

A decorative graphic on the left side of the slide, consisting of a vertical, teardrop-shaped area filled with a colorful, multi-colored grid pattern in shades of purple, blue, green, and yellow.

Self-aligned Double Patterning Layout Decomposition with Complementary E-Beam Lithography

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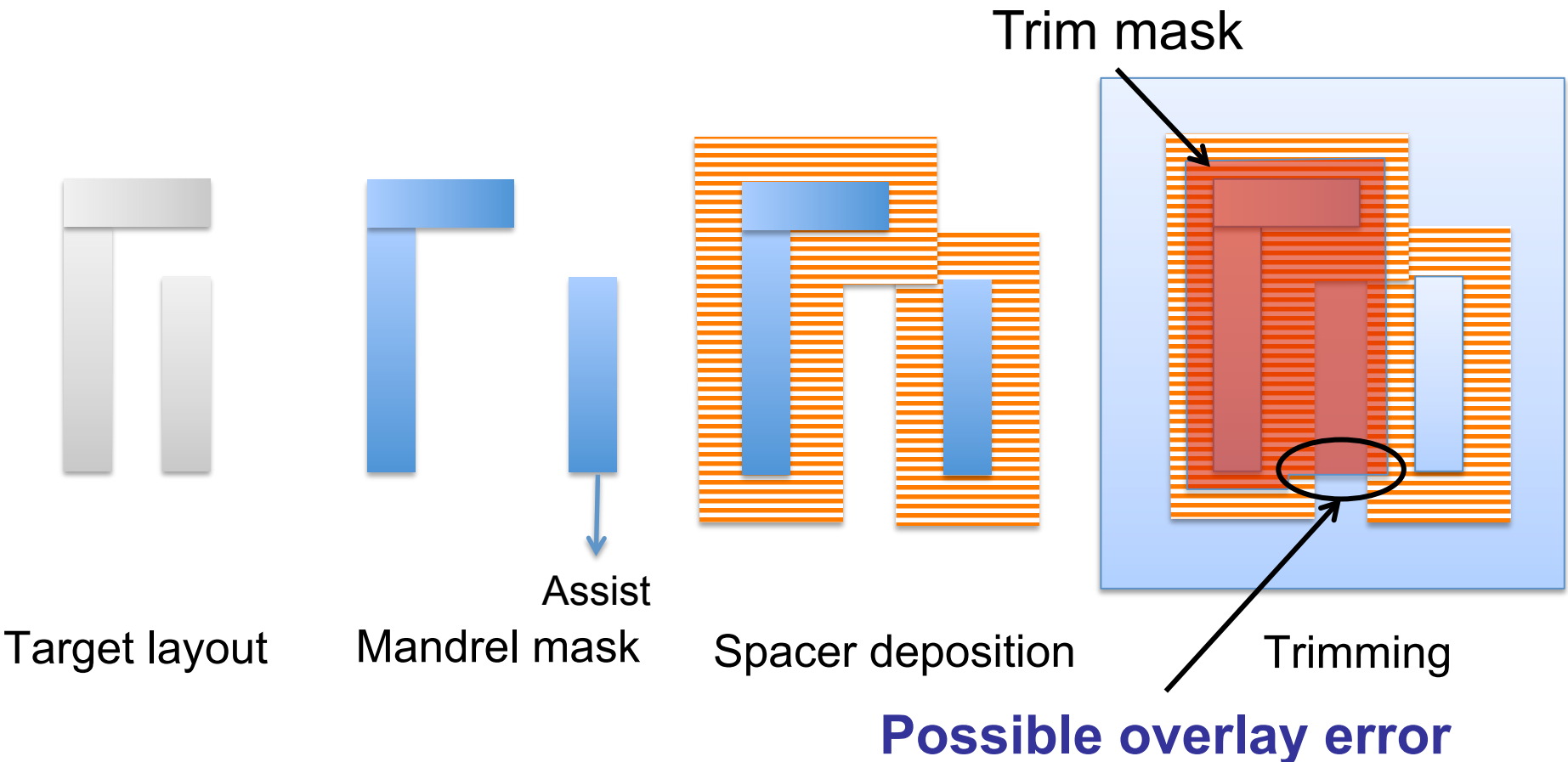
Outline



- ◆ Motivation & Problem Formulation
- ◆ Proposed Algorithms
 - › Post Processing Based Layout Decomposition
 - › Simultaneous SADP+EBL Optimization
- ◆ Experimental Results
- ◆ Conclusion

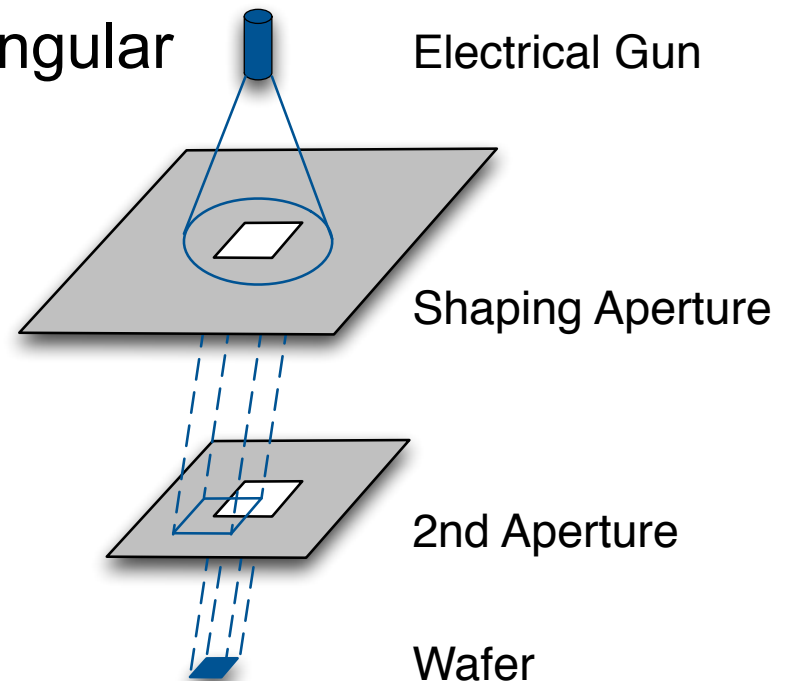
Self-Aligned Double Patterning (SADP)

- ◆ Promising double patterning technique for sub-22nm nodes
- ◆ Trim mask can be used to generate cuts
- ◆ Issue: Overlay problem caused on some trimming boundaries



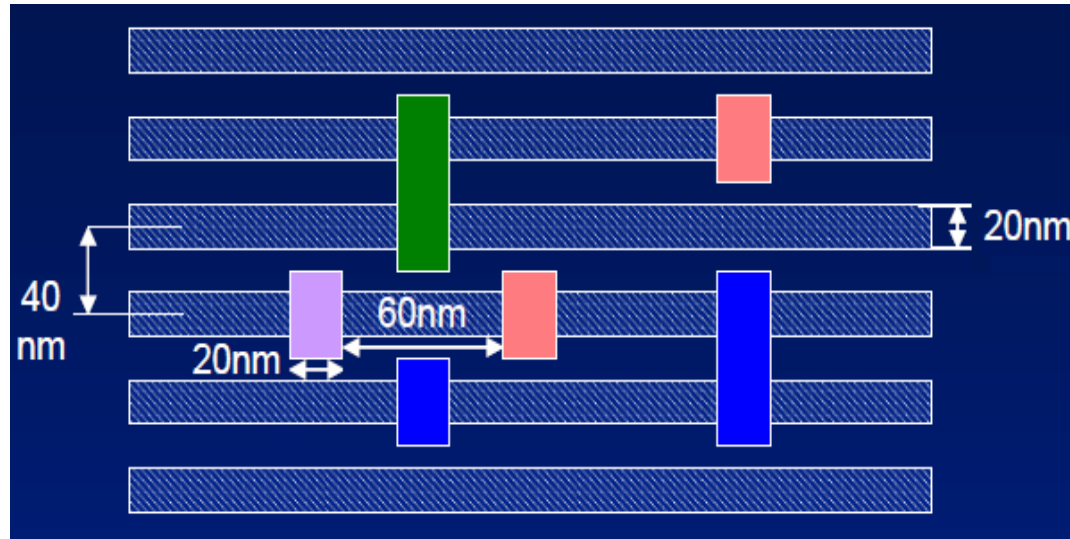
E-Beam Lithography (EBL)

- ◆ Maskless lithography
 - › High Resolution (sub-10nm)
- ◆ Issue: Low throughput
- ◆ Constraint: Variable-shaped (rectangular) beam system
 - › Each e-beam cut is a rectangular



SADP & E-beam Hybrid?

- ◆ SADP with multiple cut masks or e-beam cuts



11nm node

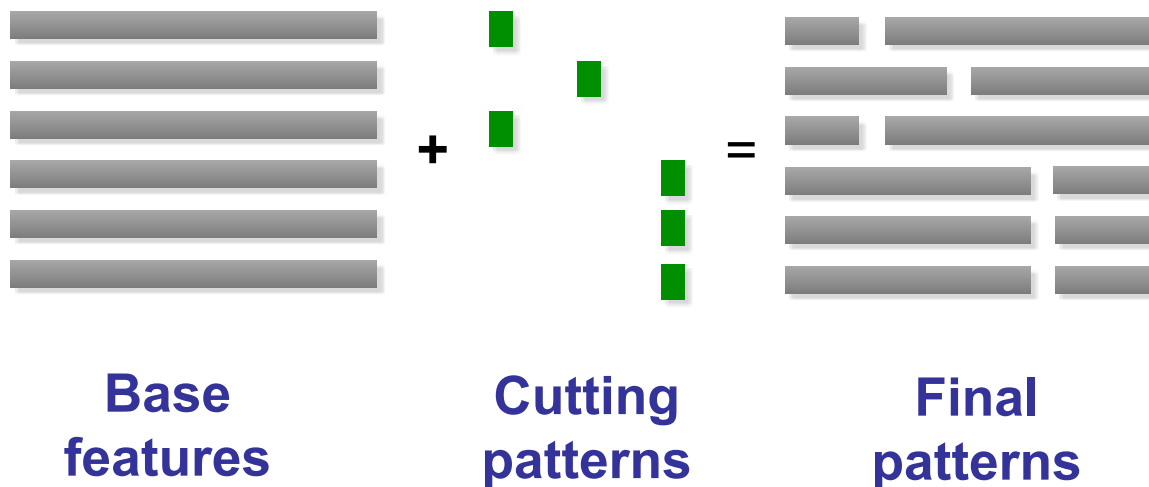
193nm immersion
1 base mask + 4 cut masks

Complementary Lithography
1 base mask + E-beam

[Y. Borodovsky, Maskless Lito and Multibeam Mask Workshop, 2010]

Complementary/Hybrid Lithography

- ◆ Different lithography techniques work together
 - › Base features: Optical lithography or SADP
 - » Low cost, low resolution
 - › Cutting technique: high-resolution MPL/EUVL/EBL/DSA
 - » High cost, high resolution
 - › Tradeoff b/t **Printing Quality** and **Manufacturing Cost**
- ◆ This work: SADP + EBL



Related Works

- ◆ Complementary lithography
 - › [Y. Borodovsky, Maskless Lithography and Multibeam Mask Writer Workshop, 2010]
- ◆ SADP with line cutting for **1D layout**
 - › [K. Oyama et al., SPIE 2010]
- ◆ SADP with EBL line cutting for **1D layout**
 - › [D. Lam et al., SPIE 2011], [Y. Du et al., ASPDAC 2012]
- ◆ SADP layout decompositions for 2D layouts
 - › [Ban+, DAC'11], [H. Zhang+, DAC'11], [Xiao+, TCAD 13]

Problem Formulation

- ◆ Given
 - › General 2D layouts
 - › Minimum pattern spacing on a single mask
- ◆ Objective: Perform layout decomposition with SADP+EBL
 - › No min-spacing conflict for mandrel/trim mask
 - › Minimize overlay error caused by trim mask
 - › Minimize e-beam shots

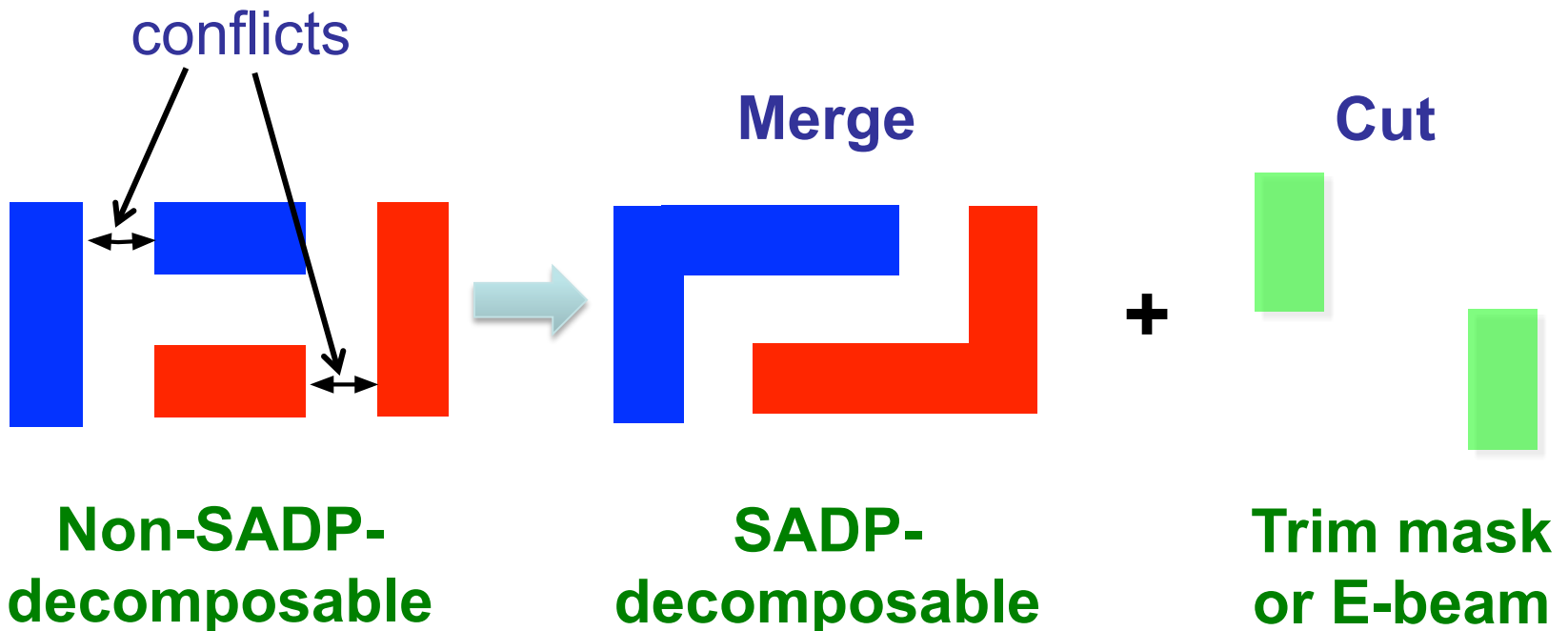
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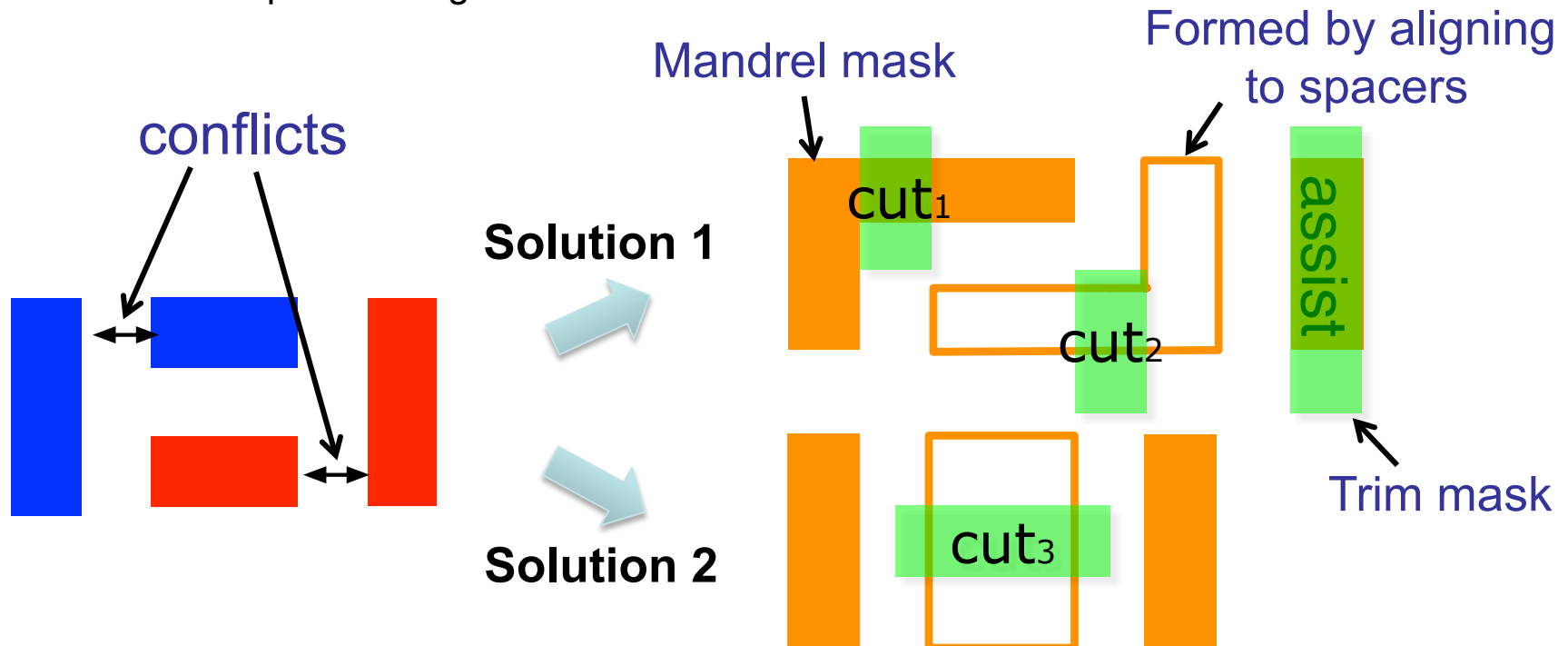
Dealing with SADP Conflicts

- ◆ Merge&Cut (M&C) technique
 - › Step1: Merge conflicting patterns
 - › Step2: Cut unwanted parts by trim mask or e-beams



Merge & Cut (M&C) Technique

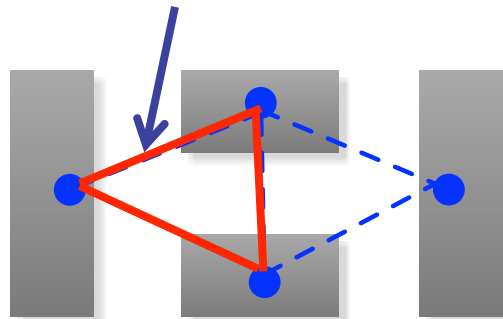
- ◆ May have multiple solution candidates
- ◆ Cut cost
 - › Cost of trim mask cut = α * Length of cutting boundary
 - » Penalty to minimize overlay error
 - › Cost of e-beam cut = β * Number of shots required
 - » Set β much larger than α to minimize e-beam shot counts



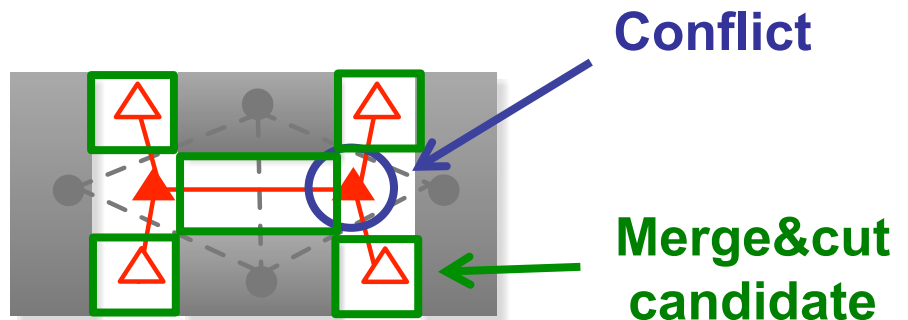
Finding M&C Solutions

- ◆ Objective: solve all conflicts with minimum cost
- ◆ Matching-based algorithm
 - › Step1: Conflict Graph construction
 - › Step2: Dual Face Graph construction
 - » Conflict node: an odd face on the conflict graph
 - » M&C node: a M&C candidate to solve a conflict
 - » Edge: b/t a conflict node and its M&C solution candidates

Odd cycle = Conflict



Conflict graph



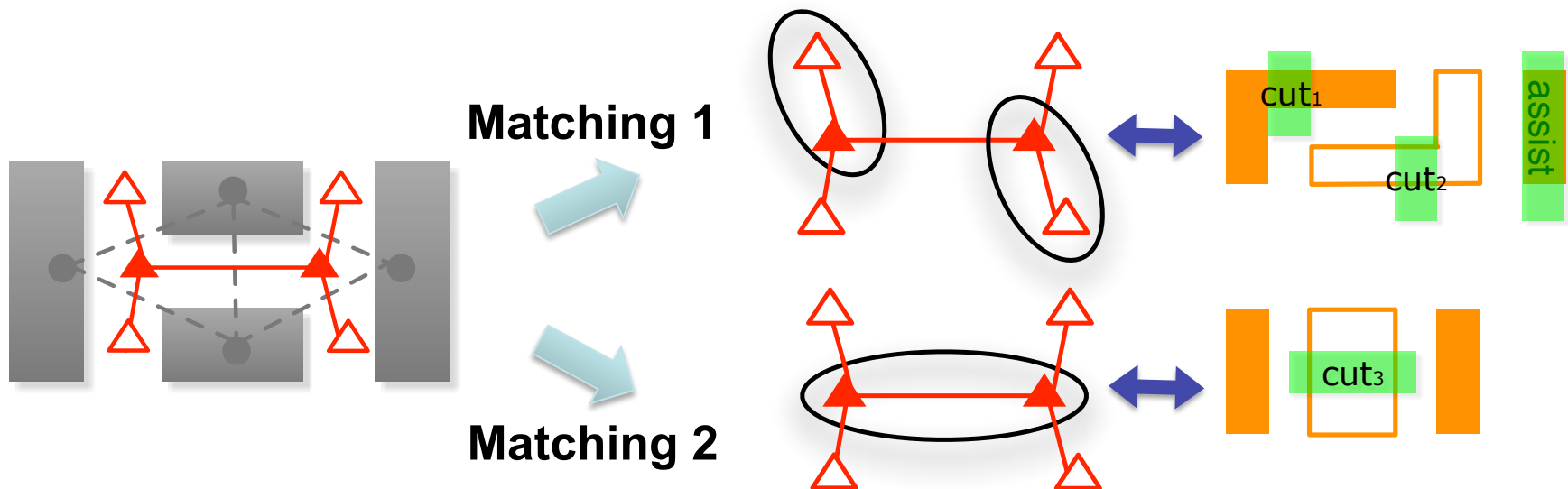
Face graph

Finding M&C Solutions (cont)

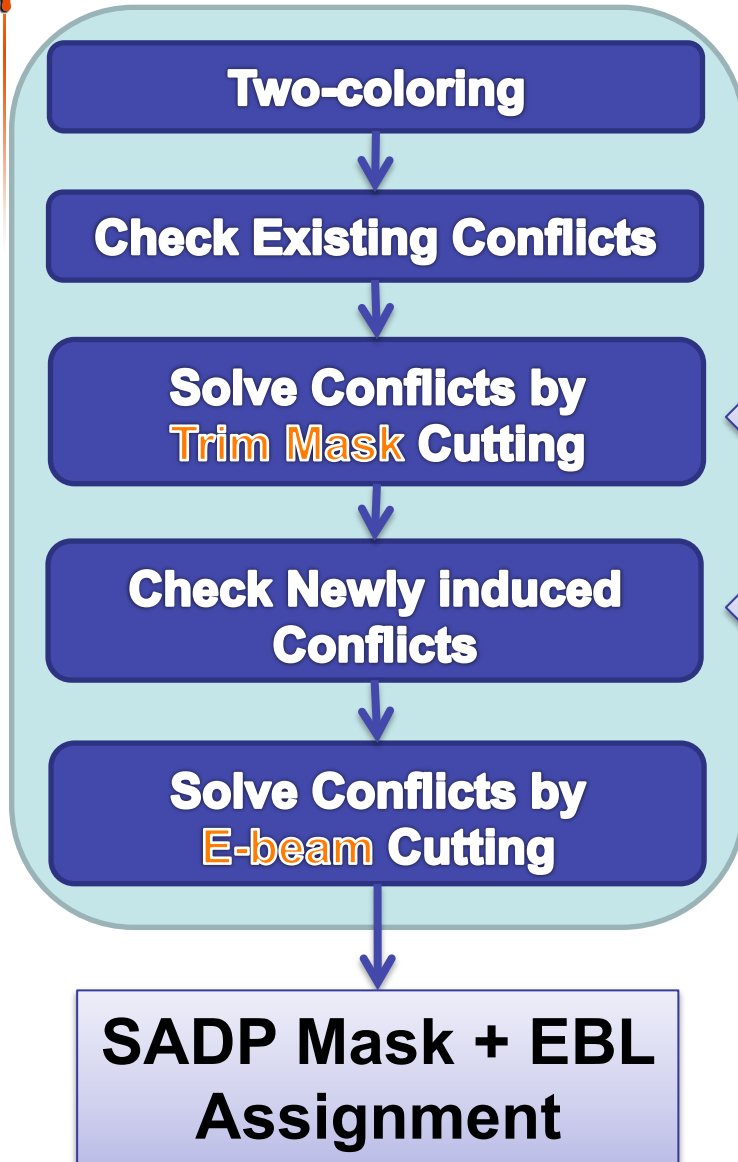
◆ Matching-based algorithm

- › Step 3: Apply min-cost matching algorithm on face graph
 - » Edge = conflict solved by a M&C candidate
 - » Each conflict node only needs to be covered once

➔ Matching solution = Selection of M&C candidates that can solve conflicts with the minimum cost

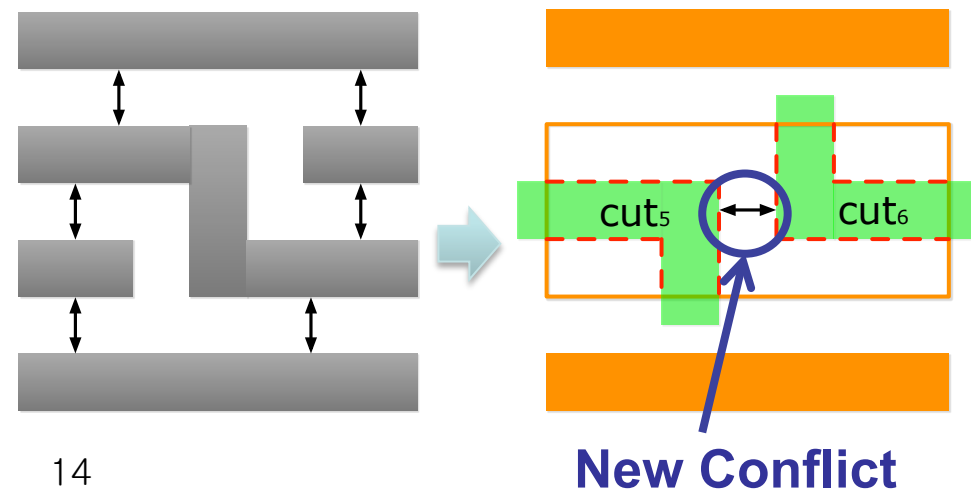


Method 1: Post Processing Based Layout Decomposition

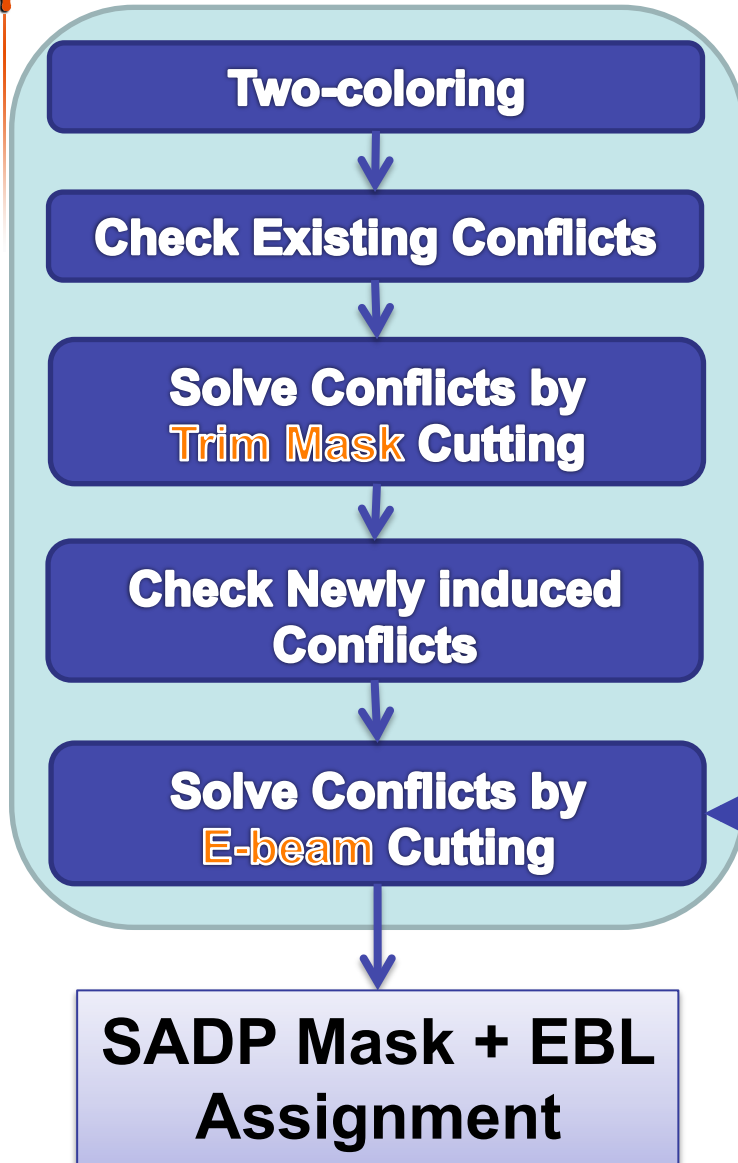


- Min-Cost Matching Algorithm
- Assign all M&C candidates with the cost of trim mask cuts

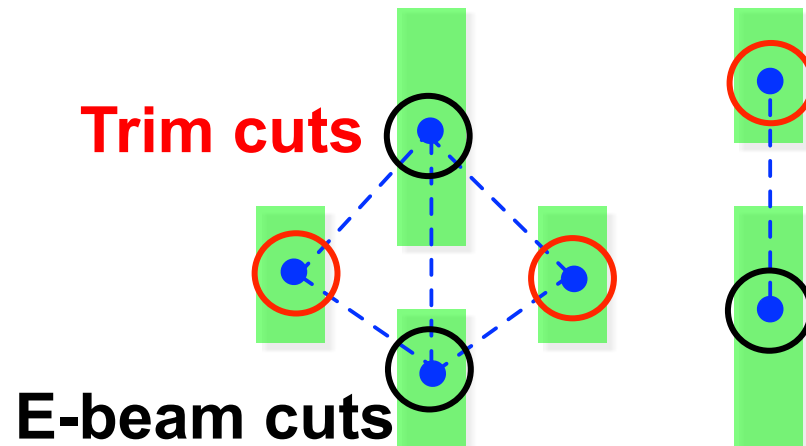
Cuts obtained may conflict each other



Method 1: Post Processing Based Layout Decomposition (cont)

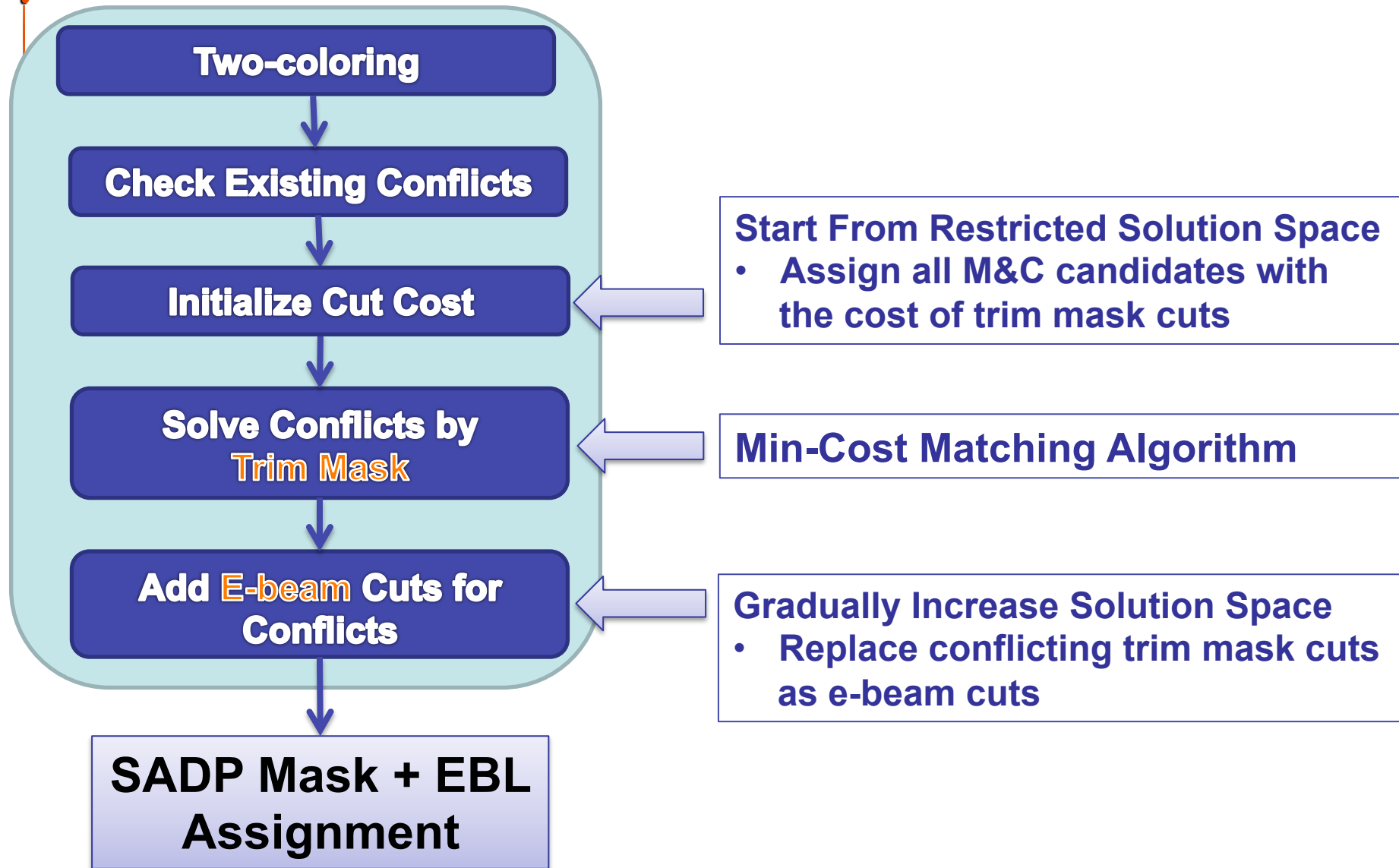


- Construct conflict graph for cuts
- Find trim cuts by Maximal Independent Set algorithm
- Assign the rest of cuts as e-beams

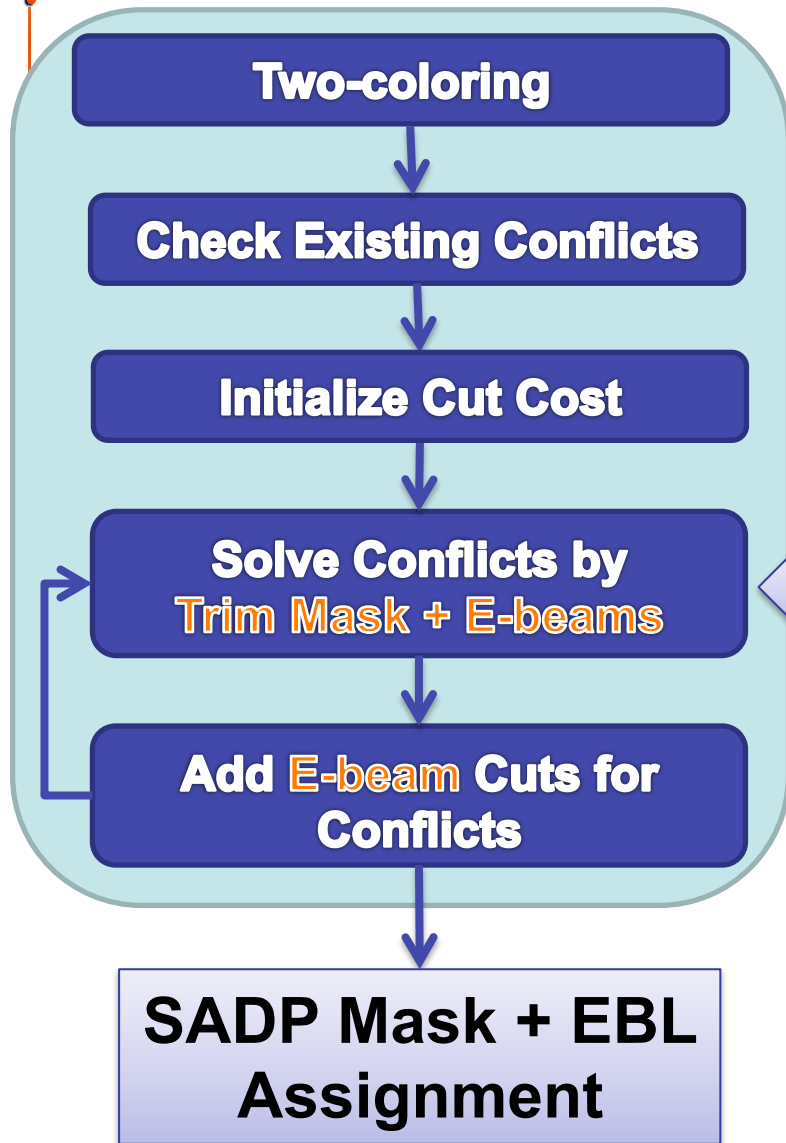


E-beam only considered at the last stage (Greedy)

Method 2: Simultaneous SADP+EBL Optimization



Method 2: Simultaneous SADP+EBL Optimization (cont)



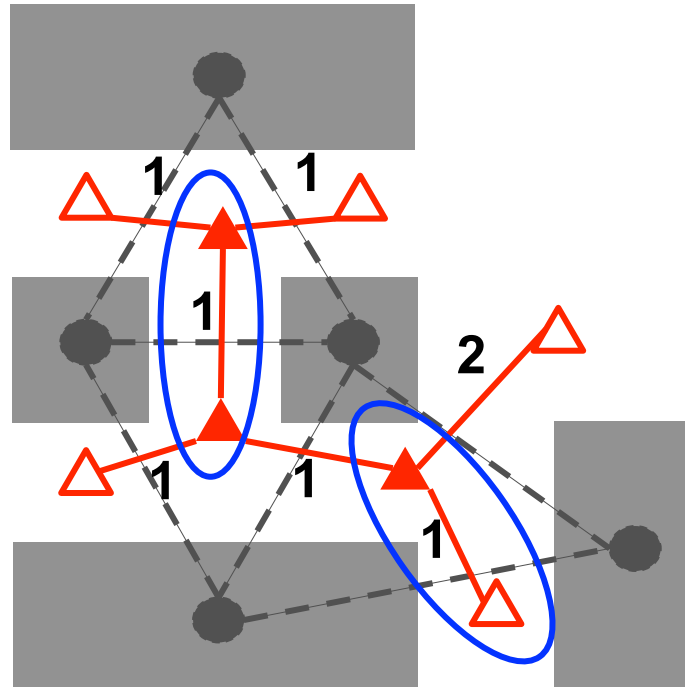
Min-Cost Matching Algorithm

- Similar to the previous iteration, but now we have two types of cuts
- E-beam Cut Cost \gg Trim Cut Cost

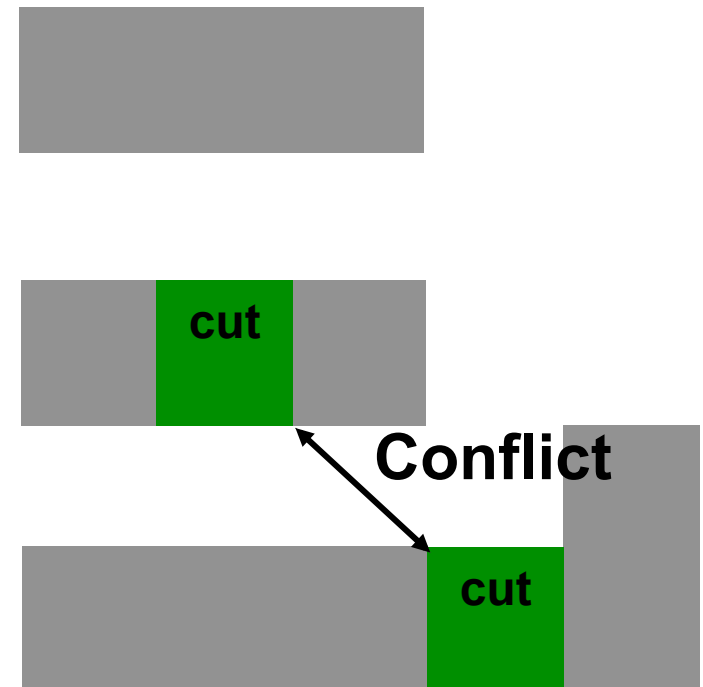
Simultaneously selecting trim mask cuts and e-beam cuts

Example of SADP+EBL Optimization

- ◆ Initialize cost of all cuts based on trim mask cutting length



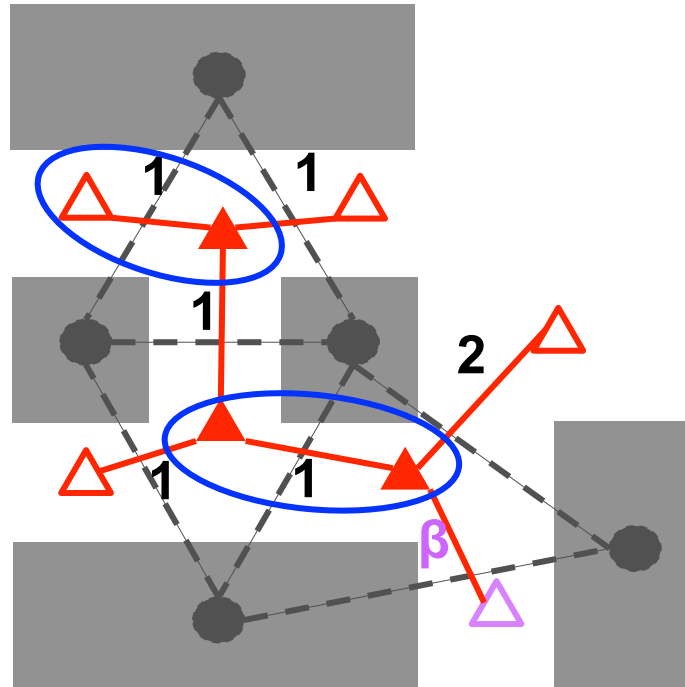
Iter. 1 Matching solution



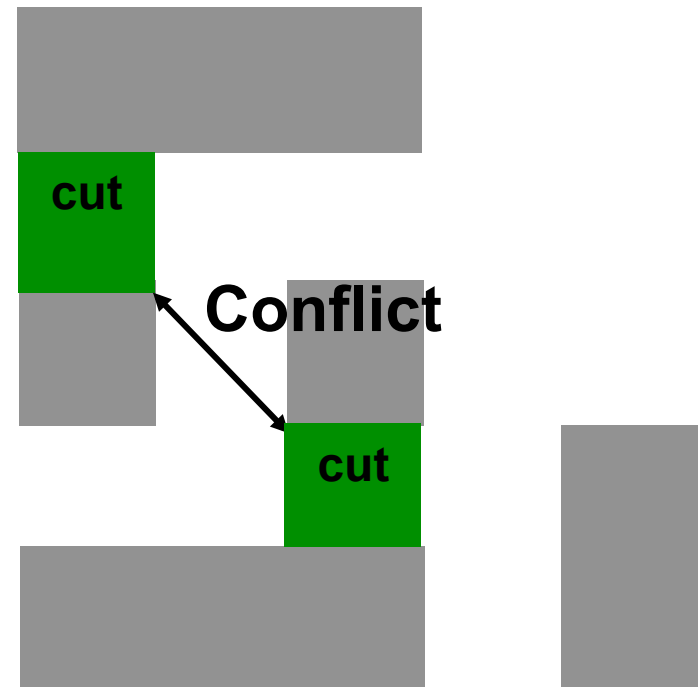
Check trim cuts

Example of SADP+EBL Optimization

- ◆ Update one conflicting cut as EBL cut (cost = β)



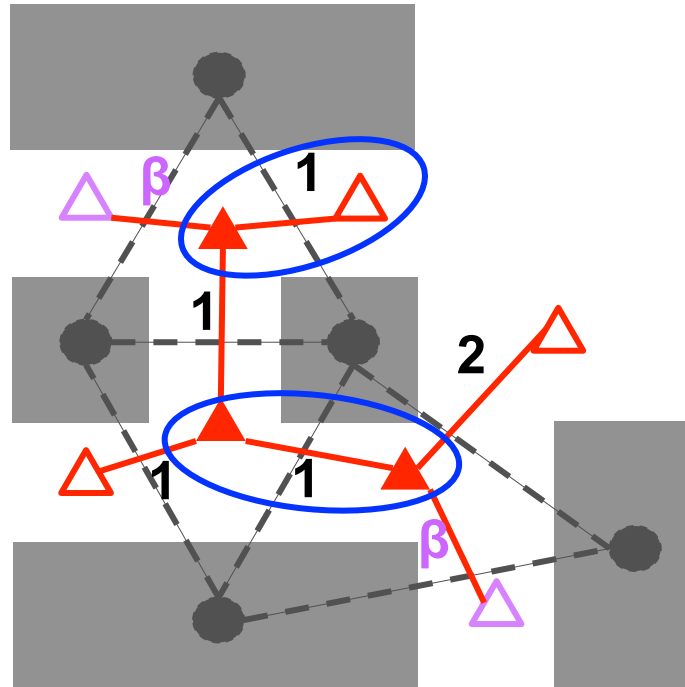
Iter. 2 Matching solution



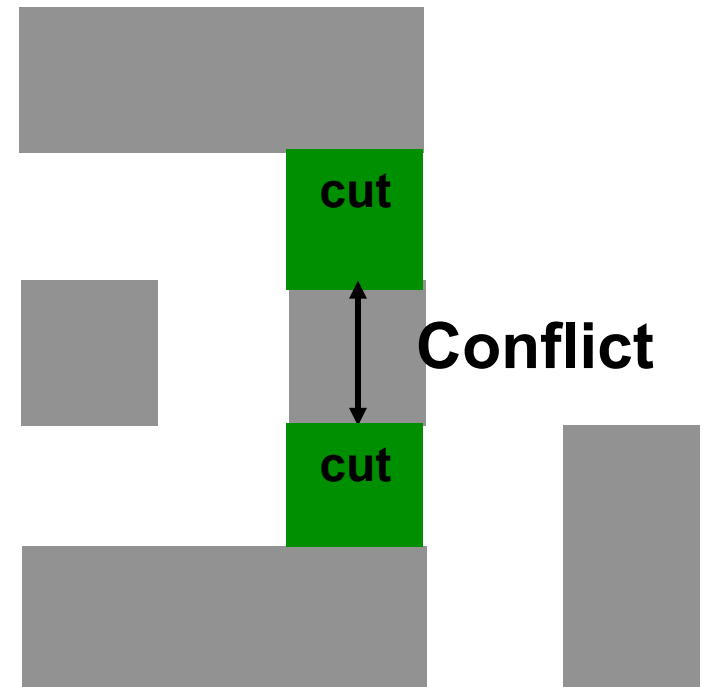
Check trim cuts

Example of SADP+EBL Optimization

◆ Update cost

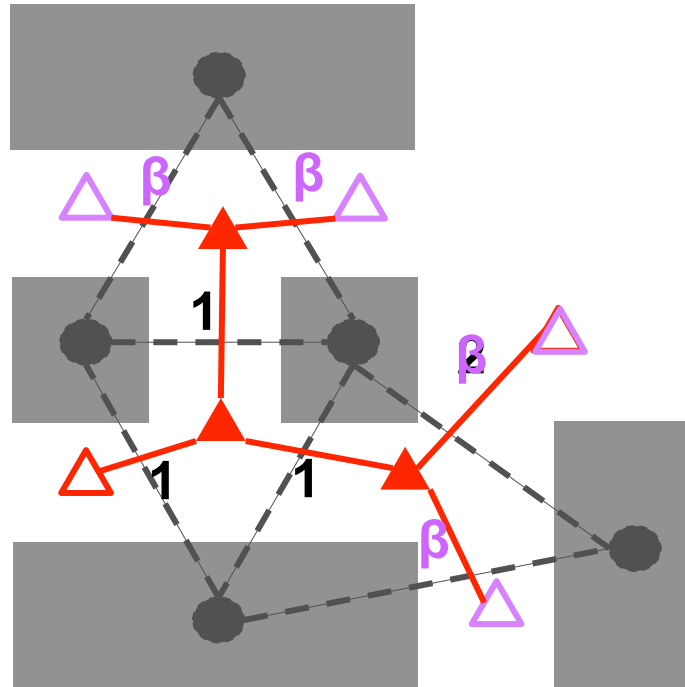


Iter. 3 Matching solution



Check trim cuts

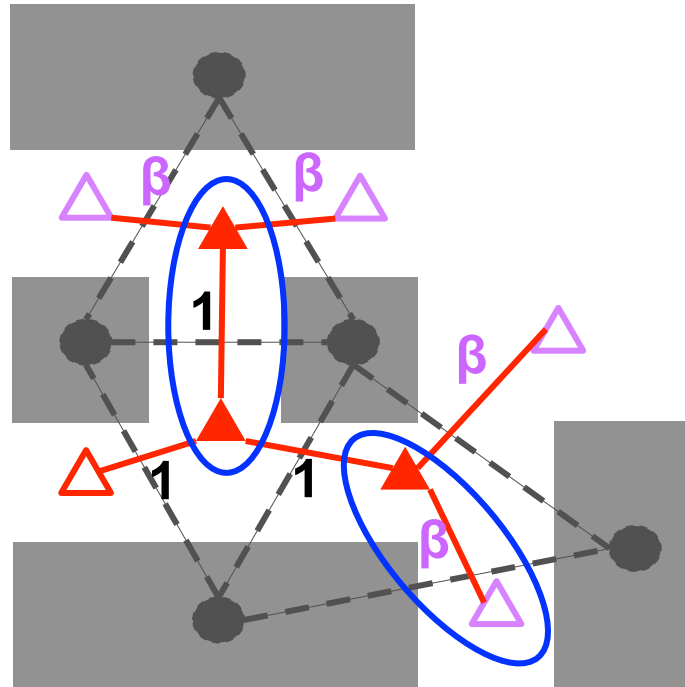
Example of SADP+EBL Optimization



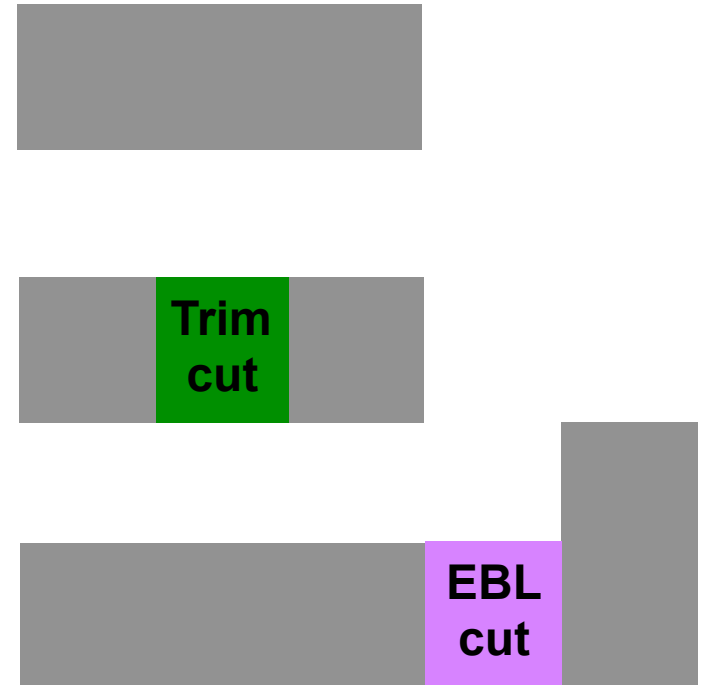
Keep going...

Example of SADP+EBL Optimization

- ◆ Continue iterations until no conflict in cuts



Final matching solution



Final cut assignment

Experiment Settings



◆ Benchmarks

- › OpenSPARC T1 designs
- › Scaled down to 22nm

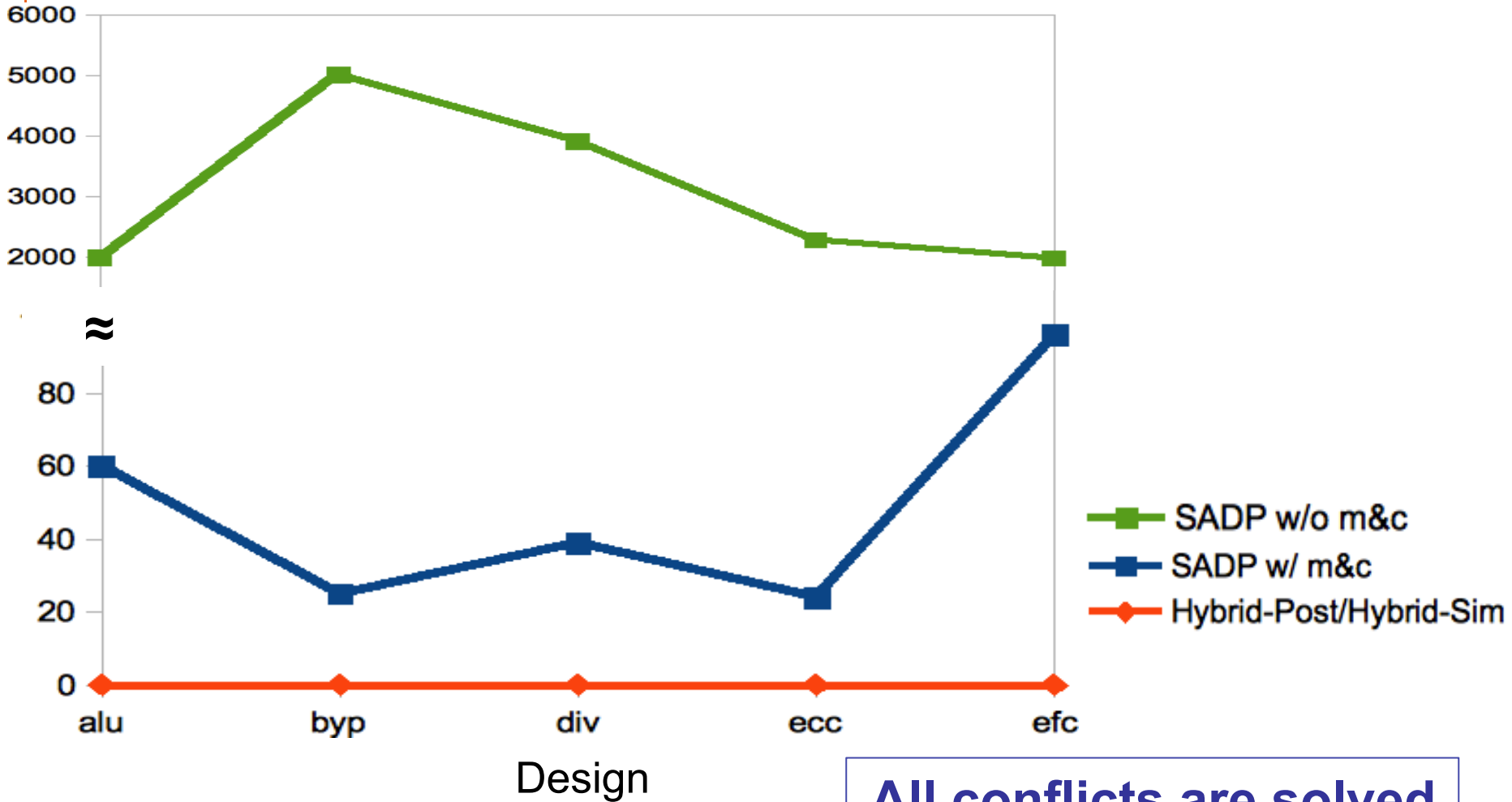
◆ Comparison methods

- › SADP w/o merge&cut
- › SADP w/ merge&cut
- › Hybrid-post: post-processing based decomposition
- › Hybrid-sim: simultaneous SADP+EBL decomposition

Comparison of Remaining Conflicts

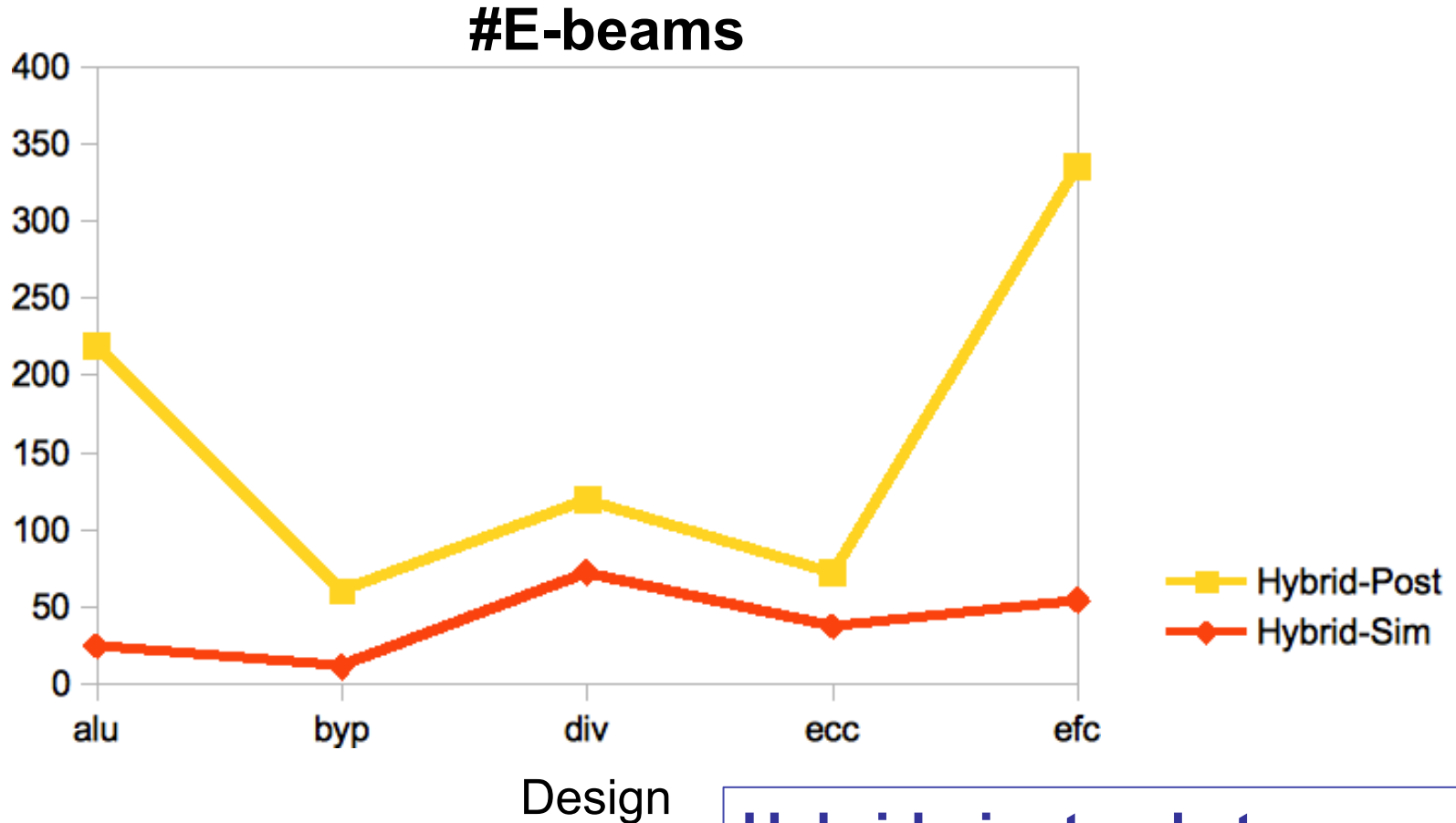


#Conflict



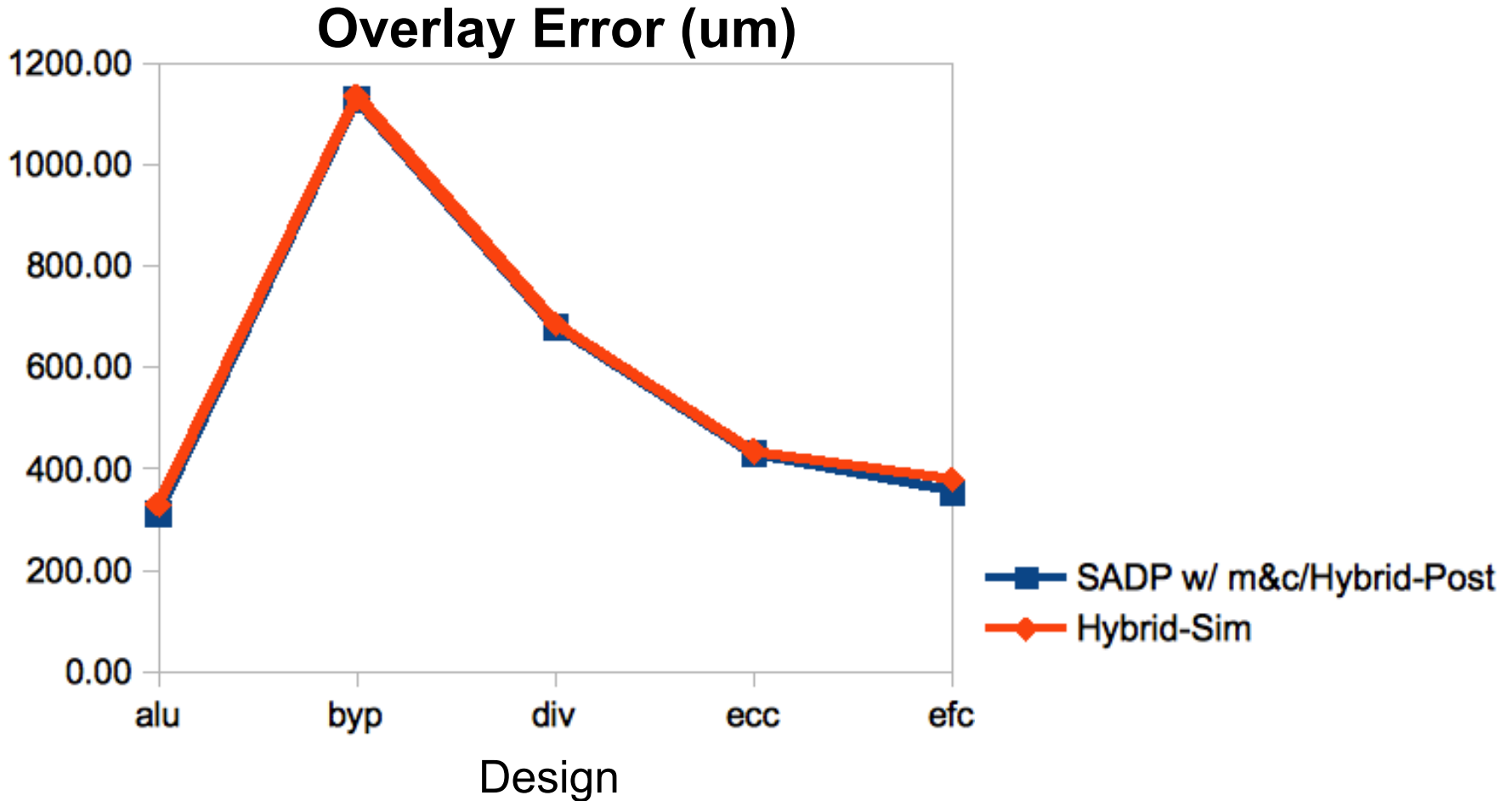
All conflicts are solved with hybrid lithography

Comparison of E-beam Utilization



Hybrid-sim tends to use more trim mask cutting and less e-beams

Comparison of Overlay Error



Overlay increase by Hybrid-sim < 3%

Conclusion

- ◆ Complementary lithography enables high quality layout with less mask manufacturing cost
- ◆ Merge & cut technique to reduces conflicts
- ◆ Simultaneous SADP layout decomposition and E-beam assignment performed effectively to minimize
 - › Conflict
 - › SADP overlay due to trim mask
 - › E-beam shot counts



Thank You