Interplay of Touschek Scattering, Intrabeam Scattering, and RF Cavities in Ultralow-Emittance Storage Rings

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4th Diffraction Limited Storage Ring Workshop, ANL/APS, November 19-21, 2014

Introduction

- Ultralow-emittance storage rings → $\varepsilon_x \ll 1$ nm rad (cf. later)
- Example: MAX IV 3 GeV storage ring

PRST-AB **17**, 050705 (2014)

20-fold 7BA lattice → 528 m, ε_0 = 328 pm rad, U_0 = 364 keV/turn

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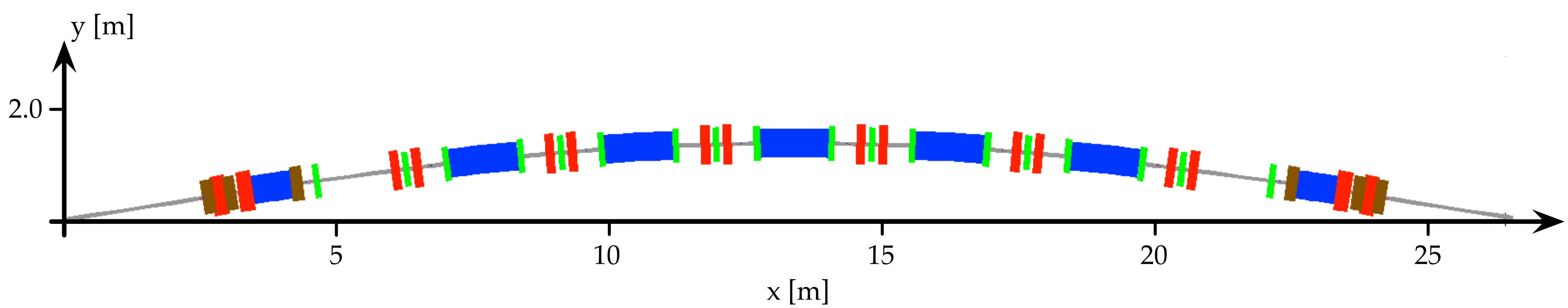
PRST-AB **12**, 120701 (2009)

IPAC'**11**, THPC059, p.3029



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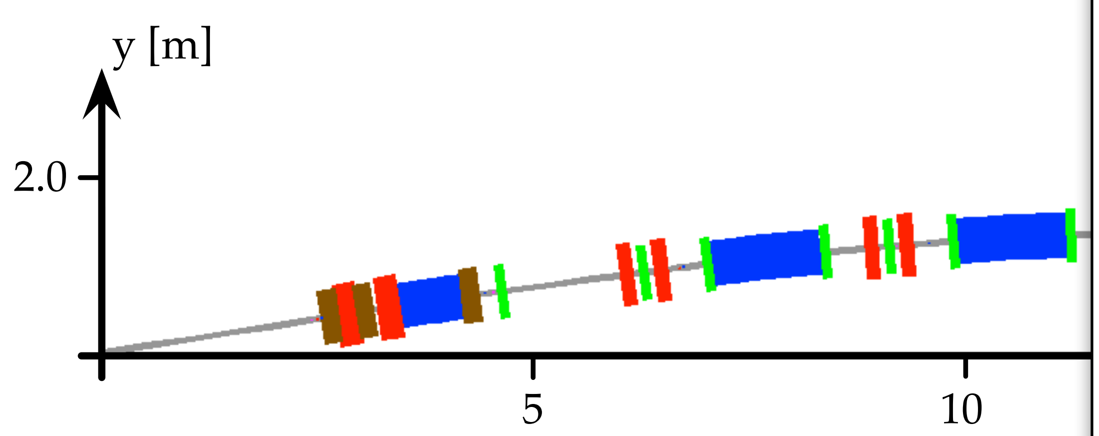

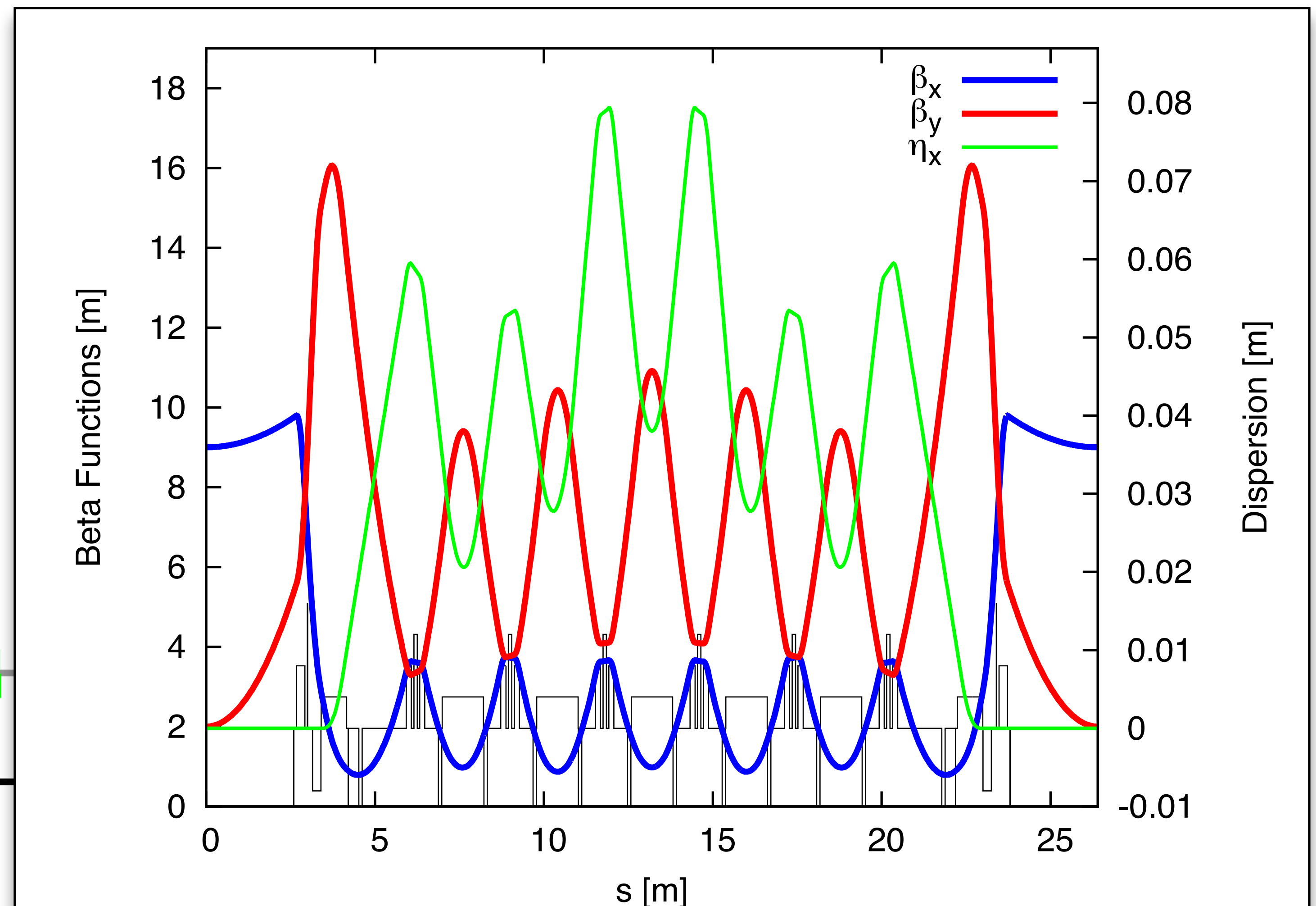

What makes these rings so different?

- 3rd generation SRs: emittance, radiated power, $\sigma_\delta \approx$ const
- Ultralow-emittance rings:
  - Use MBA lattices with many weak dipoles
  - DWs and/or IDs can have huge impact on radiated power

MAX IV 3 GeV SR:
Bare: 364 keV/turn
Loaded: ≈1 MeV/turn

$$U_0 \propto \gamma^4 I_2 \qquad I_2 = \int \frac{ds}{\rho^2}$$

$$\varepsilon_0 \propto \gamma^2 \frac{I_5}{I_2 - I_4} \qquad I_5 = \int \frac{\mathcal{H}}{|\rho^3|} ds$$

$$I_4 = \int \frac{\eta}{\rho} \left(2k + \frac{1}{\rho^2} \right) ds$$

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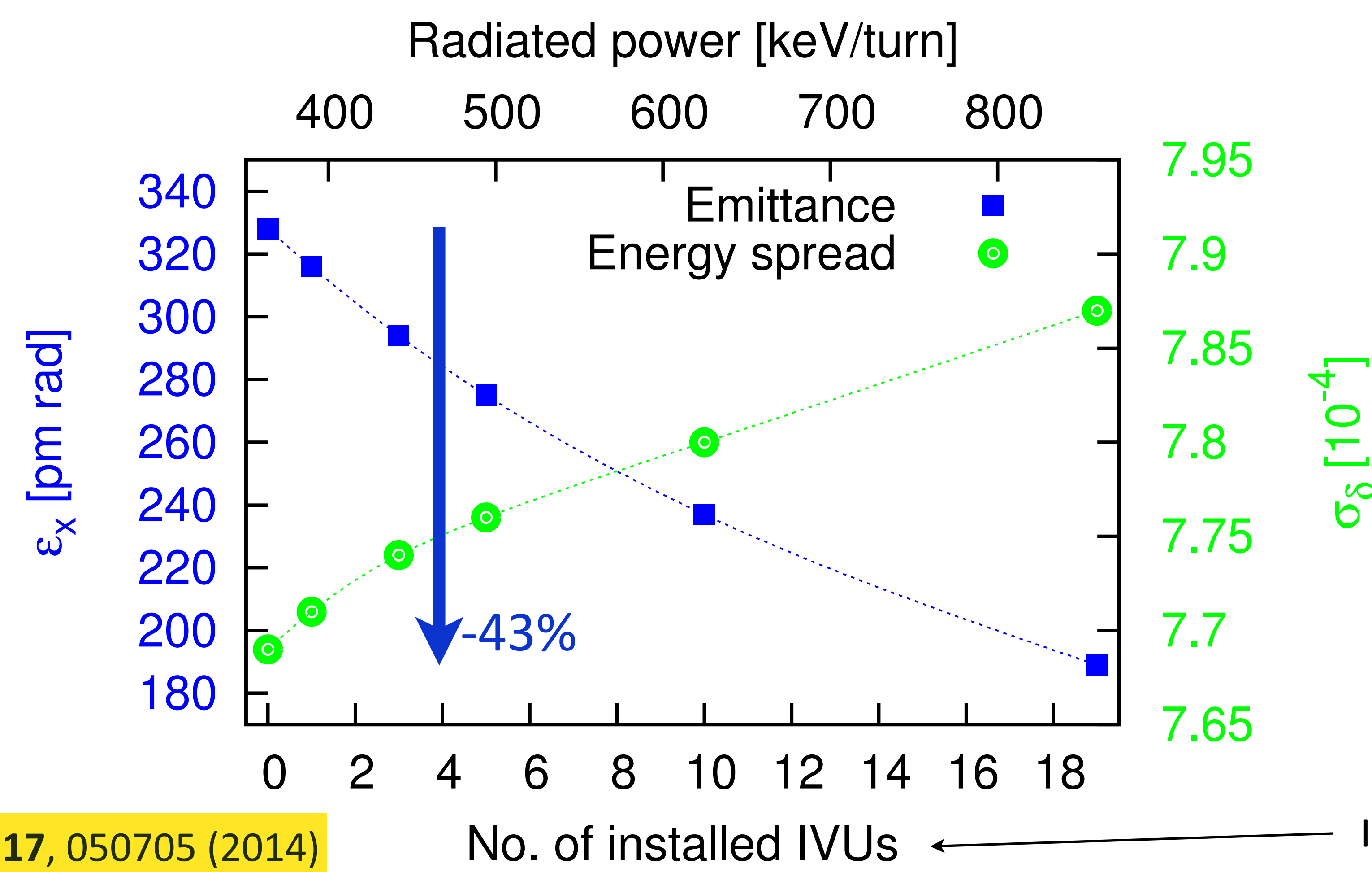

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PRST-AB **17**, 050705 (2014)

IVU: 3.7 m, λ_u = 18.5 mm, B_{eff} = 1.1 T

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➡ Emittance, energy spread, and radiated power are determined by installed IDs and gap settings

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What makes these rings so different? (cont.)

- Furthermore, strong intrabeam scattering (IBS) as a consequence of ultralow emittance <u>and</u> high bunch charge at medium energy (compounded by low coupling)

A. Piwinski, Proc. 9th HEAC, SLAC, 1974

J. Le Duff, CERN Yellow Report 1989-01

- IBS leads to emittance blowup in all three planes (→ variation of bunch length & Touschek lifetime)

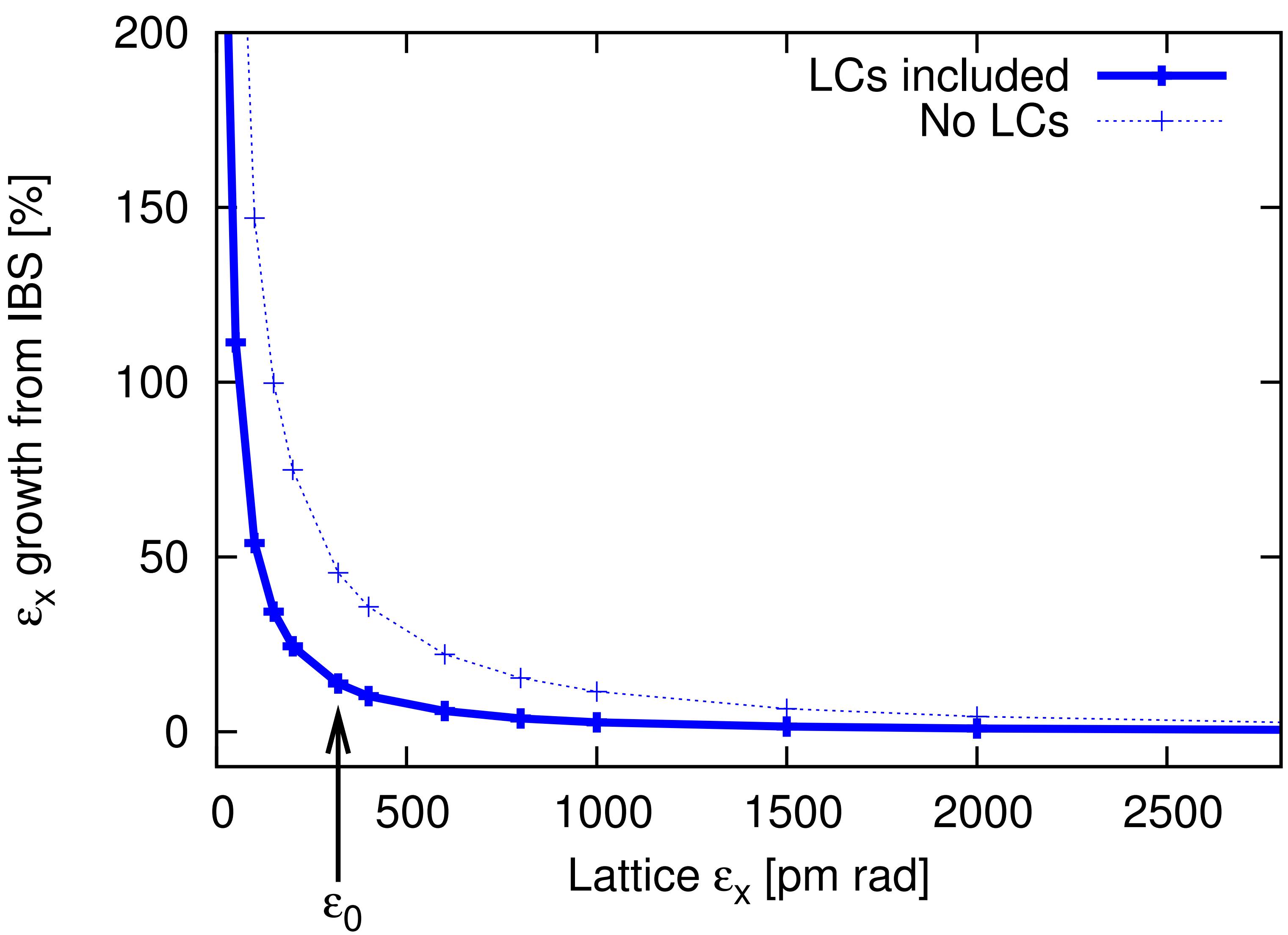
- Dependence of transverse emittance on stored current and bunch length (determined by varying radiated power & settings of main <u>and</u> harmonic cavities)

An Intricate Interplay

- ➡ In ultralow-emittance rings (at medium energy), transverse dynamics ("emittance") and longitudinal dynamics (cavities ➞ bunch length ➞ Touschek lifetime) closely linked through IBS
- ➡ As ID gaps change during user runs, all these parameters can vary (despite top-up)
- ➡ Self-consistent treatment required for proper modeling

Emittance & Intrabeam Scattering

How Serious is IBS Emittance Blowup?



I = 500 mA
δ_{RF} = 4.5%
$\sigma_\delta \approx$ const
ε_y = 8 pm rad

For MAX IV 3 GeV SR (bare lattice):

- IBS blows up emittance by 45%
- LCs ($\sigma_s \rightarrow \approx 5\sigma_s$) can reduce to 13%

PRST-AB **17**, 050705 (2014)

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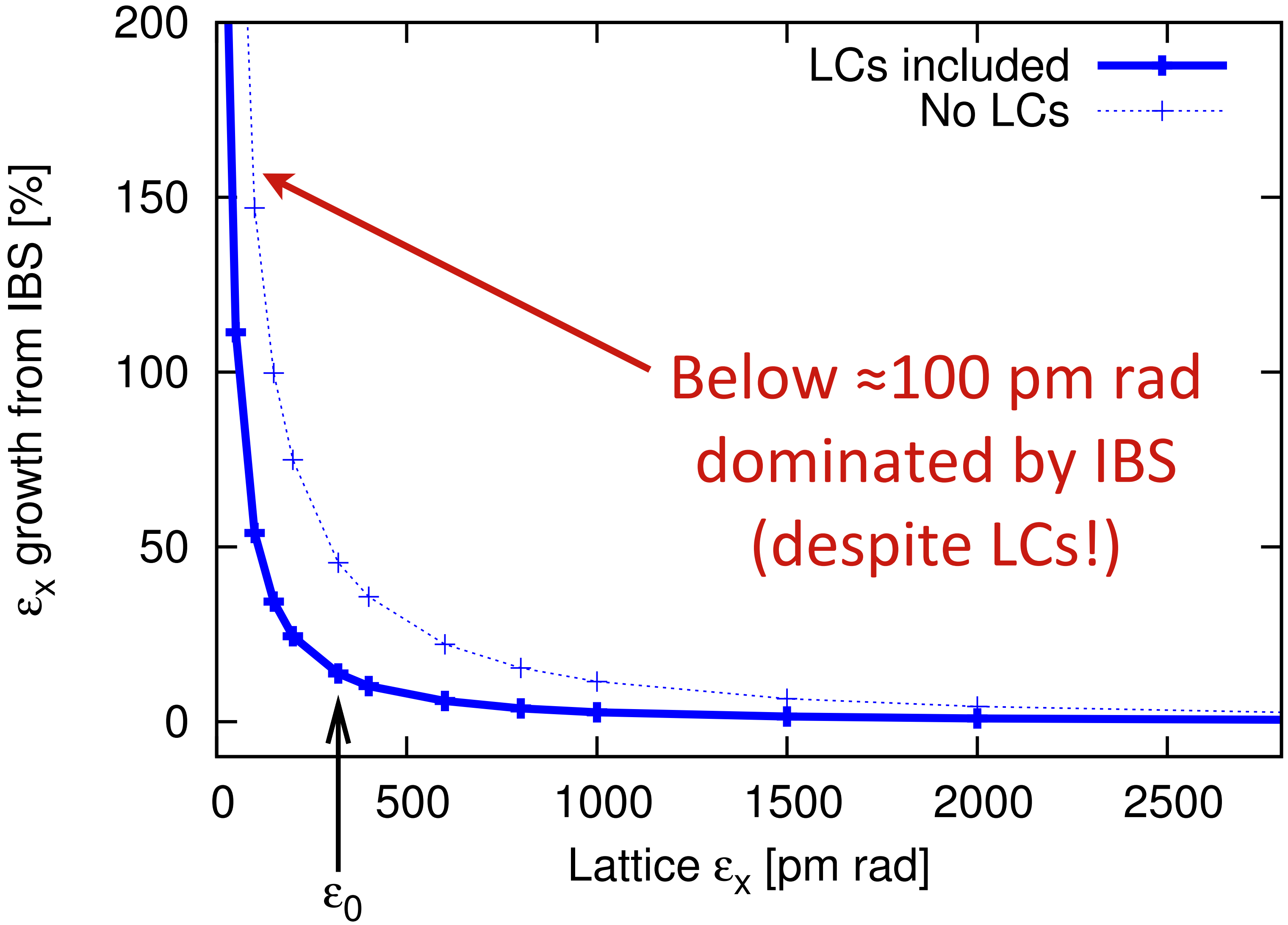

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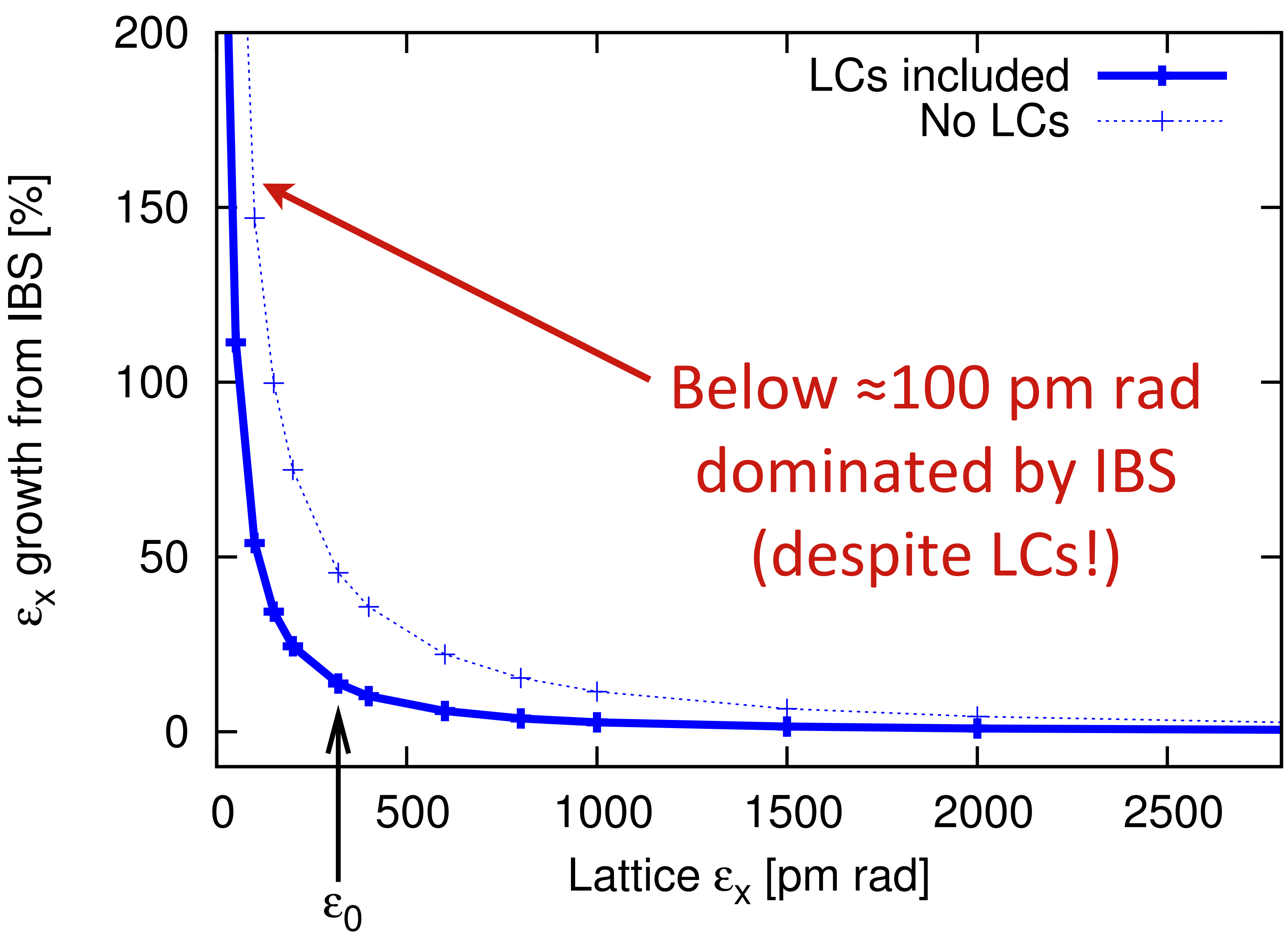

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PRST-AB **17**, 050705 (2014)

- Since emittance, energy spread, and bunch length depend so strongly on IDs and gap settings → in principle, need to calculate IBS for each storage ring configuration

Calculating Emittance with IBS

- Self-consistent approach with Tracy-3: PRST-AB **17**, 050705 (2014)
  - rad. integrals ➞ zero-current bare lattice parameters ε_0, σ_δ, U_0
  - in addition, specify:
    - number/type of IDs installed and specific gap settings ➞ ε_0, σ_δ, U_0
    - RF cavities at certain voltage <u>and</u> setting of harmonic LCs ➞ δ_{RF}, σ_s
    - choice of emittance coupling (from errors and/or set via skew quads) ➞ ε_x, ε_y
    - single-bunch charge (MAX IV: 500 mA ➞ 5 nC per bunch)
  - calculate IBS growth rates and updated emittances in all three planes (following Bjorken-Mtingwa / Conte-Martini / MAD-X)

    Part. Accel. **13**, 115 (1983)
    Part. Accel. **17**, 1 (1985)
    CERN-AB-2006-002
  - Iterate until equilibrium reached in all 3 planes

    `void IBS_BM(Qb,eps[])`
    J. Bengtsson, V. Litvinenko (BNL)

➡ New equilibrium emittances, bunch length, and energy spread

Calculating Emittance with IBS (cont.)

- A few examples:

		Zero-current	IBS	IBS & LCs
	ε_y	ε_x	ε_x	ε_x
Bare	8	320	466	364
	2	326	552	404
4 DWs / 10 IVUs	8	226	354	264
	2	232	436	302
Loaded	8	179	292	213
	2	185	365	247

PRST-AB **17**, 050705 (2014)

MAX IV 3 GeV SR

I = 500 mA
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Two coupling settings:
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PAC'**13**, MOPHO05

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+63%
(+97%)

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(+34%)

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PAC'**13**, MOPHO05

- LCs stretch bunches by up to factor ≈5 ➙ strong charge density dilution ➙ reduce impact of IBS

IPAC'**11**, MOPC051

PRST-AB **17**, 064401 (2014)

- LCs employed in many SRs for stability & lifetime, but at MAX IV will become indispensable to preserve ultralow emittance during high-current top-up operation

PRST-AB **4**, 030701 (2001)

Handling Emittance Variations

- So considering emittance variations during user runs...
  ...do we need DWs to counteract effect of varying ID gaps?
  - gap motion usually uncorrelated between different beamlines
  - gaps not routinely ramped over large ranges
  - ➡ Probably not necessary

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- However, could contemplate starting up with DWs in unoccupied straights to achieve lowest emittance; remove when user ID installed
  - Expensive! Cost of DWs & running cost (power bill)
  - Also, need to take care not to blow up electron beam's energy spread as this can spoil spectral flux/brightness

Momentum Acceptance & Touschek Lifetime

Touschek Lifetime at Ultralow Emittance

- Despite ultralow emittance, can achieve good Touschek lifetime <u>if</u> MA is sufficiently large

PRL **10**, 407 (1963)

(low emittance ➝ small transverse momenta ➝ few events lead to actual Touschek <u>loss</u>, most lead to emittance blowup)

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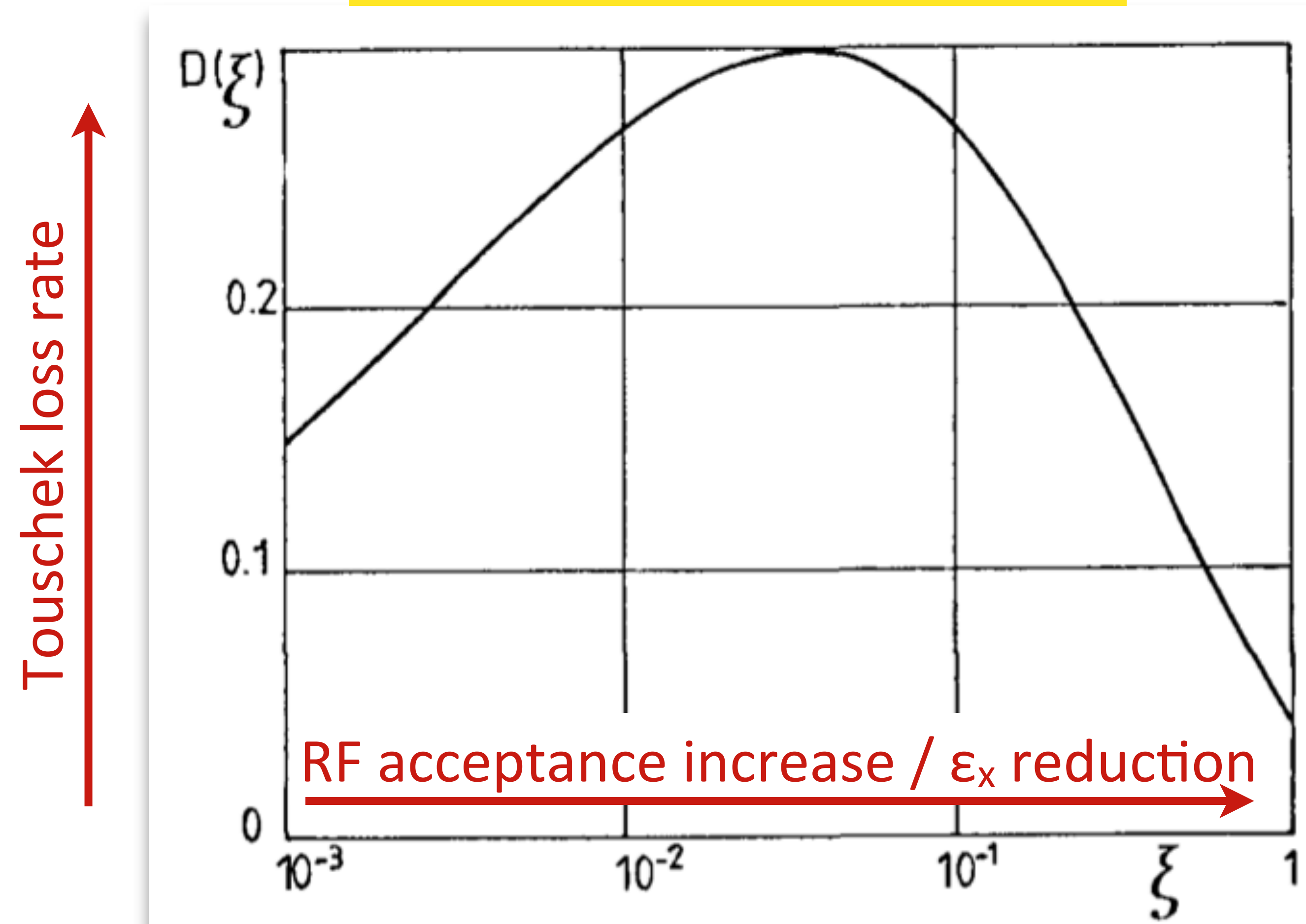

Fig. 3 Plot of D(ξ)

$$\xi = \left(\frac{\delta_{\mathrm{RF}}}{\gamma \sigma_{p_x}} \right)^2$$

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NSLS-II

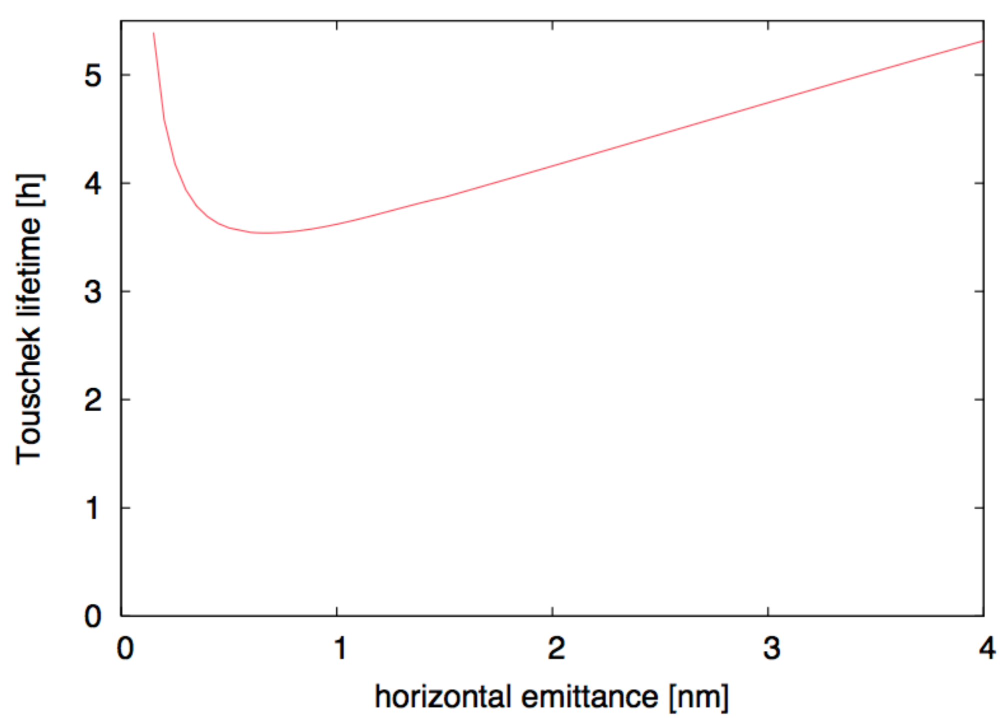

Figure 1: Touschek lifetime in NSLS-II as a function of horizontal emittance.

PAC'**07**, FRPMS113

MAX IV

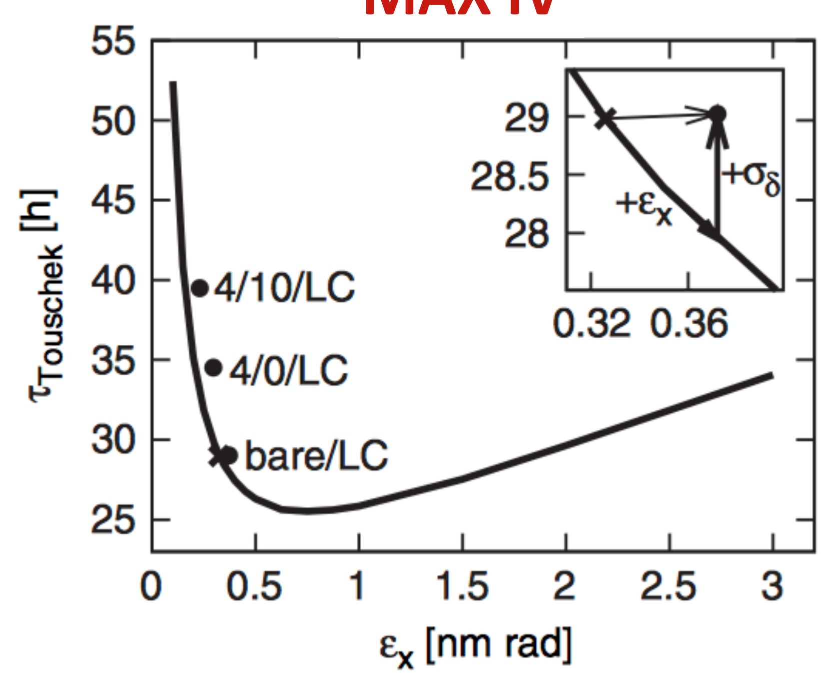

FIG. 15. The trend line shows Touschek lifetime for the bare lattice (IBS neglected) if it were possible to vary the lattice emittance while keeping the energy spread constant. Specific configurations (bare lattice, four PMDWs, and four PMDWs plus ten IVUs; all including LCs) are indicated by crosses and dots. Crosses indicate IBS neglected, dots indicate IBS included. The enlarged segment illustrates the effect of IBS for the bare lattice configuration: while the IBS emittance growth ($+\varepsilon_x$) leads to a decrease of Touschek lifetime, the IBS energy spread growth ($+\sigma_\delta$) leads to an increase of Touschek lifetime.

PRST-AB **12**, 120701 (2009)

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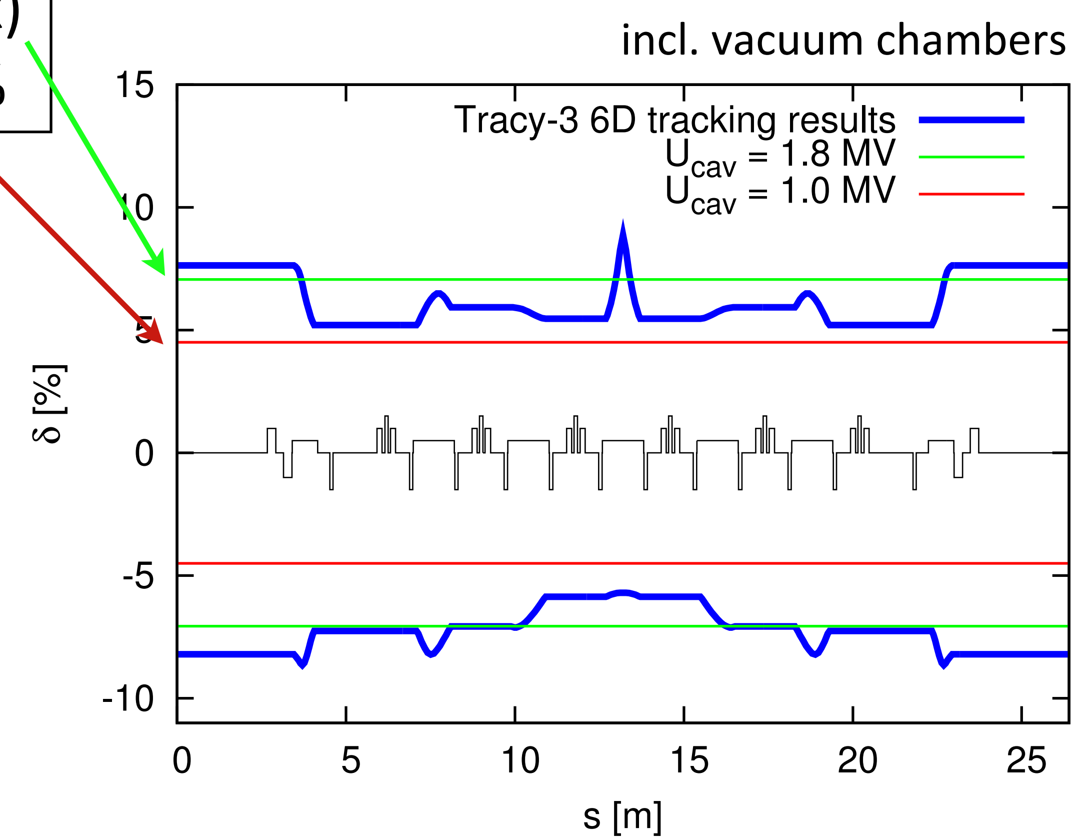
PRST-AB **17**, 050705 (2014)

MAX IV 3 GeV SR
U_{cav} = 1.8 MV (max)
Target: $\delta_{acc} > 4.5\%$



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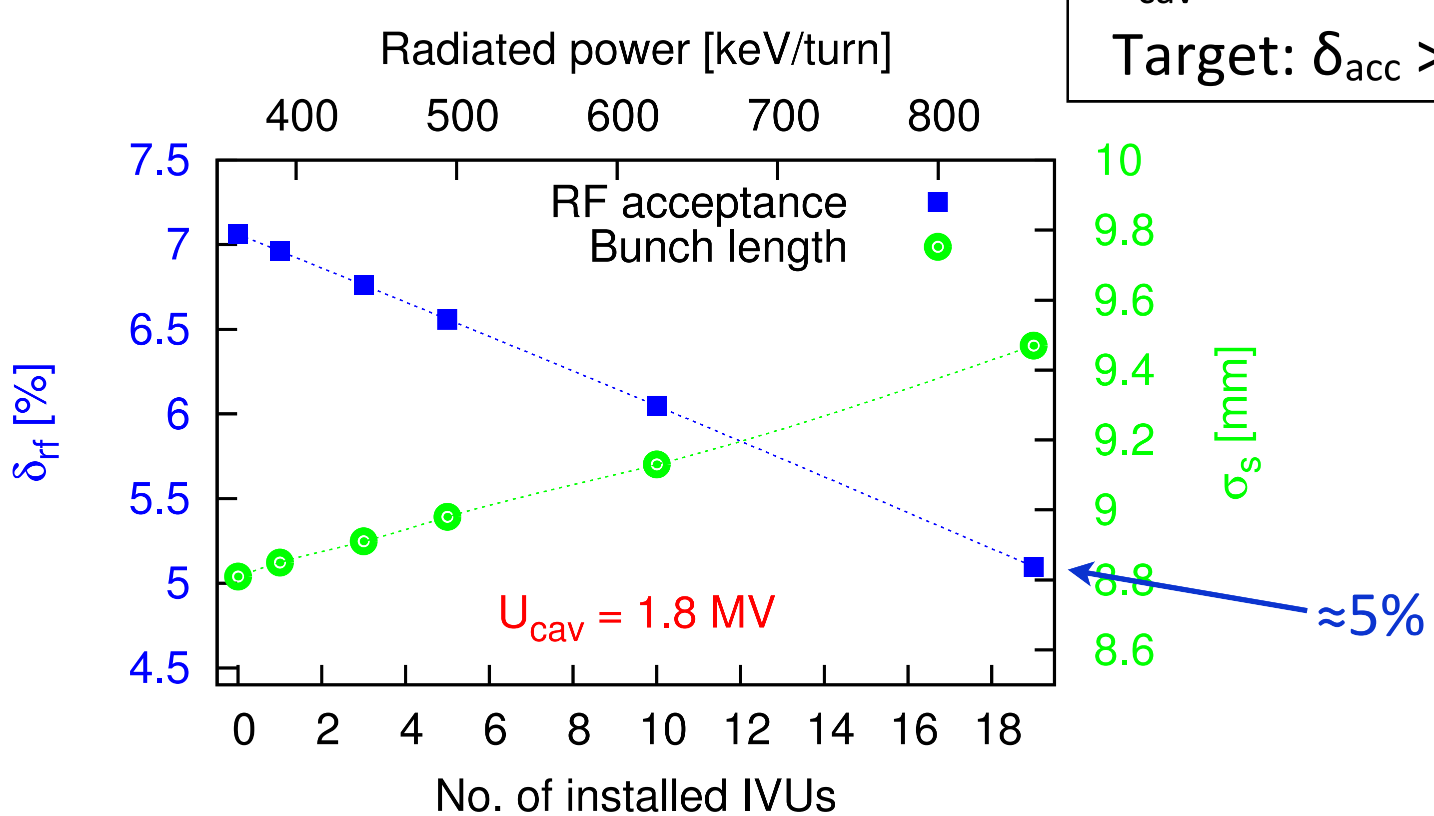

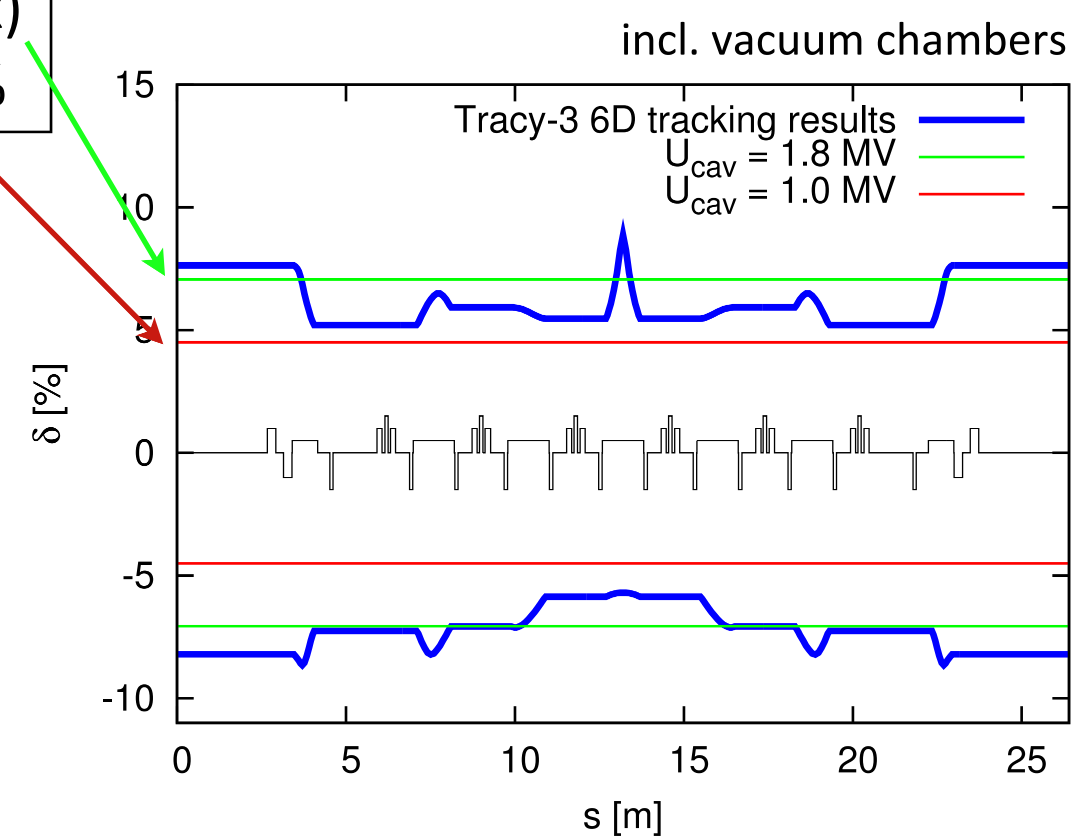

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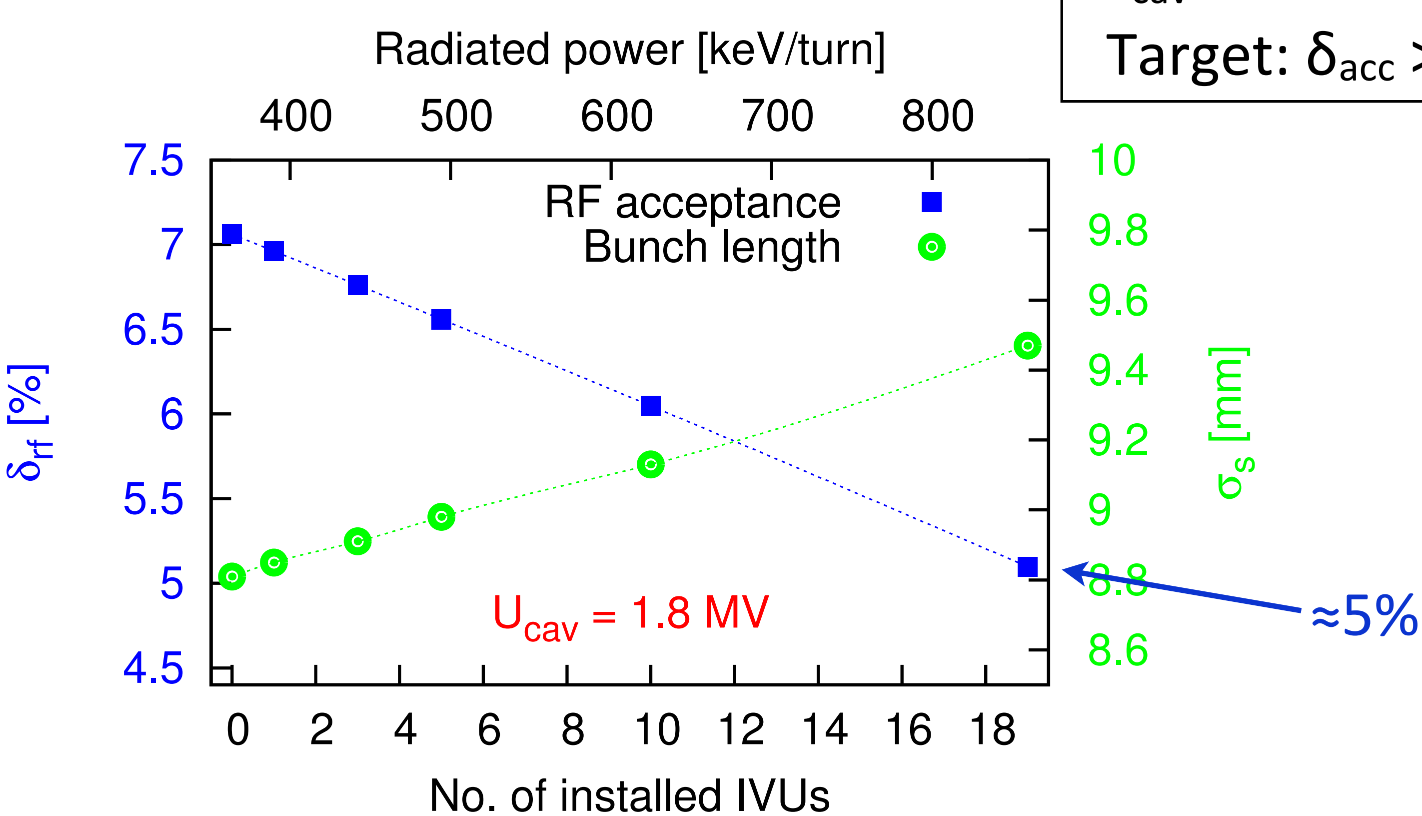
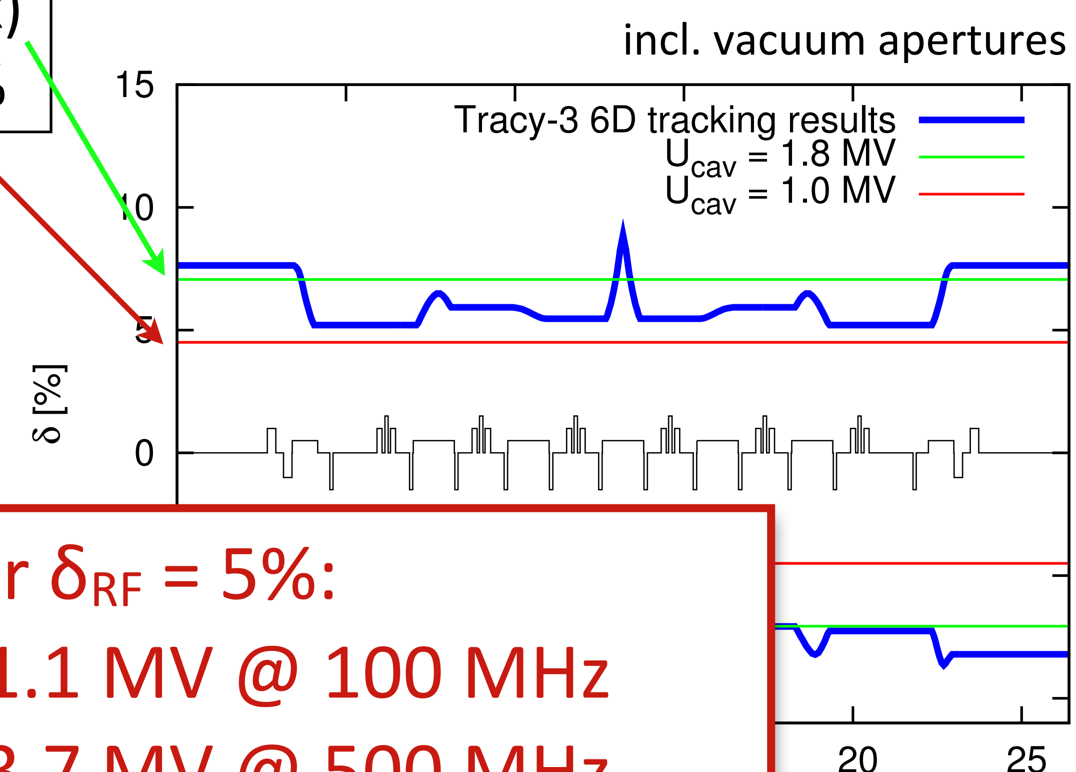


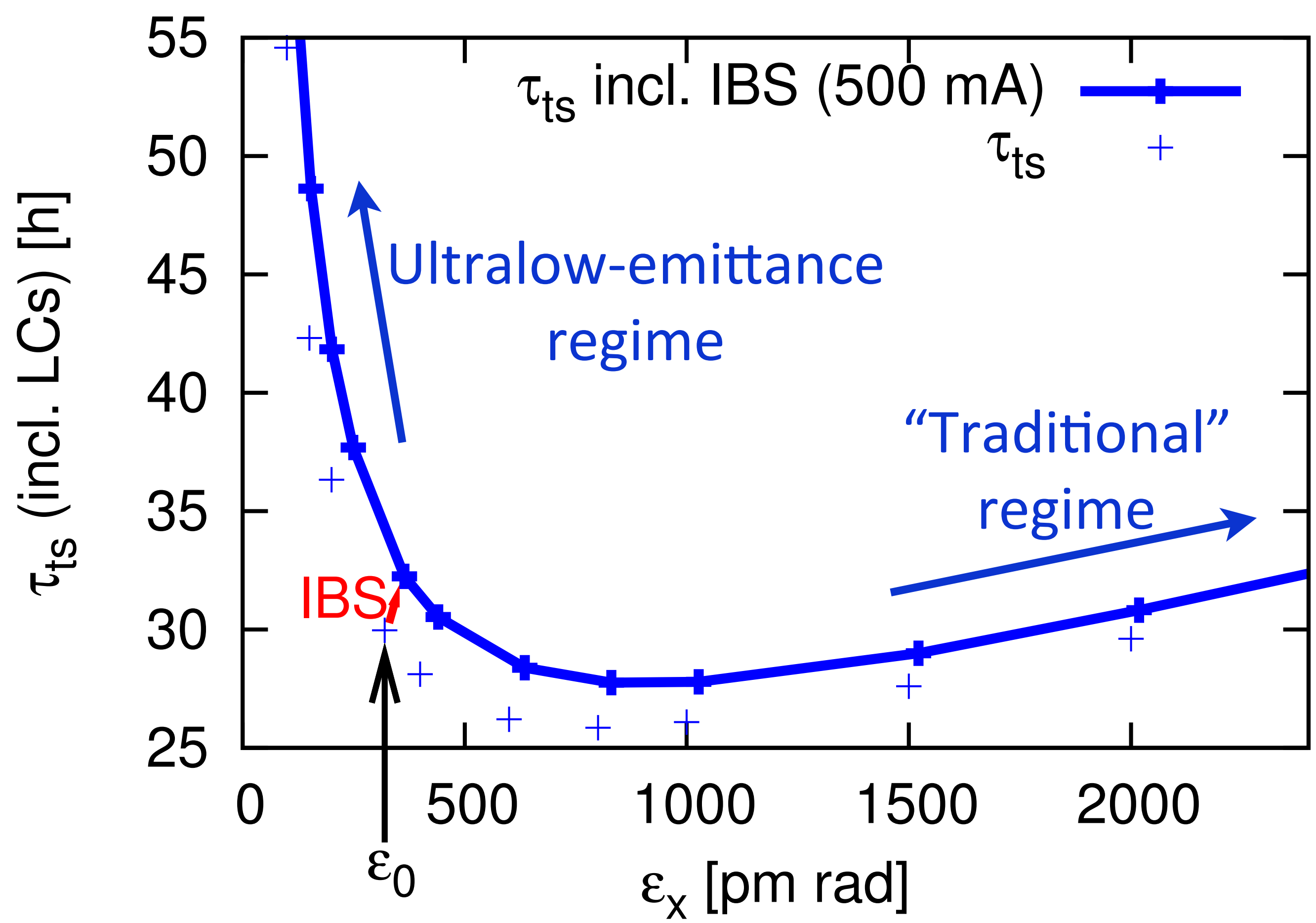


For δ_{RF} = 5%:
- 1.1 MV @ 100 MHz
- 3.7 MV @ 500 MHz

➝ Cu losses ➝ power bill

Touschek Lifetime Results

- Touschek lifetime reveals two distinctly different regimes



I = 500 mA
δ_{acc} = 4.5%
σ_δ = const
ε_y = 8 pm rad

PRST-AB **17**, 050705 (2014)

➡ So should we install DWs and/or as many IDs as possible to get lowest emittance *and* best lifetime?

Touschek Lifetime Results (cont.)

- 6D tracking results (self-consistent including IBS & vacuum apertures) for various configurations (max. RF voltage applied in each case)

PRST-AB **17**, 050705 (2014)

	ε_y [pm rad]	500 mA no LCs	500 mA incl. LCs	Incl. errors & narrow gaps[1]
Bare	8	17.4	87.1	64.3
	2	9.6	45.9	40.7
4 DWs / 10 IVUs	8	20.5	114.3	66.2
	2	10.4	56.1	48.7
Loaded	8	11.7	65.0	37.7
	2	5.8	31.4	27.3

[1] Narrow gaps have not been included in the bare lattice case.

MAX IV 3 GeV SR

I = 500 mA

U_{cav} = 1.8 MV

Two coupling settings:

ε_y = 2 vs. 8 pm rad

PAC'**13**, MOPHO05

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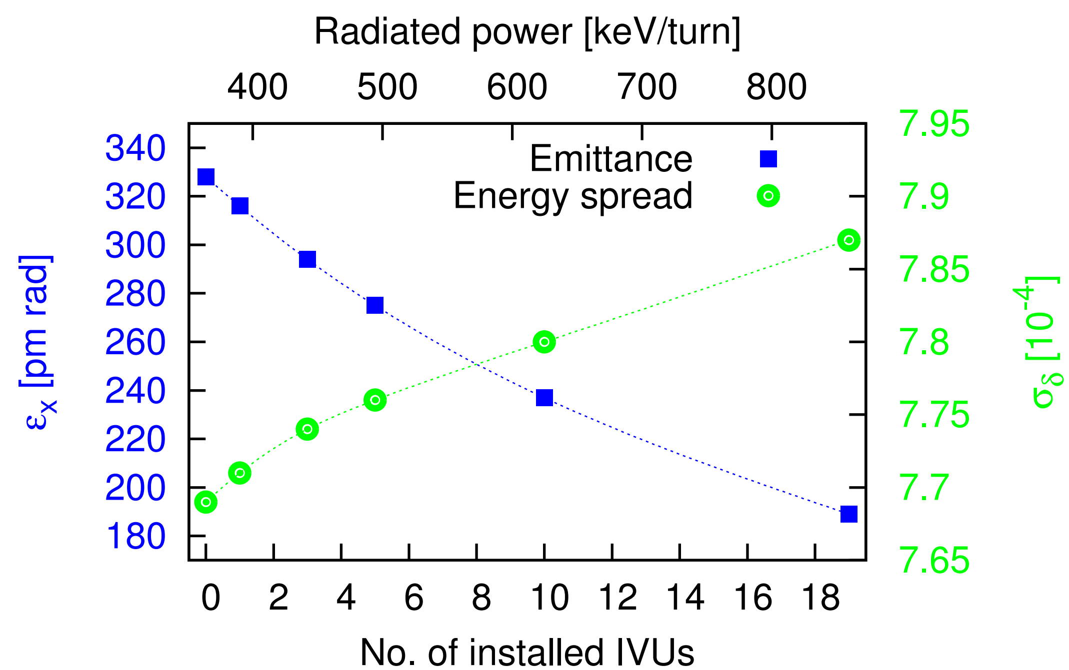
PAC'**13**, MOPHO05

As radiated power increases → two/three competing effects

- Emittance reduces → lifetime increase
- RF acceptance reduces → lifetime reduction
- Overvoltage reduces → bunches stretched → minor lifetime increase (small effect)



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Bare	δ_{RF} = 7.1%	8	17.4	87.1	64.3
		2	9.6	45.9	40.7
4 DWs / 10 IVUs	δ_{RF} = 6.1%	8	20.5	114.3	66.2
		2	10.4	56.1	48.7
Loaded	δ_{RF} = 5.1%	8	11.7	65.0	37.7
		2	5.8	31.4	27.3

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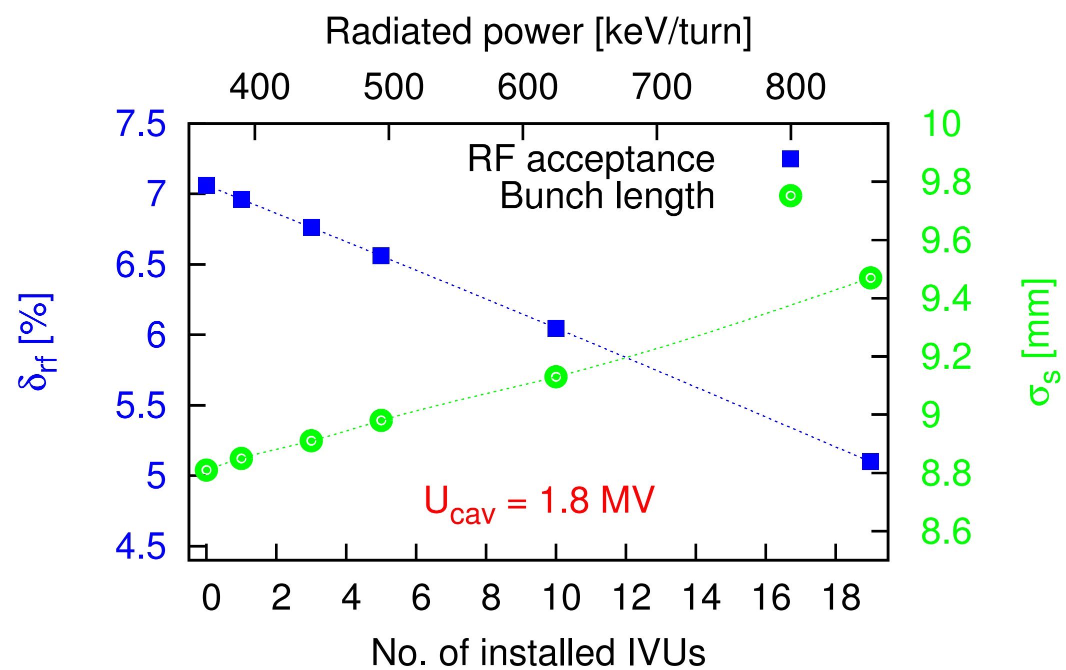

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+31% (+22%)

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-43%
(-44%)

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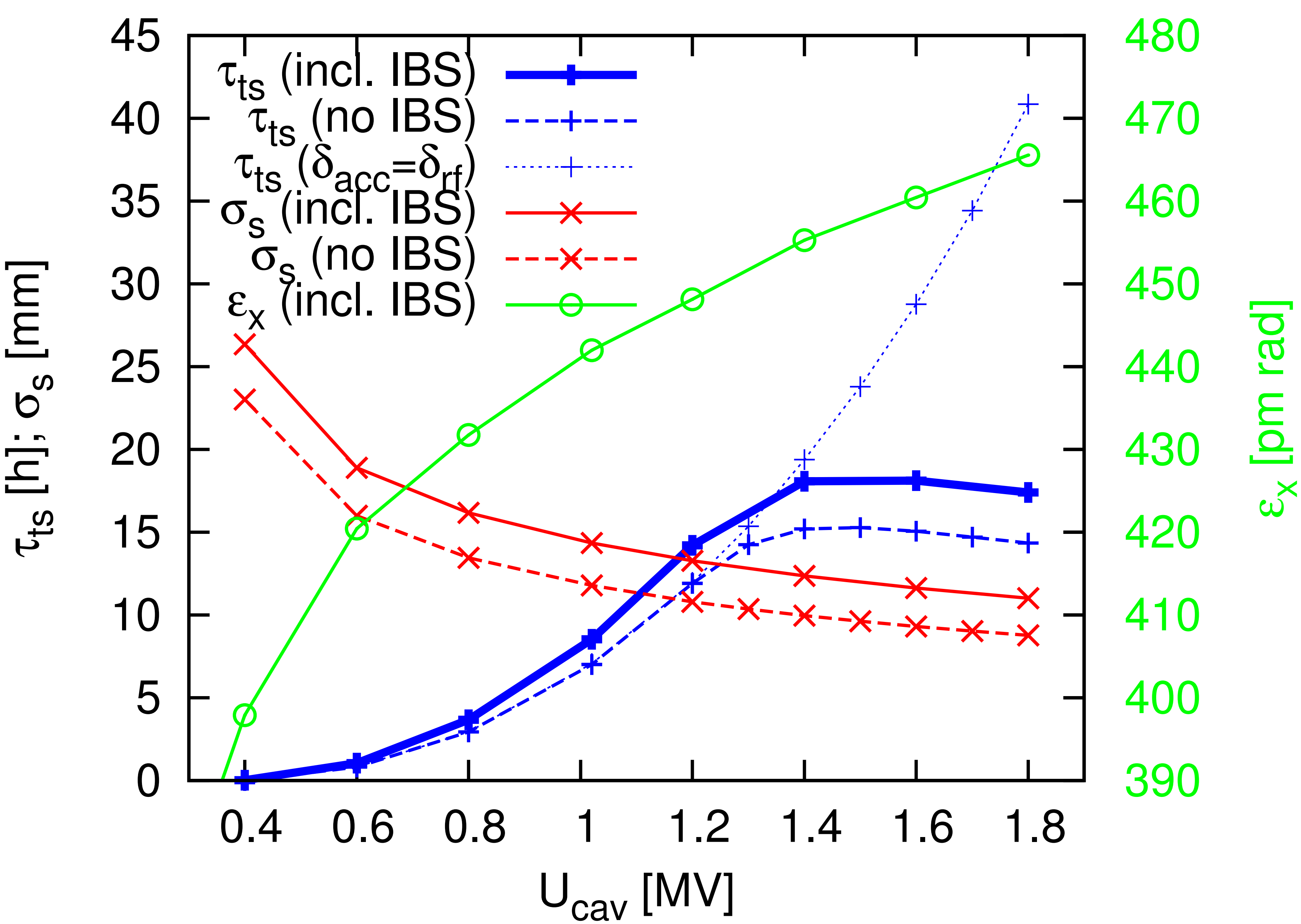
- RF acceptance reduces → lifetime reduction
- Overvoltage reduces → bunches stretched → minor lifetime increase (small effect)

➡ So, while adding many DWs and IDs will reduce emittance, this does not necessarily maximize lifetime (for a given RF system)

RF Acceptance and Touschek lifetime

- Emittance & Touschek lifetime incl. IBS as functions of δ_{RF}



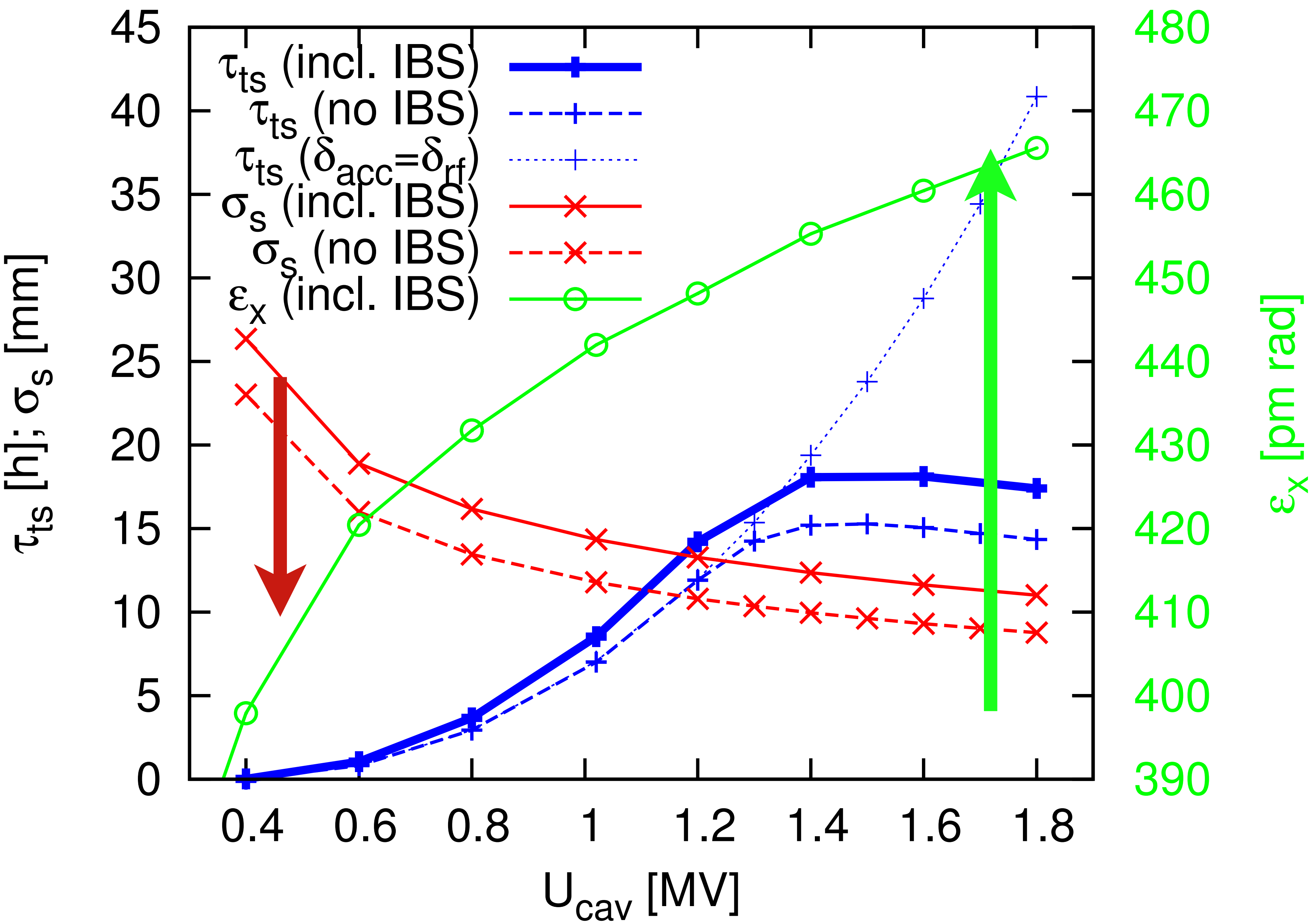
MAX IV 3 GeV SR
(bare lattice)

I = 500 mA
ε_y = 8 pm rad
LCs not included

PRST-AB **17**, 050705 (2014)

RF Acceptance and Touschek lifetime (cont.)

- Emittance & Touschek lifetime incl. IBS as functions of δ_{RF}



MAX IV 3 GeV SR
(bare lattice)

I = 500 mA
ε_y = 8 pm rad
LCs not included

$$\sigma_s = \sigma_\delta \sqrt{\frac{\alpha h c^2}{f_{\rm RF} \cos\phi_s} q^{-1}} \quad q = \frac{eU_{\rm cav}}{U_0}$$

As cavity voltage increases

⬇

σ_s decreases

⬇

Emittance increases (IBS)

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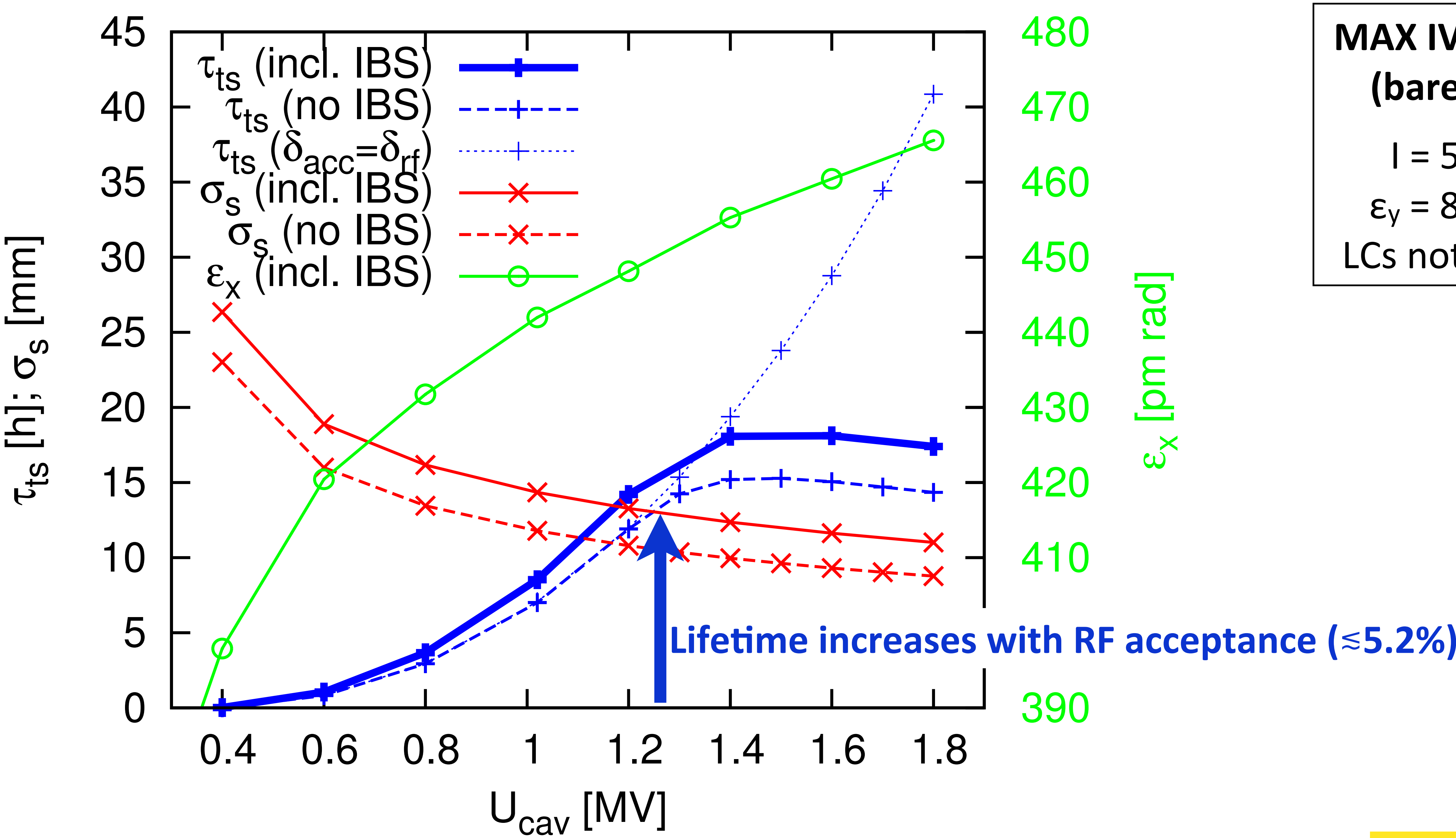
RF Acceptance and Touschek lifetime (cont.)

- Emittance & Touschek lifetime incl. IBS as functions of δ_{RF}



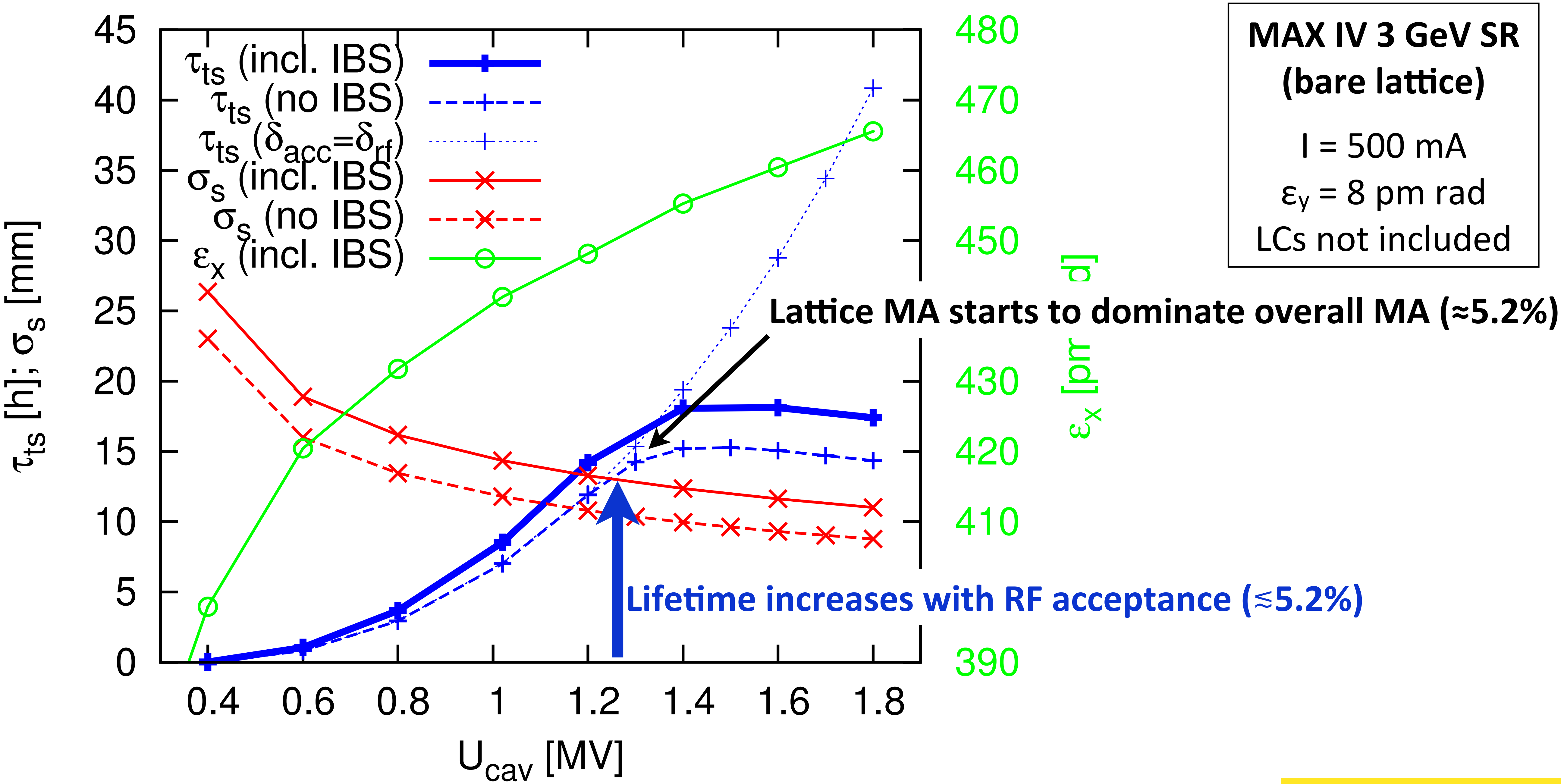
MAX IV 3 GeV SR
(bare lattice)

I = 500 mA
ε_y = 8 pm rad
LCs not included

PRST-AB **17**, 050705 (2014)

RF Acceptance and Touschek lifetime (cont.)

- Emittance & Touschek lifetime incl. IBS as functions of δ_{RF}



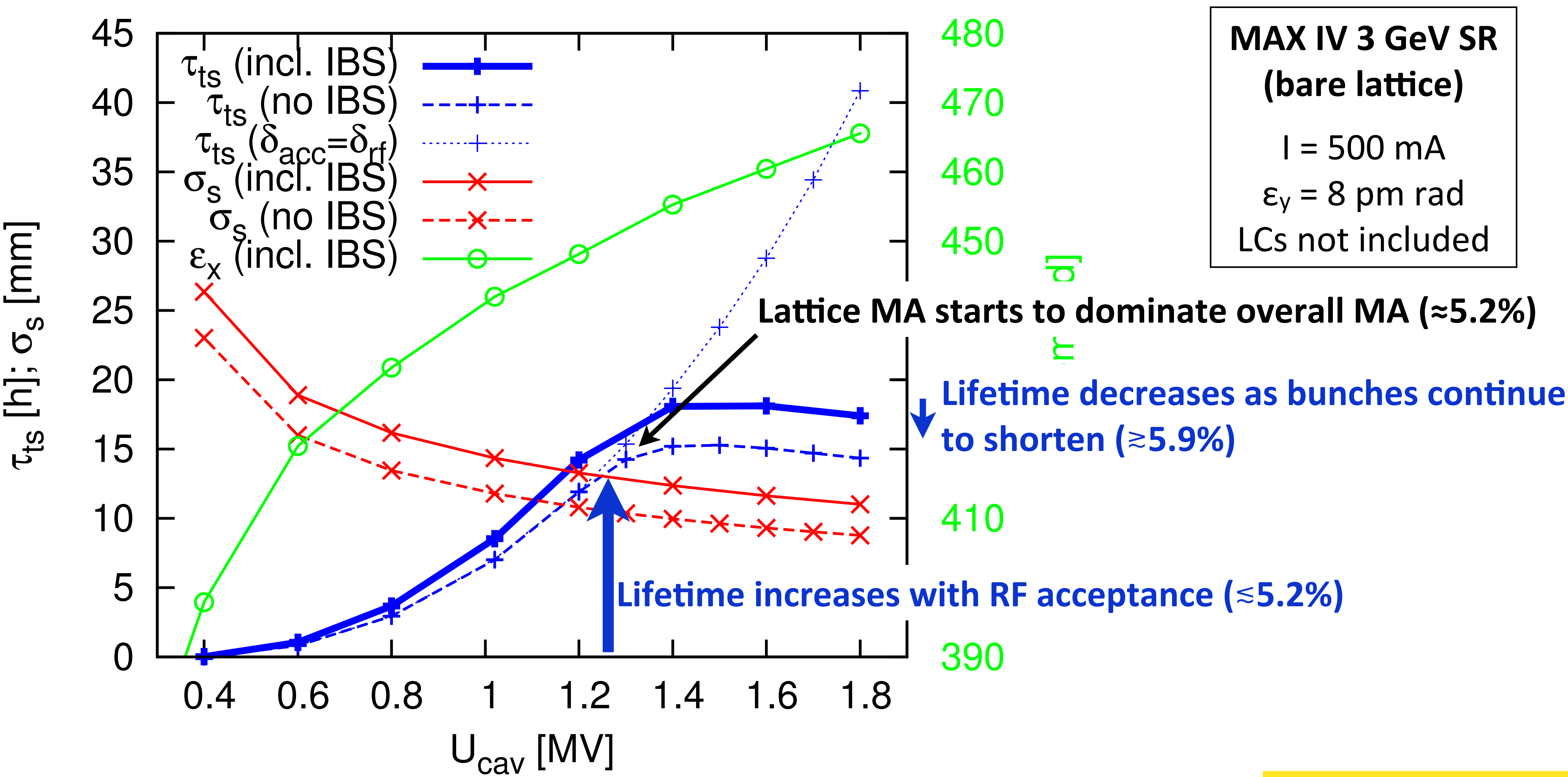
MAX IV 3 GeV SR (bare lattice)

I = 500 mA
ε_y = 8 pm rad
LCs not included

PRST-AB **17**, 050705 (2014)

RF Acceptance and Touschek lifetime (cont.)

- Emittance & Touschek lifetime incl. IBS as functions of δ_{RF}



PRST-AB **17**, 050705 (2014)

Overall Lifetime

- Touschek lifetime becomes so large, overall lifetime is no longer clearly Touschek-dominated

PRST-AB **17**, 050705 (2014)

	ε_y [pm rad]	500 mA no LCs	500 mA incl. LCs	Incl. errors & narrow gaps[1]
Bare	8	17.4	87.1	64.3
	2	9.6	45.9	40.7
4 DWs / 10 IVUs	8	20.5	114.3	66.2
	2	10.4	56.1	48.7
Loaded	8	11.7	65.0	37.7
	2	5.8	31.4	27.3

[1] Narrow gaps have not been included in the bare lattice case.

MAX IV 3 GeV SR

I = 500 mA

U_{cav} = 1.8 MV

Two coupling settings:

ε_y = 2 vs. 8 pm rad

PAC'**13**, MOPHO05

Worst-case scenario: τ_{ts} = 27.3 ± 2.1 hrs (20 seeds)

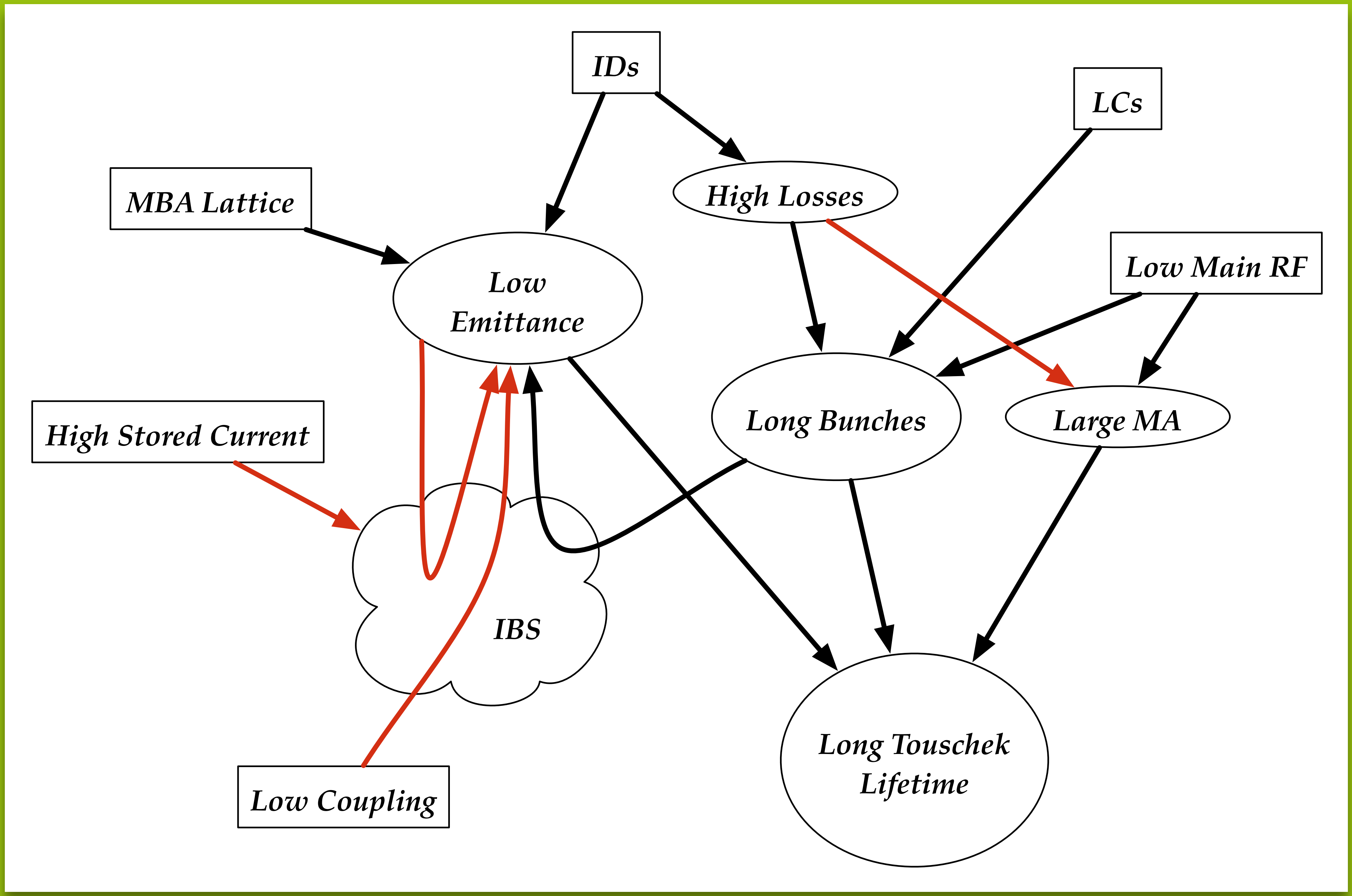
τ_{ts} = 27 hrs

τ_{el} = 25 hrs (2 pbar CO, incl. narrow gaps)

τ_{bs} = 56 hrs (weak dependence on MA, assumed 4.5%)

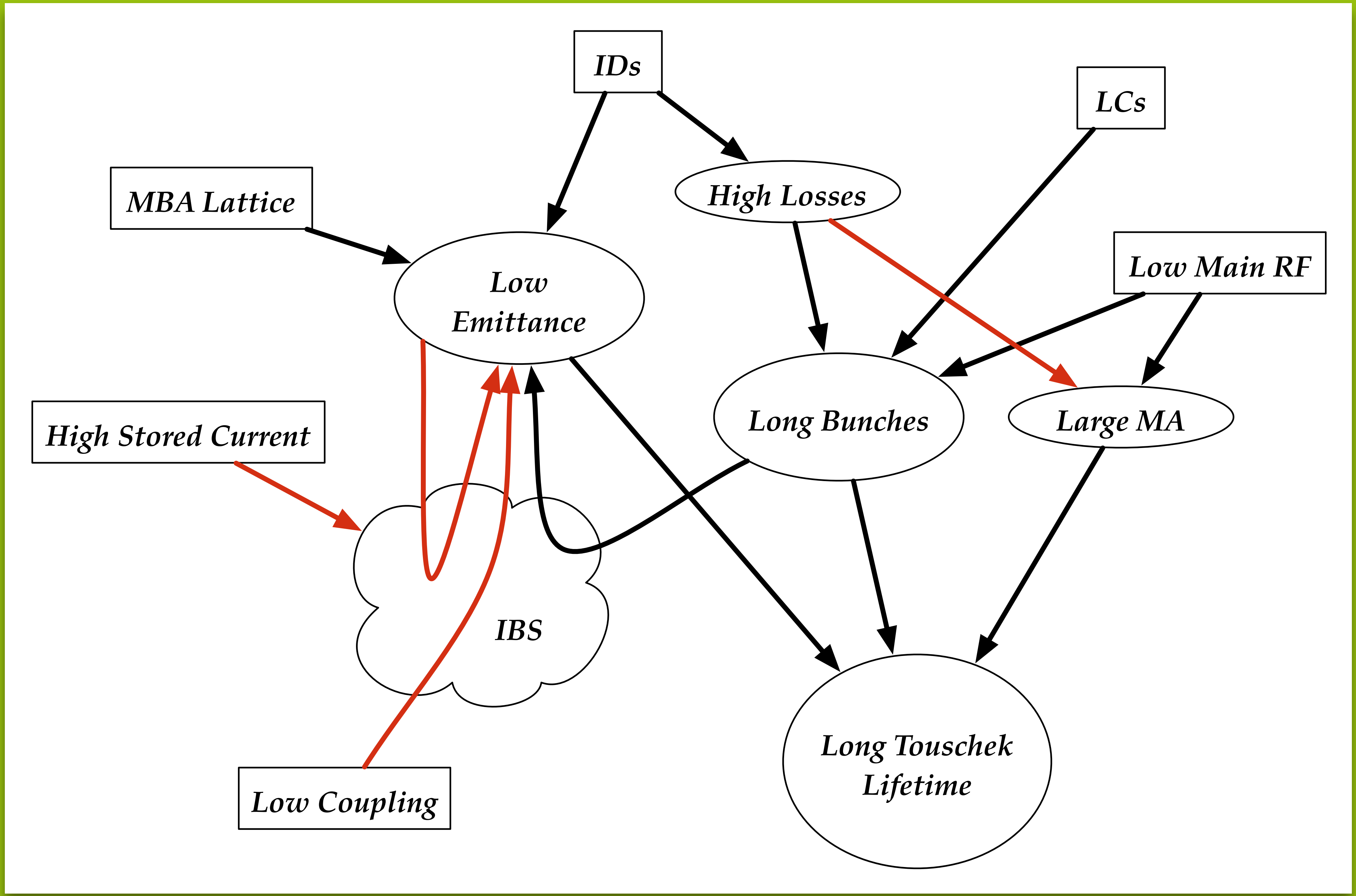
→ τ > 10 hrs (top-up shot required every few minutes @ 0.5% deadband)

Summary



- IBS (itself influenced by several factors) determines resulting emittance
- Emittance (as a result of IBS, but also ID & RF settings) determines resulting Touschek lifetime

Summary (cont.)



- LCs allow storing high current & mitigate ε blowup from IBS

➡ If overall system designed well, can achieve excellent lifetime despite ultralow ε

A Few Final Thoughts

- Operating DLSRs with round beams will reduce impact of IBS
- Further increase bunch length ➙ even lower RF?
- If short bunches are required ➙ reduce stored current?
- Reduce bunch charge? ➙ resulting spectral brightness & coherence at sample not necessarily maximized by storing largest possible amount of charge

Thank you for your attention!