Development of CW Laser Wire in Storage Ring and Pulsed Laser Wire

- CW Build-up cavity scheme
  - principle of optical cavity
  - setup and measurement
  - multi-bunch measurement
  - higher-order mode upgrade
  - pulsed laser build-up system
  - self-start recirculation system
- High power pulsed laser scheme
  - setup and lens system
  - measurement example

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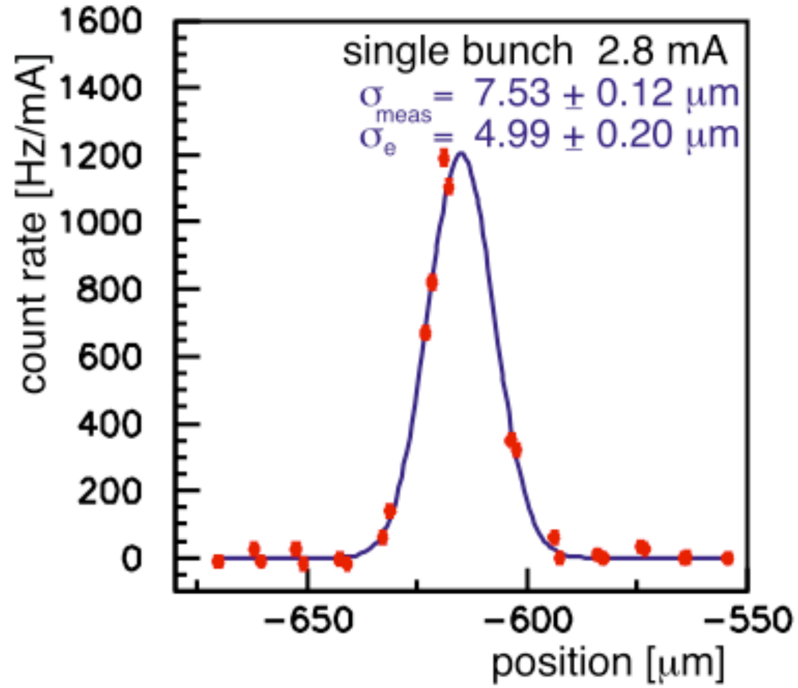
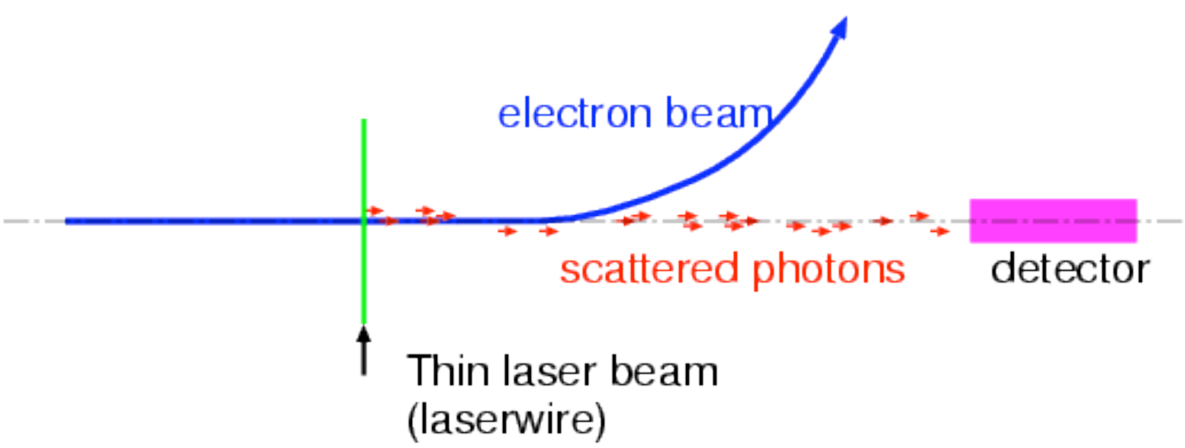
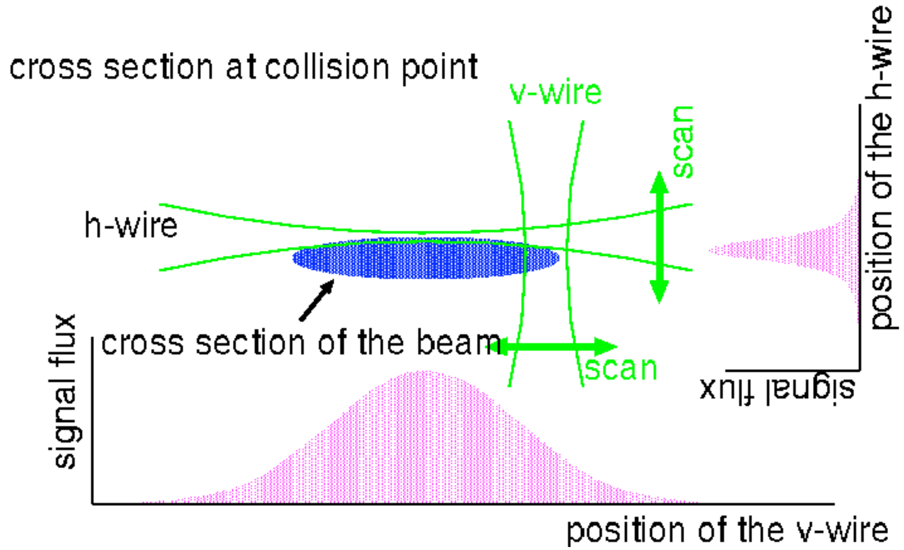
Principle of Laser Wire Monitor

- Principle of beam size measurement
  - Input a focused laser beam transversely across the electron beam.
  - Measure flux of Compton scattering signal as a function of laser position.
- Advantage of laser based monitors
  - not damaged by high intensity beam
  - non-invasive measurement
  - possible to design a thinner wire than conventional wire scanner



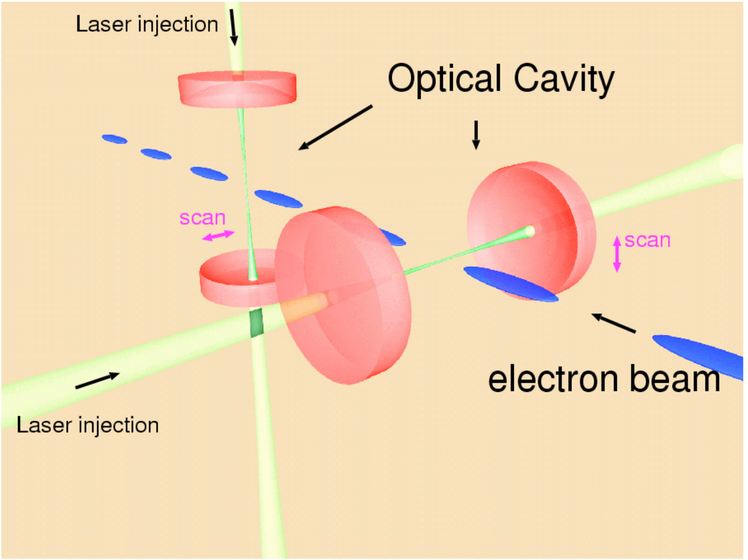


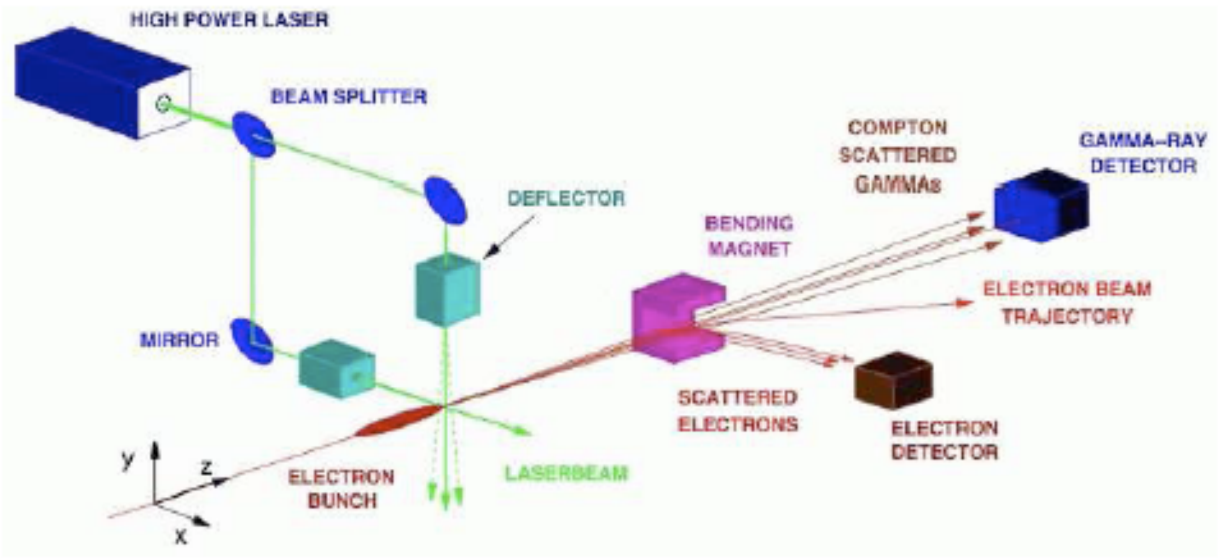


Technical challenges

- To obtain enough signal
  - high laser power (100W for storage ring, 100MW for single path)
- To realize high spatial resolution
  - thin laser width (<~5μm)
  - stable and well known laser width for subtracting its contribution
- Two possible solutions
  - build-up cavity scheme (compact and suitable for storage ring)
  - high power pulsed laser (single path, low repetition rate beam line)

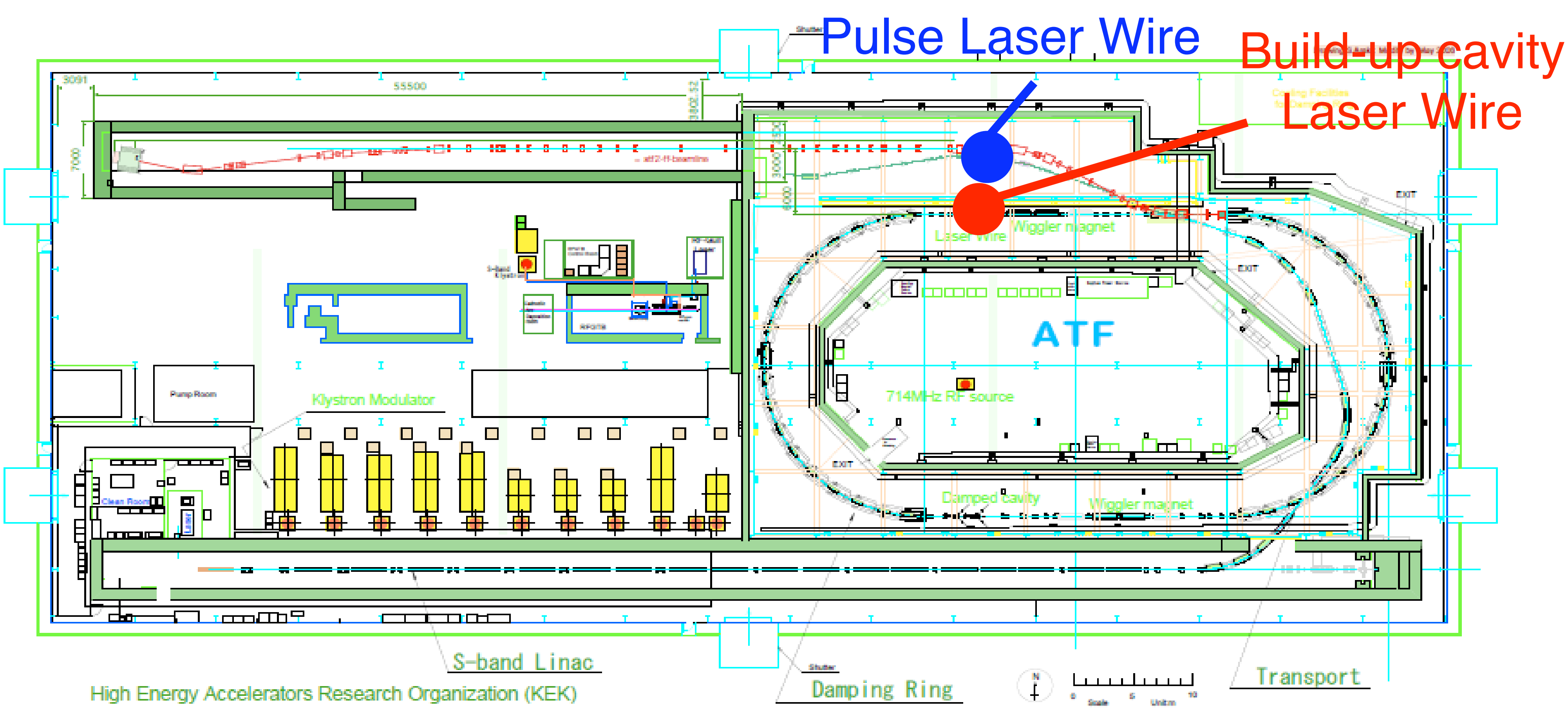
$$\sigma_e = \sqrt{\sigma_{meas}^2 - \sigma_{lw}^2}$$





Accelerator Test Facility in KEK

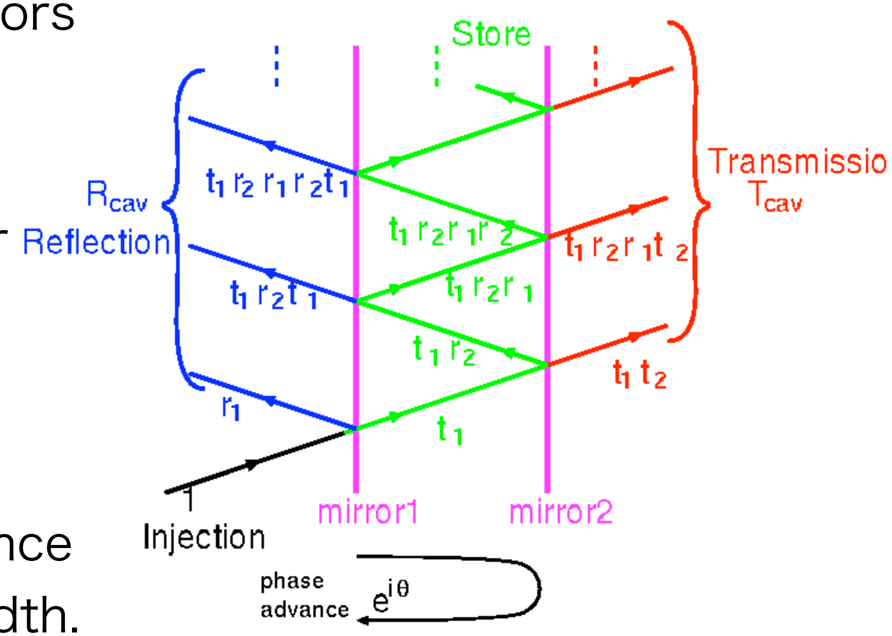
- ATF is a test accelerator to produce a low emittance beam required for LC.
- Damping ring LW (Kyoto university)
  - Build-up cavity type LW measures equilibrium condition of the ring.
- Extraction line LW (Royal Holloway university and Oxford university)
  - High power pulsed LW development aiming to demonstrate ~micron resolution.
- Electron beam to be measured: <10um (vertical), 100um (horizontal)

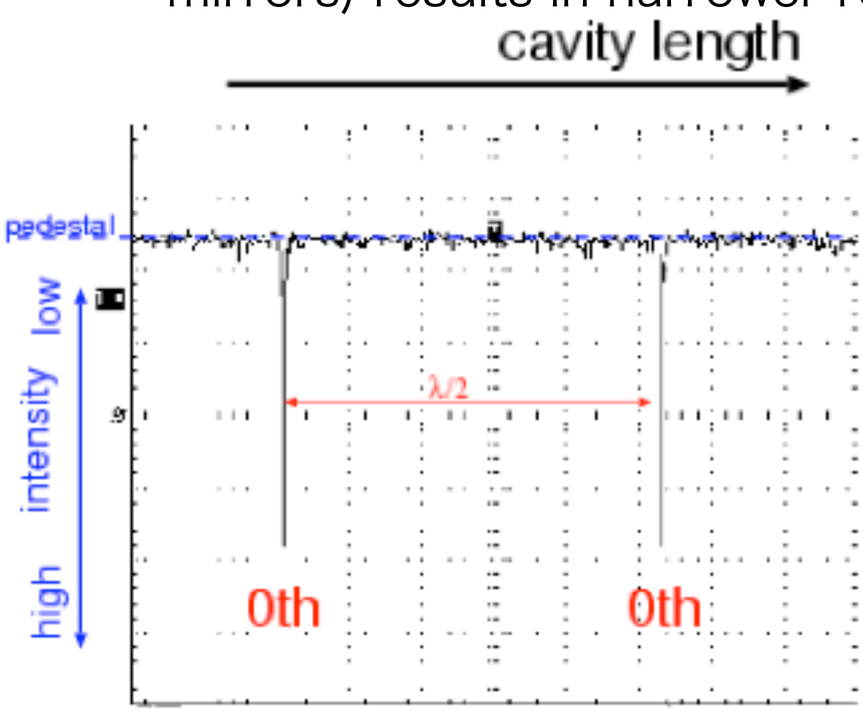


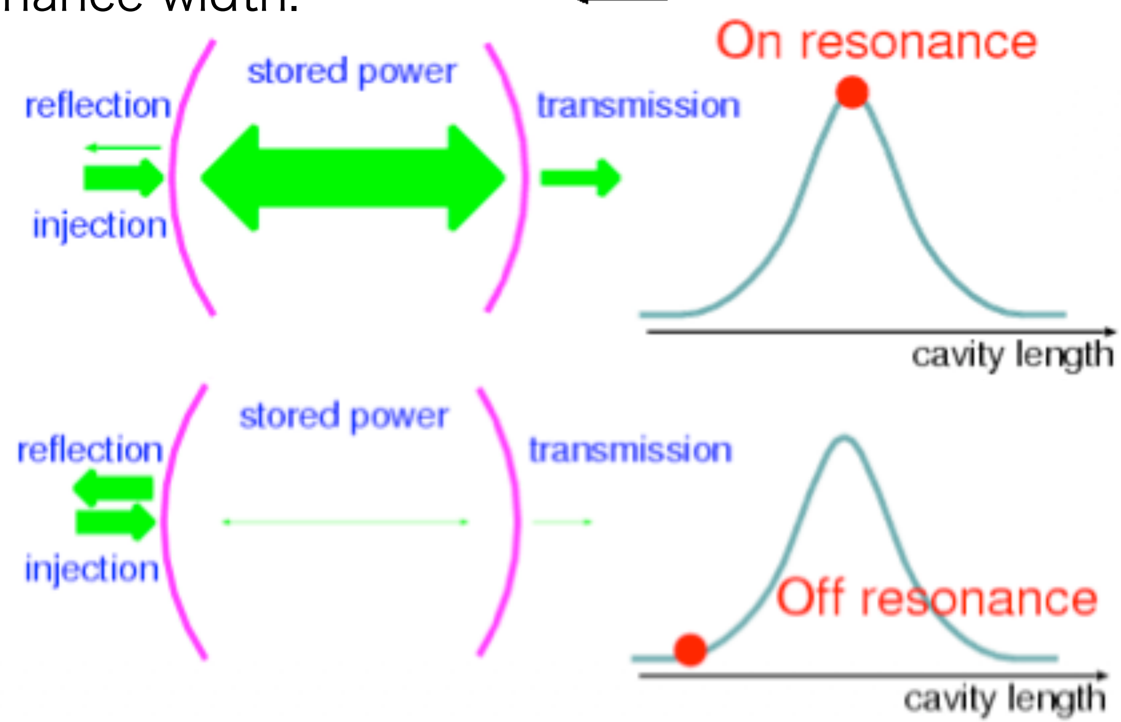
Build-up Cavity scheme

Principle of optical cavity (power enhancement)

- Optical cavity
  - closed optical path which consists of mirrors facing each other
  - laser power builds-up inside the cavity
  - much higher power than commercial laser source is available.
- Realization of power enhancement
  - resonance condition (standing wave)
  - higher enhancement factor (high reflectance mirrors) results in narrower resonance width.

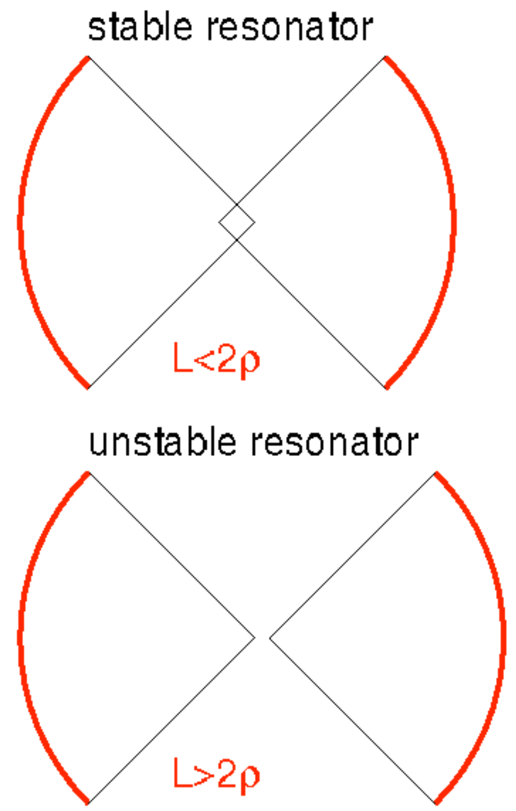


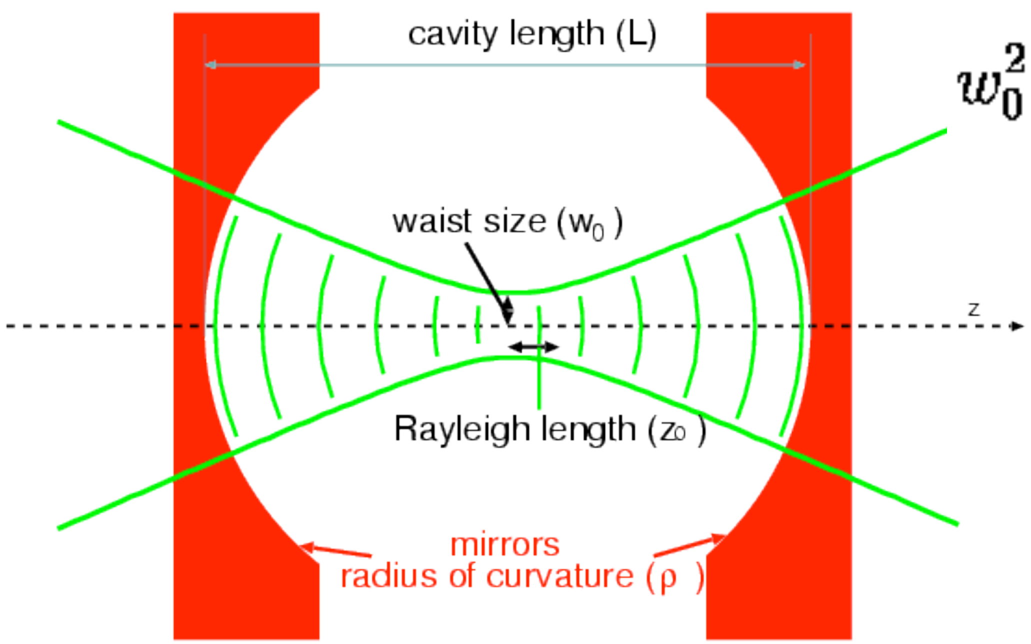




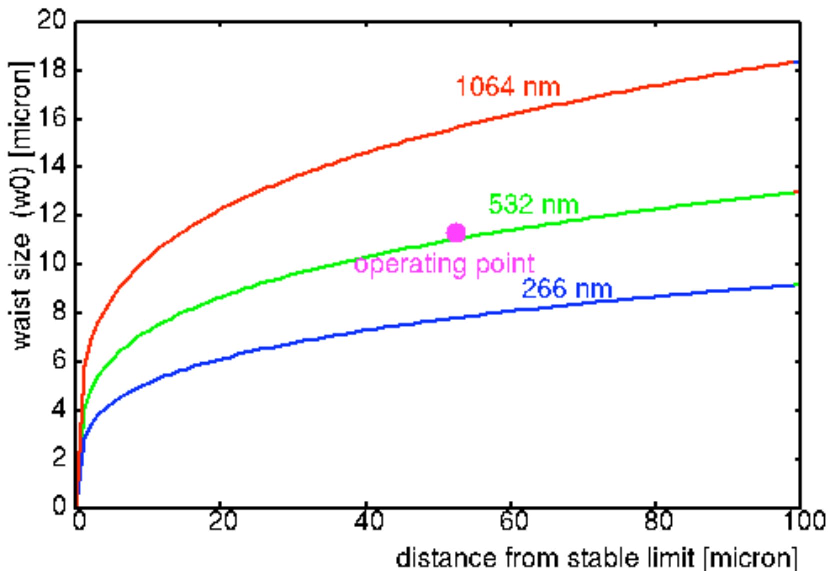
Principle of optical cavity (mode profile)

- Boundary condition introduced by the cavity mirrors defines the structure of the laser beam allowed inside the cavity.
  - Once the cavity structure is rigidly assembled, laser wire size should be stable.
- Waist size (w0) is controlled by the curvature of the mirrors and the cavity length.
  - Small w0 is realized at very close to the unstable limit.



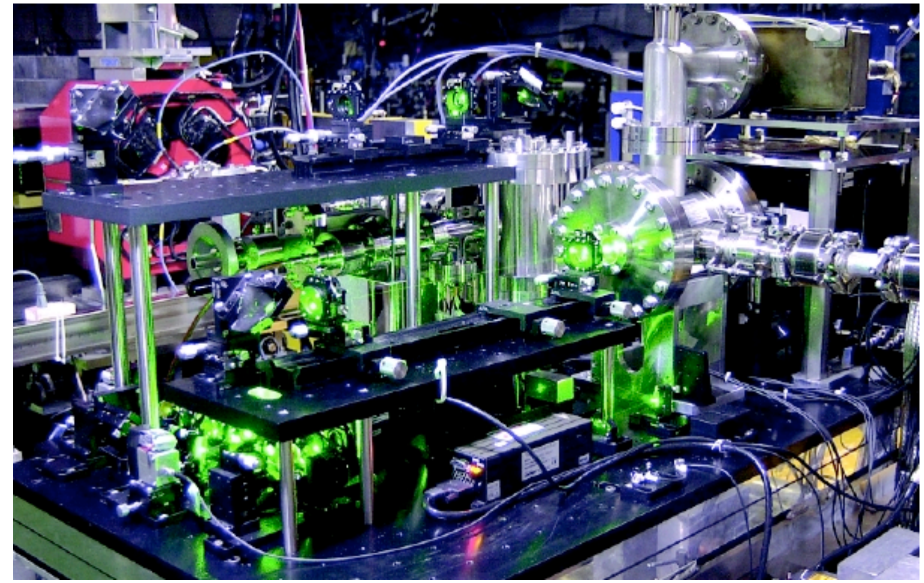


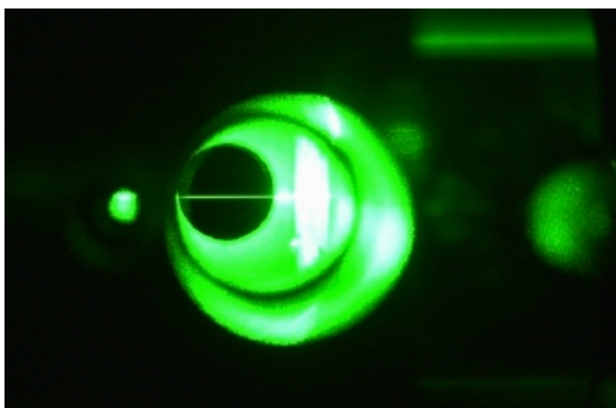
$$w_0^2 = \frac{\lambda}{\pi}\frac{\sqrt{L(2\rho - L)}}{2}$$

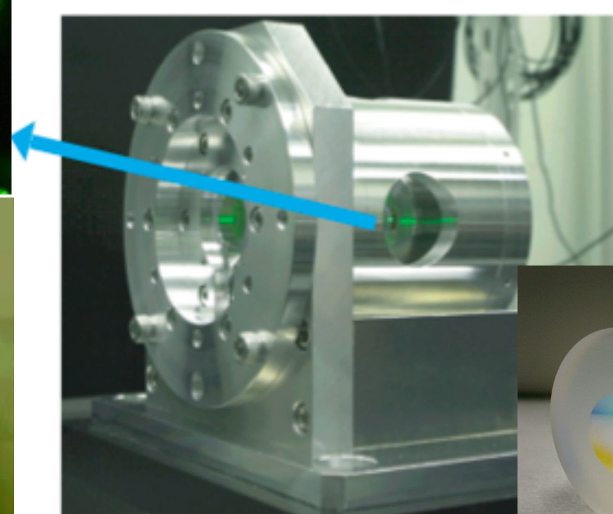


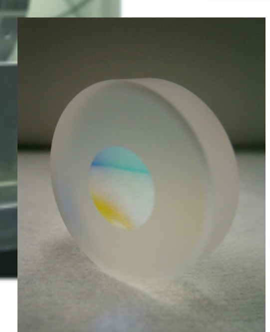
Setup of the laser system

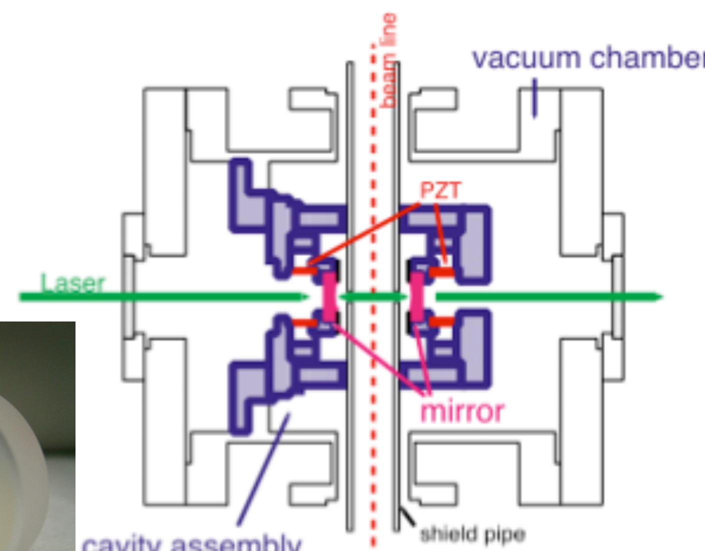
- laser source: NPRO (lightwave model 142)
  - wavelength 532nm, power 300mW
- cavity:
  - length 40mm, mirror-ρ 20mm
  - Finesse 600 (effective power 100W)
  - w0 12μm (σ= 6μm (w0/2))
  - piezo control speed ~kHz





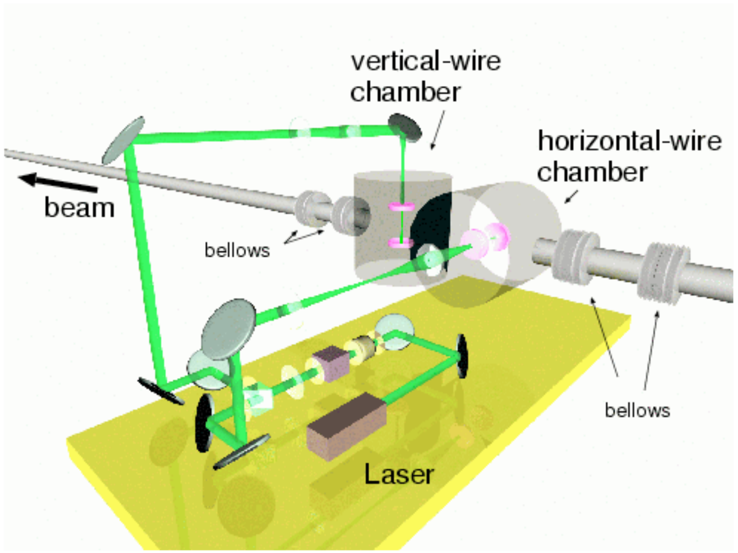


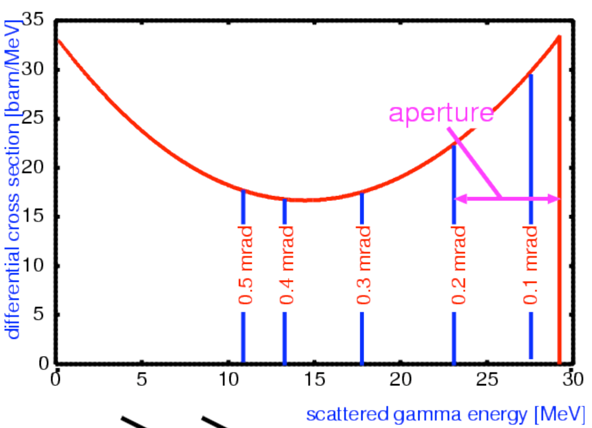


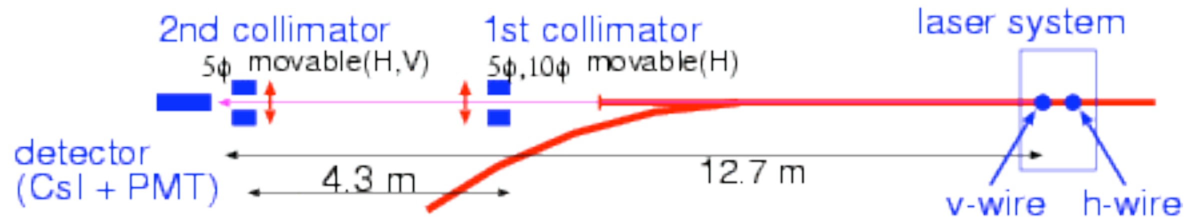


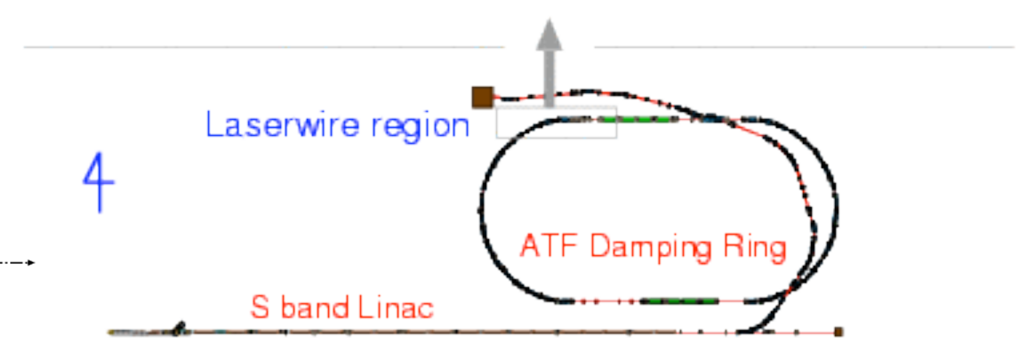
Layout of the system

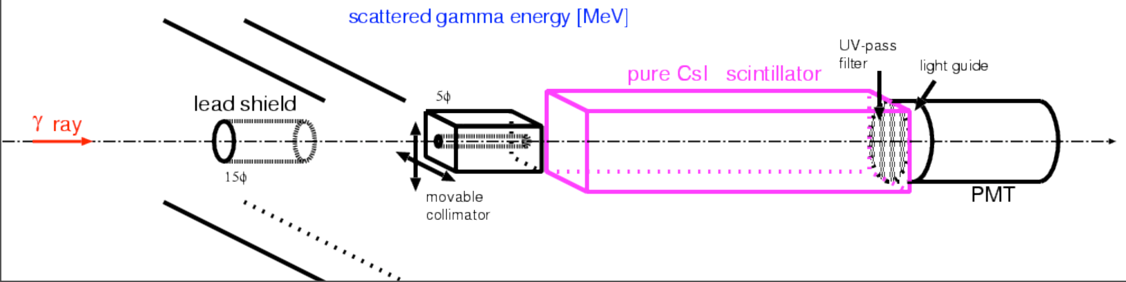
- Laser system
  - two cavity chambers (vertical and horizontal)
  - laser path is switched for each measurement
- Scanning
  - by moving the whole table (1 μm resolution)
- Detector
  - CsI scintillator at 13m downstream
  - collimators to reduce beam background
  - Compton signal: 28MeV(max)





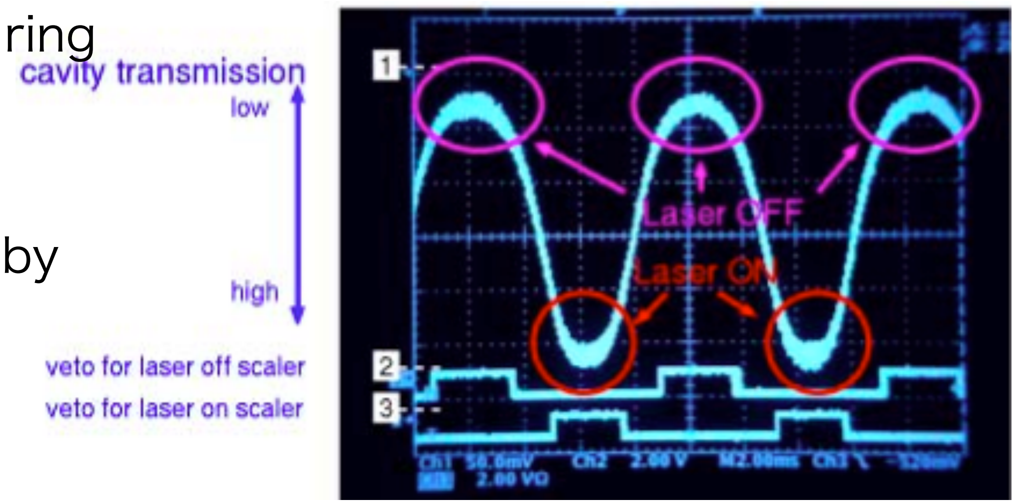


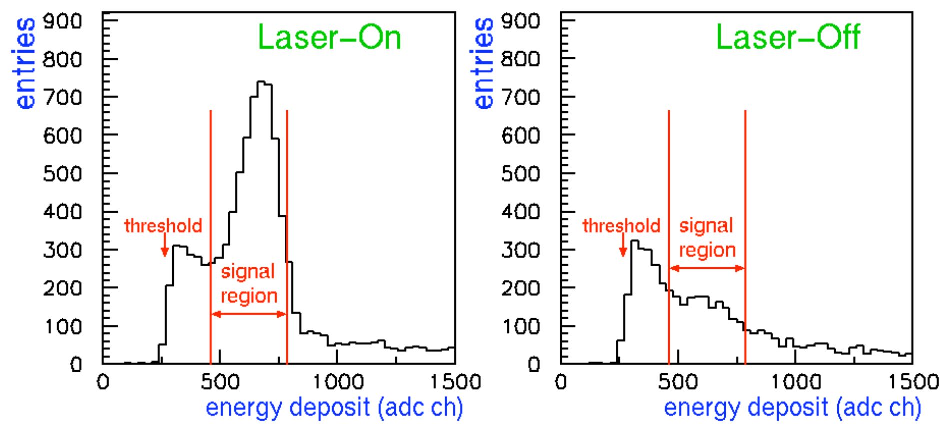


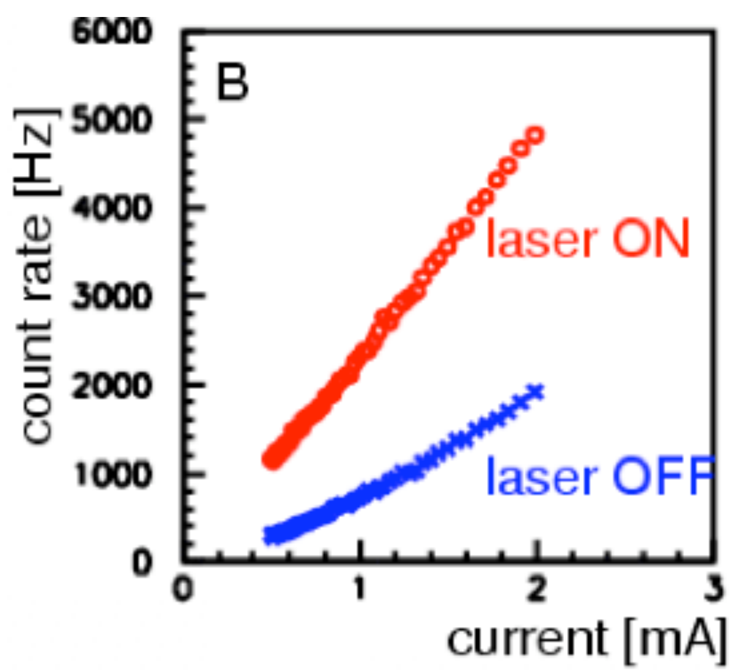


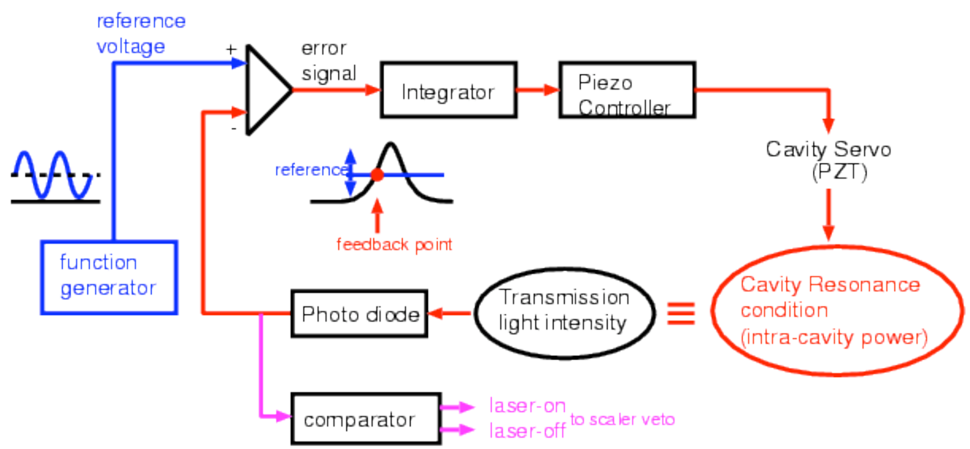
Measurement scheme

- Counting method
  - typical signal rate (~kHz), whereas ring revolution is 2MHz. Each signal is single photon.
  - Realize fast laser on/off switching by modulating cavity resonance



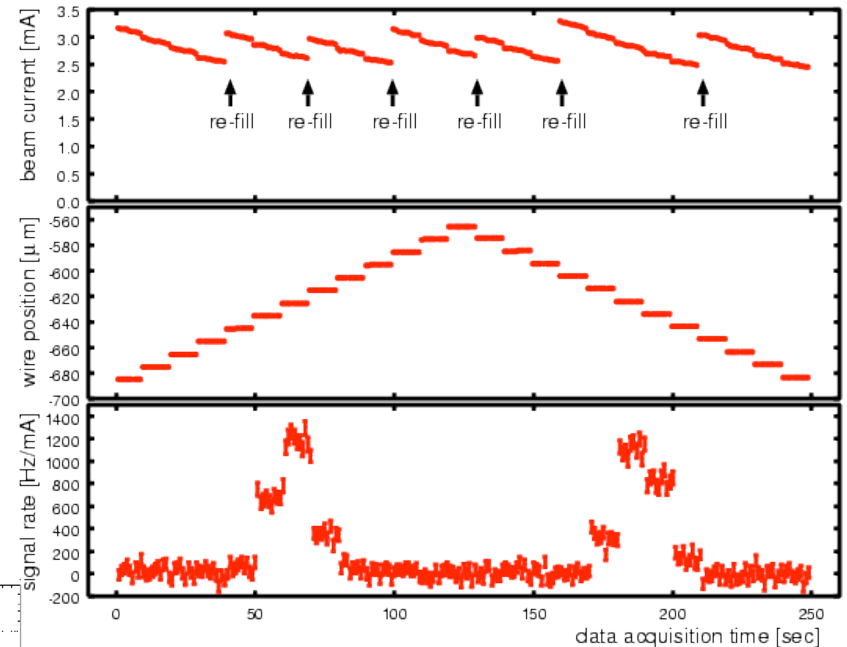


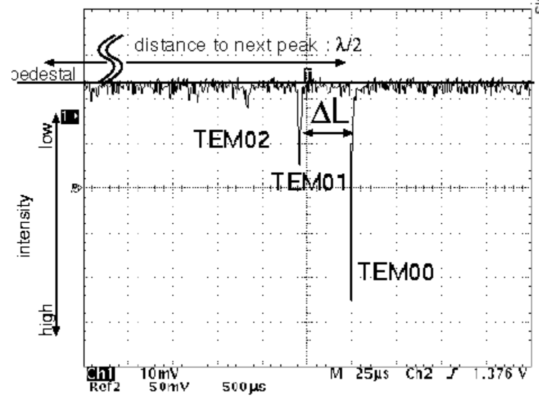


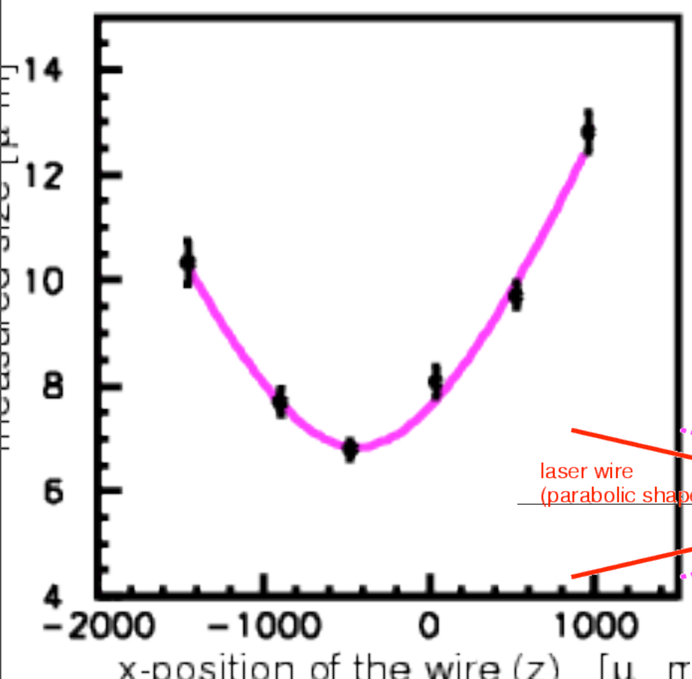


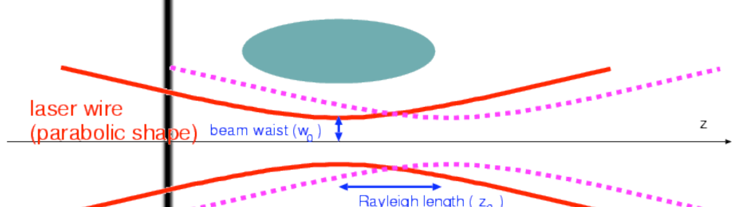
Measurement example

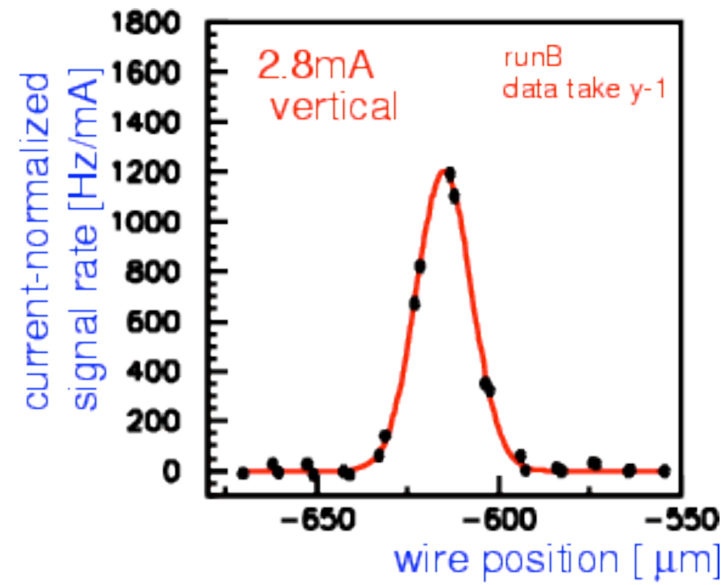
- Typical measurement
  - 10μm step, 10sec/position
  - back and force measurement
  - 6min. to complete a measurement
- Contribution of laser size subtraction
  - σ(laser) estimation
    - cavity mode property
    - waist scan by electron beam







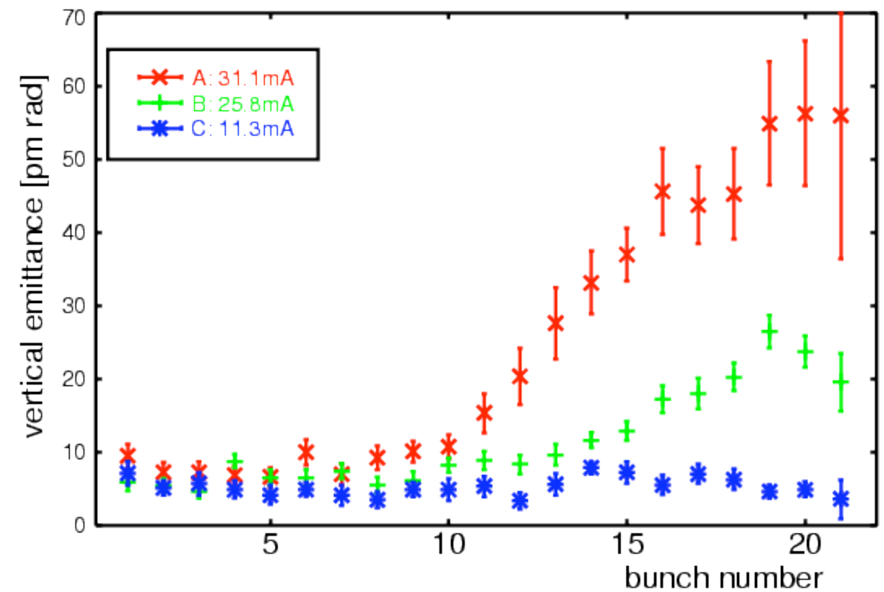


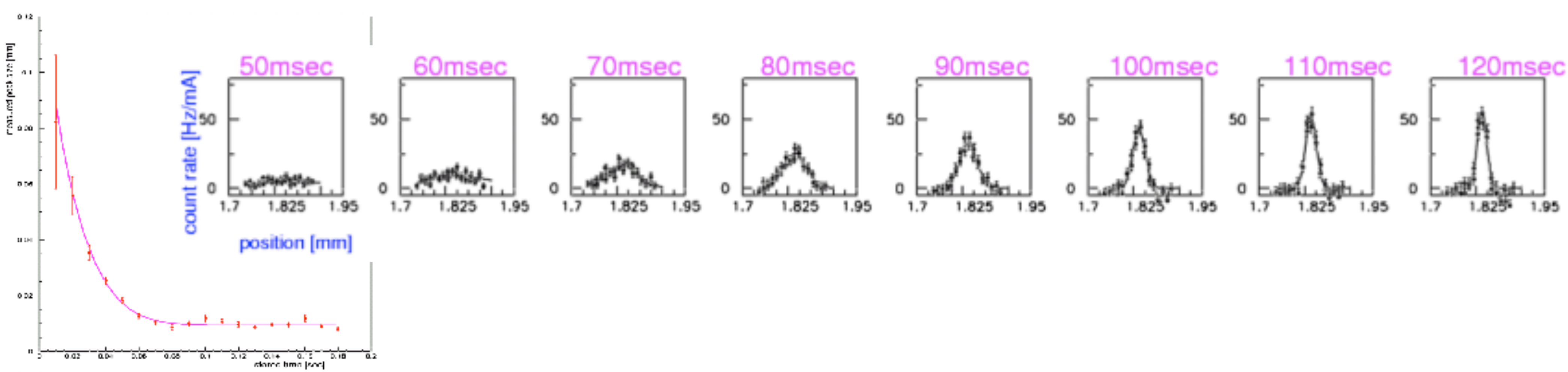


$$\sigma_e = \sqrt{\sigma_{meas}^2 - \sigma_{lw}^2}$$

Measurement example

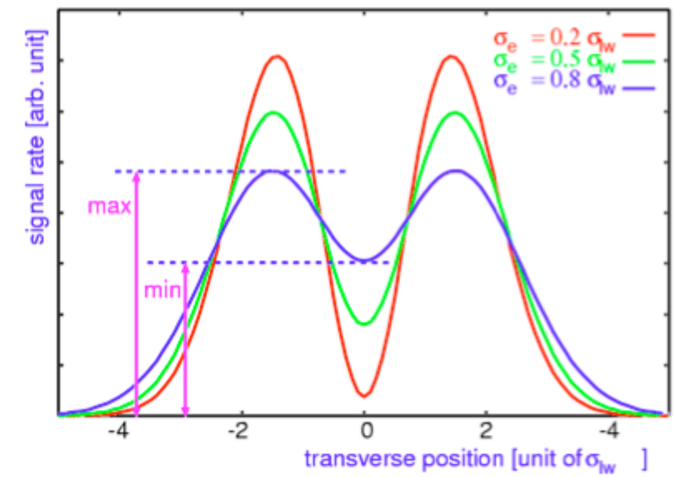
- Multi-bunch mode
  - possible to measure signals from each bunch in a multi-bunch train (2.8nsec spacing) by timing identification
  - intra-train beam size variation measurement
- Observation of emittance damping after injection
  - timing identification after injection



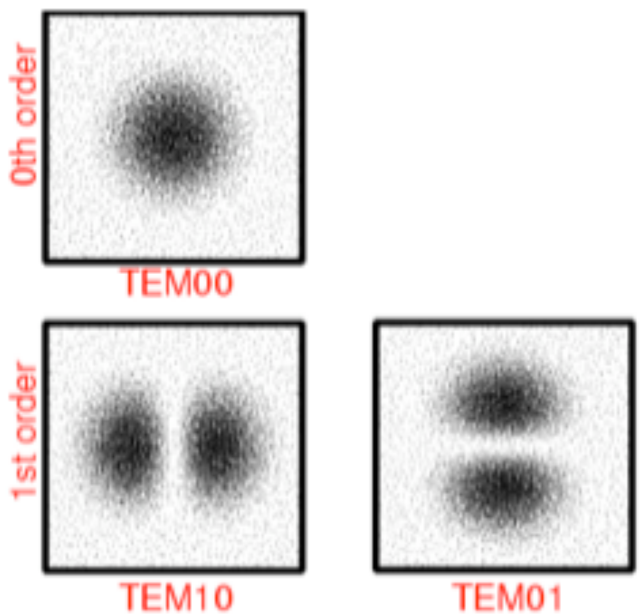


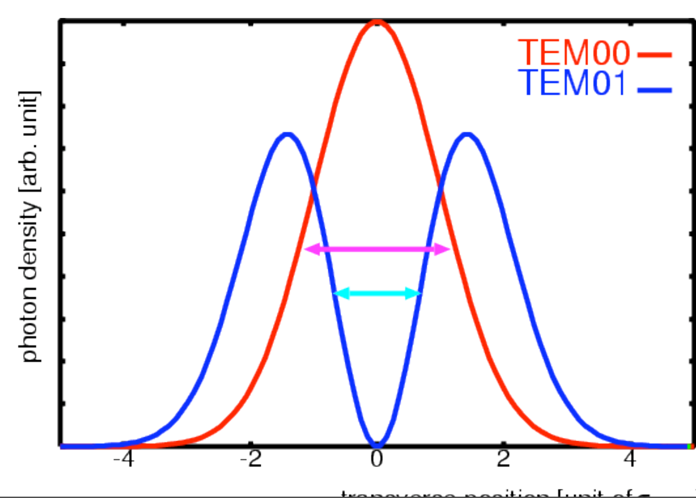
Higher-order mode for higher resolution

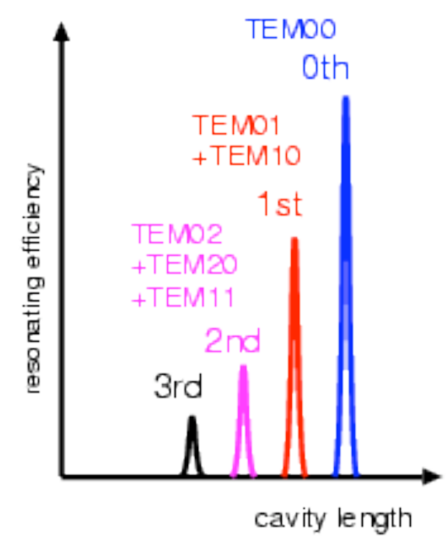
- Smaller w0 is not straight forward (diffraction limit)
- Other cavity resonances that have smaller spatial structure
  - TEM01 (vertical dipole mode)
  - resonance condition is shifted from TEM00
  - TEM10 contaminates TEM01
- Scanning by the dipole mode laser, central dip of the measured shape responses beam size smaller than laser rms size



$$E_{mn}(x,y,z) = A\frac{w_0}{w(z)}\exp\left(-\frac{x^2+y^2}{w^2(z)}\right)H_m\left(\frac{\sqrt{2}x}{w_0}\right)H_n\left(\frac{\sqrt{2}y}{w_0}\right)$$
$$\times \exp\left(-ik\cdot\frac{x^2+y^2}{2R(z)}\right)\exp\left(i\Phi(z)\right)\times\exp(i\omega t-ikz)$$

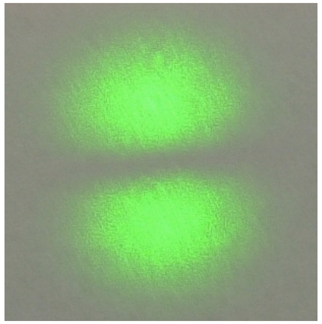


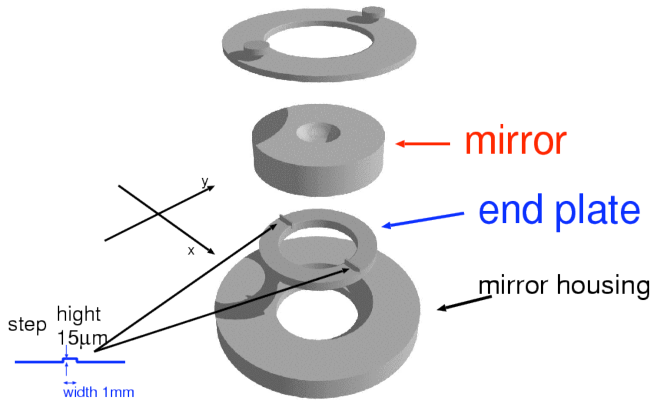


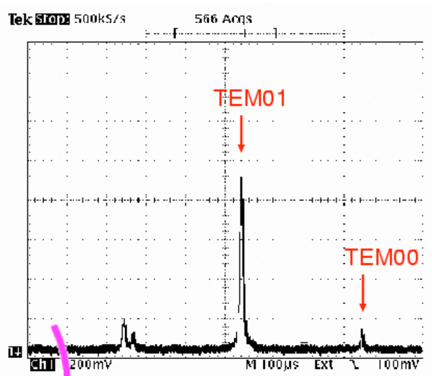


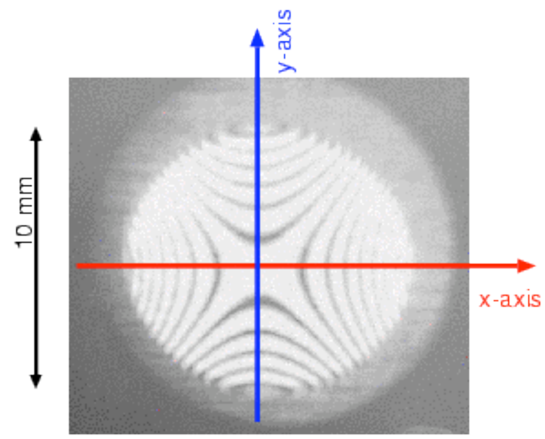
Efficient excitation of higher-order mode

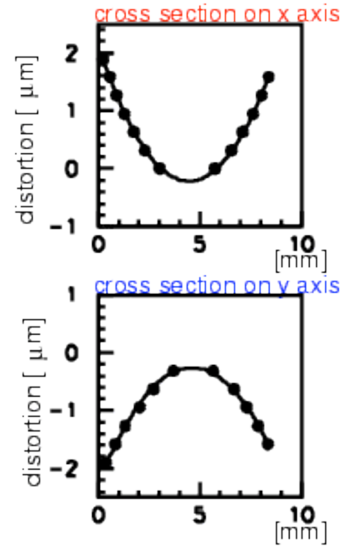
- Two ideas to control TEM01 mode
  - mode split between TEM01 and TEM10 by slight bending mirrors
  - mode converter to modify original TEM00 laser to TEM01 like phase structure

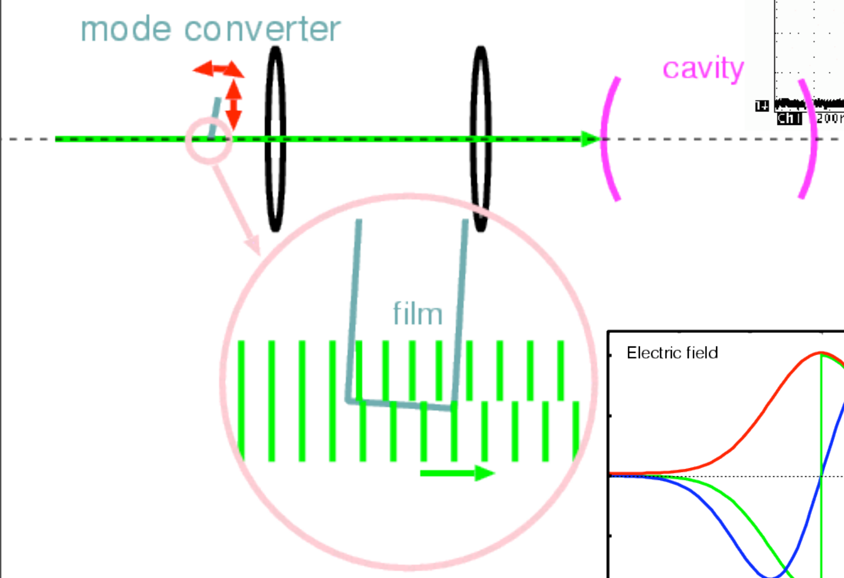


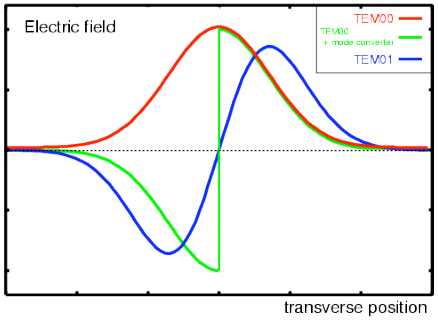


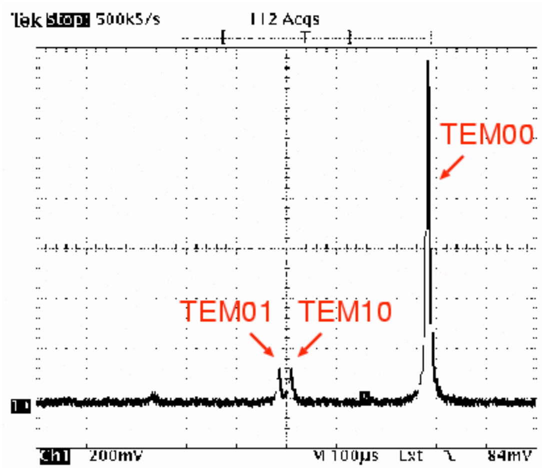












Beam measurement demonstration

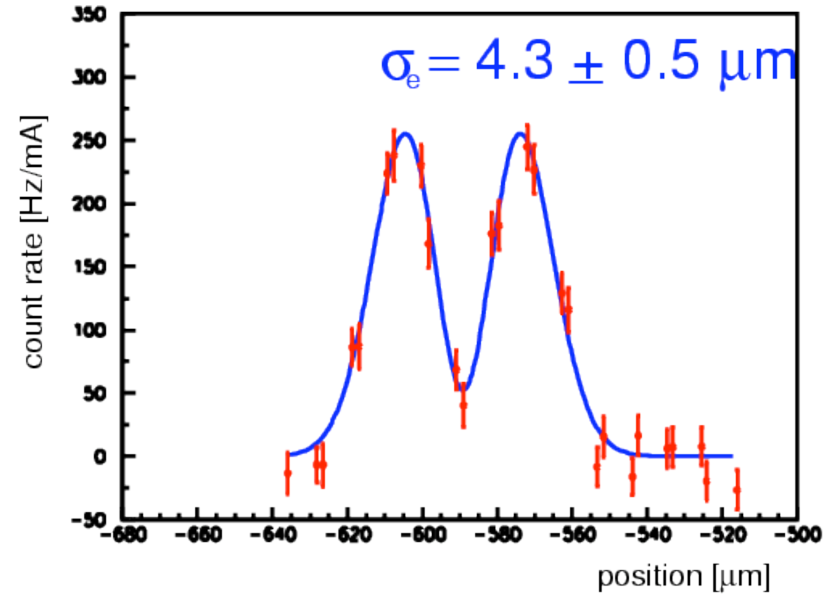
- This test was done with larger w0 setup to match usual ATF beam size.
- both laser size, e-beam size are free parameters.

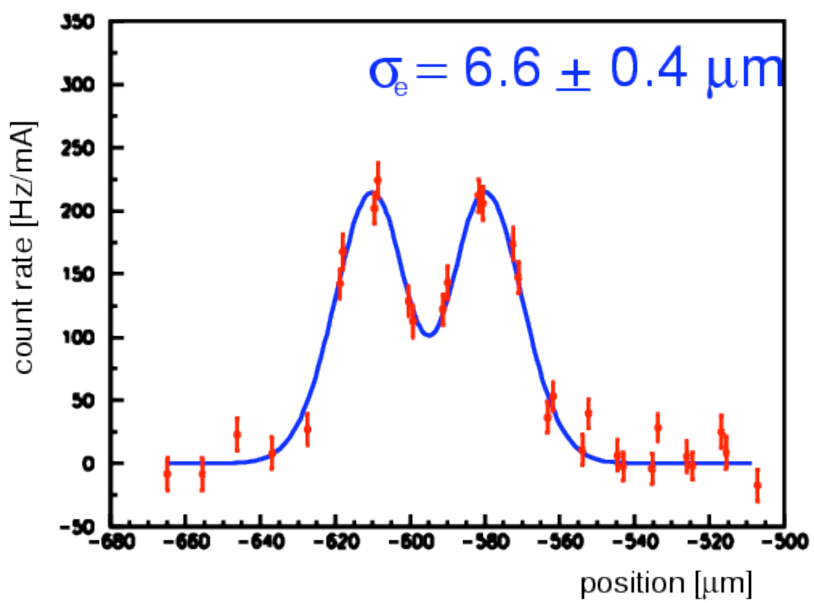
$$P(electron) \sim \exp\left(-\frac{y^2}{2\sigma_e^2}\right)$$

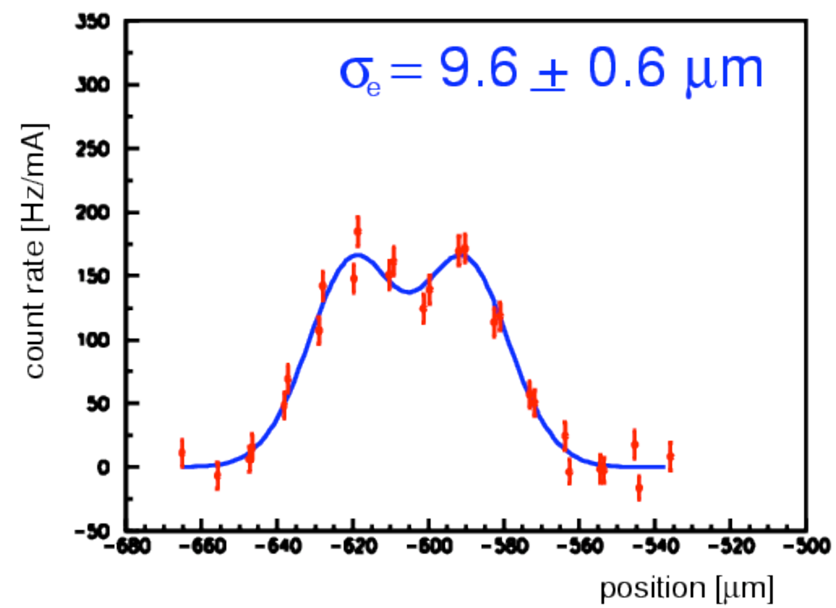
$$P(photon) \sim y^2 \cdot \exp\left(-\frac{y^2}{2\sigma_{lw}^2}\right)$$

$$L \sim \int \exp\left(-\frac{y^2}{2\sigma_e^2}\right) \cdot (y-\eta)^2 \exp\left(-\frac{(y-\eta)^2}{2\sigma_{lw}^2}\right) d\eta$$

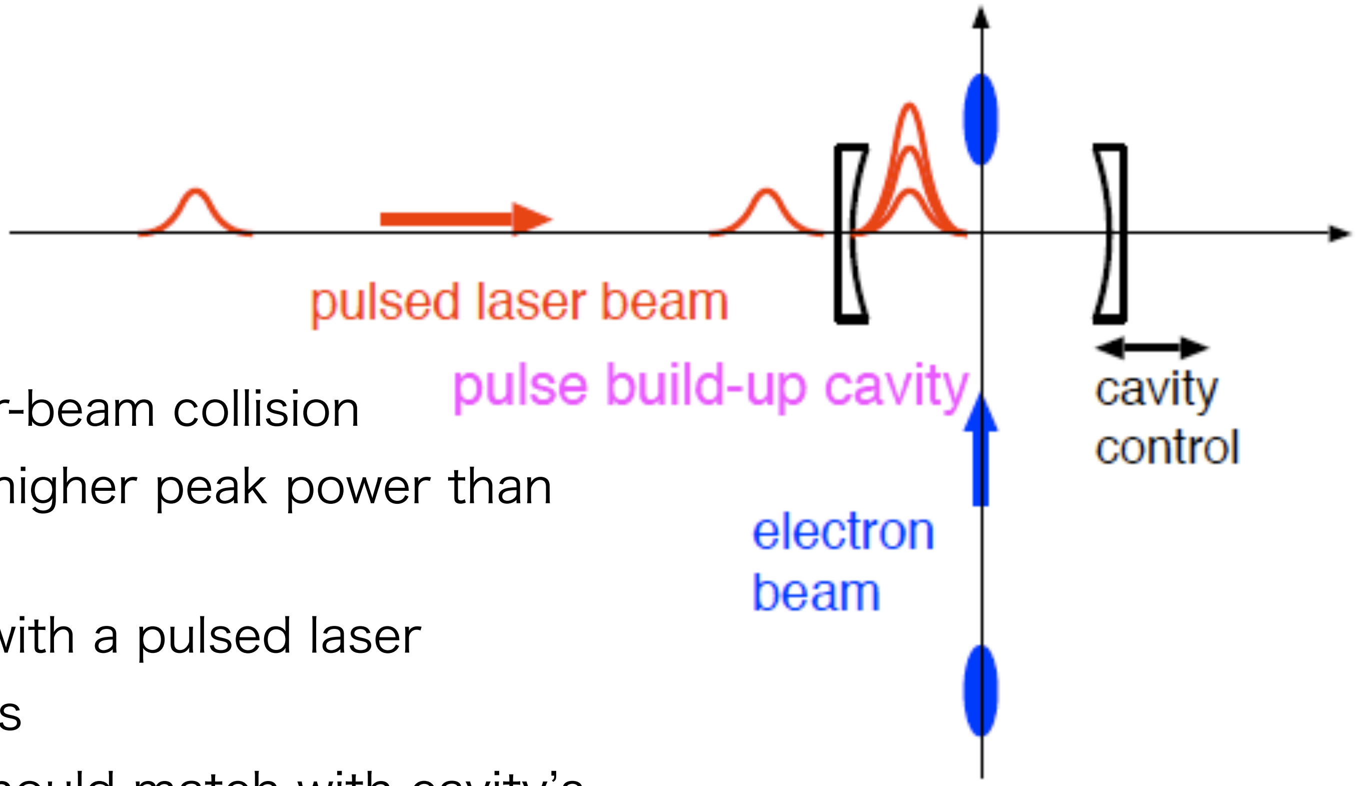
$$\sim \left(\frac{\sigma_{lw}^2}{\sigma_e^2+\sigma_{lw}^2} \cdot y^2 + \sigma_e^2\right) \exp\left(-\frac{y^2}{2(\sigma_e^2+\sigma_{lw}^2)}\right)$$







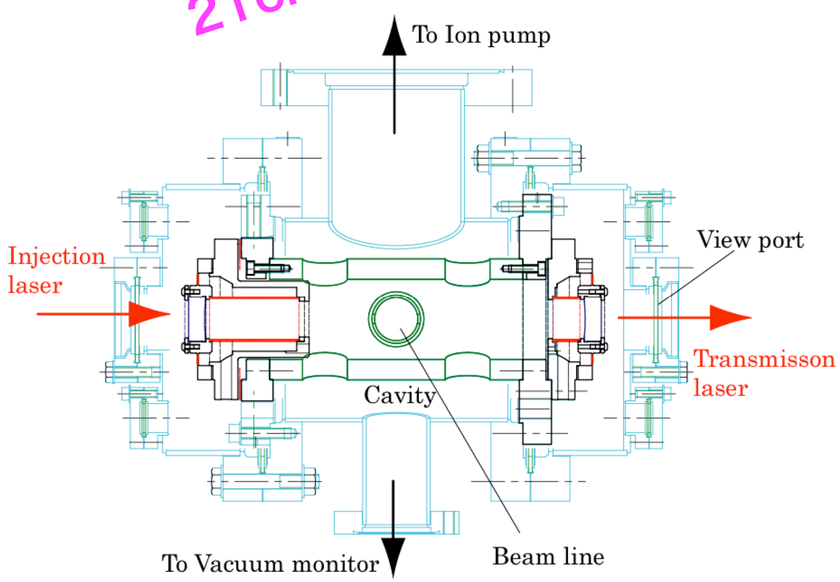
Build-up cavity with pulsed laser

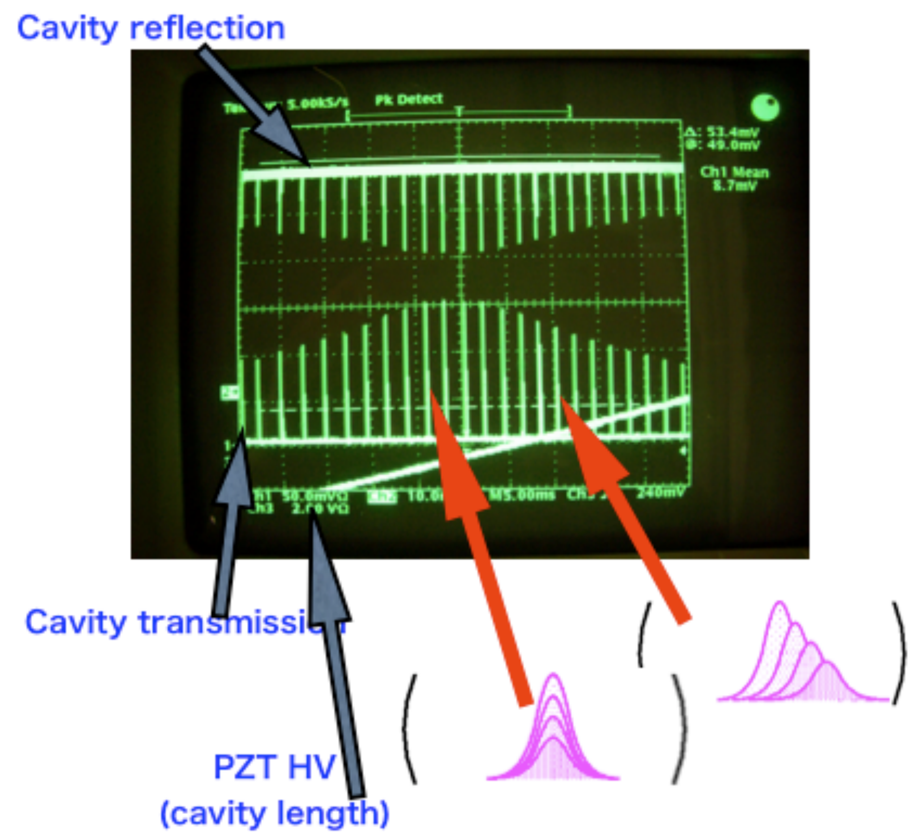


- For more efficient laser-beam collision
  - Pulsed lasers have higher peak power than cw lasers
- Build-up cavity works with a pulsed laser
  - additional conditions
    - repetition rate should match with cavity's round trip time
    - synchronization with the beam
- Cavity length is defined by beam repetition (357MHz), mirror curvature is the only parameter to control mode profile (if 2 mirror cavity case)

Setup of pulsed cavity

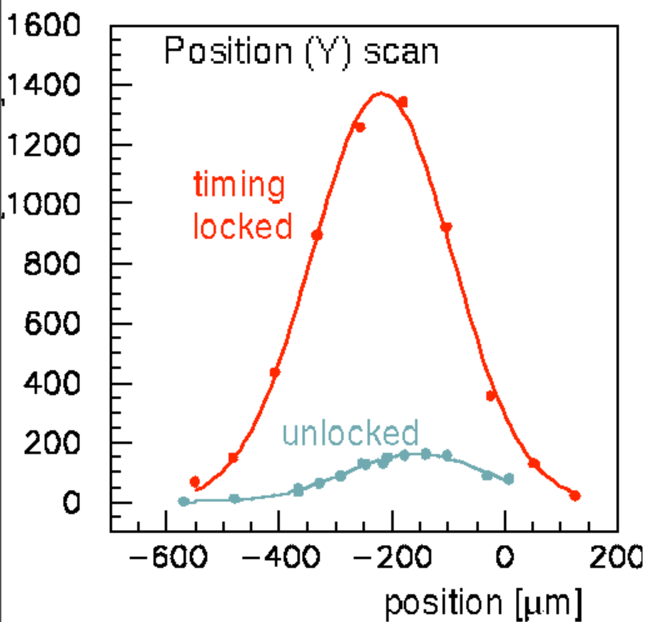
- cavity length=21cm (714MHz), two folded 357MHz cavity
- finesse 500, w0 250μm
- wavelength 1064nm, pulse dulation 7.3ps, 500mW passive mode-lock laser
- installed in ATF at the same location of cw laser wire

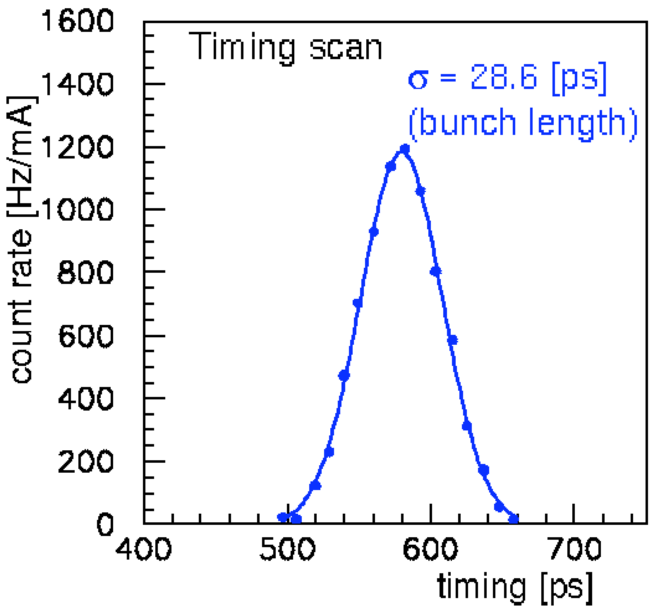


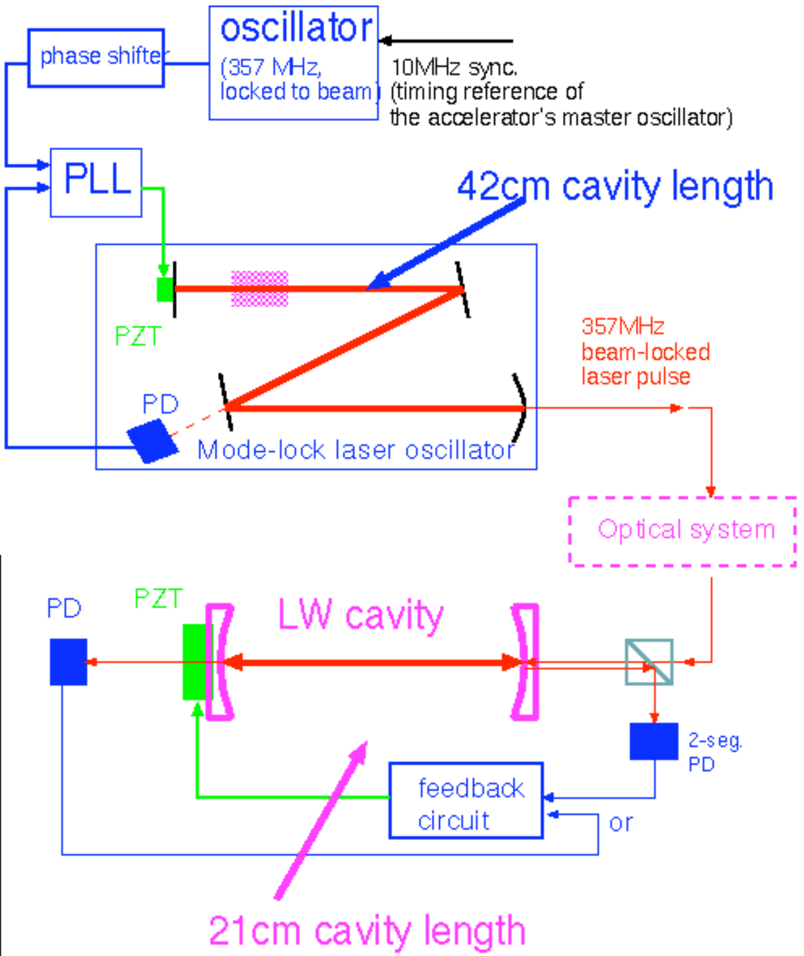


Measurement system

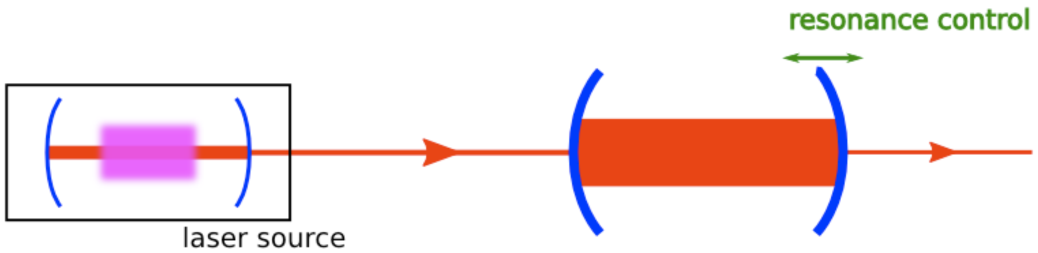
- Demonstrated stable collision with beam. (7.3ps laser and 30ps beam in 90deg. crossing)
- Bunch length of the beam can be obtained from the timing scan data



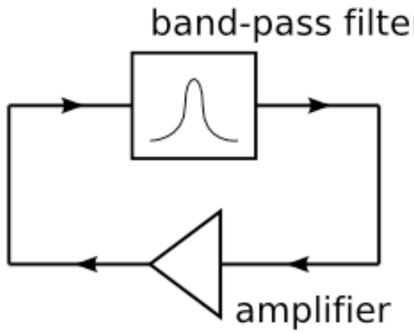


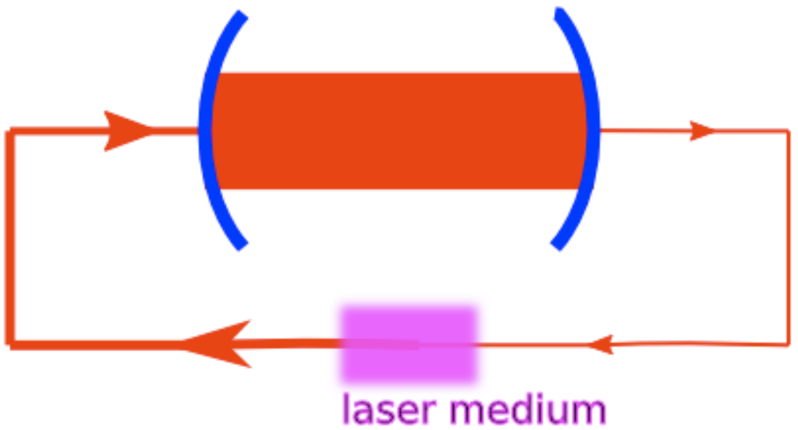


Self-start recirculation system



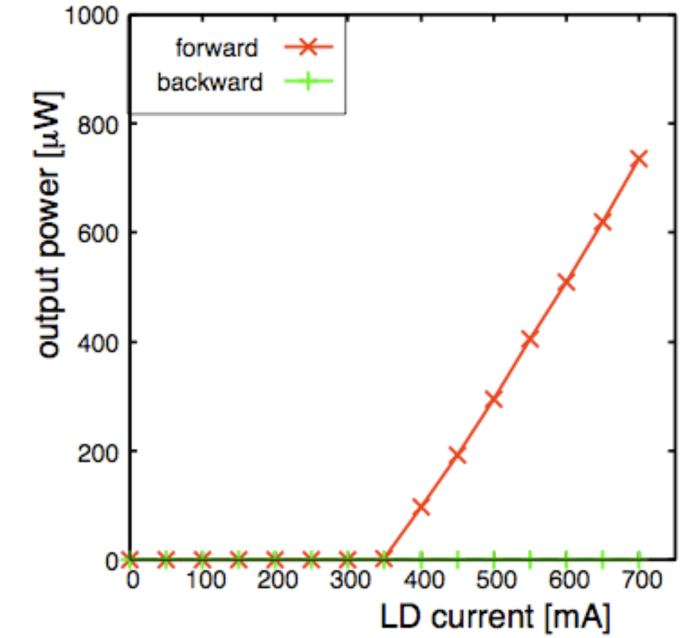
- There can be many applications with a high finesse build-up cavity.
- Higher finesse in external cavity is difficult to control
  - ~1000 can be controlled with mechanical feedback
  - >10000 may need new ideas
- Oscillator scheme
  - simple oscillator with a laser medium inside the cavity is not suitable for high power.
  - recirculation scheme with external laser amplifier can realize high finesse and self-start

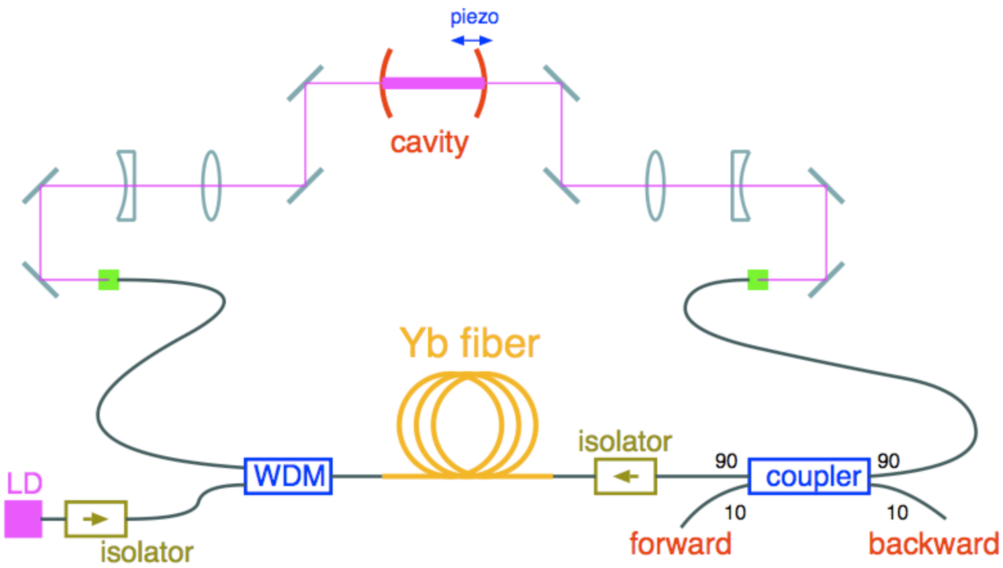


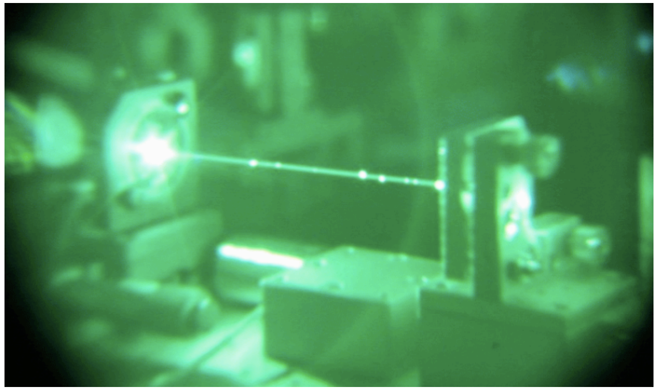


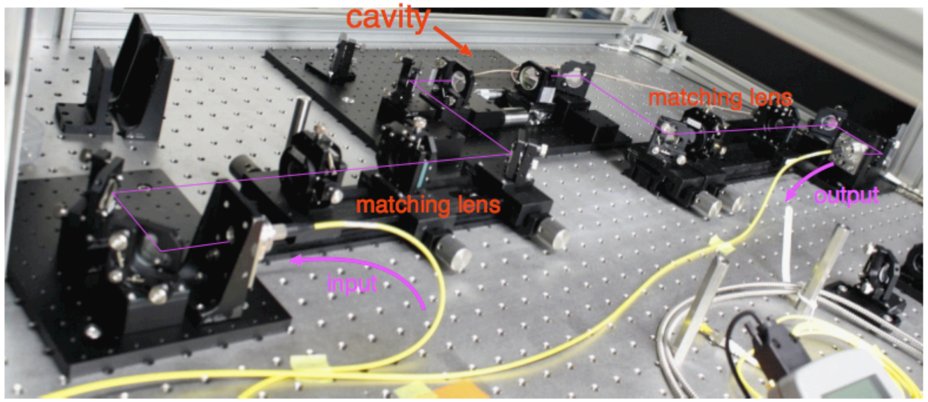
Self-start recirculation system (demonstration)

- Self-start oscillation
  - amplifier gain > round trip loss
  - high gain fiber laser amplifier
- Bench test demonstration
  - finesse 30000 cavity
  - realize resonance with no active control





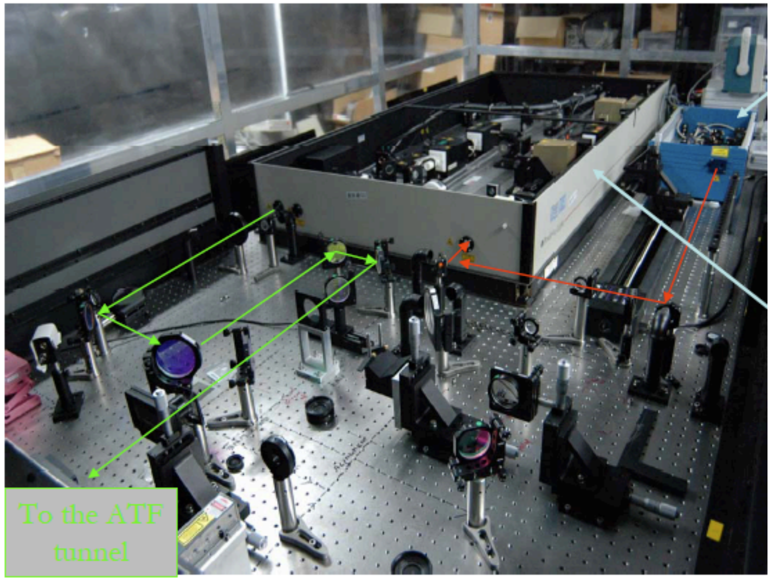


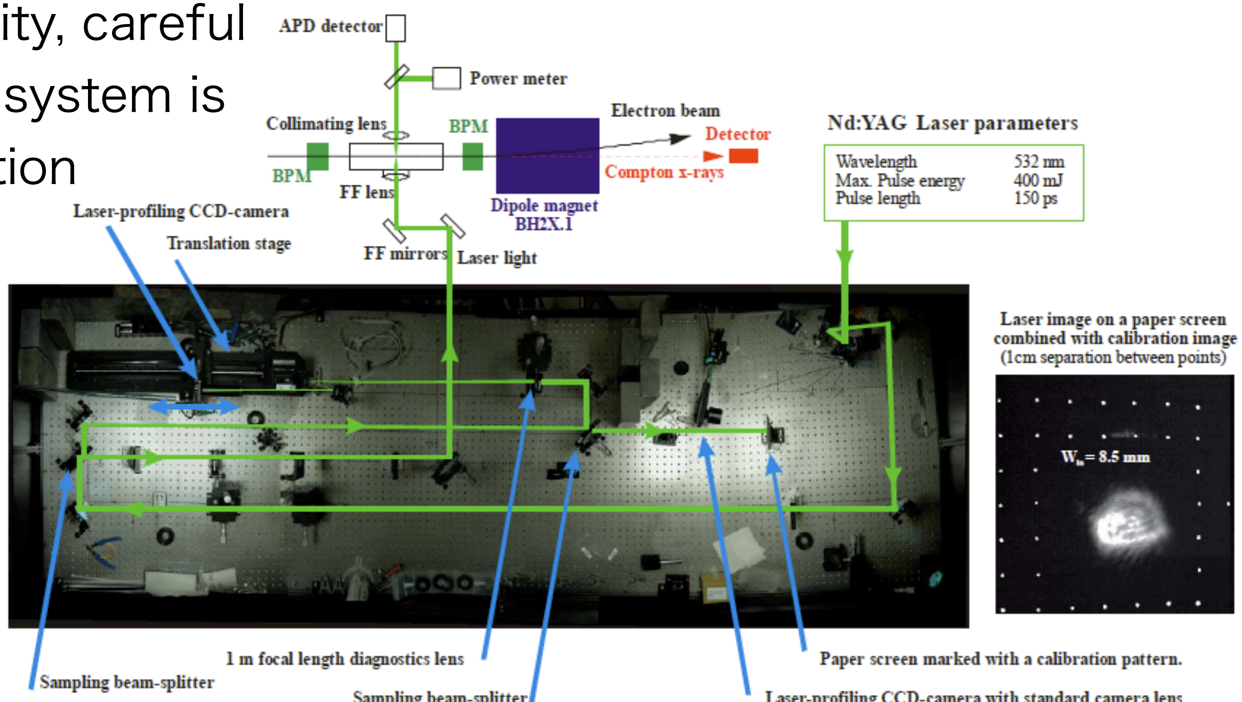


High power pulsed laser scheme

Pulse Laser Wire (laser)

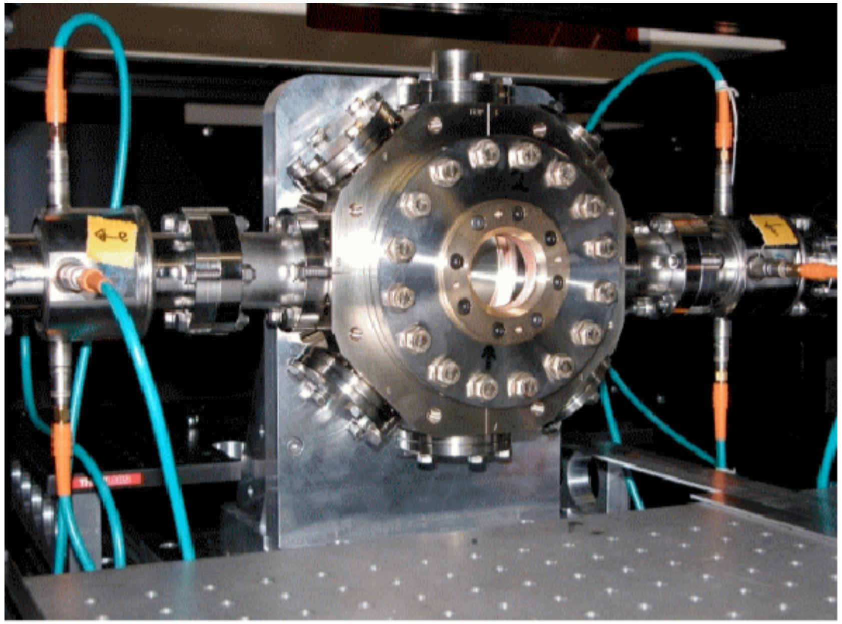
- In single path beam line of low repetition rate. Higher laser power is needed.
- With a high power pulsed laser system, enough laser power to have >1000 Compton scattering in single collision.
- Since there is no laser mode control mechanism like optical cavity, careful laser profile measurement system is needed before the interaction vacuum chamber.

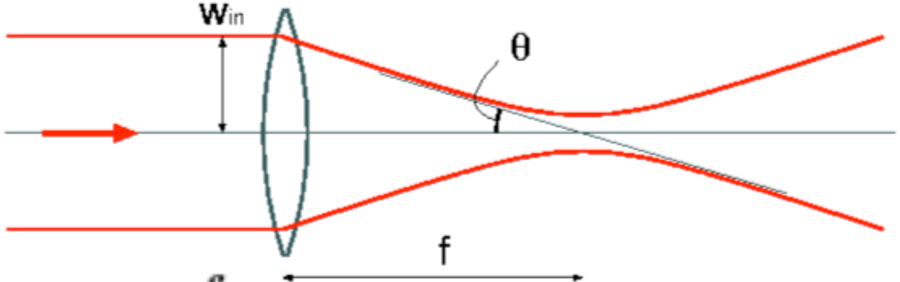




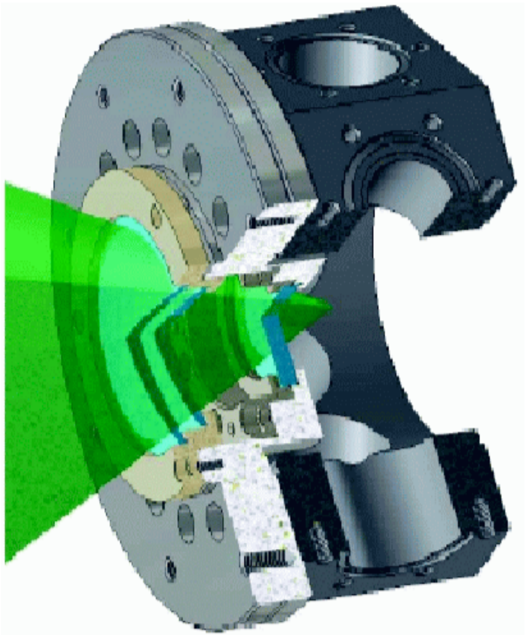
Interaction chamber design

- Aiming to demonstrate small spot size ~μm
- In order to focus as small as possible, smaller F# is required.
  - place the final lens close to the chamber
  - large aperture



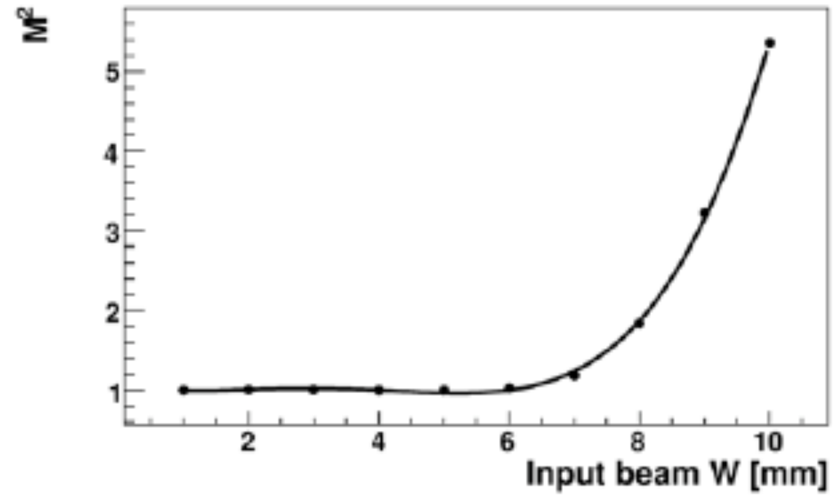


$$F\# = \frac{f}{D} \qquad w_{diff} = M^2\lambda(F\#)$$

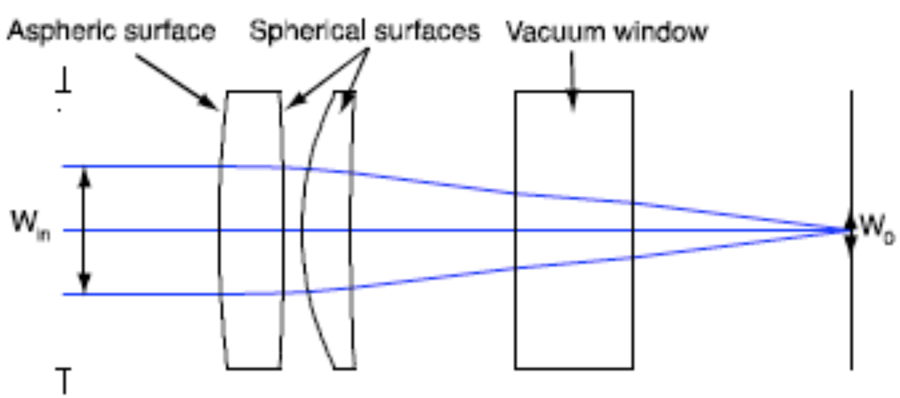


Focusing lens design

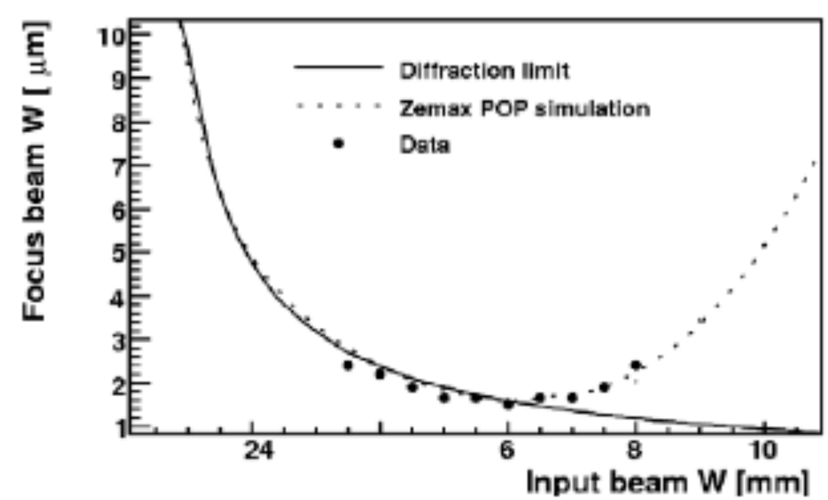
- The beam size at the focus is controlled by the input beam size.
- The minimum achievable spot size is 2.2 um with a ideal input laser. It is balance of diffraction limit and aberration effects.
- Need to care the damage of windows due to ghost reflection of high power laser



Schematic design of the aspheric lens.

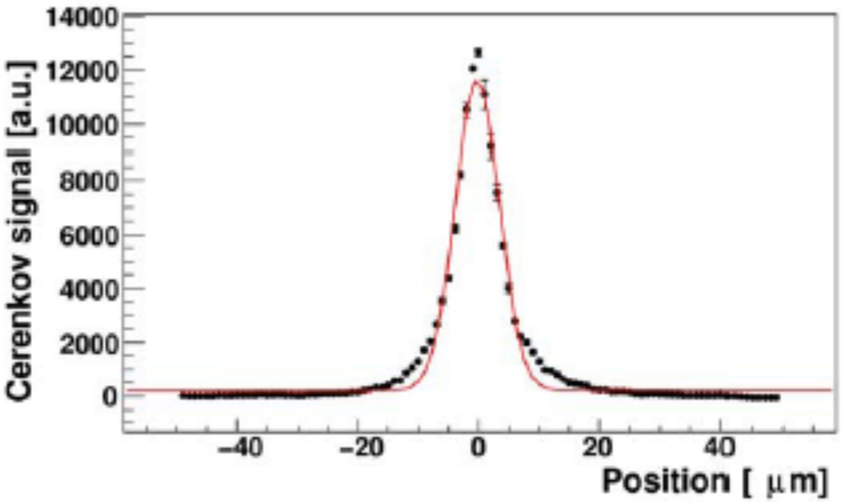


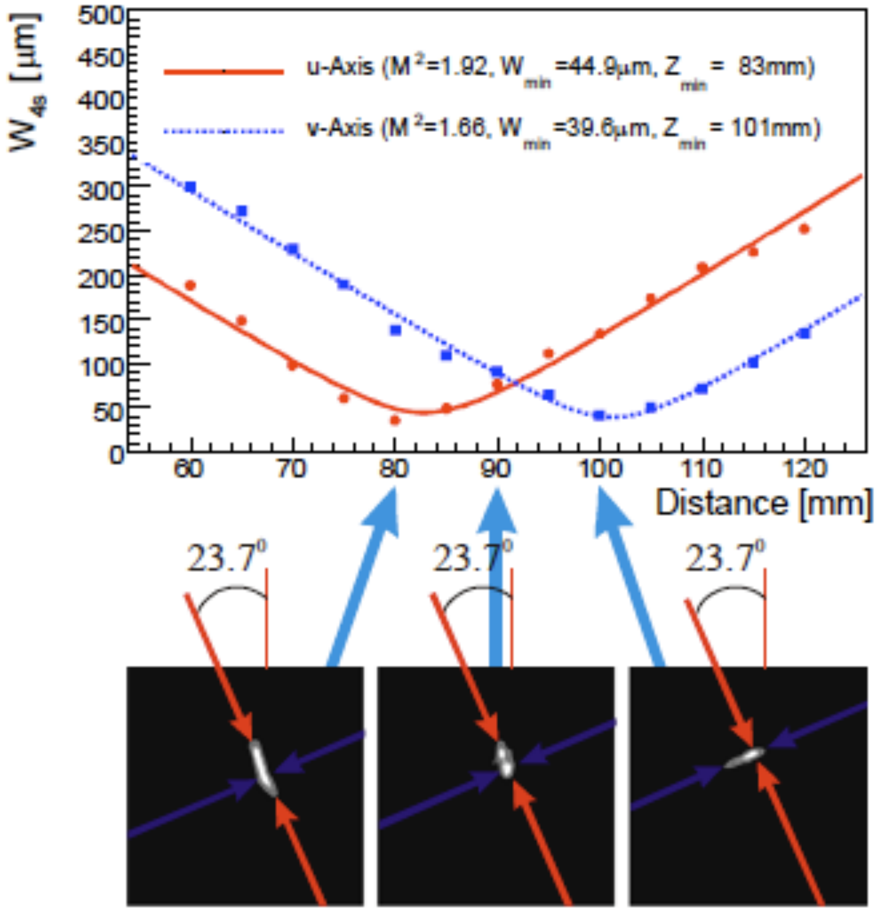
The W_{in} is the transverse laser beam radius and the W_0 is the minimal spot size at the focus



Measurement example

- σ (meas) = 3.65 um
- σ (beam) is calculated to be 2.91 um assuming σ (laser) = 2.2 um.
- Quality of the laser beam has to be improved.





Summary

- Two types of laser wire monitors have been developed at ATF
  - Build-up cavity scheme (at damping ring)
    - 6μm rms size, 100W effective power
    - multi-bunch measurement demonstration
    - resolution upgrade with higher-order mode
    - variations: pulsed cavity, self-start system
  - High power pulsed laser scheme (at extraction line)
    - lens system to realize 2.2μm spot size
    - 3.65μm measured size was demonstrated