Electron Positron Colliders and CP Violation

Hitoshi Yamamoto

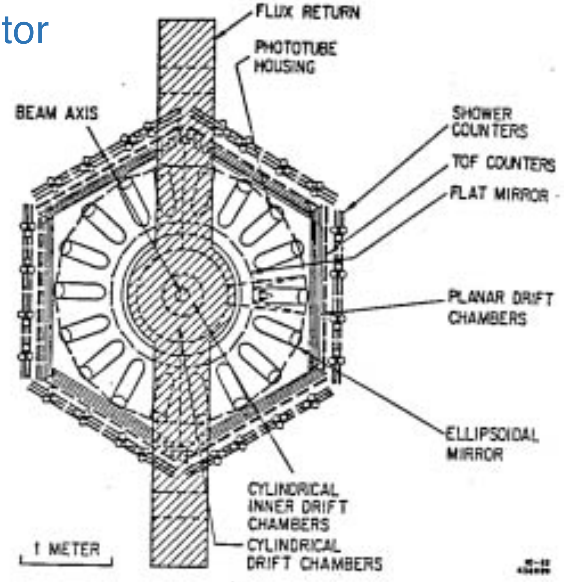
2020 Feb 12, Tohoku U.

Ph.D. Thesis:

A Study of Charged D* Mesons Produced in e+e- Annihilation at Ecm = 29 GeV

California Institute of Technology 1986

DELCO Detector



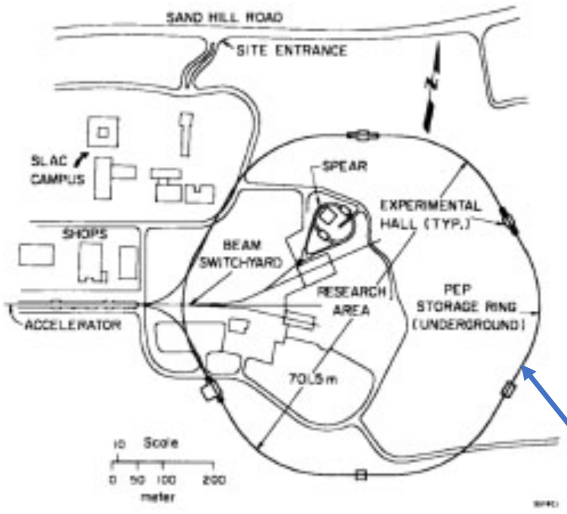


Fig. 1. Layout of the PEP ring superimposed on an aerial view of the SLAC site.

PEP Storage Ring

Stanford Linear
Accelerator Center (SLAC)

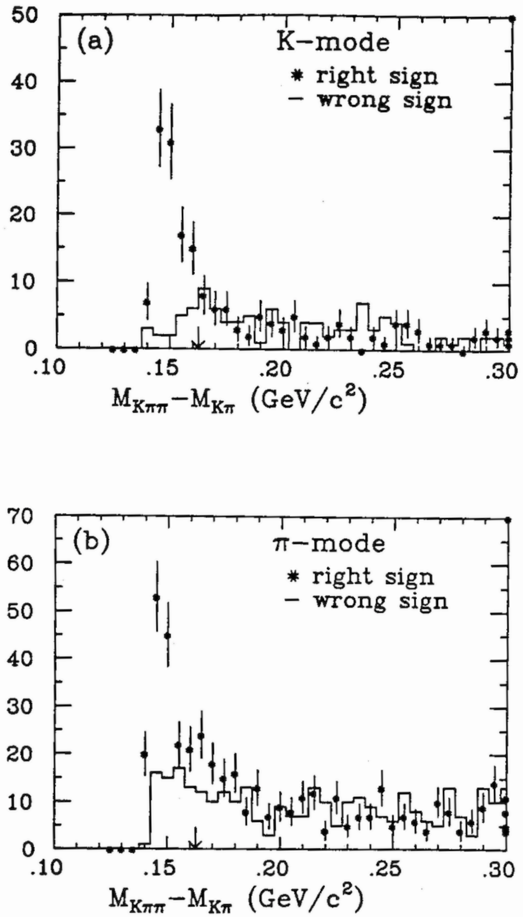


Figure 4.4. ΔM distributions after the cut $\sin\theta_{D\pi} < 0.13$ for K-mode (a) and π-mode candidates. The distributions for the wrong-sign combinations (histogram) are plotted over those for the right-signs (points with error bars). The arrows show the position of ΔM cut which defines the D^* signal region.

One of the first Ph.D. thesis in HEP to use TeX and embedded graphics (~1984)

$$e^+e^- \rightarrow D^{*+}X$$

$$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-\pi^+)\pi_s^+$$

Measurements:

1. Production cross section
2. Fragmentation function
3. D^0 lifetime
4. D^0-D^0bar mixing upper limit

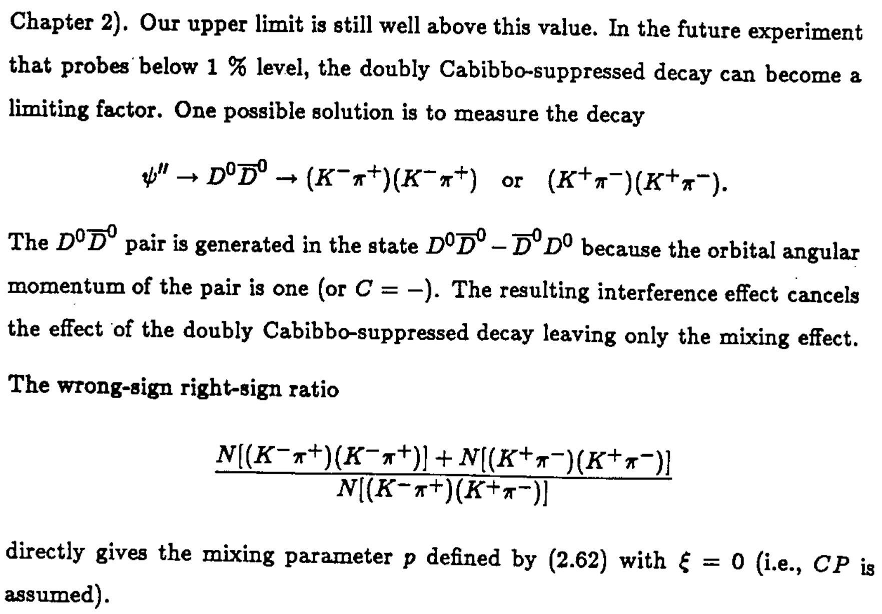
$$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow \overline{D}^0\pi_s^+ \rightarrow (K^+\pi^-)\pi_s^+$$

D^0-D^0bar mixing → 'wrong sign'

But, doubly-Cabbibo-suppressed decay (DCSD) also leads to wrong sign:

$$D^0\pi^+ \rightarrow (K^+\pi^-)\pi_s^+$$

Possible Solution for DCSD in measuring D^0 Mixing



Chapter 2). Our upper limit is still well above this value. In the future experiment that probes below 1 % level, the doubly Cabibbo-suppressed decay can become a limiting factor. One possible solution is to measure the decay

$$\psi'' \to D^0\overline{D}^0 \to (K^-\pi^+)(K^-\pi^+) \quad \text{or} \quad (K^+\pi^-)(K^+\pi^-).$$

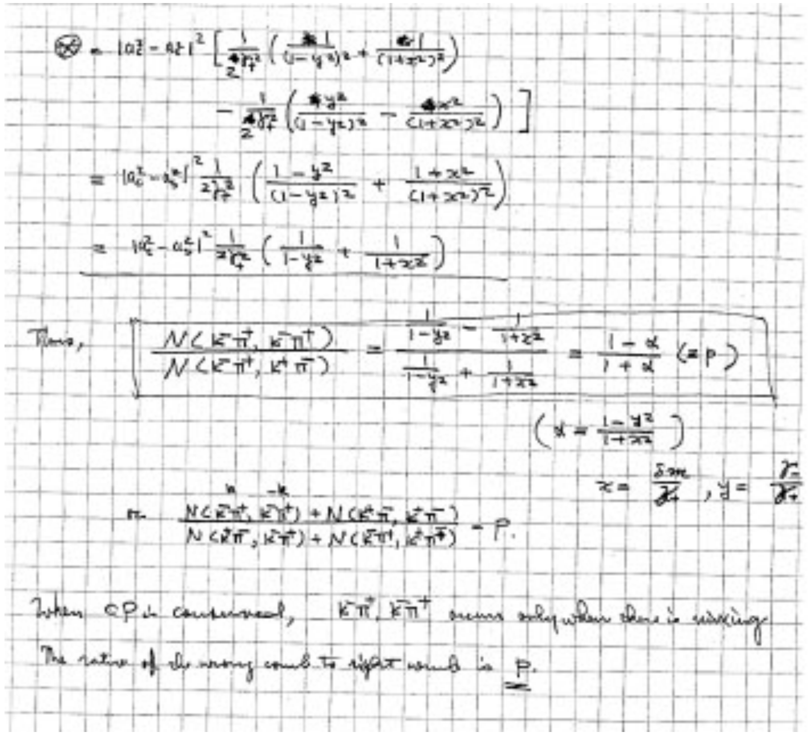
The $D^0\overline{D}^0$ pair is generated in the state $D^0\overline{D}^0 - \overline{D}^0D^0$ because the orbital angular momentum of the pair is one (or $C = -$). The resulting interference effect cancels the effect of the doubly Cabibbo-suppressed decay leaving only the mixing effect.

The wrong-sign right-sign ratio

$$\frac{N[(K^-\pi^+)(K^-\pi^+)] + N[(K^+\pi^-)(K^+\pi^-)]}{N[(K^-\pi^+)(K^+\pi^-)]}$$

directly gives the mixing parameter p defined by (2.62) with $\xi = 0$ (i.e., CP is assumed).

From the thesis



$$\otimes = |a_c^2 - a_t^2|^2 \left[\frac{1}{2\Gamma_+^2}\left(\frac{1}{(1-y^2)^2} + \frac{1}{(1+x^2)^2}\right) - \frac{1}{2\Gamma_+^2}\left(\frac{y^2}{(1-y^2)^2} - \frac{x^2}{(1+x^2)^2}\right)\right]$$

$$= |a_c^2 - a_c^{*2}|^2 \frac{1}{2\Gamma_+^2}\left(\frac{1-y^2}{(1-y^2)^2} + \frac{1+x^2}{(1+x^2)^2}\right)$$

$$= |a_c^2 - a_c^{*2}|^2 \frac{1}{2\Gamma_+^2}\left(\frac{1}{1-y^2} + \frac{1}{1+x^2}\right)$$

Thus,

$$\boxed{\frac{N(K^-\pi^+, K^-\pi^+)}{N(K^-\pi^+, K^+\pi^-)} = \frac{\frac{1}{1-y^2} - \frac{1}{1+x^2}}{\frac{1}{1-y^2} + \frac{1}{1+x^2}} = \frac{1-\alpha}{1+\alpha} \ (\equiv p)}$$

$$\left(\alpha = \frac{1-y^2}{1+x^2}\right)$$

$$x = \frac{\delta m}{\Gamma_+}, \quad y = \frac{\Gamma_-}{\Gamma_+}$$

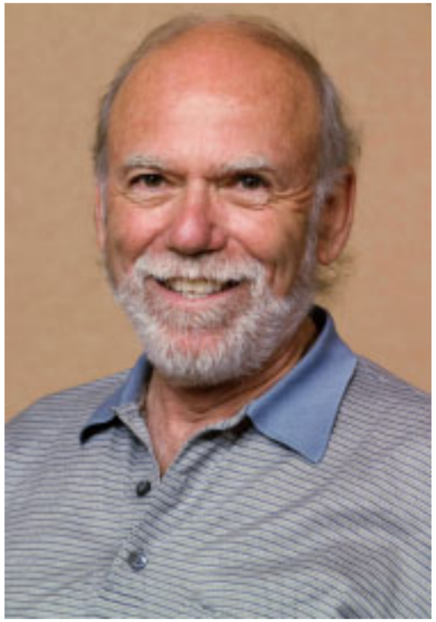
or $$\frac{N(K^-\pi^+, K^-\pi^+) + N(K^+\pi^-, K^+\pi^-)}{N(K^-\pi^+, K^+\pi^-) + N(K^+\pi^-, K^-\pi^+)} = p.$$

When CP is conserved, $K^-\pi^+, K^-\pi^+$ occurs only when there is mixing.

The ratio of the wrong comb to right comb is $\underline{p}$.

On $\Psi'' \to D^0 D^0$bar, look for (K-pi+)(K-pi+),
The effect of DCSD cancels and only the mixing effect remains.

From log book (page 7 / 7)



Advisor: Barry Barish

白金台　八芳園にて

Inclusive Decay Distributions of Coherent Two-body States

Phys.Rev.Lett. 79 (1997) 2402-2405

$$\Psi = aB^0B^0 + bB^0\overline{B}^0 + c\overline{B}^0B^0 + d\overline{B}^0\overline{B}^0$$
$$|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$$

the necessary and sufficient condition for the naive incoherent sum

$$(2|a|^2 + |b|^2 + |c|^2)\,\Gamma_{B^0\to f}(t) + (2|d|^2 + |b|^2 + |c|^2)\,\Gamma_{\bar{B}^0\to f}(t)$$

to give the correct distribution for any final state f (and independent of the details of the mixing) is

$$G \overset{\mathrm{def}}{\equiv} a^*(b+c) + d(b+c)^* = 0$$

Satisfied for $J/\Psi(3S) \to D^0\bar{D}^0$, or $\Upsilon(4S) \to B^0\bar{B}^0$ etc.

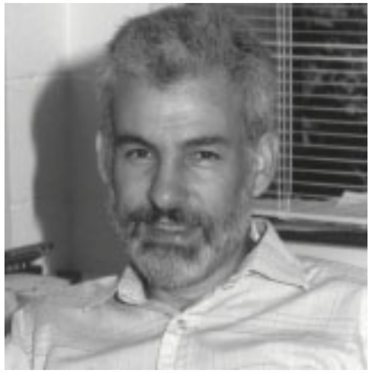
$B^0B^0 + B^0\overline{B}^0 + \overline{B}^0B^0 + \overline{B}^0\overline{B}^0$ does not satisfy

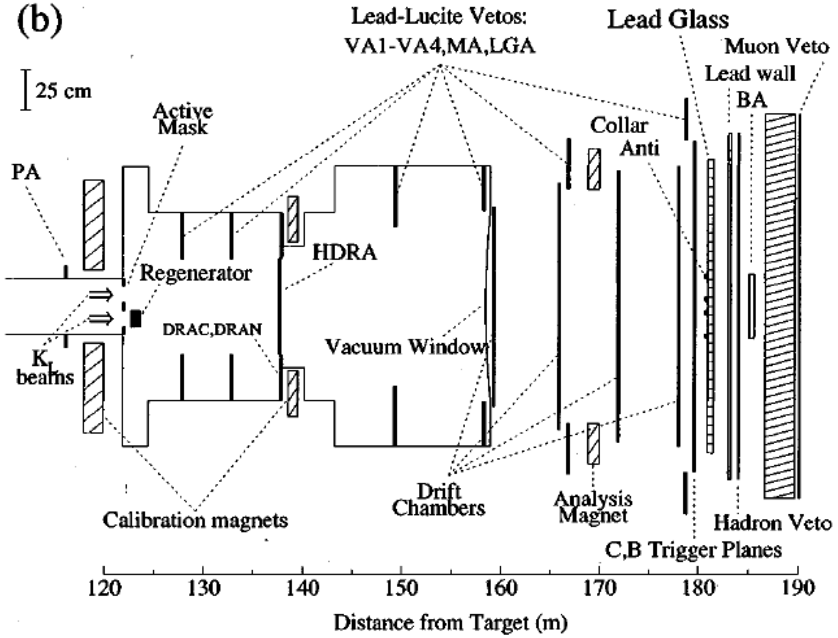
Φ Factory

- Proposed to use $\phi \rightarrow \mathrm{KK}$ to study CP violation in K decay (this had been proposed earlier by Kamae et al.)
- Bruce Winstein (U. of Chicago) was on sabbattical at SLAC, and we discussed Kaon experiments.
- It turned out that E731 (Bruce’s experiment) had already the amount of data that ϕ factory can collect in 10 years.
- So, I joined his group.

Fermilab E731: Direct CP Violation in K^0 System

PI: Bruce Winstein





Search for direct CP violation:

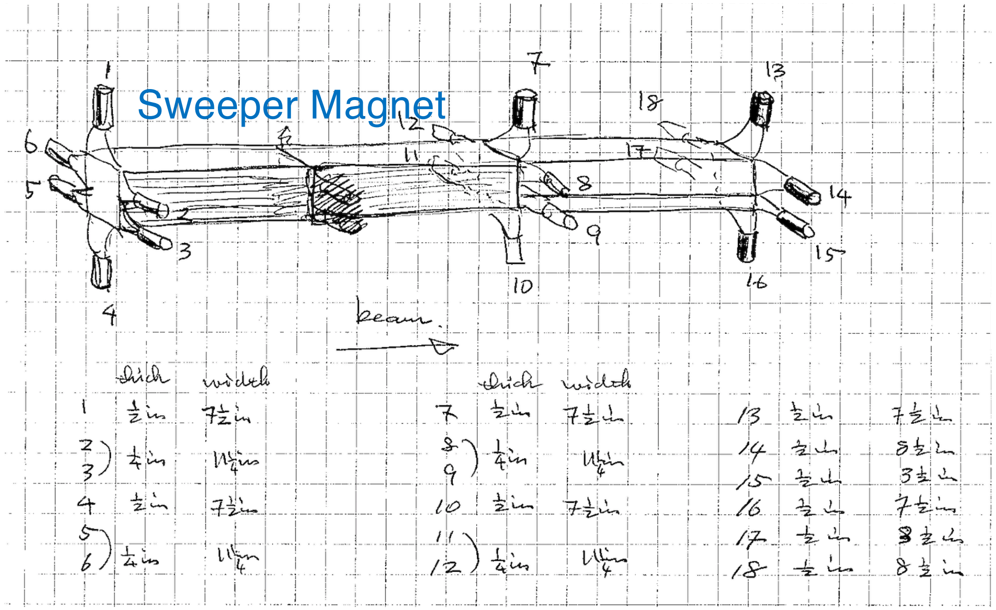
$$\frac{\Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)/\Gamma(K_L \to \pi^0\pi^0)} = 1 - 6Re\frac{\epsilon'}{\epsilon}$$

This ratio should be 1 if no direct CPV

Double K_L beam
Alternating regenerator

A key challenge: $K_L \to 3\pi^0$ background

Background from $K_L \rightarrow 3\pi^0$



	thick	width
1	½ in	7½ in
2 3	¼ in	11¼ in
4	½ in	7½ in
5 6	¼ in	11¼ in
7	½ in	7½ in
8 9	¼ in	11¼ in
10	½ in	7½ in
11 12	¼ in	11¼ in
13	½ in	7½ in
14	½ in	8½ in
15	½ in	3½ in
16	½ in	7½ in
17	½ in	8½ in
18	½ in	8½ in

A simulation study showed that $K_L \rightarrow 3\pi^0$ with photons lost in the sweeper magnet reconstructed as $K_L \rightarrow 2\pi^0$ reconstructed in the decay region.

Surround the vacuum pipe inside the sweeper magnet by scintillators.

- ✓ Photon will convert in the vacuum pipe.
- ✓ Need to protect PMT's from B field
  - 3 air gap layers with high mu cylinders

$K_L \rightarrow 3\pi^0$ background reduced by ½.

'Sweeper anti counter'
(or 'Super-nova anti'
- supernova 1987a)

Scattering in the Regenerator

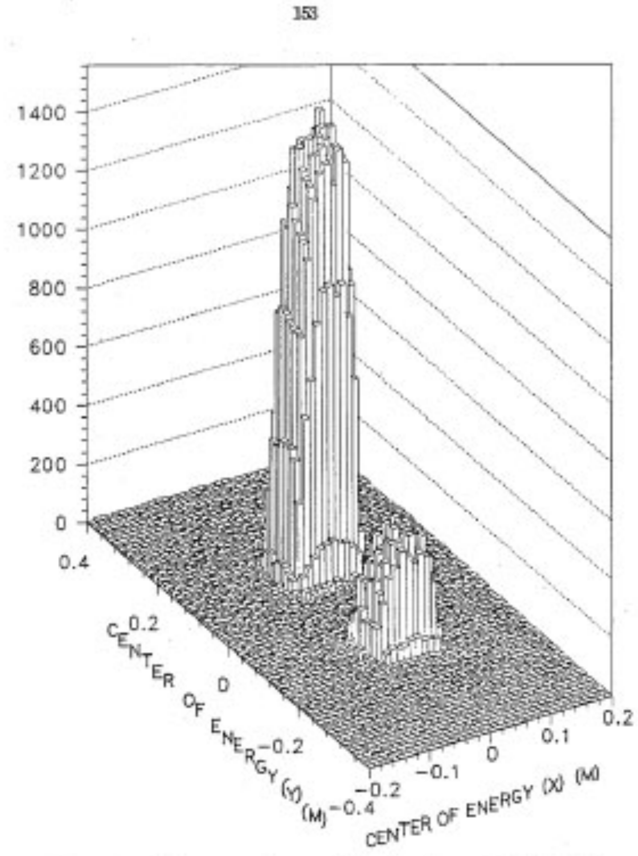
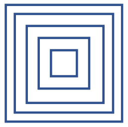
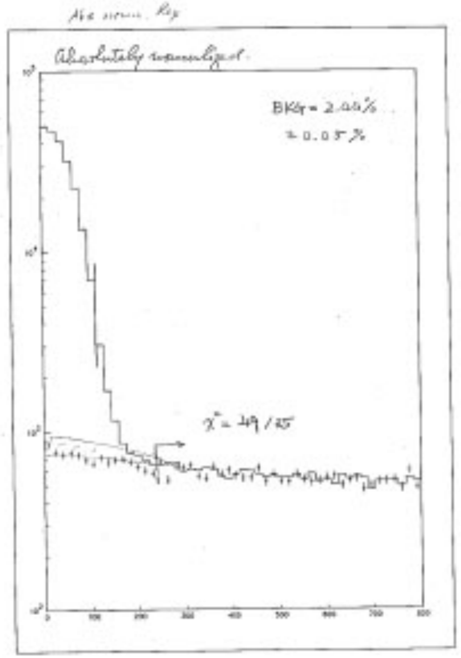


Figure 77. The center of energy of the four photons in the lead glass for reconstructed $\pi^0\pi^0$ decays which occurred while the regenerator lay in the upper beam.



ring number



ring number

Measure the scattering by $\pi^+\pi^-$ mode
and simulate it as $\pi^0\pi^0$ mode.

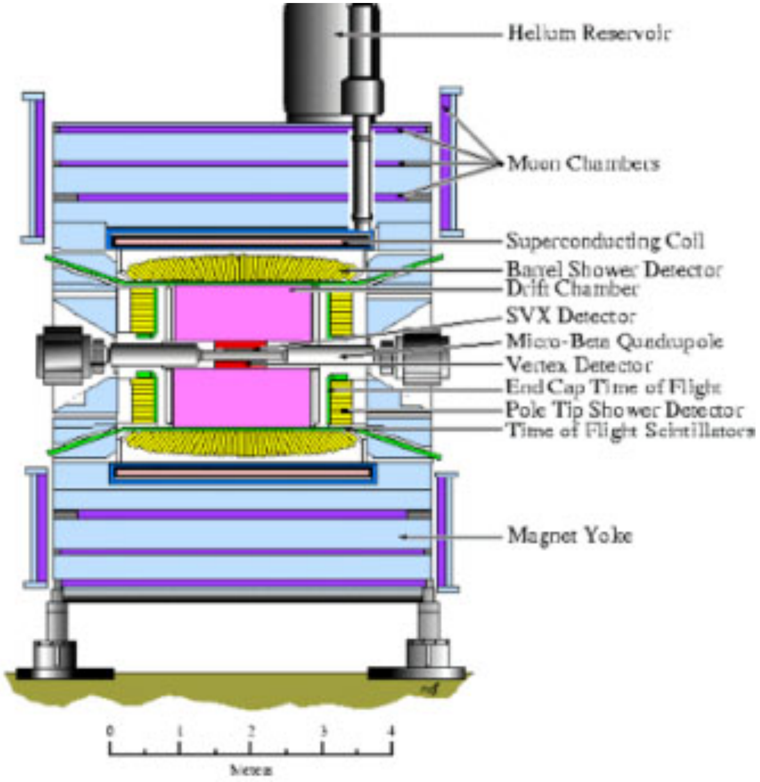
Agreed well with the tail in the ring number
(absolutely). No criticism from the competitor
Afterwards.

CLEO at CESR

(From Harvard University)

Cornell Electron Storage Ring (CESR)

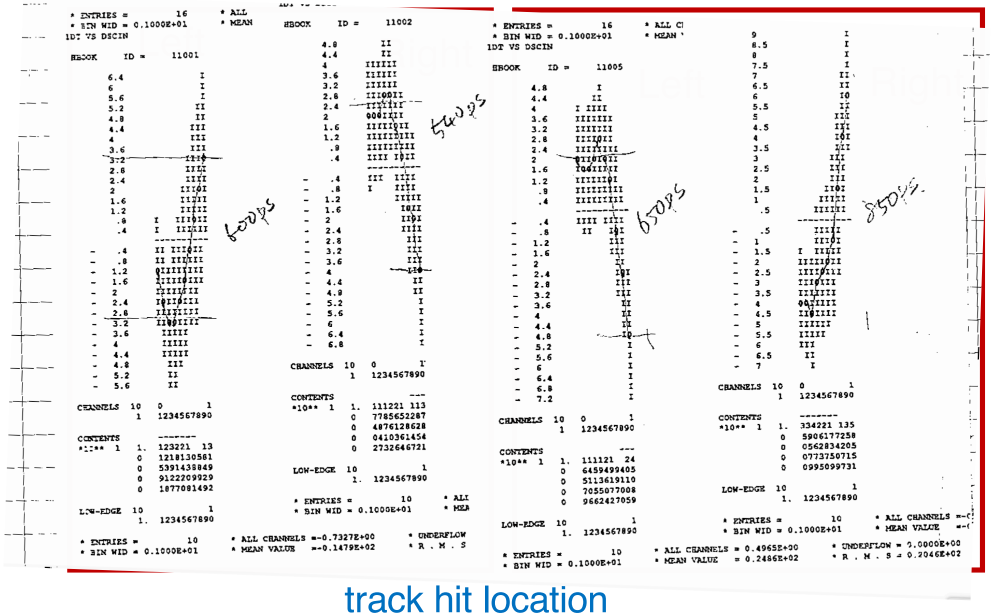
CLEO Detector



TOF Time Resolution Problem

TOF: responsibility of Harvard

Difference beween expected and actual times



track hit location

Some counters had very bad time resolution.

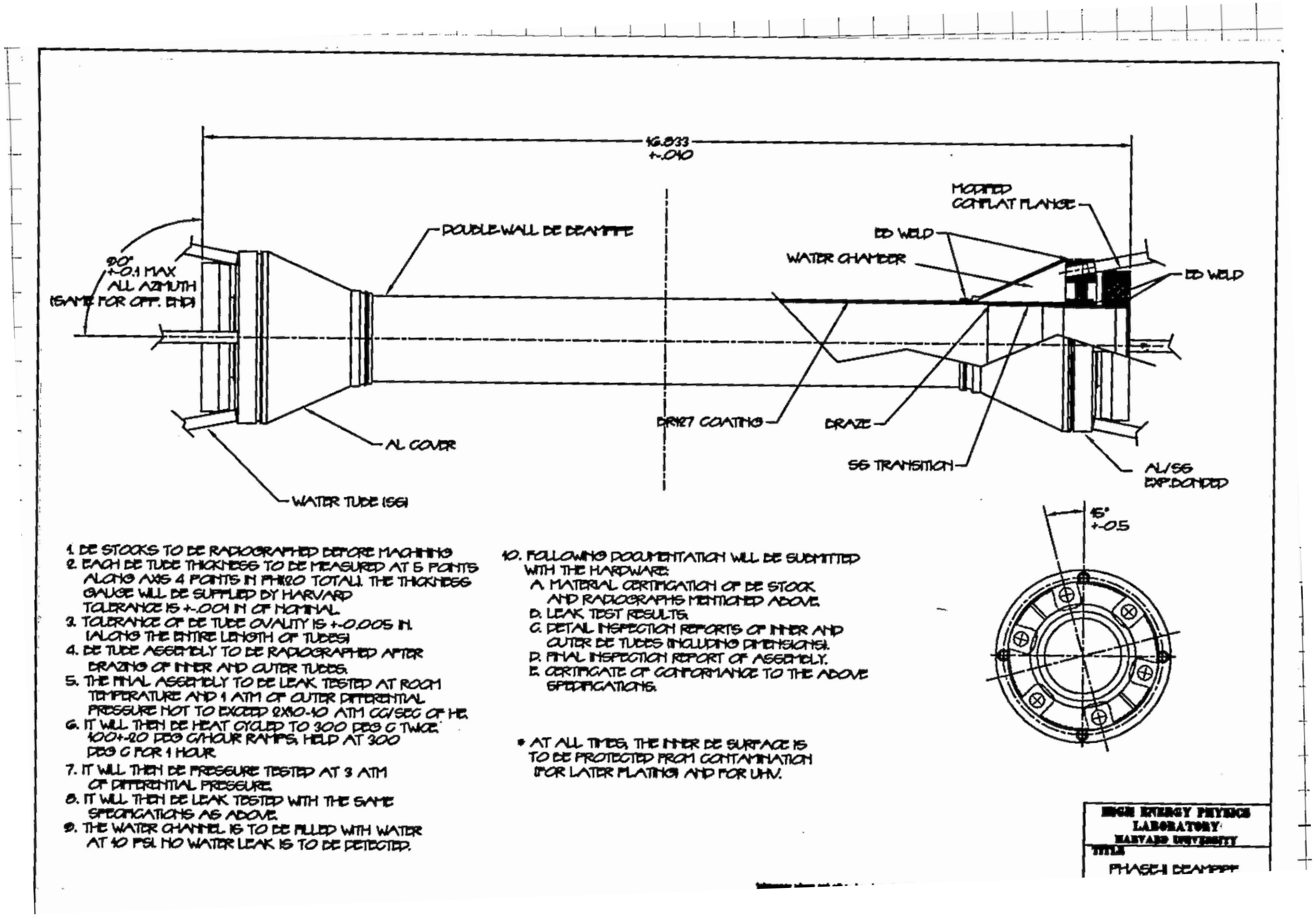
The pattern in the plots can be explained if One assumes that the speed of light is different for left and right directions.

This can happen if one side had broken joint for PMT.

Using different speed of light for left and right improved time resolution by factor of ~3. (~ 600ps → ~ 200 ps)

The analysis was complete ~1 week after I joined CLEO, and presented at a general CLEO meeting.

CLEO 1.5 IR Beampipe



1. BE STOCKS TO BE RADIOGRAPHED BEFORE MACHINING
2. EACH BE TUBE THICKNESS TO BE MEASURED AT 5 POINTS ALONG AXIS 4 POINTS IN PHI(20 TOTAL). THE THICKNESS GAUGE WILL BE SUPPLIED BY HARVARD TOLERANCE IS +-.001 IN OF NOMINAL.
3. TOLERANCE OF BE TUBE OVALITY IS +-0.005 IN. (ALONG THE ENTIRE LENGTH OF TUBES)
4. BE TUBE ASSEMBLY TO BE RADIOGRAPHED AFTER BRAZING OF INNER AND OUTER TUBES.
5. THE FINAL ASSEMBLY TO BE LEAK TESTED AT ROOM TEMPERATURE AND 1 ATM OF OUTER DIFFERENTIAL PRESSURE NOT TO EXCEED 2X10-10 ATM CC/SEC OF HE.
6. IT WILL THEN BE HEAT CYCLED TO 300 DEG C TWICE. 100+-20 DEG C/HOUR RAMPS, HELD AT 300 DEG C FOR 1 HOUR
7. IT WILL THEN BE PRESSURE TESTED AT 3 ATM OF DIFFERENTIAL PRESSURE.
8. IT WILL THEN BE LEAK TESTED WITH THE SAME SPECIFICATIONS AS ABOVE.
9. THE WATER CHANNEL IS TO BE FILLED WITH WATER AT 10 PSI. NO WATER LEAK IS TO BE DETECTED.
10. FOLLOWING DOCUMENTATION WILL BE SUBMITTED WITH THE HARDWARE:
    A. MATERIAL CERTIFICATION OF BE STOCK AND RADIOGRAPHS MENTIONED ABOVE.
    B. LEAK TEST RESULTS.
    C. DETAIL INSPECTION REPORTS OF INNER AND OUTER BE TUBES (INCLUDING DIMENSIONS).
    D. FINAL INSPECTION REPORT OF ASSEMBLY.
    E. CERTIFICATE OF CONFORMANCE TO THE ABOVE SPECIFICATIONS.

* AT ALL TIMES, THE INNER BE SURFACE IS TO BE PROTECTED FROM CONTAMINATION (FOR LATER PLATING) AND FOR UHV.

HIGH ENERGY PHYSICS
LABORATORY
HARVARD UNIVERSITY
TITLE
PHASE-II BEAMPIPE

Designed for heating
from inside = 400 W

First double-wall Be beampipe.
Became the standard for
B-factories later.

Water coolant.

No vacuum-to-liquid joints
- Electron beam welding
- Brazing

Au coated inside for X-ray blocking.

Heavy masks on both sides of this beampipe for particle background

Beam Background Studies

Two Harvard postdocs

SR Background

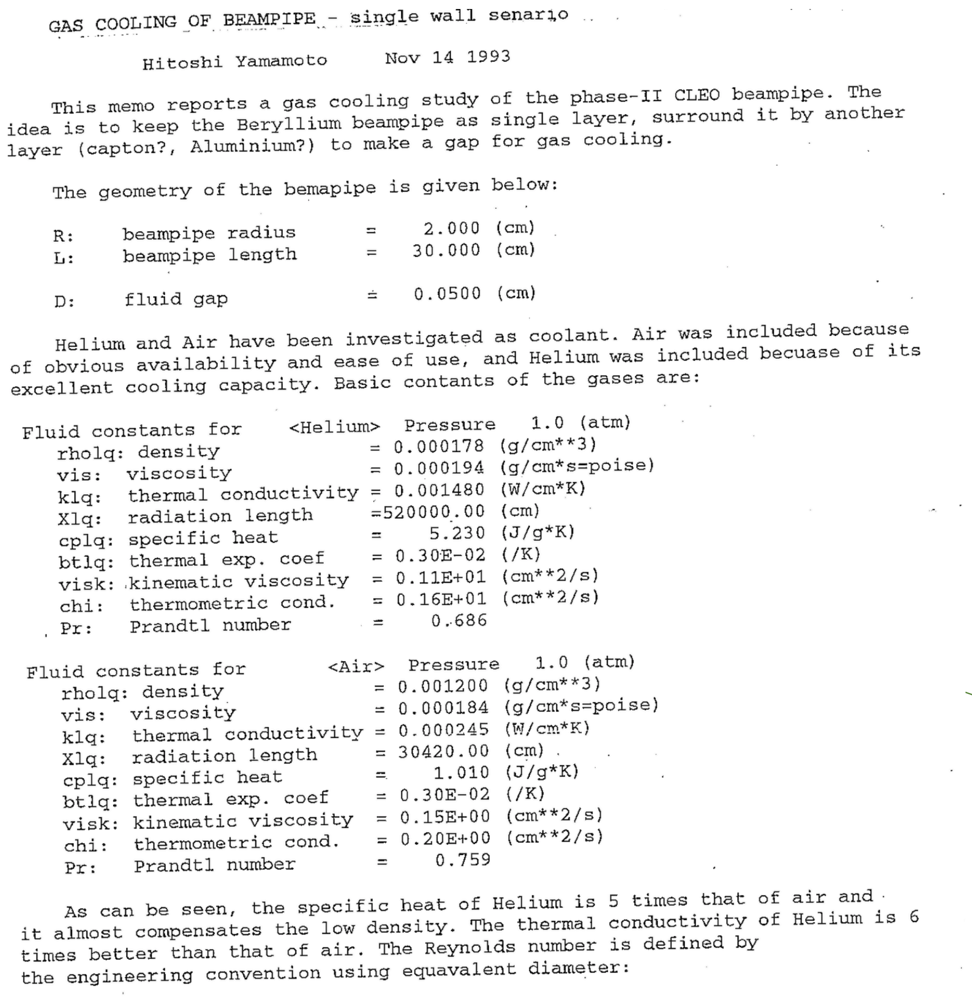
Stu Henderson

→ Cornell accelerator physics
→ SNS
→ Director, Fermilab accelerator division
→ Director, Jefferson lab

Particle Background

Dave Cinabro

→ Professor at Wane State University



GAS COOLING OF BEAMPIPE - single wall senario

Hitoshi Yamamoto Nov 14 1993

This memo reports a gas cooling study of the phase-II CLEO beampipe. The idea is to keep the Beryllium beampipe as single layer, surround it by another layer (capton?, Aluminium?) to make a gap for gas cooling.

The geometry of the bemapipe is given below:

```
R:   beampipe radius      =    2.000 (cm)
L:   beampipe length      =   30.000 (cm)

D:   fluid gap            =    0.0500 (cm)
```

Helium and Air have been investigated as coolant. Air was included because of obvious availability and ease of use, and Helium was included becuase of its excellent cooling capacity. Basic contants of the gases are:

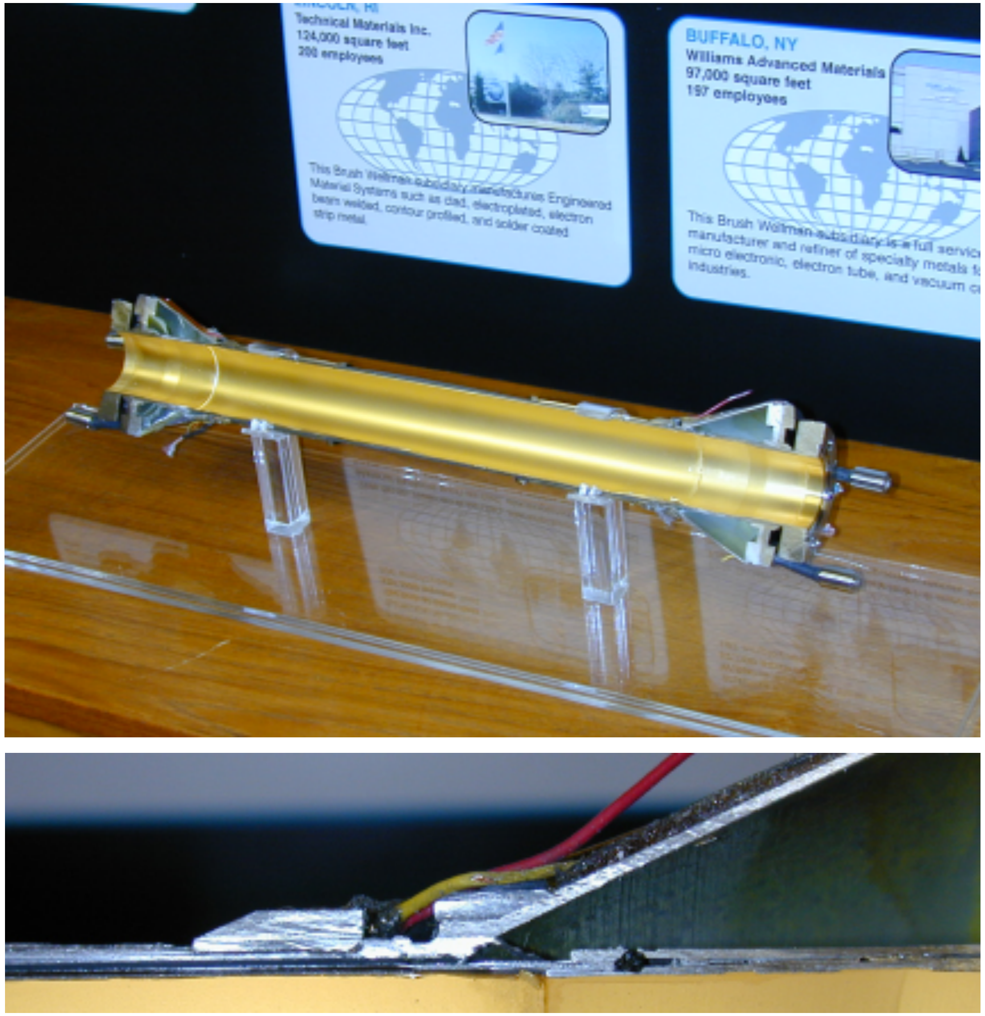
```
Fluid constants for    <Helium>  Pressure   1.0 (atm)
   rholq: density              = 0.000178 (g/cm**3)
   vis:   viscosity            = 0.000194 (g/cm*s=poise)
   klq:   thermal conductivity = 0.001480 (W/cm*K)
   Xlq:   radiation length     =520000.00 (cm)
   cplq:  specific heat        =    5.230 (J/g*K)
   btlq:  thermal exp. coef    = 0.30E-02 (/K)
   visk:  kinematic viscosity  = 0.11E+01 (cm**2/s)
   chi:   thermometric cond.   = 0.16E+01 (cm**2/s)
   Pr:    Prandtl number       =    0.686

Fluid constants for       <Air>  Pressure   1.0 (atm)
   rholq: density              = 0.001200 (g/cm**3)
   vis:   viscosity            = 0.000184 (g/cm*s=poise)
   klq:   thermal conductivity = 0.000245 (W/cm*K)
   Xlq:   radiation length     = 30420.00 (cm)
   cplq:  specific heat        =    1.010 (J/g*K)
   btlq:  thermal exp. coef    = 0.30E-02 (/K)
   visk:  kinematic viscosity  = 0.15E+00 (cm**2/s)
   chi:   thermometric cond.   = 0.20E+00 (cm**2/s)
   Pr:    Prandtl number       =    0.759
```

As can be seen, the specific heat of Helium is 5 times that of air and it almost compensates the low density. The thermal conductivity of Helium is 6 times better than that of air. The Reynolds number is defined by the engineering convention using equavalent diameter:

Cautious attitudes at Cornell Accelerator division regarding the double-wall design with liquid cooling.

Analysis of single-wall gas cooling
That showed problems



~10 years later:
CESR Exhibition room

Lecture on Quantum Field Theory

- Given at Harvard University Graduate School 1993 – 1998.
- Lectures based on the above was also given at Univeristy of Hawaii and at Tohoku University.
- Tohoku U. ‘Advanced High Energy Physics (IGPAS)’ (高エネルギー物理学特論） and ‘Science of Particle-Matter Hierarchy’（物質階層融合科学特論).

- The lecture note is to be published by Gordon and Breach as ‘Introduction to Quantum Field Theory and Applications to Particle Physics’.

Phases of Discrete Symmetries

- C, P, T Symmetries -

$$\begin{aligned}
\phi(x) &= \sum_{\vec{p}} \left(a_{n\vec{p}}\, e_{\vec{p}}(x) + a^{\dagger}_{\bar{n}\vec{p}}\, e^{*}_{\vec{p}}(x) \right) && \text{(spin 0)} \\
\psi(x) &= \sum_{\vec{p},\sigma} \left(a_{n\vec{p}\sigma}\, f_{\vec{p}\sigma}(x) + a^{\dagger}_{\bar{n}\vec{p}\sigma} g_{\vec{p}\sigma}(x) \right) && \text{(spin 1/2)} \\
A^{\mu}(x) &= \sum_{\vec{p},\sigma} \left(a_{n\vec{p}\sigma} \epsilon^{\mu}_{\vec{p}\sigma} e_{\vec{p}}(x) + a^{\dagger}_{\bar{n}\vec{p}\sigma} \epsilon^{\mu *}_{\vec{p}\sigma} e^{*}_{\vec{p}}(x) \right) && \text{(spin 1)}
\end{aligned}$$

$$e_{\vec{p}}(x) \equiv \frac{e^{-ip\cdot x}}{\sqrt{2p^{0}V}}\,, \quad f_{\vec{p}\sigma} \equiv u_{\vec{p}\sigma} e_{\vec{p}}(x)\,, \quad g_{\vec{p}\sigma} \equiv v_{\vec{p}\sigma} e^{*}_{\vec{p}}(x)\,.$$

$$\mathcal{P} a^{\dagger}_{n\vec{p}\sigma} \mathcal{P}^{\dagger} = \eta_{n\vec{p}\sigma}\, a^{\dagger}_{n\,-\vec{p}\,\sigma} \quad \xrightarrow{\text{take}\,\dagger} \quad \mathcal{P} a_{n\vec{p}\sigma} \mathcal{P}^{\dagger} = \eta^{*}_{n\vec{p}\sigma}\, a_{n\,-\vec{p}\,\sigma}\,.$$

Arbitrary phase depending on
particle type (n), momentum (p) and spin (σ).
Defines the parity operator P in Hilbert space.
Can they be taken such that P commutes with S operator?

Choice of Parity Phase

In order for the interactions such as

$$h_{QED} = \int d^3x\, \bar{\psi}\gamma^\mu\psi\, A_\mu \qquad\qquad h_Y = \int d^3x\, \bar{\psi}\psi\, \phi$$

to commute with P, the phases should satisfy

$$\boxed{\begin{array}{rcll} \mathcal{P}\phi(x)\mathcal{P}^\dagger & = & \eta_n^*\phi(Px) & (\mathrm{spin}-0) \\ \mathcal{P}\psi(x)\mathcal{P}^\dagger & = & \eta_n^*\gamma^0\psi(Px) & (\mathrm{spin}-\frac{1}{2}) \\ \mathcal{P}A_\mu(x)\mathcal{P}^\dagger & = & -\eta_n^*A^\mu(Px) & (\mathrm{spin}-1) \\ \eta_{\bar{n}} & = & \eta_n^* & (\mathrm{spin}-0,1) \\ \eta_{\bar{n}} & = & -\eta_n^* & (\mathrm{spin}-\frac{1}{2}) \end{array}}$$

(first, they should not depend on p and σ)

Are interactions essential?

open E-mail discussion with Weinberg

Space-Time and Spinor Space

space	Lorentz transformation	inner product	metric invariance
space-time	$A' = \Lambda A$	$A \cdot B \equiv A^T G B$	$\Lambda^T G \Lambda = G$
spinor	$a' = Sa$	$\bar{a}b \equiv a^\dagger \gamma^0 b$	$S^\dagger \gamma^0 S = \gamma^0$

Table 3.1: Correspondence between the space-time and the spinor space. A and B are 4-vectors and a and b are 4-component spinors.

Antilinear Operator (T etc.)

The Dirac's bra-ket notation of a matrix element $\langle a|O|b\rangle$ assumes an associativity:

$$(\langle a|O)\,|b\rangle = \langle a|\,(O|b\rangle)\,. \tag{8.296}$$

Together with the rule that $\langle a|O$ is the adjoint of $O^\dagger|a\rangle$, this reads

$$(O^\dagger a, b) = (a, Ob)\,, \tag{8.297}$$

which is nothing but the definition of adjoint operator (8.266). Thus, the Dirac's bra-ket notation naturally assumes that the operator is linear and using the bra-ket notation to antilinear operators causes confusions when inner products are involved.

Antilinear Operator (T etc.)

Formalism by Inner Products

A linear operator O is defined by

$$O(a_1\Psi_1 + a_2\Psi_2) = a_1 O\Psi_1 + a_2 O\Psi_2 \qquad (O: \text{ linear}) \tag{8.265}$$

for any states Ψ_1 and Ψ_2. The adjoint or the hermitian conjugate of O, denoted as $O^\dagger$, is defined to be the operator that satisfies

$$(\Psi, O^\dagger\Phi) = (O\Psi, \Phi) \quad \text{for any } \Psi, \Phi\,; \tag{8.266}$$

namely, when a linear operator is moved from the first state to the second, it picks up the dagger sign. As defined earlier in (8.242), an antilinear operator A satisfies

$$A(a_1\Psi_1 + a_2\Psi_2) = a_1^* A\Psi_1 + a_2^* A\Psi_2 \qquad (A: \text{ antilinear})\,. \tag{8.267}$$

Then, the product of an antilinear operator and a linear operator is antilinear:

$$\begin{aligned} AO(a_1\Psi_1 + a_2\Psi_2) &= A(a_1 O\Psi_1 + a_2 O\Psi_2) \\ &= a_1^* AO\Psi_1 + a_2^* AO\Psi_2\,. \end{aligned} \tag{8.268}$$

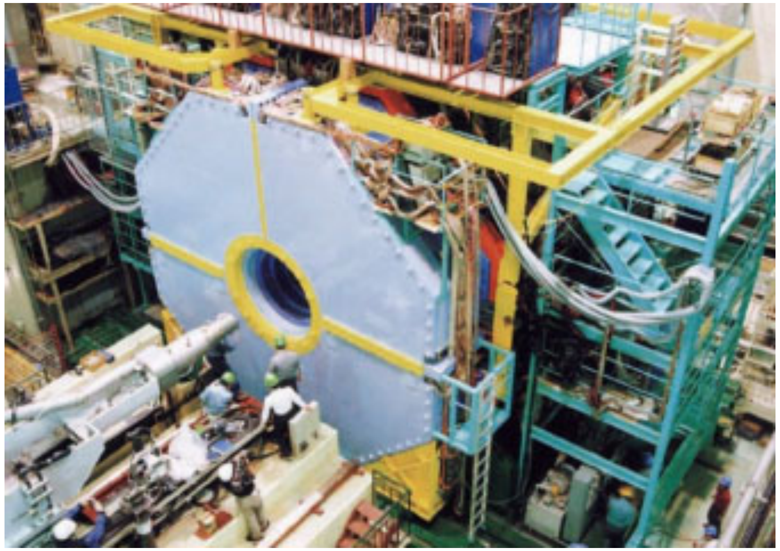
Similarly, the product of two antilinear operators is linear.

The definition of the adjoint operator (8.266) is not self-consistent for an antilinear operator as we will see below. For an antilinear operator A, suppose there exists an operator $A^\dagger$ that satisfies

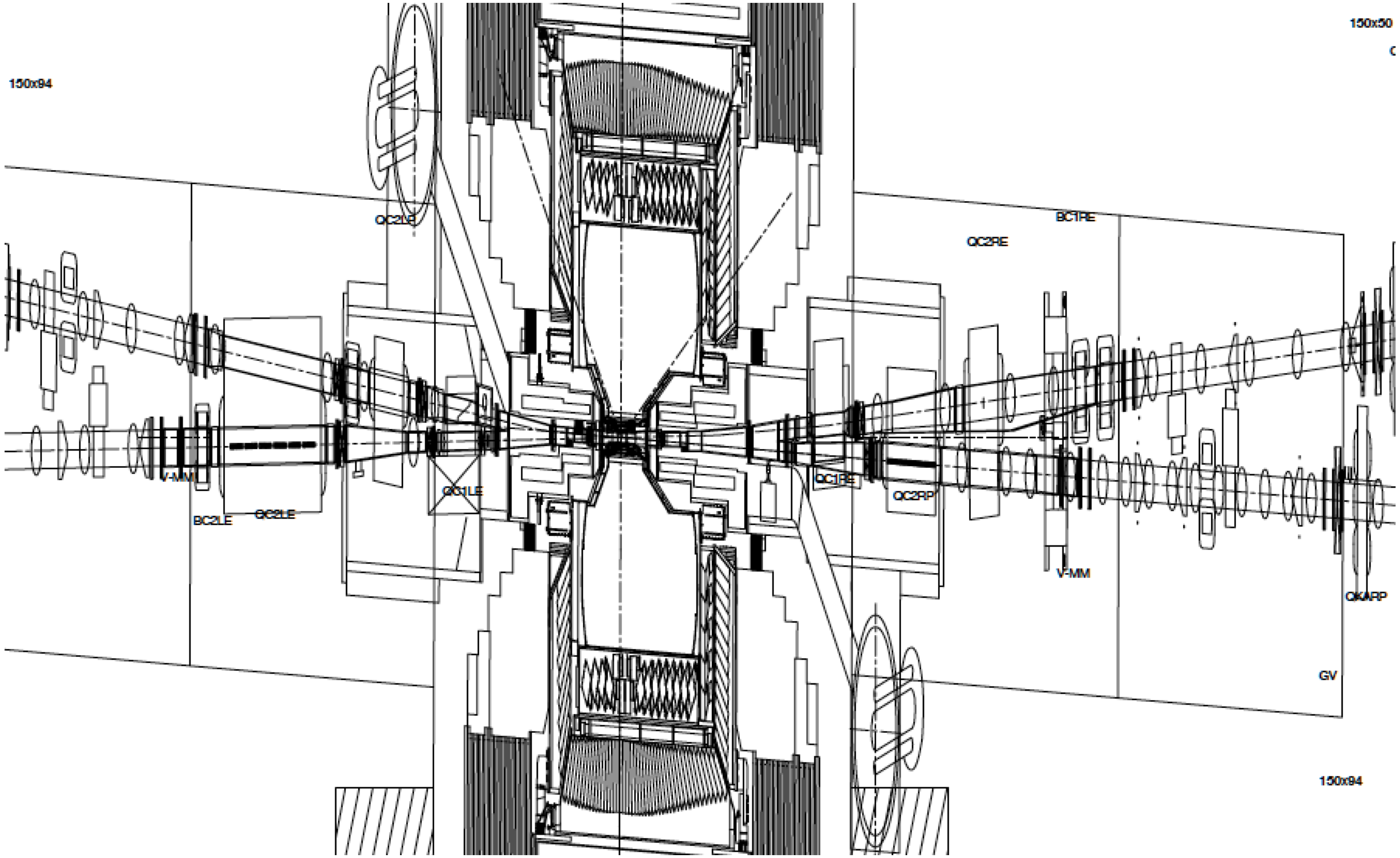
KEK B-Factory and Belle Detector

KEK B-Factory

Belle Detector

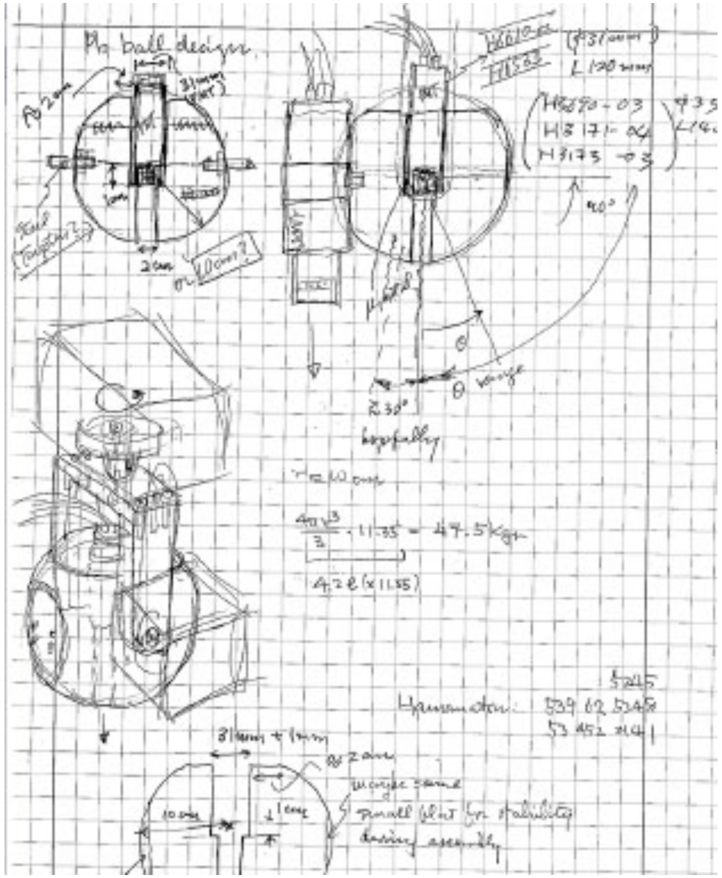


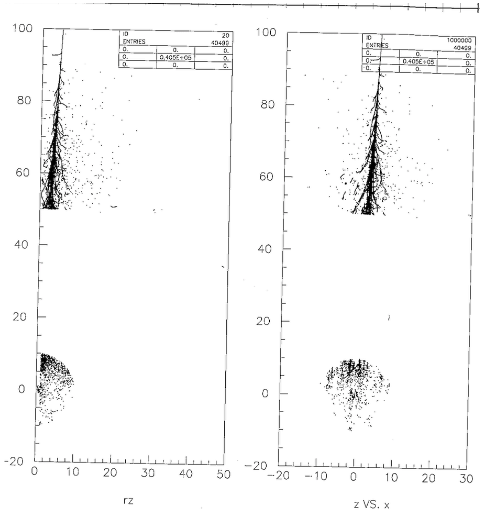
MDI and Beam Backgrounds

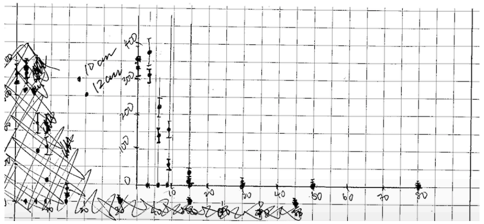


StarBall (or ‘Star Wars’)

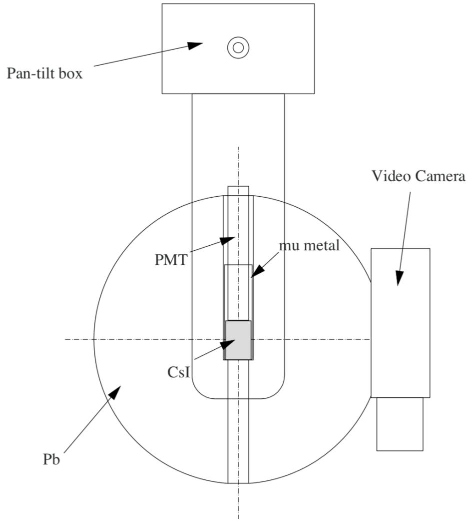
Beam background hot spot explorer







STARBALL

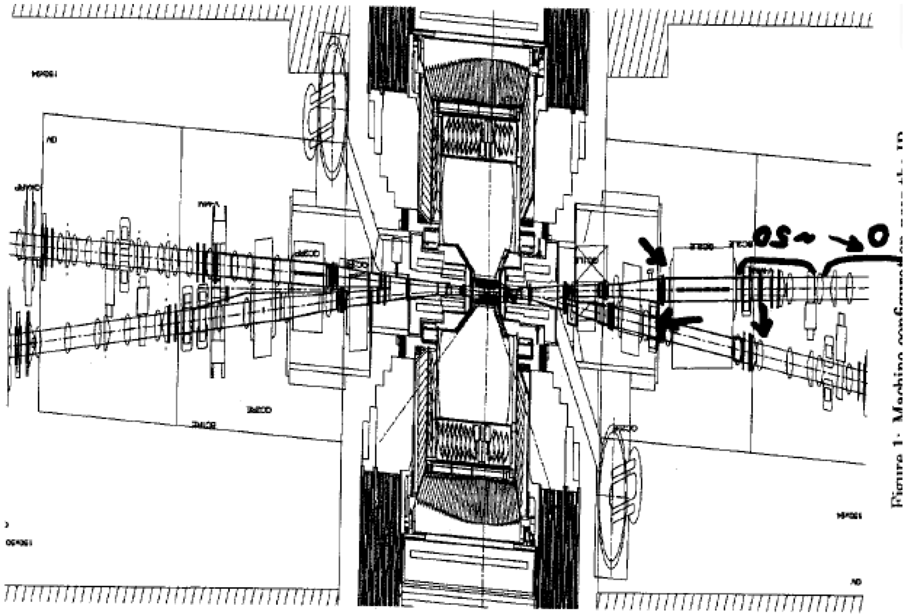


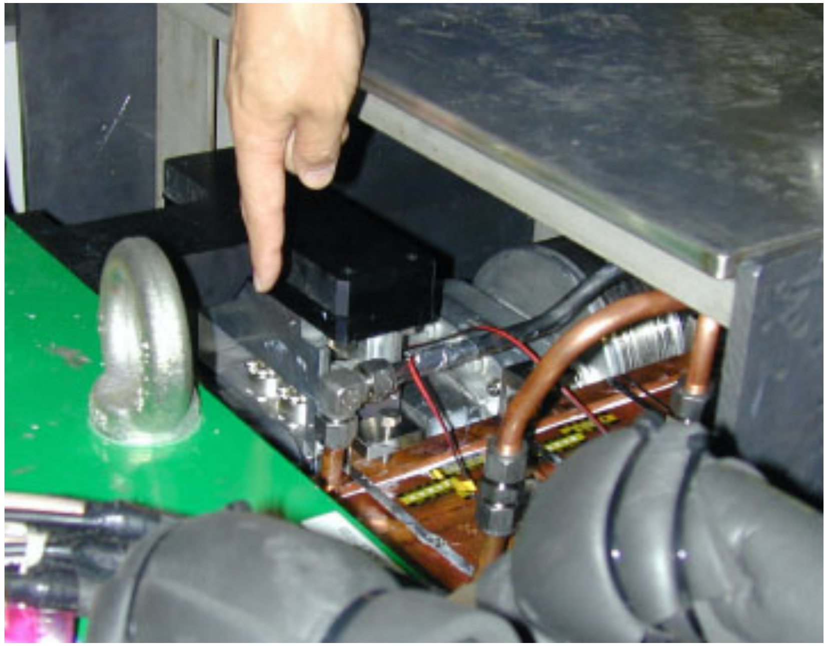
Hung from the crane and runs along the beamline.

Directional resolution:
R = 12 cm is much better
Than R = 10 cm

StarBall (or ‘Star Wars’)

Identified a few hot spots





Death of SVD (silicon vertex detector) Layer 1

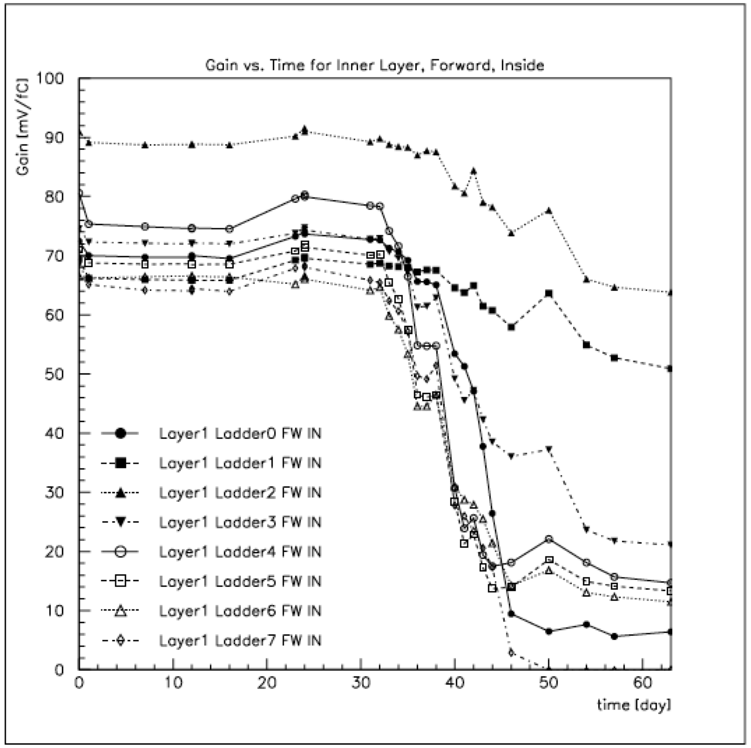


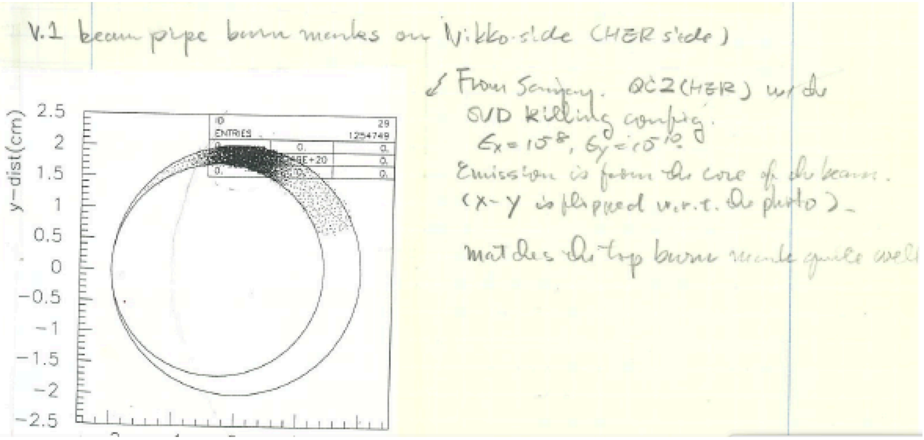
Figure 4: SVD gain vs time during summer 1999.

In 1999, in a matter of a week,
Most of the SVD layer 1 has ’died’.

What killed SVD?

SR or particles?

The IR beampipe shows that the problem is clearly SR

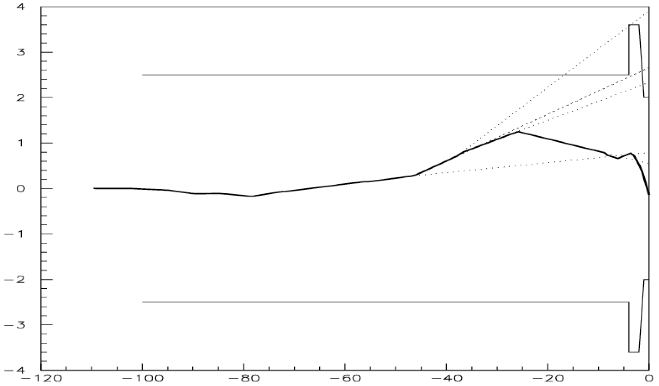


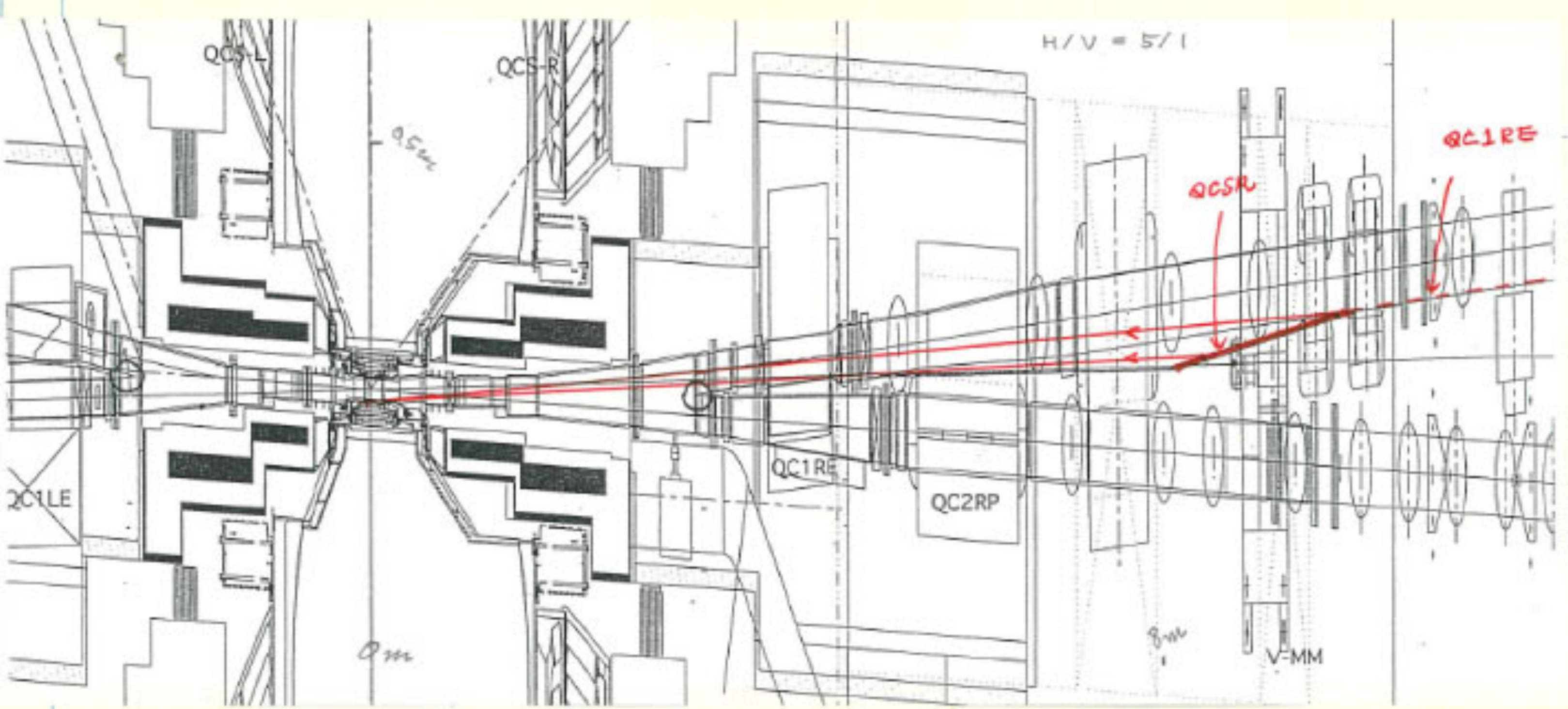
V.1 beam pipe burn marks on Nikko side (HER side)

✓ From Sanjay. QC2 (HER) w/ the SVD killing config.
$\epsilon_x = 15^{8}, \epsilon_y = 10^{10}$.
Emission is from the core of the beam.
(x-y is flipped w.r.t. the photo).

matches the top burn mark quite well

Beam steering can place the beam in a dangerous configuration



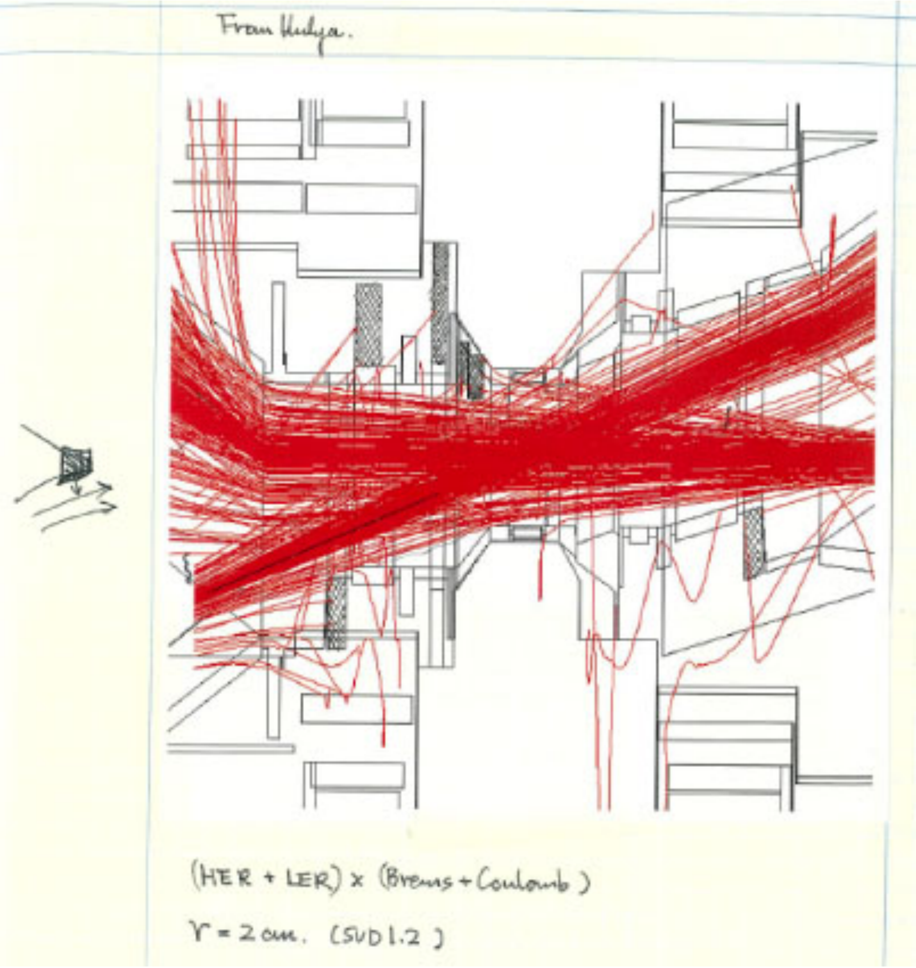


Most of the area shined by QCSR(E) is in sight of Be beampipe.
The backscattering angle is ~ 0.057 radians. (3.3°)

SR power from QC1RE is also substantial. θ is comparable to QCSR

$P \propto \frac{\theta^2}{L}$ $L(\text{QC1RE}) \sim 0.8$ m   Power ~ $\frac{1}{2}$ of QCSR.

Particle Background Study



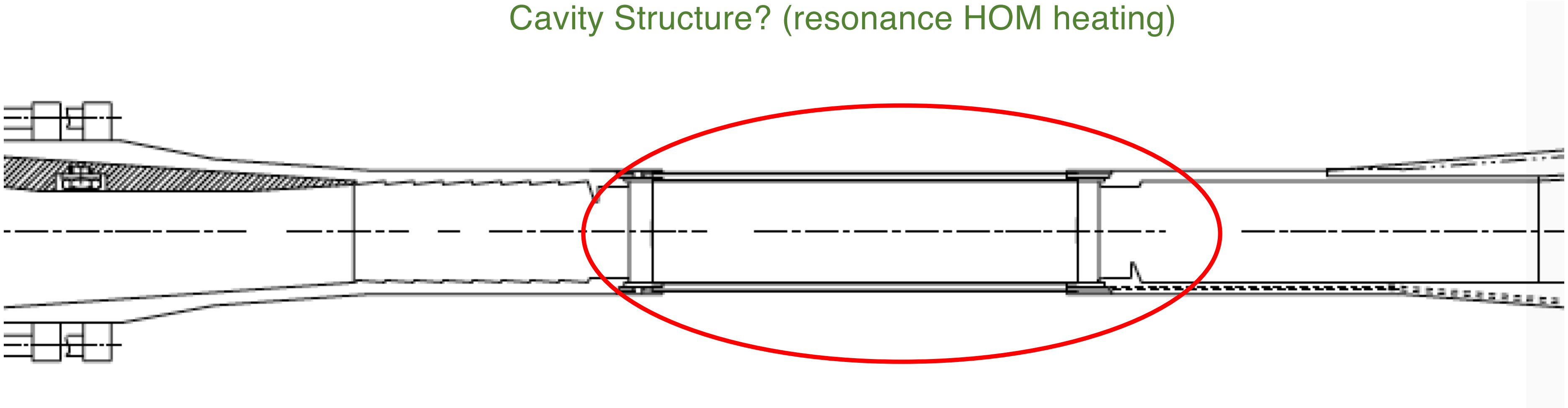
From Hulya.

(HER + LER) x (Brems + Coulomb)

r = 2 cm. (SVD 1.2)

Hulya Guler

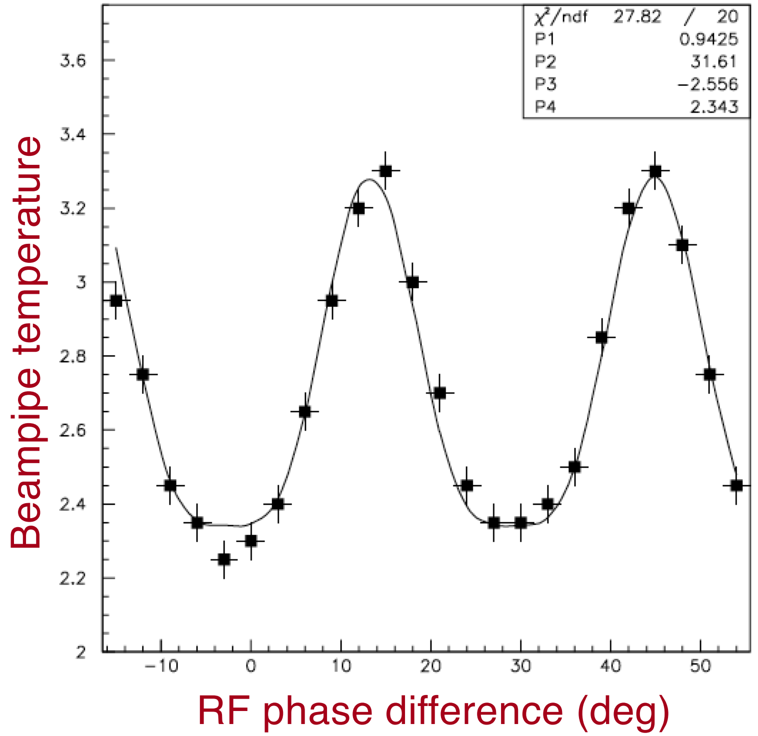
SVD 1.0 IR Beampipe



Cavity Structure? (resonance HOM heating)

HOM Resonance Study

$e+/e-$ RF phase-shift study



Period = 31.61° (TM011: 31.54° expected)

When the time difference of e+ and e- bunches is integer times the HOM resonance period, a resonance can be excited.

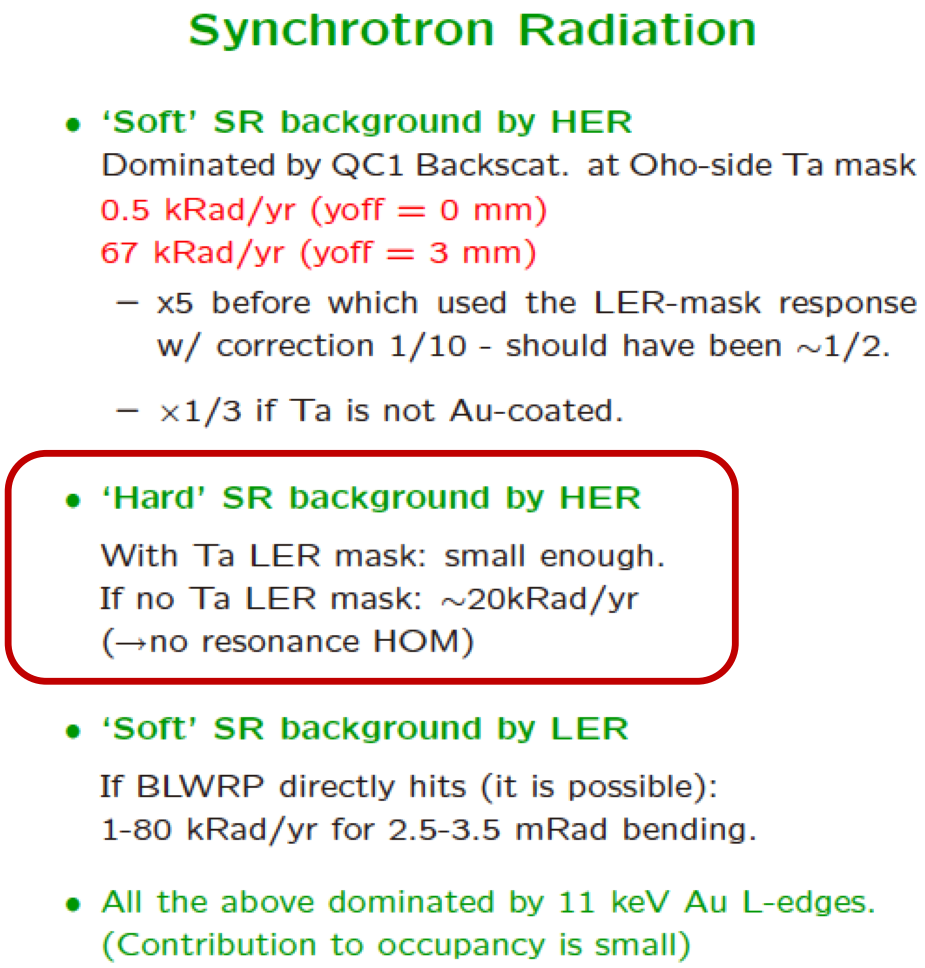
HOM resonance as expected from geometry is observed.

Can the LER Ta mask be removed?

SR Background

Sanjay Swain

Grad. student at Hawaii →
Associate prof. at INISER India



Synchrotron Radiation

- **‘Soft’ SR background by HER**
  Dominated by QC1 Backscat. at Oho-side Ta mask
  0.5 kRad/yr (yoff = 0 mm)
  67 kRad/yr (yoff = 3 mm)
  - x5 before which used the LER-mask response w/ correction 1/10 - should have been ~1/2.
  - ×1/3 if Ta is not Au-coated.
- **‘Hard’ SR background by HER**
  With Ta LER mask: small enough.
  If no Ta LER mask: ~20kRad/yr
  (→no resonance HOM)
- **‘Soft’ SR background by LER**
  If BLWRP directly hits (it is possible):
  1-80 kRad/yr for 2.5-3.5 mRad bending.
- All the above dominated by 11 keV Au L-edges.
  (Contribution to occupancy is small)

Particle Background

Karim Trabelsi

Postdoc at Hawaii → KEK
→ LAL Orsay research director

Unit = kRad/yr (1yr = 10^7 sec)
(1.1A/2.6A, 1nTorr CO)

Data: SVD lyr 1

	dose
HER	24 kRad/yr
LER	82 kRad/yr

MC: SVD ly1 1

LER Particles entering GEANT just outside of b.p.
depends strongly on materials around b.p.
The numbers in (), such contributions set to 0.

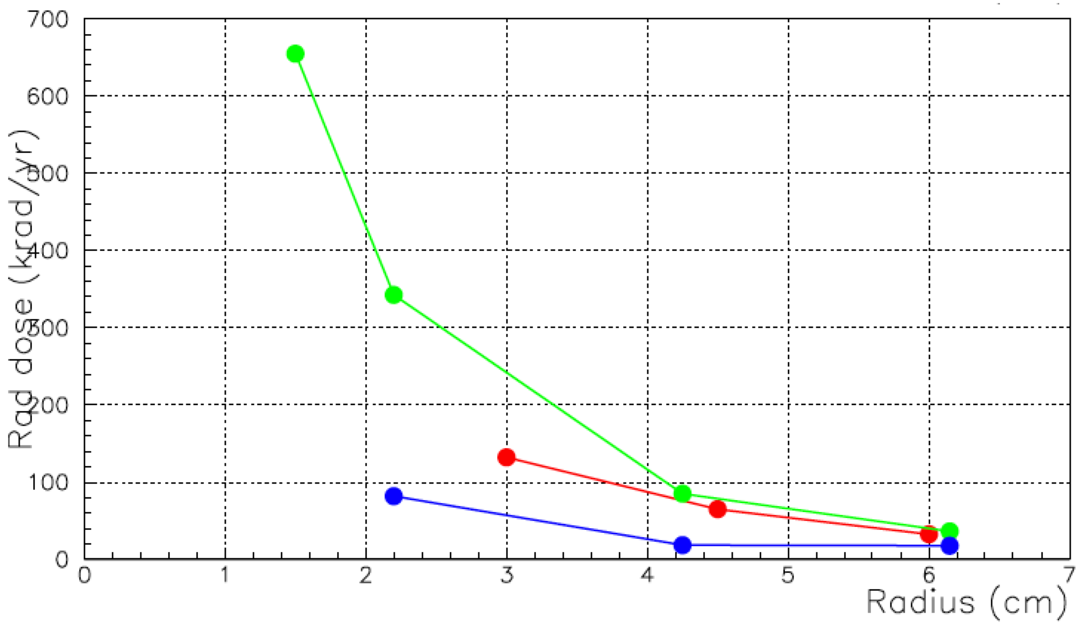
	Brem/Coul	Touschek	total
HER	40.5	-	40.5
LER	35.2(23.3)	56.5(6.5)	91.7(29.8)

Data/MC agreement is resonable.

What Beampipe Radius to Take?

- ● SVD1.4 (r=2cm) Old design
- ● SVD2.0 (r=1.5cm)
- ● SVD2.0 (r=1cm)

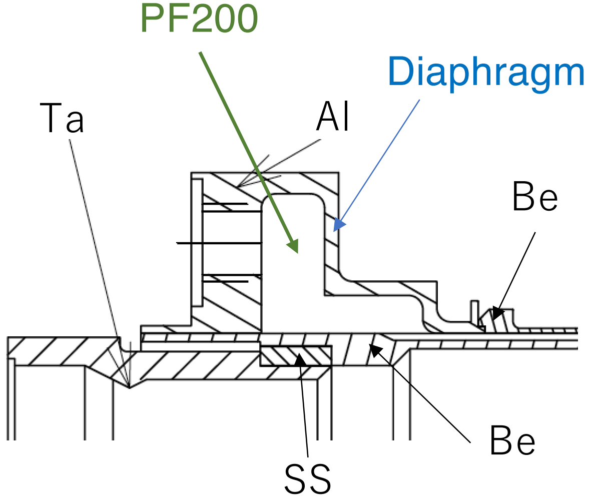
Which one to take?



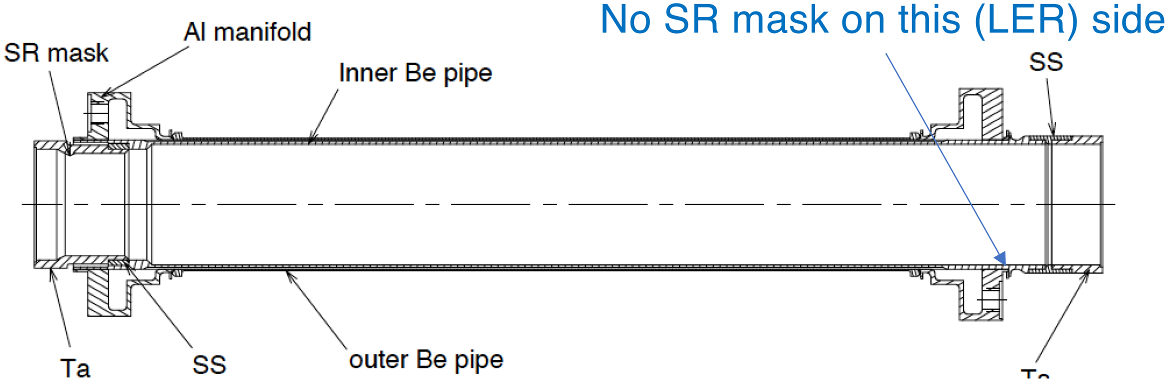
HY: ‘You should not trust this study
- I mean there is a range of uncertainty’

R = 1.5 cm was taken in the end.

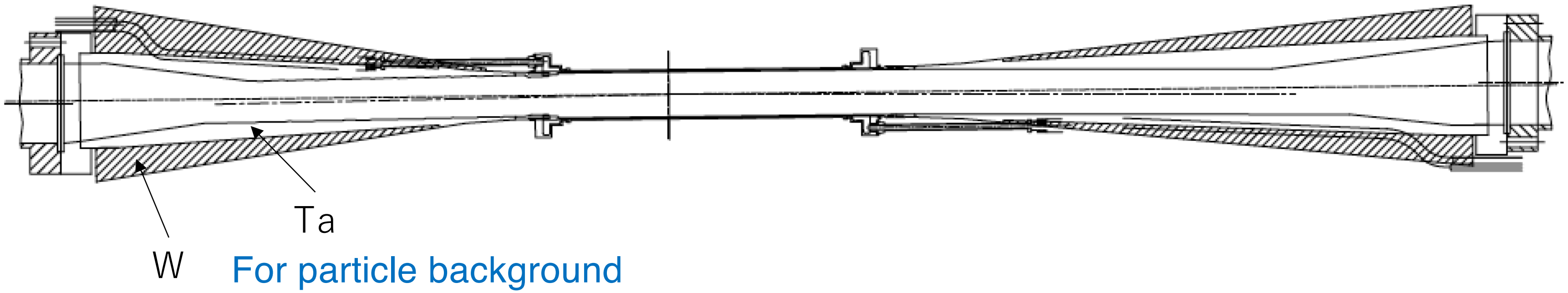
Belle SVD2.0 Beampipe



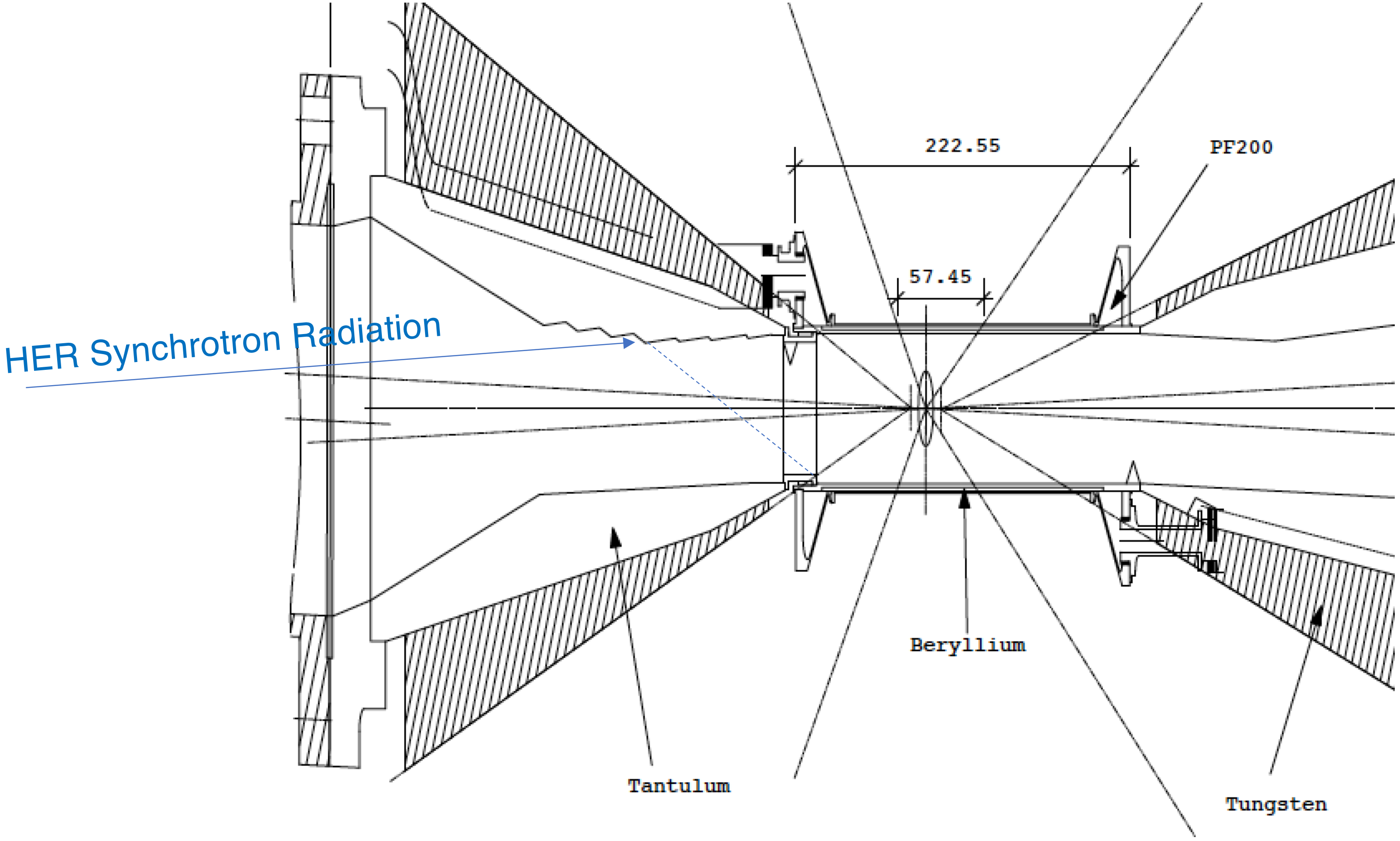
Diaphragm structure



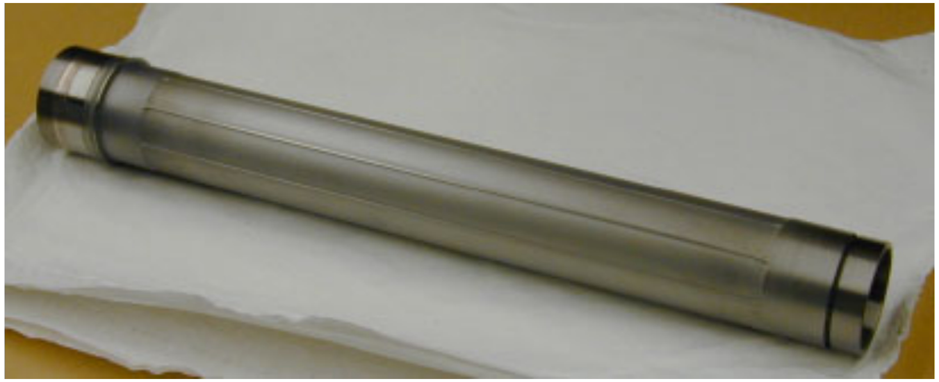
No SR mask on this (LER) side



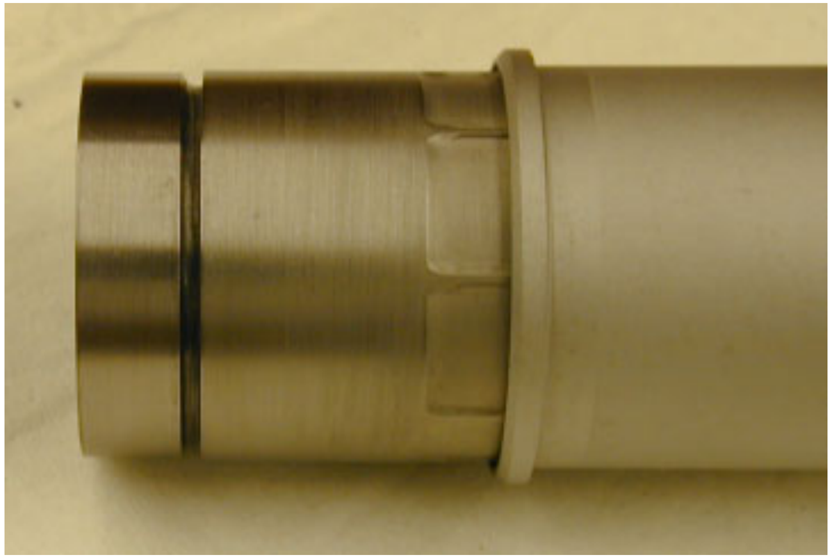
For particle background


HER Synchrotron Radiation
222.55
PF200
57.45
Beryllium
Tantulum
Tungsten

Inner cylinder

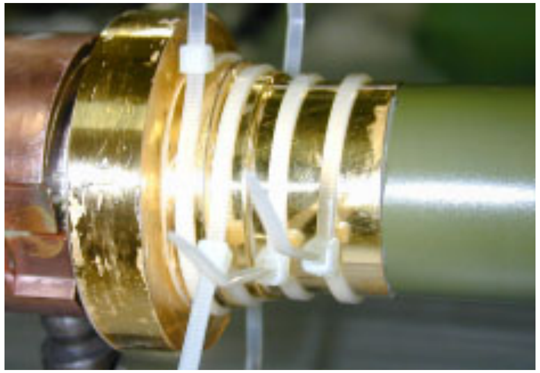


Inner and outer cylinders



Gold coating

Completed Belle SVD2.0 Beampipe



Gold sheets and BR127 coating

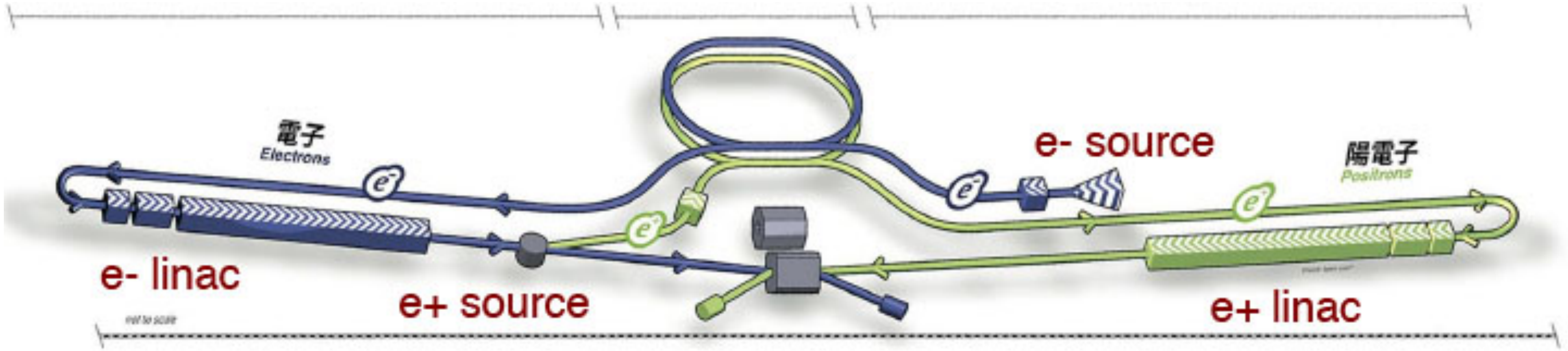
2 beampipes made
~4000 万円 each

He leak test

After 2001, SR study is handed over to
Tesuo Abe – A postdoc of Tohoku U.

2nd victim of our MDI effort to move to accelerator
(1st is Stu Henderson)
Now a associate professor in accelerator
physics at KEK, an expert in RF design.

International Linear Collider



TDR ‘Baseline’:

- Ecm = 500 GeV
- Polarization (e+/e-) = ±0.3/±0.8
- 2x10^{10} particles/bunch, 1312 bunch/train, train: 5 Hz
- Wall plug power = 163 MW

Starts as a Ecm = 250 GeV Higgs Factory

ILC Organization for Physics/Detecor

Worldwide Study (later under Research Directorate)

Asia:	HY
Europe:	David Miller → Juan Fuster
North Americas:	Jim Brau

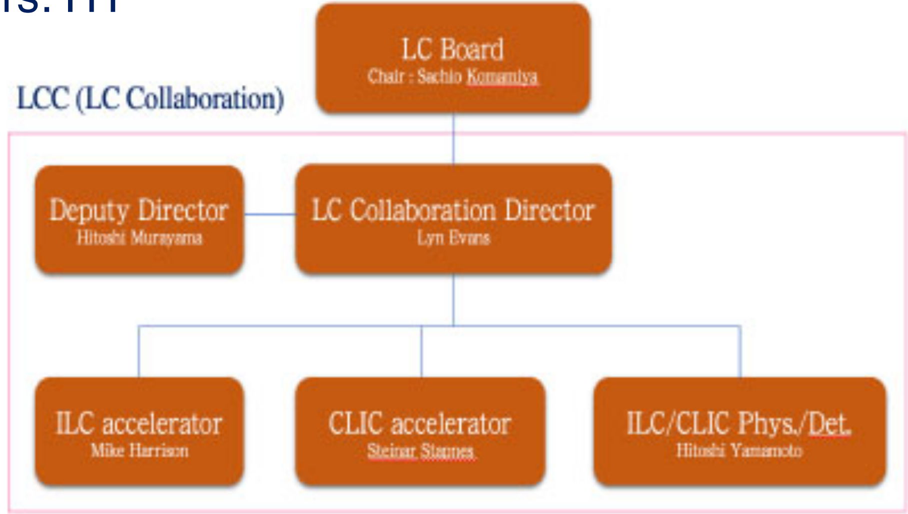
Linear Collider Collaboration (LCC) 2012 ~

Associate director for physics and detectors: HY
(until physics department chair in 2017)

- Regional reps
  - Asia: Keisuke Fujii
  - Europe: Juan Fuster
  - North America: Dimitri Denisov
- Many WG's

Juan Fuster

Jim Brau



LCC (LC Collaboration)

LC Board
Chair : Sachio Komamiya

Deputy Director
Hitoshi Murayama

LC Collaboration Director
Lyn Evans

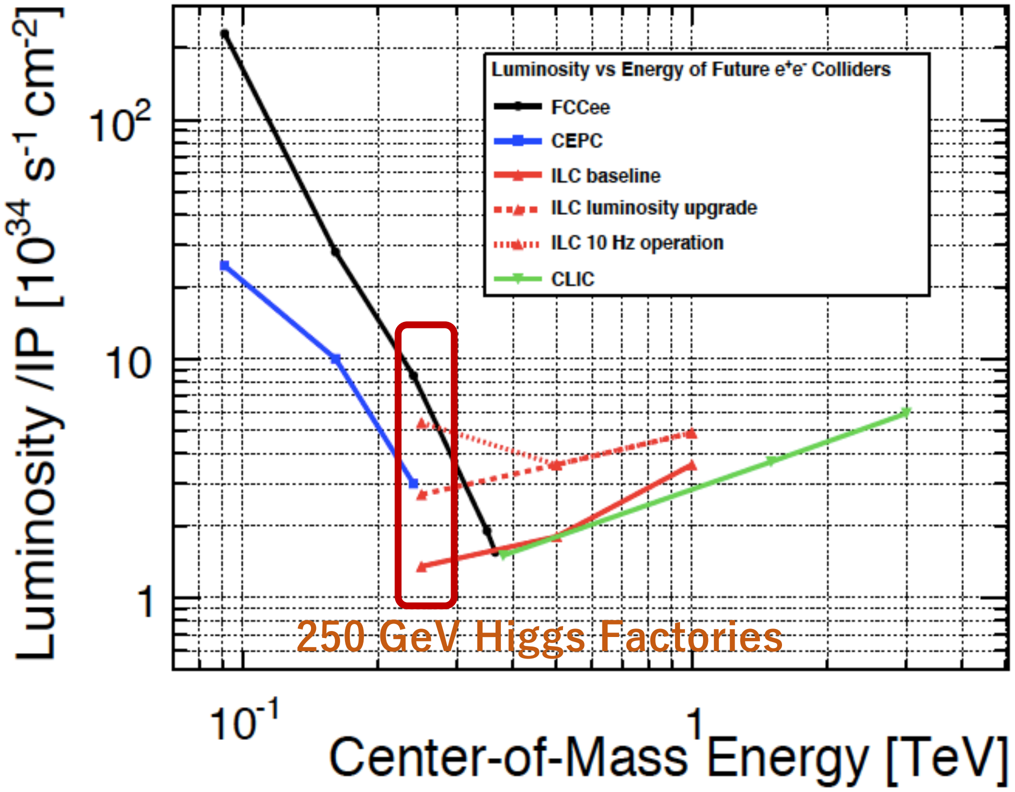
ILC accelerator
Mike Harrison

CLIC accelerator
Steinar Stapnes

ILC/CLIC Phys./Det.
Hitoshi Yamamoto

Luminosity vs Energy of Proposed e+e- Colliders

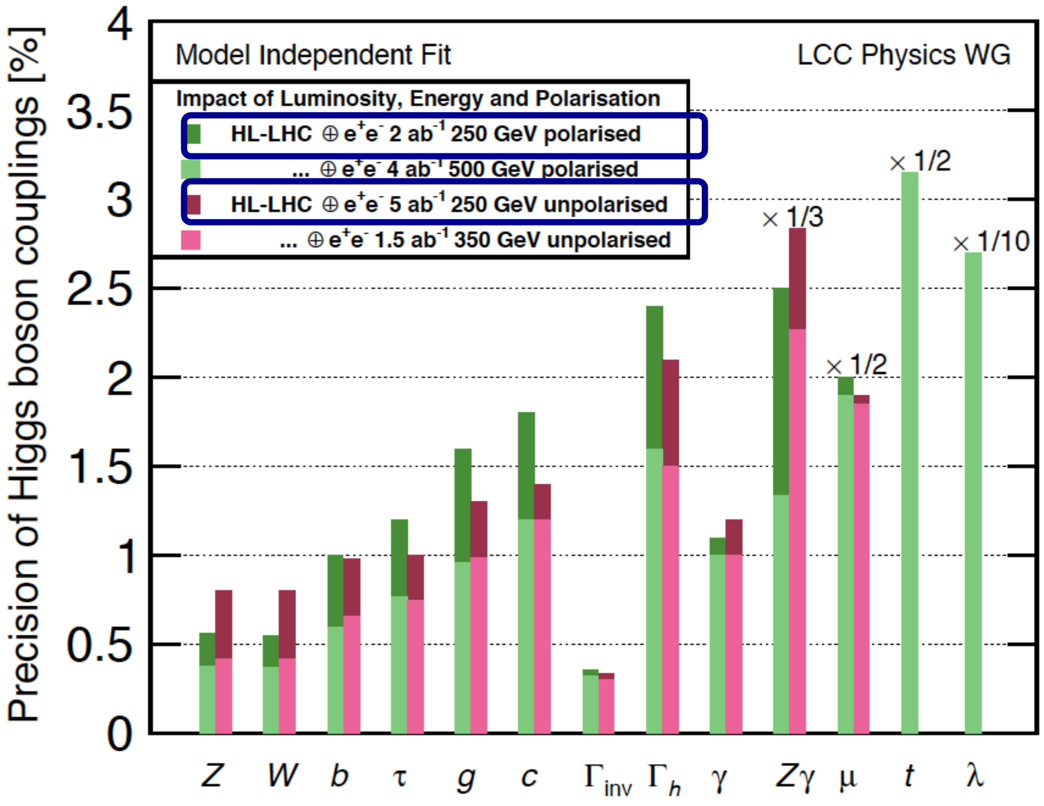
(Inputs to ESU)



- FCCee/CEPC points are for 1 IP (their CDR have 2 IPs)
- LC Higgs Factory numbers do not include effective x～2.5 by polarization
  (polarization effect next slide)
- ILC 10 Hz collision requires ~ILC500

- Capability of 250 GeV Higgs factories are similar

Power of Polarization



HL-LHC plus
ILC (polarized or
unpolarized)

ILC Polarization:
(e- e+) = (±0.8 ±0.3)
(-+, +-, ++, --) =
(45%, 45%, 5%, 5%)

- 2 ab-1 at 250 GeV (polarized) is 'roughly' equivalent to 5 ab-1 at 250 GeV (unpolarized)
- Effective luminosity ~ x 2.5 by polarization

Inclusive Decay Distributions of Coherent Two-body States

Orthogoanl states: $i, j, i', j' = 1, 2 \ldots n,$

Physical states: $\alpha, \beta, \alpha', \beta' = a, b \ldots$ (n total)

Using the generalized Bell-Steinberger Relation

$$\frac{\sum_f a^*_{\alpha f} a_{\beta f}}{\frac{\gamma_\alpha + \gamma_\beta}{2} - i(m_\alpha - m_\beta)} = \langle B_\alpha | B_\beta \rangle$$

one can prove the following orthonormality relation:

$$\begin{aligned}
\sum_f \int_0^\infty dt \;\; A^*_{B_i \to f}(t) A_{B_j \to f}(t) \\
&= \sum_{\alpha\beta} r^*_{i\alpha} r_{j\beta} \sum_f a^*_{\alpha f} a_{\beta f} \int_0^\infty dt \, e^*_\alpha(t) e_\beta(t) \\
&= \sum_{\alpha\beta} r^*_{i\alpha} r_{j\beta} \frac{\sum_f a^*_{\alpha f} a_{\beta f}}{\frac{\gamma_\alpha + \gamma_\beta}{2} - i(m_\alpha - m_\beta)} \\
&= \delta_{i\,j} \; .
\end{aligned}$$

time dependent decay amplitudes $A_{B_i \to f}(t)$