F/# Matchers for the Shamrock SR303i, SR500i and SR750

One of the key performance features of any spectrograph is its ability to collect light. This is often referred to as its 'throughput'. The main influence on throughput is the acceptance cone of light that can be delivered into and effectively used by the system; in effect the range of angles out from the optical axis that can be effectively used. Systems with longer focal lengths tend to have smaller acceptance cone angles resulting in lower collection efficiency. This may result in a significant amount of the available light signal not being coupled into the spectrograph. Such a scenario arises with a silica fiber delivering light into a Shamrock SR500i: the fiber delivers light via a cone of ~25° whilst the SR500i has an acceptance cone of ~9°. This is where F/# matching may offer benefits whereby the delivery cone of light is modified to a smaller cone angle so as to match the acceptance cone of the spectrograph. This not only offers better throughput but reduces the possibility for stray light as there should be no overfilling of the optics.

It is useful to define some terms (see figure 1) that will be used in the discussion of the F/# matchers:

- Light Collection Efficiency – the ability of the spectrograph to accept light signal
- Acceptance Cone Angle (2θ) – the full angle of the useful cone of light that can be coupled into the spectrograph
- Acceptance Angle (θ) – the angle measured from the optical axis to the outer limits of the acceptance cone
- Numerical Aperture NA – an alternative way of describing the angular aperture for acceptance of light into the system. It is defined as NA = nSin θ where n is the refractive index of the surrounding medium (usually air so n=1 in most cases)
- F-number (F/#) – another alternative way of representing the throughput capability of a system or optic. It is defined for an optic such as a mirror or lens as F/# = f/D_{eff} where f is the focal length and D_{eff} is the effective diameter (reference figure 1). It is sometimes referred to as the angular aperture.
- F/# = 1/(2*NA) – directly relates F/# to numerical aperture NA

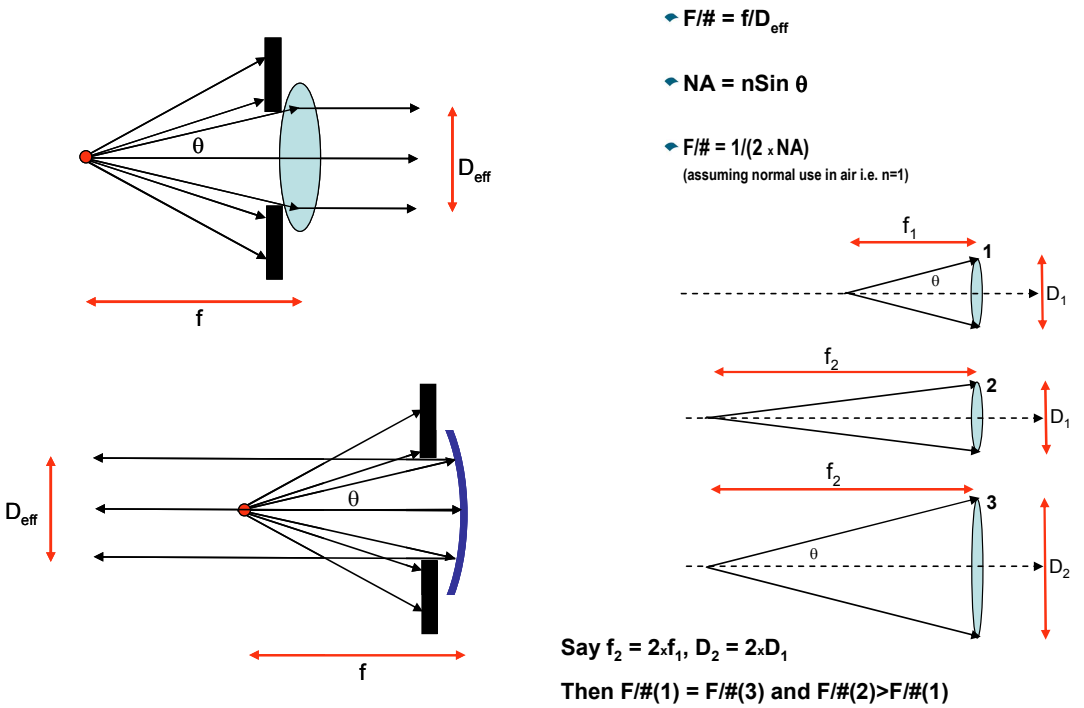

Figure 1: The acceptance cone for two optics, a lens and a mirror. The relationship between the acceptance cone, numerical aperture and F/# is illustrated on right.

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The use of an optic such as a lens or mirror to reduce the cone angle of the delivered light into the spectrograph is illustrated in figure 2. It can be seen that light is collected from a significantly larger cone subtended at the source and delivered through a significantly smaller cone into the spectrograph. What is required is the careful selection and positioning of the optic relative to the source and spectrograph entrance port.

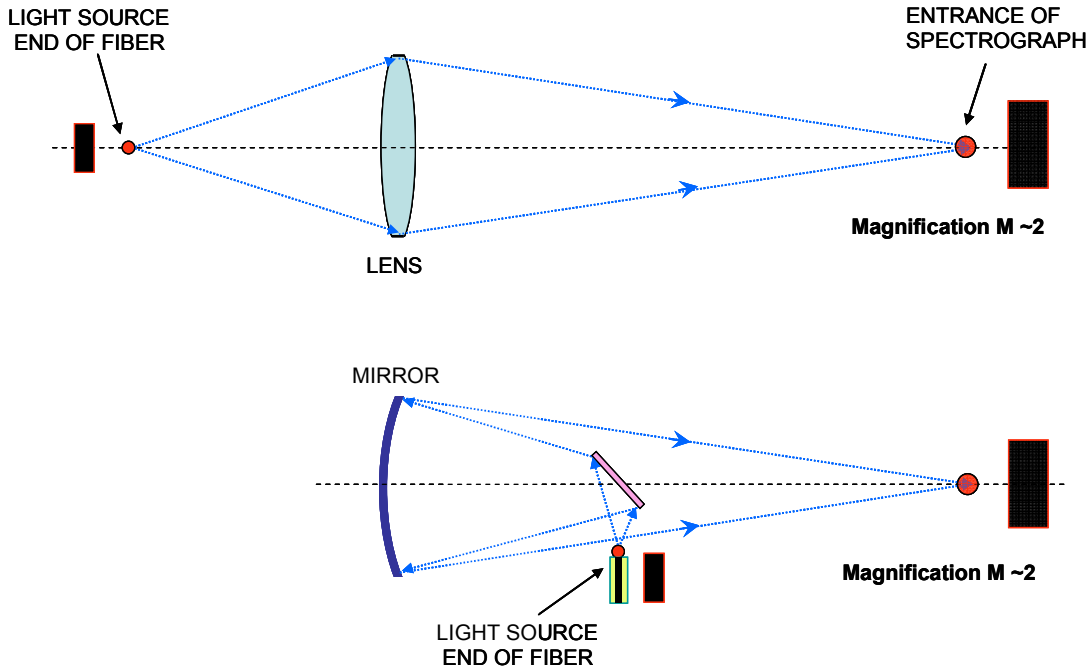

Figure 2: The F-matching process illustrated for the simplest configurations, one is based on a single lens and the other on mirrors. Note that whilst the delivery cone angle is reduced the effective source size is magnified.

Different configurations based on combinations of lenses and/or mirrors are possible; the simplest examples are illustrated in figure 2 (these configurations have limited flexibility). Reflective optics (mirrors) have been chosen for the Shamrock series of F/# matchers as they offer a number of distinct advantages over those based on transmissive optics (lenses). These include:

- A wider spectral range from deep UV up to the IR (lenses only transmit over limited range of wavelengths)
- Not susceptible to chromatic variations (refractive index of lenses is wavelength dependent)
- Optimised focussing over extensive wavelength range (lenses can only be optimised over a narrow spectral range due to variation in refractive index with wavelength)

The components of the Shamrock F/# matchers are illustrated in figure 3. A modular design approach has been adopted so that most of the main components can be used for all three spectrographs. There is an extension tube specific to each spectrograph with the longest extension required for the SR750 and the shortest for the SR303i. The tube which holds the focussing mirror can be adjusted axially by sliding along the folding mirror tube; this is the main mechanism for focussing the system. There are three principal positions of the focussing mirror tube relative to the folding mirror tube depending on which F/# matcher is being configured; small adjustments of one tube relative to the other are possible for optimising of the focussing at the entrance port of the spectrograph. A ferrule fiber adapter is supplied as standard. However as an option one can couple light in from an SMA terminated fiber. This just requires a special SMA fiber adapter sleeve which slides into the standard ferrule fiber adapter (figure 3). Ferrule fibers in general offer greater flexibility in terms of light coupling efficiency and the possibilities for multitrack spectroscopy. Figure 4 shows pictures of the three F/# matchers when assembled. An adapter plate or flange is used to attach the F/# matcher to the slit housing at the entrance port; this is illustrated for the SR500i system on the left hand side of figure 4.

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Table 1 summarizes the main specifications for each of the F/# matcher systems, including the product codes.
The overall benefit that an F/# matcher can potentially provide is an improvement in the light collection efficiency by a factor of typically 2 to 2.5.

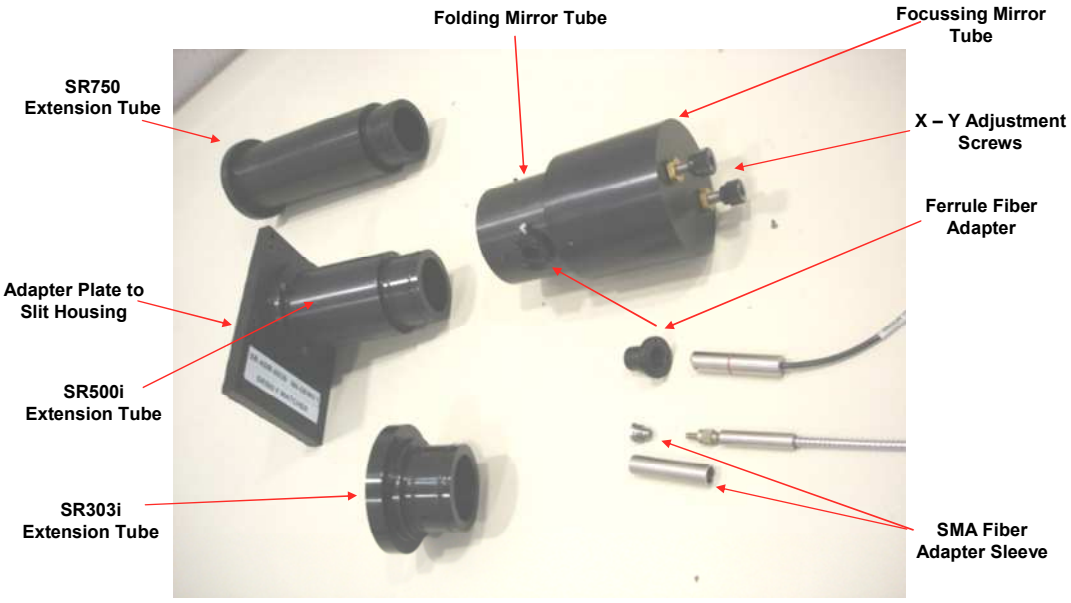

Figure 3: The main components of the F/# matchers for the SR303i, SR500i and SR750. An option is available for coupling in light from SMA terminated fibers – this just requires an SMA fiber adapter sleeve (lower right hand side).

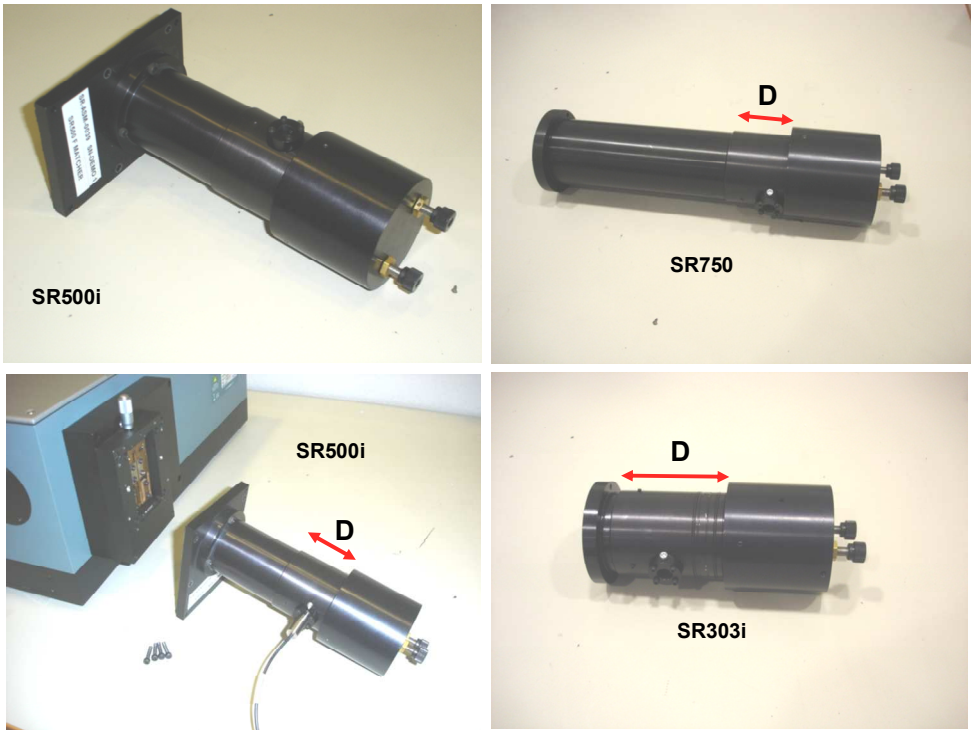

Figure 4: The assembled F/# matchers and the adapter plate for attachment to the slit housing of the respective spectrographs. The reference distance for setting up the system is indicated as distance 'D' – see later.

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Spectrograph	*Product Code*	*Numerical Aperture NA*	*F/#*	*Acceptance Angle (°)*	*Magnification*	*Reference distance (D) for setup*
SR303i	**SR-ASM-0038**	**0.125**	**4**	**14.4**	**1.8**	**66 – 68 mm**
SR500i	**SR-ASM-0039**	**0.077**	**6.5**	**8.8**	**2.9**	**53 – 55 mm**
SR750	**SR-ASM-0040**	**0.051**	**9.8**	**5.8**	**4.3**	**47 – 49 mm**

Table 1: Summary of the product codes and main parameters for the three F/# matchers. The reference distance (D) for setup is a useful guide when setting up the systems – this is explained within the text.

Figure 5 shows optical schematics of the three systems; these are referenced relative to the position of the small folding mirror. This illustrates why the longer extension tubes are required as the need arises to generate smaller acceptance cones at the input port. It also shows that the focussing mirror has to be moved to one of three positions (by moving focussing mirror tube relative to folding mirror tube) depending on which F/# matcher is being configured.

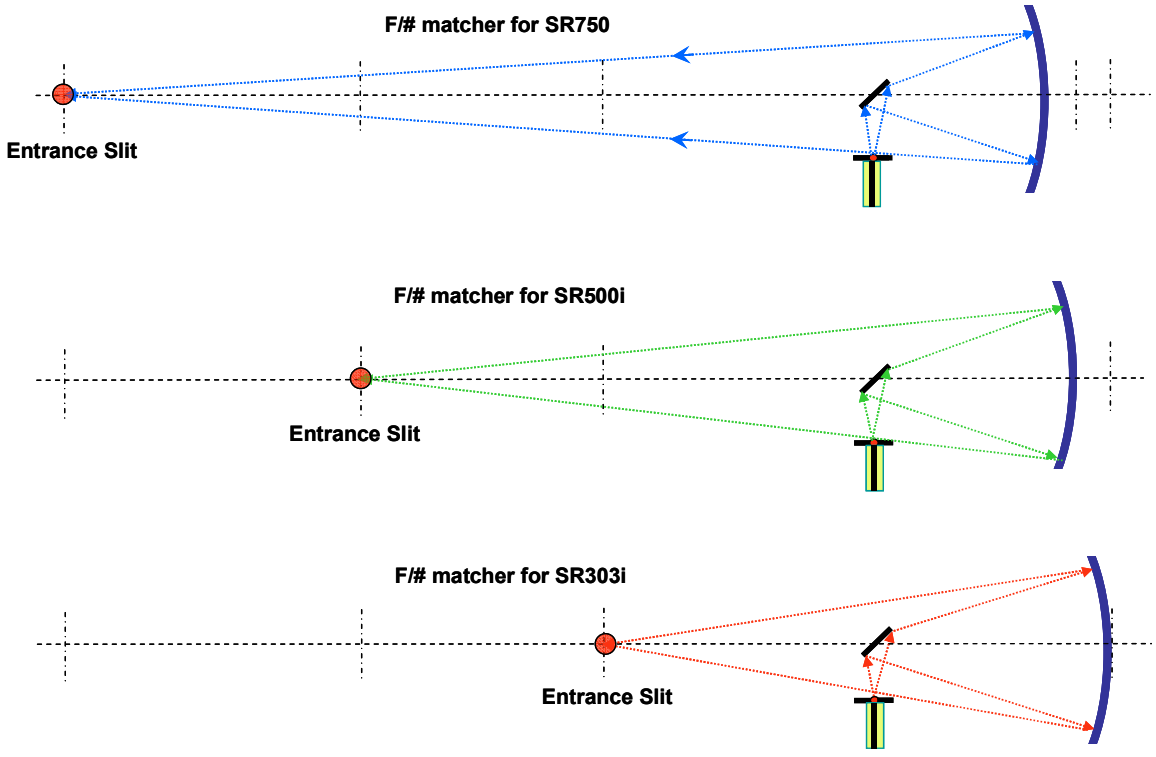

Figure 5: Optical schematics showing the layout of the three F/# matchers. The individual figures are referenced to the position of the small folding mirror. The focussing mirror is set at three different positions relative to the folding mirror depending on the system to be configured. For the SR750 the focussing mirror sits in the position closest to the folding mirror and vice versa for the SR303i. Different extension tube lengths are used for each system.

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Setting up and aligning the F/# matcher

Preliminary steps to assemble the main components – should this not be already done:
(Note if a new F/# matcher is ordered it will come pre-assembled and aligned for the relevant spectrograph, so the following 5 steps should not be needed in normal circumstances.)

1) Place the focussing mirror tube over the end of the folding mirror tube – the end which has the rings on it.
2) Push the tubes together such that the distance from the end of the folding mirror tube to the inside end of the focussing mirror tube corresponds to the reference distance for setup, D, as given in table 1. This distance is illustrated in figure 4. There are three grub screws on the focussing mirror tube which can be tightened to clamp one tube to the other.
3) Choose the appropriate extension tube for the particular F/# matcher system to be assembled. Attach the front mounting plate to the extension tube (don't attach plate to slit housing yet).
4) Push the extension tube into the other end of folding mirror tube; this should be pushed fully home and rotated so that the fiber port is either to the left, right or pointing up or down relatively to the mounting plate – see figures 4 and 7 where it is mounted to left side. The tubes can be clamped by the three grub screws on the folding mirror tube.
5) Two adjustable screws on the end of the focussing mirror tube allow for tilting of the mirror in two dimensions. Adjustment of these allow for movement of the image of the end of the fiber in two orthogonal directions labelled as x and y in figure 6. Rotate the focussing mirror tube relative to rest of assembly so that the adjustment screws for the focussing mirror will give horizontal (x) and vertical (y) adjustment of the focussed image relative to the front mounting plate. As a guide the line through the two screws should be at 45° to the horizontal – see figure 6.

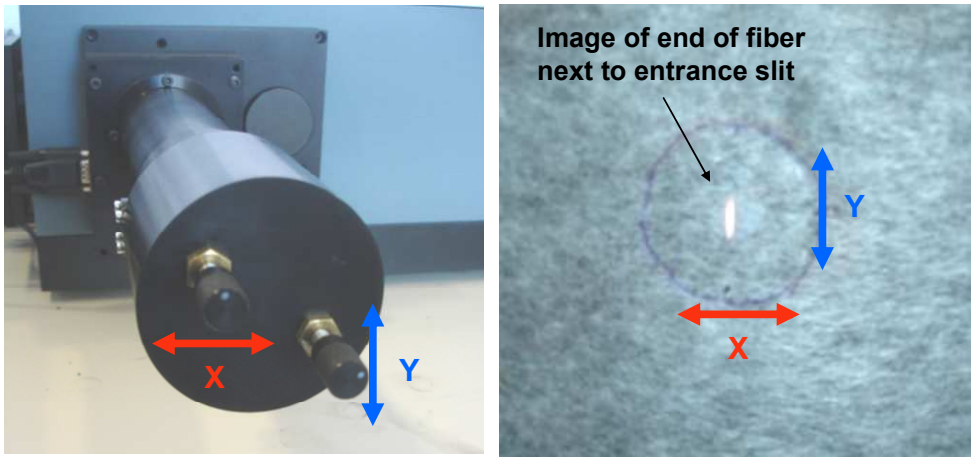

Figure 6: Orientation of the focussing mirror tube to allow for movement and alignment of the image on the entrance slit. Directions x and y refer to horizontal and vertical movement relative to the spectrograph. The image on the right just illustrates the image on a translucent screen as presented at the entrance port of the spectrograph – see text for details.

Initial alignment and focussing:

6) Mount the ferrule fiber in the fiber adapter on the side of the folding mirror tube – see figures 7 and 8. The end of the ferrule can be pushed in the full way and then withdrawn by 1 to 2 mm; this will allow for fine adjustment of the focussing at the end of the process.
7) If using an SMA fiber then use the SMA fiber adapter sleeve – see figure 7 – to attach the SMA fiber to the sleeve. Slide the sleeve into ferrule adapter flange as described in step 6 previously.
8) A small screw can be lightly tightened on the adapter to hold the fiber in place.
9) Mount a translucent screen at the front of the assembly mounting plate as shown in figure 8. Lens paper or something similar will do. This is to allow for observation of the image formed of the end of the fiber. This will be used for focussing and centring relative to the mounting flange or plate. The final focussed image of the end of

the fiber will coincide with the position of the slits on the spectrograph so it will reside a short distance (~7 mm) external to the mounting plate. However, at this point it is fine to get a good focussed image on the translucent screen to get close to optimum focus and alignment. Alternatively mount the screen to sit ~7mm out from flange face.

10) Deliver light into the fiber and observe image on exit screen. Some adjustment of the x and y screws on the focussing mirror tube (see figure 6 and step 5 above) can be used to centre the image relative to the mounting plate.
11) By adjustment of the focussing mirror tube in and out relative to the folding mirror tube, form a sharp image of the end of the fiber on the screen. Three grub screws clamp the focussing mirror tube to the folding mirror tube. These will need loosened to allow for movement and then tightened to clamp the tube in place.
12) The fiber may be rotated in its flange to bring it roughly in line with the orientation of the slits i.e in the 'y' or vertical direction relative to the spectrograph.
13) By adjustment of the mirror tilt with the x and y adjustment screws centre the image at the middle of the exit port of the extension tube.
14) When the image has been properly focussed and centred the assembly can be attached to the spectrograph.

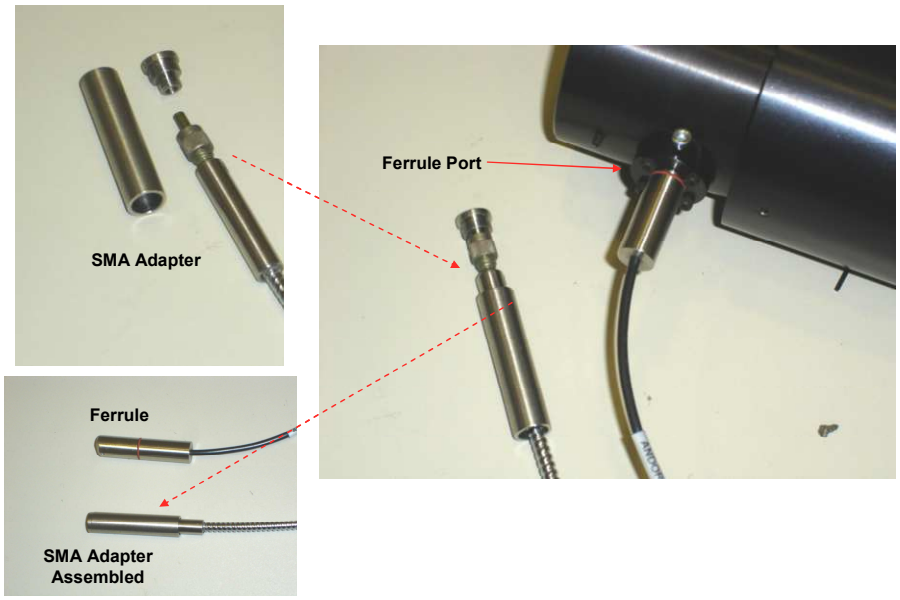

Figure 7: Attaching the ferrule or SMA fiber to the F/# matcher assembly.

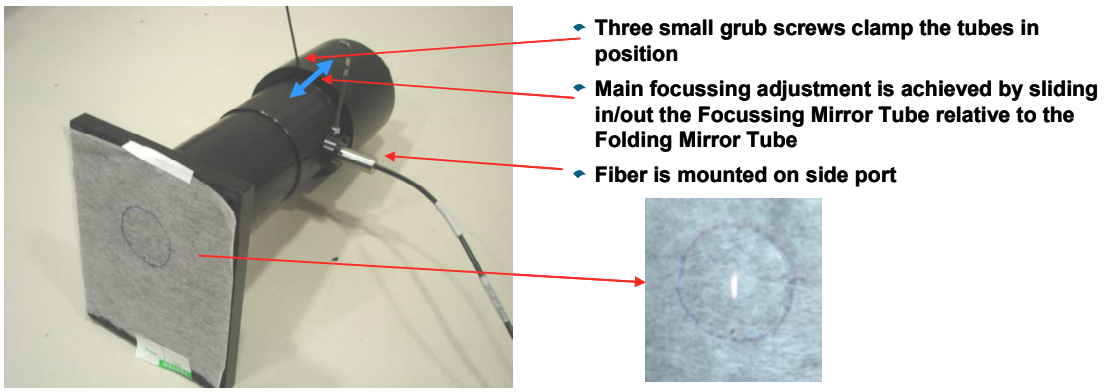

Figure 8: Making the adjustments to carry out initial alignment and focussing of the F/# matcher system. The x and y adjustment screws are used to centre the image.

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Fine alignment and focussing:

15) Open the slits up wide and set the camera to real-time image-acquisition-mode so that the relayed image of the end of the fiber can be clearly seen (see figure 9). This may require setting the grating to zero order if not using a line source of light such as the HgAr lamp.
16) Move the focussing mirror tube in/out slightly to optimise the sharpness of the image on the camera – see figure 9. Clamp the grub screws in place. Finer adjustment of the focussing will be possible if needed by movement of the fiber ferrule which is a later step in the alignment. Note the fiber may still be misaligned relative to the slit at this point.
17) Narrow in the slit whilst still acquiring images and rotate the fiber in the ferrule adapter so that it is aligned with the slits. This may require the use of the x-adjustment screw of the focussing mirror to ensure the image of the fiber is centred relative to the slit. A series of iterative steps may be needed here with the slit being gradually narrowed in each time and the fiber orientation checked.
18) Fine adjustments of the image quality (focussing) can be achieved by slight movements of the fiber in/out of the ferrule adapter flange (movement of at most 1 mm may be required). In general this allows for more sensitive adjustments than sliding the focussing mirror tube in and out. To this end setting the ferrule end of the fiber slightly back from the end position of its flange as outlined in step 6 above proves very useful. The typical quality of the image that should be achieved is illustrated in figure 9 where a standard fiber bundle has been used. Magnified images of the individual 100 μm core fibers placed side by side vertically are clearly visible.
19) At this point the other end of the fiber is ready for connection to the light source to be measured.

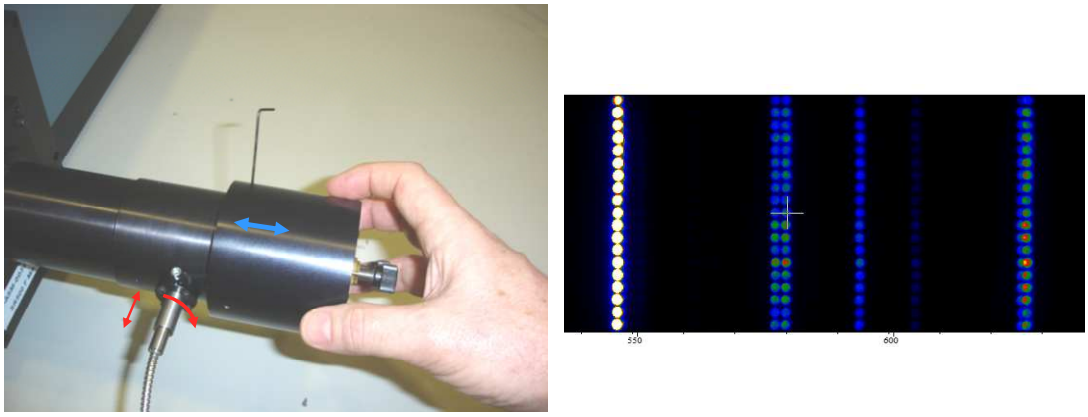

Figure 9: Making the fine adjustments when F/# matcher is attached to entrance port. The fiber ferrule may sit within 1 or 2 mm from the end of its flange. The image of the end of the fiber is monitored in real-time mode, and the focussing mirror tube is gently adjusted in and out to optimise focus (quality of image). After this step fine adjustments of the ferrule in and out can be used to give the final optimised image.

NOTE:
If an F/# matcher is ordered with a spectrograph then it should have been aligned and optimised for that spectrograph. Some fine adjustment may be needed.