Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

Beam Instability Experiments

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L2 System Manager

WBS 6.12 Pre-Operations

APEX Workshop 2025

January 22, 2025

Electron-Ion Collider

Outline

- Longitudinal Space Charge
- Particle Tracking Simulations at Injection Energy, 23.8 GeV
- Haissinski Equilibrium
- APEX on Longitudinal Instabilities in RHIC
- Summary

APEX and EIC

- **EIC** rings (RCS, ESR, HSR) are considered high-risk from an impedance standpoint.
  - Insufficient step size in impedance calculations can affect high-frequency results.
  - Limited computational resources impact wakefield and impedance simulations for some geometries.
  - Certain theoretical models do not fully describe or under/overestimate the collective effects of accelerators.
  - Particle tracking simulations with all wakefields (or impedances) are the most reliable way to estimate instability thresholds.
  - The Impedance budget is designed to ensure that the instability threshold is at least twice the required single-bunch current.
- **RHIC**
  - The longitudinal impedance of yellow and blue rings are experimentally measured, **ImZ/n = 5.4 Ω** and **ImZ/n = 1.5 Ω**, respectively.

HSR Beam Parameters At Injection Energy

Energy, E (GeV)	23.8	
Circumference, $C\ (m)$	3833.93	
Lorentz Factor, γ_0	25.37	
Transition Energy, γ_t	22.3	
Energy Spread, σ_δ	$6.4\text{x}10^{-4}$	
RF System, 24.6 MHz (h=315), V_{RF} (MV)	0.040	
Bunch Length, σ_τ (ns)	3.003	
Cooling	**Before**	**After**
Vertical Beam Size, σ_y (mm)	1.9	0.66
Horizontal Beam Size, σ_x (mm)	1.8	0.82

AGS Round Beam : $\varepsilon_{x,y}$ = 2.5e-6 / γ_0 = 98.5 nm

After Cooling: ε_x = 0.5e-6 / γ_0 = 19.7 nm

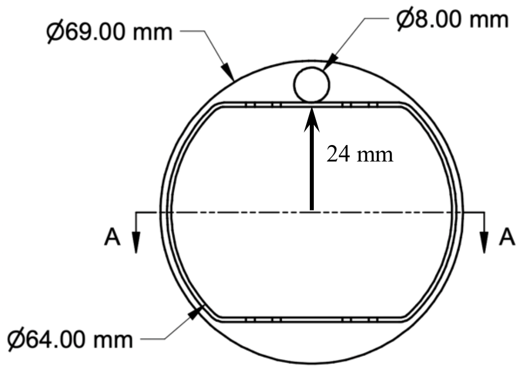
ε_y = 0.3e-6 / γ_0 = 11.8 nm

Average Betta Functions: β_x = 34.5 m & β_y = 36.6 m

Average Current, I_{av} (A)	1
Number of Bunches, M	290
Single Bunch Current, $\mathrm{I_0} = \frac{\mathrm{Ne}}{\mathrm{T_0}}$ (mA)	3.5
Num. of protons per bunch, N	$2.8\text{x}10^{11}$
Bunch Charge, Ne (nC)	44.8
Peak Bunch Current, $I_p = \frac{Ne}{\sqrt{2\pi}\sigma_\tau}$ (A)	6

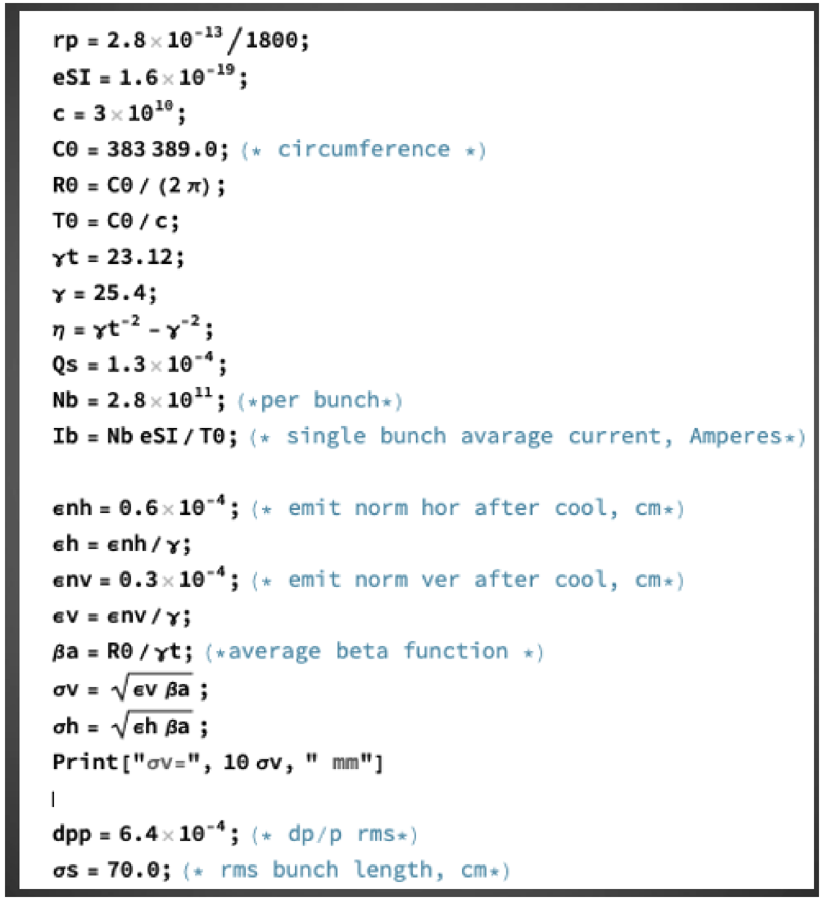
- Arcs (L=2880 m)
  - $b_{x,arc}$= 32 mm
  - $b_{y,arc}$ = 24 mm
- Straight Sections (L=953.9 m)
  - $b_{x,arc}$ = 60 mm
  - $b_{y,arc}$ = 60 mm
- Average over L=3833.93 m
  - $b_{x,ave}$ = 39 mm
  - $b_{y,ave}$ = 33 mm

Arcs



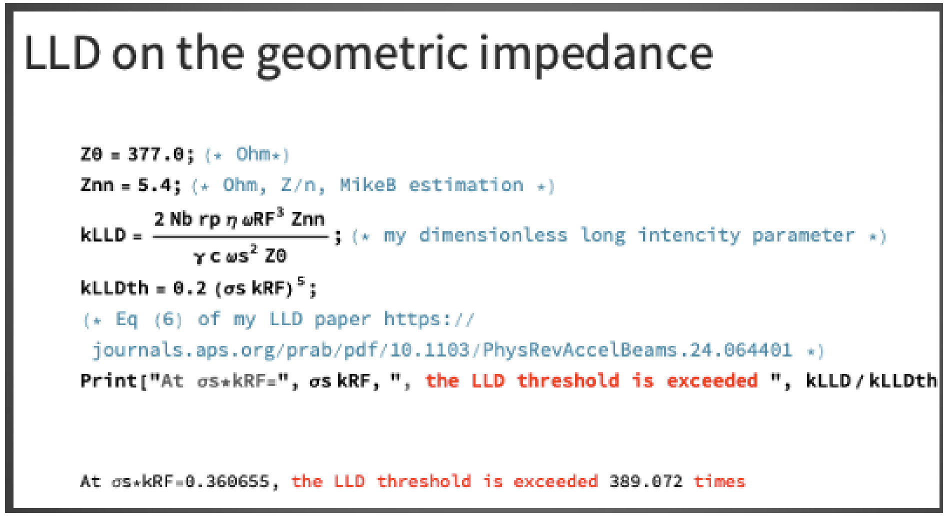
Beam Stability At Injection Energy 23.8 GeV

- Theory predicts that the beam is longitudinally unstable at **23.8 GeV** energy for the space charge impedance of **ImZ/n=2.5 *Ω*** and geometric impedance of **ImZ/n= 5.4 *Ω*** (A. Burov – Longitudinal Loss of Landau Damping).



```
rp = 2.8 × 10^-13 / 1800;
eSI = 1.6 × 10^-19;
c = 3 × 10^10;
C0 = 383 389.0; (* circumference *)
R0 = C0 / (2 π);
T0 = C0 / c;
γt = 23.12;
γ = 25.4;
η = γt^-2 - γ^-2;
Qs = 1.3 × 10^-4;
Nb = 2.8 × 10^11; (*per bunch*)
Ib = Nb eSI / T0; (* single bunch avarage current, Amperes*)

ϵnh = 0.6 × 10^-4; (* emit norm hor after cool, cm*)
ϵh = ϵnh / γ;
ϵnv = 0.3 × 10^-4; (* emit norm ver after cool, cm*)
ϵv = ϵnv / γ;
βa = R0 / γt; (*average beta function *)
σv = √(ϵv βa) ;
σh = √(ϵh βa) ;
Print["σv=", 10 σv, " mm"]
|
dpp = 6.4 × 10^-4; (* dp/p rms*)
σs = 70.0; (* rms bunch length, cm*)
```



LLD on the geometric impedance

```
Z0 = 377.0; (* Ohm*)
Znn = 5.4; (* Ohm, Z/n, MikeB estimation *)
kLLD = (2 Nb rp η ωRF^3 Znn) / (γ c ωs^2 Z0); (* my dimensionless long intencity parameter *)
kLLDth = 0.2 (σs kRF)^5;
(* Eq (6) of my LLD paper https://
 journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.24.064401 *)
Print["At σs*kRF=", σs kRF, ", the LLD threshold is exceeded ", kLLD / kLLDth


At σs*kRF=0.360655, the LLD threshold is exceeded 389.072 times
```

Long. Space Charge Impedance And Wakefield

- Longitudinal Space Charge Impedance[1]

$$Z_{||}(\omega) = i\frac{S\omega}{c^2}, \text{ where } S = \frac{2C}{\gamma_0^2}\left(ln\frac{b}{\sigma} + \frac{1}{2}\right)$$

$$Z_{||}(\omega) = -i\frac{\omega}{c}\frac{Z_0}{2\pi}\frac{C}{\gamma_0^2}\left(ln\frac{b}{\sigma} + \frac{1}{2}\right),$$

where $\boldsymbol{b}$ and $\boldsymbol{\sigma}$ are the radius of the vacuum chamber and beam, $\boldsymbol{C}$ is the ring circumference, $\boldsymbol{\gamma_0}$ is the Lorentz factor and $\boldsymbol{Z_0}$ is the impedance of free space

- Longitudinal Space Charge Wakefield[1,2]

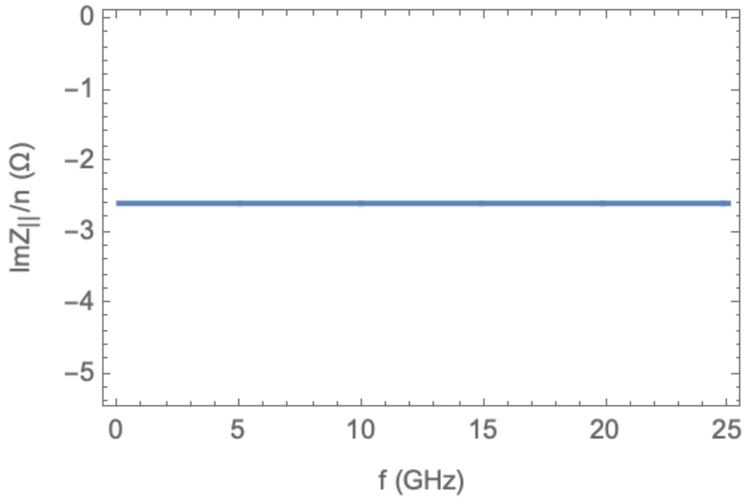
$w(z) = S\delta'(z)$ – point particle

$w_c(z) = S\lambda'(z)$ – pseudo-Green's function

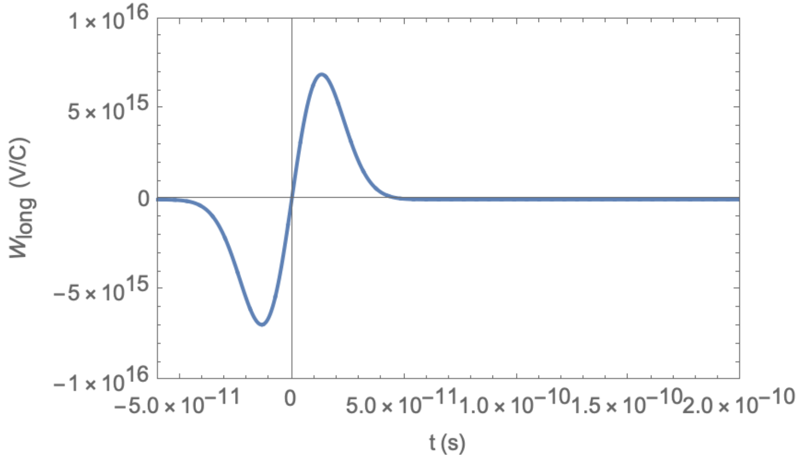
$$\lambda(z) = \frac{1}{\sqrt{2\pi}\sigma_s}\exp(-z^2/2\sigma_s^2)$$

Panageotis Baxevanis

$$w_c(z) = -\frac{Z_0 c}{(2\pi)^{3/2}}\frac{C}{\gamma_0^2\sigma_s}\left(ln\frac{b}{\sigma} + \frac{1}{2}\right)\frac{z}{\sigma_s^2}\exp(-z^2/2\sigma_s^2)$$



Imaginary part of the longitudinal impedance at low frequency divided by $\boldsymbol{n = \omega/\omega_0}$, where $\omega_0 = 2\pi \times 78.1\ kHz$



Longitudinal space charge wakefield for a 4mm bunch length

[1] A. Chao's Book

[2] P. Baxevanis, EIC Tech Note, Draft

Haissinski Solution For Longitudinal SC Wake

- Haissinski solution with longitudinal space charge[1]:

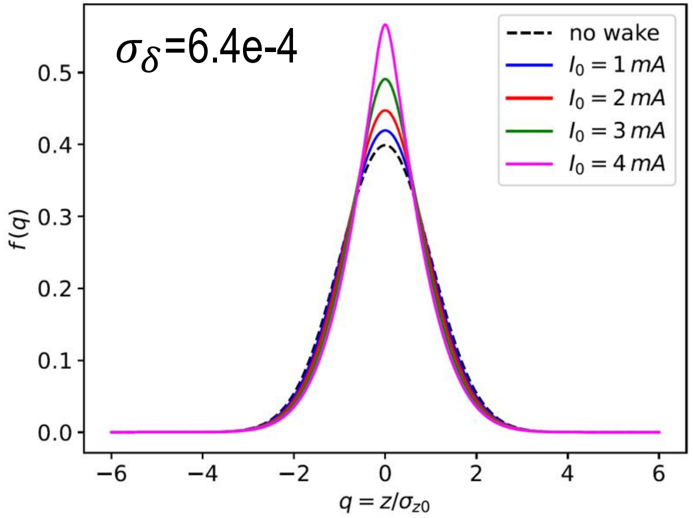
$$F(q) = \exp\left(-\frac{q^2}{2} + \frac{eI_0Z_0C\,(0.5+\ln(b/\sigma))}{2\pi E_0\eta_s\sigma_\delta^2\gamma^2\sigma_{z0}}\frac{F(q)}{\int dqF(q)}\right)$$
$$= \exp\left(-\frac{q^2}{2} + P_{SC}\frac{F(q)}{\int dqF(q)}\right) \quad (q = z/\sigma_{z0})$$

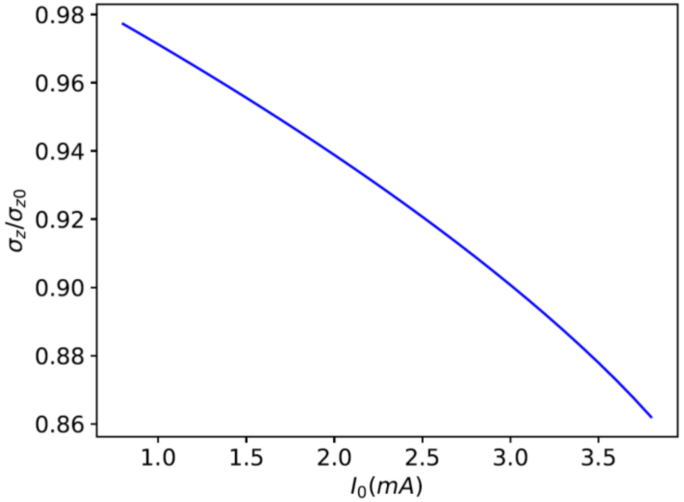
- An equilibrium solution exists as long as

$$P_{SC} \leq P_{SC,max} \approx 1.55$$

- The longitudinal instability threshold:
  - $I_{th,MWI}$ ~ 4 mA for σ_δ=6.4e-4 & σ_s=0.9 m
  - $I_{th,MWI}$ ~ 6 mA for σ_δ=7.4e-4 & σ_s=1.04 m

- The longitudinal space charge leads to bunch shortening.





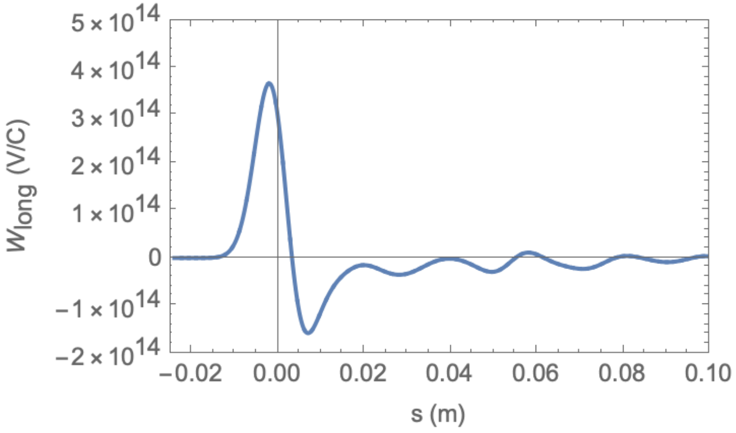
Ryan Lindberg, Panageotis Baxevanis

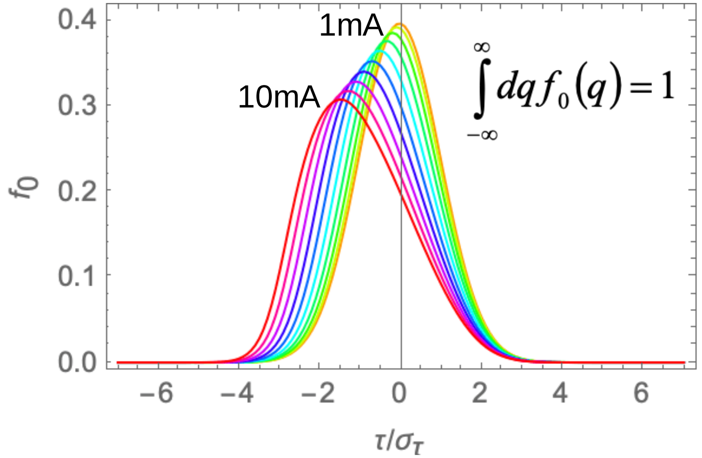
[1] R. Lindberg, APS Tech Note, Draft

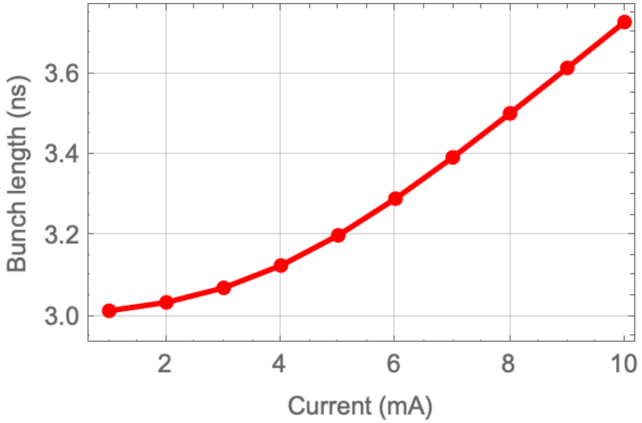
Haissinski Solution For Geom. & RW Wakefields

		Number of Component	Z/n, Ω
Resistive Wall	RW	3844.63 m	-
Beam Screen	BS	2880 m	11e-3
Cold Bellows & BPM	CBLW&BMP	250	8.3e-3
Injection Stripline Kickers	SLK	20	120e-3
Beam Screen Joints	BSJ	1000	8.6e-3
Roman Pot	RP	4	280e-3
Warm Bellows	WBLW	200	11.4e-3
Gate Valve			
Ø125	GV125	30	0.42e-3
Ø88	GV88	12	0.24e-3
Abort Kicker (Ferrite Based)	AK	5	1750e-3
Total:			2.2

- The geometric & RW wakefields lead to bunch lengthening.


Total Longitudinal Geom. & RW Wakefield

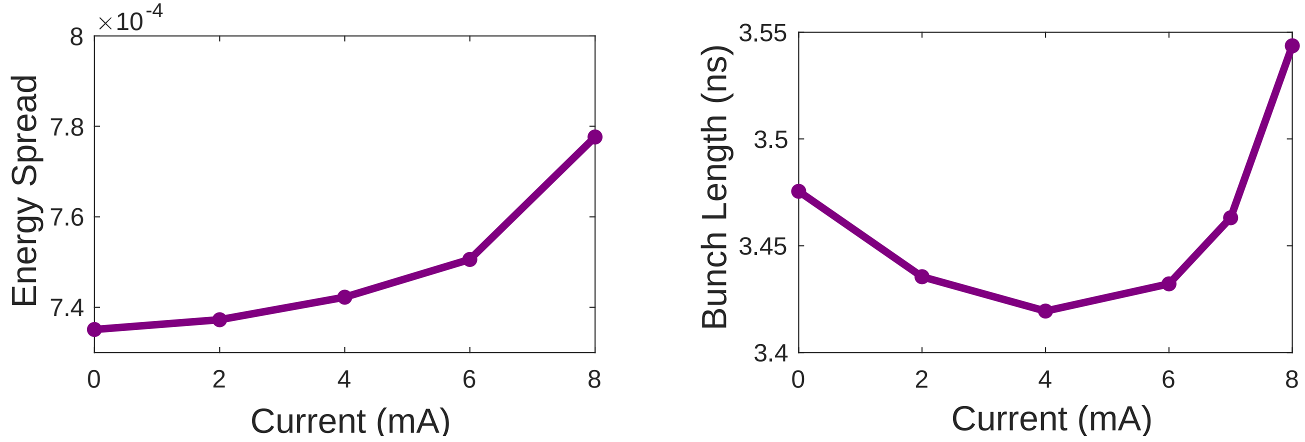




$$f_0(q) = A\exp\left[-\frac{1}{2}q^2 + S\int_q^{\infty} dq' \int_{q'}^{\infty} dq''\, f_0(q'')w(q''-q')\right] \qquad S = \frac{e I_0 R_s \omega_r}{E_0 \nu_s \omega_0 \sigma_\varepsilon}$$

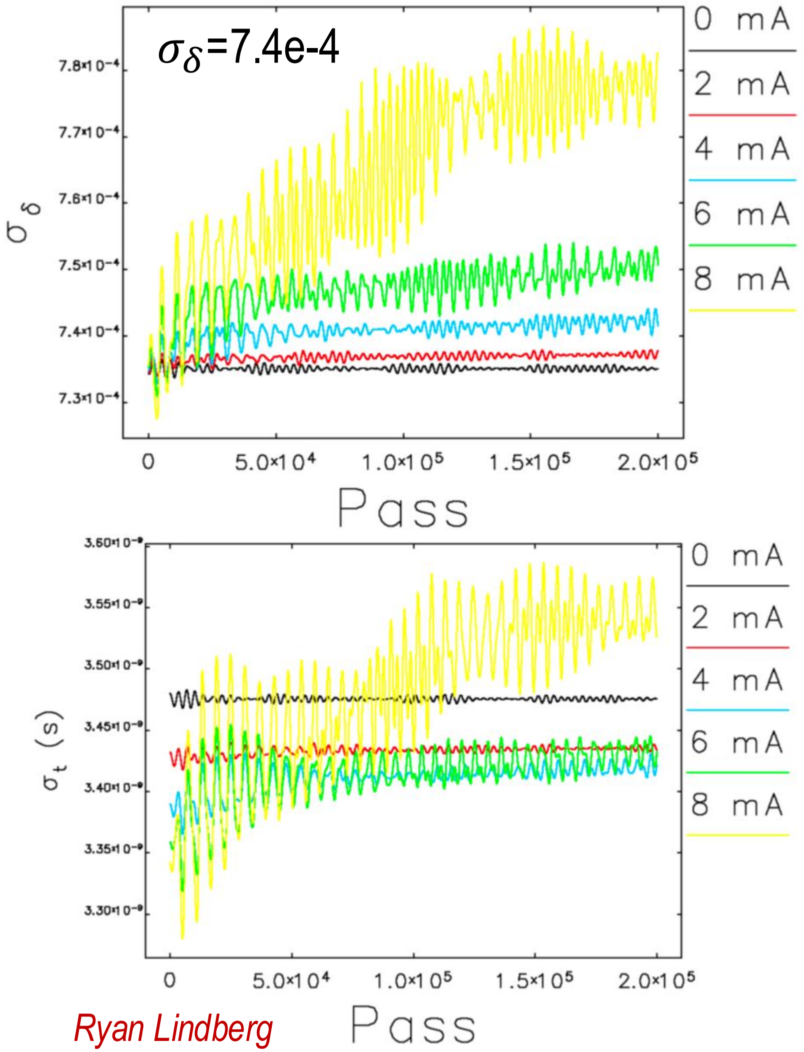
Particle Tracking And Instability Threshold

- ELEGANT particle tracking simulations[1]
- Haissinski distribution is used as the input file for ELEGANT
- Total wakefield: $W_{tot}(s) = -W_{sc}(s) + W_{gm,rw}(s)$



- The MWI threshold is ~7 mA

ELEGANT



Ryan Lindberg

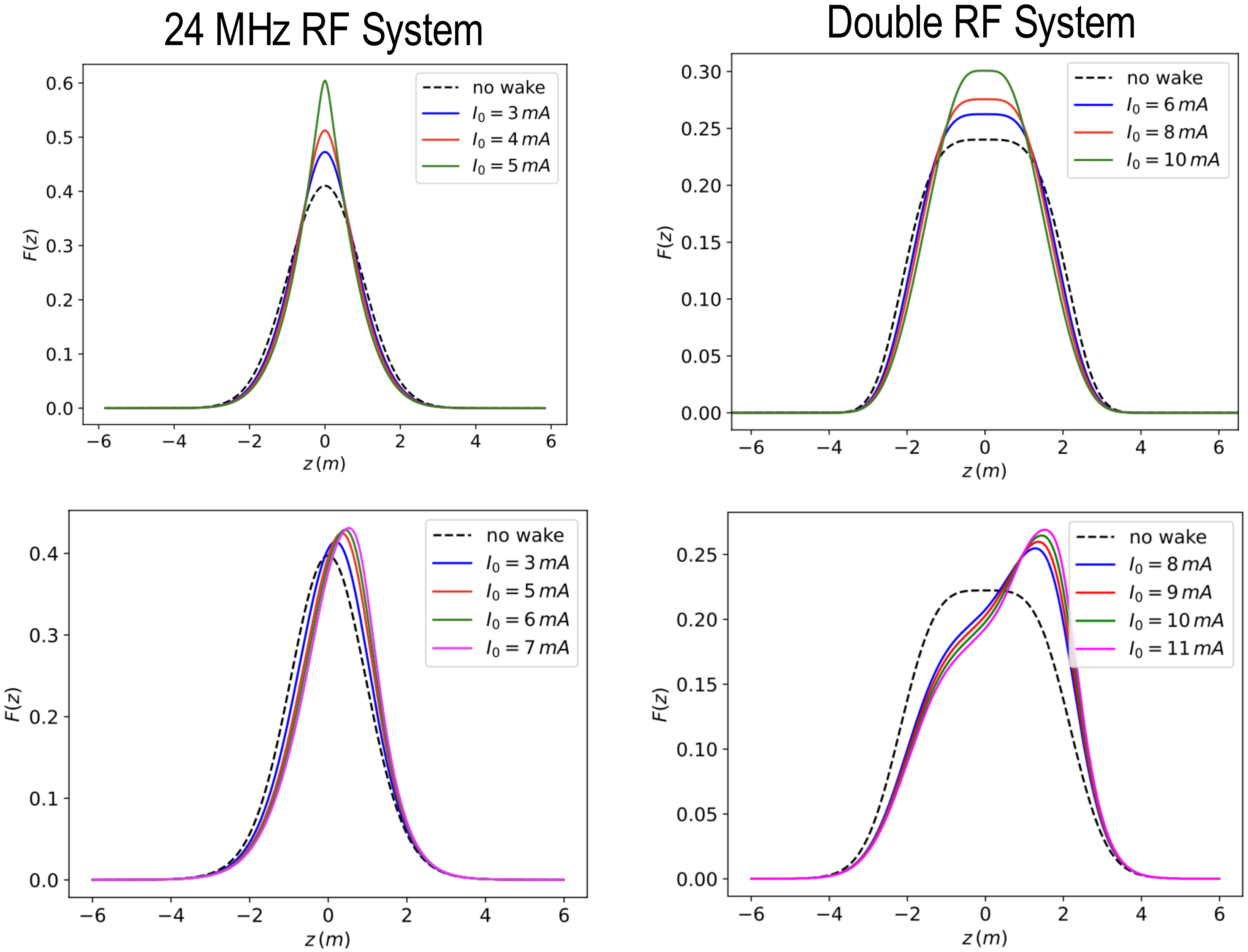
[1] M. Borland, “ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulation”, ANL, Argonne, IL, USA, Rep. ANL/APS LS-287, Aug. 2000

Double RF System (2^{nd} Harmonic)

- **Space Charge (SC) Impedance**: The Haissinski equilibrium exists at 5 mA and at twice that value with the 2^{nd} harmonic cavity.
- **Geom. + SC Impedance**: A factor of 1.5 increase in single-bunch current at which the Haissinski equilibrium exists with the 2nd Harmonic cavity[1].

- Working on the transverse space charge wake and its effect on beam dynamics.

See talk by A. Fedotov –
Low-Energy Electron Cooling Experiments



[1] P. Baxevanis and A. Blednykh, BNL-226418-2024-TECH

APEX On Longitudinal Instabilities in RHIC

- APEX
  - 11.30 – 17.30, May 16, 2024 – Yellow Ring – Z/n=5.4 Ω
  - 10.00 – 16.00, September 25, 2024 – Blue Ring – Z/n=1.5 Ω
- Participants
  - A. Blednykh, M. Blaskiewicz, V. Ptitsyn, V. Schoefer, C. Liu, K. Mernick, M. Sangroula, A. Fedotov, D. Kayran, S. Seletskiy, I. Pinaev, G. Robert-Demolaize, B. Lepore, T. Shrey, E. Becker.
- 9 MHz RF with γ_t= 23.7

Lattice with γ_t=23.7

Ramp: pp24-apex-hgt

Config: dbconfig/1700000000

Blue Species: PP

Yellow Species: PP

Options	BetaStarSlopes	DR8toDRG	DipoleHarmonics	FamilyTF	WarmTF	polyField	specificTF
State	Off	On	Off	On	On	On	On

Stone: injection

Tunes/Chroms

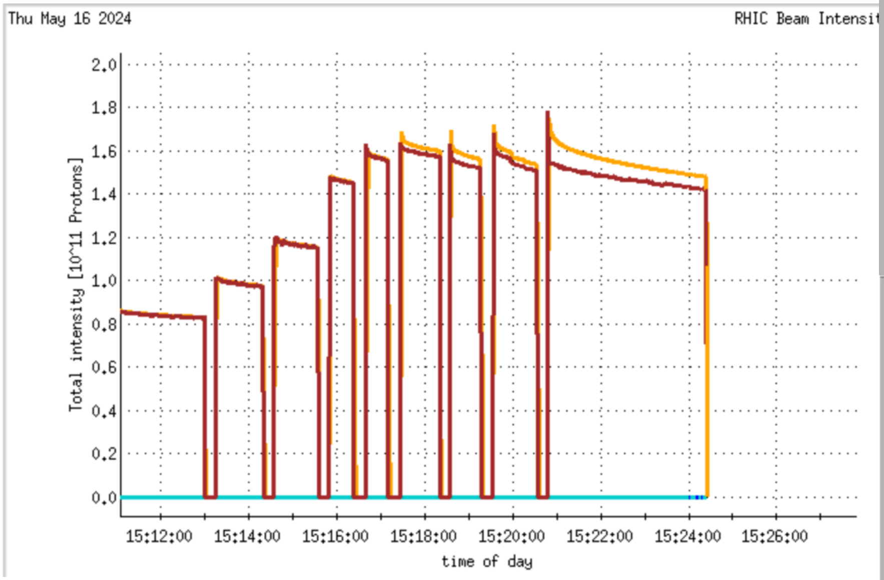
Stone #	1
Time [sec]	0
Gamma	25.3786244712
BetaGamma	25.3589151986
Brho [T-m]	79.3667745
Qx	29.6964998022
Qy	30.6931002024
ChromX	3.00000461032
ChromY	2.99999954061
ChromX2	181.969516863
ChromY2	236.164757941
ChromX3	3284.50970576
ChromY3	2584.76116087
GammaT	23.715082443

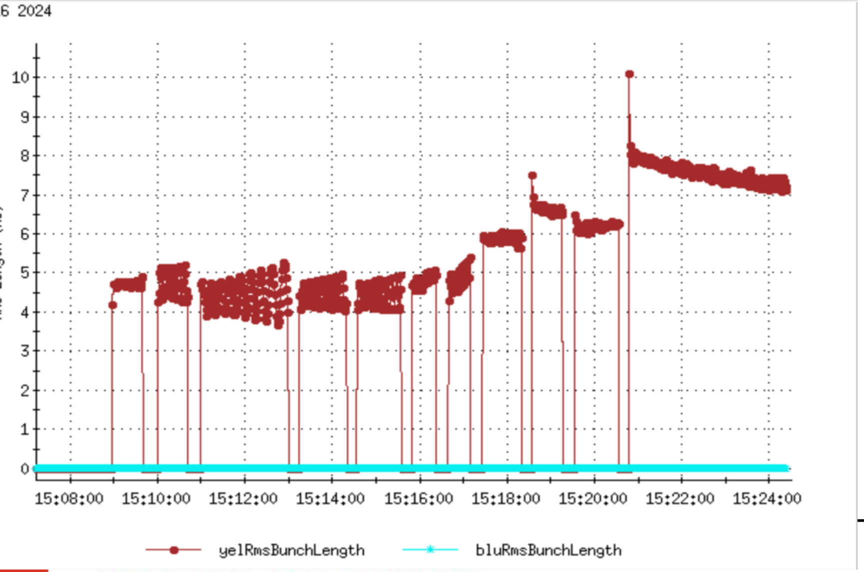
IP Parameters

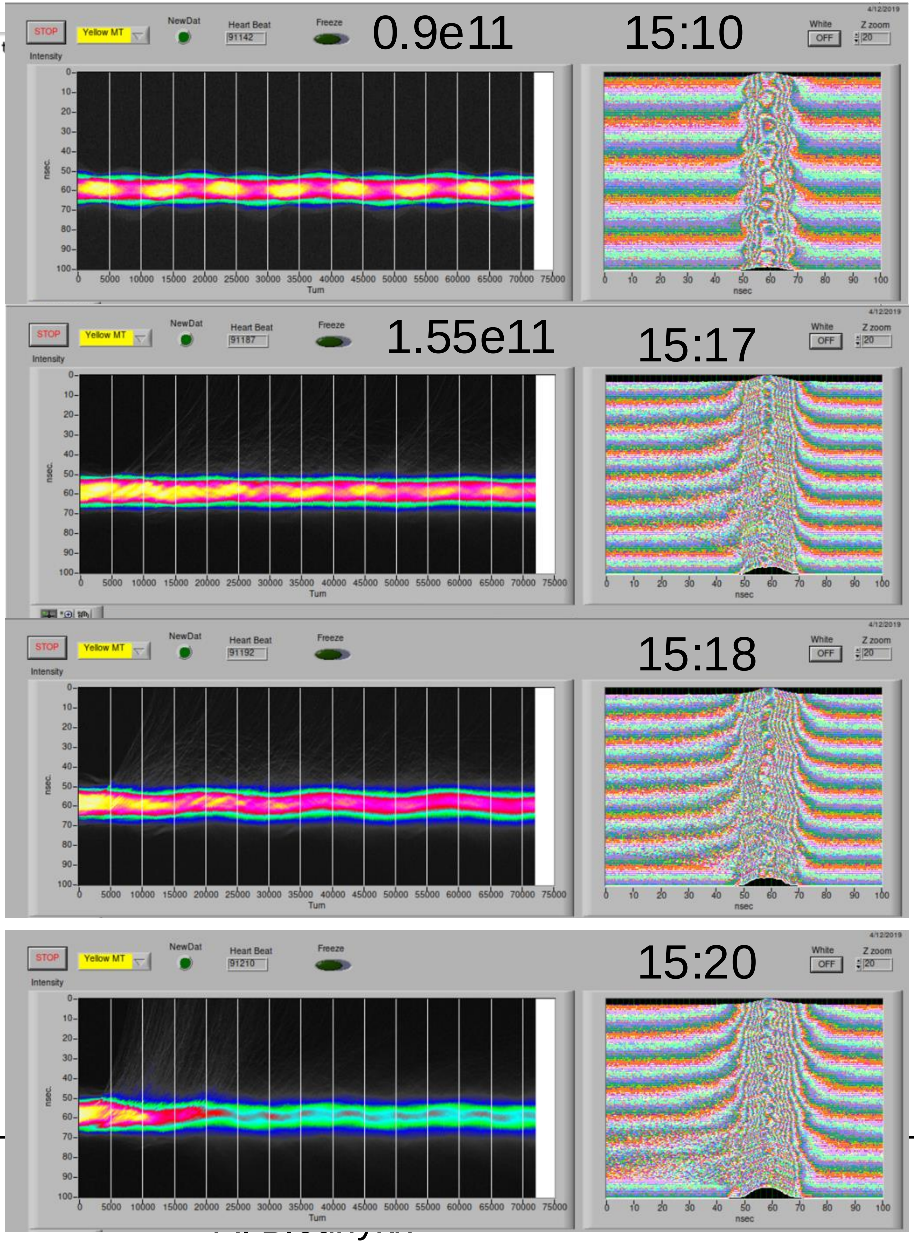
Value/IP	IP6	IP8	IP10	IP12	IP2	IP4
BetaX [m]	8.48370216	8.4161791	10.4395403	10.0906402	10.1644428	10.1328982
BetaY [m]	8.51109879	8.4320264	10.400712	9.9976126	10.077414	10.0947369
AlphaX	0.4550773	-0.420530411	0.286302215	-0.541516384	0.38850972	-0.490587207
AlphaY	-0.319439943	0.345379273	-0.163046057	0.337913215	-0.138569331	0.267417725
EtaX [m]	0.0174791949	-0.0235582254	0.0152577547	-0.00287761785	0.00737504657	0.00374350874
EtaY [m]	0	0	0	0	0	0
EtaX'	0.00052117201	-0.00167792786	0.0034823474	-0.00216633189	0.00381434996	-0.00281782221
EtaY'	0	0	0	0	0	0

G. Robert-Demolaize

9 MHz RF cavity (new γ_t=23.7)







- Instability related to beam intensity
- Beam is unstable above 1.5e11
- RF Voltage fixed at 15:12
- Beam profile needs to be compared at different intensities
- Evidence of Microwave Instability (MWI)

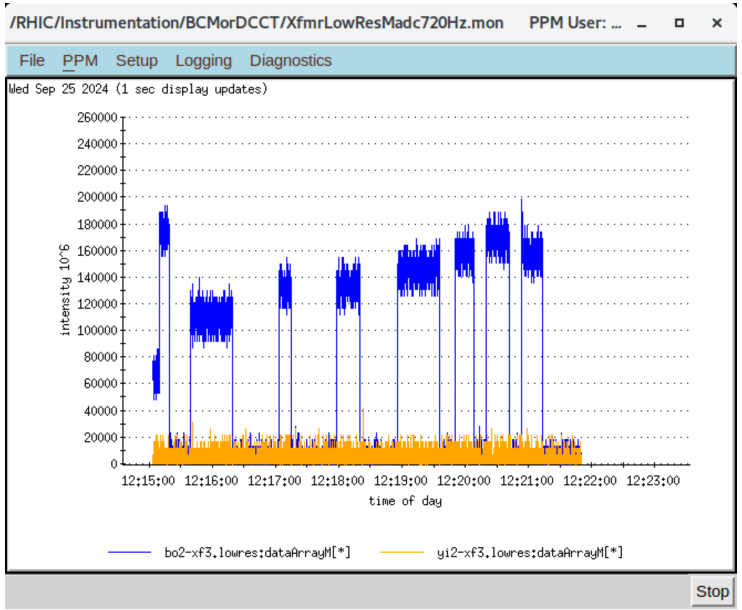
RF=18kV

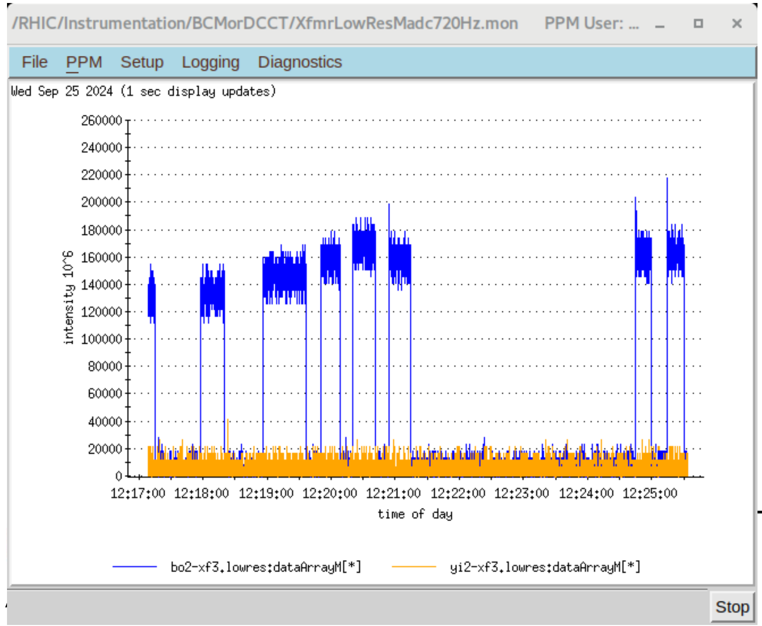
- Sep. 25, 2024

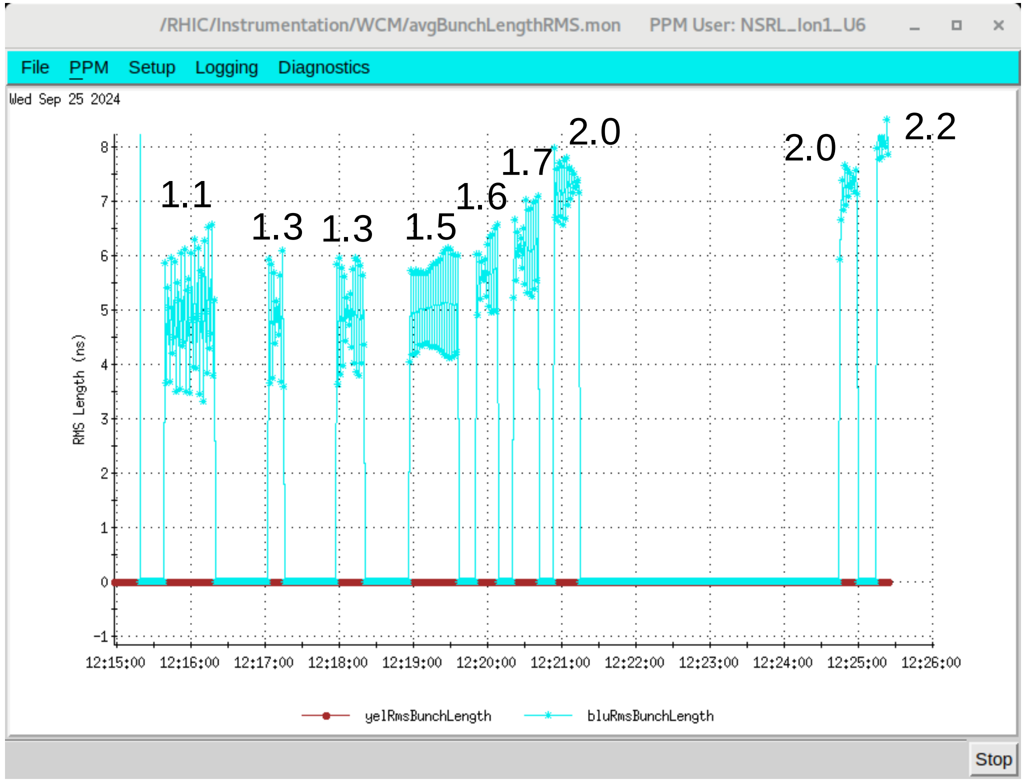
Blue Ring Measurements

$Z/n = 1.5\ \Omega$

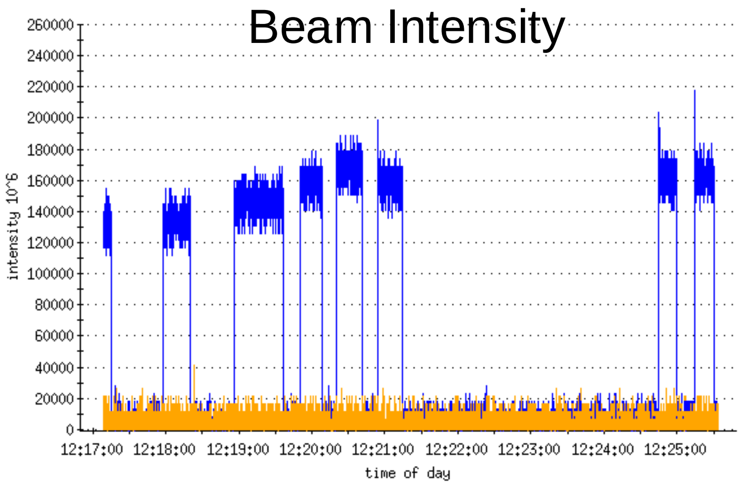
9 MHz RF Cavity (γ_t=23.7), V_{RF}=17 kV



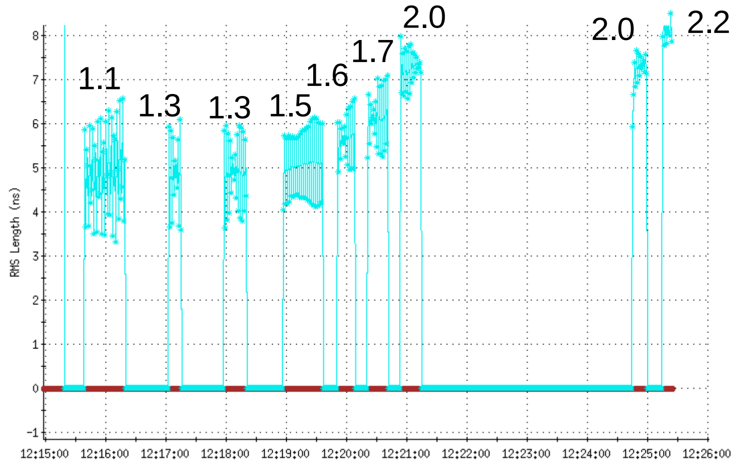


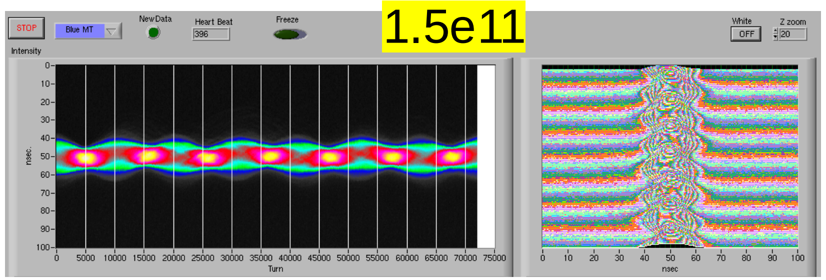


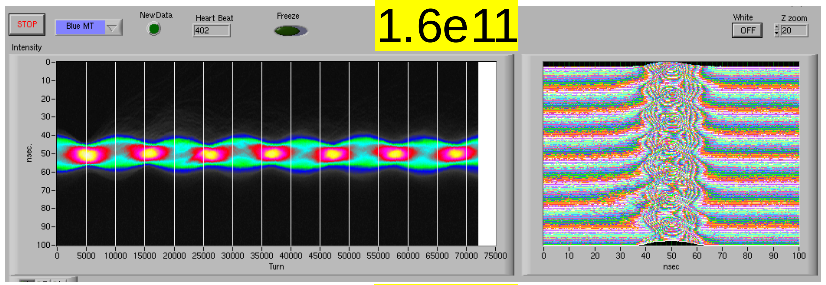
9 MHz RF Cavity (New γ_t=23.7), V_{RF}=17 kV

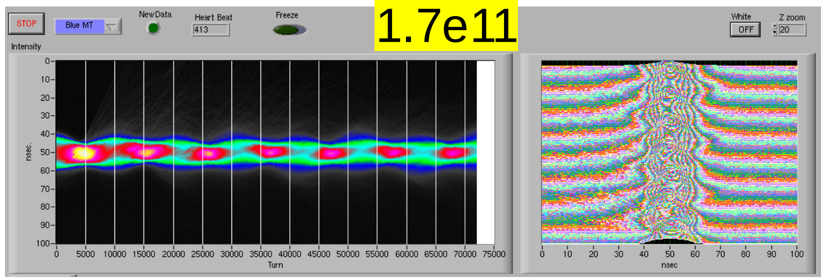

Beam Intensity

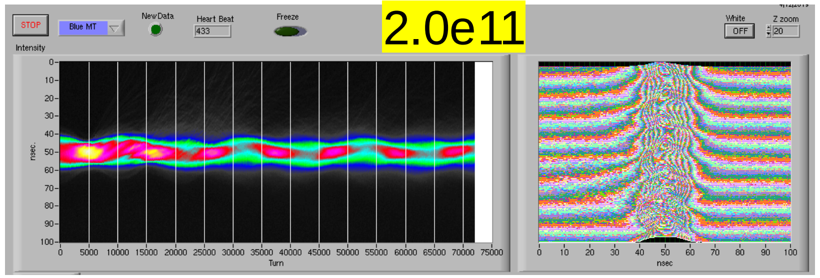
Bunch Length




1.5e11

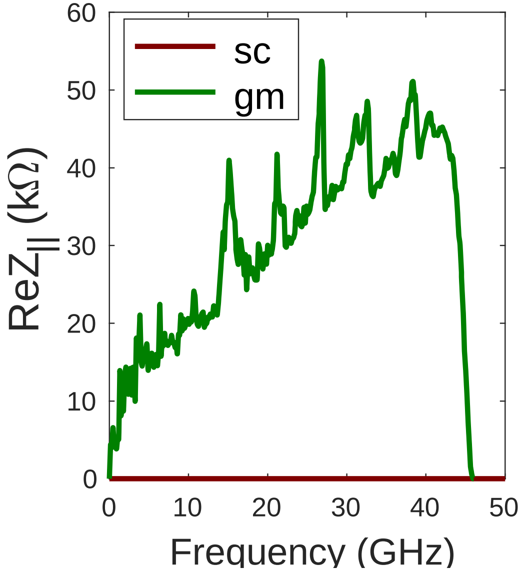

1.6e11

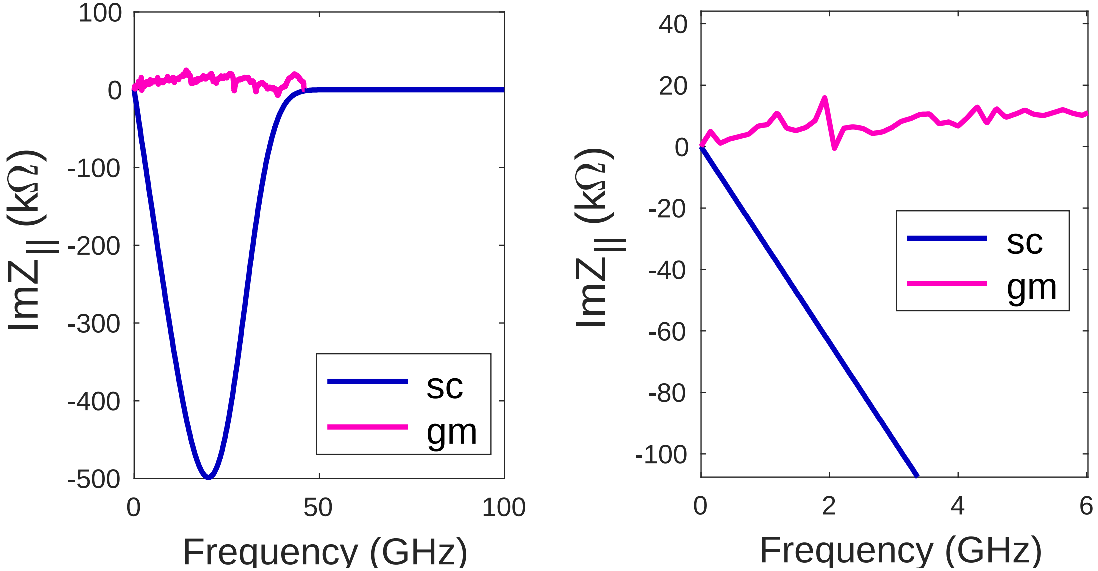

1.7e11


2.0e11

- Beam is unstable at ~1.6 mA
- The MWI threshold is approximately the same in both the Yellow and Blue Rings, while the geometric + RW impedance differs: Z/n = 1.5 Ω (Blue Ring) vs. Z/n = 5.4 Ω (Yellow Ring).

Geometric + RW vs. Space Charge Impedance


Real Part of the Longitudinal Impedance


Imaginary Part of the Longitudinal Impedance

$\mathrm{ReZ}_{||}(\omega) = 0$ for Space Charge

- The dominant effect on the microwave instability threshold is due to the space charge impedance.

APEX Summary

- Accelerator Physics Experiment (APEX) in RHIC on MWI
  - Yellow ring studies, where Z/n=5.4 Ω[1] (May 16, 2024).
  - Blue ring studies, where Z/n=1.5 Ω[1] (Sep 25, 2024)
- Beam Instability (Yellow Ring)
  - Beam is single-bunch unstable at 1.9 mA (1.5e11) with 9 MHz RF at V_{RF}= 18kV (h=115)
    - γ_t=23.7, σ_τ=4.5 ns (σ_s=1.36 m) and σ_δ=5.5e-4
  - Beam is stable with 28 MHz RF at V_{RF}= 40kV (h=358)
    - γ_t=23.7, σ_τ=4 ns (σ_s=1.2 m), $\boldsymbol{\sigma_\delta}$**=12.8e-4**
- Space Charge Impedance
  - β_x = 33.3 m, β_y = 32.1 m and b_{ave}=43 mm & σ_x=1.8 mm
  - $Z_{||}/n$ = 2.2 Ω (RHIC)
  - I_{th}=2.6 mA (σ_δ=5.5e-4) & I_{th}=12.5 mA ($\boldsymbol{\sigma_\delta}$**=12.8e-4**)

[1] M. Blaskiewicz, J.M. Brennan, K. Mernick, doi:10.18429/JACoW-IPAC2015-MOPMN020

Summary

- At injection energy, the microwave instability threshold is primarily influenced by the longitudinal space charge impedance.
- APEX at RHIC for different rings confirms this.
- The beam longitudinally is stable at 23.8 GeV
- To perform particle tracking simulations, the Haissinski equilibrium is used as the initial distribution in ELEGANT.
- The effect of vertical space charge and transverse dipole impedance on transverse beam dynamics is a work in progress.