Mechanical Effects on Beam Stability

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Outline

I. Introduction
II. The Effects on Beam Orbit and Beam Size
III. Thermo-mechanical Effects
IV. Mechanical Design
V. Sensors

I. Introduction

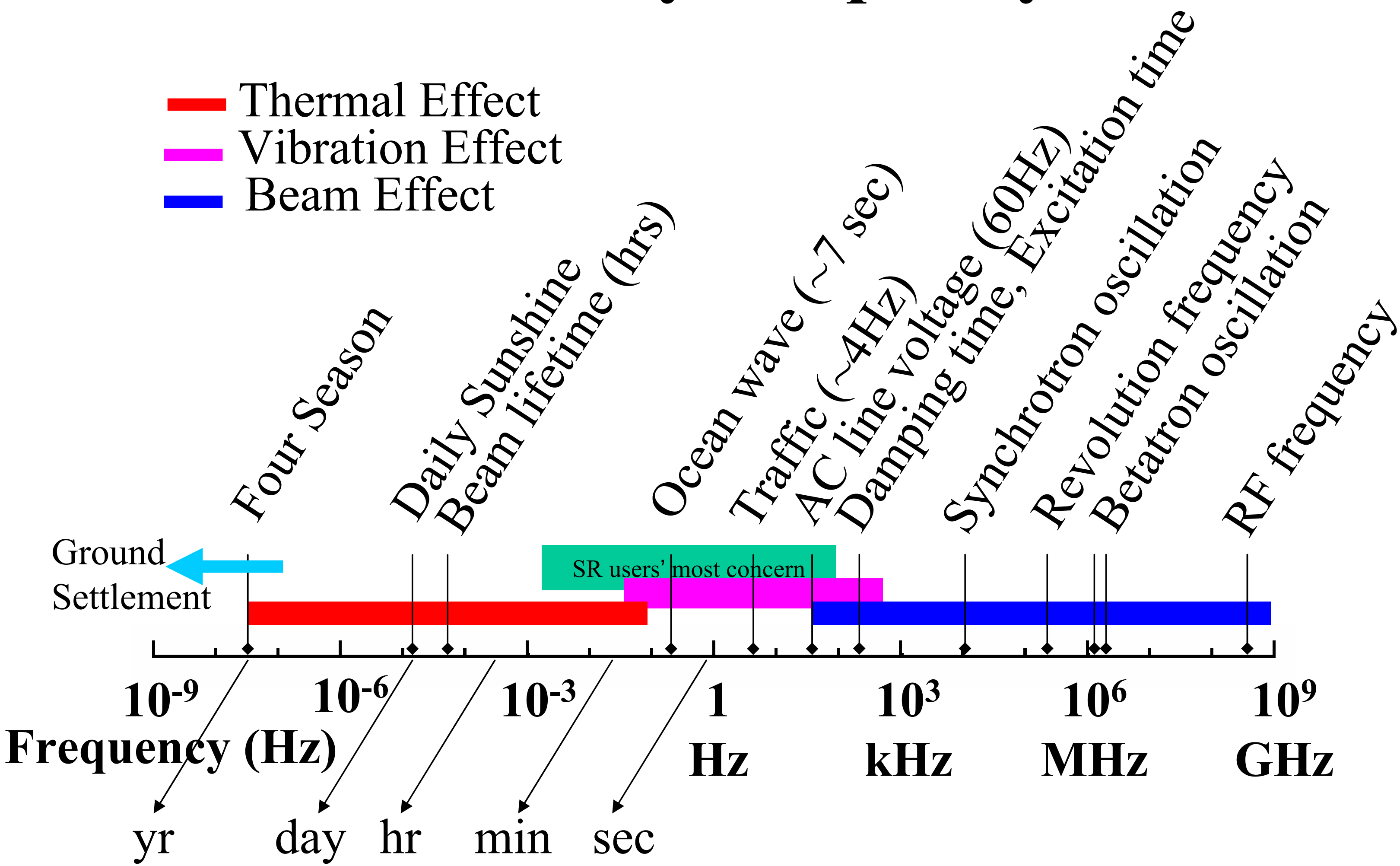
1.1 Beam Instability Frequency Domain

1.2 Heat Sources and Frequency Domain

1.3 Vibration Sources and Frequency Domain

1.4 Power Spectra Density

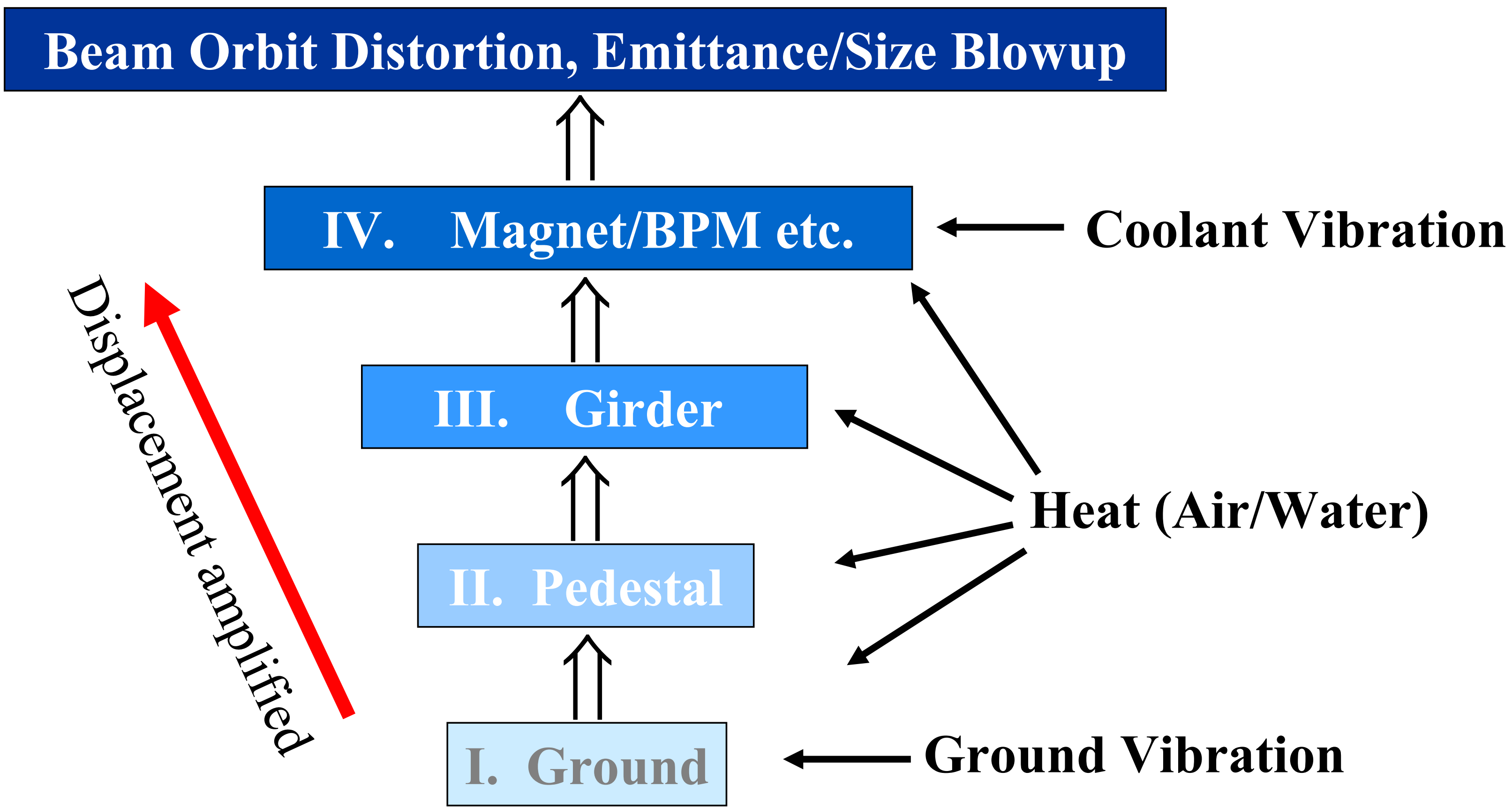
Machine Instability Frequency Domain



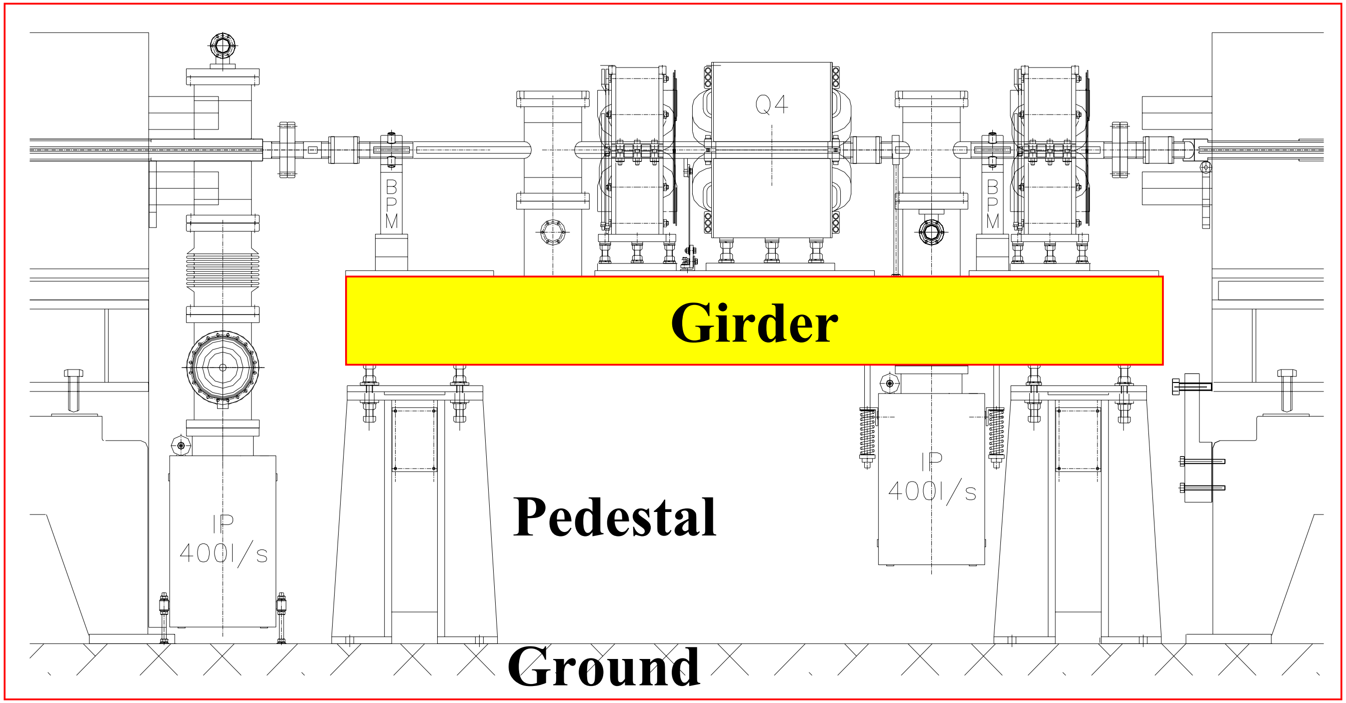
Major parameters of the TLS storage ring:

Lattice type	Combined function Triple Bend Achromat (TBA)
Operational energy	1.5 GeV
Circumference	120 m
Revolution frequency	2498.27 kHz
Orbital period	400.277 ns
RF frequency	499.654 MHz
Harmonic number	200
Bending field	1.43T
Bending radius	3.495 m
Injection energy	1.5 Gev
Natural beam emittance	2.56×10^{-8} rad-m
Natural energy spread	0.075%
Momentum compaction factor	0.00678
Damping time	
Horizontal	6.959 ms
Vertical	9.372 ms
Longitudinal	5.668 ms
Betatron tunes horizontal/vertical	7.18/4.13
Natural chromaticities	
Horizontal	-15.292
Vertical	-7.868
Synchrotron tune (RF 800KV)	$1.06*10^{-2}$
Bunch length (RF 800KV)	0.92 cm
Radiation loss per turn (dipole)	128 keV
Nominal stored current (multibunch)	200 mA
Number of stored electrons (multibunch)	$5*10^{11}$

Mechanical Effect on Beam Orbit and Size



Girder Displacement



An unstable girder will move all the components on it.

Heat Sources and Frequency Domain

1. Four Season: 1y
2. Tunnel warm up (first start up after long shutdown): ~1w
3. Sunshine: 1d
4. Beam current decay (lifetime): ~ 10 hr
5. Re-injection (energy ramp-up/down): ~ 1 hr
6. Temperature "jitter": ~ min

Vibration Sources and Frequency Domain

A. Natural

1. ATL: *PSD(f) ~ 1/f* ^{2}
2. Tide: 7 sec (Ocean wave)
3. Moon gravitation force (high/low tide): ~12 hour (long wavelength)
4. Earthquake
5. Wind: 0.03-0.1 Hz, Plane→ wind→ ground bending (HERA)
6. Long-term noise (BG): *1/f* ^{4}
7. Ground settlement

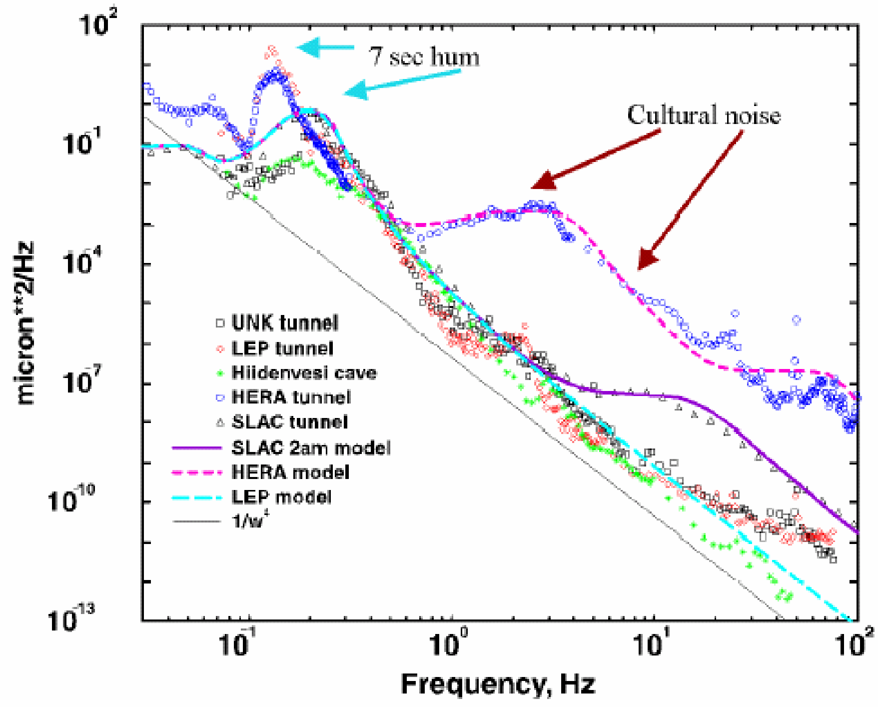
B. Traffic

1. Traffic: ~ 4 Hz (hump on road), tens Hz (peak at 30Hz, SLS)

C. Facility Equipment

1. Pumps, motors: tens Hz (15-70 Hz)
2. Water vibration : tens Hz (30 Hz, ESRF)
3. LHe flow:700-1500Hz (45g/s, SSC)

Ground vibration (A. Seryi, APAC2001)



Power spectrum of absolute ground motion measured at different sites. Smooth curves show modeling spectra. The high noise level at HERA is caused by cultural noise and, supposedly, by resonances of the clay/sandy site itself.

Power Spectra Density (vibration)

PSD (dimension: power in unit frequency band)

$$S_x(f) = \lim_{T\to\infty} \frac{2}{T} \left| \int_0^T x(t) e^{-i2\pi ft} dt \right|^2$$, Unit: μm²/Hz

$$\sigma_{rms}^2(f_1, f_2) = \int_{f_1}^{f_2} S_x(f) df$$

Spectrum of Coherence *C(f)* of two signals *x(t), y(t)*

$$C(f) = \left| \frac{\langle X(f) Y^*(f) \rangle}{\langle X(f) X^*(f) \rangle \langle Y(f) Y^*(f) \rangle} \right|$$

X(f), Y(f) are Fourier transformations of *x, y*.

II. Effects on Beam Orbit and Size

2.1 Orbit Distortion

2.2 Emittance and Beam Size Blowup

2.3 Stability Requirement for Beam Orbit and Size

Orbit Distortion

The rms closed orbit distortion $\sigma_{co}(s)$ at an azimuthal position s is

$$\sigma_{CO}(s) = \frac{\sqrt{\beta(s)}\sqrt{\langle\beta\rangle}}{2\sin\pi\nu}\frac{\sigma_q}{|F|}\sqrt{N}$$

with betatron tune ν, focal length *F*, uncorrelated transverse rms quadrupole misalignment σ_q, and number N of identical FODO cells. The average $<\beta>$ is taken at the quadrupoles.

$\sigma_{CO}(s) = K\sigma_q$ (amplification factor, $K \approx 30$ for TLS)

Emittance and Beam Size Blowup

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \text{constant}$$

$$\varepsilon_y \cong k\,\varepsilon \qquad (k = \text{coupling}, \quad k <\sim 0.1)$$

$$\alpha = -\beta'/2 \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

$$\sigma_x(s) = \sqrt{\varepsilon_x \beta_x(s) + (\eta(s)\delta E/E)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y \beta_y(s)}$$

$$\sigma_{x'}(s) = \sqrt{\varepsilon_x \gamma_x(s) + (\eta'(s)\delta E/E)^2} \qquad \sigma_{y'}(s) = \sqrt{\varepsilon_y \gamma_y(s)}$$

Couplings:
H→V: by skew quads, orbit in sextupoles, resonances
longitudinal→ transverse: $\Delta x = \eta\Delta E/E$, scattering etc.

Emittance and Beam Size Blowup (conti.)

Transverse emittance growth due to fast (turn to turn) dipole angular kicks $\delta\theta$ produced by bending field $\Delta B/B$ fluctuations in dipole magnets or by fast motion of quadrupoles σ_q which has a rate of

$$d\varepsilon_N / dt = (1/2)\gamma\langle\beta\rangle N_q f_0^2 S_{\delta\theta}(\Delta\nu f_0)$$

$$\approx (1/2)\gamma\langle\beta\rangle f_0 N_q (\sigma_q / F)^2$$

where f_0 is the revolution frequency, $\Delta\nu$ is fractal part of tune, $S_{\delta\theta}$ is the PSD of $\delta\theta = \sigma_q$ /F.

(V. Shiltsev, EPAC 96)

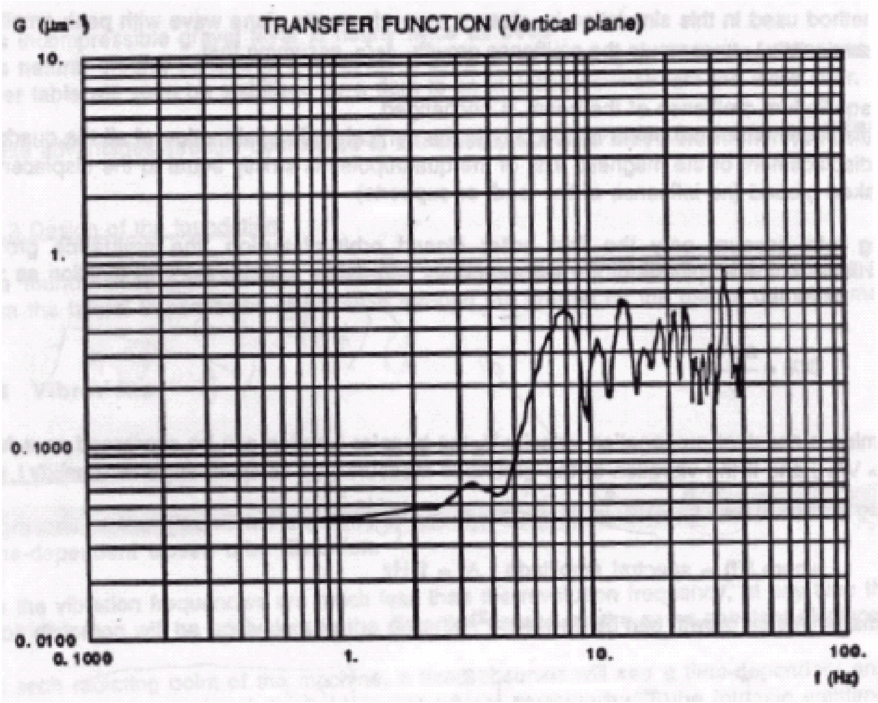
ESRF

- **Transfer function**
  (ground vibration ***d(f)*** →e-beam emittance growth $\Delta\varepsilon/\varepsilon$)

$$G(f) = \frac{\Delta\varepsilon/\varepsilon}{d(f)}$$

→ **e-beam sensitive to vibrations f > 4Hz**

"ESRF foundation phase report", 1987



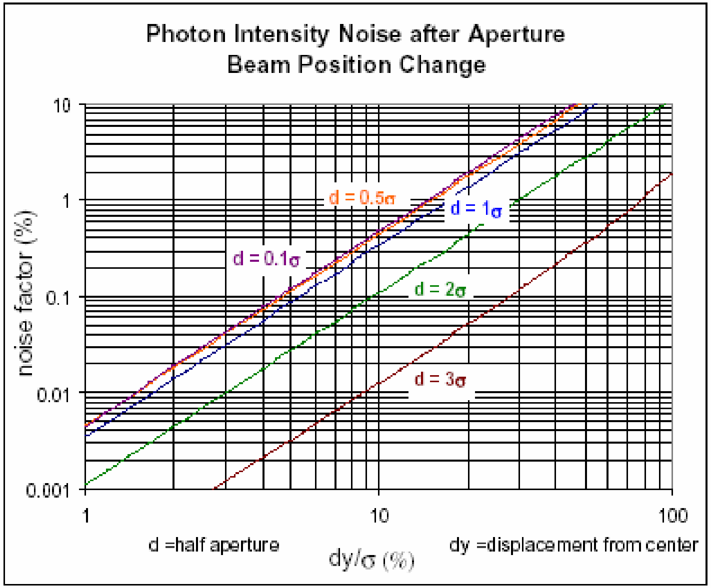
Stability Requirement on Beam Orbit and Size

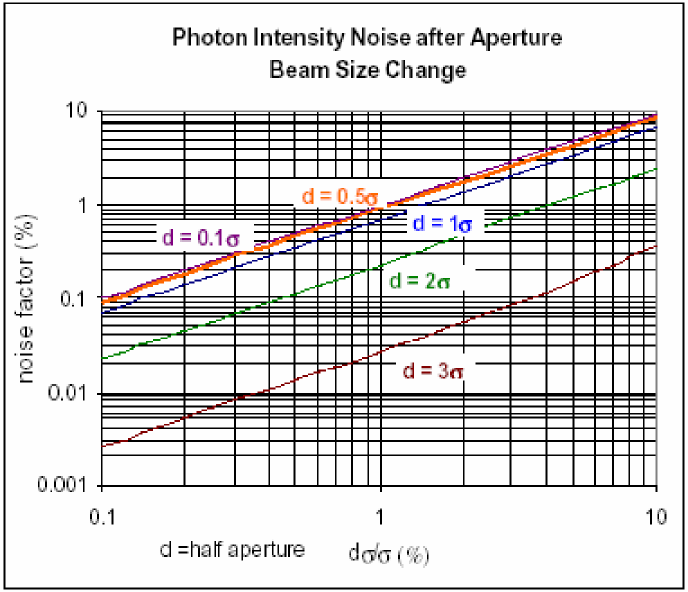
Intensity fluctuation after aperture: <0.1%
(some experiments require < 0.01%)

➔Beam orbit fluctuation < 0.05 beam size
➔Beam size fluctuation < 0.01 beam size

(Gaussian beam size)
(aperture full dimension = 1x beam size)

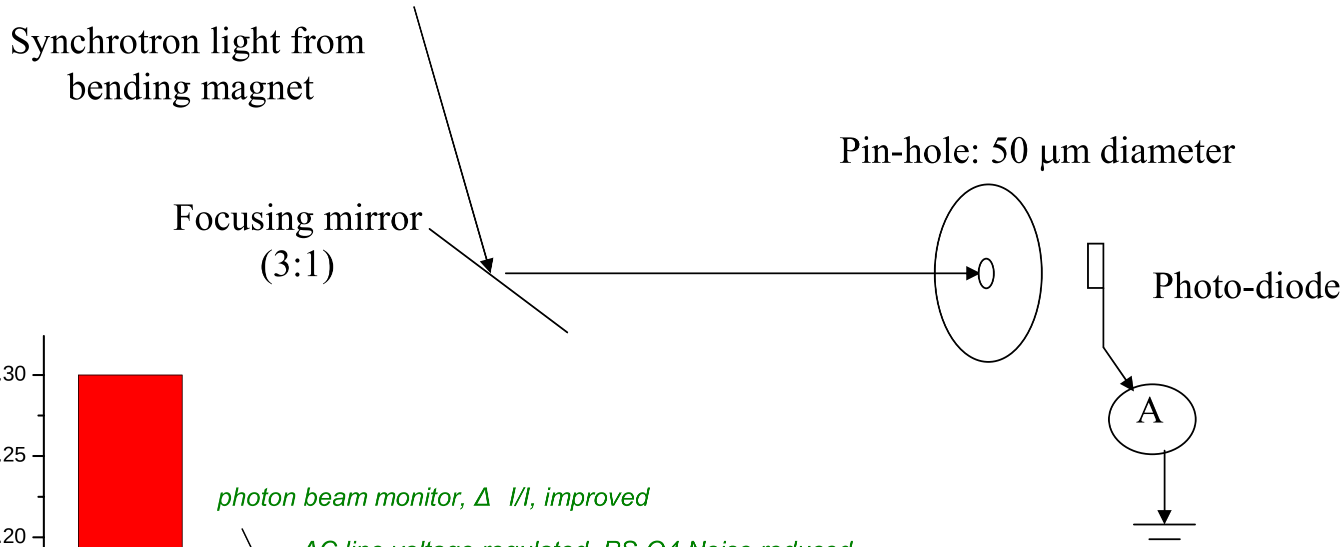
Beam Stability at Apertures

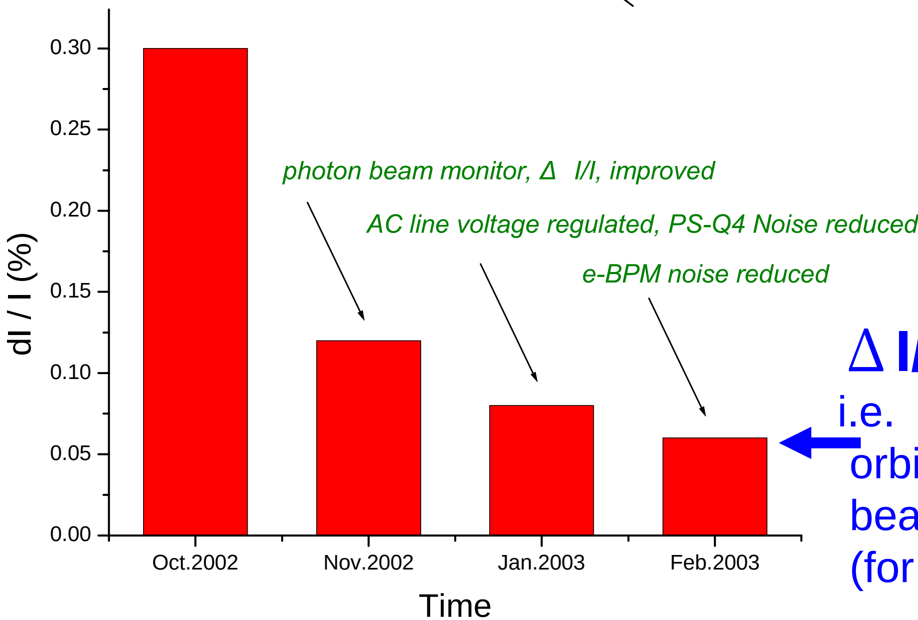




Intensity variations for beam with Gaussian size σ due to position motion dy from the center and beam size change dσ for various sized apertures.

Photon Beam Intensity Fluctuation
(ΔI Monitor)





Δ I/I ≈ 0.06%

i.e.

orbit fluctuation <2μm

beam size fluctuation <0.1μm

(for Gaussian Beam)

III. Thermo-mechanical Effects

3.1 Dynamic Mechanical Considerations

3.2 Sources, Routes and Sensitivity of the Thermo-mechanical Effects

3.3 Temperature Control

Dynamic Mechanical Considerations

*Sources of Noise
--- Air Temperature
--- Water Temperature
--- Synchrotron Light
--- Electrical Power (electrical heating)

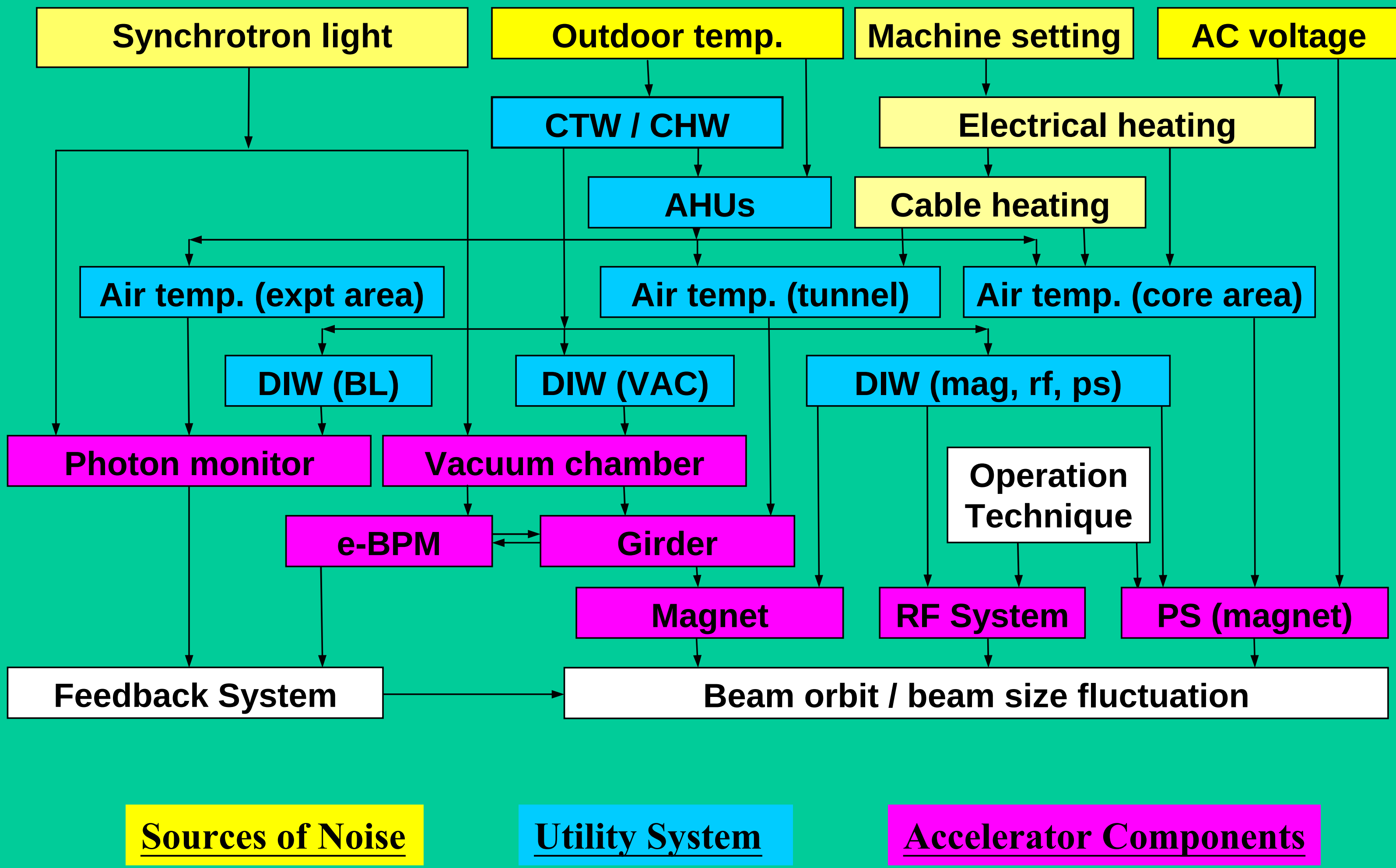
**Mechanical Effects
--- Girder
--- Vacuum Chamber
--- RF Cavity
--- Monitors

***Sensors and Control
--- Temperature/Position Sensors
--- Control Systems

Sources, Routes and Sensitivity of the Thermo-mechanical Effects

- Air Temperature Fluctuation
- Synchrotron Light Irradiation
- Power Supply and Electrical Heating
- Water Temperature Fluctuation (magnet, rf cavity, etc.)

Propagation chart from heat sources to the fluctuations in beam orbit and beam size (TLS)



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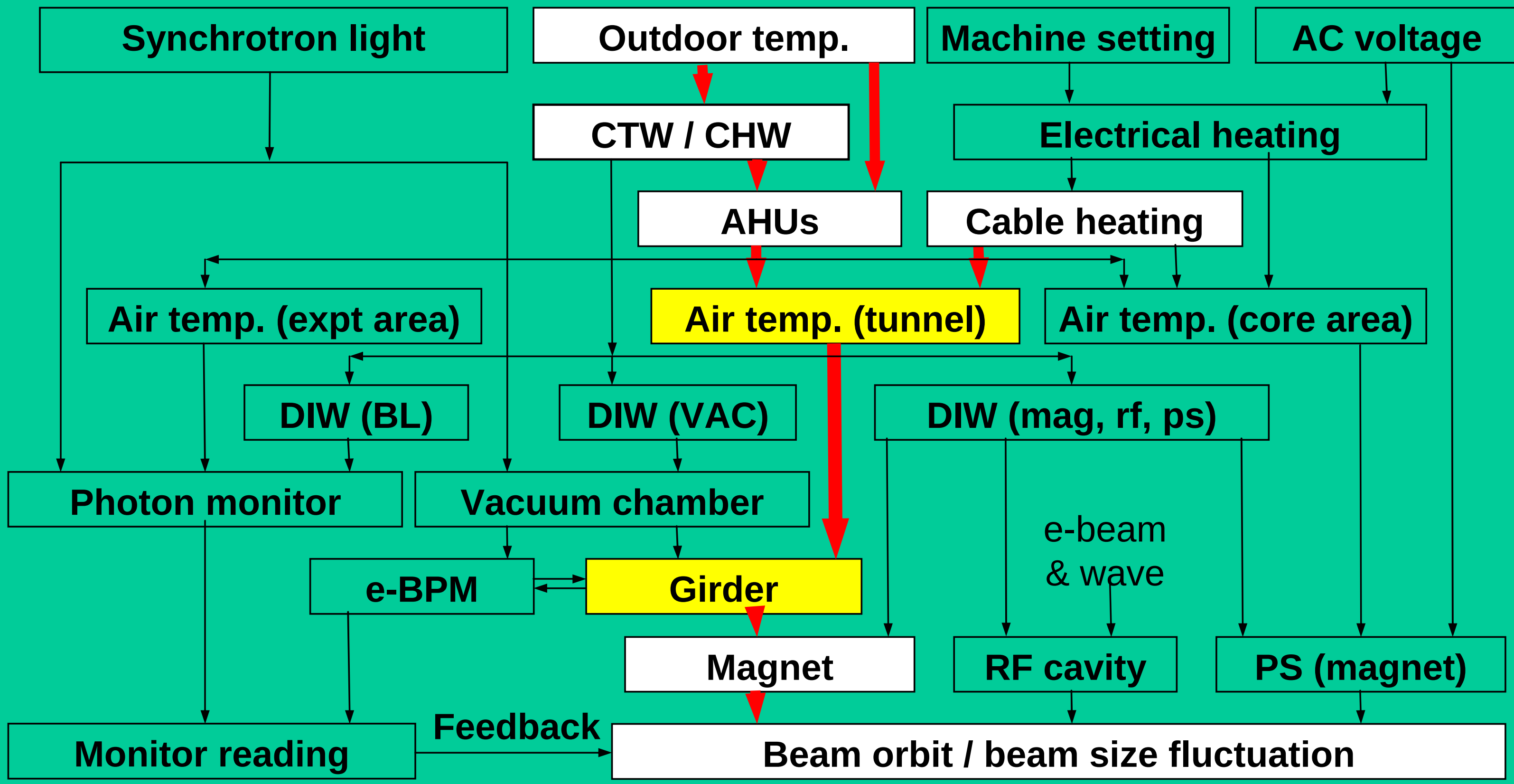
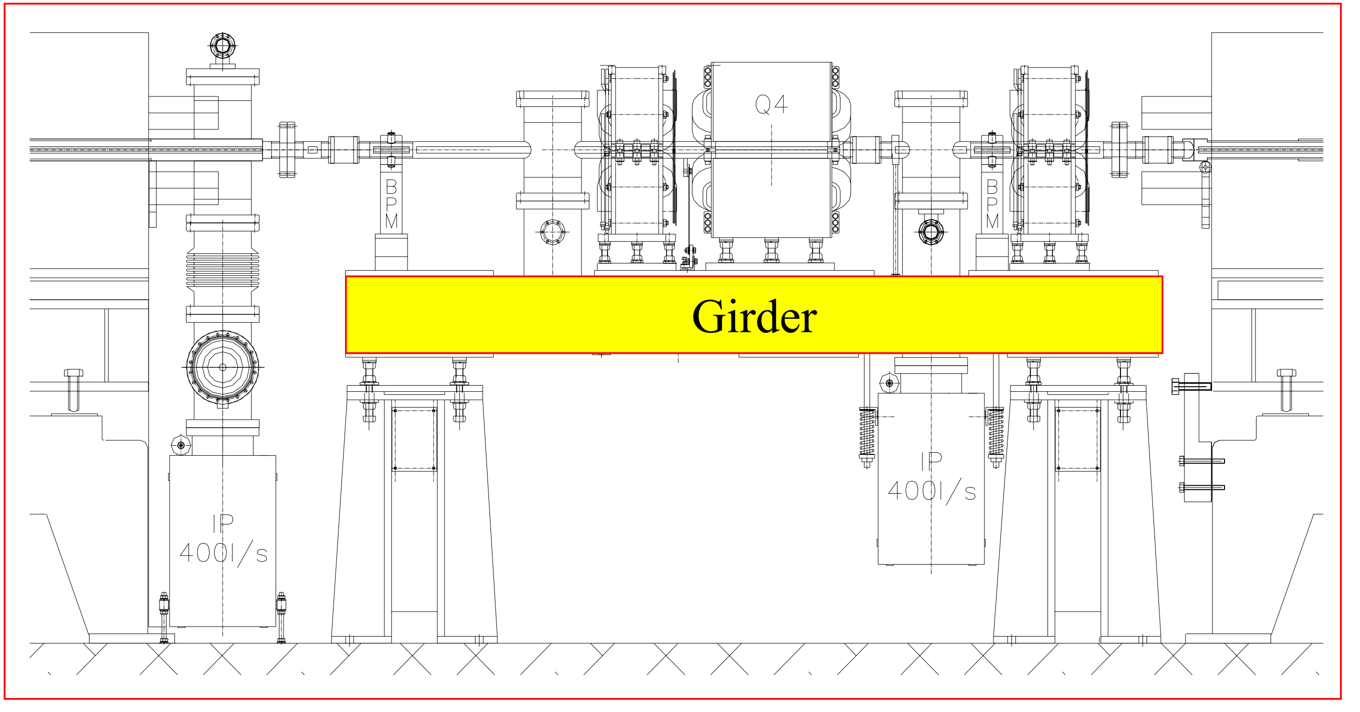
Air Temperature Fluctuation
-- Girder Displacement --

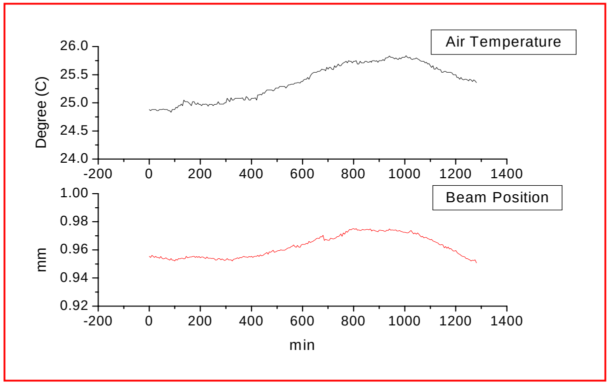


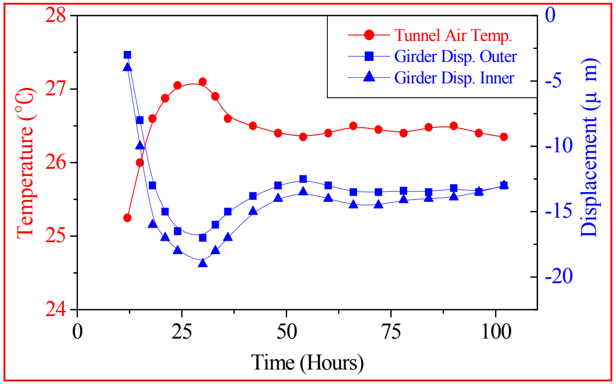
Girder Displacement



An unstable girder will move all the components on it.

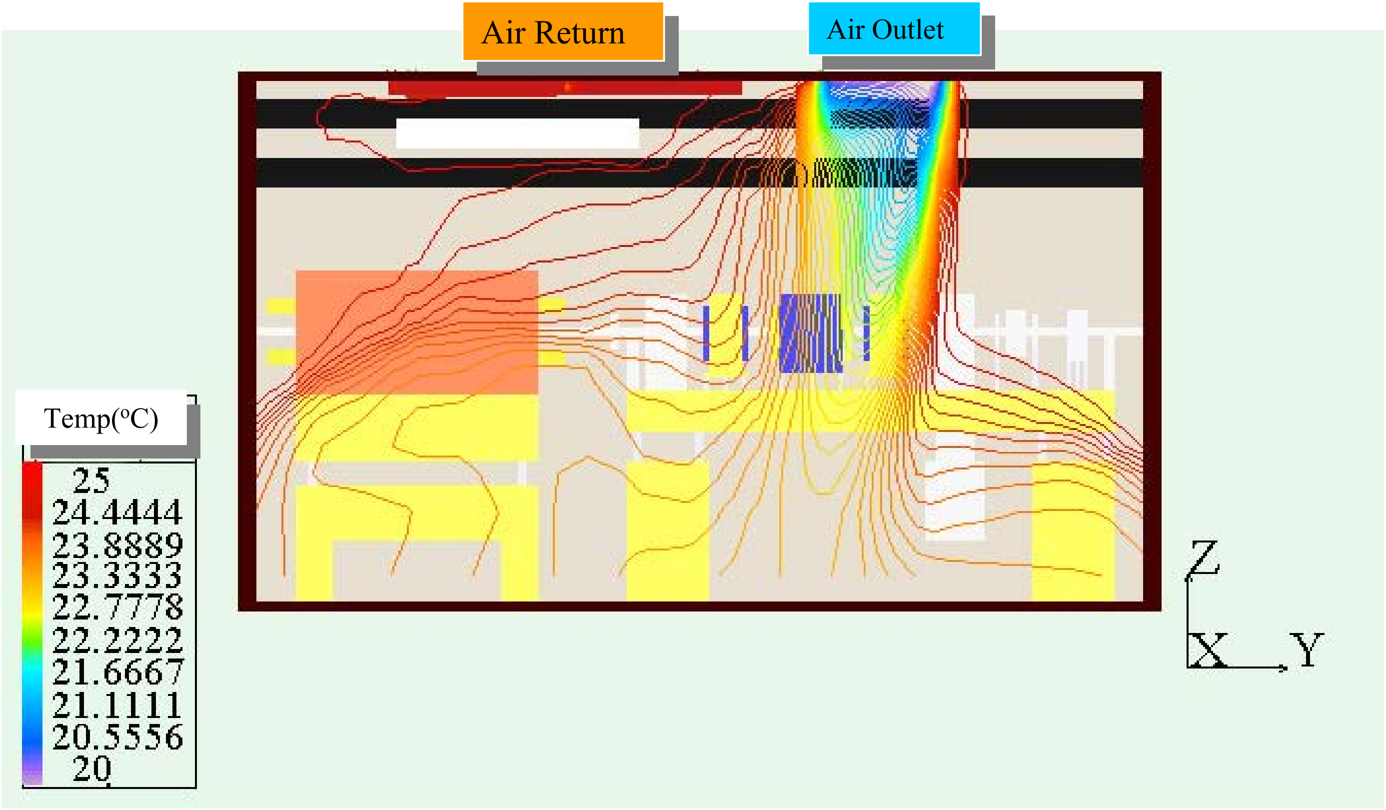
Girder Displacement



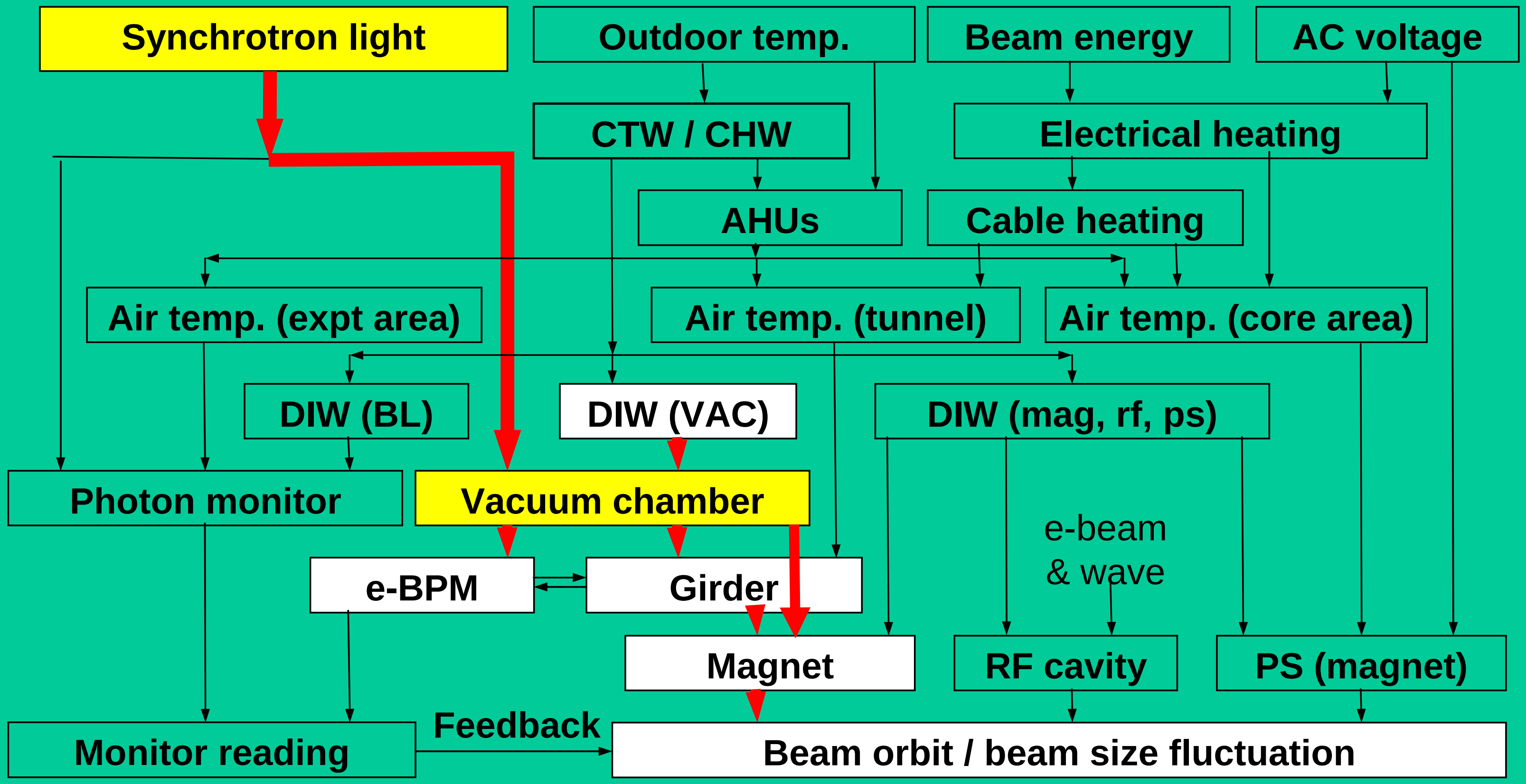


- Main cause: air temperature
  Sensitivity to air temp.: ~10 μ m / °C
  Induced beam orbit drift: 20-100 μ m / °C
- Current status: < ± 0.1 μ m per 8 hr shift
  Air temp. : < ± 0.1°C (utility control system improved)
  Thermal insulator jacket

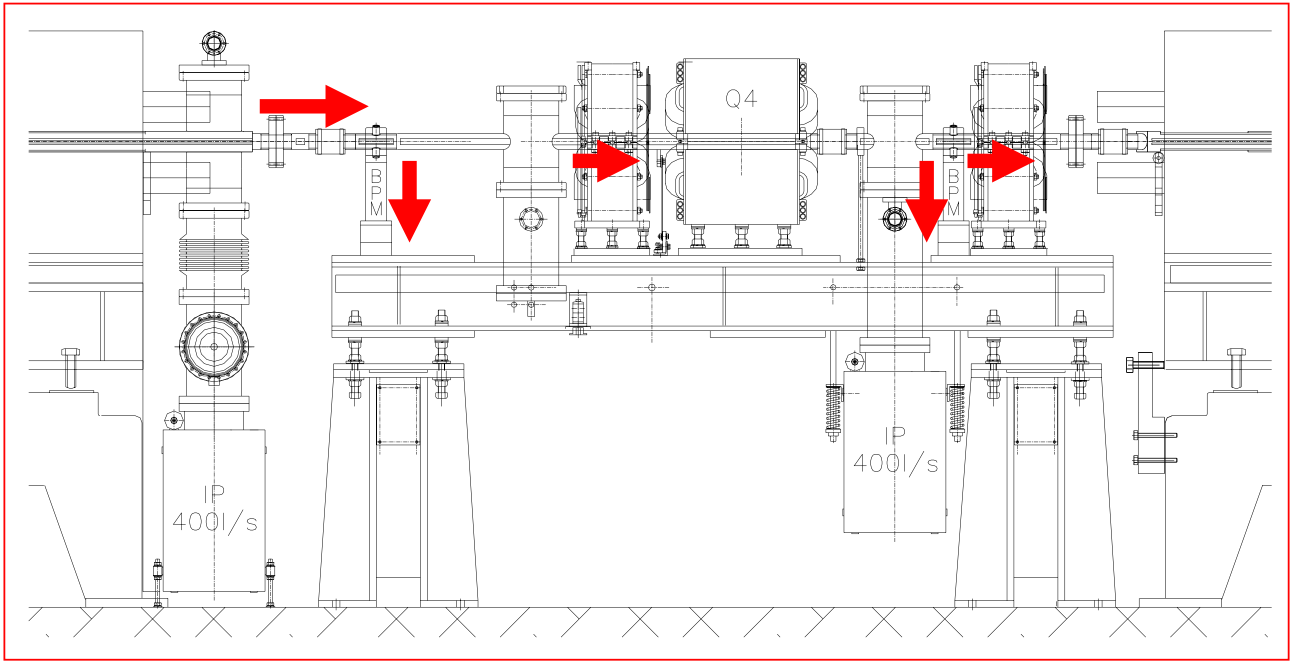
Non-uniform Temperature Distribution



Synchrotron Light Irradiation
-- Expansion of Vacuum Chamber --

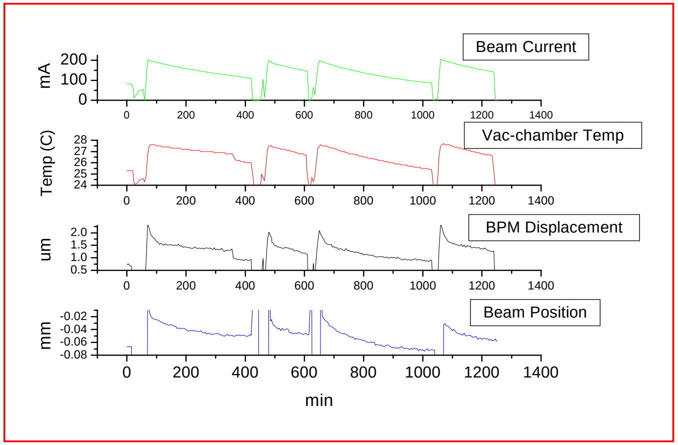


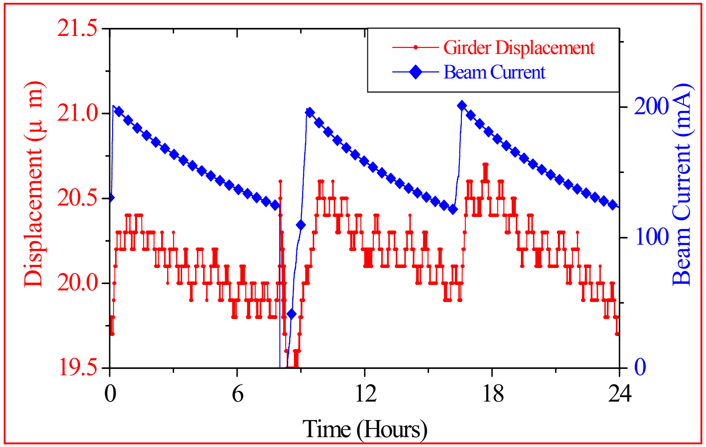
Expansion of Vacuum Chamber



The expanded vacuum chamber moves the components touched or connected to it. The force transferred to the girder.

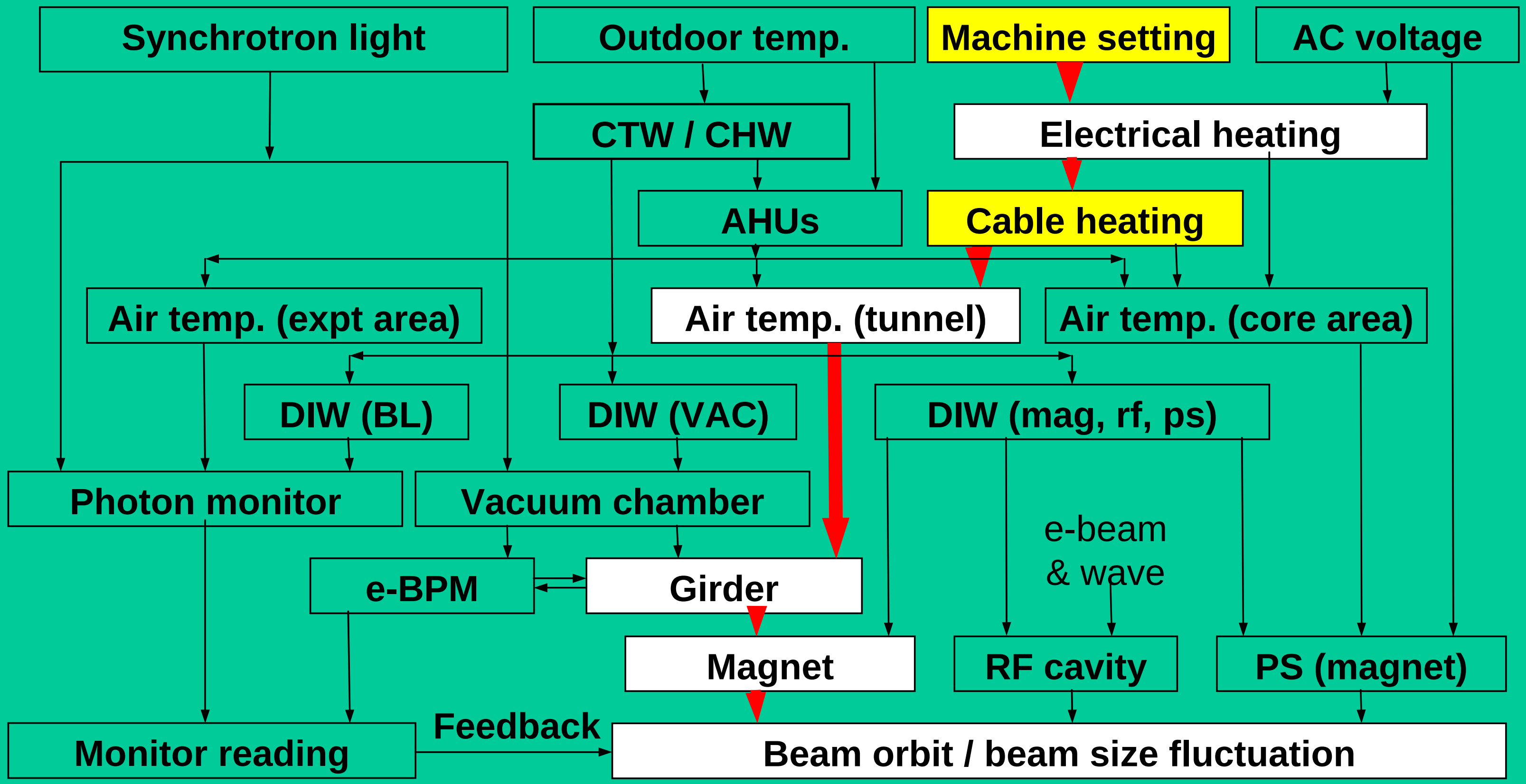
Expansion of Vacuum Chamber



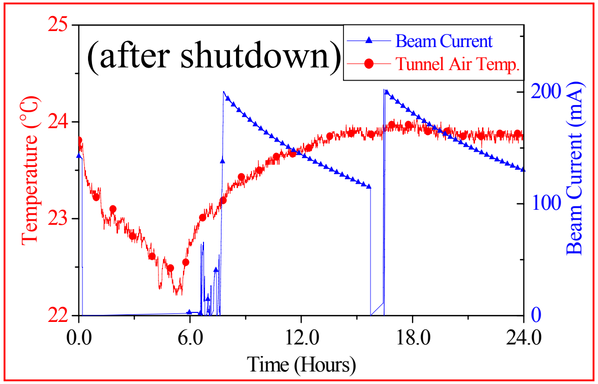


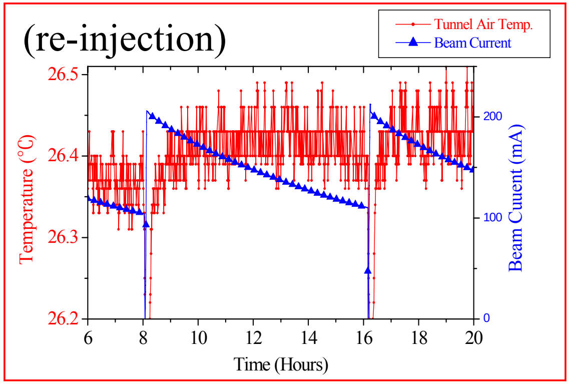
- Caused by synchrotron light irradiation.
  Sensitivity to water temp.: ~10 μ m / °C
  Move the girder (~0.3 μ m/°C) and BPM (~1 μ m/°C)
  Induced beam orbit drift: ~10-30 μ m / °C
- Current status
  Vacuum cooling water temp.: ~ ± 0.5°C
  (**Should be greatly improved after adopting Top-up Injection**)

Power Supply and Electrical Effect (1)



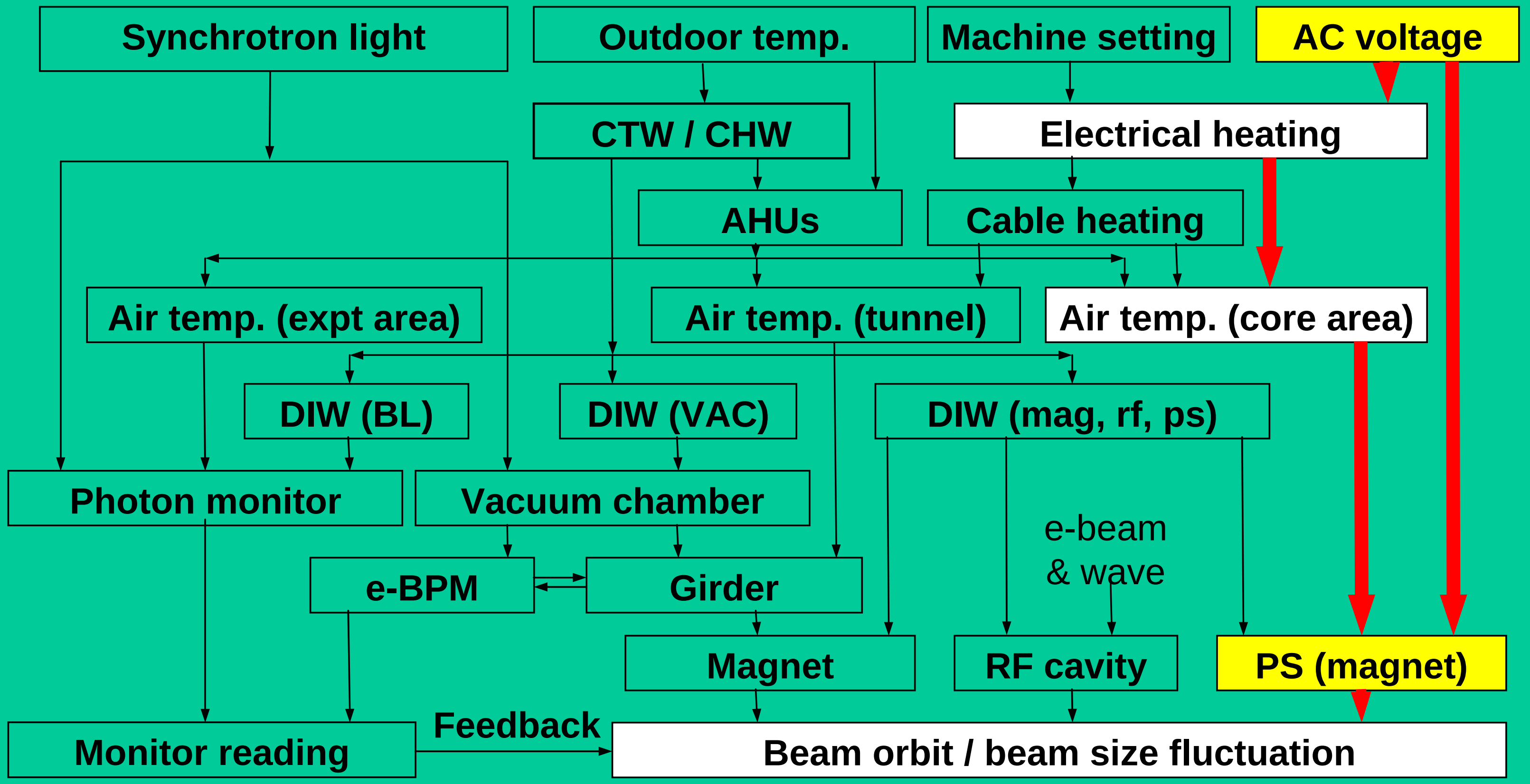
Power Supply and Electrical Heating (1)



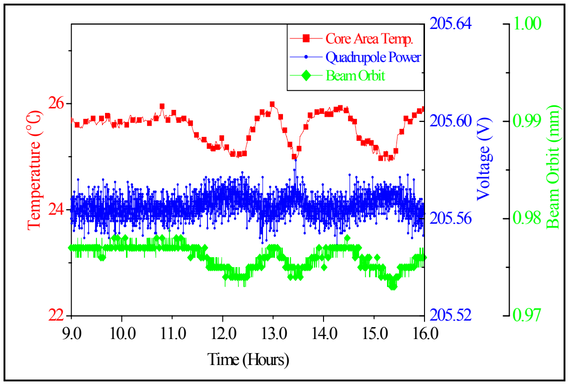


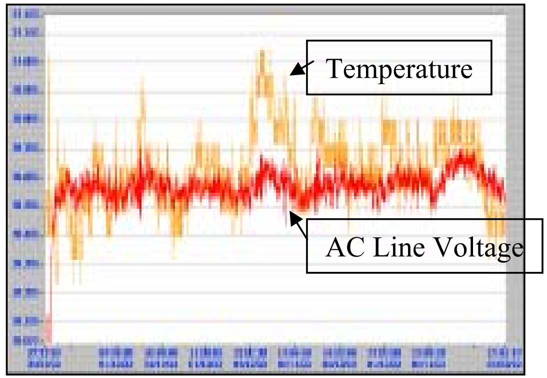
- **Transient after injection or shut down**
  Heat source: mainly dipole-cables
- **Transient time**
  ~ 0.5 hr (after injection, insignificant after injector energy increased from 1.3 GeV to 1.5 GeV)
  ΔT: > 0.5 ℃ ➔ ΔT: < 0.2 ℃
  ~ 12 hr (after shut down), it's better not to turn PS off
  ΔT: >1.5 ℃

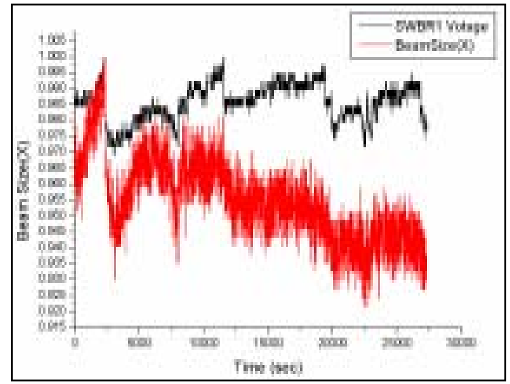
Power Supply and Electrical Effect (2)



Power Supply and Electrical Heating (2)





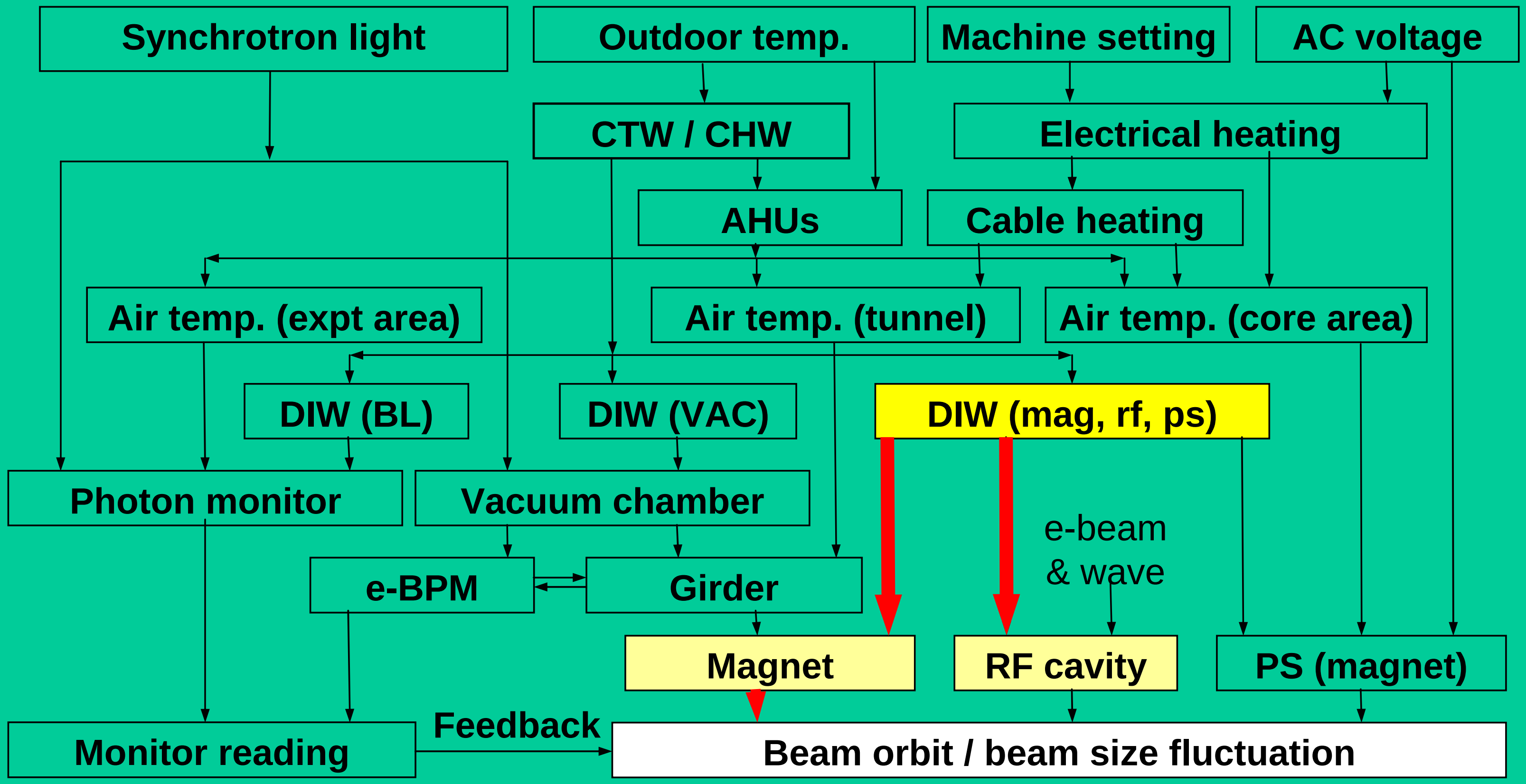


- **Phenomenon**
  - **AC line voltage ➔air temperature**
  - **AC line voltage ➔ output of DC-PS**
  - **Sensitivity: ~5 μm / ℃**
- **Current Status**
  - **Air temperature (core area): ~±0.3℃**
  - **A.C. line voltage fluctuation : ~±1.5%**
  - **(~±0.05% for PS-Q4)**

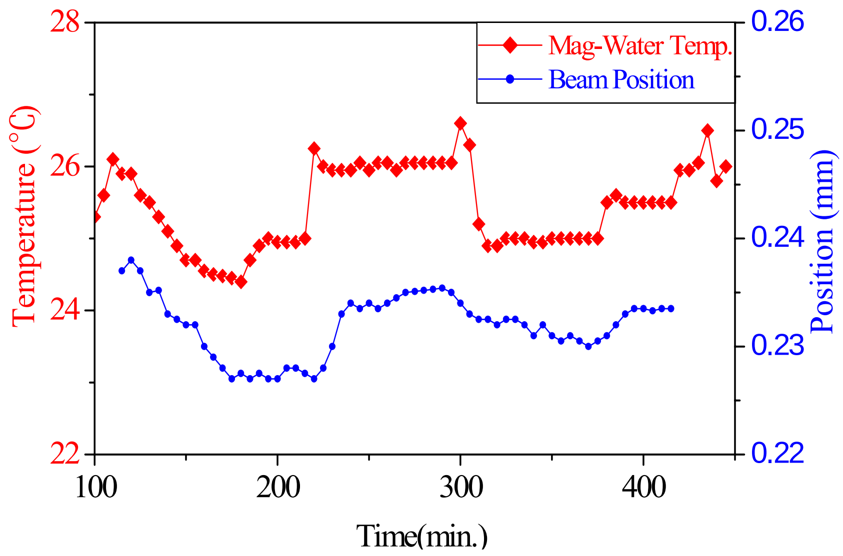
AC Line Voltage
➔Transmitter Water Temp.
➔ horizontal beam size

(Beam size): ~1 μm/Volt

Water Temperature Fluctuation
-- Magnet & RF cavity --



Magnet (Water Temp.)



Caused by the temperature fluctuations of magnet cooling water

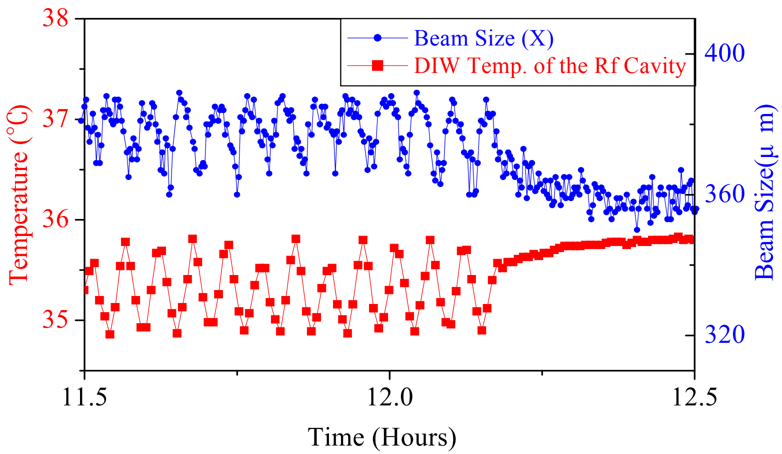
Magnet deformed ~10 μ m/℃

Induced beam orbit drift: 5-50 μ m / ℃

Current status

Cooling water temp.: ~ ± 0.1℃

Beam Size Fluctuation Induced by RF-Water Temp.



- **Phenomenon**
  Water temperature ➔ beam size (x)
  Sensitivity: ~20 μm/℃ (hor.)

- **Current Status**
  Water temperature (rf): < ± 0.02℃

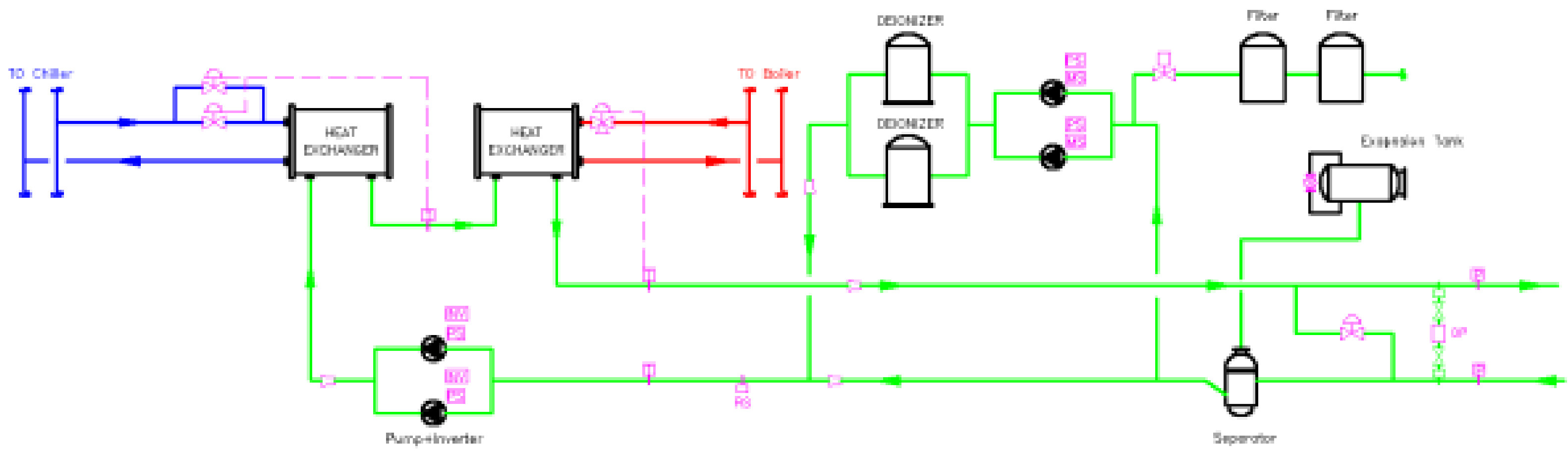
Sensitivity of the fluctuations in beam orbit, beam size and the displacements of main components to the fluctuations in the air and water temperatures

Heat source	Current Temp. Fluctuation	Amplification factor		Amplification factor (component displacement)		
		Beam orbit	Beam size	Girder	Magnet	BPM
Air Temp.	< ±0.1℃	20-100μm/℃	-	~10 μm/℃ (ver.)	-	-
Water Temp. (magnet)	< ±0.1℃	5-50 μm/℃	-	-	~10μm/℃	-
Water Temp. (rf)	< ±0.02℃	-	~20 μm/℃ (hor.)	-	-	-
Water Temp. (vac-outlet)	~ ±0.5℃	10-30μm/℃	-	~0.3μm/℃	-	~1 μm/℃

Water Temperature Control

- **Controlled step by step:**
  CTW→ CHW(&HTW) (± 0.3℃) → DIW (± 0.1℃)
- **Device linearity and resolution (e.g. valves)**
  Two smaller valves with better resolution, instead of one.
- **Variable frequency controller**
  To control the stability of water pressure (flow rate)
- **Buffer tank (or heater + mixing heat exchanger)**
  To further smooth the temperature fluctuation (± 0.01℃)
- **Capacity (heat exchanger)**

Deionized Water (Cu System)



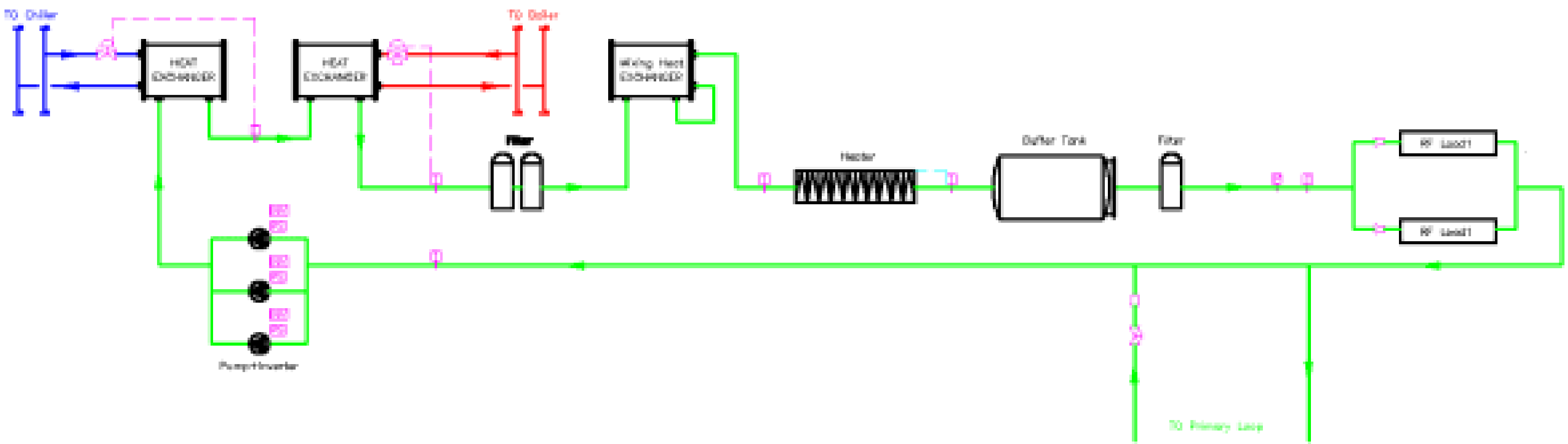
Water Pressure Control:

- **Fluctuation: <1%**
- **Sensor: Pressure Gauge**
- **Pump: Variable Frequency Controller**

Water Temperature Control:

- **Fluctuation: < ± 0.1℃**
- **Sensor: Thermocouple**
- **Valve: Electrical Actuator**

Deionized Water (RF 2nd System)



Water Pressure Control:

(same as Cu-water system)

Water Temperature Control:

Buffer Tank: Mixing

Fluctuation: < ± 0.01°C

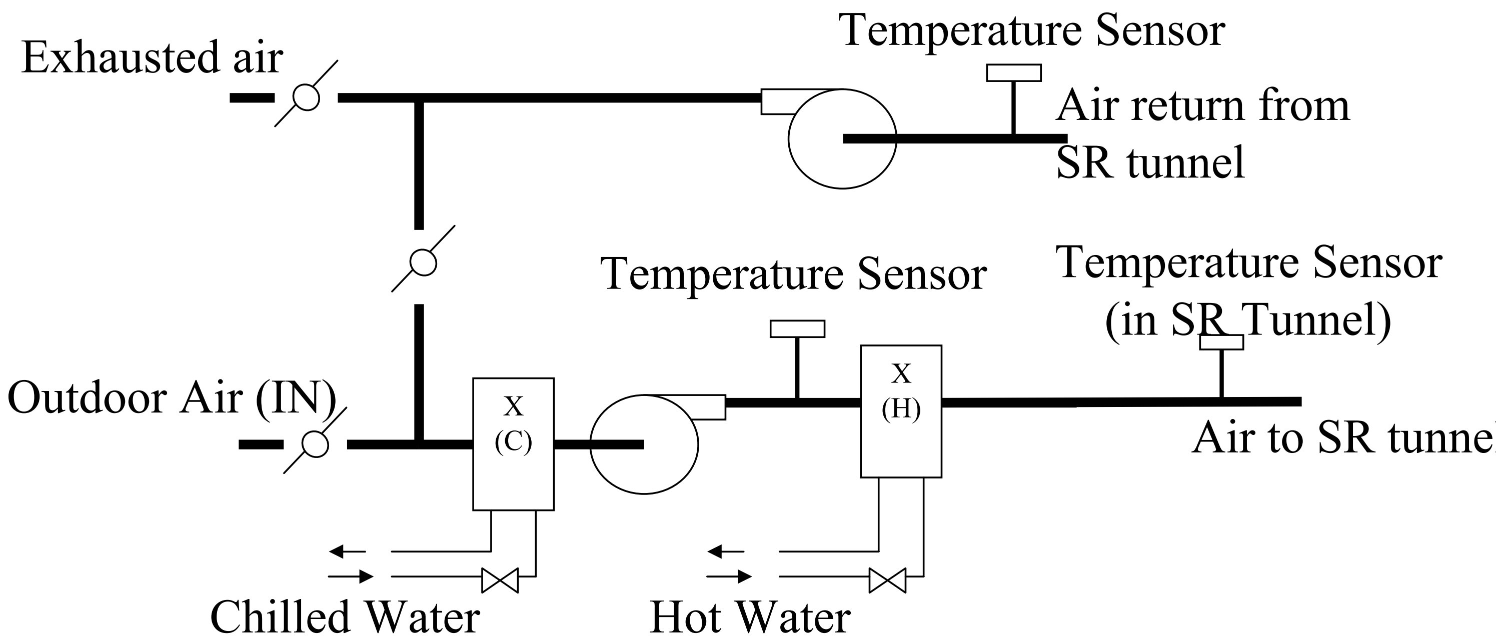
Sensor: high resolution temperature sensor

Valve: Electrical Actuator

Air Temperature Control

- AHU System
- Temperature Uniformity
- Thermal Insulator

AHU System (TLS)



CHW & HTW Temperature Control:

Fluctuation: < ± 0.3℃

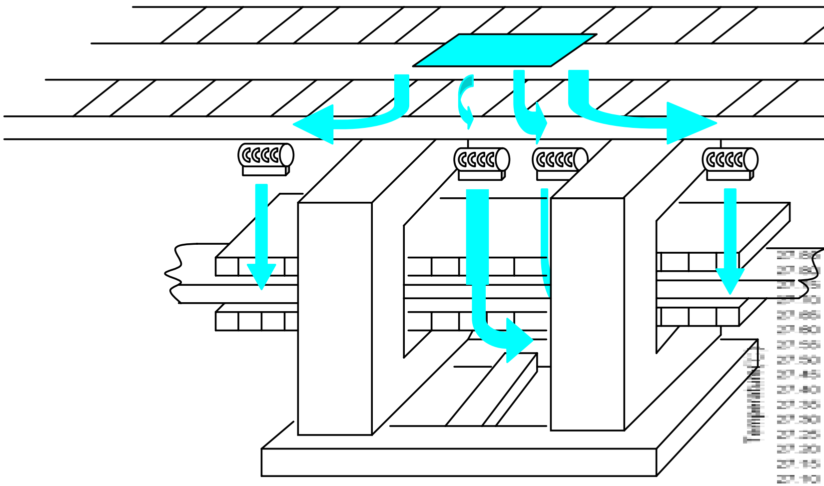
Air Temperature Control:

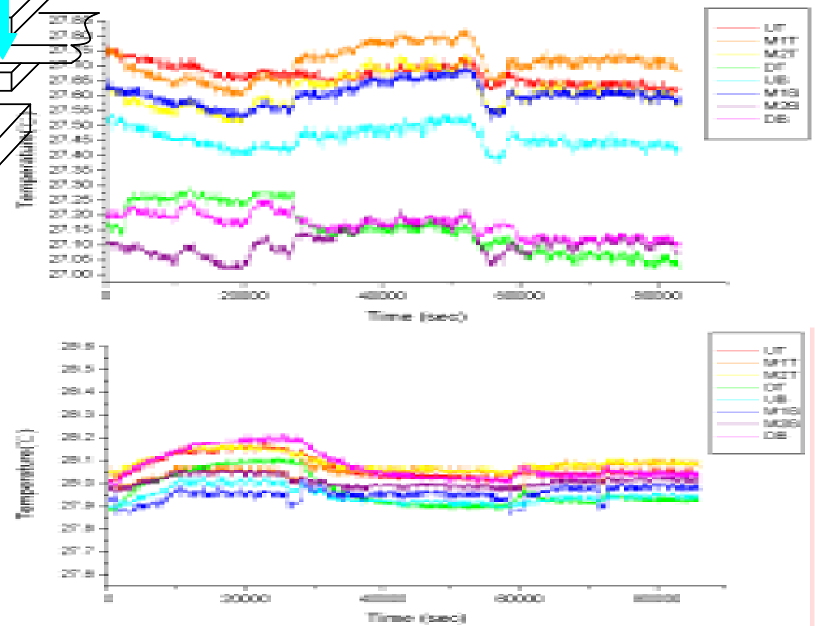
Fluctuation: < ± 0.15℃

Sensor: Thermocouple (SR)

Valve: CHW valve

Air Flow Uniformity Control (ID)





Girder with thermal insulation.
Transient time constant → Longer (smoothing effect)

IV. Mechanical Design

4.1 Ground

4.2 Structure of Girder Magnet Assembly

Ground

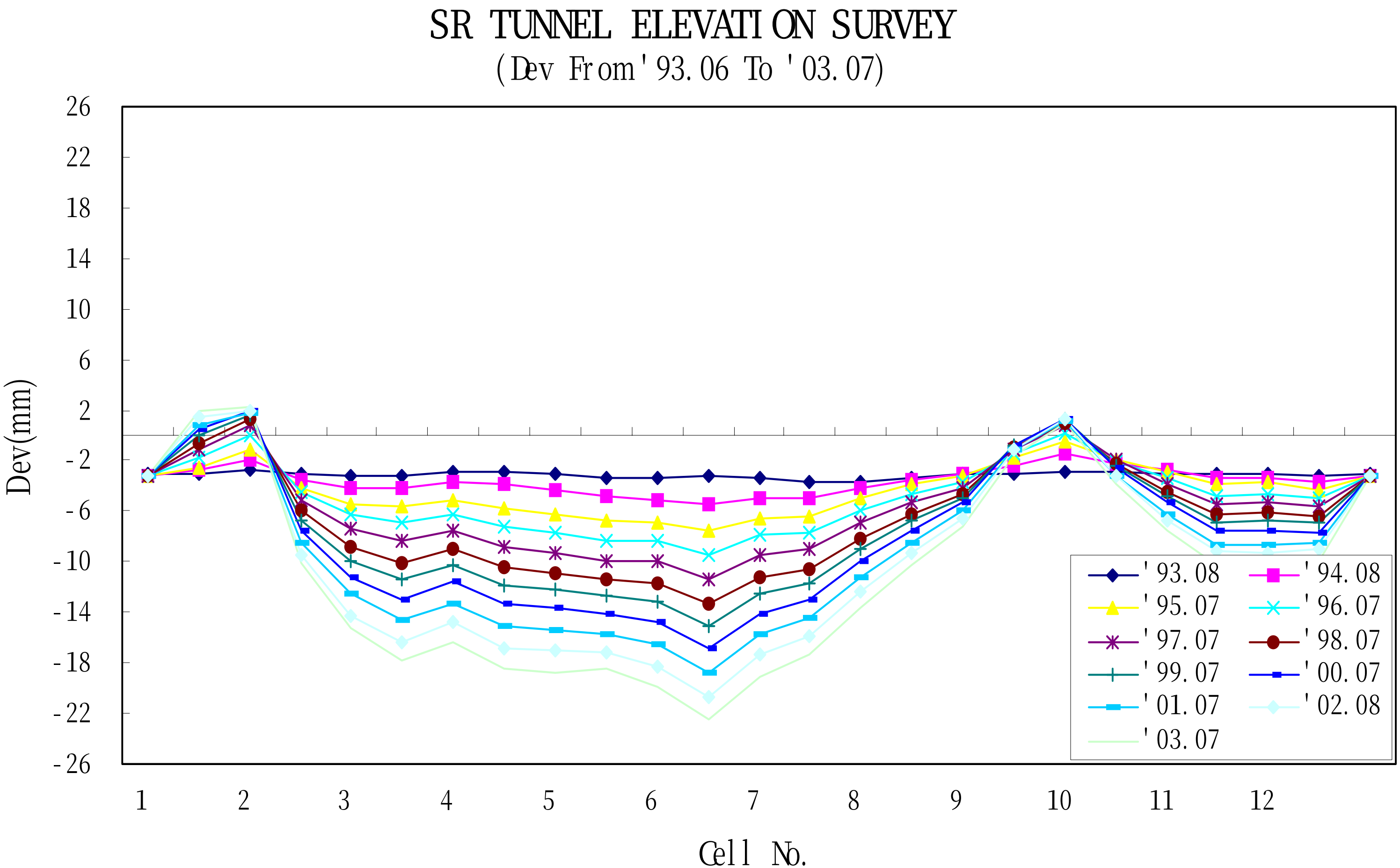
- Ground Motion
  settlement: ESRF, PLS (~2mm/year)
  ➔ Site selection (underground composition)
  ➔ Same Base (move as a whole)
  ➔ No Underground Hollow

- Ground wave isolation
  Trench around the structure: ESRF 3m deep
  Expansion joint
  Damping of soil and concrete slab

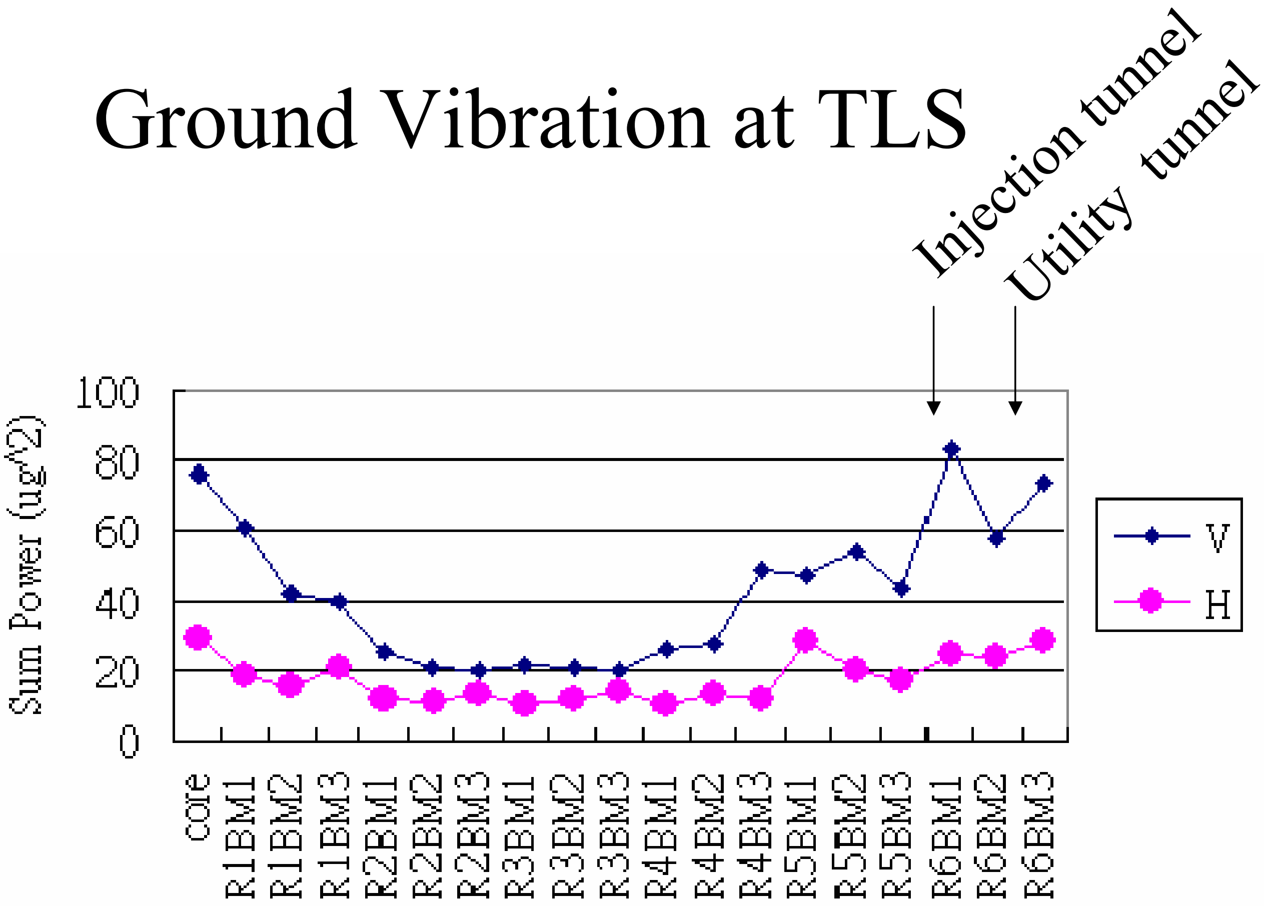
- Vibrating Equipment
  Vibration Reduction/Isolation
  Away from Light source

Ground Motion (PLS)

(In Soo Ko, APAC2004)

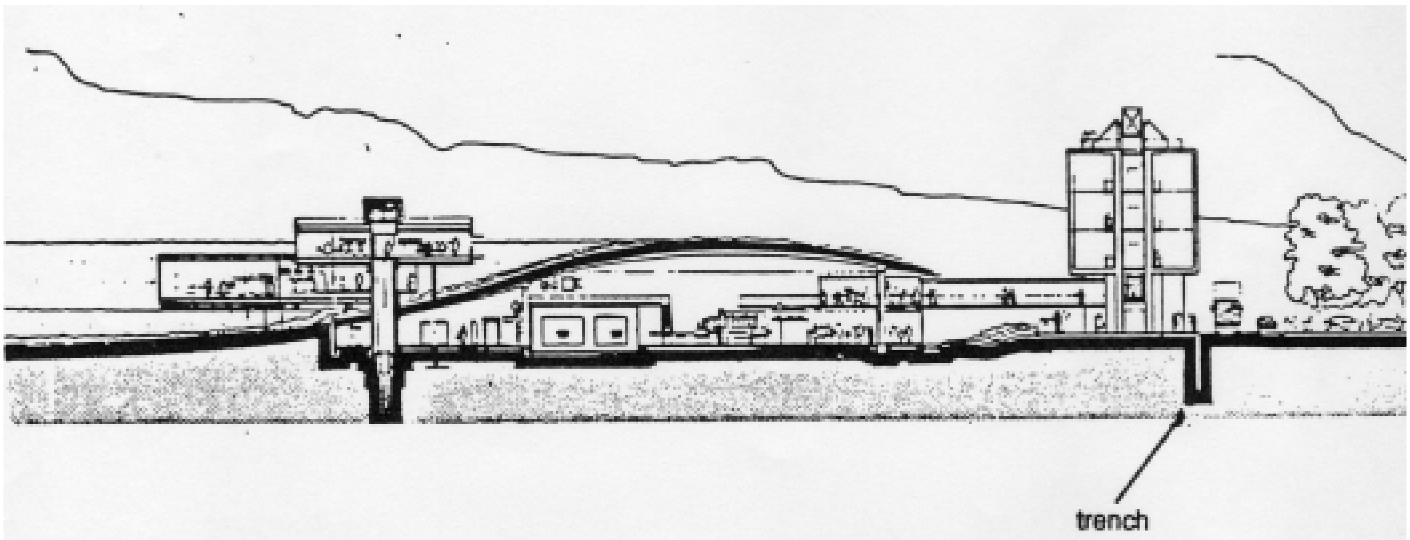


Ground Vibration at TLS

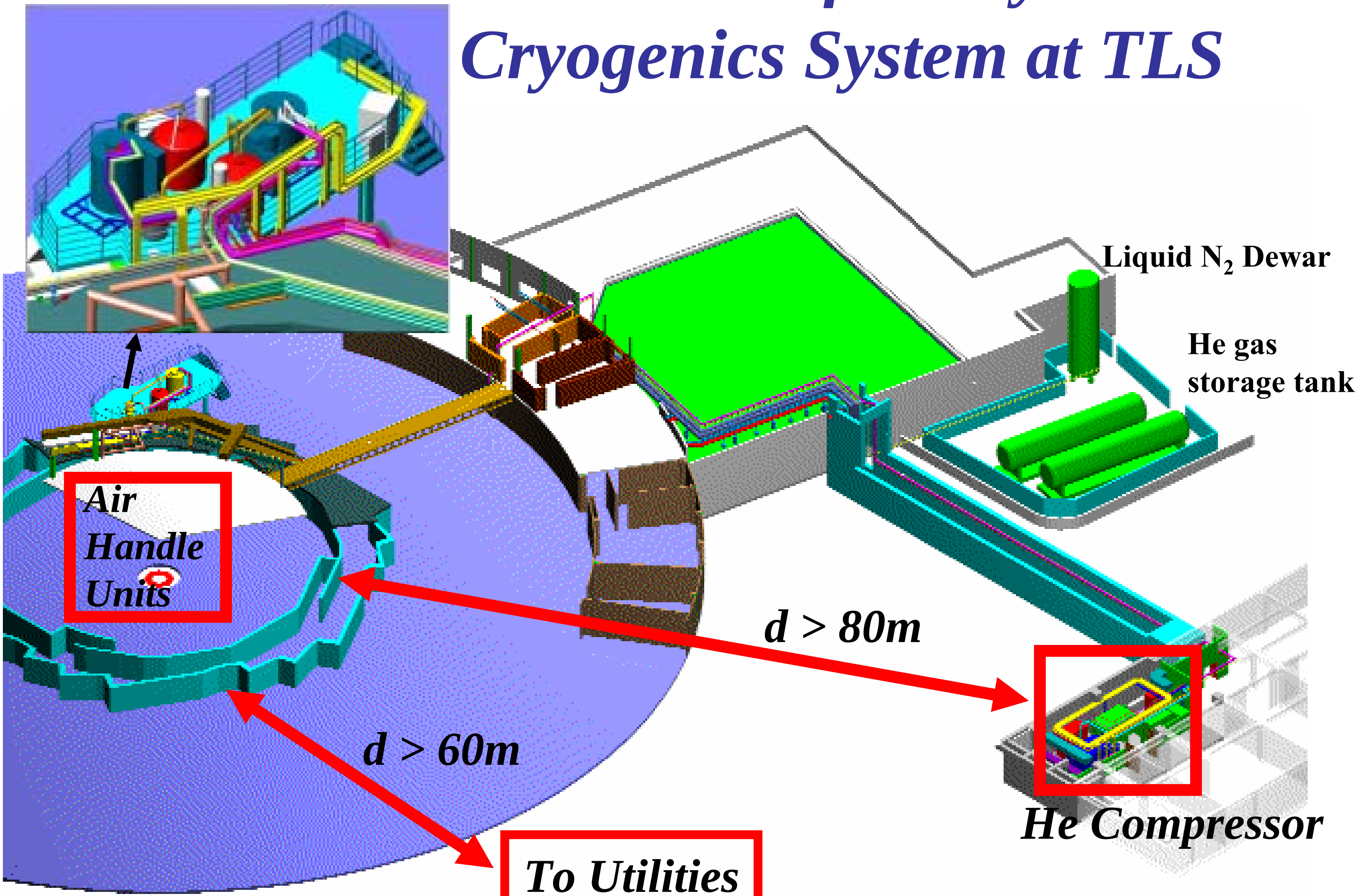


Ground wave isolation – ESRF

“ESRF foundation phase report”, 1987



Location of Utility and Cryogenics System at TLS



Structure of Girder Magnet Assembly

1. Interaction of Ground Waves with Beam
2. Vibration Suppression

Interaction of Ground Waves with Beam

Factor 1: Damping factor of soil and concrete slab (Section 4.1)

Factor 2: Amplification factor of Girder Assembly
(Ground vibration→ Pedestal→ Girder→ Magnet)

Factor 3: COD Amplification factor
(Magnet → Beam) (Section II)

Factor 4: Attenuation factors of Fast Feedback System

The characteristic wavelengths of slow ground motions are far greater than betatron wavelength, the dynamic effects to the beam can be neglected.

Betatron wavelength

$\lambda_{\beta y} = C/\nu_y = 120\ m / 4.13 = 29\ m$

$\lambda_{\beta x} = C/\nu_x = 120\ m / 7.18 = 16.7\ m$

Assume υ = 500 m/s (soft ground)

→ $f_\beta = \upsilon / \lambda$ **= 17 Hz --- vertical**

= 30 Hz --- horizontal

→ **For frequencies << f_β, the effects to the beam can be neglected.**

Vertical orbit distortion (no amplification in GA)

$$y_c(t) = \mathrm{Re}\{\frac{\sqrt{\beta_0}}{2\sin\pi\nu_y}\frac{\hat{y}}{F}e^{i(\omega t+\phi_0)}$$

$$\times[\sum_{n=2}^{2N}\sqrt{\hat{\beta}}e^{i(C/\lambda)\cos(\Phi_n/\nu_y-\theta_w)}\cos(\Phi_n-\pi\nu_y)$$

$$-\sum_{n=1}^{2N-1}\sqrt{\breve{\beta}}e^{i(C/\lambda)\cos(\Phi_n/\nu_y-\theta_w)}\cos(\Phi_n-\pi\nu_y)]\}$$

where, Φ_n is the vertical betatron phase advance between the obsevation point and the nth magnet. β_0, $\hat{\beta}$ and $\breve{\beta}$ are the values of the β-function at observation point, focusing and defocusing quads.

due to a single vertical ground wave with amplitude $\hat{y}$, phase ϕ_0, angular frequency ω=2π *f*, velocity υ, wavelength λ= υ/*f* and direction of incidence θ_ω:

$$\Delta y_n(t) = \hat{y}\,\mathrm{Re}\{e^{i[\omega t+\phi_0+\frac{C}{\lambda}\cos(\theta_n-\theta_w)]}\}$$

(A. Chao and M Tigner, “Handbook of Accelerator Physics and Engineering”, Ch-5.13, 1999.)

The ratio of the COD to the amplitude of plane ground wave is

$$R_y = \frac{\hat{y}_c}{\hat{y}} = \frac{\sqrt{\beta_0}}{2f}\{[\sum_{p=-\infty}^{\infty} J_{4p}(\frac{C}{\lambda})C_{4p} - J_{4p-2}(\frac{C}{\lambda})C_{4p-2}]^2$$

$$+\sum_{p=-\infty}^{\infty} J_{4p-1}(\frac{C}{\lambda})C_{4p-1} - J_{4p-3}(\frac{C}{\lambda})C_{4p-3}]^2\}^{\frac{1}{2}}$$

where J_p the Bessel function and

$$C_p = \frac{(-1)^{p+1}}{\sin(\frac{\pi p}{N}-\frac{\mu}{2})} \times \{\sqrt{\hat{\beta}}\cos[p(\pi\frac{N+1}{N}-\theta_w)-\frac{\mu}{2}] - \sqrt{\breve{\beta}}\cos p(\pi-\theta_w)\}$$

C_p becomes resonant for |p| = |m|N± ν_y ($\nu = N\mu/2\pi$). With $\delta\nu_y$ the distance of ν_y from the closet integer [ν_y], the maximum of the resonant term can be expressed as $1/\sin(\frac{\pi}{N}\delta\nu_y)$

The Bessel function J_p differs significantly from zero only for arguments $C/\lambda > p$. Thus R_y is small for small C/λ and rises in a step-like manner at C/λ = [ν_y], N-[ν_y], N+[ν_y], 2N-[ν_y], etc..

Horizontal orbit distortion due to a single vertical ground wave

$$\Delta x_n(t) = \hat{x}\cos(\theta_n - \theta_w) \times \mathrm{Re}\{e^{i[\omega t + \phi_0 + \frac{C}{\lambda}\cos(\theta_n - \theta_w)]}\}$$

$$Rx = \frac{\hat{x}_c}{\hat{x}} = \frac{\sqrt{\beta_0}}{2F}\{[\sum_{p=-\infty}^{\infty} J'_{4p}(\frac{C}{\lambda})C_{4p} - J'_{4p-2}(\frac{C}{\lambda})C_{4p-2}]^2$$

$$+ \sum_{p=-\infty}^{\infty} J'_{4p-1}(\frac{C}{\lambda})C_{4p-1} - J'_{4p-3}(\frac{C}{\lambda})C_{4p-3}]^2\}^{\frac{1}{2}}$$

Vibration Suppression

- Resonant frequency of mechanical structure
  -- Equation of Motion
  -- Design Considerations
- Damping design

Purpose: To reduce the amplification factor (transmissibility) of Girder Magnet Assembly
(Ground vibration→ Pedestal→ Girder→ Magnet)

Equation of Motion

$$m\ddot{y} + c(\dot{y} - \dot{y}_0) + k(y - y_0) = 0, \text{ for viscous damping}$$

$$m\ddot{y} + k(1 + i\eta)(y - y_0) = 0 \text{ , for hysteretic damping}$$

where, m: mass, k: spring constant, y_0: excitation,

c: damping constant,

loss factor: $\eta = \dfrac{Energy\ Loss\ per\ Cycle}{Total\ Stored\ Energy}$

Resonant frequency of the system: $f_0 = \sqrt{\dfrac{k}{m}} / 2\pi$

(A. Chao and M Tigner, "Handbook of Accelerator Physics and Engineering", Ch-5.14, 1999.)

The steady-state amplitude Y of the system in response to a base excitation *$y_0 = Y_0 \cos(2\pi f_a t)$ is*

$$\frac{Y}{Y_0} = \frac{\sqrt{1+(2\varsigma\frac{f_a}{f_0})^2}}{\sqrt{[1-(\frac{f_a}{f_0})^2]^2+(2\varsigma\frac{f_a}{f_0})^2}} \qquad \text{(viscous)}$$

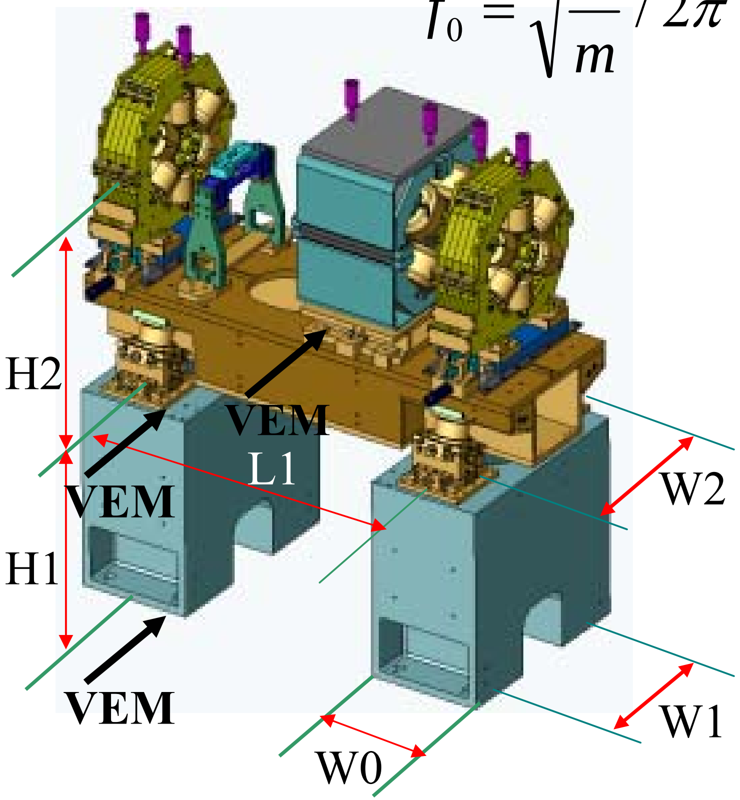
$$\frac{Y}{Y_0} = \frac{\sqrt{1+\eta^2}}{\sqrt{[1-(\frac{f_a}{f_0})^2]^2+\eta^2}} \qquad \text{(hysteretic)}$$

where, $\varsigma = \frac{c}{2m(2\pi f_0)}$ and $f_0 = \sqrt{\frac{k}{m}}/2\pi$

Design Considerations

1. As the amplitude of the excitation source increases at lower frequencies, **the resonant frequency of the MGA system should be as high as possible**.
2. *m*: Mass of magnets is the most dominant mass in the system but hard to change. To use hollow box structure with ribs to reduce the weight of girder but keep the strength. ***k*: It is crucial in designing the dimensions of the girder assembly and selecting the material of pedestal and girder.** (H1, H2, L1-- as small as possible; W0, W1, W2-- as large as possible)
3. **Damping design (ViscoElastic Material, VEM) is quite effective to reduce the amplification factor.**

$$f_0 = \sqrt{\frac{k}{m}} / 2\pi$$



Damping Design

- Damping Materials

- Cases Study
  APS - Damping Pad
  ESRF - Damping Link
  TLS - Composite Damping Material

Damping Material (I)

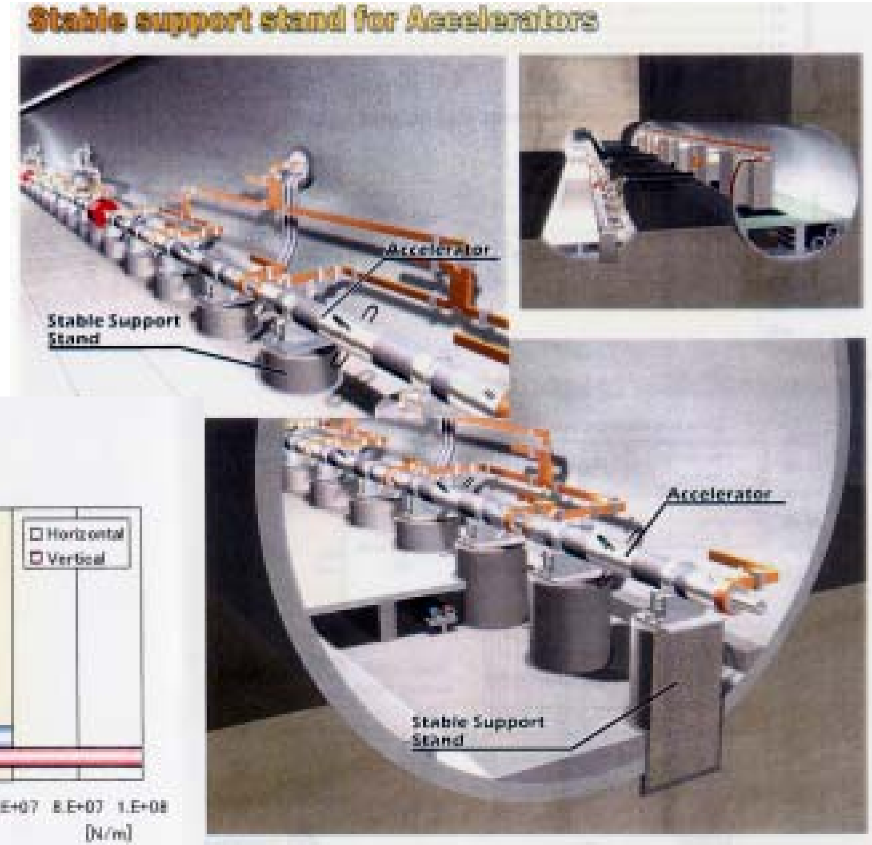
Table 1 Relevant material properties

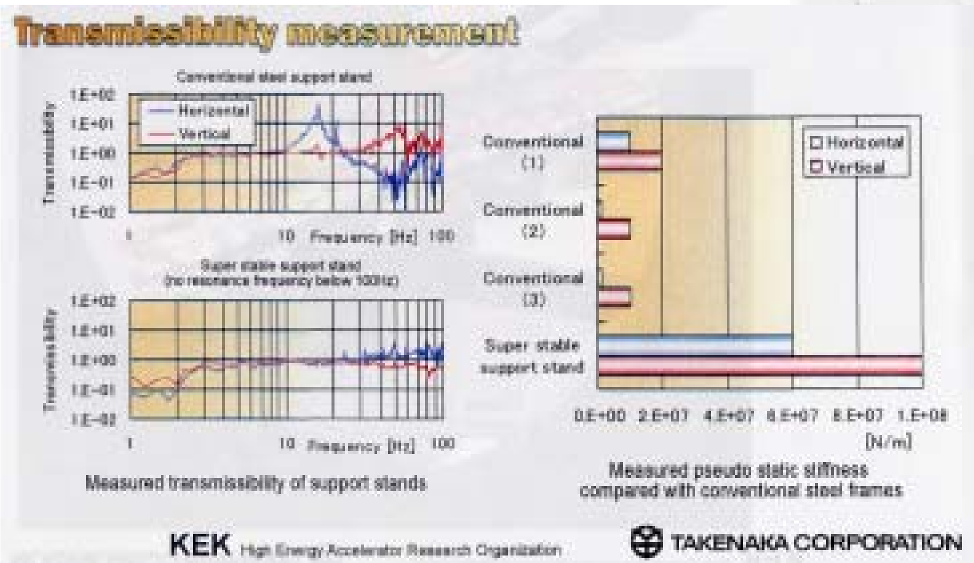
Material	Loss Factor, η	Modulus (E) [psi]
Al	10^{-4}	10×10^{6}
Steel, Fe	**1×10^{-4} - 6×10^{-3}**	**30×10^{6}**
Cu	0.002	10×10^{6}
Concrete	**0.001 (light) to 0.05 (dense)**	**10×10^{3} to $100 \times l0^{3}$**
Wood, cork, plywood	0.01 (oak) to 0.02 (cork)	5000 to 25000
Sand, granular media	0.01 to 0.05, 0.1 for dry sand	10,000 to 30,000
Rubber, plastic	**0.001 to 10**	**0.1 to 5000**

(A. Chao and M Tigner, "Handbook of Accelerator Physics and Engineering", Ch-5.14, 1999.)

Pedestal
High Strength Concrete

(S. Seko et al., APAC2004)





Concrete: high stiffness & low transmissibility of acceleration.

Damping Material (II)

Table.2 Properties of viscoelastic damping material (VEM) at 50 to 100°F and 5 - 15 Hz frequency range

VEM	η	G [psi]
3M ISD 112	0.8	20 - 100
3M NPE 3128	0.6 - 1	10 - 70
Anatrol AN 217	0.7 - 1	20 - 70
Anatrol AN 218	0.5 - 1	40 - 300

$G = E/2(1+\mu)$ (μ: Possion's ratio, μ≈0.5 for VEM)

(A. Chao and M Tigner, "Handbook of Accelerator Physics and Engineering", Ch-5.14, 1999.)

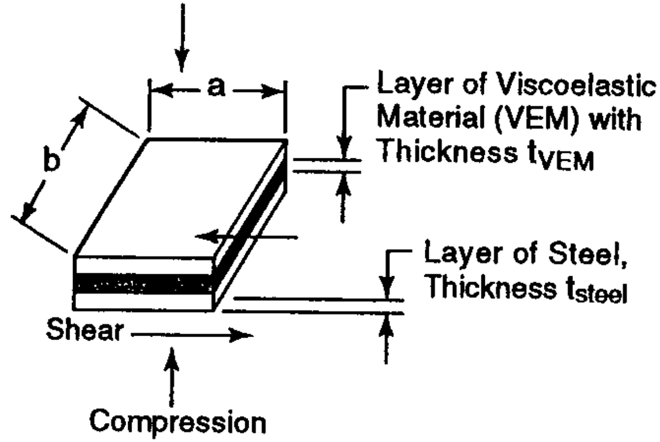
VEM

- The property of VEM is environmental dependent.
  (temperature, frequency, strain amplitude, static pre-strain, radiation dose)
- Must be carefully used.

Damping Pad

$$\frac{1}{K_{SYM}} = \frac{1}{K_I} + \frac{1}{K_{VEM}} \quad \text{(series)}$$

$$K_{SYM} = K_I + K_{VEM} \quad \text{(parallel)}$$



$$K_{VEM} = k_{VEM}(1 + i\eta_{VEM})$$

In compression:

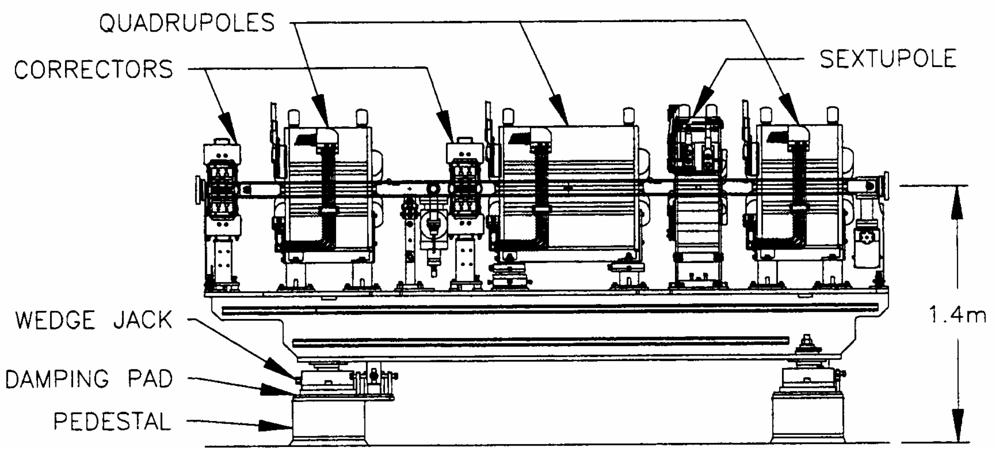
$$k_{steel} = \frac{E_{steel} ba}{t_{steel}} \qquad k_{VEM} = \frac{E_{VEM} ba}{t_{VEM}}\left[1 + \left(\frac{ba}{2(b+a)t_{VEM}}\right)^2\right]$$

In shear:

$$k_{steel} = \frac{G_{steel} ba}{t_{steel}} \qquad k_{VEM} = \frac{G_{VEM} ba}{t_{VEM}}$$

Damping Pad – APS

(D. Mangra et al., MEDSI 2000)



An APS girder-magnet assembly

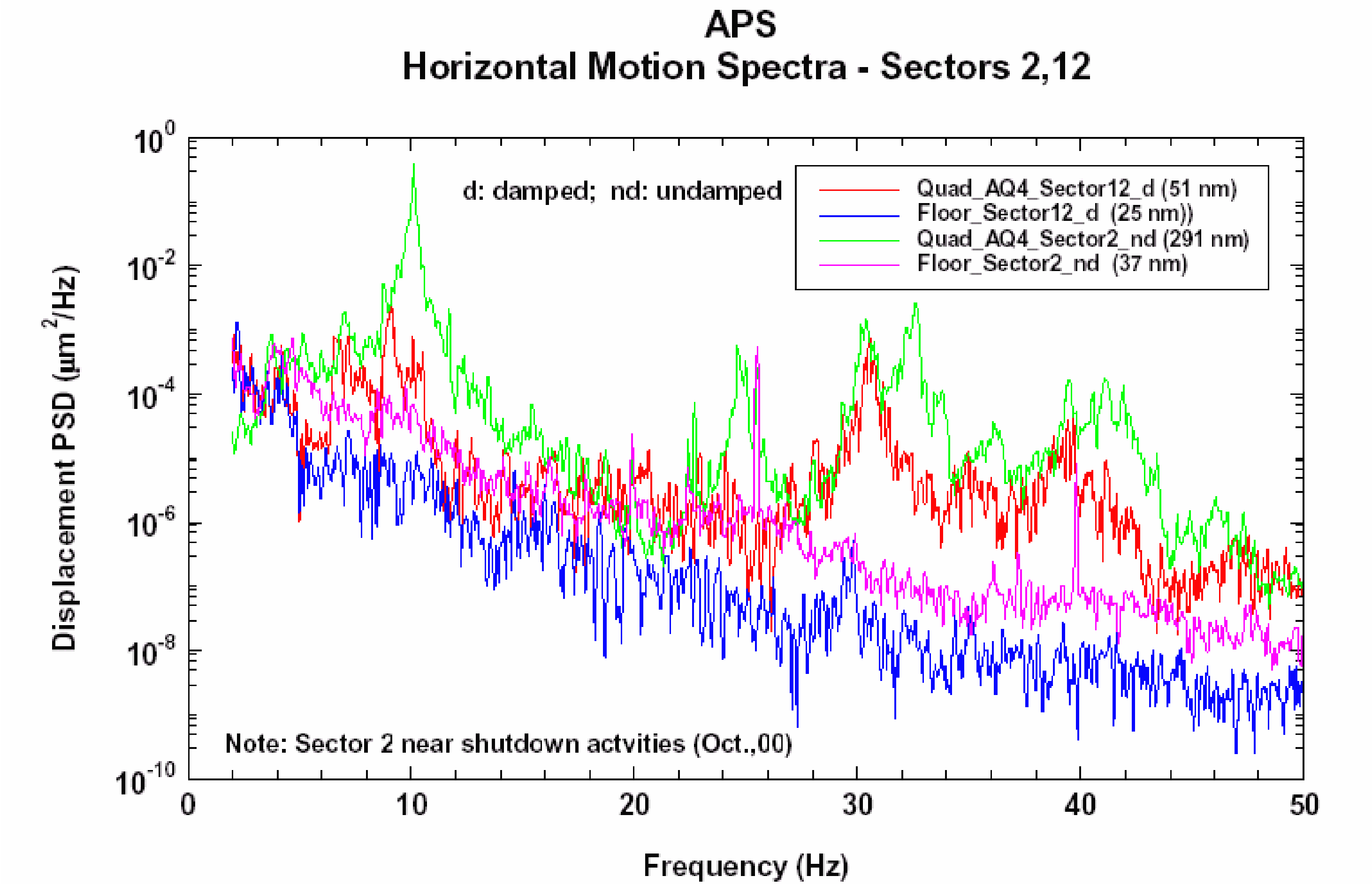
Damping pad:
Anatrol 217 films: (2x)
Stainless plates
16"d-3/4"t,
12"d-1/8"t,
12"d-1/2"t

Damping pads under the pedestals can reduce the displacement magnification by a factor of 4-6. The peak displacements at natural frequencies can be reduced by more than one order of magnitude.

Damping pads provide a more cost-effective solution for reducing vibration levels than increasing the support stiffness.

The damping pads should be installed closer to the ground in order to intercept the ground excitation before it is magnified by the weaker elements of the support system (e.g. alignment jacks).

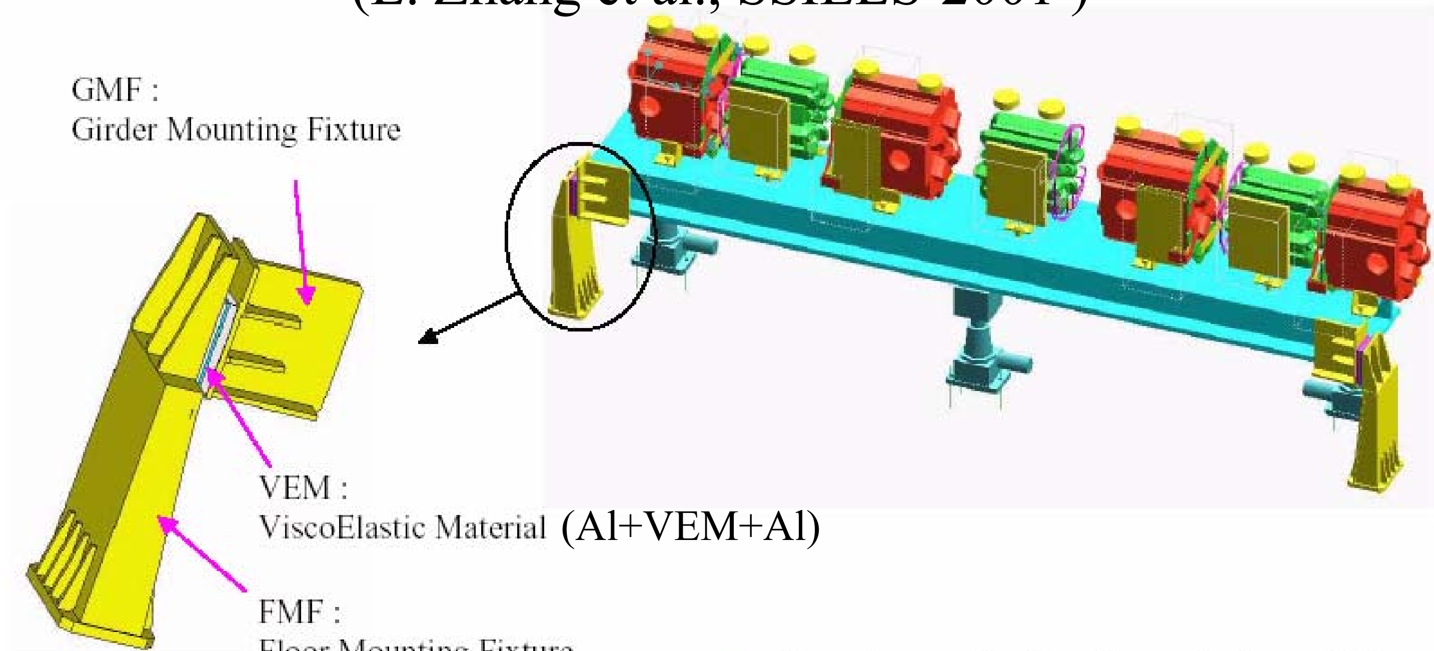
APS



APS
Horizontal Motion Spectra - Sectors 2,12
d: damped; nd: undamped
Quad_AQ4_Sector12_d (51 nm)
Floor_Sector12_d (25 nm))
Quad_AQ4_Sector2_nd (291 nm)
Floor_Sector2_nd (37 nm)
Note: Sector 2 near shutdown actvities (Oct.,00)
Displacement PSD (μm²/Hz)
Frequency (Hz)
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
0
10
20
30
40
50

Damping Link - ESRF

(L. Zhang et al., SSIELS-2001)



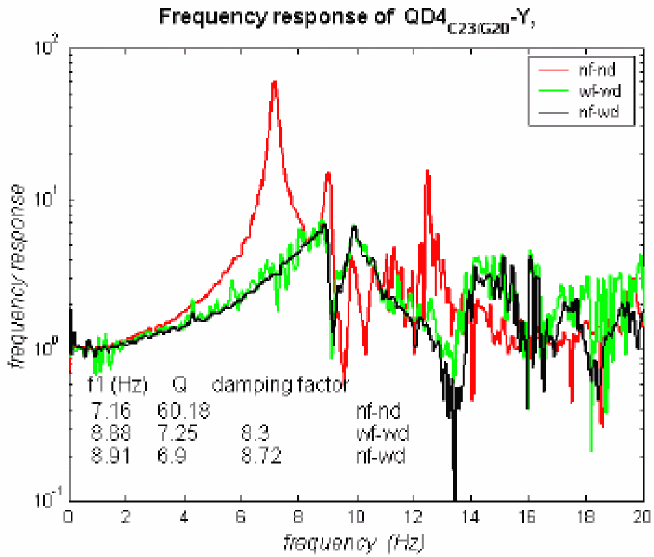
- **Q-value reduction by a factor of 6**
- **Stiffness increase : 1st natural frequency shifted to higher frequency**

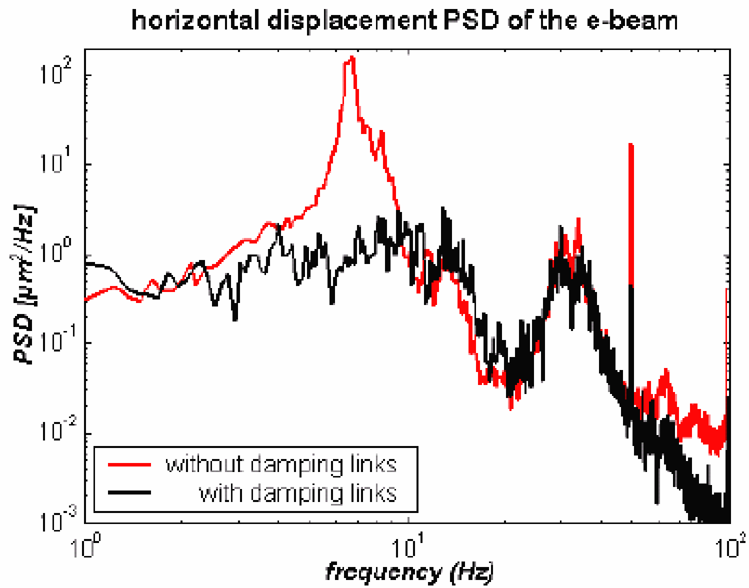
The damping links are compatible with the alignment operation. (2mm tolerance)

Why damping links in ESRF?
Damping pad had weak stiffness in horizontal. (e.g. 0.6mm displacement)

ESRF

Damping link for machine girder



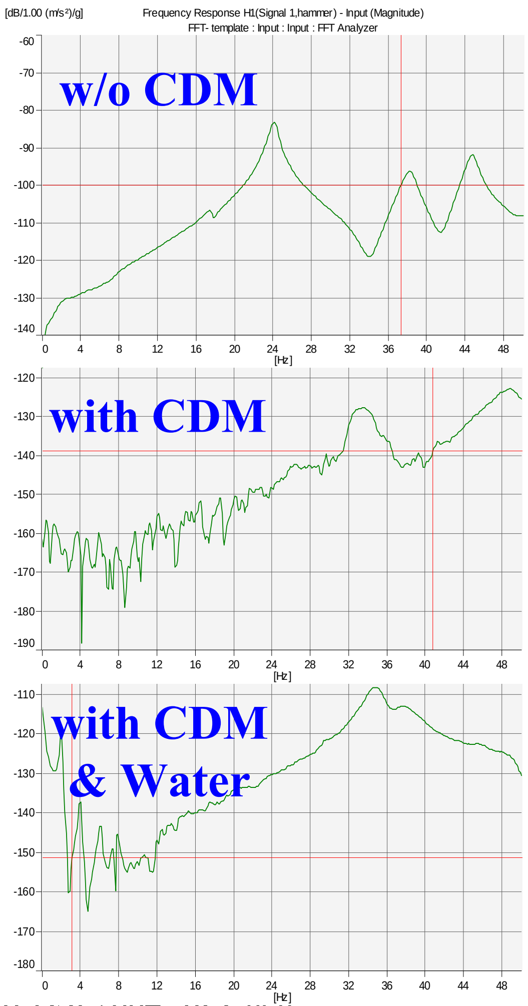


(wf: water flow on, wd: with damping links)

	PSD_{pk}		rms_{4-12Hz}	
	$\mu m^2/Hz$	*ratio*	μm	*ratio*
noDL	158		11.7	
DL	3.2	49	3.1	3.8

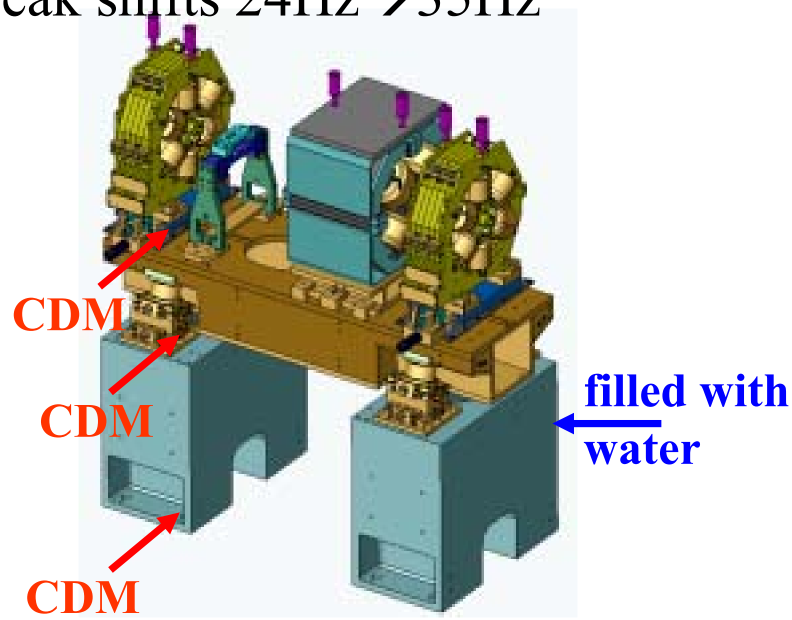
Composite Damping Material - TLS

(D.J. Wang et al., APAC 2004)



Composite damping material (CDM)

- -- a mixing of epoxy and sand (similar to polymer concrete)
- -- high stiffness
- -- peak shifts 24Hz→35Hz

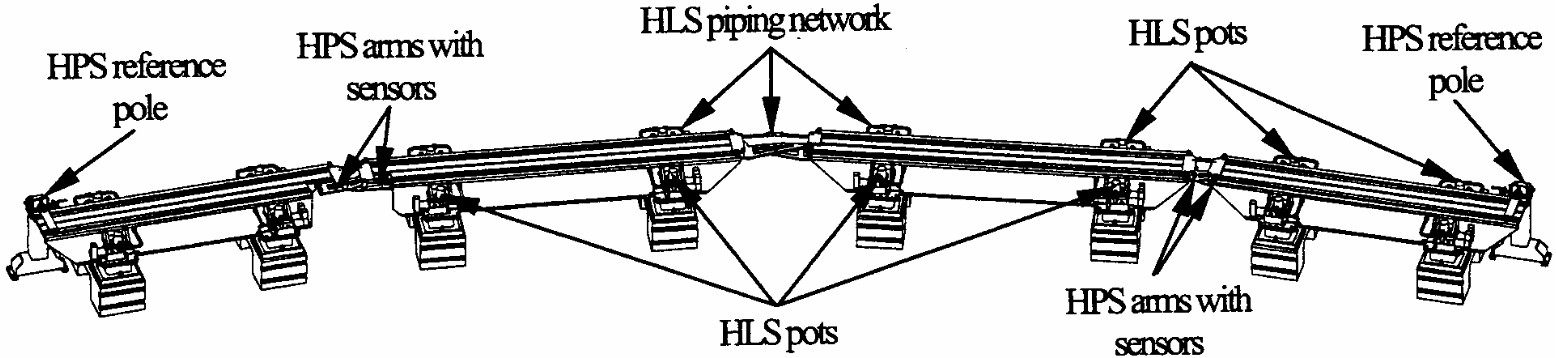


V. Sensors

- Hydrostatic Leveling System
- Potentiometer
- LVDT
- Accelerometer
- Vibrometer
- Autocollimator

Positioning and Positioning Monitoring System (SLS)

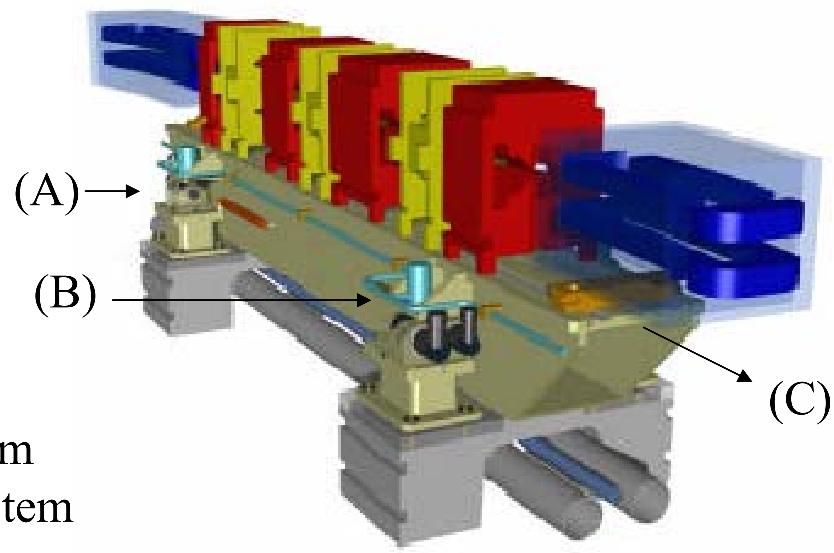
(S. Zelenika et al., MEDSI 2000)



A 30° sector of the SLS storage ring

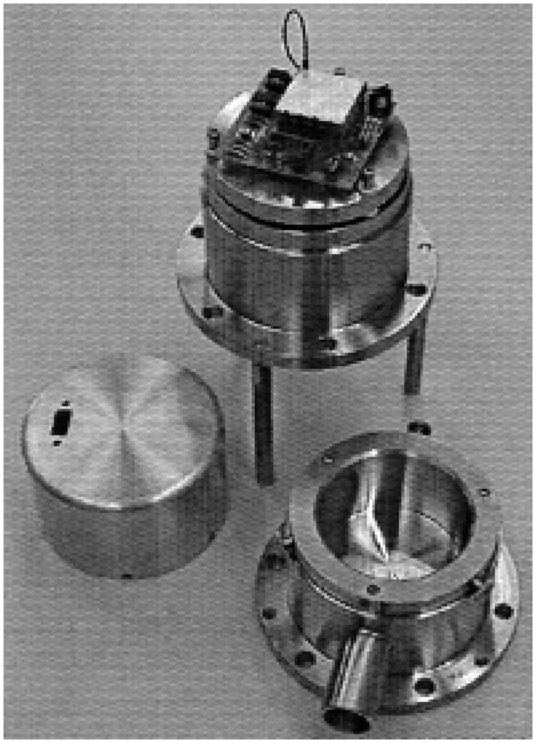
Dynamic Alignment

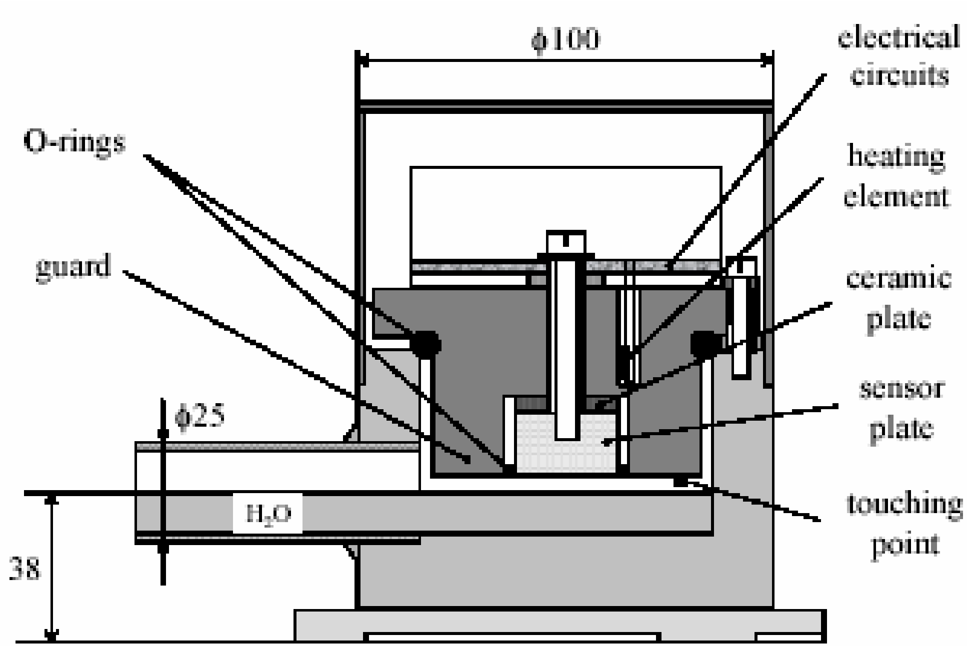
(A) mover + encorder
(B) HLS
(C) HPS



HLS: hydrostatic leveling system
HPS: horizontal positioning system

Hydrostatic Leveling System





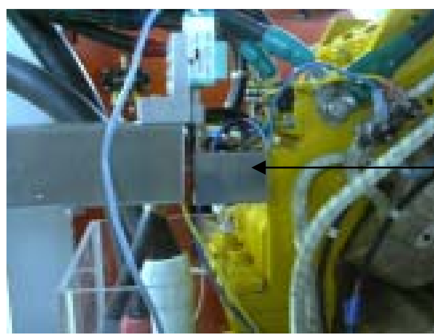
Features:

Stability ±10μm
Settling time ~5 min
Long term drift

Measurement Setup (TLS)

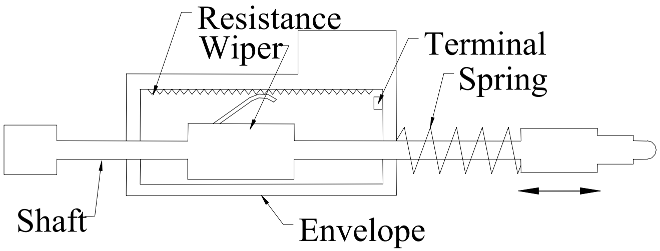
LVDT

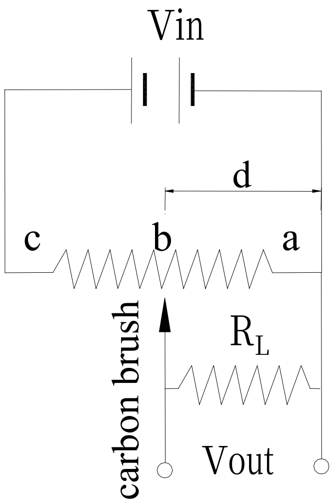
Granite Stand



Potentiometer

Potentiometer



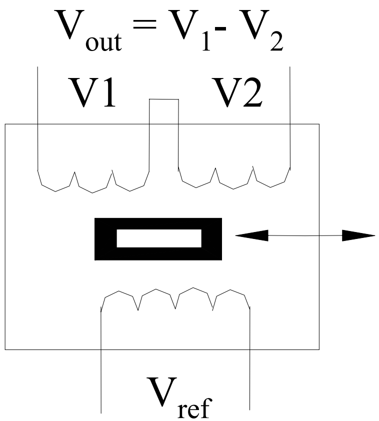


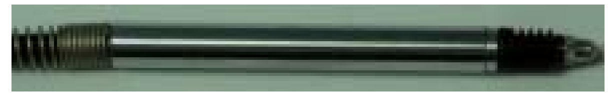
$$V_{out} = \frac{R_{bc}}{R_{ac}} \times V_{in} = \frac{d}{L} \times V_{in} \text{ , } R_L = \infty$$

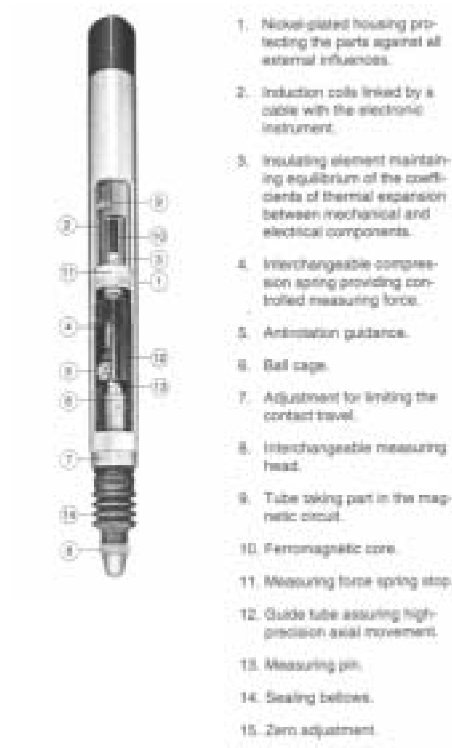
$$\Rightarrow \text{Displacement} \quad d = \frac{L}{V_{in}} \times V_{out}$$

- Signal : DC Max. 14 V (GEFRAN PY2)
  - Linearity : ± 0.3%
- Resolution : Depends on the resolution of AD/DA card
- Noticeable friction load
- Need for a contact with the object
- Low speed
- Friction and excitation voltage cause heating
- Low environment stability

LVDT







- Len’s Law : $E = L(dI/dt)$
- Input Voltage : AC, V_{ref}
- Output Voltage : AC, $V_{out} = V_1 - V_2$
- Displacement = k V_{out} (DC)

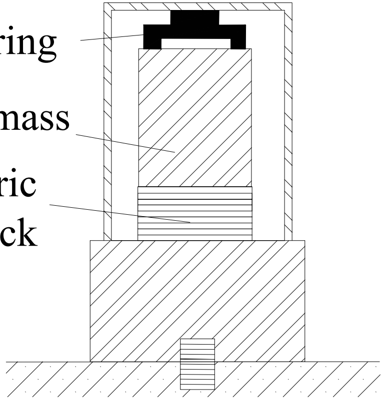
- Linearity : ±0.1%
- Resolution : 0.1 μm
- Very little friction resistance
- Hysteresis is negligible (mechanical and electric)
- Output impedance is very low
- Low susceptibility to noise and interferences
- If LVDT is put in the high electromagnetic field, the measurement of noise is increased.

Accelerometer

- Piezoelectric accelerometer : The electric charges output of piezo is proportional to the force.
- Transfer function

$$\frac{e_o}{\ddot{x}_i}(D) = \frac{[K_q/(C\omega_n^2)]\tau D}{(\tau D+1)(D^2/\omega_n^2 + 2\xi D/\omega_n + 1)}$$

- e_o : output voltage
- $\ddot{x}_i$: acceleration
- τ : time constant, RC, s
- $\frac{K_q}{C}$: sensitivity , V/cm
- ω_n : natural frequency
- D : d/dt



- Measurement range : 2.5g pk (PCB-393C)
  - ➢ Range : 0.025-800 Hz
  - ➢ Non-Linearity : $\leqq$ 1 %
  - ➢ Sensitivity : 100mV/g
- Generally the range of Piezoelectric accelerometer is from 2 to 25kHz.
- Below 1 Hz must be carefully, always the signal is not so reliable.
- Mount the sensor assembly to the prepared test surface by “rocking” or “sliding” it into place.

Vibrometer

- Laser Doppler Vibrometer : two head, one for reference, one for measurement.
- Mach-Zehnder interferometer

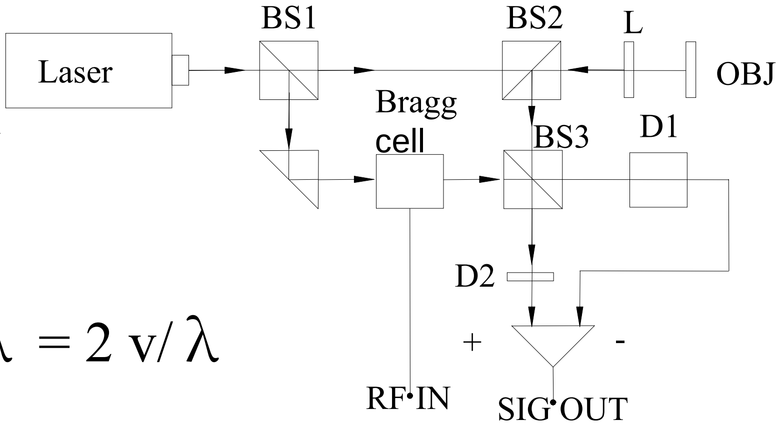
$I(1)=1/2\ A^2\ (1+\cos(2\pi(f_B + 2\triangle z/\lambda)))$

$I(2)=1/2\ A^2\ (1-\cos(2\pi(f_B + 2\triangle z/\lambda)))$

SIG OUT voltage $u=K\cos(2\pi(f_B + 2\triangle z/\lambda))$

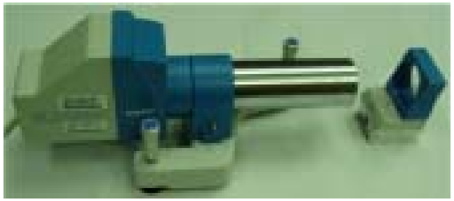
$\triangle z$: Displacement

f_B : frequency shift by Bragg cell



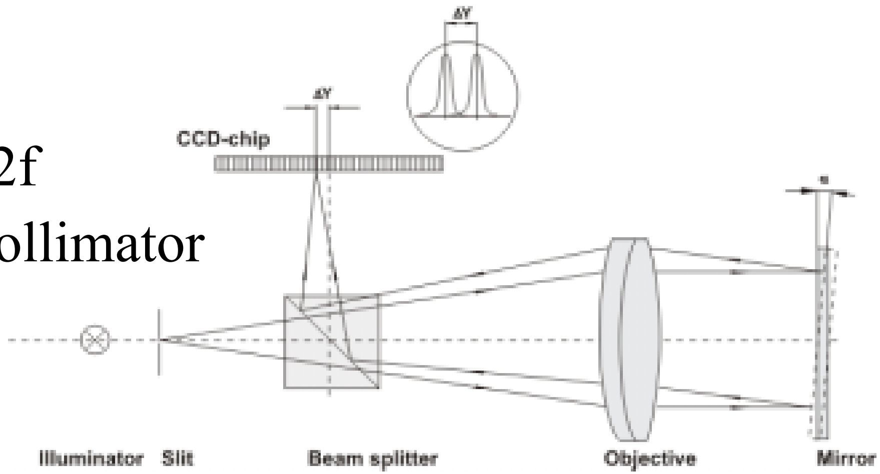
- The Doppler effect :
  - RF signal : $\theta_{RF} = 4\pi\triangle z/\lambda$
  - Doppler shift $f_D = 2\triangle z/\triangle t/\lambda = 2v/\lambda$
  - $f_{out} = f_B + f_D$
  - The sign of v denotes the moving direction.

Autocollimator



- High-precision instrument for measurement of **angular settings**.
- The autocollimator projects the image of a reticle marking in collimated beam path to the mirror. When the mirror is titled with an angle α, the reflected beam is shifted △Y from the center.

- The angle of tilt : $\alpha = \triangle Y/2f$
- f : focal length of the autocollimator



Sensor	Range	Resolution	Frequency range	Accelerator Velocity Displacement	Remark
Potentiometer	**10mm**	**1.15 μ m (16 bits)**	**5Hz**	**D**	**GEFRAN PY2F**
LVDT	**±0.2mm**	**0.1 μ m**	**60Hz**	**D**	**TESA GT21**
Accelerometer	**2.5g(peak)**	**0.1mg(rm s)**	**0.025-800 Hz**	**A**	**PCB-393C**
Vibrometer	**100 mm/s**	**0.5 μ m/s**	**250 kHz**	**V**	**Polytec OFV-2200**
Autocollimator	**±100arcsec (~ 7500mm)**	**0.05arcsec**	**25 Hz**	**D (angle)**	**Moller-Wedel Elcomat-2000**