Beams Stability at Fermilab Complex

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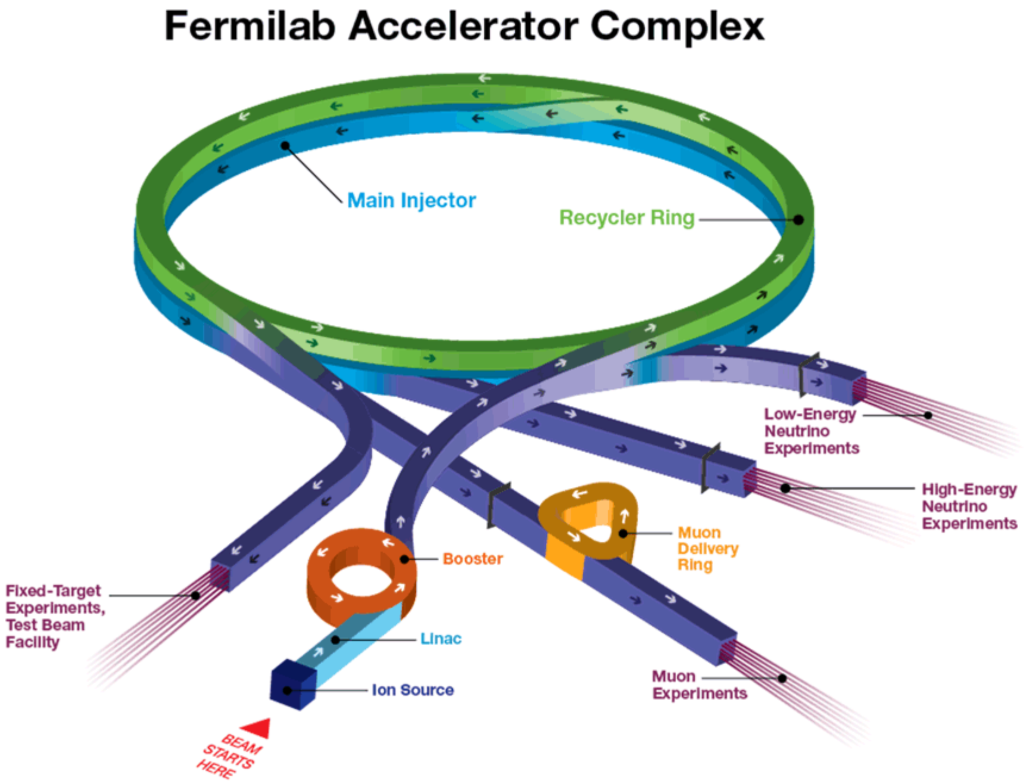
Fermilab

Many thanks to
R. Ainsworth, Y. Alexahin, C. Bhat, V. Lebedev, A. Macridin, E. Metral, K. Seiya, C.Y. Tan, T. Zolkin

MW Rings, Fermilab, May 2018

Accelerator complex

- H^- linac
- Booster
  - h = 84
  - 15 Hz
  - 400 MeV -> 8 GeV
- Recycler
  - h = 588
  - Slip-stack 12 batches (double bunch intensity)
- Main Injector
  - 8 GeV -> 120 GeV



Power evolution

- PIP
  - 700 kW (~0.5 x 10^{11} ppb)
  - 15 Hz Booster
  - 80 kV RF for recycler
  - 1260 Hz separation for slip-stacking
- PIPII
  - 1.2 MW (~0.8 x 10^{11} ppb)
  - 20 Hz booster
  - 140 kV RF for recycler
  - 1680 Hz separation for slip-stacking
- PIPIII
  - 2.4 MW
  - No more slip-stacking, most likely replace booster with new RCS

Transverse Impedances

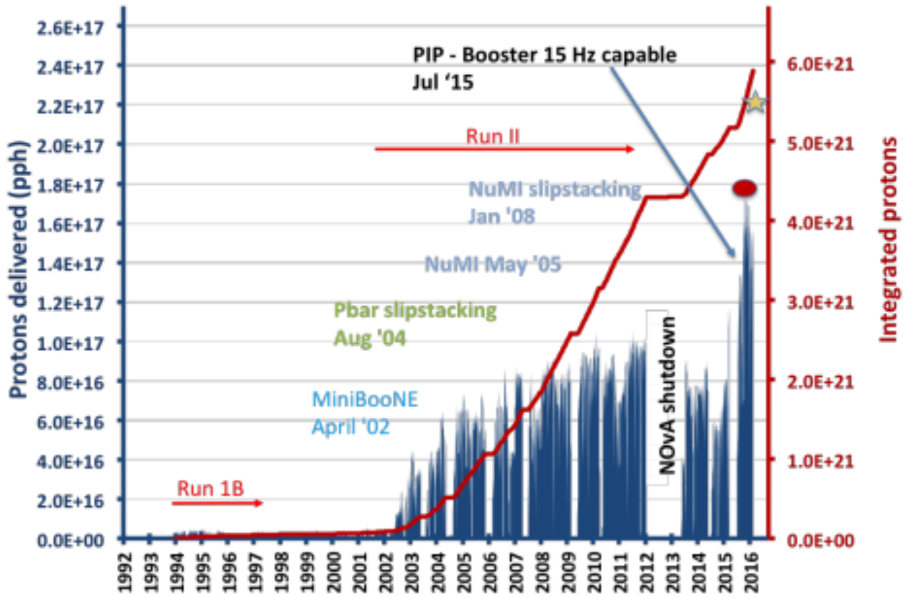


Figure 1: The proton flux per hour in Booster increased from $< 10^{16}$ to $> 10^{17}$ over a decade.

C. Bhat & C.Y. Tan, HB2016

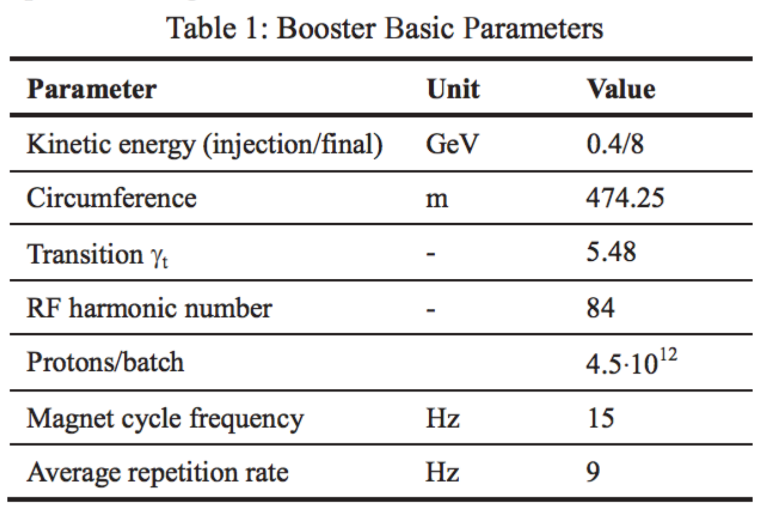


Table 1: Booster Basic Parameters

Parameter	Unit	Value
Kinetic energy (injection/final)	GeV	0.4/8
Circumference	m	474.25
Transition γ_t	-	5.48
RF harmonic number	-	84
Protons/batch		$4.5 \cdot 10^{12}$
Magnet cycle frequency	Hz	15
Average repetition rate	Hz	9

Proceedings of IPAC2012, New Orleans, Louisiana, USA WEPPR085

OBSERVATION OF INSTABILITIES OF COHERENT TRANSVERSE OSCILLATIONS IN THE FERMILAB BOOSTER*

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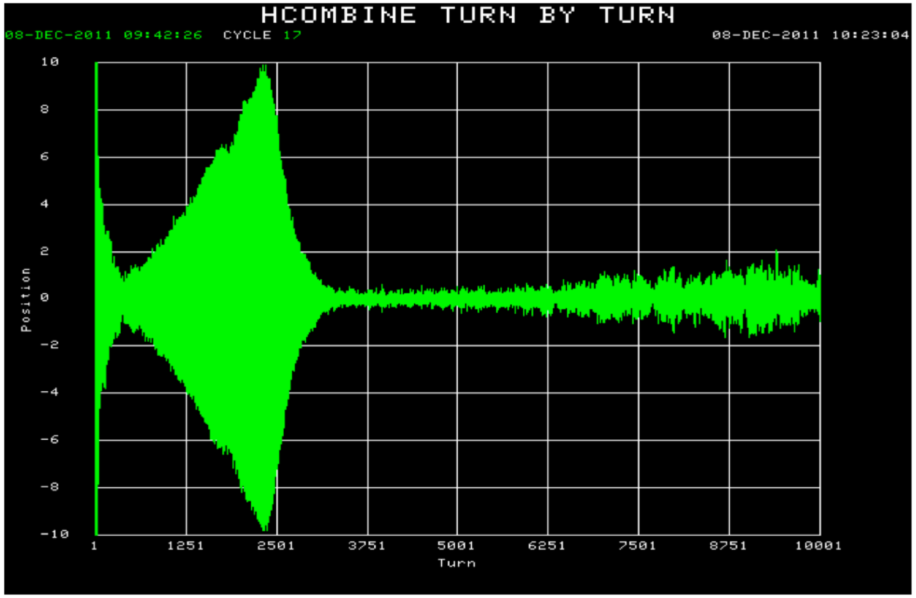
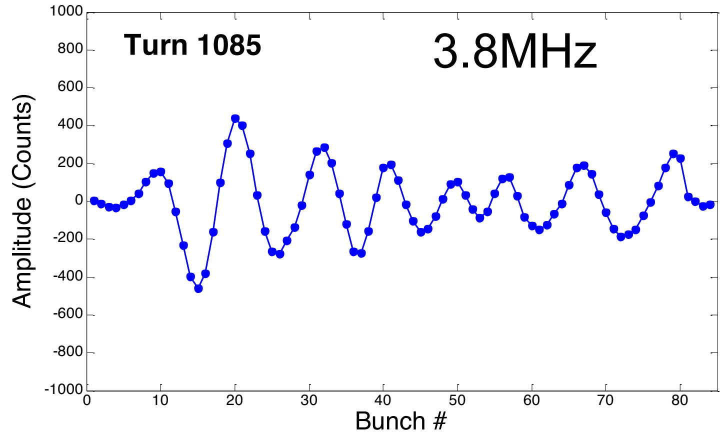
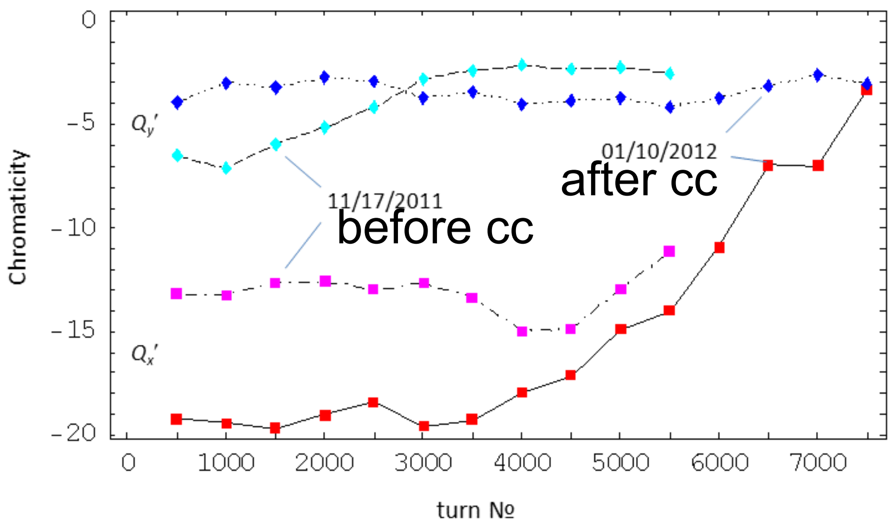


Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4\cdot 10^{12}$ after coupling correction.

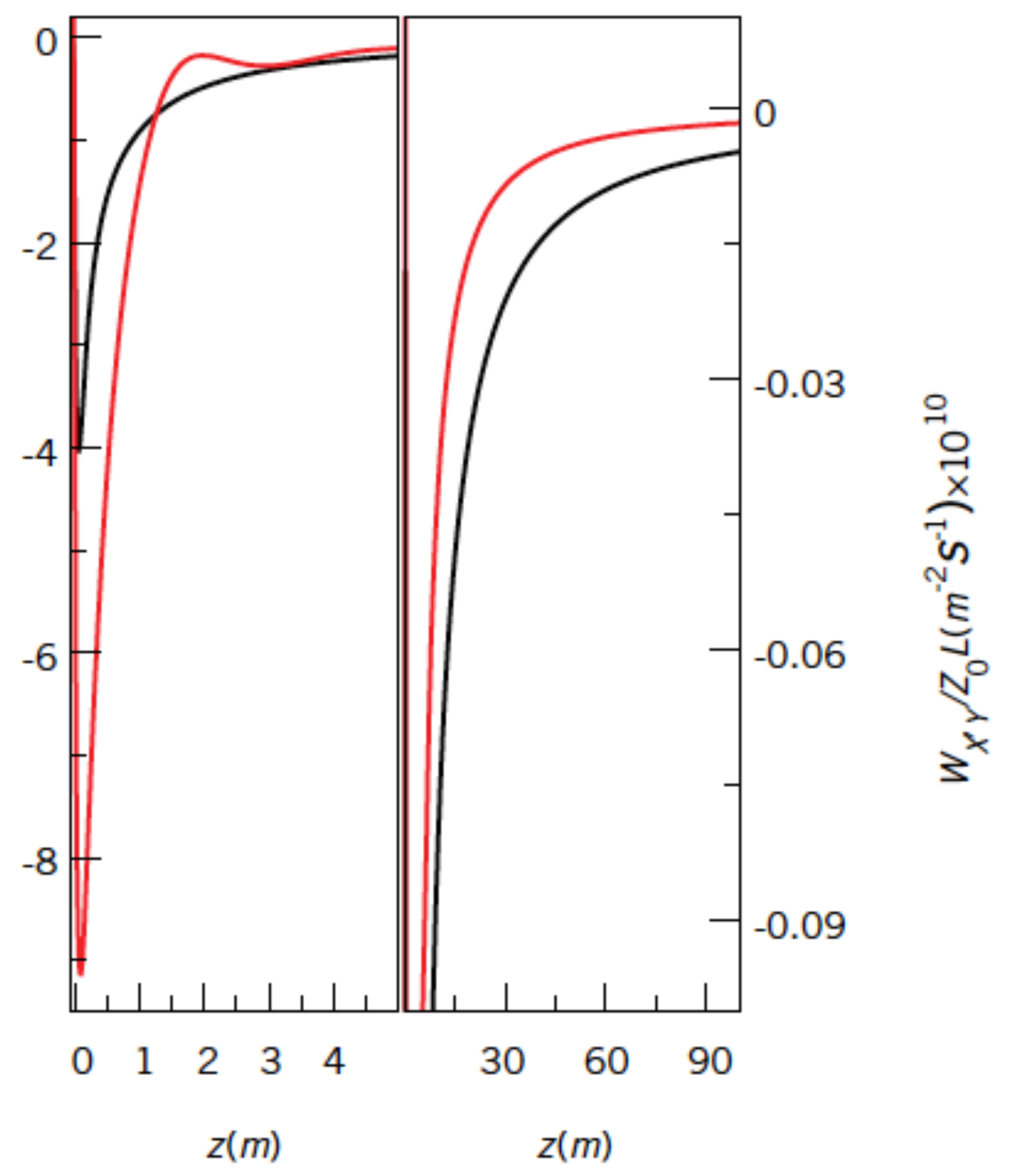


Horizontal Instability, damper off.

$$\text{growth rate} \approx 2\cdot 10^{-3}\omega_s$$



Transverse Wakes

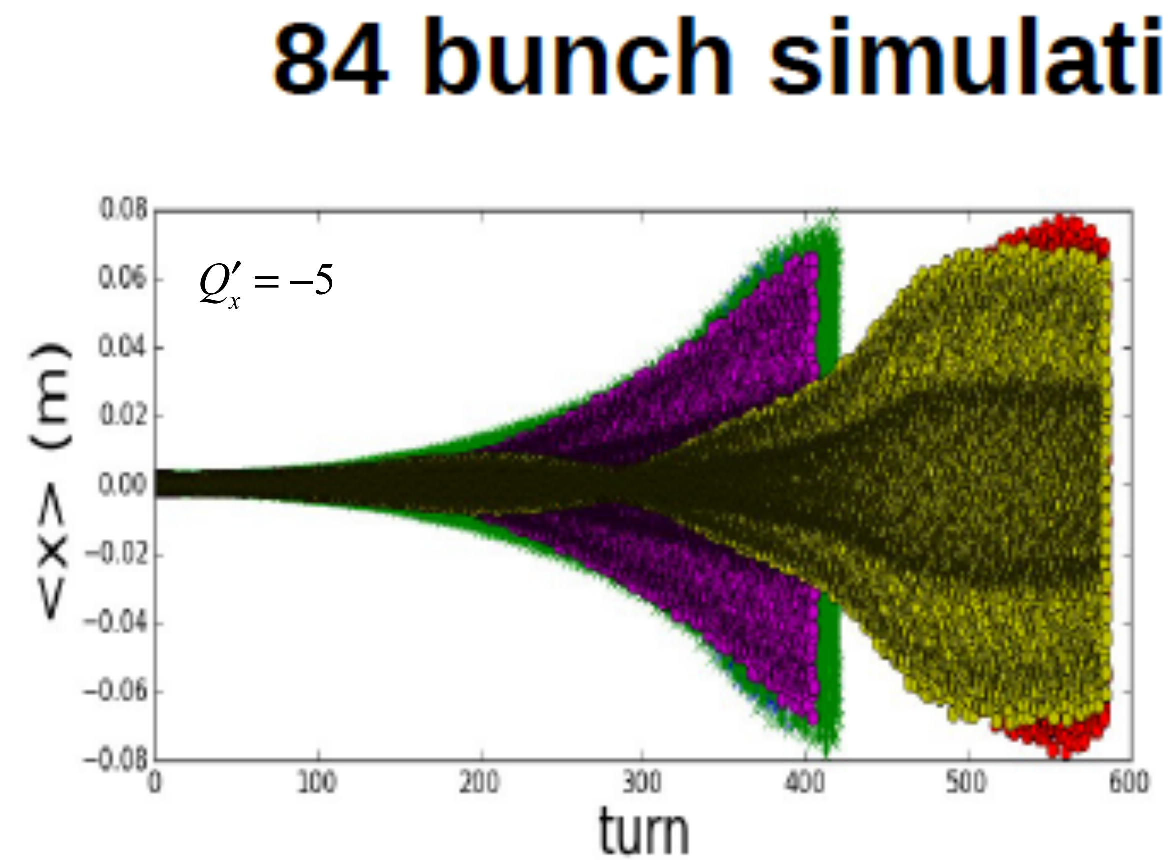


X and Y wakes are dominated by the laminated magnets

(Alex Macridin et al)

Synergia Simulations (A. Macridin et al)

With these wakes, A. Macridin et al. got very good agreement between the Synergia tracking and observations $Q'_x\big|_{\text{th}} \approx -19$ and the most unstable CB modes 1-10 (all very close):



Initial horizontal modes excited:
m=0 (red)
m=1 (blue)
m=4 (green)
m=8 (magenta)
m=12 (yellow)

Some qualitative explanations

1. At the threshold chroma, the head-tail phase is: $\chi_x \equiv \frac{Q'_x \sigma_s}{\eta R_0} \approx 0.25$

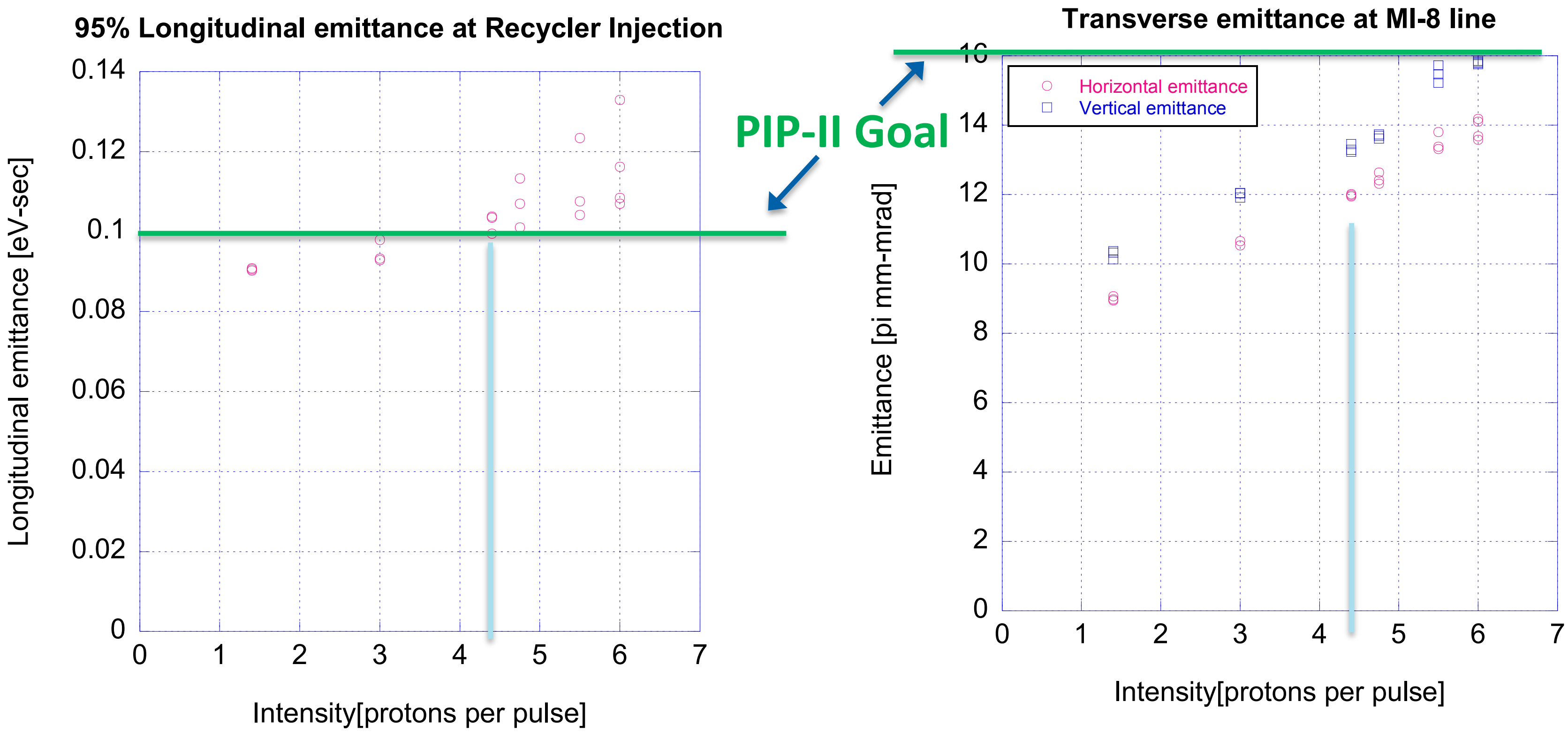
It's value is determined by relative values of the destabilizing long-range wake and the stabilizing short-range one, $\chi_{\mathrm{th}} \sim \frac{\mathrm{CBwake}}{\mathrm{SBwake}}$.

2. The coupling helps, allowing smaller $|Q'_x|_{\mathrm{th}}$. Why?
At the threshold, the vertical chroma is too small, so the *chroma sharing* (E. Metral) cannot be the answer. However, there is also the *wake sharing*,

$$\beta_x W_x \rightarrow \beta_{xn} W_x + \beta_{yn} W_y$$

which increases SBwake more than CBwake, qualitatively explaining the stabilization by coupling (Y. Alexahin et al, 2012).

Booster: Emittance (2017 results)



Intensity @4.4E12 ppp

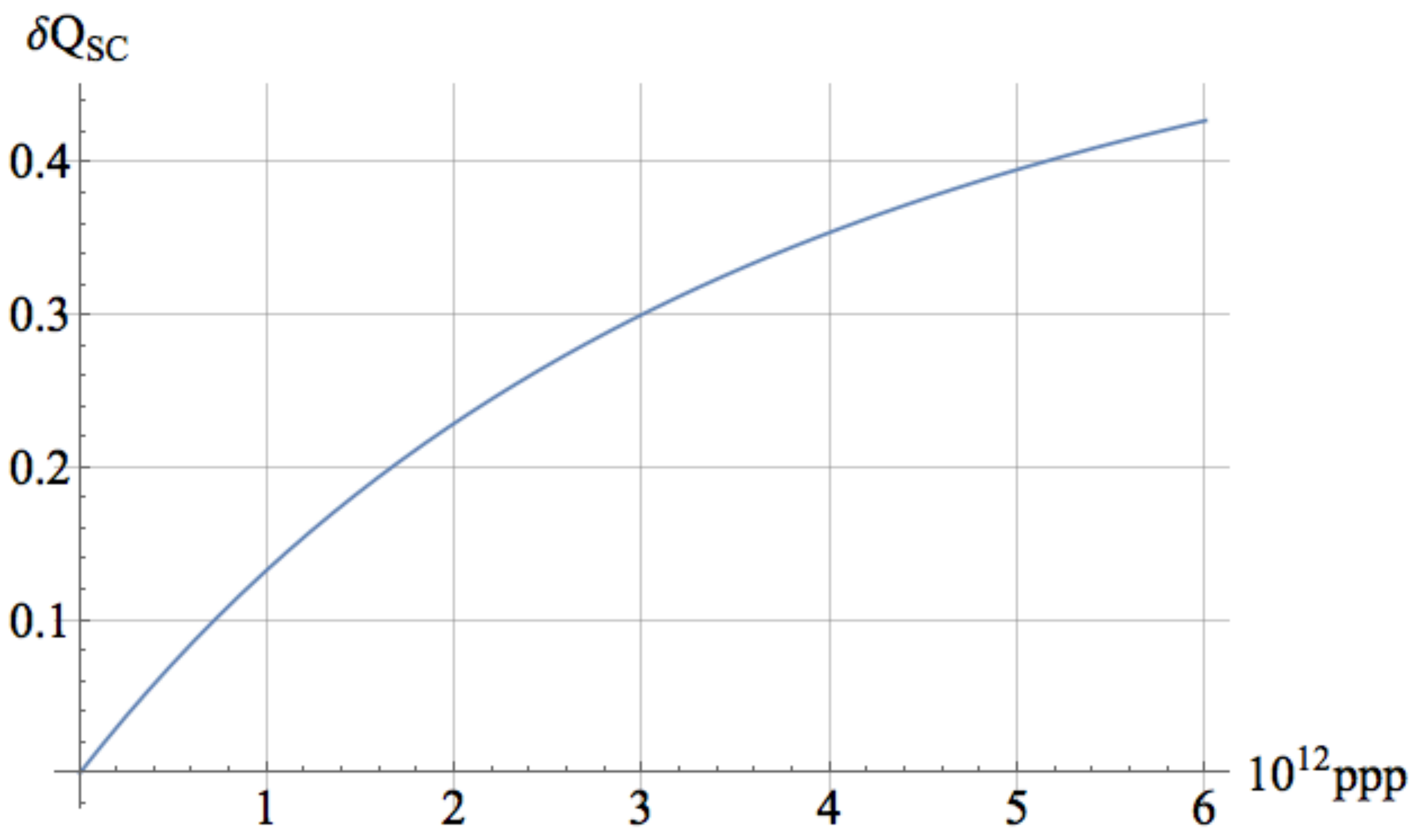
H_emittance: 12pi mm-mrad

V_emittance: 13pi mm-mrad

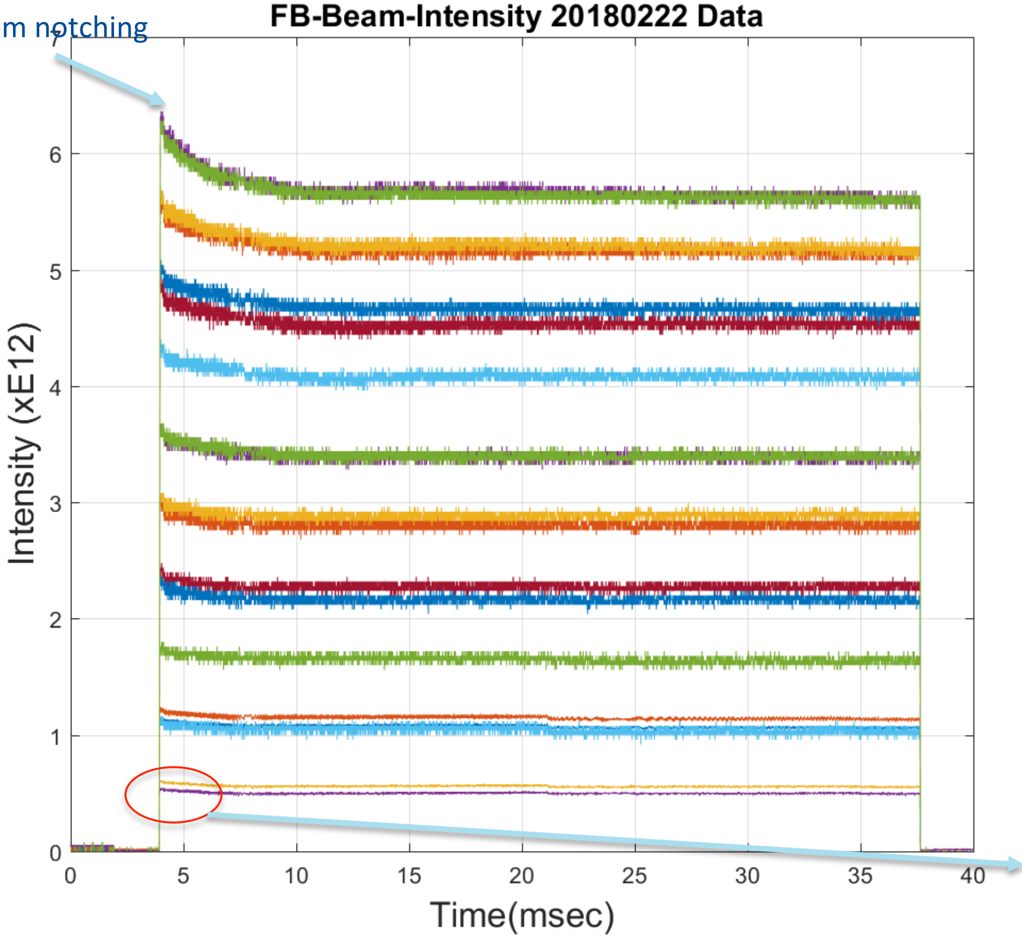
L_emittance: 0.1 eV-sec

Kiyomi Seiya
PIP-II Machine Advisory Committee
10-12 April, 2017

SC Tune Shift



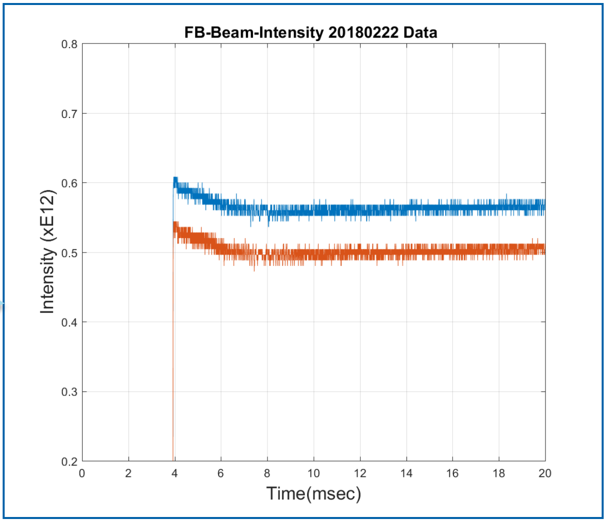
Beam loss occurs in first 2-3 ms after injection


Small fast loss from notching

There is beam loss at the 4-6 ms in the cycle. Time scale for loss is about 2-3 ms after injection.

We see this loss even at low intensity < 0.6e12, ~8%. Similar to high intensity! Therefore, it is *not* space charge.

This unexplained loss now dominates the losses in Booster.



2 turns at low intensity
20 turns at high intensity

Could the head-tail modes get unstable ?

In principle, it can happen at higher intensity.

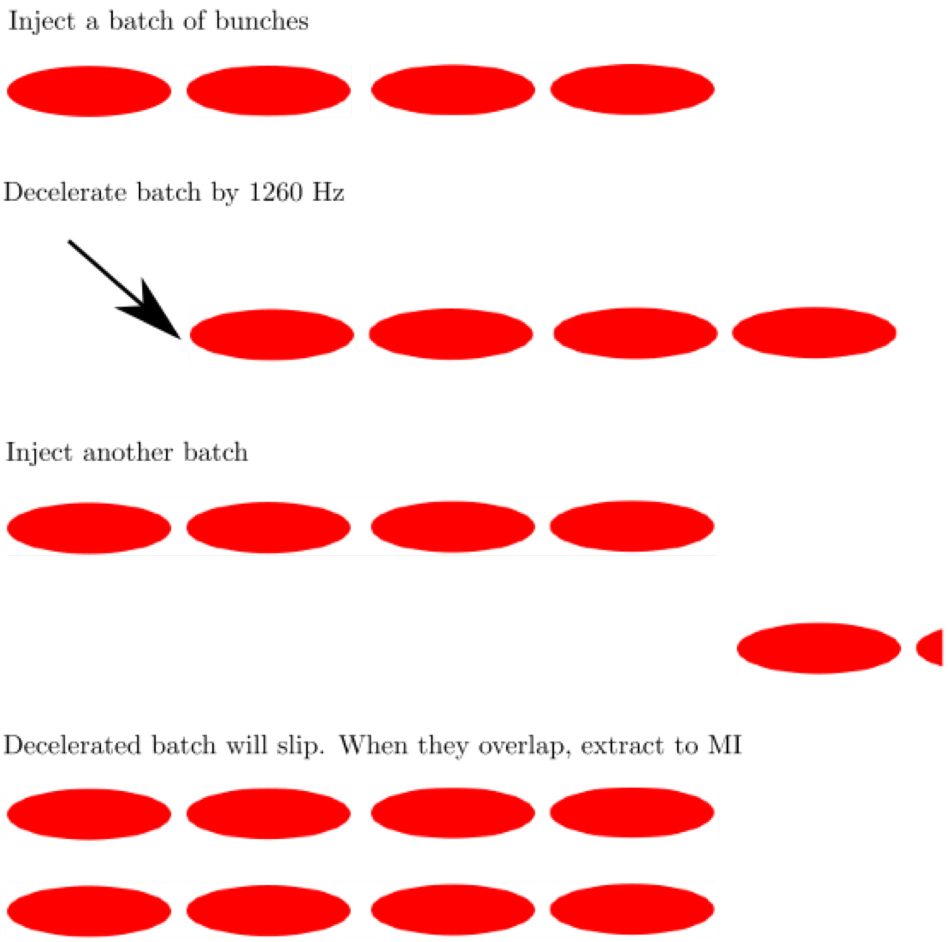
If so, we may run the Booster with the Damper ON and slightly positive chromas.

In this case, the rigid-bunch mode would be stabilized by the damper;
thus, CB modes would be stable,
while the HT modes would be stabilized by the SBwakes.

E-cloud has never been seeing in the Booster; we do not know why.

Slip-stacking at RR

- Slip-stacking allows us to double the intensity of the bunches in the Recycler



Inject a batch of bunches

Decelerate batch by 1260 Hz

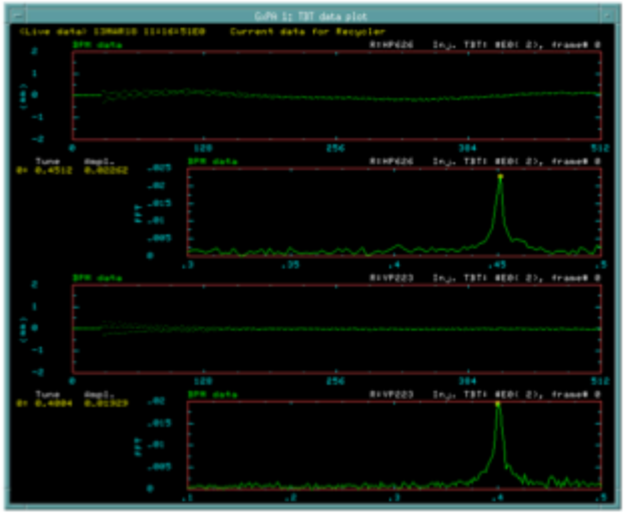
Inject another batch

Decelerated batch will slip. When they overlap, extract to MI

Operations + instabilties at RR

- No observed instabilities currently operationally in RR or MI
- RR has two damper systems,
  - bunch by bunch damper, 26 MHz BW
  - Slip-stack damper, 5MHz BW
- MI has transverse and longitudinal damper, 26 MHz BW

Typical RR parameters	
Emittance, norm, 95%	*15 π mm mrad*
Long. emittance	*0.08eV s*
Chromaticity	*-7,-8*
Tunes	*25.415, 24.42*
Intensity	*5e10 ppb*



BPMs show no sign of blowup

Transverse Instabilities

CB instabilities, f < 2.5MHz are suppressed by the LF damper

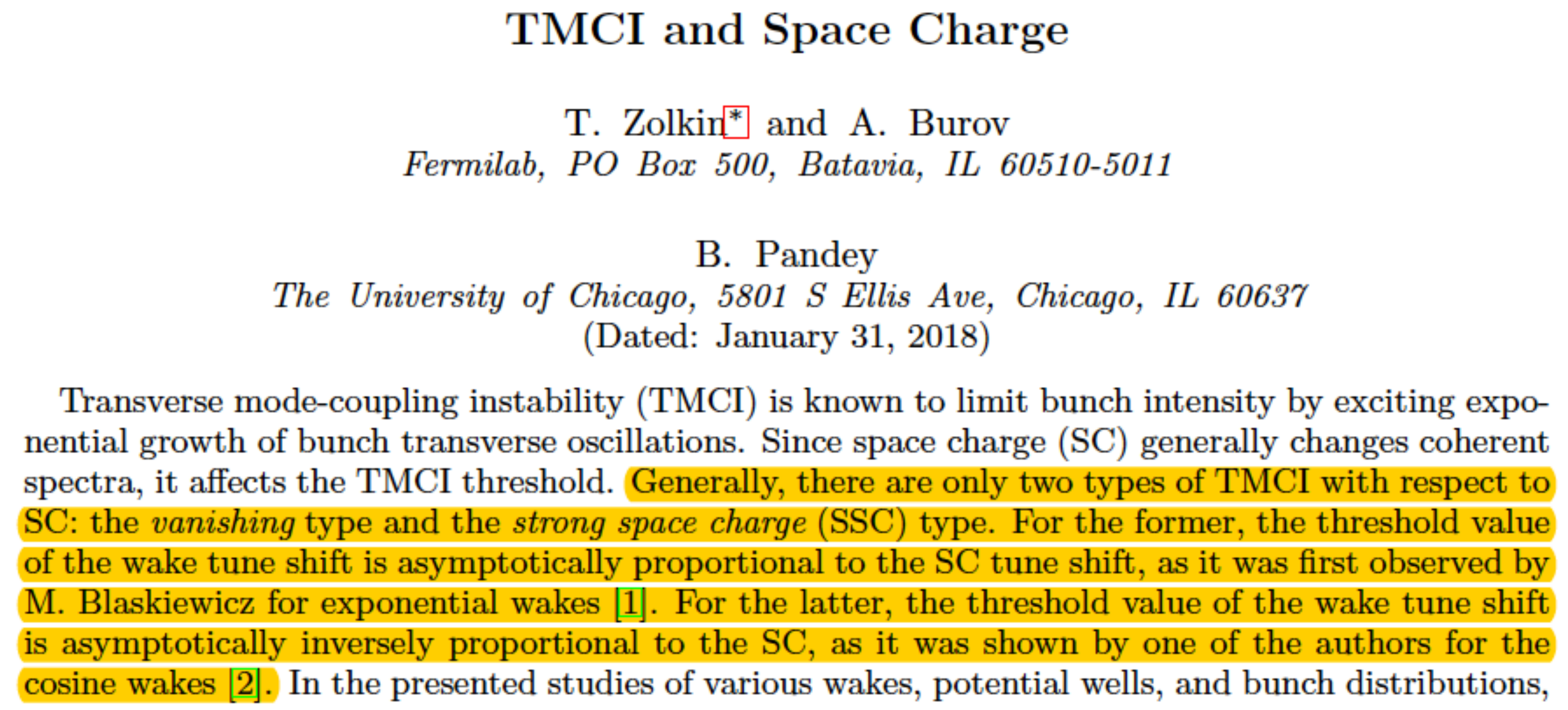
CB instabilities, f > 2.5 MHz are suppressed by SB impedance at Q’<0;

this requires |Q’| > something.

SB instabilities for HT modes do not have enough time to manifest;

this may require |Q’| < something

TMCI with SC: only 2 types are possible



TMCI and Space Charge

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(Dated: January 31, 2018)

Transverse mode-coupling instability (TMCI) is known to limit bunch intensity by exciting exponential growth of bunch transverse oscillations. Since space charge (SC) generally changes coherent spectra, it affects the TMCI threshold. Generally, there are only two types of TMCI with respect to SC: the *vanishing* type and the *strong space charge* (SSC) type. For the former, the threshold value of the wake tune shift is asymptotically proportional to the SC tune shift, as it was first observed by M. Blaskiewicz for exponential wakes [1]. For the latter, the threshold value of the wake tune shift is asymptotically inversely proportional to the SC, as it was shown by one of the authors for the cosine wakes [2]. In the presented studies of various wakes, potential wells, and bunch distributions,

https://arxiv.org/abs/1711.11110

TMCI with SC: vanishing TMCI

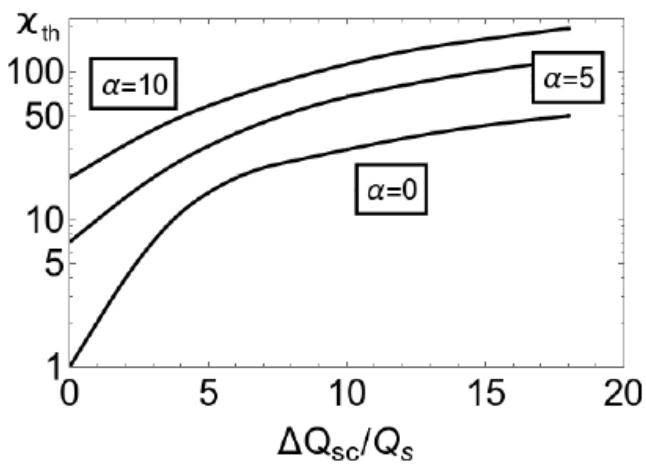


FIG. 5. TMCI threshold as a function of SC for the ABS model with the exponential wakes (reproduction of Ref. [1]).

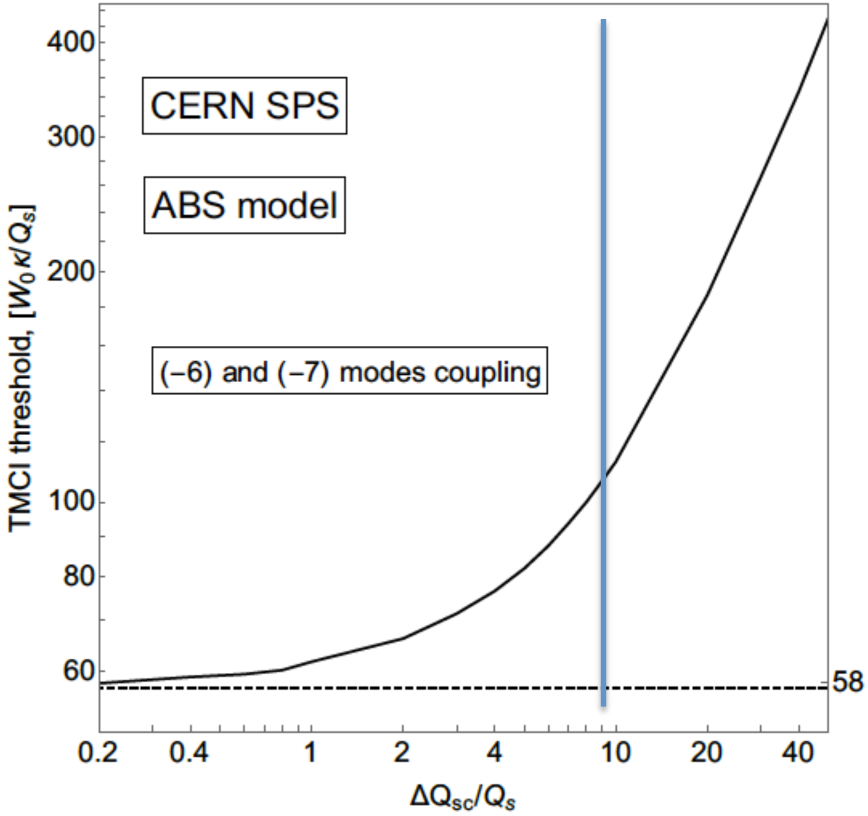
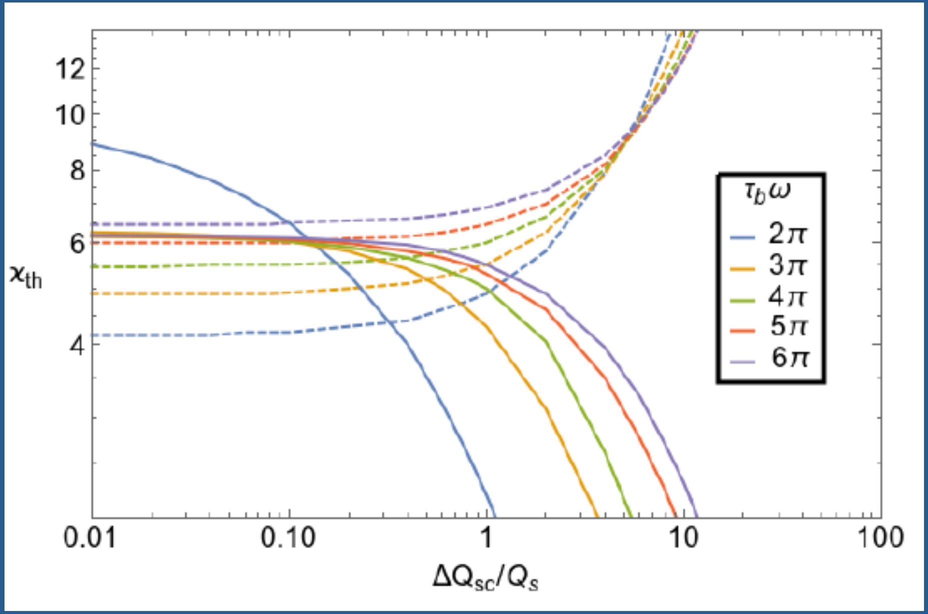


FIG. 18. The lowest TMCI threshold as a function of space charge for CERN SPS ring (ABS model). Dashed line shows the value of threshold at zero ΔQ_{sc}.

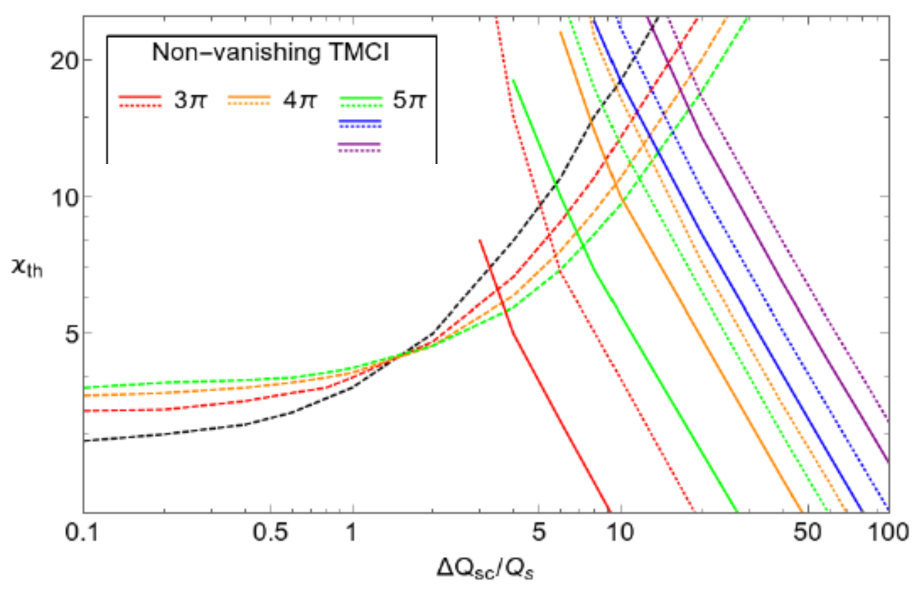
Coherent tune shift ~ SC tune shift

BB impedance model f=1.3GHz
sigma_s = 30cm
(Quatraro & Rumolo, IPAC'10)

TMCI with SC: SSC case



ABS, cos wake



ABS, sin wake

Coherent tune shift ~ 1/SC tune shift

In the parabolic potential and sin wake, there is no TMCI at SSC (contrary to ABS)

Thus, for the smooth potential and realistic wakes, all TMCI are of the vanishing type.

Many thanks!