Electromagnetic Design and Bench Testing of ALS-U BPM Buttons and Assemblies

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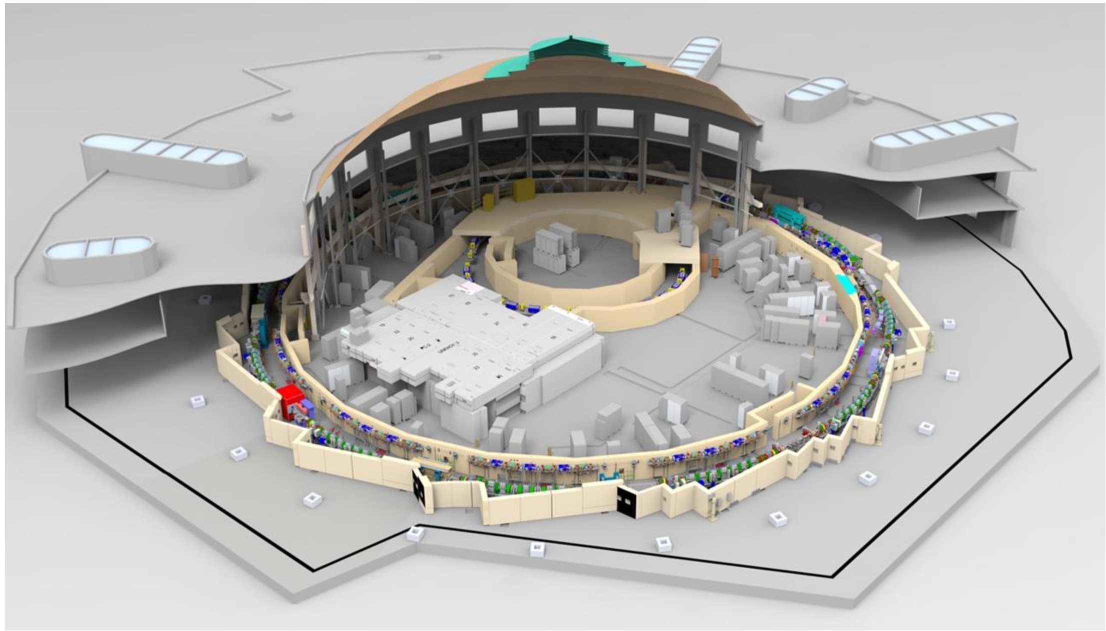
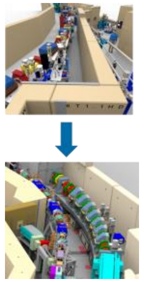
Button BPMs for Synchrotron Light Sources, Dec 11 – 12 2024, ALBA Synchrotron

ALS-Upgrade: a world-leading light source to provide high brightness, high-coherent-flux soft x-rays

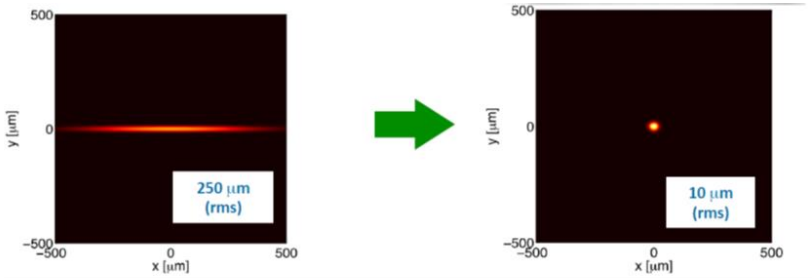


ALS 3BA



ALS-U 9BA

Electron Beam Profile



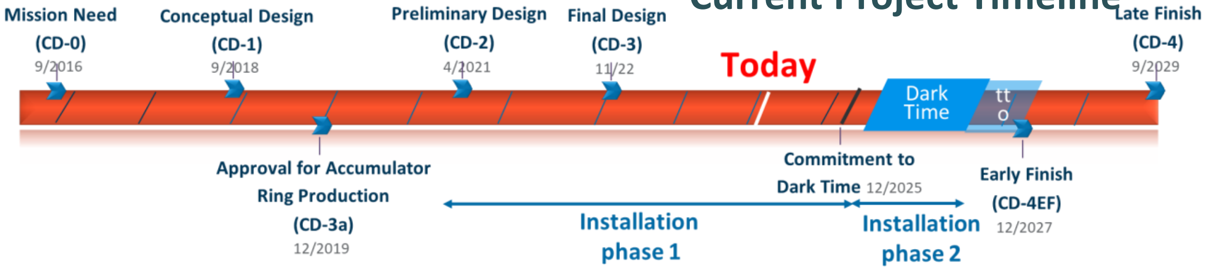
Scope items:

- New 2-GeV, high-brightness storage ring fed by a new full-energy accumulator ring and transfer lines in the existing ALS storage-ring tunnel
- 6 high-field bends and realignment of bend-magnet beamline front ends
- Adding a suite of 2 feature world-leading undulator beamlines.
- Seismic/ALARA shielding upgrade: to improve seismic safety and minimize dose rates

ALS-U Key Performance Parameters (KPPs)

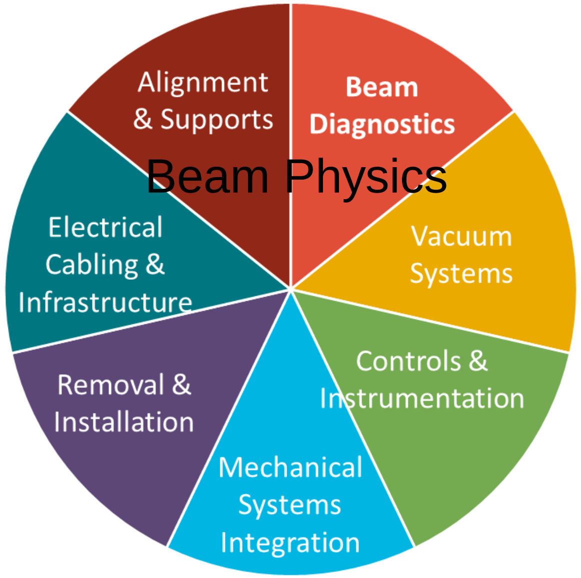
Performance Measure	Threshold	Objective
Storage ring energy	≥ 1.9 GeV	2.0 GeV
Beam current	> 25 mA	500 mA
Horizontal emittance	< 150 pm rad	< 85 pm rad
Calculated brightness at 1 keV	> 2.0 x 10^{19}	2.0 x 10^{21}
Number of feature MBA beamlines installed	2	≥ 2

Current Project Timeline



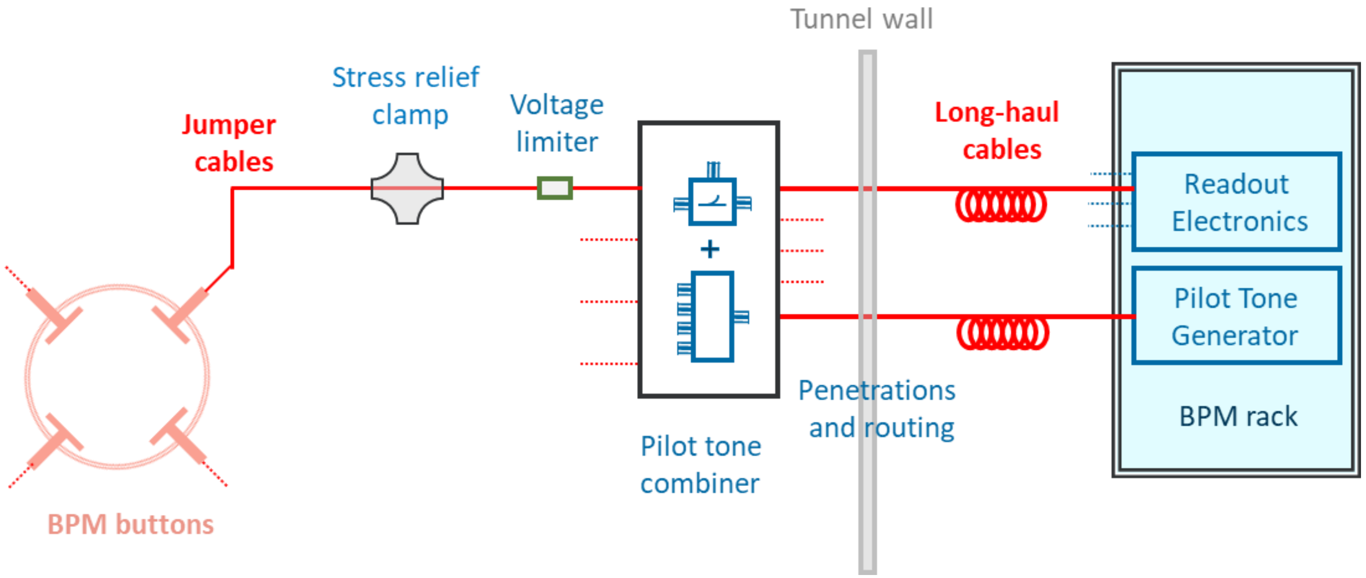
ALS-U BPM system overview

ALS-U subsystems related to BPM



- The ALS-U BPM system scope spans several subsystems.
- The BPM beam pickup electromagnetic design and testing is carried out by the diagnostics group.
- Pickup design is a tight collaboration between Diagnostics (EM) and Vacuum (mechanical).

General layout of the BPM system



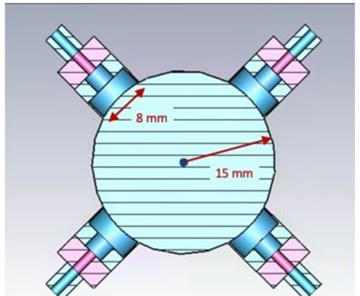
BPM system supports:

- Orbit feedback in machine operation, with average position measurement over many turns.
- Fast commissioning and machine development, with single bunch/single pass measurements.
- The resolution requirements vary with the locations and the beam condition.

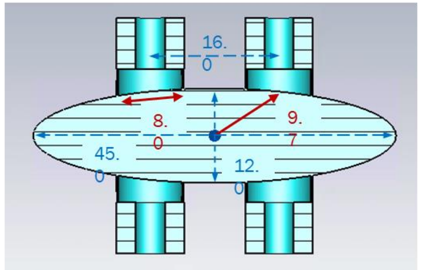
ALS-U BPM pickups overview

- All ALS-U BPM pickups are button BPMs.
- In Accumulator Ring (AR), 6 BPM per arc in 12 arcs.
- In Storage Ring (SR), 17~22 BPM per sector, with 17~18 in arc and 0~4 in straight.
- A dozen BPMs in the transfer lines.

AR: 70 round BPMs and 2 elliptical BPMs in the injection straight



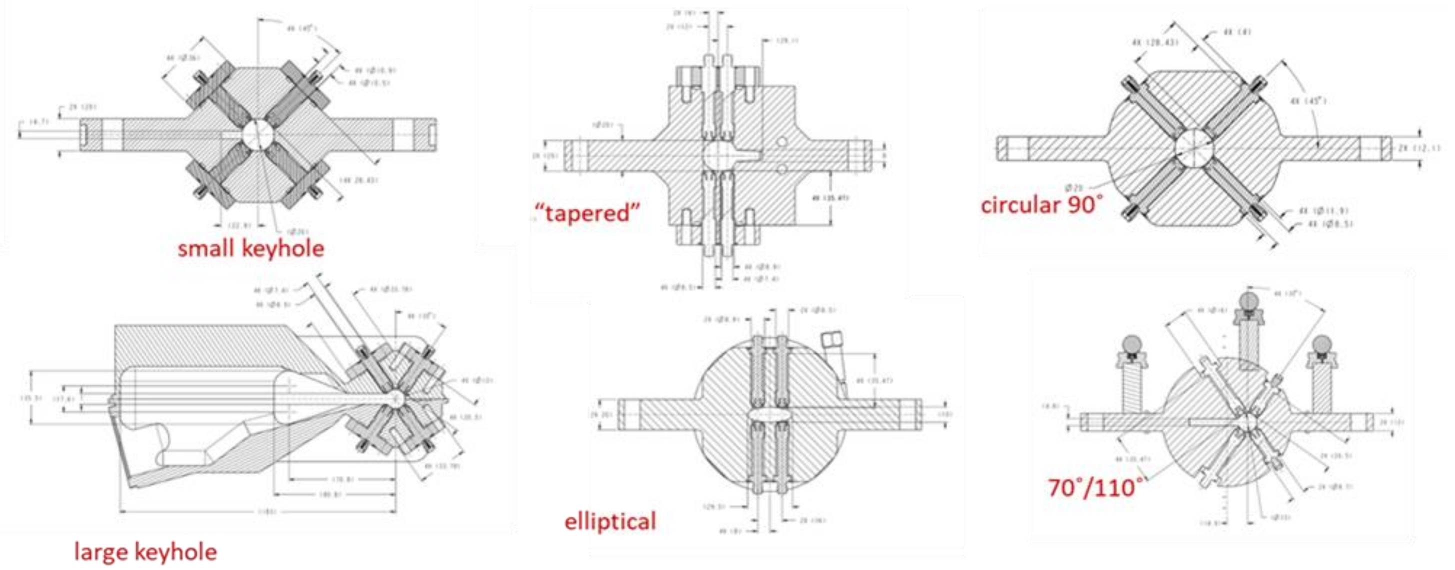
Standard BPM



Special BPM for injection kicker vac. chamber.

SR: 12 unique geometries in arcs, fitting into the tight space in SR.

- circular chambers (20, 18 or 13 mm ID), elliptical, or complicated tapered chambers.
- button (4 or 6 mm ID), oriented at 90 degree, 70/110 degree, or upper/lower pairs.
- small or large “keyhole” antechambers.



Electromagnetic design of the BPM pickups

Resolution requirements by beam physics

Expect the readout electronics performance similar to ALS

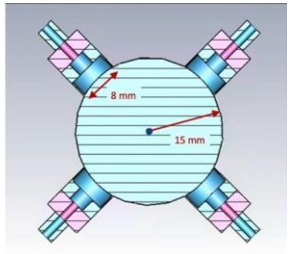
Pickup performance: transfer impedance, sensitivity, time response, etc.

Surrounding beampipe apertures, button production feasibility, other mechanical consideration, etc.

Button size, thickness, location, orientation, gap width, vacuum chamber, etc.

Validate the performance with numerical simulation.

For example in AR BPM:



$$Z_{PU}(500\ MHz) = \begin{cases} 250\ \mathrm{m}\Omega & \text{AR} \\ 170\ \mathrm{m}\Omega & \text{ALS} \end{cases}$$

Z_{PU} transfer impedance can be obtained from either CST simulation or analytical formula

Pickup voltage:

$$V_{PU} = 2 \cdot q_b \cdot F(\sigma, \omega) \cdot Z_{PU}(f = 500\ MHz) \cdot 20\ MHz = 10^7 \cdot q_b = \begin{cases} 10\ mV & \text{Nominal bunch} \\ 2-3\ mV & \text{Single shot in BTA} \end{cases}$$

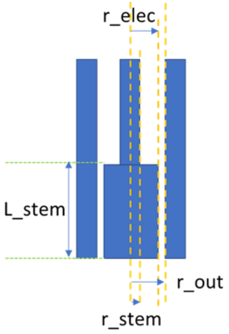
Resolution:

$$\delta x = \frac{r_p \cdot \phi_{butt}}{16 \cdot \sin(\frac{\phi_{butt}}{2})} \cdot \frac{1}{\sqrt{SNR}} \approx \begin{cases} 1.5\ \mu m & \text{Nominal bunch single pass resolution} \\ 6.3\ \mu m & \text{Single pass resolution with single BTA shot} \end{cases}$$

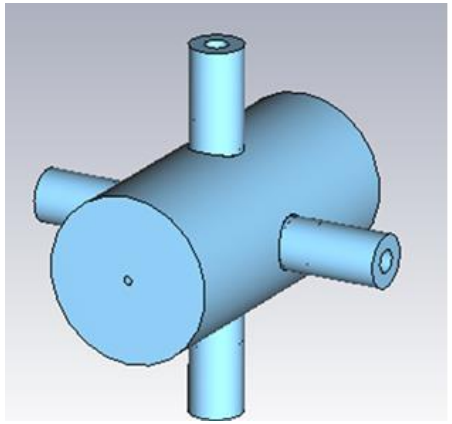
Comprehensive CST simulation to evaluate the BPM EM properties

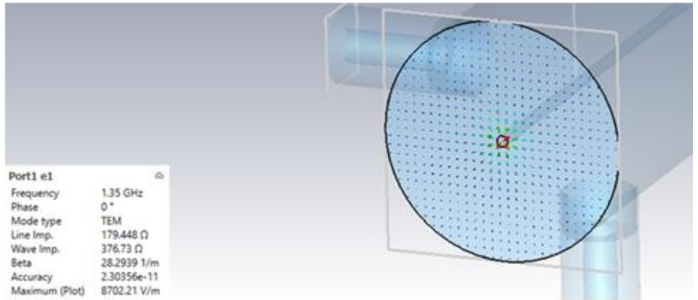
- Analytical formulas are only valid for circular BPMs with small buttons around the center area. Numerical simulation is required to accurately and thoroughly to evaluate ALS-U BPM EM properties, especially for the SR BPMs with irregular vacuum chambers.
- Numerical results are checked with analytical formulas whenever applicable.

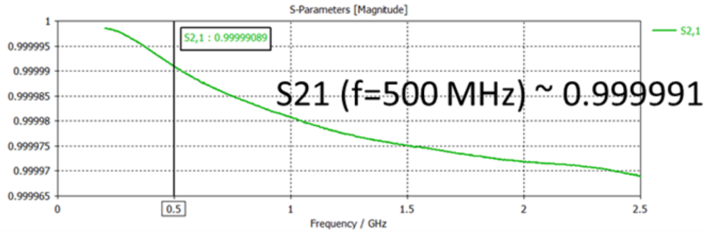
Transfer impedance is calculated from the transmission coefficients at 500 MHz by the virtual wire method.

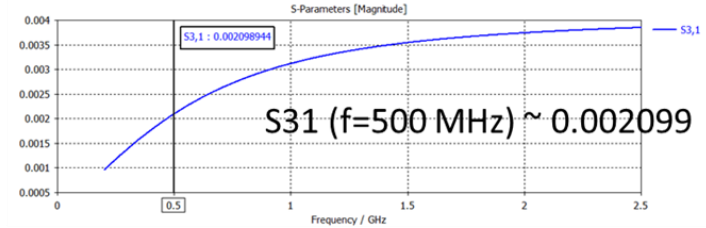


An stepped BPM buttons with a capacitance of 3pF and a termination of 50 Ohm are integrated to the BPM models. The button dimensions are determined by analytical formulas.









At f=500 MHz:

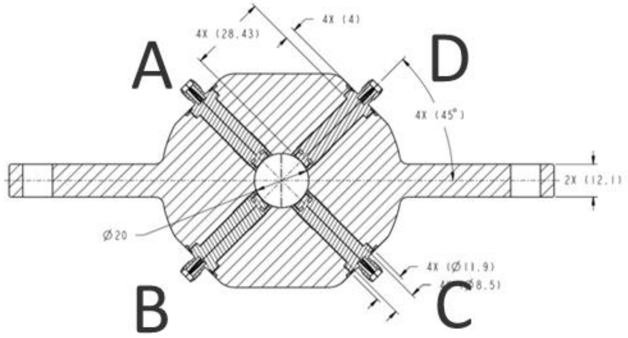
$$Z_{transfer\_31} = \frac{S31}{S21}\sqrt{Z_{coax} * Z_{port}} \sim 199\ m\Omega$$

2D fitting and the non-linear errors

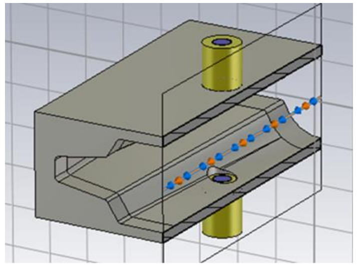
BPM position calculation based on linear fitting

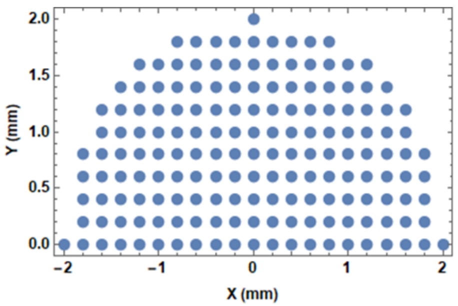
$$x_{linear} = K_x \frac{V_A + V_B - V_C - V_D}{V_A + V_B + V_C + V_D} + C_x = K_X \frac{\Delta}{\Sigma} + C_x$$

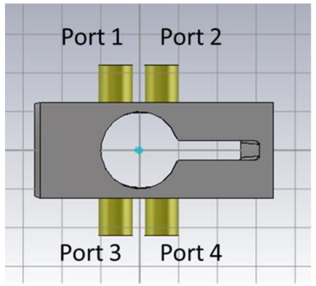
Sensitivity S=1/K



- The further away from the center, the more nonlinearity: aka beam cushion effect.
- Irregular vacuum chamber further increase the non-linearity and shift the electric center.







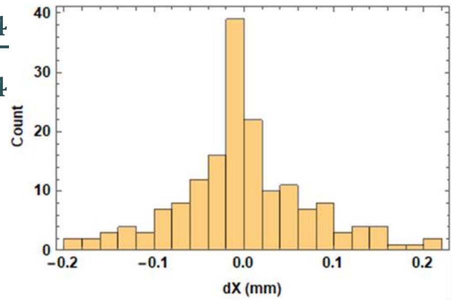
$$(\frac{\Delta}{\Sigma})_x = \frac{V_1 + V_3 - V_2 - V_4}{V_1 + V_2 + V_3 + V_4}$$

$$(\frac{\Delta}{\Sigma})_y = \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

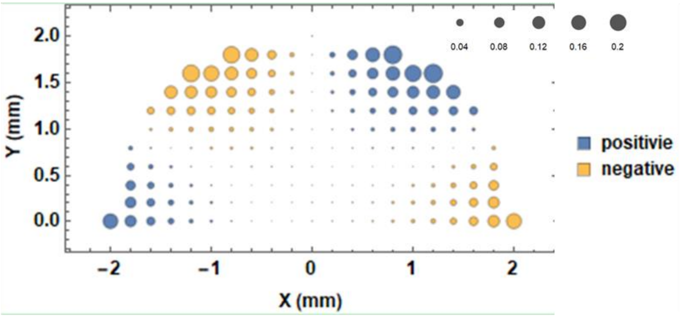
- CST particle solver to scan beam induced signal on a grid within r<2cm.
- $(\Delta/\Sigma)_x$ and $(\Delta/\Sigma)_y$ are calculated for each point in the grid.
- Acceptable error: Abs|X_{real}-X_{cal}|<100um
- Fitting K and C: maximize the area with acceptable error.

Nonlinearity is quantized by the area percentile of the acceptable errors. All BPM designs are > 80% within r<2mm.

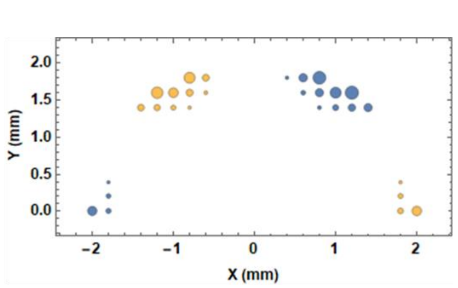
Absolute error histogram



Absolute error bubble chart

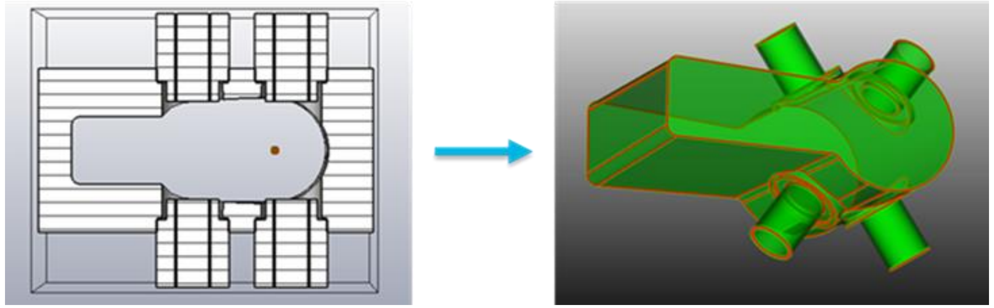


Location of unacceptable errors

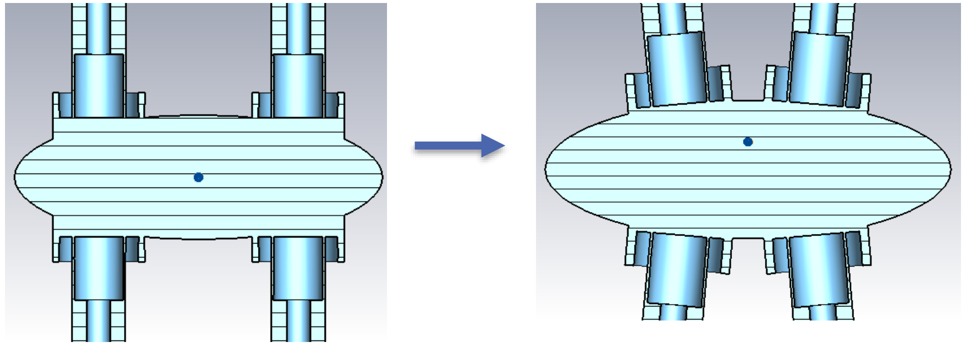


Some SR BPM designs were modified to improve their performances during the design iteration

Redesign to suppress the non-linearity



Redesign to improve the transfer impedance and the vertical sensitivity



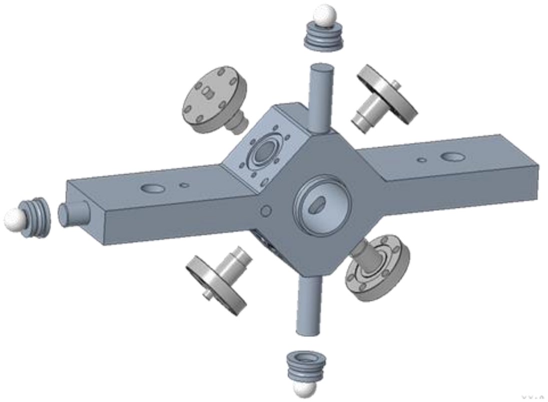
SR arc BPM EM property summary

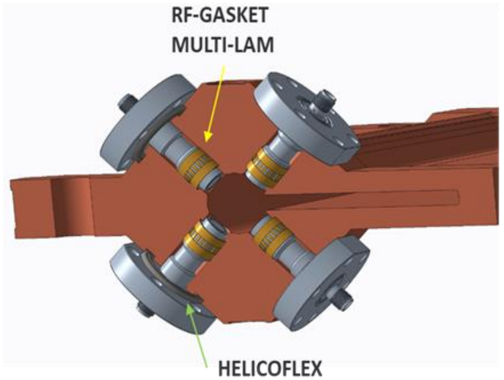
BPM type	beampipe ID (mm)	button ID (mm)	Transfer Impedance (mΩ)	Horiz. Sensitivity (%/mm)	Vert. Sensitivity (%/mm)
A1	13	4	140	21.3	21.3
A2	18	6	212	15.4	15.4
A3	13	4	164	21	20.7
E1	29.5*10	6	101	30.3	7.5
E2	29.5*10	4	138	26.9	13.9
K1	13	4	171	17.4	22.6
K2	13	4	172	17.6	23.2
F1	18	6	219	15.4	15.3
F2	20	6	197	13.9	13.8
F3	13	4	162	21.4	20.5
J1	20	4	52	10.4	14.6
L1	13	4	158	19.5	22.2
ALS Arc			170	7	6

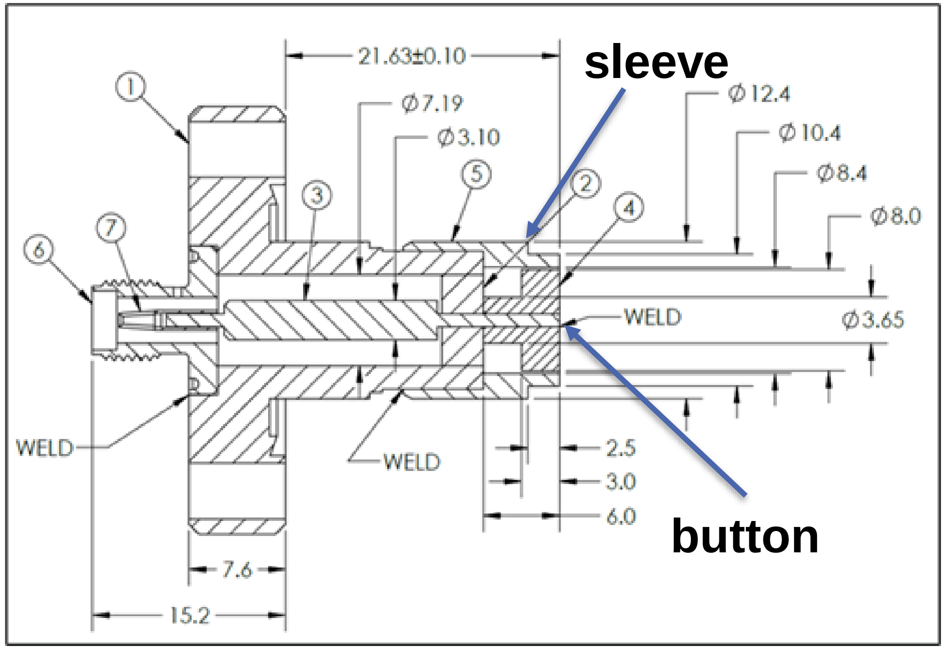
- EM evaluation is carried our for all 12 BPM designs in SR arc.
- Most have comparable or better EM performance than ALS BPMs. All the transfer impedances and the sensitivities are acceptable for the required accuracy.

Feedthrough and button design

- The feedthrough and button electrode are integrated together as one commercial product.
- The design work is a close collaboration between ALS-U Vacuum, Diagnostics and the commercial vendors.
- The "sleeved" button is adopted by all the BPMs to facilitate centering.
- Flange feedthrough is adopted by all the AR BPMs and majority of the SR BPMs. They are bolted to the housing chamber.
- Some SR BPMs are flangeless due to the limited space and are welded to the housing chamber.







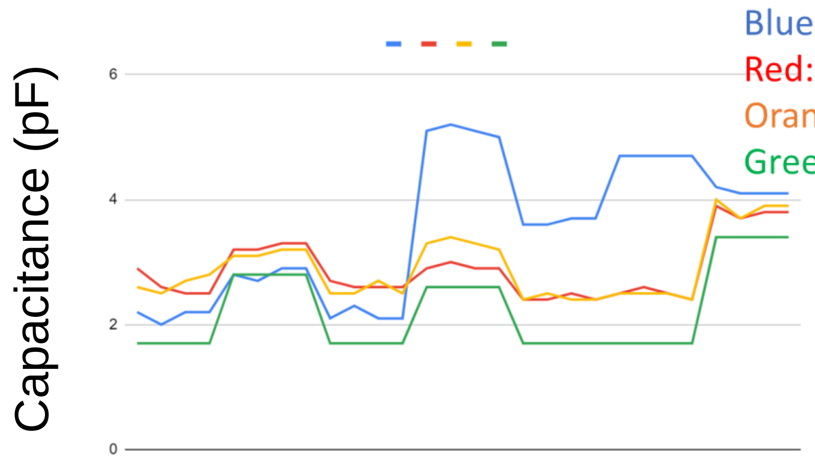
Comprehensive bench testing has been carried on the prototype buttons from potential commercial vendors

- The EM measurements on the prototypes to validate the button performance and provide the information for choosing the vendors.
- The mechanical measurements (vacuum, dimension, etc) are carried out by Vacuum group separately.
- EM properties to check:
  - Isolation to the ground: > 1MOhm, by multimeter.
  - Capacitance: by Time Domain Reflector (TDR) and fitting, and by Network analyzer (NWA).
  - Electrical length: by TDR.
  - Feedthrough impedance: 50+/- 3 Ohm, by TDR.

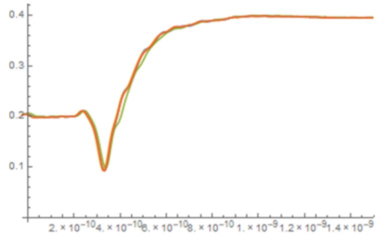
AR single button

SR single and double button

Capacitance for difference prototype buttons



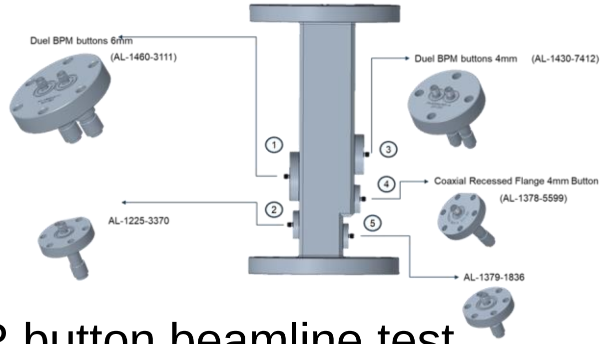
Typical TDR signal

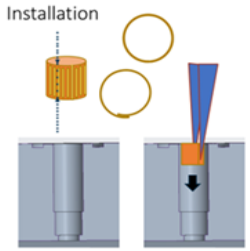


Beamline test of prototype buttons at ALS

A custom-made testing chamber accommodating five different SR buttons was installed on ALS and tested up to the full current of 500mA.

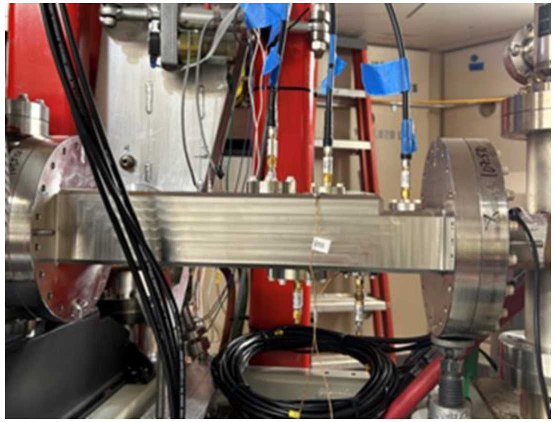
- Test the beam signals in time and frequency domain.
- Validate the mechanical design and the button installation procedure, especially the RF seal to prevent the local trapped modes.
- A good exercise for BPM cable pulling and termination.





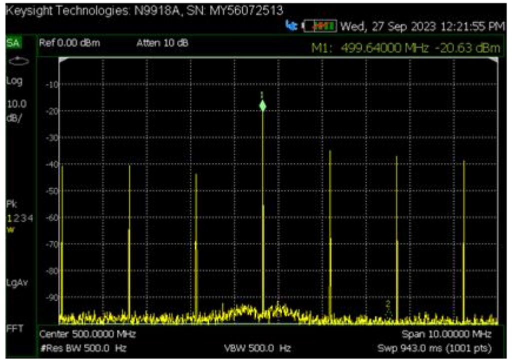
- No excessive heating with full ALS current at 500 mA.
- Port signals are as expected and agree well with the CST simulation values.

SR button beamline test

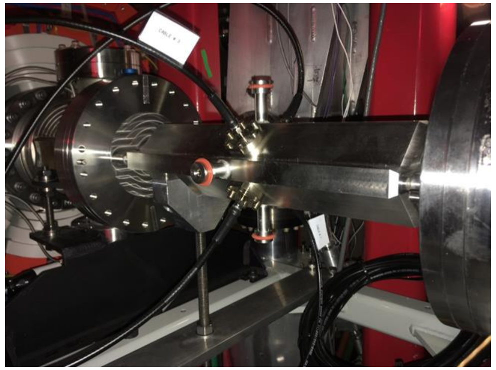


Signal in time domain

Signal in frequency domain

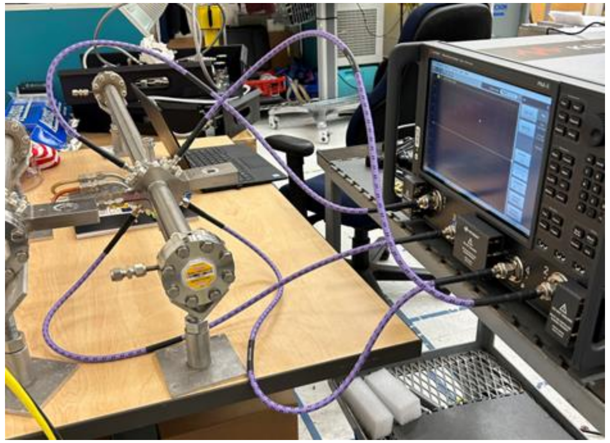


AR button beamline test

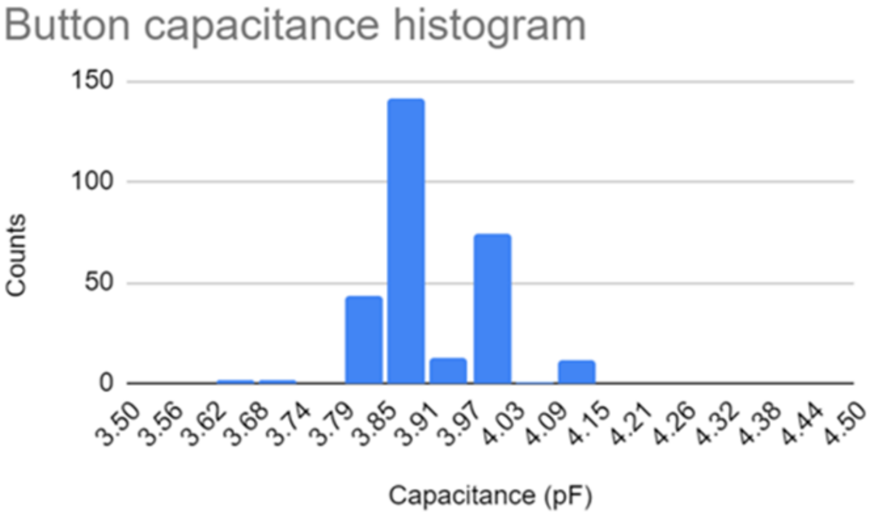


Bench test of AR production buttons and BPM assemblies

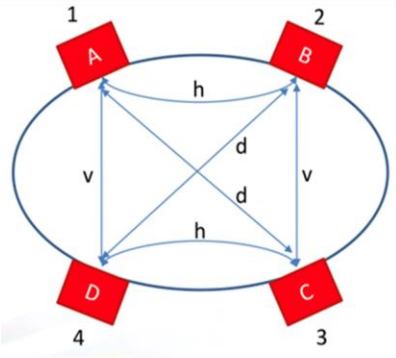
For the 350 AR production button, capacitance is measured for every button. Every 4 buttons with close capacitances are grouped to be installed on the same assembly. The characteristic impedance and ground isolation are tested on 44 randomly selected buttons.



For every assembly block, we measure its electrical center by the Lambertson method. If the center offset is larger than the specified threshold of 100um, we fine tune the button insertion depth by tightening the flange bolts slightly. The elasticity of the vacuum gasket provides a small tunable range.



Lambertson method



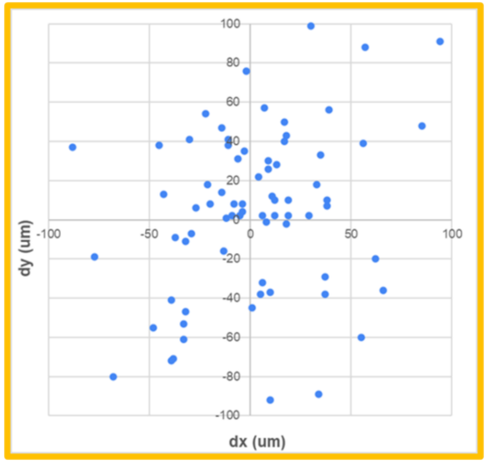
Unknown gains A, B, C, D can be determined via S parameters:

$$A = cost.\sqrt{\frac{S_{21}S_{14}}{S_{42}}}$$

$$\Delta x = \frac{1}{S_x}\frac{A+B-C-D}{A+B+C+D}$$

$$\Delta y = \frac{1}{S_y}\frac{A+D-B-C}{A+B+C+D}$$

E center of 72 AR BPM assemblies



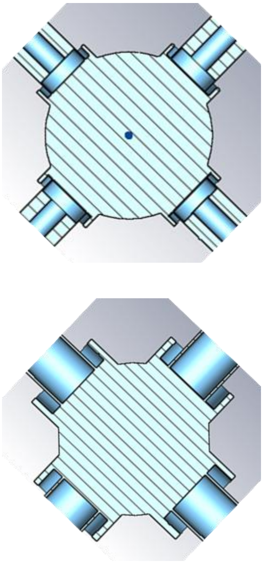
Small SR aperture (13mm ID) imposes stringent requirement on the button mechanical tolerance

AR: chamber ID 28.5mm button ID 8 mm

Recession (um)	E center offsets (um)	Transfer Z (mOhm)
0	0	255
50	9	246
150	67	240
250	126	232

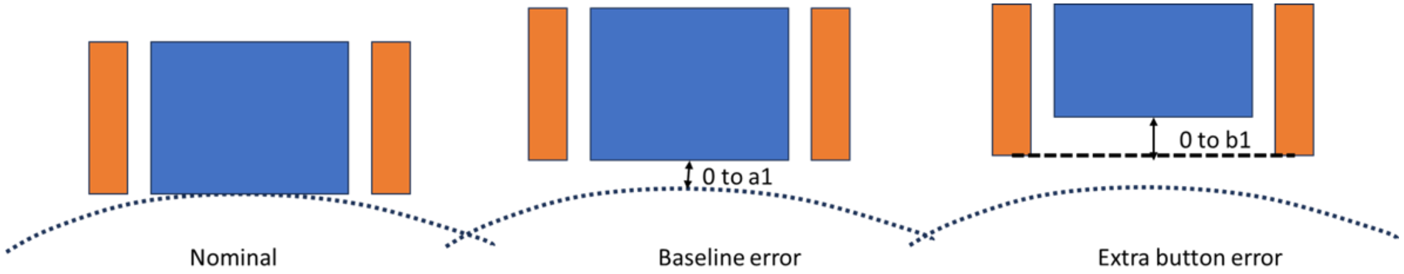
SR: chamber ID 13mm button ID 4 mm

Recession (um)	E center offsets (um)	Transfer Z (mOhm)
0	0	164
50	2	160
150	127	153
250	228	146



The same recession of the button induces larger E center offset in SR than AR.

Besides the nominal recession relative to the housing wall, the button can recess/intrude relative to the sleeve. This can be described by two mechanical tolerance *a1* and *b1* as shown below:

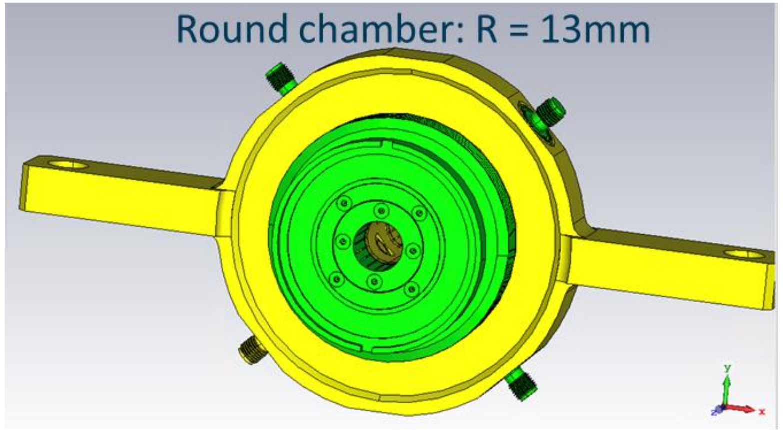


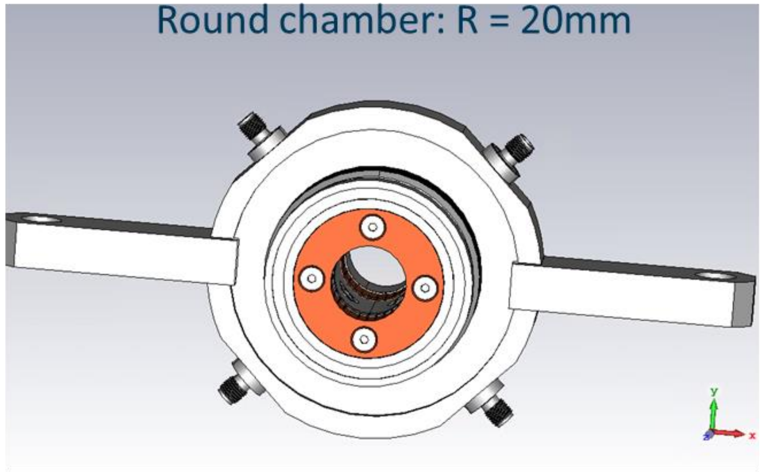
The worst-case center offset (WCO) can be linearly calculated by a1 and b1, with the coefficient determined by CST simulation. For round 13mm ID 4mm button BPM:

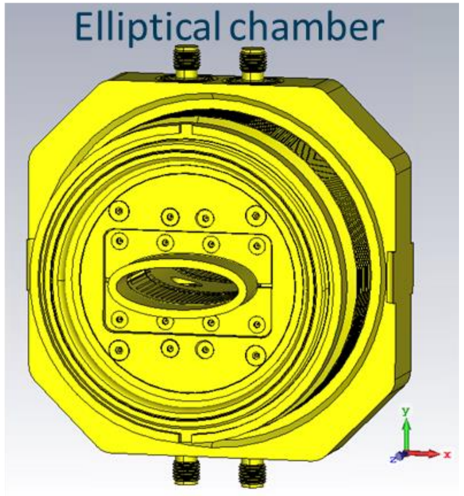
$$wco = 0.9* a1 + 2.8*b1$$

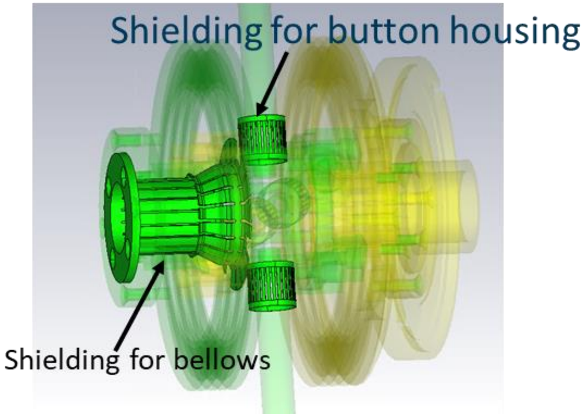
WCO is much more sensitive to b1 than a1.

BPM beam impedances are small compared to the dominant impedance components in both AR and SR









- SR BPM
  - Bellows associated with BPMs, and the BPM housing are both well-shielded with RF fingers, thus BPMs are low impedance components
  - Longitudinal loss factor 1.43e-4 V/pC per BPM,
  - $92\mu\Omega$/BPM inductive impedance contribution, total imaginary part $\frac{Z}{n} = 19.8\ m\Omega$, small contribution compared to resistive wall in the SR.
- AR BPM
  - Broadband impedance imaginary part Z/n < 3 mΩ, which is a small contribution to the AR budget, dominated by flanges and transitions.
  - Major narrow-band impedance is the coaxial mode in the narrow gap ~ 11.6 GHz.

Status and outlook for the ALS-U BPM EM work

- We have finished the EM testing for all the AR BPM assemblies. All 72 assemblies have been installed on the rafts. The installation of AR is going on during every ALS shutdowns.
- For the more challenging SR BPM, we have finished all the EM designs and the bench testing of the prototype buttons. The button contracts have been awarded to the selected vendors. The production of the first prototype assembly is in progress. We will measure the performance of this prototype once it arrives.
- We will work with the vendors to measure and sort out the production SR buttons.
- The current plan is to measure the electrical centers of all the SR assemblies and do the fine tuning if needed. We will see how the Lambertson method works for the asymmetric BPM with keyhole or tapering. The alternative approach could be the wire method.

Thank you!