

Series Measurements of the SLS2.0 Longitudinal Gradient Bends Magnets

Challenges and Results

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- 23rd International Magnetic Measurement Workshop Location, 08 October 2024, Bad Zurzach, Switzerland.

Summary

- The SLS2.0 Arc
- The Triplet's Magnets (The LGB)
- Measurements' Challenges & Requirements
- Measurement Procedures
- Series Measurements Results
- Conclusions

➤ The SLS2.0 Arc

➤ The Triplet's Magnets

➤ Measurements' Challenges & Requirements

➤ Measurement Procedures

➤ Series Measurements Results

➤ Conclusions

The SLS2.0 Arc



- **SLS2.0 keeps the same footprint of SLS-> magnets density along the ring increases of a factor 3.8**
- An SLS2.0 arc is based on a multi-bend achromatic structure (7BA)->emittance reduction by a factor ~ 40
- The multi-bend design is implemented through Longitudinal Gradient Bends magnets-> Triplets in the PSI jargon
- Each arc has 5 triplets installed

➤ The SLS2.0 Arc

➤ **The Triplet's Magnets**

➤ Measurements' Challenges & Requirements

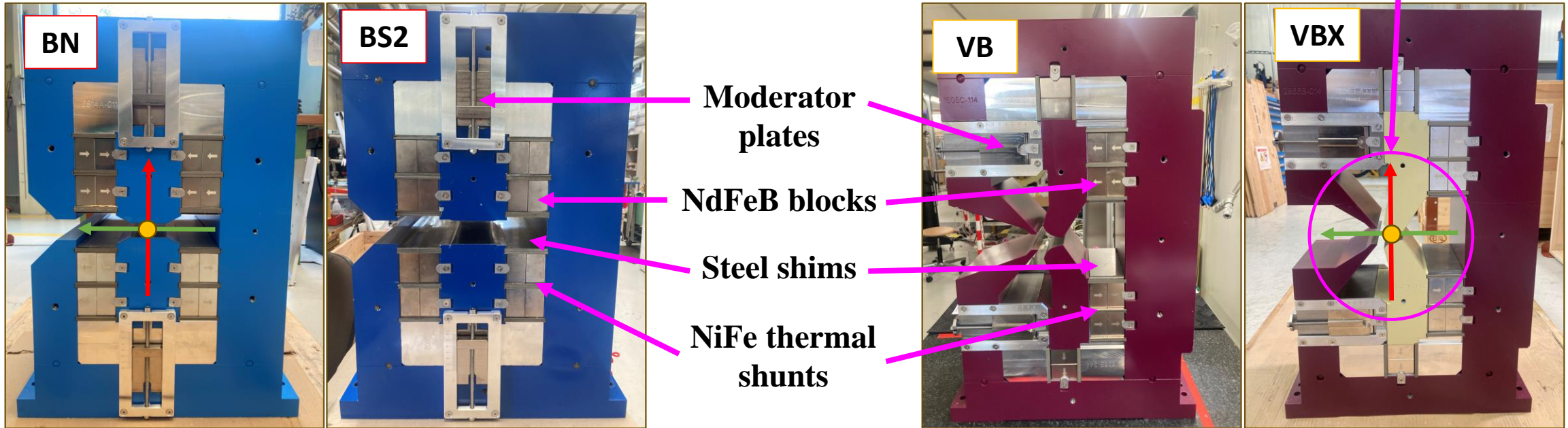
➤ Measurement Procedures

➤ Series Measurements Results

➤ Conclusions

Triplet's Permanent Magnets

Mechanical reference frame



- **BN and BS2**

- BN is a normal dipole (56)
- BS2 is a longitudinal gradient dipole (4)

- **VB and VBX**

- VB is a combined function: quadrupole+dipole (96)
- VBX is a combined function: quadrupole+ dipole (24)

Arc type	Triplet 1	Triplet 2	Triplet 3	Triplet 4	Triplet 5	Number of Arcs
1	VBX(I)-BN ¹ -VB ¹	VB ² -BN ² -VB ²	VB ² -BN ² -VB ²	VB ² -BN ² -VB ²	VB ³ -BN ³ -VBX(O)	8
2	VBX(I)-BN ¹ -VB ¹	VB ² -BN ² -VB ²	VB ⁴ -BS2-VB ⁴	VB ² -BN ² -VB ²	VB ³ -BN ³ -VBX(O)	4

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Measurements' Challenges

❖ Main Challenges

- Each individual magnet must be tuned according to the standalone requirements (see also C. Zoller talk)
- As an assembly an extra tuning step is needed to accommodate for cross-talk effects (see also R. Riccioli talk)
- **From beam dynamics:** the Triplet integral function must be tuned with an overall uncertainty of $2 \cdot 10^{-3}$ (or 20 (u)) relative to the nominal design ($1 \text{ (u)} = 10^{-3}$)
- Specific tuning parameters depending on the triplet type
 - VB-> 4 sets of tuning parameters
 - VBX-> 2 sets of tuning parameters
 - BN-> 3 sets of tuning parameters
 - BS2-> 1 set of tuning parameters

(true also for other SLS2.0 magnets)

- Several measurements steps: time consuming

❖ Defining Requirements

- The cross-talk effect, due to extreme dense lattice, obliges to optimize a Triplet as a full assembly with neighbours (iterative process)
- From an optimized triplet the magnetic axis of the single magnets must be extracted
- Each single magnet must be simulated as a standalone entity
- From field maps, simulations of the measurement process are carried out to calculate the design parameters for the tuning and adjustment of magnets (field quality and integral quantities)
- Each single step needs careful revision to avoid pitfalls

Measurements' Requirements (1)

❖ Systems Requirements

- VB(X): Rotating Coil (RC) and Moving (Stretched) Wire (MV_W) systems
- BN(BS2): Moving (Stretched) Wire
- Assembled Triplet: Moving (Stretched) Wire
- Each of the above steps needs survey operations

- VB's axis: line parallel to the mechanical axis that minimizes the L2 distance with the particle trajectory inside the magnet

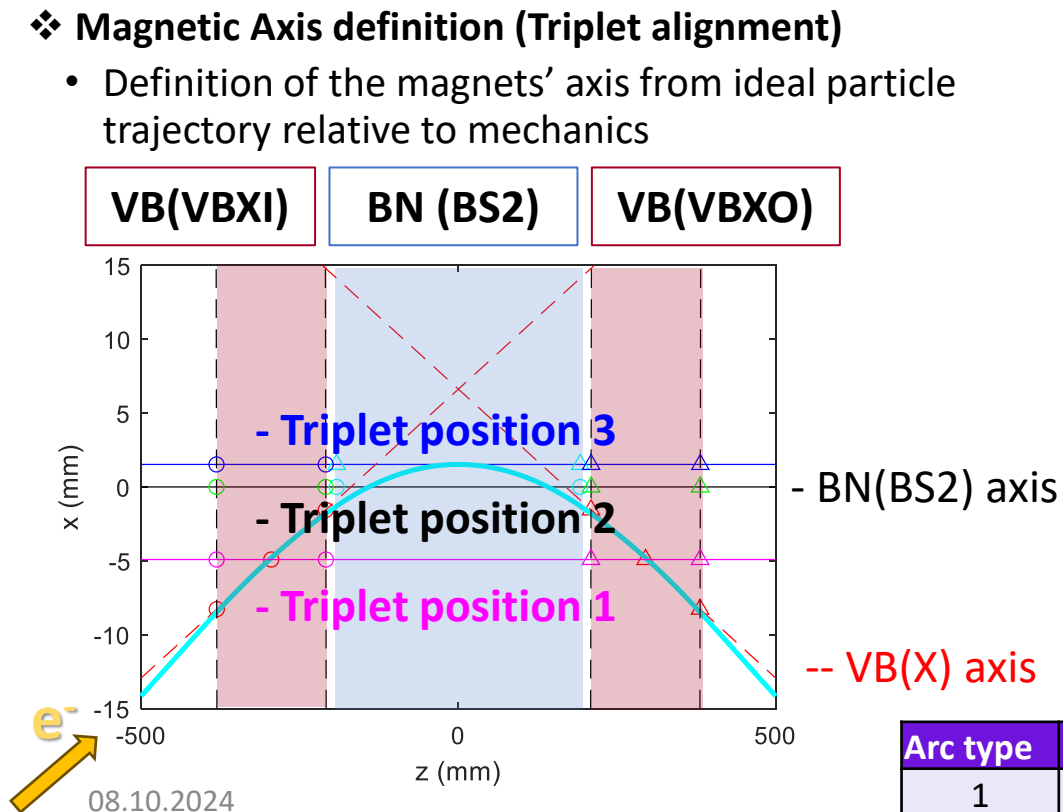
❖ Desing Parameters: standalone (field quality->see slides 14-17)

Magnet name fDipole (Tm) fGradient (T) x0 (mm)

VBX(I)	-0.15244	5.5740	-0.435	} 0.8 m
VB ¹	-0.15669	7.0332	1.080	
VB ²	-0.15358	6.9398	1.261	
VB ³	-0.15640	7.0011	1.025	
VB ⁴	-0.15100	6.8722	1.413	} 1.5 m
VBX(O)	-0.15240	5.5726	-0.435	
BN ¹	-0.57086		0	
BN ²	-0.57265		0	
BN ³	-0.57149		0	
BS2	-0.57698		0	

❖ Desing Parameters: Triplets->Integrals for MV_W meas. at Positions 1 to 3 over 1.5 m (slide 24)

Arc type	Triplet 1	Triplet 2	Triplet 3	Triplet 4	Triplet 5	Number of Arcs
1	VBX(I)-BN ¹ -VB ¹	VB ² -BN ² -VB ²	VB ² -BN ² -VB ²	VB ² -BN ² -VB ²	VB ³ -BN ³ -VBX(O)	8
2	VBX(I)-BN ¹ -VB ¹	VB ² -BN ² -VB ²	VB ⁴ -BS2-VB ⁴	VB ² -BN ² -VB ²	VB ³ -BN ³ -VBX(O)	4



Measurements' Requirements (2)

- RC Bench 2 (0.5 m): Tuning VB(X) magnets
- MV_W Bench 1 (0.8 m): VB(X) axis measurements
- MV_W Bench 2 (1.5 m): BN/BS2 and Triplet tuning

RC Bench 2

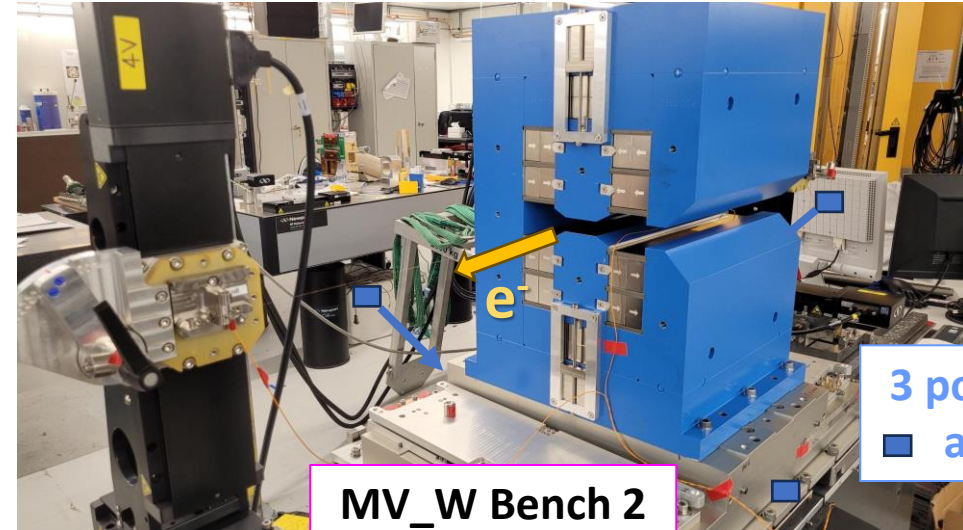


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MV_W Bench 1

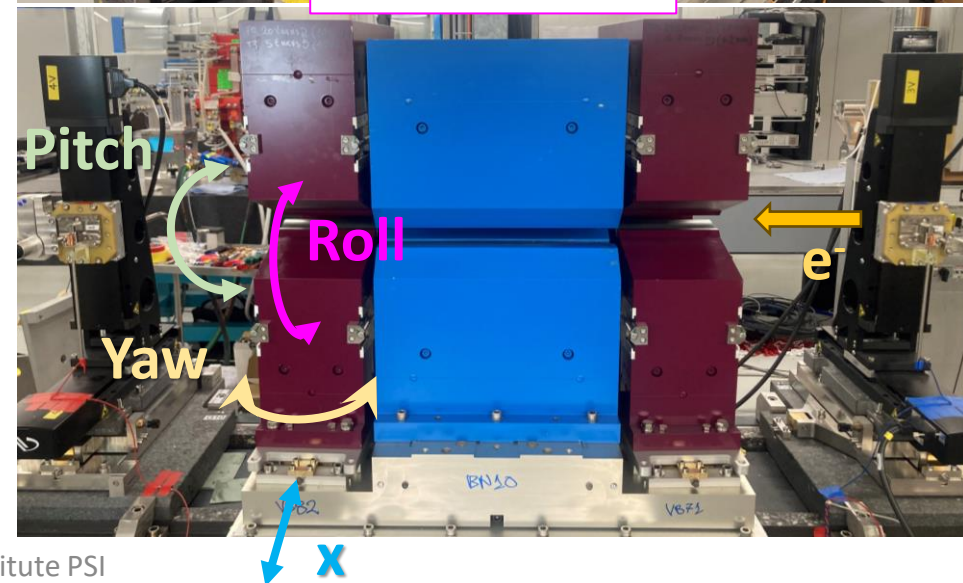


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3 points plane
■ adjustment

MV_W Bench 2



10

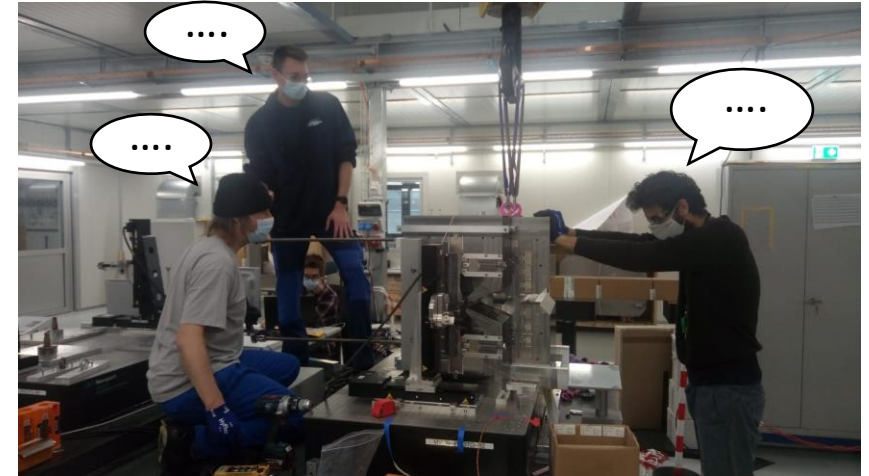
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Triplet Measurement Procedures

TRIPLET ASSEMBLY PROCESS

- **Step 1: VB and VBX measured and tuned with Rotating Coil**
 - 2 Steps measurement
 - Reference position: Adjustment of field value
 - Flip position: evaluation of magnet roll
 - Fiducialization with hexagon arm: referencing magnetic axis 'estimation' to magnet fiducials
- **Step 1: BN and BS2 measured and tuned with Moving Wire**
 - Fiducialization of the mechanical axis on a reference granite table (AT960 Hexagon)
 - Alignment on measurement bench: transfer of axis for stages starting position definition (AT960 Hexagon)
 - Measurement: Adjustment of field value
- **Step 2: VB and VBX axis measurement with Moving Wire**
 - Fiducialization of magnet's fiducials on reference granite table (AT960 Hexagon)
 - Roll angle alignment on Moving Wire bench (AT960 Hexagon)
 - Transfer of magnetic axis from Rotating Coil for initial wire positioning
 - Measurement: magnetic axis search
 - Fiducialization with AT960 Hexagon: referencing magnetic axis to magnet fiducials
- **Step 3: Triplet measurement and adjustment with Moving Wire**
 - Assembly of the Triplet
 - Alignment of the 3 magnets by survey team using fiducialization data from Step 1 (BN,BS2) and Step 2 (AT960 Hexagon)
 - Cross check of alignment, AT960 Hexagon, and calculations of initial wire set of starting positions
 - Measurement and tuning
 - Fiducialization with AT960 Hexagon: referencing Triplet magnetic axis to the magnets' assembly fiducials
 - **Cross the fingers until first beam :)!**

Prototyping phase (COVID era....)

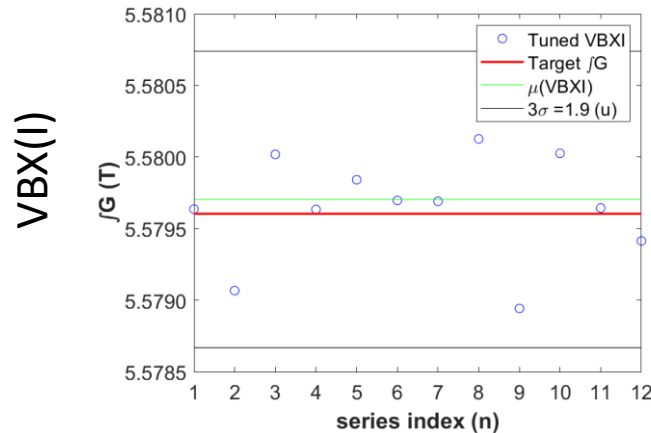


Series (intermediate steps not shown ...)

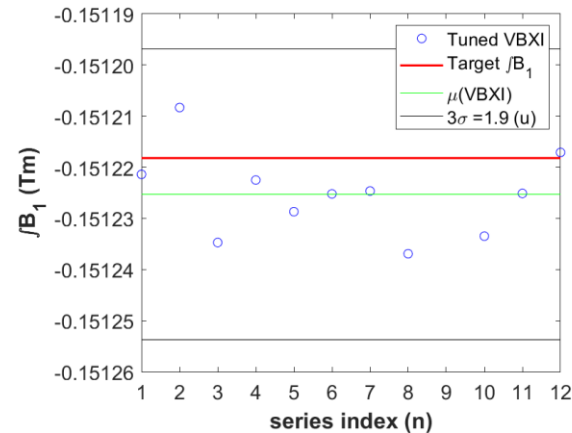


- The SLS2.0 Arc
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- Measurement Procedures
- **Series Measurements Results: Rotating Coil -> VB and VBX**
- Conclusions

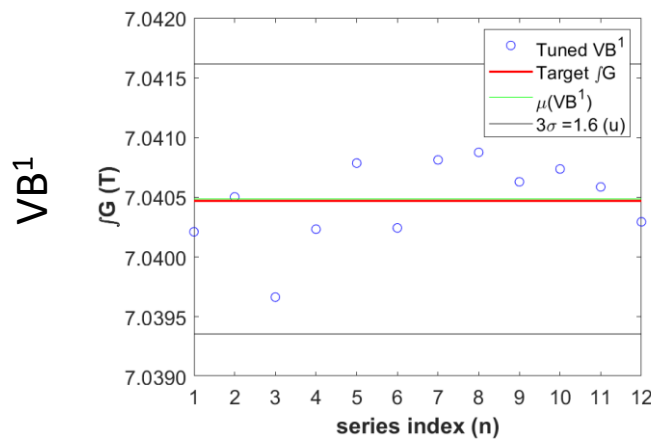
RC measurement Results: VBX(I) and VB¹



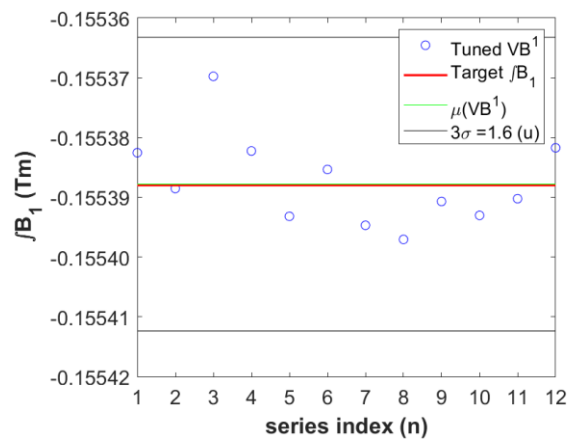
• Tuned Integral B2/R_{ref} @ 8.8 mm



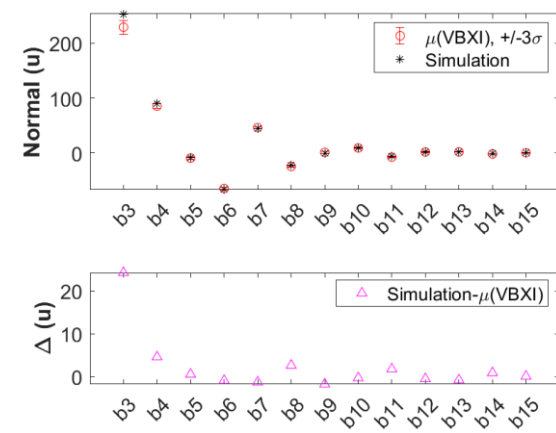
• Tuned Integral B1 @ 8.8 mm



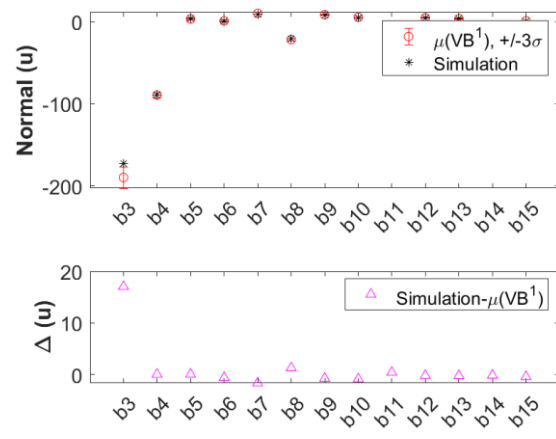
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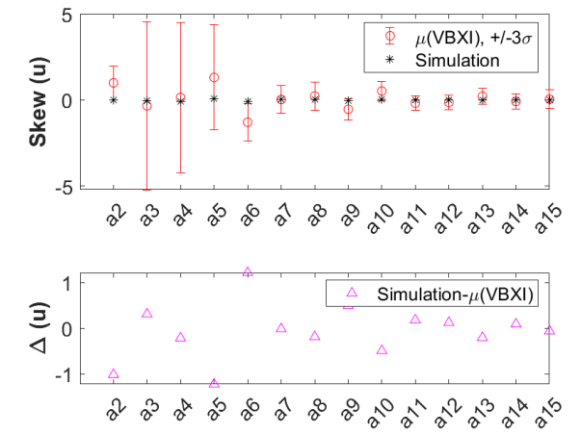
• Tuned Integral B1 @ 8.8 mm



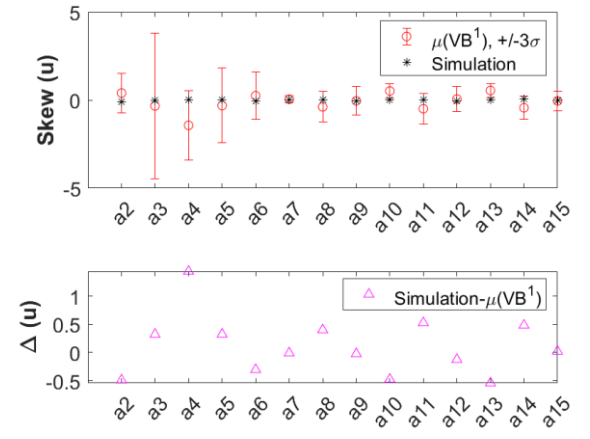
• Normal harmonics vs Simulated one



• Normal harmonics vs Simulated one

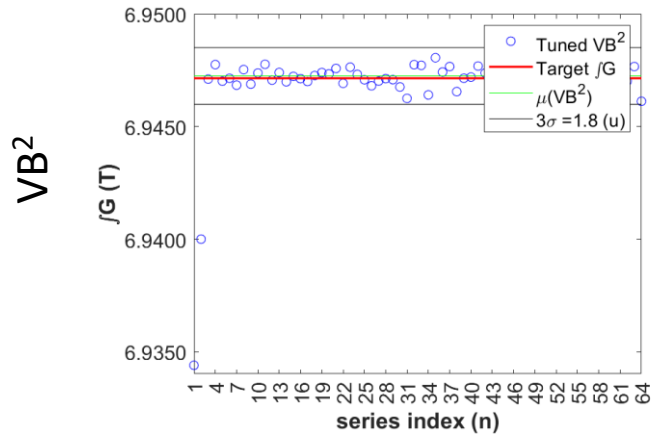


• Skew harmonics vs Simulated one

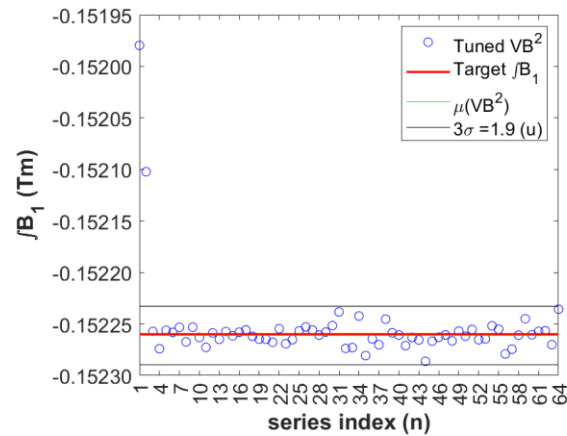


• Skew harmonics vs Simulated one

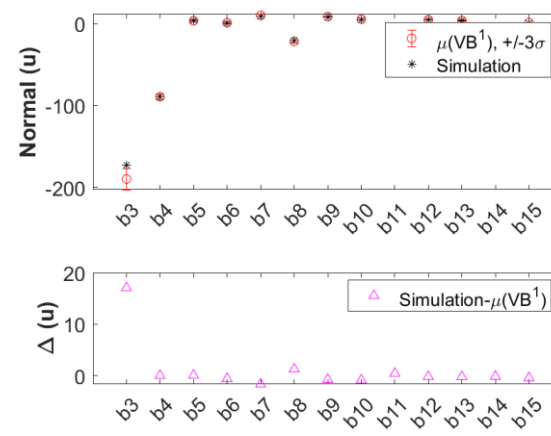
RC measurement Results: VB^2 and VB^4



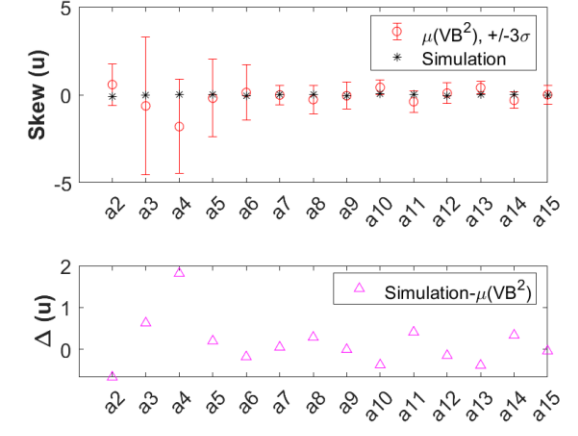
• Tuned Integral B2/ R_{ref} @ 8.8 mm



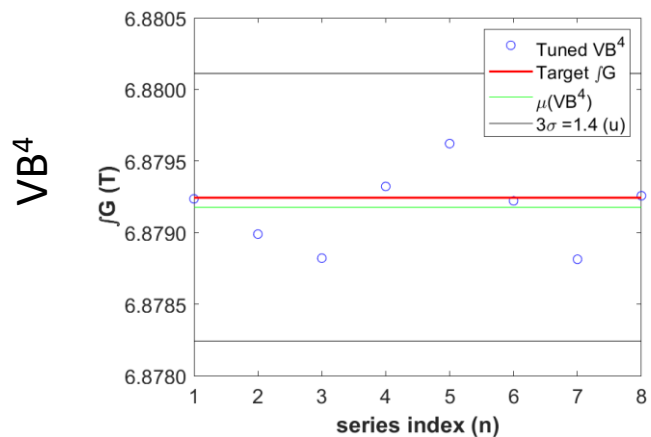
• Tuned Integral B1 @ 8.8 mm



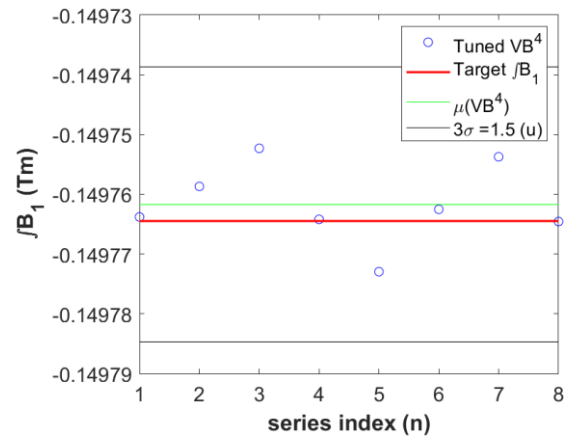
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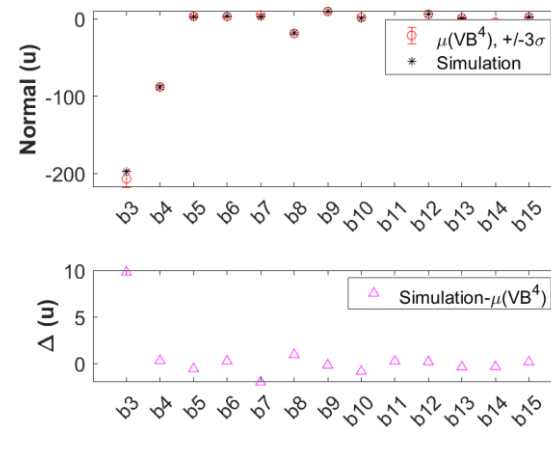
• Skew harmonics vs Simulated one



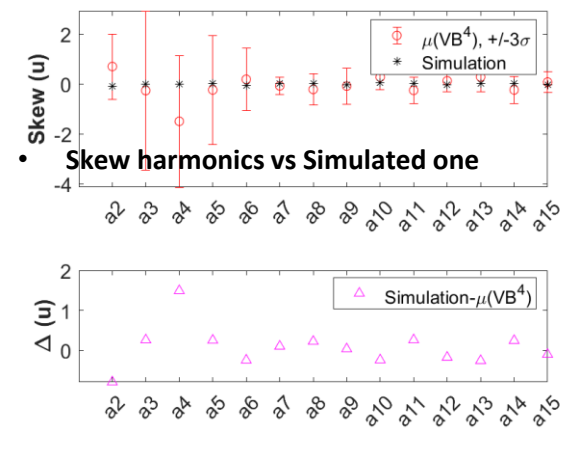
• Tuned Integral B2/ R_{ref} @ 8.8 mm



• Tuned Integral B1 @ 8.8 mm

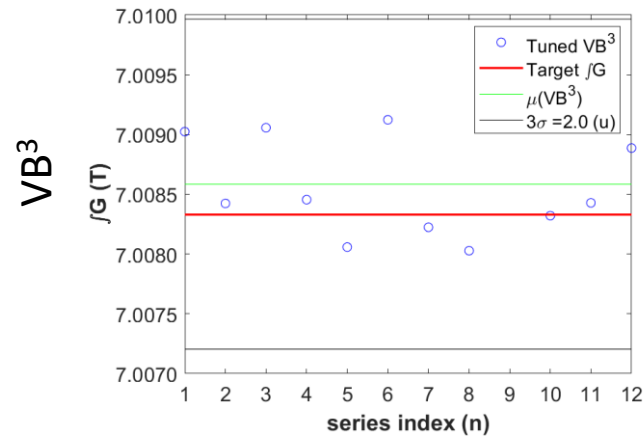


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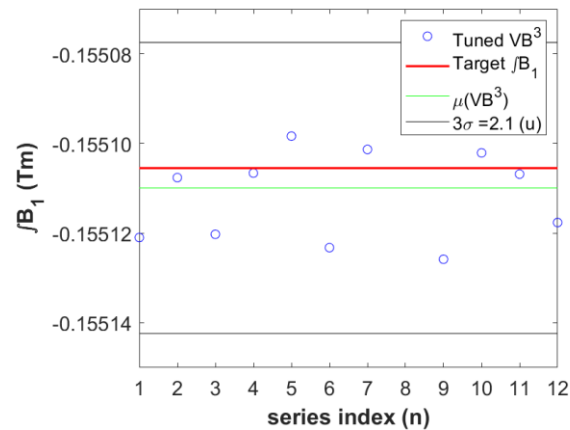


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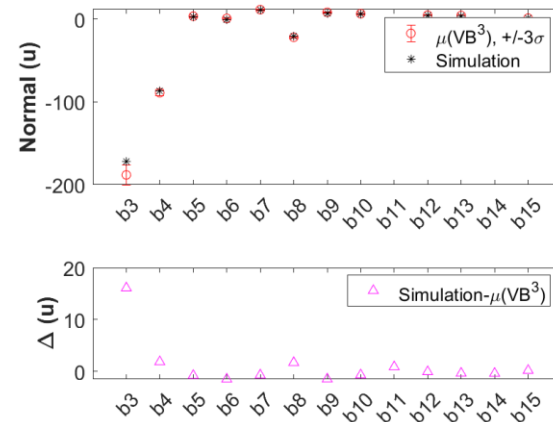
RC measurement Results: VBX(I) and VB¹



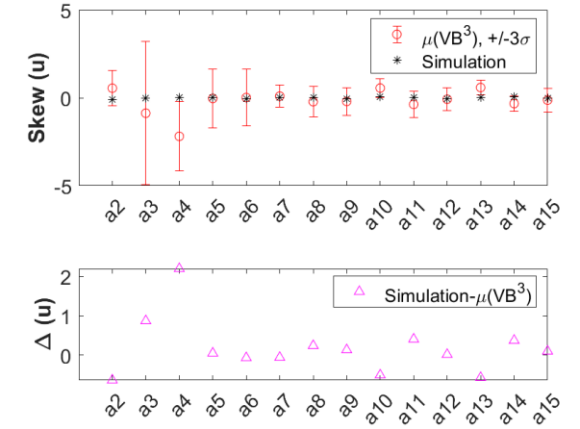
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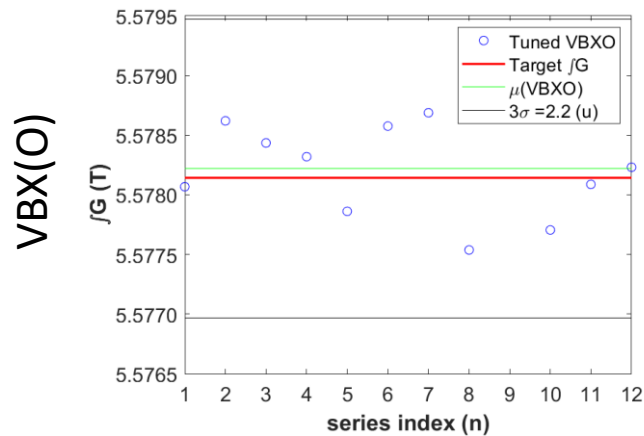
• Tuned Integral B1 @ 8.8 mm



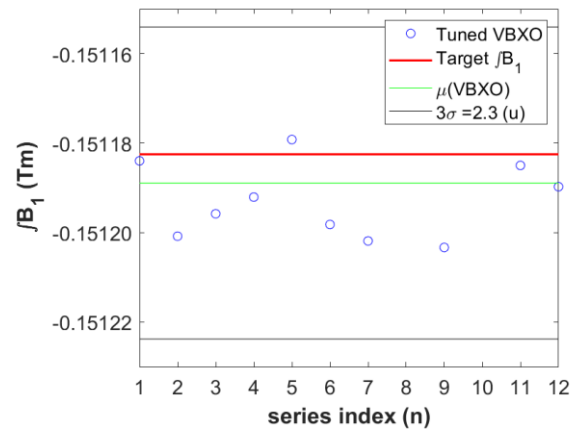
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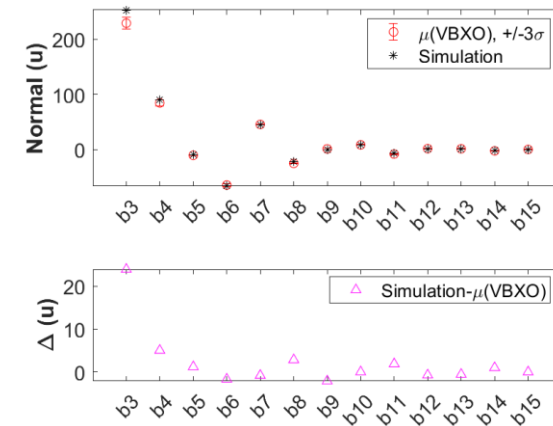
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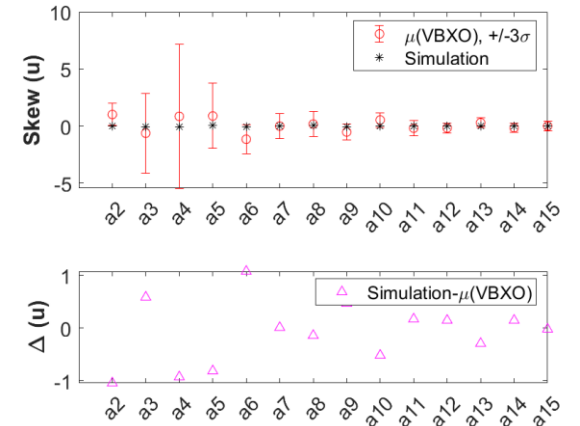
• Tuned Integral B2/R_{ref} @ 8.8 mm



• Tuned Integral B1 @ 8.8 mm

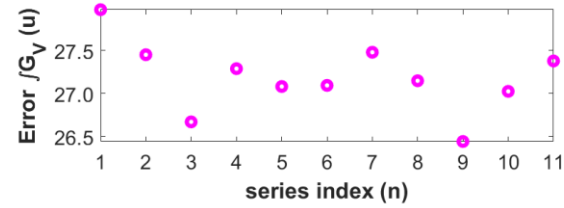
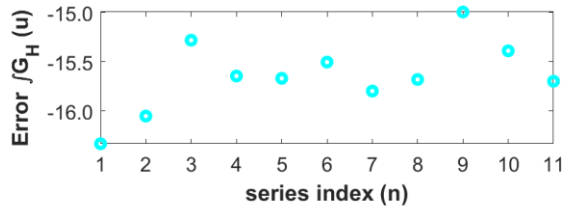


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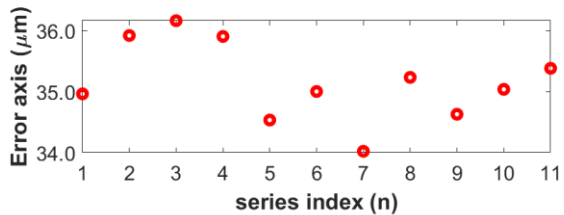
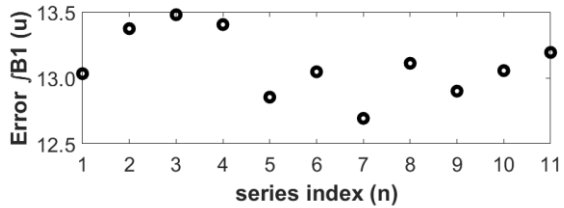


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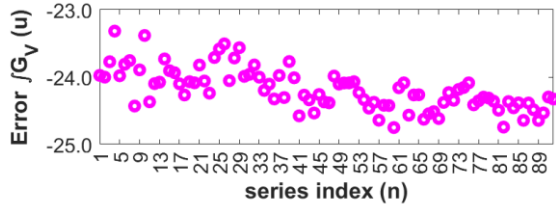
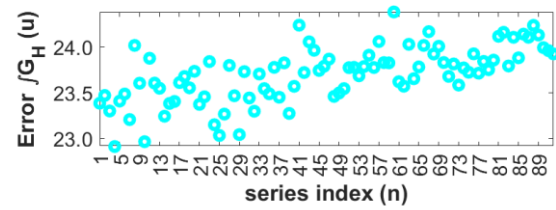
RC measurement Results: MV_W Correction(d=6.36mm)



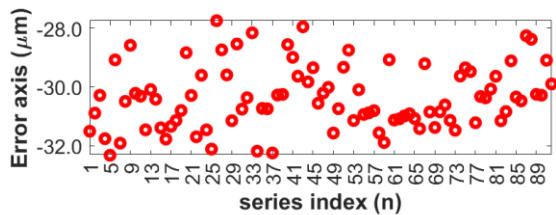
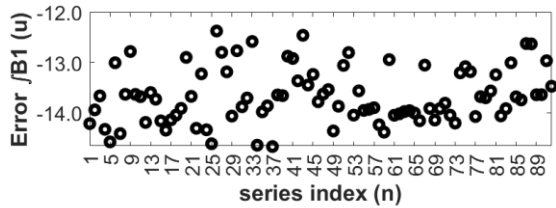
- **VBX(I) gradient error MV_W measurements**



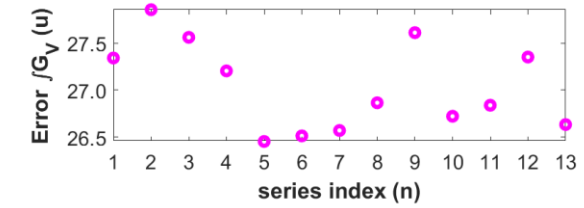
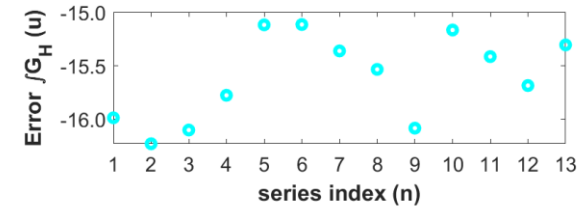
- **VBX(I) dipole error**
- **Axis error**



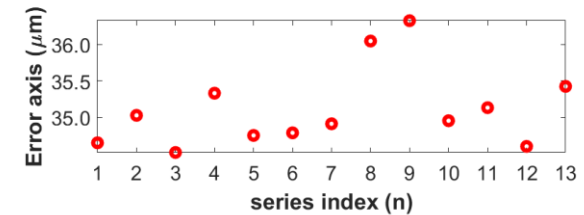
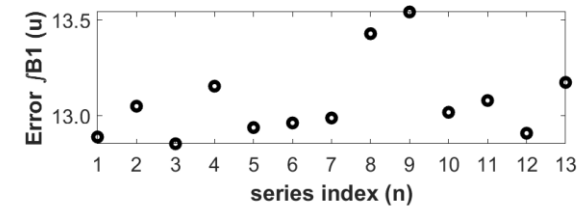
- **VB1, VB2, VB3, VB4 gradient error MV_W measurements**



- **VB1, VB2, VB3, VB4 dipole error**
- **Axis error**



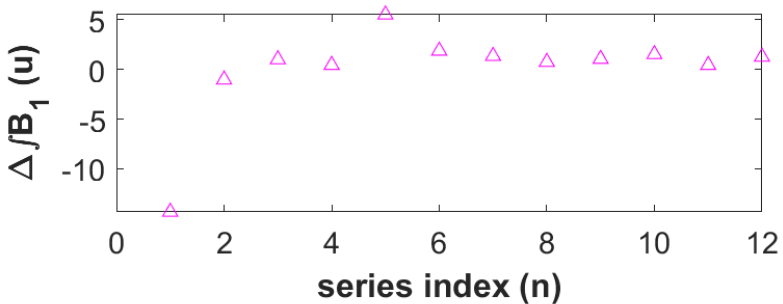
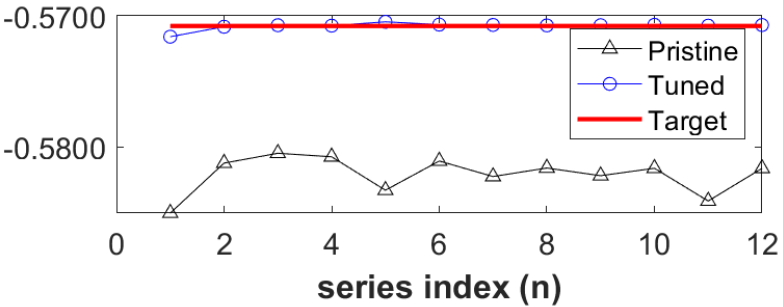
- **VBX(O) gradient error MV_W measurements**



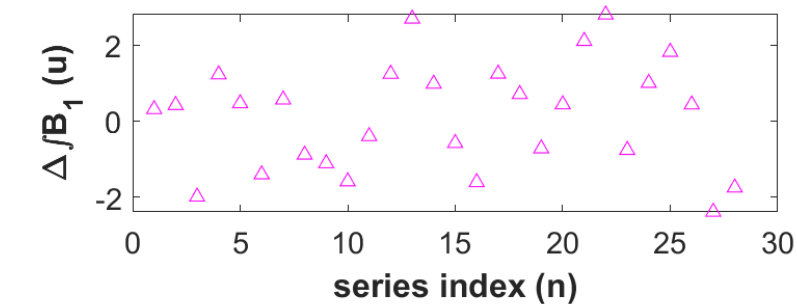
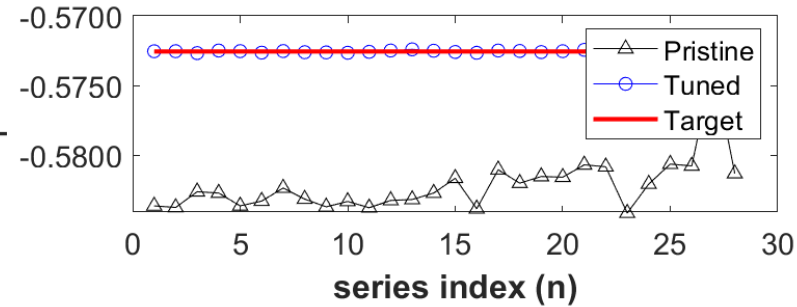
- **VBX(O) dipole error**
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- **Series Measurements Results: Moving Wire-> BN, VB, and VBX**
- Conclusions

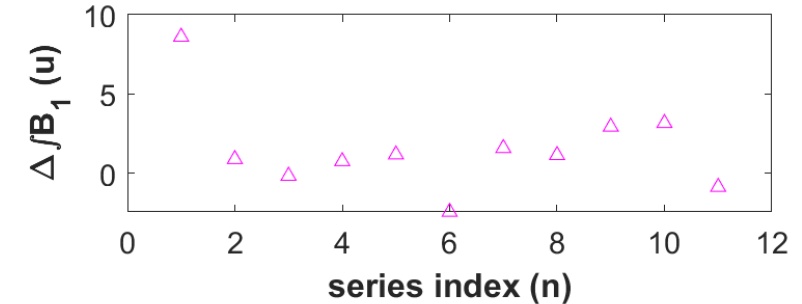
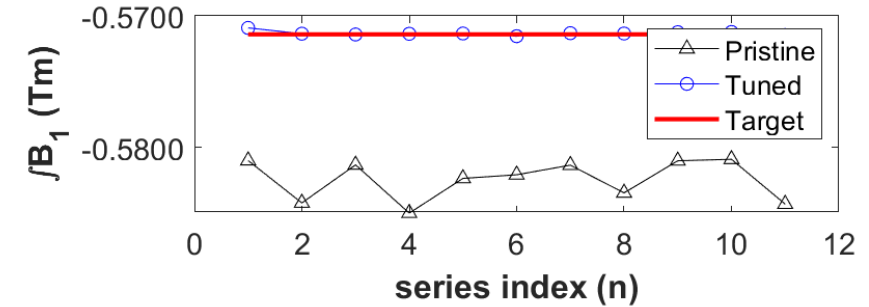
Moving Wire (d=6.36mm) Measurement Results: BN



- **BN¹**
 - Tuning process
 - Residual mismatch

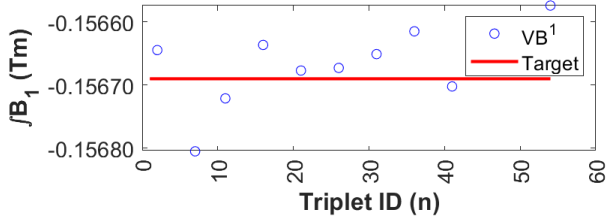
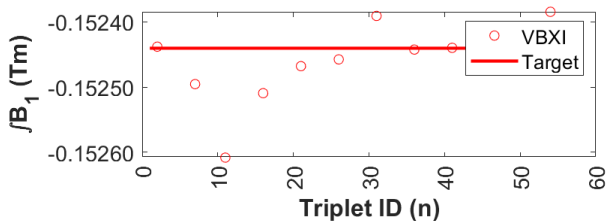


- **BN²**
 - Tuning process
 - Residual mismatch

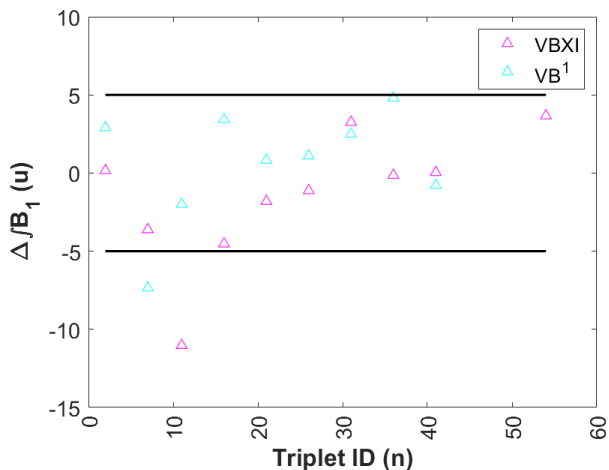


- **BN³**
 - Tuning process
 - Residual mismatch

Moving Wire Measurement Results: VBX(I) and VB1

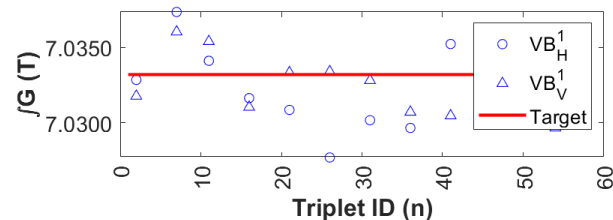
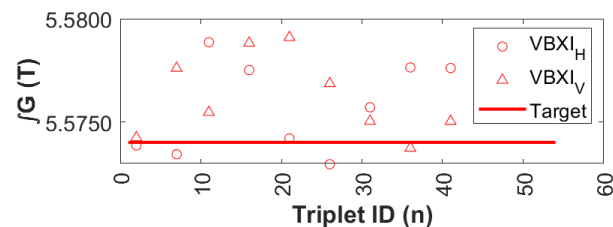


- Dipole on axis
- $d=6.36$ mm

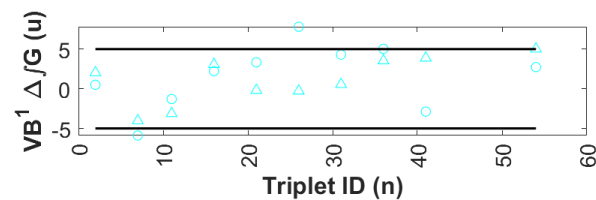
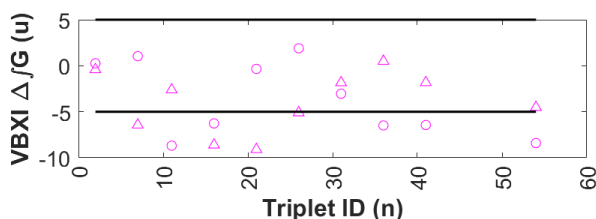


- Correction from RC measurements

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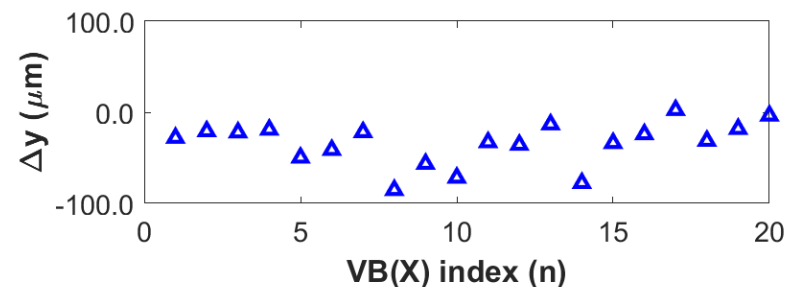
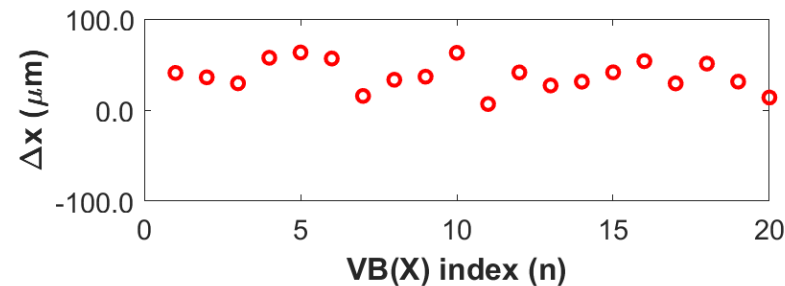


- Gradient from Horizontal and vertical measurements
- On axis $\rightarrow d=6.36$ mm



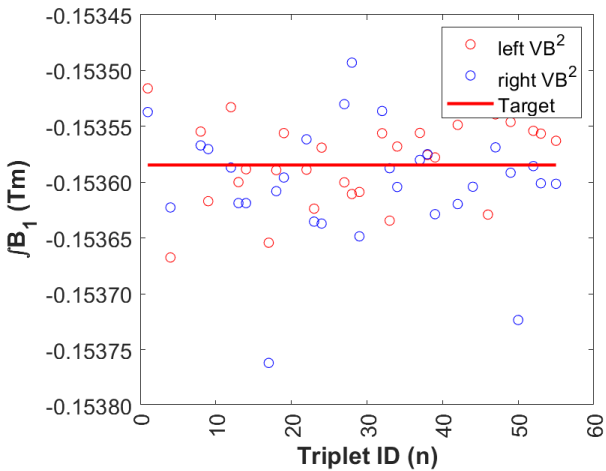
- Correction from RC measurements

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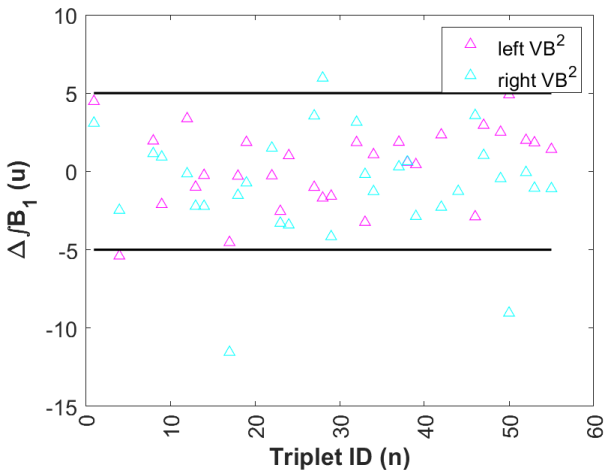


- Initial wire offset w.r.t. magnetic axis from RC axis transfer
- RC uncertainty below $100 \mu\text{m}$
- Machine requirements $30 \mu\text{m}$

Moving Wire Measurement Results: VB2

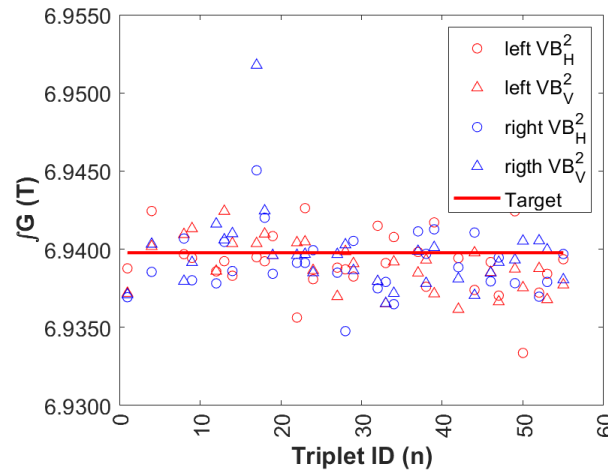


- Dipole on axis
- $d=6.36$ mm

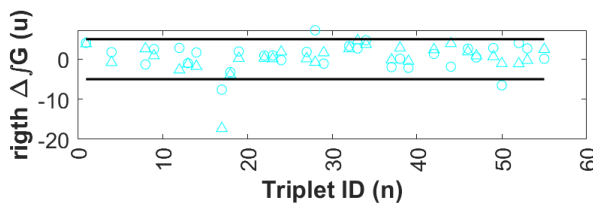
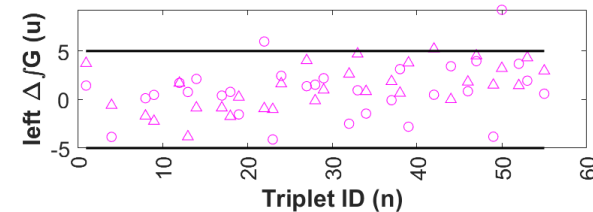


- Correction from RC measurements

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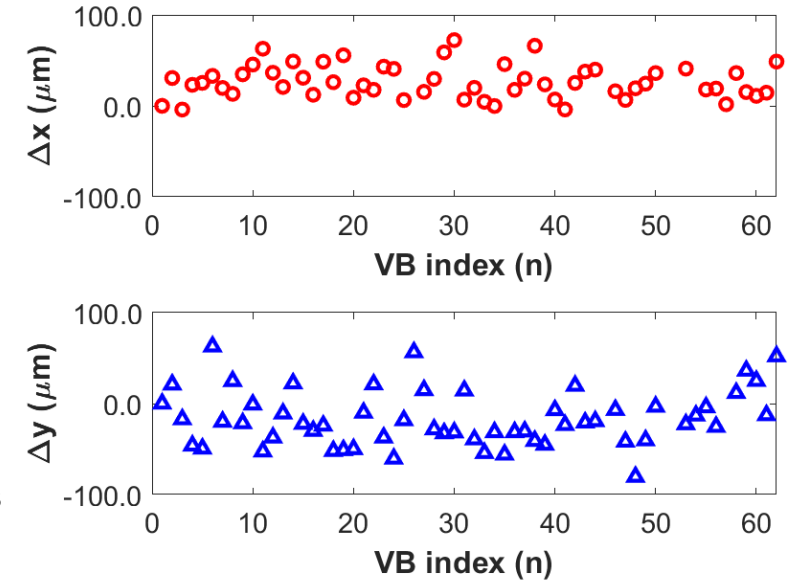


- Gradient from Horizontal and vertical measurements
- On axis $\rightarrow d=6.36$ mm



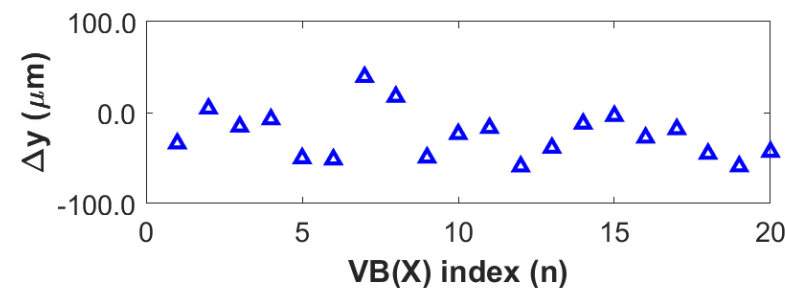
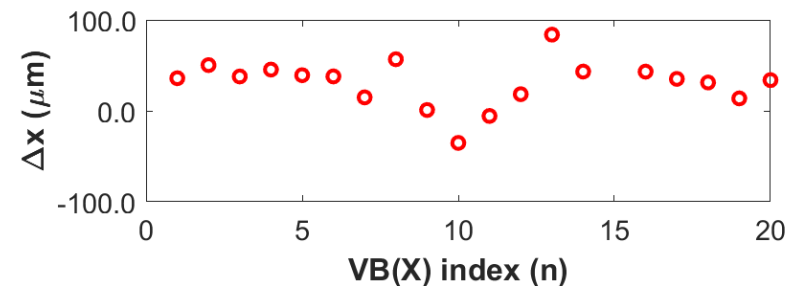
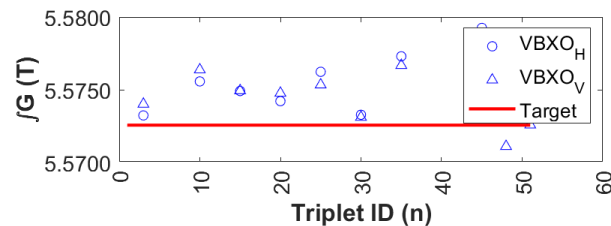
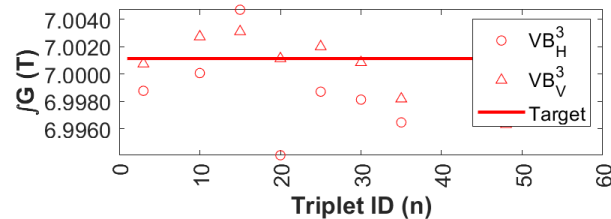
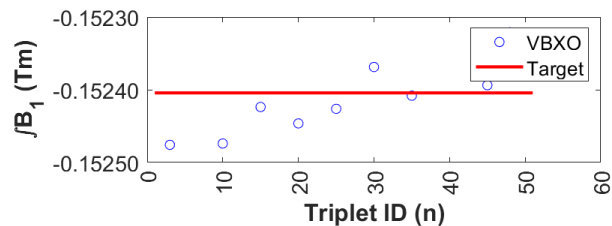
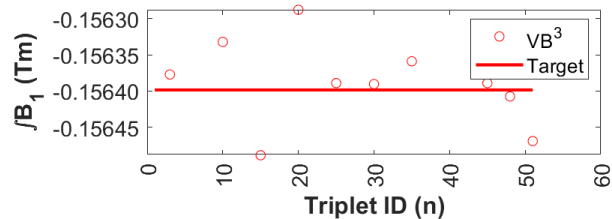
- Correction from RC measurements

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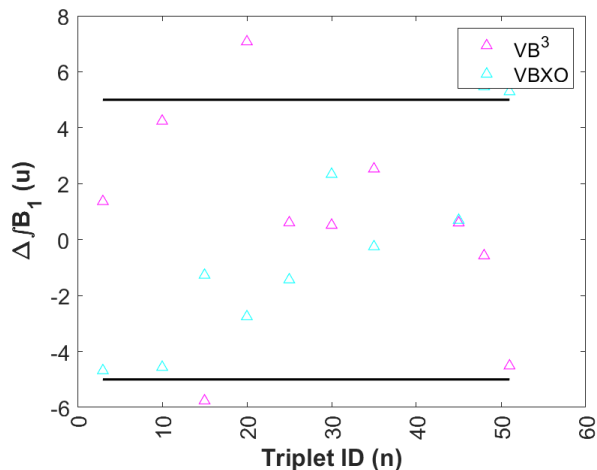


- Initial wire offset w.r.t. magnetic axis from RC axis transfer
- RC uncertainty below $100 \mu\text{m}$
- Machine requirements $30 \mu\text{m}$

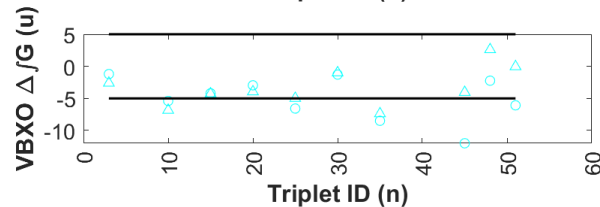
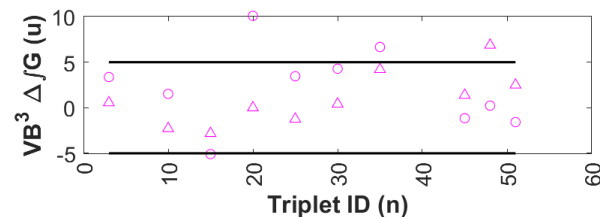
Moving Wire Measurement Results: VB and VBX(O)



- Dipole on axis
- $d=6.36$ mm



- Gradient from Horizontal and vertical measurements
- On axis $\rightarrow d=6.36$ mm



- Initial wire offset w.r.t. magnetic axis from RC axis transfer
- RC uncertainty below $100 \mu\text{m}$
- Machine requirements $30 \mu\text{m}$

- Correction from RC measurements

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- Correction from RC measurements

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- The SLS2.0 Arc
- The Triplet's Magnets
- Measurements' Challenges & Requirements
- Measurement Procedures
- **Series Measurements Results: Moving Wire-> Triplets**
- Conclusions

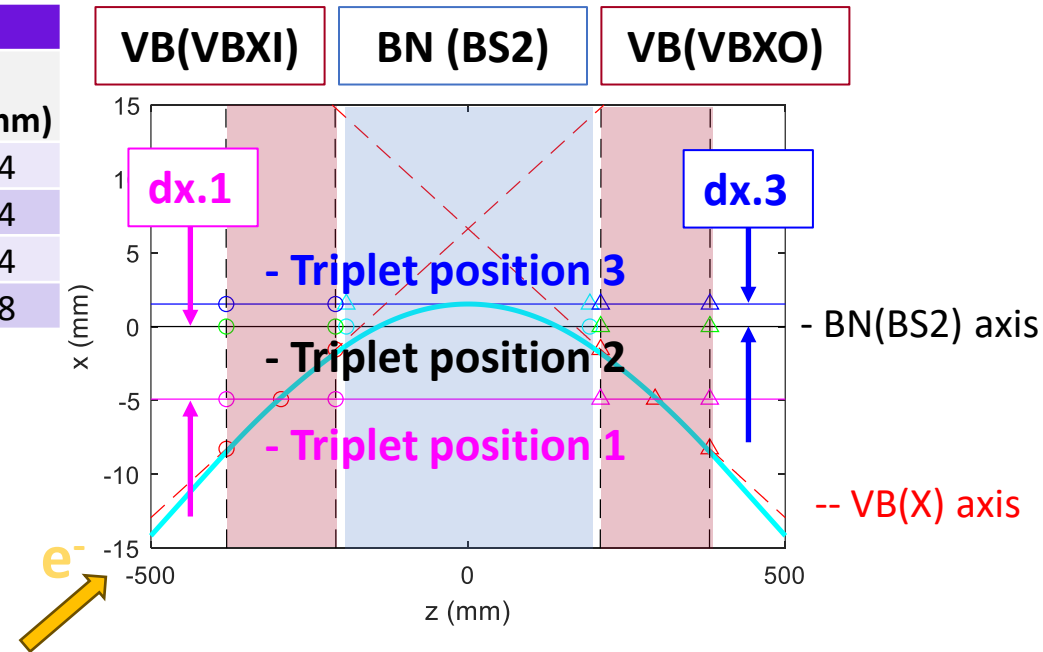
Moving Wire Measurement: Triplets Tuning

	Pos.1			Pos.2			Pos.3		
Triplet Type	$\int G$ (T)	$\int B_1$ (Tm)	dx.1 (mm)	$\int G$ (T)	$\int B_1$ (Tm)	dx.2 (mm)	$\int G$ (T)	$\int B_1$ (Tm)	dx.3 (mm)
VBX(I)-BN ¹ -VB ¹	14.002	-0.87687	-4.920	13.920	-0.80819	0	13.860	-0.78761	1.484
VB ² -BN ² -VB ²	15.356	-0.87746	-4.914	14.839	-0.80328	0	14.617	-0.78088	1.524
VB ³ -BN ³ -VBX(O)	13.969	-0.87709	-4.921	13.884	-0.80857	0	13.824	-0.78804	1.484
VB ⁴ -BN ⁴ -VB ⁴	15.282	-0.87619	-4.922	14.799	-0.80217	0	14.510	-0.77309	1.988

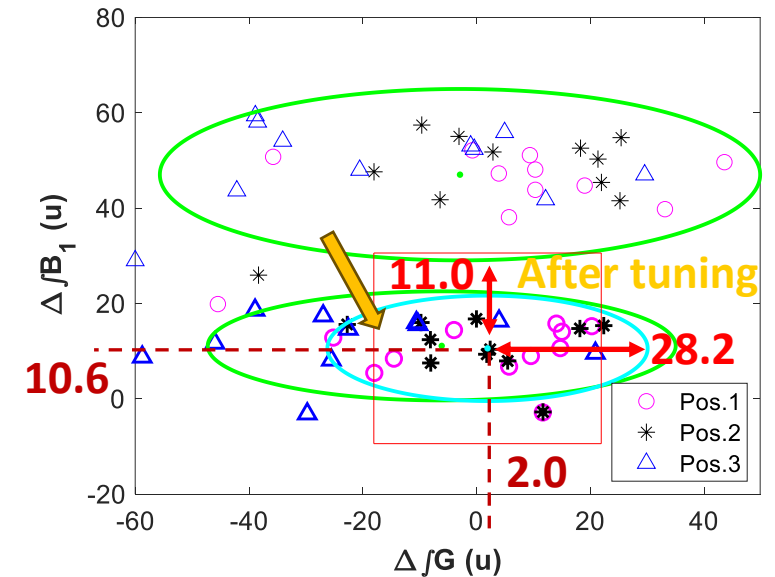
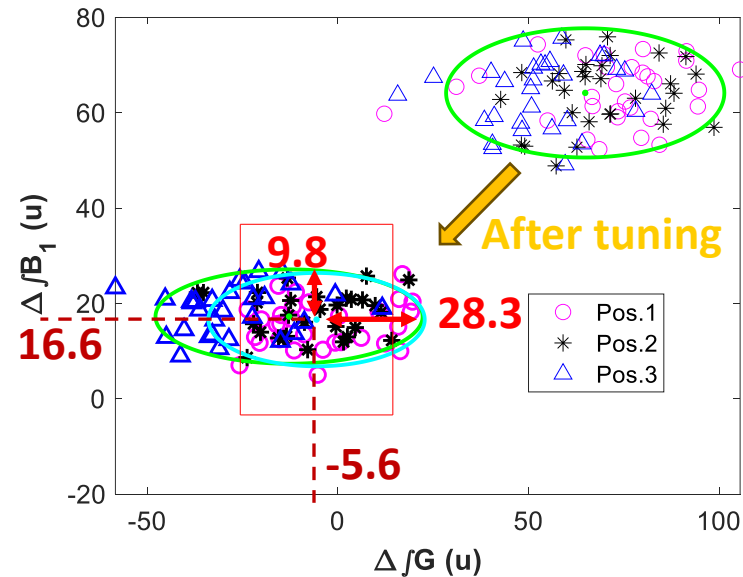
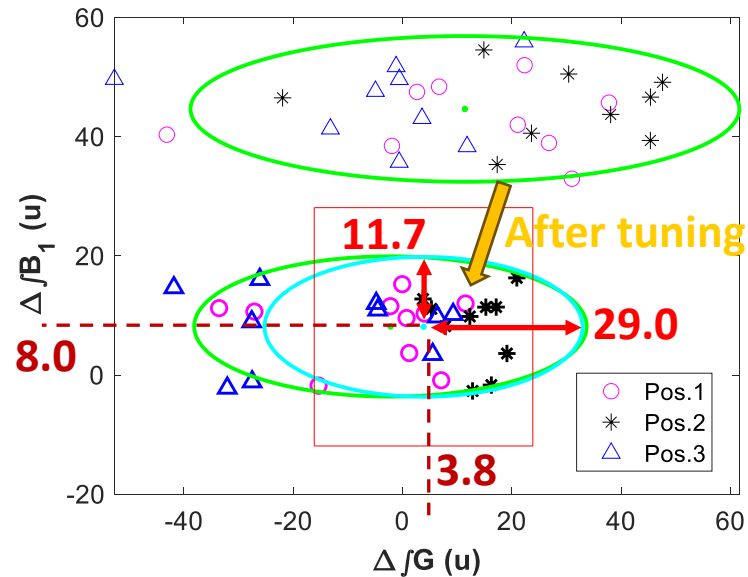
Tuning Strategy

- A. Initial measurement set on the calculated 3 positions
- B. Differences from model assessed
- C. Tuning strategy
 - i. Adjust moderator plates VB(X) to minimize gradient difference
 - ii. Use wire offset on the 3 positions to accommodate dipole residual mismatch

Wire displacement $d=3.5$ mm to minimize multipole effects



Moving Wire Measurement Results: Triplets



- Triplets VBX(I)-BN¹-VB¹
- Residuals of integral dipole vs gradient

- Triplets VB²-BN²-VB²
- Residuals of integral dipole vs gradient

- Triplets VB³-BN³-VB³O
- Residuals of integral dipole vs gradient

- ✓ During series, Triplets tuning process successful mainly on position 1 and 2
- ✓ At position 3 data have a higher spread
- ✓ Systematics are within specs

- The SLS2.0 Arc
- The Triplet's Magnets
- Measurements' Challenges & Requirements
- Measurement Procedures
- Series Measurements Results: Moving Wire-> Triplets
- **Conclusions**

CONCLUSIONS

- A complex measurement procedure was devised and resulted effective
- A model-based Triplet tuning process gave good results
- Time schedule is going to be respected (3 triplets every two weeks since beginning of this year)
- Tomorrow Triplet 55 (hopefully) will be delivered out of 60
- It has been an incredible journey: Thanks to everybody has been involved