# THE FIRST ELECTRON BUNCH MEASUREMENT BY MEANS OF DAST ORGANIC EO CRYSTALS

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*Abstract*

A pilot user experiment with the seeded FEL have been demonstrated at the Prototype Test Accelerator (EUV-FEL), SPring-8 from July, 2012. A precise measurement of the electron bunch charge distribution (BCD) is crucial key to keep both spatial and temporal overlaps between high-order harmonic (HH) laser pulses and electron bunches. In addition, R&D of a 3D-BCD monitor with a single-shot detection has been extensively promoted at SPring-8. The monitor adopts a spectral decoding based Electro-Optic (EO) sampling technique that is non-destructive and enables real-time reconstruction of the 3D-BCD with temporal resolution of 30 to 40 fs (FWHM). So far, such EO sampling based BCD monitors have been developed by using inorganic EO crystals such as ZnTe or GaP and their temporal resolutions are limited by 110 $\sim$ 130 fs (FWHM). As a part of this project, the first BCD measurement with an organic EO crystal; DAST has been successfully demonstrated at the facility. Signal intensities, temporal resolutions and radiation related issues for both ZnTe and DAST are discussed.

## INTRODUCTION

In general, XFEL (X-ray Free Electron Laser) accelerator drives ultra-short electron bunches such as $\sim$100 $\mu$m (rms) for transverse and $\sim$30 fs (FWHM) for longitudinal directions. In order to drive such ultra-short electron bunches, it is required not only to measure bunch length with a few tens of femtoseconds temporal resolution, but also to simultaneously measure transverse bunch charge distribution (BCD) with real-time, non-destructive, and shot-by-shot measurement. For example, for SACLA (SPring-8 Angstrom Compact Free Electron Laser), RF deflectors have been utilized to measure the temporal distribution of electron bunches, so far [1, 2]. However, since this method is beam-destructive, real-time reconstruction and shot-by-shot detection of the electron bunch cannot be realized during the operation of SASE-FEL oscillation.

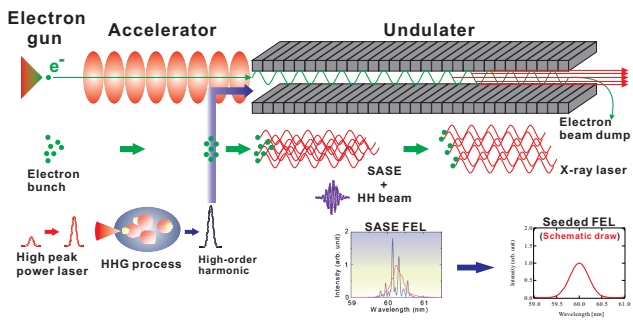


Figure 1: A schematic drawing of SASE-FEL and seeded FEL operation.

Furthermore, for user experiment with HHG-seeded FEL, both high-order harmonics (HH) laser pulse and electron bunch are required to be spatially and temporally overlapped at all times as shown in Fig. 1. Therefore, both longitudinal and transverse BCD measurements, i.e., 3D-BCD measurements with probe laser, that is split from the HHG process, realizes to make shot-by-shot feedback to the HHG-seeded FEL operation.

The Electro-Optic (EO) sampling is one of the practical techniques to realize the 3D-BCD measurements [3, 4]. In this method, the Coulomb field distribution of a relativistic electron bunch is encoded on to a probe laser pulse as modulation of polarization due to phase retardation by EO effect. Intensity spectrum of the probe laser is modulated after a polarized splitter. In case we measure the intensity spectrum modulation with a multi-channel spectrom-

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eter, single-shot temporal measurement of electron bunch can be achieved and this method is well known as the spectral decoding [5].

Temporal resolution of the spectral decoding based EO sampling is mainly limited and determined following four factors:

1) A limitation of the temporal resolution ($T_{res}$) in the spectral decoding is expressed with the Fourier transform limitation ($\tau_0$) and a chirped pulse width ($\tau_c$) of a realistic probe laser pulse as shown in Fig. 2 and Eq. (1):

$$T_{res} \approx \sqrt{\tau_0 \tau_c} \tag{1}$$

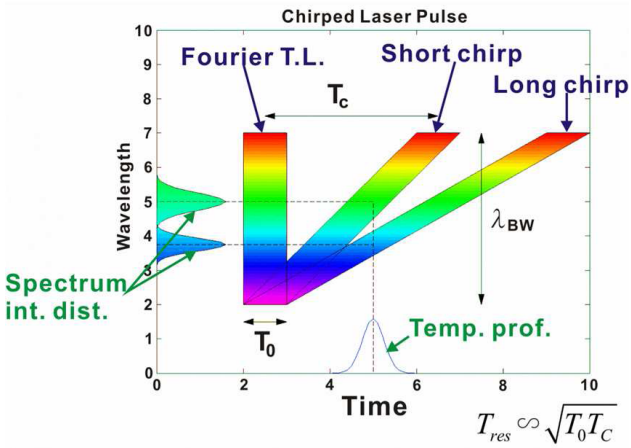


Figure 2: EO-encoded spectra with different chirp rate.

2) Dispersion of Pockels EO crystals depend on crystal thickness and frequency domain in use (both optical and THz domain). Since the THz pulse is distorted and broadened inside the Pockels EO crystal, it is difficult to realize femtoseconds order of temporal resolution, especially in THz region.

3) Since electric field of the relativistic electron bunch has an opening angle of $2/\gamma$, the temporal resolution ($T_{geo}$) is defined as

$$T_{geo} = \frac{2r}{\gamma c}, \tag{2}$$

where $\gamma$ is Lorentz factor, $r$ the distance between the electron bunch axis and a probing point of EO media, and $c$ the light velocity.

4) A velocity mismatch between the electric field of the electron bunch in vacuum and the probe laser pulse inside the EO media. Since refractive indices of EO crystals, especially the Pockels EO crystals, are generally as high as $\sim$2, which is almost half the light velocity in vacuum.

These above summarize characteristics of the longitudinal BCD measurements. In order to demonstrate precise spatial BCD detection, transverse BCD measurements are also required. For actual operation in SACLA, electron bunches should be guided in a straight line at a undulator section with a pointing stability of $< 10$ $\mu$m. Although many RF-beam position monitors (BPMs) with less than 1 $\mu$m (rms) resolution and screen monitors (SCMs) with 2.5 $\mu$m (rms) resolution have been successfully developed for SACLA [6], single-shot measurements with real-time reconstruction of bunch charge distribution, which can simultaneously measure both longitudinal (temporal) and transverse (spatial) Bunch Charge Distribution (3D-BCD), enable fine optimization of electron BCD and energy chirping conditions during the SACLA operation.

While there are other methods of EO sampling, such as temporal or spatial decoding based techniques, we adopt spectral decoding method due to the following two reasons:

1) Transverse measurements of a sliced BCD is available which is direct detection comparing to projected BCD measurements with BPM and so on. Thus such direct detection is necessary to precise control of the X-ray lasing.

2) Since, in SACLA, the transverse beam size (40 $\mu$m in rms) is larger than the longitudinal one (30 fs in FWHM, corresponding to 10 $\mu$m in the scale), a slight tilt of the beam trajectory can disturb precise bunch duration measurements. Introducing our non-destructive and real-time 3D-BCD monitor, we can correct the bunch tilt and perform precise longitudinal measurements.

Eventually, fine beam tuning can be realized just before the undulator section.

## PRINCIPLE OF 3D-BCD MEASUREMENT

Characteristics of the 3D-BCD monitor are 1) non-destructive, 2) single-shot, 3) real-time reconstruction, and 4) three dimensional measurement of BCD with 30-fs (FWHM) of temporal resolution. Schematic drawing of the 3D-BCD measurement based on the spectral decoding is represented in Fig. 3 (*upper*). A broadband ($\sim$350 nm in FWHM @ 800 nm) and linear chirped probe laser pulse are generated and its intensity spectrum is squarely shaped by an Acoust-Optic modulator (DAZZLER). The probe laser's polarization is transferred from linear to radial with a radial polarization converter. And probe laser profile is converted from Gaussian to hollow (anti-Gaussian) beam by an axicon lens or a mirror pairs. Figure 3 (*lower*) shows a conceptual design of 3D-BCD monitor. The electron beam passes through total three Pockels EO detectors. In each EO detector, eight Pockels EO crystals azimuthlly surround the electron beam axis. And the independent three hollow-shaped probe laser pulse split from the original laser source are synchronized to probe the same electron bunch at each EO detector. The longitudinal distribution of the Coulomb field associated with the relativistic electron bunch is encoded as a phase retardation on the probe laser spectrum at



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each crystal. In addition, both incident angles and positions of the sliced BCD are determined by the set of two EO detectors at both ends. Details of longitudinal and transverse detections of the BCD are individually discussed as follows.

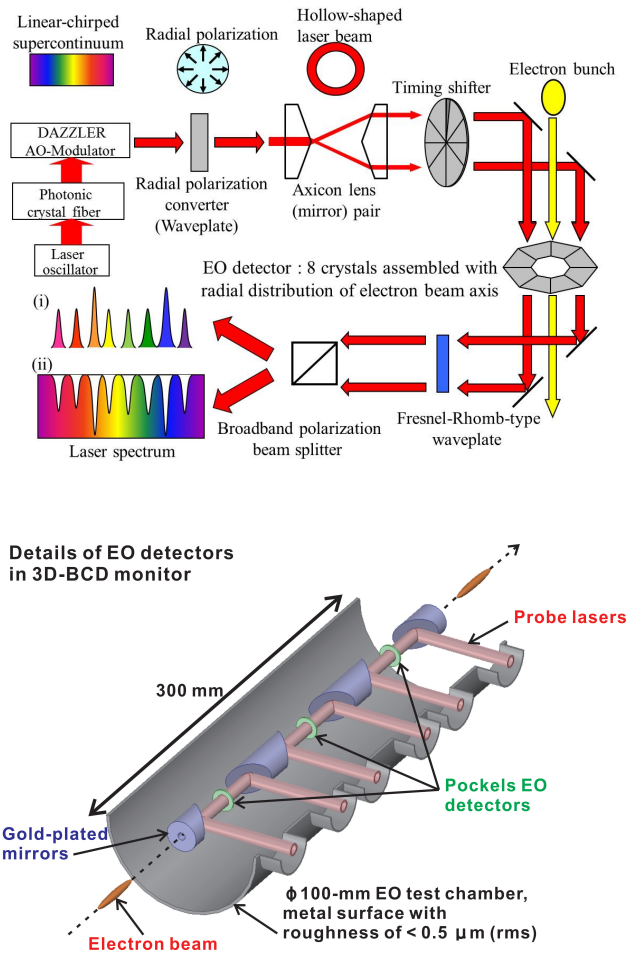


Figure 3: Schematic drawing of element of the 3D-BCD monitor (*upper*) and total system of 3D-BCD monitor (*lower*)

## *Longitudinal Detection*

In SACLA, 30-fs of temporal resolution (FWHM) is required to measure longitudinal charge distribution of the electron bunch. In order to achieve such temporal resolution, 1) broadband and linear chirped probe laser generation and 2) transparency of the Pockels EO crystals in frequency domain of use are essential keys. As we discussed above, since we prepare ∼350 nm (FWHM) @ 800 nm of broadband probe laser, the Fourier limited pulse width of the probe laser is evaluated to $\tau_0 \approx 3$ fs (FWHM).

First, in case the BCD measurement with one Pockels EO crystal, temporal resolution is estimated to $T_{res} \approx 30$ fs (FWHM) with $\tau_c \approx 300 - 400$ fs (FWHM) of linear-chirped probe laser pulse. In the actual 3D-BCD measurement, eight Pockels EO crystals should be probed without any spatial overlap of each other. When the arrival timing jitter between the probe laser pulse and the electron bunch is 50 fs (FWHM), $\tau_c \approx 600$ fs of linear-chirped probe laser pulse is required and $T_{res} \approx 40$ fs (FWHM) is expected.

Second, following three spectral transmission characteristics, which affect temporal resolution of the system, should be taken care:

1) absorption in THz range emitted from electron bunch,

2) velocity mismatch inside Pockels EO crystals between the Coulomb field associated with the electron bunch and the probe laser pulse,

3) dispersion inside Pockels EO crystals in optical range in addition to THz range.

So far, inorganic Pockels EO crystals, such as ZnTe and GaP have generally been utilized for BCD measurements in EO sampling. However, since each crystal has noticeable photon absorption around 5 and 11 THz, respectively, temporal resolution with such crystals is limited by 110 ∼ 130 fs (FWHM) [7]. Therefore, Pockels EO crystals should be transparent in wide frequency range. Thus we introduce an organic Pockels EO crystal, DAST (4-$N$, $N$-dimethylamino-4'-$N$'-methyl stilbazolium tosylate) [8].

## *Transverse Detection*

Next, we evaluate signal intensity modulations for eight Pockels EO crystals to investigate feasibility of transverse BCD measurement. In our calculation, we assume 8 GeV of electron beam energy, 100 pC of bunch charge and 30 fs (FWHM) Gaussian distribution of bunch duration based on a SACLA operation condition. Since Pockels EO crystal (detection point) is expected to be close to the electron beam axis as much as possible according to Eq. (2), each detection point are set as $r = 2$ mm in both calculation and experiment. Figure 4 (*left*) shows a longitudinally sliced BCD profile with overlays of relative coordinates of eight Pockels EO crystals. Here, the aspect ratio of the sliced profile is $r_{hol} : r_{ver} = 2 : 1$ ($\sqrt{r_{hol} \cdot r_{ver}} = \sqrt{2} \times 75$ $\mu$m $\approx 100$ $\mu$m), where $r_{hol}$ and $r_{ver}$ are horizontal and vertical beam size in rms, respectively.

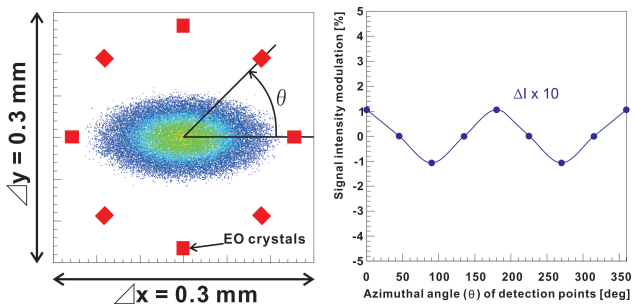


Figure 4: Longitudinally sliced BCD profile with relative coordinates of eight Pockels EO crystals (*left*) and calculation results of signal intensity modulations at each crystal position (*right*).

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First, for the sliced profile is true circle not ellipse, electric field at each detection point ($r = 2$ mm) are described as

$$E(r) = \frac{Q}{(2\pi)^{3/2}\epsilon_0 c r \sigma_0}, \quad (3)$$

where $Q$ is bunch charge, $c$ light velocity, $\epsilon_0$ electric permittivity in vacuum, and $\sigma_0$ bunch length in sigma. A change of refractive index ($\Delta n$) of isotropic EO media is expressed as

$$|\Delta n| = \frac{n_0^3}{2}\left\{\xi_p E(r) + \xi_k E(r)^2\right\}, \quad (4)$$

where $\xi_p$ is Pockels EO, $\xi_k$ Kerr EO coefficients and $n_0$ refractive index of the EO media. Here, ZnTe with 1 mm thick is utilized as Pockels EO media and $n_0 = 2.85$ and $\xi_p = 3.97 \times 10^{-12}$ m/V are adopted for the calculation. Figure 4 (*right*) compares signal intensity modulations ($\Delta I$) at eight Pockels EO crystals while $\Delta I$ is defined as

$$\Delta I = \frac{I_{sig} - I_{org}}{I_{org}}, \quad (5)$$

where $I_{sig}$ and $I_{org}$ are signal intensities for ellipse and circle profiles of longitudinally sliced BCD, respectively. And definition of the signal intensity is described as

$$I = I_0 \sin^2\left(\frac{\pi}{2\lambda}\Delta n L\right) = I_0 \sin^2\left(\frac{\pi n_0^3 \xi_p E L}{4\lambda}\right), \quad (6)$$

where $L$ is crystal thickness and $\lambda$ wavelength of probe laser pulse. According to the calculation results as shown in Fig. 4 (*right*), The EO signal intensity modulation is evaluated to maximum 0.2% with ~100 $\mu$m of beam size. On the other hand, actual beam size in SACLA is estimated to $\sqrt{r_{hol} \cdot r_{ver}} \approx 40$ $\mu$m, thus transverse BCD measurement with the above criterion is expected to be much difficult. For such a small intensity modulation, we measure a $s$-wave spectrum instead of $p$-wave one for higher S/N ratio as described in Fig. 3 (*upper*).

## FEASIBILITY

A feasibility test of the BCD measurement via spectral decoding based EO sampling was demonstrated at the Prototype Test Accelerator, SPring-8 on February 2012. Experimental setups and conditions are shown in Fig. 5 and Table 1. A linear-chirped probe laser pulse was generated with 5 nm (FWHM) of band width (central wavelength is 795 nm) and 5 ps (FWHM) of pulse duration in a laser hatch outside the accelerator tunnel. Arrival timing of the probe laser pulse was adjusted to be the same with electron bunch on the Pockels EO crystal position by a streak camera for coarse adjustment. Timing signal of the electron bunch (300 fs in FWHM of bunch duration) and probe laser pulse were monitored by a CT located behind a EO chamber and a photodiode detector right before the EO chamber, respectively. And precise timing adjustment was demonstrated by a timing delay module (Candox System inc.) for

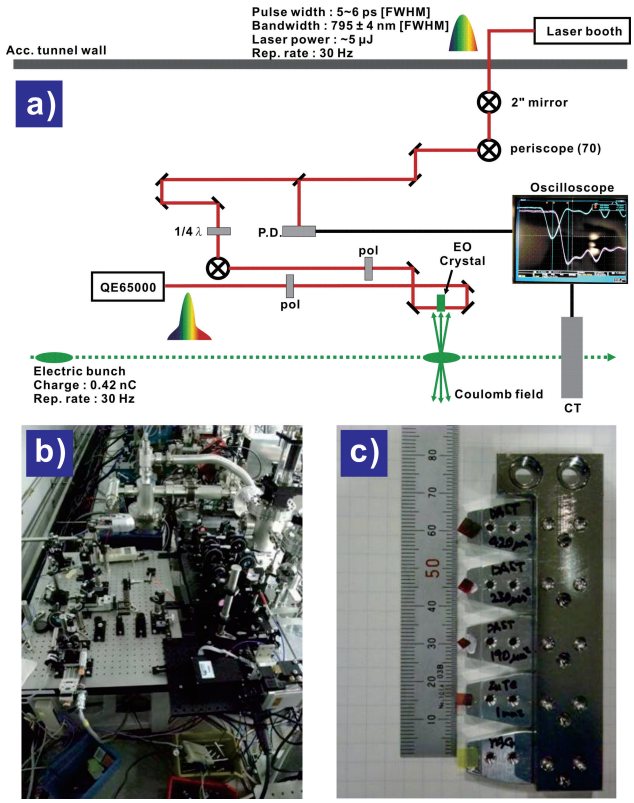


Figure 5: Experimental setups of the BCD measurement at the Prototype Test Accelerator, SPring-8 ($a$ and $b$), and crystals for beam detection ($c$, starting from the top, 420, 230, 190 mm thick of DAST crystals, 1 mm thick ZnTe and Ce:YAG).

Table 1: Experimental Conditions

| | |
|---|---|
| Electron beam | |
| Energy | 250 MeV |
| Bunch charge | 30 ~ 420 pC |
| Bunch duration | 300 fs (FWHM) |
| Reputation rate | 30 Hz |
| Peak current | > 300 A |
| Probe laser | |
| Bandwidth | 5 nm (FWHM) @ 795 nm |
| Pulse energy | 5 $\mu$J |
| Pulse duration | 5 ps (FWHM) |
| Linear chirp rate | 0.6 ps/nm |
| Reputation rate | 30 Hz |
| EO crystal | |
| $3^W \times 4^H \times 1^T$ mm$^3$ | |
| Distance from e-beam axis | 2 mm |
| Phase retardation | ~50 degree |



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the probe laser. Next, coordinates of the Pockels EO crystal for electron beam axis was aligned with Ce:YAG phosphor and remote monitoring with a CCD camera.

Figure 6 shows EO signal intensity dependency on the electron bunch charge. In addition, calculation results, which is taken into account only the Pockels EO effect as described in Eq. (6), are overlaid as a solid line on Fig. 6. Measured EO signal intensity spectrum (average of ten shots) by a spectrometer (OceanOptics, QE65000) are fitted with a single Gaussian and their peak values for five bunch charge sets are plotted on Fig. 6. From Fig. 6, EO signal intensities are saturated beyond 0.28 pC of bunch charge. On the other hand, signal intensity evaluation is difficult for lower bunch charge due to degenerated signal to noise ratio of the spectra.

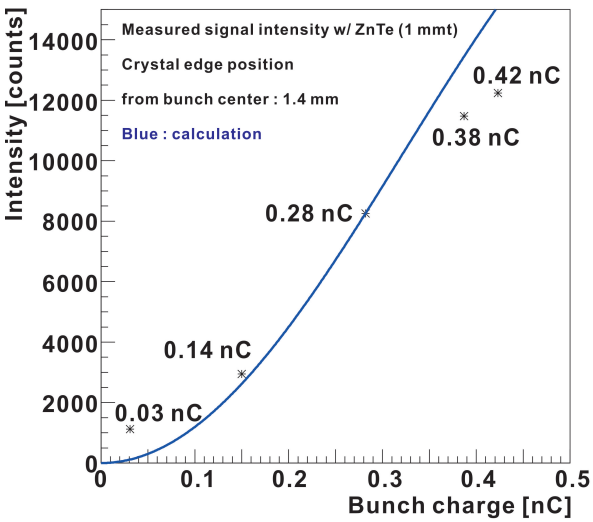


Figure 6: Dependency of the EO signal intensities on the bunch charge.

Next, signal intensity spectra (single shot) of the BCD measurement with an inorganic (1 mm thick ZnTe) and an organic (230 $\mu$m DAST) Pockels EO crystals are measured and compared in Fig. 7.

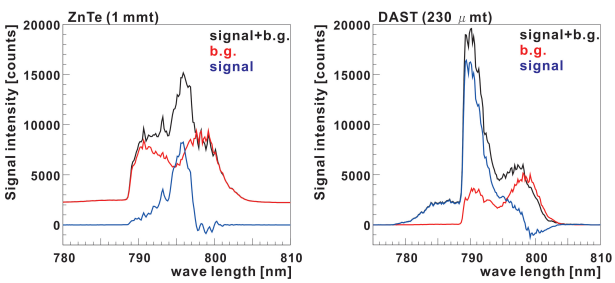


Figure 7: Signal intensity spectra of BCD measurement via 1 mm thick ZnTe (*left*) and 230 $\mu$m thick DAST (*right*) Pockels EO crystals. Average bunch charge is fixed as 0.28 nC.

In Fig. 7, signal intensity spectra directly measured by the spectrometer are plotted as *black* lines which include both signal and background. *Red* lines represent background spectra which is measured without electron beam and *blue* lines are signal only spectra (*black* - *red*). EO signal intensity derived with DAST crystal is twice higher than that with ZnTe crystal. In addition, rise time, i.e., temporal response of the signal spectrum with DAST crystal is apparently fast. Electron bunch duration evaluated by the BCD measurement with ZnTe and DAST crystals were 1.5 and 1.8 ps (FWHM), respectively. On the other hand, EO signal with DAST crystal was not maintained more than one hour since we started the measurement. We are investigating DAST crystals on damages due to radiation or laser illumination.

## SUMMARY

We establish the 3D-BCD detection system that realizes non-destructive, single-shot measurement, and real-time reconstruction with 30 fs (FWHM) of temporal resolution. This 3D-BCD measurement system is spectral decoding based EO sampling and consists of 1) eight organic Pockels EO crystals azimuthlly surrounding electron beam axis, 2) linear-chirped, broadband, and square-shaped probe laser with radial polarization and hollow-shape, and 3) optical components which have extremely higher extinction ratio ($1 :\sim 10^7$) in one octave wavelength domain. With these above powerful configurations, not only longitudinal, but also transverse BCD measurements can be realized. Feasibility test of the BCD monitor was demonstrated at the Prototype Test Accelerator, SPring-8 on February 2012. The first observation of the EO signal with an organic Pockels crystal; DAST was successfully achieved. Further investigation about radiation or laser illumination damages for organic crystals are extensively proceeded.

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