Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Introduction to Impedance and Instabilities

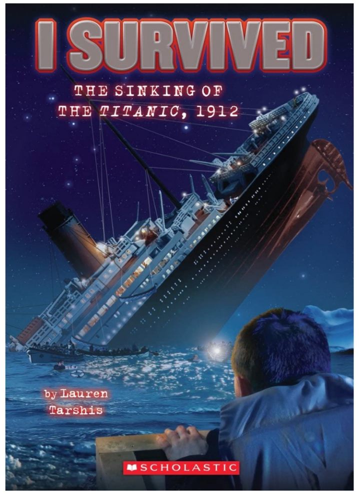
Medani P. Sangroula, Steve Peggs, Todd Satogata, Alex Coxe

USPAS Accelerator Physics

01/31/2024

@BrookhavenLab

I SURVIVED



January 2015: Hampton, VA

January 2024: Hampton, VA

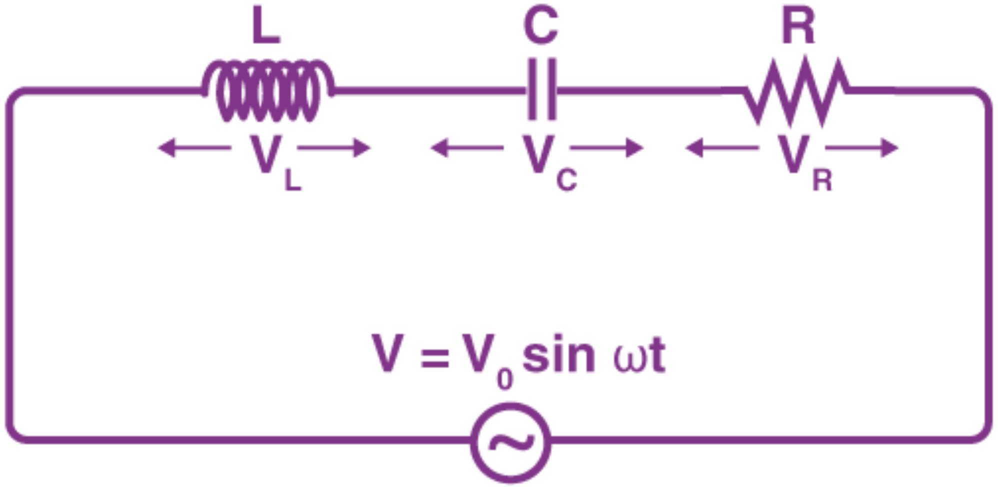
Impedance of LCR circuit

For purely resistive circuit, Z = R

$$V_L = IX_L, V_C = IX_C, V_R = IX_R$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Phase = tan^{-1}\left(\frac{X_L - X_C}{R}\right)$$



$$V = I\,Z$$

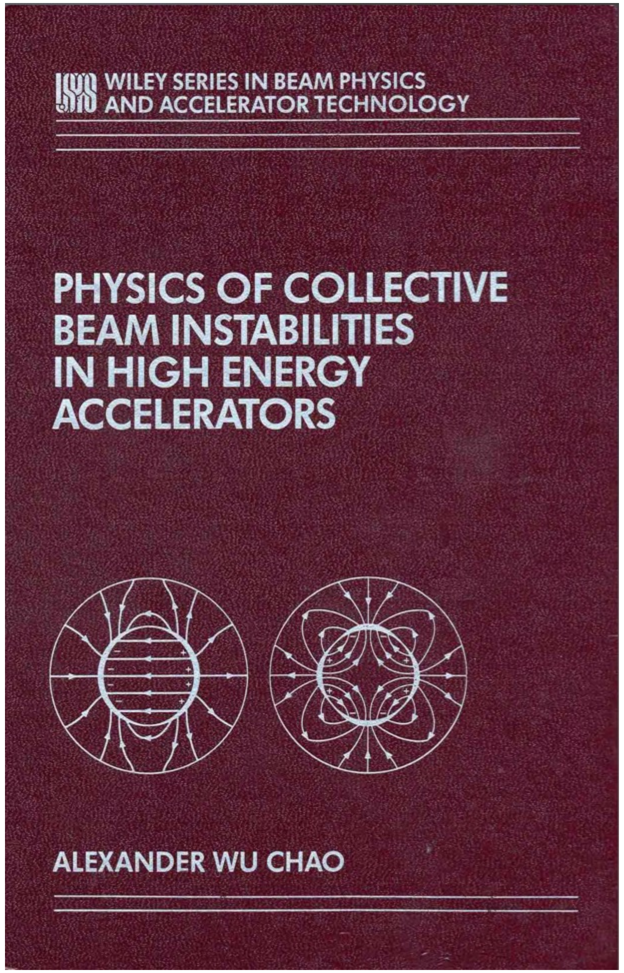
Outline

- Introduction to instability
- Wakefield and impedance
- Overview of the APS Upgrade
- Motivation behind the impedance measurements
- Measurement techniques : Goubau line, and results
- Impedance optimization: an example
- Resistive wall (RW) loss calculation
- Thermal analysis

Introduction to collective instability

- The intense particles beam (medium to high intensity) inside the vacuum chamber generates electromagnetic fields.
- These self-generated fields interreacts with with its surroundings (wall of the vacuum chamber) to generate another electromagnetic field, known as the wakefield.
- The wakefield then acts back on the subsequent beam, perturbing its motion.
- Under unfavorable conditions, the perturbation in the beam further enhances the wakefield and then leads to an instability, known as a collective instability.
- **The collective instability ultimately results beam loss!!**
- The beam and its surroundings form a self-consistent dynamical system:

Dynamical system = beam + surroundings,
Mediator for interaction = wakefields



WILEY SERIES IN BEAM PHYSICS AND ACCELERATOR TECHNOLOGY

PHYSICS OF COLLECTIVE BEAM INSTABILITIES IN HIGH ENERGY ACCELERATORS

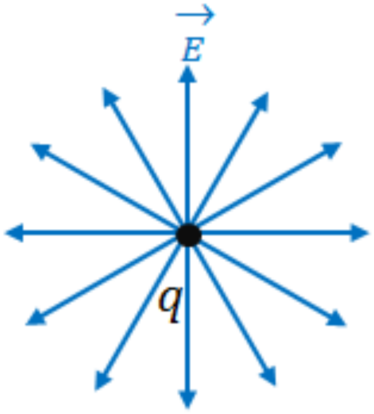
ALEXANDER WU CHAO

https://www.slac.stanford.edu/~achao/wileybook.html

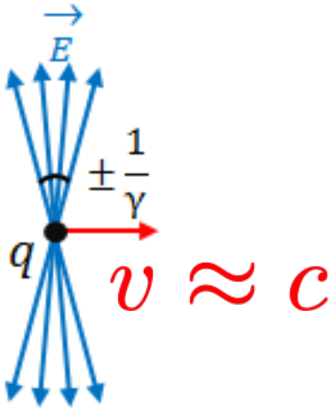
Wakefields and Impedances

- The Coulomb field of a relativistic charge particle appears “flattened” into a pancake shape.

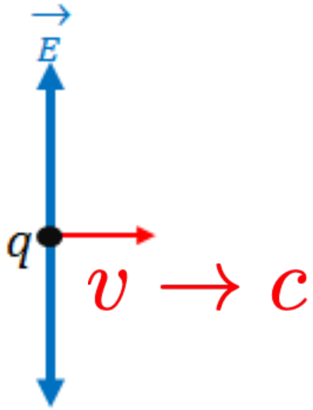
- These fields must also satisfy boundary conditions on vacuum chamber walls.
- Field lines can be arranged to satisfy appropriate boundary conditions for arbitrary geometries.



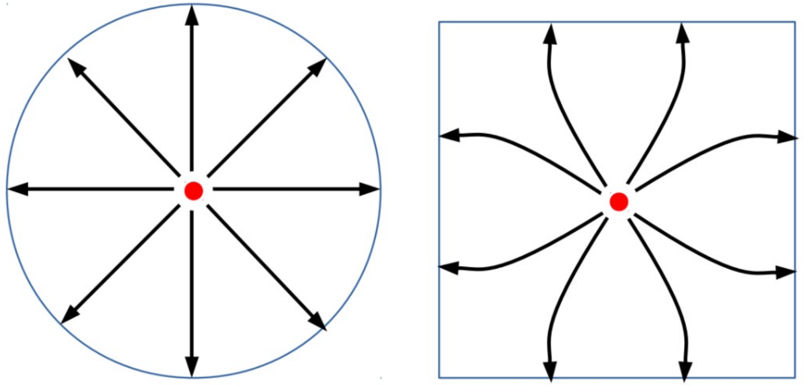
(a) stationary charge



(b) relativistic charge



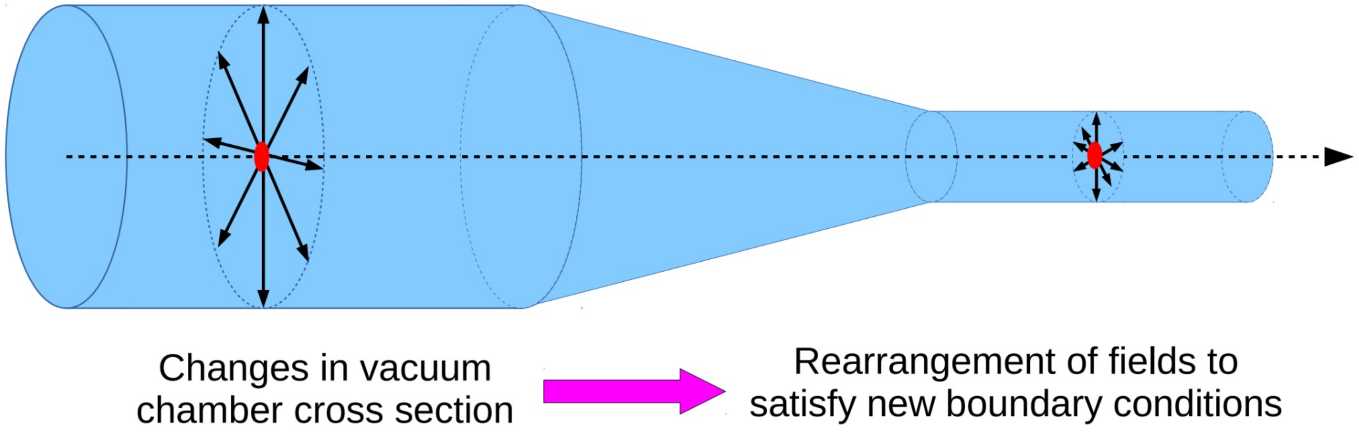
(c) ultra-relativistic charge



Field lines on two different cross section

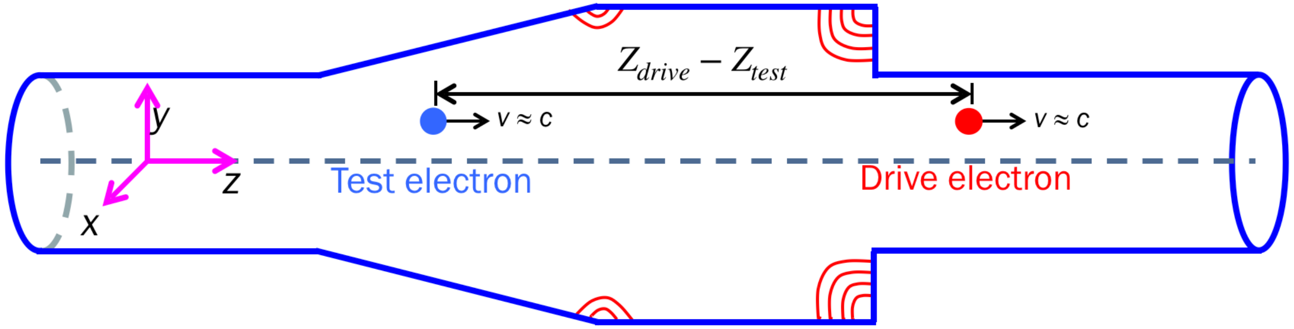
Wakefields and Impedances

- If a change in cross-section occurs (beam pipe), rearrangement of em fields occurs to satisfy new boundary condition (BC).
- The new BCs result in **EM fields** behind the exciting particle (since v ~ c) which are called **wakefields**.



Water wakes

Wakefields and Impedances



- The Fourier transform of the wakefield is called the impedance.

$$Z_{\parallel}(\omega) = \frac{1}{c}\int d\xi\, e^{i\omega\xi/c} W_{\parallel}(\xi)$$

$$\xi = z_{drive} - z_{test}$$

$$\text{Impedance}(Z_{\parallel}) \propto \frac{1}{\text{beam pipe radius}}$$

- The test electron energy changes because of the EM fields of drive electron. This energy change can be characterized in terms of wakefields.

$$\boxed{\Delta\gamma} = -\frac{e}{mc^2}\int_{-\infty}^{\infty} ds E_z \equiv -\frac{e^2}{mc^2}\boxed{W_{\parallel}(x,y,z)}$$

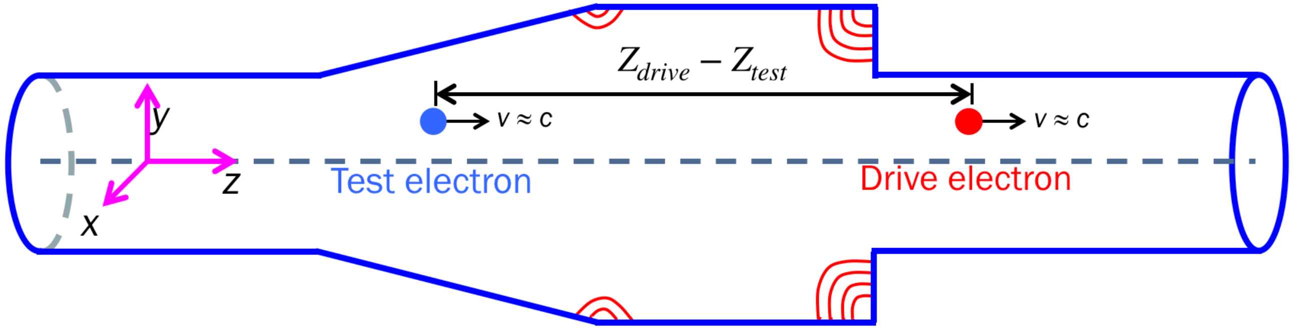
energy change

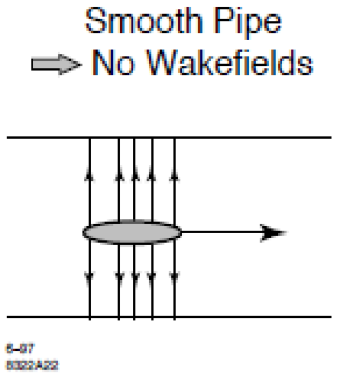
wakefield

- The **strength of wakefields** depends upon the **conductivity and the cross-section variation** of the chamber.

Longitudinal vs Transverse Wakefields

- As the particle moving in an accelerator has two type of oscillations: longitudinal (synchrotron) and transverse (betatron), wakefields are also of two types; **longitudinal and transverse**.
- Longitudinal Wakefield causes **energy loss** of the beam while the transverse wake **deflects beam trajectory**.





PEC: No Wakefield

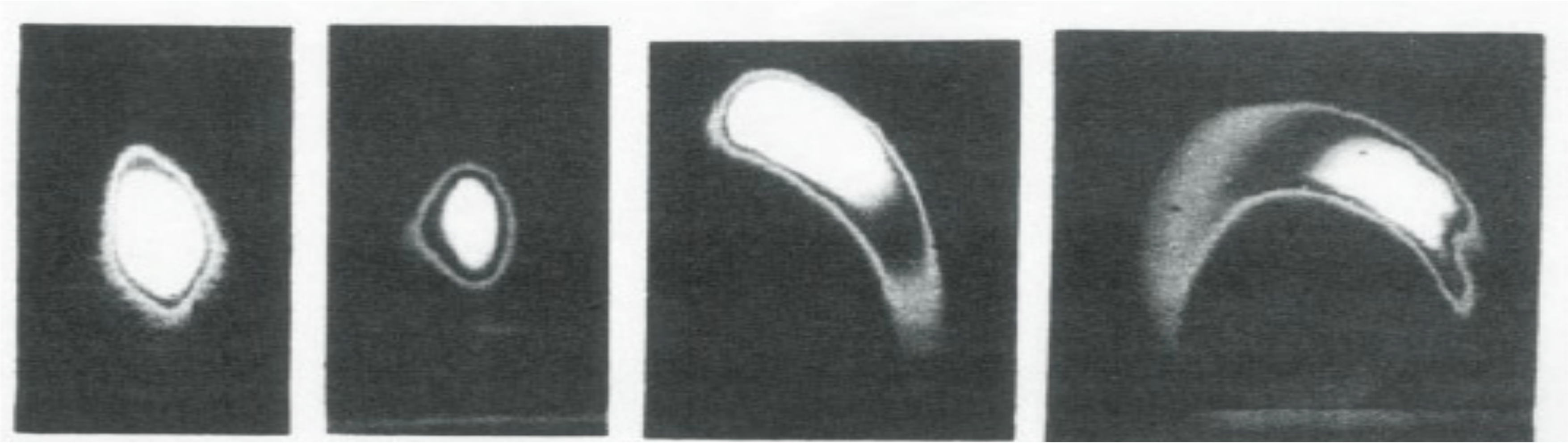
Effects of Longitudinal Wake/Impedance

Impedance type	Causes	Effects
• Broad Band Impedance (short term wakefield)	• Heating of vacuum chamber components due to energy loss • Bunch lengthening • Microwave instability	• Component damage • Increase in energy spread (not a severe effect)
• Narrow Band Impedance (long term wakefield)	• Heating of cavities • Multi-bunch instabilities	• Component damage • Increase in emittance

Effects of Transverse Wake/Impedance

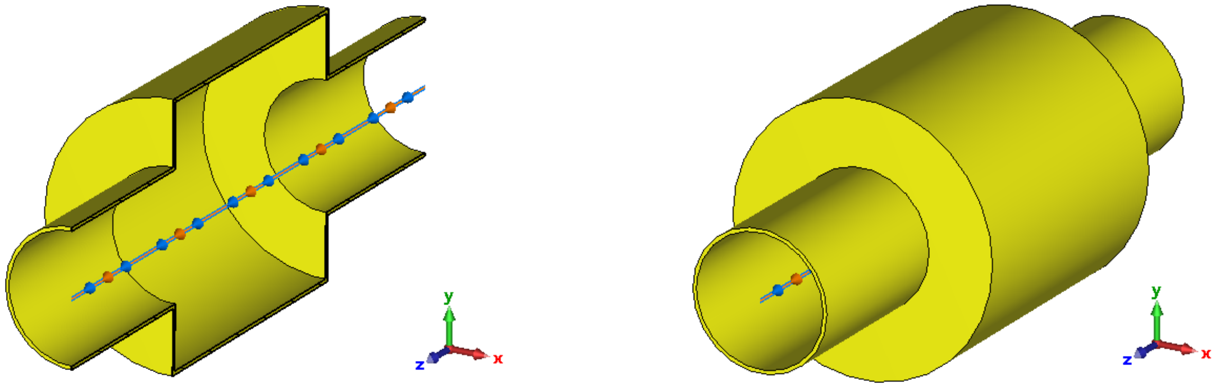
- Wakefield interacting with immediate surroundings will perturb external prescribed fields.
- If the perturbation is strong enough, beam becomes unstable.
- Different types of instabilities (longitudinal and transverse) may occur. Beam might be lost completely.
- Effects are prominent for high energy beam (beam with high intensity).

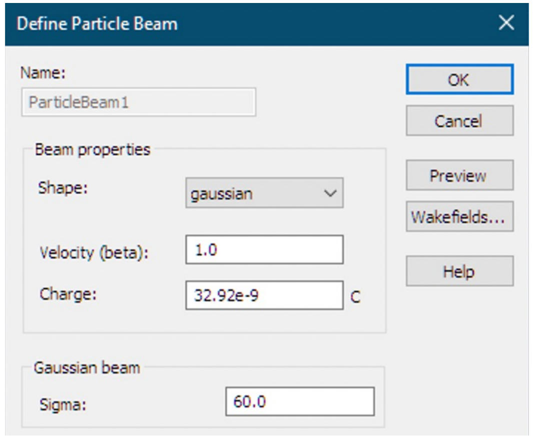
Fig: example of beam break up (transverse) instability observed at SLAC



Transverse beam profiles at the end of the SLAC linac for on axis beam and offsets of 0.2 mm, 0.5 mm and 1.0 mm respectively

Wakefields and Impedances




Define Particle Beam

Name: ParticleBeam1

Beam properties

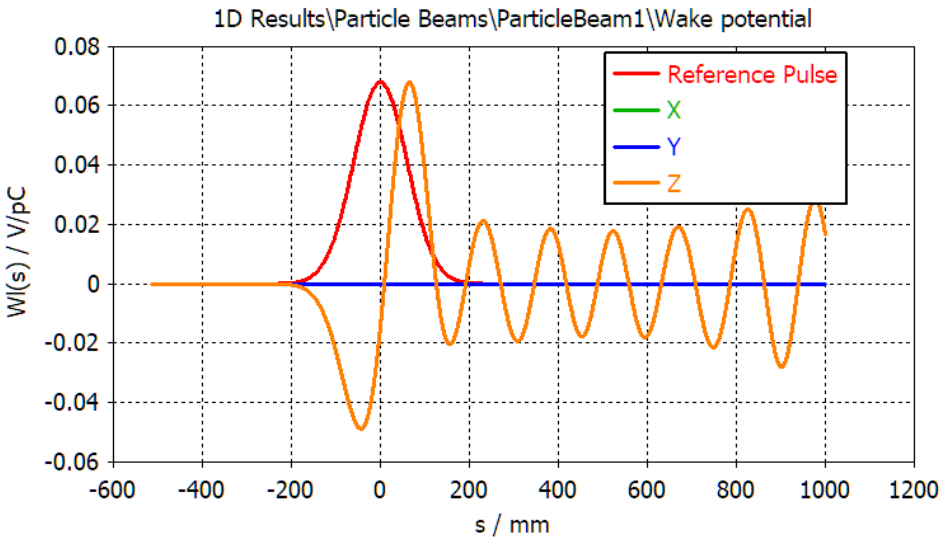
Shape: gaussian

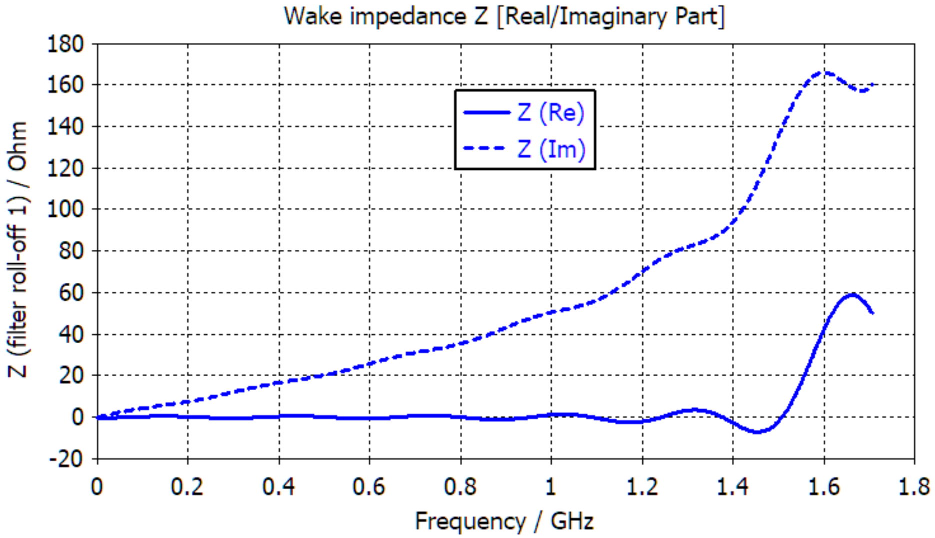
Velocity (beta): 1.0

Charge: 32.92e-9 C

Gaussian beam

Sigma: 60.0



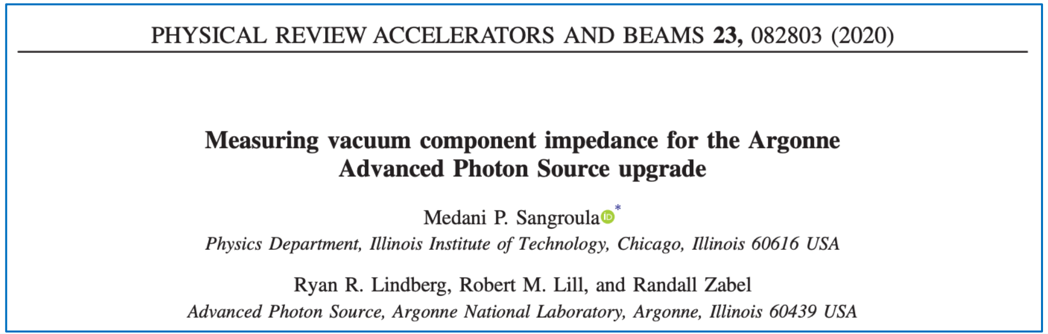


Recap

- What is wakefield?
- What is impedance?
- What are the effects of longitudinal and transverse impedances?

http://www.gdfidl.de/

https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.082803



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 082803 (2020)

Measuring vacuum component impedance for the Argonne Advanced Photon Source upgrade

Medani P. Sangroula[*]
Physics Department, Illinois Institute of Technology, Chicago, Illinois 60616 USA

Ryan R. Lindberg, Robert M. Lill, and Randall Zabel
Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439 USA

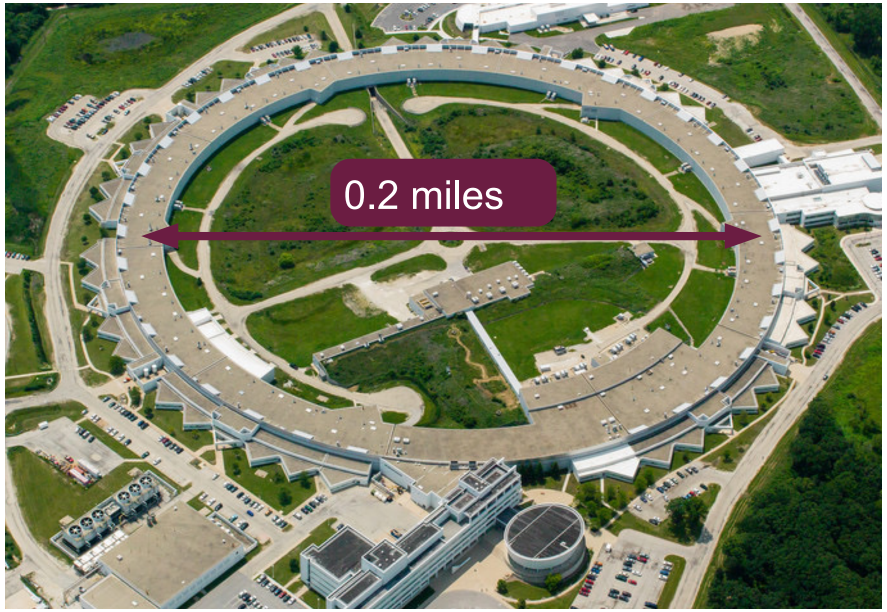
Coupling Impedance Measurement and Analysis of Vacuum Components for the APS-Upgrade

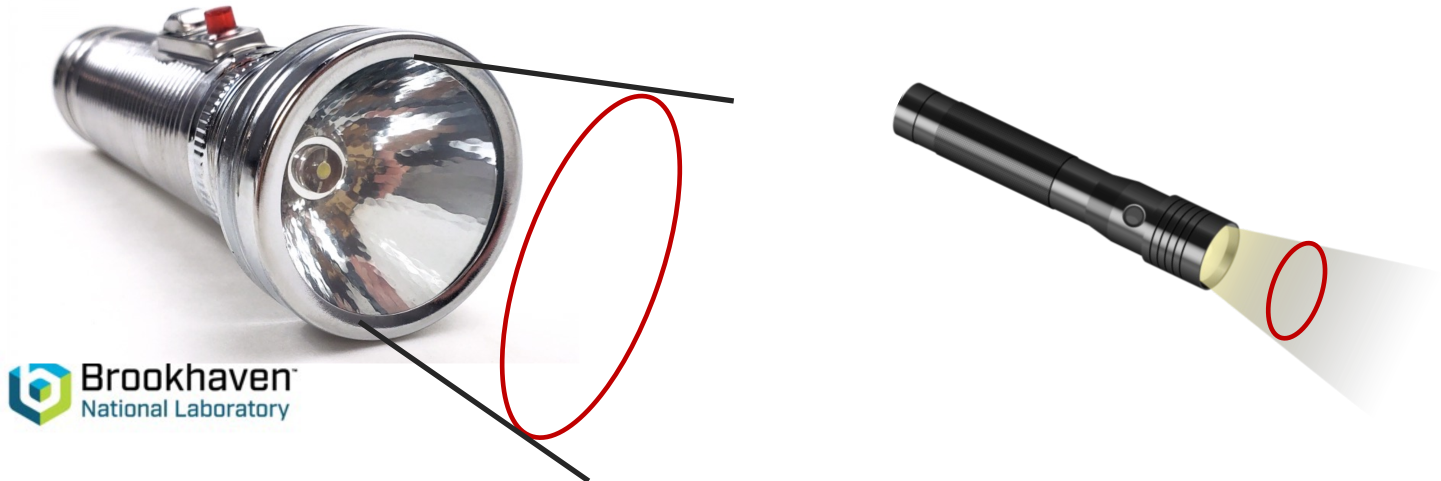
- Overview of the APS-Upgrade
- Motivation behind the impedance measurements
- Measurement techniques: Goubau line
- Results

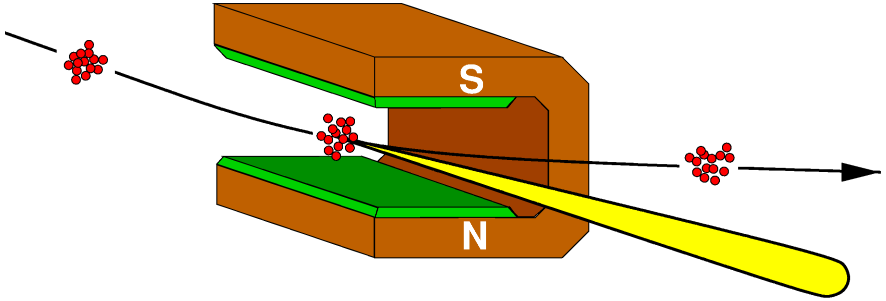
Background Information

- A relativistic charged particle such as an electron emits radiation when it moves through a curved path. This radiation is called synchrotron radiation.
- An accelerator facility that generates this type of powerful X-rays or radiation is called a storage ring.
- The quality of the synchrotron radiation can be characterized in terms of brightness.

$$\text{Brightness}(\lambda) = \frac{\text{Photon Flux}(\lambda)}{\text{Area of Phase Space (Emittance)}}$$





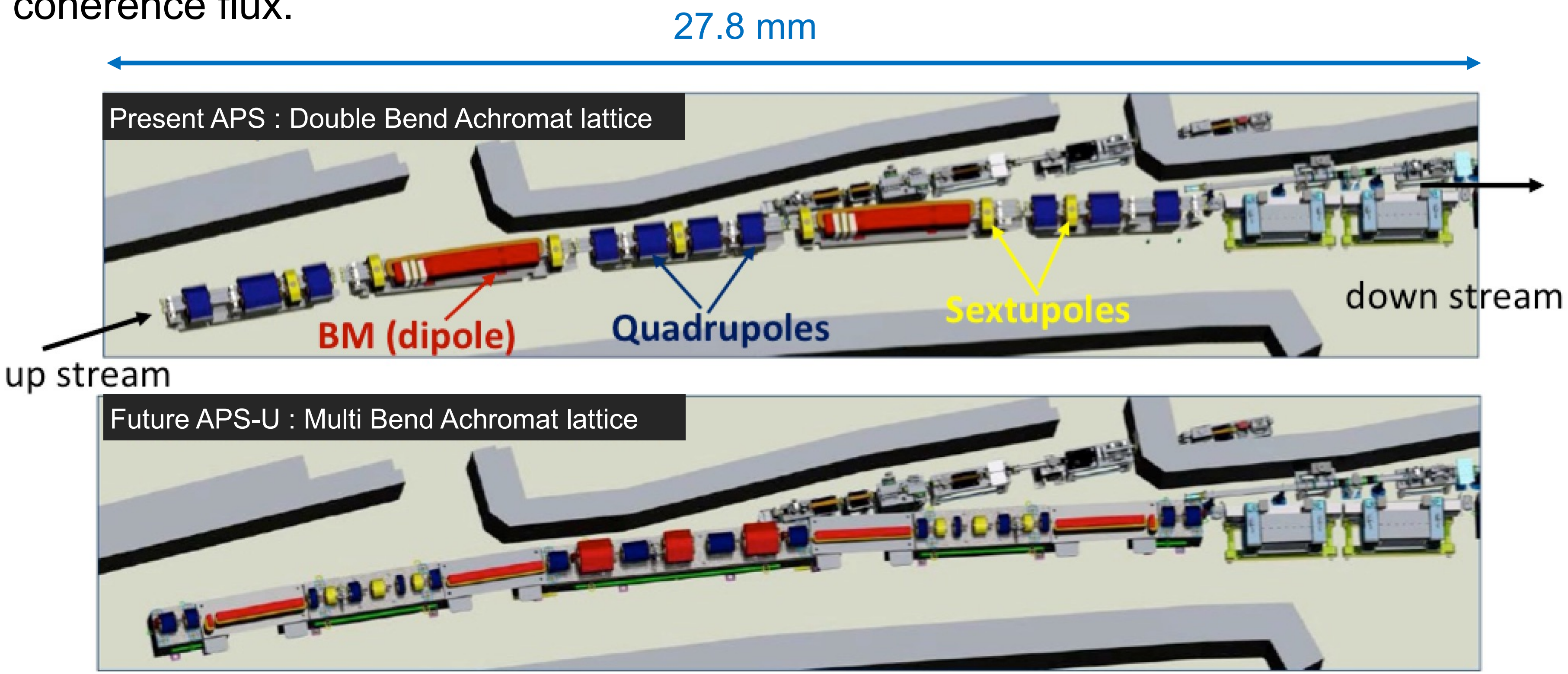


http://photon-science.desy.de/

Overview of the APS Upgrade (APS-U)

APS-U provides;

- Incorporation of the fourth generation MBA lattice
- Reduction of emittance by a factor of ~100 and installation of superconducting undulators, and
- Generation leap in storage ring performance with a factor of 100 -1000 increase in brightness and coherence flux.



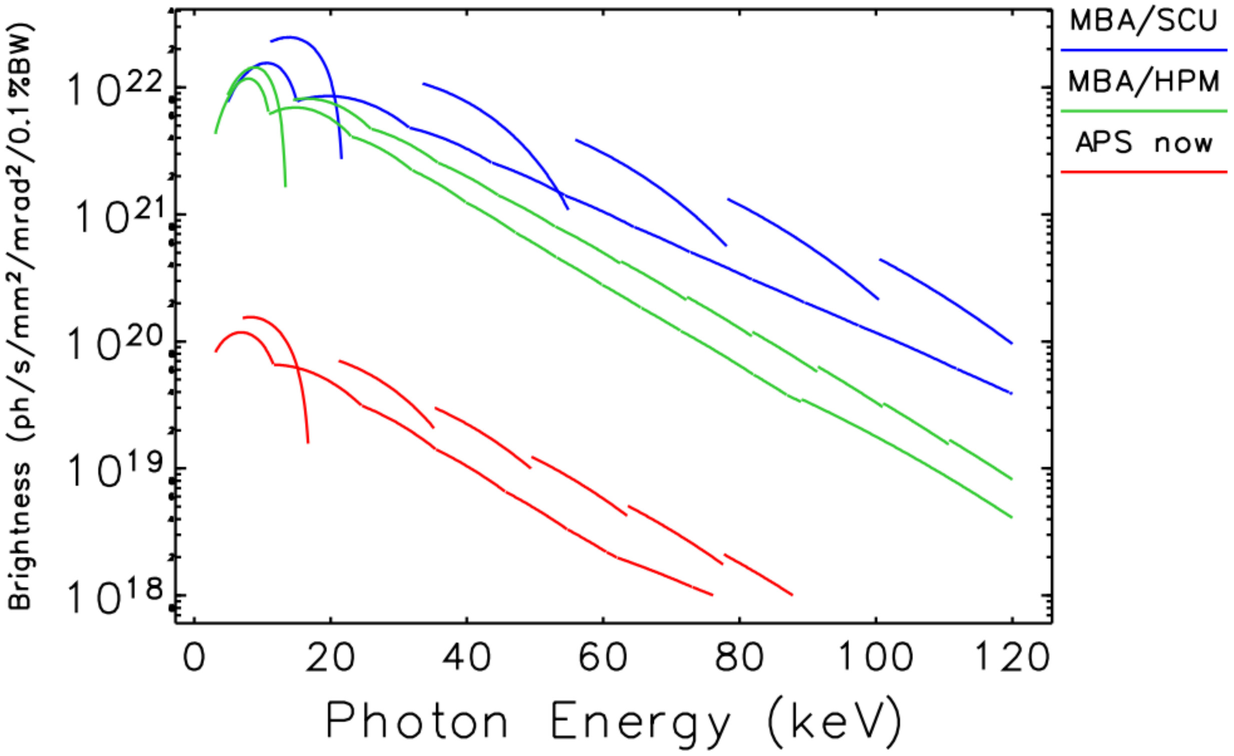
$$\text{Emittance} \propto \frac{E^2}{N_d^3}$$

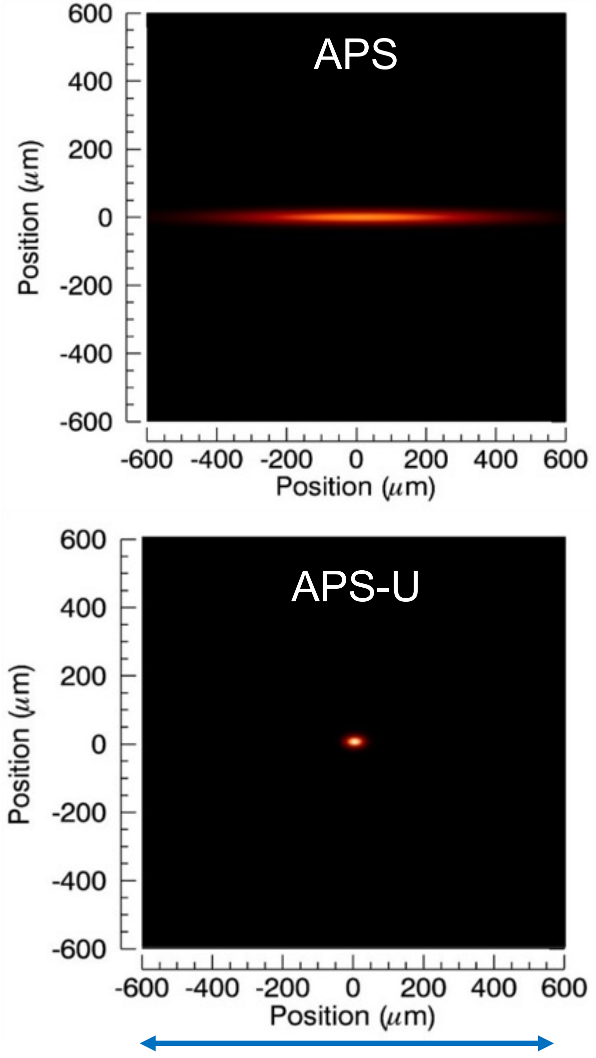
3200 pm-rad

↓

~42 pm-rad

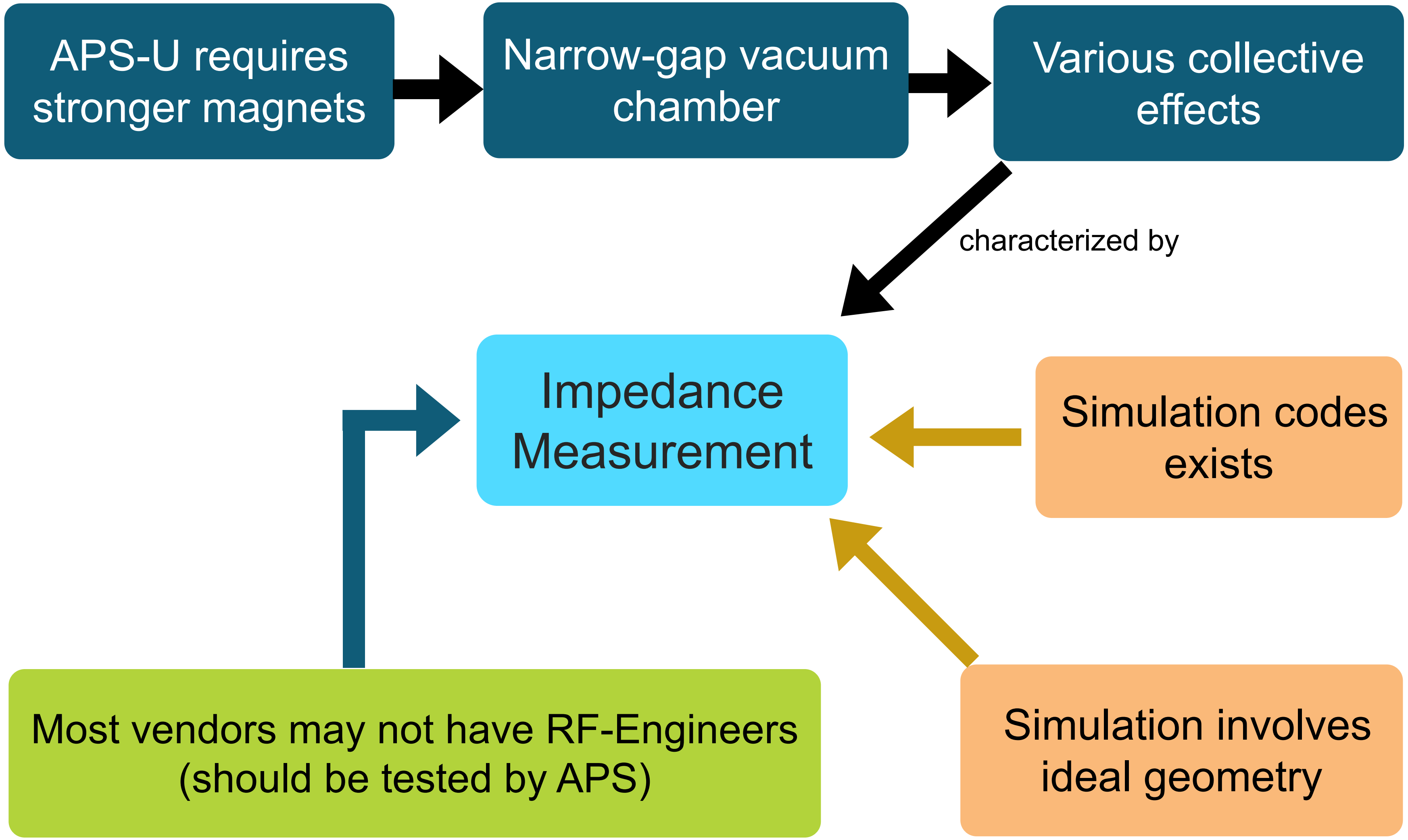
Overview of the APS Upgrade (APS-U)





1.2 mm

Motivation Behind the Impedance Measurement



APS-U requires stronger magnets

Narrow-gap vacuum chamber

Various collective effects

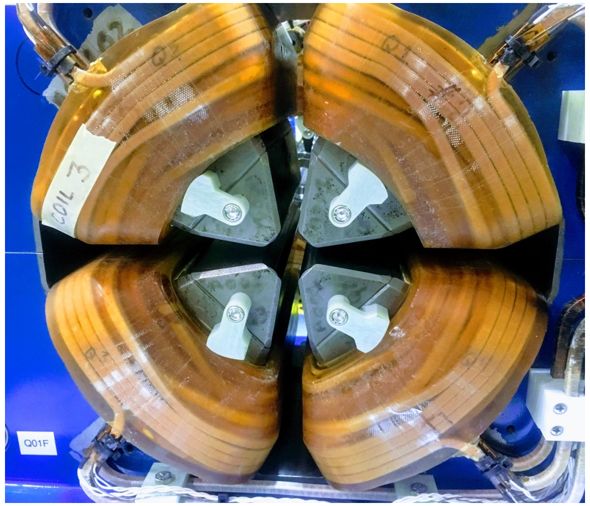
characterized by

Impedance Measurement

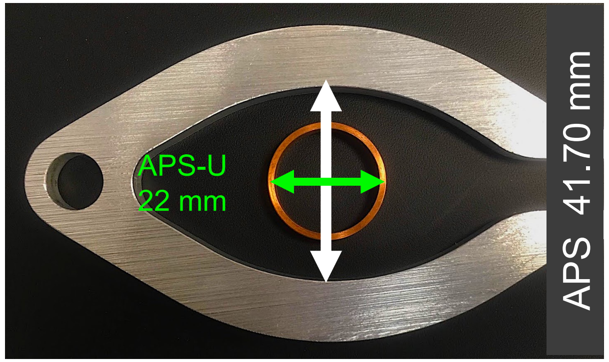
Simulation codes exists

Simulation involves ideal geometry

Most vendors may not have RF-Engineers (should be tested by APS)



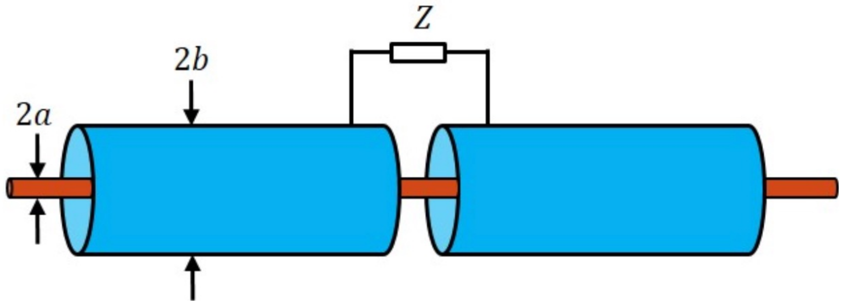
APS-U Quadrupole



Vacuum chamber cross section comparison

S-parameters for a lumped impedance Z

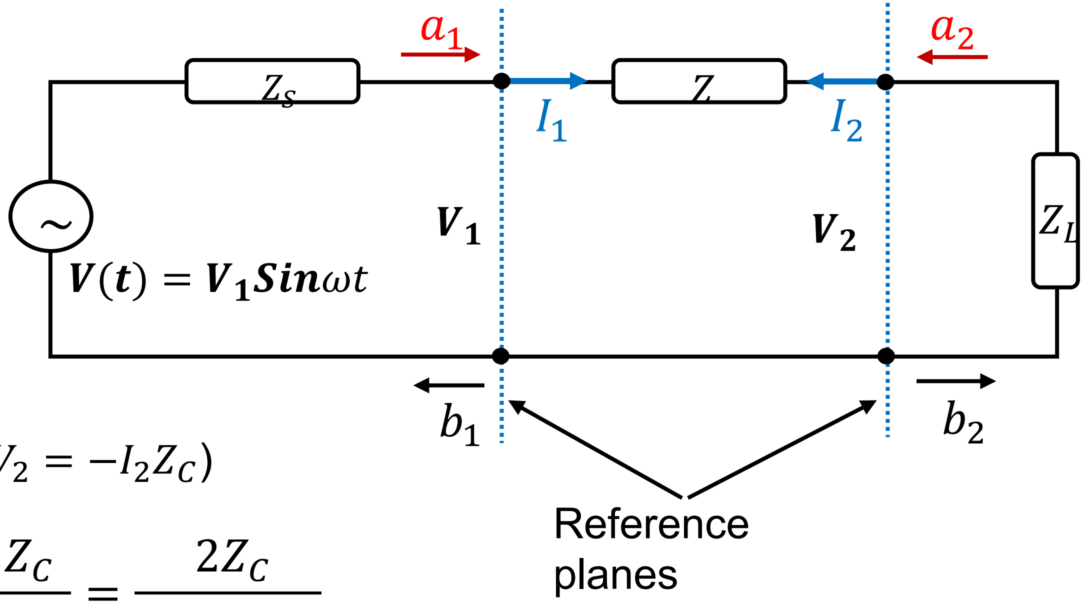
Lumped element : If the physical length of DUT is less then the diameter of the beam pipe.



Examples of two port network:

$$a_1 = \frac{V_1+I_1Z_C}{2\sqrt{Z_C}} \qquad a_2 = \frac{V_2+I_2Z_C}{2\sqrt{Z_C}}$$

$$b_1 = \frac{V_1-I_1Z_C}{2\sqrt{Z_C}} \qquad b_2 = \frac{V_2-I_2Z_C}{2\sqrt{Z_C}}$$



- **Special case:** $(Z_S = Z_C = real,\ Z = 0)$

(When $a_2 = 0, V_2 = -I_2Z_C$)

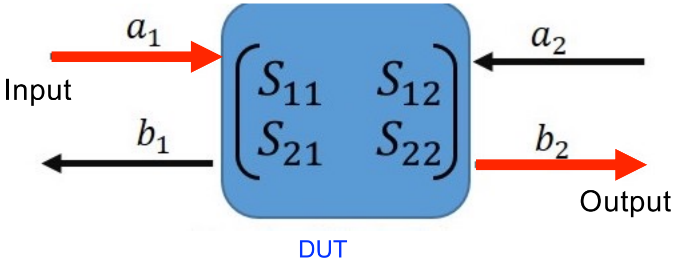
$$S_{21} = \frac{b_2}{a_1}\Big|_{a_2=0} = \frac{V_2 - I_2Z_C}{V_2 + I_1Z_C}\Big|_{a_2=0} = \frac{-I_2Z_C - I_1Z_C}{I_1Z_L + I_1Z_C} = \frac{(-I_2)2Z_C}{I_1(Z_L + Z_C)} = \frac{2Z_C}{(Z_L+Z_C)}$$

If $Z_L = Z_0\ , S_{11} = 0\ and\ S_{21} = 1$(maximum power would transfer)

$|a|^2$ or $|b|^2$ = power
(Dimensionally)

Impedance Measurement: Modeling a Vacuum Component as a Transmission Line

- We model the device under test (DUT) as a two port transmission line, and measure its insertion loss (S_{21}-parameter).



Symmetric matrix

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ \boxed{S_{21}} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

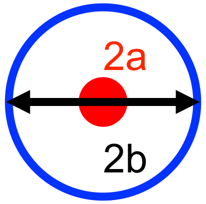
$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0}$$

- By measuring the S_{21}-parameters for the DUT and a corresponding reference pipe (REF), we can calculate the impedance of the DUT using appropriate formula.

$$Z_{\parallel}^{HP}(\omega) = 2Z_c \left(\frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{REF}} \right)$$

Lumped impedance

$$Z_c = 60 \ln\left(\frac{b}{a}\right)$$



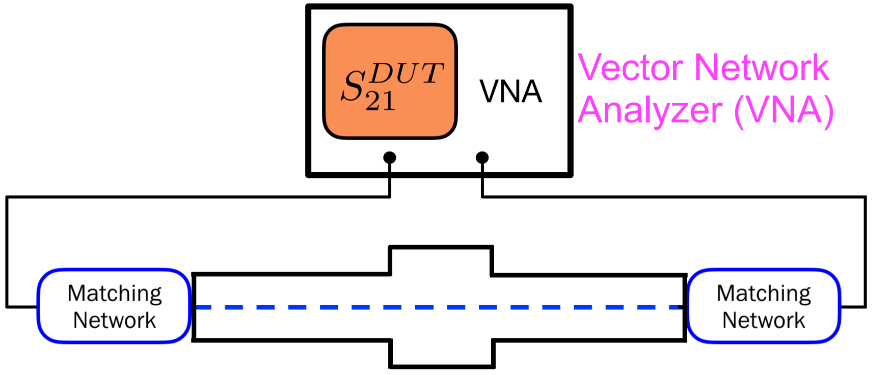
Impedance Measurement Methods

1. Traditional coaxial wire method

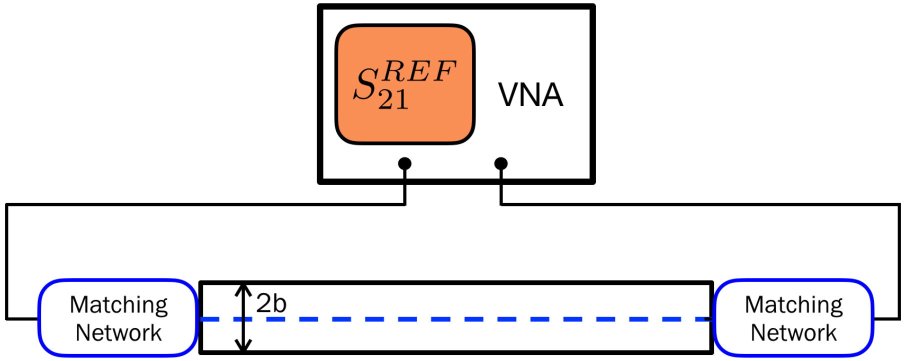
- **TEM mode** of coaxial cable represents Coulomb field of a relativistic particle beam.
- Gives better results mainly at lower frequencies.

Limitations:

- Matching network complicates bench setup.
- Large central conductor produces more perturbation to boundary conditions (less accurate beam profile).
- Passive circuits (resistors/inductors) may behave differently at higher frequencies.
- Limited to narrow band measurements due to frequency range of active devices (balun and transformer) used for impedance matching.



Device Under Test (DUT)

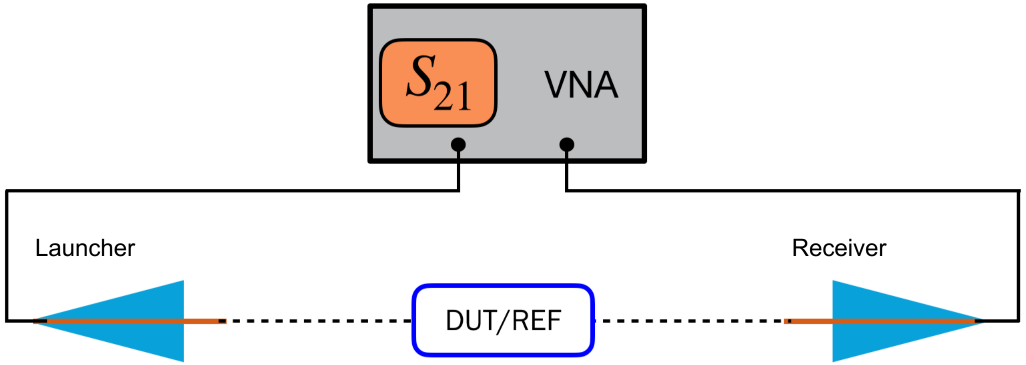


Reference Pipe (REF)

Impedance Measurement Methods

2. The novel Goubau line (G-line) setup

- Fundamental **TM mode** of a surface wave mimics the Coulomb field of a relativistic particle beam*.
- Gives better results at higher frequencies.
- We are among the first to use the G-line for the impedance measurement.

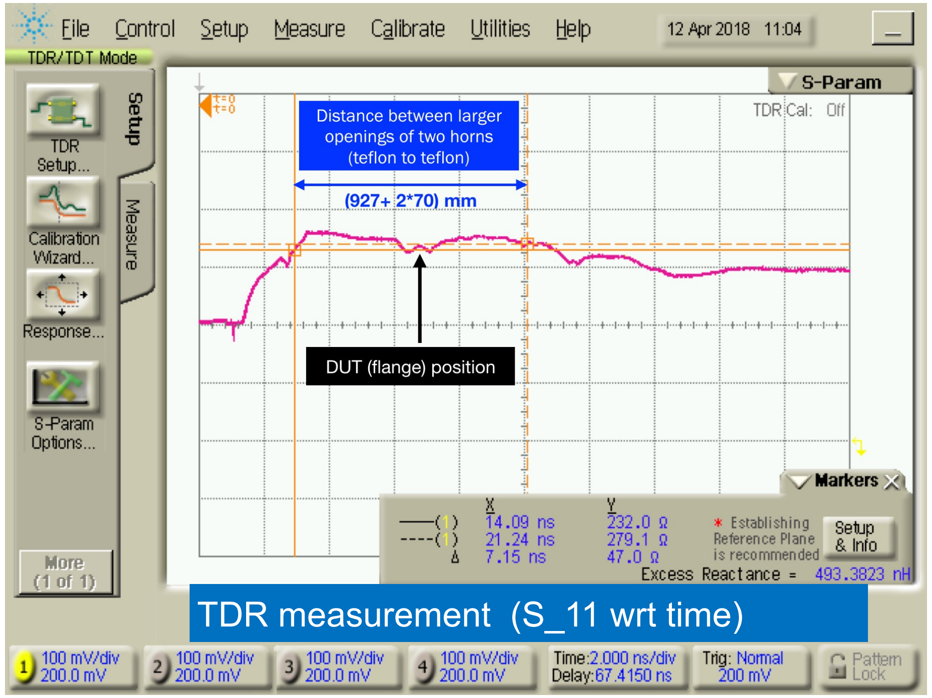


Advantages:

I. Does not require complicated matching network, simple setup.
II. Provides more accurate impedance matching.
III. Perturbs boundary condition less due to micron-sized wire.
IV. Enables wide band measurement.
V. Empowers quick data acquisition.

Limitation:

- Challenging to setup for a long structure.



Distance between larger openings of two horns (teflon to teflon)

(927+ 2*70) mm

DUT (flange) position

	X	Y
——(1)	14.09 ns	232.0 Ω
----(1)	21.24 ns	279.1 Ω
Δ	7.15 ns	47.0 Ω

* Establishing Reference Plane is recommended

Excess Reactance = 493.3823 nH

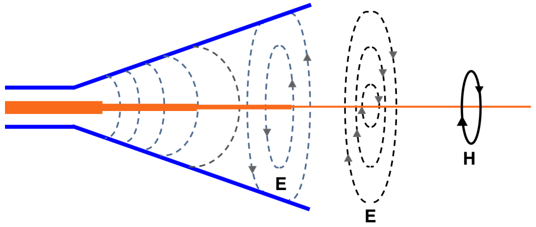
TDR measurement (S_11 wrt time)

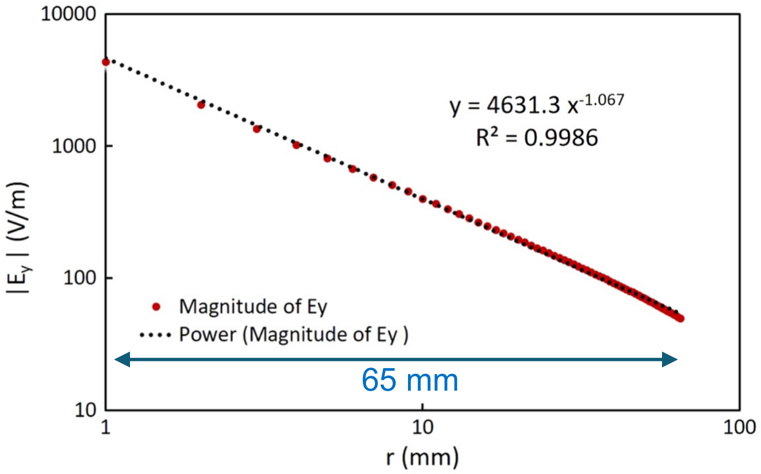
Time domain reflectometry (TDR)

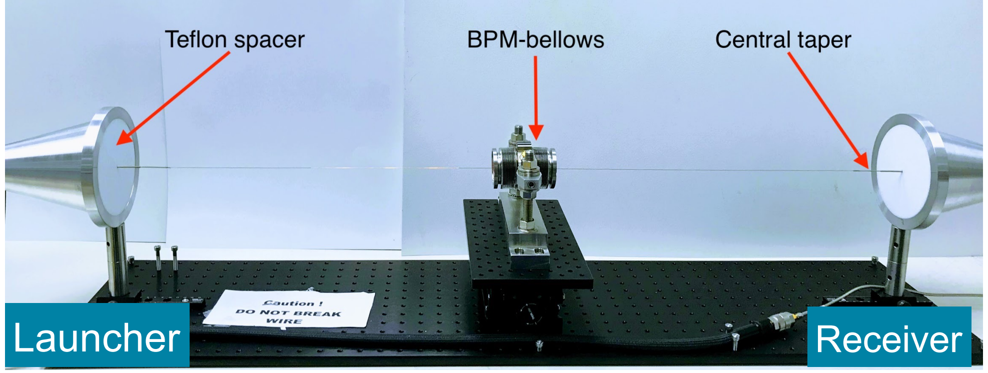
*J. Musson, K. Cole, and S. Rubin, PAC, 2009.

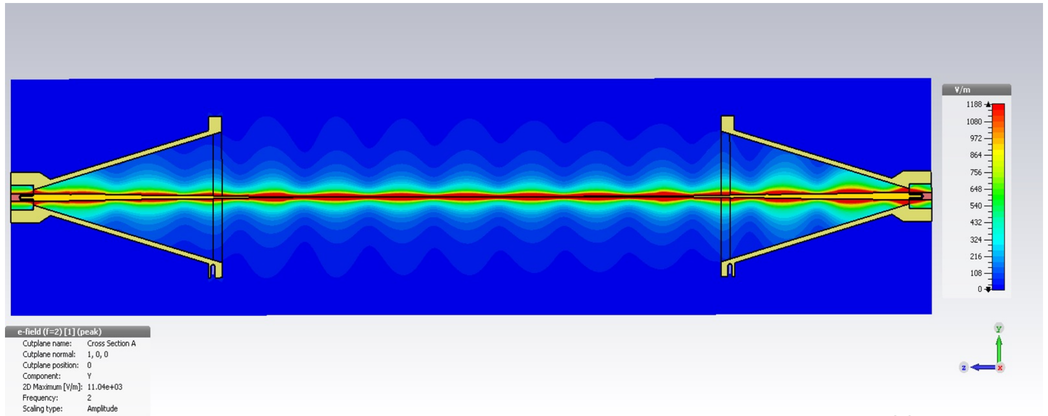
Goubau Line (G-line)

- The Goubau line is a dielectric coated single wire transmission line that works on the principle of Sommerfeld like electromagnetic surface wave.
- The fundamental TM mode close to the dielectric coated wire resembles the EM properties of particle beam.
- Excitation of the fundamental TM mode to the single wire, and impedance matching from coax to the wire is done by a launcher or horn.









e-field (f=2) [1] (peak)
Cutplane name: Cross Section A
Cutplane normal: 1, 0, 0
Cutplane position: 0
Component: Y
2D Maximum [V/m]: 11.04e+03
Frequency: 2
Scaling type: Amplitude

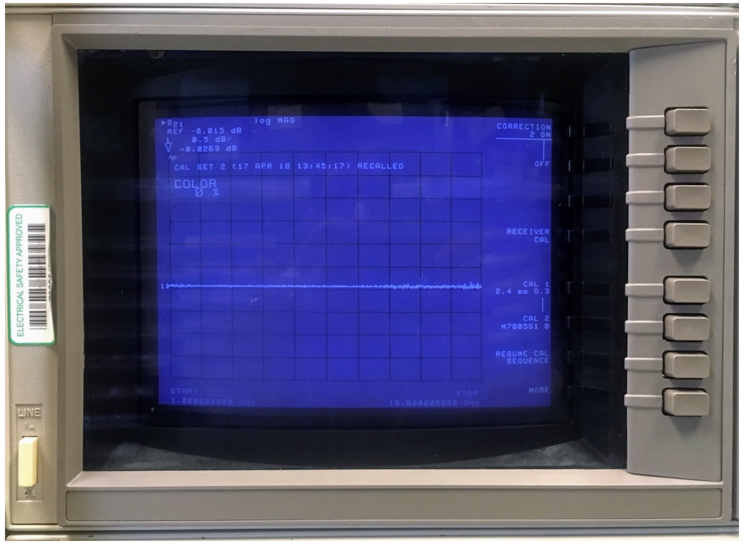
M. Sangroula and et. al., PRAB 23, 082803 (2020)

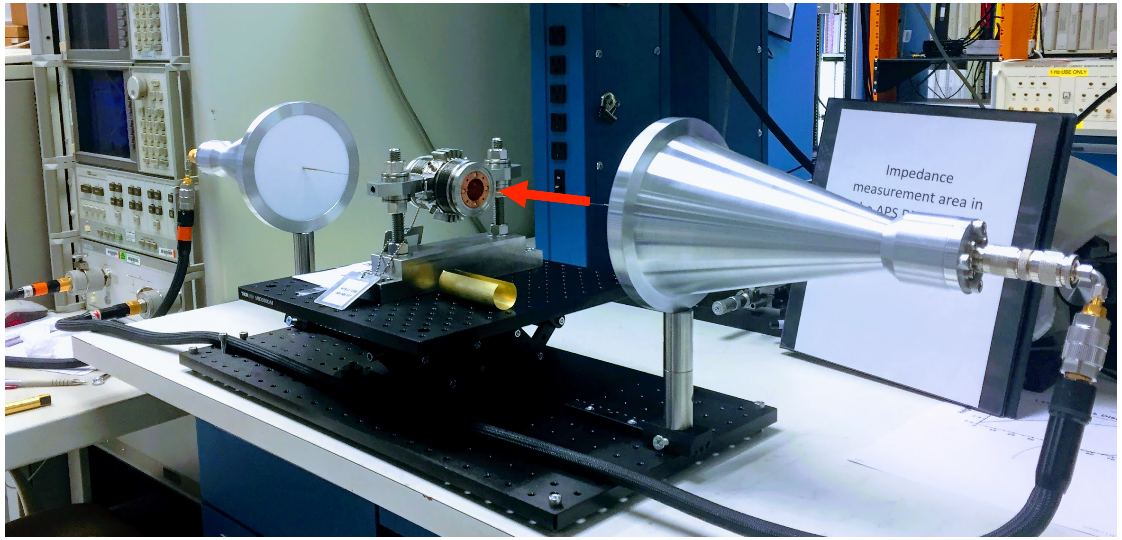
Brookhaven National Laboratory

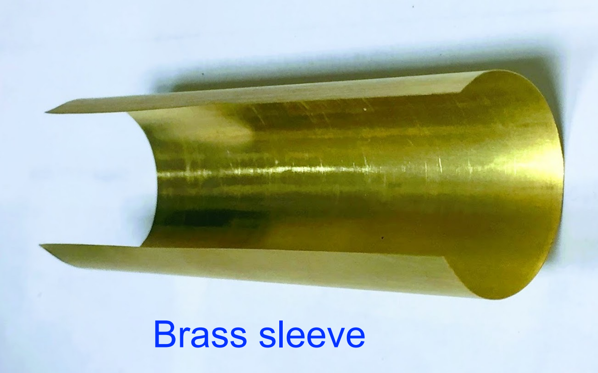
Experimental Measurements Procedure

1. Adjust the DUT position to place the wire at its center.
2. Insert a brass sleeve into the DUT.
3. Calibrate the VNA (flat S_{21}-signal).
4. Carefully remove the brass sleeve.
5. Record the data.

VNA: 1-10 GHz

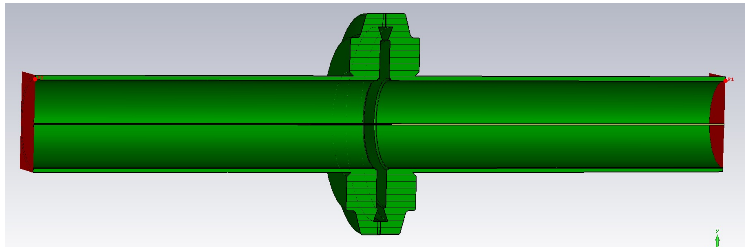


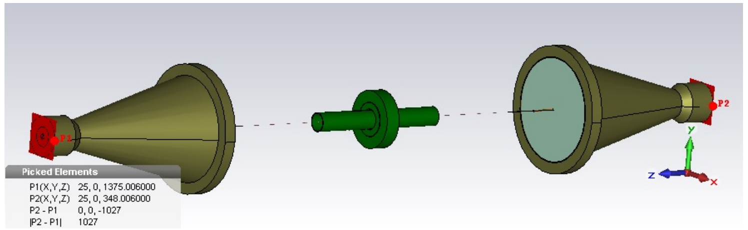



Brass sleeve

Benchmarking of the G-line Method from Simulations and Measurements

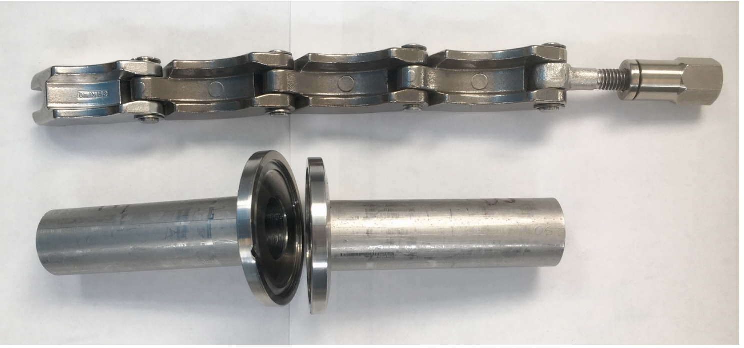
- Since the application of the G-line to impedance measurement is new, we would like to see in simulation if we can get the same S_{21} as we want.
- We first benchmarked the G-line setup with well-known results of cylindrical cavity (2.54 mm wide and 24.2 mm radius).
- We formed the same cylindrical cavity (2.54 mm wide and 24.2 mm radius) for experiment by joining two flanges together.

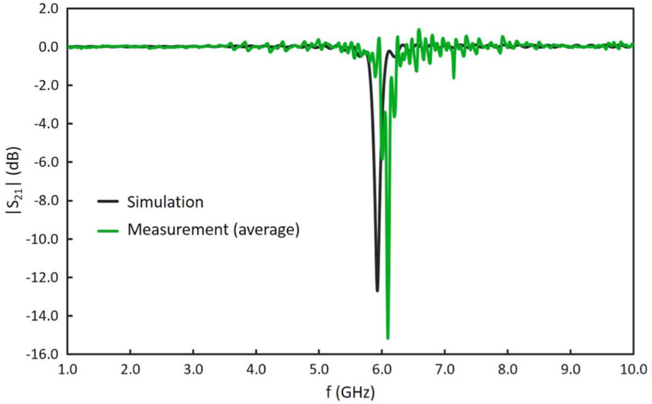


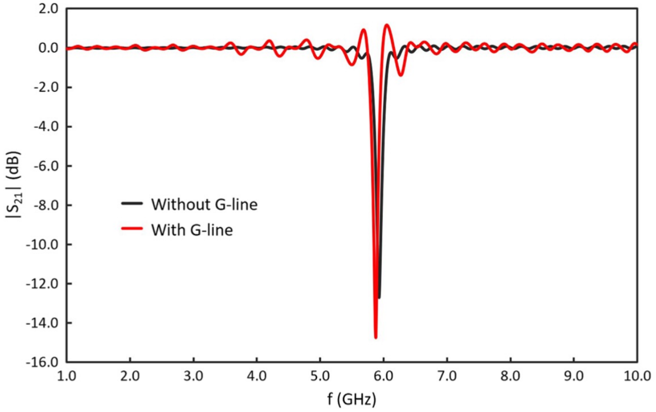


Picked Elements

P1(X,Y,Z)	25, 0, 1375.006000
P2(X,Y,Z)	25, 0, 348.006000
P2 - P1	0, 0, -1027
|P2 - P1|	1027

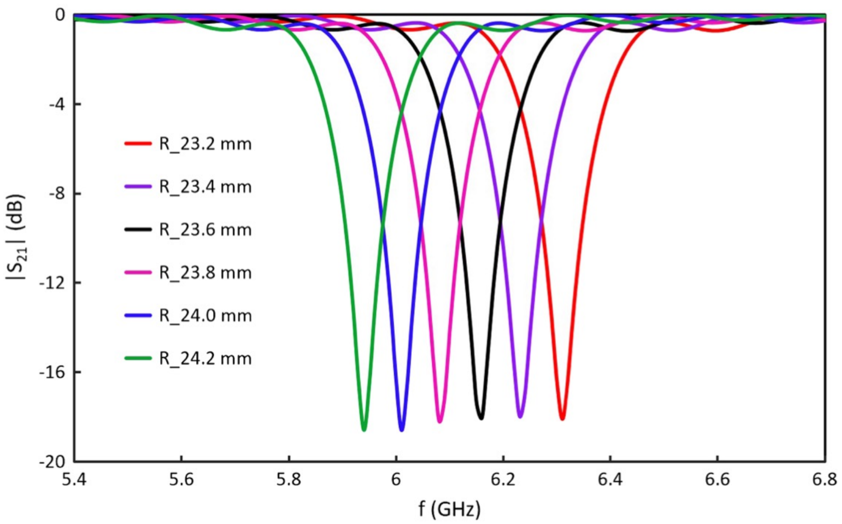


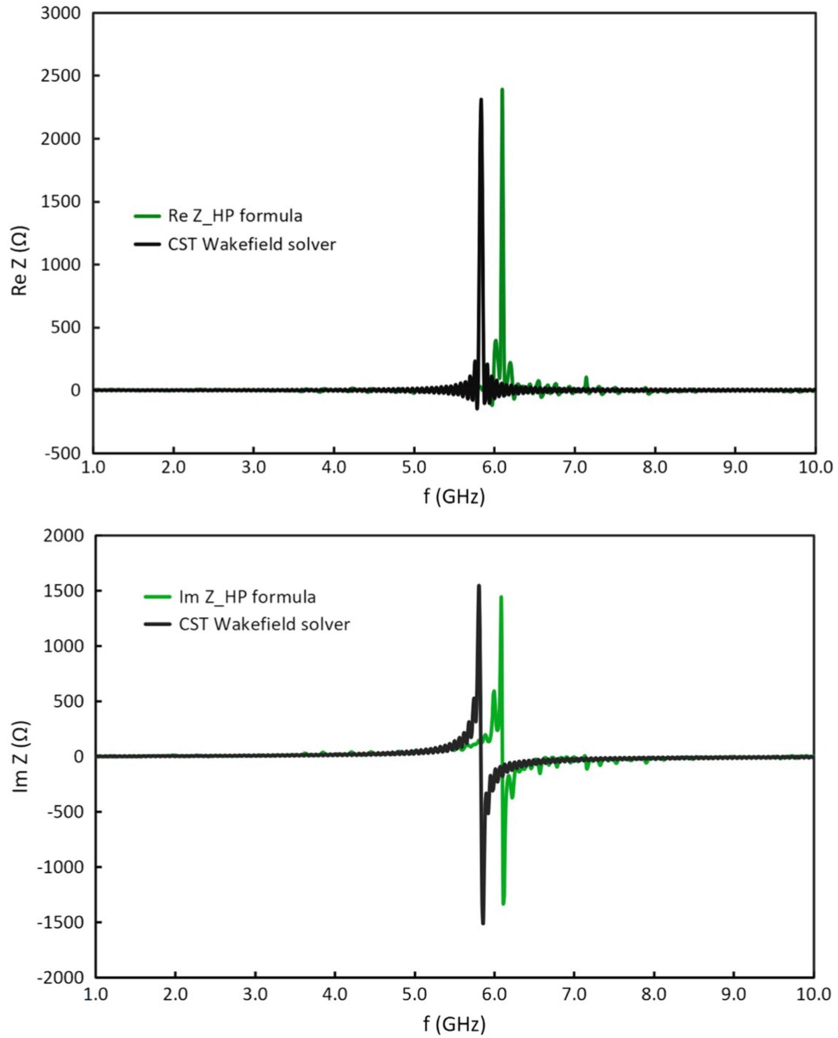




Impedance Comparison of the Benchmarking Cavity

- Looks very similar but the peak position is slightly shifted.
- Did some investigations to figure out the sensitivity of this shift in terms of geometry.
- CST simulations showed approximately 0.4 mm difference in the radial size of the cavity.

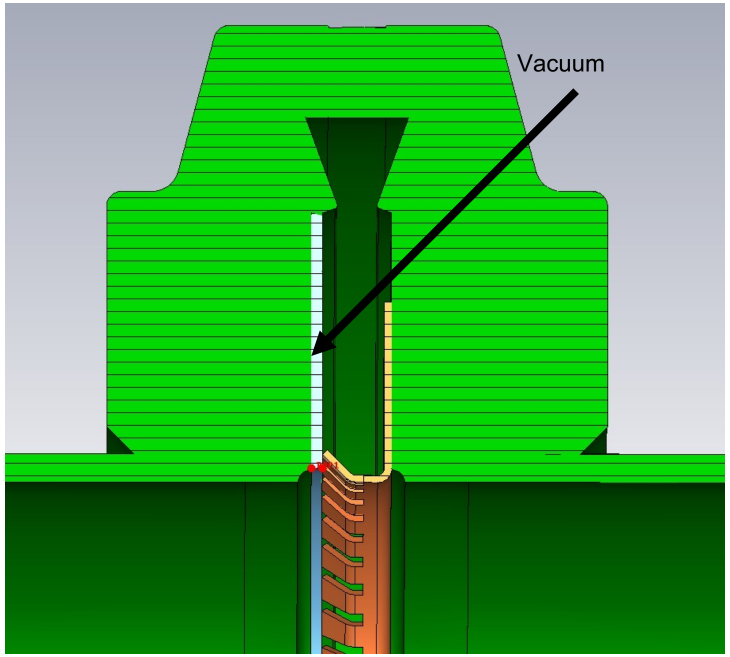


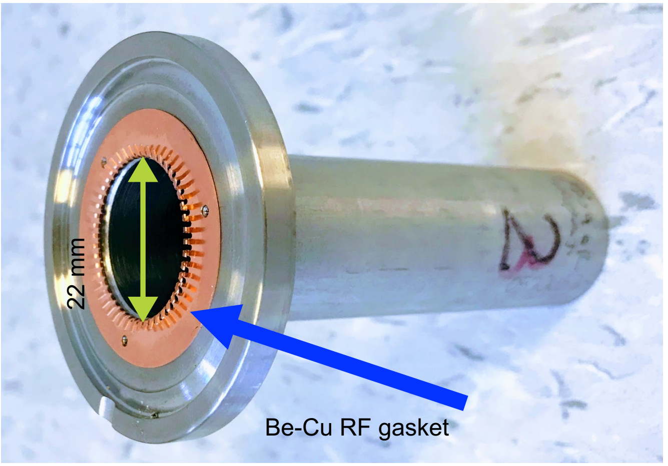


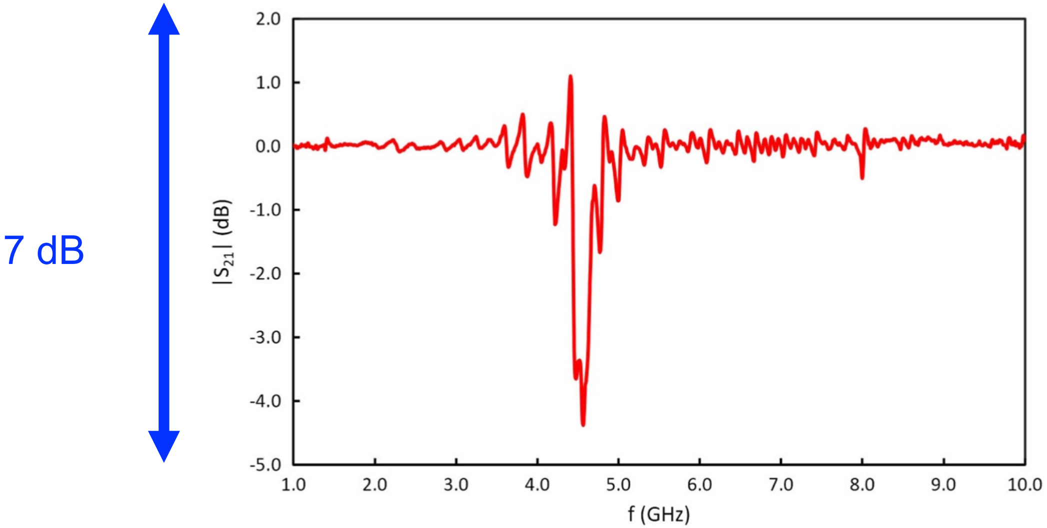
M. Sangroula and et.al,, in Proc. IPAC’18 Vancouver, Canada THPAK005

Flange with the Be-Cu RF Gasket

- Surprisingly, we observed a resonance peak during initial measurement, which was not predicted by simulation.
- Found an RF-gap.

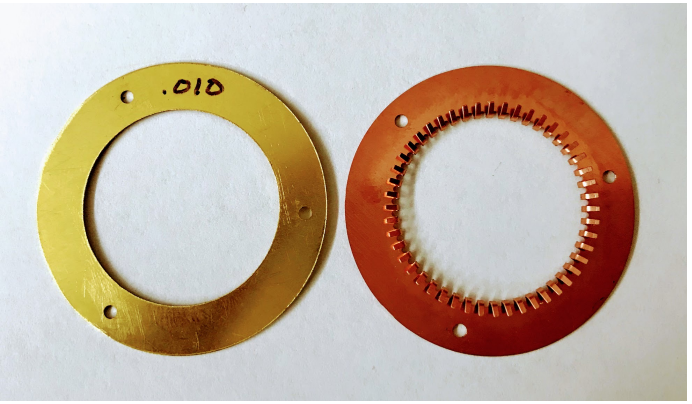


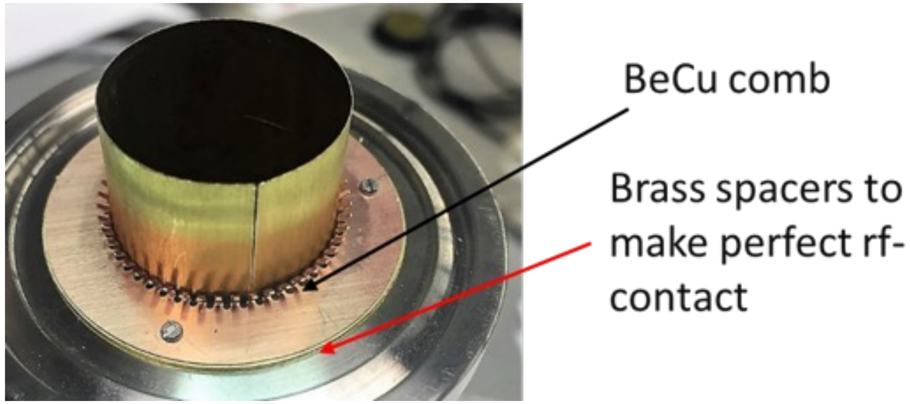


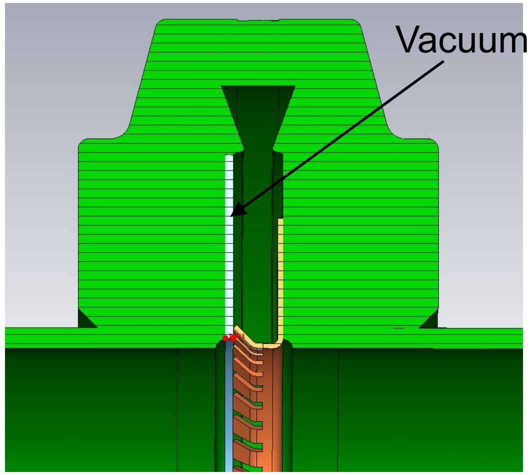


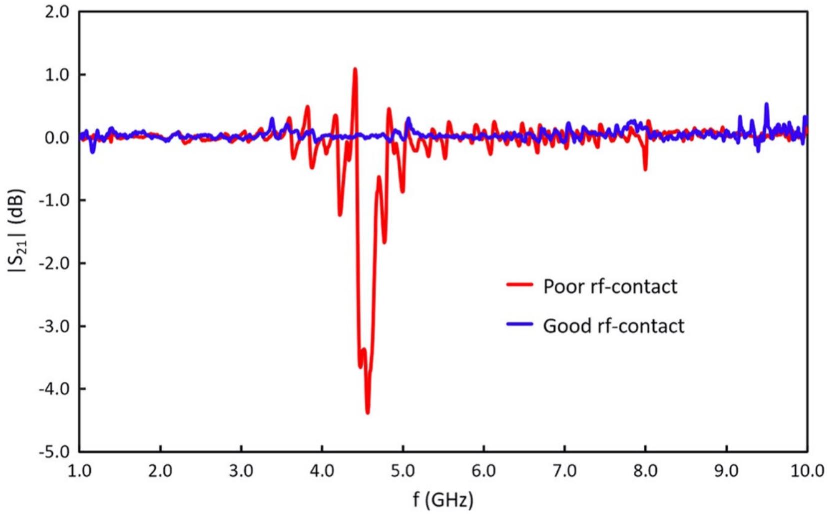
Flange with Be-Cu RF Gasket

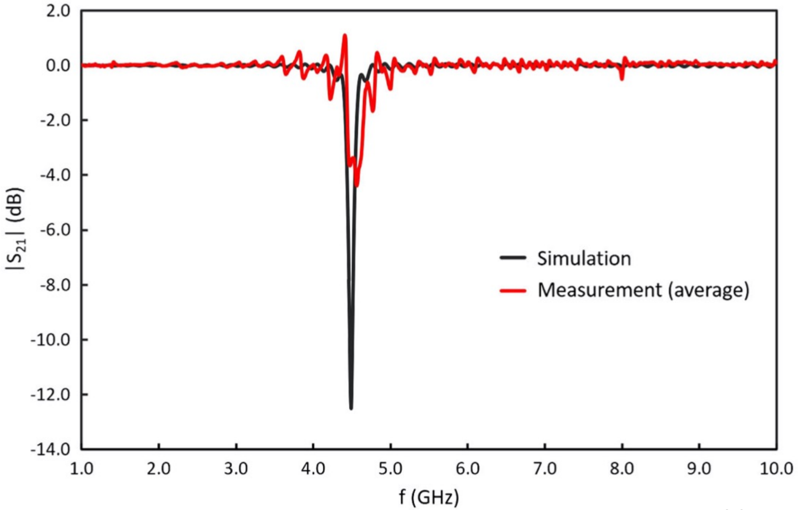
- Used brass spacers to eliminate this RF-gap.











Takeaway

- APS-U provides generation leap in storage ring performance with a factor of 100 -1000 increase in brightness and coherence flux.
- We developed a novel G-line method to measure the beam coupling impedance of the APS-U vacuum chamber components.
- We demonstrated that the G-line is a relatively simple tool to measure vacuum component impedance over a broad frequency range.

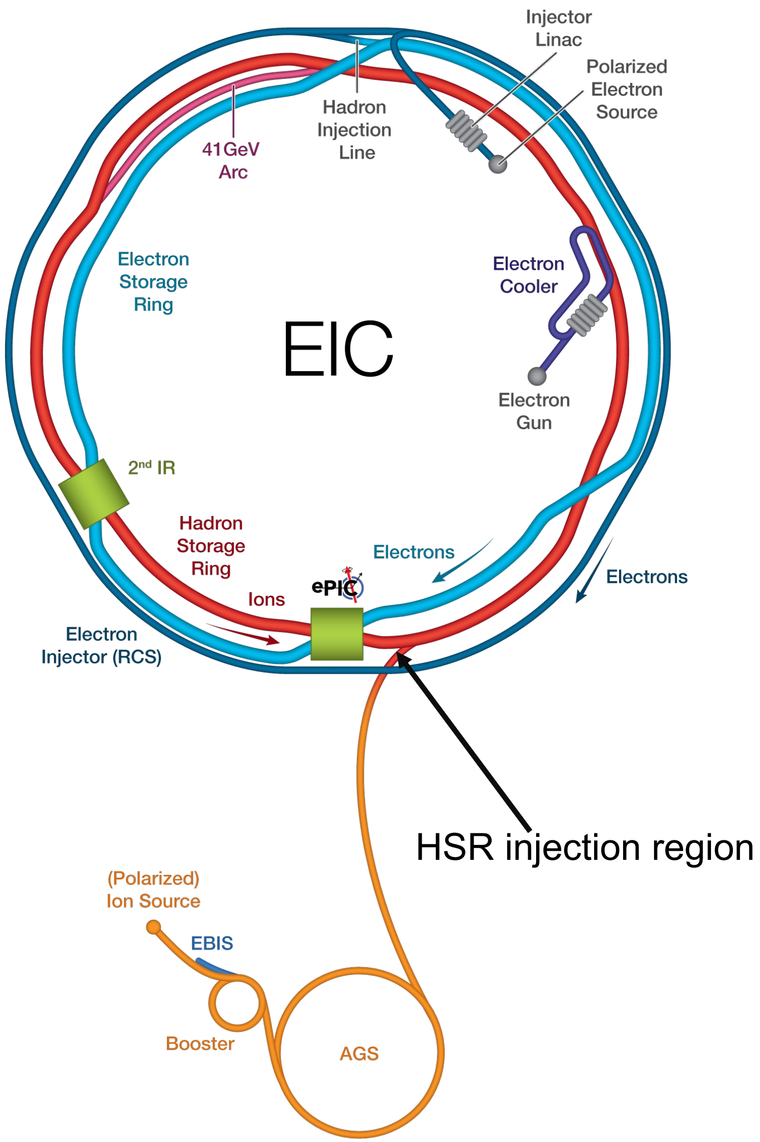
Impedance Optimization and Thermal Analysis of EIC HSR Components

- Coupling Impedance optimization
- Power loss calculation
- Thermal Analysis

HSR injection kicker

- A kicker is an accelerator component that utilizes both electric and magnetic fields to kick the circulating beam.
- Why kicker in stead of bending magnet?

- We may require up to 20 kickers to kick the HSR beam with the beam rigidity of 81 T-m.
- The length of the kicker is about 1 m.

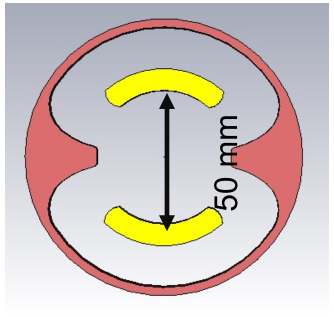


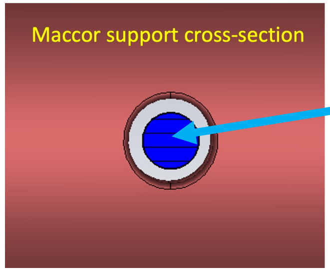
Geometry of the HSR injection kicker

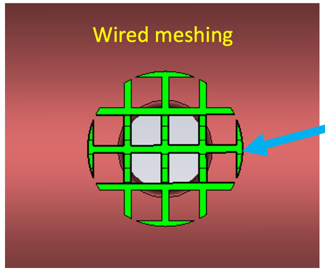
- CJ prepared the mechanical design of this stripline injection kicker (horizontal kicker).
- Length of the electrodes is 0.9 m

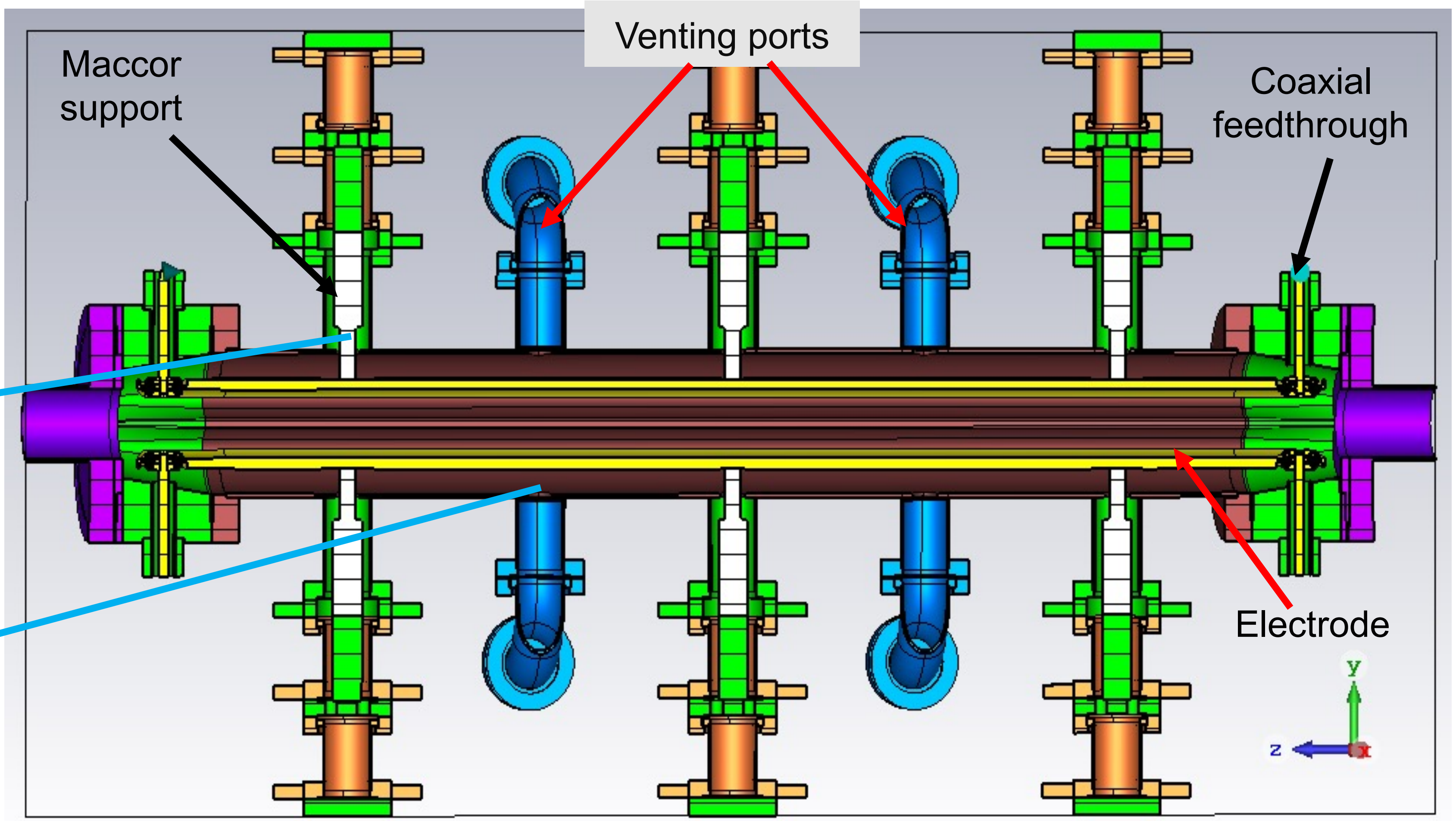
M. Sangroula and et. al., WEPAB193, IPAC 21

Cross-section





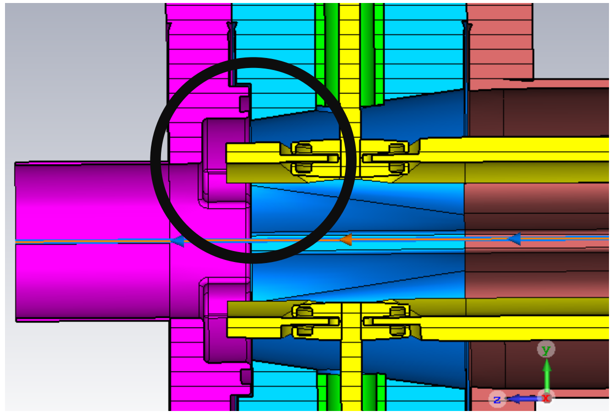


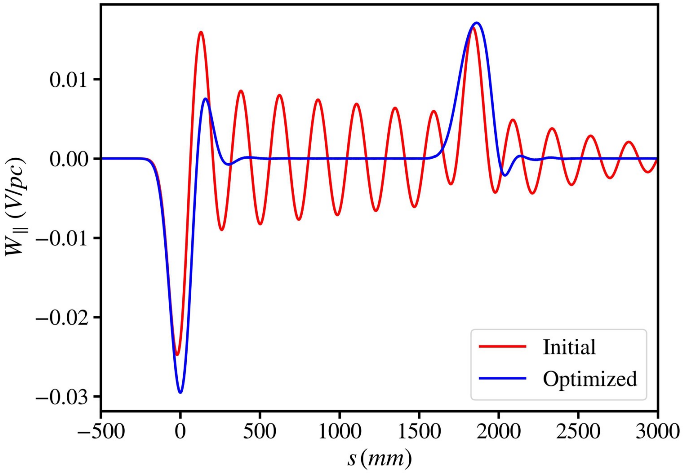


Impedance Optimization: Removal of flange's pockets

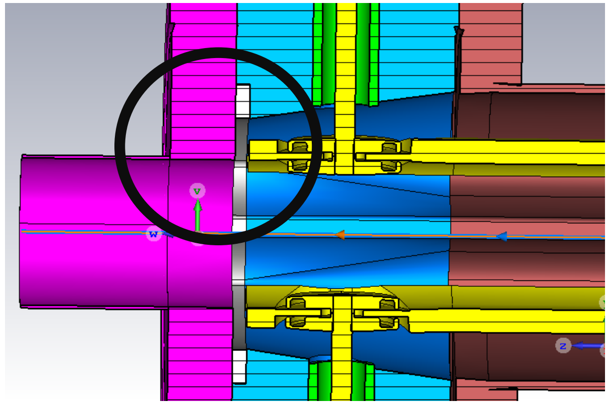
- Performed wakefield simulations, at first, using the 6 cm bunch length.

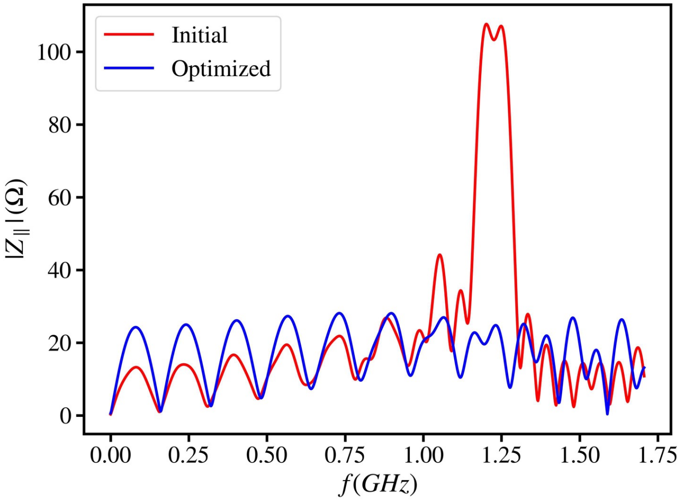
Initial design: Deep pockets on the end-flange





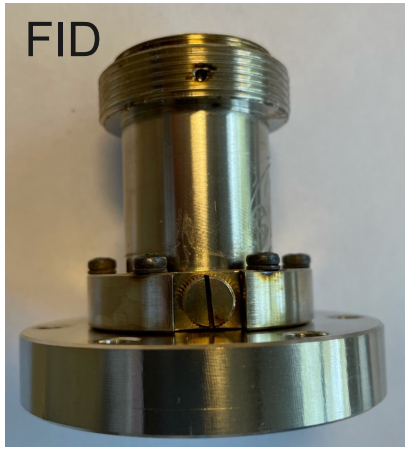
Improved design: Flat end-flange

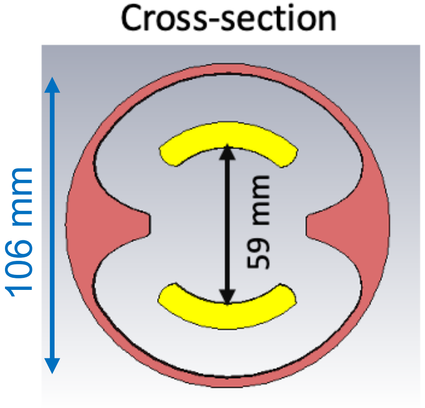




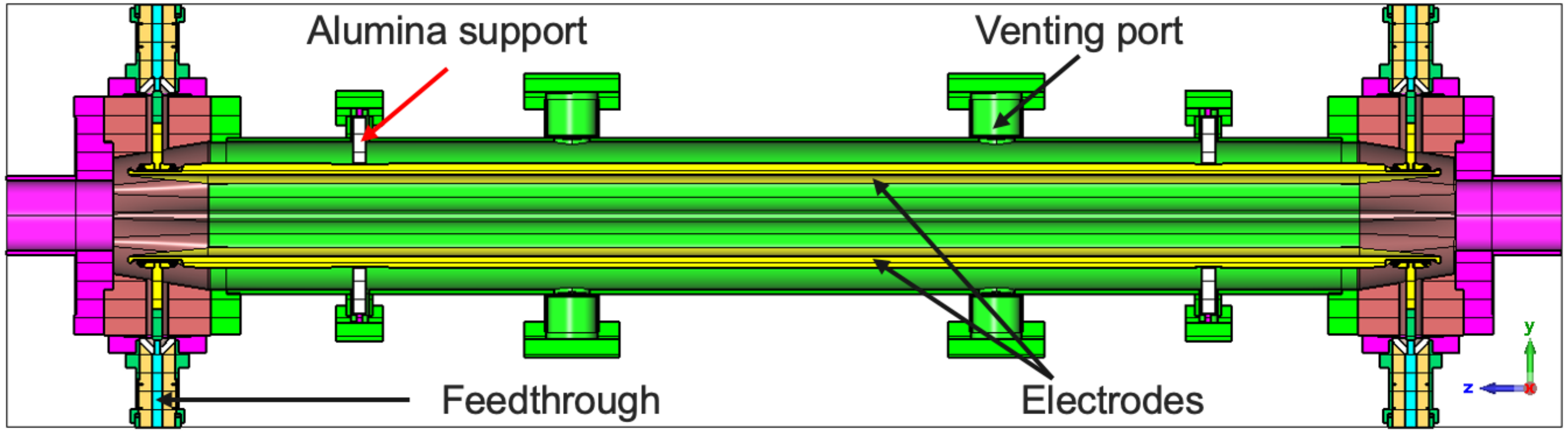
HSR Injection Kicker: Updated model

- **Main concern:** Deformation of electrodes
- We modified kicker geometries to include the tuning capability of characteristic impedances: (48 – 52) Ω.
- The updated kicker model will have a thin NEG coating (2-3 um), to reduce electron cloud formation when the kicker is off, on top of copper plating (~25 um).





Geometry: CJ Liaw



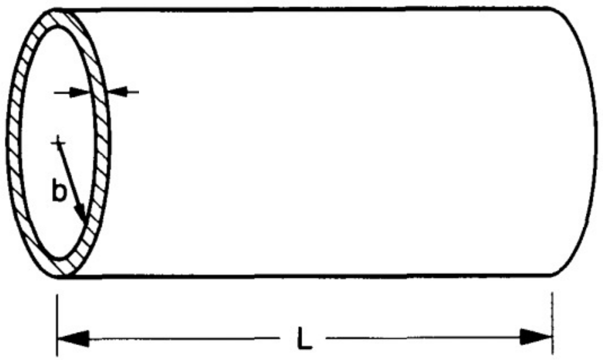
Resistive Wall (RW) Impedance

- The RW impedance is purely due to the conductivity of the vacuum chamber.
- RW loss per unit length (P') for a cylindrical pipe

A W Chao; Handbook of Accelerator Physics and Engineering

$$P' = \Gamma\left(\frac{3}{4}\right)\frac{Q^2M}{4\pi^2 bT_0}\sqrt{\frac{\mu}{2\sigma_c}}\left(\frac{1}{\sigma_t}\right)^{\frac{3}{2}}$$

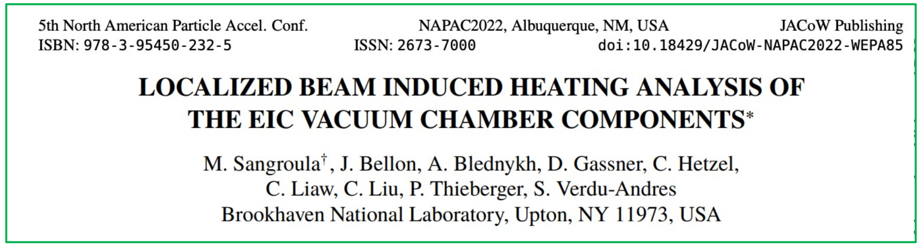
Bessel function



Q = charge of a bunch
M = number of bunches
b = beam pipe radius
T_0 = time period of the revolution
μ = permeability of free space
σ_c = conductivity of the material
σ_t = bunch length

HSR Injection Kicker: Thermal Analysis

- **Main concern:** Deformation of electrodes
- Performed CST simulation to evaluate the RW loss for the worst-case requirement (**σ = 60 mm, Q_b = 30.5 nC, M = 290**).
- Copper plated electrode and the internal housing showed **small increase in electrode's temperature**.

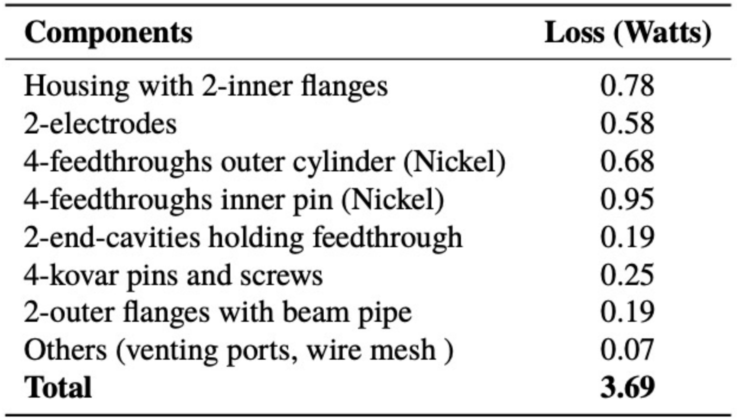


5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA85

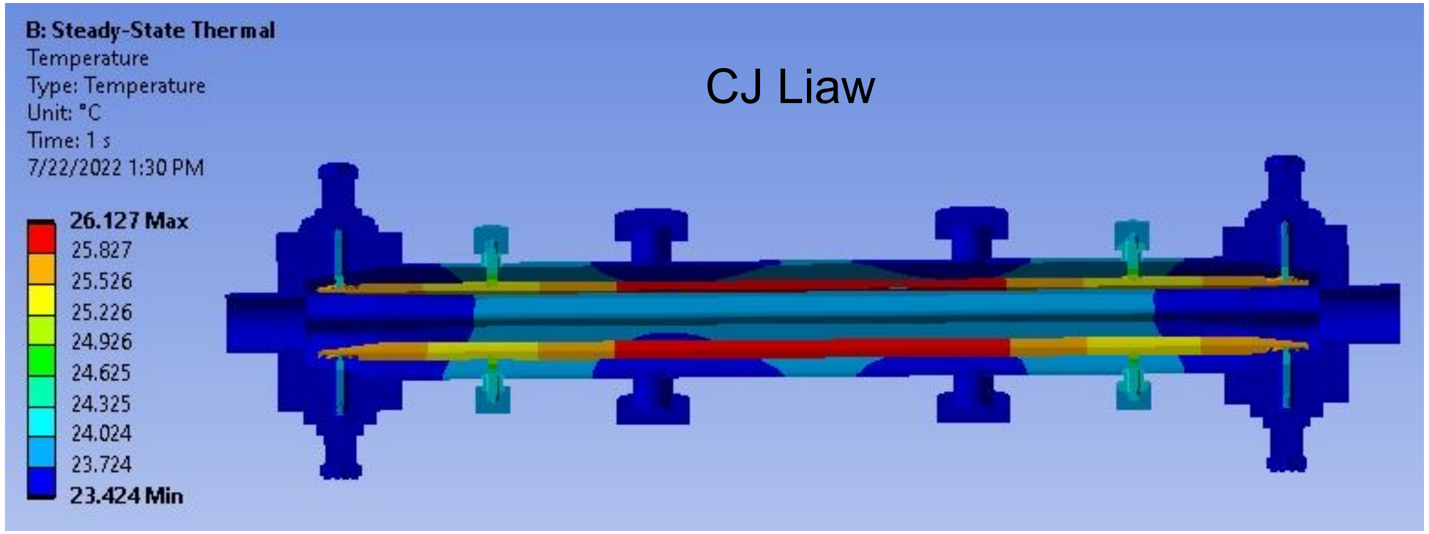
LOCALIZED BEAM INDUCED HEATING ANALYSIS OF THE EIC VACUUM CHAMBER COMPONENTS*

M. Sangroula†, J. Bellon, A. Blednykh, D. Gassner, C. Hetzel,
C. Liaw, C. Liu, P. Thieberger, S. Verdu-Andres
Brookhaven National Laboratory, Upton, NY 11973, USA

Resistive Wall Loss



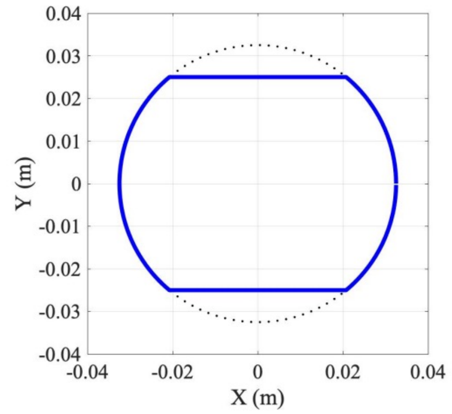
Components	Loss (Watts)
Housing with 2-inner flanges	0.78
2-electrodes	0.58
4-feedthroughs outer cylinder (Nickel)	0.68
4-feedthroughs inner pin (Nickel)	0.95
2-end-cavities holding feedthrough	0.19
4-kovar pins and screws	0.25
2-outer flanges with beam pipe	0.19
Others (venting ports, wire mesh)	0.07
Total	**3.69**



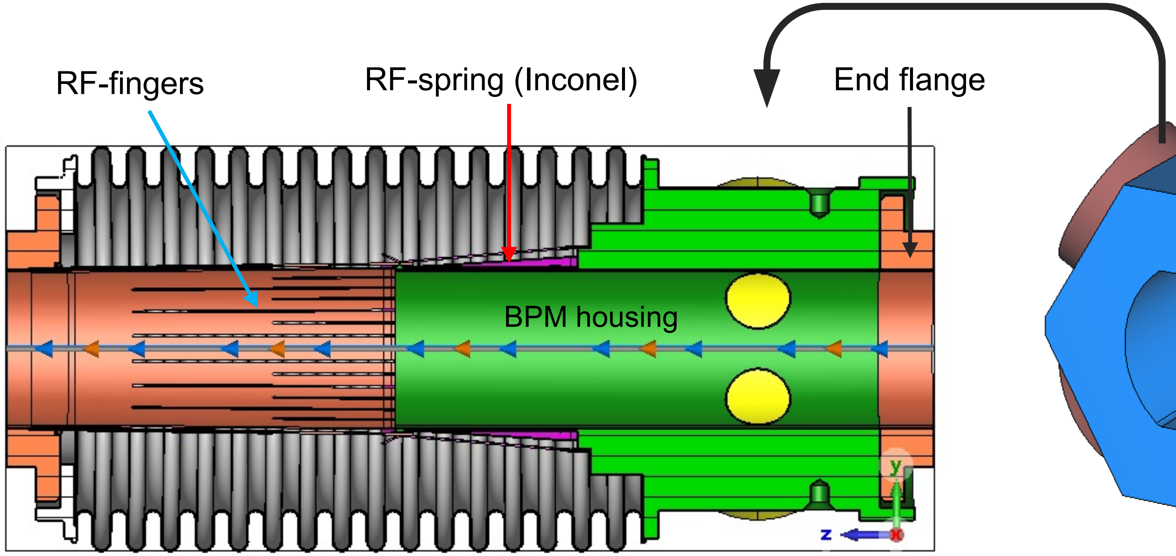
CJ Liaw

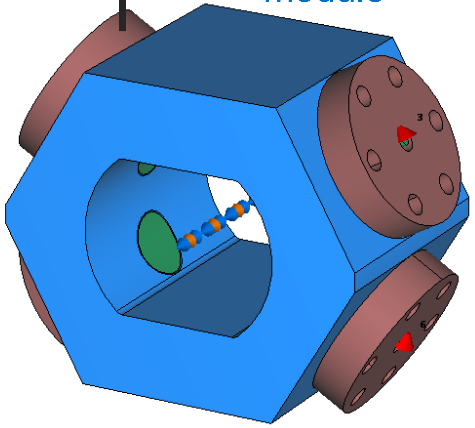
HSR Cryogenic BPM

- **Main Concern:** Overheating of the BPM button due to beam offsets.
- Because of the large radial offsets, we chose the design with corner buttons.
- Button surface is made of aC-coated copper on top of stainless steel 316 L.
- **Heating** on the BPM button is mainly due to the **beam induced RW loss** and due to the **heat conduction via cryogenic cable** from room temperature.

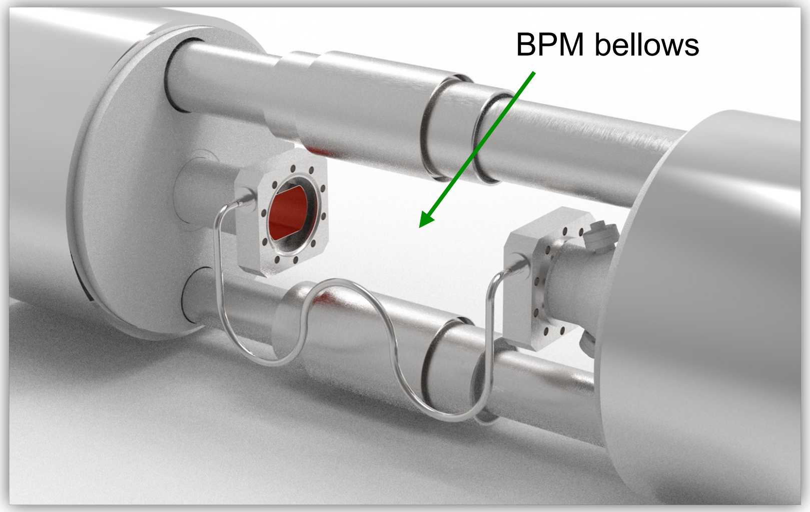


HSR beam screen profile





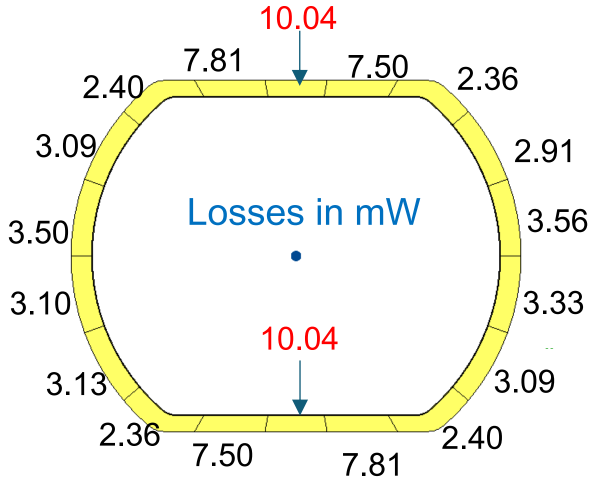
HSR BPM button module



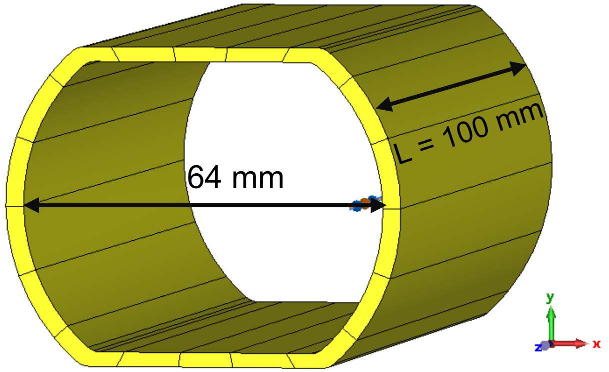
Cold-mass interconnect section

HSR cryo-BPM: RW Loss Calculation

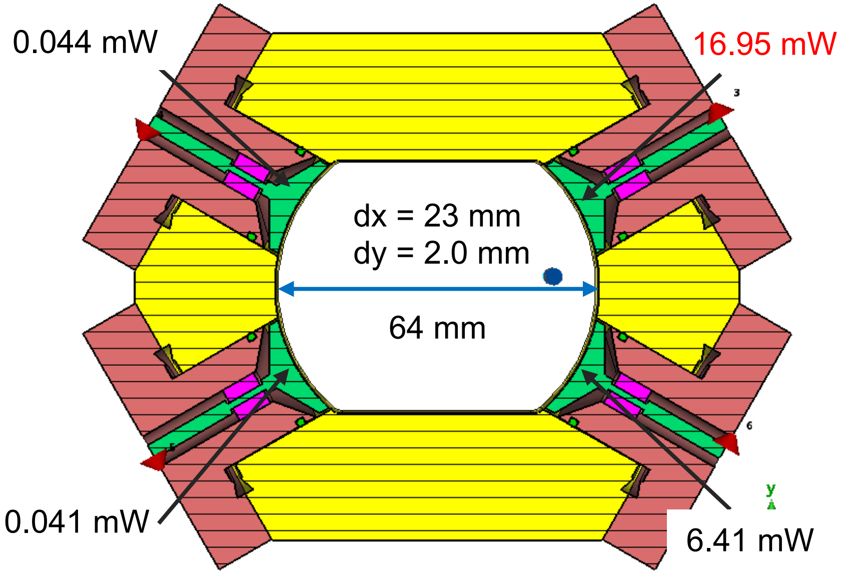
- Beam screen is sliced into 18 pieces (each slice = 20^0) to evaluate piecewise loss for housing due to offset beam.
- $\boldsymbol{\sigma}$ = 60 mm, Q_b = 30.5 nC, M = 290
- **Worst-case requirement** for the transverse beam offsets: dx = 23 mm and dy = 2 mm (part of the requirement)



Beam pipe/screen profile

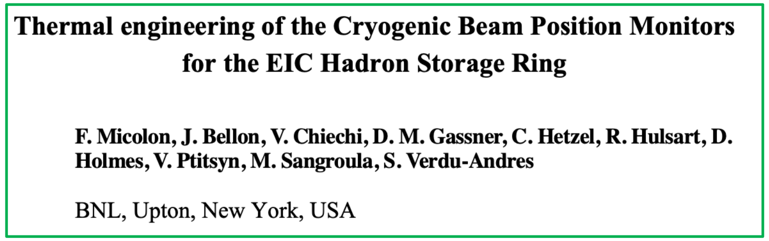


Components	Loss (mW), dx = 23 mm, dy = 2 mm
2-buttons (near to beam)	16.95 (top) 6.41 (bot)
2-buttons (far)	0.044 (top) 0.041 (bot)
4-flanges (button bodies)	4.3169
Housing	171.2
Total	**198.962**



HSR Cryo-BPM: Thermal Conduction

- Inevitable heat conduction from room to cryogenic temperature.
- To reduce this heat leak, we plan to use the magnet heat shield (50 – 80) K as a heat sink (done for RHIC).
- For EIC, conduction with two cryo-cables has investigated.
- Compared the data between EIC, RHIC and LHC.
- The smaller cable (0.090-inch) for the EIC showed the lowest total heat conduction among all.


Thermal engineering of the Cryogenic Beam Position Monitors for the EIC Hadron Storage Ring

F. Micolon, J. Bellon, V. Chiechi, D. M. Gassner, C. Hetzel, R. Hulsart, D. Holmes, V. Ptitsyn, M. Sangroula, S. Verdu-Andres

BNL, Upton, New York, USA

F. Micolon

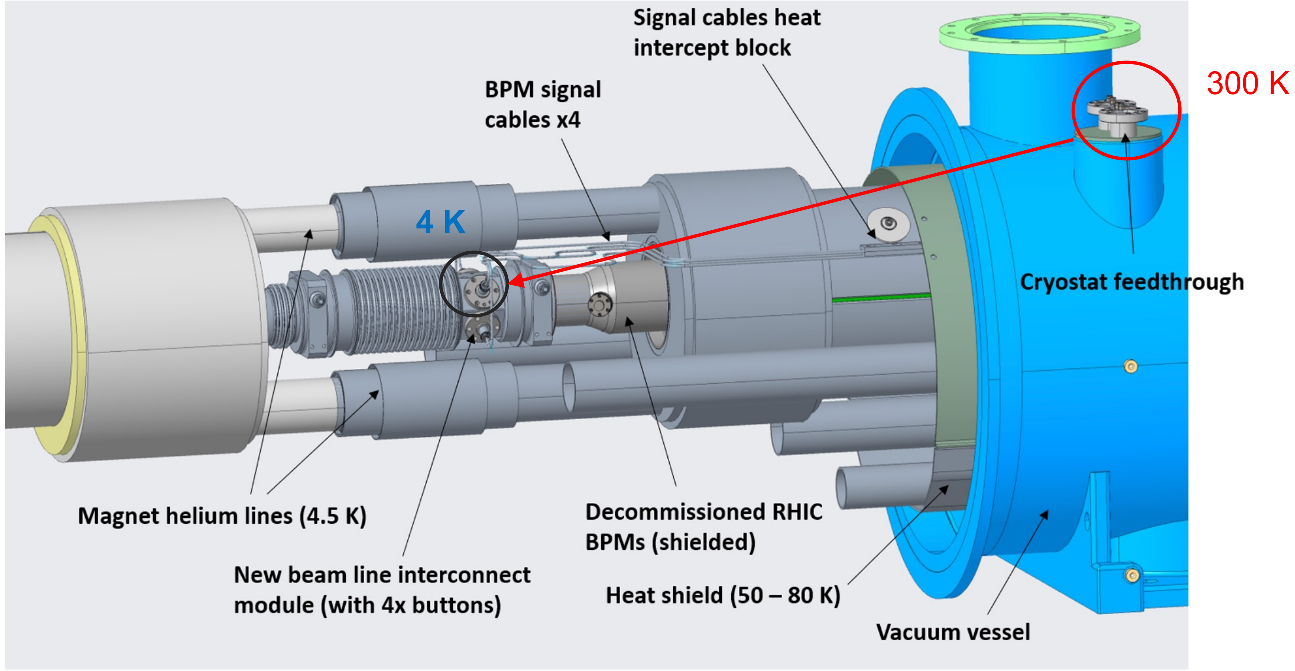


Figure 2 Integration of the interconnect module in the HSR

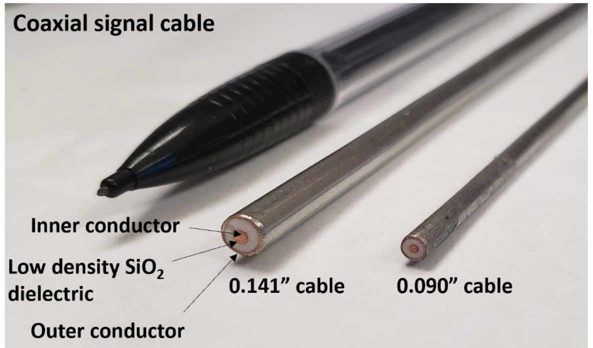
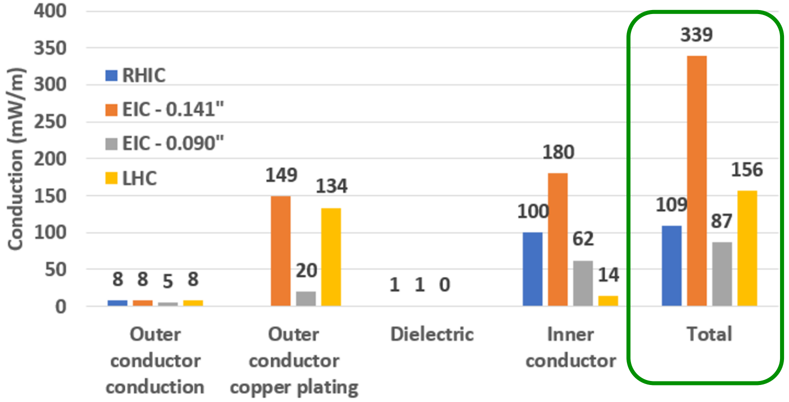


Figure 3: Cross section of sample SiO2 coaxial signal cables

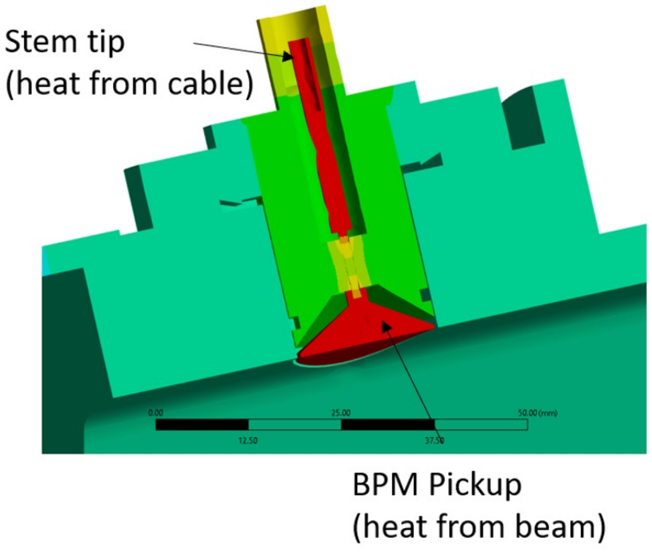
Thermal conduction comparison: (300 → 4) K



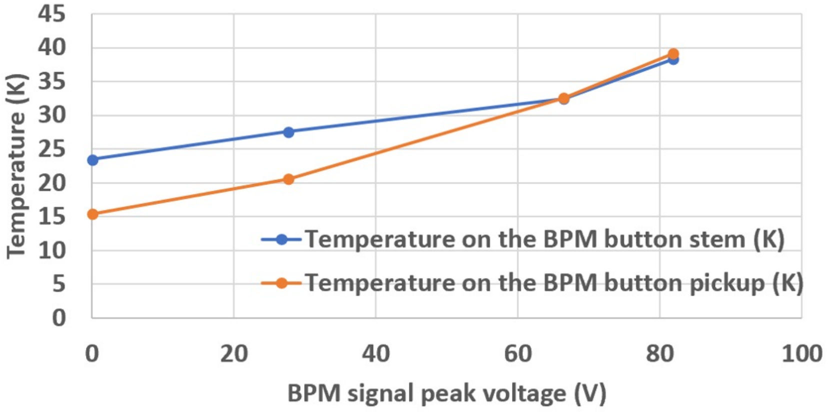
HSR Cryo-BPM: Thermal Analysis

- The maximum button/stem temperature is about 39 K.
- The goal is to keep the button temperature < 40 K.

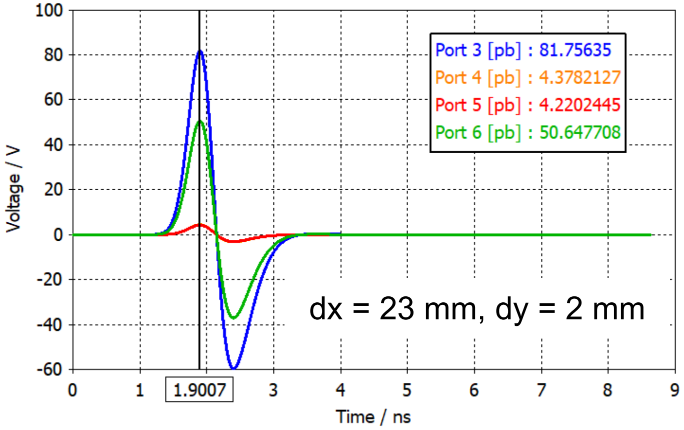
- From geometric point of view the buttons are optimized. The choice of the cable is under consideration.
- We are investigating if there is a room to further lower down the temperature.



BPM button temp with the 0.090" cable



Voltage signals: CST simulations



dx = 23 mm, dy = 2 mm

Acknowledgements

- Prof. Carlo Segre (Ph.D. supervisor, IIT)
- Dr. Ryan Lindberg (Ph.D. supervisor, Argonne)
- Prof. Janet Conrad (Postdoc supervisor, MIT)
- Dr. Chuyu Liu (Supervisor, BNL)
- All the folks working together with me at BNL

Thank you for your time and attention!

Extra slides

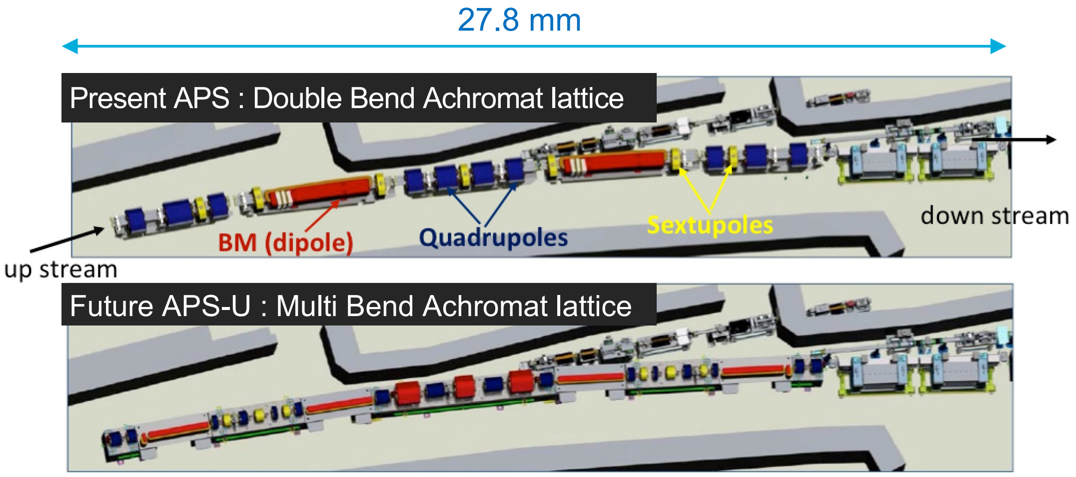
Overview of the APS Upgrade (APS-U)

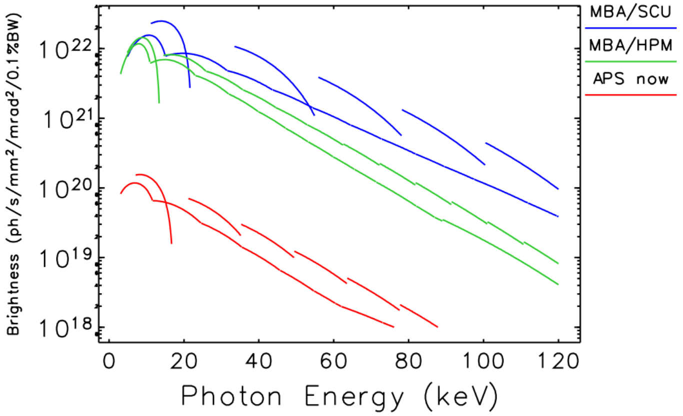
APS-U provides;

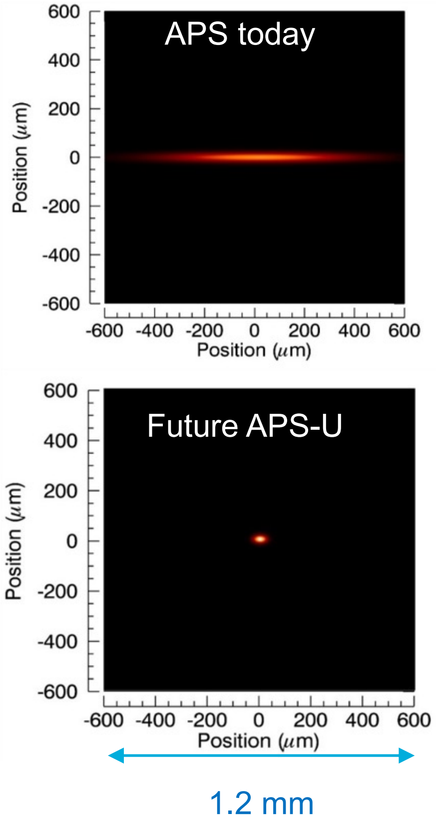
- Incorporation of the fourth generation MBA lattice
- Reduction of emittance by a factor of ~100 and installation of superconducting undulators, and
- Generation leap in storage ring performance with a factor of 100 -1000 increase in brightness and coherence flux.

$$\text{Emittance} \propto \frac{E^2}{N_d^3}$$

3200 pm-rad
↓
~42 pm-rad



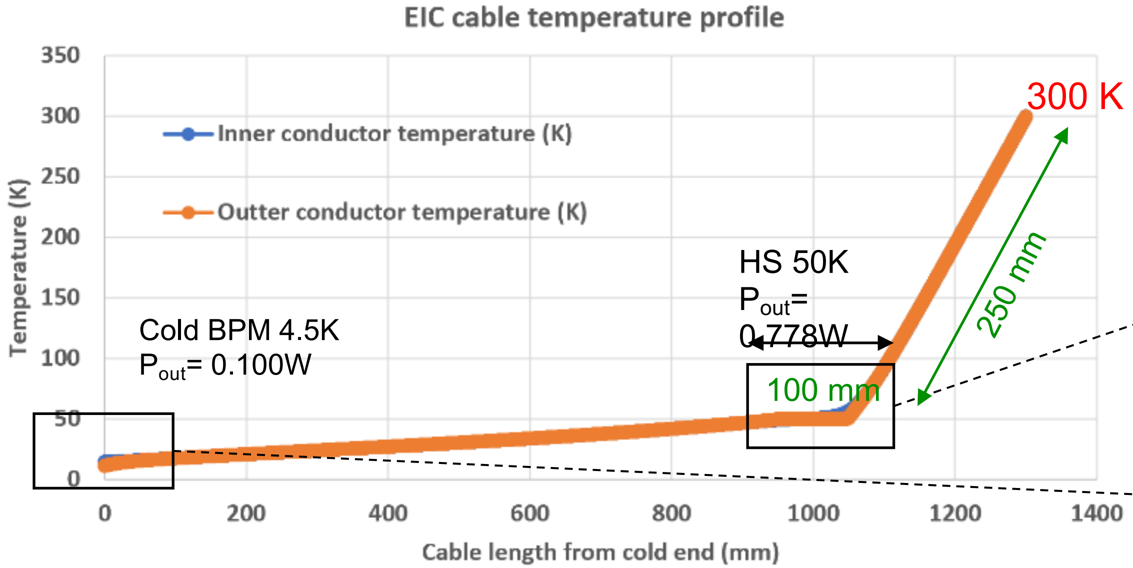




FE simulation of the EIC cable

The thermalization simulated is placed 250 mm from the room temp (300 K) end and has a length of 100mm.

Total cryo-cable length = 1.3 m



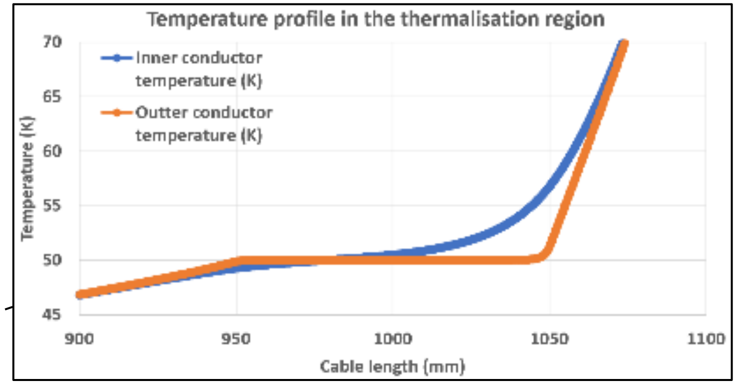
300 K

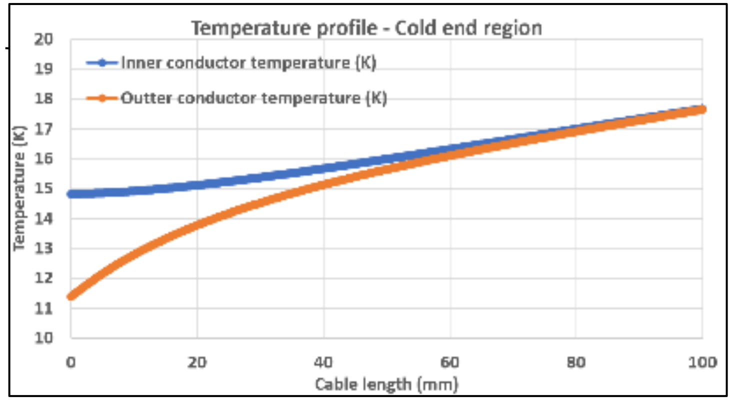
HS 50K P_{out}= 0.778W

Cold BPM 4.5K P_{out}= 0.100W

100 mm

250 mm





- After 100mm of thermalization the inner conductor is thermalized, this length is sufficient.
- The heat leak per cable is 0.778W to the heat shield and 0.1W to the 4.5K BPM end.

- For a two-plane BPM this means **0.4W** leaking to the 4.5K BS circuit (on this
- *Note: this is a static in-leak. The resistive heating in the cable will increase these numbers.*
- *Note 2: the thermal resistivity from the BPM itself is included (so the cable cold temp is above 4.5K).*

Scattering parameter and impedance

$$\left.\begin{aligned} S_{11} &= \left.\frac{b_1}{a_1}\right|_{a_2=0} \\ S_{22} &= \left.\frac{b_2}{a_2}\right|_{a_1=0} \end{aligned}\right\} \text{Reflection coefficients} \qquad \left.\begin{aligned} S_{12} &= \left.\frac{b_1}{a_2}\right|_{a_1=0} \\ S_{21} &= \left.\frac{b_2}{a_1}\right|_{a_2=0} \end{aligned}\right\} \text{Transmission coefficients}$$

Definition of travelling waves:

Dimensionally, $|a|^2$ or $|b|^2$ = power

a_2= 0 is maintained from the matched circuit.

In order to make the definition consistent with conversion of energy, the power waves or voltage waves are normalized to arbitrary reference impedance Z_0 (but usually the characteristics impedance of the transmission line)

$$a_i = \frac{U_i + I_i Z_0}{2\sqrt{Z_0}} \qquad b_i = \frac{U_i - I_i Z_0^*}{2\sqrt{Z_0}}$$

Note: Transmission coefficients can be measured more accurately than reflection coefficients (as the exact positon of reference plane do not require).