MOCLA02

# Design of a Compact L-band Transverse Deflecting Cavity with Arbitrary Polarizations for the SACLA Injector

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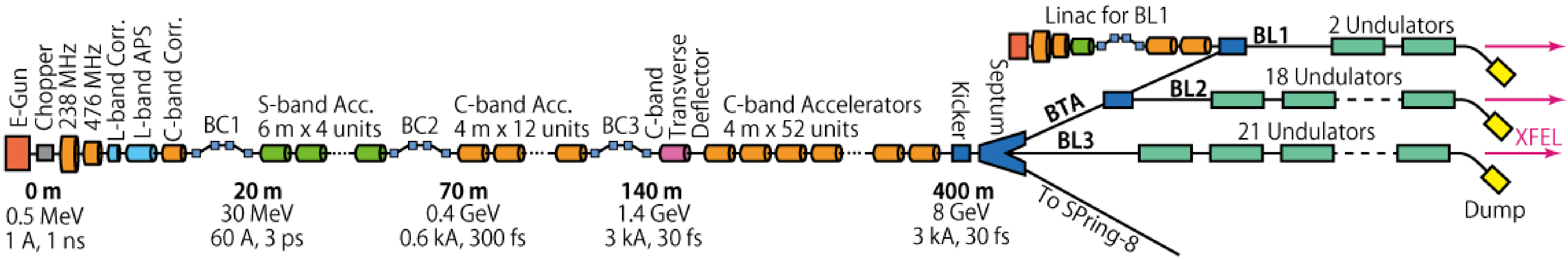
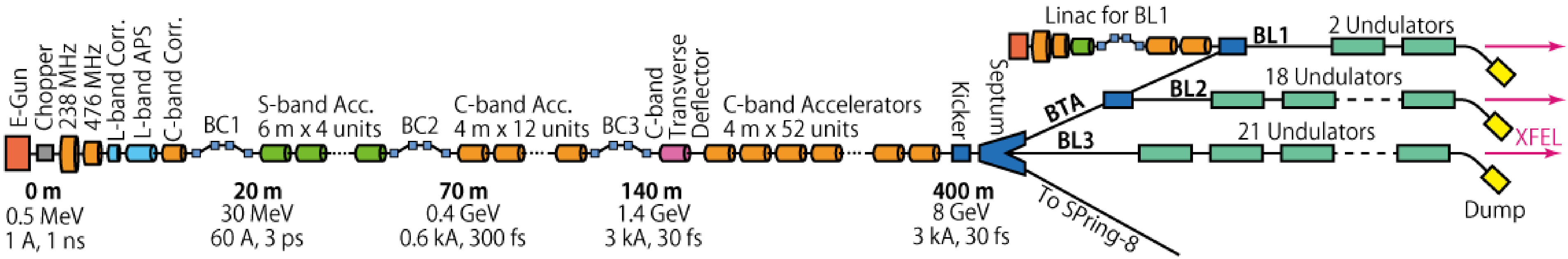
# Outline

- Introduction
  - X-ray Free Electron Laser (XFEL) “SACLA”
- Temporal Profile Measurement
  - Transverse Deflector Cavity (TCAV) System
- TCAV System for the SACLA Injector
  - Requirements
  - Time Resolution and Measurement Range
  - Polarization (Linear and Circular)
- TCAV Design
  - RF Simulation
- Summary

# Introduction

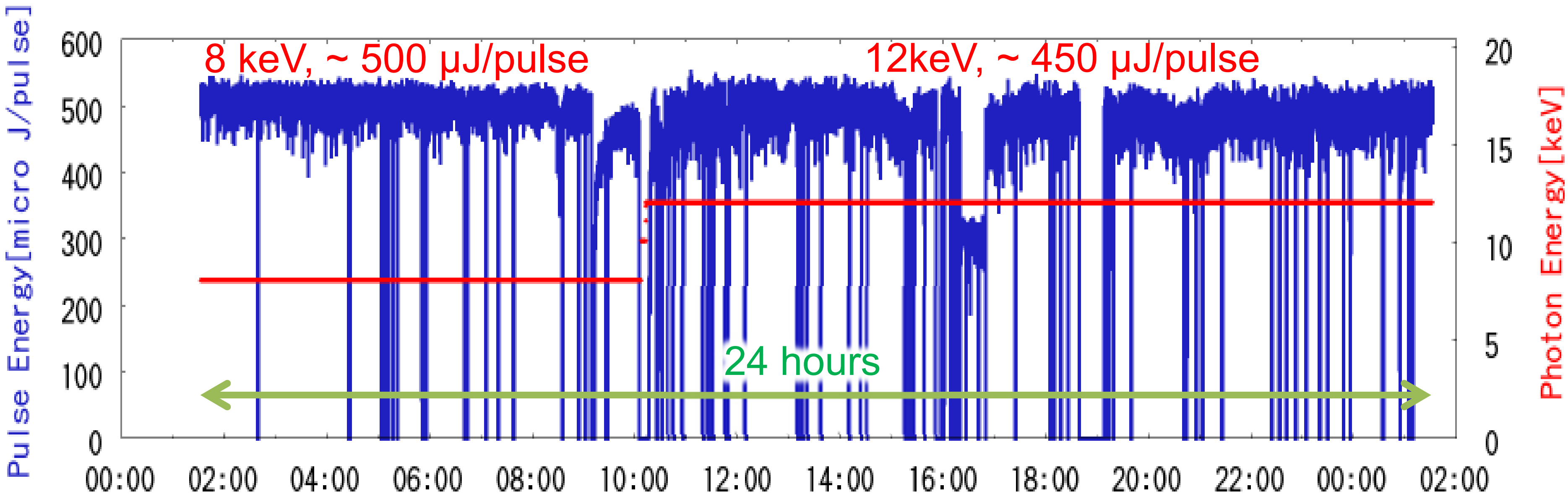


# Introduction



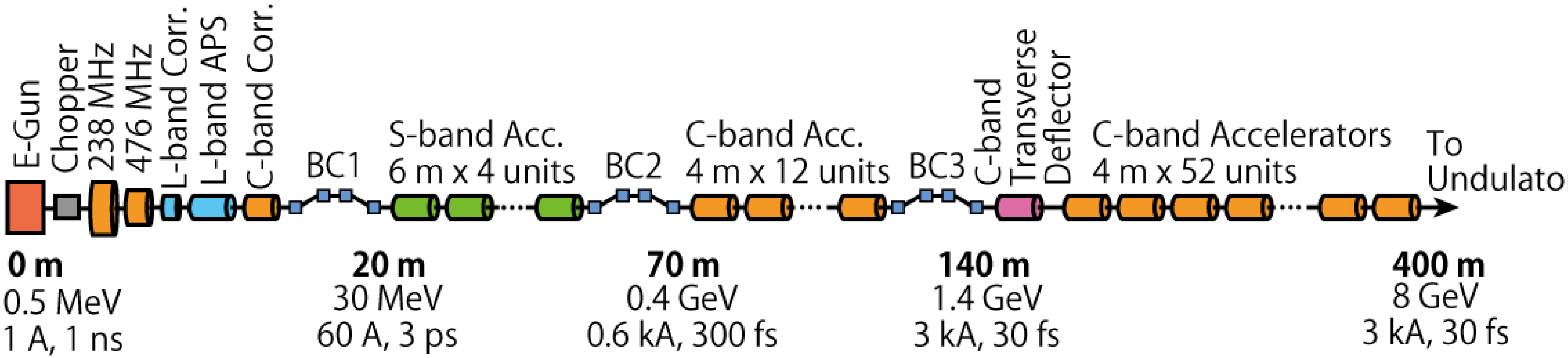

- X-ray Free Electron Laser Facility “SACLA”
  - Low-emittance 500 kV thermionic electron gun ($\varepsilon_n$ ~ 1 μm rad)
  - 238 MHz, 476 MHz, L-band (1428 MHz) and S-band (2856 MHz) accelerators for acceleration and bunch compression
  - High-gradient C-band Main Linac (5712 MHz, > 35 MV/m)
  - Short-period in-vacuum undulator ($\lambda_u$ = 18 mm)
- Precise bunch compression for > 3 kA peak current is necessary
  - Velocity bunching in the injector section
  - Three bunch compressor chicanes (BC1, BC2, BC3)
- Recent progress
  - New undulator beamline “BL2” was built
  - Kicker magnet was installed for pulse-to-pulse beamline switching
  - SCSS test accelerator was moved to the upstream of SACLA-BL1
- Reliability of the accelerator is extremely important

# XFEL Performance




- Present performance of SACLA
  - 24-hour trend graph during a user operation
- XFEL Intensity: ~500 μJ/pulse
- Intensity fluctuation: ~10% (std. dev.)
- Pointing Stability: ~10 μm (std. dev.)

# Accelerator Tuning



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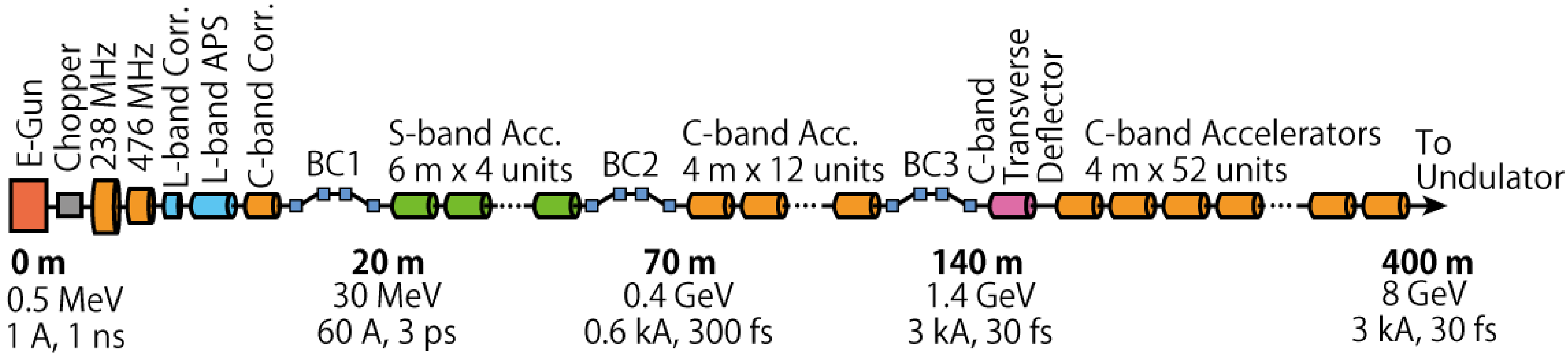
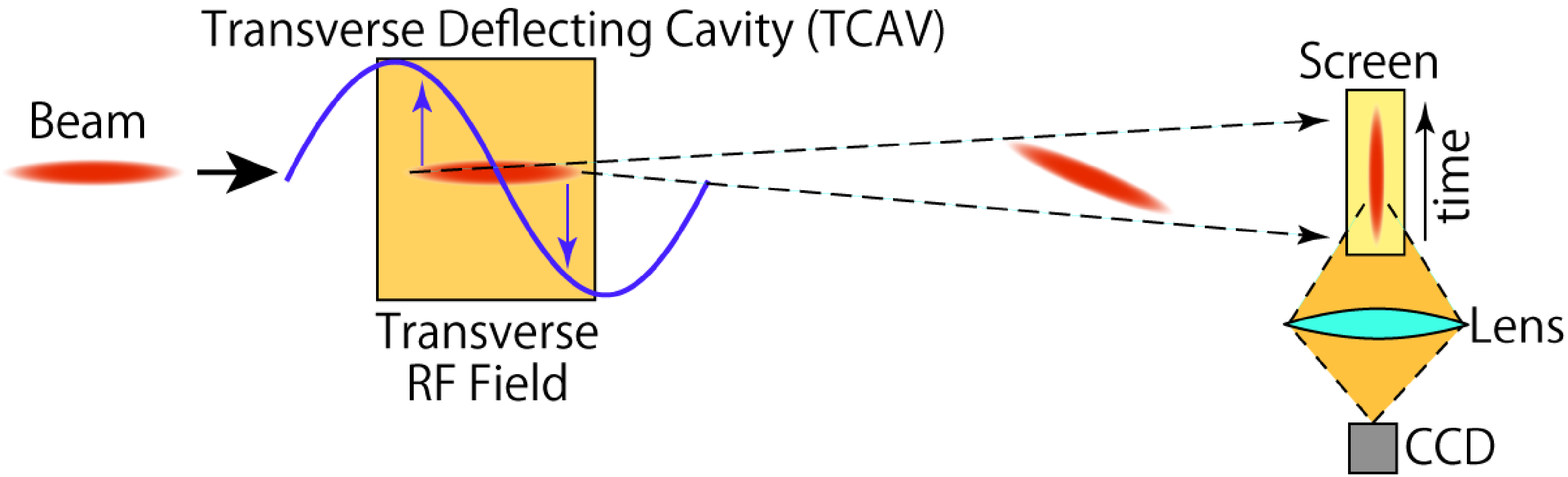


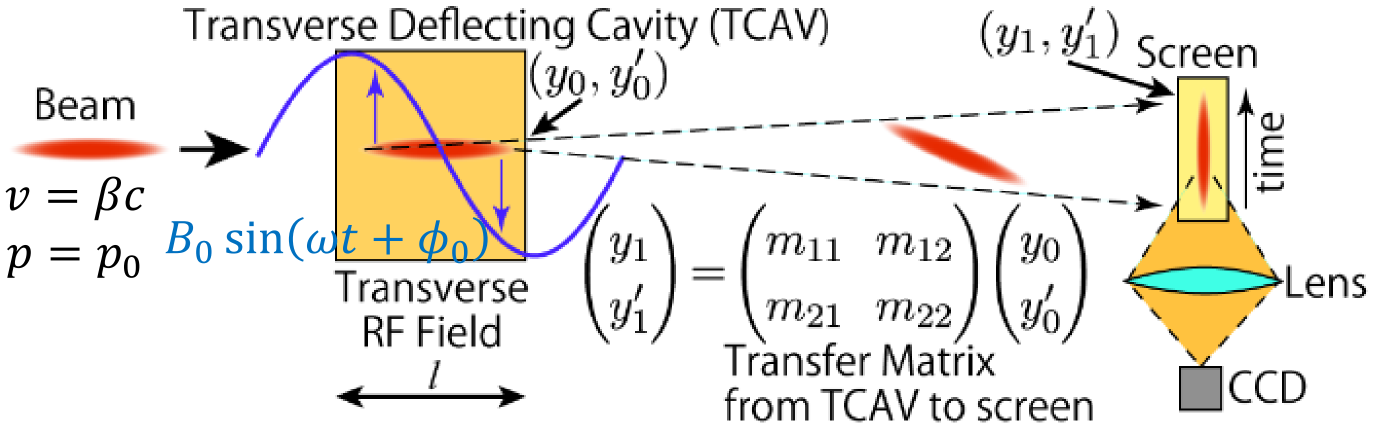

- Bunch compression condition is highly sensitive to the XFEL performance
- Longitudinal bunch profile monitor is required for fine-tuning of the bunch compression
  - C-band transverse deflector system (C-TDS) was installed downstream of BC3
  - C-TDS is useful for tuning of BC2 and BC3
- Tuning of the injector section is quite important
  - Injector section determines the initial condition of an electron beam
  - No longitudinal bunch profile monitor is prepared in the injector section
  - RF parameters are set to a simulation result or a previous operation condition
  - Fine-tuning is performed so as to maximize the XFEL pulse energy
- Transverse deflector system is demanded for the velocity bunching section

# Temporal Profile Measurement




- A Transverse Deflecting Cavity (TCAV) gives a transverse kick to an electron beam
  - e.g. TM110 mode in a pillbox cavity
  - RF phase is set to zero-crossing
- The temporal structure of the electron beam is converted to a transverse profile.
- The beam profile is taken by a screen monitor

# Time Resolution



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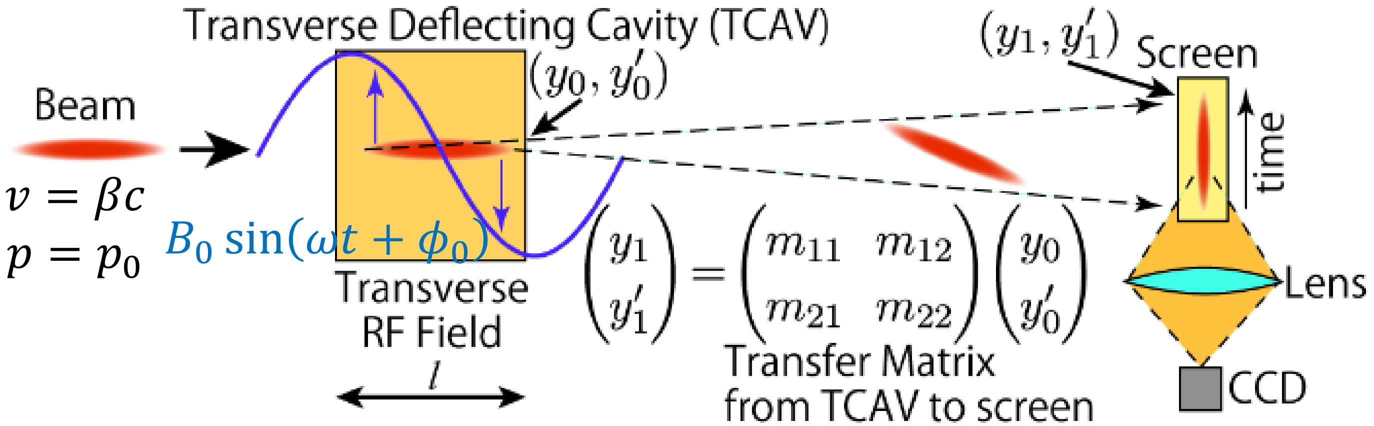


- TM110-mode in a pillbox cavity is assumed
  - Only magnetic field on the cavity axis
  - Field strength is constant along the axis
- Transverse force in the TCAV

$$F_y = -e\beta c B_0 \sin(\omega t + \phi_0)$$

- Transverse momentum given by the TCAV

$$p_y = \int_{-\frac{l}{2\beta c}}^{\frac{l}{2\beta c}} F_y dt = -eB_0 l\, T \sin\phi_0 \simeq -eB_0 l\, T\phi_0$$

$$T \equiv \sin\frac{\omega l}{2\beta c} \Big/ \frac{\omega l}{2\beta c} \quad \text{(transit time factor)}$$

- Kick angle

$$y_0' = \frac{p_y}{p_0} \simeq -\frac{eB_0 l\, T\phi_0}{p_0}$$

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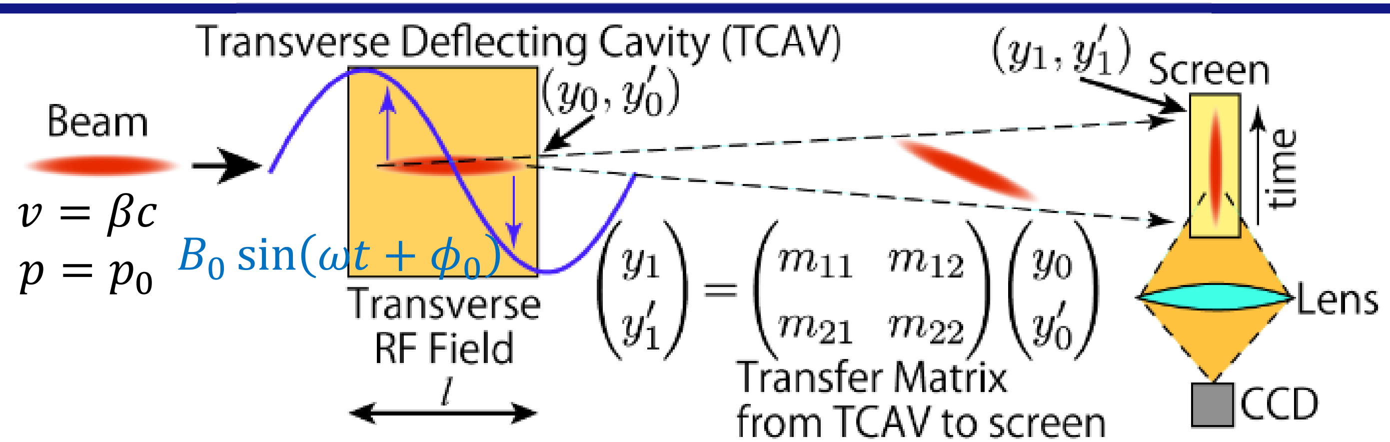


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$$y_0' = \frac{p_y}{p_0} \simeq -\frac{eB_0 l\, T\phi_0}{p_0}$$

- Position-to-time conversion factor

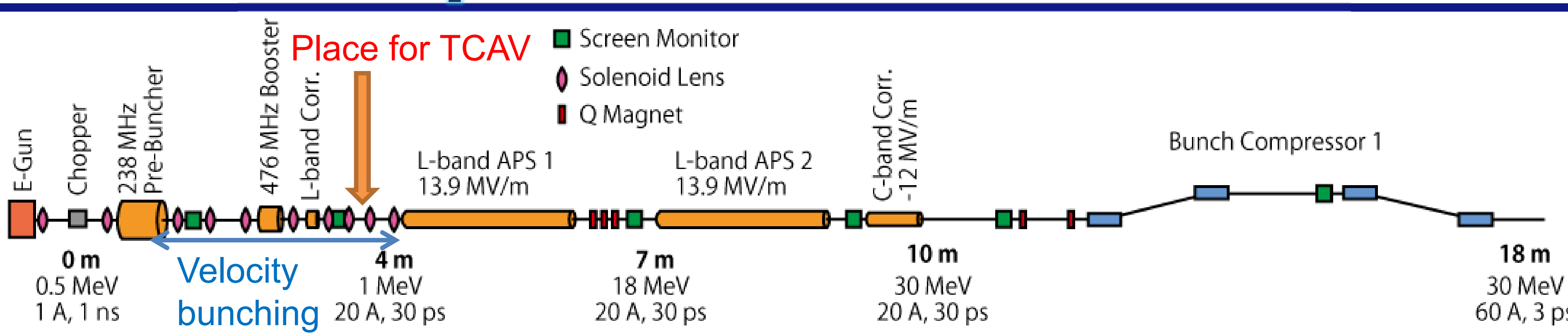
$$C = \frac{\phi_0}{y_1 \omega} = -\frac{p_0}{m_{12} e B_0 l\, T}$$

- Time resolution $\sigma_t$ is limited by the beam size at the screen, $\sigma_y$

$$\sigma_t = |C\sigma_y| = \frac{p_0 \sigma_y}{|m_{12}| e B_0 l\, T\omega}$$

- For better time resolution…
  - Lower beam energy
  - Smaller beam size
  - Larger $m_{12}$
  - Higher RF power
  - Higher frequency

# Requirements for TCAV



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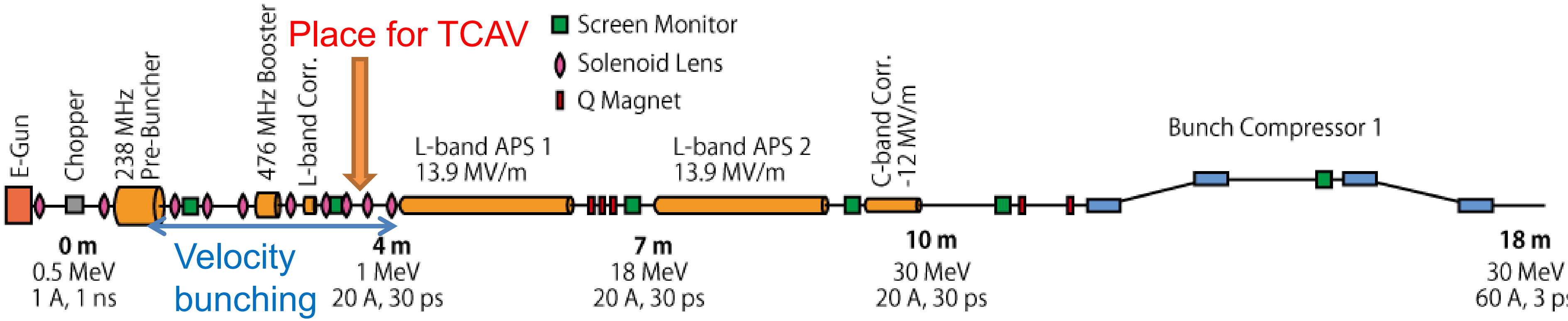
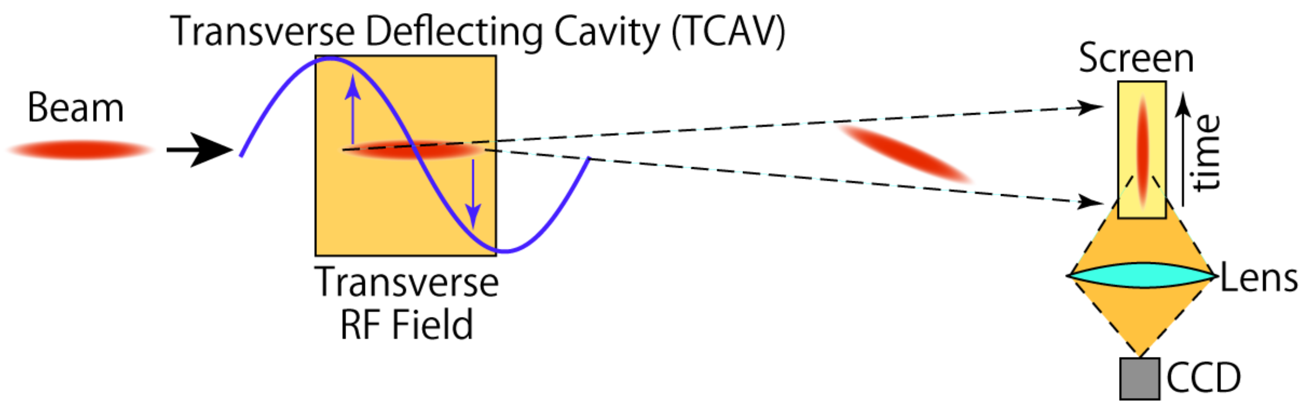



- TCAV for velocity bunching
  - Upstream of the L-APS is the best position for TCAV
  - The end of the velocity bunching section
- Low energy beam doesn't need high deflecting field
  - Several 10 kV is enough for 1 MeV beam
  - Single-cell cavity can be used. → Compact
- Bunch length ranges from 10 ps – 1 ns
  - High time resolution (< 3 ps) for a short bunch → Large kick angle
  - Wide measurement range for a long bunch (1 ns) → Low frequency
- Longitudinal magnetic field in a solenoid should be taken into account
  - Transverse momentum is rotated
  - Stretched image can be distorted
- Screen monitor is downstream of L-APS
  - Beam dynamics in the L-APS should also be considered.

# For Wide Measurement Range



# For Wide Measurement Range

- Only linear part of a sinusoidal wave can be used for a conventional TCAV system
- Circular polarization field provides a circular beam image and enables us to use full RF period
- Two input ports intersecting with a right angle
  - Pillbox cavity has 2 dipole modes, which are degenerated and are orthogonal each other
  - Each port excites each orthogonal mode
- Polarization can be controlled by the phase difference
  - $\phi_2 - \phi_1 = 0 \text{ or } \pi$ : Linear polarization
  - $\phi_2 - \phi_1 = \pm\pi/2$ : Circular polarization
- Circular image is not affected by longitudinal magnetic field
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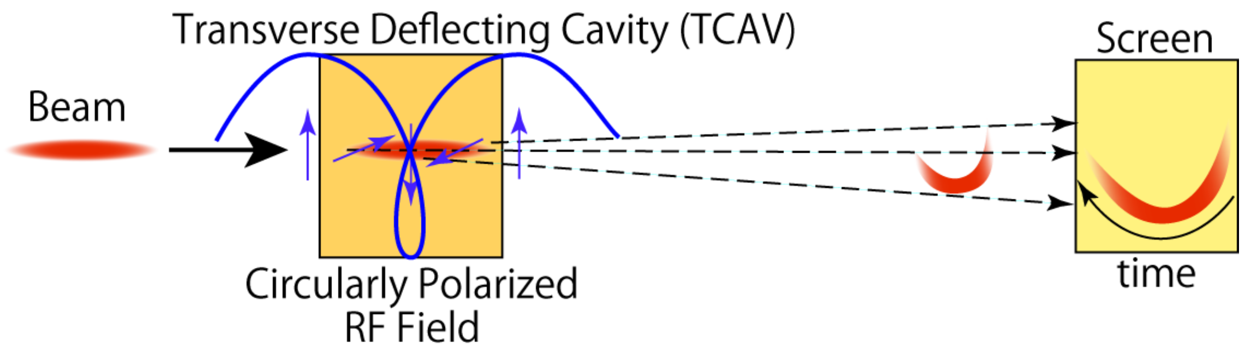

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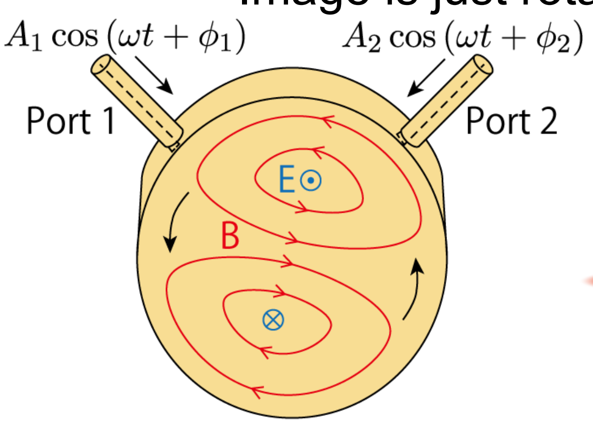


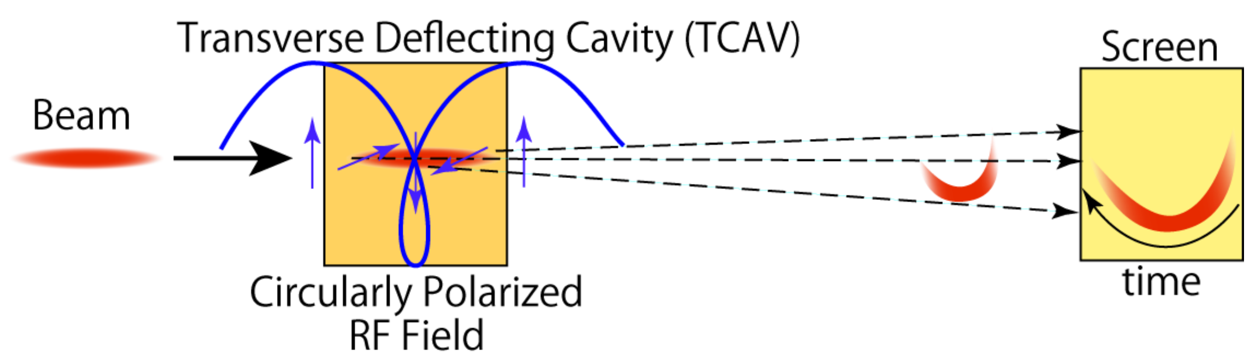

# Linear Polarization

Vertical Deflection

$$\phi_2 - \phi_1 = 0$$

Horizontal Deflection

$$\phi_2 - \phi_1 = \pi$$

Contour: E-field
Arrows: H-field

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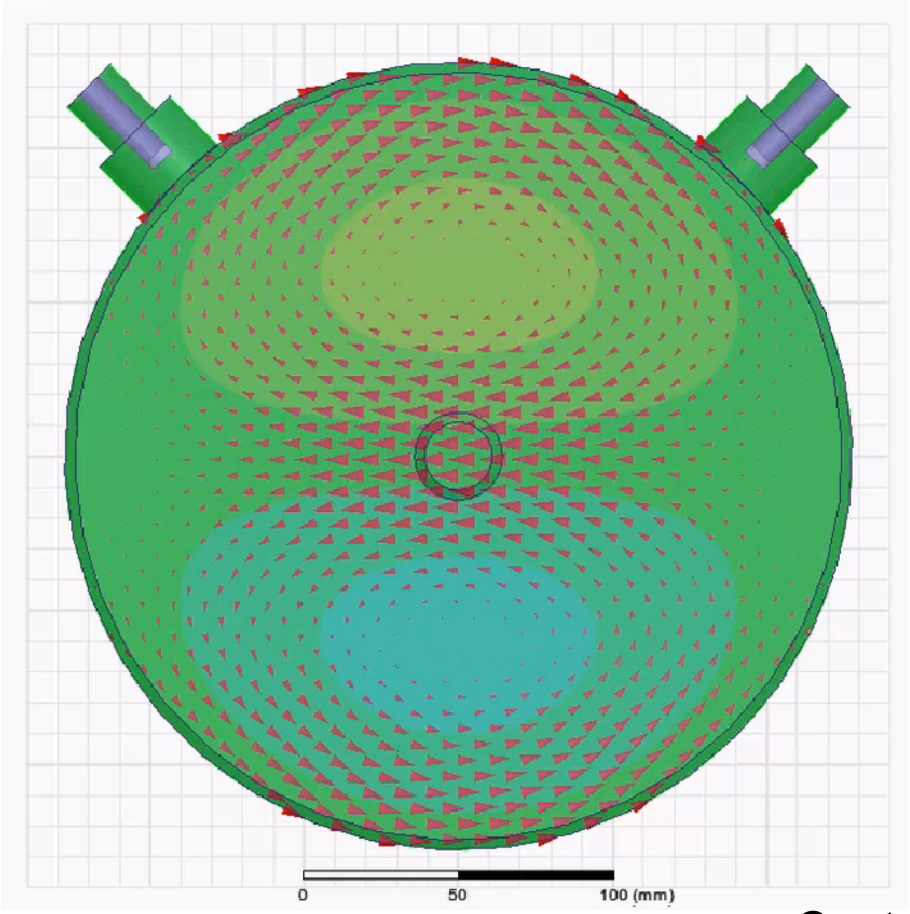


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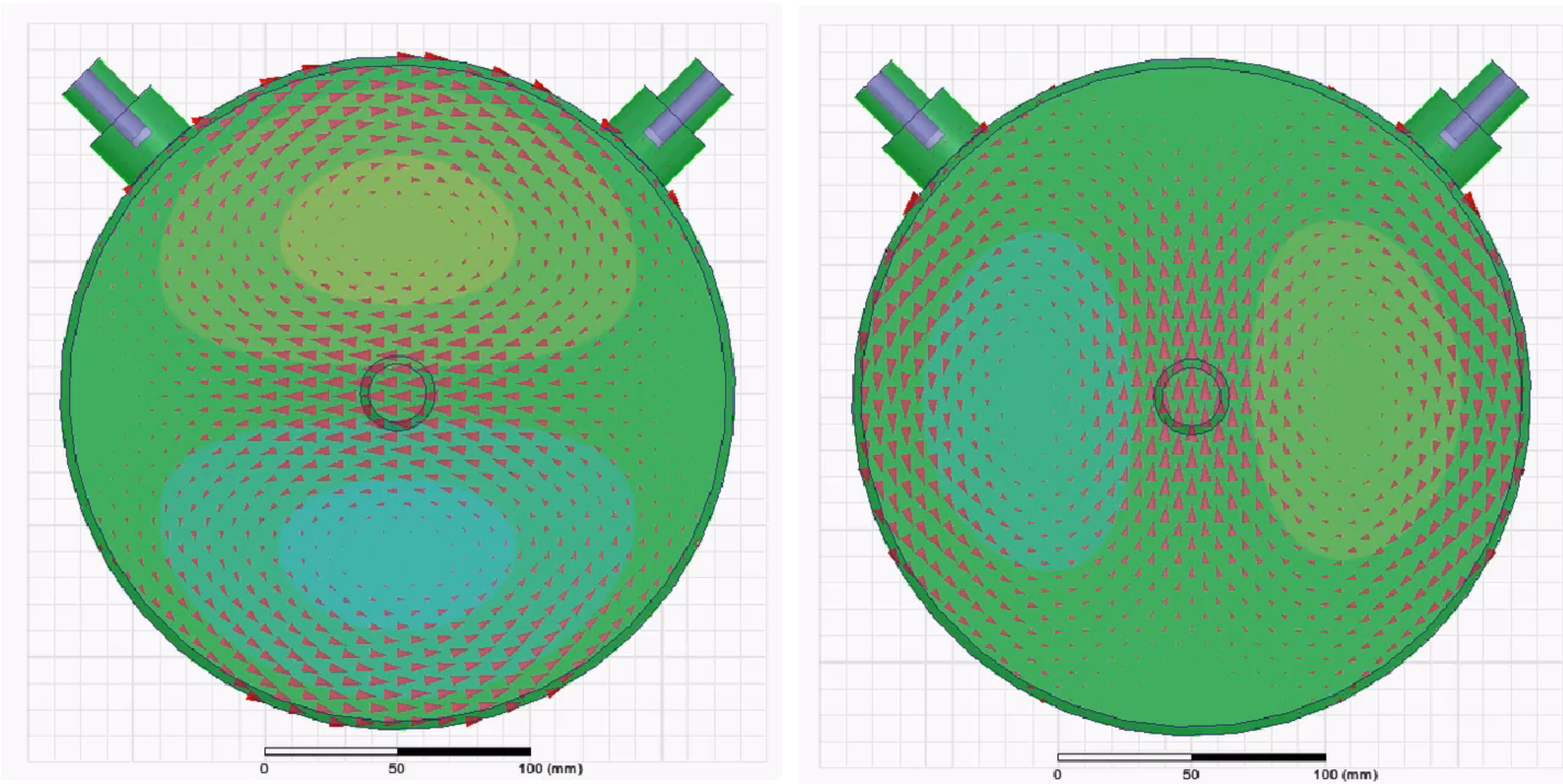
# Linear Polarization

| Vertical Deflection | Horizontal Deflection |
| --- | --- |
| $\phi_2 - \phi_1 = 0$ | $\phi_2 - \phi_1 = \pi$ |

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# Circular Polarization

Clockwise Deflection

$$\phi_2 - \phi_1 = -\frac{\pi}{2}$$

Counter Clockwise Deflection

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$$\nabla \times B = \frac{1}{c^2}\frac{\partial E}{\partial t}$$

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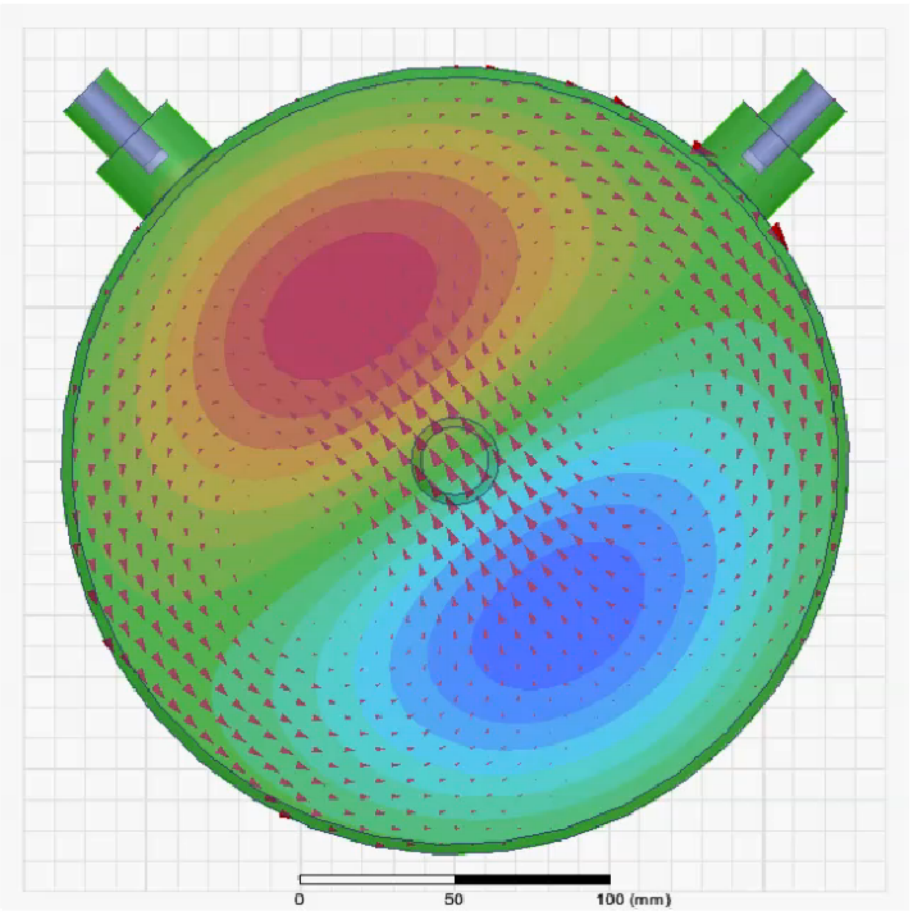


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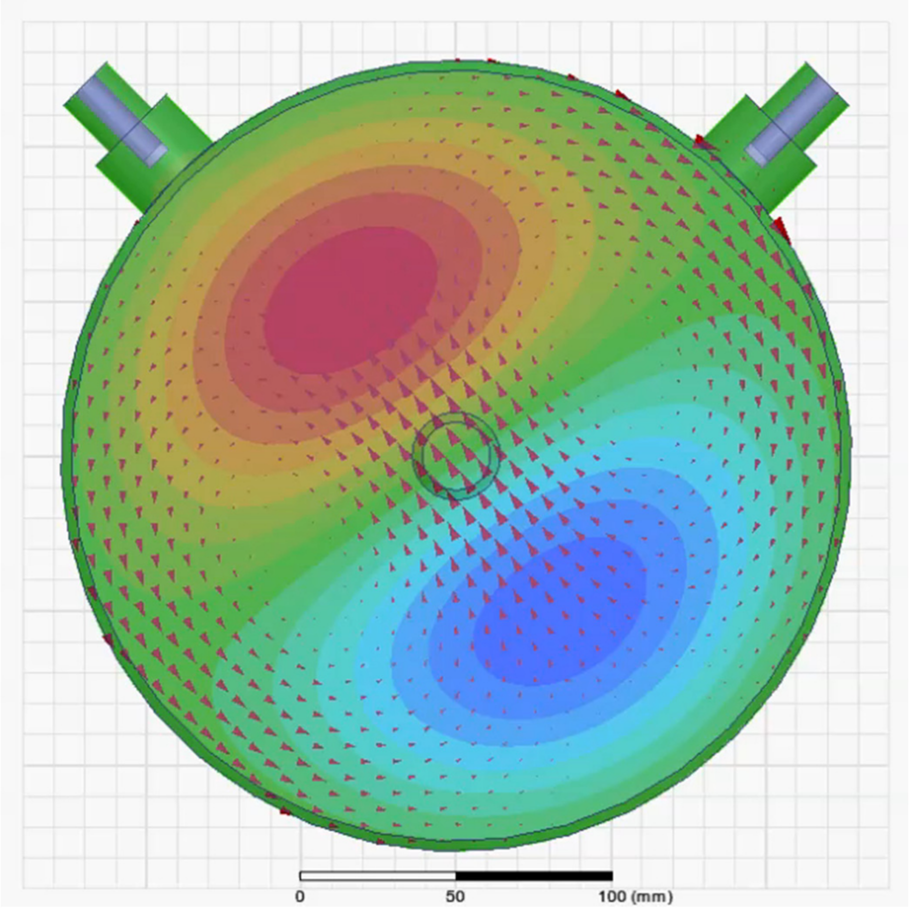


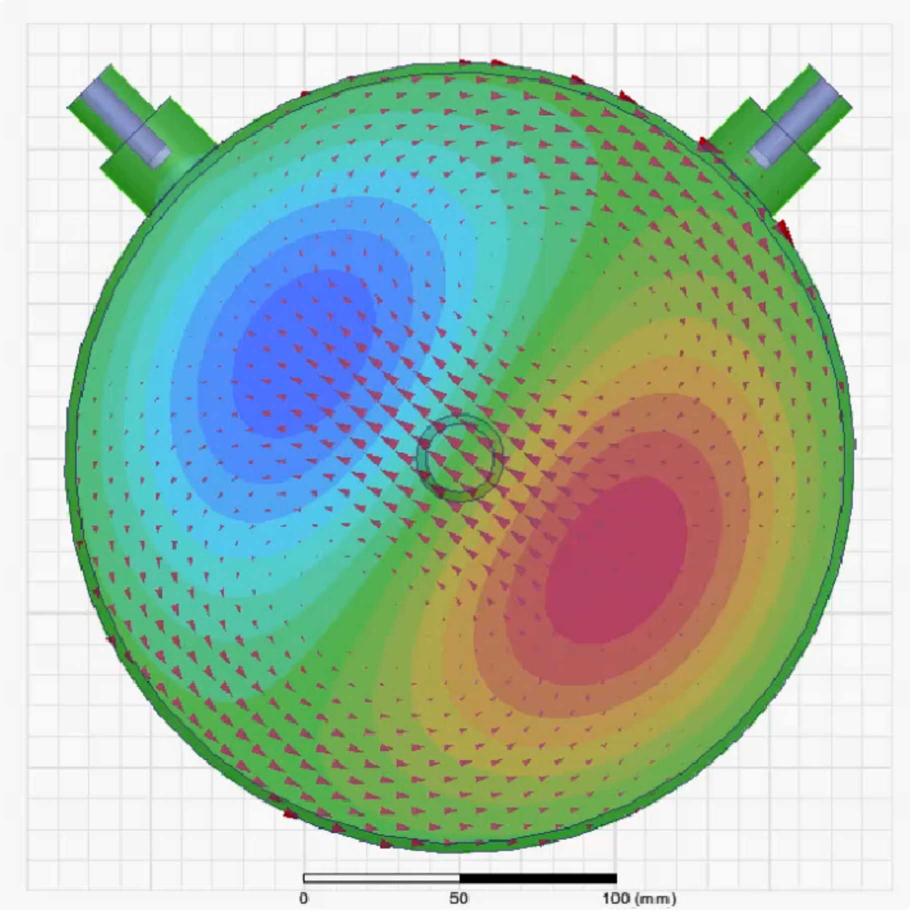


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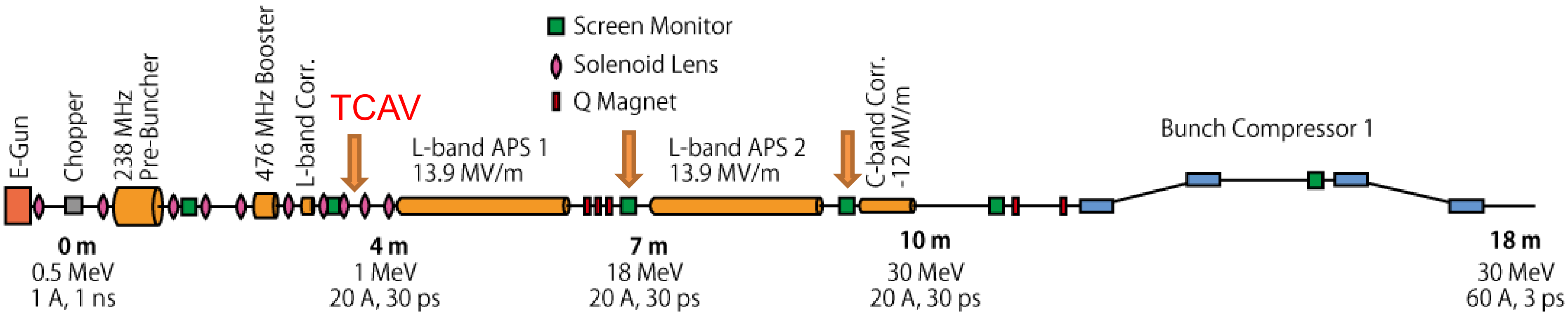
# RF Frequency

- We decided to use 1428 MHz (L-band).
- RF period: 700 ps
  - Bunch length as long as 700 ps can be measured
  - Covers most of the measurement range
- We can utilize L-band apparatus
  - Such as 2.5 kW solid-state amplifiers for L-band corr. cavity
- Required deflecting angle for 3 ps time resolution

$$y'_{\mathrm{crest}} = \frac{eB_0 l\, T}{p_0} = \frac{\sigma_y}{|m_{12}|\sigma_t \omega} \simeq 60\ [\mathrm{mrad}]$$

  - Beam size at the screen after L-APS ($\sigma_y$): 0.5 mm rms
  - Beam energy: 1 MeV
  - (1,2) element of the transfer matrix ($m_{12}$): ~ –0.3 m
- Time resolution for circular polarization measurement
  - Kick angle is limited by the screen size (10 mm diameter)
  - We set the image radius $r_{\mathrm{img}}$ to 3 mm.
  - Time resolution: 19 ps ($= 700\ \mathrm{ps} \times \sigma_y / 2\pi r_{\mathrm{img}}$)

# RF Capture by L-APS

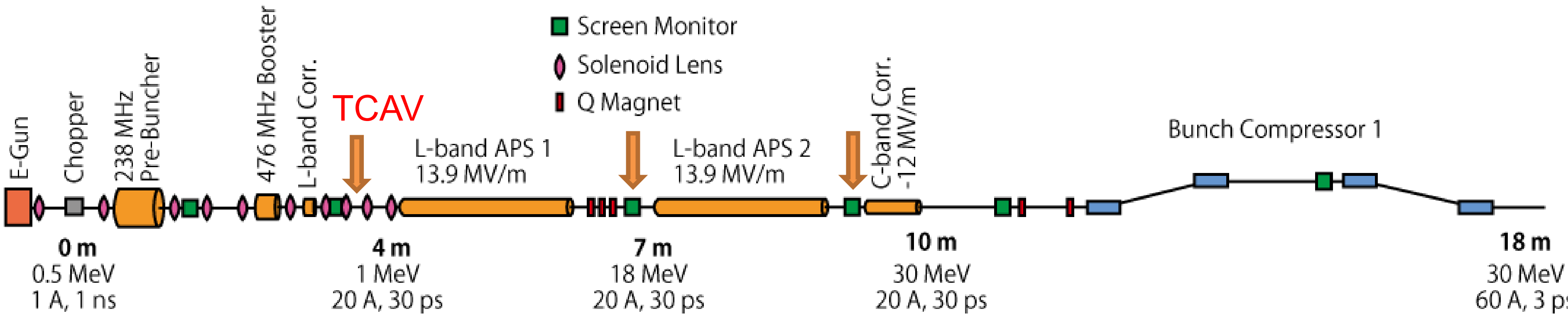


# RF Capture by L-APS

- L-APS accelerator between the TCAV and the screen monitor
- Beam must be captured by the L-APS accelerating rf field
- Longitudinal phase space orbit of the L-APS

$$\cos\theta - \cos\theta_\infty = \frac{kc}{eE_0}\left[\sqrt{p^2 + (mc)^2} - p\right]$$

  - $\theta$: RF phase
  - $\theta_\infty$: Constant determined by an initial condition
  - $k$: Wave number of the RF field
  - $E_0$: Accelerating electric field amplitude
  - $p$: Beam momentum
- Captured region: $-156\ [\mathrm{deg.}] < \theta < 84\ [\mathrm{deg.}]$
  - For 1 MeV electrons
  - Phase coverage: ~ 240 deg. → ~ 470 ps
- If the bunch length is longer than 470 ps, phase scan of the L-APS is needed.



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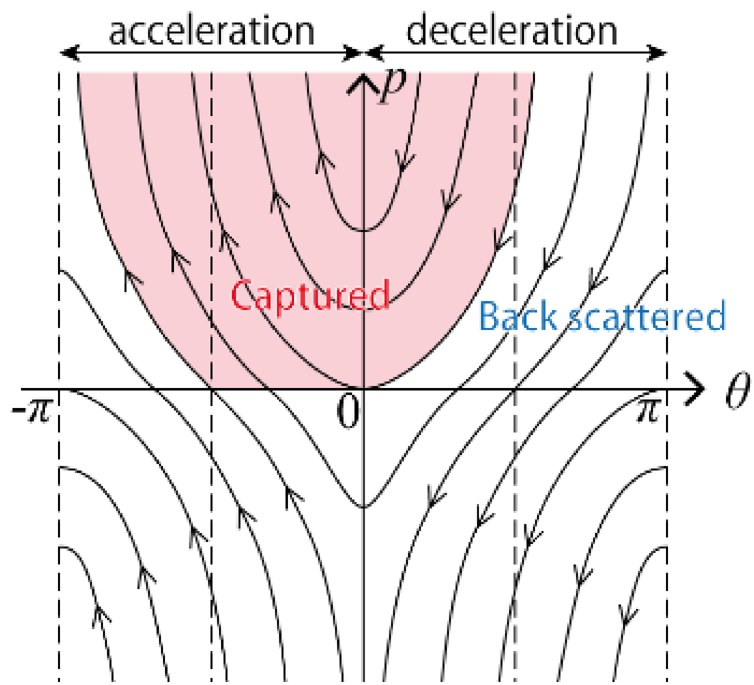


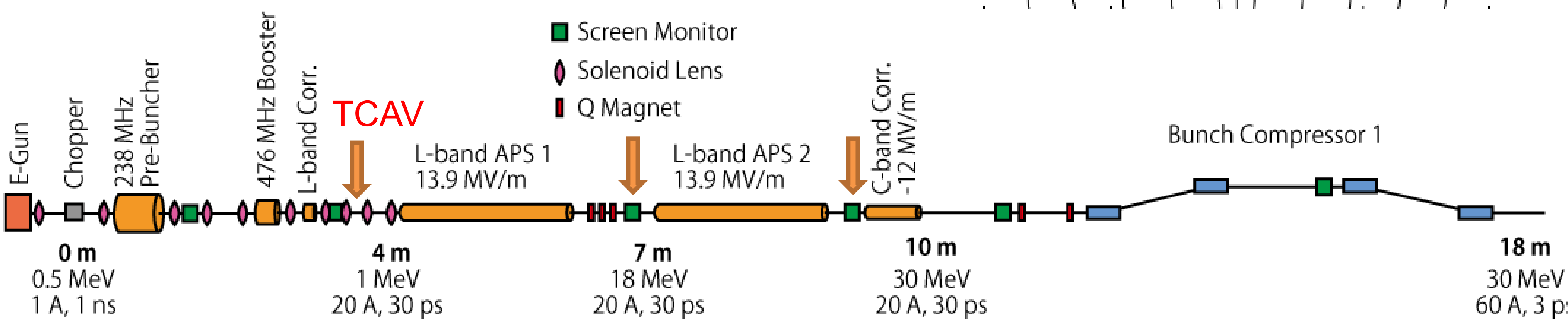

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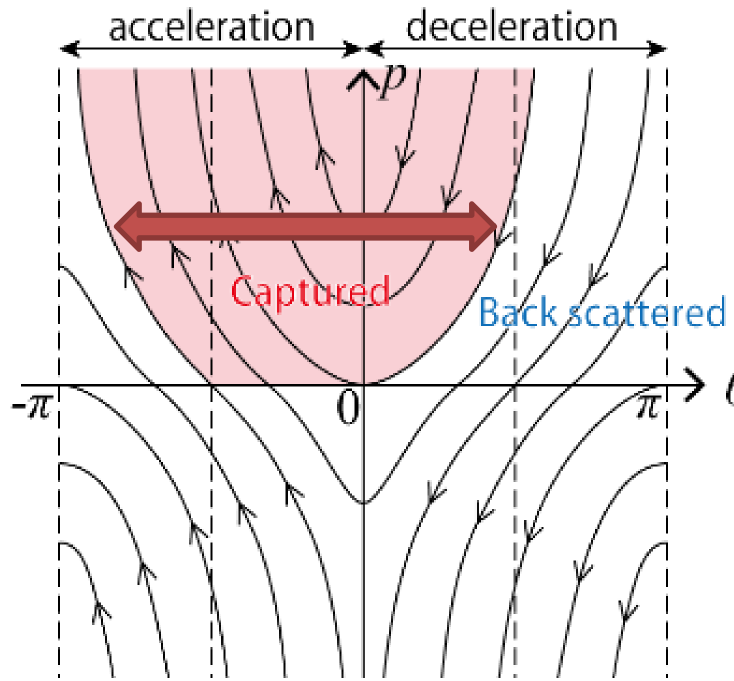
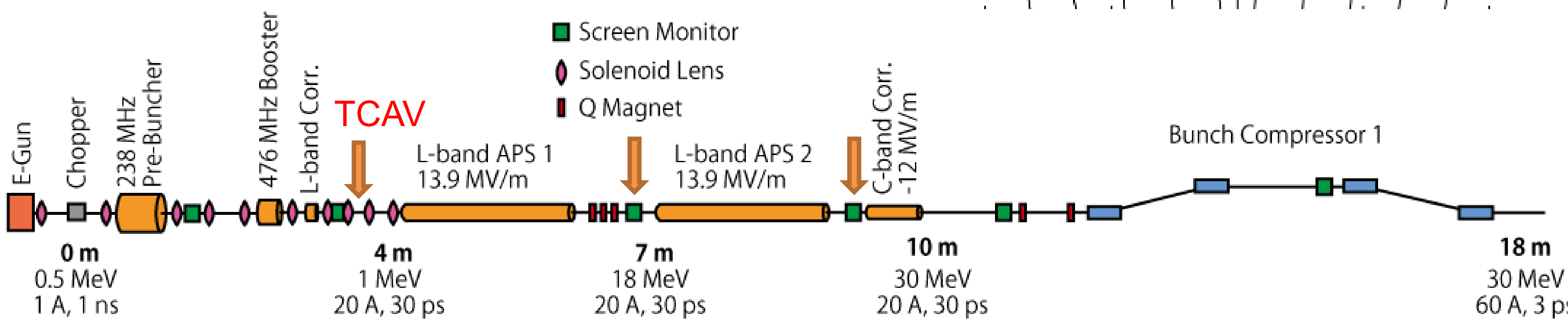
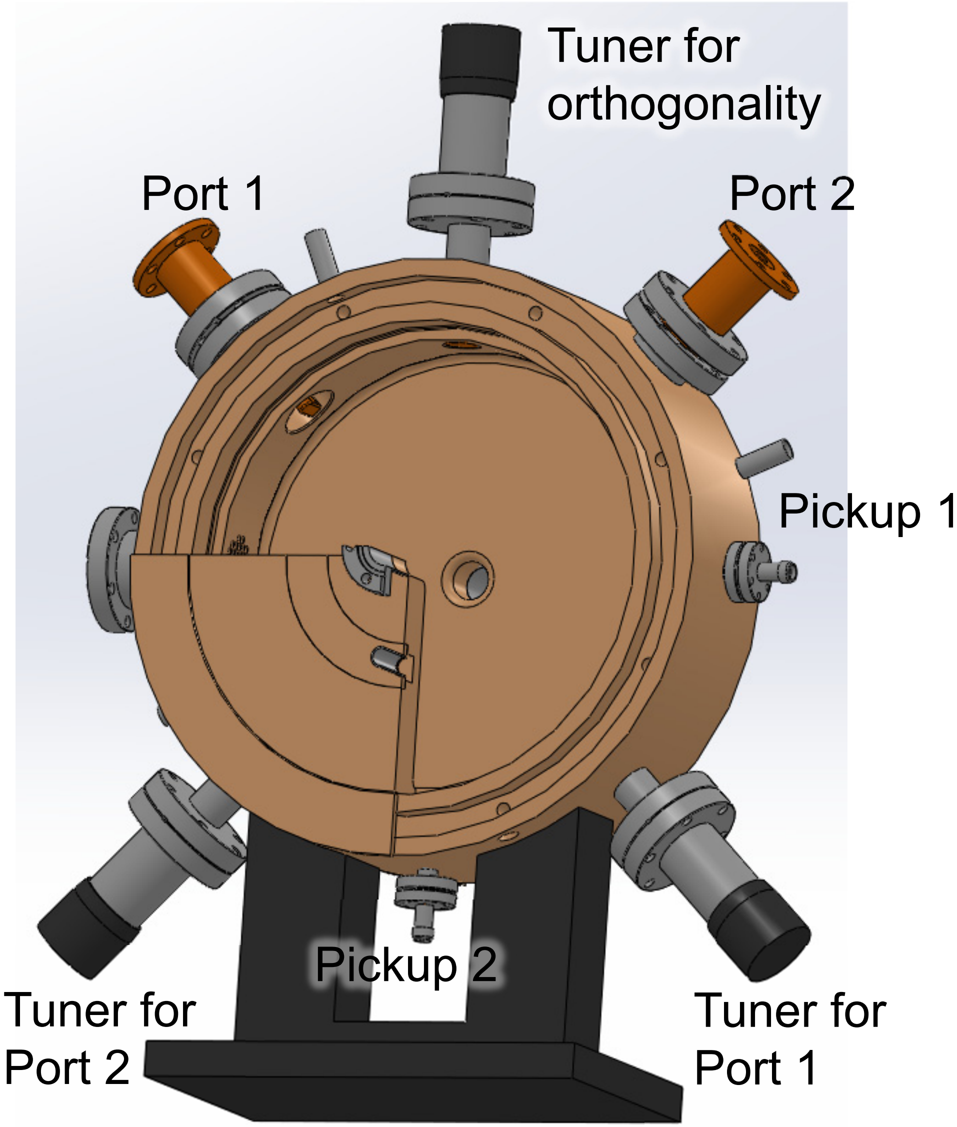


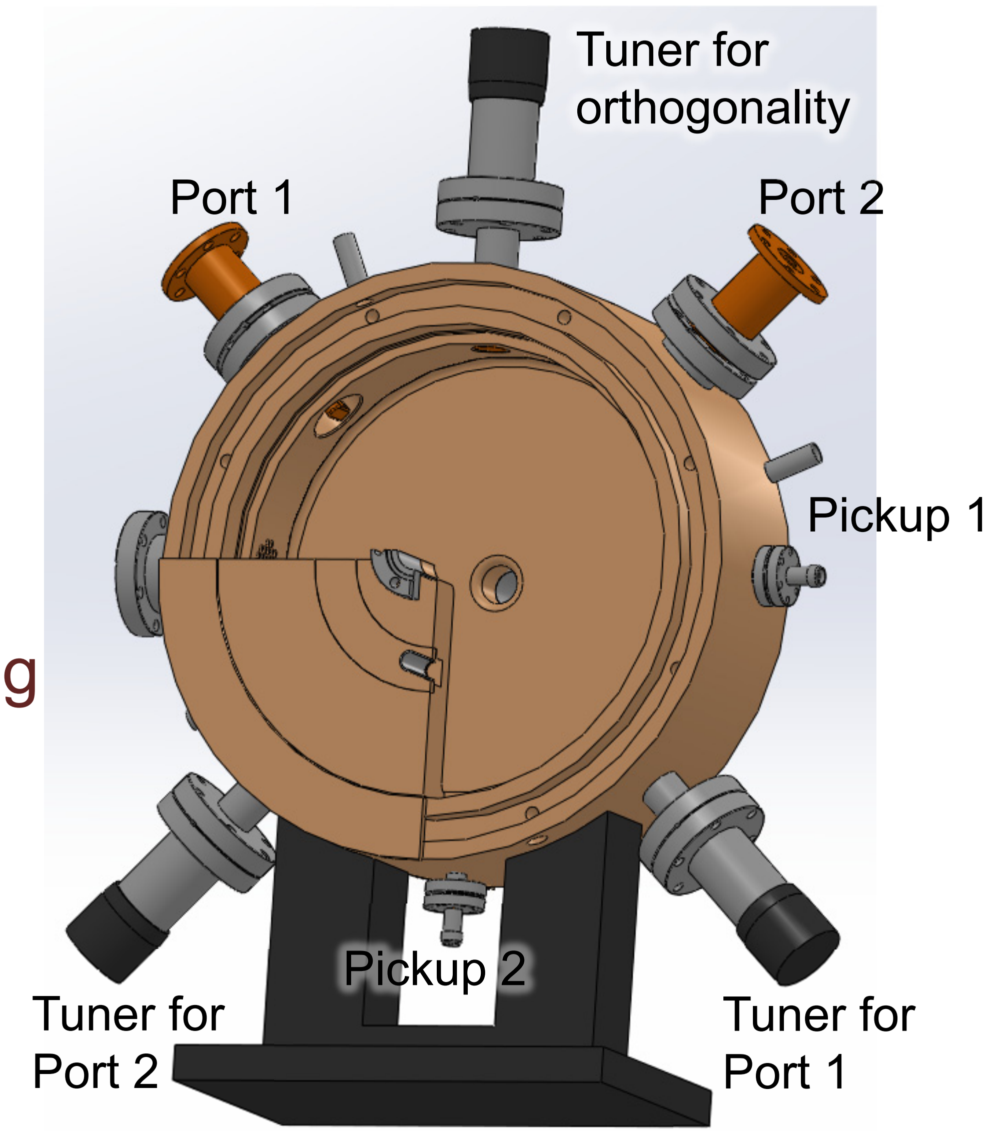



# Cavity Design



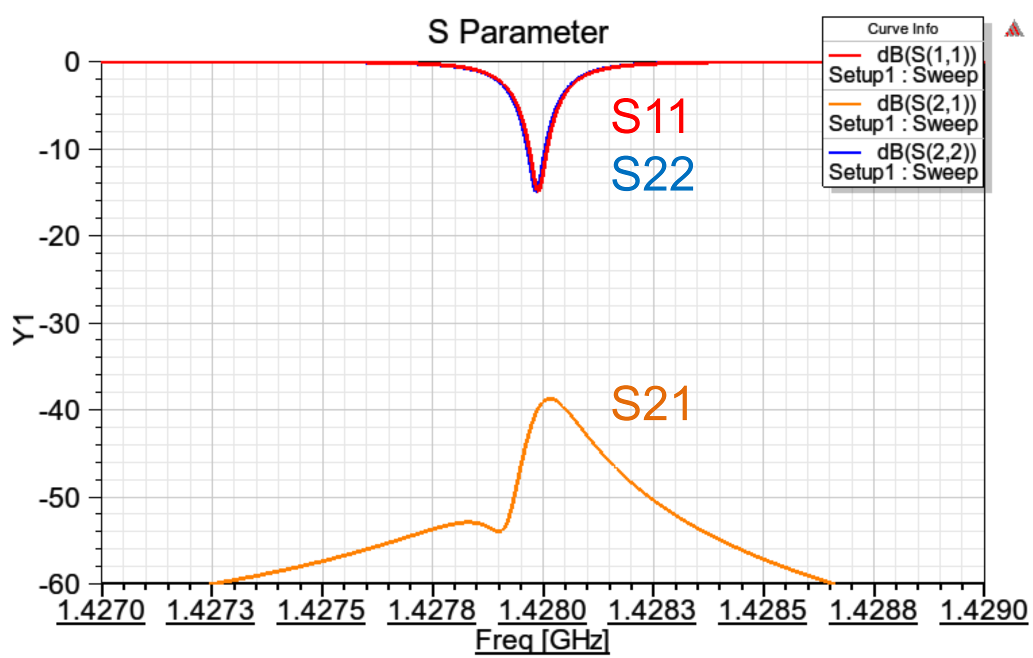
# Cavity Design

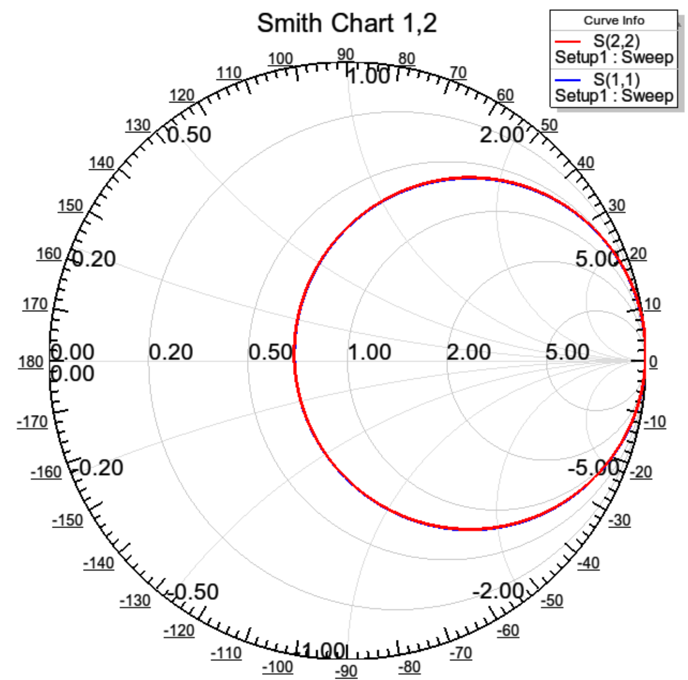
- Resonant Frequency: 1428 MHz
- Resonant Mode: TM110
- 2 input ports for arbitrary polarization
- 3 tuners
  - Port 1 frequency
  - Port 2 frequency
  - Orthogonality
- 2 pickup ports for monitoring
- Inner length: 60 mm
- Inner diameter: ~256 mm
- Flange-to-flange distance: 160 mm
- Input power: 2.5 kW each
  - From Solid-state amplifier



# RF Simulation

- Unloaded Q factor $Q_0$: 2.3 x $10^4$
- External Q factor $Q_{\mathrm{ext}}$: 1.6 x $10^4$
- Loaded Q factor $Q_\mathrm{L}$: 9.5 x $10^3$
- Coupling factor $\beta$: 1.44
- Filling time: 6.6 μs
- Small coupling between the 2 input ports ( –40 dB)



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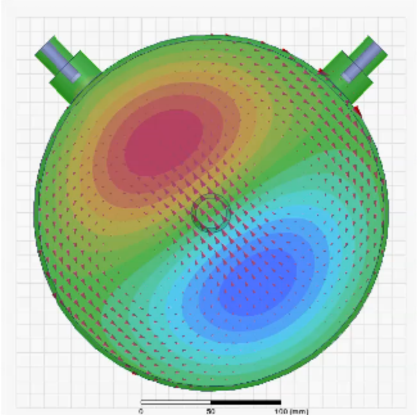

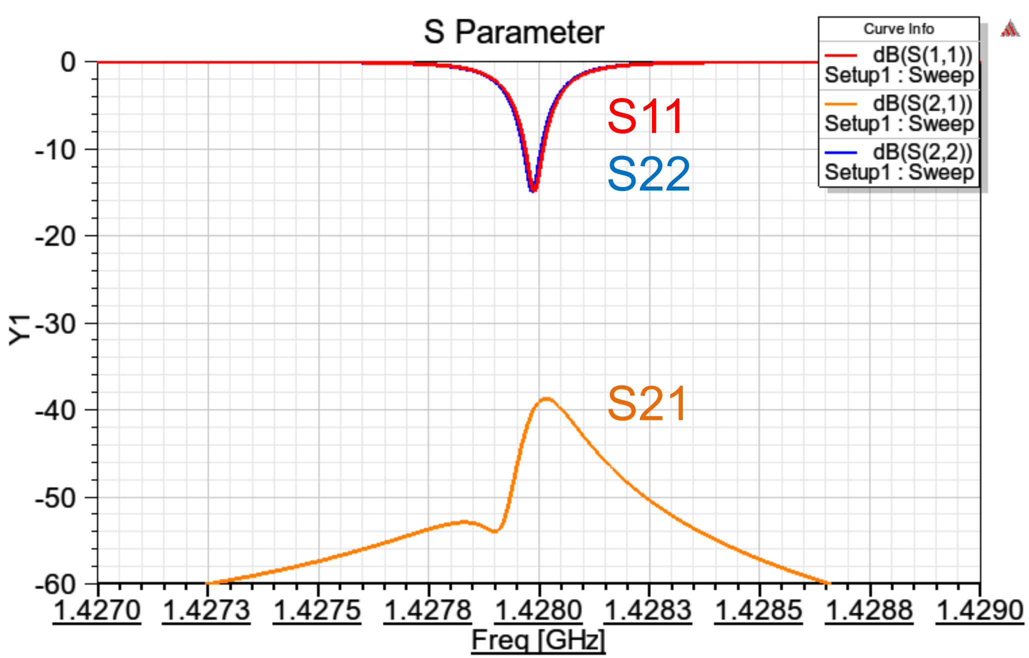


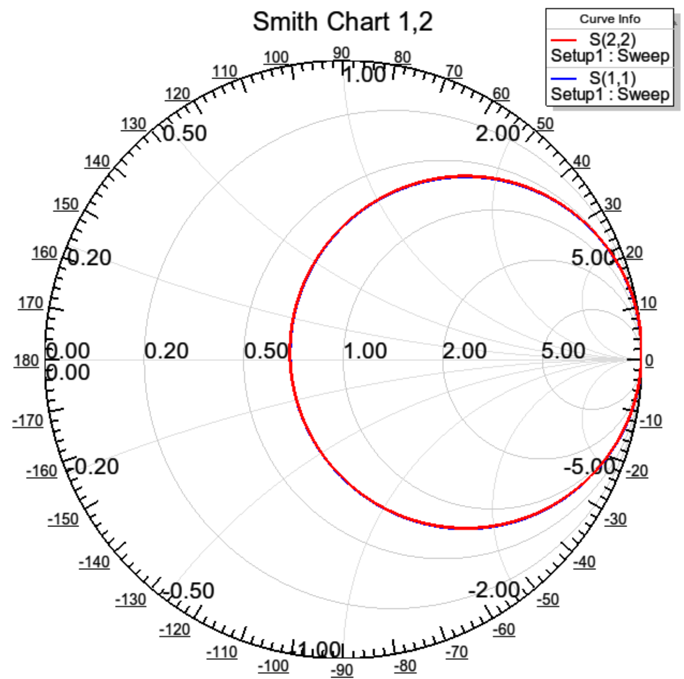

# Deflecting Angle

- Deflecting angle was evaluated by integrating the RF electromagnetic field on the cavity axis
- Transverse Shunt Impedance: 2.1 MΩ
- Deflecting angle at crest ($y'_{\mathrm{crest}}$): 63 mrad for 1 MeV electron
  - 2.5 kW input for each port
- Sufficient for the required time resolution of 3 ps

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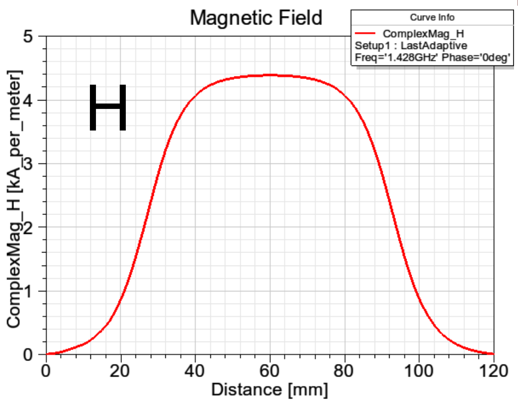


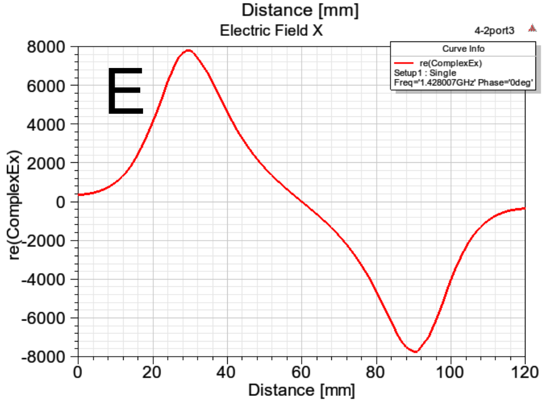

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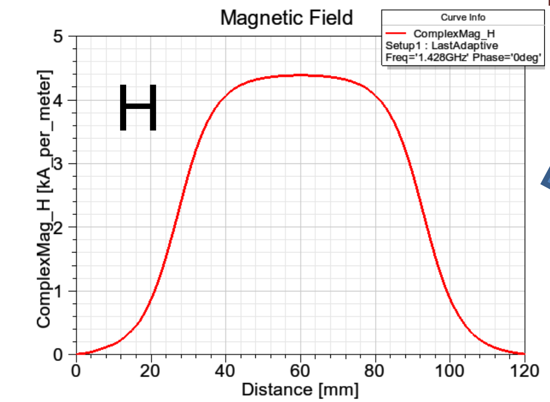


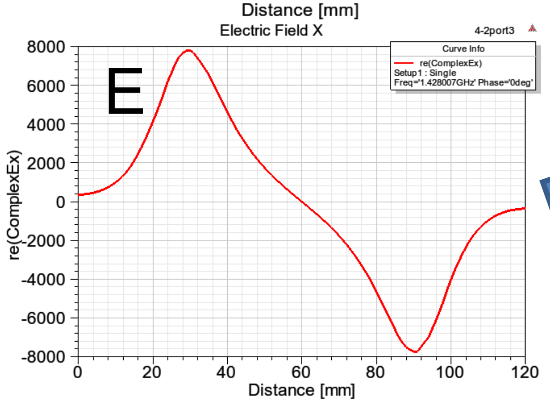


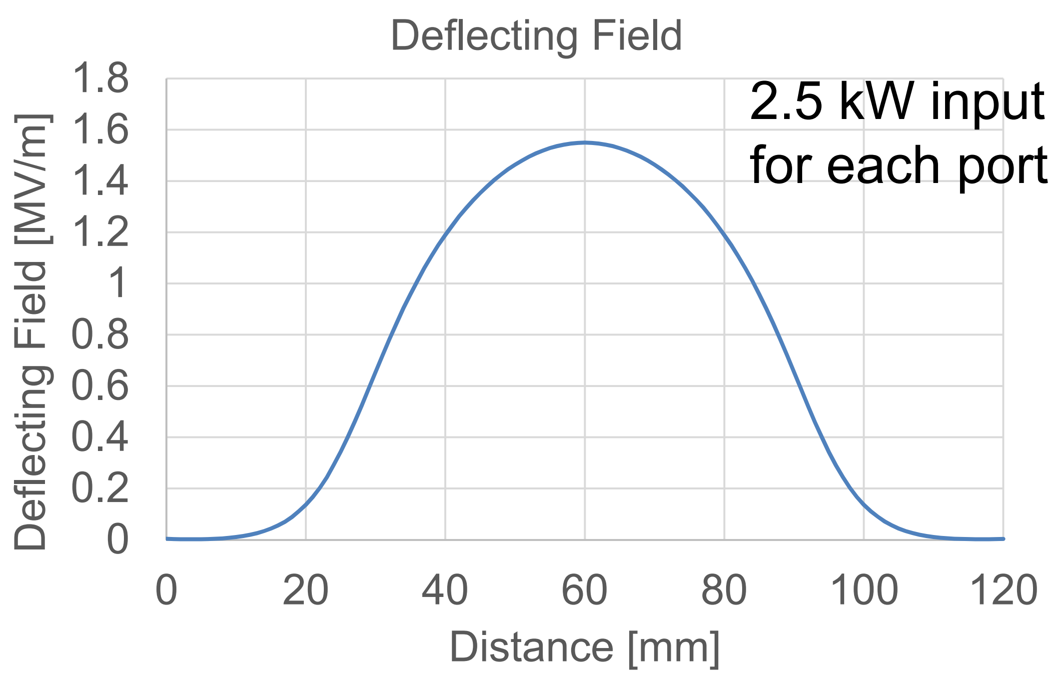

# Summary

- Temporal bunch structure measurement is demanded in the velocity bunching section at SACLA
  - Beam Energy: ~ 1 MeV
  - Bunch Length: 10 ps – 1 ns
  - Time Resolution: 3 ps for 10 ps bunch
- We designed a compact L-band transverse deflector system
  - RF Frequency: 1428 MHz (L-band)
  - Arbitrary polarization selection
    - 2 input ports intersecting at a right angle
  - Linear polarization: high time resolution
  - Circular polarization: long bunch
  - Inner cavity length: 60 mm
  - 2.5 kW input for each port
- Wide measurement range up to 700 ps
- High time resolution down to 3 ps