Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT of ENERGY | Office of Science

Beam Stability in the EIC ESR: Contribution of the 591 MHz RF Cavities

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Pre-Operations System Manager

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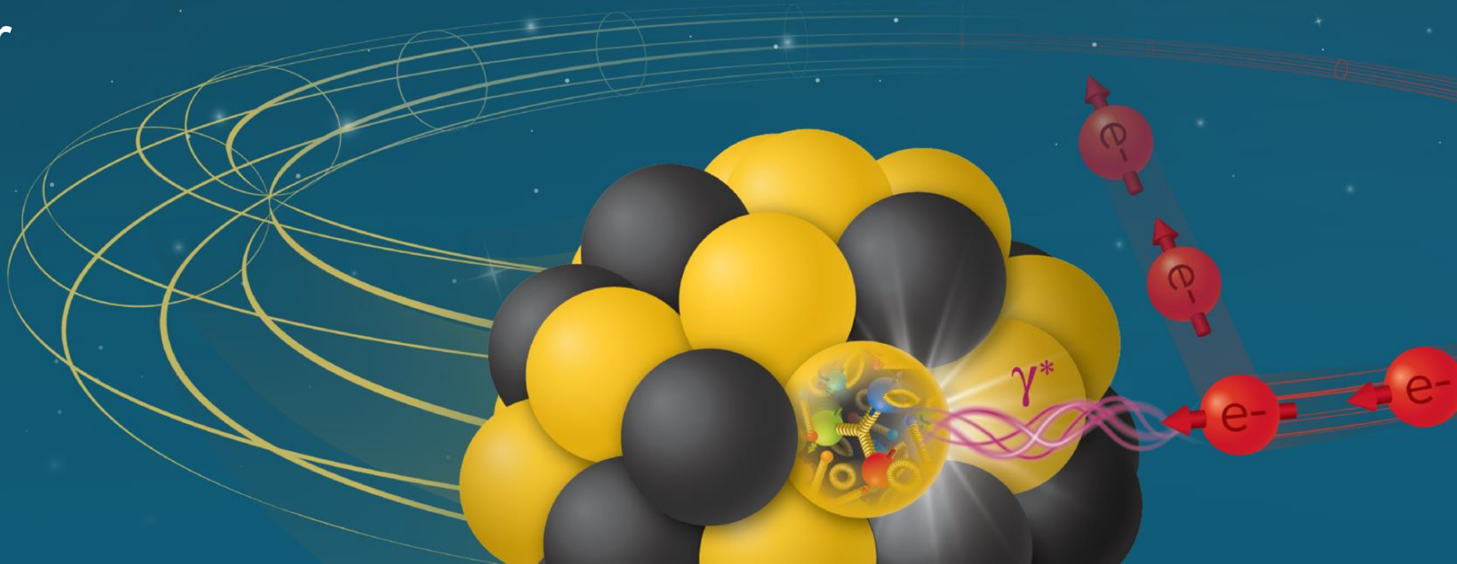
Electron-Ion Collider

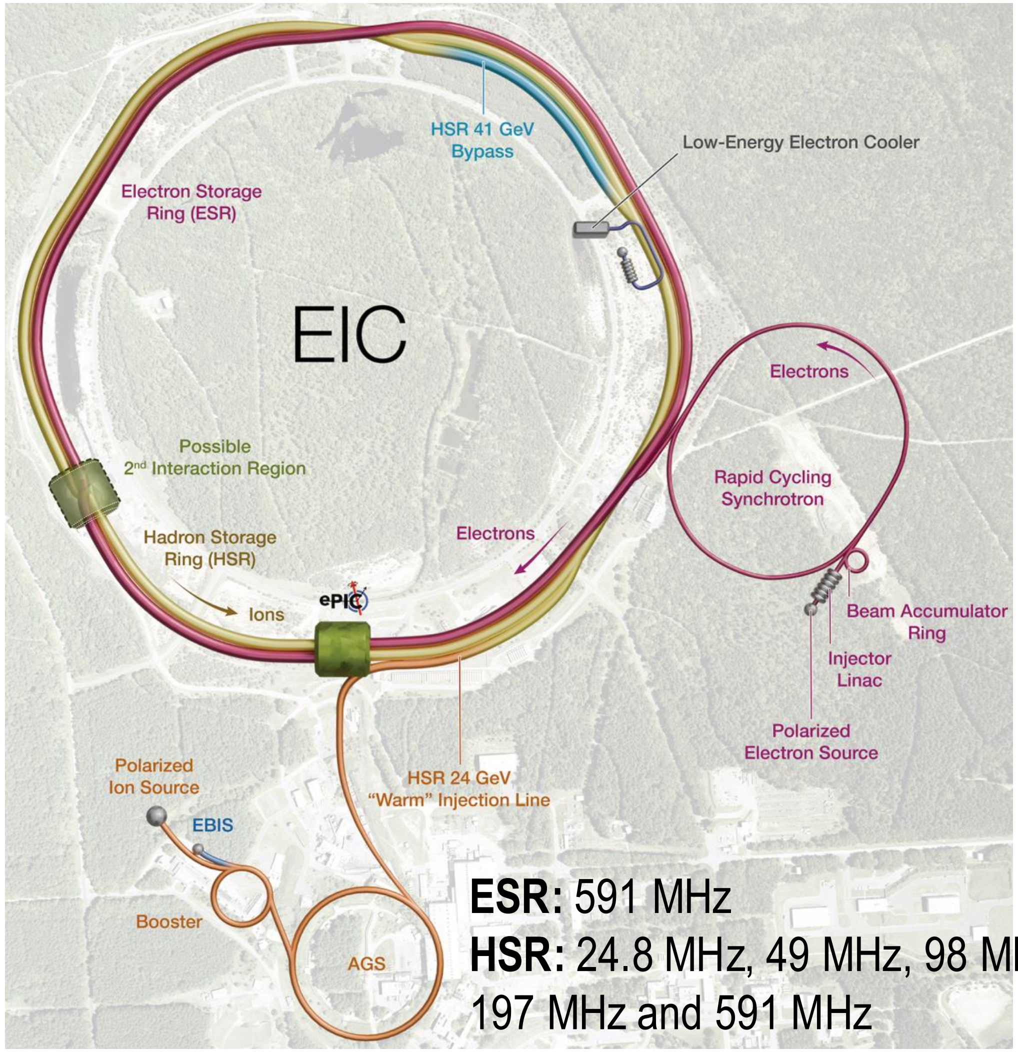


Outline

- Beam Intensity Parameters
- Impedance Modeling and Database
- Wakefield Simulations of the 2-Cavity String
- Total Wakefileds
- Instability Threshold Analysis
- Summary

EIC Project Overview

- **Electron Injection System**
  - **DC Photoelectron Gun**
    - 320 keV, ~85% polarization, 1.5 nC per bunch
  - **S-band LINAC**
    - 750 MeV energy, normalized emittance: ~80 μm (x), ~50 μm (y)
- **Beam Accumulator Ring (BAR, C≈50 m)**
  - 750 MeV energy, single-bunch accumulation: **28 nC**
  - Design lead by the NSLS-II team
- **Rapid Cycling Synchrotron (RCS, C≈1.4 km)**
  - **0.750→18 GeV** in 100 ms, **1 Hz**
  - Spin-transparent lattice, **28 nC**, normalized ε_n: 16-24 nm (x), 1.4-2.4 nm (y)
- **Electron Storage Ring (ESR, C≈3.8 km)**
  - Beam energy: **5-18 GeV**, current : **up to 2.5 A,** SR power: up to 10 MW
  - Polarized bunches, swap-out injection
- **Hadron Storage Ring (HSR, C≈3.8 km)**
  - **Beam energy:** Injection at 23.8 GeV, accelerated to 41-275 GeV
  - **Beam current:** up to 1 A / 0.7 A with M = 1160 / 290 bunches
  - **Crossing angle:** 25 mrad with crab cavities
  - **Spin rotators** (longitudinal) for p, d, He^3
  - **Cooler:** low-energy electron and stochastic cooling
  - **Luminosity:** up to 10^{33}-10^{34} cm^{-2}s^{-1}



ESR: 591 MHz
HSR: 24.8 MHz, 49 MHz, 98 MHz, 197 MHz and 591 MHz

Ultimate Beam Intensity Parameters

	5 GeV	10 GeV	18 GeV
Num. of electrons per bunch, N	1.72×10^{11}		6.25×10^{10}
Bunch Charge, Ne	28 nC		11 nC
Number of Bunches, M	1160		290
Single Bunch Current, $\mathrm{I}_0 = \frac{\mathrm{Ne}}{\mathrm{T}_0}$	2.2 mA		0.8 mA
Bunch Length, σ_τ	22.7 ps	25.4 ps	30 ps
Peak Bunch Current, $I_p = \frac{Ne}{\sqrt{2\pi}\sigma_\tau}$	484 A	433 A	155 A
Average Current, I_{av}	2.5 A	2.5 A	0.23 A

- High intensity beams at 5 GeV and 10 GeV

ESR Vacuum System Component Database

Documents > Components > ESR > **Mahoney ESR Vacuum**

+ New ⌄ | Upload ⌄ | Edit in grid view | Share | Sync | Copy link | Download

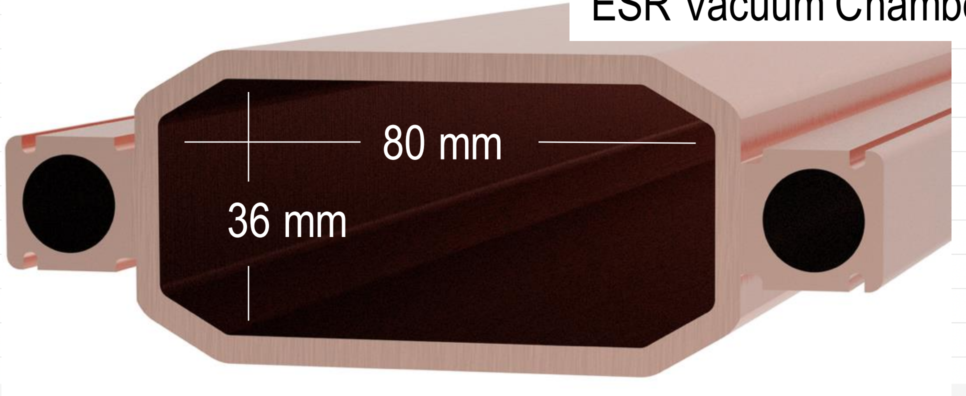
Name	Modified	Modified By
2604m0012bellows-ideal_070124.pdf	May 12	Mahoney, Matthew
2604m0012bellows-ideal_070124.stl	May 12	Mahoney, Matthew
80mm-GV_080524.pdf	May 12	Mahoney, Matthew
80mm-GV_080524.stl	May 12	Mahoney, Matthew
crotch_and_y_chmbr_05272025.stl	30 minutes ago	Sankar, Poopalasing
CROTCH_IMPEDANCE_05272025.pptx	29 minutes ago	Sankar, Poopalasing
DRW_4_SLM_CROTCH_IMPEDNZ.pdf	29 minutes ago	Sankar, Poopalasing
esr_80mm_pa_65min_080524.pdf	May 12	Mahoney, Matthew
esr_80mm_pa_65min_080524.stl	May 12	Mahoney, Matthew
esr_80mm_pa_69min_080524.stl	May 12	Mahoney, Matthew
esr_80mm_pa-pump_080524.pdf	May 12	Mahoney, Matthew

- **Accelerator Physics**
  Xiaofeng Gu, Gang Wang, … .
- **Vacuum System**
  Mathew Mahony, Charlez Hetzel, … .
- **Mechanical Design**
  George Dacos (IR10), Sankar Poopalasingam, Kentaro Matsushima, … .
- **Instrumentation System**
  David Gassner, … .
- **RF System**
  Zack Conway, Silvia Verdú – Andrés, Wencan Xu, Jiquan Guo, … .

List of Vacuum Components and Their Status

Element	Qty	Simulation geometry	Notes:
RF shielded bellows (80x36mm)	810	2604m0012bellows-ideal_07012024.stl	Previous file name: 2604m0012-physics-ideal_07012024.stl
Integrated photon absorber (69mm min gap)	869	esr_80mm_pa_69min_080524.stl	Previous file name: esr_80mm_photonabsorber_physics.stl
Integrated photon absorber (65mm min gap)	52	esr_80mm_pa_65min_080524.stl	Previous file name: esr_80mm_pa_v2.stl
Integrated photon absorber (69mm) with pump	200	esr_80mm_pa-pump_080524.stl	Previous file name: esr_80mm_pa-pump_physics.stl. Not included in the 869 photon absorbers or
Vacuum chamber (80x36mm)	3400		Approximate total length in meters
80mm flange step	1121	esr_flange_051425.stl	Previous file name: esr_flange_physics.stl. Previous version esr_flange_071624.stl
Pump port (80mm)	200	esr_80mm_pumpport_080524.stl	Previous file name: esr_80mm_pump_physics.stl
RF shielded gate valve (80mm)	52	80mm-GV_080524.stl	esr_gatevalve-80mm_physics.stl
BPM (80blank)	300	alexei_2025-04-18_final.stl unit of meter	Latest STL generated April 18. No changes planned.
BPM (80mm) 20mm simplified geometry	300	simple_###_2024-08-06_mm	Note: for file names, ### should be either "alum" or "vac"
BPM (80mm) 20mm original geometry	300	original_###_2024-08-06	Note: for file names, ### should be either "alum" or "vac"
BPM (80mm) 22mm	300	esr_22mm_spacing_###_2025-03-26.stl	Note: for file names, ### should be either "alum" or "vac"
RF cavities (1 cell, 591 MHz)	18		RF Group
IR10			
591 MHz RF Cavity	18		
Bellows, 274 mm aperture	18		
Bellows, 180 mm aperture	40		
Tapered Transition	2		
Gate Valve, 180 mm aperture	20		
Beam Line Absorbers, 274 mm aperture	9		
Beam Pipes,180 mm aperture, L~5 m	10		
Beam Pipes, 150 mm aperture, L~2.5 m	8		
IR6			

ESR Vacuum Chamber Profile

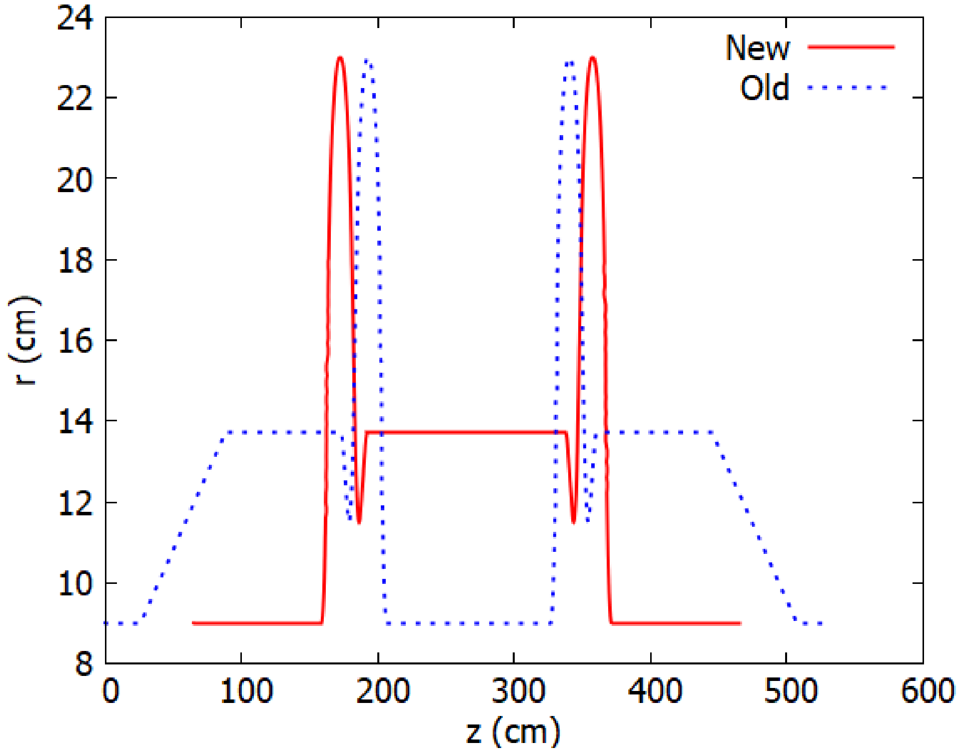


- Total wakefield simulations for the ESR are in progress.

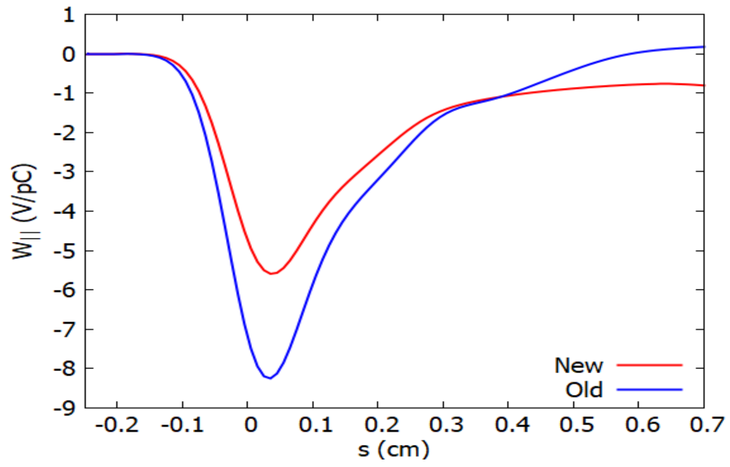
IR10 SRF and Beam Line System

Components	Abbreviation	Previous Number	New Number
IR10			
591 MHz RF Cavity	CAV	17	18
Bellows, 274 mm aperture	BLW 274	17	18
Bellows, 180 mm aperture	BLW 180	0	40
Bellows, 150 mm aperture	BLW 150	17	0
Tapered Transition	TPRD	19	2
Gate Valve, 180 mm aperture	GV 180	0	20
Gate Valve, 150 mm aperture	GV 150	17	0
Beam Line Absorbers, 274 mm aperture	BLA 274	17	9
Beam Line Absorbers, 150 mm aperture	BLA 150	17	0
Beam Pipes,180 mm aperture, L~5 m	BP 180	0	10
Beam Pipes, 150 mm aperture, L~2.5 m	BP 150	18	0

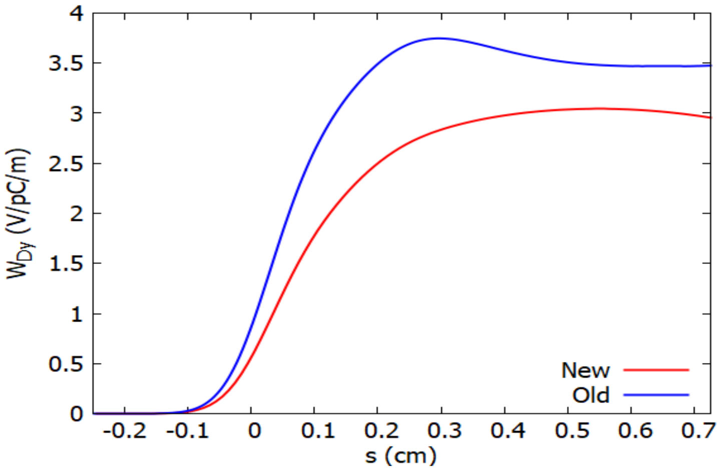
Two Back-to-Back 591 MHz Cavities



Longitudinal Wakefield



Vertical Dipole Wakefield



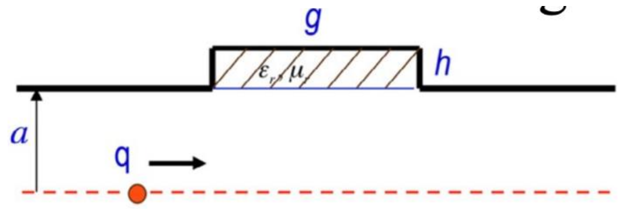
- Large-aperture connection eliminates tapered transitions between cryomodules.
- ~40% reduction in $W_{||}(s)$ and $W_{Dy}(s)$ from old to present geometry
- Design meets ESR wakefield requirements

Gang Wang

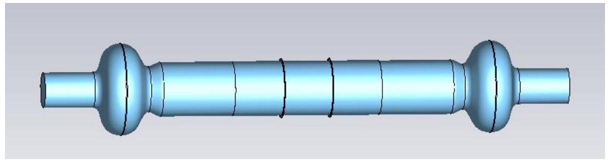
Wakefield Simulations for 2-Cavity String

- **Simulated Vacuum Components**
  - Two Back-to-Back 591 MHz RF Cavities
  - Beam Line Absorbers, 274 mm aperture

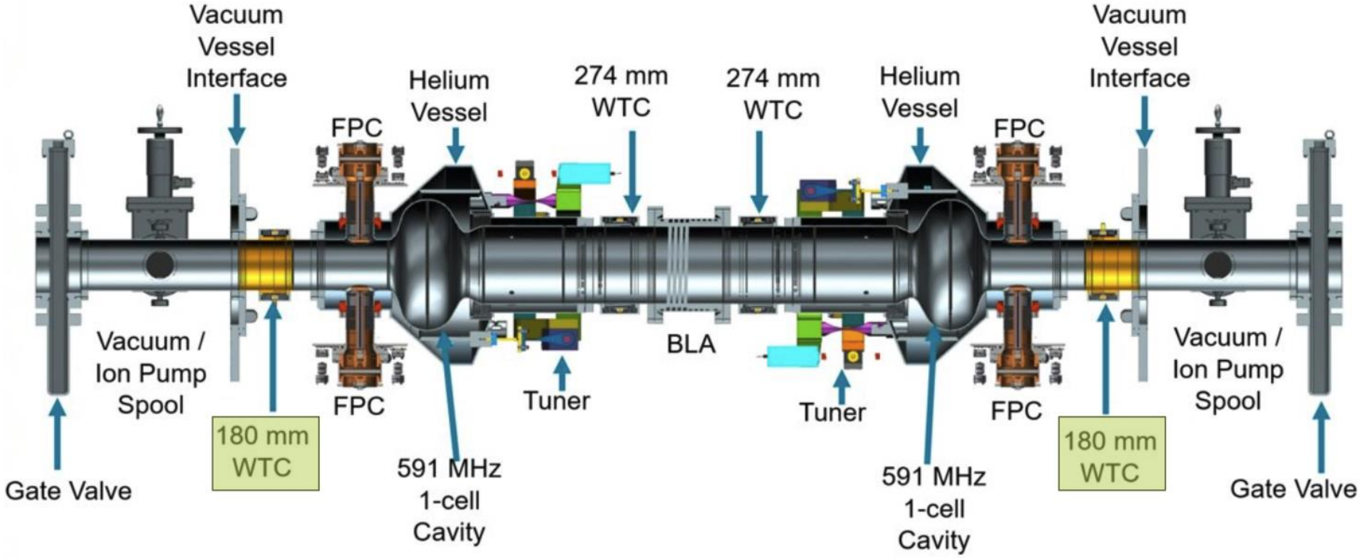
Beam Line Absorber



Two Back-To-Back Cavities

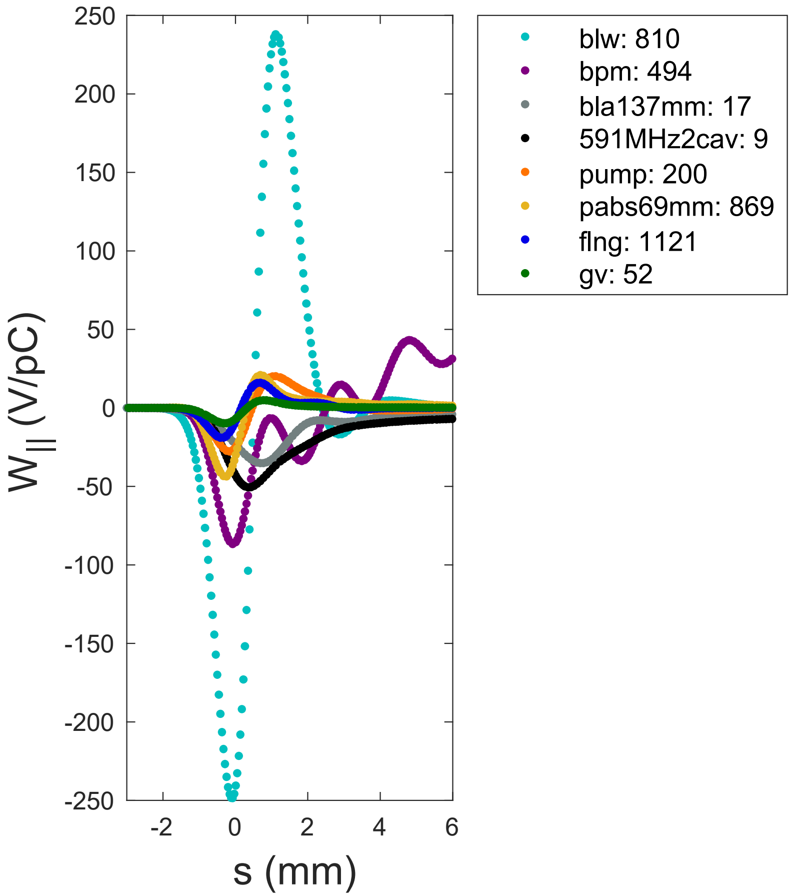


- **Remaining Components to Simulate**
  - Bellows, 274 mm aperture
  - Tapered Transition (Arc to Straight Section)
  - Gate Valve, 180 mm aperture
  - Beam Pipes,180 mm aperture, L~5 m

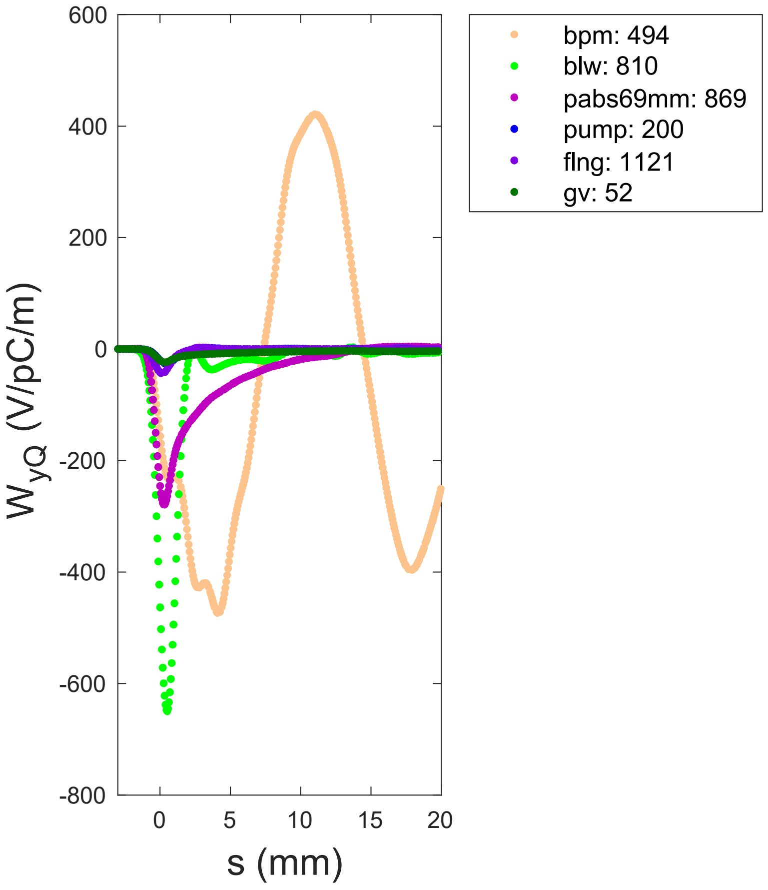


- No significant impact is expected from adding $W_{||}(s)$ and $W_{Dy}(s)$ of the remaining cryomodule components to the total wakefield.

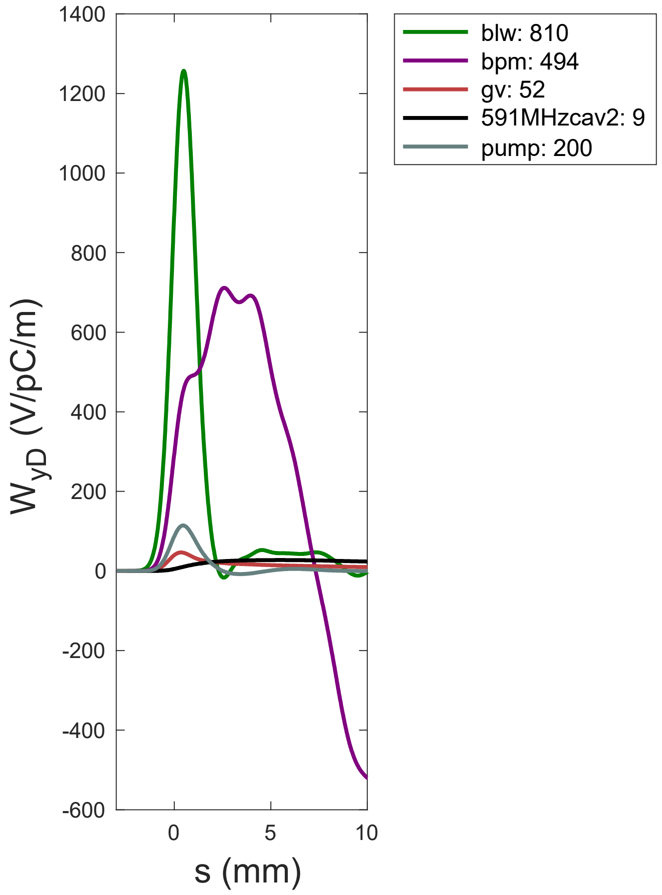
Breakdown of Wakefields by Component



Longitudinal Wakefield



Quadrupole Wakefield



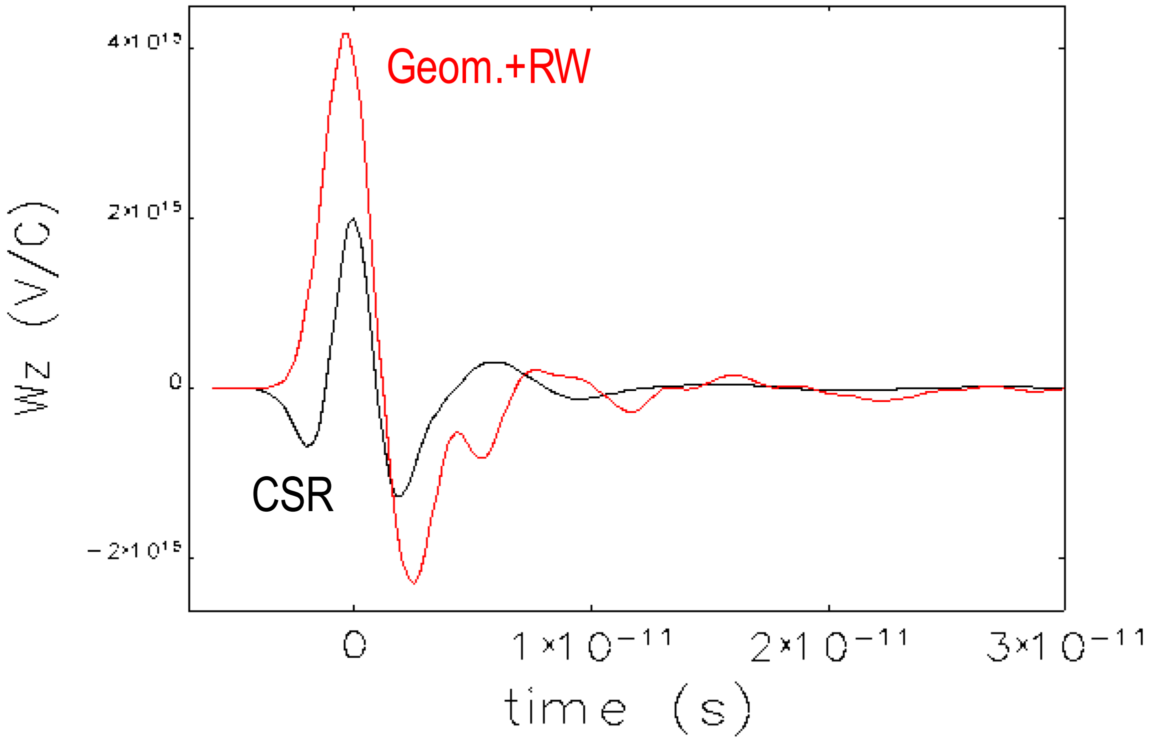
Vertical Dipole Wakefield

- Wakefields have been simulated for a 0.5 mm bunch length (Pseudo Green Functions).

Main Parameters At 5 GeV

Lattice v6.3

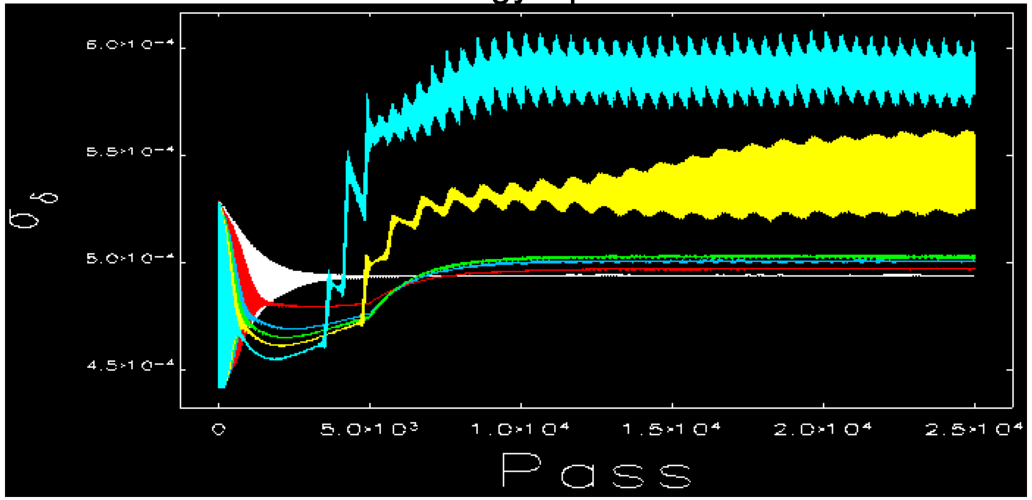
Energy, E	GeV	5
Average Current, I_{av}	A	2.5
Revolution Period, T_0	μs	12.79
Gammat		29.6
Momentum Compaction, α		1.14×10^{-3}
Number of Bunches, M		1160
Energy Loss, U_0	MeV	1.2
RF Voltage, V_{RF}	MV	12
RF Acceptance	%	1.2
Synchrotron Tune, ν_s		0.057
Damping Time, $\tau_{x,y}, \tau_s$	ms	54, 27
Energy Spread, σ_δ		4.93×10^{-4}
Bunch Length, σ_s	mm	6.0



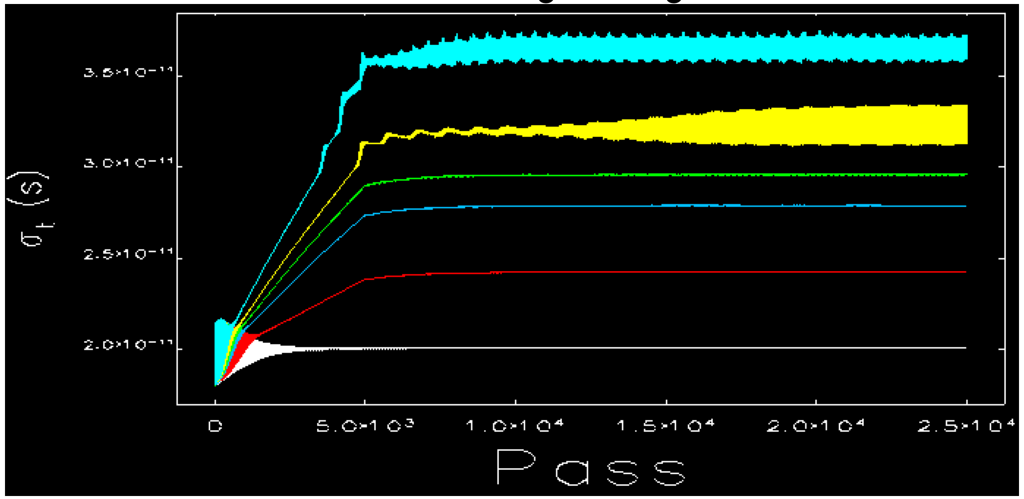
- A safety factor of 2 was applied to the Geom. + RW Wakefield.

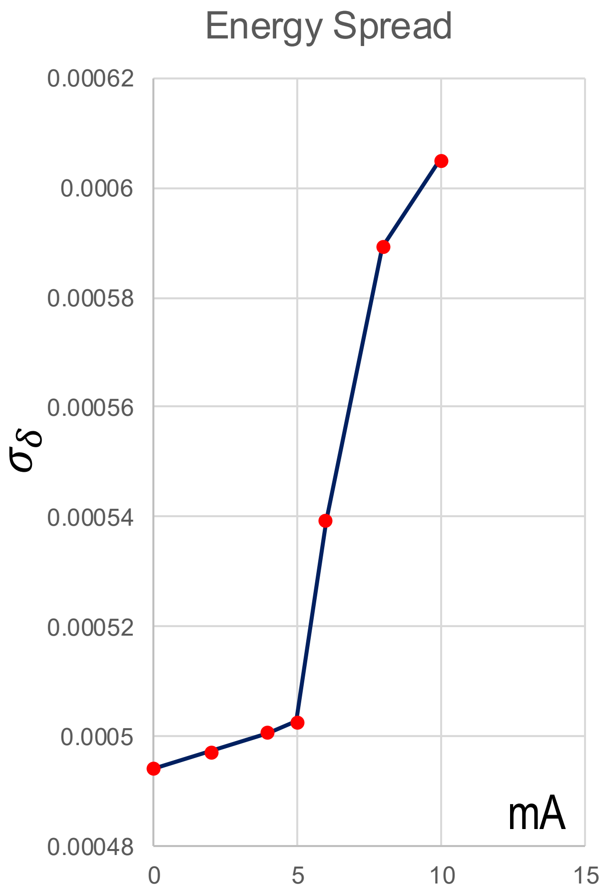
ELEGANT Simulations of MWI

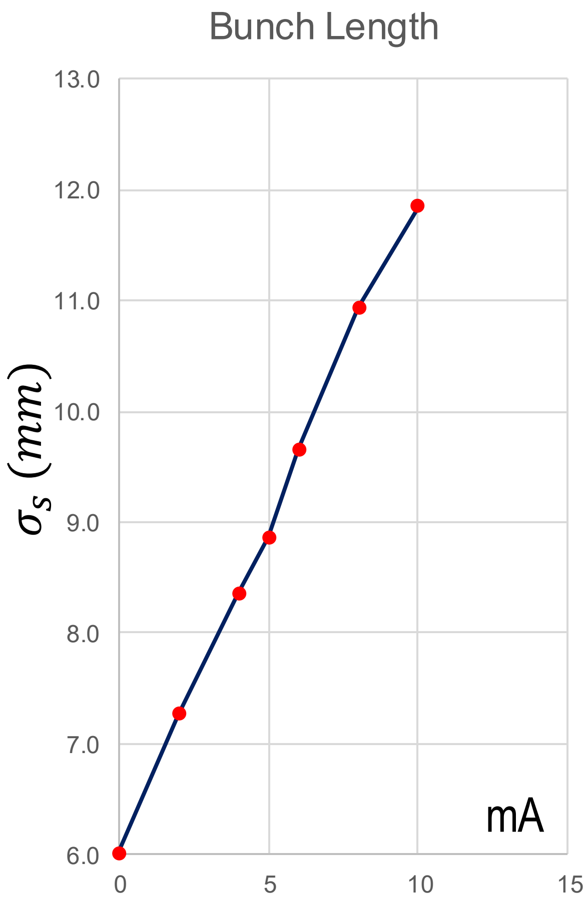
Energy Spread



Bunch Lengthening







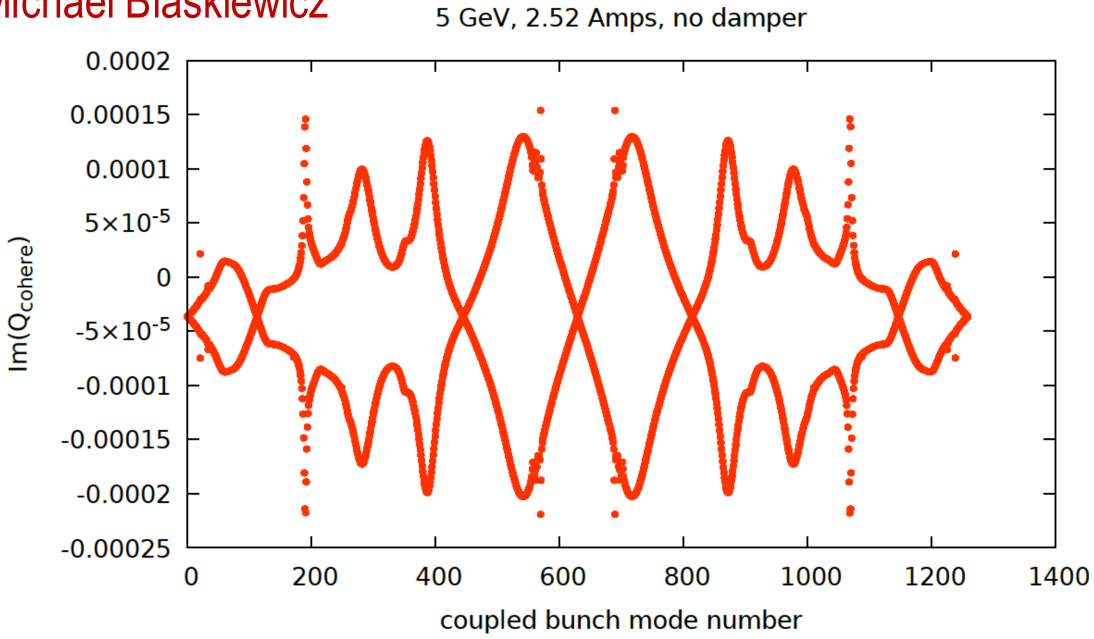
- MWI threshold, $I_{MWI,th} > I_0$

Coupled Bunch Instabilities at 5 GeV

- Longitudinal multiple coupled-bunch modes are unstable at 2.5 A average current. The growth time is 20 ms.

$$\Omega^2 - \omega_s^2 = \frac{iq\alpha\omega_0^2 \bar{I}}{2\pi E} \sum_{j=-\infty}^{\infty} (Mj + \mu)\, e^{-(Mj+\mu)^2\sigma^2} Z_{\|}(\omega_0\,[Mj+\mu] + \Omega)$$

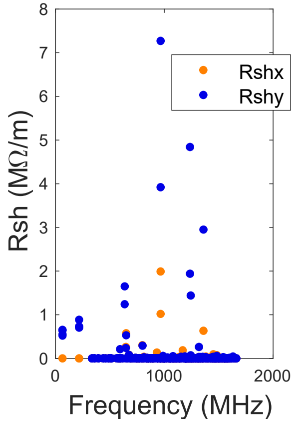
Michael Blaskiewicz



$$\Omega_\mu - \omega_0\nu_\perp = -i\frac{ecI_{av}}{2E}\frac{\beta_\perp^{cav}}{C}\sum_{j=-\infty}^{\infty} Z_\perp\left[\left(Mj + \mu + \nu_y\right)\omega_0\right]$$

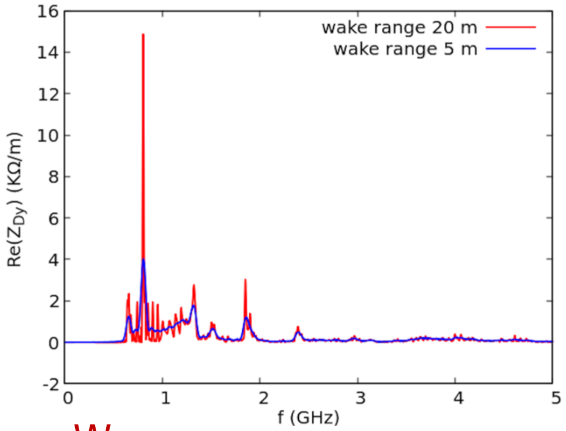
- The beam is stable against vertical coupled-bunch instabilities during beam-beam collision.
- The vertical shunt impedance <12 MΩ/m (Eng. def.).
- Cross-checking beam stability, RW+HOM's w/o beam-beam collision.

CST (Frequency Domain)



Wencan Xu

ECHO (Time Domain)



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- **Longitudinal** bunch-by-bunch feedback (damper) is required
- **Vertical** bunch-by-bunch feedback is under investigation

Summary

- 2-cavity 591 MHz string contribution analyzed for single-bunch dynamics and HOM-driven effects.
- Wakefield and Stability Analysis:
  - A longitudinal damper is required to suppress coupled-bunch instabilities driven by HOMs from the 2-cavity string.
  - A transverse damper is under investigation to address potential transverse coupled-bunch instabilities (without beam-beam effect)
  - The beam is single-bunch stable
- Cryomodule impedance meets the requirements
  - Remaining components will be incorporated into the impedance budget; No significant impact is expected due to their shielded and standardized designs.