Beam Instrumentation Challenges for the Electron-Ion Collider Project

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for the EIC instrumentation team

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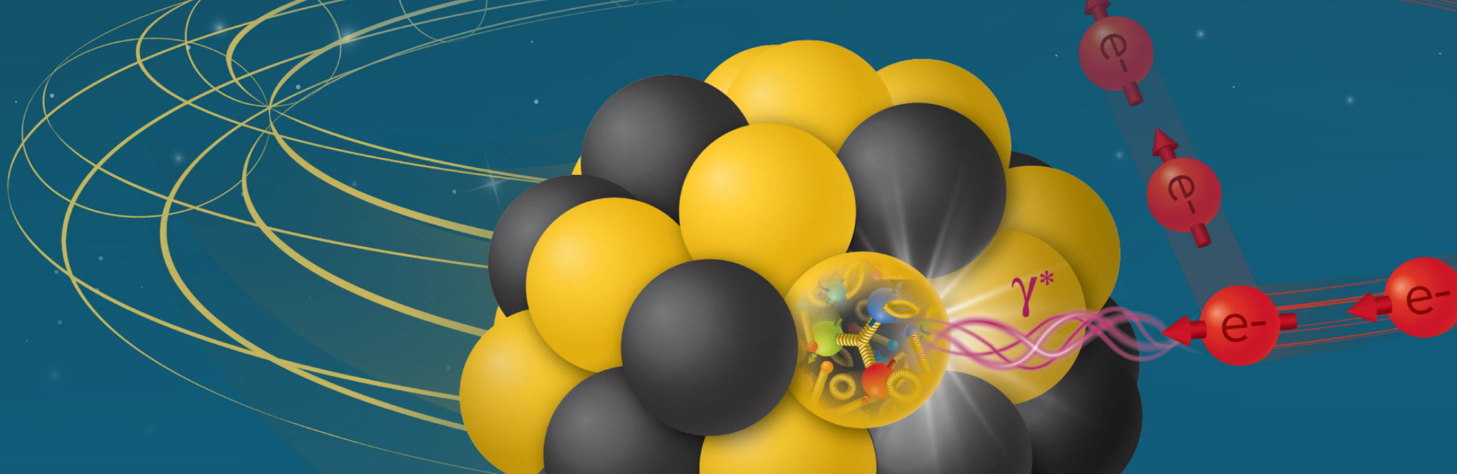
Electron-Ion Collider



Outline

- **What is the Electron-Ion Collider (EIC)?**

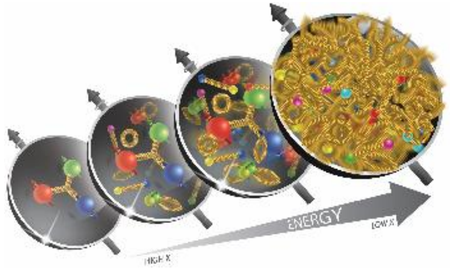
- **The BPM Pickup Challenge in the EIC Hadron Storage Ring**
  - **HSR arc BPM pickup design**
  - **BPM signals and signal conditioning**
  - **BPM button feedthrough measurements**

- **Challenges for the EIC Electron Beam BPMs**
  - **ESR arc BPM pickup design**
  - **BPM signals, signal reflections & signal conditioning**

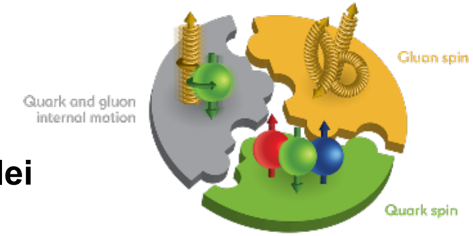
- **More beam instrumentation challenges ahead…**
  - **Crabbed bunches and crab cavity noise feedback**
  - **Lorentz reciprocity, beam voltage, and pickup transfer impedance**

Nuclear Physics Motivations for the EIC

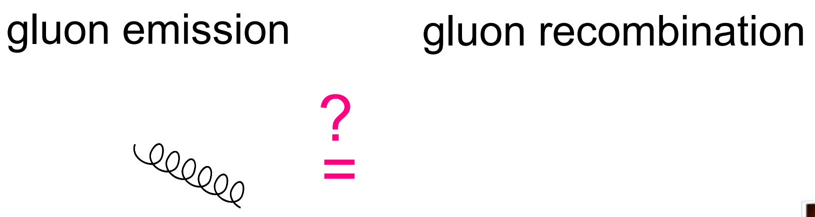
- **wide range center-of-mass energies: ~20 – 140 GeV**
  - map the out nucleon and nuclei structure from high to low x



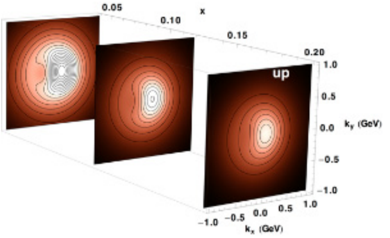
- **polarized electron and hadron (p, He-3) beams**
  - access to spin structure of nucleons and nuclei
  - spin as vehicle to access the spatial and momentum structure of the nucleon in 3D
  - full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei



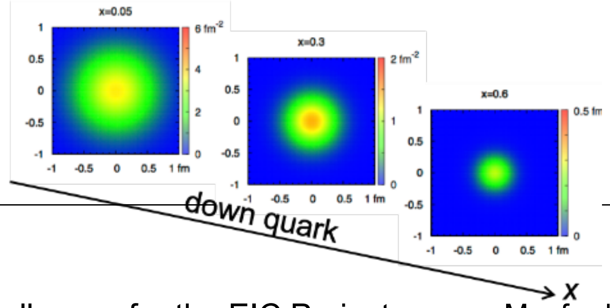
- **nuclear beams: p to U**
  - accessing the highest gluon densities → saturation
  - quark and gluon interact with a nuclear medium



- **high luminosity 10^{33}-10^{34} $cm^{-2}s^{-1}$:**
  - mapping the spatial and momentum structure of nucleons and nuclei in 3D
  - access to rare probes, i.e. Ws



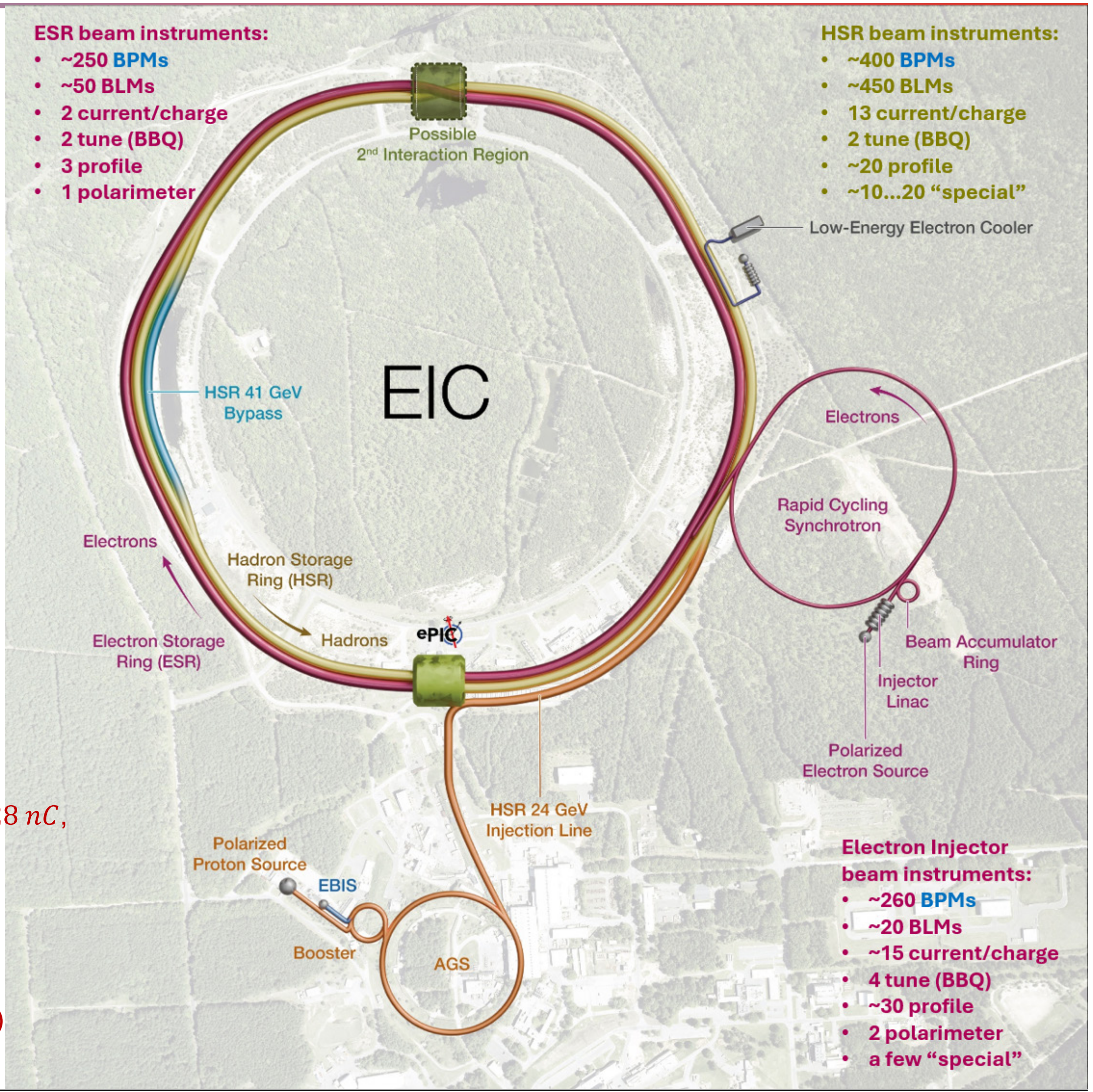
- **large acceptance (0.2 – 1.3 GeV) through forward focusing IR magnets**
  - spatial imaging of nucleons and nuclei



Electron-Ion Collider (EIC) Project Overview

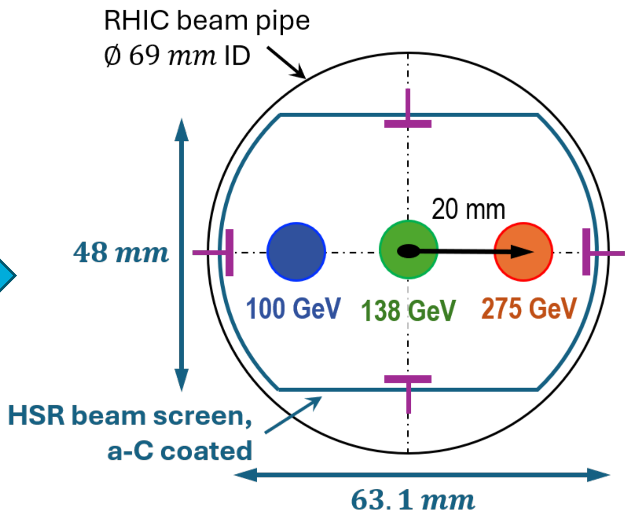
- **Electron Injector**
  single bunches only
  - **DC photoelectron gun**
    - $E_{beam} = 320\ keV$, ~85 % polarization, $q_{bunch} \cong 0.5 \dots 1.5\ nC$
  - **S-Band linac**
    - $E_{beam} = 750\ MeV$, $f_{rep} = 30\ Hz$
  - **Beam Accumulator Ring (BAR, $C \approx 50\ m$)**
    - $E_{beam} = 750\ MeV$, single bunch accumulation, $q_{bunch} = {\sim}1\ nC \Rightarrow 28\ nC/sec$
  - **Rapid Cycling Synchrotron (RCS, $C \approx 1.5\ km$)**
    - $E_{beam} = 0.75 \Rightarrow 5, 9\ \{18\}\ GeV$ (in $100\ ms$), $f_{rep} = 1\ Hz$, $q_{bunch} =$ up to $28\ nC$, spin-transparent lattice

- **Collider (HSR & ESR)**
  up to 1160 (290) bunches, $L = 10^{33} \dots 10^{34}\ cm^{-2}s^{-1}$, $E_{CM} = 20 \dots 100\ \{140\ GeV\}$,
  bunch crabbing at the IP $\theta_{hc} = 25°, \sigma_h/\sigma_v \cong 11$, $\sigma_v \approx 9\ \mu m$,
  $> 70\ \%$ spin polarization (in average for e, p and light ions)
  - **Electron Storage Ring (ESR, $C \approx 3.8\ km$, located in the RHIC tunnel)**
    - $E_{beam} = 5, 9\ \{18\}\ GeV$ $[\beta \cong 1]$, $I_{beam} = 2.5\ (0.23) A$, $\sigma_z = 7\ mm$, $q_{bunch} = (1.6)\ 5 \dots 28\ nC$, single bunch swap-out injection (up to $1\ Hz$)
  - **Hadron Storage Ring (HSR, $C \approx 3.8\ km$, located in the RHIC tunnel)**
    - $E_{beam} = 41 \dots 275\ GeV$ (p), $10 \dots 110\ GeV/u$ (Au^{79+}) $[\beta \neq 1]$, $I_{beam} = 1\ (0.57) A$, low-energy cooling and bunch splitting ($1 \rightarrow 4$) / compression RF gymnastics, $h = 315 \dots 7560$, $\sigma_z = 60 \dots 1250\ mm$ (non-Gaussian), $q_{bunch} = (5)\ 26 \dots 44\ nC$ (inj.)
    - Re-use of RHIC SC magnets, new beam screen and arc BPMs

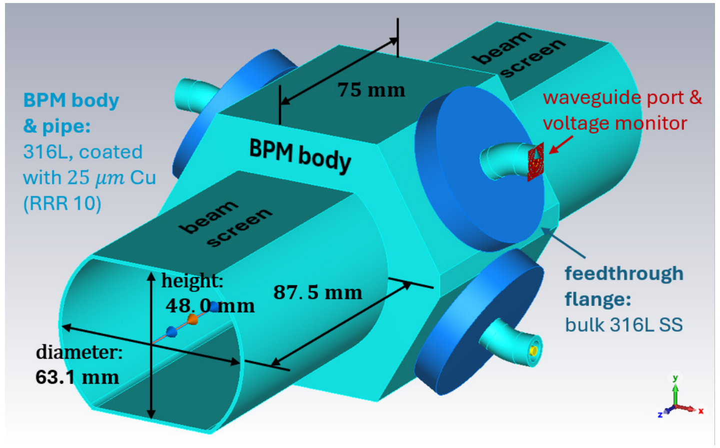


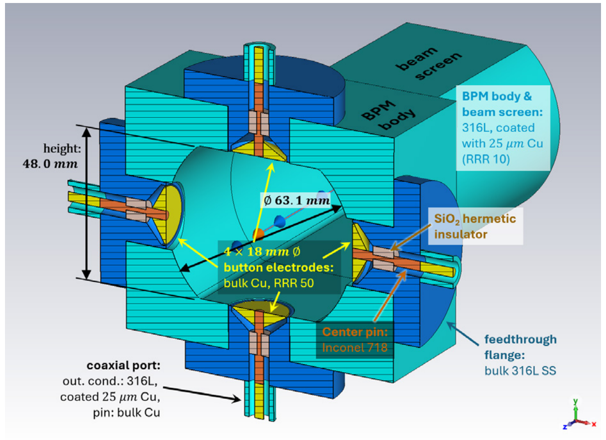
The HSR Button BPM Pickup Challenge

- **To mitigate electron cloud instabilities at high beam intensities, a beam screen with amorphous carbon coating is inserted into the RHIC beam pipe (SC arc sections).**
  - **Requiring the now ``shielded'' RHIC stripline BPMs to be replaced by compact button BPMs for EIC HSR operation.**
- **Synchronization of hadron (HSR) and electron (ESR) beams in the range $100\ GeV < E_{HSR} < 275\ GeV$ requires a radial beam orbit shift $-20\ mm < x_{pos} < +20\ mm$ in the HSR SC arcs**
  - **Challenging the HSR arc button BPM design to meet the required specifications, e.g. orbit resolution ($20\ \mu m$ RMS) and accuracy, under the various HSR beam conditions.**
- **Which type of button arrangement is better for the HSR beam diagnostics?!**

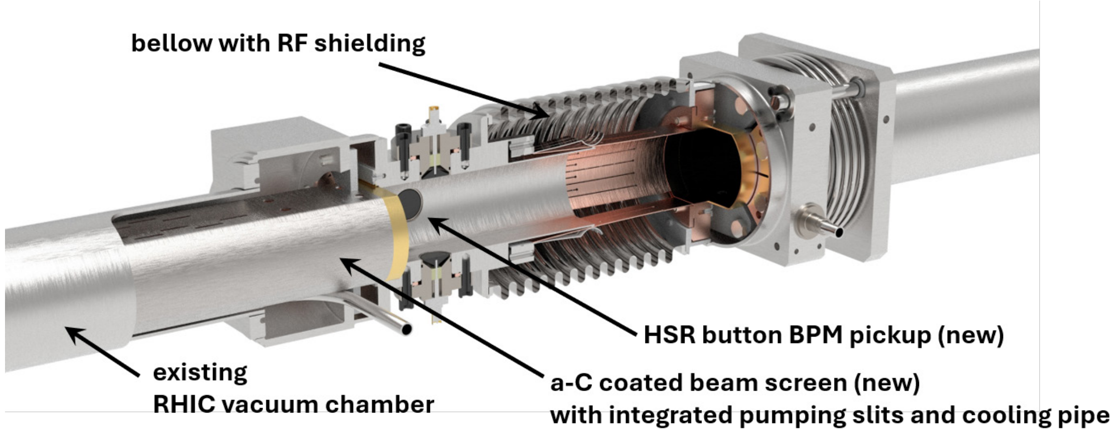


corner BPM or orthogonal BPM ?!



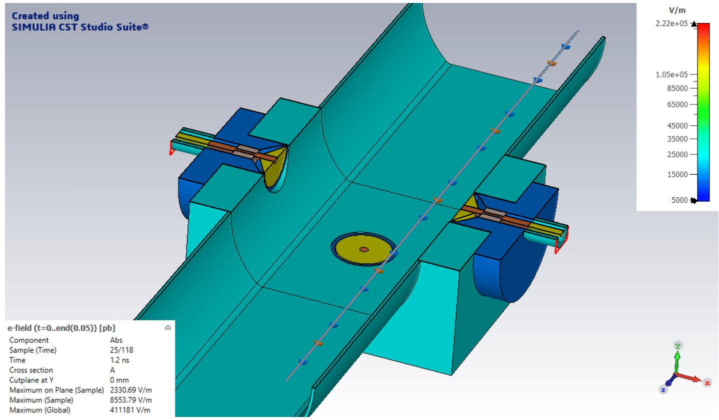


HSR SC arc quad-dipole interconnect



Beam-induced Power Losses

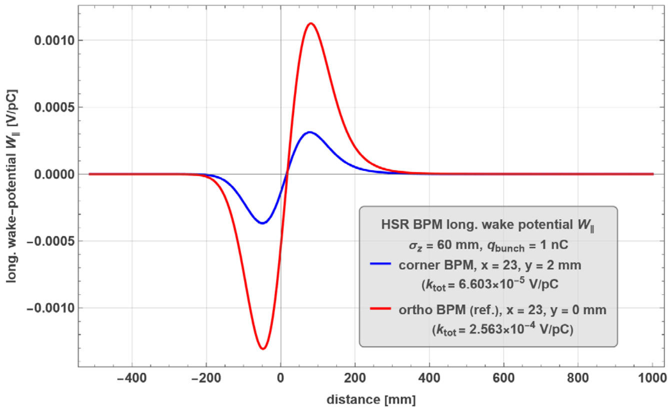
- **Wakefield effects can cause instabilities, the longitudinal wakes results in high local power losses in vacuum devices, here we focus on the BPMs for the HSR arc BPM pickups and briefly for the ESR.**
  - **That power is dissipated in the metals and due to the finite conductivity converted into heat.**
  - **There are two flavors of wakefield effects that generate power losses:**
    - Bunched-beam excited, trapped resonances due to eigenmodes, e.g., in a BPM pickup, generating high local losses to the finite conductivity of the metals
    - Bunched-beam related, H-field induced surface currents causing losses in the beam-field exposed metals of finite conductivity, called "resistive wall losses".
  - **The high intensities of the bunched beams in the EIC storage rings, $I_{HSR} \cong 1\,A$, $I_{ESR} \cong 2.5\,A$, can generate high beam-induced power losses in the vacuum devices such as the BPM pickups**
    - The large radial beam offset in the HSR SC arcs further increases the resistive wall power losses on the ``hot'' BPM pickup electrode
      - *Note the HSR arc BPMs are part of a SC cryostat, any beam caused **heat dissipation is not a good idea!***



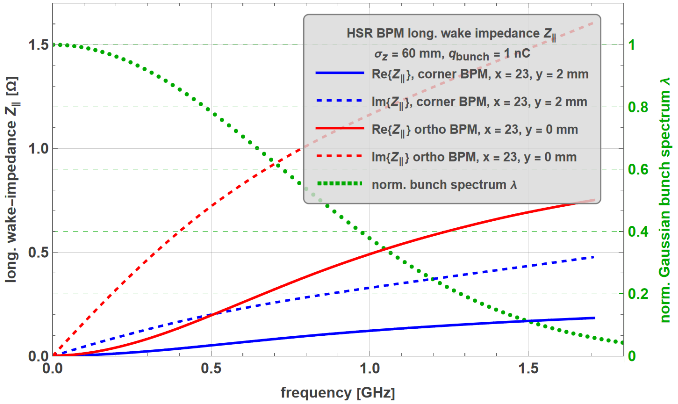
- **Total power loss estimation based on EM field losses:**
  - **HSR arc BPM: Numerical wakefield analysis with a Gaussian line charge $\lambda(s)$, $q_{bunch} = 1\,nC$, $\sigma_z = 60\,mm$, at a large horizontal beam offset $x_{pos} = 23\,mm$**
  - **Field loss calculation:** $\Delta E_{bunch} = \frac{q_{bunch}^2}{k_{tot}}$

$$\boxed{P_{loss,field} = \frac{\Delta E_{bunch}}{t_{rev}} N_{bunch}}$$

HSR BPM long. wake potential

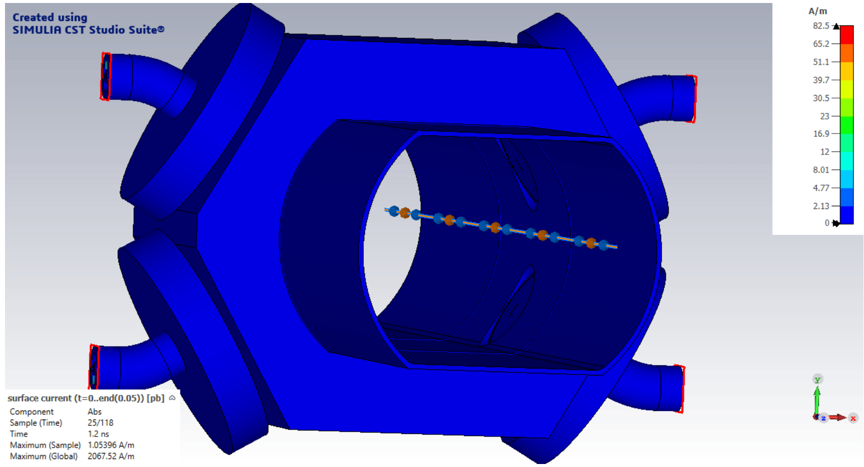


HSR BPM long. wake impedance



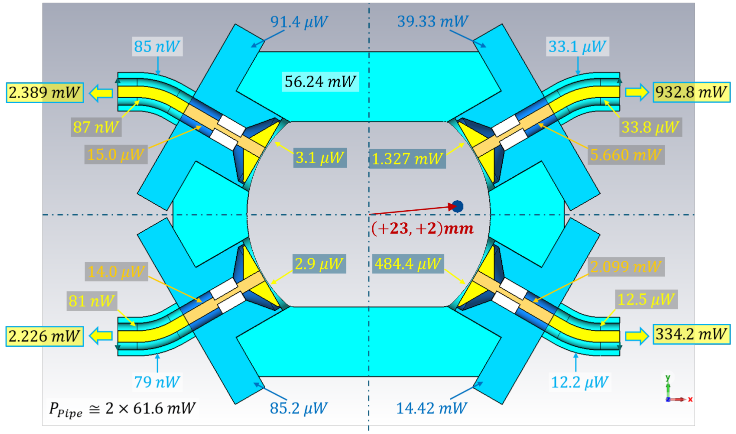
Power Dissipation in Metals

- **Numerical wakefield analysis software (CST Studio, GdfidL, A3P, Echo 3D, etc.) has many field analysis features, including the recording of E- and H-fields vs. time or frequency.**
  - **The beam's H-field related surface currents and the resulting power losses due to the finite conductivity of the metals are of relevant for the BPM design**
  - **The HSR arc BPM was analyzed with the CST Studio wakefield solver, that allows to separate the power losses by material type and sub-component.**
    - **H-field ⇒ surface current ⇒ power losses in metals ($\rho \neq 0$) ⇒ heating**
      - ***Please note, $\sum P_{loss,metal} < P_{loss,field}$ as we need to include the power dissipated into the ports, e.g. for BPM, kickers the coaxial ports and the beam (waveguide) ports!***

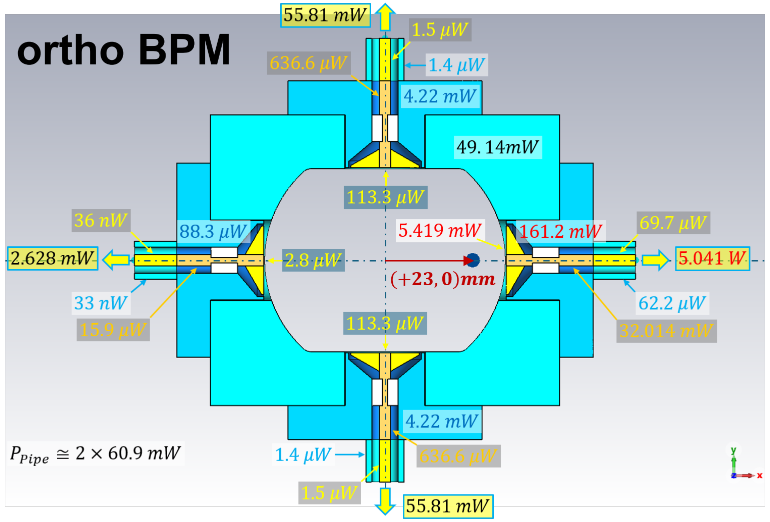


- **Power dissipation in HSR SC arc BPM button pickup in worst case scenario**
  - **290 bunches, $q_{bunch} = 30.6\,nC$, $\sigma_z = 60\,mm$, $x_{pos} = +23\,mm$, $y_{pos} = 0\,(+2)\,mm$**

corner BPM



ortho BPM



$$\Delta E_{loss\_metal\_CST} = \int P_{loss\_metal\_CST}(t)dt$$

$$k_{qScale} = \left(\frac{q_{bunch}}{q_{bunch\_CST}}\right)^2$$

$$\Delta E_{loss\_metal} = k_{qScale}\,\Delta E_{loss\_metal\_CST}$$

$$\boxed{P_{loss\_metal} = \frac{\Delta E_{loss\_metal}}{t_{rev}} n_{bunch}}$$

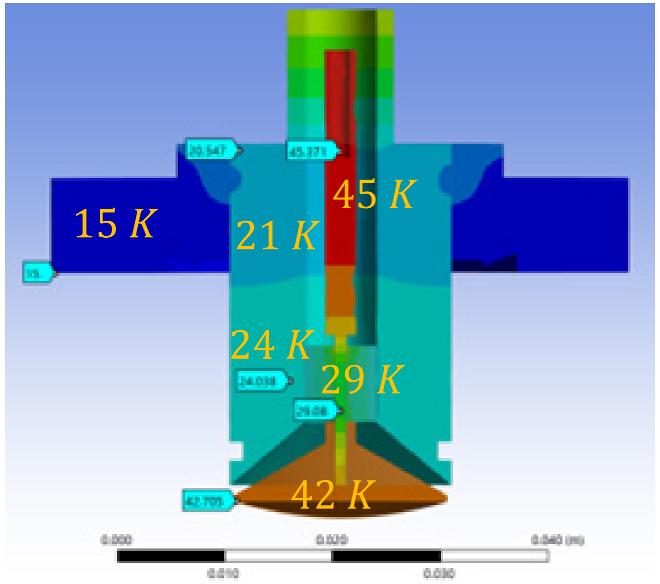
Power Losses & Metal Heating

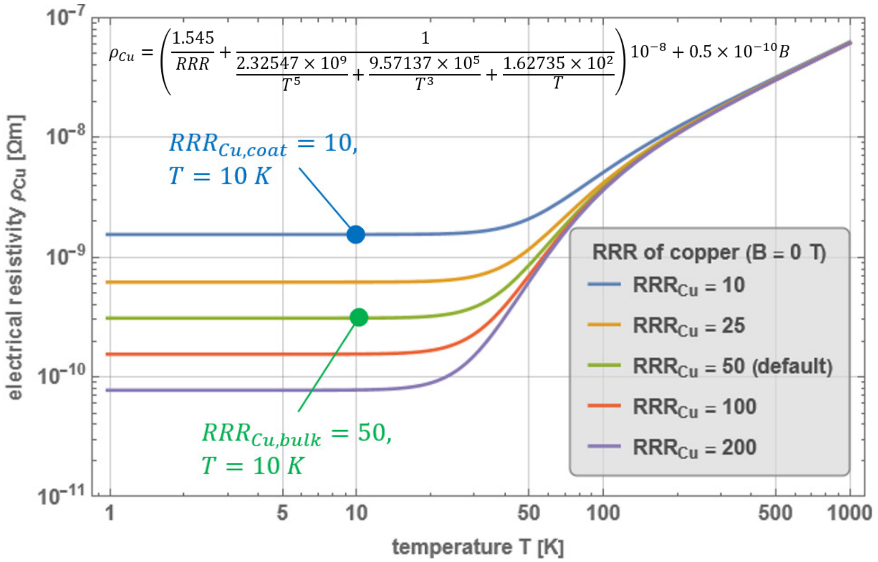
- **Clearly, the power dissipation for beams with large radial shifts ($x_{pos} \cong \pm 20\ mm$) in the corner BPM is lower, compared to the orthogonal BPM!**
  - **Why did Manfred (when still new to the EIC project) proposed (almost insisted) a major, last minute BPM design change towards the orthogonal BPM?!**
    (Answer in the next pages)
    - Please note, to limit the heating of the “hot” button electrode, the button size was reduced, $\emptyset\ 20\ mm \Rightarrow \emptyset\ 18\ mm$ and the button material was changed to bulk copper, with $RRR_{Cu} \cong 10$ (or higher).

$$P_{loss\_field} \cong P_{loss\_metal} + \sum P_{port}$$

$$P_{loss,corner} = 1.402\ W \approx 0.234\ W + 1.272\ W = 1.515\ W$$

$$P_{loss,ortho} = \underbrace{5.442\ W}_{P_{loss\_field}} \approx \underbrace{0.375\ W}_{P_{loss\_metal}} + \underbrace{5.155\ W}_{\sum P_{port}} = 5.530\ W$$



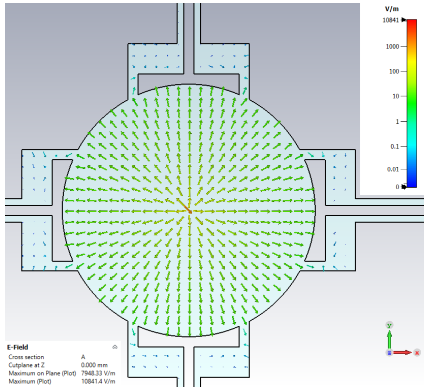


- **Materials used in the CST Studio analysis:**
  - **BPM body and beam pipe:**
    316L (lossy metal),
    coated with $25\mu m$ Cu (normal, $RRR_{Cu,coat} = 10$)
  - **BPM button feedthrough flanges:**
    bulk 316L (lossy metal)
  - **BPM button electrodes and coaxial output pin:**
    bulk Cu (lossy metal, $RRR_{Cu,bulk} = 50$)
  - **BPM coaxial center pin:**
    Inconel 718

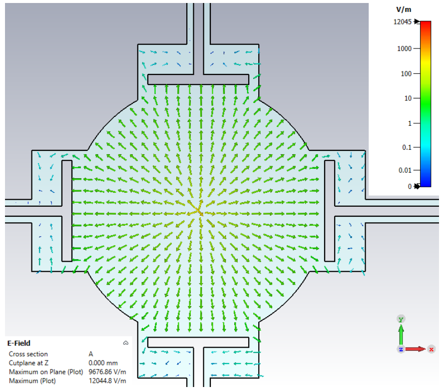
- A detailed analysis, taking the material properties at $T = 10\ K$ into account demonstrated the temperature of the orthogonal, **“hot” button electrode will stay below the limit of $T_{max} \leq 50\ K$**

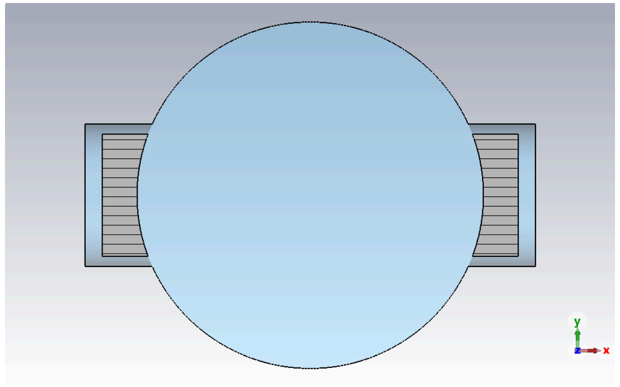
Numerical analysis of the BPM position characteristic

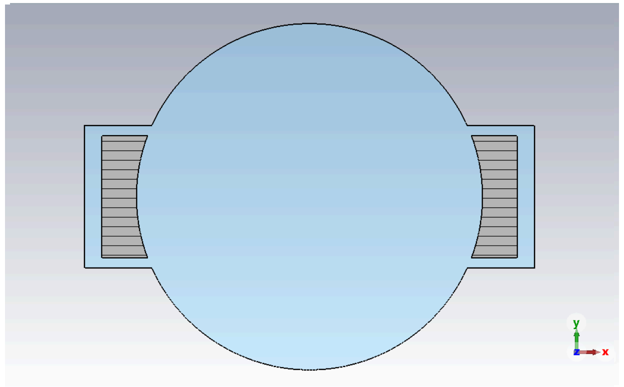
curved electrodes



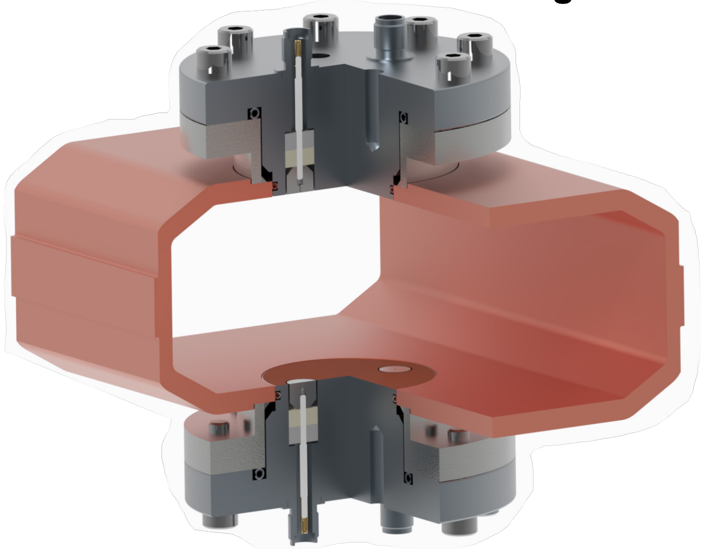
flat electrodes







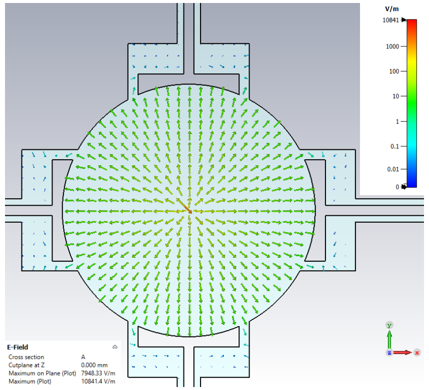
octagonal-shape ESR vacuum chamber with button BPM feedthroughs



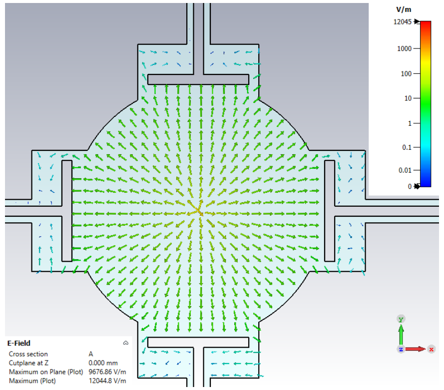
- **BPM pickup housings / beam-pipe cross-sections are not always circular!**
  - Analytical solutions for the normalized beam position characteristic rarely apply
- **BPM electrodes have different shapes**
  - e.g., curved or flat, following (flush) or not the vacuum pipe cross-section shape

Numerical analysis of the BPM position characteristic

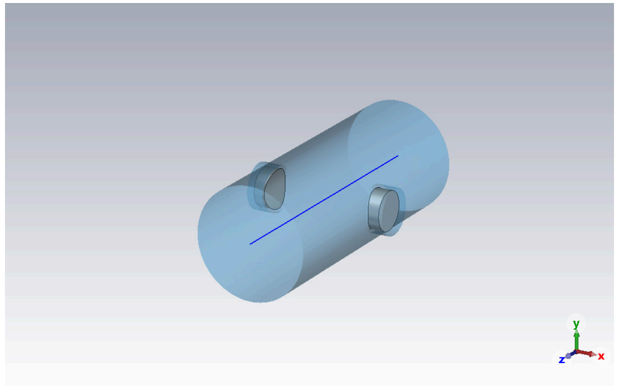
curved electrodes



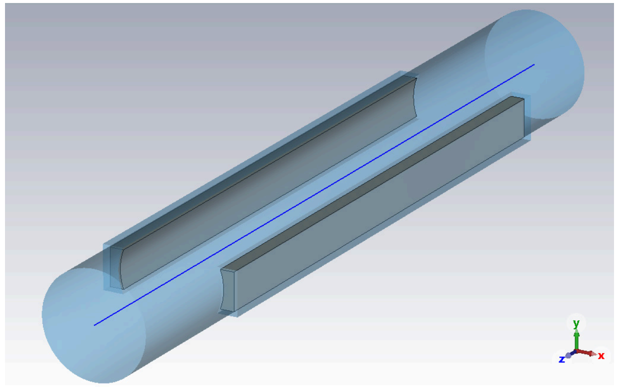
flat electrodes



“button”-style electrodes

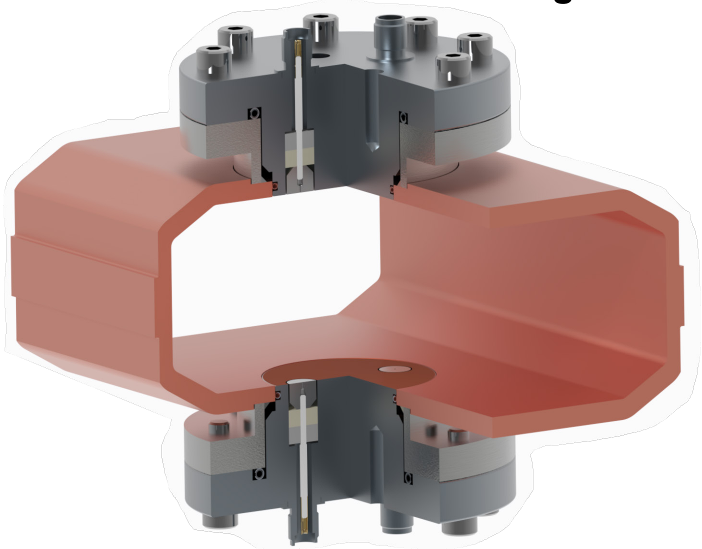


stripline electrodes



- **BPM pickup housings / beam-pipe cross-sections are not always circular!**
  - Analytical solutions for the normalized beam position characteristic rarely apply
- **BPM electrodes have different shapes**
  - e.g., curved or flat, following (flush) or not the vacuum pipe cross-section shape
- **BPM electrodes are not 2D objects**
  - circular-shaped “button” electrodes, very popular
  - long, strip-like, “stripline” electrodes
    - ➢ which are a rather good match to the 2D analytical model
  - many other shapes and styles…

octagonal-shape ESR vacuum chamber with button BPM feedthroughs

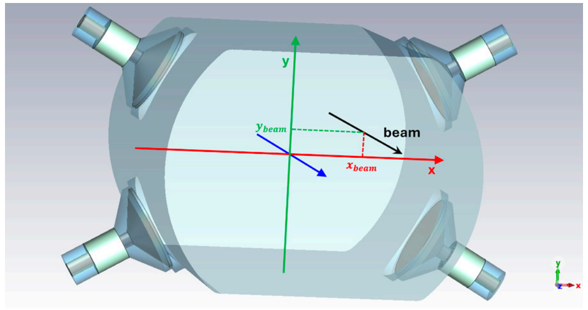


Poisson Equation ⇒ *Green*'s Reciprocity Theorem

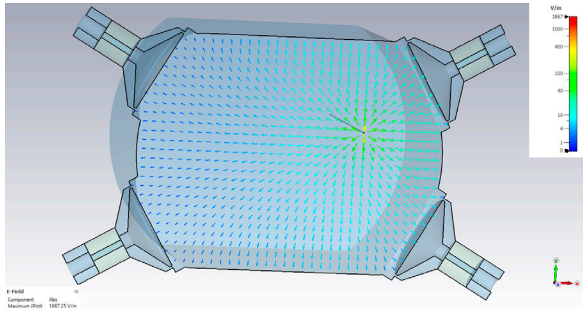
- **To analyze the coupling between the beam particles to the BPM electrode we need to numerically solve the Poisson equation:**

$$\nabla^2\Phi(\vec r) = -\rho/\varepsilon_0$$

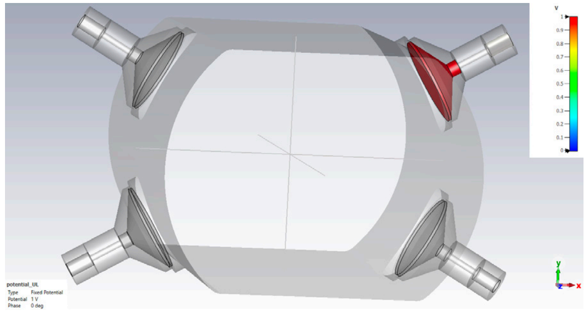
  - **for a point charge $\rho(\vec r) = q\delta(\vec r - \vec r_0)$ travelling at relativistic velocity $\beta = v/c \cong 1$**
    - **In the following the point charge is replaced by a line charge density $\rho(\vec r) = \lambda(z)\delta(x-x_0)\delta(y-y_0)$, mimicking a pencil beam with small transverse dimensions $\sigma_x, \sigma_y \ll a$ wrt. to the beam pipe aperture a**



HSR button BPM with a line-charge excitation



line-charge E-field in the xy-plane at $z = 0$



fixed potential $\mathcal{V} = 1\,V$ set on the UR electrode

- **Instead of scanning the line charge (beam) across the xy-plane and recording the potential at the BPM electrodes through many calculations, we apply *Green*'s reciprocity theorem:**
  - **Applied to one BPM electrode,**
    - scalar potential $\phi_1 = \phi_{elec}(\vec r)$
    - set to a fixed voltage potential $\mathcal{V} = 1V$, it simplifies to:
      - *Assuming all other electrodes and the beam pipe cylinder being on ground potential*

$$\int_V \phi_1\rho_2\, dV + \overbrace{\int_S \phi_1\rho_2\, da}^{=0} = \int_V \phi_2\rho_1\, dV + \overbrace{\int_S \phi_2\rho_1\, da}^{=0}$$

$$\int_V \phi_{elec}(\vec r)\underbrace{\rho_2(\vec r)}_{=\lambda(\vec r_0)}\, dV = -\underbrace{\mathcal{V}}_{=1\,V} q_{elec}$$

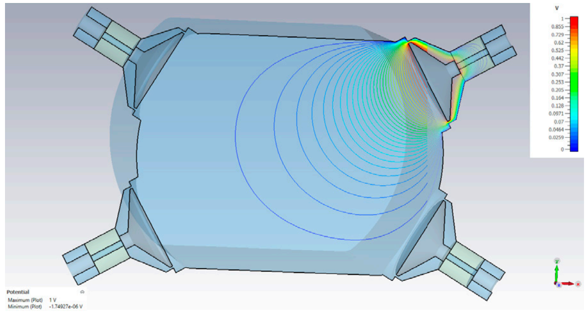
Green's Reciprocity Theorem ⇒ *Laplace* equation

– furthermore, assuming $\rho_2 = \lambda(\vec{r}_0)$
we retrieve the scalar potential $\phi_{elec}(\vec{r}_0)$ at $\vec{r}_0$ (line-charge = beam location):

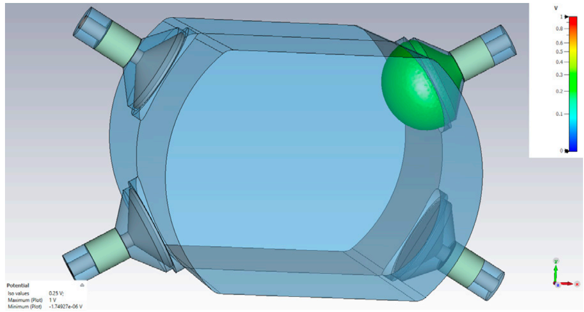
$$q_{elec} = -\frac{\lambda(\vec{r}_0)\phi_{elec}(\vec{r}_0)}{\mathcal{V}}$$

➢ $\phi_{elec}(x=0,\ y=0) = g$ is called the "geometric constant" or "coupling constant", expressing the coupling between a centered beam $(x=0,\ y=0)$ and the pickup electrode

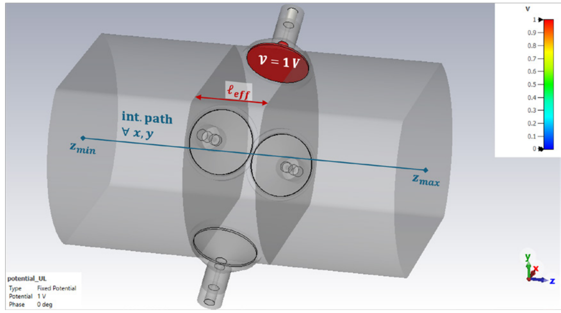
- The resulting *Laplace* equation $\nabla^2 \Phi_{elec}(\vec{r}) = 0$ needs to be solved in 3D
  – as of the geometric symmetry of the BPM, the calculation requires to be performed only for one (or two) electrode(s) (making use of of symmetries), by putting it on a fixed potential, e.g. $\mathcal{V} = 1\,V$

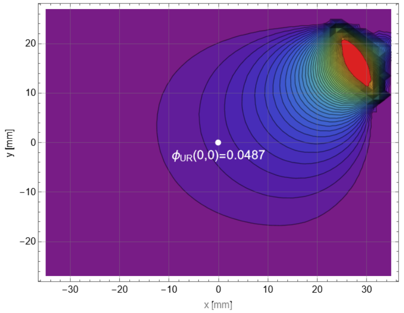


2D equipotentials $\phi_{UR}(x,y,z=0) = const.$



3D isometric surface potential $\phi_{UR}(x,y,z) = 0.25$



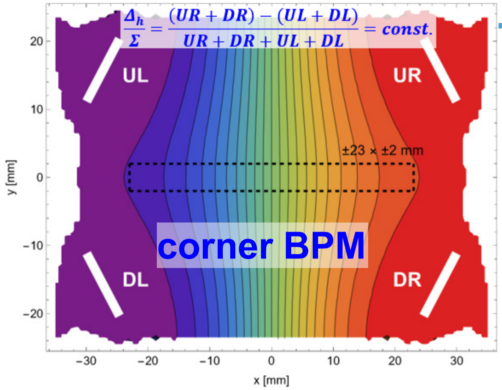


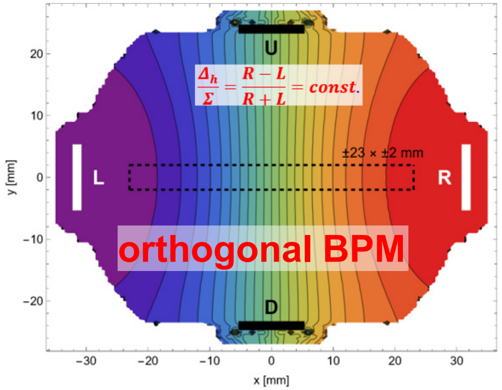
2D equipotentials $\phi_{UR}(x,y) = const.$

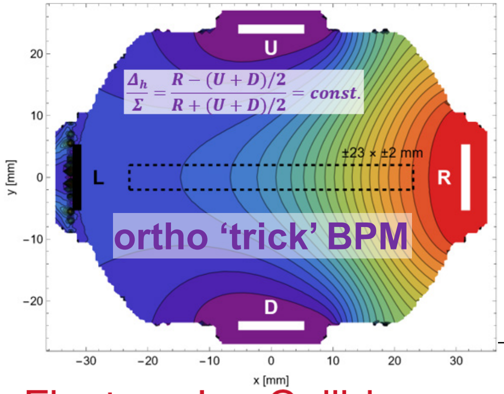
➢ The resulting 3D scalar potential,
here for the upper-right electrode $\phi_{UR}(x,y,z)$,
needs to be mapped to a 2D-plane to account
for the induced image charge on the electrode:
  – with $\ell_{eff} \cong \ell_{elec} + w_{gap}$ (here: $\ell_{eff} \cong d_{button} + w_{gap}$)

$$\boxed{q_{elec} \propto \phi_{elec}(x,y) = \frac{\int_{z=z_{min}}^{z_{max}} dz\, \phi_{elec}(x,y,z)}{\ell_{eff}}}$$

Normalized Position Characteristic & Sensitivity







- **Normalized beam position characteristic:**

$$pos. = \frac{\Delta}{\Sigma} = \frac{\phi_{elec,A} - \phi_{elec,B}}{\phi_{elec,A} + \phi_{elec,B}}$$

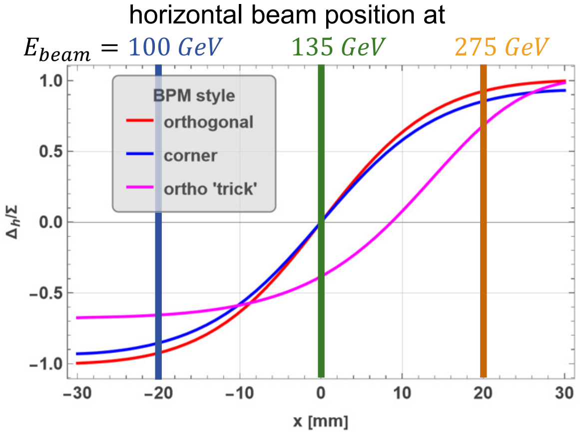
  - **based on the numerically calculated 2D scalar potentials of the BPM electrodes**
  - **here for the horizontal plane:** $-1 \leq \frac{\Delta_h}{\Sigma} = f(x, y=0) \leq +1$

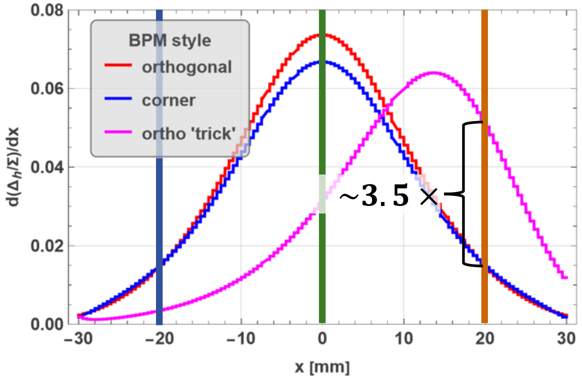
- **Position sensitivity:** $\frac{d(\Delta_h/\Sigma)}{dx} = f(x, y=0)$
  - **gradient of Δ/Σ**
  - **is quite similar for corner and orthogonal BPM, but:**
    - the vertical electrodes enable for a "virtual" center electrode $(U+D)/2$ that improves the sensitivity at large horizontal beam offsets

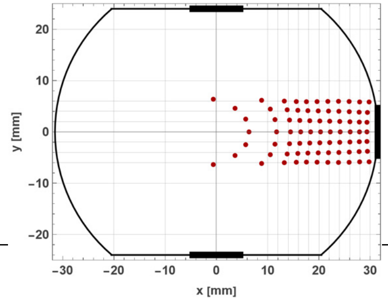
- **Calibration (scaling) and non-linearity correction is performed by a 5th-order 2D polynomial fit**
  - **need to invert the 2D position function for each plane…**
  - **…and perform the 2D poly fit:**

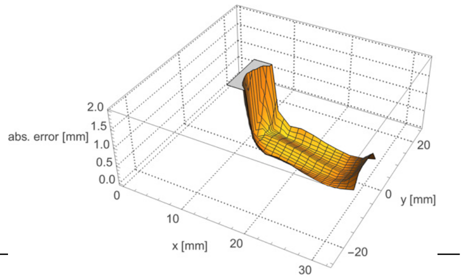
$$\begin{cases} x = f^{-1}(x_{raw}, y_{raw}) \\ y = g^{-1}(y_{raw}, x_{raw}) \end{cases}$$

$$\begin{cases} x_{bpm}^{2D} = \sum_{i,j=0}^{p,q} \left(c_{ij} x_{raw}^{i} y_{raw}^{j}\right) = Q_{p,q}(x_{raw}, y_{raw}) \approx x \\ y_{bpm}^{2D} = \sum_{i,j=0}^{p,q} \left(c_{ij} y_{raw}^{i} x_{raw}^{j}\right) = Q_{p,q}(y_{raw}, x_{raw}) \approx y \end{cases}$$









BPM button electrode signals

- **The button output signal (waveform) into a load impedance R_{load} is analyzed for a centered beam $(x, y = 0)$**
  - **analytical approximation (*Ohm*'s law):**

$$V_{elec}(f) = Z_{button}(f) I_{bunch}(f) \rightarrow v_{elec}(t) = \int_{-\infty}^{+\infty} df\, Z_{button}(f) I_{bunch}(f) e^{-i2\pi f t}$$

  - **With the transfer impedance for a BPM button:**

$$\boxed{Z_{button}(\omega) = g R_{load} \frac{\omega_1}{\omega_2} \frac{i\omega/\omega_1}{1 + i\omega/\omega_2}}$$

    - and parameters:

angular frequency, $\omega = 2\pi f$ geometric coverage factor, $g = \phi_{elec}(x, y = 0)$

1/time constant, $\omega_1 = \frac{1}{R_{load} C_{button}}$ 1/transit time, $\omega_2 = \frac{c}{d_{button}}$

BPM button electrode signals

- **The button output signal (waveform) into a load impedance R_{load} is analyzed for a centered beam $(x, y = 0)$**
  - **analytical approximation (*Ohm*'s law):**

Fourier transform

$$V_{elec}(f) = Z_{button}(f) I_{bunch}(f) \rightarrow v_{elec}(t) = \int_{-\infty}^{+\infty} df\, Z_{button}(f) I_{bunch}(f) e^{-i2\pi ft}$$

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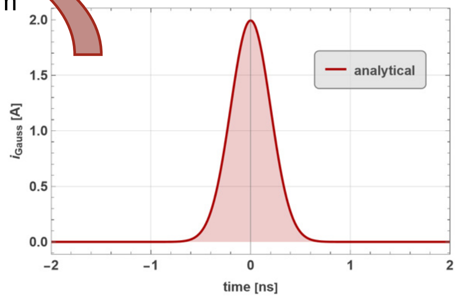
Ideal *Gaussian* bunch



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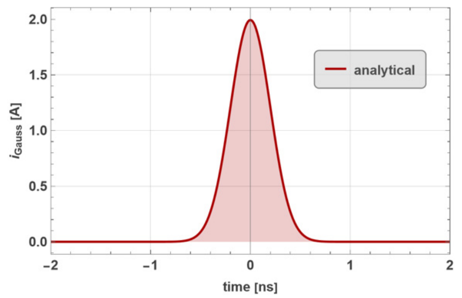

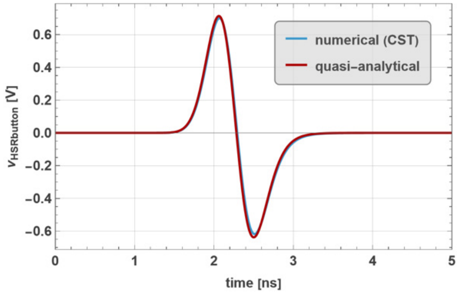

BPM button electrode signals

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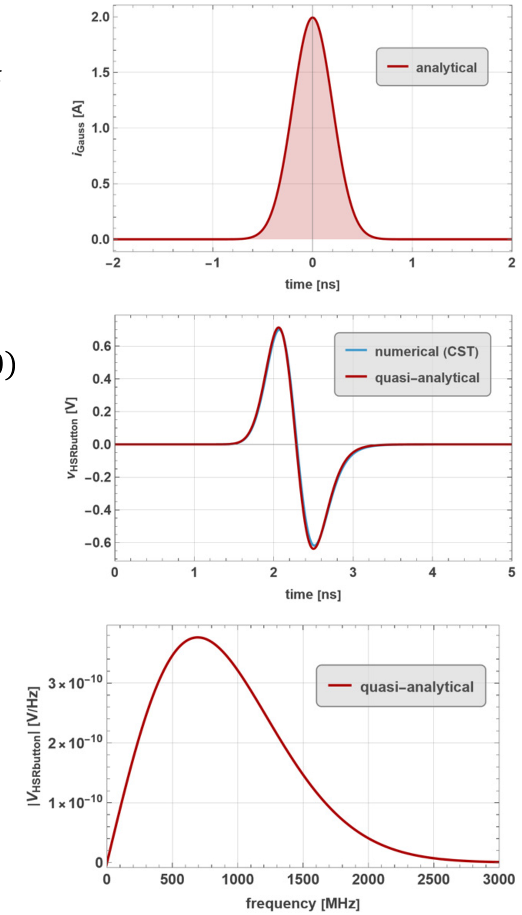
1/time constant, $\omega_1 = \frac{1}{R_{load} C_{button}}$ 1/transit time, $\omega_2 = \frac{c}{d_{button}}$

Ideal *Gaussian* bunch



BPM button electrode signals

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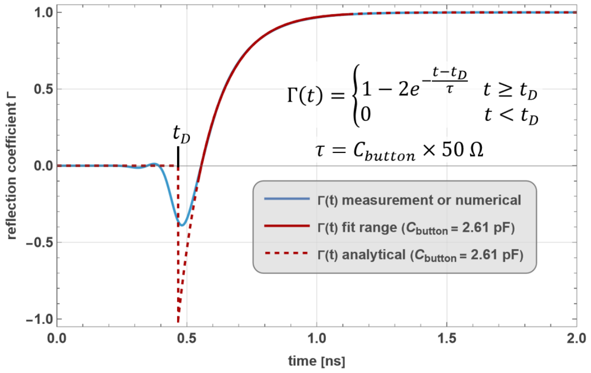
    - and parameters:

angular frequency, $\omega = 2\pi f$ geometric coverage factor, $g = \phi_{elec}(x, y = 0)$

1/time constant, $\omega_1 = \frac{1}{R_{load} C_{button}}$ 1/transit time, $\omega_2 = \frac{c}{d_{button}}$

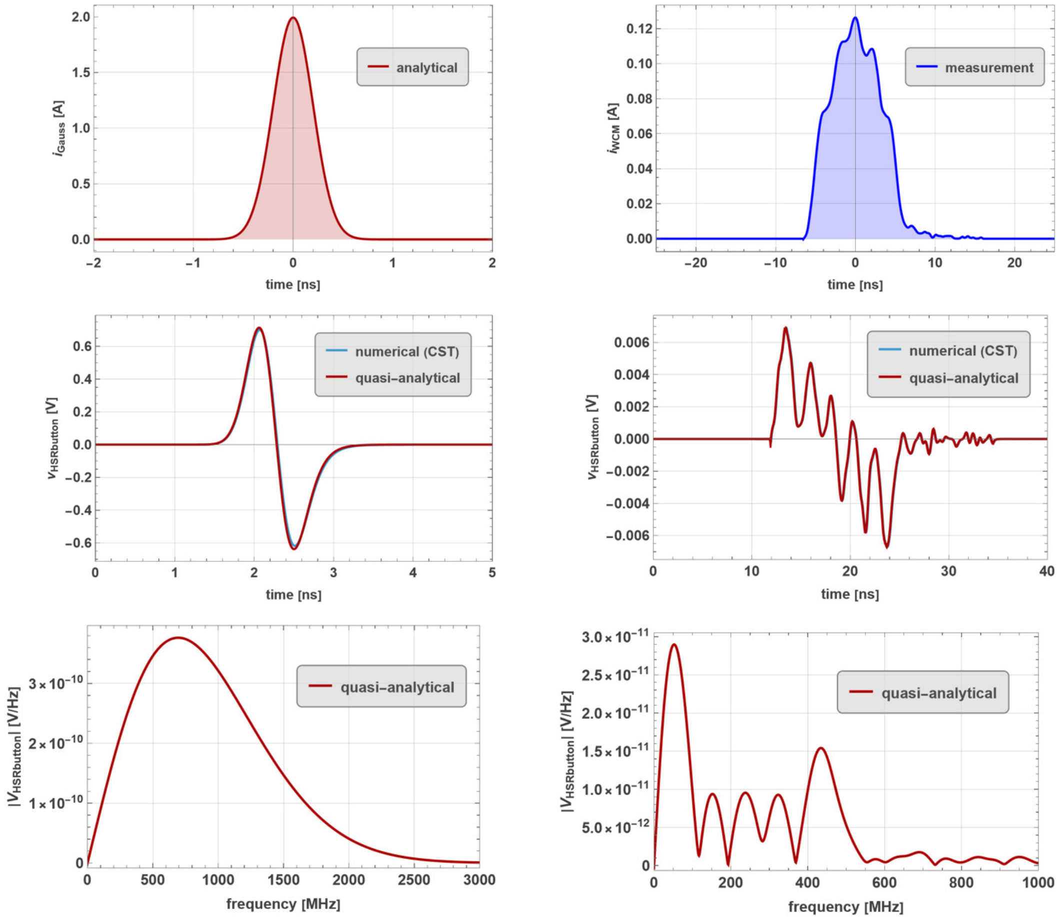
  - **The button capacitance is difficult to calculate analytically**
    - Measurement or numerical calculation and fit



  - **Time-domain reflectometry (TDR) reveals the reflection coefficient Γ**
  - **Fit the exponential function of the TDR measurement or numerical analysis with two parameters**
    - button capacitance C_{button}, time delay t_D

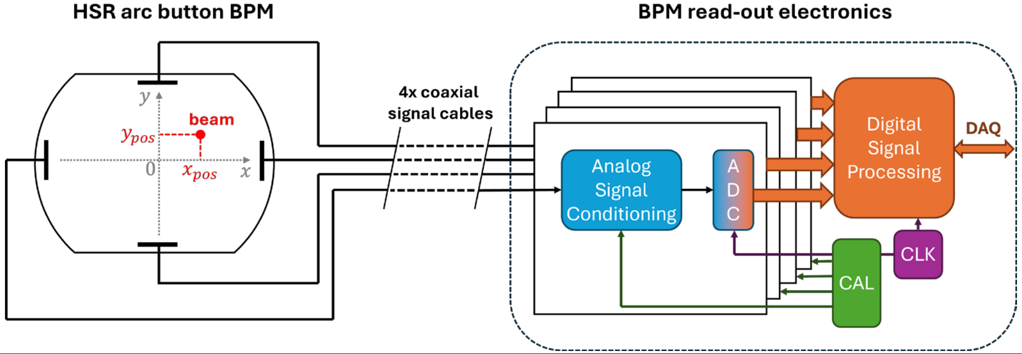
Ideal *Gaussian* bunch

RHIC proton bunch (WCM measurement, during "rebucketing")

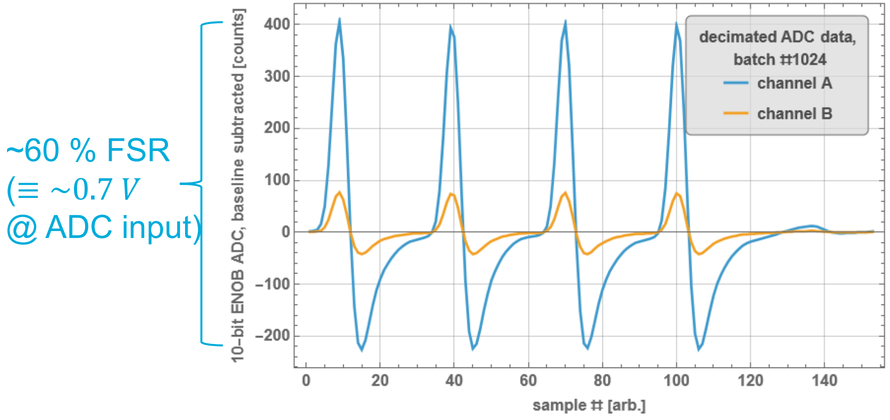


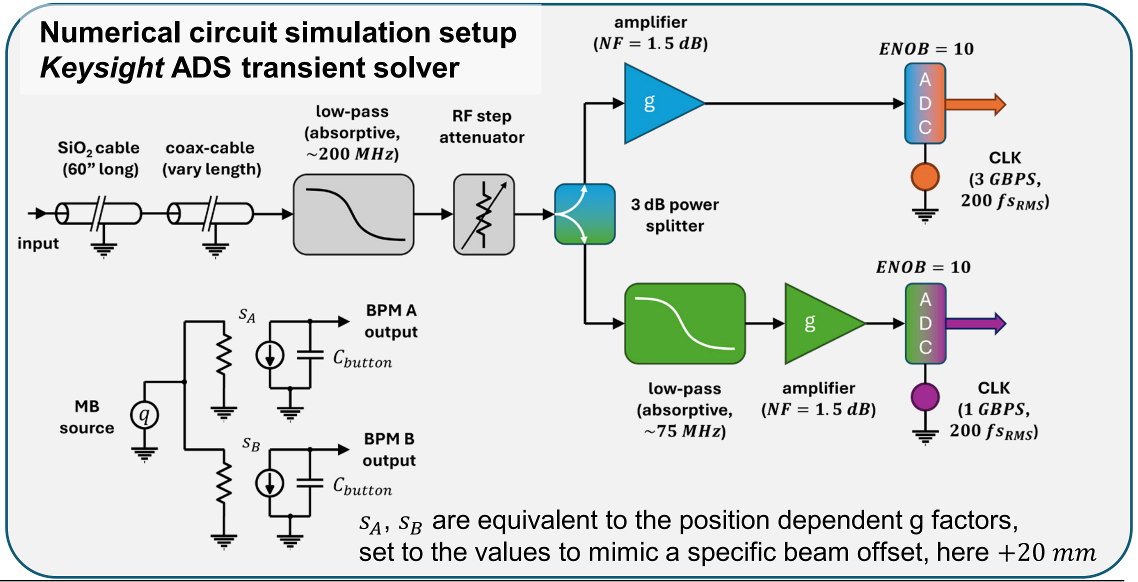
HSR BPM Signal Analysis (under ideal conditions)

- **Simulated beam conditions**
  - **4 proton bunches: $q_{bunch} = 5\,nC$, $10.15\,ns$ spacing, $\sigma_z = 60\,mm$**
    - ➢ horizontal beam orbit at $x_{pos} = +20\,mm$
- **Read-out BPM electronics**
  - **$240\,m$ long 3/8” Heliax coaxial signal cables**
  - **simplified signal processing, separately of each button electrode**
- **BPM resolution estimation (RMS)**
  - **Single batch / single turn resolution – HSR requirement: n/a corner BPM: $\sim 300\,\mu m$, ortho “trick” BPM: $\sim 80\,\mu m$**
  - **Multi-turn (~1000 turns or more) resolution limit – HSR requirement: $20\,\mu m$ corner BPM: $\sim 20\,\mu m$, ortho “trick” BPM: $\sim 5\,\mu m$**
- **Benchmarking the simulation**
  - **Test read-out electronics on a button BPM with proton and ion beams in RHIC**
    - ➢ Amazingly good agreement within a few percent!



Signal acquired from the horizontal BPM buttons

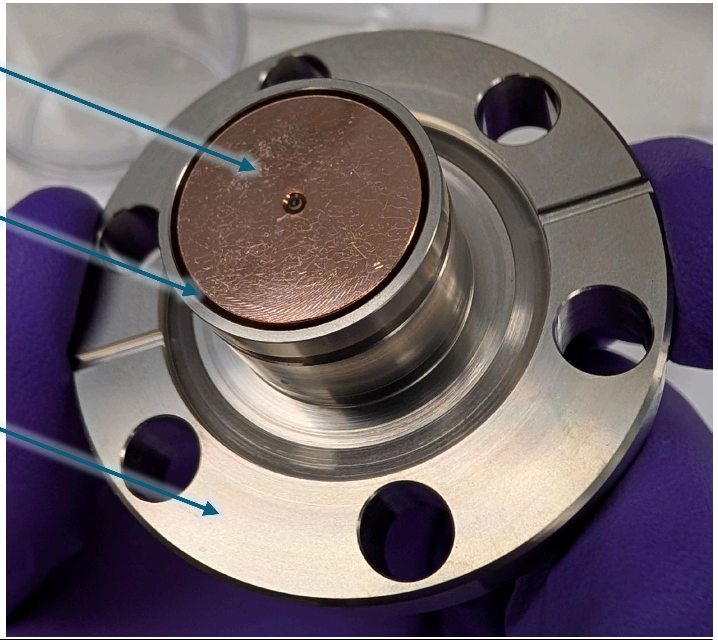




HSR button BPM feedthrough vendor selection

- **~1500 HSR button feedthroughs will be required in the EIC project**
  - **Including spares and special locations**
- **Three manufacturers, each delivered up to 35 pre-series units**
  - **In-depth testing of those HSR BPM feedthroughs was performed**
    - Visual inspection
    - CMM-based mechanical tolerances
    - Cryo-shock, vacuum leak and outgasing tests
    - CT scans
    - Electrical tests:
      - *High-voltage (DC) and insulation*
      - *DC contact resistance*
      - *Faraday-cage S11, TDR RF measurements*
      - *S21 RF measurements on a slabline test-setup*
      - *4-port Lambertson-style S-parameter measurement (TBD)*

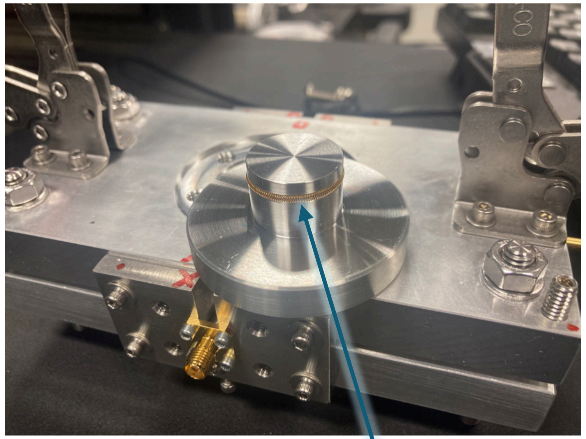
HSR button BPM feedthrough
(vendor C)



Impressions of the RF measurement setups…

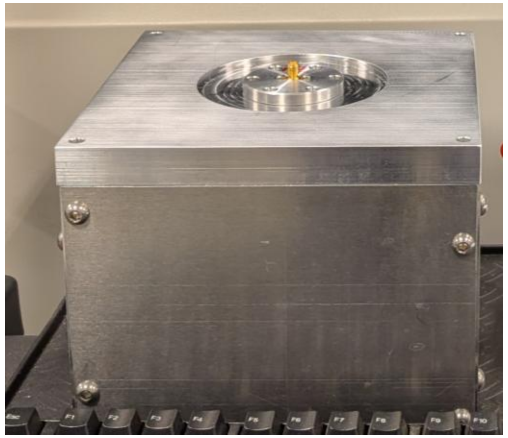
slabline measurement setup in action

dummy button for slabline reference measurement

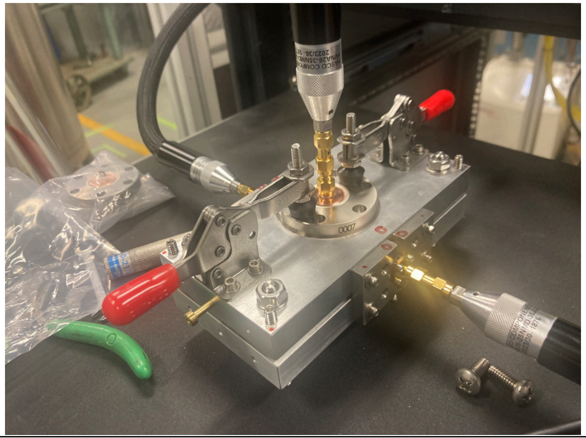


canted coil-spring for grounding

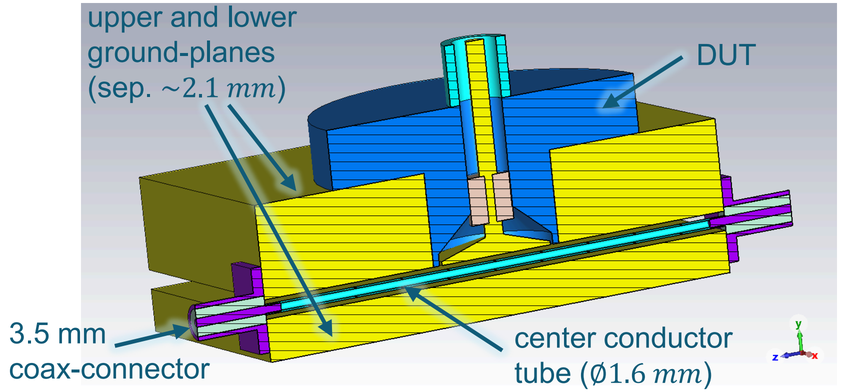
resonance-free *Faraday*-cage, lined with RF foam absorbers



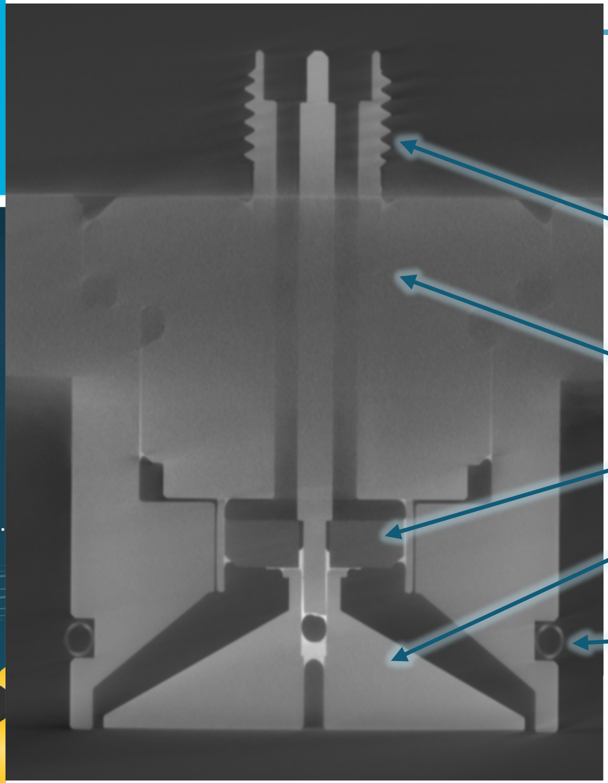
slabline 3-port setup



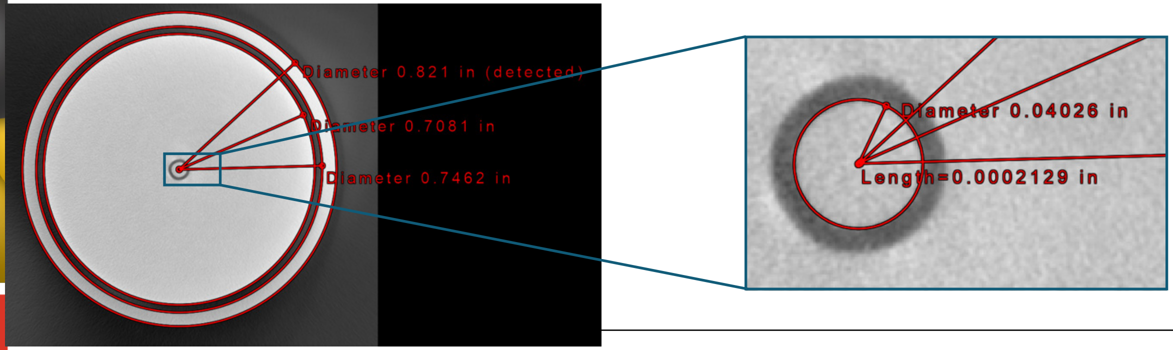
mode-free slabline (cross-section)



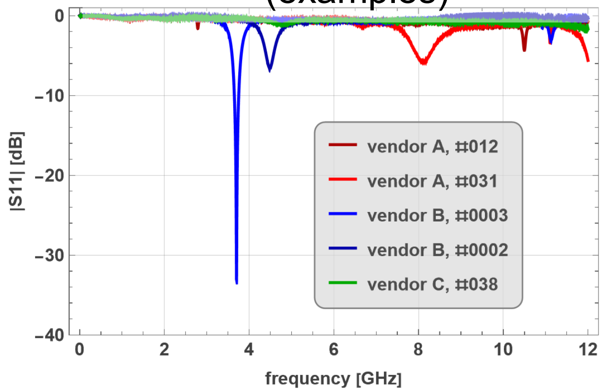
…and some preliminary results



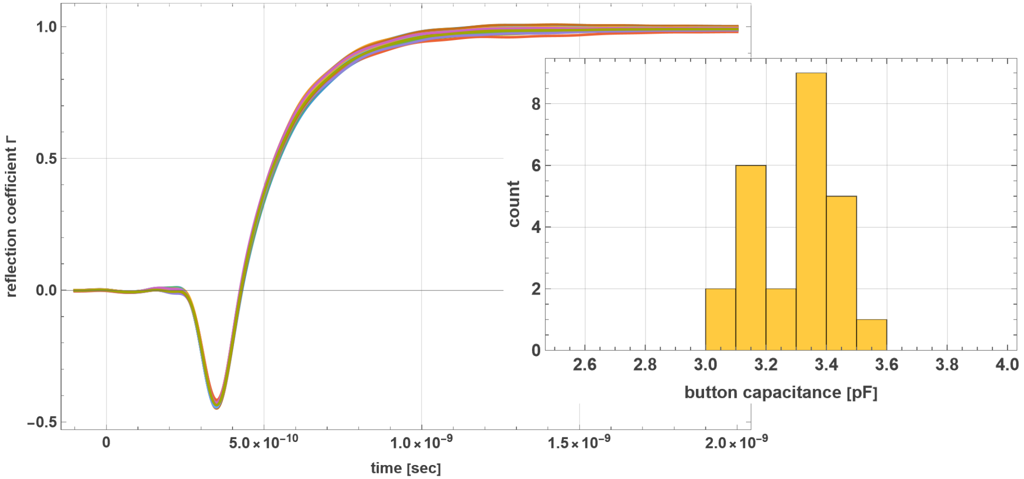
3D CT-scans
(example vendor B)



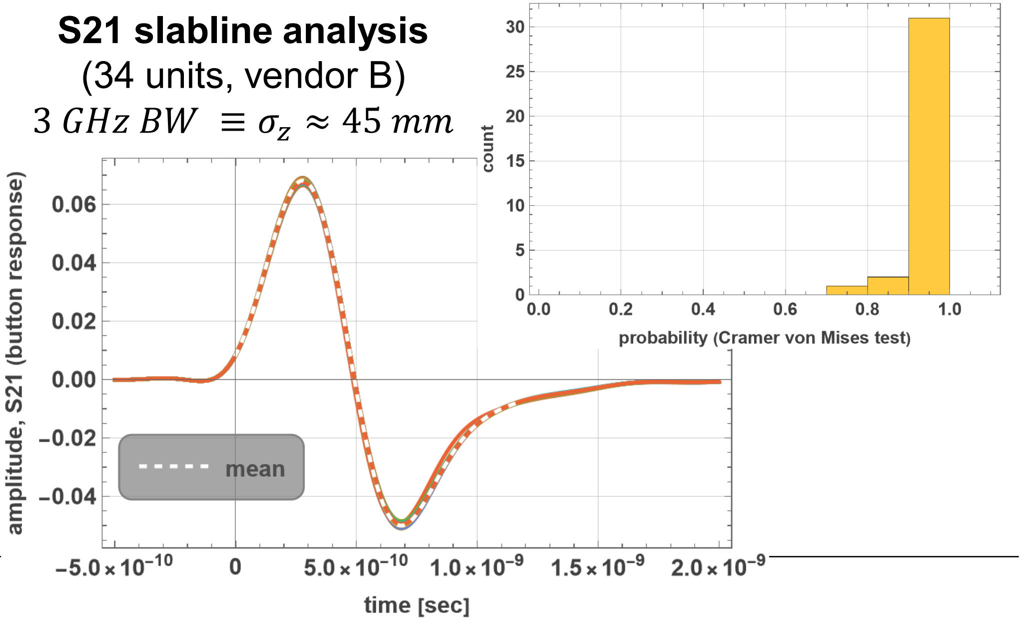
$|S11(f)|$ eigenmode analysis (examples)



TDR for capacitance analysis (25 units, vendor C)



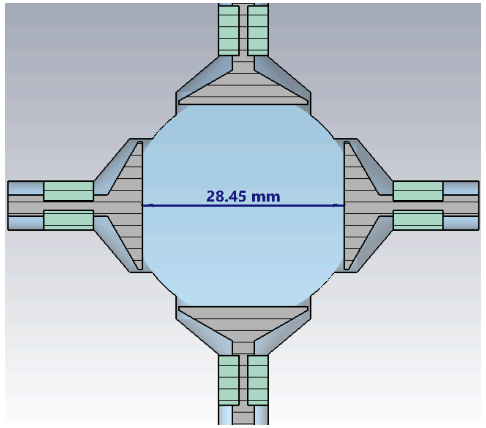
S21 slabline analysis
(34 units, vendor B)
$3\ GHz\ BW\ \equiv \sigma_z \approx 45\ mm$



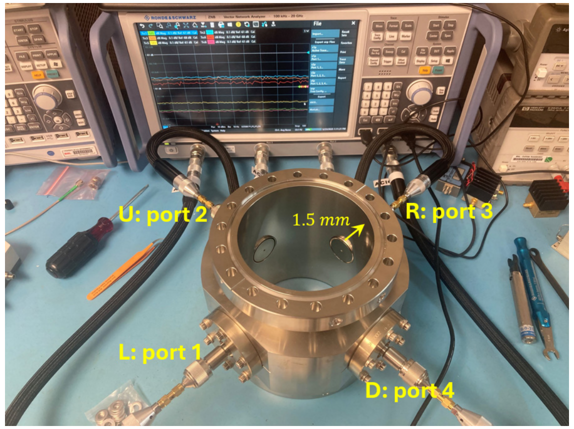
In-situ cryo Lambertson RF measurement

Cold test setup

***Lambertson* test BPM housing**



4-port *Lambertson* proof-of-principle VNA measurement investigation



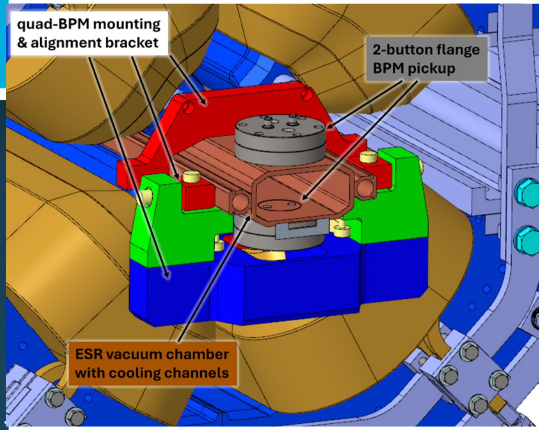
- **Motivation**
  - **Estimate the change of the electrical BPM center, when going from warm to cold**

- **4-port S-parameter characterization**
  - **So-called *Lambertson* method to evaluate the electrical center of a dual-plane BPM pickup, here: warm vs. cold**
  - **VNA operating at a single frequency**
    - Very challenging VNA measurement in zero-span mode with $10\ Hz$ IF bandwidth to achieve a low-noise S_{ij} coupling measurement in the range $-60 \ldots -70\ dB$
    - Need to be far away from eigenmodes of BPM or setup!
  - **Achieved performance on a LEReC test BPM ($\emptyset 121\ mm$)**

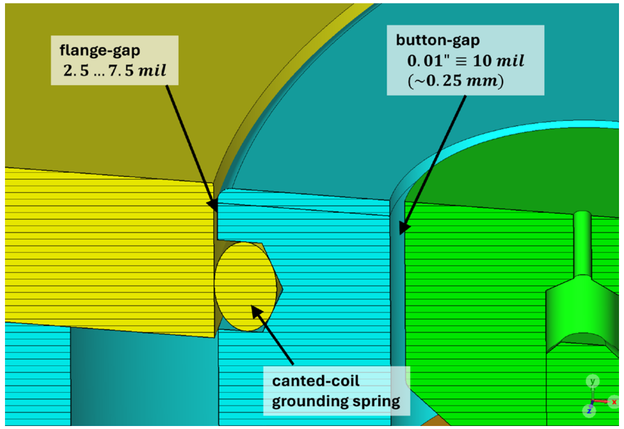
$500\ MHz\ [1000\ MHz]$	reference	$1.5\ mm$ offset	verification	ref − offset	ref − verify
horizontal $x_e\ (mm)$	$-0.072\ [-0.132]$	$+2.124\ [+2.125]$	$-0.097\ [-0.178]$	$\mathbf{+2.196\ [+2.257]}$	$-0.026\ [-0.046]$
vertical $y_e\ (mm)$	$+0.055\ [+0.005]$	$+0.046\ [-0.011]$	$+0.047\ [-0.005]$	$-0.009\ [-0.016]$	$-0.008\ [-0.010]$

BPMs for the Electron Storage Ring (ESR)

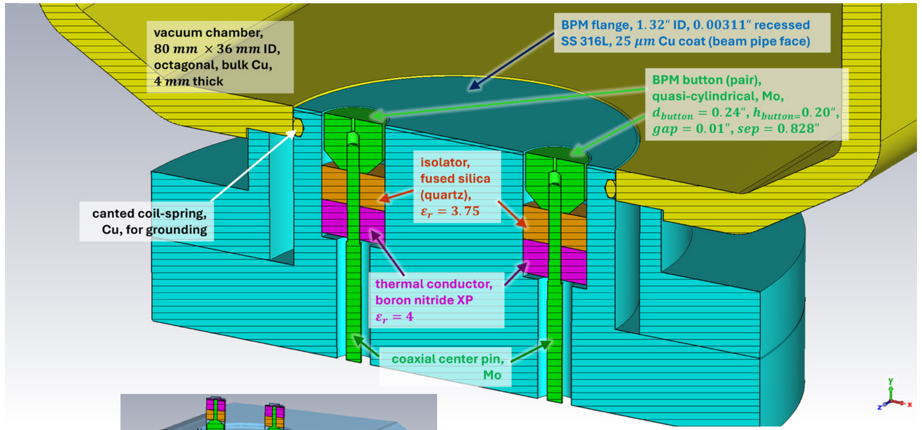
BPM-to-quad mount



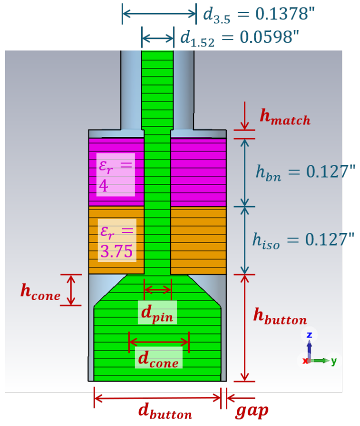
BPM-flange to beam-pipe el. contact

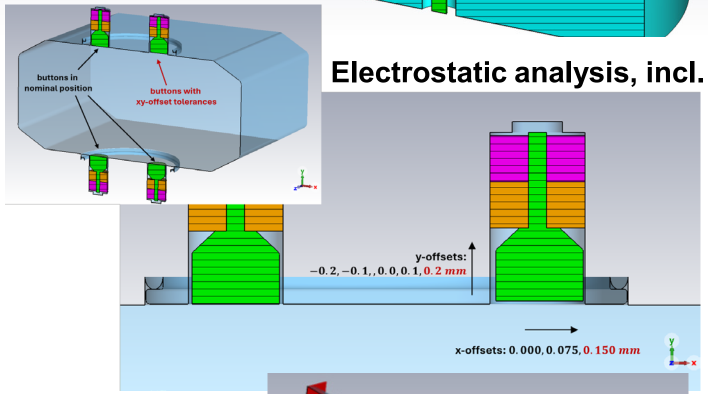


2-button BPM-flange for the ESR arc locations

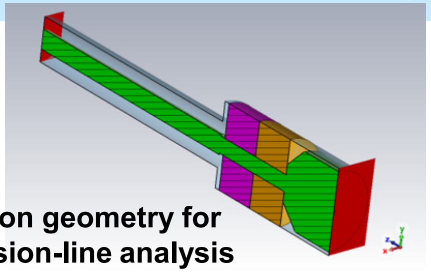


ESR BPM button



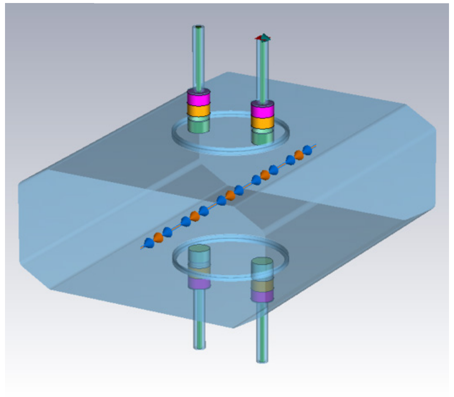


Electrostatic analysis, incl. tolerances



BPM button geometry for transmission-line analysis

ESR BPM geometry for wakefield analysis

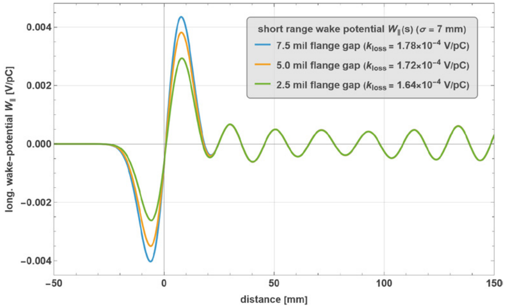


- **Short bunches ($\sigma_z = 7\ mm$) with high-frequency spectral content (up to $\sim 15\ GHz$) and high beam intensities ($I_{beam} = 2.5\ A$) gives challenges to the BPM pickup design**
  - Balance between low wake-potential (small button size) and sufficient output signal level (large button size)
  - Other details need to be considered, e.g. rigid BPM-to-quadrupole mounting, mechanical symmetry of the two 2-button flanges, etc.
- **EM design optimization of the mechanical details was based on three pillars:**
  - Wake-field analysis → loss factor (k_{tot}), resonances, output signal ($v_{elec}(t)$, $V_{elec}(f)$)
    - Optimize: $d_{button} = 0.24"$, $gap = 0.01"$, $h_{button} = 0.2"$, $h_{cone} = 0.06"$
  - Transmission-line analysis (button only) → impedance-matching
    - optimize $d_{pin} = 0.05"$, $h_{match} = 0.016"$
  - Electrostatic analysis → position characteristic
    - optimize button separation $sep = 0.828"$ (for same position sensitivity, $\left.\frac{d(\Delta_h/\Sigma)}{dx}\right|_{x,y=0} = \left.\frac{d(\Delta_v/\Sigma)}{dy}\right|_{x,y=0}$)

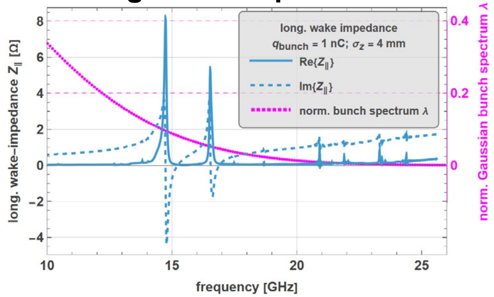
Some results from the EM analysis

Wakefield & Signal Analysis

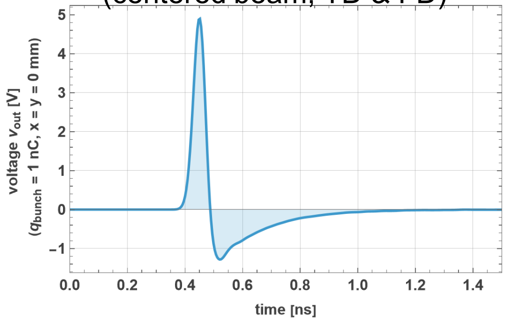
long. wake potential (short range)

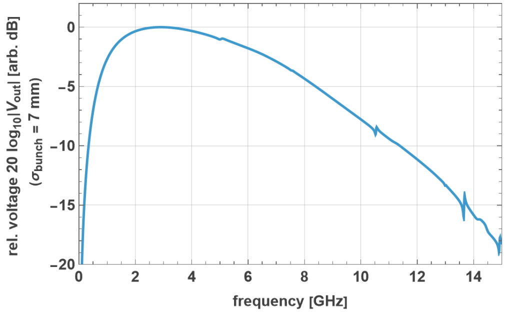


long. wake impedance

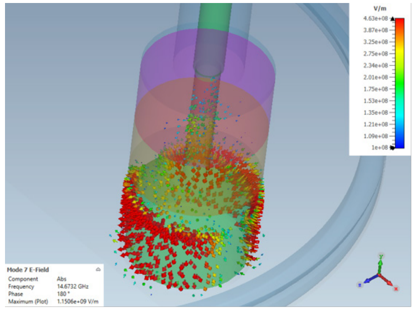


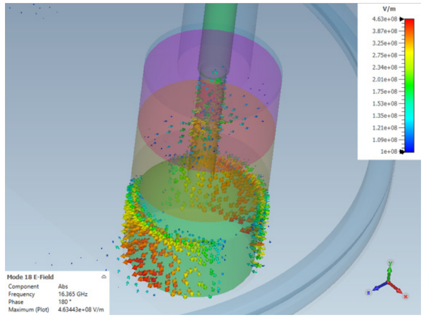
voltage output signal
(centered beam, TD & FD)





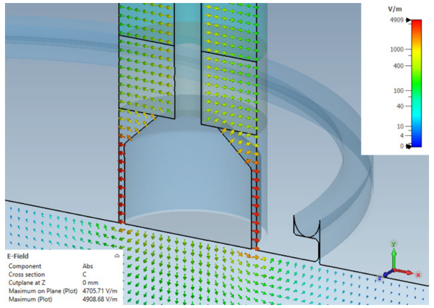
eigenmode analysis



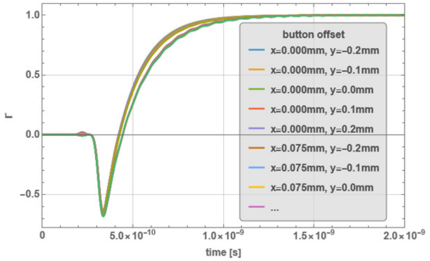


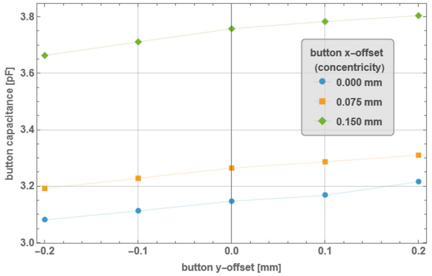
Electrostatic Analysis

peak E-field analysis

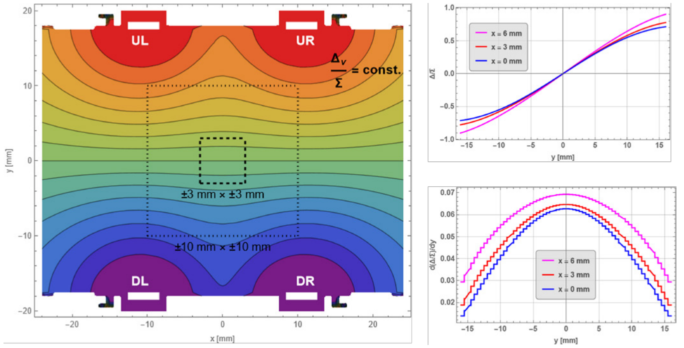


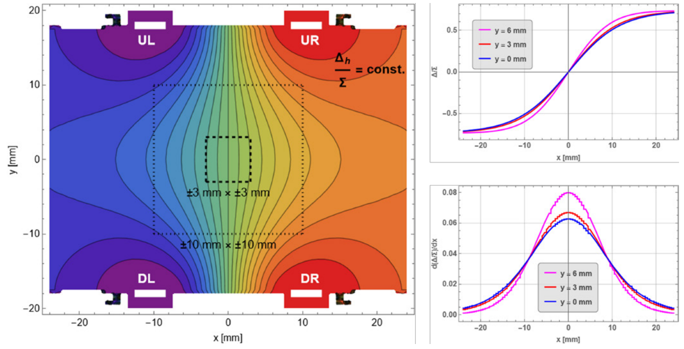
mech. tolerance analysis
(impact on C_{button})



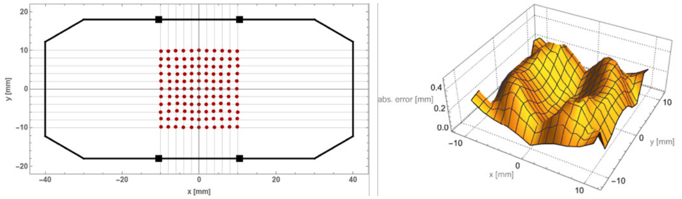


position characteristic, hor. & vert.



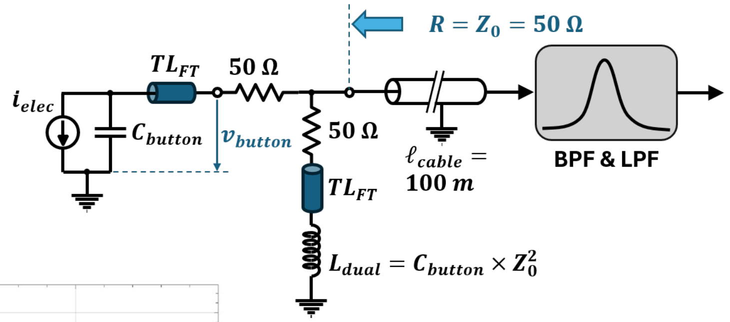


scaling and non-linear correction

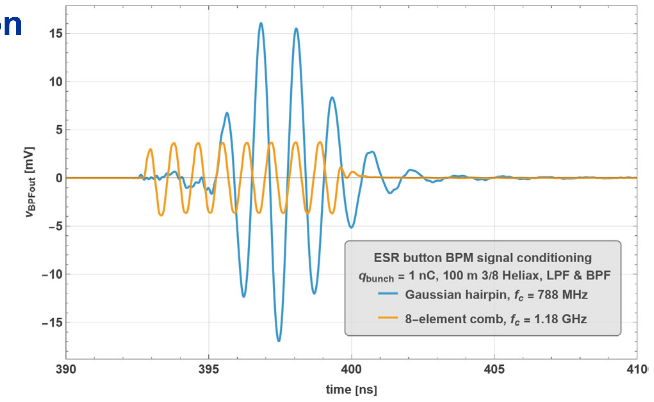


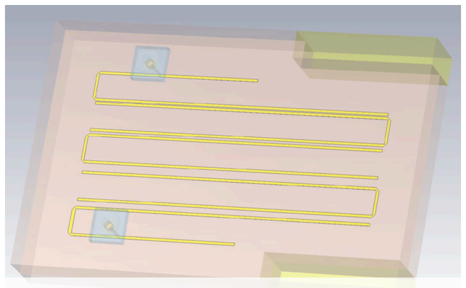
Electron-Beam BPM Signal Conditioning

- **Signal reflections between BPM pickup electrode and FE signal conditioning electronics**
  - **Broadband impedance-matching dual network at the pickup button feedthrough**
    - Price: $6\ dB$ insertion loss
    - Need to keep the feedthrough internal transmission-line TL_{FT} short or comparable wrt. the bunch length



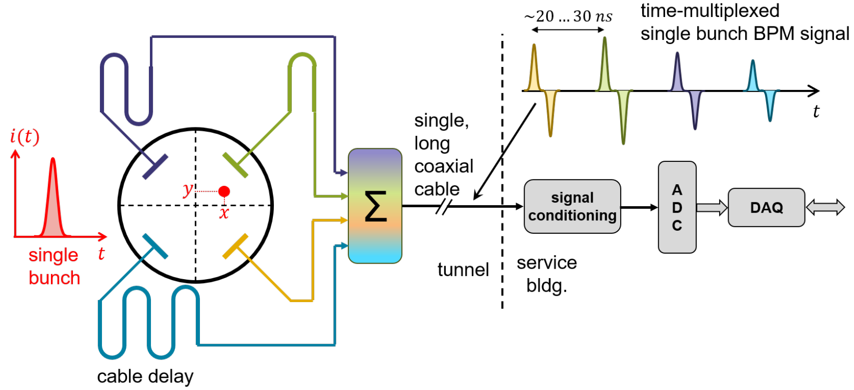
- **Pulse-forming band-pass filter to improve digital signal acquisition**
  - **5th-order Gaussian hairpin resonator band-pass filter**
    - Low insertion loss, tight PCB tolerances
  - **8-element delay-lin comb band-pass filter**
    - $6\ dB$ insertion loss, rectangular envelope waveform
  - **Requires 'cleanup' absorptive low-pass filter**
    - Dual-network style, attenuation peak at the 1st spurious passband





EM analysis stripline hairpin BPF

- **Time-multiplexing of BPM electrode signals**
  - **In the EIC electron injector only**
    - single bunches (linac) or long bunch spacing, $\Delta t_{bunch} \cong 5 \mu s$ (RCS), $120\ ns$ (BAR)
  - **single read-out channel**
  - **Cost savings on signal cables and electronics**
  - **Immune to environmental conditions**
    - ambient temperature variations, other slow drift effects
  - **Immune to aging effect of electronic components**



More challenges ahead…

- **CCNFB = Crab Cavity Noise Feedback**
  - **Hadron only crabbing**

    $\sigma_{\ell e} = 7\ mm$
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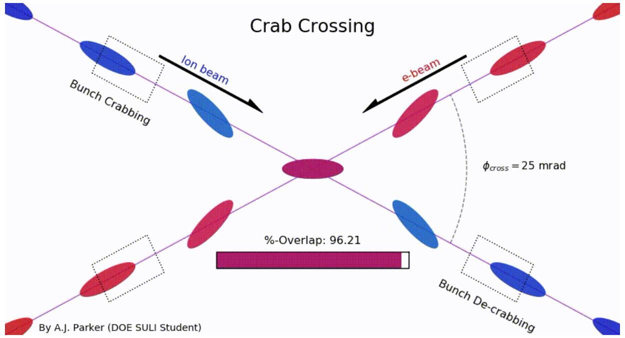

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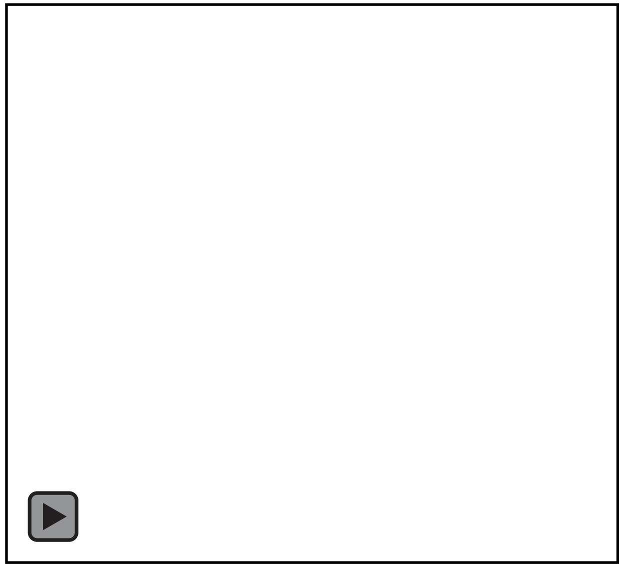

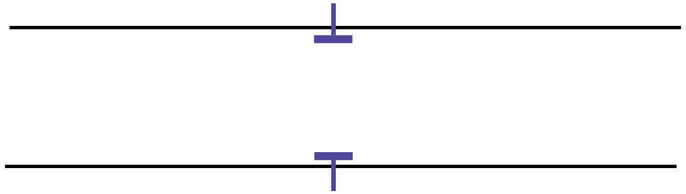

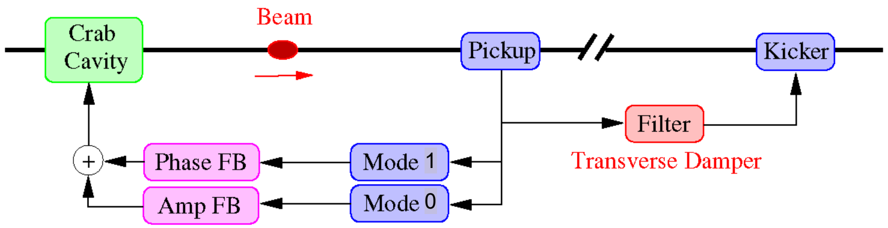

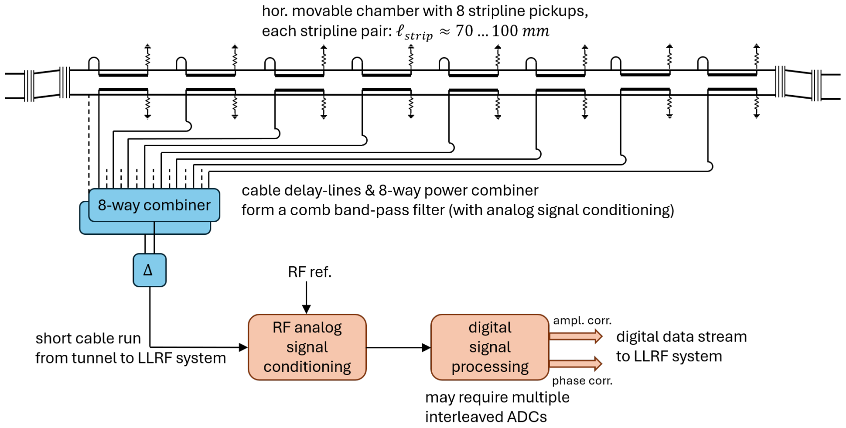

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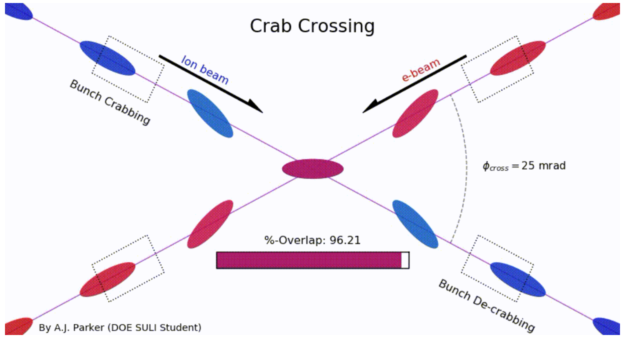

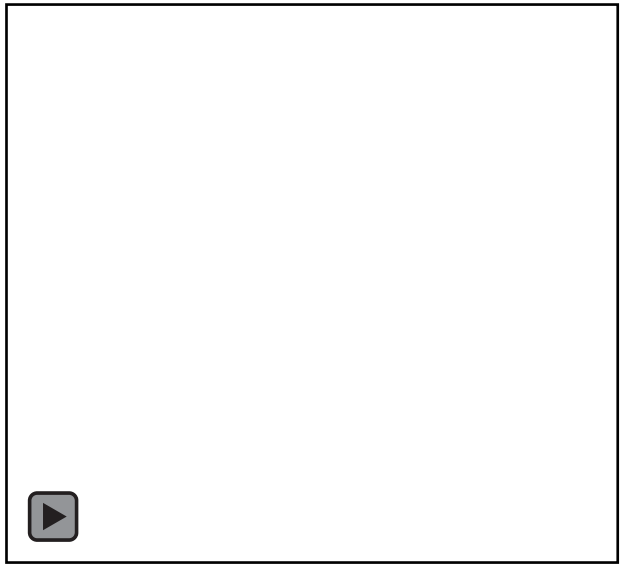

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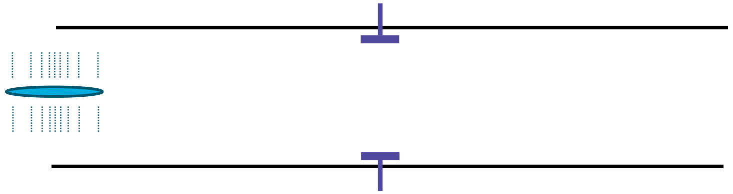
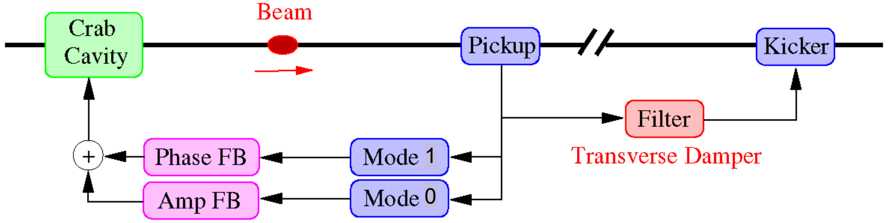
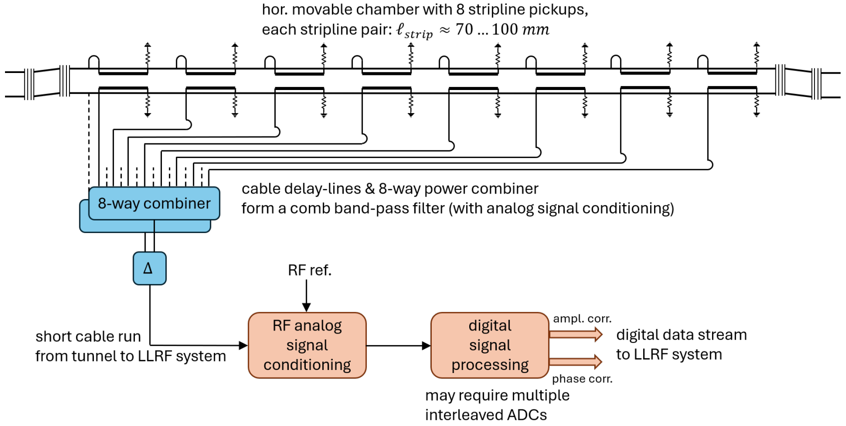
straight







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tilt angle

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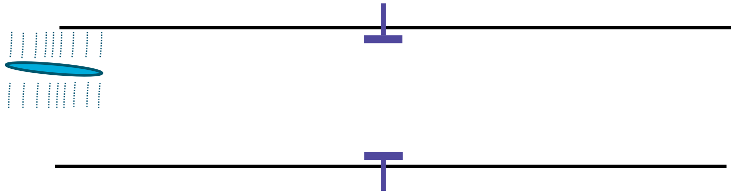

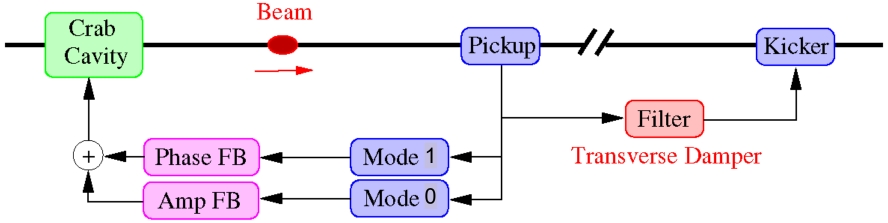

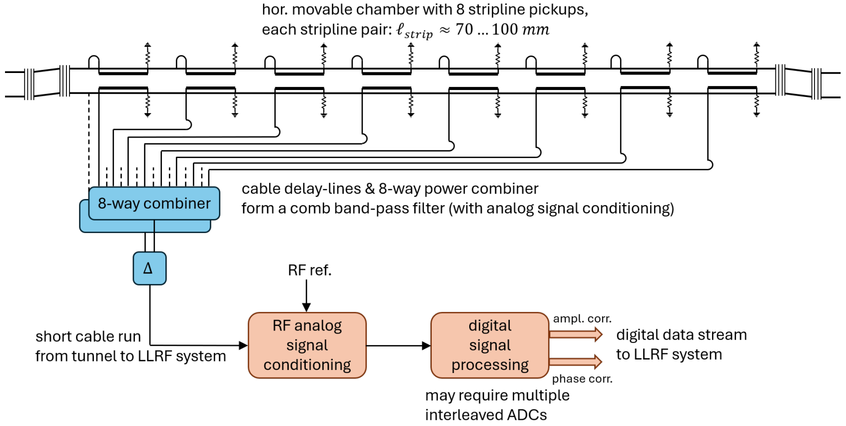

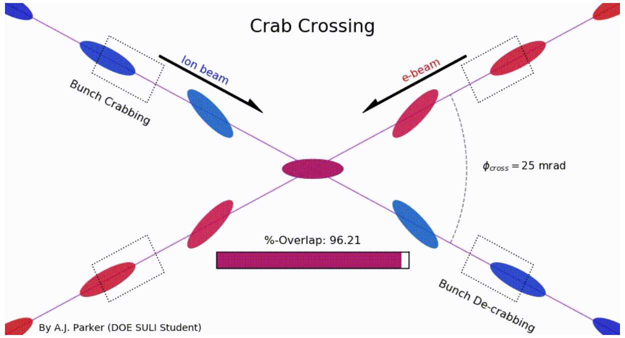

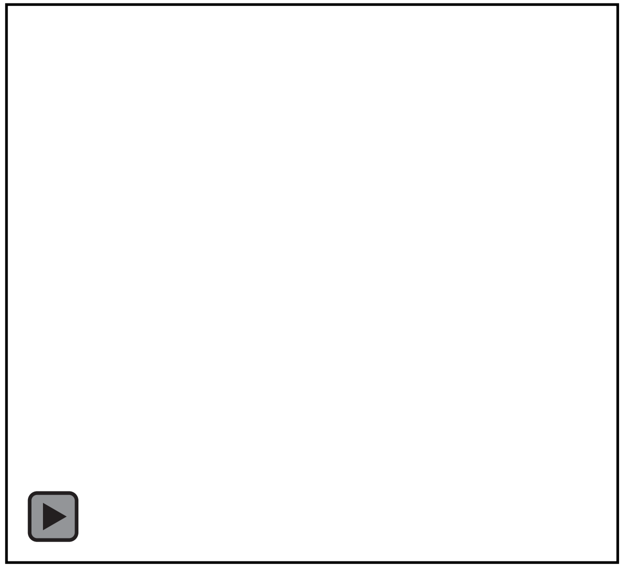

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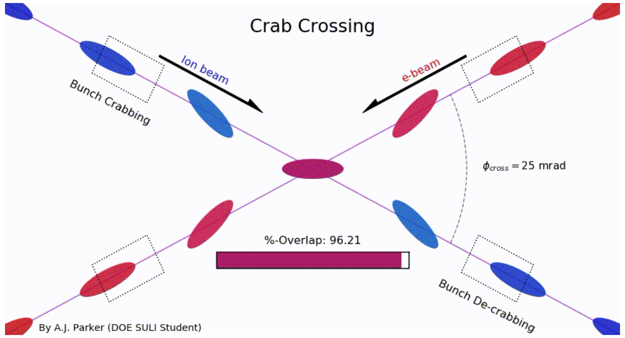

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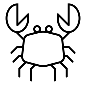

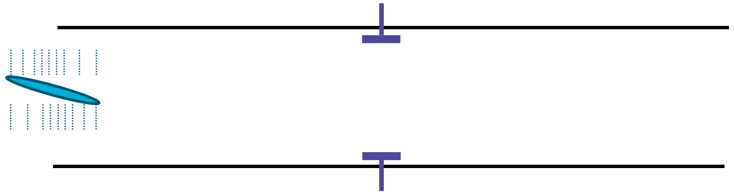

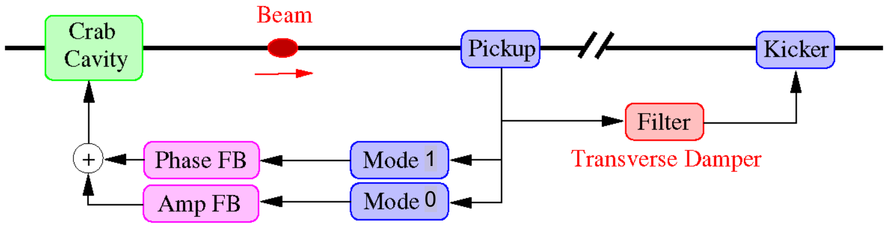

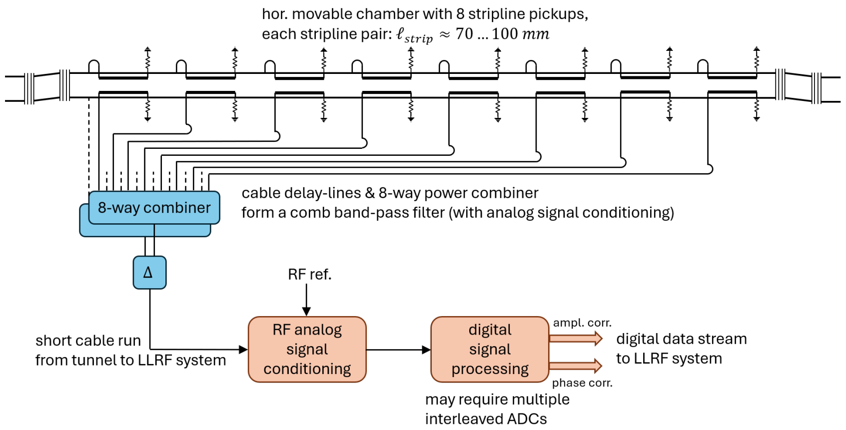

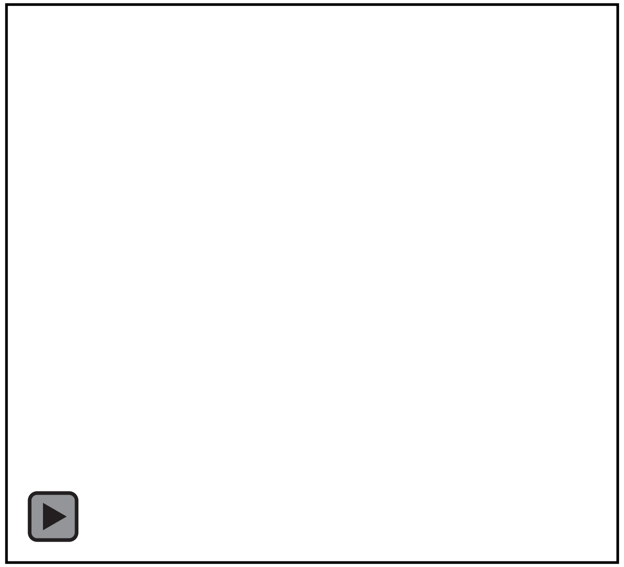

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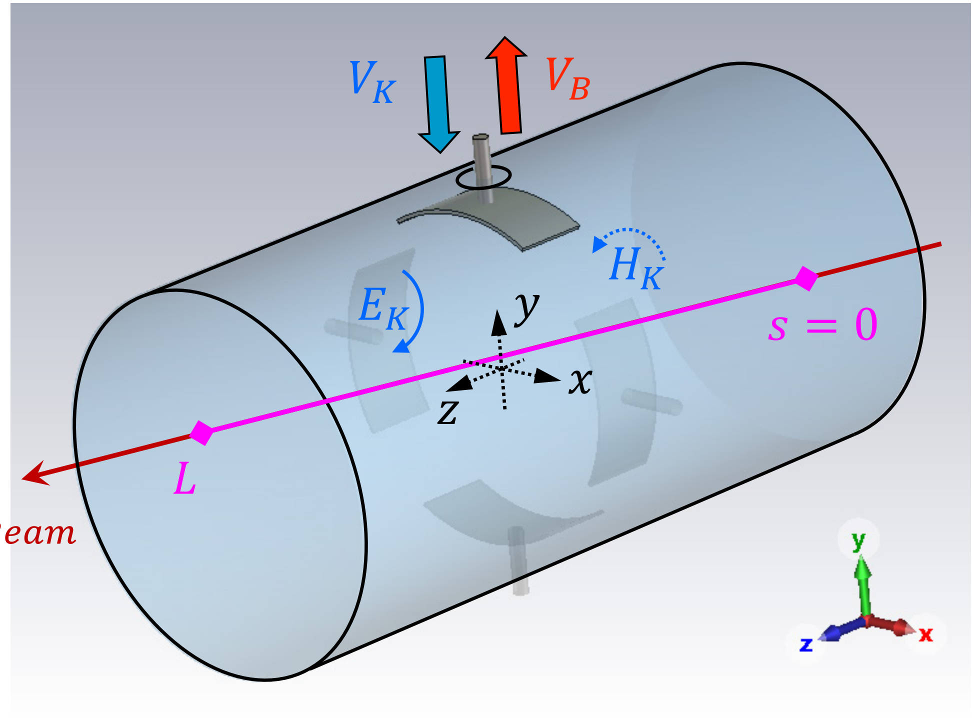
EM Beam Pickup & Kicker: *Lorentz* Reciprocity



- **Applying the *Lorentz* Reciprocity Theorem:**

$$\int_S dS\,\left(\vec{E}_K \times \vec{H}_B - \vec{E}_B \times \vec{H}_K\right) = \int_{vol} dvol\,\left(\vec{E}_B\,\vec{J}_K - \vec{E}_K\,\vec{J}_B\right)$$

  - **indices B: beam (pickup), K: kicker**
  - **leads to the beam voltage:**

$$\Longrightarrow\ V_B = V = -\frac{Z_0}{2\,V_K}\int_{vol} dvol\ \vec{E}_K\,\vec{J}_B$$

    - **with transit time $T = |V/V_0| = K_{\parallel}\,V_K/V_0$**
  - **which is analyzed numerically:**

$$V(x,y,f) = V_0 T = \int_{s=0}^{L} ds\,E_s(s,f)\exp\left(i\underbrace{\frac{2\pi f}{\beta c}}_{=k_B\ \text{(wave number)}}s\right)$$

- **Kicker constant $K_{\parallel}$ and shunt impedance $R_{\parallel}T^2$ are related:** $R_{\parallel}T^2 = Z_0\,|K_{\parallel}|^2$
  - **and are related to the beam voltage:** $\left|R_{\parallel}T^2\right| = \frac{|V_0 T|^2}{2}$
    - **with Z_0: ch. impedance of the port(s)**

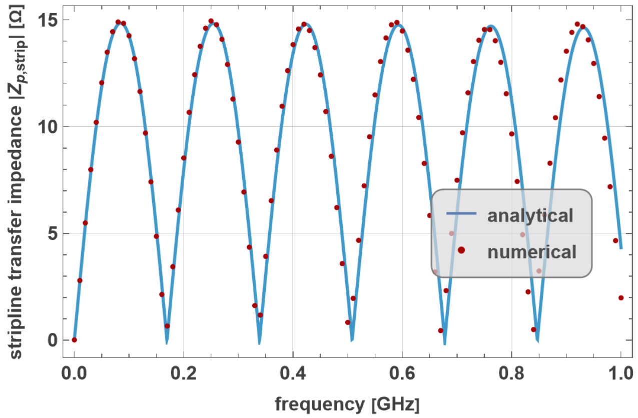
- **Which finally leads to the long. impedance $Z_{p,elec}$ of a beam pickup electrode ≡ transfer impedance Z_{elec}**

$$\boxed{Z_{p,elec}(f) = \frac{Z_0\,K_{\parallel}(f)}{2} = \frac{\sqrt{Z_0 R_{\parallel} T^2(f)}}{2}}$$

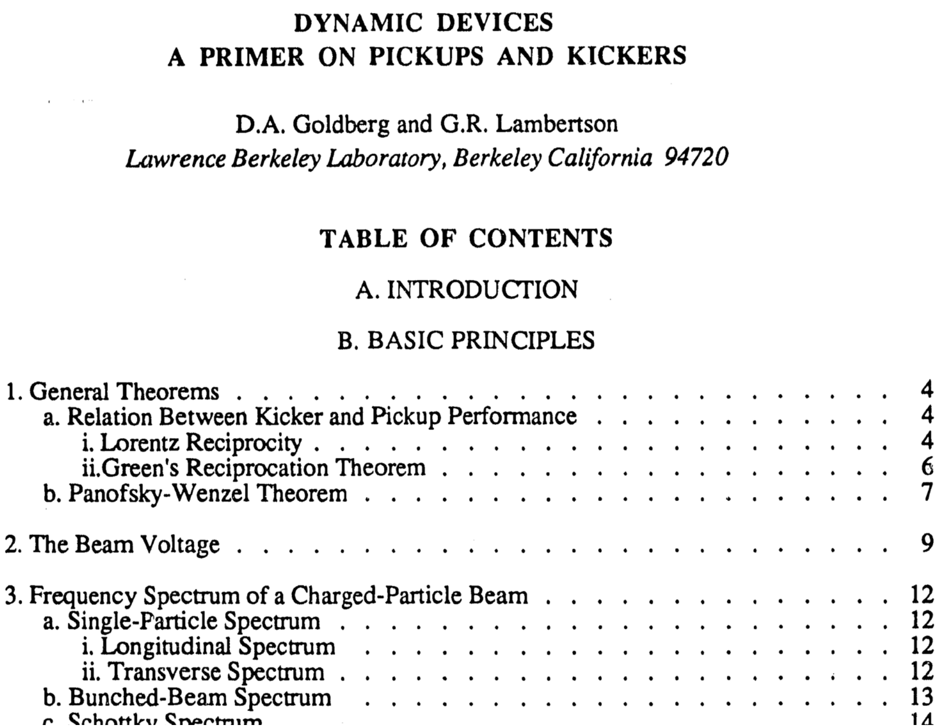
Beam Voltage and Pickup Transfer-Impedance

- **The Lorentz reciprocity method**
  - **Alternative / verification to line-charge stimulus or particle tracking codes, e.g. particle-in-cell (PIC) solvers**
  - **Requires only a single numerical computation of the beam pickup structure**
    - Stimulus signal, e.g. in time-domain, feed into the pickup output port
    - Recording of E- and H-fields vs. frequency for the entire volume, or a sub-volume of interest
      - *Computation with GPU support gives results quickly*
      - *Postprocessing needs to handle large data files*
  - **E-field integration along the beam path**
    - Beam voltage → transfer impedance for a point charge with velocity βc
    - LTI system → superposition principle applies
  - **The EM field in the volume holds all information of the beam pickup!**

- **Proof of principle**
  - **Transfer impedance of a single, $0.9\ m$ long stripline electrode**



- **More details in:**



DYNAMIC DEVICES
A PRIMER ON PICKUPS AND KICKERS

D.A. Goldberg and G.R. Lambertson
Lawrence Berkeley Laboratory, Berkeley California 94720

TABLE OF CONTENTS

  - **Highly recommended!**

Summary

- **The Electron-Ion Collider project has many challenges, here we highlighted just a few BPM examples**
- **The demand towards higher beam intensities in colliders, as well as in other particle accelerators under construction, puts wakefield effects in the spotlight**
  - **Valid for beam pickups and kickers, and for any other accelerator component exposed to the EM-field of the bunched beam.**
- **The challenges at the EIC are not limited to technical or scientific aspects**
  - **Funding, schedule, changes in the project scope, workforce, social and other aspects may be even more challenging!!**

Thank you!

In memory of my mentor
Willi Radloff, RIP 2026