Application Note ISOMET

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Acousto-Optic Scanning and Deflection

These application notes should provide the reader with a basic understanding of AO deflectors and scanners. Emphasis is placed on the practical rather than theoretical principals. For the majority of cases the simple equations given here are all that are required to describe the performance of AO deflectors in laser based systems.

Typical figures for a range of interaction materials are listed below:

Material	Acoustic Velocity (mm/µS)	Figure of Merit $(x10^{-15}m^2/W)$	Refractive Index @ um	Wavelength Range
$Te0_2$ (on-axis shear)	0.617	793	2.26 @0.633	NUV/VIS/NIR
$Te0_2$ (off-axis shear)	0.650	660	2.26 @0.633	NUV/VIS/NIR
$Te0_2$ (long)	4.2	34.5	2.26 @0.633	NUV/VIS/NIR
$PbMo0_4$	3.63	36.3	2.38 @0.633	VIS/NIR
GE	5.5	150	4 @ 10.6.	IR
SF Glass	3.41	8	1.8 @ 0.633	VIS/NIR
Quartz	5.7	2.38	1.54 @ 0.633	UV / VIS
Fused Silica (long)	5.96	1.51	1.46 @ 0.633	UV/NIR

$Te0_2$ (slow shear) is particularly suited for scanning applications. This material has a high figure of Merit (M_2) yet slow acoustic velocity (V). These characteristics give an AO deflector high efficiency, high resolution and large scan angle for a relatively low RF bandwidth.

Vector scanning

When an AO deflector is utilised in a vector scanning mode, beam pointing accuracy is normally the prime concern. Performance is defined by the accuracy and stability of the driver frequency source.

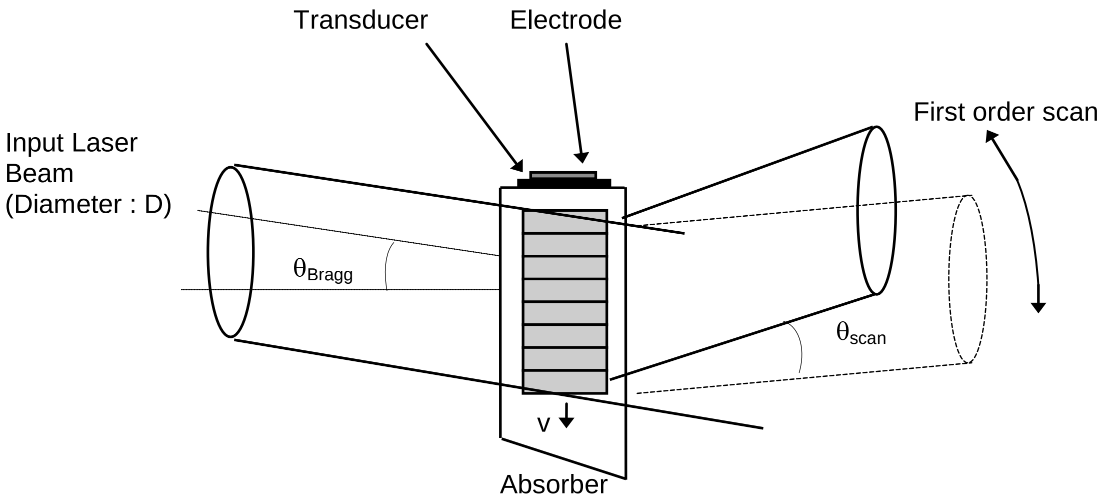
The maximum scan angle is given by: $\theta_{scan} = \frac{\lambda.\delta f}{v}$

where : λ = optical wavelength,
δf = device RF bandwidth

For the LS55, δf = 40MHz thus at λ = 532nm, θ_{scan} = 34.5 mrad (1.98°)

Nevertheless the equivalent spot resolution needs to be defined in order to specify the AO deflector and input beam parameters.

Deflector Configuration



The diagram depicts an acousto-optic deflector showing the sound column, of frequency f , travelling at velocity V through the AO crystal. The straight through zero order beam is not shown for clarity.

Resolution

The spot resolution of a deflector is determined by the ratio of the scan angle to the divergence of the input laser beam. For a uniformly illuminated aperture, this equates to the product of the acoustic fill or access time of the cell and the RF bandwidth of the device. The access time (τ) is simply the laser beam dimension along the acoustic (scan) axis (D) divided by the acoustic velocity (v).

Take for example the Isomet model LS55 AO deflector featuring a maximum access time (τ) of 11.3 µS and bandwidth (δf) of 40 MHz:

The intrinsic resolution is given by : **$N = \tau . \delta f$** i.e. 450 spots.

In practice this figure may get reduced, as described later.

NOTE: Resolution is not a limit on the scan angle increment.
The resolution calculation above refers to two resolvable adjacent points (or angles).

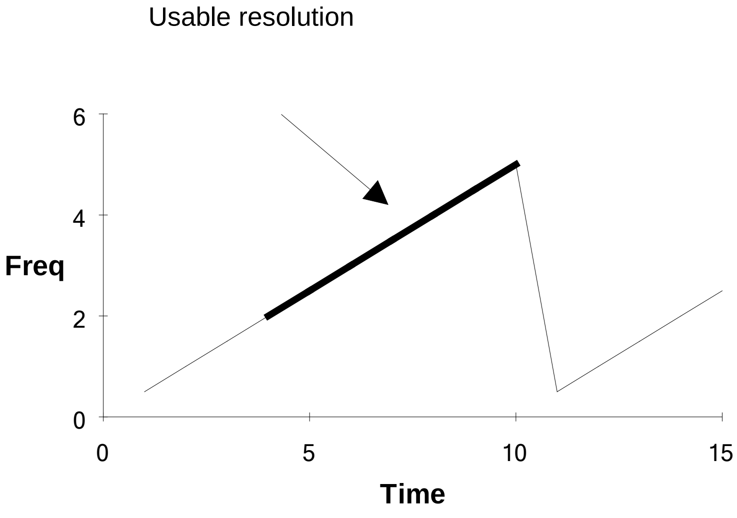
If resolving discrete points is not a requirement, then the angular step size is limited only by the driver frequency resolution, which typically equates to 1000+ non-resolvable points.

Spot deflector

In an AO deflector system featuring random position control, a packet of single frequency is generated for each spot position to be addressed. For maximum resolution the frequency or spot duration is equal to the access time of the cell. The occurrence and amplitude of each frequency generates the spot pattern. However this method does not provide the highest scan rates, since the fastest time to switch from one spot to another is the access time (=.τ)

To achieve higher scan speeds the AO deflector is utilised as a 'continuous' linear scanner and a separate AO modulator provides the necessary amplitude control. However there are limitations. If the scan period is not much greater than the fill time of the cell, the number of usable resolvable spots is reduced.

This effect is illustrated in the diagram below :



Let 't' be the scan time including any fly back and 'τ' be the access time of the deflector cell. The resolution (Rayleigh criterion) assuming uniform illumination is given by:

$$\mathbf{N = \tau.df.\left[\frac{(t-\tau)}{t}\right]}$$

i.e. the inherent resolution is reduced by the finite fill time of the AO cell

Hence for a scan time of 22.4 µs (say) and an access time of 11.3 µs, the number of resolvable spots (N) is 224.

Chirp effect

At high scan rates there is an appreciable linear variation of frequencies across the laser beam within the cell, often referred to as a "chirp effect". Adjacent points across the input laser beam 'see' different frequencies and hence are deflected at different scan angles. The cell thus acts as a cylindrical lens, either positive or negative depending on the frequency ramp. The equivalent focal length is given by:

$$\mathbf{FL} = \frac{\mathbf{v^2}}{\boldsymbol{\lambda} \,.\boldsymbol{\delta} \mathbf{f}/\boldsymbol{\delta} \mathbf{t}}$$

where : v = acoustic velocity
$\delta f/\delta t$ = scan rate
λ = wavelength

In practice, for a uni-directional scanning system, this effect can be negated by the addition of a cylindrical lens with opposite power and same focal length f_1 placed after the deflector.

Take the LS55 example, with:
Sweep rate of $\delta f/\delta t$ = 40 MHz in 22.4µs
v = 0.617 mm/µs
λ = 532 nm

then the focal length FL = 400mm.

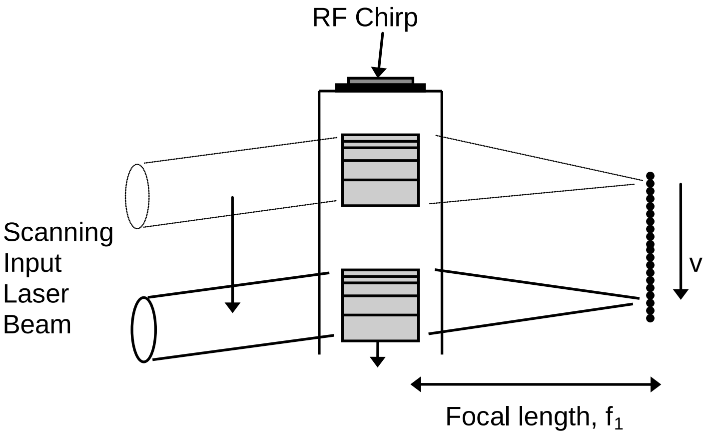
As described above, the performance of a deflector degrades with increasing scan rate. At very high scan rates the acoustic fill time of the deflector aperture becomes a large fraction of the scan period (t) and this limits the available resolution.

For unidirectional scanning, these limitations can be overcome by use of the Chirp Deflector.

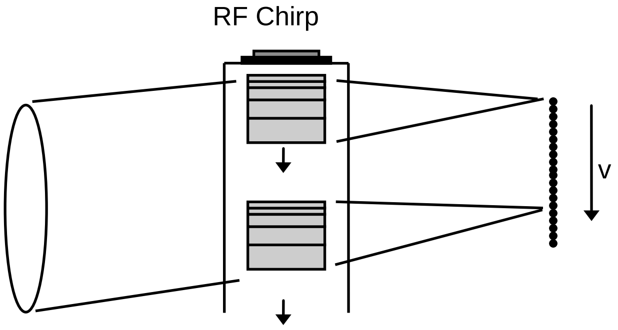
Chirp Deflector*

The chirp deflector capitalises on the self focusing properties (see Chirp effect above) of an AO deflector and overcomes the loss of resolution due to the finite access time of a conventional deflector. Here the drive signal is in the form of RF pulses shorter in duration than the total transit (or access) time of the deflector cell.

- **Scanning Mode**



- **Flooded Mode**



Each pulse is composed of a linearly swept RF signal that ranges from f_a to f_b.
If a collimated laser beam is made to track the RF pulse as it travels down the crystal (Figure a:), the result is a linearly scanned spot at an image plane located at a constant distance from the deflector, f_1 . (Of course, self-focusing only occurs in the diffraction plane; in the orthogonal plane a cylindrical lens is required to focus the beam.) As the RF pulse leaves the crystal, the laser beam is made to flyback and track the next RF pulse that has just entered. This can be achieved with a relatively low resolution AO deflector. Since the laser beam can be made to flyback in nanoseconds, the difficulty encountered because of the fill time of the standard deflector is circumvented. Indeed, if one is willing to waste some laser energy, the optical aperture can be filled with light (Figure b:), permitting each RF pulse to create a linearly scanning focused spot with literally zero flyback.

The resolution of the device is given by the product of the acoustic transit time of each RF pulse across the aperture (τ) and the bandwidth of the chirp pulse (f_b - f_a). Thus to achieve 2000 spots of resolution, the bandwidth must be 50MHz for an acoustic transit time of 40us.

The actual duration of each chirp pulse can be selected more or less arbitrarily; the choice will be made on the basis of the actual optical design, i.e., setting a reasonable chirp focal length based on f_1.

e.g. A ten microsecond chirp pulse duration would result in a focal distance of 114mm at 632.8nm (for TeO_2 with v=0.617mm/us).

The acoustic transit time of the Chirp deflector equals the required line scan time.

For large apertures, it is also necessary to consider the acoustic attenuation along the crystal. In TeO_2 this figure is 17.9dB/us/GHz^2. This will reduce the efficiency of the deflected spot as the chirp pulse travels across the aperture. To compensate, the input laser beam can be weighted to give higher optical input toward the absorber end of the crystal.

* U.S. Patent 3,851,951

Bragg Angle and Beam Steering

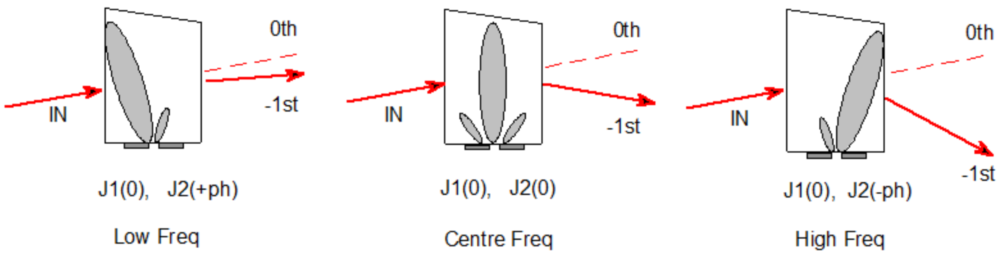
First order deflection efficiency is maximised when the angle (θ) of the input laser beam satisfies the Bragg condition:

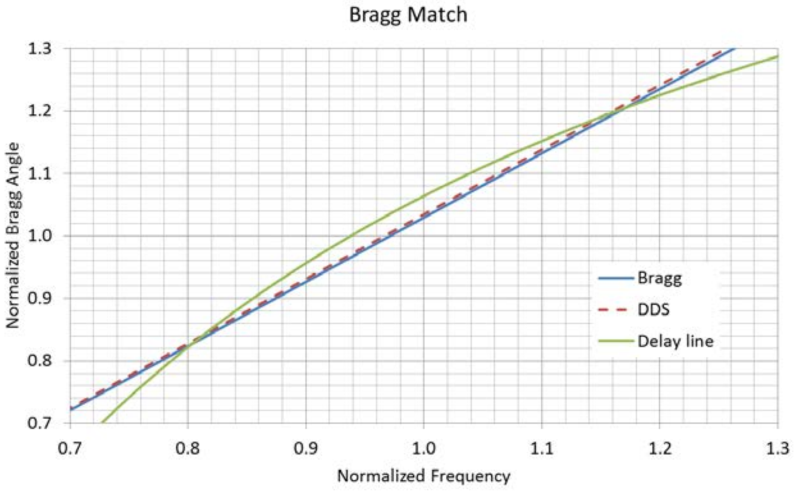
$$\theta_{Bragg} = \frac{\lambda.fc}{2.v}$$

Obviously, this can only be exactly true for one chosen frequency. As the frequency is swept about the centre frequency fc so the efficiency will vary. Transducer characteristics of AO deflectors are designed to minimise this effect. However to remain within the Bragg regime there is a limit to the amount of bandwidth a single electrode AO device can provide.

To circumvent this difficulty and achieve greater bandwidth and hence scan angle, the acoustic signal in the AO material can be steered and made to track the optimum Bragg conditions over a wider range of frequencies. This requires an array of electrodes on the device transducer, each with an RF input signal progressively delayed in phase. One simple method involves the use of fixed delay line(s) to change the phase proportional to the drive frequency. A more sophisticated and precise solution employs multi-output frequency synthesizers (e.g. Isomet iMS4-P) . Either way, the phase offset results in a change in launch angle of the acoustic beam from the transducer.

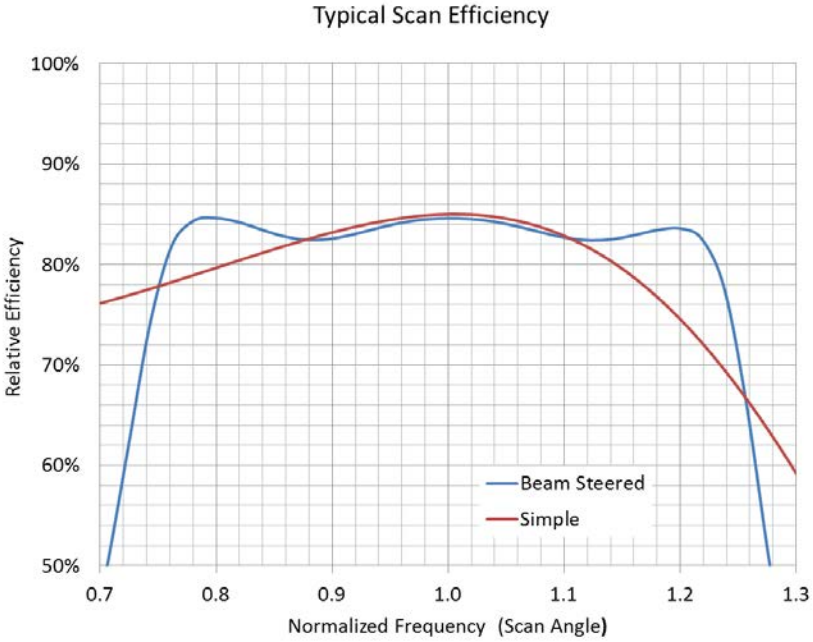
Beam steering techniques are used in many Isomet AO deflectors. e.g. LS110, D1135, D1340, D1384, AOD600 and LS700 deflectors.





The plot above illustrates the Bragg matching error of fixed delay line vs, synthesiser approach (DDS)

The benefit of acoustic beam steering is shown below.



The blue trace represents an efficiency sweep for a Beam steered AO deflector.
The red trace is without beam steering. This is typical of an AO modulator used as a deflector.
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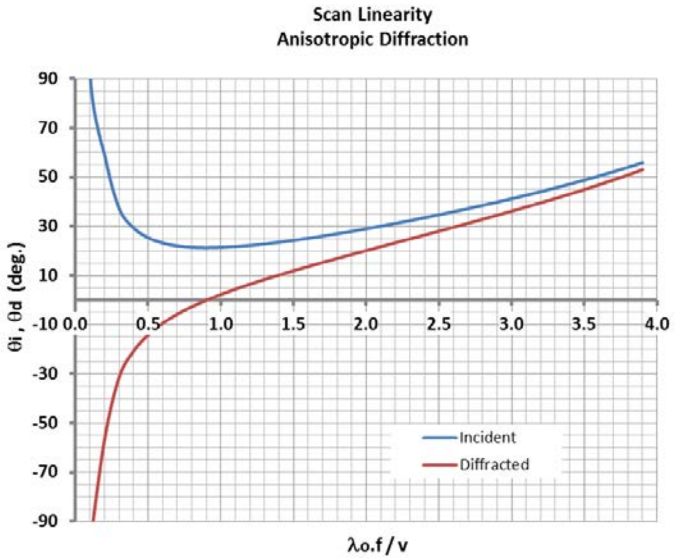
Off-axis AO deflectors (OADxxxx)

Exploiting Anisotropic Interaction

Off-axis AO devices exploit the birefringence properties of anisotropic materials in which the refractive indices for the incident (n_i) and diffracted (n_d) beams differ.

The ‘Dixon’ equations describe the angles of incidence and diffraction for interaction in birefringent materials. The result is illustrated in the simplified plot below:



There are two significant regions. For deflector applications, the region of interest is about the turning point of the ‘Incident’ curve (0.5 – 1.5 on the x-axis). This is the ideal operating point for AO deflectors i.e. a small change in incident ‘Bragg’ angle over a relatively large change in drive frequency (or wavelength λ_o).

This is an ideal characteristic for wide bandwidth AO deflectors where large scan angles require large frequency tuning ranges. The very low sensitivity to input Bragg angle results in a flat efficiency response for the diffracted beam.

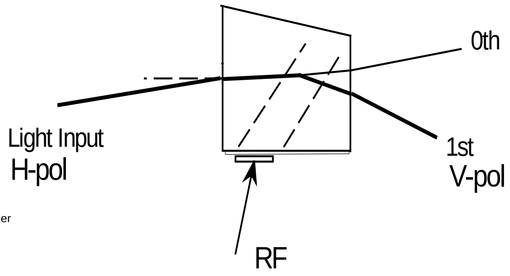
(The second significant region applies to AOTF operation (< 0.2 on the x axis)).

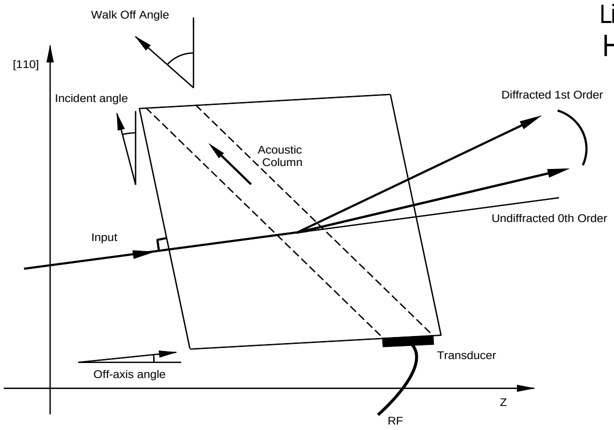
Typical characteristics of off-axis AOD’s:

- Relatively slow acoustic velocity (= larger scan angles).
- Low sensitivity to input Bragg angle. (= no beam steering required).
- High AO Figure of Merit (= low RF drive).
- Diffracted output polarization is rotated with respect to the input and zero order beams.
- Device orientation is defined by the design.

Typical Off-axis devices and orientations

Off-axis deflector schematics





As illustrated above, the crystal volume must accommodate the walk-off angle of the acoustic beam from the transducer. For large aperture devices, this will mean large crystal volume.

Dual Axis

Two AO deflectors can be mounted orthogonally to provide dual axis scanning e.g. LS110-XY OAD1344-XY, D1384-XY deflectors.

For XY scanning, a limitation in scan angle (resolution) is due to the finite distance between the X and Y deflectors and the maximum aperture height of the second deflector.

Assume the beam is first deflected in the X-axis then the Y. The maximum scan angle of the X-axis is limited by the active aperture of the following Y-axis deflector otherwise clipping of the output beam will result.

Thus: [max. scan angle of X] x [distance between AOD’s'] = [aperture height of Y]

Deflection Efficiency

Diffraction efficiency is a function of the acoustic drive power. The optimum (saturation) power is given by:

$$\mathbf{Psat} = \frac{\lambda^2 . H}{2.L.M_2}$$

where:

λ = optical wavelength
H = electrode height of transducer
L = electrode length
M_2 = figure of merit for interaction material

For a given device L, H and M_2 are constant and thus the value will depend on the operating wavelength (squared).

RF power limitations

If the device is operated at a power (P) less than Psat, the reduction in efficiency can be determined from the formula:

$$\text{Relative eff' } \varepsilon = \sin^2 \frac{\pi}{2} . \sqrt{(P/Psat)}$$

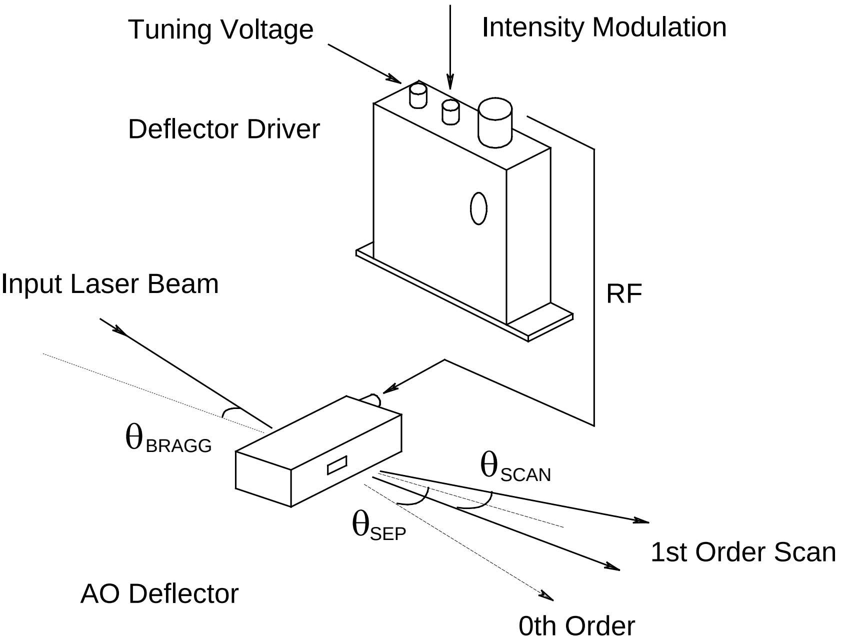
This may be the case when operating at longer wavelengths and with a limitation on the maximum input RF power. In addition, the RF drive power is often tailored or programmed to flatten the amplitude of the deflected output.

Benefits

Although AO deflection angles are small compared to mechanical techniques, AO scanning offers significant advantages:

- solid state
- true random access control
- raster with minimal 'fly-back' delay
- high speed
- inherent stability and accuracy

Schematic of a basic acousto optic deflector and tunable driver



Key angles : (fc=deflector centre frequency)

$$\theta_{BRAGG} = \frac{\lambda.fc}{2.v} \qquad \theta_{SEP} = \frac{\lambda.fc}{v} \qquad \theta_{SCAN} = \frac{\lambda.\delta f}{v}$$