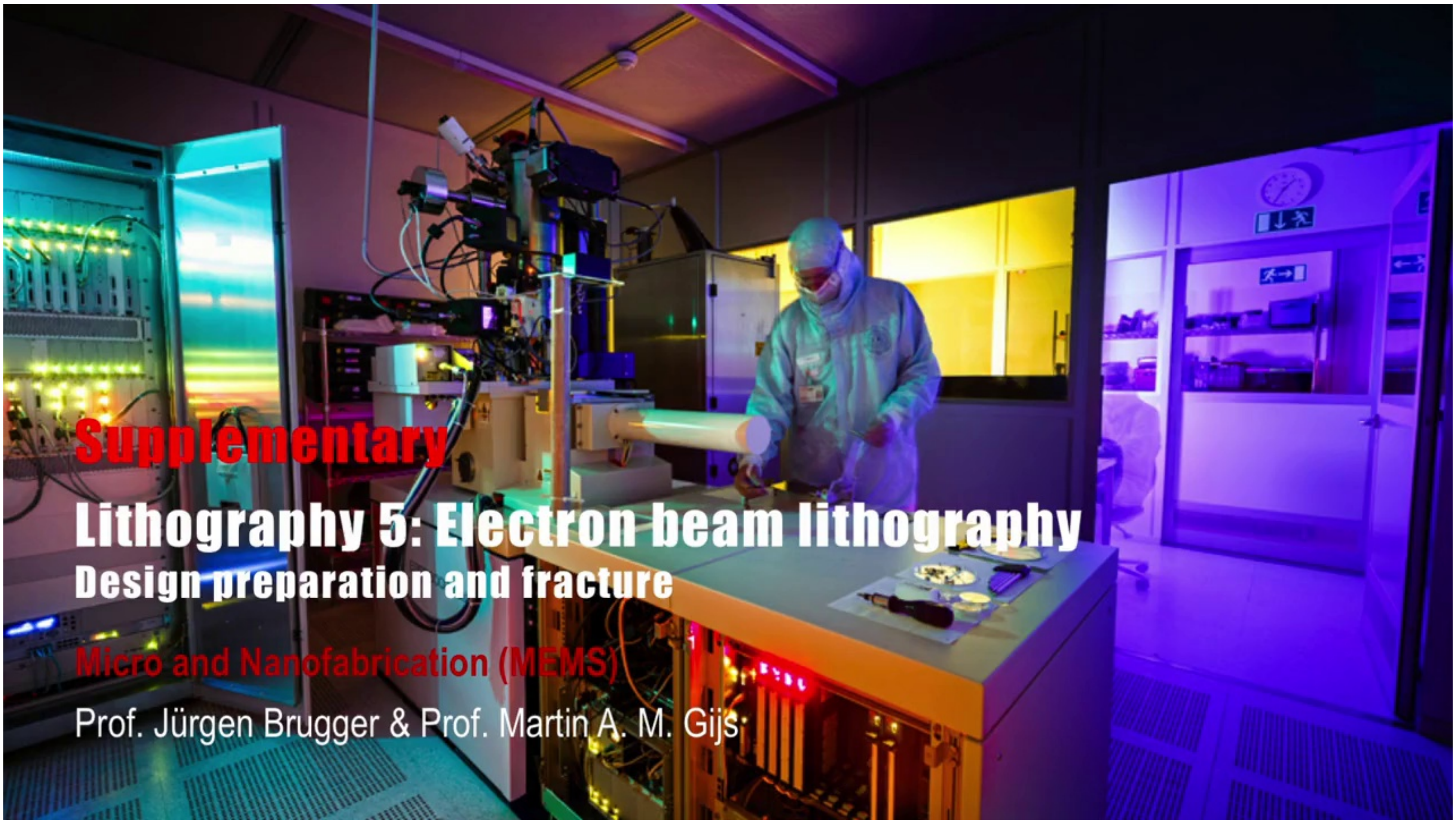

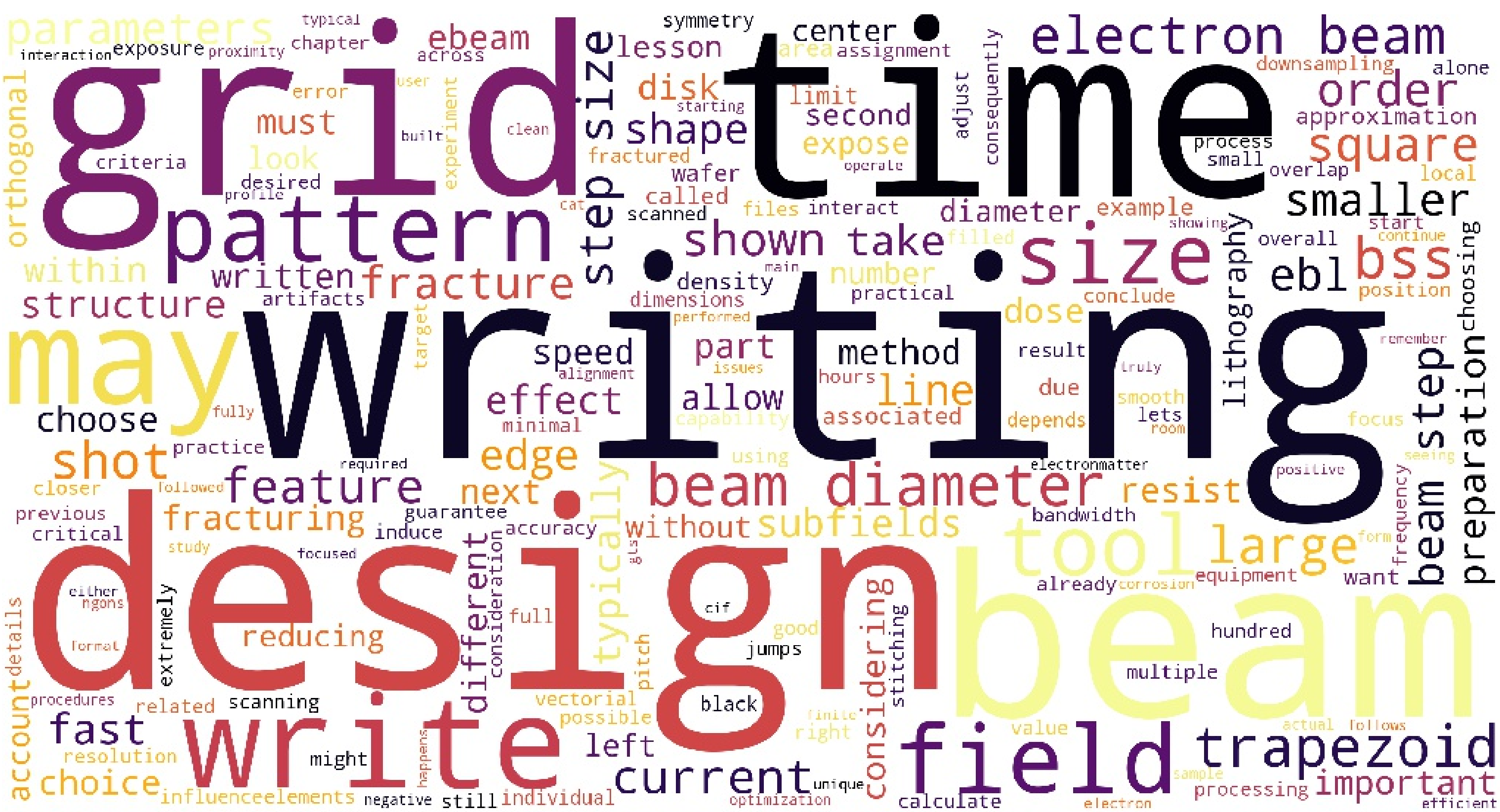

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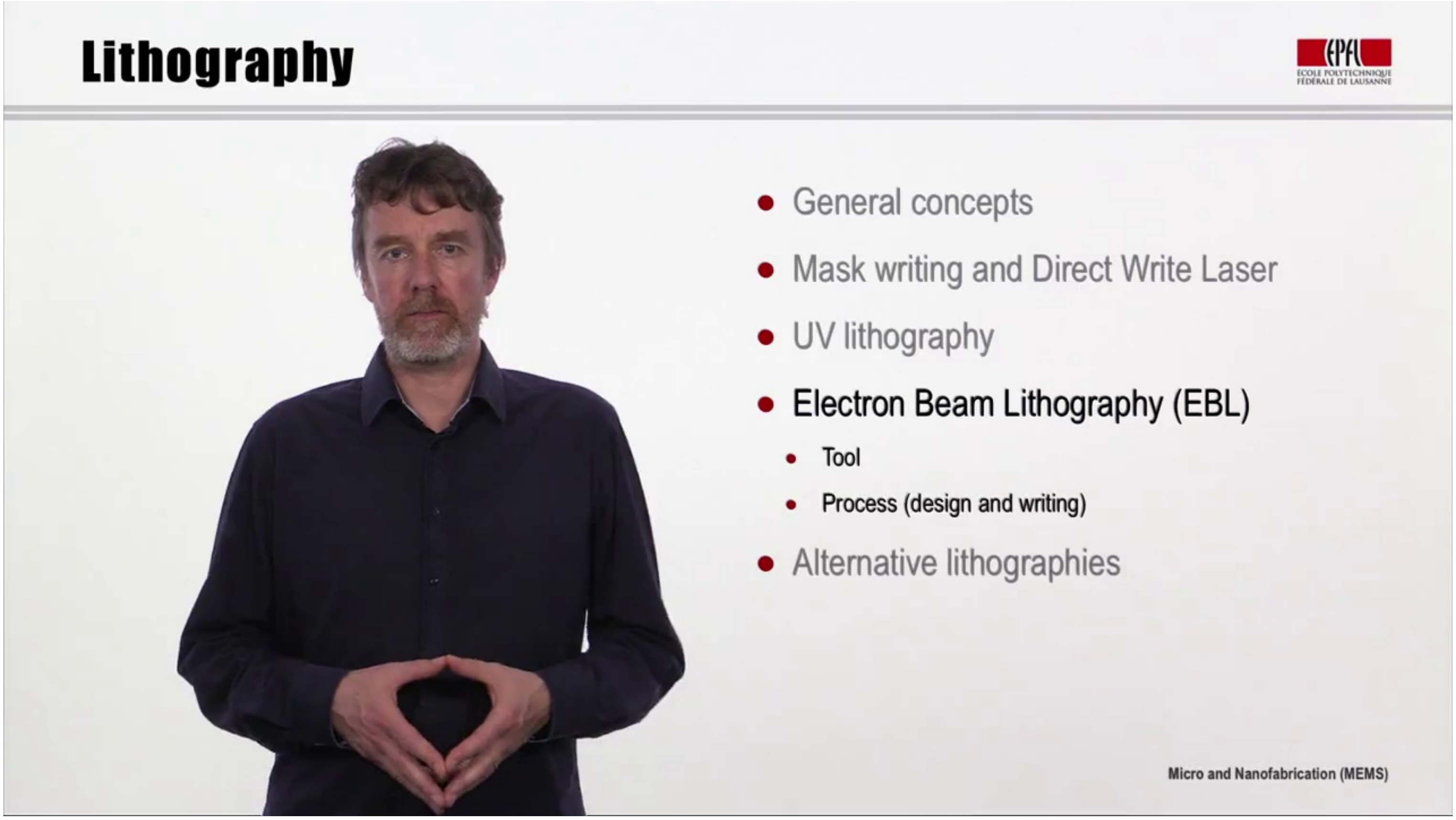
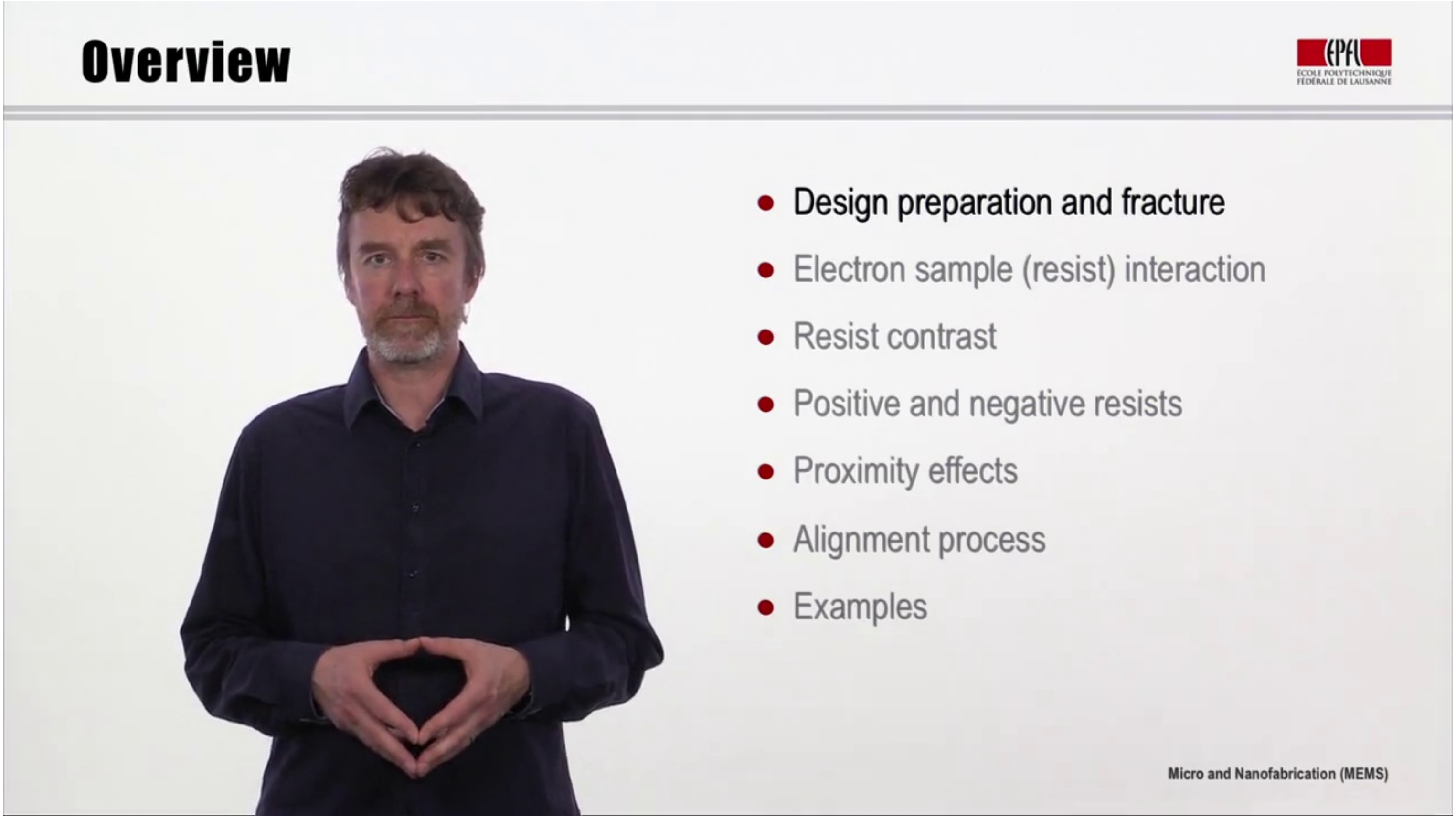
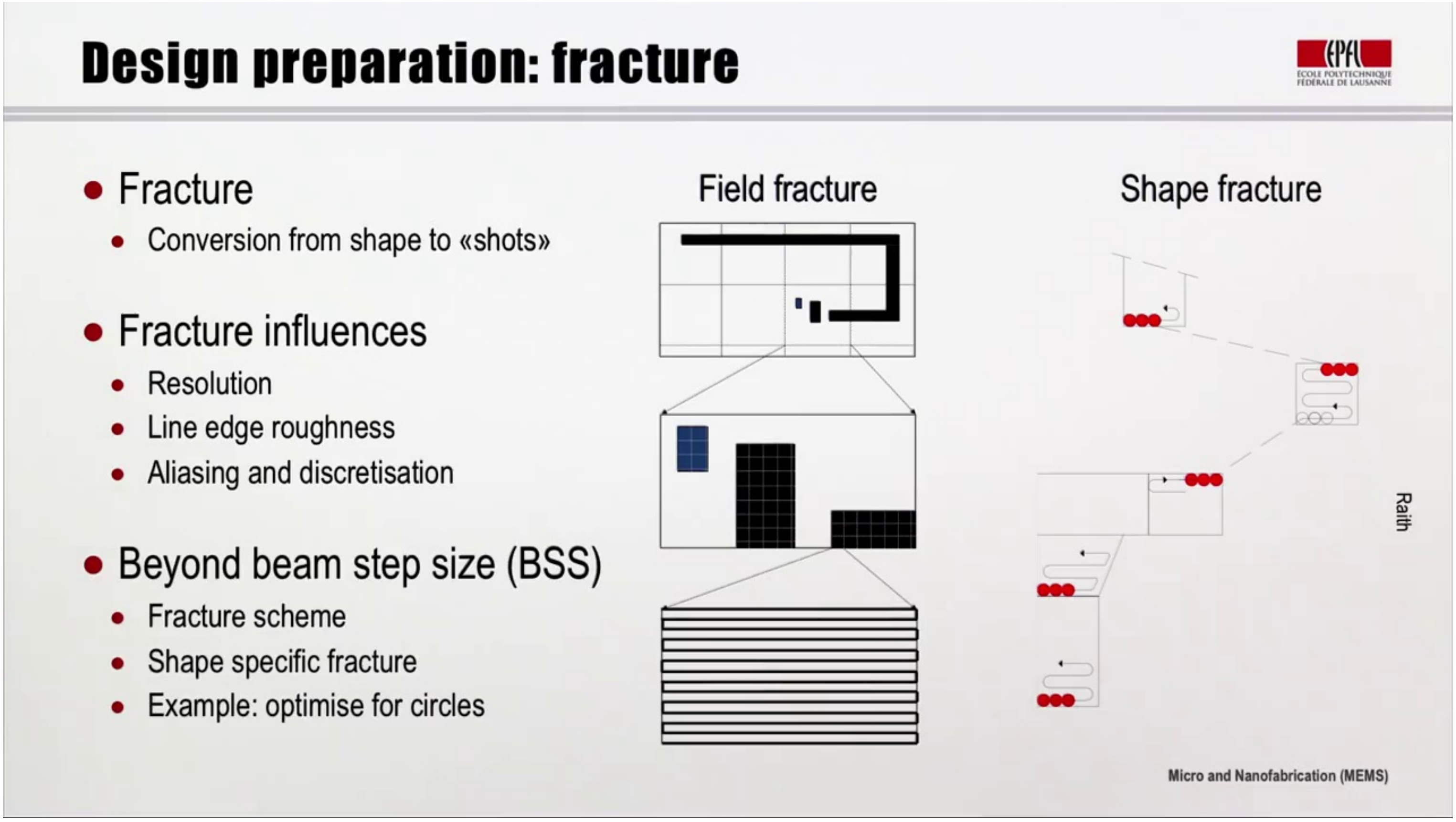


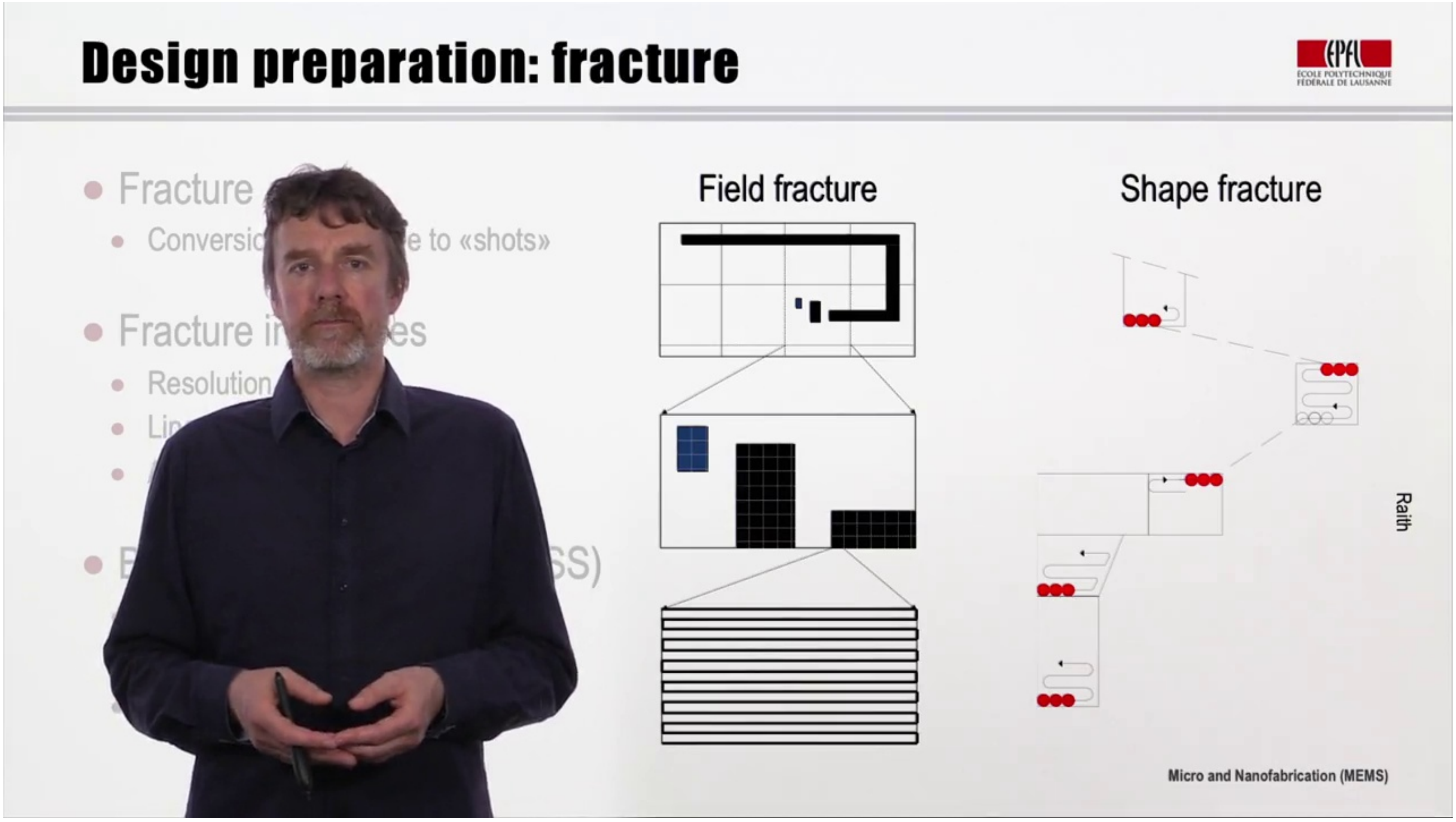
In this second lesson on Electron Beam Lithography We will now focus on the different processing issues for EBL, that are the design optimization and the writing parameters.



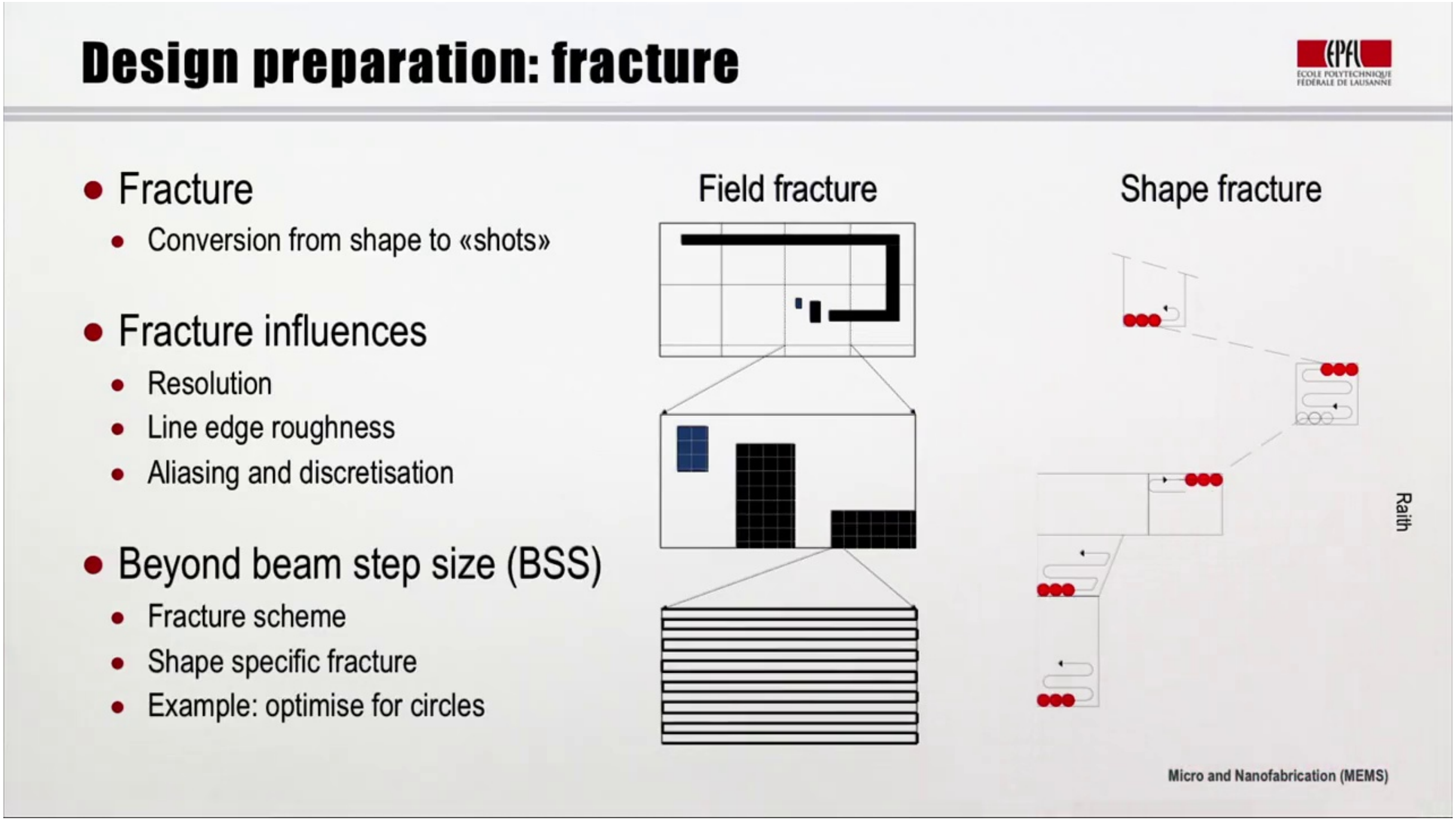
Remember that in the previous lesson we have seen the main elements that are required to form a focused electron beam, and how these different elements operate and interact to guarantee efficient scanning of the electron beam on the sample. In the second chapter on EBL, we will now focus on the actual process of writing with the EBL tool and that a user typically follows in the clean room. Starting with the design preparation we will study electron-matter interaction, followed by practical examples of positive and negative resist exposure. We will continue by seeing how proximity effect and alignment procedures are performed in EBL. I will conclude the chapter by showing a few examples that are typical and unique for Electron Beam Lithography.



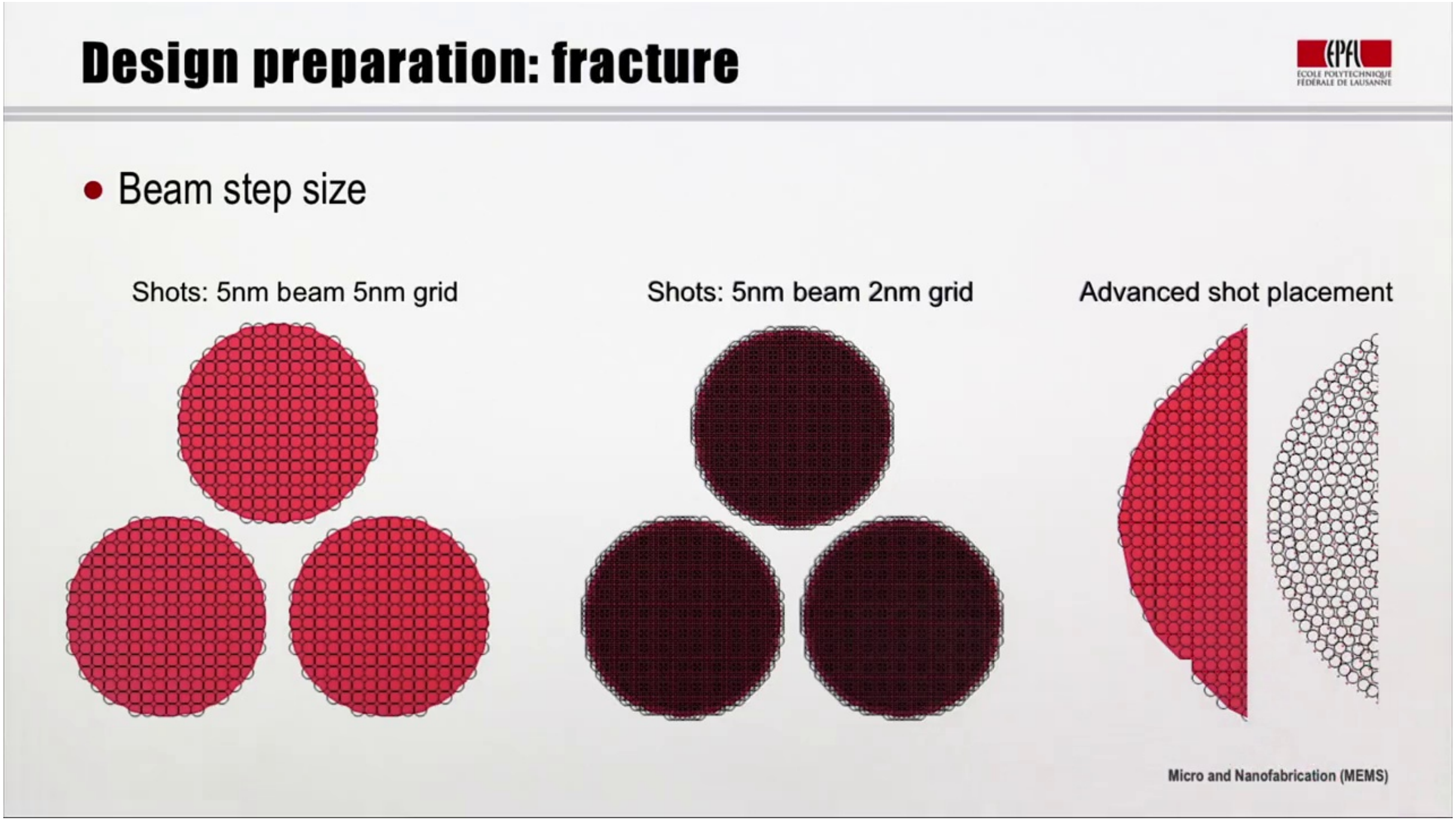
The electron beam is typically of corrosion profile, and is scanned across fields and sub-fields to expose the resist with the desired patterns. Here, we will take a closer look at what truly happens within one of the sub-fields. The CAT design files are typically in .cif or .gts format. The patterns in these files are either fully vectorial or built from n-gons, with a finite number of edges. They must be discretized in a number of basic trapezoids that are filled by shots that will be exposed. This process is referred to as Fracturing. Besides the fracturing of design into shapes and shots, additional steps may be included at this preparation stage for the EBL writing, in order to specify local design modifications or those assignments. These details will be presented towards the end of this lesson. The essential principle related to fracturing is the assignment of a physical beam step size BSS, to split the design in individual shapes and exposer shots. Essentially, one must choose a grid size where the e-beam tool will lay down individual shots. The choice of BSS is related to two important considerations: one, the resolution target, and two, the beam diameter. As for the first criteria concerning the design and resolution target the BSS must be a multiple integer of the minimal features for appropriate discretization.



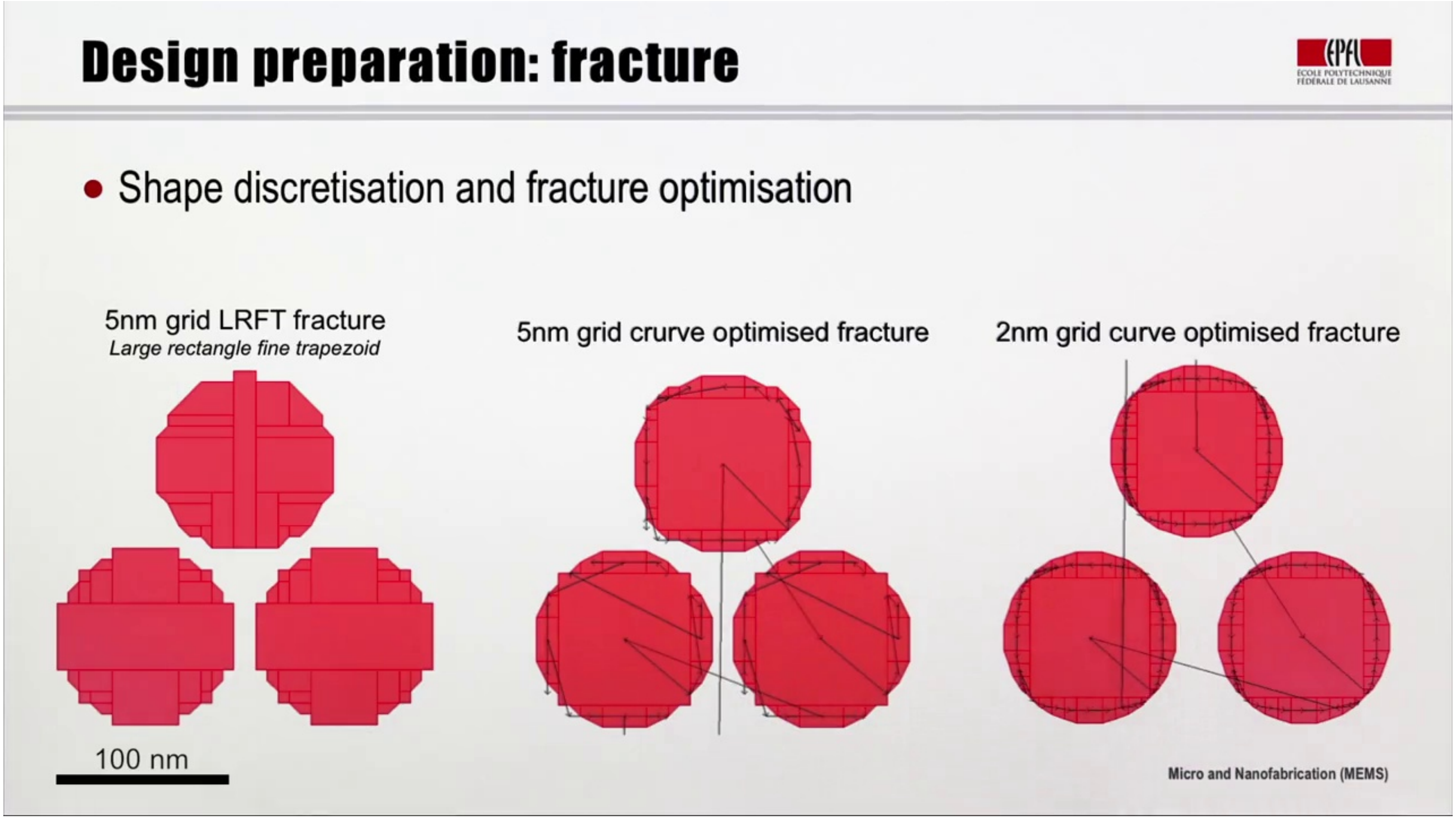
The choice of BSS is basically a down-sampling of the vectorial design. For features that do not lie strictly on the fracture grid this down-sampling may induce aliasing and artifacts requiring a grid size significantly smaller than for simple horizontal vertical lines. The second criteria is the beam diameter. In order to expose patterns with the homogeneous dose the BSS should be equal, or ideally smaller than the beam diameter. If this is not the case, wavy line edges or disconnected dots will be written instead of smooth filled patterns.



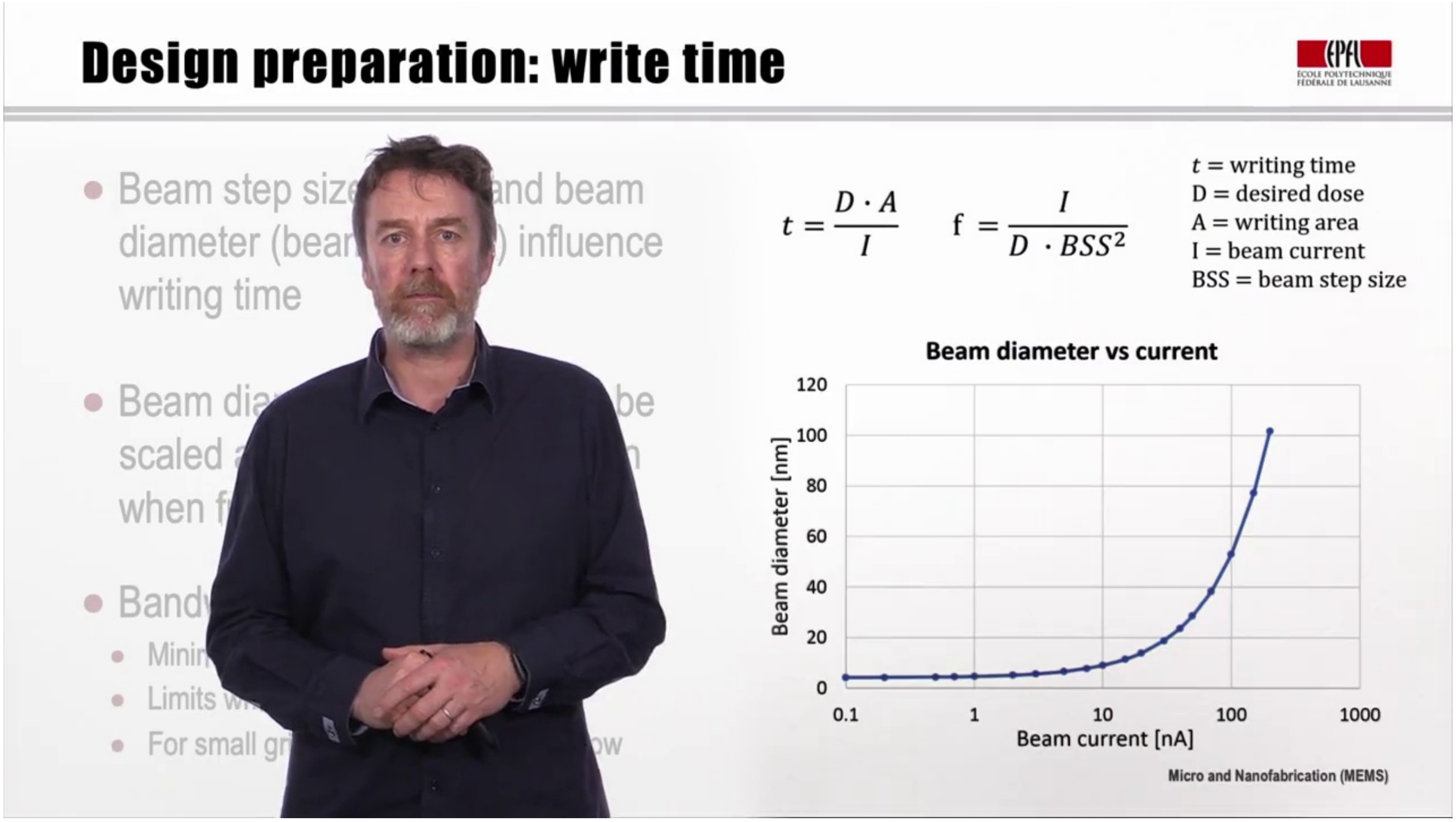
The left figures here show the black structure that is to be written with the electron beam. Each of the squares represents the sub-fields in which the beam can be scanned quickly. In the sub-fields, there are shapes which are themselves cut into trapezoids, which are shown here, which are here simply squares but can be any trapeze-shapes. Each trapezoid is written line by line, shown here, by the scanning e-beam. The same concept is shown on the right for a more complex shape here the beam jumps from one trapezoid, which is here, to the next one and then raster scans in each of them and jumps to the next one to write the next pattern.



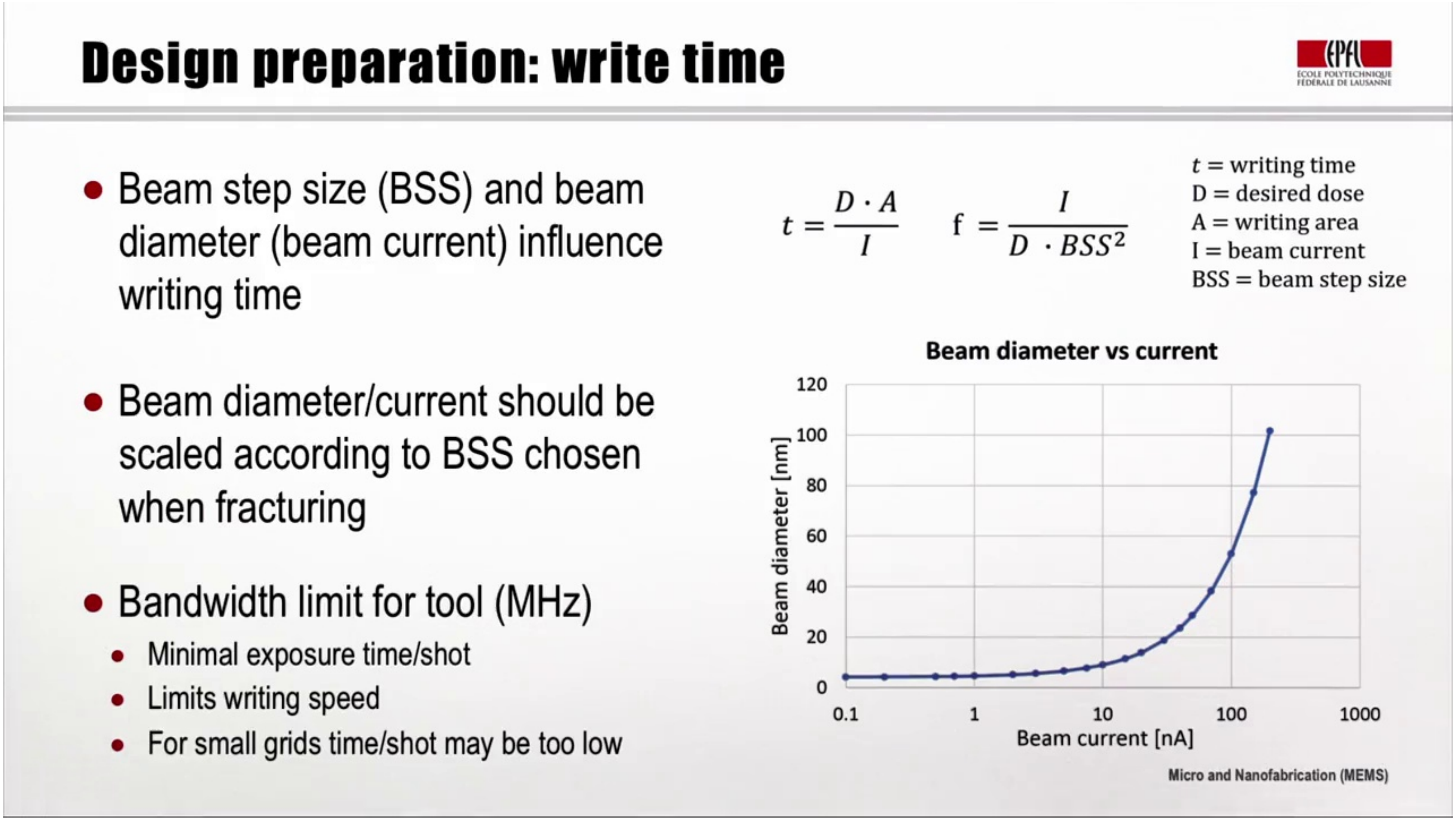
Let's start by only considering the effect of BSS alone without taking into account the trapezoid fracture. The goal here on this slide is to expose three round disks with the electron beam. We choose a beam diameter 5nm, but vary the grid size from 5nm here on the left to 2nm here on the center. We can see step-like artifacts on the edge of the disk at 5nm grid, but less on the 2nm grid, which is obvious. We see that by reducing the grid of 2nm minimizes this effect even though the beam diameter is still the same. An advanced method, shown here on the right, allows for the positioning of the shots beyond an orthogonal grid. This method offers good shape approximation associated with the limited number of shots, but it implies specific design preparations.



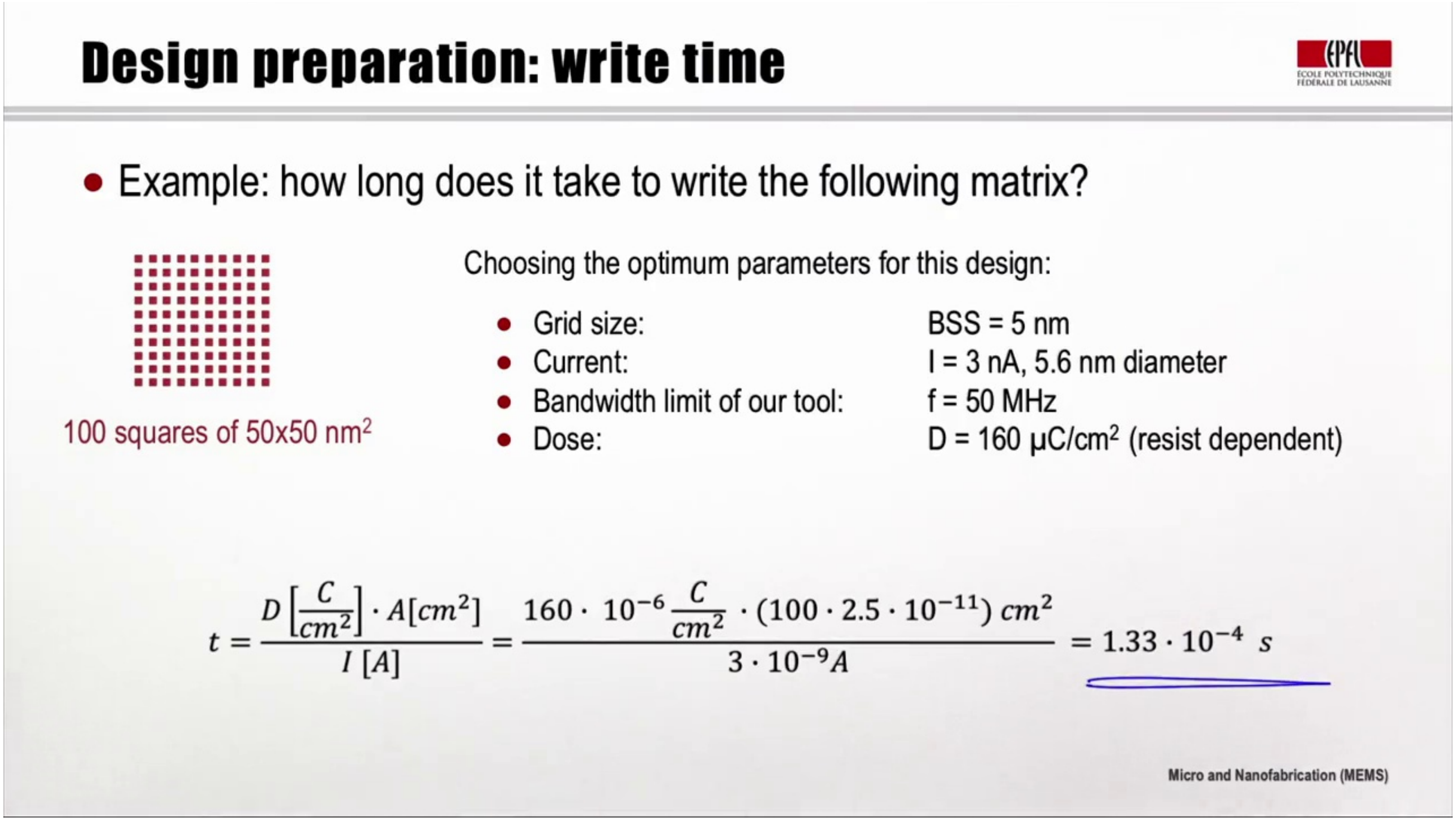
In practice, depending on the position of the features on the orthogonal BSS grid, large deformation may be unintentionally induced by the fracturing of the design into the trapezoids that the tool can write. This may effect the structure symmetry, pitch or overall dimensions and may be critical for the final device. Here on the left, we see a result of a large rectangle fine trapezoid LRFT fracture on a 5nm BSS. In the center, the design was fractured to optimize the structure symmetry in curve-edge approximation. The trapezoids are now symmetric on both axes on the disk. Following the same example as before reducing the BSS further to 2nm improves the disk approximation. Still considering a 5nm beam, this 2nm grid size also benefits from a a smoother line edge due to the beam overlap. The black lines shown here, and here, indicate the writing order of the electron beam across the trapezoids.



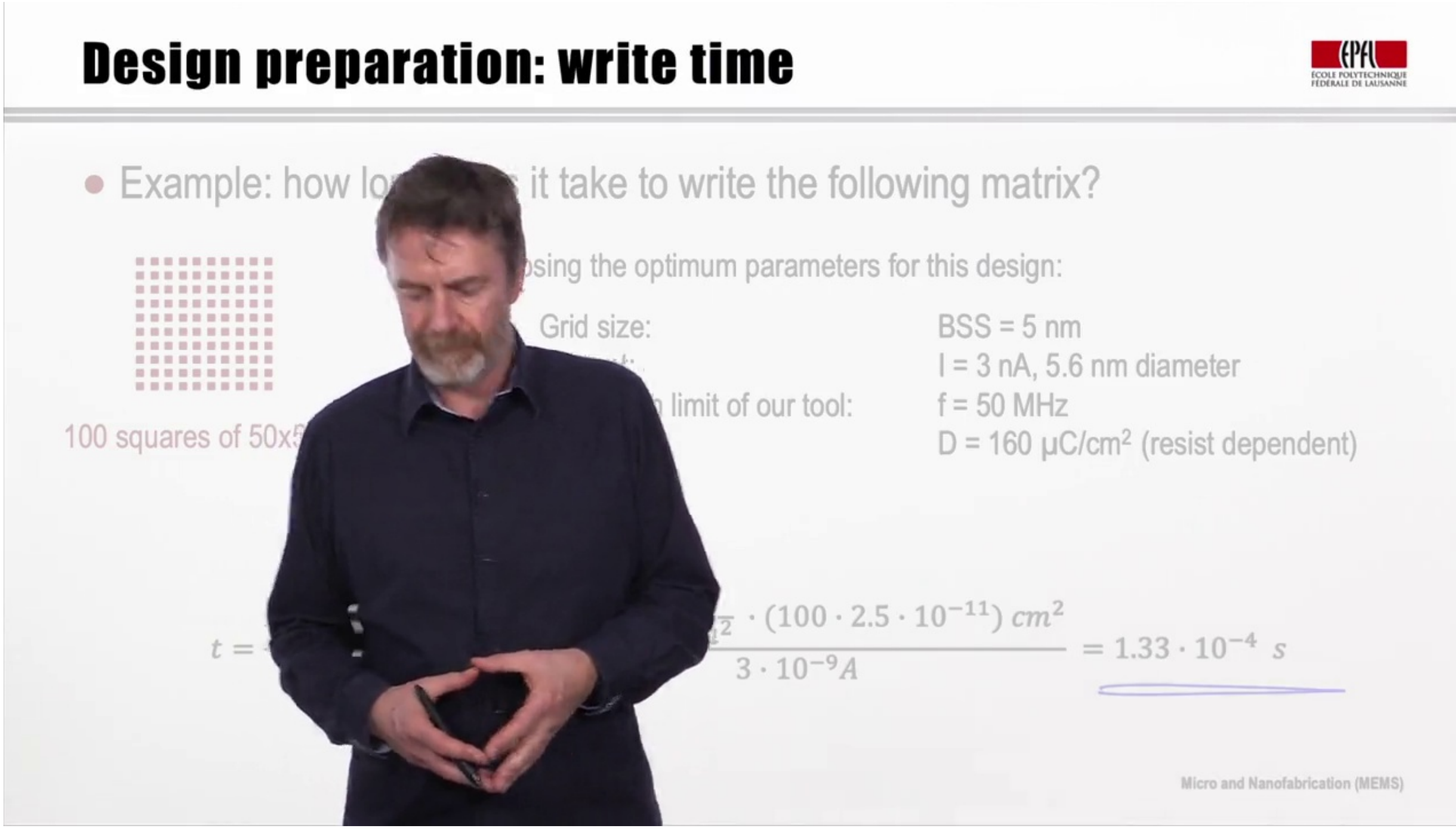
Let's now have a look how the fracture method influences the EBL write time. A total writing area is a major component in the design write time but is not affected by fracture. On the other hand, the direct link between beam step size, beam diameter, and therefore the current, has a large influence on write time. Typically, beam current may be varied over three orders of magnitude, from 100 pA, to over 100 nA. Thereby, effectively decreasing write time by the same order. With the beam step size equal to the beam diameter moving from a 5nm to a 50 nm step size will decrease write time by a factor of 100, as we can see from the diameter versus current relation shown here in this graph. When choosing a beam step size for fracture, one usually scales the choice of beam and associated diameter accordingly. In practice, large beam step size and associated beam, therefore allow for faster writing.



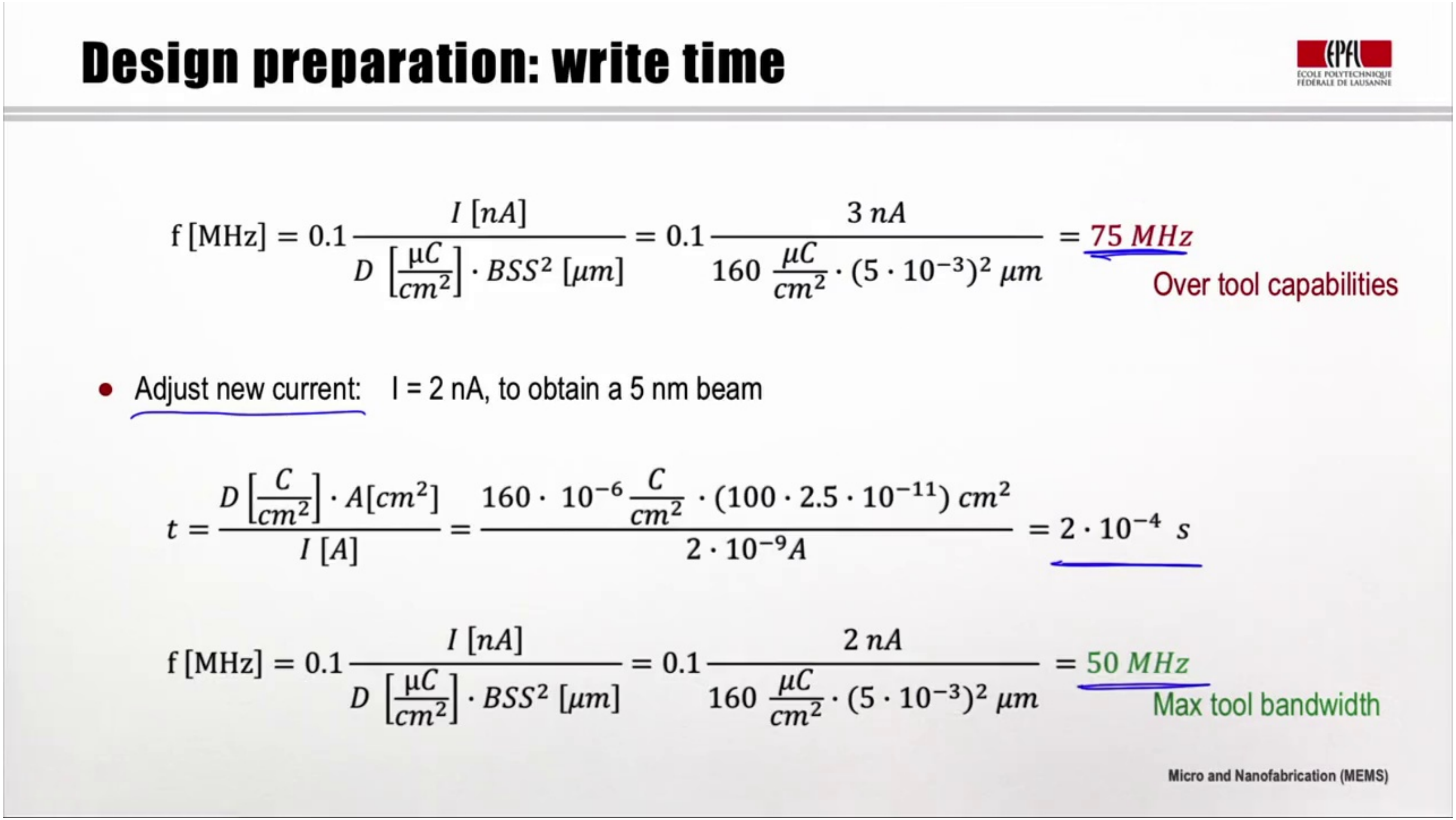
Another important consideration for the choice of beam current and beam step size is the EBL tool speed, also called bandwidth limit. It determinates the minimal exposure time per shot that the equipment is capable of controlling. This value is in the range of several tens of MHz. For grid sizes where large shot overlap is desired and where the beam step size is smaller than the beam diameter, the dwell time per shot is too short for the tool capability.



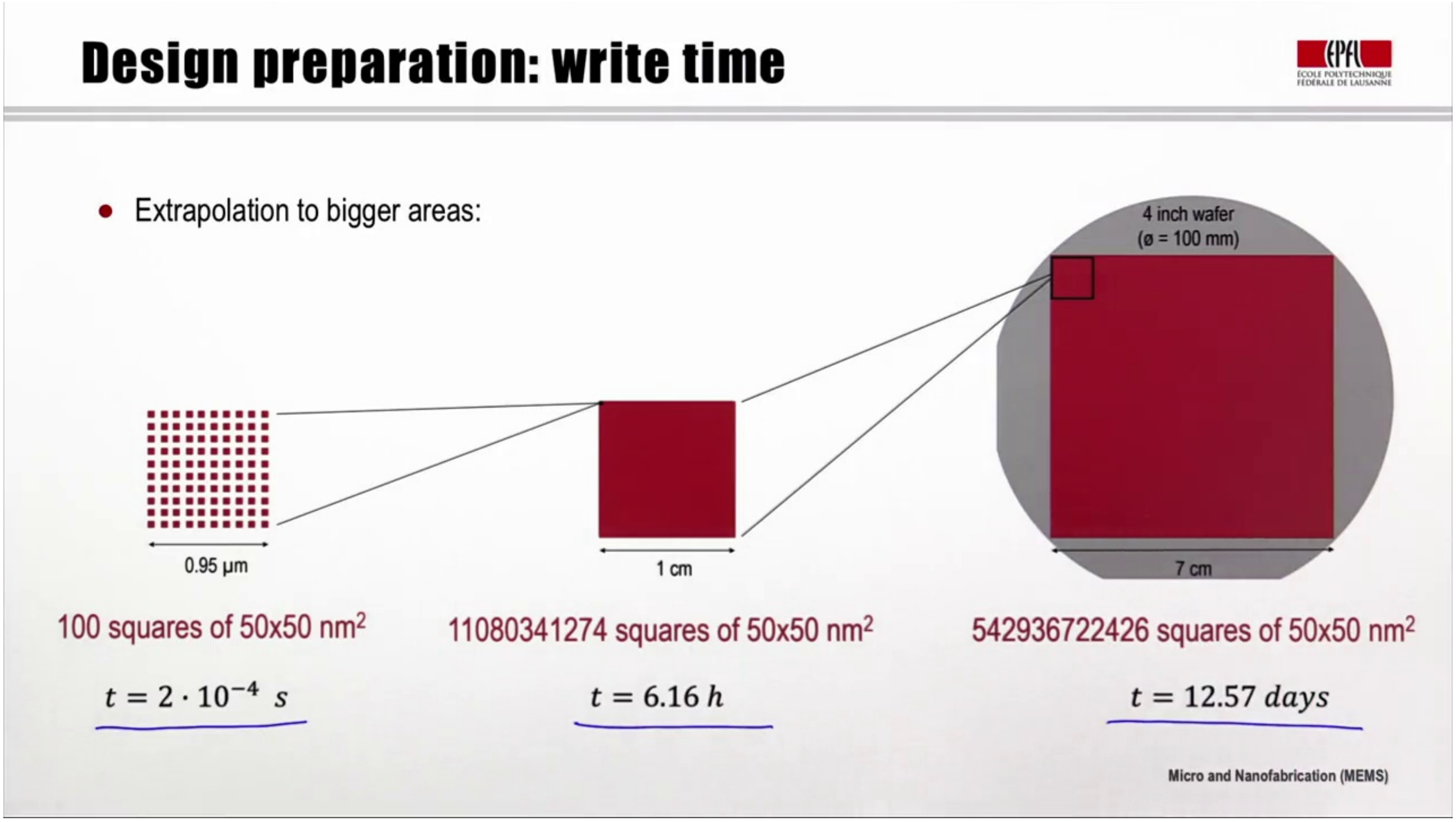
Imagine that we want to write the pattern shown here, consisting of one hundred squares of 50x50nm each. We start by choosing the parameters for the experiment. A grid size of 5nm is a good first approach to this design as the minimum feature size is 50nm. Smaller grids would be possible, but would require reducing current and consequently would take longer writing time. The next step is to choose the current and beam diameter. As each fraction of the grid is 5nm the beam diameter should be similar in size to have smooth contours in our shapes. From our tool specification. a 5.6nm beam is generated by choosing a 3nA current. We know that our particular tool has a bandwidth limit of 50MHz. This depends of the equipment, and we are now trying to determine the parameters as close as possible to this limit to be able to write as fast as machine can do. This is not only because of the time, but also because of the processing cost. The dose speed depends of the resist we are using. For this, typically some dose tests are done to confirm the proper value. With these parameters we now calculate the time, according to this formula. Here it takes 1.33x(10^(-4))s for the electron beam writing alone.



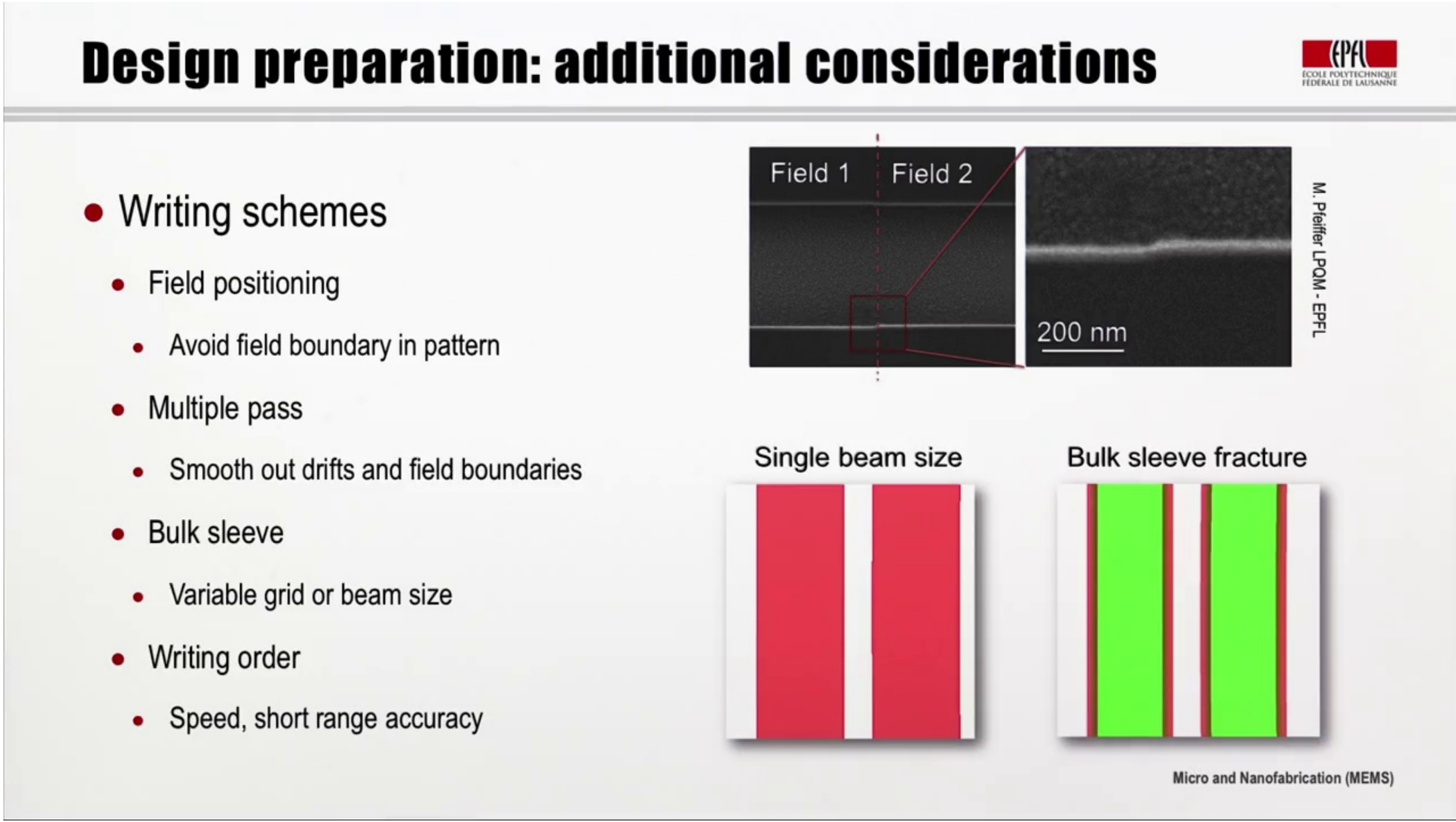
To this time we must add about 30 minutes of pumping, loading, and unloading of the wafer, and the time commuting from one square to the other without the writing. Also, this may seem extremely fast, when scaled to the area of practical designs and full wafer sizes writing may easily reach hours.



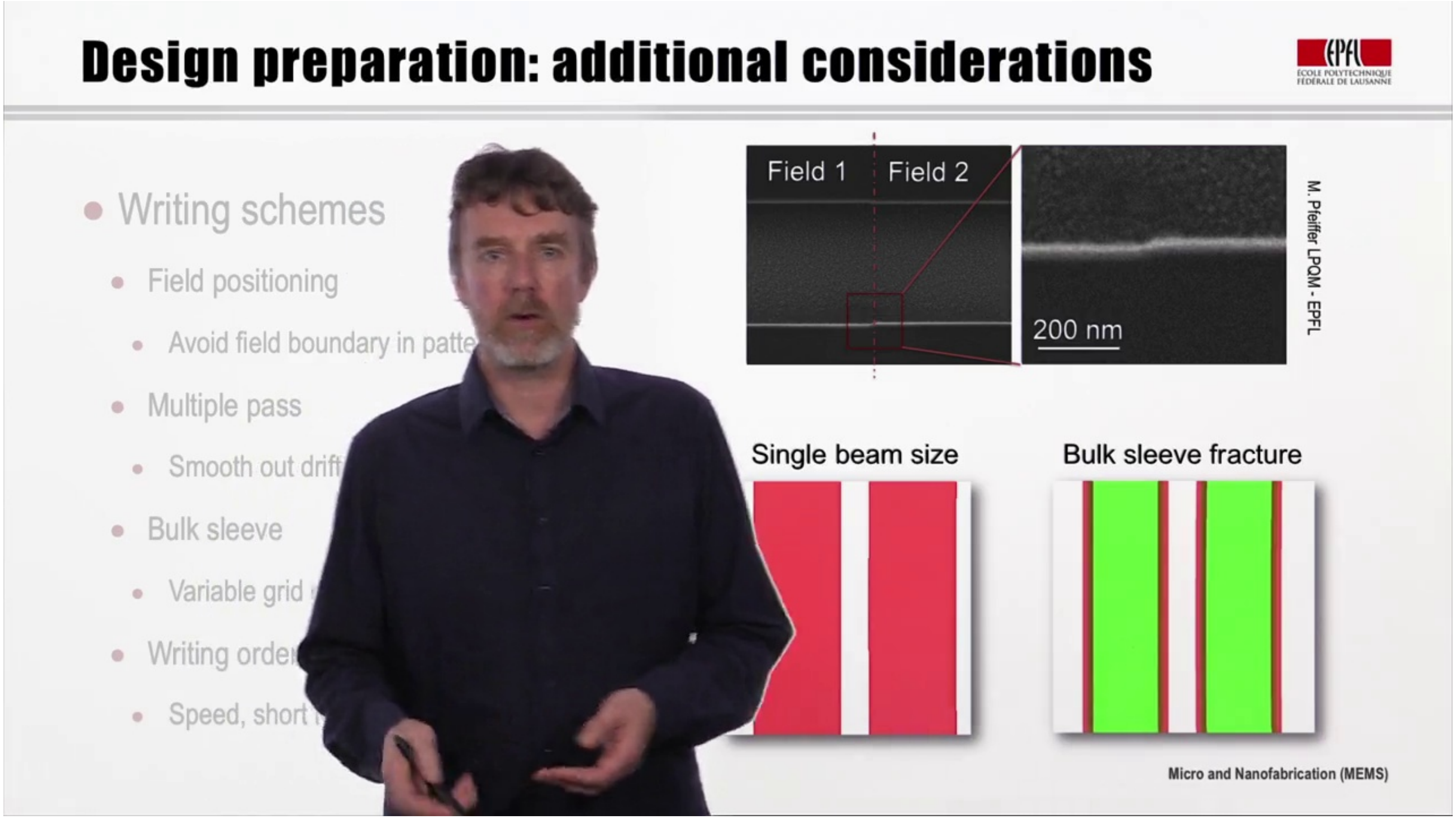
If we now calculate the frequency with the previous parameters we see that this writing experiment is over the tool capability, as it is over 50MHz that we have defined before. The tool cannot write as fast as we are asking to and it cannot control and blank the e-beam fast enough and we have to adjust the writing parameters. The best alternative we have is to adjust the beam current, and choose a smaller beam. As you see, it now takes more time than before, but now the frequency is at the maximum speed of the tool. Thus we can write with these parameters our pattern.



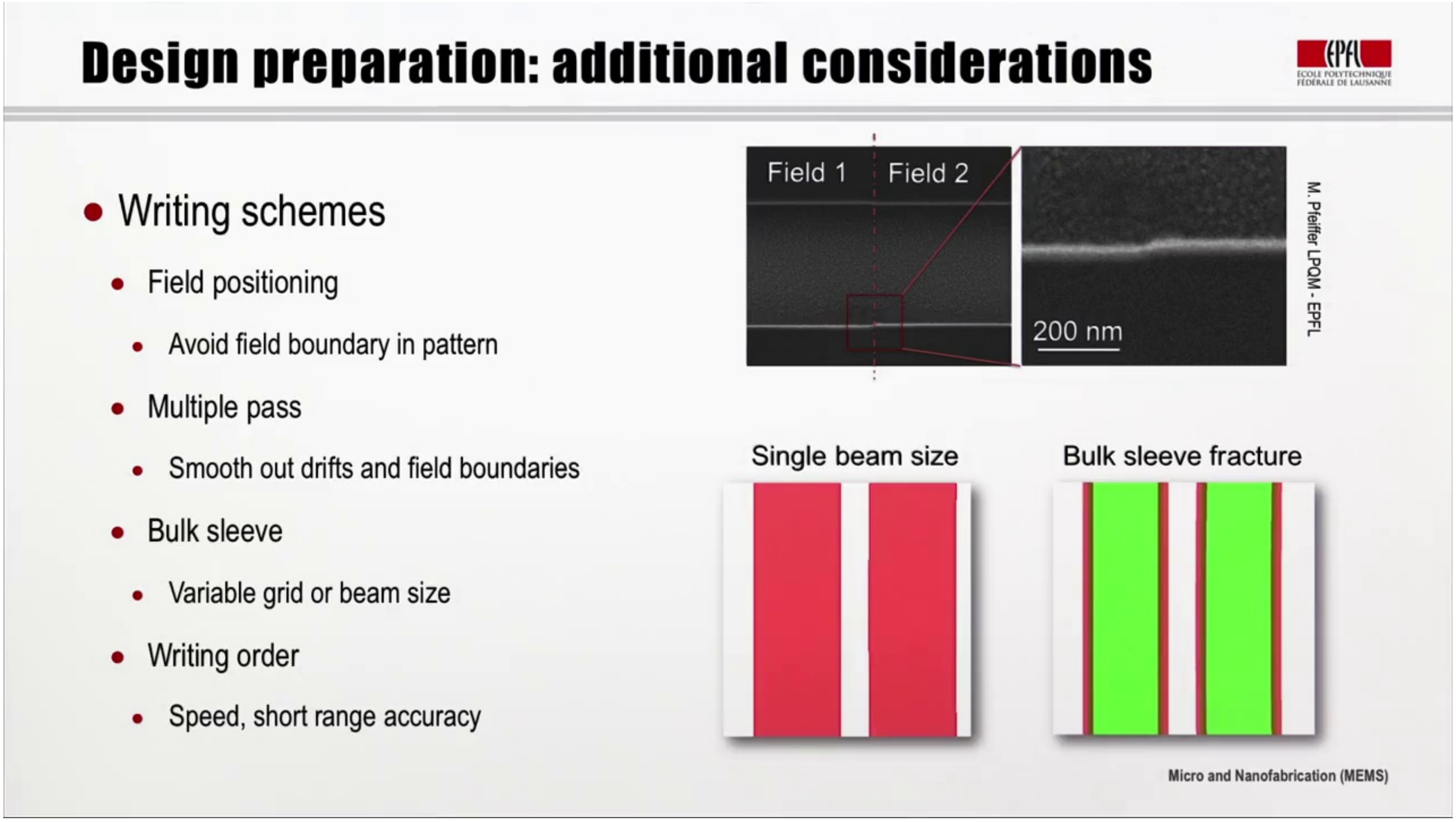
If you now extrapolate these writing patterns to bigger areas which are more meaningful for applications, we can see again our small square, hundred squares of 50x50nm square each, takes about 2x(10^(-4))s, so extremely fast. If you want to write the same density pattern over one centimeter square, of the same density and pitch, we already have to account for more than six hours e-beam writing time, and if you want to write a full wafer of 100mm diameter, with the same pattern density we already have to take into account a writing time of more than twelve days.



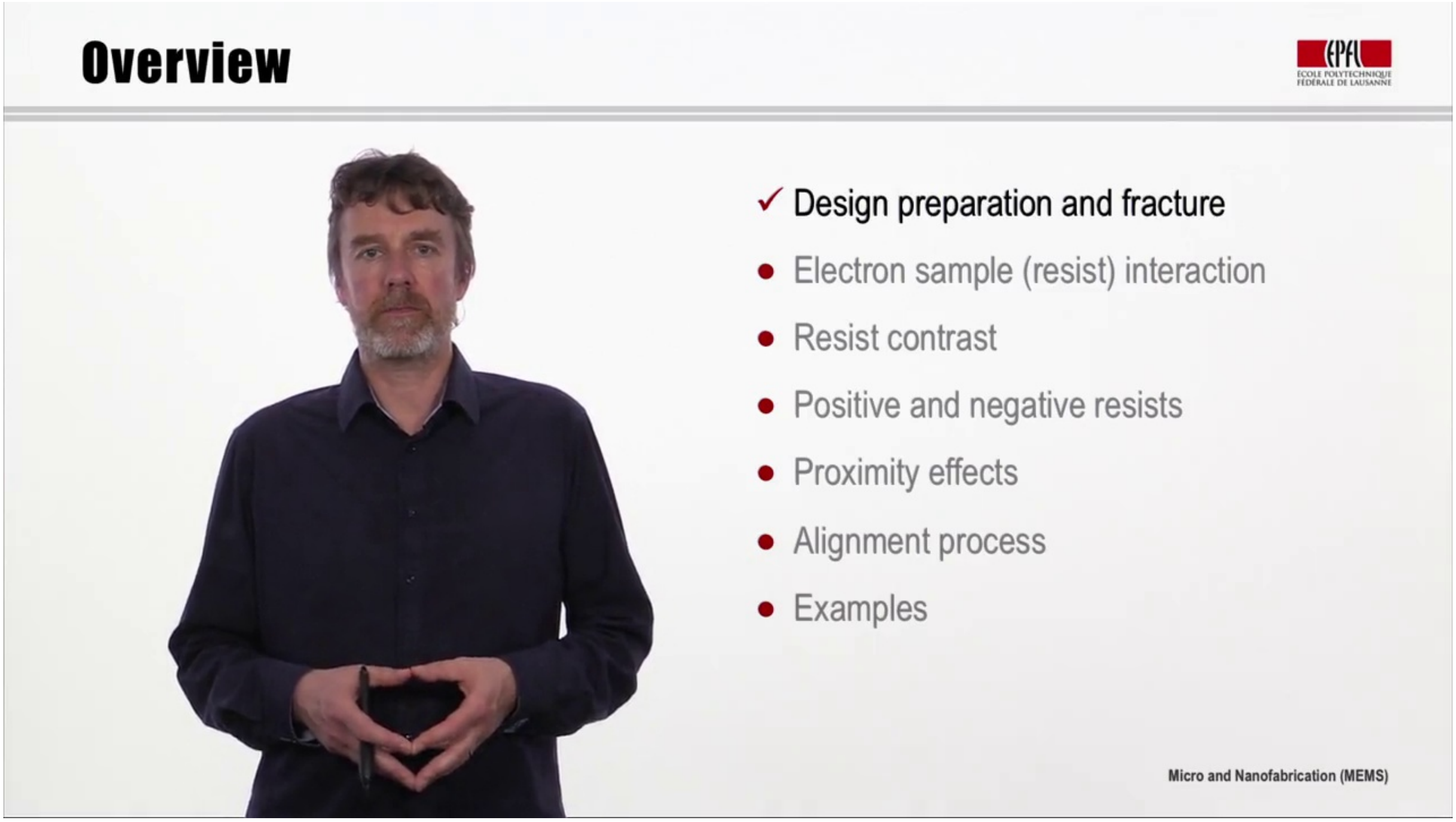
When preparing the design for writing and before considering local dose or design changes, a few other options are important to consider. The first one concerns field placement, although one might intuitively position the fields adjacent to each other on an orthogonal grid, this might result in field boundaries within the pattern that will induce field stitching errors as seen in these images. So, here two fields are stitched together, but they are not perfectly aligned, which is due to the error in the tool drifts and other effects. If the features are smaller than the field size one may allow, so called, floating fields in order to encompass all the features smaller than the field size within single fields. If the designs are larger than the fields writing the structure in multiple passes may reduce the sharpness of the field boundary, due to the random nature of field stitching.



As we mentioned, large patterns, when considering advance design preparation, it is important to mention that patterns may be fractured using varying BSS. This may for one, allow the writing of large and small features with different beams to speed up the writing. Alternatively, a large beam may be used for the inner part of the pattern that will be written fast, and a finer beam for the outer part in order to guarantee low edge roughness and overall critical dimensions accuracy.



This method is called "Bulk Sleeve", shown here. To use different beam diameter for the center part and to the edge of the structure. Without going into further details, writing order of the trapezoid within fields and sub-fields may play a large role on short-range accuracy and periodicity and consequently will have an impact on the writing time.



So this concludes this introduction part for the design preparation and fracture of electron beam lithography, and now we have a closer look at how the electrons interact with the resist to write nano features on substrates.