# Large Angle Beamstrahlung at SuperKEKB

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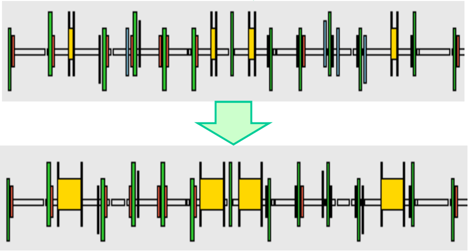
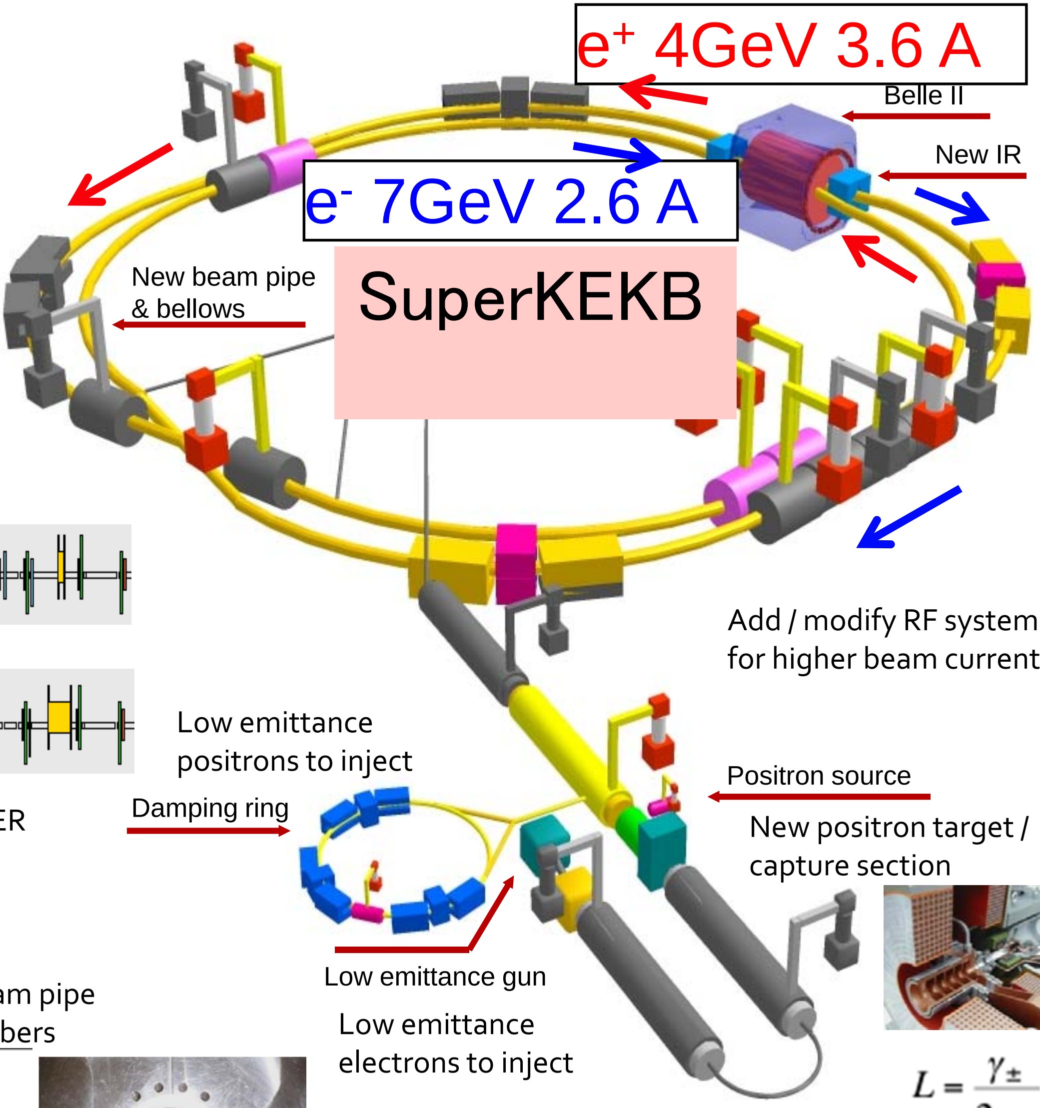
National Science Foundation
WHERE DISCOVERIES BEGIN

# SuperKEKB collider

Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

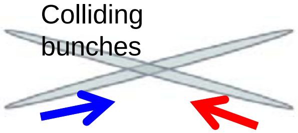


Low emittance positrons to inject

Low emittance electrons to inject

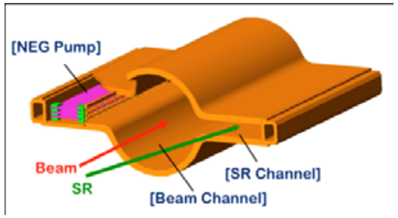
Add / modify RF systems for higher beam current

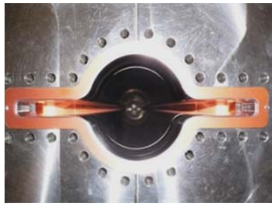
New positron target / capture section



New superconducting /permanent final focusing quads near the IP

TiN-coated beam pipe with antechambers





$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\boxed{\frac{I_\pm \xi_{\pm y}}{\beta_y^*}}\left(\frac{R_L}{R_y}\right)$$

Target: L = $8\times10^{35}/\mathrm{cm}^2/\mathrm{s}$

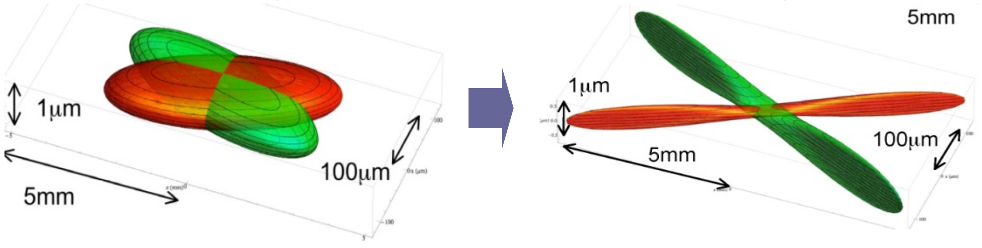
# Super KEKB in nano-beam scheme

- To increase luminosity:

→ squeeze beams to nanometer scale and
enlarge crossing angle (minimize $\beta_y^*$)

→ decrease beam emittance (keep current $\xi_y$)

- Squeezing beams in stronger magnetic field saturated by hourglass effect → intersect bunches only at highly focused region



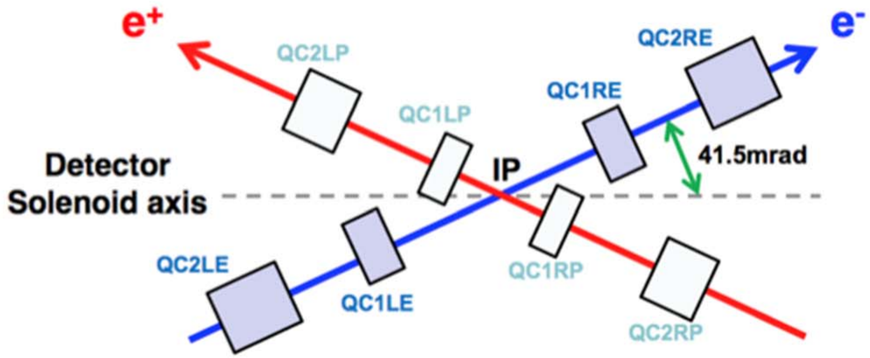
**$\sigma_x$~100μm, $\sigma_y$~2μm** **$\sigma_x$~10μm, $\sigma_y$~60nm**

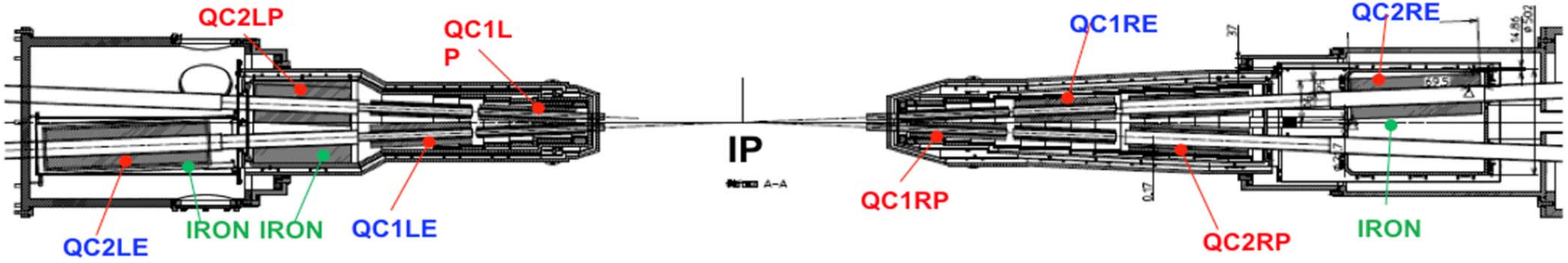
# Comparison of Parameters for KEKB and SuperKEKB

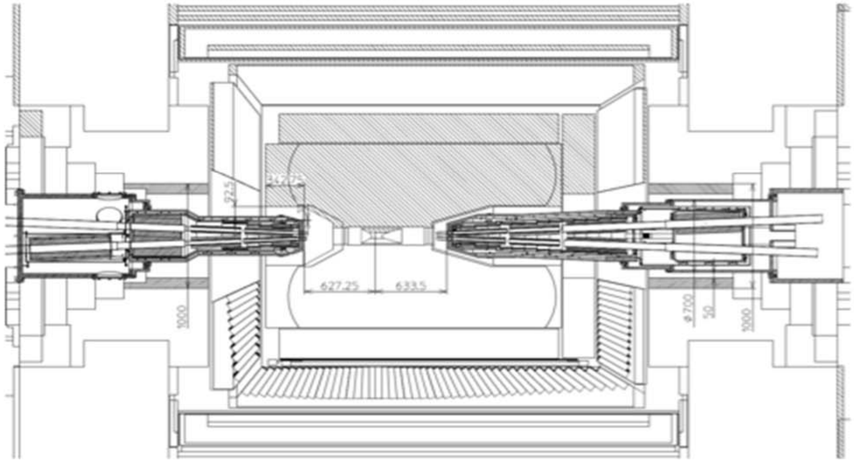
| | **KEKB Design** | **KEKB Achieved : with crab** | **SuperKEKB Nano-Beam** |
|---|---|---|---|
| Energy (GeV) (LER/HER) | 3.5/8.0 | 3.5/8.0 | 4.0/7.0 |
| $\beta_y^*$ (mm) | 10/10 | 5.9/5.9 | 0.27/0.30 |
| $\beta_x^*$ (mm) | 330/330 | 1200/1200 | 32/25 |
| $\varepsilon_x$ (nm) | 18/18 | 18/24 | 3.2/5.3 |
| $\varepsilon_y/\varepsilon_x$ (%) | 1 | 0.85/0.64 | 0.27/0.24 |
| $\sigma_y$($\mu$m) | 1.9 | 0.94 | 0.048/0.062 |
| $\xi_y$ | 0.052 | 0.129/0.090 | 0.09/0.081 |
| $\sigma_z$ (mm) | 4 | 6 - 7 | 6/5 |
| $I_{beam}$ (A) | 2.6/1.1 | 1.64/1.19 | 3.6/2.6 |
| $N_{bunches}$ | 5000 | 1584 | 2500 |
| Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 1 | 2.11 | 80 |

# SuperKEKB Interaction Region

Many new superconducting magnets at the IP; Belle detector currently aligned with LER will have to be rotated.





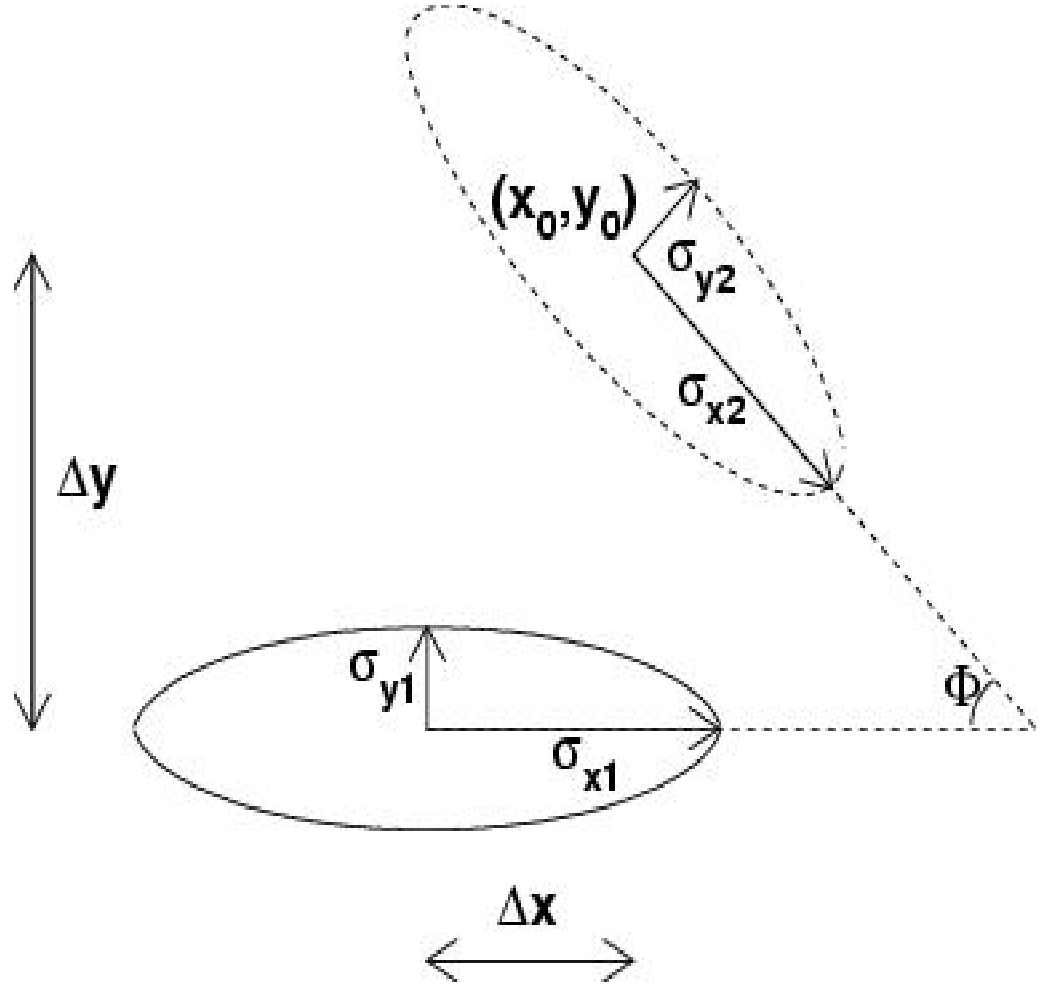


N. Ohuchi et al.

# What is beamstrahlung

- The radiation of the particles of one beam due to the bending force of the EM field of the other beam
- Used to monitor the beam-beam interaction already at SLC (in the gamma ray part of the spectrum), it produced fundamental information about the beam conditions.
- Produced at SuperKEKB, 1.3kW for LER and 5.4 kW for the HER at nominal conditions
- Many similarities with SR but
- Also some substantial differences due to very short “magnet” ($L=\sigma_z/2\sqrt{2}=2$mm). Short magnets produce a much broader angular distribution

# Beam-beam interaction limits the achievable luminosity and has many d.o.f. (7 in the transverse plane)

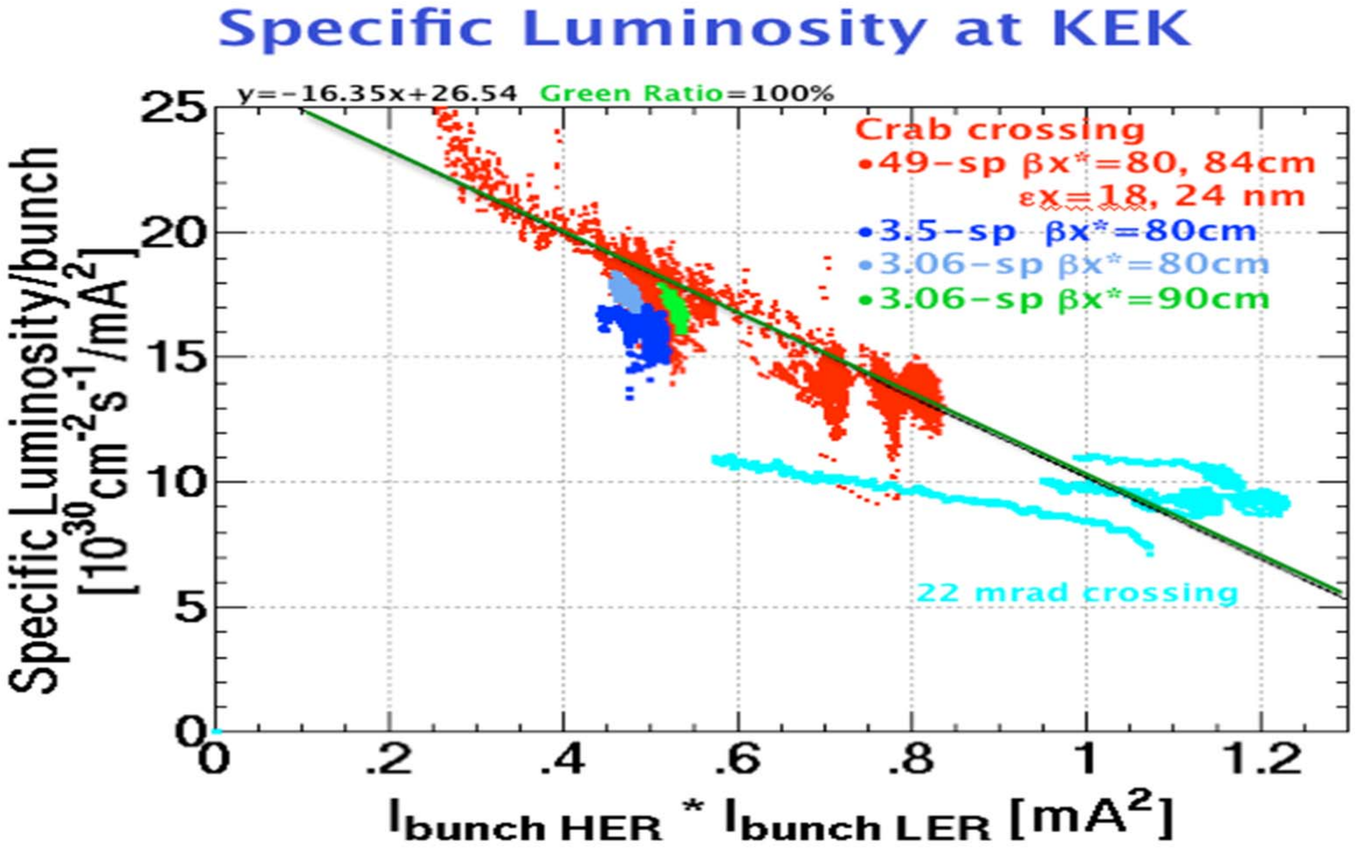


# ‘There is no comparable device to provide such information at the IP” (K. Oide) “A quantum leap in Beam-Beam diagnostics” (P. Raimondi)

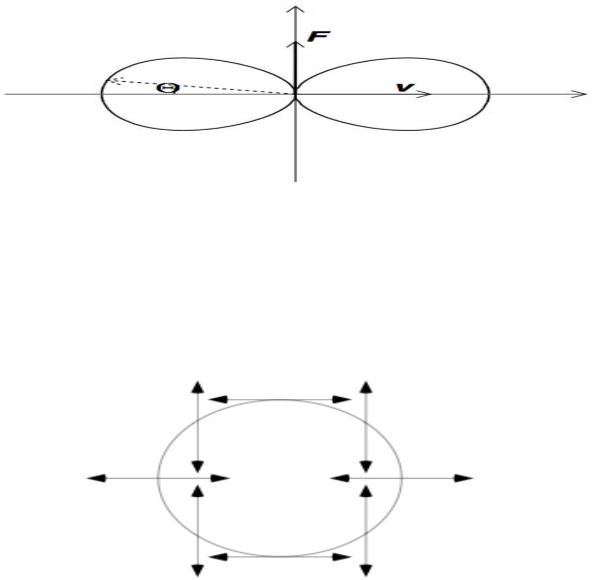
- SR Interf.: indirect, measures $\sigma_x$ and may measure $\sigma_y$ in the arcs, does not measure the overlap function
- X-ray interf.: indirect, measures $\sigma_x$ and $\sigma_y$ in the arcs, does not measure the overlap function
- BPM system measures only two quantities at IP
- Radiative Bhabha monitor at zero degrees
- BMST Monitor: direct, passive, measures the overlap function

Raster scan strategies are not possible at a storage ring and feedback systems also require redundancy

# Major efforts in diagnosing luminosity degradation already at KEKB - BMST Monitor improves instrumentation. $L=(I_+I_-)$Xspec. Lum.

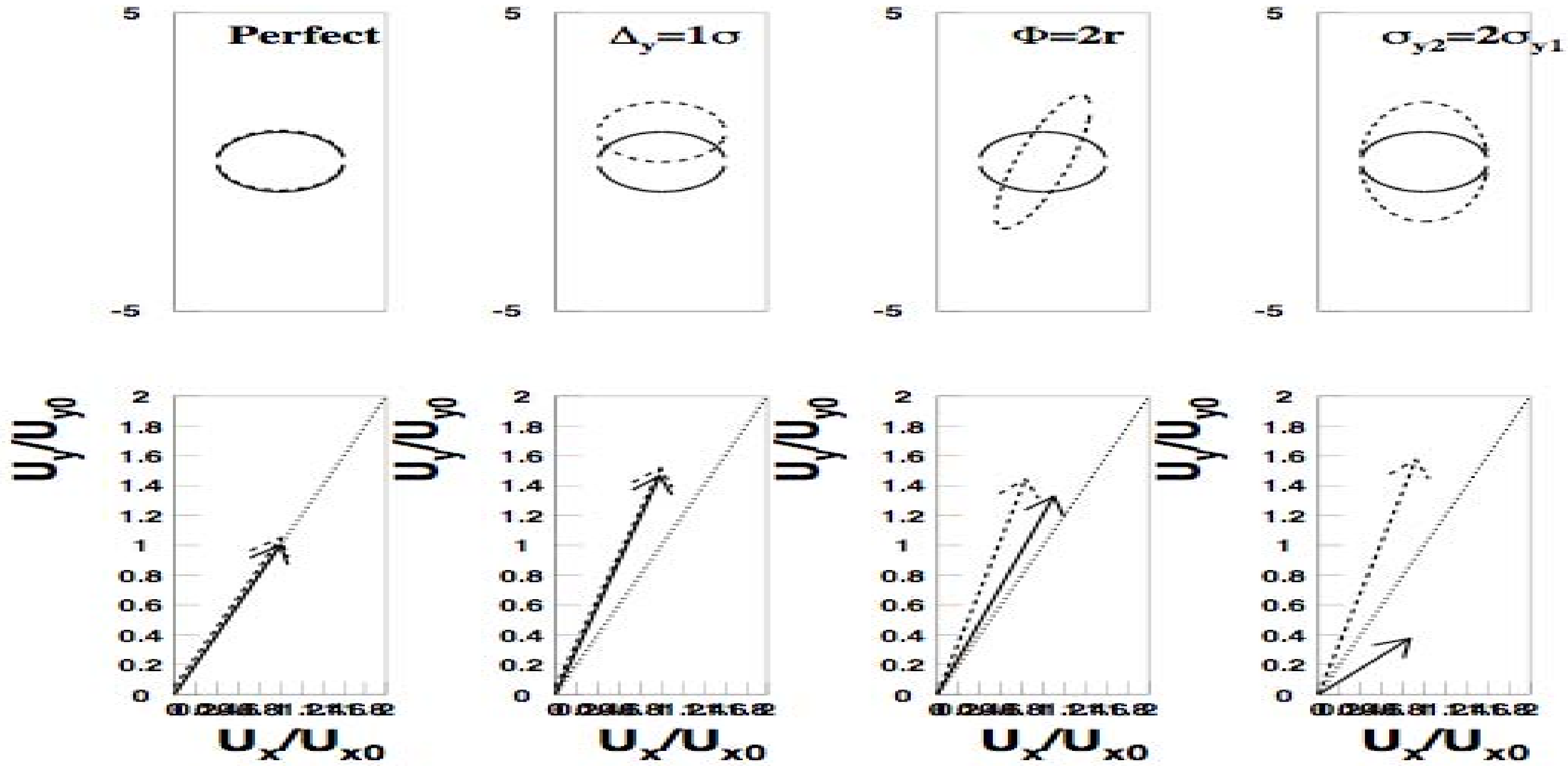


# Properties of large angle radiation

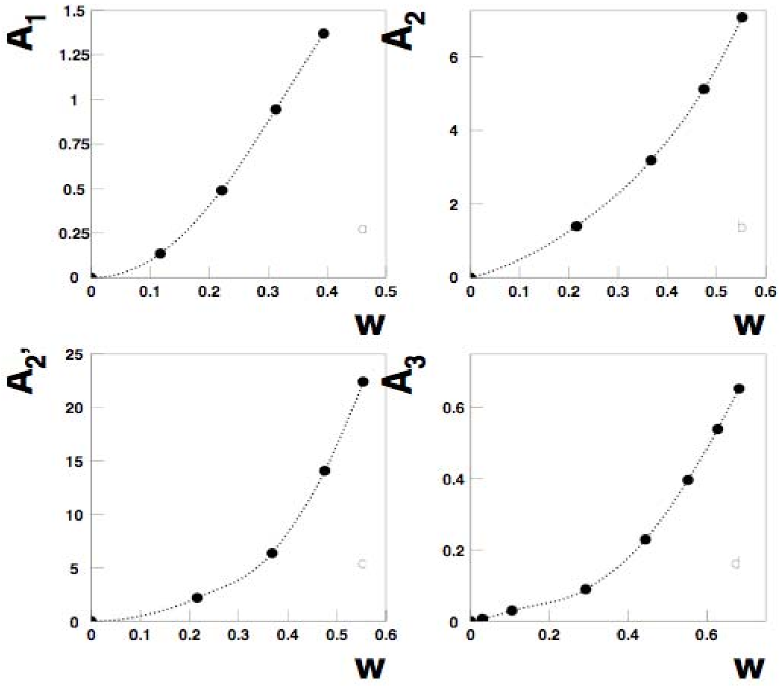


- It corresponds to the near backward direction in electron rest frame (5 degrees at CESR, 2-4 degrees at KEKB/SuperB, 7 degrees at DAPHNE)
- Lorentz transformation of EM field produces a 8-fold pattern, unpolarized as whole, but locally up to 100% polarized according to $\cos^2(2\phi)$, $\sin^2(2\phi)$ with respect to direction of bending force (M. Bassetti et al., IEEE Trans., Nucl. Sci. 30, 2182, 1983)

# Some examples of Large Angle BMST pattern recognition (collinear beams case) 3 asymmetries are defined (4 are possible)

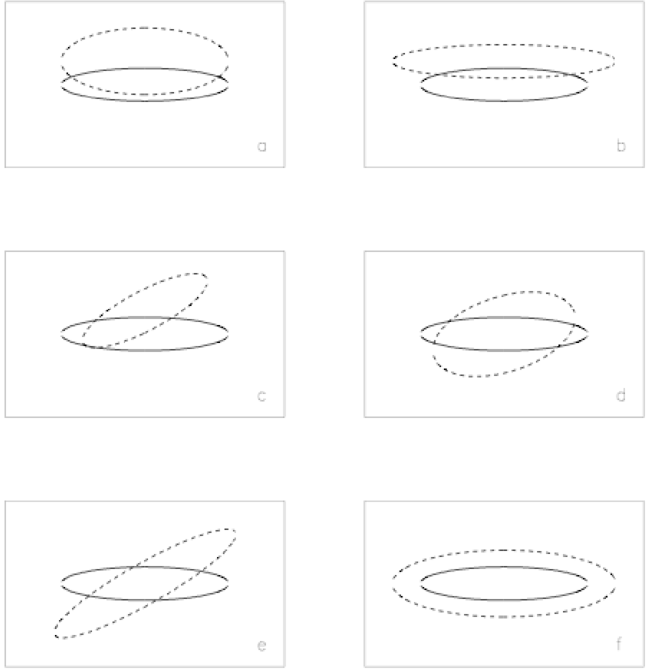


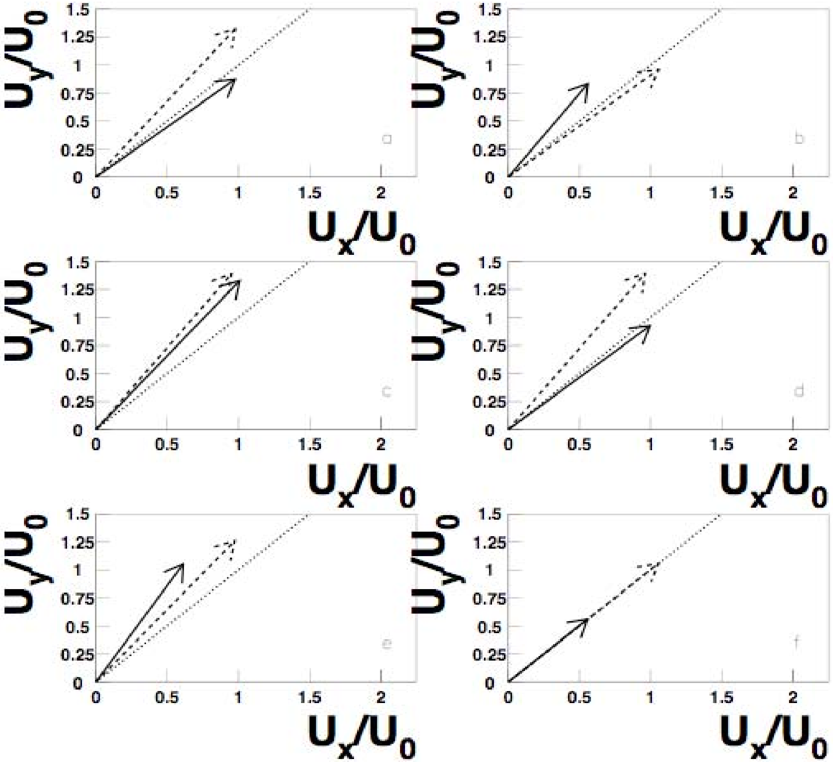
# From diagrams to asymmetries



- Derive asymmetry parameter from diagram and plot versus waste parameter ($w=1-L/L_0$ ), or ($w=1-S/S_0$ ), S the specific luminosity
- Apply correction based on measured asymmetry
- The whole collinear beams analysis depends on two parameters, $L_0$ and $U_0$

# Multiple pathologies (collinear case) showed complete convergence of the correction process and 6 out of 7 transverse degrees of freedom measured from diagram and its derivatives





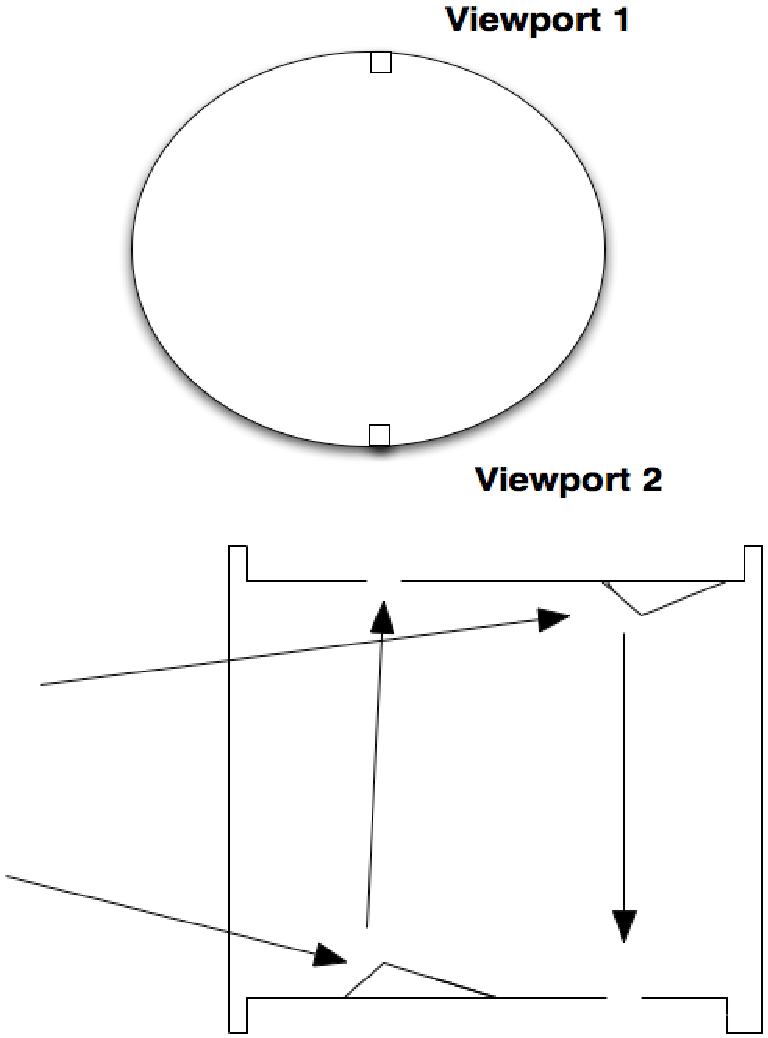
# Large angle beamstrahlung power

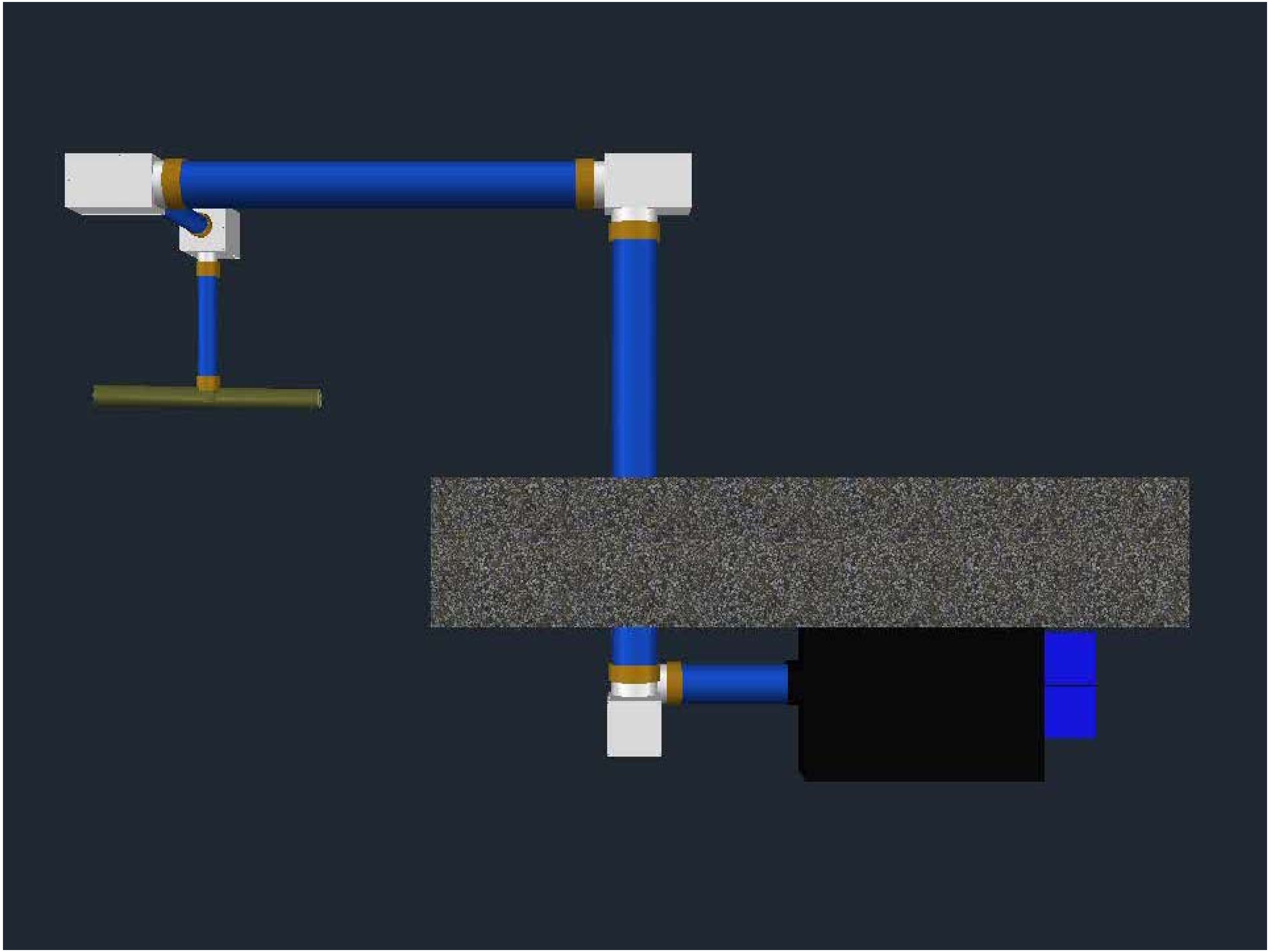
- Energy for collinear collision by beam 1 is: $P_0=0.11\gamma^2 r_e^{\,3} mc^2 N_1 N_2^{\,2}/(\sigma_x^{\,2}\sigma_z)$
- Wider angular distribution (compared to quadrupole SR) provides main background separation
- CESR regime: exponent is about -4.5
- SuperKEKB: exponent is -0.13 to -1.2

$$\frac{d^2 I}{d\Omega d\omega} = \frac{3\sigma_z}{4c\pi\sqrt{\pi}} P_0 \frac{1}{\gamma^4\theta^4} \exp\left(\frac{-\omega^2\theta^4\sigma_z^{\,2}}{16c^2}\right)$$

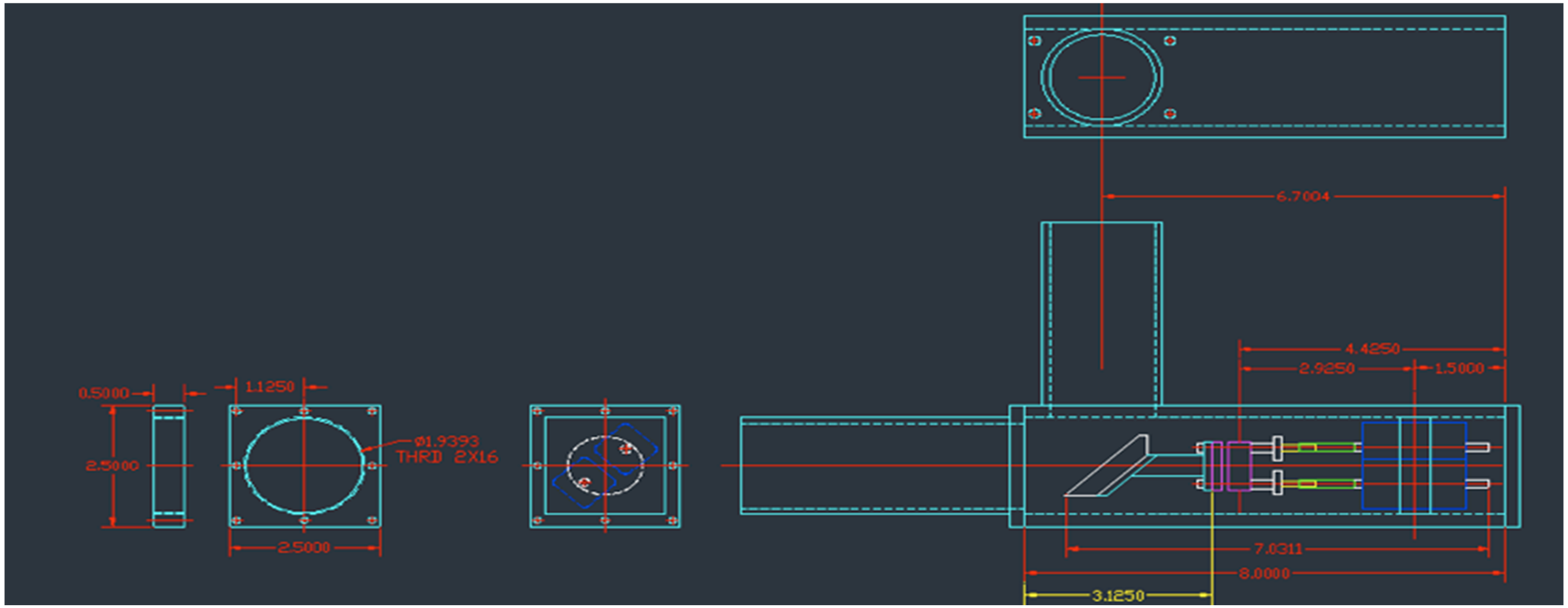
# Beam pipe insert

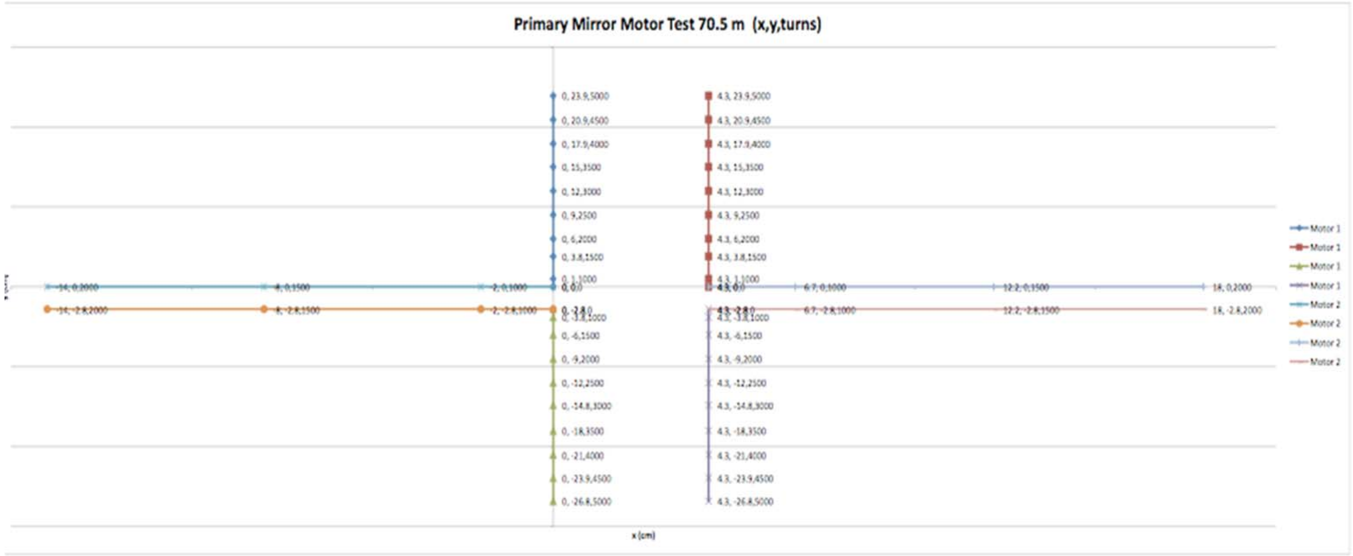
- View port location at ±90 degrees minimizes backgrounds, polarization measurement errors, and provides redundancy against beam orbit errors
- To be located anywhere between 5 and 10 mrad from the beam direction at the IP
- mirror and window sizes: 2X2.8mm2 and 6X6 mm2. Mirror is collimator 1
- Well measured distance between mirrors provides a constraint against beam pipe misalignments





# Primary mirror (remotely controlled)

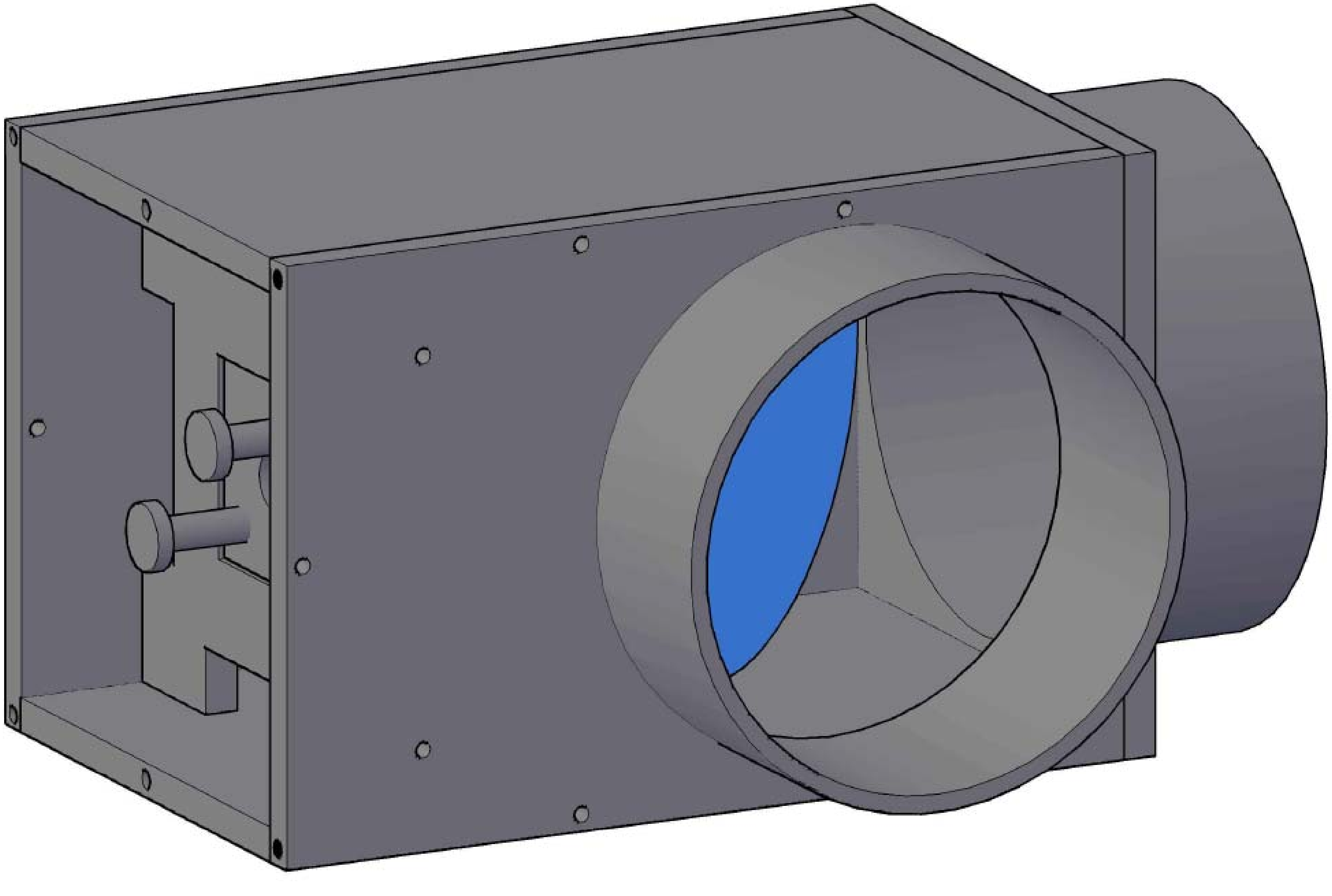




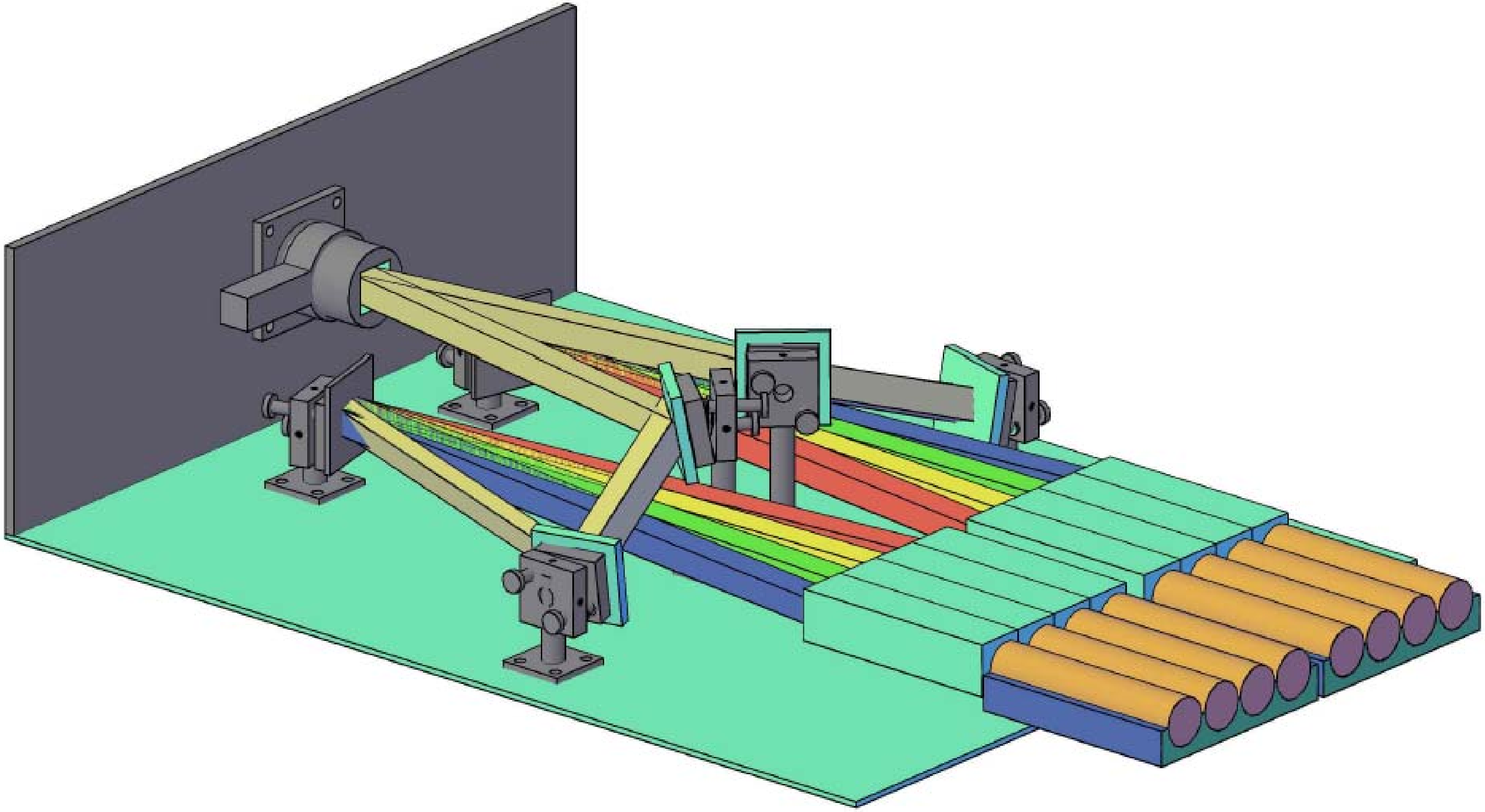
Mechanical
Hysteresis can
Be controlled to
0.1 mrad

# Primary mirror and Optics Box

# Elbow

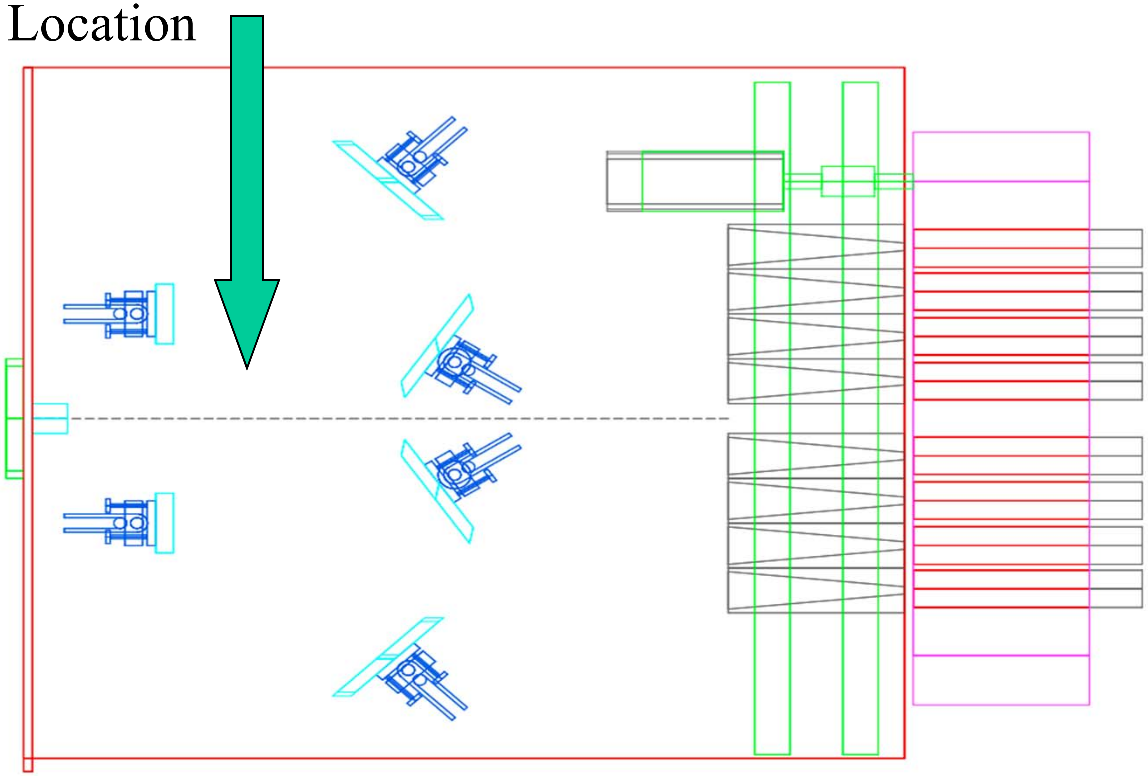


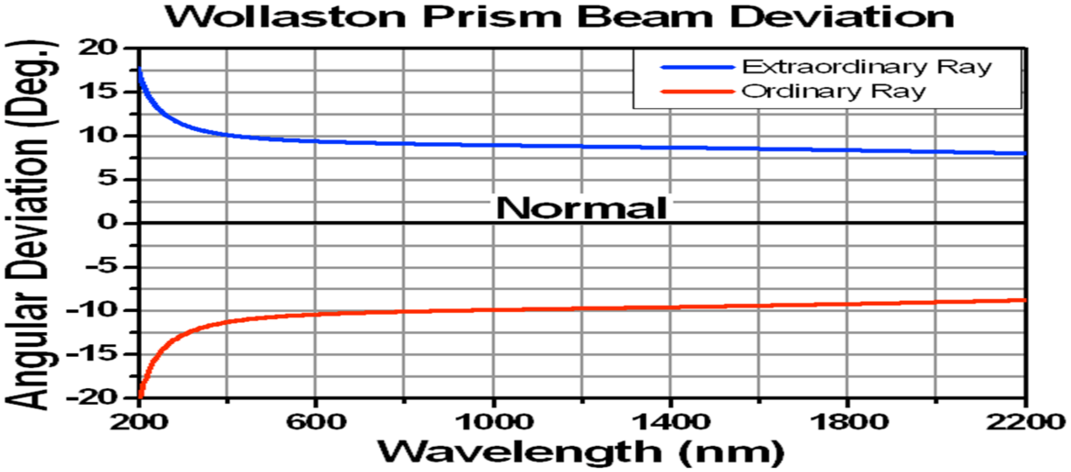
# Optics Box



# Nanocathode location

Nanocathode
Location

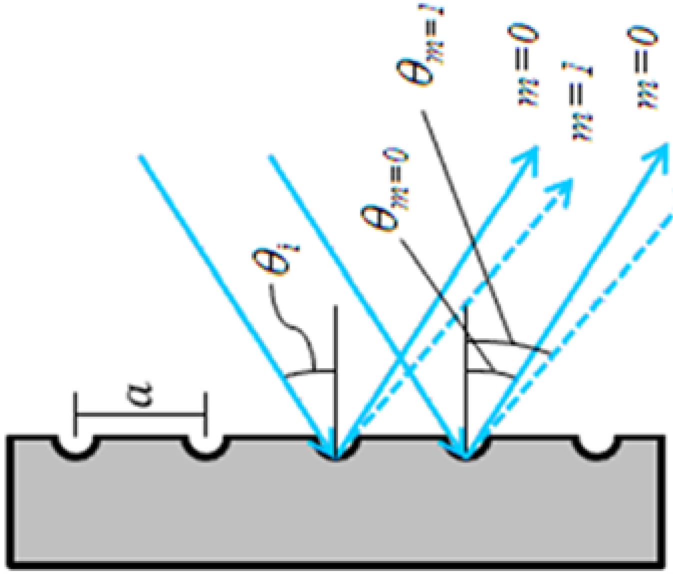




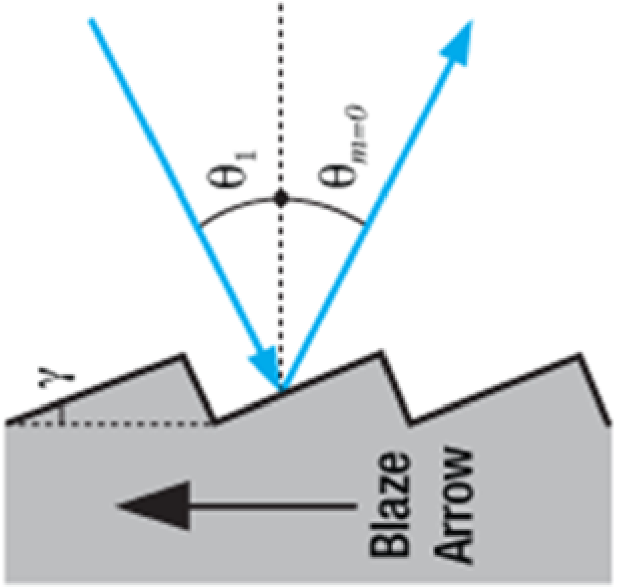
The non-linearity
Of the prism can
Be used to add
A nano cathode
Device to the
Optical line

# Grating

**Normal Reflecting Grating**

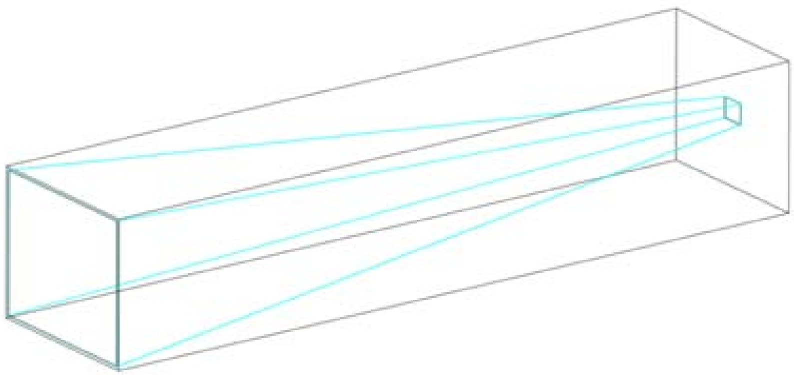


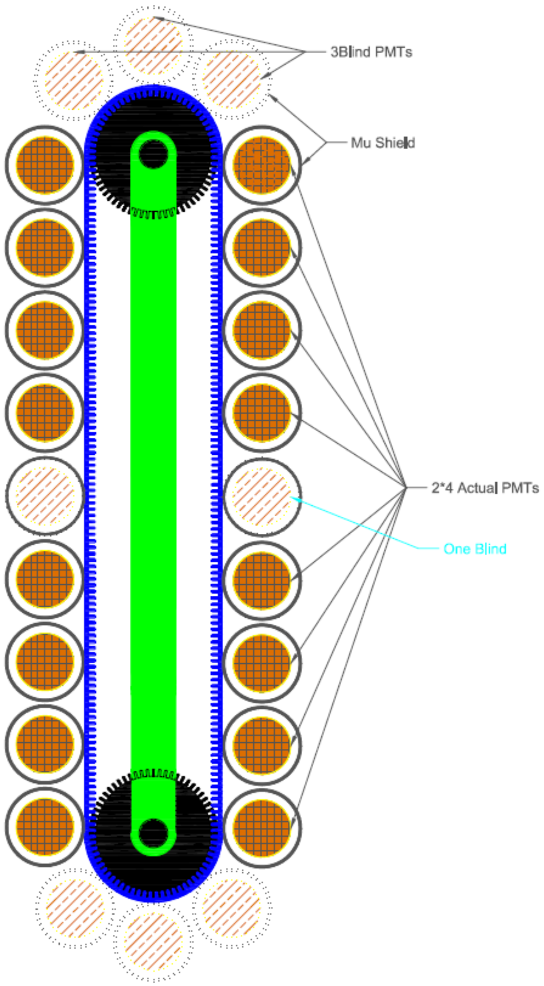
**Ruled or Blazed Grating**



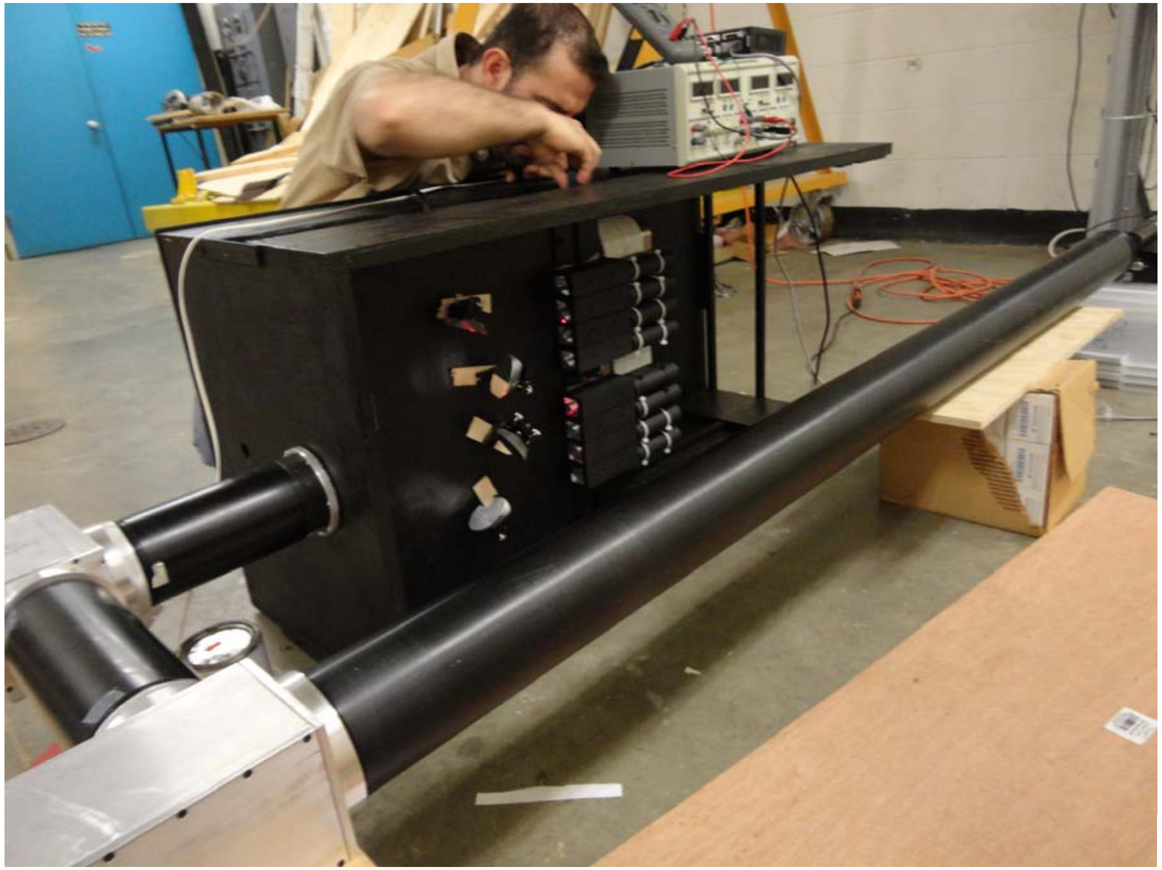
The reason we use such a grating is because ruled gratings have higher efficiencies(or intensities) in the first peak.

# Light Collector & Conveyor Belt

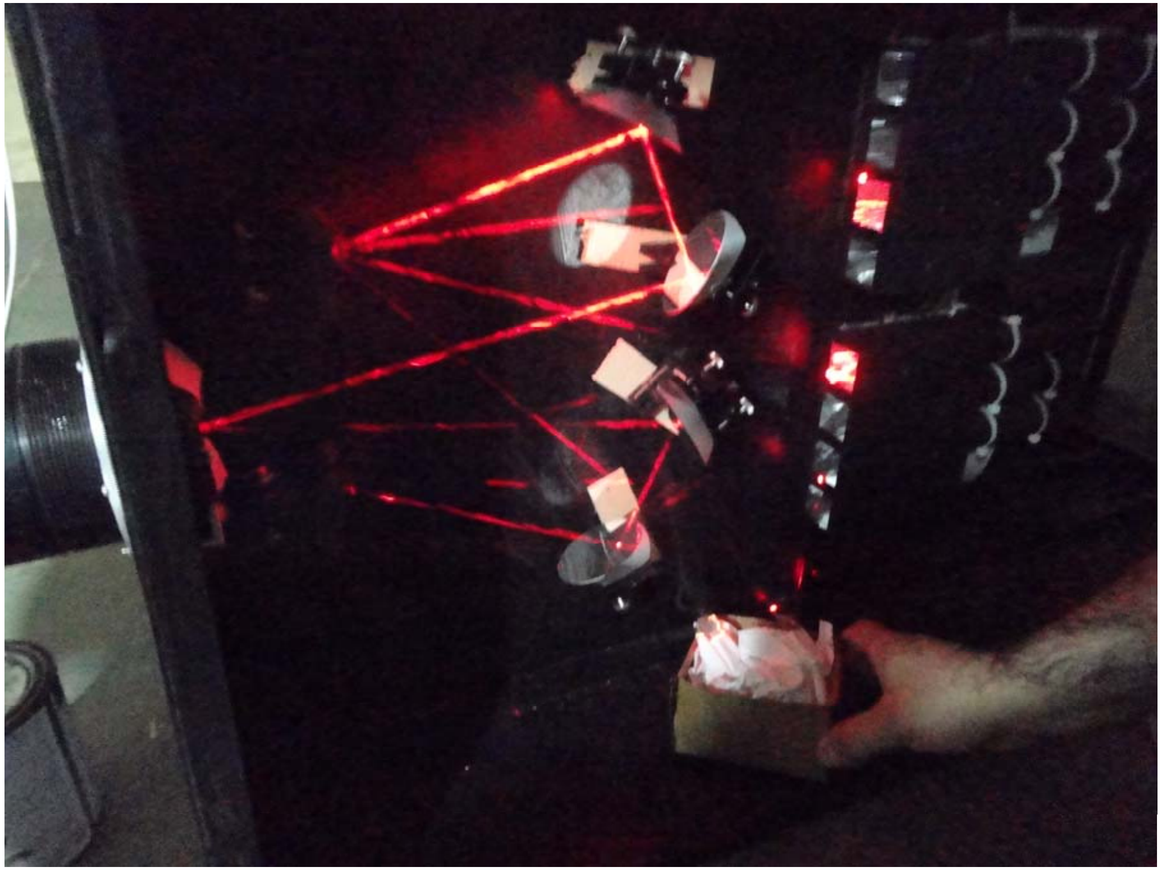




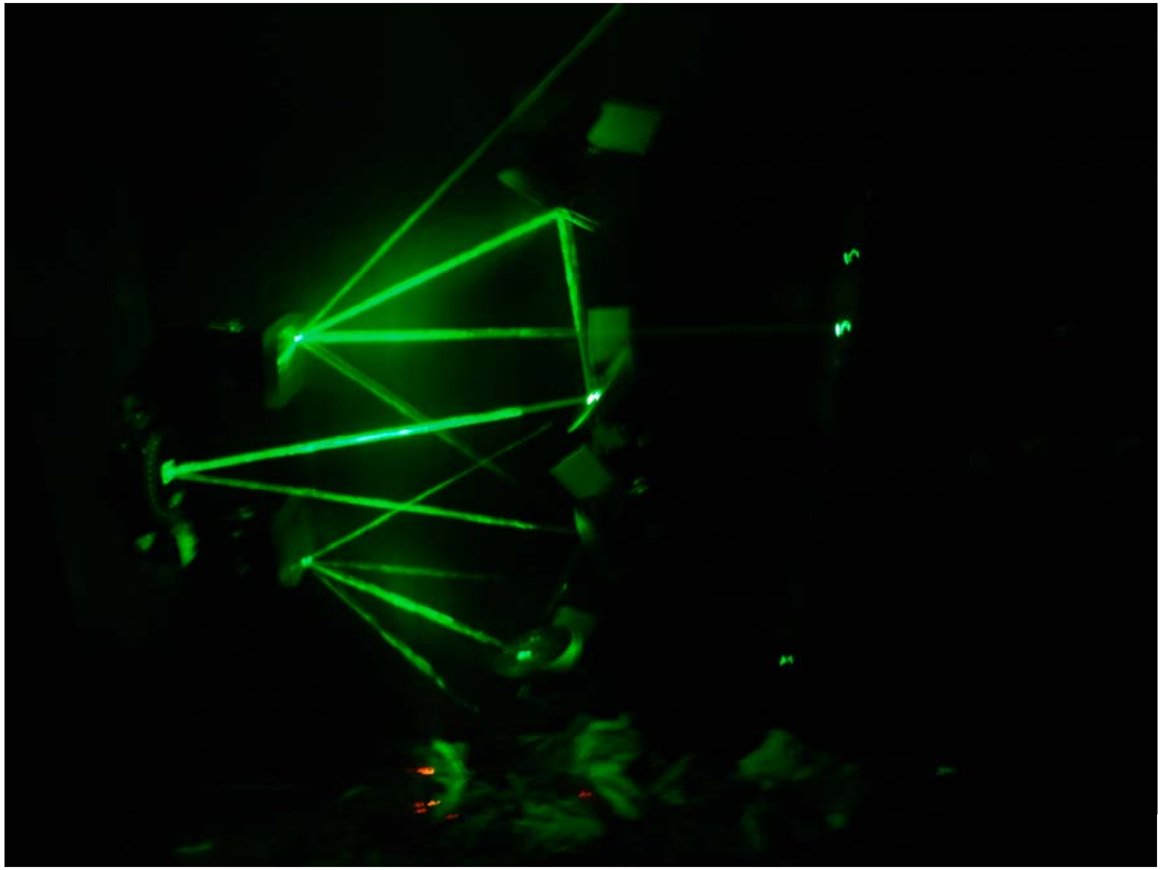
# Optics Box Prototype (I)



# Optics Box Prototype (II)



# Optics Box Prototype (III)



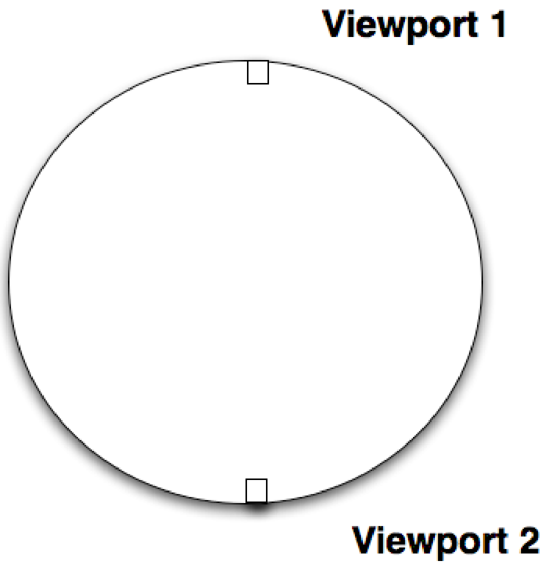
# Status of the device

- All pipes and elbows designed. To be built to last minute specs
- First Optics Box designed, built and tested successfully after prototyping
- All metal primary mirror stepper designed, built and tested
- Slated for installation in Summer 2014, data taking to start October 1, 2014
- Electronics to be done now (with Tabuk Univ.)
- The second Optics Box and the last three primary mirrors to be built starting Dec. 1, 2012
- Side-by-side PMT calibration, and design of LED calibration
- There is quite a bit of integration to be done with SuperKEKB system (event builder, interface)

# Need and uses for UV nanocathode

- Besides the 3 asymm., $A_{ud}$ can be defined $A_{ud}=(U_u-U_d)/(U_d+U_u)$
- This measures beam offset and is most sensitive in the UV. By measuring beam offset solely through $A_{ud}$, other beam-beam parameters can be had from $A_1$
- Best measurement of bunch length

- The nanocathode measures the most collimated radiation, and provides the single best measurement for the tails, useful for disentangling Touschek tails from beam-beam interaction tails



# Beam test at DAPHNE?

- The hardware except the electronics will be ready in Spring 2013
- A DAPHNE test, perhaps in Summer 2013, by a wide collaboration (KEK, Naples, Tabuk, WSU, perhaps LNF) would be advantageous to all parties involved

- The suggested location and long beams are not optimal, however some signal can be had in the 900 nm range by using SiPMT or IR PMTs.

# Box tests

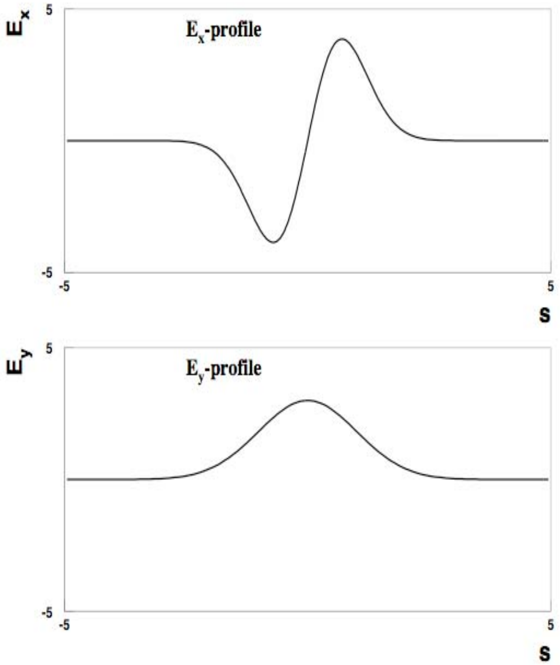
- Box is dark
- 3 lasers (382, 511, 632 nm) all illuminate one or two PMTs per string
- UV PMT needs a filter (design provides for it) to eliminate 2nd diffraction peak for 632 nm light
- $\varepsilon_x/\varepsilon_y$ is 95% as expected
- Efficiency of each light collector is within 1% of average

# Conclusions

- A powerful new method for beam monitoring and data-driven beam optimization
- Directly observing beams at the IP, purely passive. It is the only method able to measure vertical beam mismatches
- Spectral information provides measurements of the beam length, the beam-beam vertical offsets, and the beam tails
- A prototype has been built and tested. The final detector is being built.

# PMT array

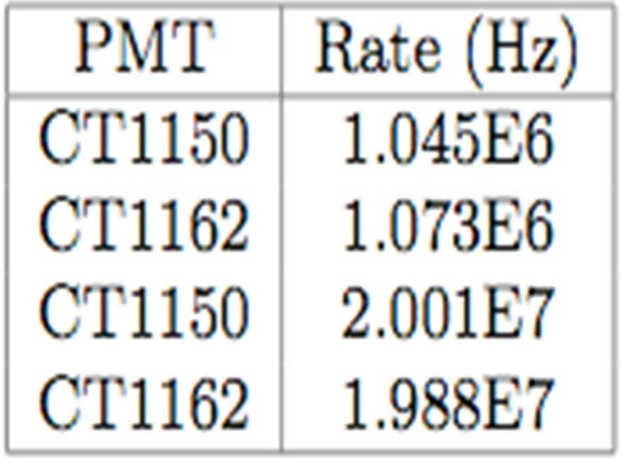
- From VIS/IR at CESR to 4 bands at SuperKEKB
- Useful for background determination, and also for bunch length direct measurement from different spectra in x- and y- PMTs



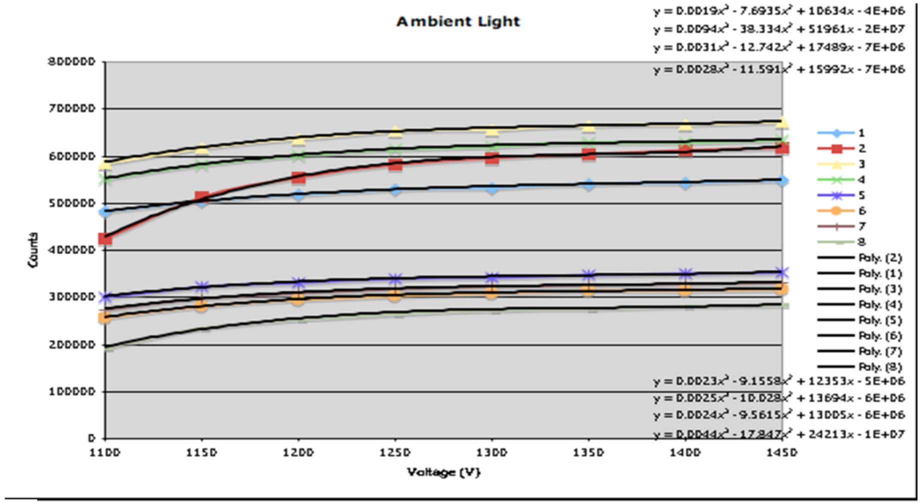
# Some results from current activities

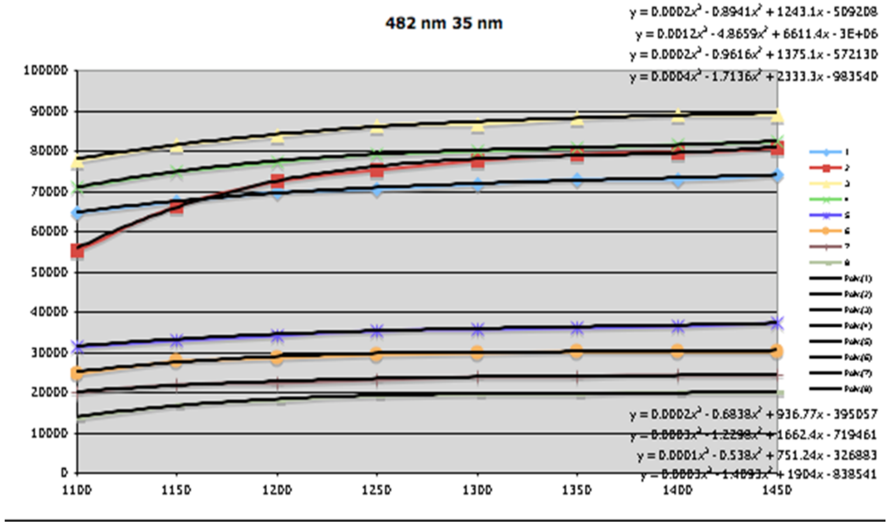
The Test bench shows ratios of efficiencies that depend on rates. PMT response Characterization:

$$R=R_0*\varepsilon*(1+aR/K_1)*(1+b\lambda/K_2)$$

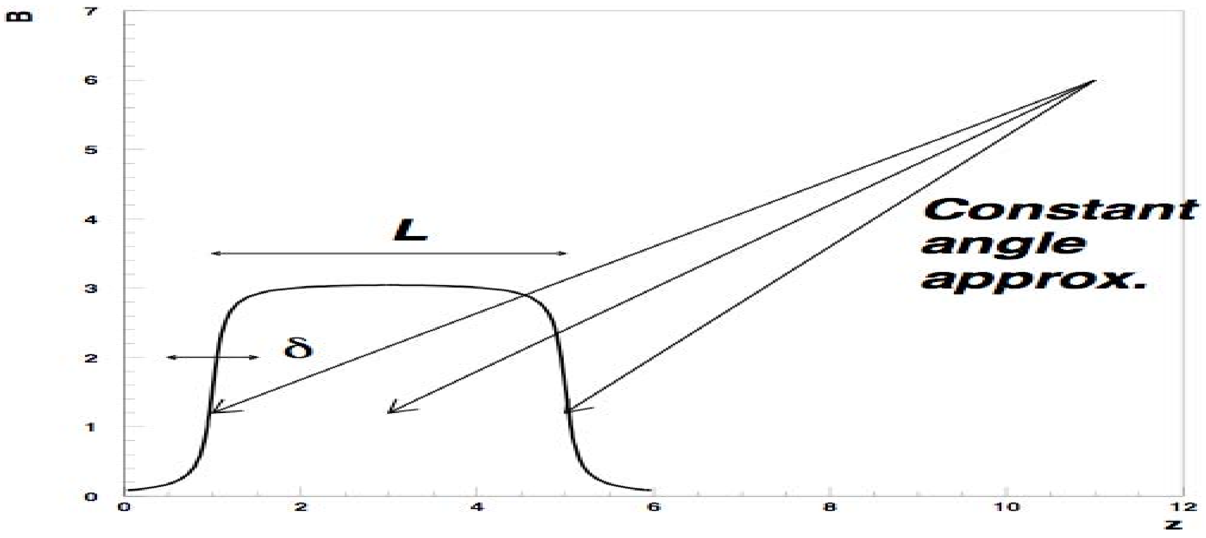


| PMT | Rate (Hz) |
|---|---|
| CT1150 | 1.045E6 |
| CT1162 | 1.073E6 |
| CT1150 | 2.001E7 |
| CT1162 | 1.988E7 |





# Short magnet approximation for the background (quadrupoles)



# If the angle can be considered large and constant…

- Assuming (atan($z/\delta$)+atan(($L-z$)/ $\delta$) as the field profile, one gets ($u=\gamma\theta$, $s,c=\cos,\sin(\phi)$)

$$\frac{d^2P}{d\Omega d\omega} \propto \frac{(1-uc)^2+(su)^2}{(1+u^2)^6}\frac{1}{\omega^2}\exp(-\omega\delta\theta^2/c)$$

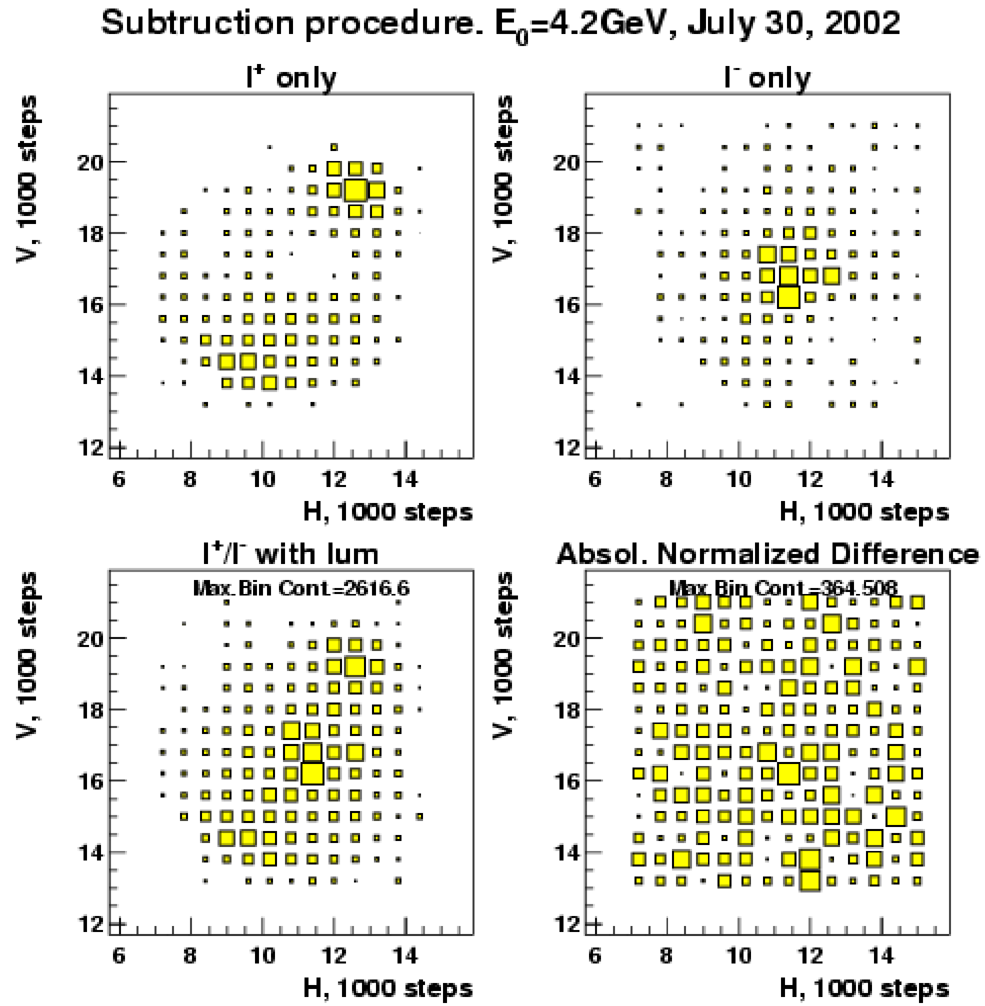
# Methods to measure the Beam-Beam Interaction

- A very difficult experimental problem - few measurements, many degrees of freedom
- Gamma ray part of the Beamstrahlung spectrum used with great success at SLC
- Beam-beam scanning and scattering also very successful at SLC (two quantities)
- Frequency locked vertical oscillation successful at CESR (one quantity)
- Other methods indirect

# Backgrounds

- At CESR, S/B~0.02-0.7
- Signal per collision will increase by 2-400,000 at SuperKEKB (at equal angles), while backgrounds will remain approximately the same or decrease
- Backgrounds are dominated by the beam tails. At CESR, beams were off center in the quadrupoles, and that further increased backgrounds

# Check for alignment @ 4.2GeV



# Beam Dump: direct measurement of background

- When one beam is lost, the other beam goes from the colliding beam envelope to the single beam envelope over several damping times (50 msec or so)
- Triggering on such an event, or storing and retrieving data, would measure backgrounds directly.

# Design Summary

- Double, opposite mirrors minimize backgrounds and eliminate beam position systematics
- Different possible locations of primary mirrors are dealt with by observing at different wavelengths
- Small PMT and optics systematics are controlled by Test Bench measurements and online calibration
- Box can be made as small as 25X25X40 $cm^3$, and it can go anywhere from (0-3) meters from Pipe

# Data analysis system

- Where algorithms are tried offline before they go in EPICS
- One server (non-EPICS) with 50 TB of disk space (at 1kHz sampling, 2.5 years of data)
- Substantial analysis platform by T. Pedlar (ROOT-based), including periodometer, advanced fitting and other statistical software, global data analysis
- Event record of order 100 variables including all beam monitors (LABM, Interferometers, BPM, Luminosity Monitors, Ground Motion sensors)

# Electronics

- Front end electronics from G. Varner, Hawaii
- Some work needed about data packaging and algorithms to extract needed information from EPICS. PNNL, Luther College interested in this part

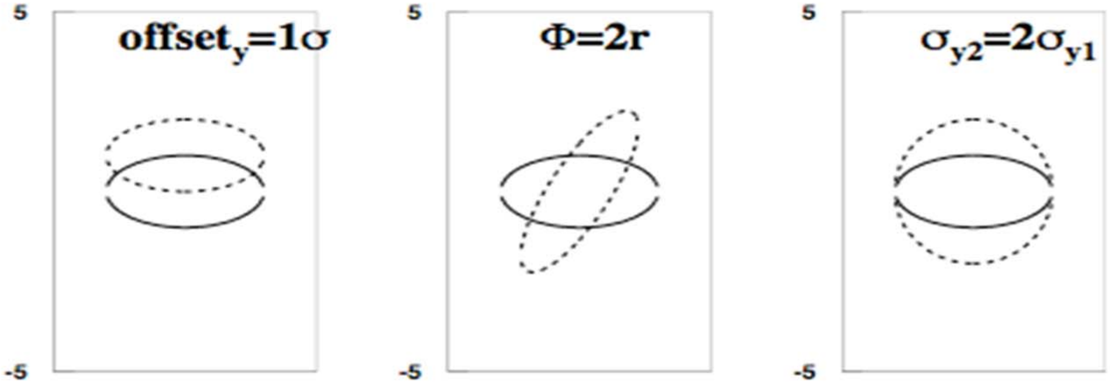
# Some examples of potentially interesting special data taking

- Bunch-to-bunch effects
- Measurement of beam tails at IP during fill
- Ground motion effects on IP Beam Spot
- frequency-locked measurements at IP (1nm IP variations)

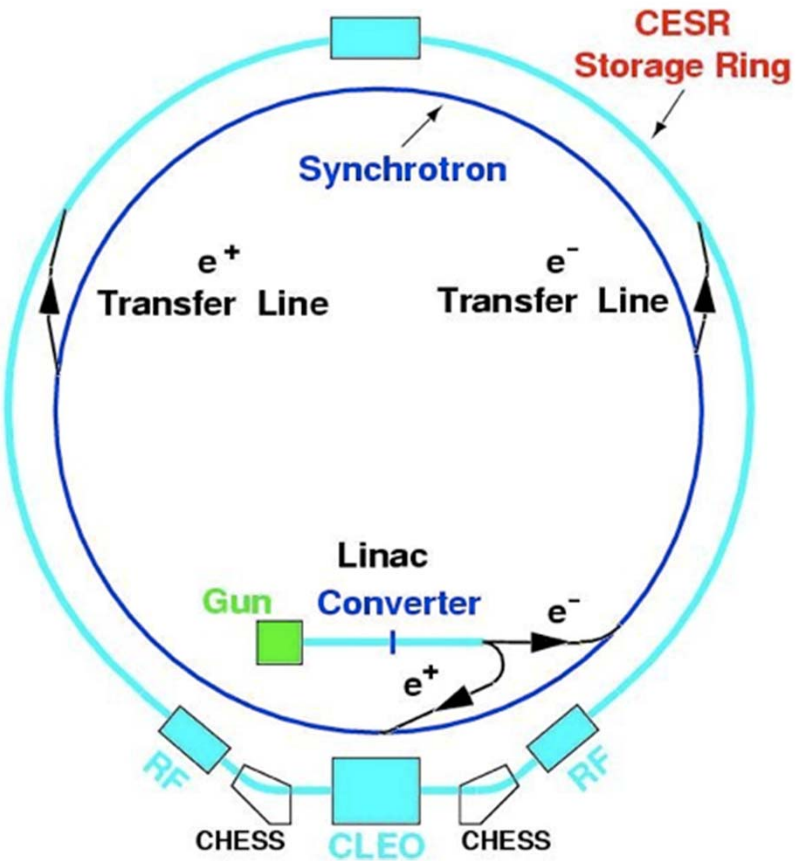
ALL THESE ARE PASSIVE MEASUREMENTS EXCEPT FREQUENCY-LOCKED

# Ground motion: LABM vs luminosity monitor

- A luminosity monitor does not pick out higher corrections. If luminosity decreases due to defocussing, and luminosity feedback is activated, the luminosity will decrease further
- Even if the motion is purely offset-y, a luminosity monitor will not specify whether the correction is up or down
- LABM can produce an asymmetry, $A_{u\text{-}d}=(R_u-R_d)/(R_u+R_d)$, which will specify the direction of deflection. For offset-y=1nm, $\theta$=7.5mrad, and the UV PMTs, $A_{u\text{-}d}$=0.01-0.02, recorded on two sides and two polarizations

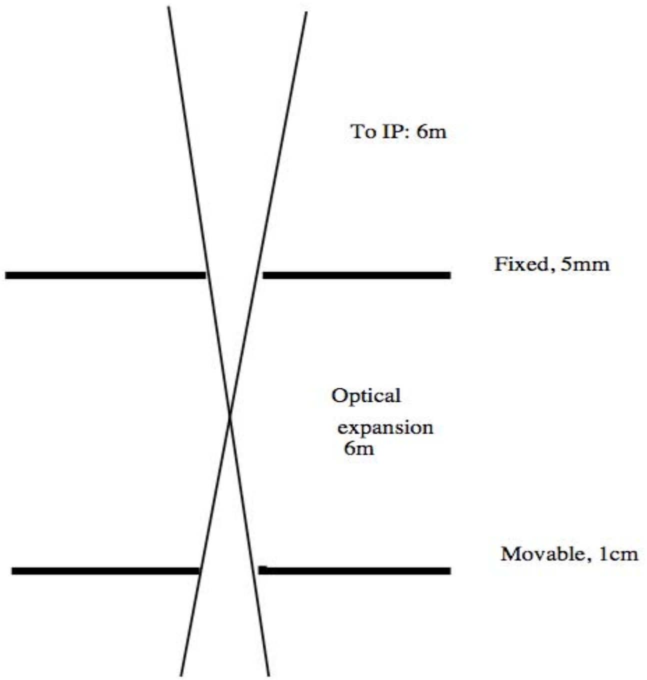


# CESR location



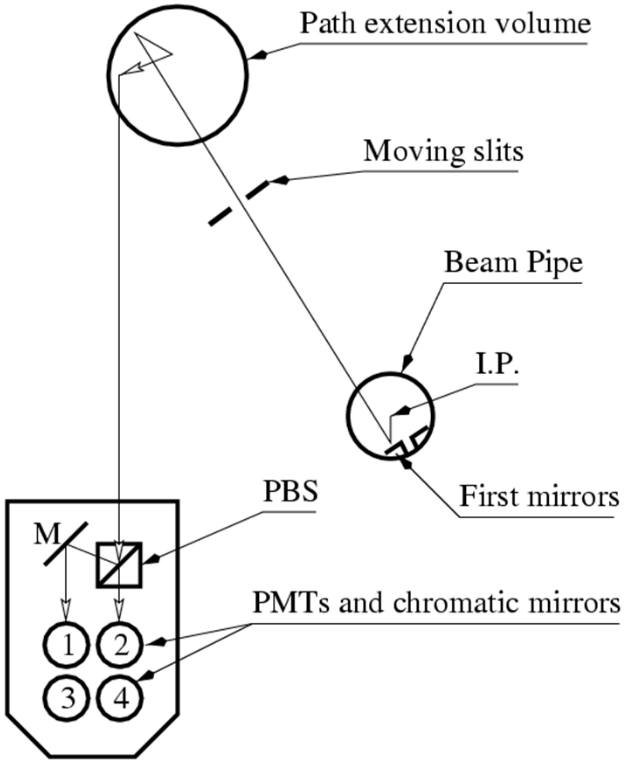
# Detector parameters of interest

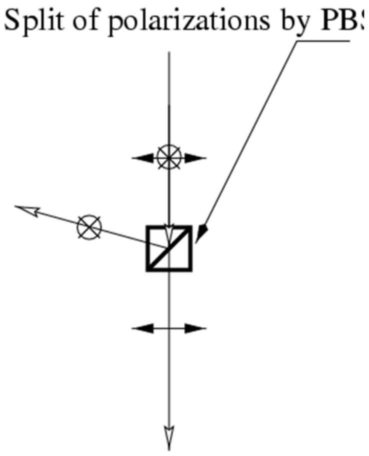
- Diffraction limit is 0.1 mrad (0.15-0.3mrad at SuperKEKB). Sharp cutoff can be assumed
- Optics is double collimator. Has triangular acceptance with max width of 1.7mrad
- At IP, accepted spot is about 1cm (0.4cm at SuperKEKB)



# ¼ CESR Set-up principal scheme

- Transverse view
- Optic channel
- Mirrors
- PBS
- Chromatic mirrors
- PMT numeration





# Set-up general view

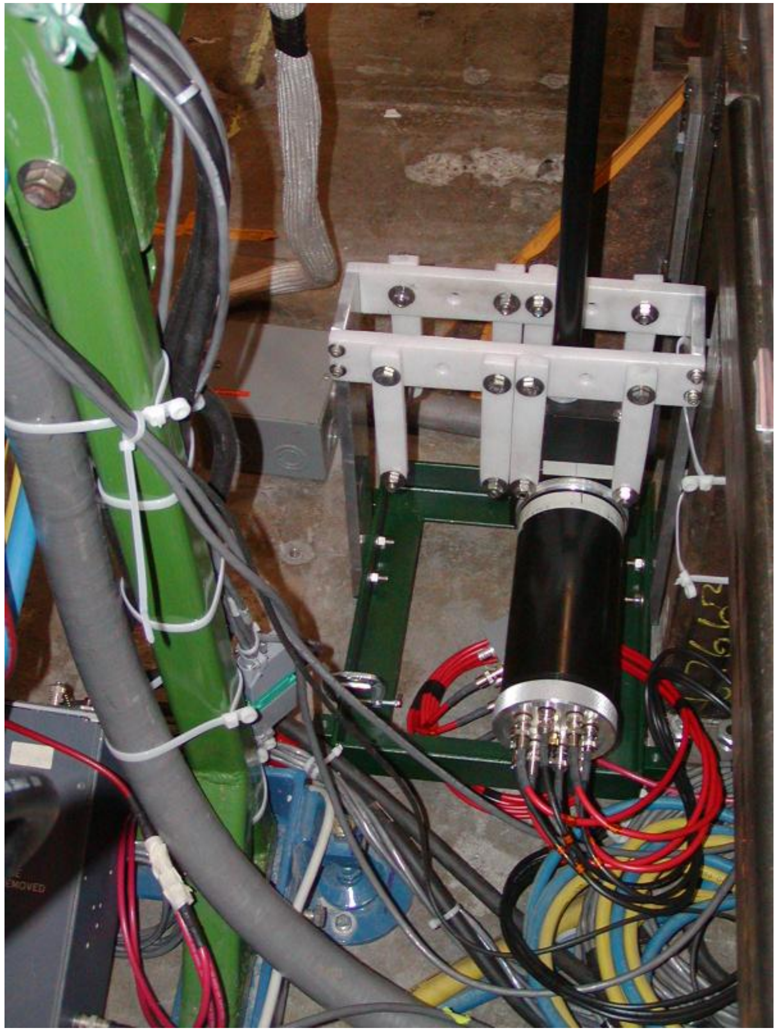
- East side of CLEO
- Mirrors and optic port ~6m apart from I.P.
- Optic channel with wide band mirrors

# On the top of set-up

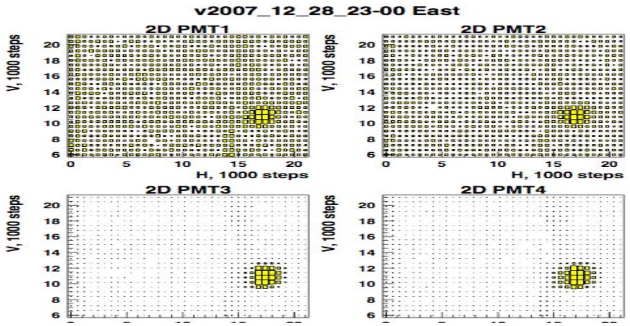
- Input optics channel
- Radiation profile scanner
- Optics path extension volume

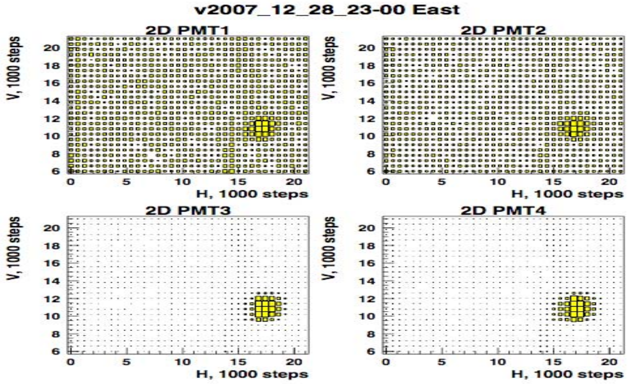
# The ¼ detector

- Input channel
- Polarizing Beam Splitter
- Dichroic filters
- PMT's assembly
- Cooling…



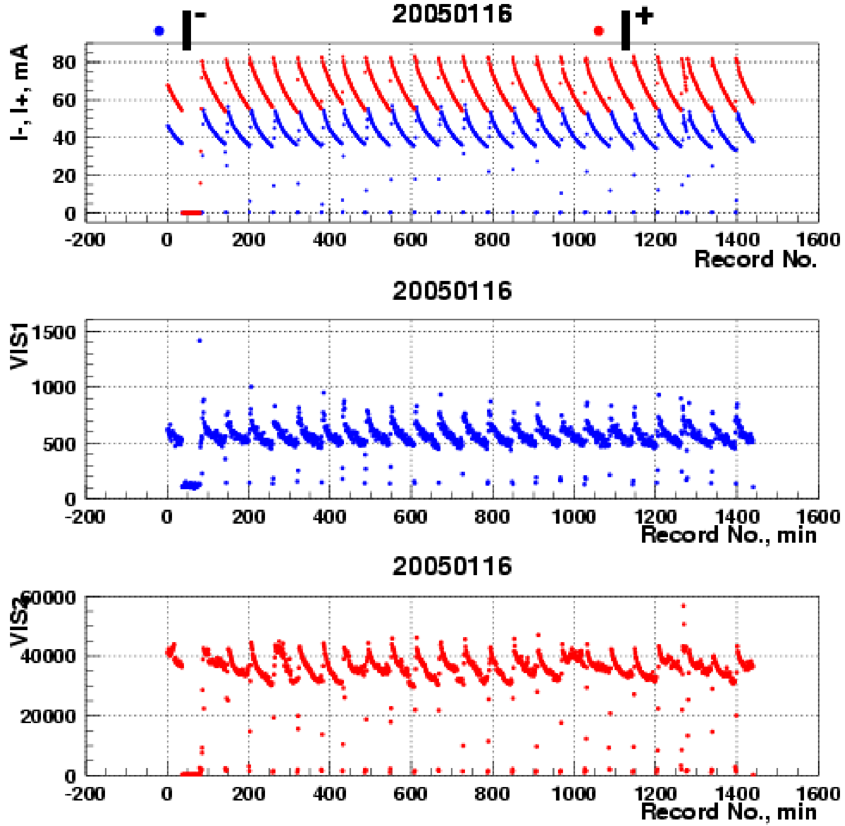
# Directionality

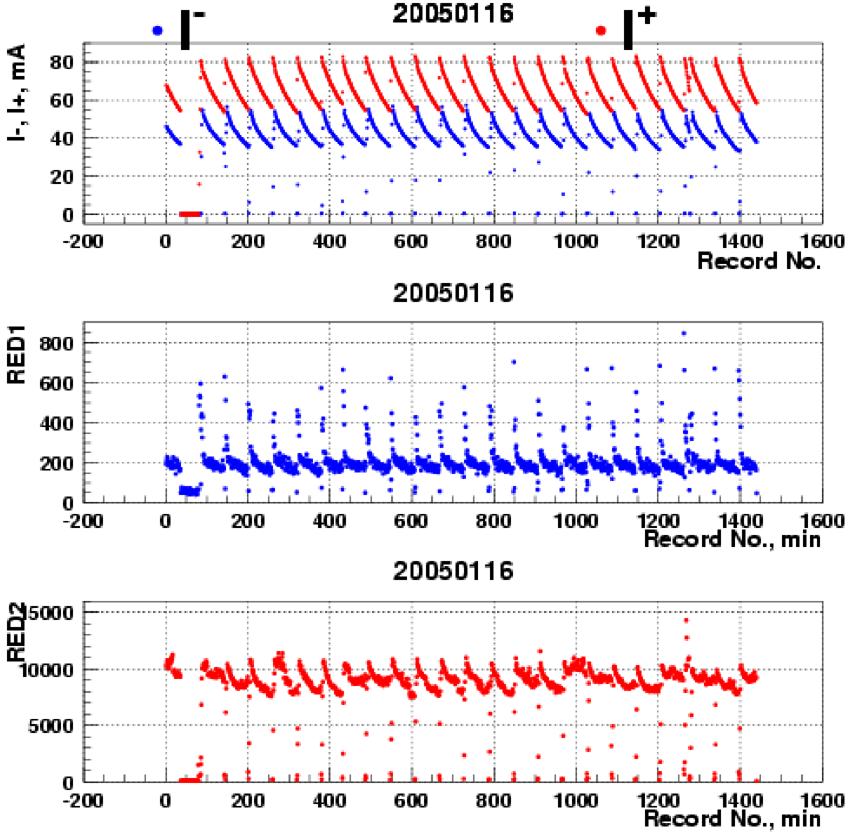




- Scanning is routinely done to reconfirm the centroid of the luminous spot.

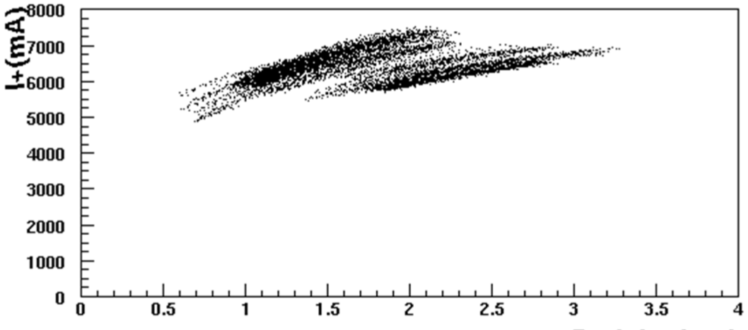
# PMT rate correlations with beam currents



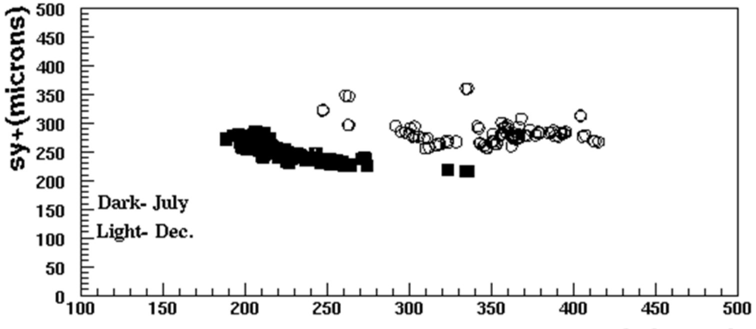


# Natural variability of machine provided crucial evidence

- In July, relatively high e+ current and relatively low e- current. In December, currents are more balanced, providing a stronger expected BMST signal
- In July, e- beam was smaller than e+. In December, the reverse was true. Differing polarizations expected



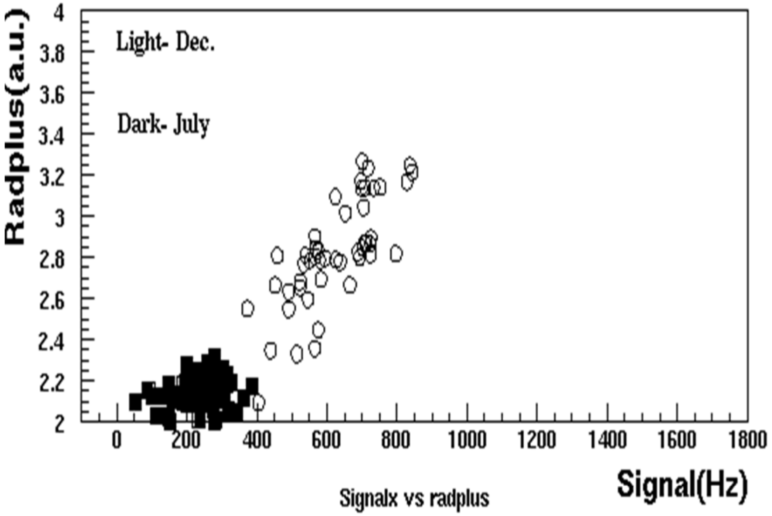
radplus vs ipos



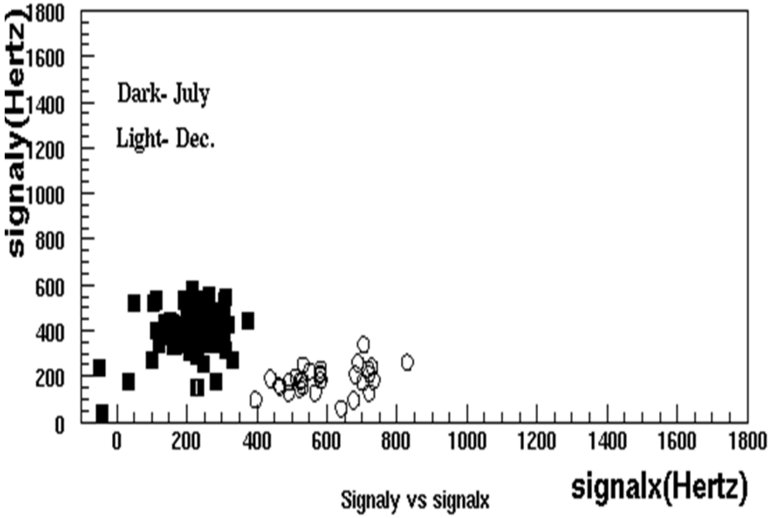
Sigyp vs sigym

# Main results page

- Signal(x) strongly correlated to $I_+I_-^2$
- Signal strongly polarized according to ratios of vertical sigmas
- Total rates consistent with expectations at 10.3 mrad



Signalx vs radplus



Signaly vs signalx

# How to increase the luminosity

$$N = \sigma \int dt \mathcal{L} = \sigma f T L$$

$$L = |\mathbf{v_1} - \mathbf{v_2}| \int dV dt \rho_1(\mathbf{r}, t) \rho_2(\mathbf{r}, t)$$

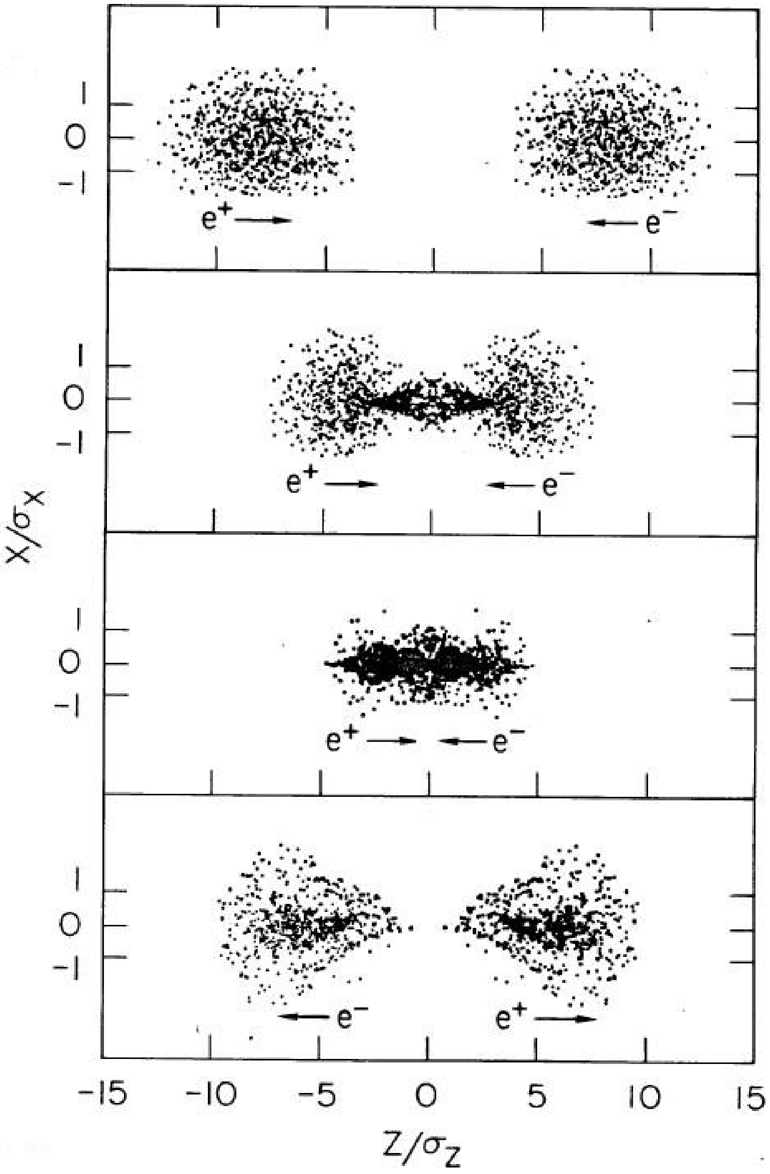
$$\mathcal{L} = \frac{f N_1 N_2}{4\pi \sigma_x \sigma_y}$$

$$\mathcal{L} = \frac{f N_1 N_2}{4\pi \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

Integrated luminosity is the fundamental parameter. Small gains (w.r.t. KEKB) can be had by increasing the frequency of collisions, but the largest gains are from the increase in geometric overlap

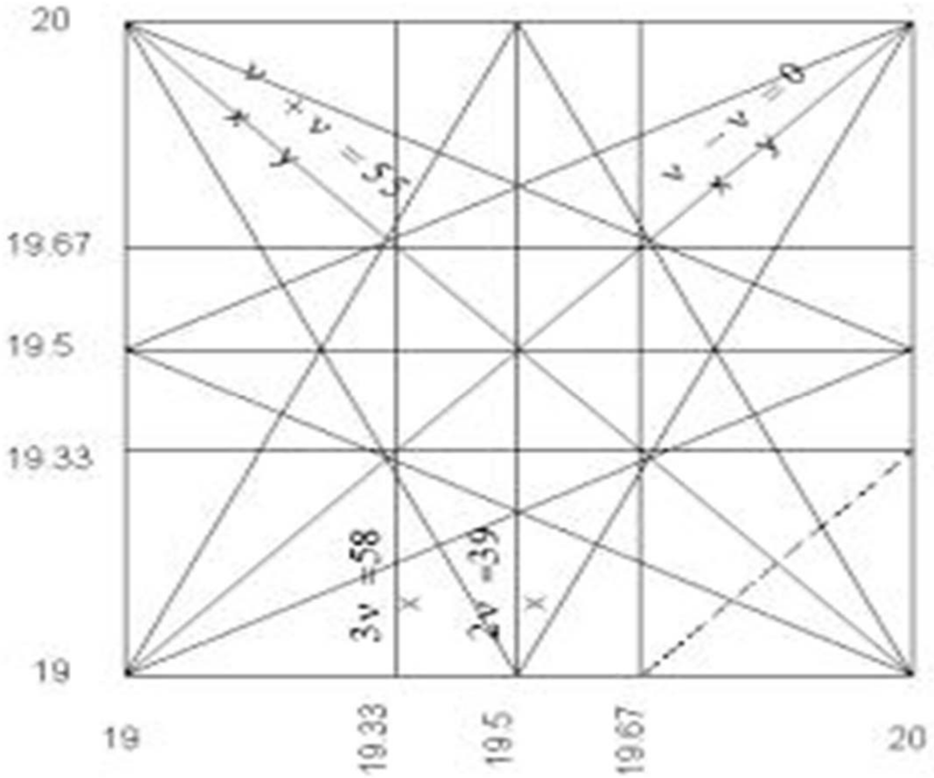
In the case of collinear, equal, Gaussian beams the overlap can be calculated easily. One can introduce terms that depend on the beams, and terms that depend on the machine

# Beam-beam limit

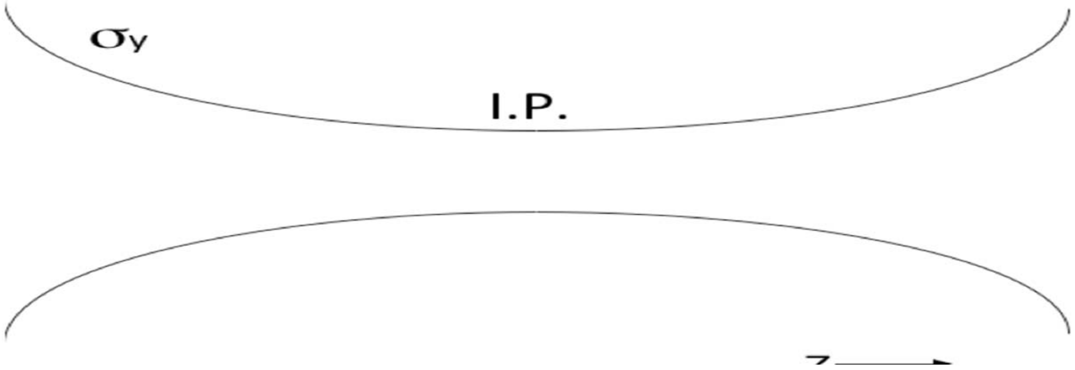


Tune shift limit

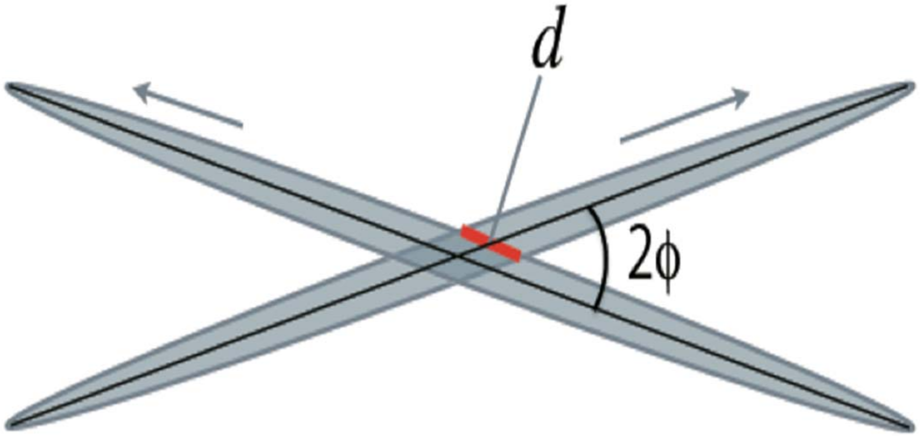
$$\xi_{y,2} = \frac{r_e n_1 \beta^*_{y,2}}{2\pi\gamma_2\sigma_{y,1}(\sigma_{x,1} + \sigma_{y,1})}$$



# Hourglass effect, high crossing



Making the beta function very small will not work either, because it can not go below the bunch length without losing luminosity.



A solution is to make the crossing angle so large that only a small fraction of the beams are colliding

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$