BPM ELECTRODE AND HIGH POWER FEEDTHROUGH – SPECIAL TOPICS IN WIDEBAND FEEDTHROUGH

Makoto Tobiyama[#]

KEK Accelerator Laboratory, 1-1 Oho, Tsukuba 305-0801, Japan

Abstract

Since most of the beam in accelerator runs in the vacuum chamber consists of metal, it is needed to have 'feedthrough' to get or to put the RF signal from or to beam. For example, we can get the beam signal by using button-type electrode which have electrical isolation material to seal the vacuum. Now, many types of vacuum feedthrough with coaxial structure are available commercially. Nevertheless, it is meaningful to understand the design principle of the feedthrough needed for the beam instrumentation, especially for short bunch length, high beam current machine. I will show the design method of the feedthrough such as BPM electrodes or high power feedthroughs using 3D EM-codes such as HFSS or GdfidL based on several examples developed for SuperKEKB accelerators.

INTRODUCTION

In particle accelerators, so many wideband feedthroughs are used to monitor the electromagnetic signal and to excite or damp the beam. Figure 1 shows examples of the feedthroughs used in KEKB rings. Though it is easy to purchase good feedthroughs commercially in the market, understanding the characteristics of the feedthrough is still very important.
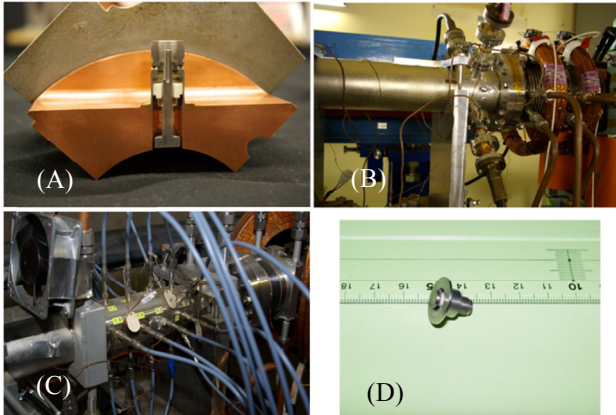

Figure 1: Feedthroughs used in KEKB rings: (A) Cut-model of N-type button electrode for LER. (B) High power feedthrough for the transverse kicker. (C) Bunch position detection chamber for bunch-by-bunch feedback. (D) SMA-type button electrode.

In this tutorial, we at first briefly review the transmission line theory which is needed to understand the specification of the feedthrough. Next, we show the example of the two widely used simulation tools to design the feedthrough: one is the frequency domain method to

_____

#makoto.tobiyama@kek.jp

optimize the S-Parameters, and the other is time domain method to calculate the beam induced signal such as wake filed or the output signal of the electrode. Finally, several examples of the button electrodes and feedthroughs used KEKB and SuperKEKB accelerators are shown.

REVIEW OF THE TRANSMISSION THERORY

There are many good textbooks such as reference [1, 2] to introduce the microwave theory and techniques, we here only show several definitions used afterwards.

Frequency Domain View

Figure 2 shows a trans-mission line with characteristic impedance of Z_0 with a termination Z_r and a resulting SWR for wavelength λ.
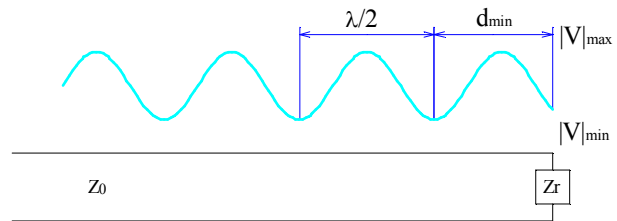

Figure 2: Transmission line with a termination.

The Standing Wave Ratio (SWR) S can be written using V_{max} and V_{min} or reflection constant ρ as

$$S = \frac{|V|_{max}}{|V|_{min}} = \frac{1+|\rho|}{1-|\rho|}$$

and the load impedance can be estimated as

$$z_r = \frac{Z_r}{Z_0} = \frac{1+\rho}{1-\rho} = \frac{1-jS\tan\beta d_{min}}{S-j\tan\beta d_{min}}$$

where $\beta = \omega\sqrt{LC}$ in the case of loss less transmission line.

In a linear two port network shown in Fig. 3, we can define the S-Parameters as follows:

$$\begin{pmatrix} \mathbf{b_1} \\ \mathbf{b_2} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} \mathbf{a_1} \\ \mathbf{a_2} \end{pmatrix}.$$
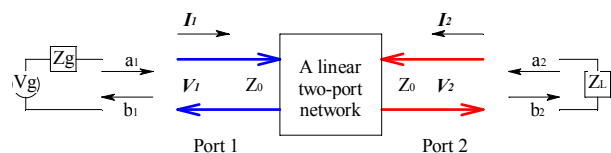

Figure 3: A linter two-port network.

S_{11} is the input reflection coefficient (input match) and S_{22} is the output reflection coefficient (output match). S_{21} is the forward transmission coefficient (gain or loss) and S_{12} is the reverse transmission coefficient (isolation). The S-Parameter has many good points, such as:

- It is relatively easy to measure S-Parameter at high frequency region.
- It is related to familiar measurements such as gain, insertion loss SWR, or return loss.
- It can be easily cascaded with multiple devices.
- It has good compatibility with the E-M simulation software.

Time Domain View

We can estimate the impedance of the load using the voltage ratio between the forward and reflecting wave. If we send a short pulse with sharp rise time and flat top, it is easy to distinguish the forward pulse and the reflecting pulse using very wideband oscilloscope. This method is called as Time Domain Reflectometry (TDR). As this method is so intuitive and very easy to understand, it is widely used to hunt the failure point in transmission line components such as cables, connectors or feedthroughs around the accelerator. Note that theoretically it is possible to estimate the impedance with imaginary components such as capacitor or inductor, the estimation easily includes huge error coming from the loss of the cables or small impedance mismatch. Also, theoretically it is possible to de-convolute the multiple mismatch effect from the source to the DUT (device under test), reflections from the far point is easily smeared and not easy to distinguish the effect.

Comparison of the Two Method

As most of the feedthrough has only one RF port (air side) and the other side is open, measuring the S-Parameters is not easy. Only S_{11} measurement is possible and meaningful. In case if there exist dangerous high-Q trapped structure in the feedthrough, it might show sharp drop structure in S11 measurement. Nevertheless, if one need to measure the pure RF characteristics of the feedthrough, it might be a good idea to prepare specially designed feedthrough with both side has good RF connector.

On the other hand, TDR measurement does not need impedance matched port on the vacuum side. You can easily measure and check the internal structure of the feedthrough and the connected components after the installation to the beam chamber.

ITEMS NEEDED TO CONSIDER BEFORE DESIGNING THE FEEDTHROUGH

Size of the Feedthrough—Cutoff Frequency of TE11 Mode

The signal attenuation of a coaxial cable comes from imperfect conductors and insulator (loss tangent). Both contributions of the attenuation length (dB/m) are proportional to the frequency. If the insulator is fixed, it is inversely proportional to the diameter of the coaxial line.

The lowest higher-mode propagation in the coaxial line is the TE11 mode. The cutoff frequency f_c of a coaxial line with inner conductor radius of a and inter radius of the outer conductor b is expressed as:

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

where c is the speed of light and ε_R is the relative permittivity of the insulator. For example, the cutoff frequency of RG-223 cable is around 30 GHz and EIA 7/8" cable is around 6.8 GHz. Part of the signals with frequency higher than the cutoff frequency change the propagation mode in the coaxial line from TEM to TE11 mode and cannot be received correctly with the termination designed to receive TEM mode signal. Also as in the higher-mode propagation, the phase velocity of the signal depends on the frequency, the shape of the signal in the time domain is wildly deformed. The size of the feedthrough should be chosen much smaller than the size which passes TE11 mode cutoff frequency.

Support of the Inner Conductor

In a connector or a feedthrough, most of the material between the two conductors is air or vacuum, with ε_R is almost 1. It is needed to support the inner conductor at some point with other dielectric materials. In the air, we can use lower ε_R materials of around 2, such as polyethylene or Teflon. There are mainly four types of low-reflection bead supports [1] and used as the wideband connectors in the air. Unfortunately for the feedthrough for vacuum use, it is not so easy to directly apply such method because of much large ε_R in vacuum sealing material and required mechanical toughness there.

On the feedthrough for vacuum use, alumina ceramic of $\varepsilon_R \sim 10$ or glass $\varepsilon_R \sim 4$ are widely used for the support of the inner conductor and the vacuum sealing. The seal needed to be stand the mechanical stress coming from the vacuum pressure, thermal stress due to baking process of the chamber and heating up due to the passing the beam power, and huge pressure when connecting the cable or attenuator to the feedthrough. In the view of signal condition, it is needed to keep good RF contact under much severe conditions such as many heat cycles and radiation effect. Note that use of materials including halogen, such as Teflon or polyvinyl is extremely dangerous because they easily decompressed by the radiation and damage other accelerator components including feedthrough itself.

During the fabrication process of the feedthrough, high temperature (around 800 deg. C) brazing or melting is applied. For the outer or inner conductor metal, it is desirable to have very similar thermal expansion coefficient with the sealing materials. Kovar (Nickel-cobalt ferrous alloy) is widely used as it is designed to be

compatible with the thermal expansion characteristics of borosilicate glass. Note that Kovar is magnetic substance so need care to use near the strong magnetic field such as quadrupole magnets. Thermal conductivity of the Kovar is also not so good so need to care about the heating up of the inner conductor or stripline plate or button connected to the inner conductor. For the use of strong magnetic field such as near the superconducting magnets, use of titanium might be a good candidate. Other materials, such as cupper or aluminium might be used.

FREQUENCY DOMAIN SIMULATION

For the example of the frequency domain EM simulation, we show ANSYS HFSS[3]. It is 3D full-wave electromagnetic field simulator and can calculate S-parameters, field patterns, eigen values or impedances. Figure 4 shows an example of BPM model for SuperKEKB BPM feedthrough. Note that both ports (RF connector port and the button head) are assigned to be the completely matched port on the simulation.
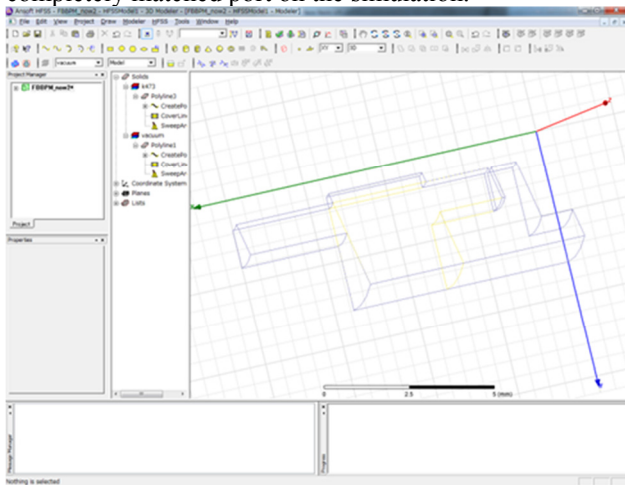

Figure 4: HFSS Modeler.

We set the target frequency, accepted delta-S and frequency range to sweep. HFSS automatically generate suitable mesh and iterate the calculation until delta-S condition satisfies. An example of calculated S-parameters of this model is shown in Fig. 5.
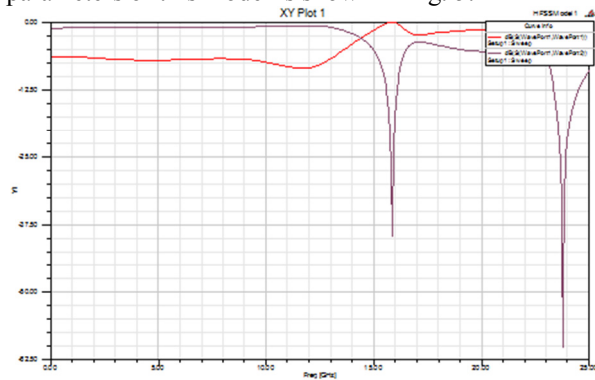

Figure 5: Simulated S-parameters.

In the case of most feedthroughs, HFSS simulation time needed is fairly short.

TIME DOMAIN SIMULATION

Another kind of 3D electromagnetic simulation is the time domain simulation which simulate the beam response such as wake function or port outputs in time domain. For an example, GdfidL[4] simulator is shown.

GdfidL is an electromagnetic filed simulator which can calculate time dependent fields in loss-free or lossy structure. The field may be excited by port mode or relativistic line charge. Also resonant fields in loss-free or lossy structure can be calculated. From the calculated results we can easily extract the S-parameters, including time evolution of the extracted power to the port, wake potentials including loss factor, coupling impedance, or Q values and shunt impedance of a resonant structure. As it is time domain simulator, it needs large-scale parallel computing resources to finish the simulation within a realistic time. Also, as the input is the simple text, unlike the beautiful 3D CAD like HFSS, it is not so user friendly. The text input has, however, merit we can change some parameters by changing only one line in the input. Translation script from other CAD interface or 3D EM simulation code[5] might help for complicated structure.

Figure 6 shows the cut plot of BPM electrode for KEKB feedback system. In Fig. 7, the simulated BPM output for the σ=6 mm bunch (A) and the longitudinal wake potential (B).
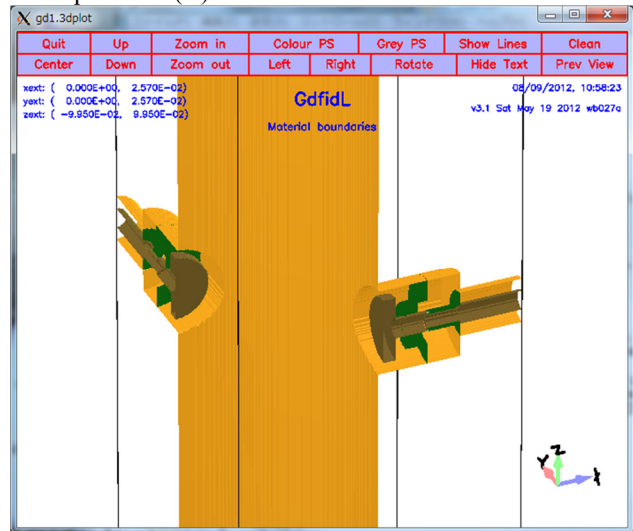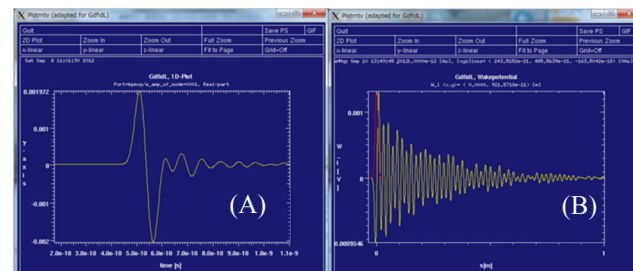

Figure 6: GdfidL model of KEKB-FB BPM .

Figure 7: Examples of simulated results of GdifdL : (A) Output of BPM with 1 pC charge with σ=6 mm, (B) Longitudinal wake potential and loss factor.

In GdfidL, the user needs to decide the mesh size and wake length. Typical simulation time strongly depends on the mesh size, total size of the object and the length of wake. The example shown here (wake calculated up to 5m) took about 4 hours using 64 cpu cores.

EXAMPLE OF FEEDTHROUGH DESIGN

Button electrode

The design of the button electrodes for SuperKEKB rings has already been reported in Ref. [6] so here we show some tips to design the electrode.

- Normal SMA-J connector, which has split-pin on the feedthrough side, has difficulty in RF contact because we cannot expect any spring action of the center-pin material after the blazing process. We have modified the split-pin to solid-pin like P-side connector ("Reverse J-type connector") for better contact.
- We prefer gold-plating at the RF connector also for better RF contact. During the blazing process, gold easily diffused into the bulk metal. It is not so easy to control the thickness. Also, we need to care about the reduction of the resistance between the center conductor and outer conductor due to the plating residuals.
- We need to pay attention to the possible trapped modes in the sealing structure, which might damage the seal on high beam, multi-bunch condition. The trapped mode can be estimated using eigen-mode solver or fine frequency sweep in S-parameter calculation.
- The narrow gap between the button electrode and the vacuum chamber might cause multipactoring after passing the bunch, especially for high single-bunch current machine such as light source or traditional high energy colliders.
- The longitudinal coupling impedance of the button electrode might not be negligible on large circumference, high beam current machine. It might cause longitudinal coupled-bunch instability.

Though the current simulation codes are fairly reliable, it is still meaningful to test the devices using real beam,
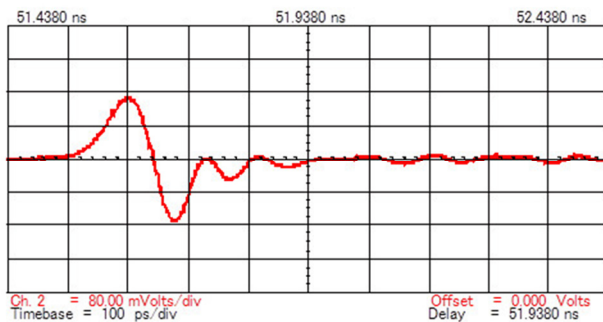

Figure 8: Measured beam signal from FB electrode of KEKB-LER. Sampling scope of bandwidth of 20 GHz was used.

such as short pulse from linac. Figure 8 shows an example of measured beam signal from KEKB-LER FB electrode.

We can make the bunch length of the linac beam much shorter than the beam in the ring using pulse compression at the transport line. The beam response of the device form such short beam includes very high frequency characteristics of the target device. In this case, the use of very wideband realtime oscilloscope might be needed because the beam from linac might change pulse by pulse, and preparing good timing signal for the trigger might not be easy. Figure 9 shows examples of beam response of (A) KEKB-FB button electrode and (B) SuperKEKB-FB button electrode using test beam line of KEK-PF beam transport line. As expected, better time response is shown in SuperKEKB-FB button electrode which uses low ε_R glass as sealing material.
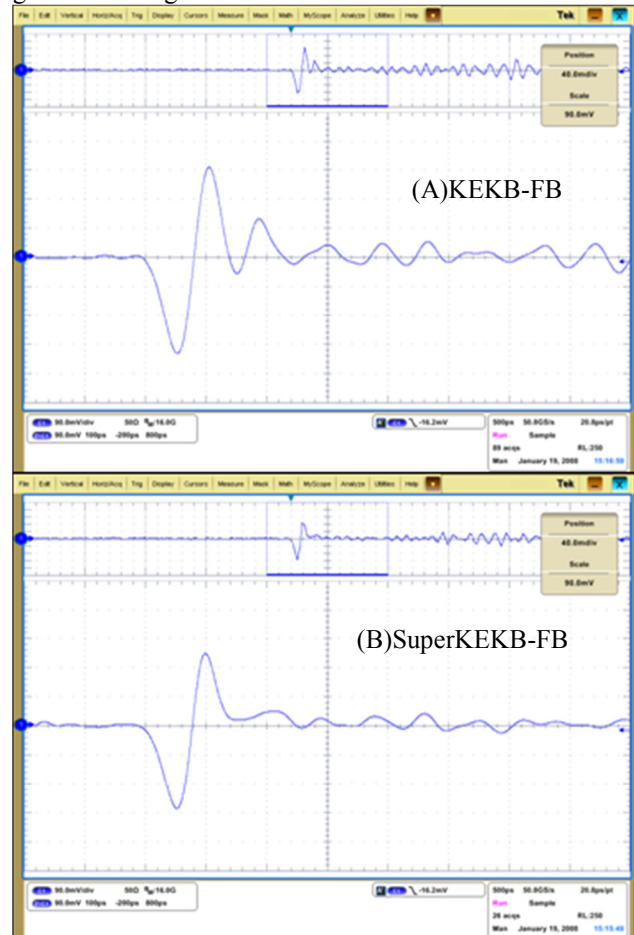

Figure 9: Button signal using short linac pulse: (A) KEKB-FB type electrode (B) SuperKEKB-FB type electrode with glass seal.

High Power Feedthrough

For the bunch feedback use, we need (semi-)wideband feedthrough to pass power at the range of kW. As the target center frequency and the bandwidth is much smaller and narrower than the case of button electrode, we can use simple but solid structure for the vacuum sealing. In KEKB, we have used 20D-type structure, the size were just same as EIA-7/8", for the feedthroughs of

the transverse stripline kickers and cavity-type longitudinal kickers. They worked very well without almost no trouble until the shutdown of the rings. Only one exception was the vacuum leak of one feedthrough of the longitudinal kicker due to intrinsic inferior of the 20D anchor contact at the air side: the RF contact had failed due to passing beam power and became open-contact so gigantic SWR had attacked the ceramic structure to break it.

During the design work of the new longitudinal kicker for PEP-II, we found that the small change of SWR of the feedthrough within the pass band affects the quality factor of the kicker too much[7]. For the longitudinal kicker for SuperKEKB rings, we have designed the EIA-7/8" feedthrough with the VSWR in the pass band (500 MHz to 2 GHz) less than 1.4. Also, to reduce the insertion loss at the vacuum seal, Si_3N_4 was used as the ceramic. Figure 10 shows simulated S-parameters and SWR. We have confirmed this type of feedthrough does not affect the Q of the longitudinal kicker for SuperKEKB by the HFSS simulation.

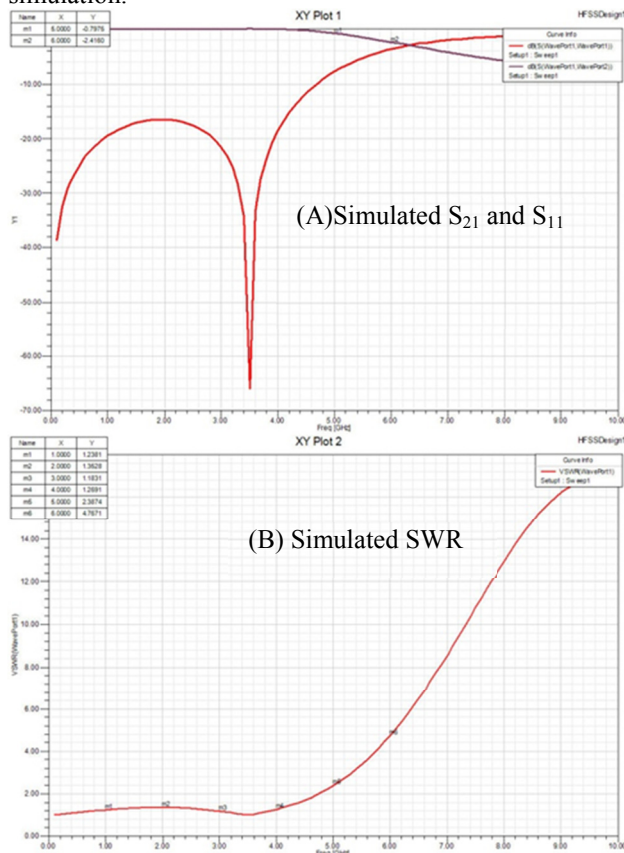
(A)Simulated S_{21} and S_{11}

(B) Simulated SWR

Figure 10: Simulated frequency response of the high power feedthrough for SuperKEKB longitudinal kicker.

We have also tested the increase of the temperature of the ceramic using 1.3 GHz high power amplifier. The measured temperature rise without water cooling outside the ceramic was 4 deg per 100 W. Using water cooling channel outside the ceramic structure, we expect the feedthrough can be usable up to around 5 kW CW.

SUMMARY

In this tutorial, we at first reviewed the transmission line theory briefly. The S-parameters, SWR, reflection constant and the Time Domain Reflectometry has been reviewed.

Next, two well-known 3D E-M simulation software, HFSS for frequency domain simulation and GdfidL for time domain simulation has been shown.

Finally, we showed several examples of the feedthroughs used KEKB rings and prepared for SuperKEKB rings with some tips useful to design the button electrodes and feedthroughs.

Though it is fairly easy to buy good feedthroughs commercially available in the market, designing and fabricating your own special feedthrough might help to increase the total performance of your diagnostic system because the feedthroughs are placed nearest position to the beam.

ACKNOWLEGEMENT

REFERENCES

[1] Peter A. Rizzi, "Microwave Engineering", Prentice Hall, ISBN 0135867029.

[2] Harry A. Atwater, "Introduction to Microwave Theory", Krieger Pub Co; ISBN 0898741920.

[3] ANSYS HFSS, http://www.ansys.com/

[4] GdfidL : http://www.gdfidl.de/

[5] T. Abe, Transportation script from Microwave Studio to GdfidL, private communication

[6] M. Tobiyama et. al., in proceedings of BIW10.

[7] P. McIntosh, et. al., in proceedings of PAC 2003, p3141 (2003).