HEBT-Ring-RTBT Physics Design and Issues

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SNS/BNL

November 4-6, 2003

DOE 03/11/4-6

Ring AP Activities

- **Identifying and Solving problems:**
  -High Multipoles in 30Q44/30Q58 Quad
- **Improvements:**
  -Sorting schemes to minimize effect of nonlinear resonances
  -Nonlinear resonances and their correction
  -Emittance growth due to “banana-shape effect” - c.o. offset in Kickers
  -Understanding of working of clearing electrode for e-p
  -Extraction kicker impedance measurements
  -Reduction of ELS Multi-poles
- **Quality Assurance:**
  -Checking magnet and power supply parameter list
  -Accepting magnets and ½ cells
- **Installation and Commissioning Support:**
  -Sorting dipoles and quadrupoles
  -Magnet assignment to lattice
  -Global coordinates
  -Checking installation drawings

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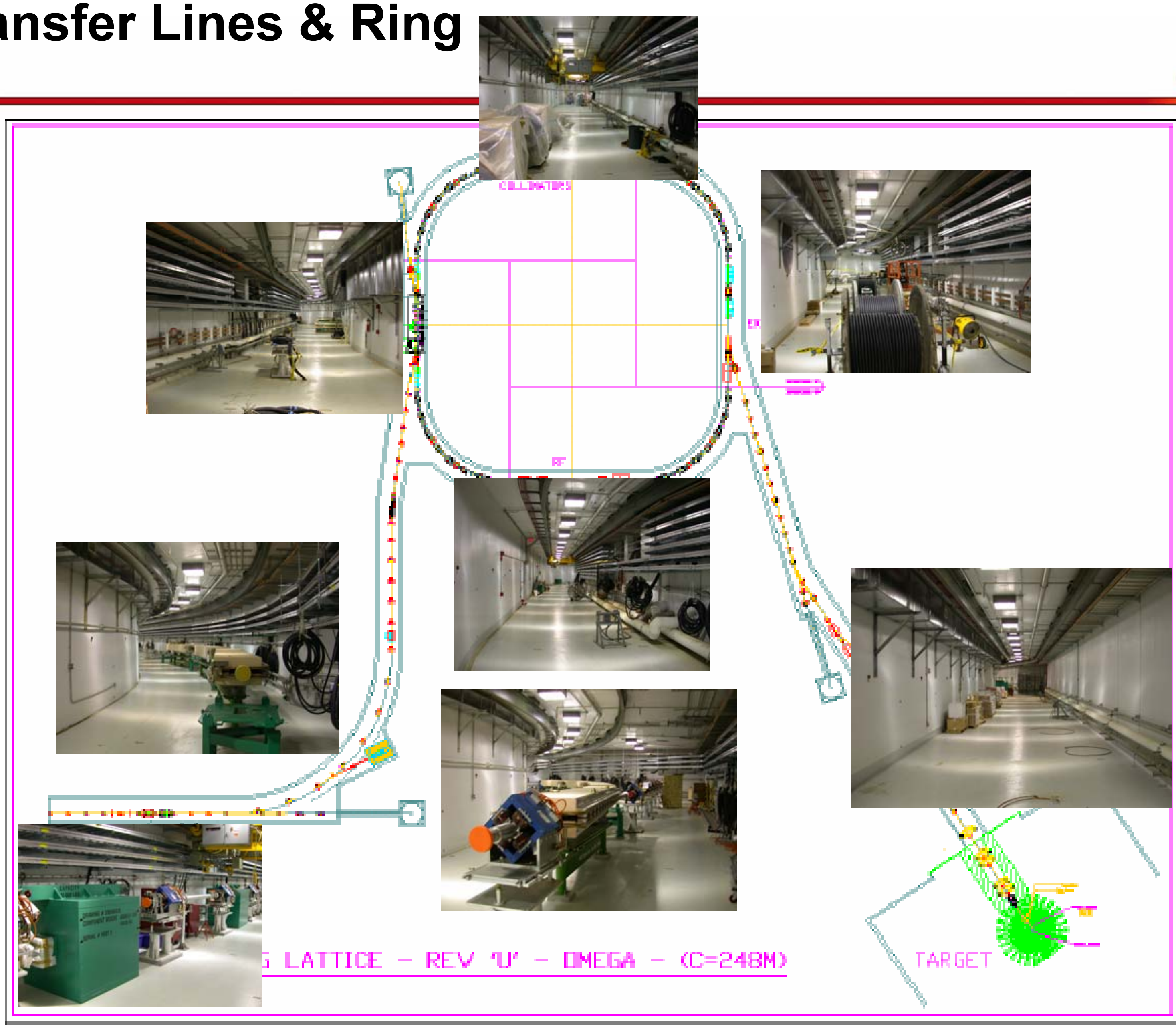
Acknowledgements

Contributors :

M. Blaskiewicz, P. Cameron, A. Fedotov, C. Gardner, H. Hahn, J. Jackson, A. Jain, Y. Y. Lee, N. Malitsky, W. Meng, G. Parzen, S Tepikian,N. Tsoupas ,L. Wang, J. Wei, S.Y. Zhang

S. Cousineau,V. Danilov S. Henderson, J. Holmes, J. Galambos, M. Plum

Transfer Lines & Ring



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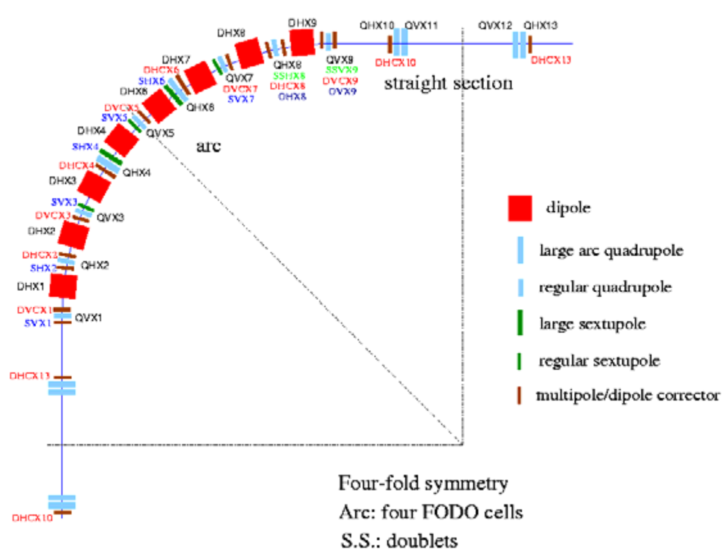
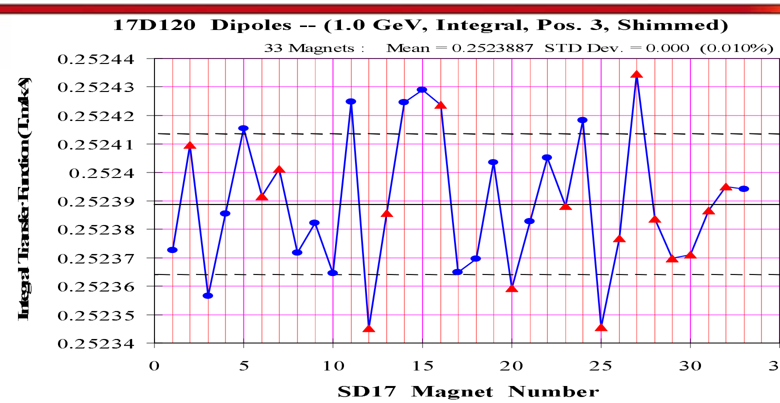
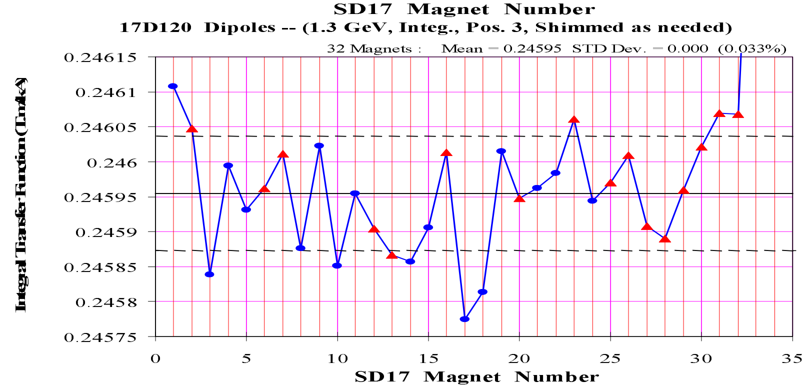
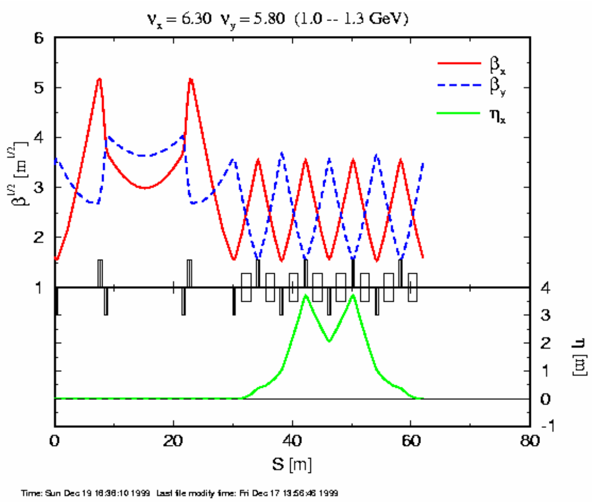
RING Dipole Sorting

(D. Raparia, Y. Y. Lee, A. Fedotov et al.)









- **Ring dipoles need to be sorted for 1.3 GeV operation**
- **Pair the out of range dipoles in the arcs**

-Place two dipoles of equal errors 180° apart in phase for cancellation

-Or place two dipoles with opposite errors 360° apart

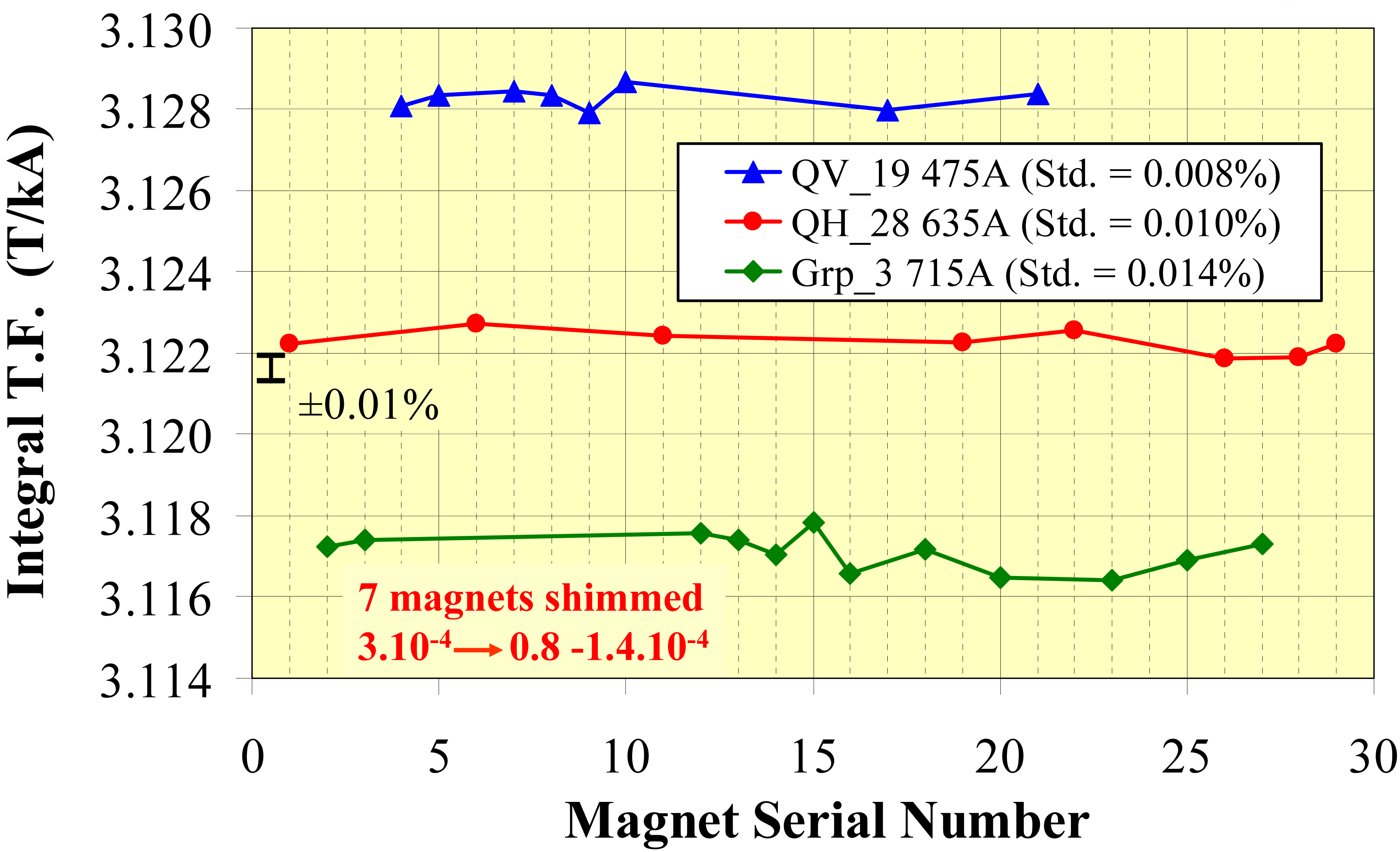
1GeV: sorted: max COD - 1.2mm (within corrector capability)

1.3 GeV: unsorted: max COD – 7mm;

sorted: max COD - 2.5mm (within corrector capability)

21Q40 I.T.F. Trend Plots at 1.0 GeV

(P. Wanderer, A. Jain, J. Jackson, et al.)



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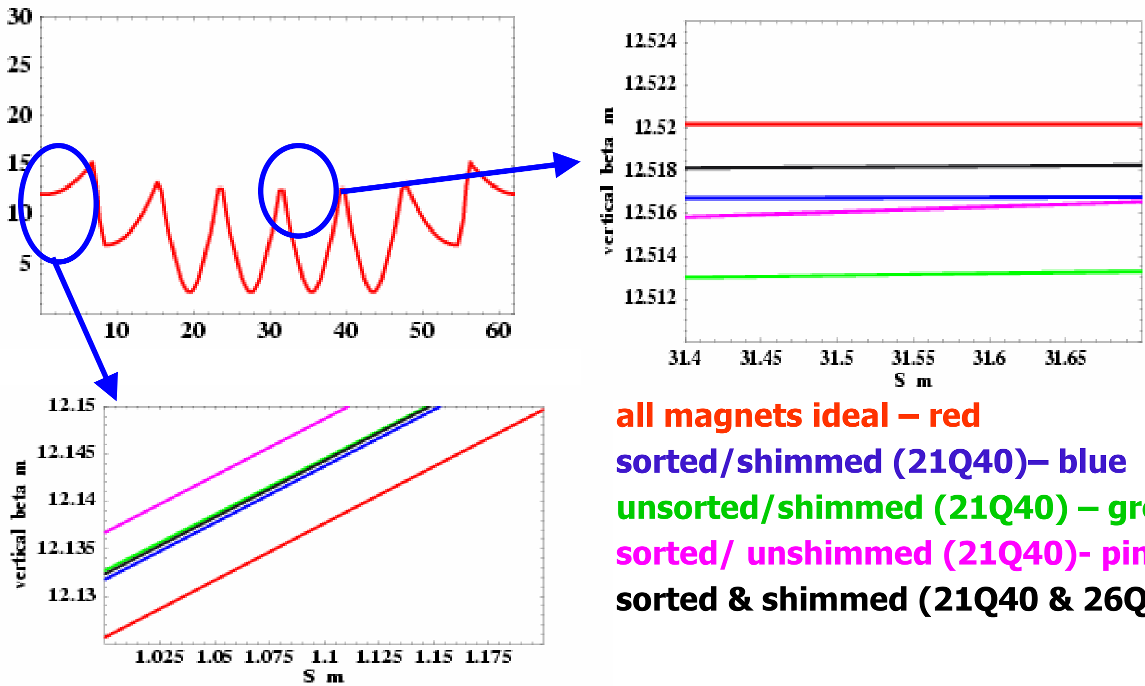
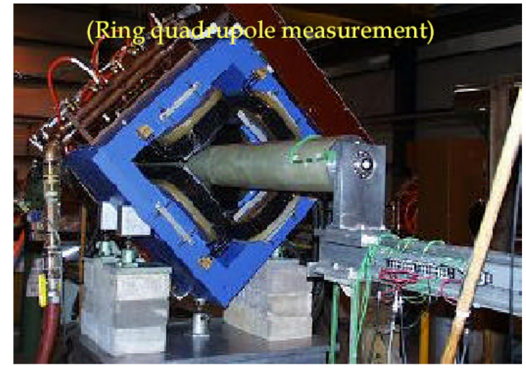
RING Quad Sorting

(D. Raparia, Y.Y. Lee, A. Fedotov et al.)





all magnets ideal – red
sorted/shimmed (21Q40)– blue
unsorted/shimmed (21Q40) – green
sorted/ unshimmed (21Q40)- pink
sorted & shimmed (21Q40 & 26Q40) -black

	Ideal-base case	Sorted/ shimmed 21Q40	Sorted/ unshimmed 21Q40	Unsorted/ shimmed 21Q40	Sorted/ shimmed 21Q40 & 26Q40
Q_x	6.22984	6.22985	6.22975	6.22984	6.22986
Q_y	6.19986	6.19985	6.20038	6.19989	6.19985
ΔQ_x		$+1*10^{-5}$	$-1*10^{-4}$	$< 1*10^{-5}$	$+2*10^{-5}$
ΔQ_y		$-1*10^{-5}$	$+5*10^{-4}$	$+3*10^{-5}$	$-1*10^{-5}$

We are interested only in $1*10^{-3}$ accuracy

- Two string of 8 ,21Q40
- One string of 12, 21Q40
- One string of 8, 26Q40
- All 21Q40 were sorted and 7 were shimmed. Three 26Q40 were shimmed and one re-aligned
- **All measured quads=> 0.05% beta wave for and 10^{-5} tune shift.**

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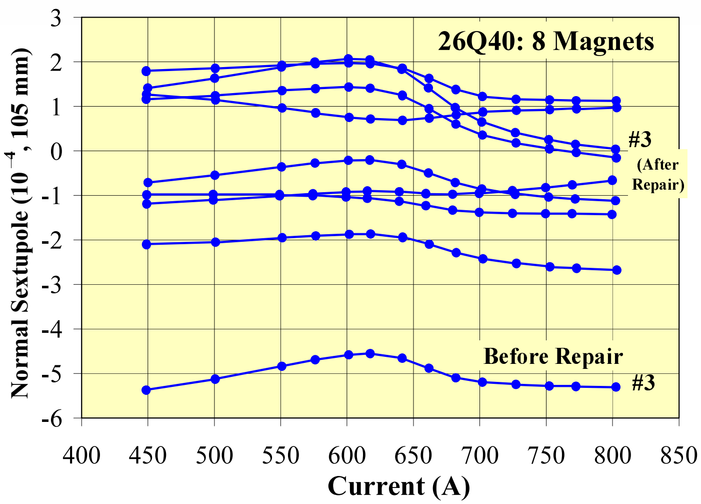
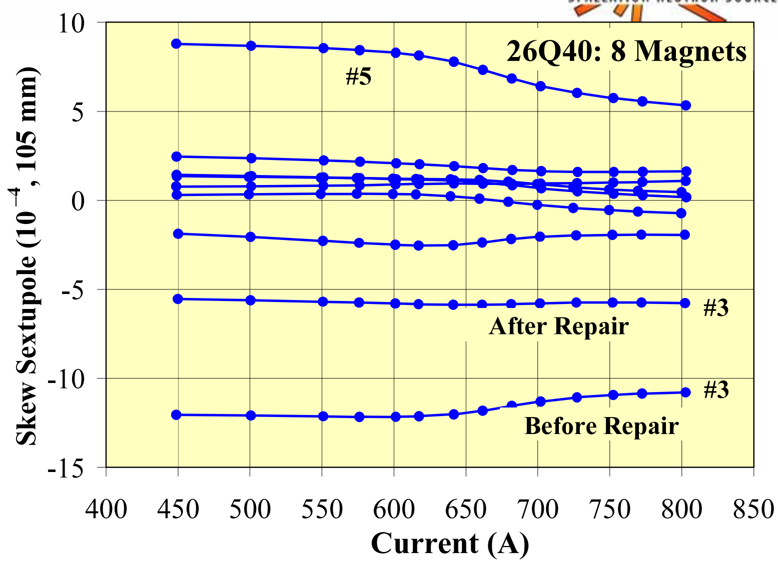
26Q40 Quadrupoles: Multipoles

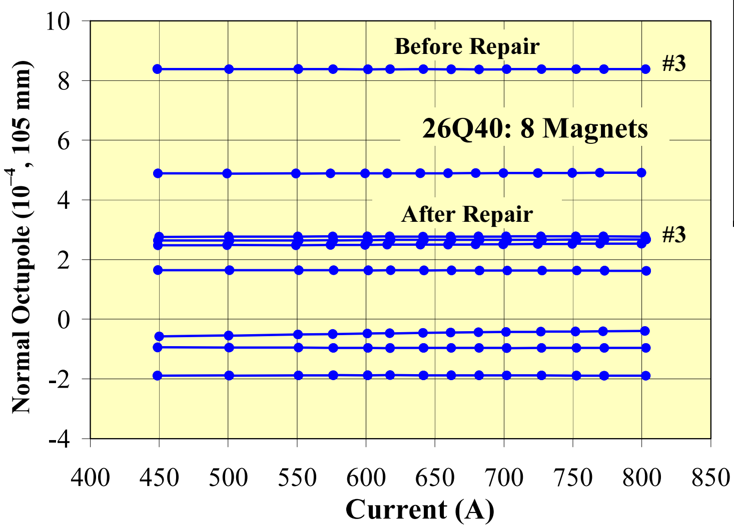
(P. Wanderer, A. Jain, J. Jackson, et al)

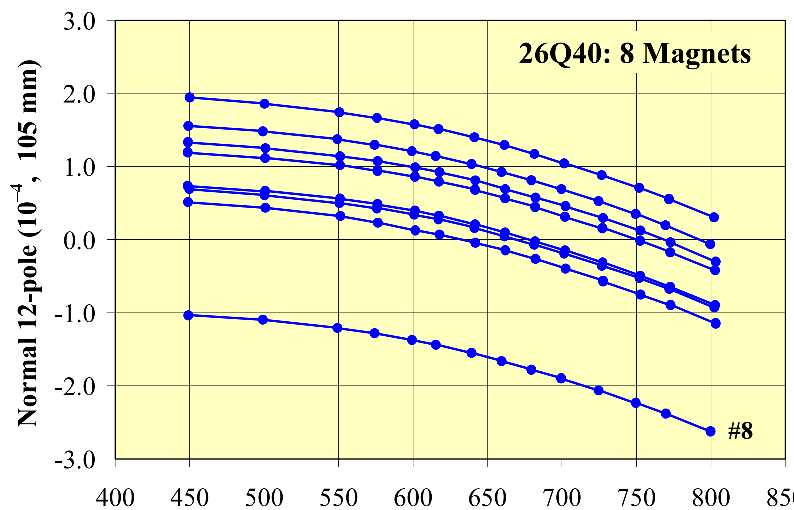


Harmonics at reference radius (480 π mm mrad)

N	RMS (10^{-4})
b_2	1.35
a_2	3.27
a_3	2.53
b_6	0.95
b_{10}	0.36







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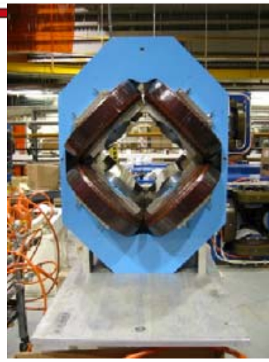
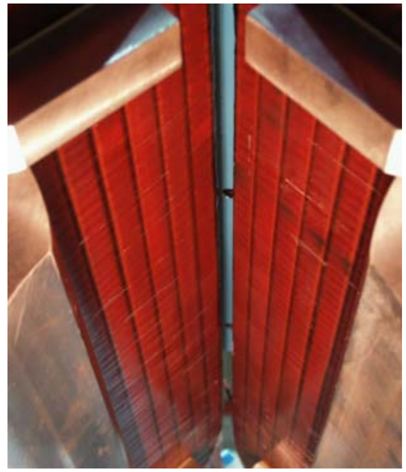
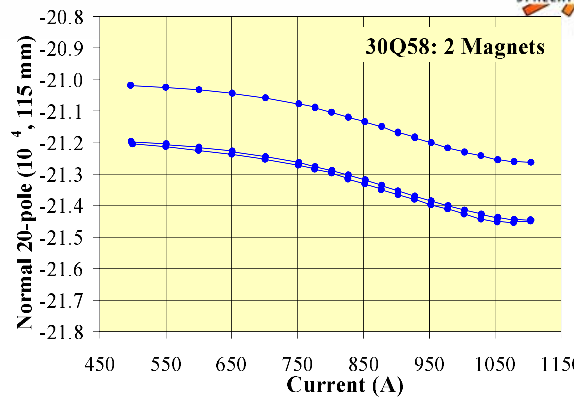
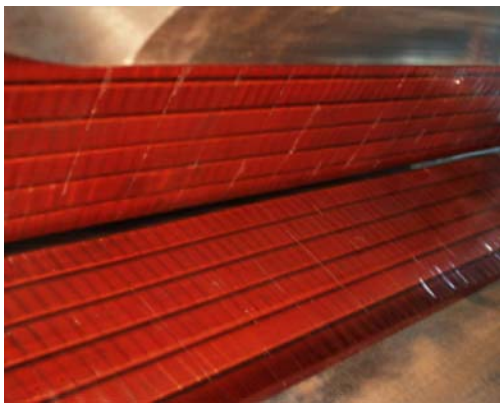
30Q58 Measurements and Coils Position Relative to Poles

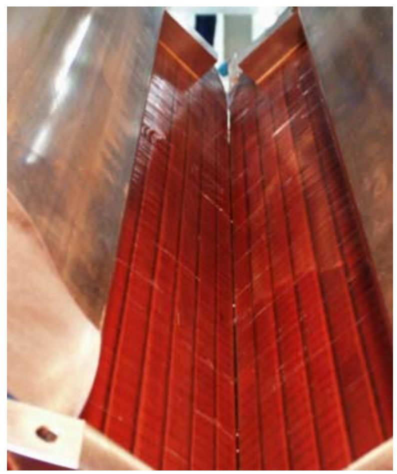
(P. Wanderer, A. Jain, J. Jackson, et al)

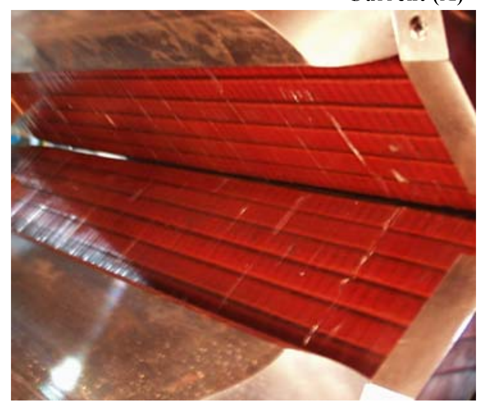


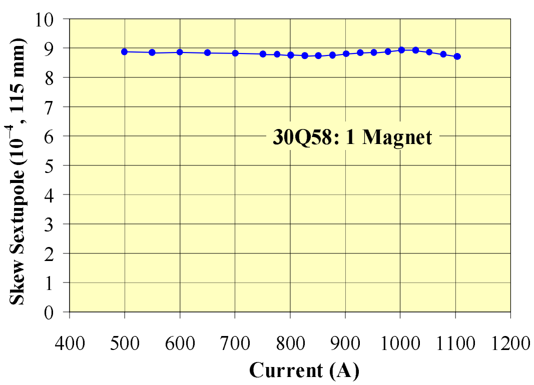












-b_2 and a_2 are related to manufacturing error and can be corrected

-20-pole are by design and have negligible effect on emittance .

2D simulation for 30Q58

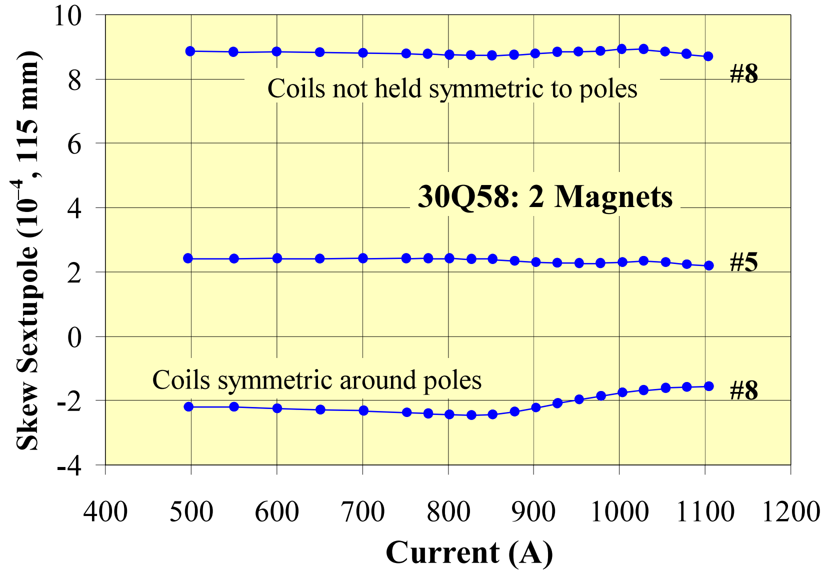
(N. Tsoupas, A. Jain, J. Jackson, et al)

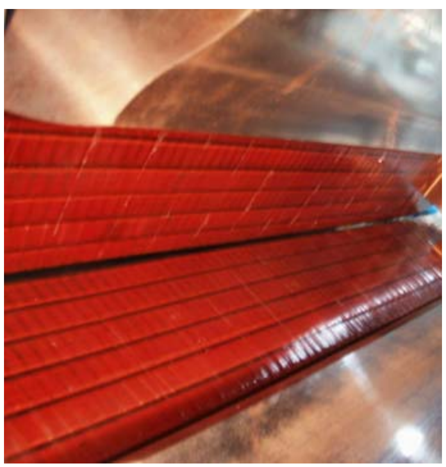
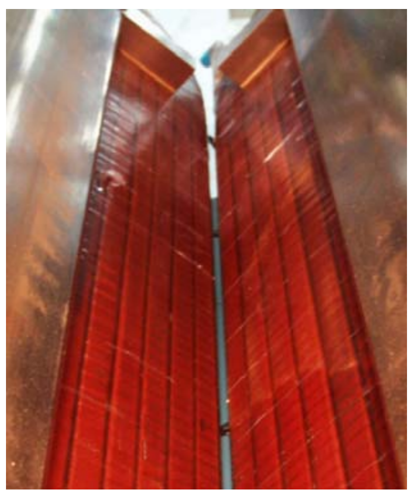
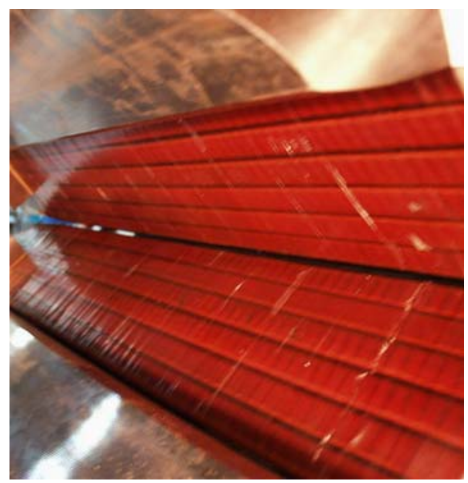
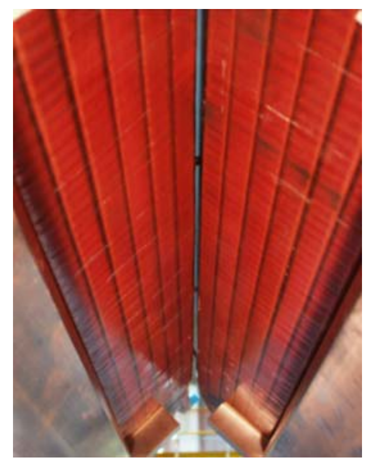
	B_rho=B1cos(2q)+B2cos(4θ)		+A1sin(2θ)+A2sin(4θ)-	Radius=12.78 cm
	Normal Bn	Normal Bn	Skew An	Skew An
Multipole	Symmetric coil	Assymetric coil	Symmetric coil	Assymetric coil
Quad	10000.00	10000.00	0.05	0.05
Sex t	0.00	0.00	0.00	23.26
Oct	0.00	-0.02	0.00	0.00
Dec	0.00	0.00	0.00	15.70
Duo	-0.08	-0.04	-0.02	-0.02
14 pole	0.00	0.00	0.00	10.33
16 pole	0.00	-0.01	0.00	0.00
18 pole	0.00	0.00	0.00	1.23
20 pole	-42.00	-42.00	-0.01	-0.01
22 pole	0.00	0.00	0.00	1.03
24 pole	0.00	0.00	0.00	0.00
26 pole	0.00	0.00	0.00	-0.30
28 pole	-24.00	-24.00	0.05	0.05

30Q measurement and Strategy

"The only way to escape a problem is to solve it"

- Fix the coil problem for all quads
- Choose 16 quads out of 24
- If ITF less than desire shim poles to achieve 10^{-4} tight field variations
- Sort for reduce 3rd order resonance
- Fix any other problem e.g. pole alignment like 26Q40



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Design Requirement of #2 and #3 Chicane Magnets

(W. Meng, YY Lee, J. Jackson et al)

#2 --- Bo=3.0 kG

B (foil) = 2.5 kG > B(bottom);

$\tan^{-1}$(Bz/By) >>65 mrd

Gap = 23.5 cm (8.750 inch)

#3 --- Bo = 2.4 kG (must smaller than 2.5 kG)

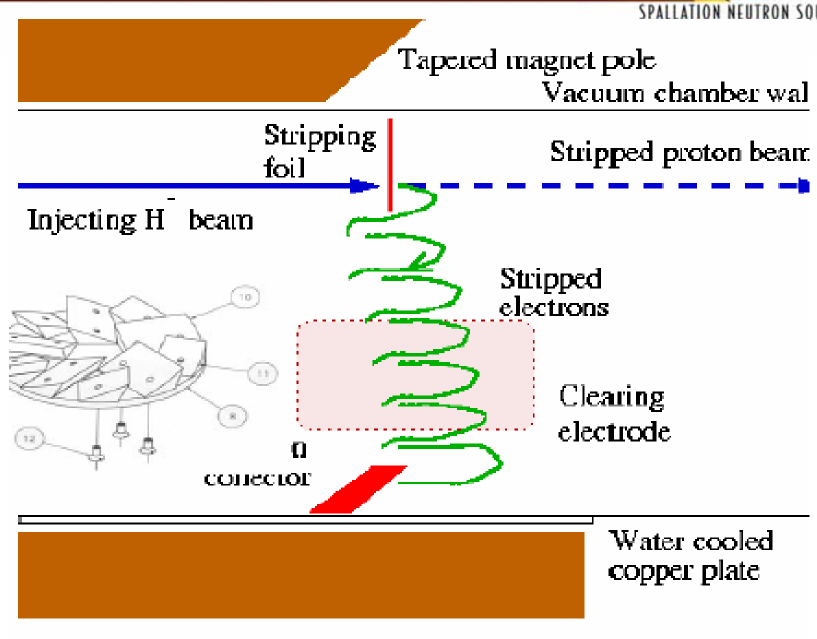
Distance (center to center) = 181.4 cm

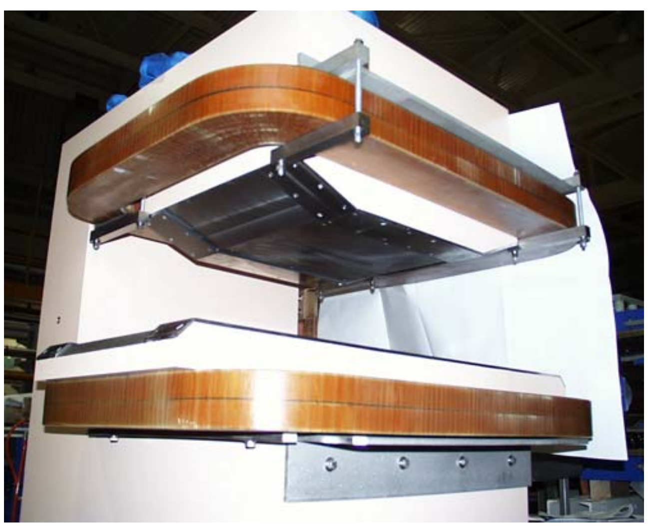
Field Integrals

$\int_{-\infty}^{\mathrm{Foil}}$ **By**= 237.6 kG-cm $\int^{\infty}_{\mathrm{Foil}}$ By = 261.4 kG-cm

Two C magnets = 499 ± 5×10^{-4} kG-cm,

Goal <1×10^{-3} error





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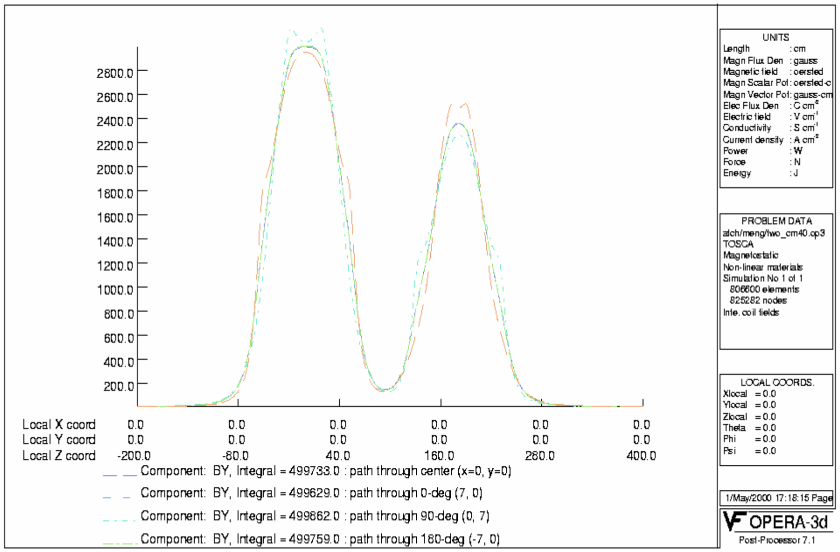
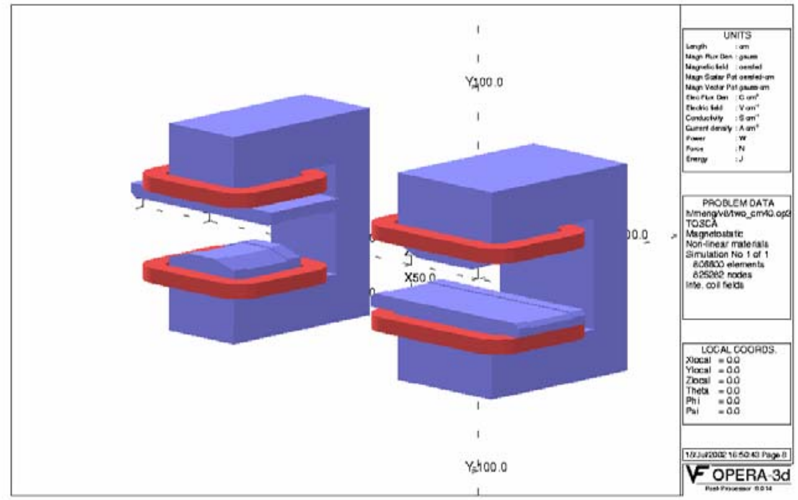
Total Integral for Chicane #2 & #3

(W. Meng, Y.Y. Lee, J. Jackson, et al)





- Total Integral along 0, 90, 180, 270 degree lines

Foil Location (0, 2, 30.7 cm)

By = 2.50 kG; Bz = -0.532 kG;

|B|=2.556 kG; $\tan^{-1}(Bz/By) = 0.2$ rad

Bottom pole B = 2.475 kG near the foil

$\int_{-\infty}^{foil} By = 237997$ g-cm,

$\int_{foil}^{\infty} By = 261751$ g-cm

Total Integral 2&3 499712.5 g-cm ±3.2×10^{-4} (R=7cm)

Operation current:

#2 I = 2168 A, N = 14 turn (per pole)

#3 I = 1716 A, N = 14 turn (per pole)

Integrated Multipoles (R=8 cm; z from –200 to 400 cm)

n	$\int (b_n)/(b_1)$	$\int (a_n)/(b_1)$
1	1.00000e+00	0.00000
2	-2.70378e-04	1.28250e-05
3	-1.81282e-04	-1.05606e-05
4	1.42300e-04	-4.70315e-06
5	1.77773e-04	-4.11747e-07
6	1.72624e-05	9.51574e-06

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Chicane #2 & #3 Measurement & Simulations

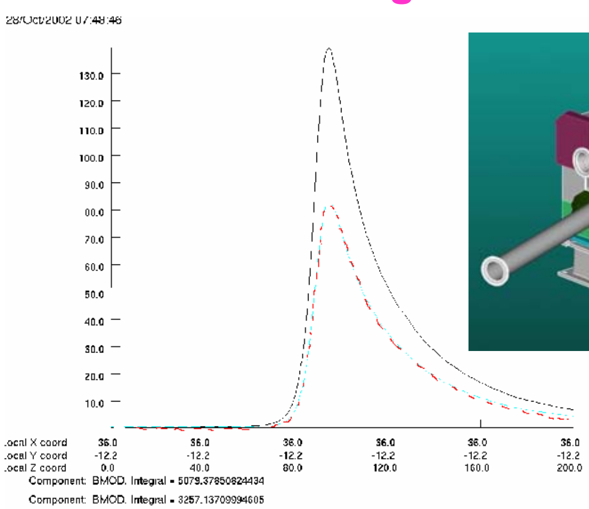
(J.. Jackson, W. Meng, Y.Y. Lee al)

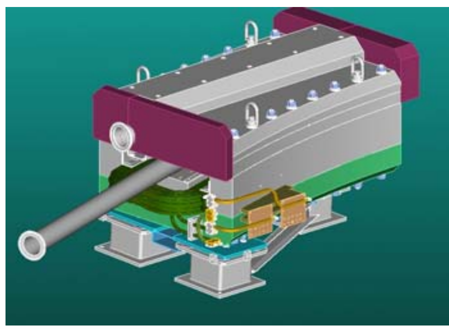
			#2				
	Simulation				Measurement		
(Integral from -3ft to +3ft)				(Coil total length = 6ft)			
(Expansion B_r on R=8.0 cm)				**(B_r Based Expansion R=7.94 cm)**			
N	An (%)	Bn (%)		N	An (%)	Bn (%)	
1	-	100		1	0.080	100	
2	1.140	-0.020		2	1.200	-0.030	
3	-0.072	-0.026		3	-0.080	-0.080	
4	0.069	0.015		4	0.080	0.010	
5	-0.005	-0.003		5	0.000	0.000	
			#3				
1		100		1	-0.080	100.000	
2	-1.7	-0.1		2	-1.660	-0.070	
3	0.11	-0.02		3	0.090	-0.100	
4	-0.1	0.01		4	-0.110	0.010	
5	0.01	0		5	0.000	0.000	

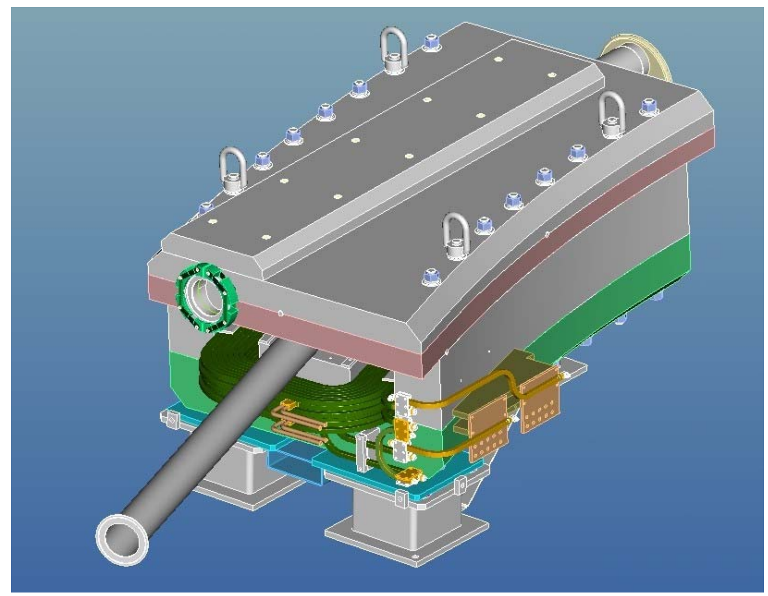
The ELM design

(N. Tsoupas, J. Rank, Bill McGahern)

- **The Extraction can accommodate all four working points. (6.23,6.20; 6.3,5.8; 6.4,6.3; 6.23,5.24)**
- **Minimize the fringe field at the circulating beam region of the Lambertson magnet. The effect of the fringe field on the circulating beam is negligible .**
- **New Coil design to reduce resistance.**

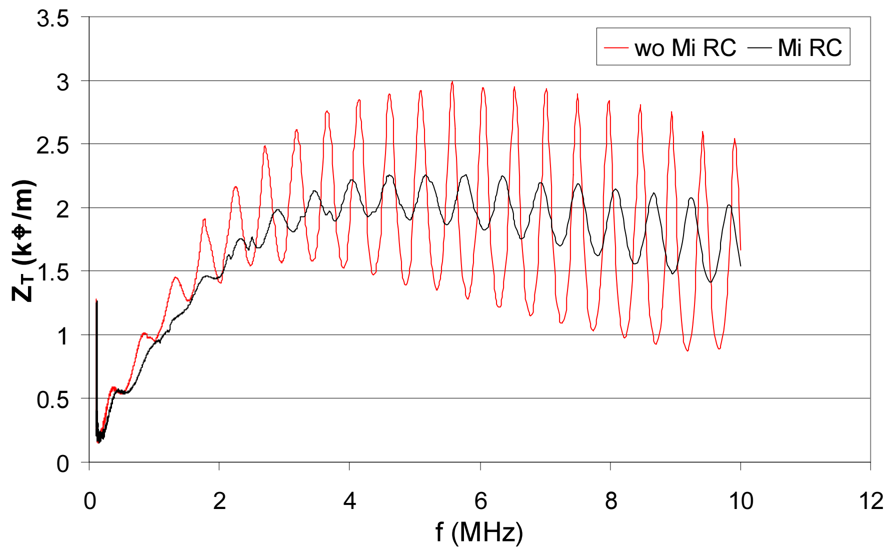






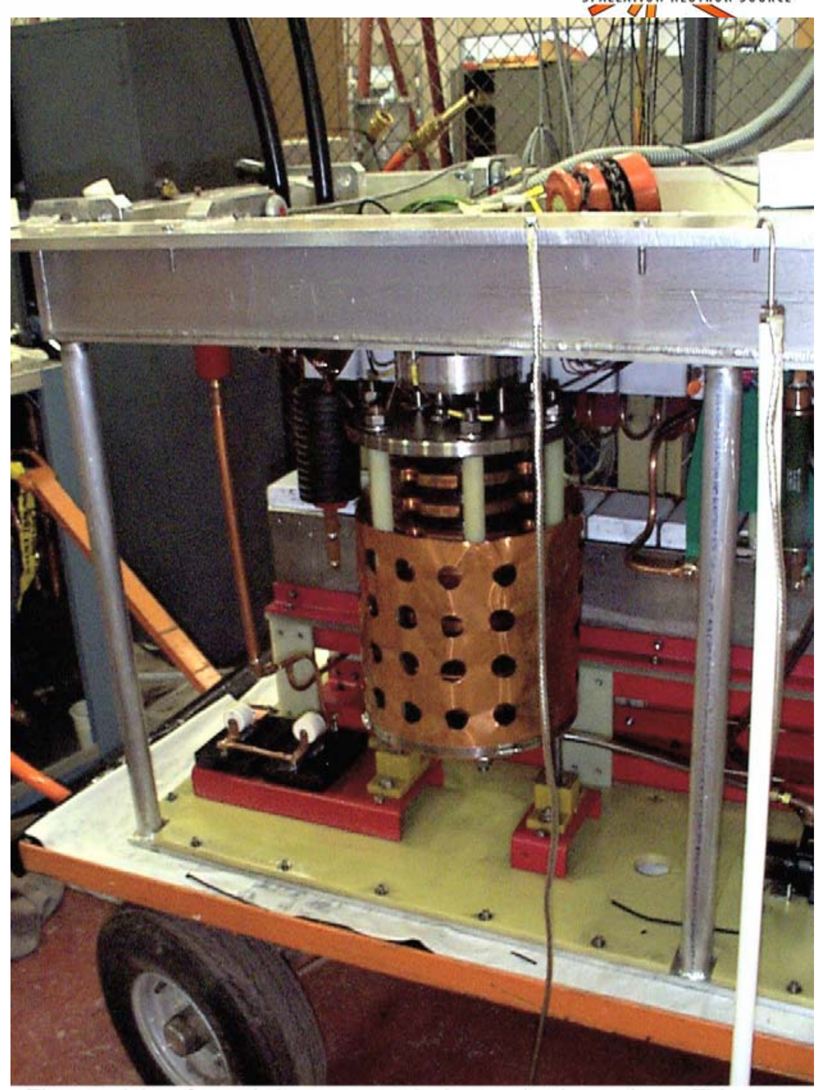
Multipoles	b0/a0	b1/a1	b2/a2	b3/a3	b4/a4
$B_nL/BL(10^{-4})$ @480.0 π	-.5/-.2	0.8/1.0	0.18/0.17	0.01/-0.06	-0.02/0.01

Z_{tr} of Extraction Kicker Magnet with/without Mi RC (D.Davino, H.Hahn et al.)



Coaxial shield inserted to shield the terminating resistance of the PFN; reducing cable reflection from PFN

Resonance structure of coupling impedance at MHz range is eliminated



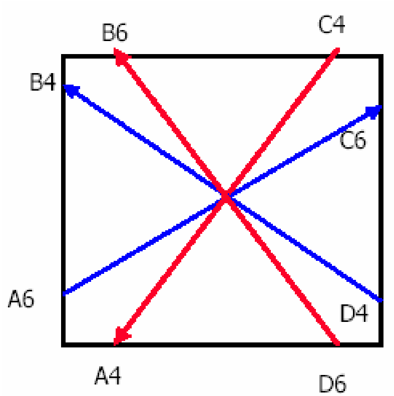
The coaxial perforated sheet surrounds the terminating resistor. This was used for testing. The production units will use aluminum screens as is presently done with the thyratron.

Minimizing effect of nonlinear resonances by magnet sorting (Y.Y. Lee, D. Raparia, A. Fedotov et al)

Primary goal – sort magnets, for example 26Q40, to minimize odd harmonics – for our typical tune-box we have dangerous resonances with primarily odd harmonics.

We tried:

1. **4 identical magnets – 1 per super period – removes odd harmonics nicely but of course finding 4 identical magnets is not possible.**
2. **Sort by pairs: several sorting schemes were tried – the best sorting corresponded to the case when "TOTAL" field is matched – "ITF+multipoles" – not easy to do in reality.**
3. **Sorting by Phase advance**

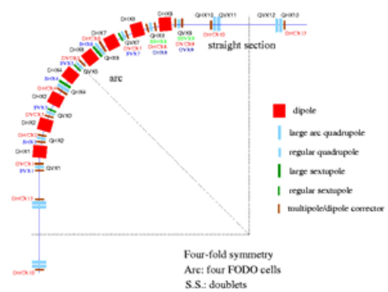


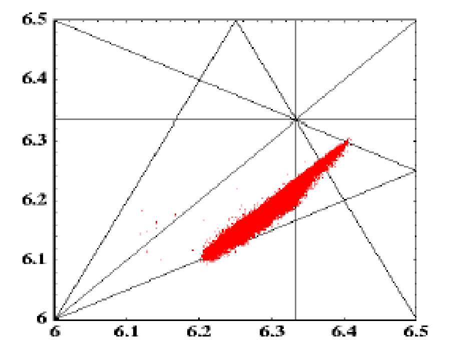
A4-C4=19*2*π/2=18* π = π

=B4-D4=A6-C6=B6-D6

A4-B6 =19*2* π /4 +3* π /2=10* π + π

=B4-C6=C4-D6





Tune spread for 2MW beam with dp/p=0.6 %

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Sorting of 26Q40 to minimize effect of nonlinear resonances: compensation of emittance growth due to skew-sextupole resonance

(Y.Y. Lee, D. Raparia, A. Fedotov et al)

Primary goal – sort magnets, for example 26Q40, to minimize odd harmonics – for our typical tune-box we have dangerous resonances with primarily odd harmonics.

After sorting technique was demonstrated to work, real measured multipoles were used and best sorting schemes were developed

Measured 26Q40 multipoles:	beam halo
1. No correction:	0.3% at 240 pi
2. Sorting based on total field:	0.2% at 240 pi
3. Sorting based on phase advances:	0.3% at 240 pi

Measured errors multiplied by a factor of 9:	
1. No correction:	6.0
2. Sorting based on phase advances:	0.8%

To develop the most effective scheme measured errors were further scaled to a factor of 9 which results in beam halo of 6% at 240 pi without magnet sorting or resonance correction

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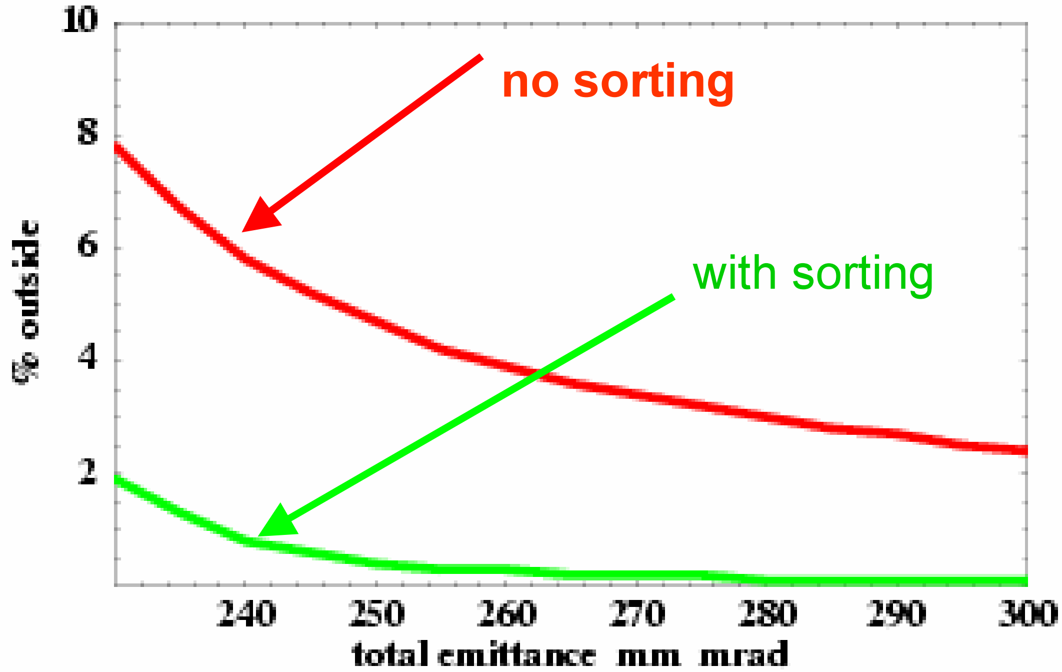
Minimizing Effect of Skew-Sextupole Resonance by Sorting (Y.Y. Lee, D. Raparia, A. Fedotov et al)



Demonstration of sorting scheme to minimize effect of skew-sextupole resonance: w.p. (6.4,6.3), N=1.5*10^14, measured skew-sextupole multipoles in 26Q40 magnets multiplied by a factor of 9 – no resonance correction.

- **Measured multipoles in 26Q40 give noticeable but small contribution to emittance growth due to skew-sextupole resonance.**
- **In addition we have correctors to correct this resonances.**
- **It was demonstrated that sorting can minimize odd harmonics for our working tune-box thus minimizing effect of skew-sextupole resonance even further.**
- **However, such sorting will increase effect of even harmonics for the tune below Q_x=6.0. So, if in the future one decides to choose the tune below Q_x=6.0 effect of sextupole resonance will be stronger for such a tune box.**

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Nonlinear Resonance Correction

(A. Fedotov, G. Parzen et al.)

SPALLATION NEUTRON SOURCE

Last DOE: We reported successful correction of 3rd , 4th order, dynamic correction of several, resonances for high-intensity operation, using the source of lumped errors.

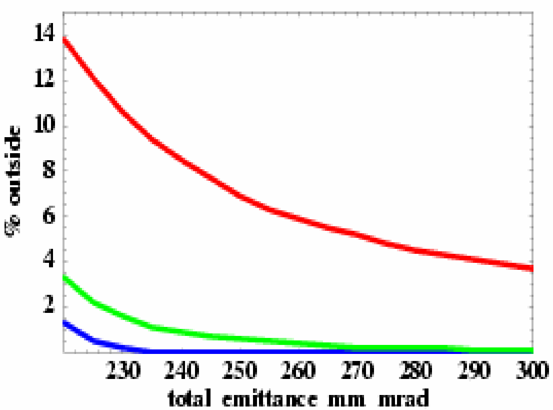
Since last DOE these studies were extended to:

Random errors

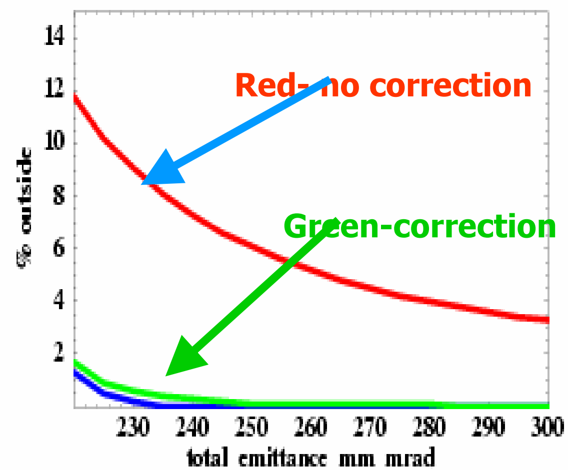
Successful correction of isolated resonances driven by random errors in magnets for high-intensity operation

Dynamic correction of several resonances

Realistic error budget, halo and correction based measurements of SNS magnets



w.p. (6.36,6.22),
$N=1.0*10^{14}$
red – no correction,
b_2=5 units rms,
b_3=10 units rms
green – correction of 3Qx=19 and 2Qx+2Qy=25



b_2 = 5 units rms in all magnets
$N=1.0*10^{14}$

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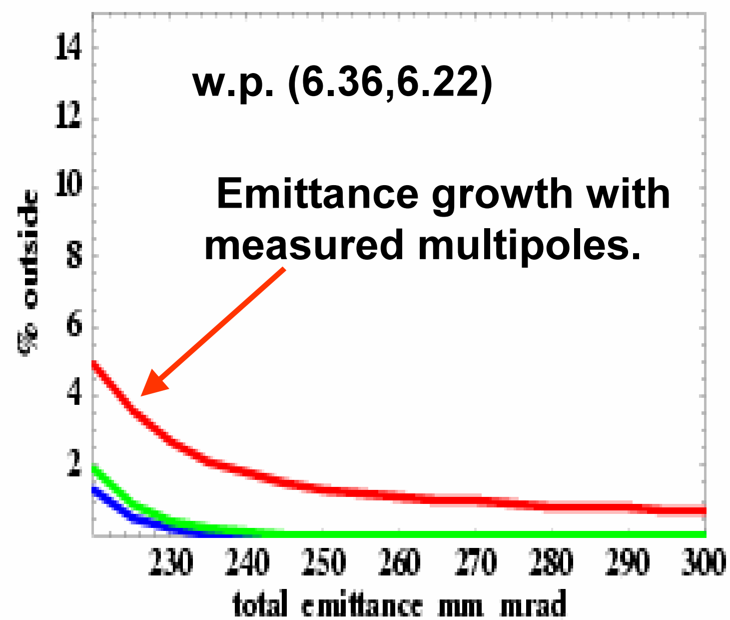
Correction of Realistic Emittance Growth Expected for High-Intensity w.p. Based on Measured Magnets (A. Fedotov, G. Parzen)

High-intensity w.p. (Qx:6.36):
Realistic loss/emittance growth due to nonlinear resonances is actually much smaller than used in resonance studies. However, it is not zero - main contribution comes from b_2 errors in 30Q58. Required corrector strength is well within specifications.
Base line w.p. (Qx: 6.22) (up to $1.5*10^{14}$): such b_2 errors are not a problem – low loss: 10^{-4} level.

red – emittance growth due 3Qx=19 and 2Qx+2Qy=25 driven by a distribution of random errors based on real measured multipoles.

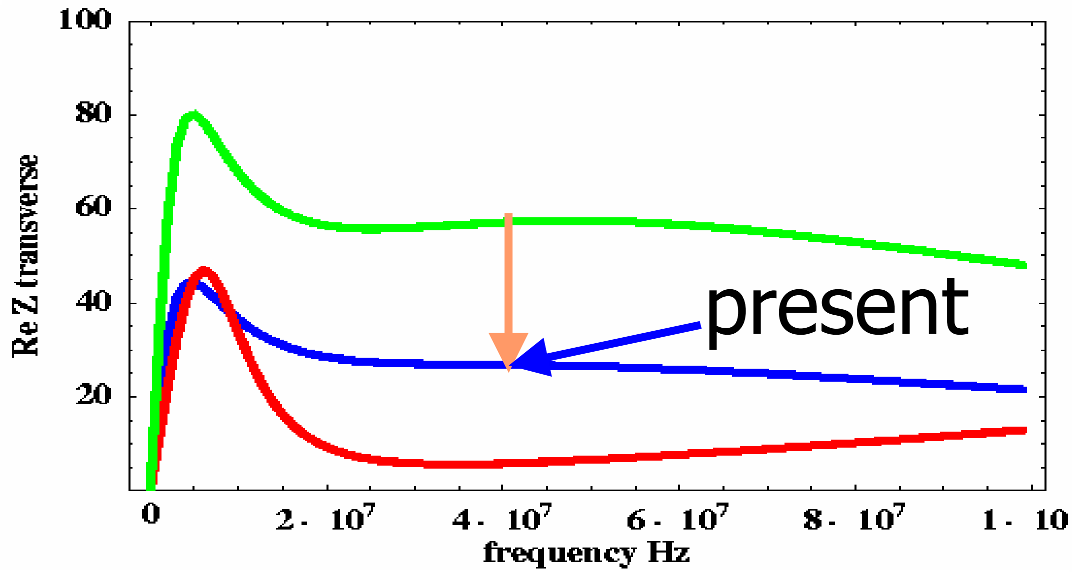
Green – correction of corresponding resonances: maximum sextupole gradient used 0.09 T/m^2; octupole: 0.7 T/m^2

maximum available in correctors:
normal sextupole: 2.6 T/m
normal octupole: 2.9 T/m^2

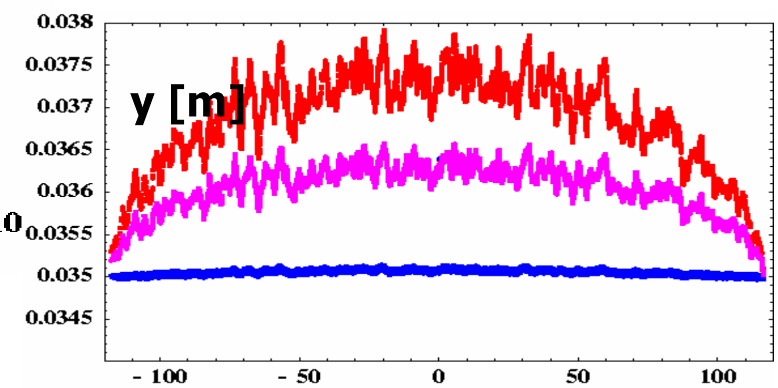


DOE 03/11/4-6

Reduction of Extraction Kicker Impedance -Modeled Impedance Used in Simulations (A. Fedotov, J. Wei, et al)



Pencil beam – y distribution along the bunch after turns 1, 2 and 3.



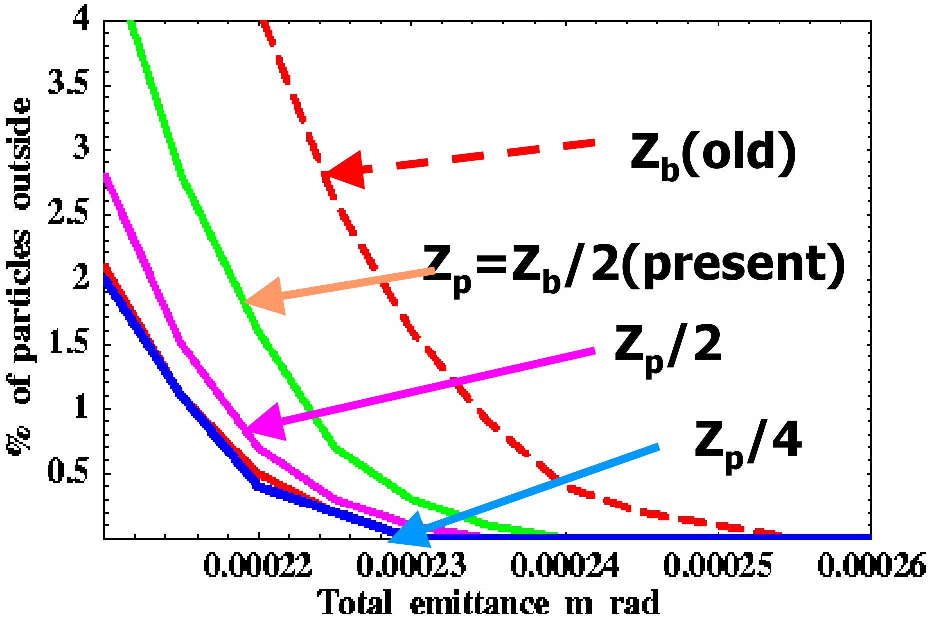
Green – model of old impedance with 25 Ω termination (Feb. 2002). Result of R&D to minimize impedance - significantly reduced compared to open termination (not shown in this figure).

Blue – reduced impedance due to increased vertical size of first 7 kicker modules

Red – updated reduction due to the contribution uncoupled from external termination

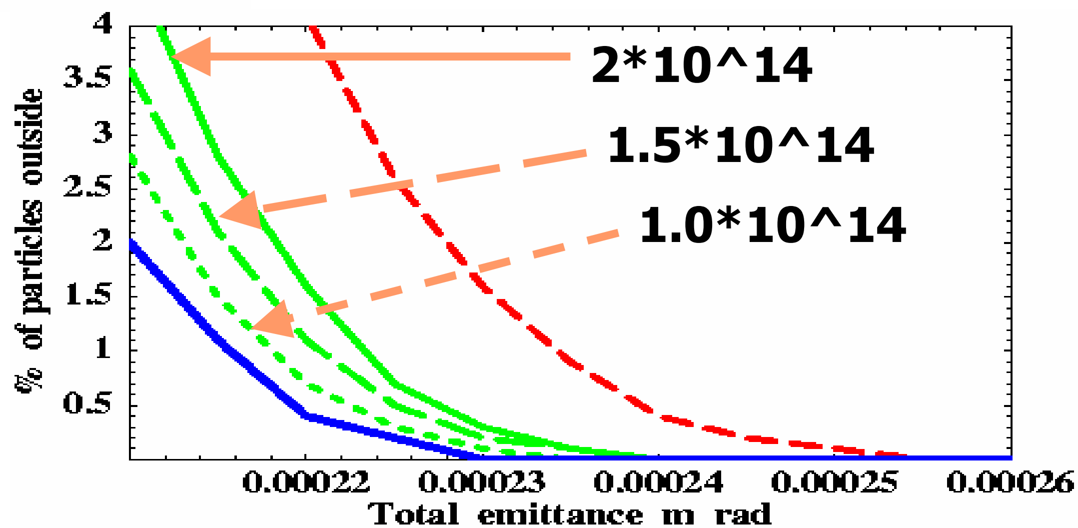
DOE 03/11/4-6

Impedance & Intensity Dependence (A. Fedotov, J. Wei, et al)



- Emittance growth due to "banana-shape" was a problem for old impedance
- Present impedance:

1. Halo is decreased to 0.3% at primary scraper (for 2*10^14)
2. Additional intensity dependence leads to 0.2% (for 1.5*10^14) and 0.1% (for 1.0*10^14)

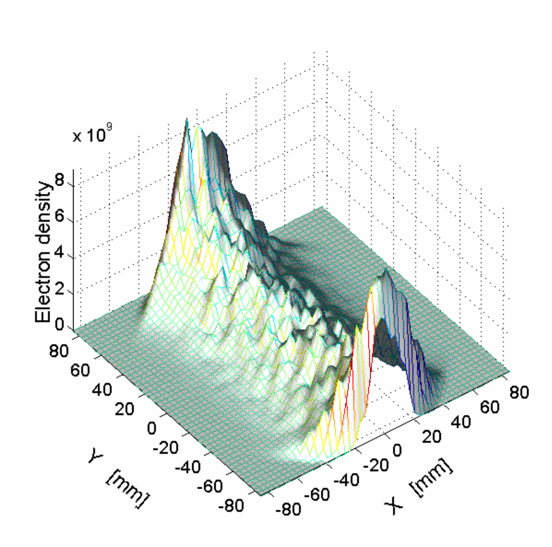


1) For high-intensity operation (1.5-2 * 10^14) small adjustment of primary scrapers may be required.
2) For 1*10^14 – negligible effect.

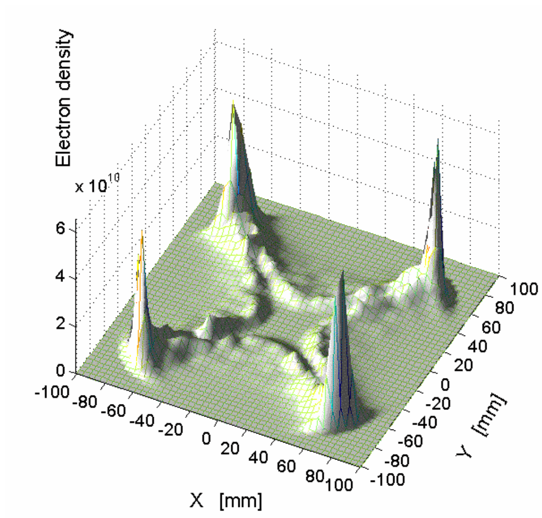
E-cloud in Dipole, Quadrupole & Sextupole

(L. Wang, J. Wei, M. Blaskiewicz, et al)

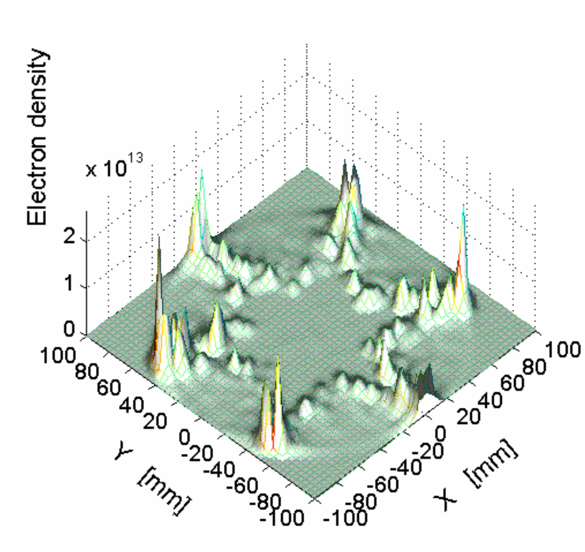
Ecloud in Dipole



Ecloud in quadrupole



Ecloud in sextupole



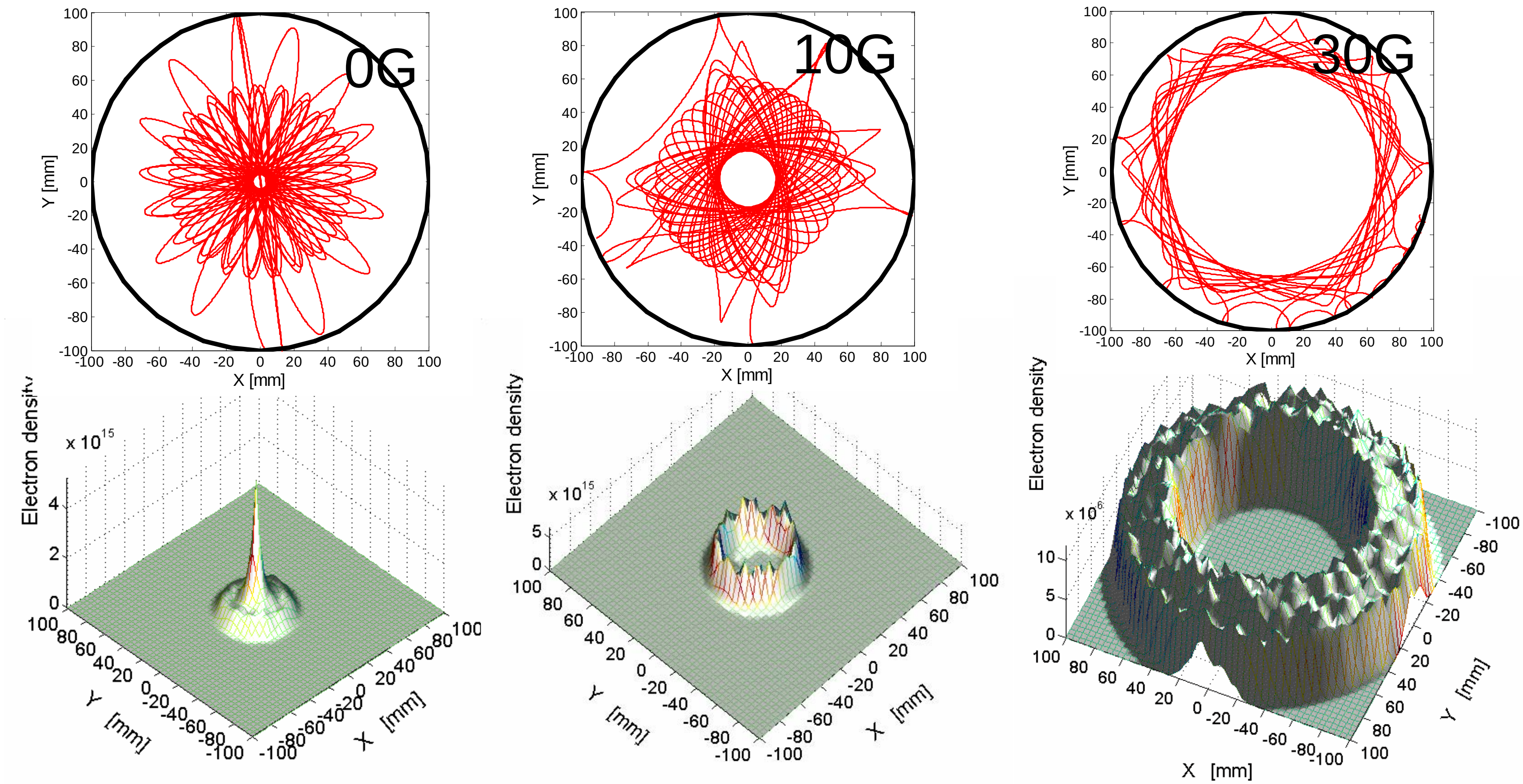
- **Multipacting happen at the horizontal chamber center E-cloud is about 2 times smaller than drift region**

- **Weak multipacting happens only near the middle of the pole surface**
- **No Trapping for long bunch! (trap was suspected, PSR-94-005)**

DOE 03/11/4-6

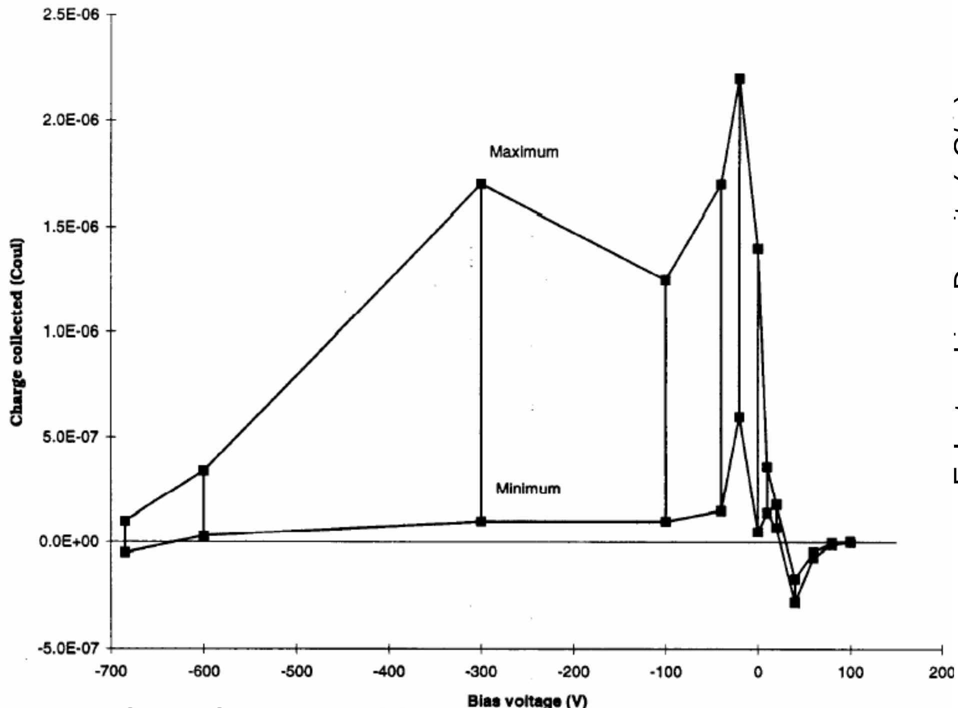
Solenoid effects (L. Wang, J. Wei, M. Blaskiewicz, et al)

- **30G Solenoid field can reduce the e-cloud density with a factor 2000 !**
- **Zero density within beam**
- **Solenoid winding in the collimator straight section**

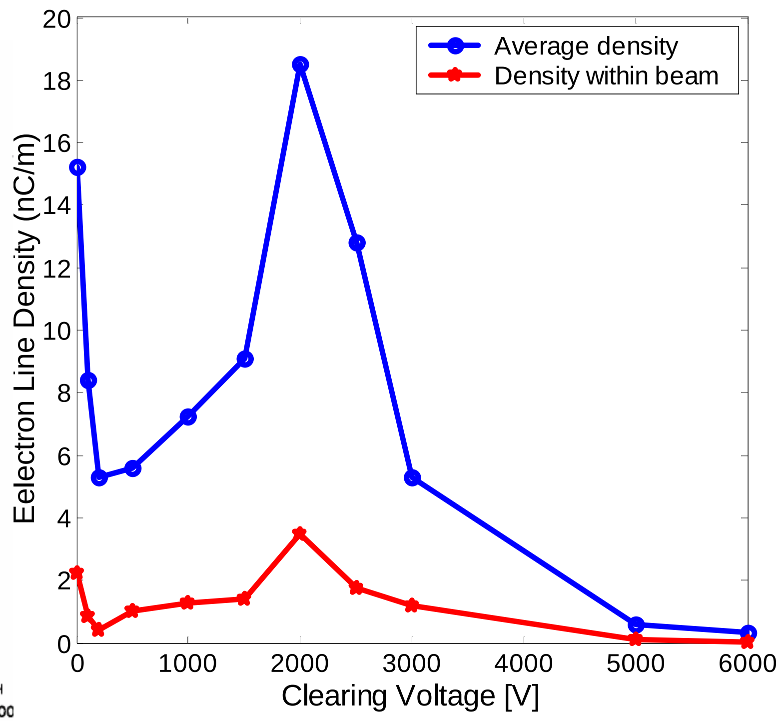


Electrode clearing effect vs Clearing voltage

(L. Wang, J. Wei, M. Blaskiewicz, et al)



PSR(PSR-94-03,M. Plum, etc.)



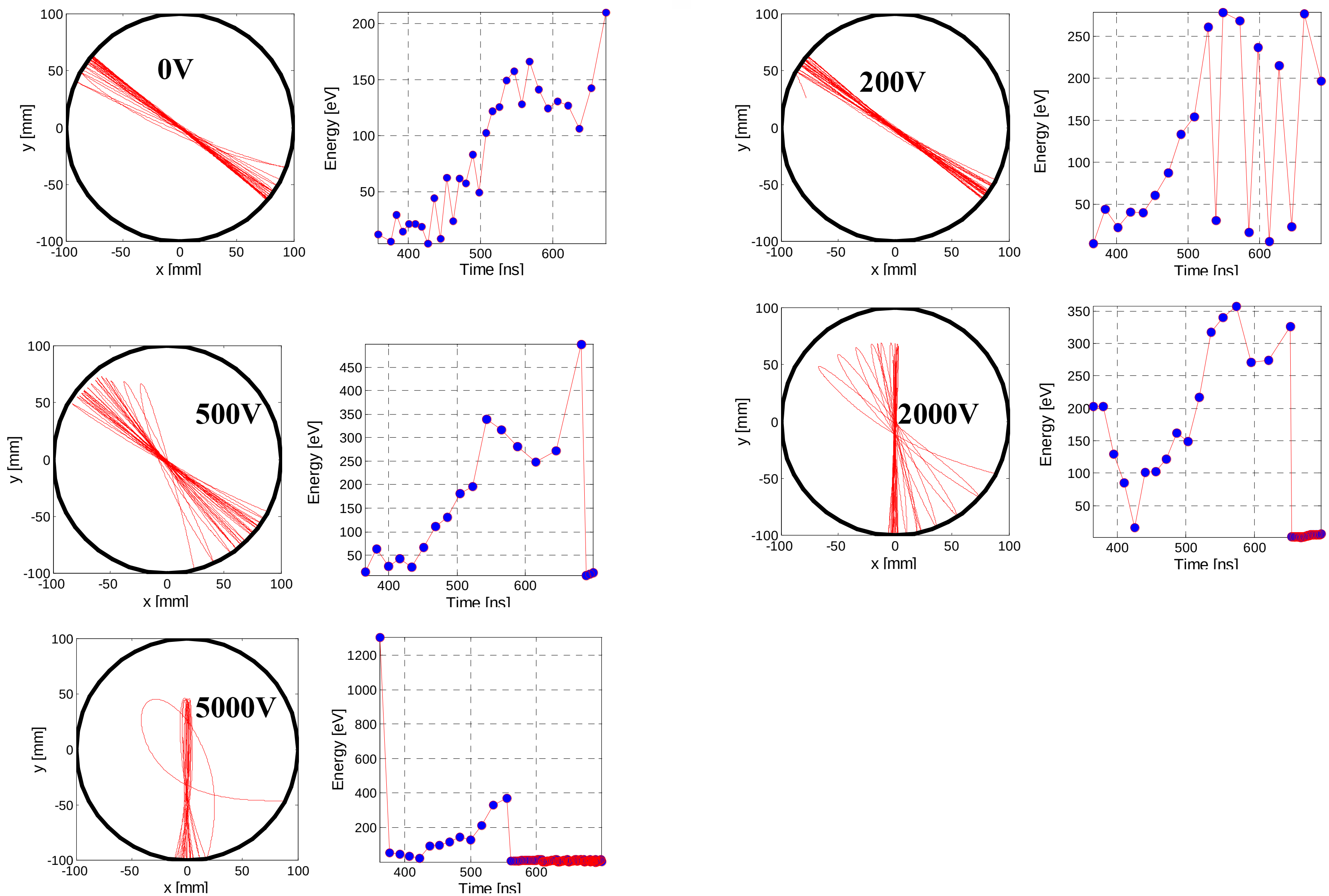
e-cloud density vs clearing fields

- **Weak field(~200V) is very helpful**
- **Strong Multipacting at 2kV, which could be stronger than zero field case**
- **Clearing electrode in injection (10 kV), and BPM +/- 1kV**

DOE 03/11/4-6

Mechanism of strong Multipacting due to clearing field

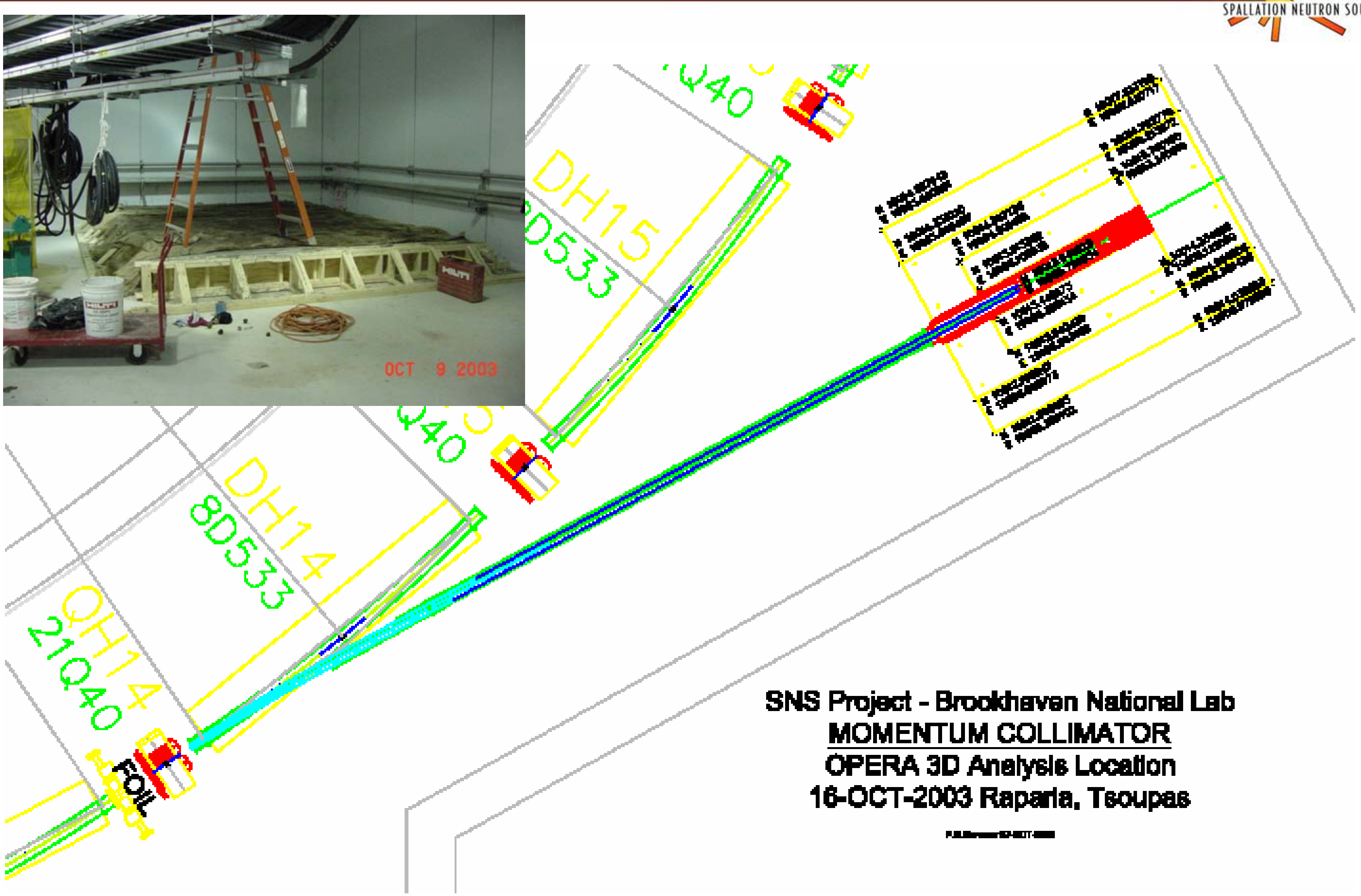
(L. Wang, J. Wei, M. Blaskiewicz, et al)



DOE 03/11/4-6

Global Coordinates

(M. Hammer, N. Tsoupas, D. Raparia et al)



DOE 03/11/4-6

Summary

- Continue to improve and and maintain beam performance:

  -Successfully achieved tight field variations in all magnets (10E-4,rms)

  -Sorting schemes were developed to reduce the effect of ITF variation

  -Sorting schemes were developed to minimize effect of nonlinear resonances

  - Better understanding of working of clearing electrode

  - Nonlinear resonance correction

  -Emittance growth due to “banana-shape effect” - c.o. offset in Kickers

  -Multi-poles in ELS magnet is below 1E-04.

  -Sorted 21Q40 and 26Q40 based on power supply

  -Assigned magnets to lattice locations
- Quality Assurance:

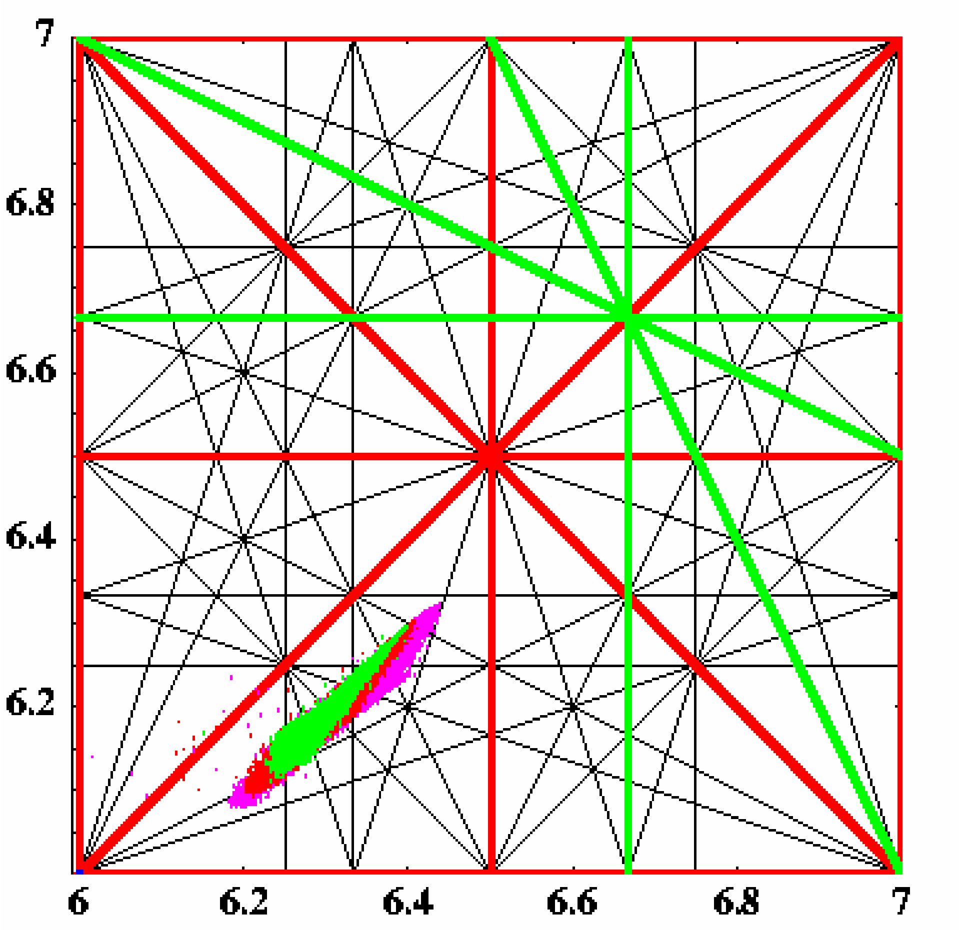
  -Accept magnets and ½ cells
- Support installation and commissioning :

  -Generate global coordinates complete

  -Checked installation drawings
- Continue to explore ring capabilities beyond base line (1.4 MW)

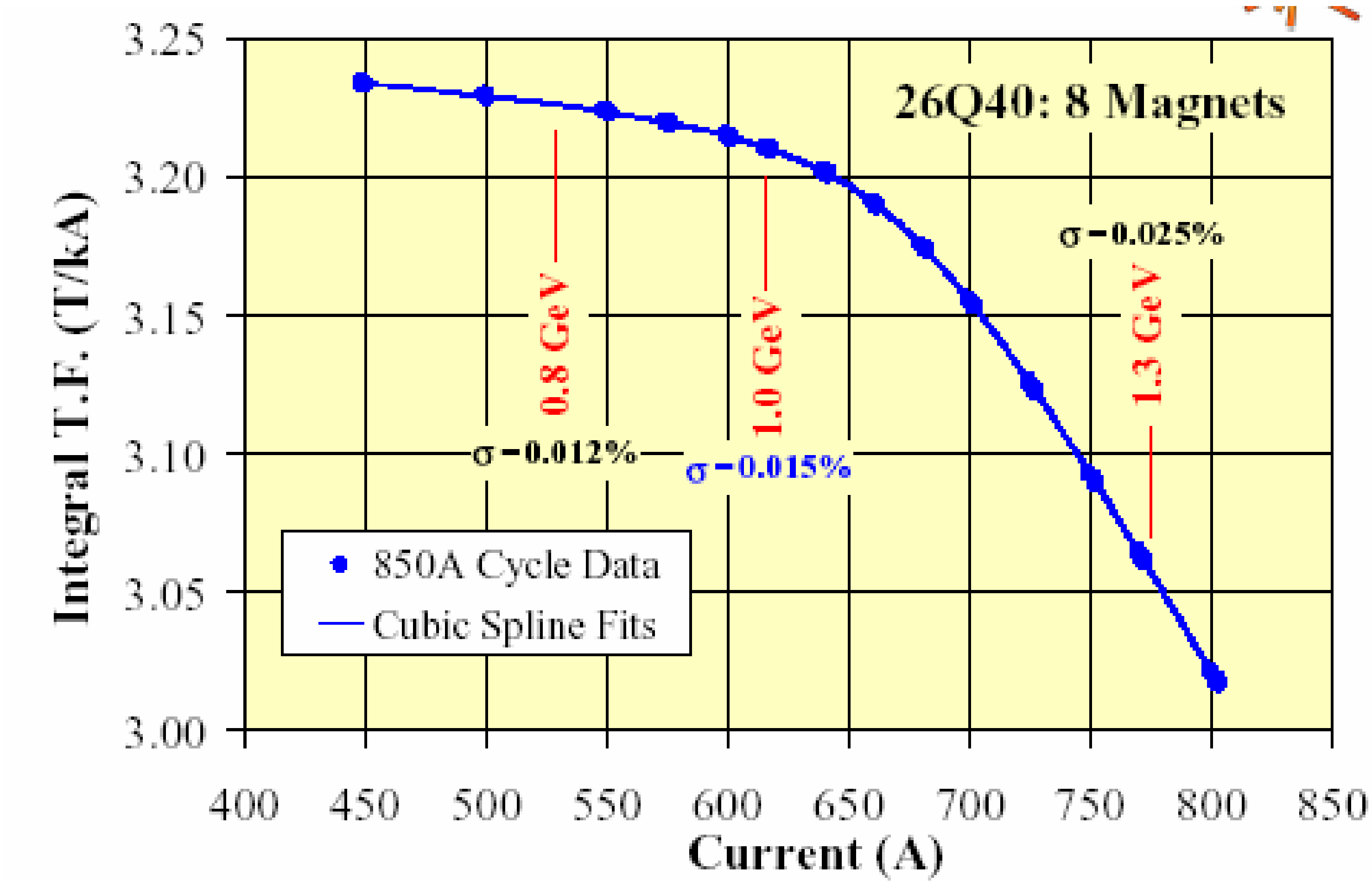
DOE 03/11/4-6

Ring tuning spread



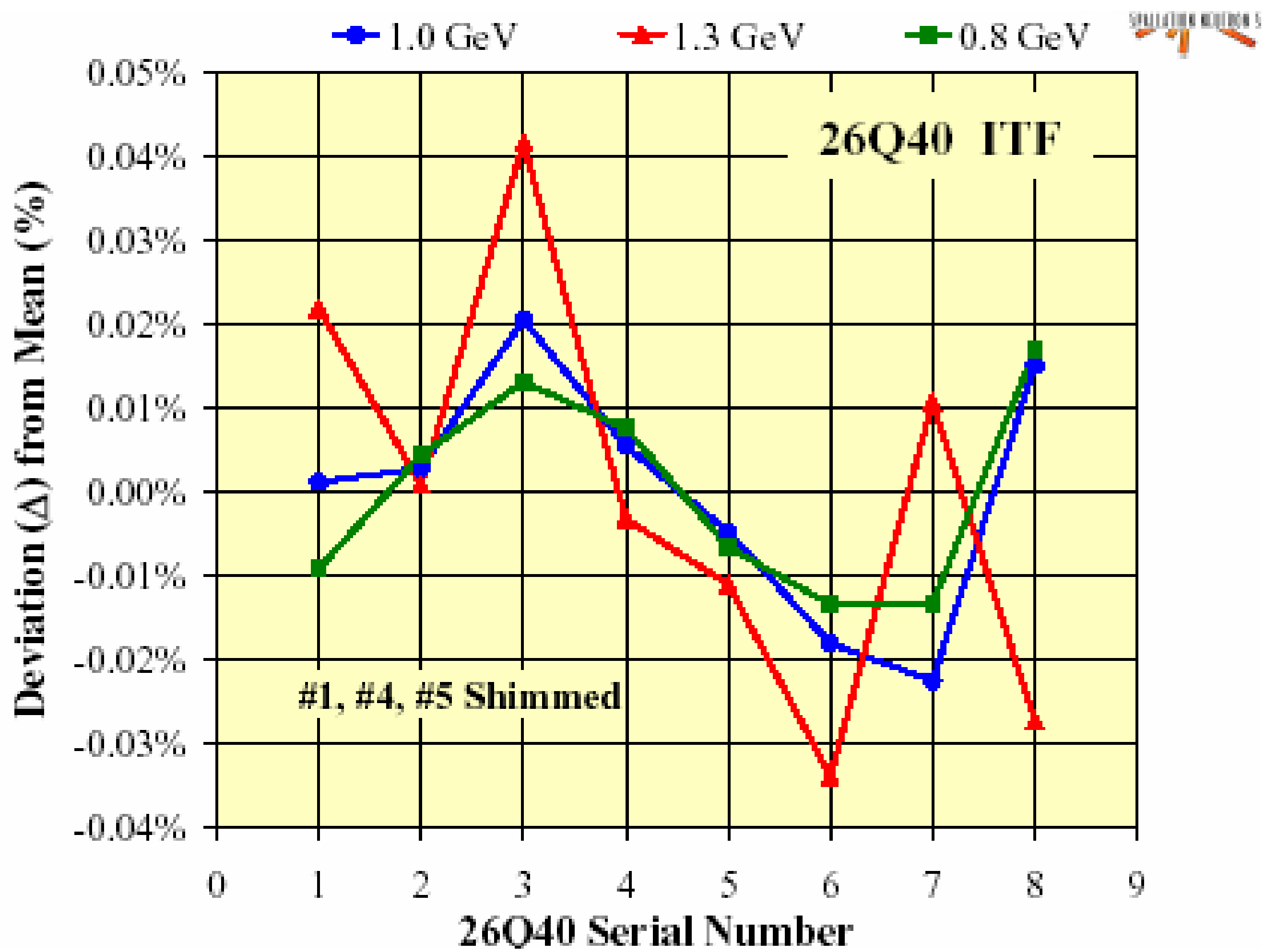
- 2 MW beam at 1 GeV
  - Space charge tune spread about 0.2 (green)
  - Chromatic tune spread must be controlled by Sextupole (red: beam core Dp/p=+/-0.6%; pink: partial halo Dp/p=+/-1.0%)
- Imperfection non-structure resonances are shown in black

26Q40 ITF



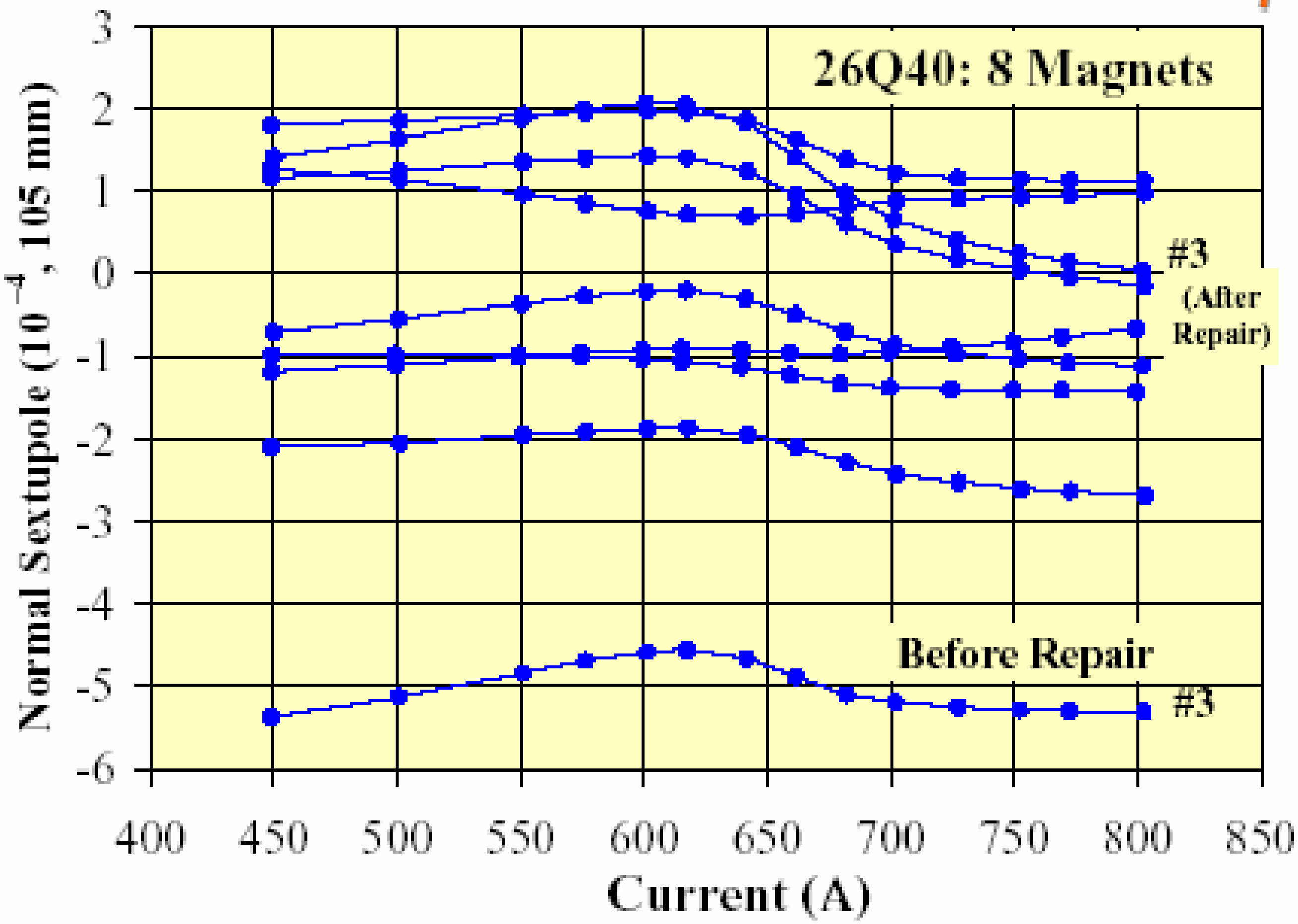
DOE 03/11/4-6

26Q40 ITF Variation



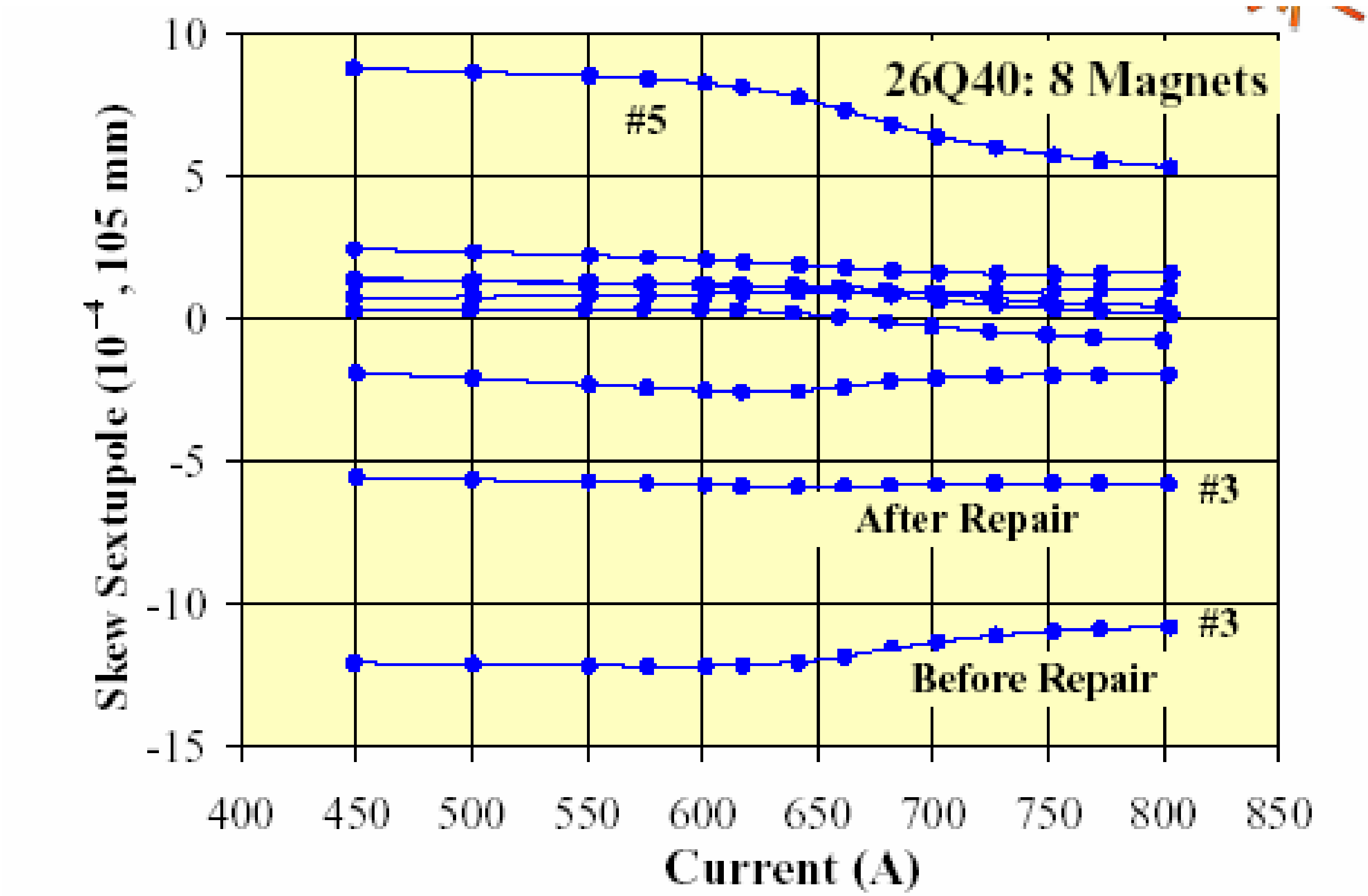
DOE 03/11/4-6

26Q40: Normal Sextupole @480 Pi



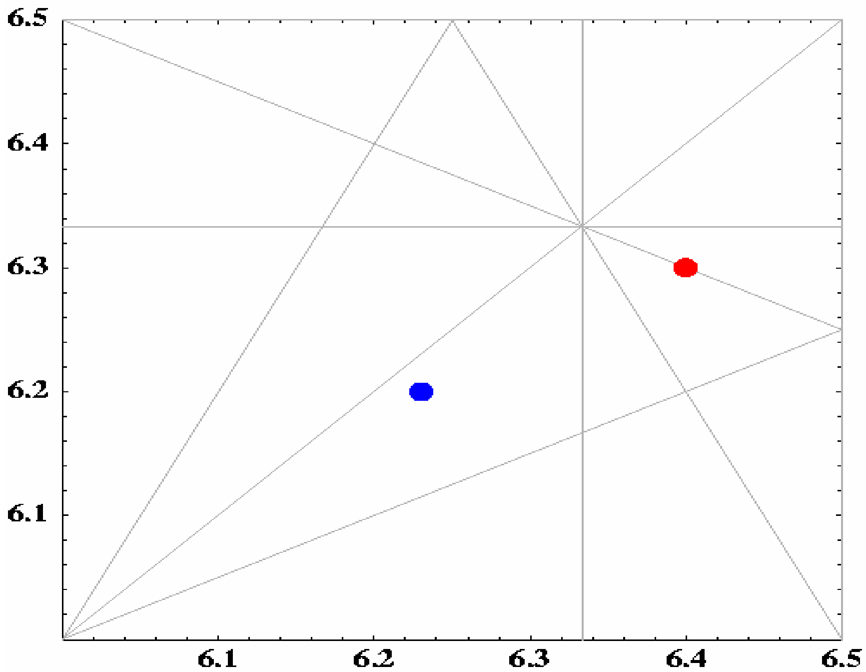
DOE 03/11/4-6

26Q40: Skew Sextupole @480 Pi

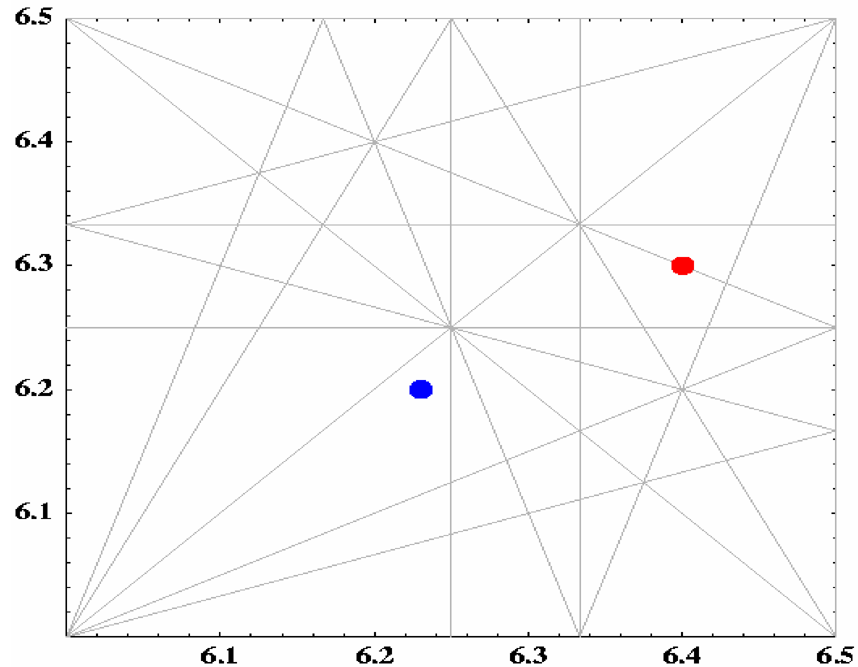


DOE 03/11/4-6

Two regions of working points



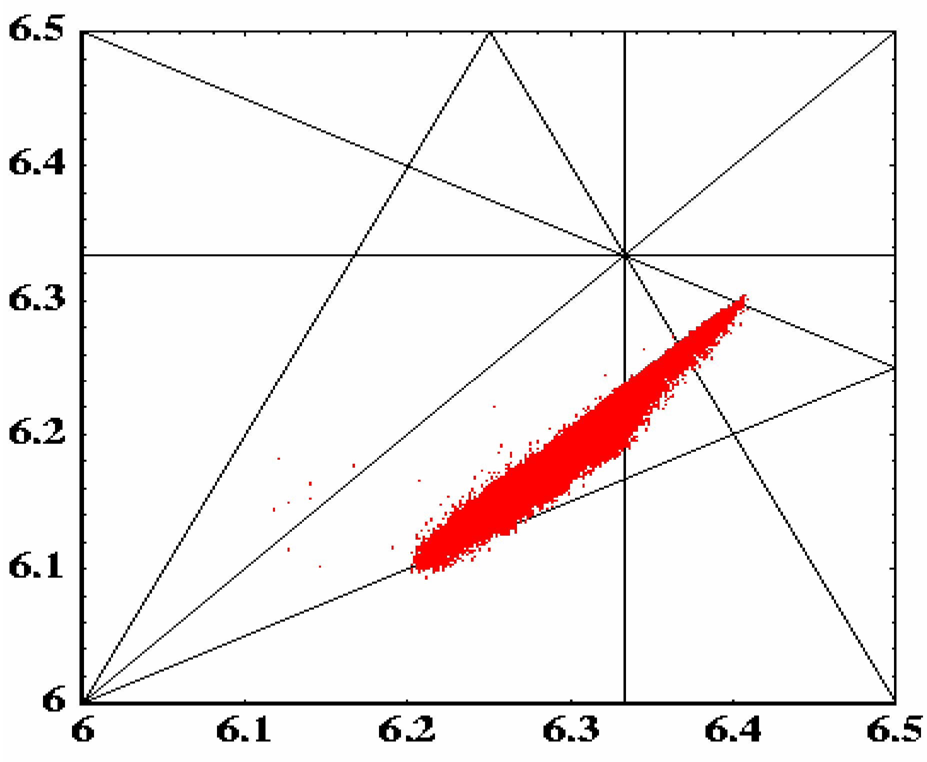
Imperfection resonances up to 3rd order



Imperfection resonances up to 4th order

DOE 03/11/4-6

w.p.(6.4,6.3)



Tune spread for 2MW beam with dp/p=0.6 %

26Q40: Skew & Normal Sextupole

A4-C4	C6-A6	B4-D4	B6-D6	(A4-C4)-(B6-D6)	(C6-A6)-(B4-D4)		Emit G
-5.84-1.20 = -7.04	0.33-(-2.45) =-2.87	2.03-0.92 =1.11	1.17-8.13 =-6.96	-7.04 -(-6.96) =-0.08	2.87-1.11 =1.76	-0.08-1.76 =1.84	0.8%
-5.84-(-2.54) =-3.30	0.92-0.33 =0.59	2.03-1.20 =0.83	1.17-8.13 =-6.96	-3.30-(-6.97) =3.67	0.59-0.83 =-0.24	3.67-(-.24) =3.91	1.1%
1.17-1.20 =-0.03	0.92-2.03 =-1.11	8.13-(-5.84) =13.97	0.33-(-2.54) =2.87	-0.03-(-2.87) =-2.90	-1.11-(13.97) =15.08	-2.90-15.08 =17.98	6%
2.05-(-.90) =2.95	-0.20-1.96 =-2.16	-1.87-(-1.06)=-0.81	0.72-1.41 =-0.69	2.95-(-.69) =3.66	-2.16-(-.81) =-1.35	3.66-(-1.35) =5.01	
2.05-0.20 =2.25	1.96-(-1.06) =3.02	-1.82-(-.9) =-0.92	0.72-1.41 =-0.69	2.25-(-.69) =2.94	3.02-(-.92) =3.94	2.94-3.94 1.00	
0.72-(-.9) =1.62	-1.87-1.96 =-3.83	1.41-2.05 =-0.64	-1.06-(-.2) =-0.86	1.62-(-.86) =2.48	-3.83-(-.64) =-2.19	2.48-(-2.19) =4.67	

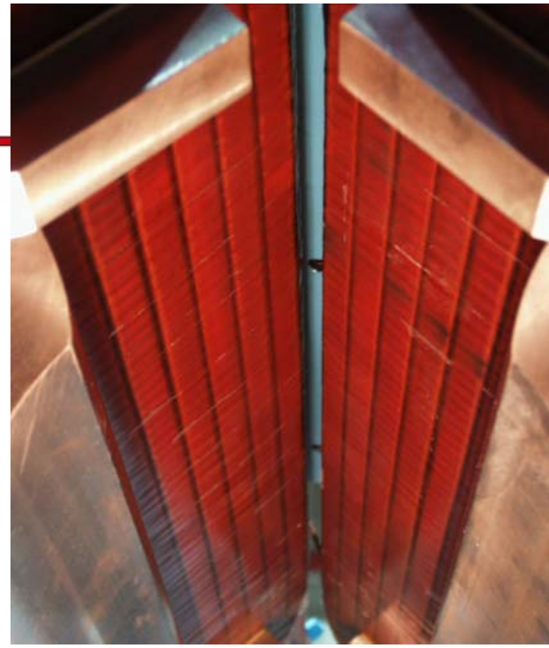
30 Q measurement and coil position -Introduction

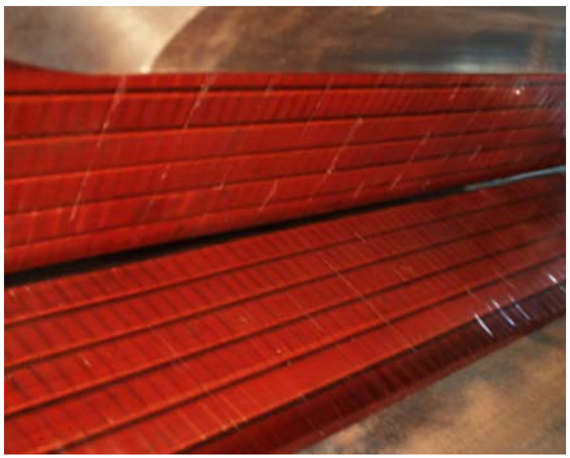
- First production measurements were made on 30Q58 serial no. 8.
- The magnet showed large skew sextupole, and also some higher order skew terms.
- Mechanical measurements of the pole gaps did not show any significant asymmetries in the poles of this magnet.
- On further inspection, all the magnet coils were found to have moved relative to the poles due to gravity.
- 2-D simulations by N. Tsoupas showed significant effect of such a coil displacement on the field quality.
- The coils were properly positioned using G-10 shims, which resulted in a much better field quality.

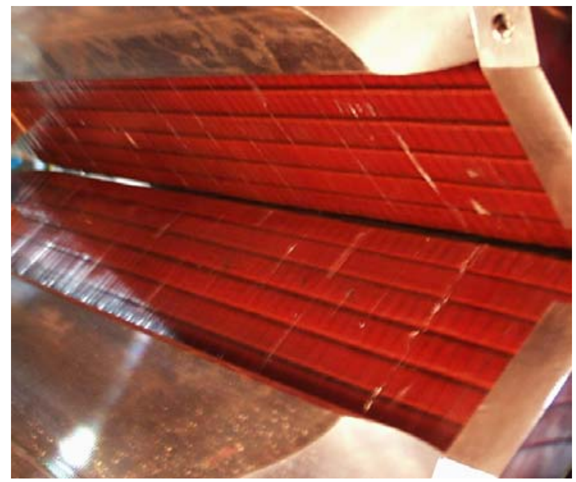
30Q58 serial no. 8

(As received)

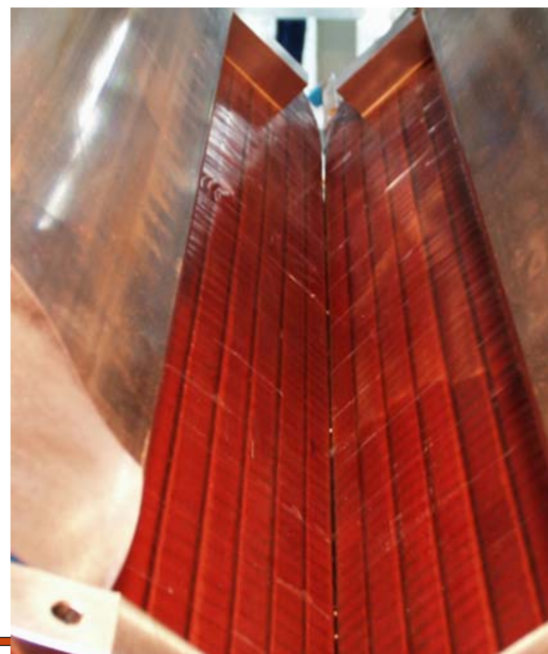
Large gap on the top







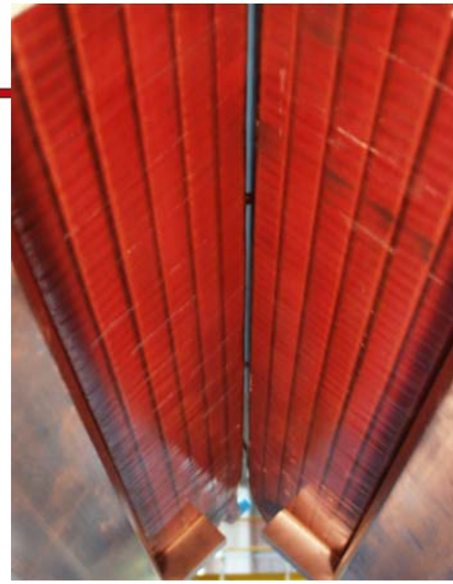
Similar gaps on the left and the right

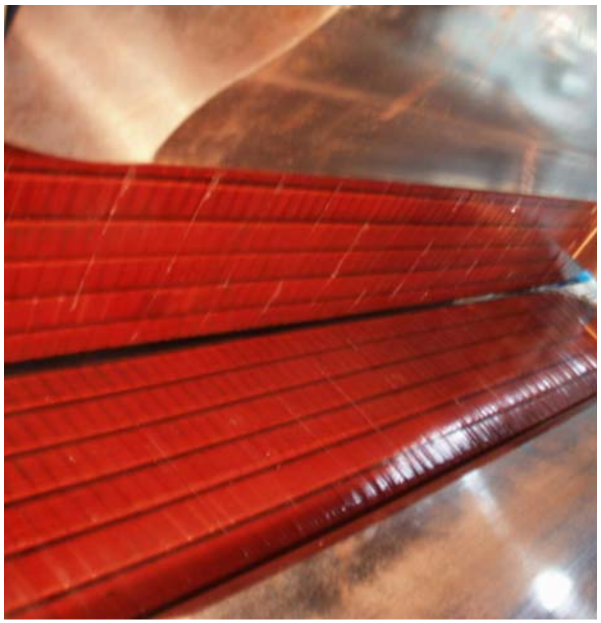


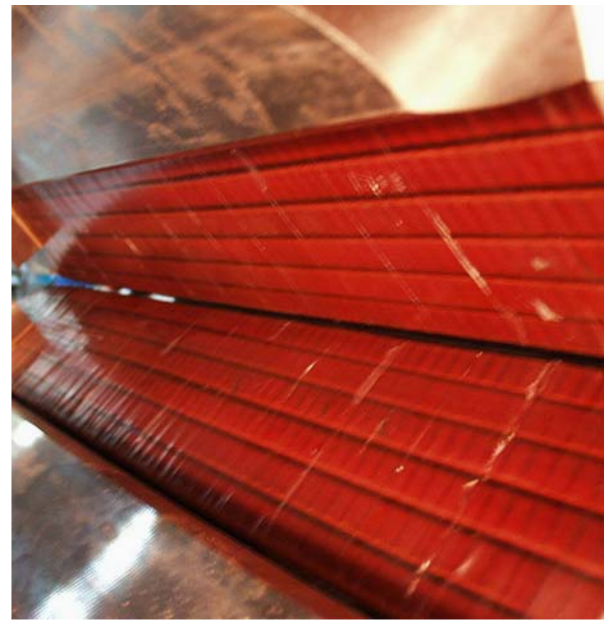
Practically zero gap on the bottom

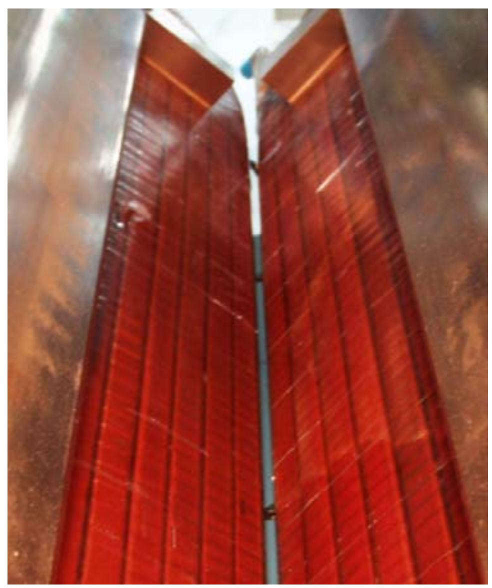
30Q58 serial no. 8

(Coils shimmed into proper position)





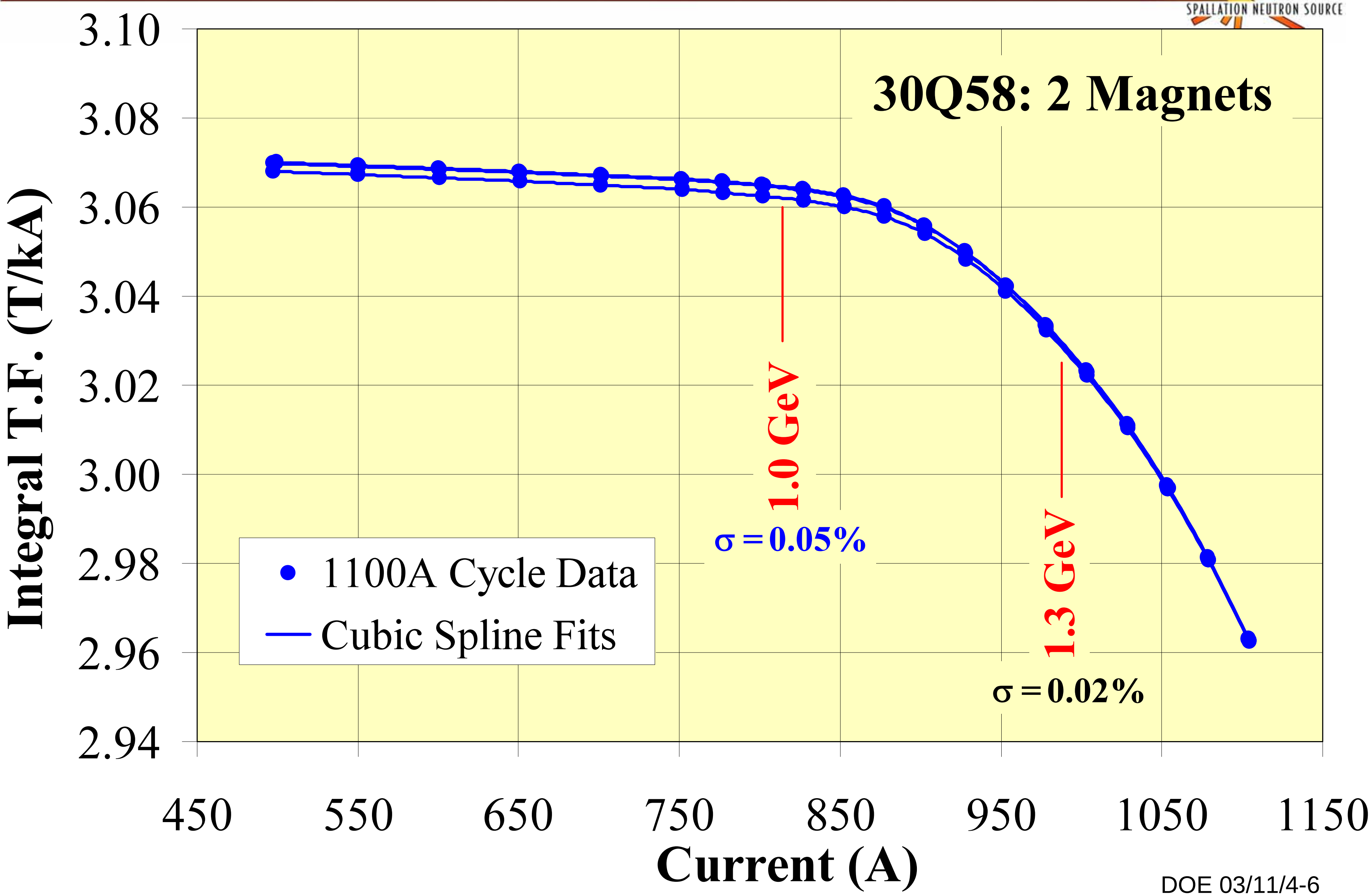




Similar gaps on all the four sides.

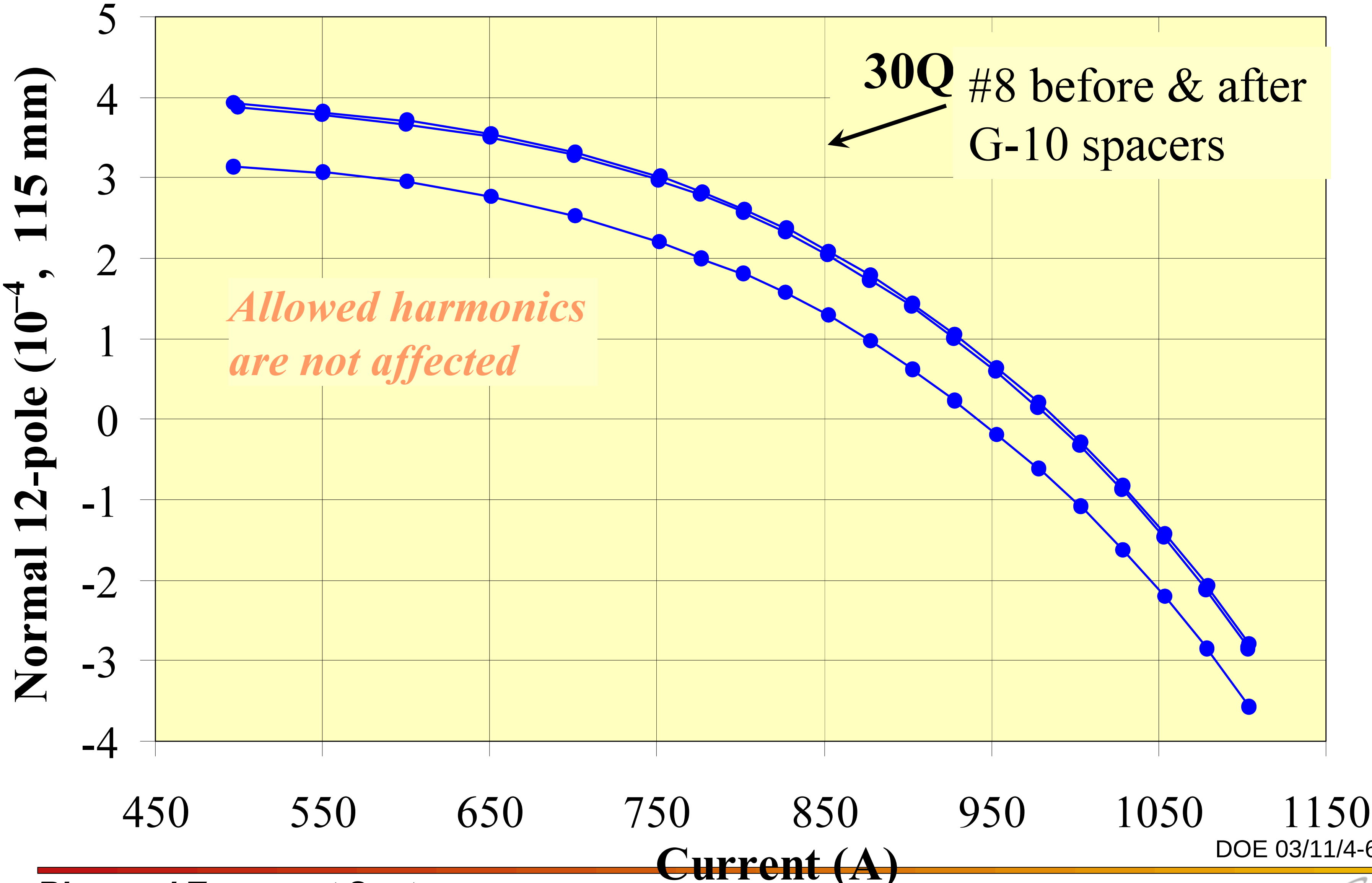
DOE 03/11/4-6

30Q: ITF

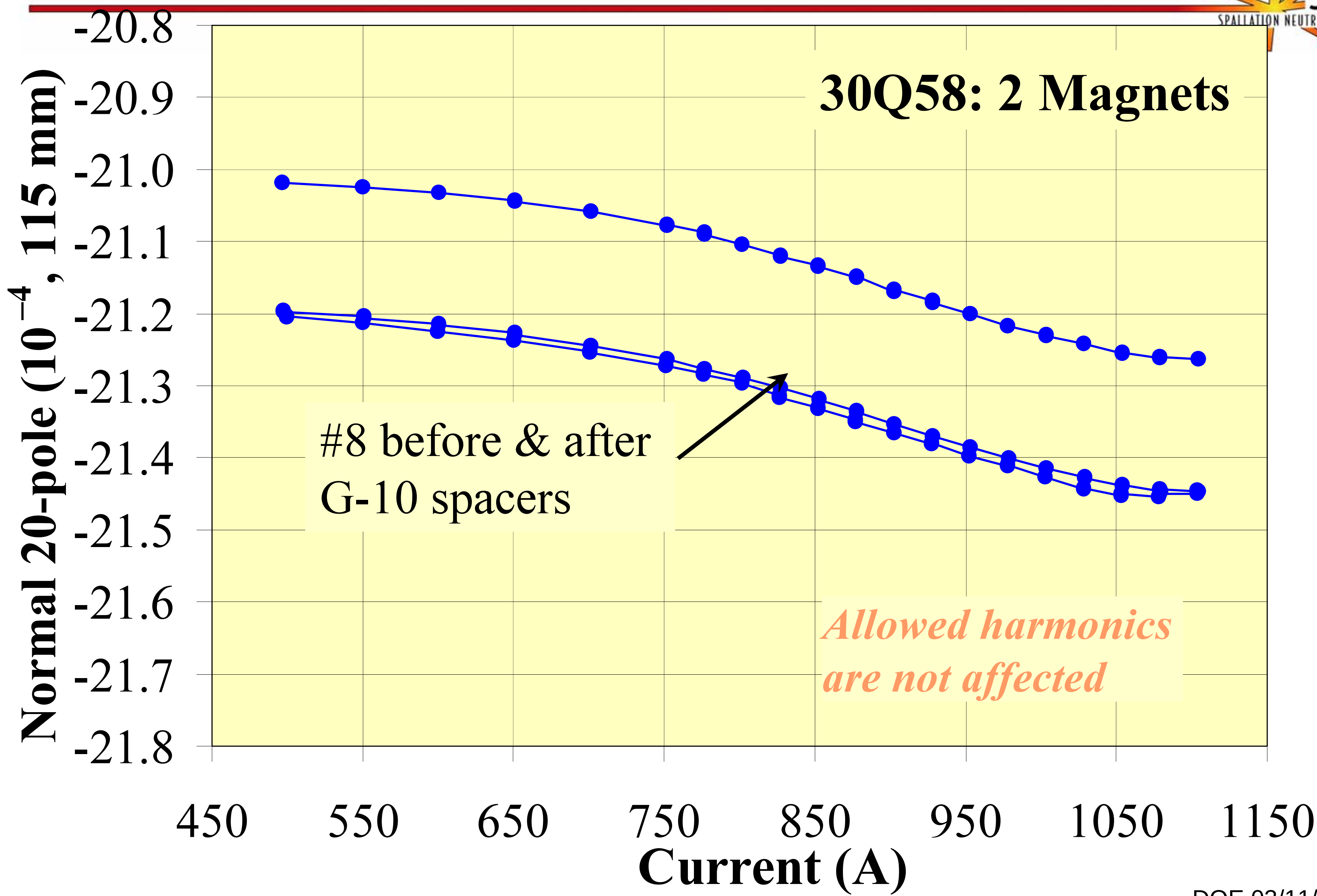


DOE 03/11/4-6

30Q: Normal 12-Pole

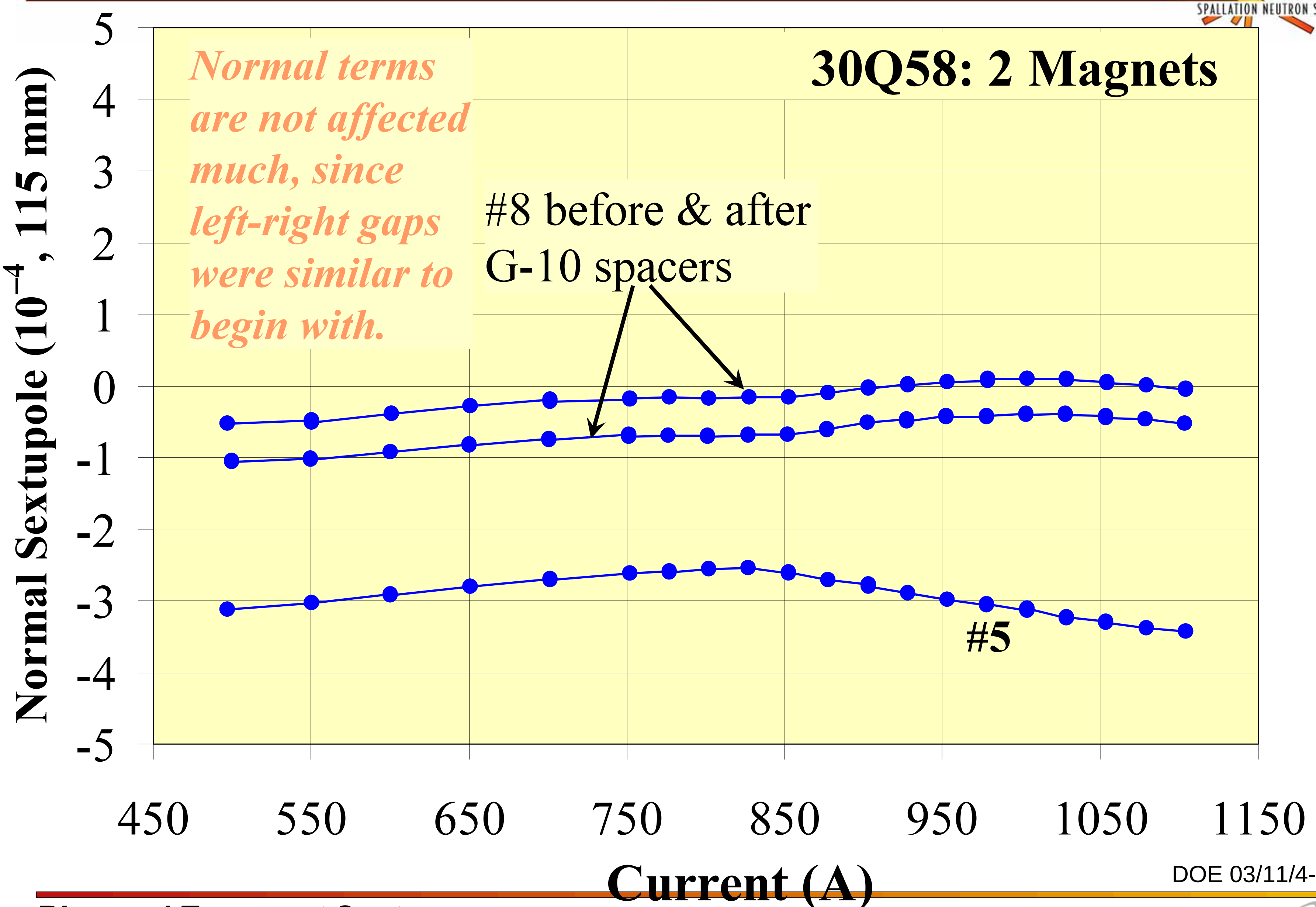


30Q: Normal 20-Pole



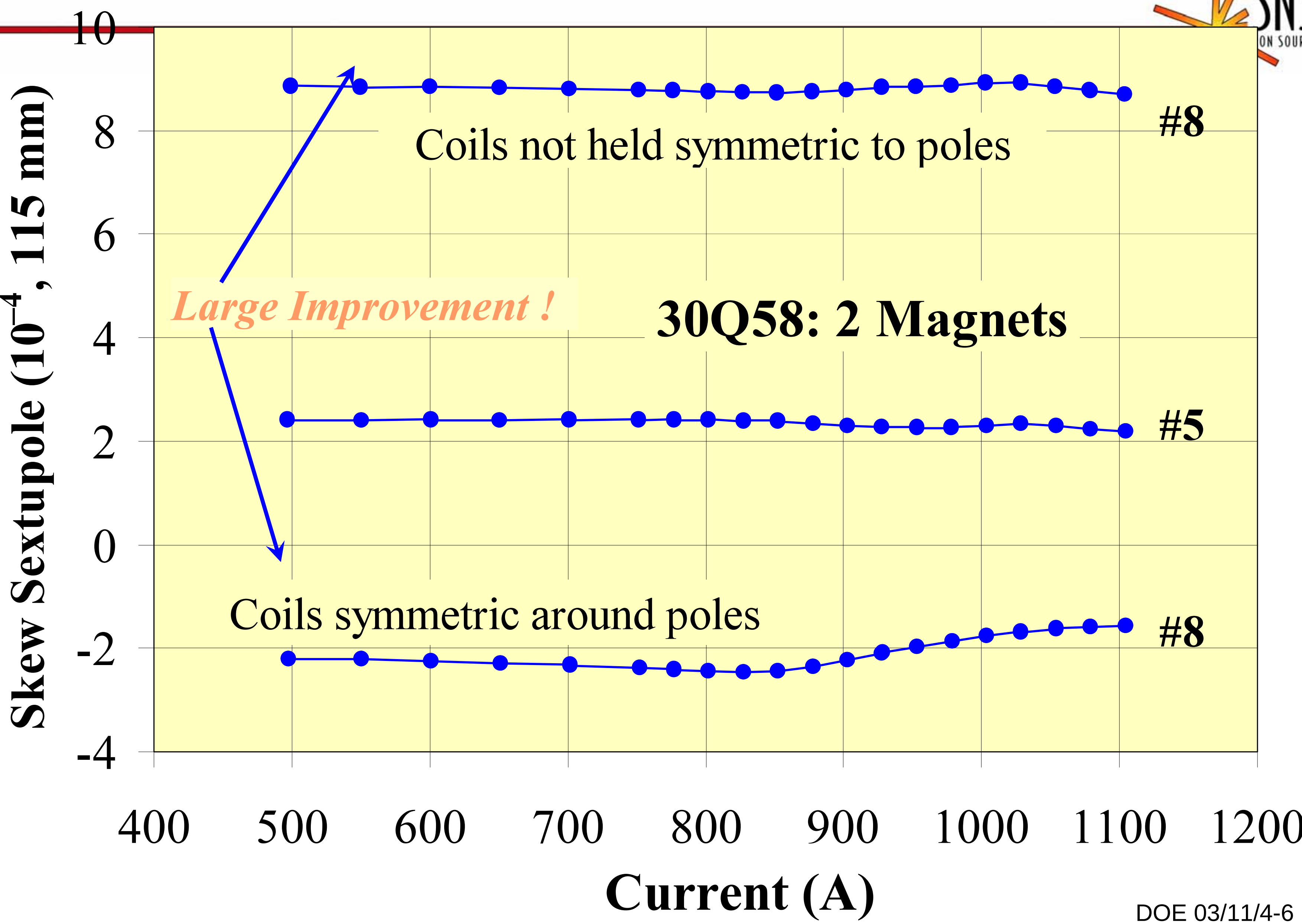
DOE 03/11/4-6

30Q: Normal Sextupole



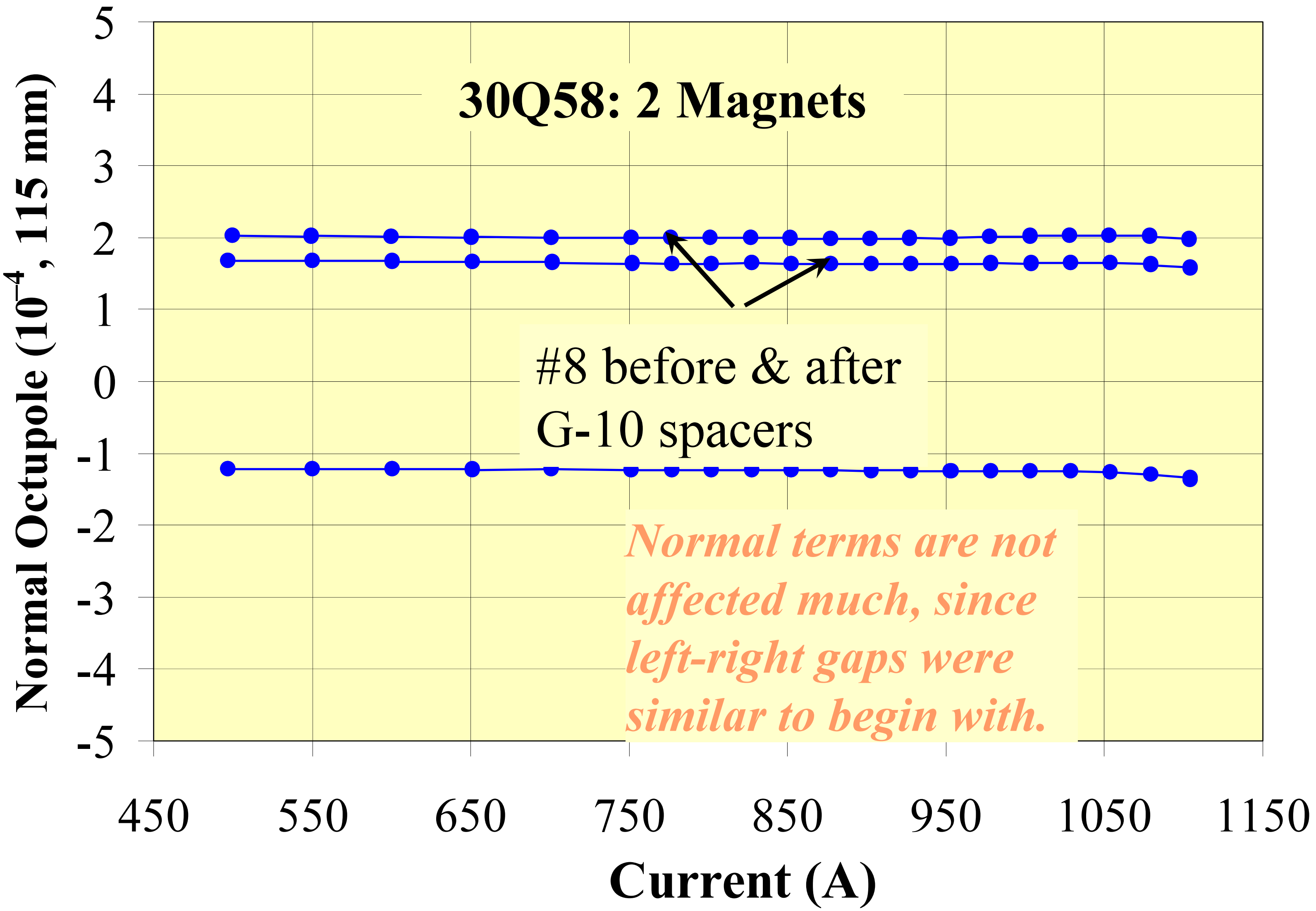
DOE 03/11/4-6

30Q: Skew Sextupole



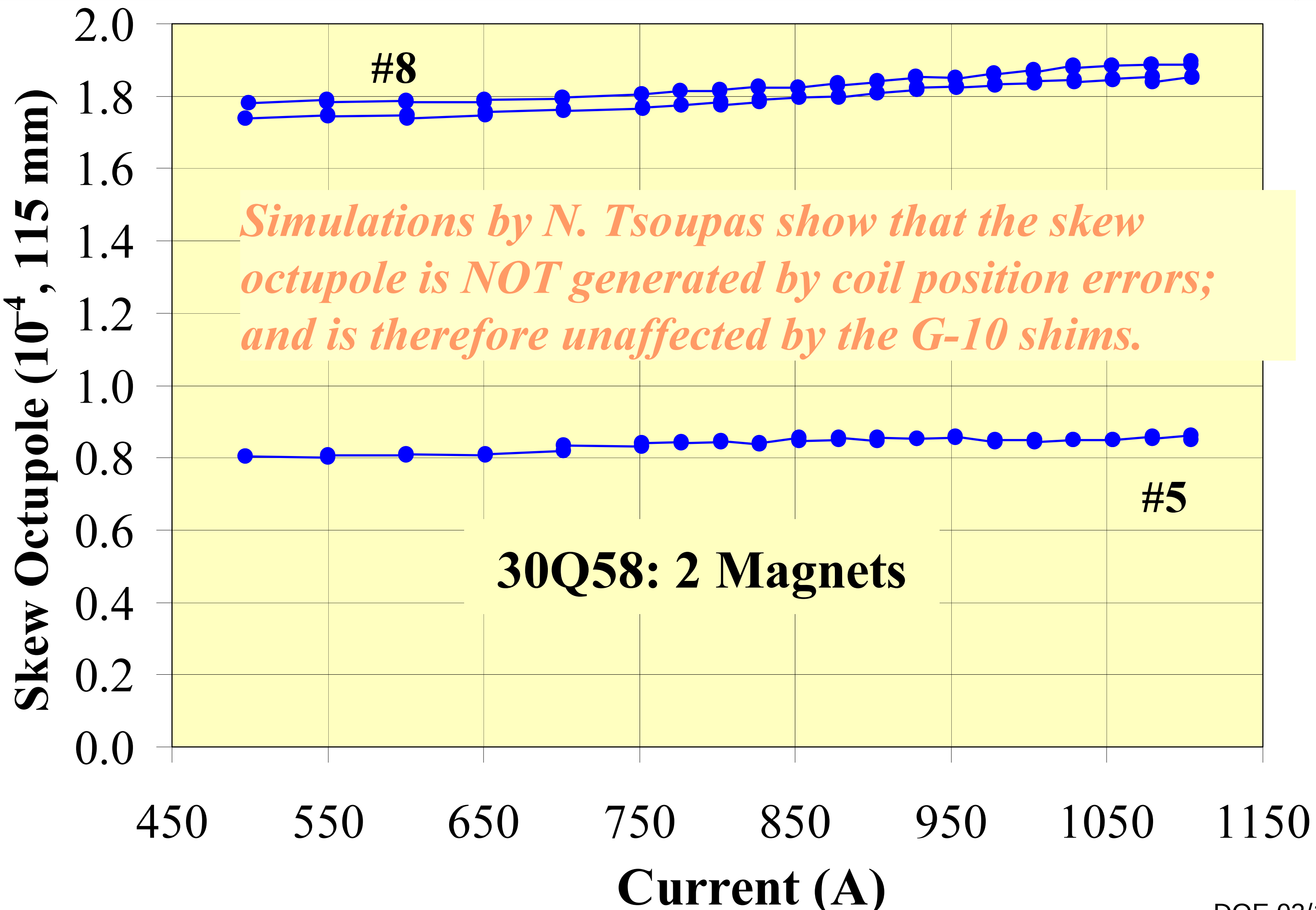
DOE 03/11/4-6

30Q: Normal Octupole



DOE 03/11/4-6

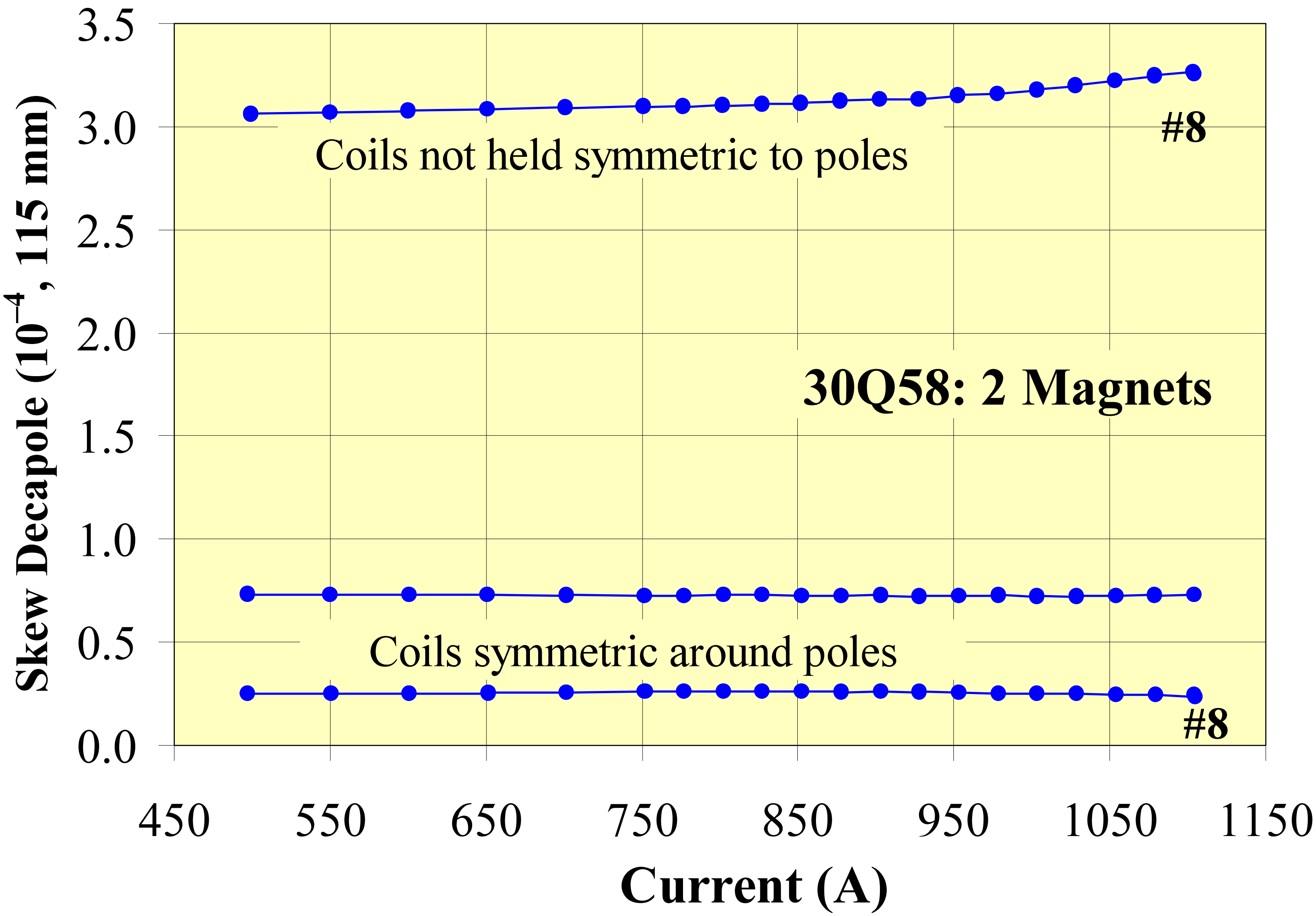
30Q: Skew Octupole



Simulations by N. Tsoupas show that the skew octupole is NOT generated by coil position errors; and is therefore unaffected by the G-10 shims.

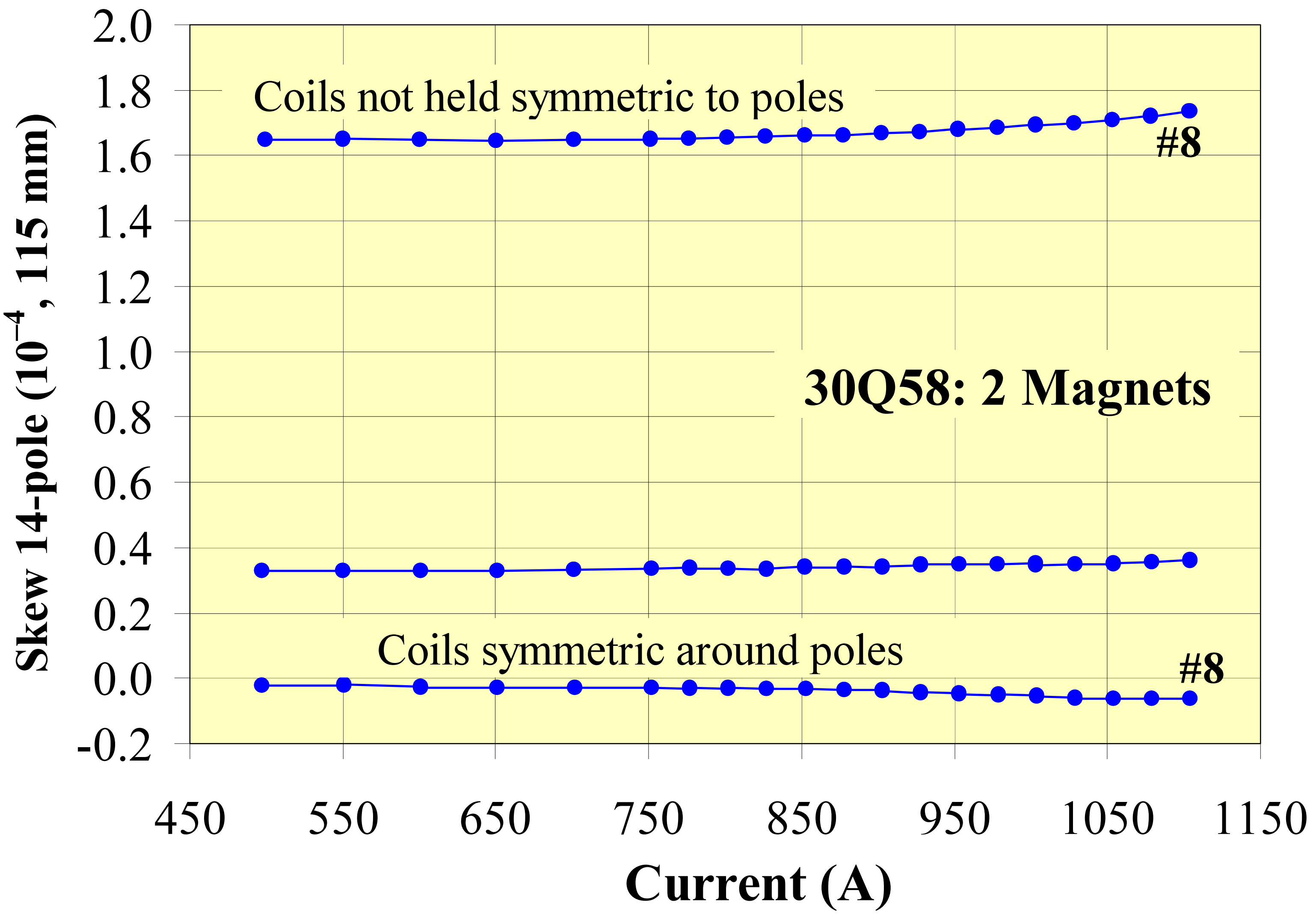
30Q58: 2 Magnets

30Q: Skew Decapole



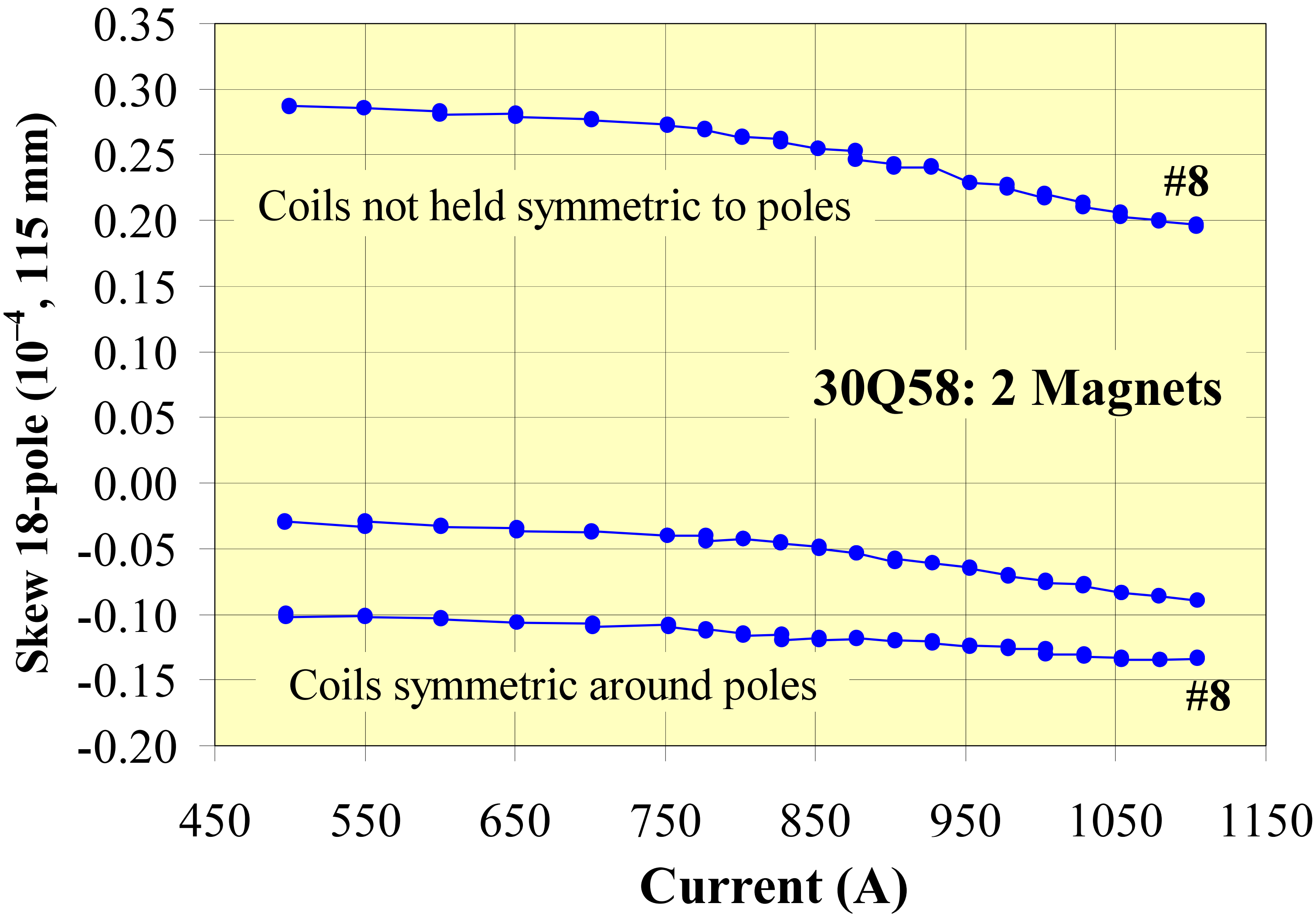
DOE 03/11/4-6

30Q: Skew 14-Pole



DOE 03/11/4-6

30Q: Skew 18-Pole

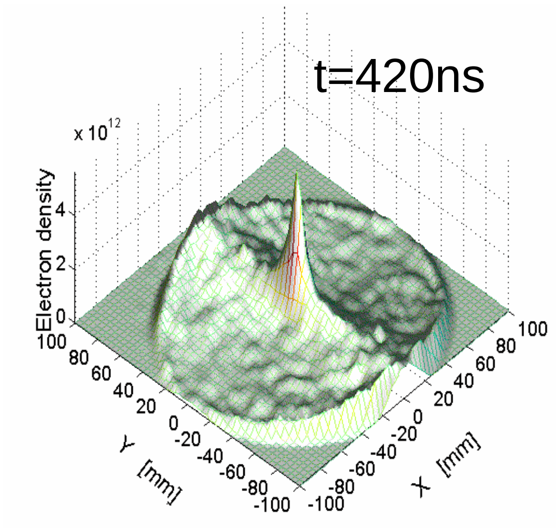


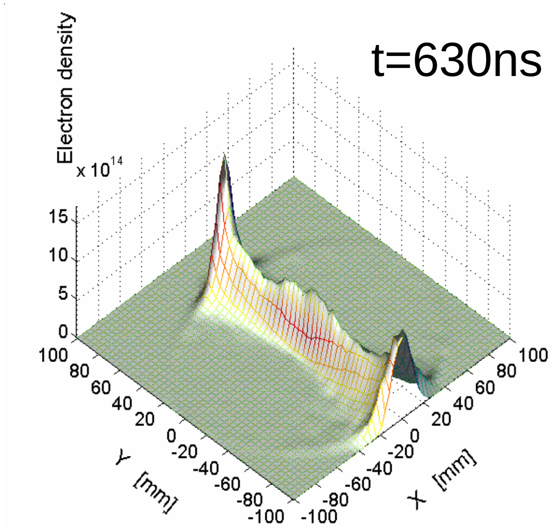
DOE 03/11/4-6

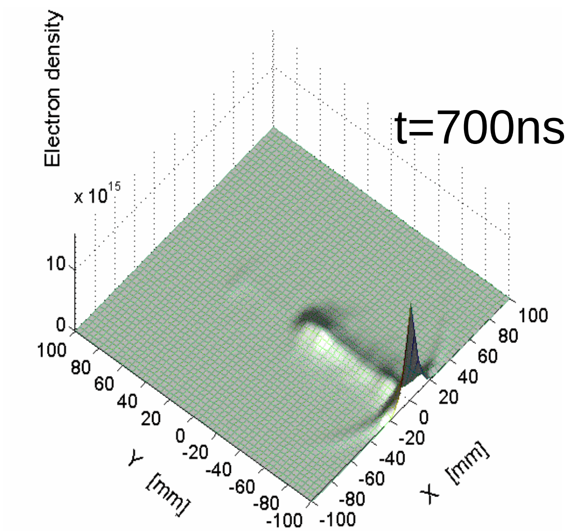
Summary of 30Q measurement and coil position

- Large harmonics have been linked to misplaced coils in the poles.
- Significant improvement in field quality is obtained after the coils are held in proper place with G-10 shims.
- Harmonics affected are consistent with simulations
- No appreciable change in ITF, or allowed harmonics.
- **Due to a potential of coil movement subsequent to measurements, it is desirable that all 30Q58's be fitted with the G-10 shims prior to measurements.**

E-cloud distribution at different time for 500V clearing field







- **Clearing field can cause the particle polarized toward the clearing field direction. As a result, it causes strong Multipacting near the positive electrode.**

DOE 03/11/4-6