BPM electrode and high power feedthrough
-Special topics in wideband feedthrough-

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Introduction

- **Beam runs in vacuum chambers (mostly) made of good-conducting metal.**
  - Vacuum chambers shield (fast) electro-magnetic wave from / to the beam.
  - Need some kind of “Feedthrough” to get / feed the electro-magnetic signal from / to beam.

- **Wideband coaxial feedthrough**
  - Button-type electrode
  - Stripline kicker / monitor
  - Plate-type position monitor
  - Ion (or electron cloud) clearing electrode
Feedthrough
Need to consider..

- Specification of the feedthrough
  - Structure
    - Total size
    - Kind of RF connector, vacuum structure...
    - Mechanical (and heating) toughness
  - Frequency range, allowed SWR, reflection..
  - Power range
    - Beam induced power
    - Supplied power from outside
    - allowed (V)SWR
In this tutorial

- **Review of transmission line theory**
  - S-Parameter, (V)SWR
  - Time domain behavior (TDR)
- **Frequency-domain simulation**
  - Ansys HFSS
- **Time-domain simulation**
  - GdfidL
- **Design, evaluation of the button electrodes**
- **Design, evaluation of the high-power feedthroughs**
- **Summary**
Circuit representation of a uniform transmission line

\[ \Delta V = -IZ \Delta z \]
\[ \Delta I = -VY \Delta z \]
\[
\begin{align*}
\frac{dV}{dz} &= -IZ \\
\frac{dI}{dz} &= -VY \\
\frac{d^2V}{dz^2} &= \gamma^2 V, \quad \frac{d^2I}{dz^2} = \gamma^2 I \\
\gamma^2 &= ZY
\end{align*}
\]
Transmission line (cont.)

- **Solution**

\[ V = V_1 e^{-\gamma z} + V_2 e^{\gamma z} \]

- **Normal transmission line**

\[ Z = R + jL\omega \]

\[ Y = G + jC\omega \]

\[ \gamma = \left( LC\omega^2 \right)^{1/2} \left[ 1 - \frac{RG}{LC\omega^2} - j \left( \frac{G}{C\omega} + \frac{R}{L\omega} \right) \right]^{1/2} \]

\[ \approx j\omega \sqrt{LC} \left[ 1 - j \left( \frac{G}{C\omega} + \frac{R}{L\omega} \right) \right]^{1/2} \]

\[ \approx j\omega \sqrt{LC} \left( 1 - j \frac{R}{2L\omega} \right) \]
Propagation constant

\[ \gamma = \alpha + j\beta \]

\[ \alpha = \frac{R}{2} \sqrt{\frac{C}{L}}, \quad \beta = \omega \sqrt{LC} \]

- **Phase velocity**

\[ v_p = \frac{dz}{dt} = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} \]

- **If phase velocity = group velocity**

\[ \beta = \frac{2\pi f}{f\lambda} = \frac{2\pi}{\lambda} \]

\[ V = V_1 e^{j(\omega t - \beta z)} e^{-\alpha z} + V_2 e^{j(\omega t + \beta z)} e^{\alpha z} \]
Loss less line

\[ V = V_1 e^{-j\beta z} + V_2 e^{j\beta z} \]
\[ I = \frac{1}{Z_0} \left( V_1 e^{-j\beta z} - V_2 e^{j\beta z} \right) \]
\[ Z_0 = \frac{Z}{\gamma} = \sqrt{\frac{L}{C}} \]
\[ \beta = \omega \sqrt{LC} \]
Impedance matched line

\[
\frac{V(A)}{I(A)} = Z_0 = Z_0 \frac{V_1 e^{-j\beta A} + V_2 e^{j\beta A}}{V_1 e^{-j\beta A} - V_2 e^{j\beta A}} \quad V_2 = 0
\]

- No reflection! (Only forwarding wave exist)
To satisfy $V(A)/I(A)=Z$, we need both forwarding and reflecting wave.

\[ V = V_1 e^{-j\beta z} \left( 1 + 2 \frac{|V_2|}{|V_1|} \cos \chi + \left( \frac{|V_2|}{|V_1|} \right)^2 \right)^{1/2} \exp \left( j \tan^{-1} \frac{|V_2|}{|V_1|} \sin \chi \right) \]

\[ \chi = 2 \beta z + \theta_2 - \theta_1 \]
Standing wave

\[ V = V_1 e^{-j\beta (A-s)} + V_2 e^{j\beta (A-s)} = V'_1 e^{j\beta s} + V'_2 e^{-j\beta s} \]

\[ = V'_1 e^{j\beta s} \left( 1 + \rho e^{-2j\beta s} \right) \]

- \( \rho \): reflection constant

\[ \rho = \frac{V'_2}{V'_1} = |\rho| e^{j\phi} \]

\[ V = V'_1 e^{j\beta s} \left( 1 + |\rho| e^{j(\phi-2\beta s)} \right) \]
Standing wave ratio

\[ \phi - 2\beta d_{\text{min}} = \pi \]

- Standing wave ratio (SWR)

\[ S = \frac{|V|_{\text{max}}}{|V|_{\text{min}}} = \frac{1 + |\rho|}{1 - |\rho|} \]

\[ |\rho| = \frac{S - 1}{S + 1} \]
Example of standing wave!

Broken attenuator

$\lambda/2$?

Upstream port of stripline kicker
Impedance of the load

- We can estimate the load impedance using

\[
Z_r = Z_0 \frac{1 + \rho}{1 - \rho}
\]

Reflection constant

\[
z_r = \left( \frac{Z_r}{Z_0} \right) = \frac{1 + |\rho|e^{j\varphi}}{1 - |\rho|e^{j\varphi}} = \frac{(S + 1) + (S - 1)e^{j(2\beta d_{min} + \pi)}}{(S + 1) - (S - 1)e^{j(2\beta d_{min} + \pi)}}
\]

SWR

\[
= \frac{1 - jS \tan \beta d_{min}}{S - j \tan \beta d_{min}}
\]
Linear two port network

\[
\begin{pmatrix}
    b_1 \\
    b_2
\end{pmatrix} =
\begin{pmatrix}
    S_{11} & S_{12} \\
    S_{21} & S_{22}
\end{pmatrix}
\begin{pmatrix}
    a_1 \\
    a_2
\end{pmatrix}
\]
**S-parameters**

- **Input Reflection Coefficient with** $Z_L=Z_0$
  \[ S_{11} = \frac{b_1}{a_1} \bigg|_{a_2=0} \]  
  Input match

- **Output Reflection Coefficient with** $Z_G=Z_0$ and $V_G=0$
  \[ S_{22} = \frac{b_2}{a_2} \bigg|_{a_1=0} \]  
  Output match

- **Forward Transmission Coefficient with** $Z_L=Z_0$
  \[ S_{21} = \frac{b_2}{a_1} \bigg|_{a_2=0} \]  
  Gain or loss

- **Reverse Transmission Coefficient with** $Z_G=Z_0$ and $V_G=0$
  \[ S_{12} = \frac{b_1}{a_1} \bigg|_{a_2=0} \]  
  Isolation
Why Use S-Parameters?

- relatively easy to obtain at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don’t need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to familiar measurements (gain, loss, reflection coefficients...)
- can cascade S-parameters of multiple devices to predict system performance
- can compute H, Y or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in electronic-simulation tools
RF Network Analyzer
S11 and SWR(VSWR)

- Return loss
  \[ 20 \log_{10} \left| S_{11} \right| \text{dB} \]

\[ \text{SWR}_{\text{input}} = \frac{1 + \left| S_{11} \right|}{1 - \left| S_{11} \right|} \]
Example (50dB attenuator)
Example (800MHz Bessel LPF)
Using voltage ratio between forward and reflecting wave

\[ Z_r = \frac{1 + \rho}{1 - \rho} Z_0 \]

\[ \rho = \frac{V_r}{V_i} \]
(A) Open Circuit Termination ($Z_L = \infty$)

Therefore $\frac{Z_L - Z_0}{Z_L + Z_0} = +1$
Which is true as $Z_L \to \infty$

$\therefore \ Z = \text{Open Circuit}$

(B) Short Circuit Termination ($Z_L = 0$)

Therefore $\frac{Z_L - Z_0}{Z_L + Z_0} = -1$
Which is only true for finite $Z$

When $Z_L = 0$

$\therefore \ Z = \text{Short Circuit}$

(C) Line Terminated in $Z_L = 2Z_0$

Therefore $\frac{Z_L - Z_0}{Z_L + Z_0} = +\frac{1}{3}$
and $Z_L = 2Z_0$

(D) Line Terminated in $Z_L = \frac{1}{2}Z_0$

Therefore $\frac{Z_L - Z_0}{Z_L + Z_0} = -\frac{1}{3}$
and $Z_L = \frac{1}{2}Z_0$
Science Camp 2011 (for High School students)
Matching of 50-ohm line

Reflection (V)

Resistivity (Ω)

Reflection pulse height (V)
Real TDR
Tips

- Good matched two-ports (such as J–J structure) is needed to measure the S-parameters of the feedthrough structure.
  - For the TDR measurements, open structure (button or rod on vacuum side) might usually be OK
Ideal feedthrough?

- **Mechanical**
  - Completely satisfy required mechanical toughness
  - Satisfy vacuum requirements

- **Frequency domain**
  - $S_{21}$ (and $S_{12}$) ~1 (0dB)
  - $S_{11}$ (and $S_{22}$) ~ -inf dB

- **Time domain**
  - Impedance=50 Ohm, completely matched structure
Which connectors do you want to use?
- N?, SMA?, BNC?, 7/16-DIN?, 7/8-EIA?

\[ Z_0 = 60 \sqrt{\frac{\mu_R}{\varepsilon_R}} \ln \frac{b}{a} \]

Attenuation Length
\[ \alpha \approx \alpha_c + \alpha_d \]
\[ \alpha_c = 13.6 \frac{\delta_s \sqrt{\varepsilon_R} \{1 + (b/a)\}}{\lambda_0 b \ln(b/a)} , \]
\[ \alpha_d = 27.3 \frac{\sqrt{\varepsilon_R}}{\lambda_0} \tan \delta \]
Higher-mode propagation in coaxial lines.

- **TE11 mode**

\[ \lambda_c \approx \pi(a + b) \]

\[ f_c \approx \frac{c}{\pi(a + b)\sqrt{\varepsilon_R}} \]

- Type-N: 18GHz
- SMA: 34GHz
- RG-223: \(~30\)GHz
- EIA 7/8": \(~6.8\)GHz
Connectors in the air

\[ l = \frac{\lambda}{2} = \frac{\lambda_0}{2\sqrt{\varepsilon_R}} \]

\[ l < 0.02\lambda \]

\[ Z_{01} = \frac{Z_0}{\sqrt{\varepsilon_R}} \]

Figure 6–8 Four types of dielectric bead supports for coaxial lines.
Feedthrough for vacuum

- **Vacuum seal (and support for inner conductor)**
  - Alumina ceramic ($\varepsilon_R \sim 10$), $\text{Si}_3\text{N}_4$ ($\sim 8$)
  - Glass ($\varepsilon_R \sim 4–5$)
    - Much larger than the support used in the air ($\sim 2$)

- **Need to stand mechanical stress coming from**
  - Vacuum pressure
  - (huge) pressure when connecting the cable (or attenuator) to the feedthrough
  - Thermal stress
    - Baking
    - Heating by the beam power

- **Need to keep good RF contact under severe condition**
  - Heat cycle
  - Radiation, active gas
Outer/inner conductor

- **Kovar (Nickel–cobalt ferrous alloy)**
  - Designed to be compatible with the thermal expansion characteristics of borosilicate glass
  - Ferromagnetics: Not so good for use near strong magnet.
  - Thermal conductivity: Low

- **Ti**
  - Non-magnetic material

- **Cu, Al, Stainless steel**
  - Also be usable. Consult your ceramic company.
Feedthrough process

- **Brazing temperature**
  - ~800 degC
  - After brazing process, metal parts will be well annealed – original characteristics might be changed.
    - No spring action at all!

- **Braze to vacuum chamber OK?**
  - Second (third?) brazing process
  - There exist brazing materials with lower temperature
    - Not so easy to control the temperature
Frequency domain design

- **ANSYS (Ansoft) HFSS**
  - 3D full-wave electromagnetic field simulator
  - Multiple state-of-the-art solver (finite element method or integral equation method)
  - calculate S-parameters, field patterns, eigen values, impedances..
  - Good user interface, Good interface to other tools such as ANSYS, etc.
  - Automatic mesh handing
  - (Very) Fast simulation speed
(Fast) Frequency sweep

![Graph showing frequency sweep data](image-url)
E-Field pattern
Time domain simulation

- **GdfidL Electromagnetic Field simulator**
  - Time dependent Fields in loss-free or lossy structure
  - Fields may be excited by port mode or relativistic line charge
  - Resonant fields in loss-free or lossy structure

- **Calculated result**
  - S-parameters, including power (voltage) value
  - Wake potentials including loss factor, impedance etc.
  - Q values and Shunt impedance

- **Need (some)large-scale parallel computing resources**
  - KEKB: 256 cores, 512GB Linux cluster
  - Text-base user interface, longer simulation time
Example of GdfidL input(1)

```plaintext
define(EL,1) define(MAG,2)
define(INF, 1000)
define(PipeRadius, 25.40e-3/2)
define(PipeStart, 100.0e-3)
define(PipeEnd, 100.0e-3)
define(BpmAdd, 13.5e-3)
define(STPSZE, 0.1e-3)

#general
outfile = /users/tobiyama/GD/bpm-CL22/temp/
scratchbase = /users/tobiyama/GD/scratch/

#material
material = 10
type = electric
material = 15
type = normal, epsr = 9.7, muer = 1, kappa = 0, mkappa = 0

#mesh
spacing = 0.1e-3
pxlow = 0
pxhigh = (PipeRadius + BpmAdd - 5*STPSZE)
pylow = 0
pyhigh = (PipeRadius + BpmAdd - 5*STPSZE)
pzlow = -PipeStart + 5*STPSZE
pzhigh = PipeEnd - 5*STPSZE
cxlow = magnetic, cxhigh = electric
cylow = magnetic, cyhigh = electric
czlow = electric, czhigh = electric

#brick
material = EL
xlow = -INF, xhigh = INF
ylow = -INF, yhigh = INF
zlow = -INF, zhigh = INF
doit
```
Example of GdfidL input(2)

#
# cave beam pipe
#
-gbor
material=0
origin=(0,0,0)
zprimedirection=(0,0,1)
rprimedirection=(1,0,0)
range=(0,360)
clear

point(-PipeStart,0)
point(-PipeStart,PipeRadius)
point(PipeEnd,PipeRadius)
point(PipeEnd,0)
point(-PipeStart,0)
show=all
doit

macro BpmBlock
define(Dist, @arg1)
define(Angle, (@arg2)*@pi/180)
define(BpmDiskRadius, 6e-3/2)
define(BpmRodRadius, 1.8e-3/2)
define(BpmairRadius, 1.1e-3/2)
define(BpmOutRadius1, 8e-3/2)
define(BpmOutRadius2, 4.1e-3/2)
define(BpmCera1Radius, 4.1e-3/2)
define(BpmCera2Radius, 8e-3/2)
define(BpmDiskLength, 1e-3)
define(BpmRod1Length, 2.9e-3)
define(BpmRod2Length, 3e-3)
define(BpmRod3Length, 6.1e-3)
define(Cerastart, 1.9e-3)
define(Cera1Length, 2e-3)
define(Cera2Length, 3e-3)
define(DP1, (5e-3+BpmDiskLength+BpmRod1Length+BpmRod2Length))
define(DP2, (DP1+Dist − 5e-3))
Example of GdfidL input(3)

```plaintext
# gccylinder
material=0, radius=BpmOutRadius1,length = DP1
origin=(cos(Angle)*(Dist - 5e-3), sin(Angle)*(Dist - 5e-3), 0)
direction=(cos(Angle),sin(Angle),0)
doit

gccylinder
material=0, radius=BpmOutRadius2
length= BpmRod3Length
origin=(cos(Angle)*(DP2),sin(Angle)*(DP2), 0)
direction=(cos(Angle),sin(Angle),0)
doit

# ceramic

# gccylinder
material=15, radius=BpmCera1Radius,length=Cera1Length
origin=(cos(Angle)*(Dist+Cerastart), sin(Angle)*(Dist+Cerastart), 0)
direction=(cos(Angle),sin(Angle),0)
doit

gccylinder
material=15, radius=BpmCera2Radius,length=Cera2Length
origin=(cos(Angle)*(Dist+Cerastart+Cera1Length), sin(Angle)*(Dist+Cerastart+Cera1Length), 0)
direction=(cos(Angle),sin(Angle),0)
doit

# air again

gccylinder
material=0, radius=BpmRodRadius,length =
(Cera1Length+Cera2Length)
origin=(cos(Angle)*(Dist+Cerastart),sin(Angle)*(Dist-Cerastart), 0)
direction=(cos(Angle),sin(Angle),0)
doit

# bpm disk

gccylinder
material=10, radius=BpmDiskRadius,length=BpmDiskLength
origin=(cos(Angle)*(Dist), sin(Angle)*(Dist), 0)
direction=(cos(Angle),sin(Angle),0)
doit

gccylinder
material=10, radius=BpmRodRadius, length=BpmRod1Length
origin=(cos(Angle)*(Dist+BpmDiskLength), sin(Angle)*(Dist+BpmDiskLength), 0)
direction=(cos(Angle),sin(Angle),0)
doit

....still many definitions...

e ndmacro #BpmBlock
```
Example of GdfidL input (4)

- mesh 0.1 mm
- bunch length 6 mm
- beam = (0,0) [center]
- wake up to 5 m

```
call BpmBlock(13.2e-3,90)
call BpmBlock(13.2e-3,0)
call BpmBlock(13.2e-3,-90)
call BpmBlock(13.2e-3,180)

-fdtd
-lcharge
  charge=1e-12
  sigma=6e-3
  xposition=0, yposition=0
  shigh=5
  showdata=no
-ports
  name=beamlow, plane=zlow, modes=0, npml=40, doit
  name=beamhigh, plane=zhigh, modes=0, npml=40, doit
  name=bpmyp, plane=yhigh, modes=1, npml=15, doit
  name=bpmxp, plane=xhigh, modes=1, npml=15, doit

-fdtd
-doit
```
Post processing (using gd1.pp)
wakes, impedances
- Ports must be placed orthogonally to the boundaries.
Button electrode (KEKB-FB)

Feedback用SMAフィードスルーC型概略図
作図：飛山真理 19/Mar/2004
縮尺4:1
Using normal SMA–J connector (or N–J, too) usually encounter difficulty in RF contact at the split–pin of the center conductor due to brazing process – No spring action might be expected after the process.

- Using P–structure.. not easy to handle..
- Use pin on the J–structure (“Reverse type J”)

Gold–plating of at the RF connector is desirable

- Not easy to maintain the thickness of the gold during brazing process (Gold will be diffused into the bulk metal..)
HFSS model
Simulated S-Parameters

S-parameter (dB) vs. Frequency (GHz)
GdfidL model

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Material boundaries

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GdfidL

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20/04/2008, 12:45:45

v1.9b Fri Oct 8 2006 w523
Simulated Port output

Graph 1: Time (ns) vs. Output (V/nC)
- Output (V/nC) ranges from -0.8 to 0.8
- Time (ns) ranges from 0 to 3

Graph 2: Frequency (GHz) vs. Power
- Power is on a logarithmic scale ranging from $10^{-32}$ to $10^{26}$
- Frequency (GHz) ranges from 0 to 30
Tips

- Need to pay attention to the possible trapped modes in the sealing structure, which may damage the seal on high beam current operation.
  - Use Eigen-mode solver to estimate the frequency of the trapped mode.
  - Fine frequency sweep to find dip structure in S11
  - Coupling to coaxial mode might be difficult.

- Need to pay attention to the multipacting around the button gap, especially for high single-bunch current machine.

- Longitudinal beam coupling impedance might not be negligible on large circumference, high beam current machine.
Measured signal (20GHz scope)

9nC/bunch LER 43dB attenuation, LER upstream

Maximum beam current at KEKB: 2A+1.3A=3.3A with large horizontal offset
Feedthrough with low $\varepsilon_r(\sim 4)$ sealing
Center pin pulling-out test

![Graph showing breaking point (kgf) vs. diameter of inner conductor (mm). The graph includes data points for Glass (ref), D01-Glass, D01 Mean value, and KEKB-FB (ceramic).]
Beam test using Linac short pulse
SuperKEKB進行方向キッカー用7/8-EIA FT
*印寸法(3カ所)は試験成績書記載箇所とする。
Simulated S-Parameters

S21 and S11

VSWR(S11)
High power test

- Temperature rise: 4 deg/100W (without water cooling)

1.3GHz power source
To enhance thermal conductivity between the center conductor and the outer wall, it might be considered to fill BN ($\varepsilon_R \sim 4$) at the air side.

$\text{Si}_3\text{N}_4$ has lower $\varepsilon_R$ and has better (lower) loss tangent
- Expensive
- Mechanically weaker than alumina–ceramic
Summary

- Briefly reviewed the transmission-line theory
  - S-Parameters, SWR, Time-domain response
- Introduced E-M simulation software
  - HFSS (Frequency domain)
  - GdfidL (Time domain)
- Shown several examples
  - KEKB-FB button electrode
  - SuperKEKB-FB button electrode
  - High power feedthrough for SuperKEKB longitudinal kicker.
“Microwave Engineering Passive Circuits”,
by Peter A. Rizzi, ISBN 0135867029

“Introduction to Microwave Theory”,
by Harry A. Atwater, ISBN 0898741920

Ansys HFSS,
- http://www.ansys.com/Products/Simulation+Technology/Electromagnetics/High-Performance+Electronic+Design/ANSYS+HFSS

GdfidL, http://www.gdfidl.de/

Kyocera Corporation

Orient Microwave Corp.
Transmission line

- Coaxial cable

- plastic jacket
- dielectric insulator
- metallic shield
- centre core
Standing wave

\[ |V_1| + |V_2| \]

\[ |V_1| - |V_2| \]

\[ V \]

\[ z \]
例: ボタン電極型ビーム位置モニタ

四つの電極に出てきた電荷の差から、パンチの重心位置を求めるためのモニターです。レンズの働きをする四極電磁石に固定してあります。
アバランシェトランジスタパルサー（正極性）
アバランシェパルサー（負極性）
固定端での反射

http://www.wakariyasui.sakura.ne.jp/2-1-0-0/2-1-2-4koteitannjiyuutann.html
出力は

- トリガーが入ってトランジスタがONになり、約10ns後にOFFになっている。
- このとき、PFNには1mの同軸線をつけていた。ここにたまっていった高電圧が抜けて、パルス高が0に戻った。
アバランシェパルサーの使用例

線形加速器の熱電子銃から出る電子ビームの長さを非常に狭く（1ns以下とか）したいとき、アバランシェパルサーを使ってビームが出るタイミングを制御します
高圧電源
SuperKEKB Transverse FB plan

SuperKEKB Transverse Bunch Feedback System
Bunch position detector prototype
Vacuum chamber

- Aluminum alloy antechamber
- Cutoff frequency <1 GHz
BPM head

SuperKEKB BPM model-E1
Impedance/button output simulation

(A) Time-domain response

(B) Amplitude spectrum