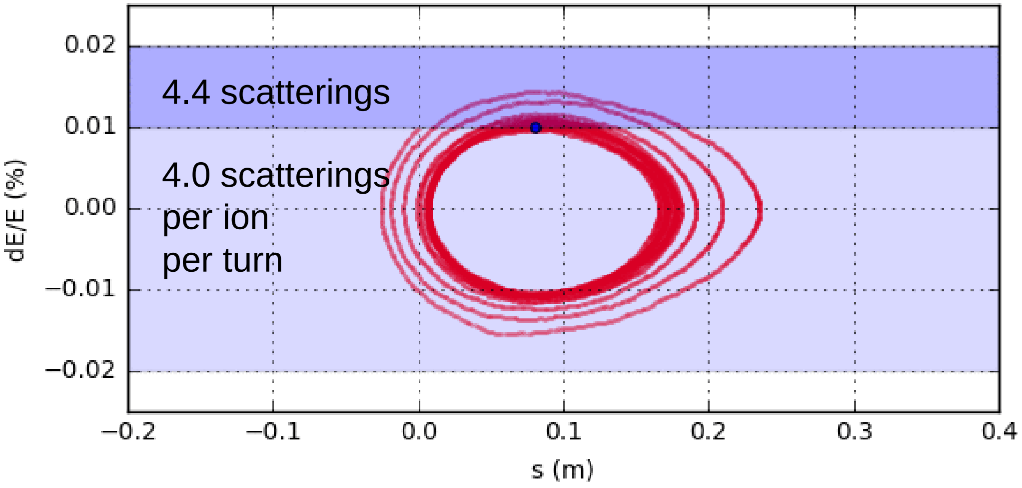
Longitudinal laser cooling is important to stabilize the ion motion:

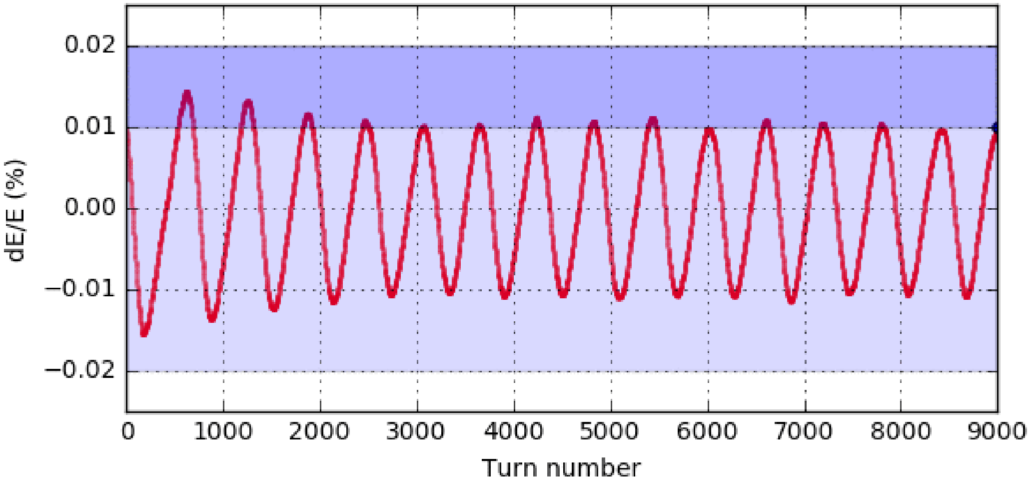


The important effect of photon emissions on ion beam dynamics is in the energy loss of the partially stripped ion. This energy loss is randomly distributed from 0 to 400 MeV in this case of Pb ion with one remaining electron in the LHC. This randomness excites uncontrolled growth of synchrotron oscillations leading to a loss of ion from the RF-bucket:



The synchrotron oscillations can be stabilized by a small change in the spectral distribution of the laser beam (or by adding another low-power laser):





Simulation details: http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

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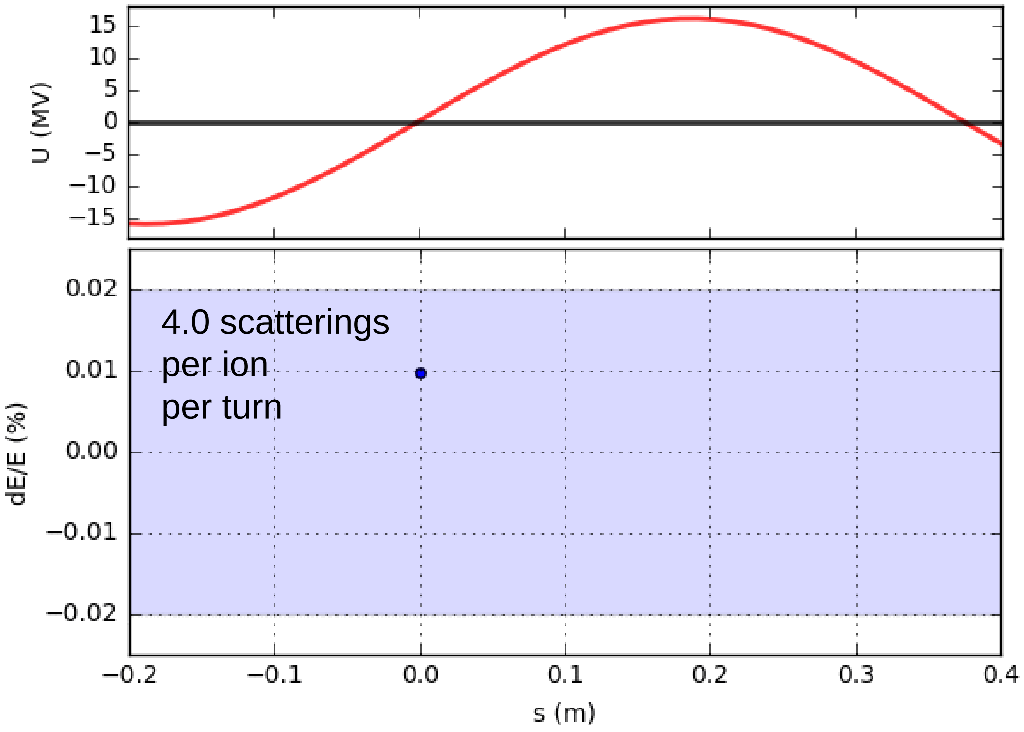

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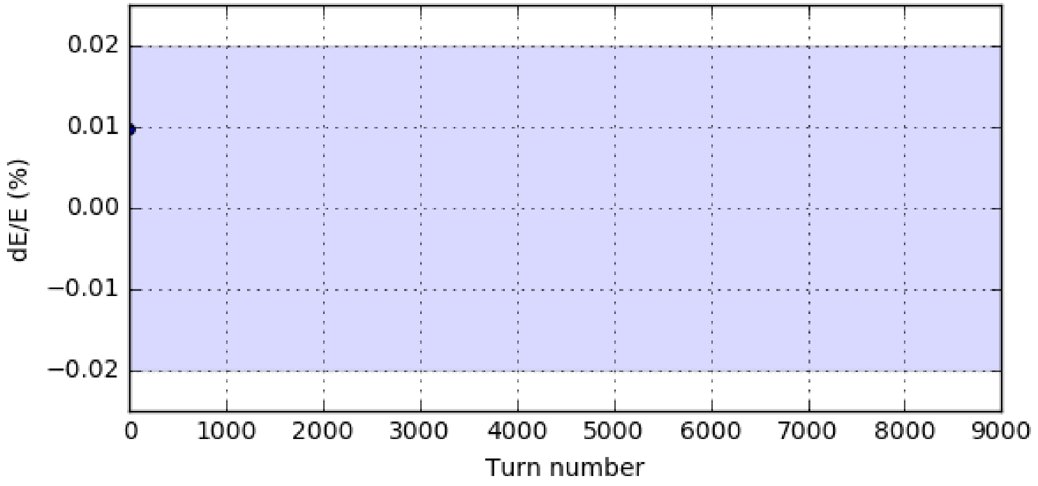

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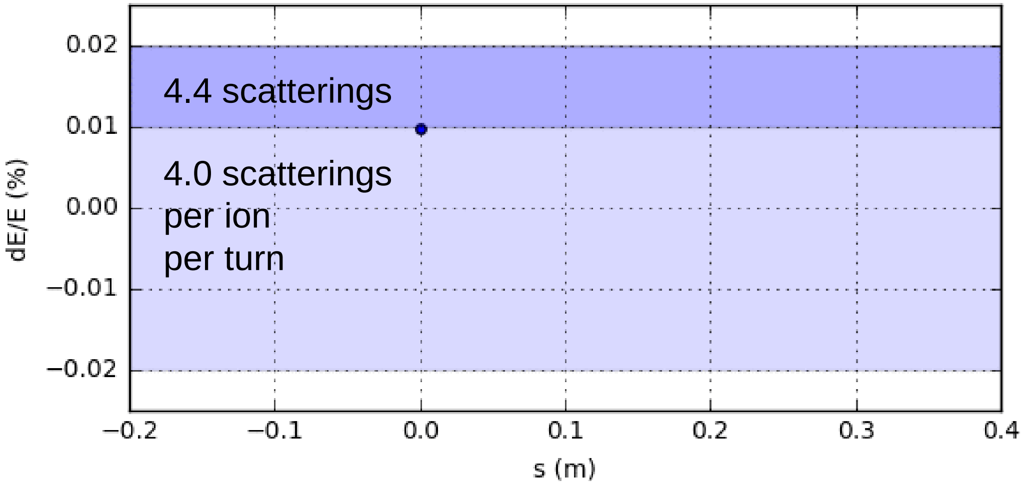

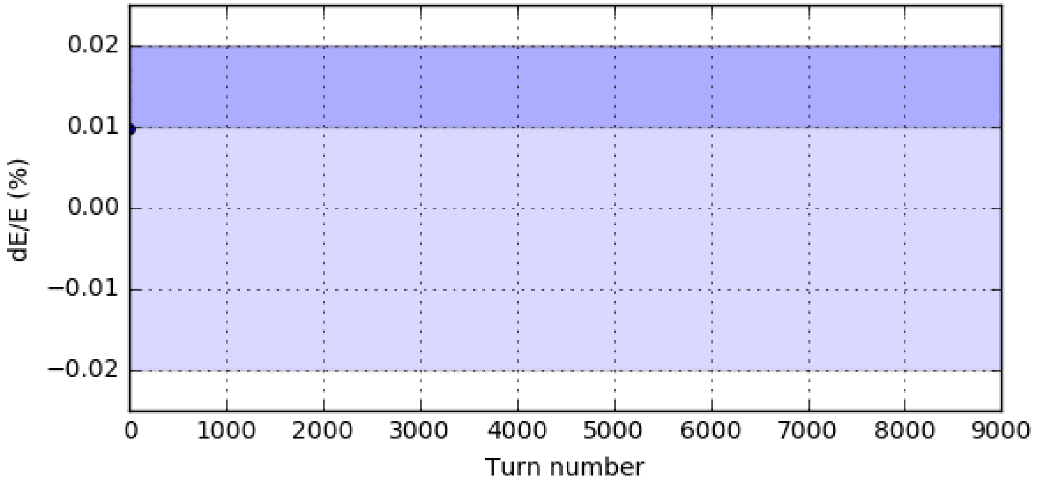

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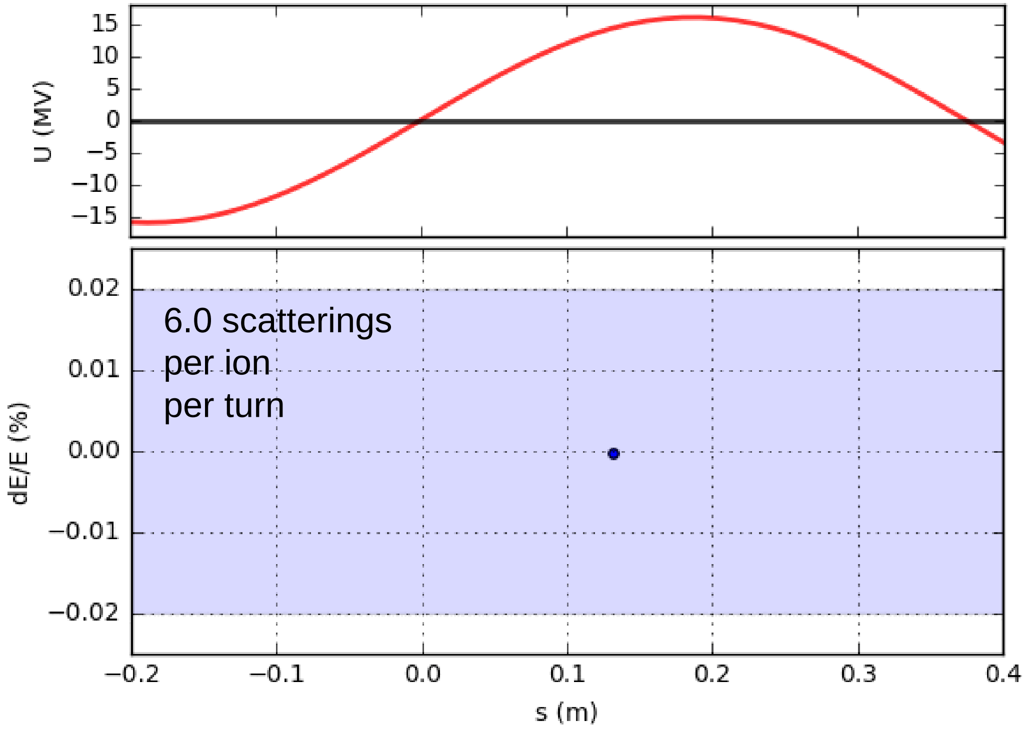

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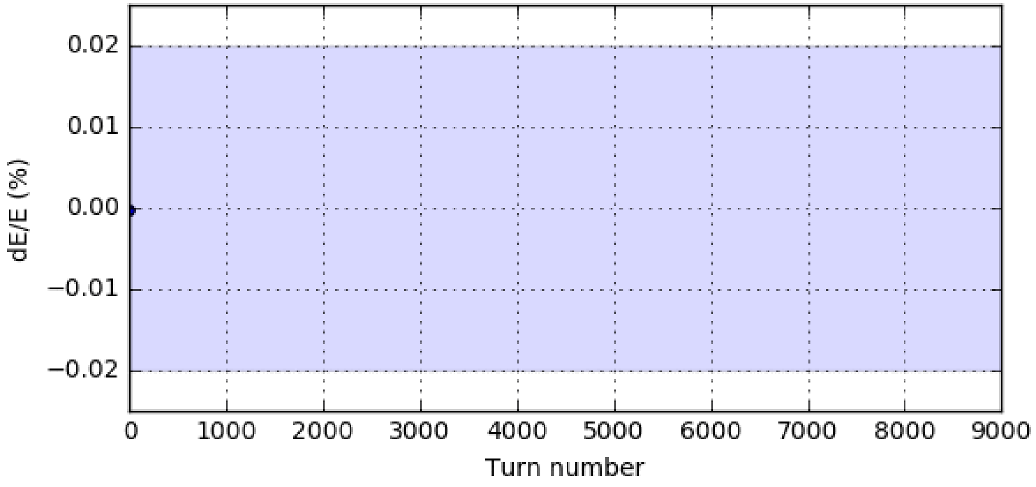

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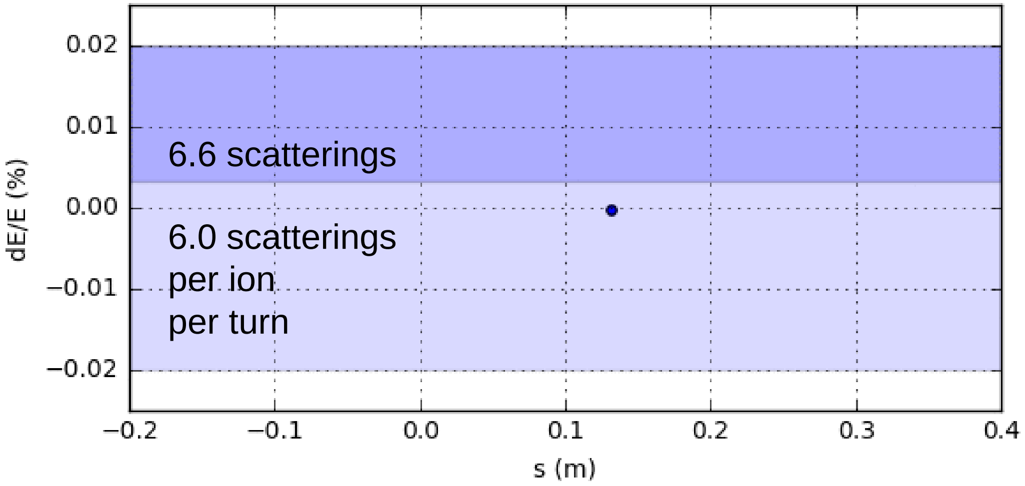

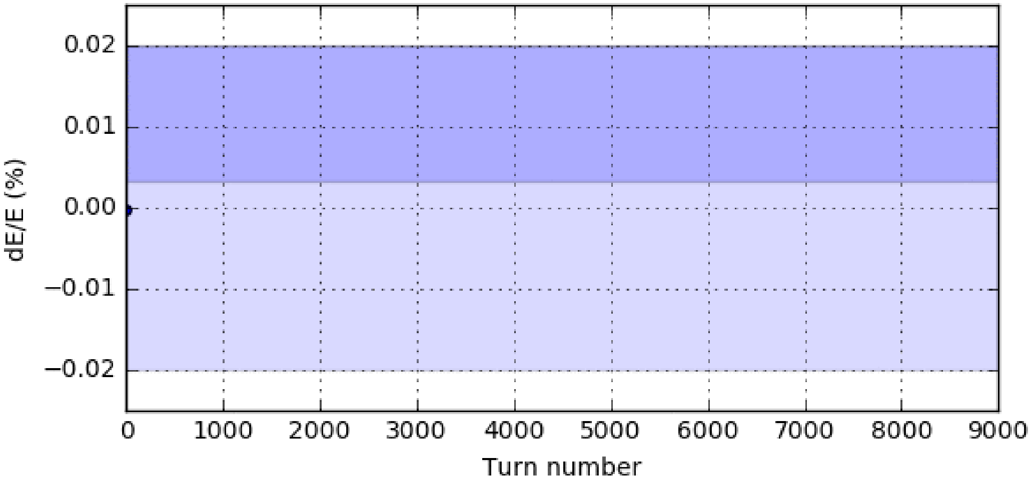

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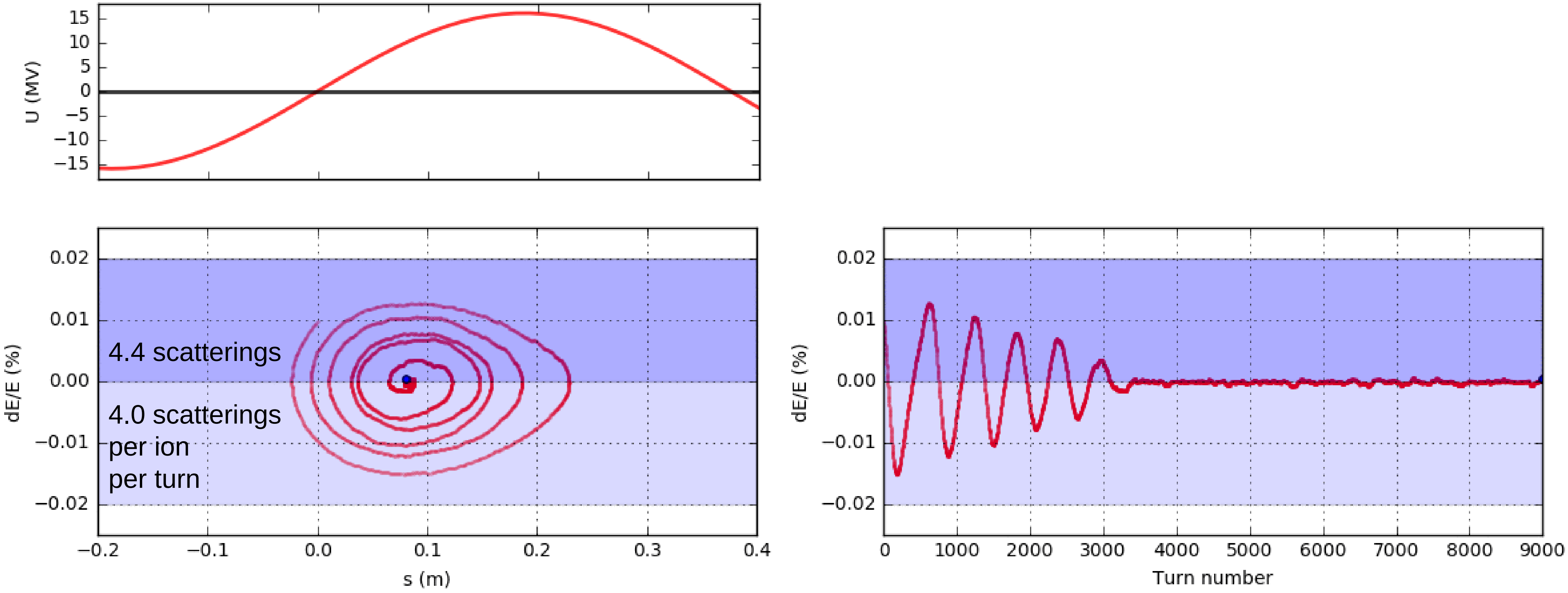
Fast longitudinal cooling



4.4 scatterings

4.0 scatterings
per ion
per turn

Fast longitudinal cooling idea: E. G. Bessonov, R. M. Feshchenko [Stimulated Radiation Cooling](). RuPAC’2008.

Simulation details: http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

There are several ways to cool high-energy hadron beams

1. Synchrotron radiation cooling

For protons and ions occurs naturally at very high energies. Takes hours. For the AWAKE-like PWFA applications probably practical only starting from the energy of High-Energy LHC (a project to upgrade LHC to 12-16 TeV).

2. Optical stochastic cooling

Was seriously considered for the Tevatron. Can be applied for protons in the LHC (for luminosity leveling and beam halo control). The test experiment with electrons is under construction at Fermilab. For details see: V. Lebedev. Optical Stochastic Cooling (2012).
V. Lebedev and A. Romanov. Optical Stochastic Cooling at IOTA Ring (2015).
E. Bessonov, M. Gorbunkov, A. Mikhailichenko. Enhanced optical cooling system test in an electron storage ring (2008) – fast version of optical stochastic cooling.

3. Laser cooling of partially stripped ions

Well-developed at low-energy. Cooling is faster at high energy because the energy radiated by the ion grows as γ^2. Never tested above few 100 MeV/u. Also interesting as an intense source of gamma-photons: see the talks of W. Krasny on The Gamma Factory Initiative.

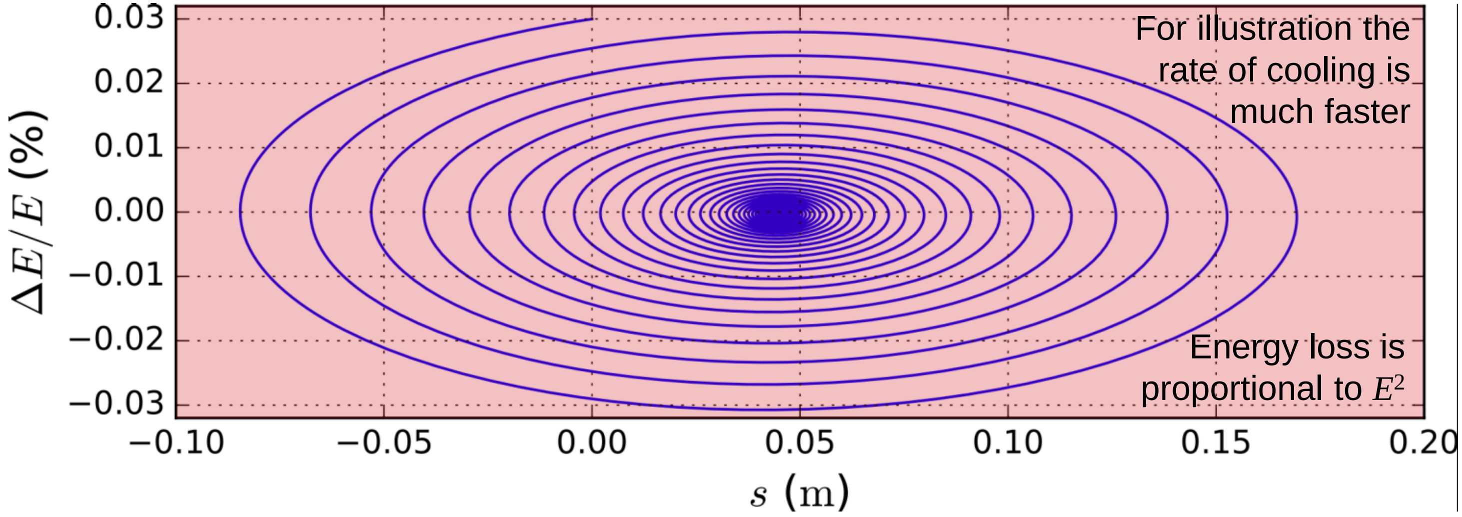
4. Coherent electron cooling V. Litvinenko and Ya. Derbenev, PRL **102**, 114801 (2009).

Broad-band cooling vs fast cooling (SPS):

The natural width of the absorption line (~10^{-6}) typically << Doppler shift due to energy spread (~10^{-4})

1. Broad-band laser covers the full spectrum of particle energies:

See: E. G. Bessonov and K.-J. Kim. Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers, PRL, 1996.

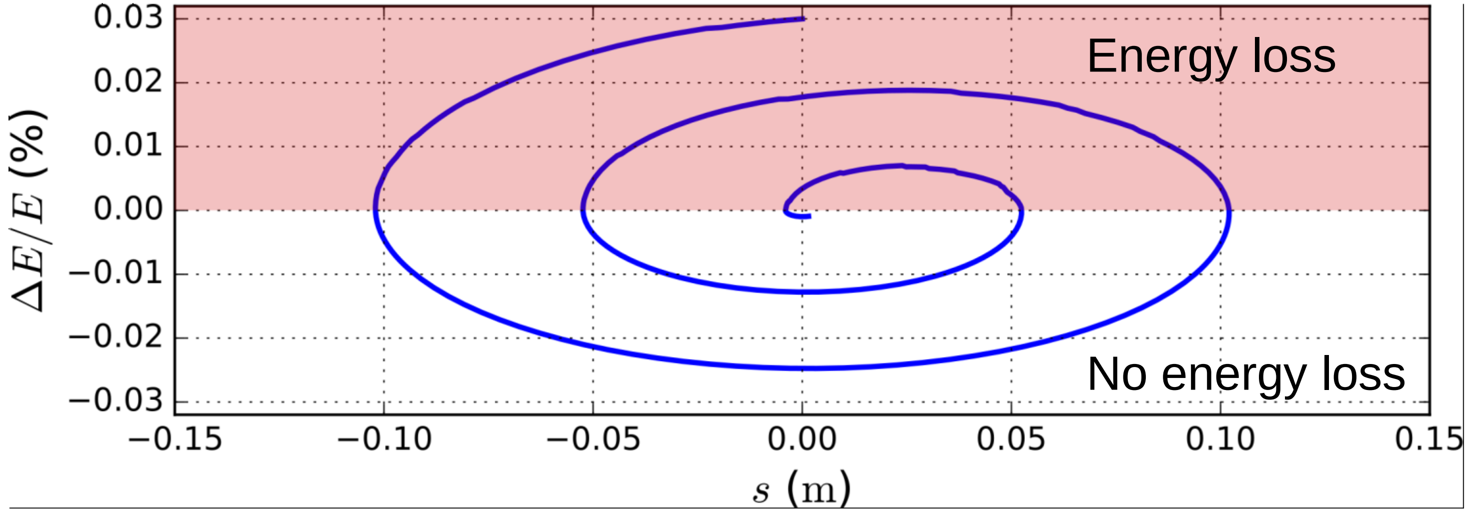


Cooling in all planes. The time of cooling is the time to **radiate full ion energy** E.

For the SPS at gamma = 200, and $Z = 14$ (H-like Si), scattered light ~100 keV => assuming ~100 scatterings per ion per turn (intense laser) $N_{\text{turns}} \sim 200\cdot14\cdot2\cdot0.932$ GeV / (100e-6 GeV · 100) ~ 10^6 turns or 20 sec.

2. Broad-band laser with a sharp low-frequency cut-off:

See: E. G. Bessonov, R. M. Feshchenko Stimulated Radiation Cooling. RuPAC'2008.

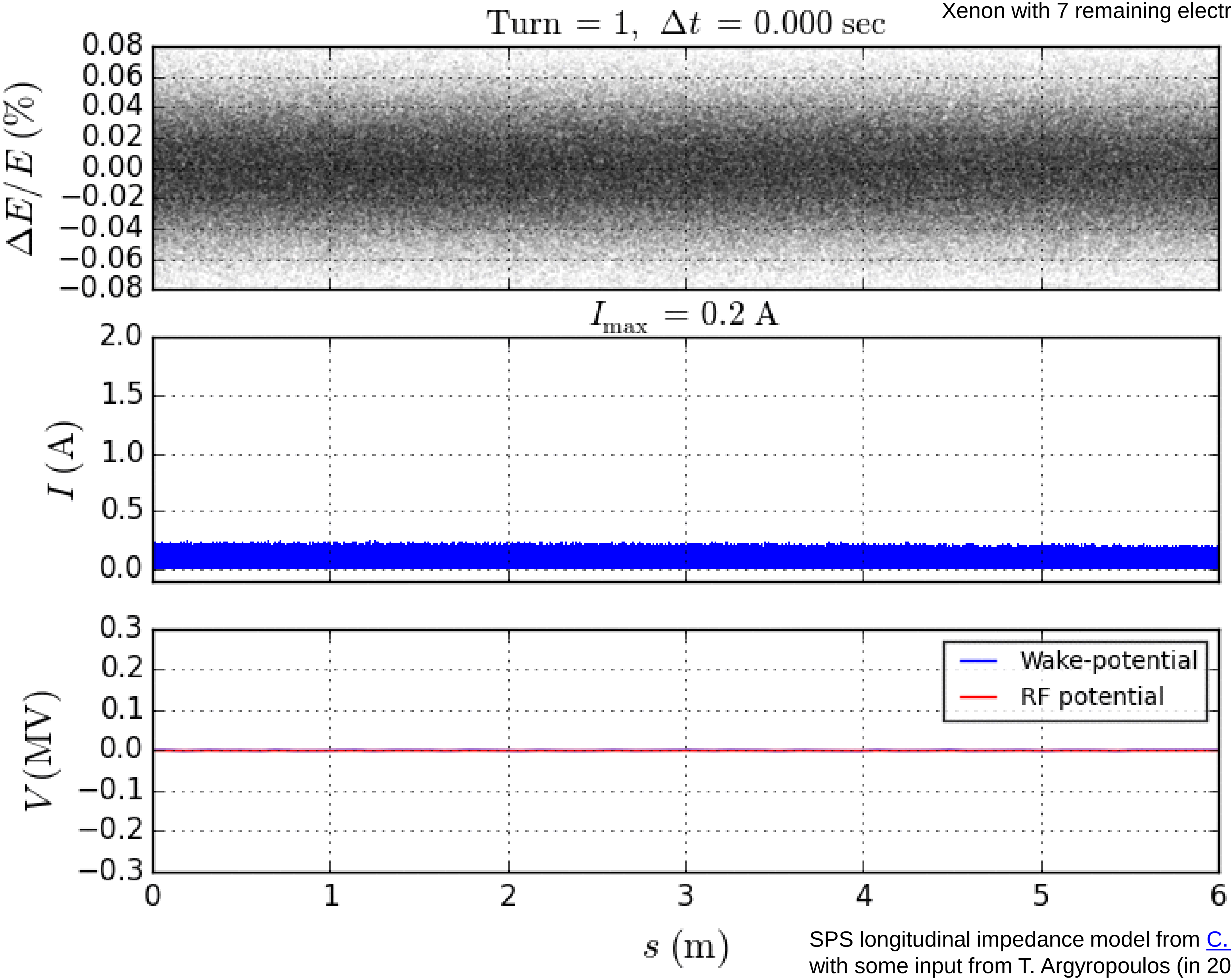


Much faster cooling, but only longitudinal. Time of cooling is the time to **radiate energy spread** ΔE.

Similar estimate for the SPS gives ~100 turns. This method is fast enough for the SPS even with only one scattering per ion per turn (t_{cool} ~ **0.1 sec**)

Some collective effects: fast cooling of unbunched beam (SPS)

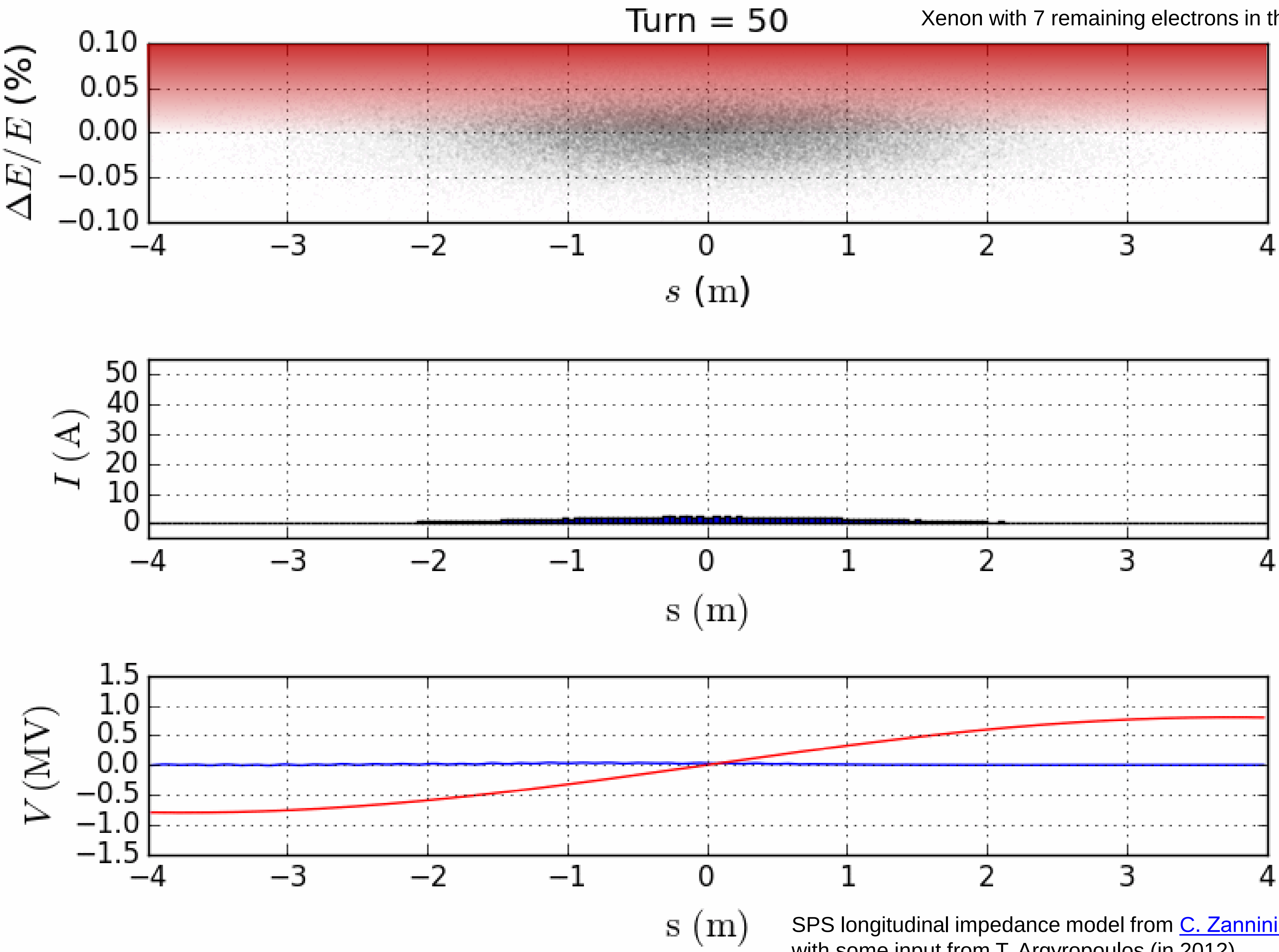
Xenon with 7 remaining electrons in the SPS



SPS longitudinal impedance model from C. Zannini's talk
with some input from T. Argyropoulos (in 2012)

Some collective effects: bunch compression by triang. laser spectr.

Xenon with 7 remaining electrons in the SPS



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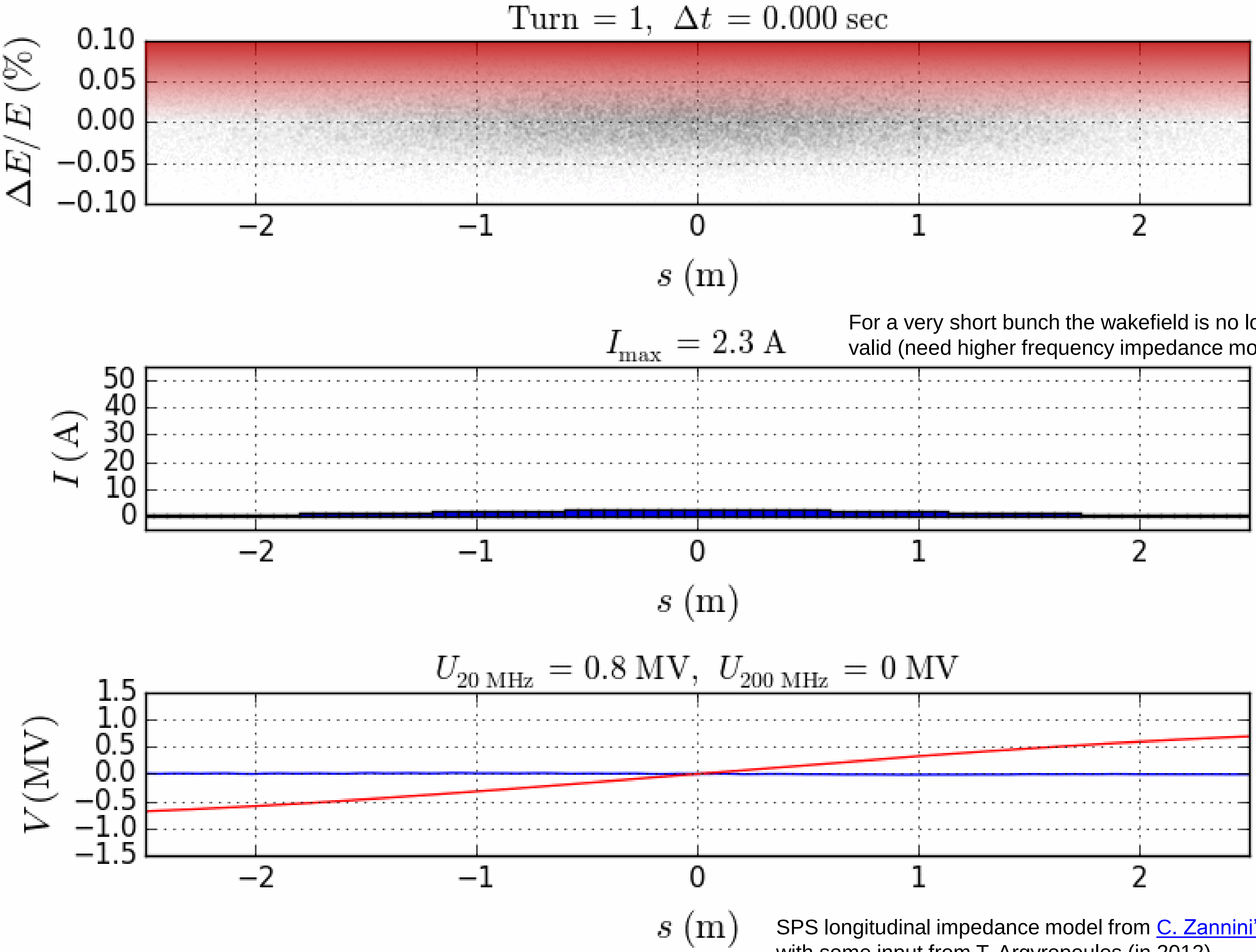
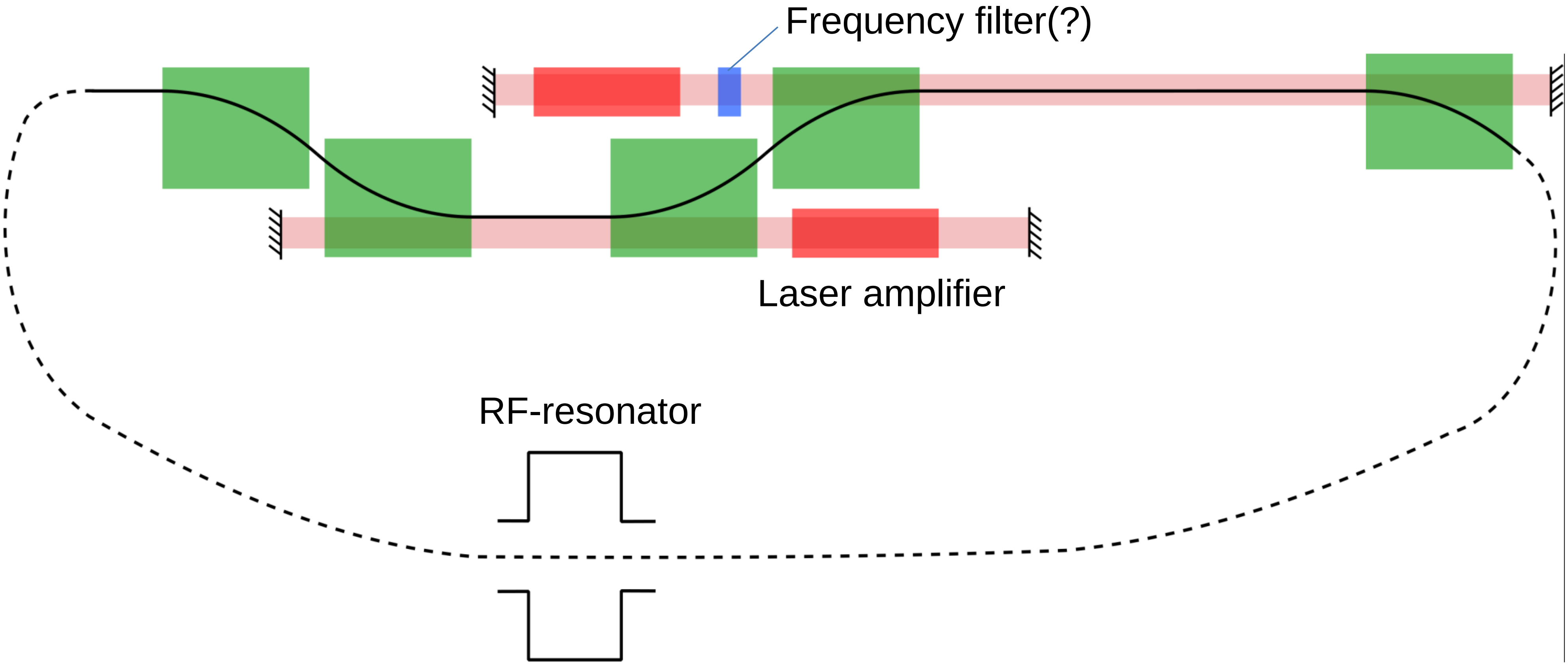


For a very short bunch the wakefield is no longer valid (need higher frequency impedance model)

SPS longitudinal impedance model from C. Zannini’s talk with some input from T. Argyropoulos (in 2012)

Possible transfer of fast longitudinal cooling to transverse plane:

To achieve fast cooling of transverse betatron oscillations the coupling between x and E should be employed. For example two laser cooling systems can be used: one in the region with negative dispersion which converts transverse oscillations into longitudinal, and another one in the region with zero dispersion which cools the longitudinal oscillations:



Cooling of vertical betatron oscillations can be achieved by coupling them to the horizontal oscillations with a skew quadrupole for example (such coupling is normally present in the ring because of small tilts of dipoles and quadrupoles).

Also one laser combining both functions can be used. Such laser should have modulation of intensity both in frequency and in space and it should be placed in the location with significant dispersion function.

Conclusions

- The main effect of the resonant photon scattering off the ultra-relativistic partially stripped ions is the longitudinal momentum loss of the ion.

- The resonant nature of photon absorption opens many interesting possibilities for selective manipulations with such ion beams: fast longitudinal cooling (or heating), collimation, compression, micro-bunching, etc.

- The Gamma-Factory at the top LHC energy will require some form of longitudinal cooling in order to deal with excitation of synchrotron oscillations due to the random emitted photon energy (randomness in the photon emission angle).

- Plenty of things to study, especially different collective effects:

  PSI stripping due to the intrabeam scattering (V. Teltov’s suggestion).

  Longitudinal and transverse stability due to collective effects (impedances).

Many thanks to W. Krasny and E. Bessonov for stimulating discussions!

Back-up slides

Partially stripped ions in the SPS

D. Manglunki et al. CERN's Fixed Target Primary Ion Programme. IPAC’2016.

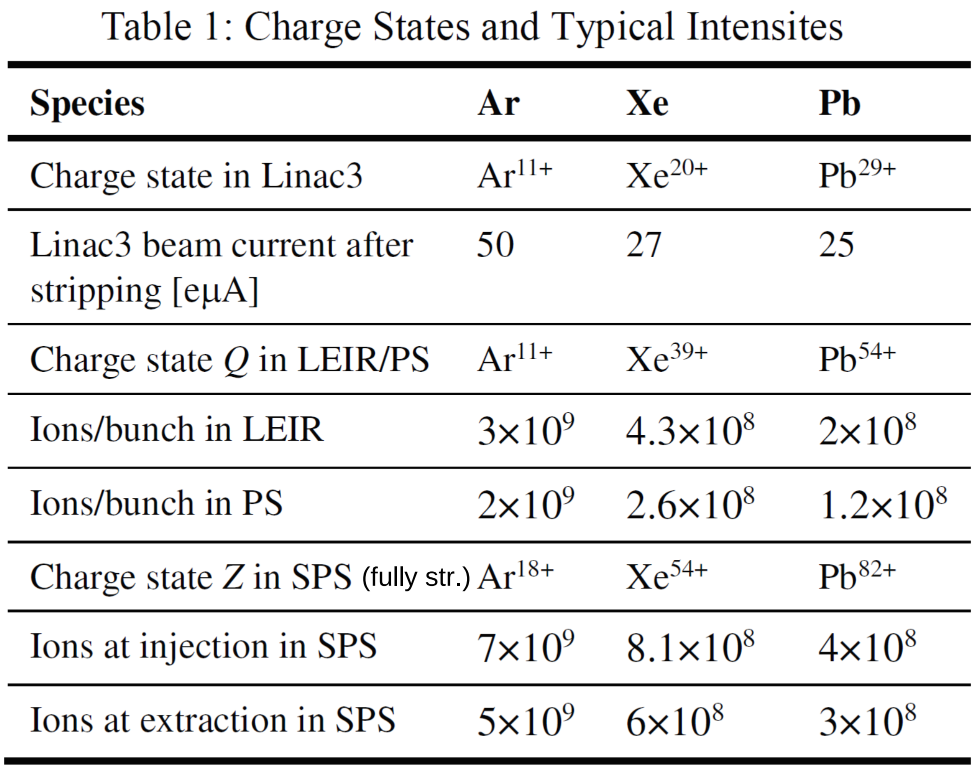


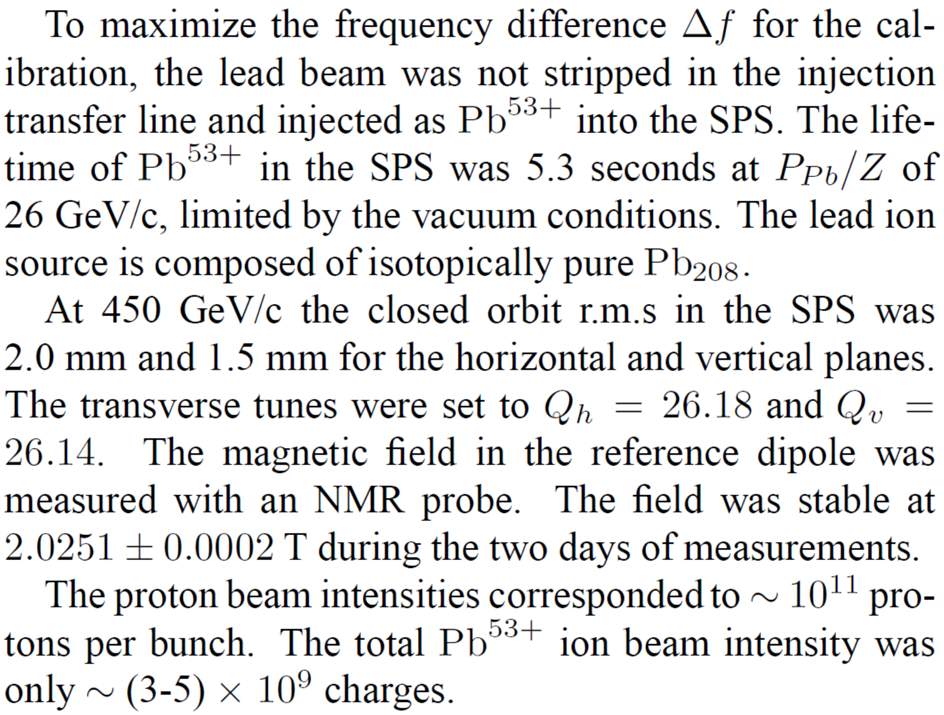
Table 1: Charge States and Typical Intensites

Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state Q in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^{9}	4.3×10^{8}	2×10^{8}
Ions/bunch in PS	2×10^{9}	2.6×10^{8}	1.2×10^{8}
Charge state Z in SPS (fully str.)	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^{9}	8.1×10^{8}	4×10^{8}
Ions at extraction in SPS	5×10^{9}	6×10^{8}	3×10^{8}

Number of charges:	$9\cdot10^{10}$	$3.2\cdot10^{10}$	$2.5\cdot10^{10}$
Less than in AWAKE	**3x less**	**10x less**	**10x less**

Production efficiency for partially stripped ions can be higher than for the fully stripped ions.

J. Wenninger et al. Energy Calibration of the SPS with Proton and Lead Ion Beams. PAC’2005:



To maximize the frequency difference Δf for the calibration, the lead beam was not stripped in the injection transfer line and injected as Pb^{53+} into the SPS. The lifetime of Pb^{53+} in the SPS was 5.3 seconds at P_{Pb}/Z of 26 GeV/c, limited by the vacuum conditions. The lead ion source is composed of isotopically pure Pb$_{208}$.

At 450 GeV/c the closed orbit r.m.s in the SPS was 2.0 mm and 1.5 mm for the horizontal and vertical planes. The transverse tunes were set to $Q_h = 26.18$ and $Q_v = 26.14$. The magnetic field in the reference dipole was measured with an NMR probe. The field was stable at 2.0251 ± 0.0002 T during the two days of measurements.

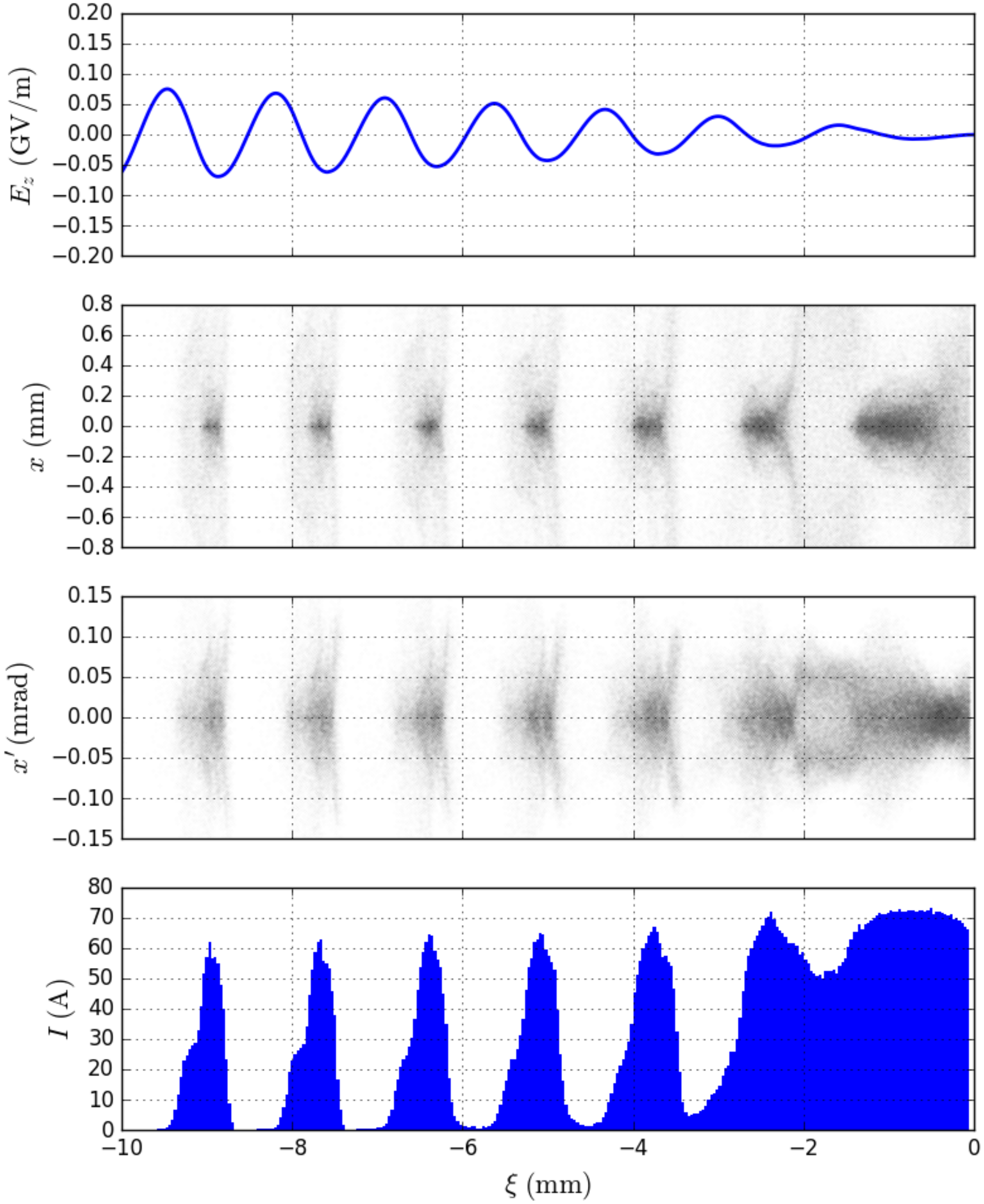
The proton beam intensities corresponded to $\sim 10^{11}$ protons per bunch. The total Pb^{53+} ion beam intensity was only $\sim$ (3-5) $\times$ 10^{9} charges.

100x less than in AWAKE.
Maybe could be optimized for high beam charge.

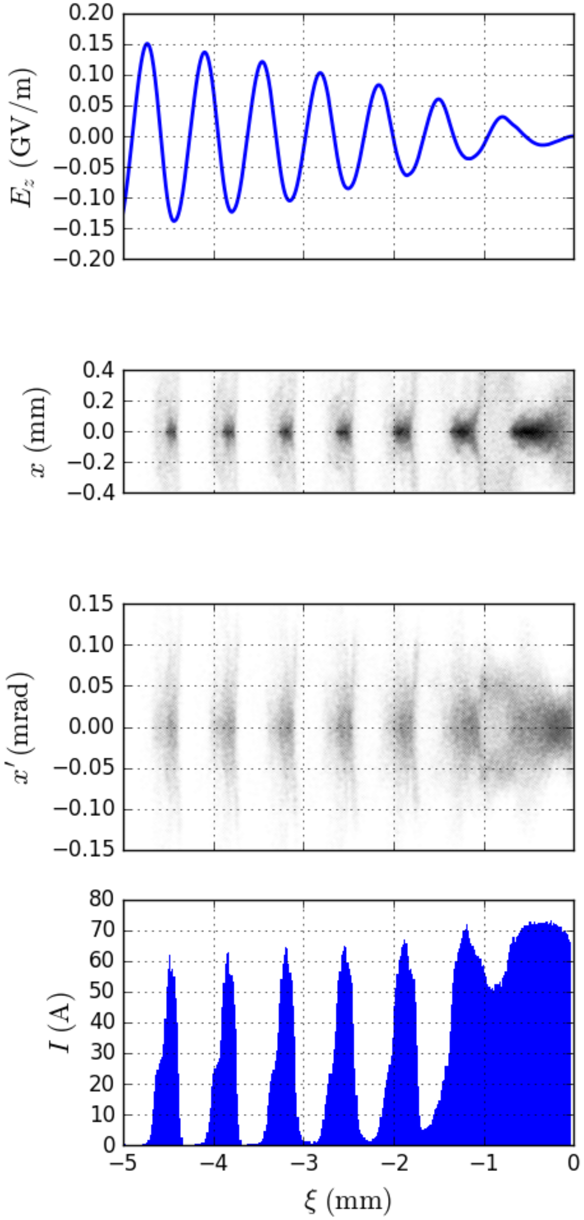
Possible variant: Xe^{47+} (7 electrons left, N-like). $\gamma = 162$. Atomic excitation $^4S_{3/2} \rightarrow {}^4P_{3/2}$. Krypton laser: 647 nm (1.87 eV) will be converted to gamma-photons with $E_{max} = 196$ keV. $I_{sat.} = 1.7\cdot10^8$ W/cm^2 , decay length = 3.4 cm => with a 1 mm wide beam to have one interaction per turn we need a single laser pulse energy ≈ $1.7\cdot10^8$ W/cm^2 · $0.1\cdot0.1$ cm^2 · 3.4 cm / ($3\cdot10^{10}$ cm/sec) ≈ 0.2 mJ => Average laser power ~ $0.2\cdot10^{-3}$ J / (7000 m / $3\cdot10^8$ m/sec) ~ 10 W. (Xe^{47+} suggested by Bessonov and Kim PRL’1996 and in W. Krasny’s proposal for gamma-factory test at SPS).

General scaling of beam parameters with plasma density

$n_{\mathrm{plasma}} = 7\cdot10^{14}\ \mathrm{cm}^{-3}$



$n_{\mathrm{plasma}} = 4\mathrm{x}(7\cdot10^{14}\ \mathrm{cm}^{-3})$



2x higher wakefield

2x smaller transv. size => 4x higher beam density.

The same angular spread => 2x lower beam emittance required.

The same current => 2x less particles needed to drive 2x higher wake.
(Also 2x less accelerated particles).

10x less particles with 10x lower emittance and the same current can potentially drive 10x higher wakefield.
Maximum plasma density is essentially defined by the transverse beam emittance.
Higher peak current is needed to reduce the number of micro-bunches => less strict tolerances on plasma density.

Beam cooling due to synchrotron radiation

For details see A. Valishev. Synchrotron Radiation Damping, Intrabeam Scattering and Beam-Beam Simulations for HE-LHC.

Transverse oscillations are damped because all components of particle momentum are lost due the SR but only the longitudinal component is restored in RF-resonator => transverse oscillations are damped over the time it takes to radiate the whole energy of the particle. Synchrotron oscillations (energy) are damped over the similar time because energy loss per turn U_0 is increasing with the particle energy (as E^4/R):

Minimum equilibrium emittance and energy spread is defined by the quantum fluctuations of the SR. For heavy particles this limit can be very low.

$$U_0=\frac{C_\gamma}{2\pi}E^4 I_2 \qquad \tau_{x,y}=\frac{ET_0}{U_0},\tau_E=\frac{ET_0}{2\cdot U_0} \qquad \frac{d\varepsilon_x}{dt}=-\frac{\varepsilon_x}{\tau_x}+\frac{55}{48\sqrt{3}}\frac{\hbar c}{T_0}\frac{r_0}{mc^2}\gamma^5 I_5$$

Parameter	**LHC (p-p)**	**HE-LHC 12.5**	**HE-LHC 16.5**	**FCC (p-p)**
Beam energy	7 TeV	12.5 TeV	16.5 TeV	50 TeV
Number of protons in a single bunch	$1.2\cdot10^{11}$	$2.5\cdot10^{11}$	$1.3\cdot10^{11}$	10^{11}
Damping time of transverse oscillations	25.8 hours	4.5 hours	1.9 hours	1.1 hour
Damping time of longitudinal oscillations	13 hours	2.3 hours	1 hour	0.5 hour
Initial normalized emittance	3.8 mm·mrad	2.5 mm·mrad	3 mm·mrad	2.2 mm·mrad
Min. equilibrium normalized emittance	0.001 mm·mrad	0.006 mm·mrad	0.01 mm·mrad	0.05 mm·mrad
Initial relative energy spread	10^{-4}	10^{-4}	$0.9\cdot10^{-4}$	
Min. equilibrium relative energy spread	$1.4\cdot10^{-6}$	$2.5\cdot10^{-6}$	$3.4\cdot10^{-6}$	

Some data also from W. Bartmann et al. Beam dynamics issues in the FCC

Intra-beam scattering introduces heating proportional to the beam intensity:

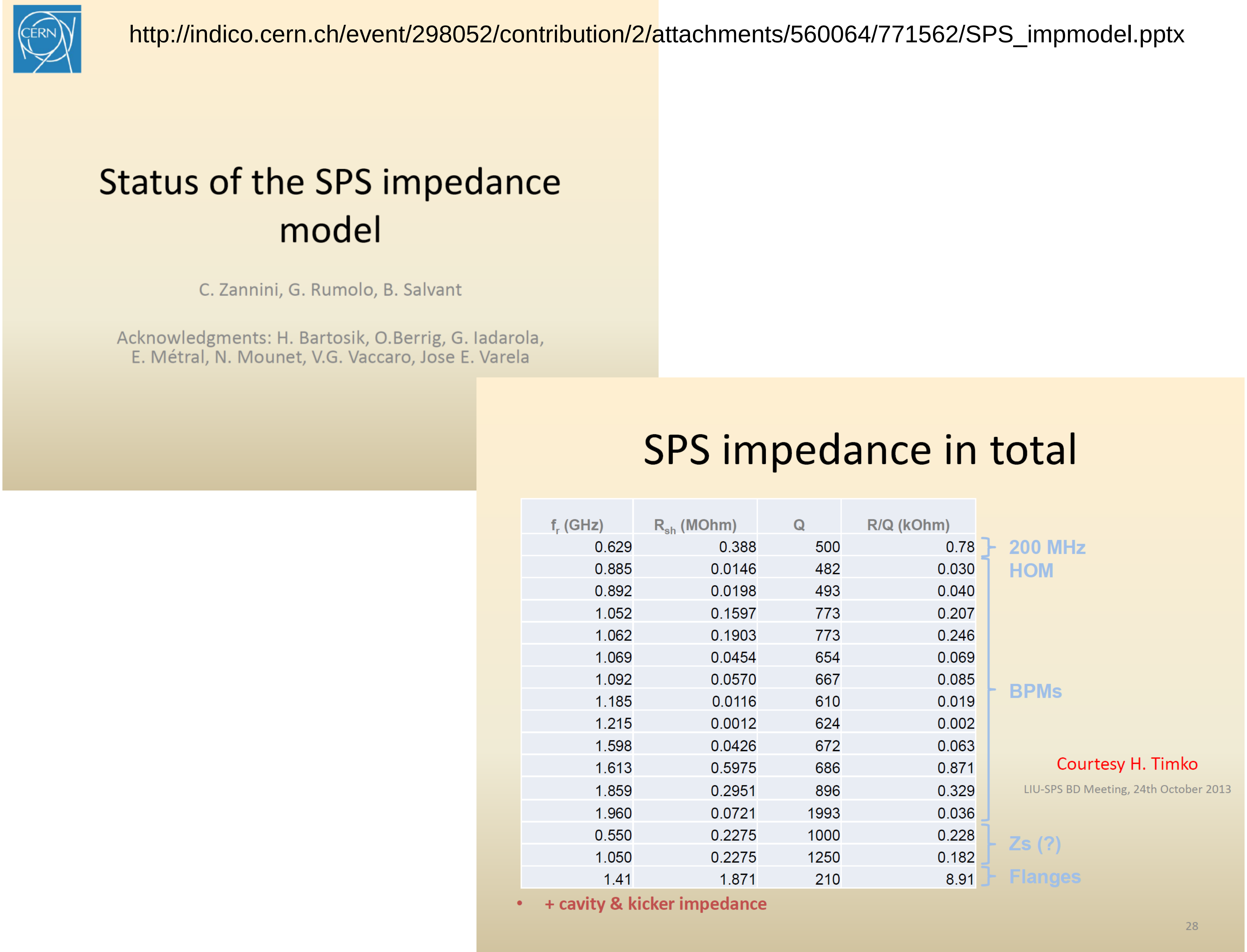
$$\frac{d}{dt}\begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \sigma_E^2\end{pmatrix}=\frac{Nr_0^2cL_c}{4\sqrt{2}\beta^3\gamma^3\sigma_x\sigma_y\sigma_z\theta_\perp}\begin{pmatrix}\langle A_x\rangle_s\\ 0\\ 1\end{pmatrix}$$

	HE-LHC (16.5 TeV)	LHC
Horizontal emittance growth time	82 h	100 h
Longitudinal emittance growth time	72 h	60 h

At lower bunch intensity initial growth time will be proportionally longer.

For details see V. Lebedev. Tevatron Luminosity Evolution Model and its Application to the LHC.

http://indico.cern.ch/event/298052/contribution/2/attachments/560064/771562/SPS_impmodel.pptx



Status of the SPS impedance model

C. Zannini, G. Rumolo, B. Salvant

Acknowledgments: H. Bartosik, O.Berrig, G. Iadarola,
E. Métral, N. Mounet, V.G. Vaccaro, Jose E. Varela

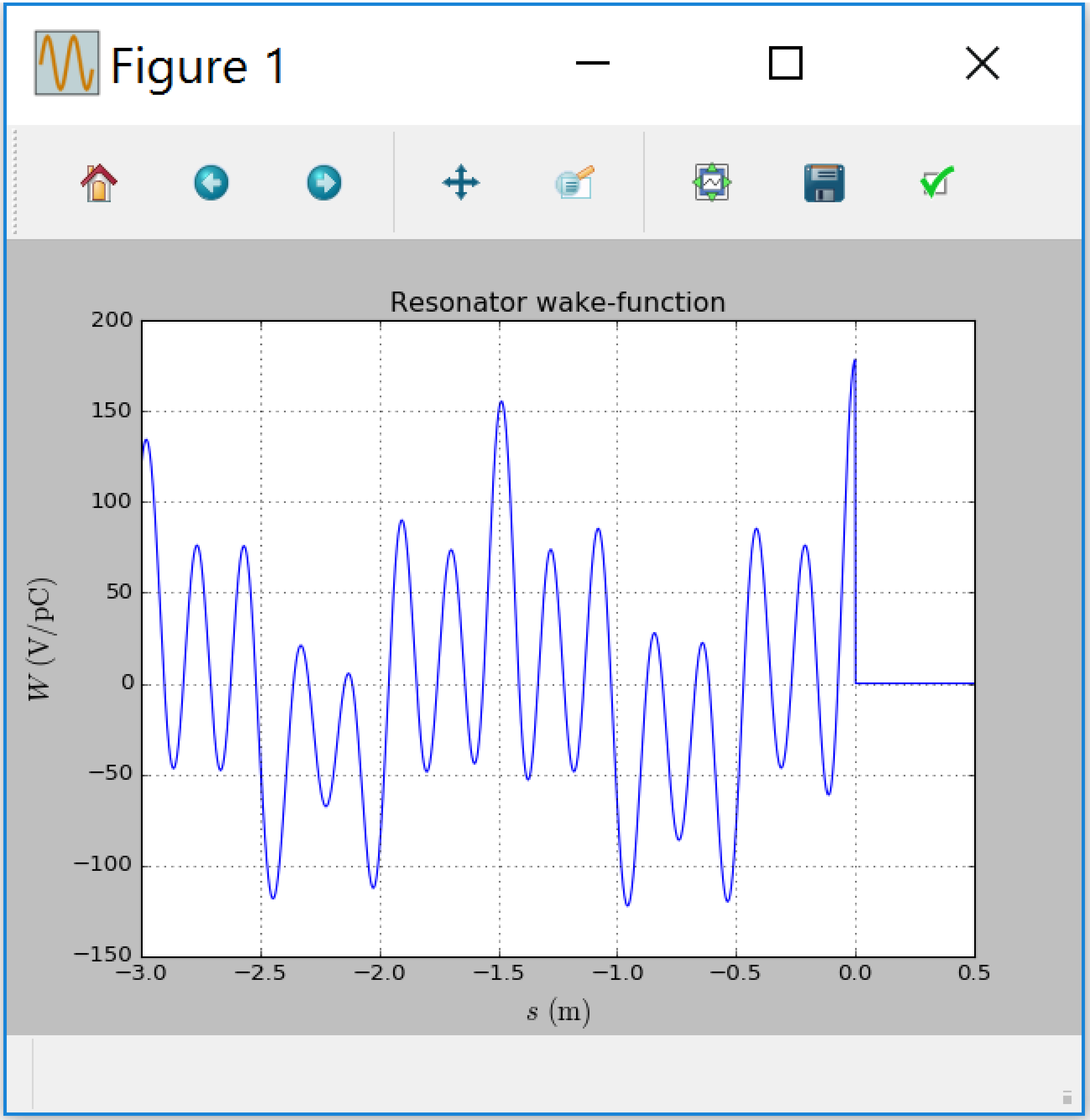
SPS impedance in total

f_r (GHz)	R_{sh} (MOhm)	Q	R/Q (kOhm)	
0.629	0.388	500	0.78	200 MHz HOM
0.885	0.0146	482	0.030	BPMs
0.892	0.0198	493	0.040	
1.052	0.1597	773	0.207	
1.062	0.1903	773	0.246	
1.069	0.0454	654	0.069	
1.092	0.0570	667	0.085	
1.185	0.0116	610	0.019	
1.215	0.0012	624	0.002	
1.598	0.0426	672	0.063	
1.613	0.5975	686	0.871	
1.859	0.2951	896	0.329	
1.960	0.0721	1993	0.036	
0.550	0.2275	1000	0.228	Zs (?)
1.050	0.2275	1250	0.182	
1.41	1.871	210	8.91	Flanges

- **+ cavity & kicker impedance**

Courtesy H. Timko

LIU-SPS BD Meeting, 24th October 2013

Figure 1
Resonator wake-function
W (V/pC)
200
150
100
50
0
−50
−100
−150
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
s (m)