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Evaluating linear motion solutions for vacuum deposition chambers in industrial-scale PV manufacturing

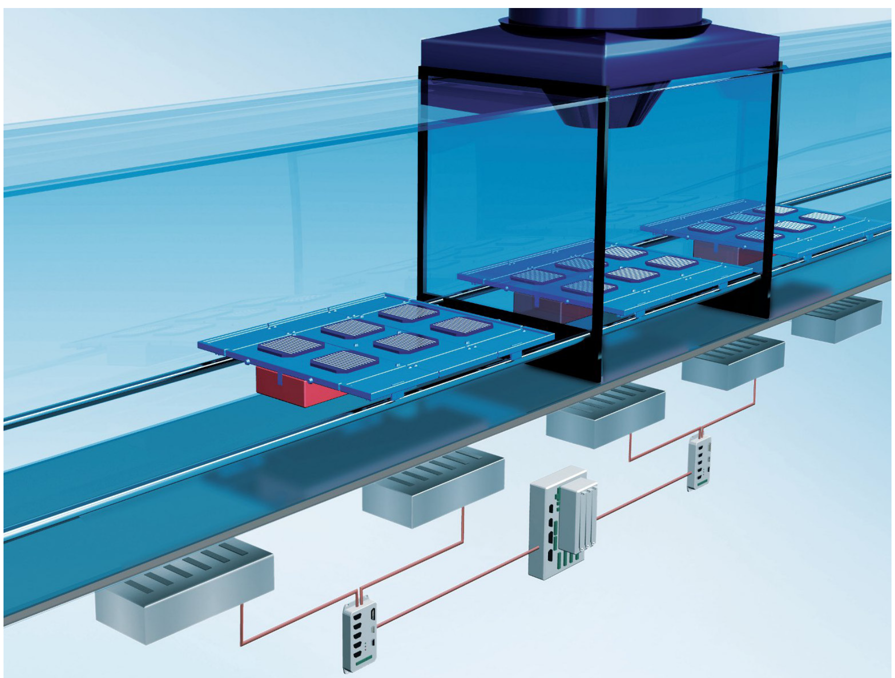

Figure 1: Inverted linear motor deposition chamber example

As manufacturers ramp up photovoltaic (PV) manufacturing lines, one key production challenge is designing and operating linear transport systems that move substrates through multiple fabrication steps. Several different PV production processes utilize vacuum deposition chambers to fabricate the solar absorber layer; typically these processes require multiple chambers and/or tools where the substrates are moved from point to point.

Transporting substrates through large vacuum chambers, or in and out of multiple vacuum chambers, requires specialized linear transport systems engineered for high-volume automated production. This article evaluates various types of linear transport

Vacuum Deposition Transport Challenges

- Maintain hard vacuums (up to 10^{-9} mbar) for long process runs
- Some transport system elements (cables, belts, power lines) must run from outside to inside chambers
- Deposition involves high temperatures and caustic vapors which cause excessive wear
- High electrostatic/electromagnetic conditions inside can affect electronics
- Requires precise control of movement and acceleration

Optimum Solution: Linear Motion Transport

- "Inverse" linear system such as Rexroth LMS places a magnet on the carrier
- Multiple intelligently controlled electronic coils outside vacuum chamber drive carrier forward
- Increased uptime due to minimized service and longer component life
- Improved yield potential, with no moving parts to cause particle contamination
- Improved quality of vacuum deposition processes
- Increased throughput

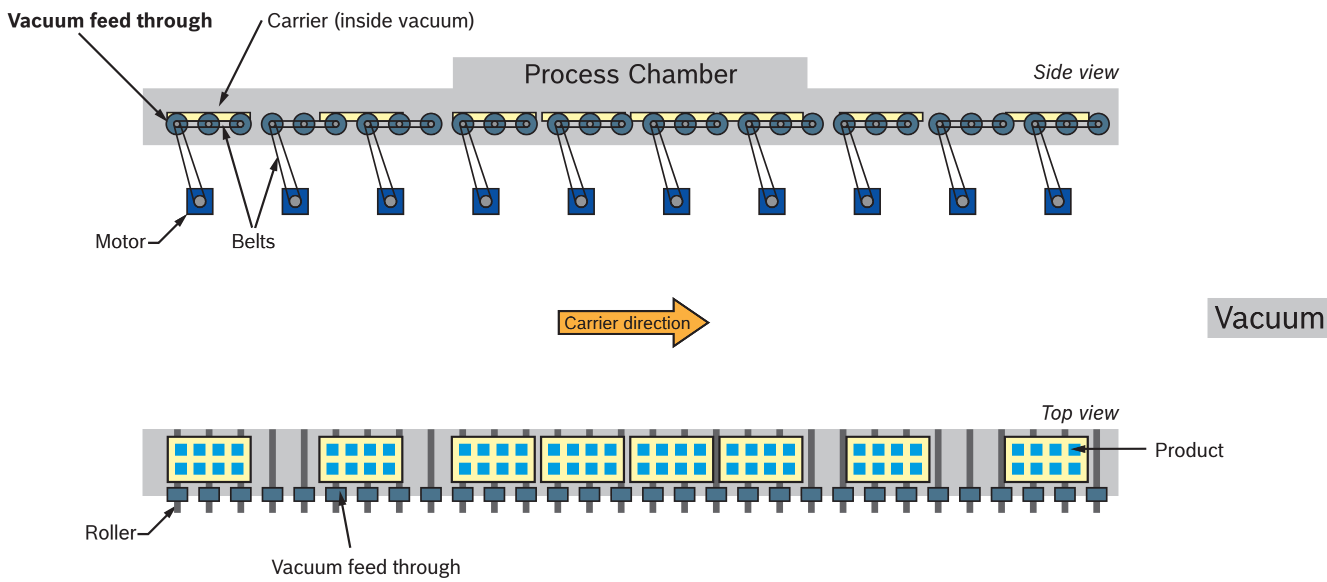

Figure 2: Roller transport system

systems used for moving rigid and thin-film substrates from chamber to chamber, covering functional advantages and drawbacks while highlighting the design, engineering and operational advantages of transport systems that utilize linear motor technology for transport.

PV vacuum chamber unique operating conditions

Vacuum deposition is a standard production process used to produce multiple PV cell types, including c-Si, CdTe, and CIGS technologies. Although specific processes may vary, all share common characteristics: Vapors of pure materials, some at very high temperatures, are deposited at highly controlled rates onto substrates as they move through the chambers.

Linear motion systems are used to transport both rigid and thin-film PV substrates from chamber to chamber. In this process there are several fundamental operating conditions that can impact the choice and design of linear transport technologies. They include:

Vacuum environment: Deposition systems typically feature large chambers which must maintain a relatively hard vacuum, up to 10^{-9} mbar for some processes. Industrial-scale production requires maintaining these vacuums for long periods of time. Therefore, linear transport systems that need frequent maintenance, or have wires, belts or other connections leading from outside into the chamber can make it more difficult to maintain the vacuum and the optimum level of throughput.

PV manufacturers have been developing high-volume vacuum deposition systems, thus creating ever-larger vacuum chambers. After any maintenance work is performed, significant downtime can be incurred in order to cycle these chambers from room atmosphere through to hard vacuum; minimizing these maintenance outings can be crucial to controlling costs, productivity and ultimately the cost per Watt.

High-temperature production: In some cases deposition minerals are vaporized at very high temperatures (i.e. 1300°C for copper in CIGS). Certain processes also require heating the substrate for successful material deposition; this temperature can reach 800°C. Although the material transport system itself would not be heated to these levels, these high temperatures need to be considered when designing the transport system. Components that cannot withstand high temperatures need to be shielded, and technologies like heat sinks may be needed to remove heat from the vacuum chamber, adding to system costs.

Electrostatic conditions: Electromagnetic and electrostatic conditions within process chambers can negatively impact electronics (sensors, motors, connections, etc.) for linear transport systems;

the presence of high-temperature plasmas, magnetrons and the use of UV technologies to heat substrates can create a very active electromagnetic environment, so transport systems need to be engineered accordingly.

Controlled motion: PV production lines utilize either batch or continuous processes, and often move substrates through multiple chambers. Linear transport systems must have highly variable motion capabilities: fast motion when moving materials between chambers, slower and very precise motion during deposition. Depending on a manufacturer's specific process, the speed of movement, acceleration and jerk control capability within the chamber is critical for optimizing deposition rates.

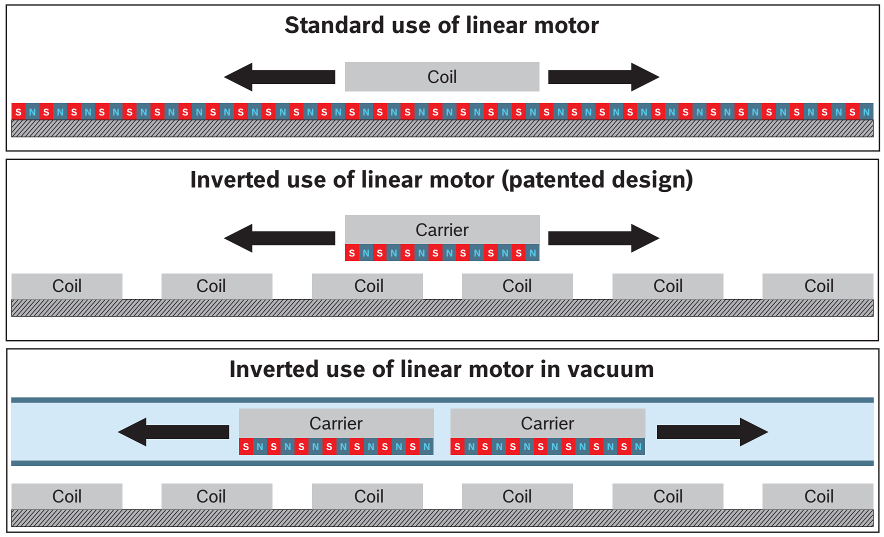

Figure 3: Standard and inverse linear motor systems

Evaluating linear transport system options

Given these manufacturing conditions, different linear transport solutions have been developed. All have characteristics that need to be evaluated against the unique conditions of PV vacuum deposition processes.

1) Mechanical belt transport system: Mechanical belts are typically composed of flexible stainless steel and provide a comparatively low-cost linear transport solution. The substrate usually rests directly on the belt, whereas other linear transport systems may use an attached carrier platform. Typically the belt (or chain) is driven by one or two stationary electric servo or stepper motors situated at one or both ends of the belt. All components are mounted within the vacuum chamber, with power and control cables being fed through the chamber walls. This type of transport usually supports simple motion profiles (i.e. movement in one direction only) and the speed can be varied to control deposition rates.

Since mechanical belts are also used across a wide range of other applications, their operation and motion programming are familiar to many design engineers. The disadvantages of a belt transport system are primarily associated with operating electric motors and mechanical rollers and belts within a vacuum environment. Although most components are made of stainless steel, whenever there is mechanical motion there is friction, with the potential to generate particles that can contaminate material deposition.

High temperatures can also impact belt transport systems. Since the substrate is not mounted on a separate carrier, heating of the substrate will also heat the belt. The materials being deposited on the substrate will also be deposited on the belt, which can degrade over time through exposure to caustic materials. Also, the motors and electronic controls are located within the chamber, making these electronic components vulnerable to electrostatic and electromagnetic interference; this could disrupt efficient long-term functioning of the belt systems.

2) Roller transport system: This mechanical system uses rollers controlled by separate motors mounted outside the vacuum chamber, and uses belts or chains to turn the rollers. The substrate is mounted on separate carriers which are moved forward by the rollers (Figure 2). This type of system is comparatively simple to design and engineer. By mounting the motors and drives outside the vacuum chamber, these components are not affected by conditions within the deposition chamber. However, this design requires more motors and belt components, since separate motors drive a series of rollers, rather than

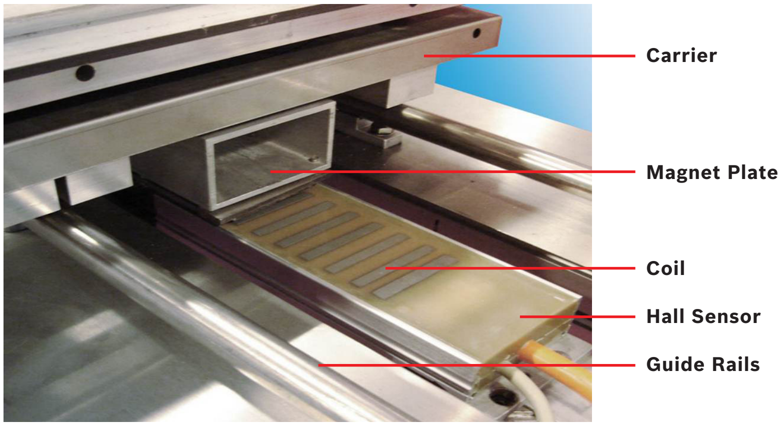

Figure 4: Inverted linear motor system elements

all of the rollers being controlled by one motor.

This can increase component costs; it does, however, allow stop/start movement at different stages if needed for the deposition process. Also, the belts must be fed from the motors outside the chamber into the vacuum environment; this requires specially made, expensive feedthrough components, adding to capital costs.

Mechanical belt and roller systems have moving parts within the vacuum chamber; these parts are vulnerable to breakdown and failure due to conditions within the chamber (high temperature, vacuum, chemicals). Regular system shutdown to maintain mechanical parts and remove contaminants is required.

Mechanical systems also require placement of optical or proximity sensors within the chamber so the position of each substrate or carrier can be tracked. These electronic devices use cabling that goes outside the chamber, and will require maintenance or replacement.

3) Magnetically coupled roller system: This approach enables the use of roller transport, while maintaining the vacuum seal. One set of magnets is mounted on the motor outside the chamber, and another set of magnets is mounted on the rollers. As the motor turns, the transport rollers in the chamber turn through magnetic coupling. However, there are still mechanical elements within the chamber that turn, potentially generating particles through friction. These parts are also susceptible to excess wear and tear due to vacuum chamber conditions.

4) Standard linear motor system: Linear motors provide an alternative to mechanically-based systems, utilizing magnets and coils to provide horizontal motion. In a standard linear motor system, the substrate carrier has a coil mounted in it. Fixed magnets are attached all along a frame beneath the carrier: when the coil is activated, electromagnetic interaction moves the carrier forward.

This approach greatly reduces the number of moving parts in the chamber, although power and control cabling must be fed into the chamber from outside. The only part that moves is the carrier; there are no rotating axes within the chamber to generate particles. It also provides more flexibility with motion profiles, including the ability to move the carrier in both directions, and have it stop at precisely determined points within the chamber.

In a standard linear motor, one of the most costly components is the track: it must be equipped with magnets for the full length of the transport track. Both the carrier and the attached power and sensor cables move, which can still generate friction and particles within the vacuum; if the cabling is sheathed in a polymer/plastic, the motion of the cables can also lead to outgassing, creating potential contaminants.

5) “Inverse” linear motor system: This approach to the use of linear motors is designed to provide maximum effectiveness for vacuum deposition environments. Instead of having the magnets mounted along the frame, the inverse approach places a magnet on the carrier, with multiple intelligently controlled electronic coils mounted outside the vacuum chamber (Figures 3, 4). The carrier moves when the electronic coils are activated in a controlled sequence, allowing the carriers to move precisely to any position within the vacuum chamber.

The most significant benefit of this design is that there is no mechanical, cabling or electronic feedthrough required from outside to inside the chamber. This design also makes it possible for multiple carriers to move independently, with different speeds, or form an array (train) of carriers for high-volume throughput.

This design has less particle generation and lower maintenance requirements, because the only moving part is the carrier. It is a lower cost linear motor design, because magnets are only required on the carrier, not the entire track.

It also provides more precise motion capabilities, compared with non-linear motor based mechanical transport solutions: Repeatable endpoint accuracy lets operators stop a carrier within 50 micrometers, so process engineers can optimize how slow or fast the carriers move through different deposition steps. Since the motion of each carrier is controlled by the coils, carrier position within the chamber is always known, providing better control over substrates in the vacuum without the need for additional external sensors and electronics (Figure 1).

Multiple deposition chambers can be linked together and still maintain vacuum integrity between chambers. A pre-heat chamber can be used to bring the c-Si substrate temperature up to the desired level, and then the carrier (or array) can be moved from one chamber to the next for anti-reflective silicon nitride deposition. Similarly, if a CIGS deposition process uses a two-chamber process in which deposition of the copper, indium and gallium occurs in the first step, and then selenization and annealing in the second chamber, the CIG substrates can be automatically transported to the next chamber with peak efficiency, and without exposing them to oxygen.

Considering TCO advantages of linear motor systems

Inverse linear motor transport systems require a more complex control set up than typically required for belt or roller transport platforms, since multiple electronic coils need to be controlled in close synchronization. However, this complexity lives "behind" the scenes, invisible for the user. Ideally, the linear motor system, like the LMS from Bosch Rexroth, will feature extensive software tools and standard programming languages, plus built-in motion-control functionality such as carrier management, move profiles and synchronization to make it easier for engineers to commission.

Comparing solely on a component basis, linear motor technology may have a higher initial cost than stepper or servo motors that drive belts or rollers. However, considering these "traditional" solutions still require expensive vacuum feedthrough valves, significant costs can be saved by using systems that eliminate those feedthroughs.

In conclusion, when evaluating from a total cost of ownership (TCO) perspective, inverse linear motor systems offer several advantages for high-volume PV vacuum deposition systems:

- Increased uptime due to minimized service and longer component life
- Improved yield potential, with no moving parts to cause particle contamination
- Vacuum chamber integrity, thus helping improve quality of vacuum deposition processes
- Increased throughput due to higher speeds and flexible routing of substrates
- More precise motion control that enables optimized deposition rates and reduced breakage from vibration or sudden starts/stops.

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