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

Trim mask

Assist

Target layout

Mandrel mask
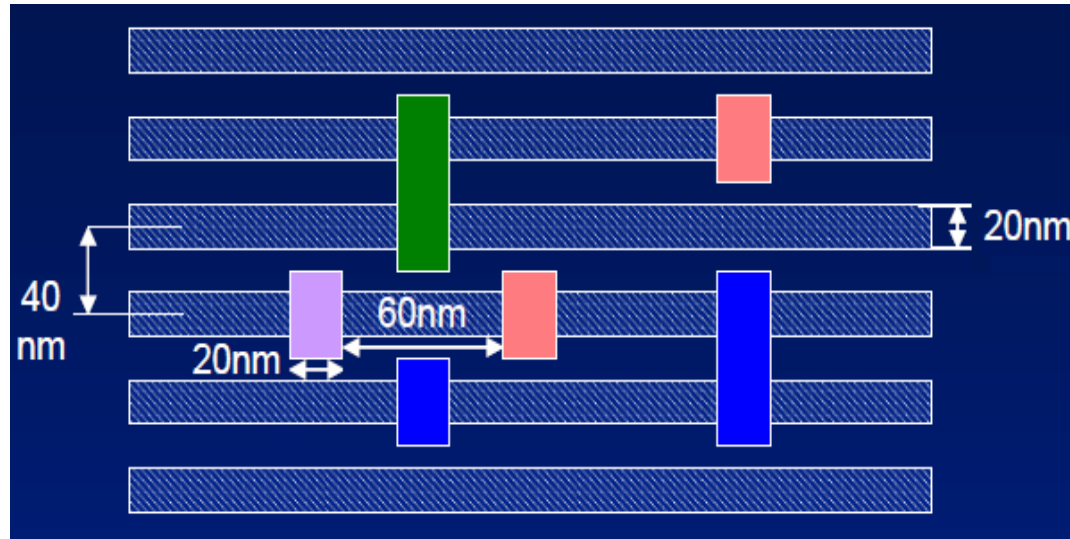
Spacer deposition

Trimming
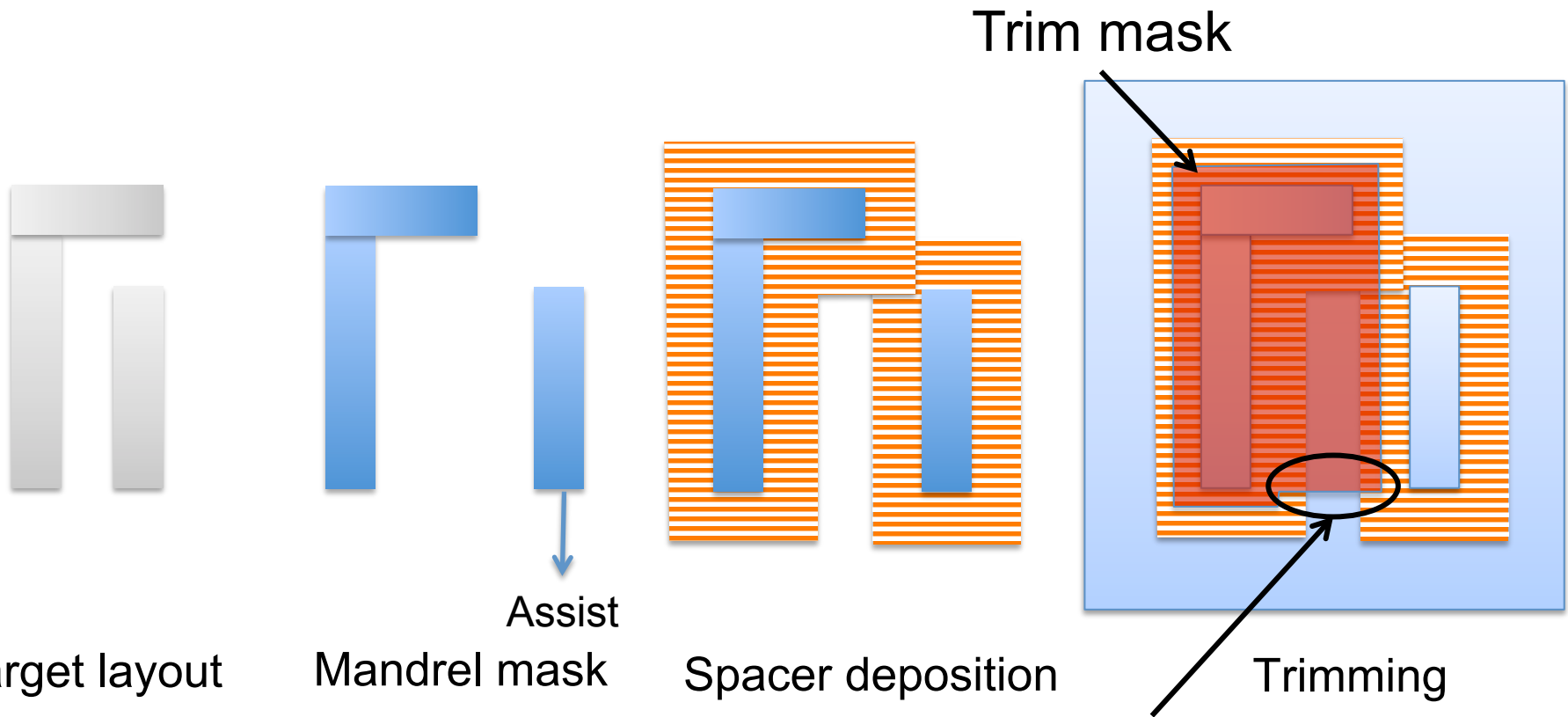
Possible overlay error

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

Electrical Gun

Shaping Aperture

2nd Aperture

Wafer

4
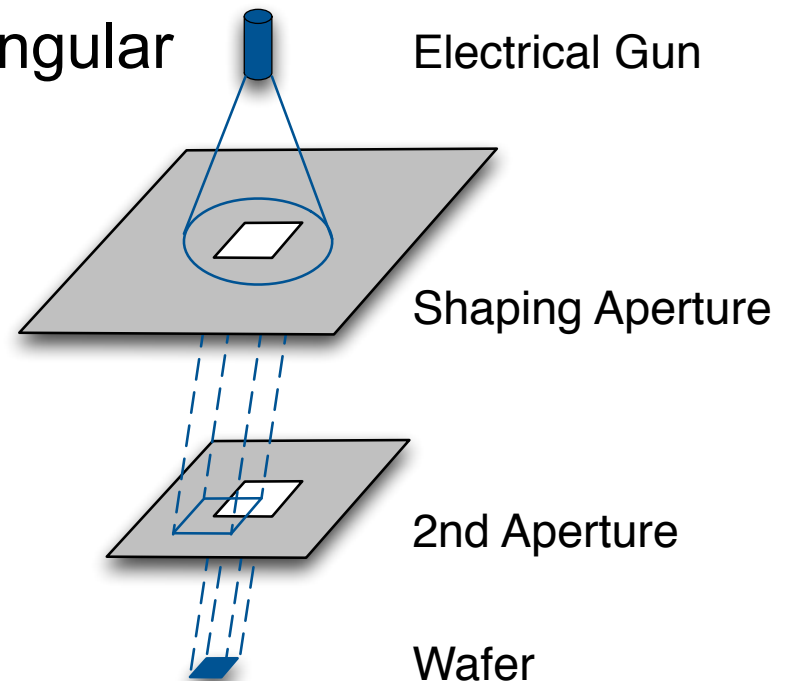
SADP & E-beam Hybrid?

♦ SADP with multiple cut masks or e-beam cuts

11nm node

193nm immersion	Complementary Lithography
1 base mask + 4 cut masks	**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

Base features   +   **Cutting patterns**   =   **Final patterns**
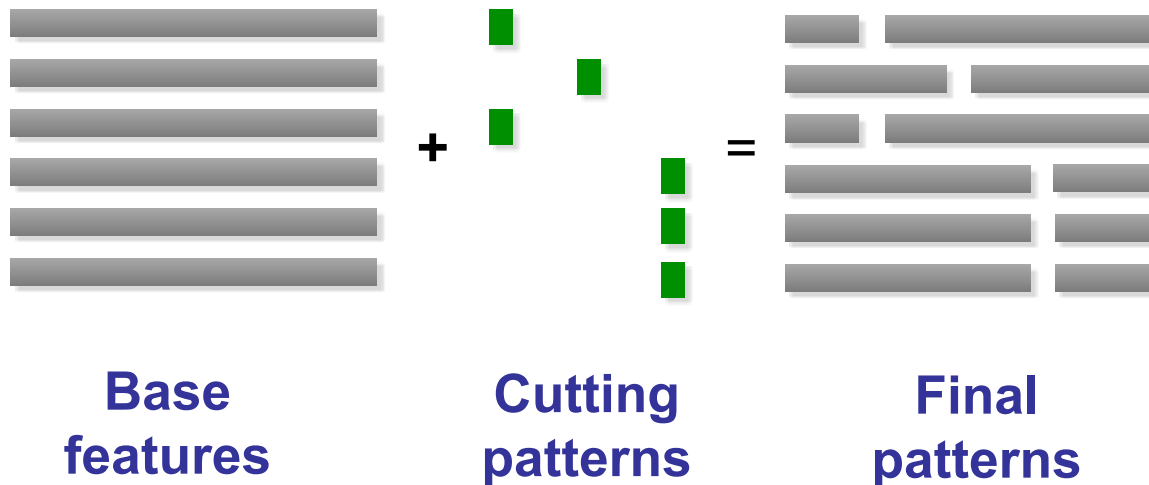
Related Works

♦ 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
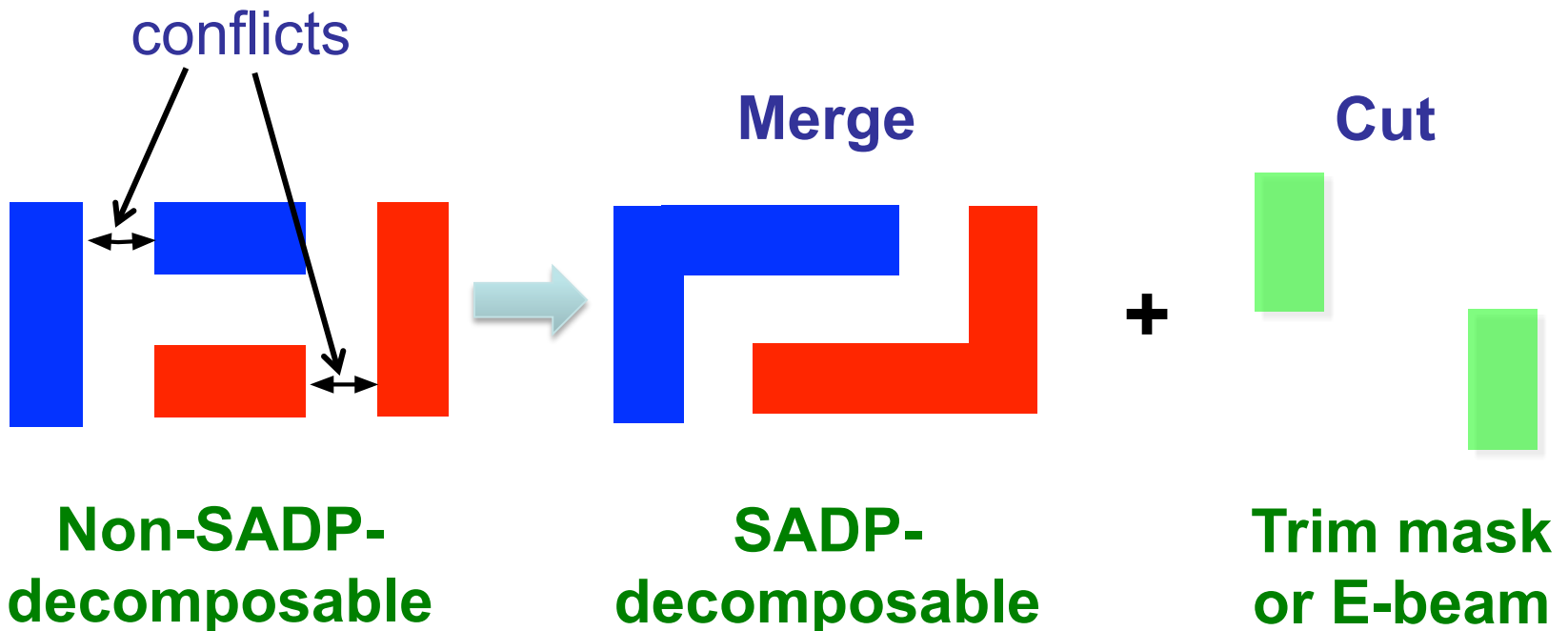 - › Minimize e-beam shots

Outline

♦ Motivation & Problem Formulation

♦ Proposed Algorithms

  › Post Processing Based Layout Decomposition

  › Simultaneous SADP+EBL Optimization

♦ Experimental Results

♦ Conclusion

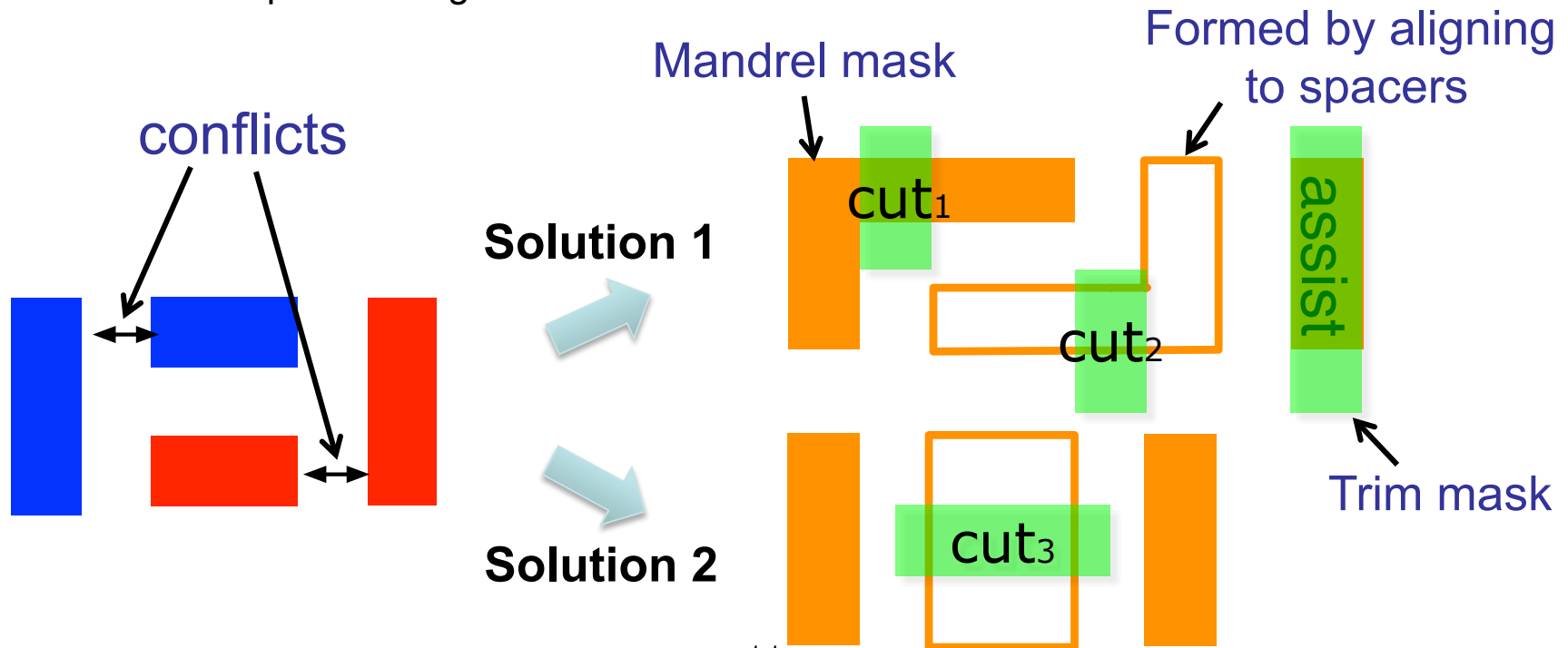# Dealing with SADP Conflicts

♦ Merge&Cut (M&C) technique

› Step1: Merge conflicting patterns

› Step2: Cut unwanted parts by trim mask or e-beams

conflicts

Merge

Cut

Non-SADP-decomposable

SADP-decomposable

+

Trim mask or E-beam

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
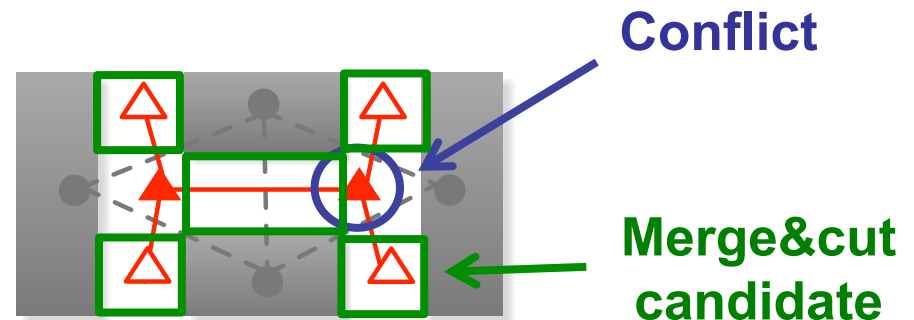

conflicts

Mandrel mask

Formed by aligning to spacers

Solution 1

cut$_1$

cut$_2$

assist

Trim mask

Solution 2

cut$_3$

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
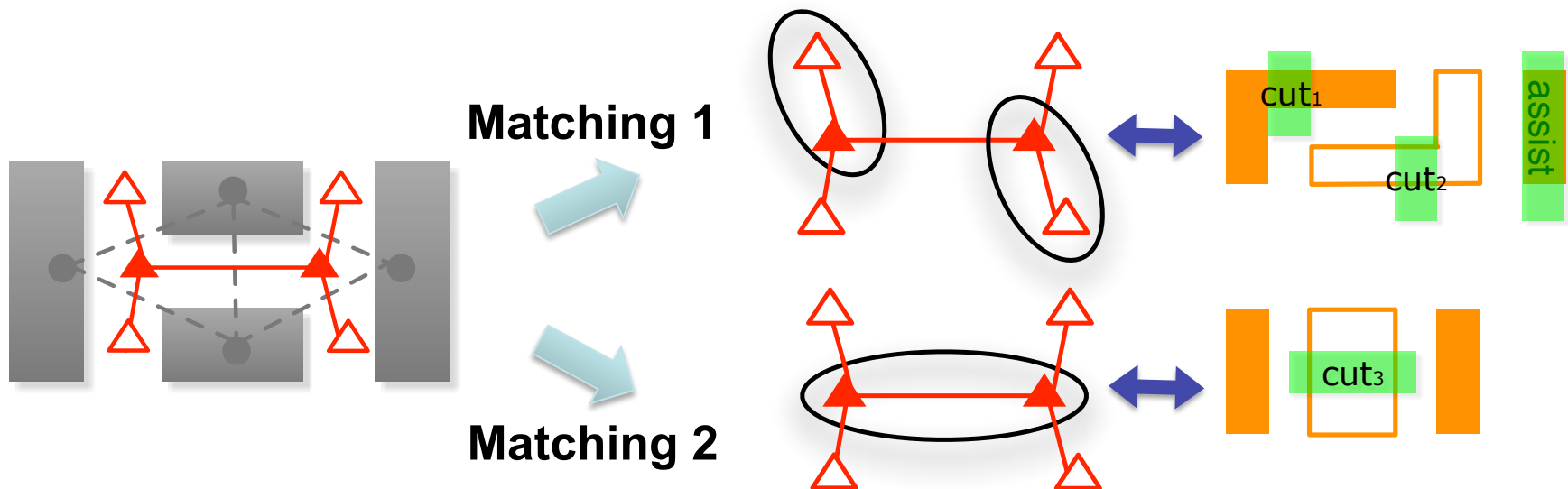
Odd cycle = Conflict

Conflict

Merge&cut candidate
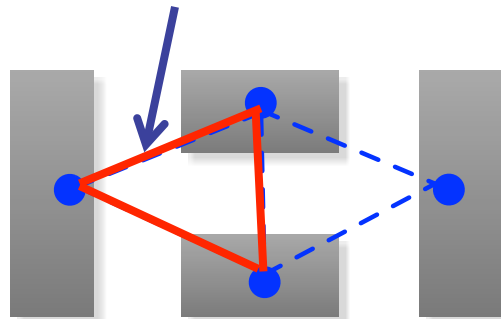
Conflict graph

Face graph

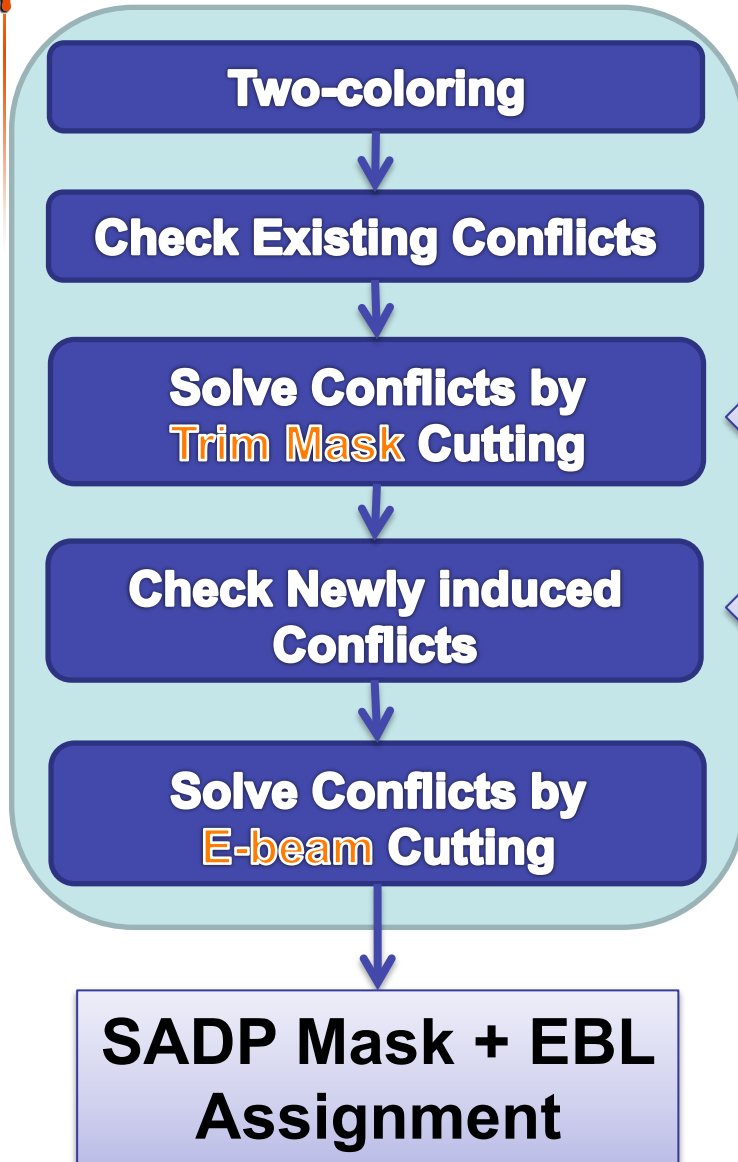# Finding M&C Solutions (cont)

♦ **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**

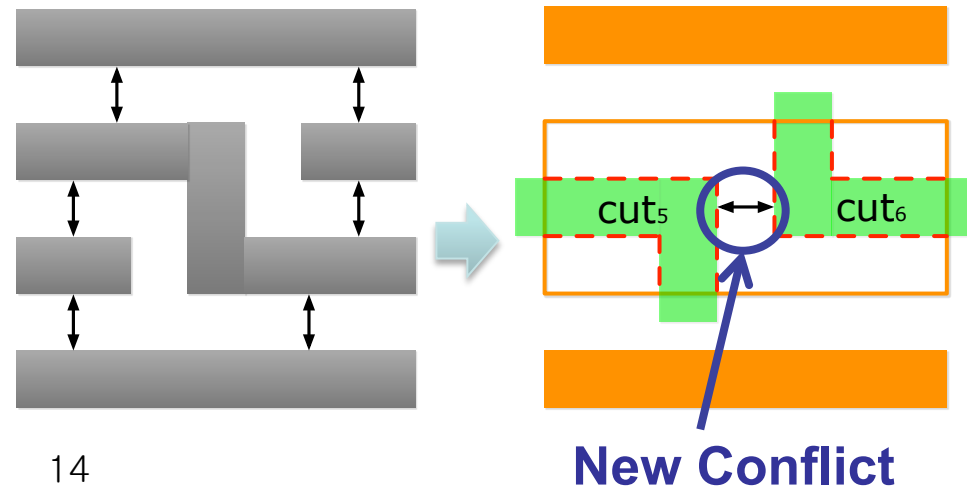 ➔ **Matching solution = Selection of M&C candidates that can solve conflicts with the minimum cost**

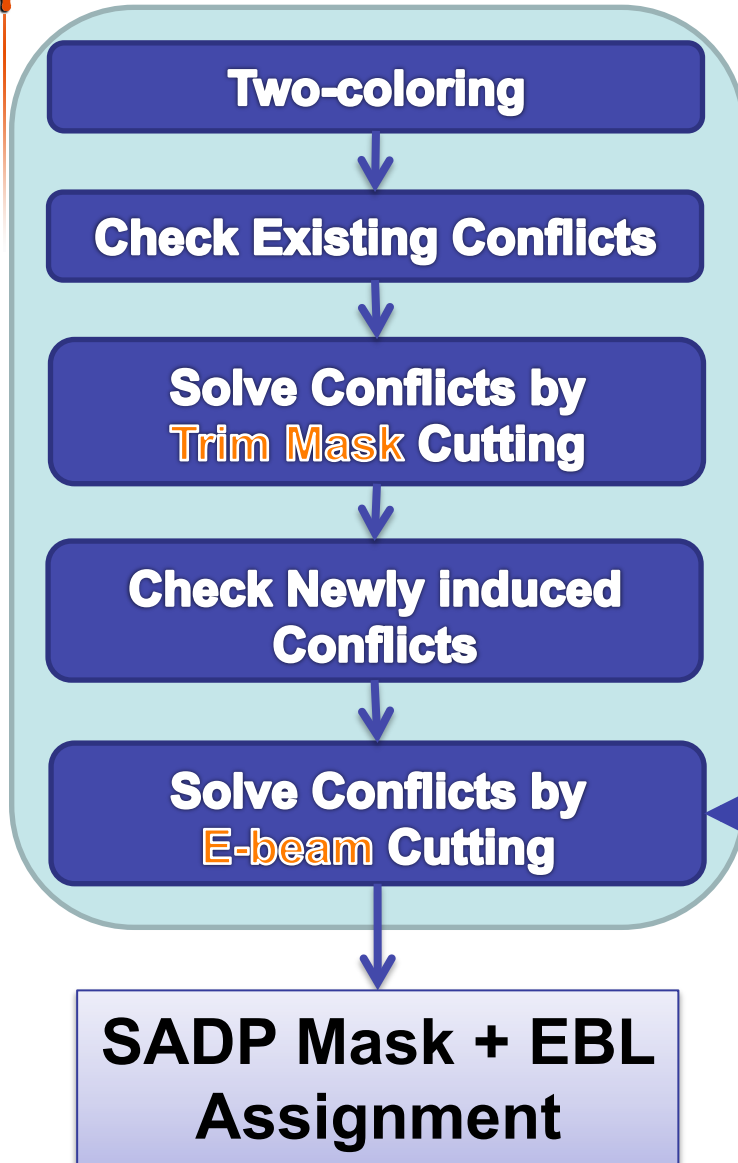# Method 1: Post Processing Based Layout Decomposition

Two-coloring

↓

Check Existing Conflicts

↓

Solve Conflicts by Trim Mask Cutting

↓

Check Newly induced Conflicts

↓

Solve Conflicts by E-beam Cutting

↓

SADP Mask + EBL Assignment

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

Cuts obtained may conflict each other

cut_5 cut_6

New Conflict

14

Method 1: Post Processing Based Layout Decomposition (cont)

Two-coloring

↓

Check Existing Conflicts

↓

Solve Conflicts by **Trim Mask** Cutting

↓

Check Newly induced Conflicts

↓

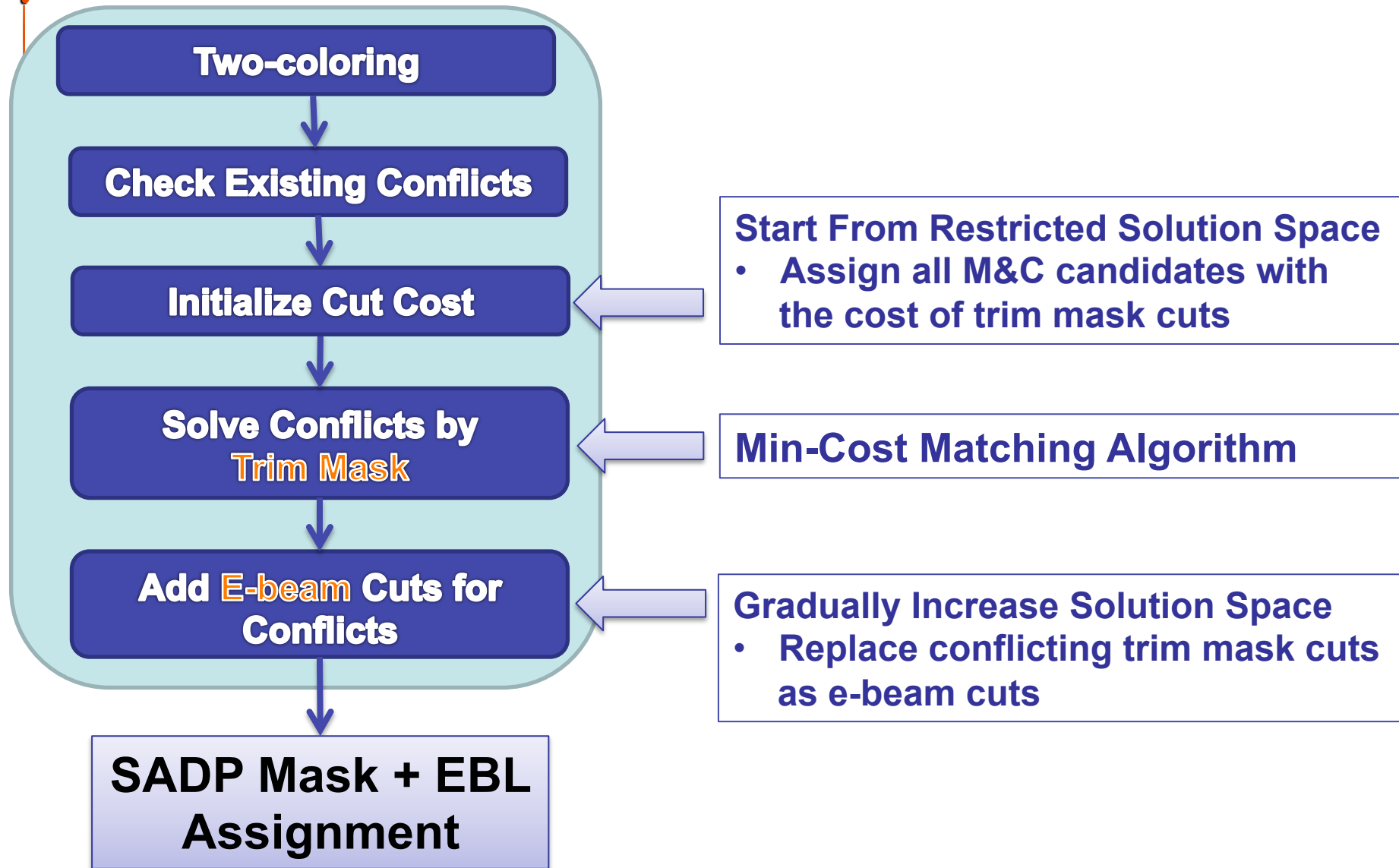Solve Conflicts by **E-beam** Cutting

↓

SADP Mask + EBL Assignment

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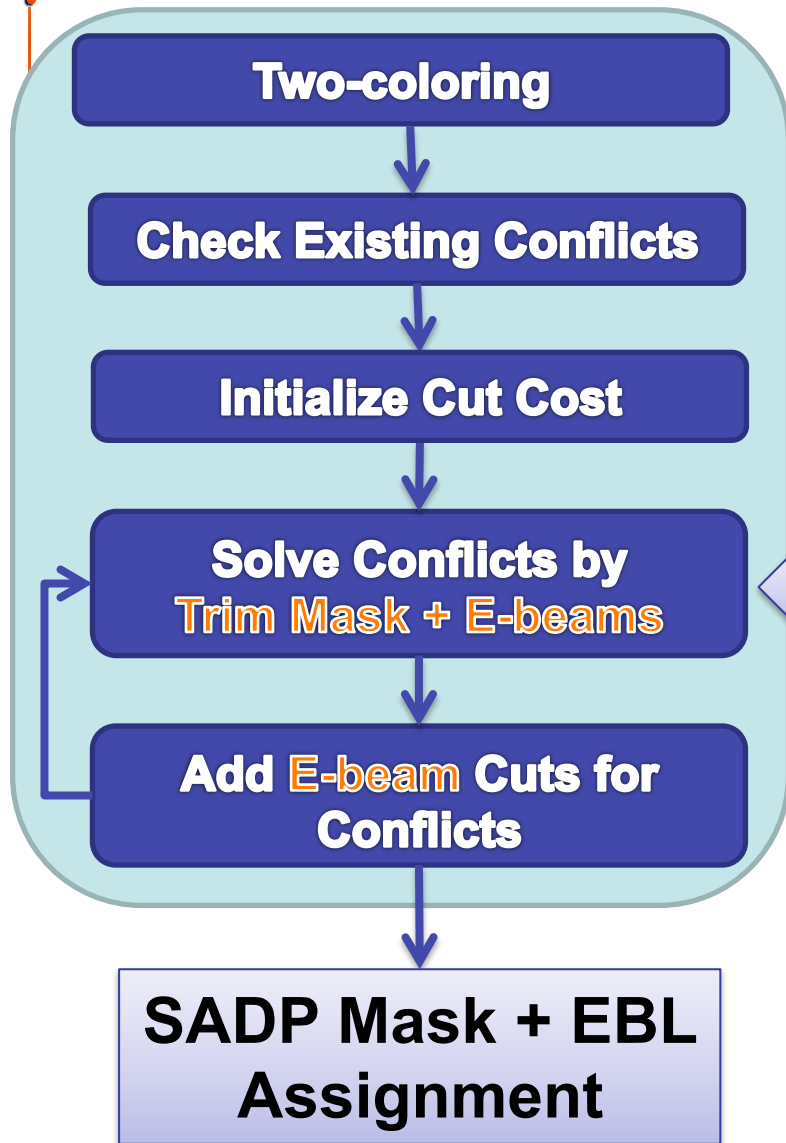- **Assign the rest of cuts as e-beams**

Trim cuts

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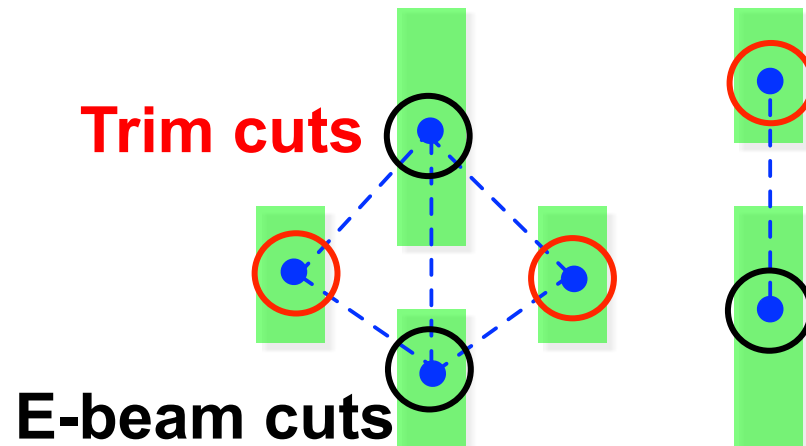
E-beam only considered at the last stage (Greedy)

Method 2: Simultaneous SADP+EBL Optimization

Two-coloring

↓

Check Existing Conflicts

↓

Initialize Cut Cost ⟵ **Start From Restricted Solution Space**
- **Assign all M&C candidates with the cost of trim mask cuts**

↓

Solve Conflicts by Trim Mask ⟵ **Min-Cost Matching Algorithm**

↓

Add E-beam Cuts for Conflicts ⟵ **Gradually Increase Solution Space**
- **Replace conflicting trim mask cuts as e-beam cuts**

↓

SADP Mask + EBL Assignment

Method 2: Simultaneous SADP+EBL Optimization (cont)

```
Two-coloring
      ↓
Check Existing Conflicts
      ↓
Initialize Cut Cost
      ↓
Solve Conflicts by
Trim Mask + E-beams
      ↓
Add E-beam Cuts for
Conflicts
      ↓
```

SADP Mask + EBL Assignment

Min-Cost Matching Algorithm
- **Similar to the previous iteration, but now we have two types of cuts**
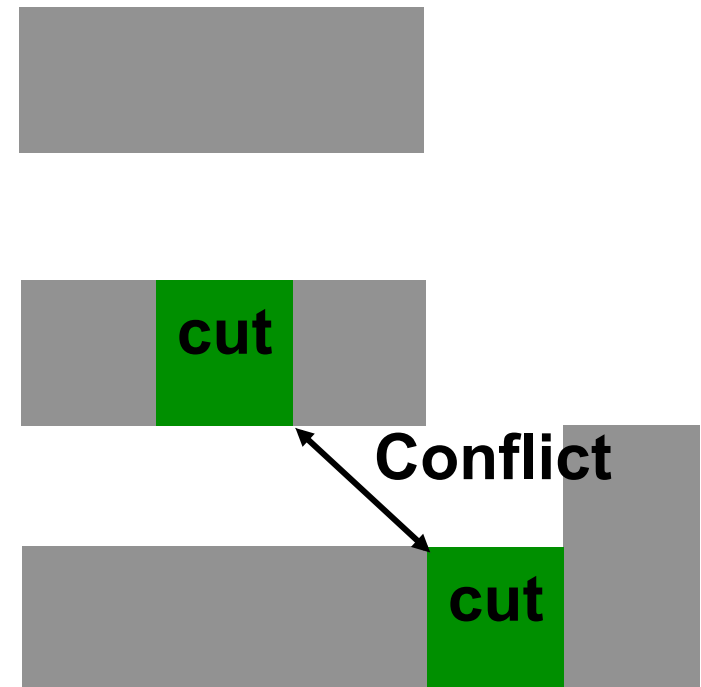- **E-beam Cut Cost >> Trim Cut Cost**

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
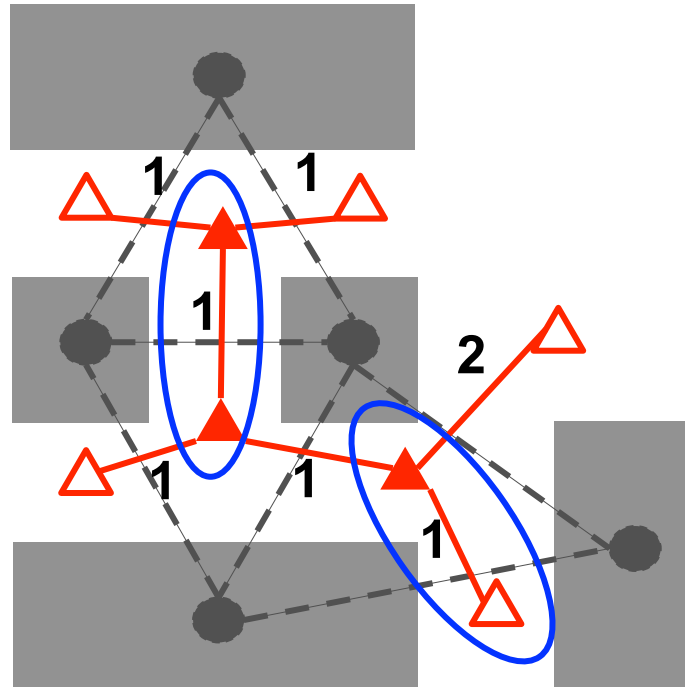
Iter. 1 Matching solution

Check trim cuts

♦ Update one conflicting cut as EBL cut (cost = β)
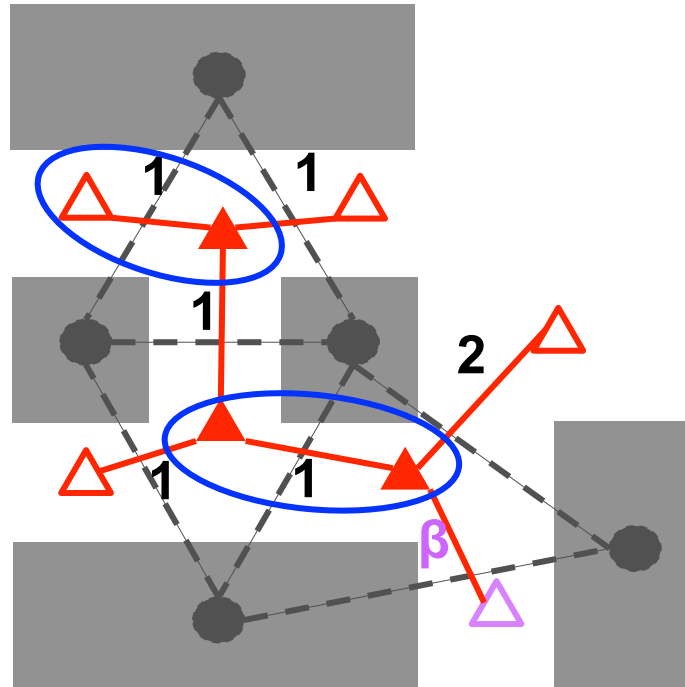
Iter. 2 Matching solution   **Check trim cuts**
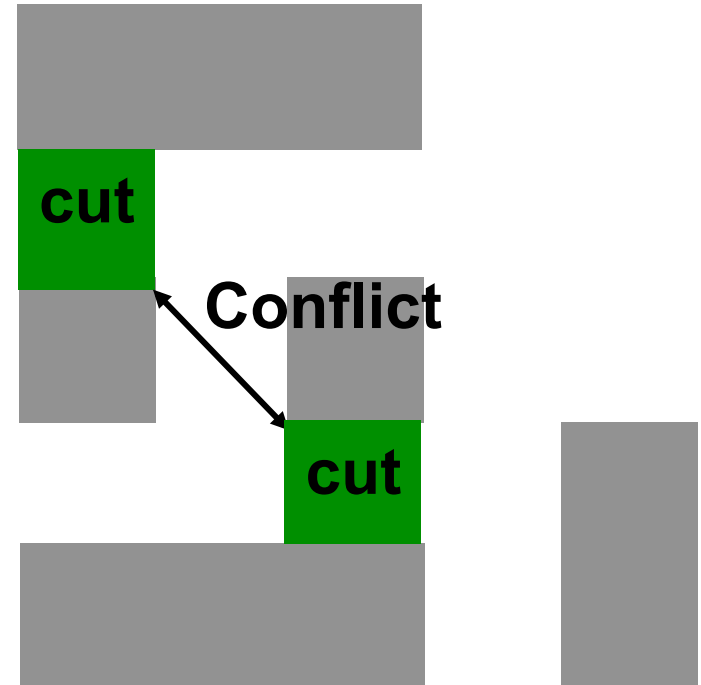
♦ Update cost
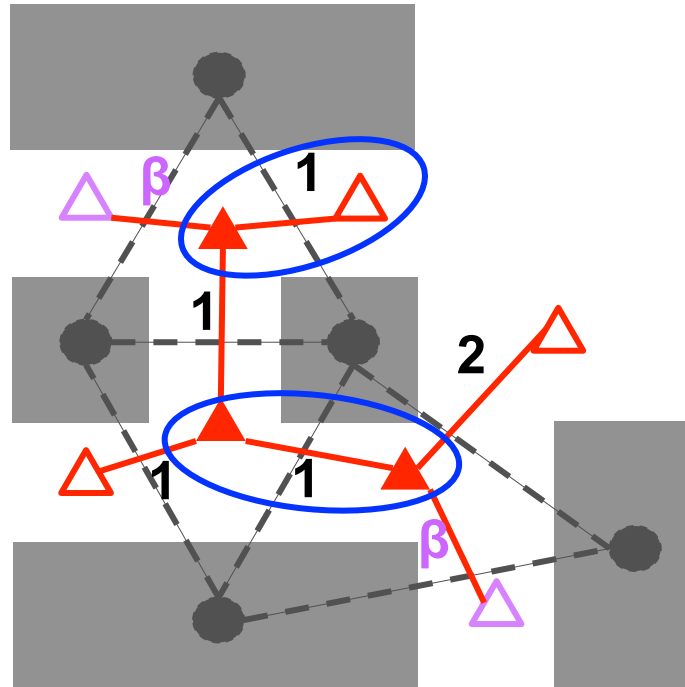
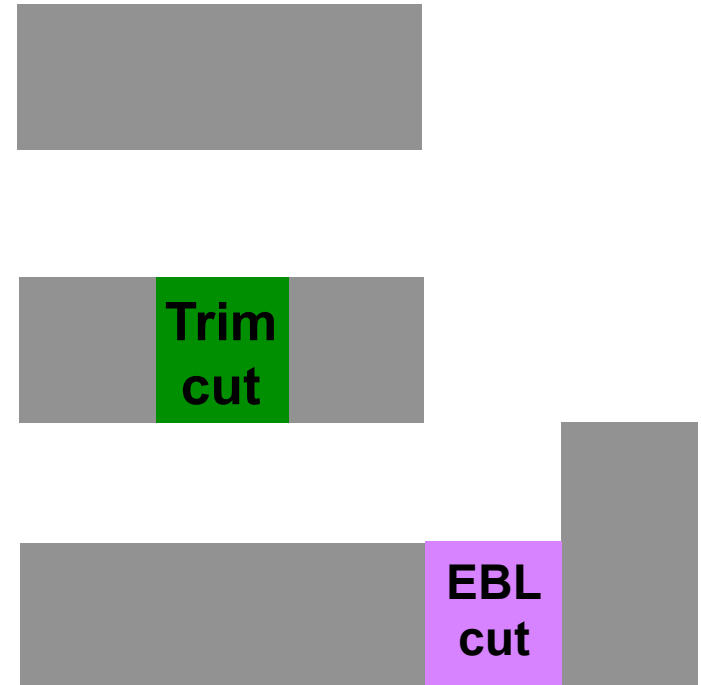**Iter. 3 Matching solution**   **Check trim cuts**
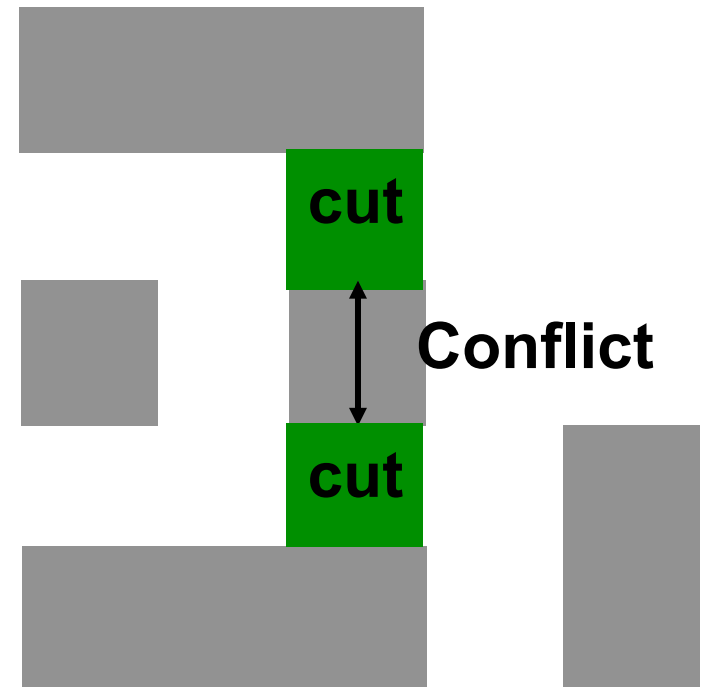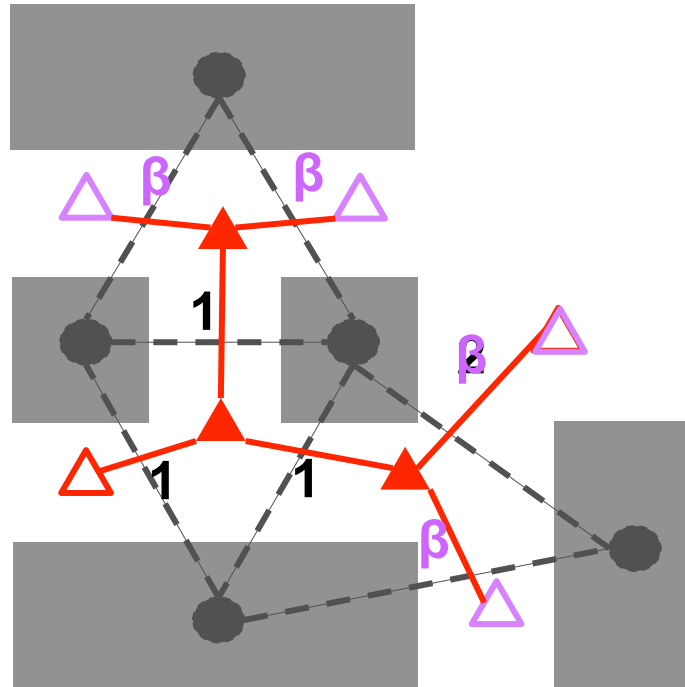
Keep going…

Example of SADP+EBL Optimization

♦ Continue iterations until no conflict in cuts
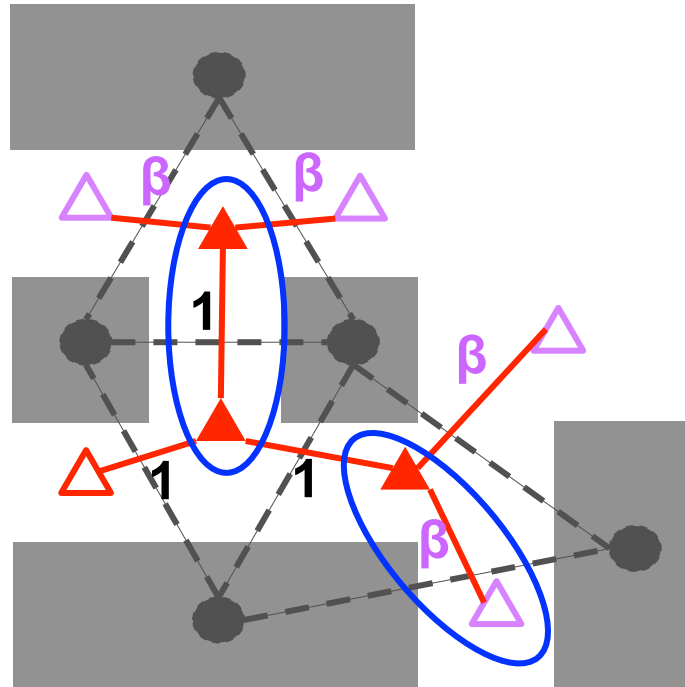
Final matching solution   **Final cut assignment**

Experiment Settings

♦ Benchmarks

  › OpenSPARC T1 designs

  › Scaled down to 22nm
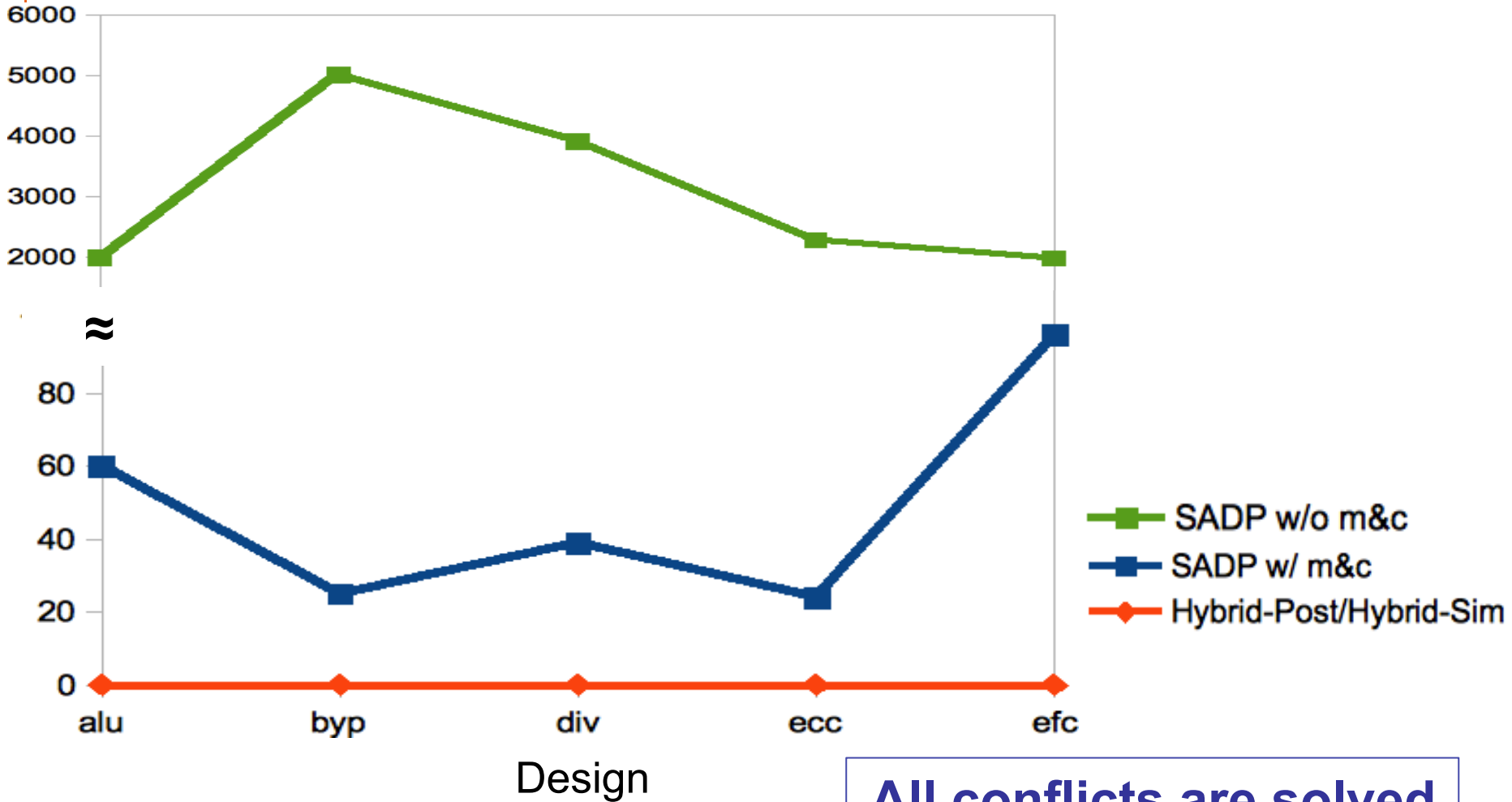
♦ Comparison methods

  › SADP w/o merge&cut

  › SADP w/ merge&cut

  › Hybrid-post: post-processing based decomposition

  › Hybrid-sim: simultaneous SADP+EBL decomposition
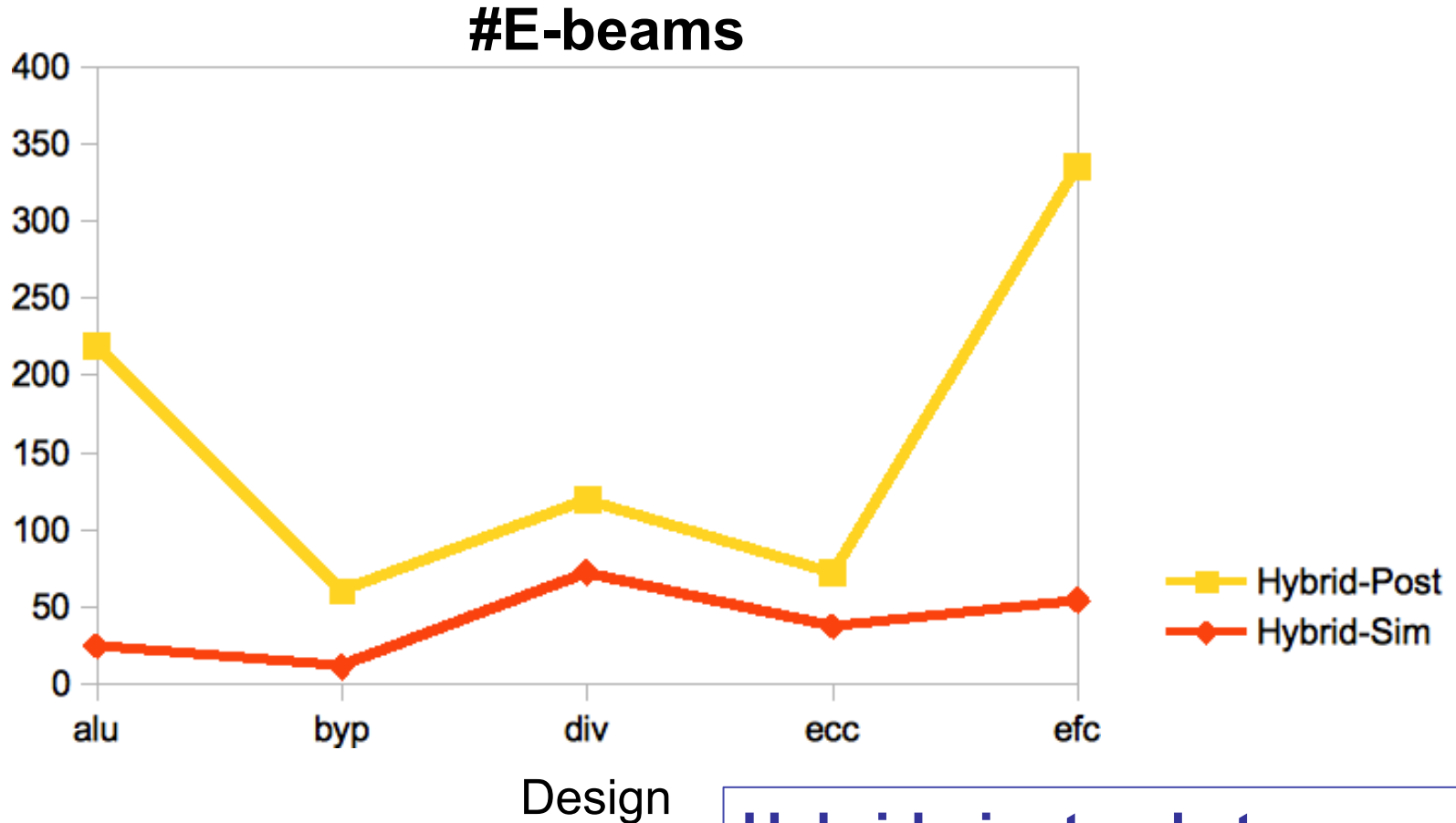
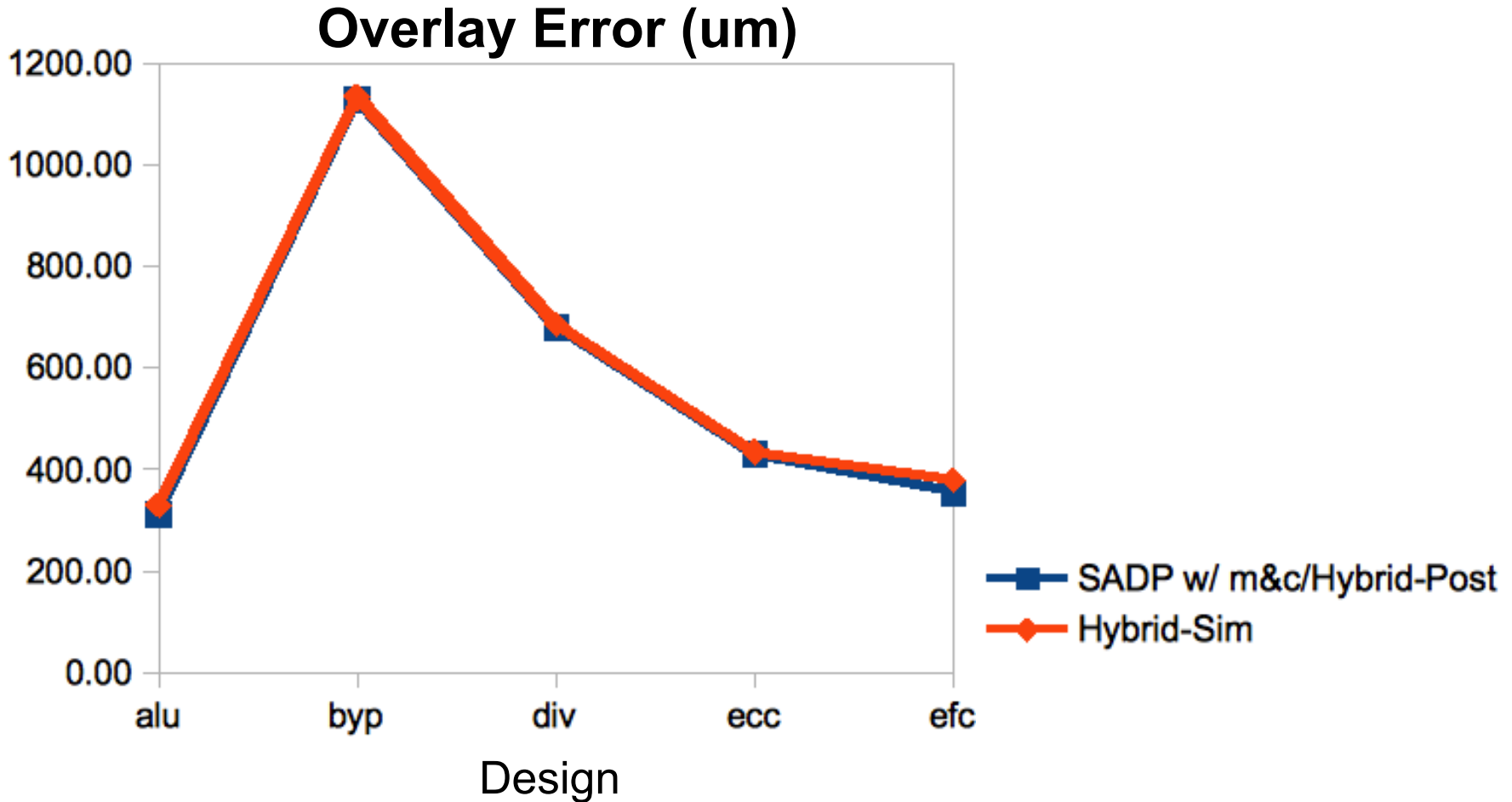# Comparison of Remaining Conflicts

#Conflict

All conflicts are solved
with hybrid lithography

Comparison of E-beam Utilization

#E-beams

Design

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

Comparison of Overlay Error

Overlay Error (um)

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