Measuring Bulk Fuel Velocity at the National Ignition Facility with Neutron Activation

Presentation to

248th American Chemical Society National Meeting

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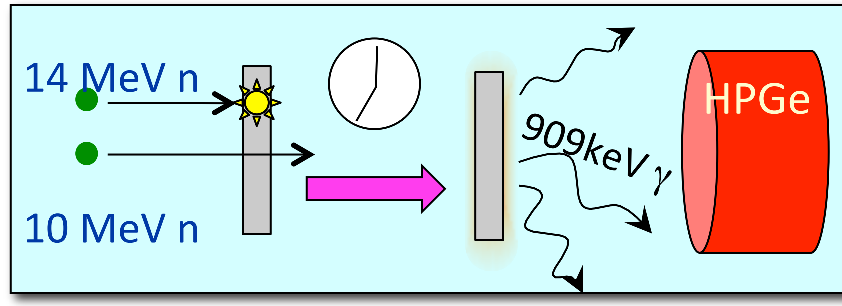
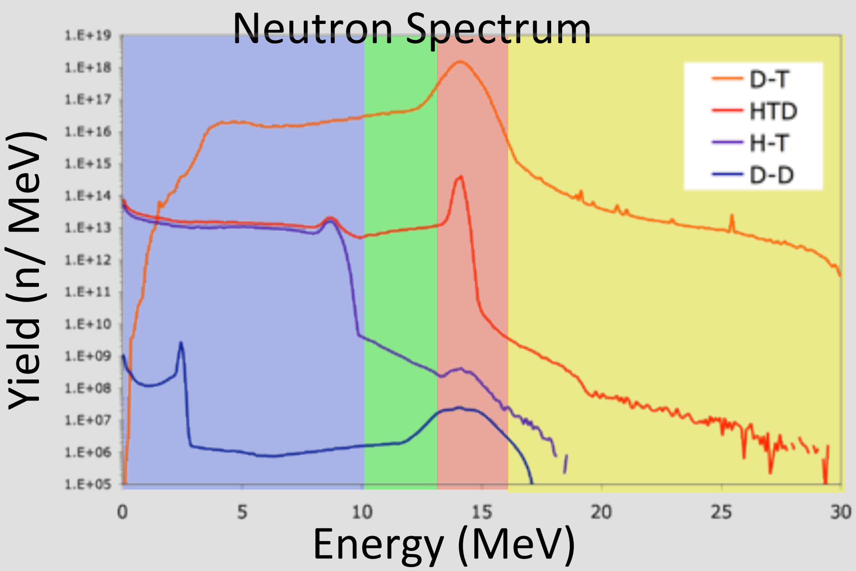
NAD Physics Basis
Activation Concept

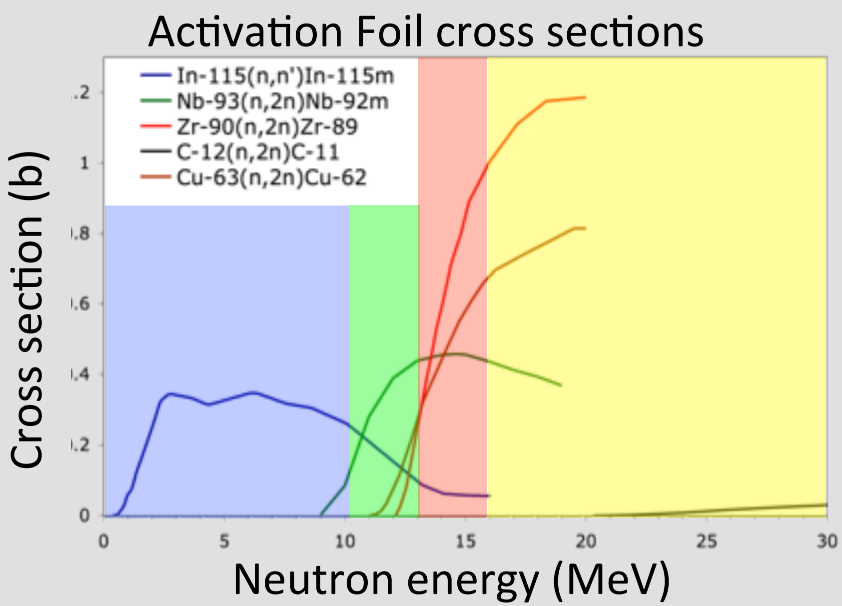
$$Y_n = \frac{4\pi R^2 A N_c}{m f_{BR} f_a N_A \varepsilon_{irr} \varepsilon_{det} < \sigma > [e^{-\lambda(\Delta t_{start})} - e^{-\lambda(\Delta t_{end})}]}$$





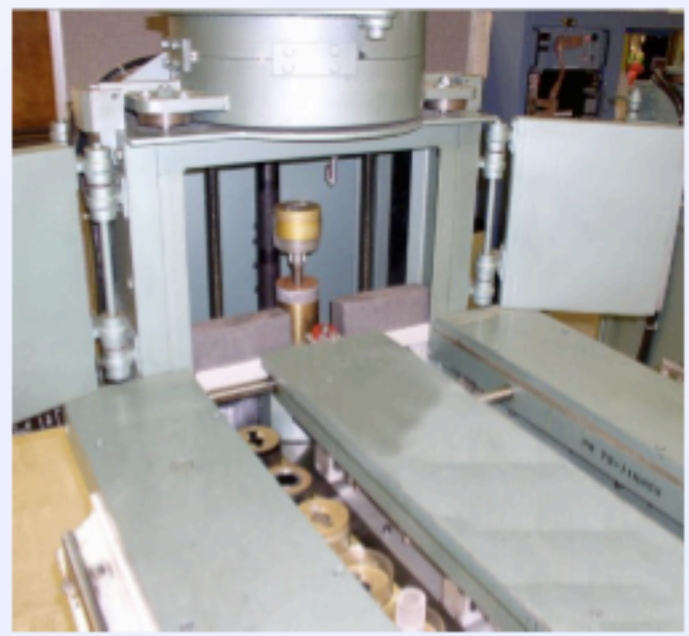
Four energy regions of interest:

1-10 MeV	(T-T / D-D spectrum)
10-13 MeV	(Downscattered)
13-15 MeV	(Primaries)
15-30 MeV	(Tertiaries)



^{115}In(n,n') ⇒ ^{115m}In	($t_{1/2}$=4.5 h)
^{93}Nb(n,2n) ⇒ ^{92m}Nb	($t_{1/2}$=10 d)
^{90}Zr(n,2n) ⇒ ^{89}Zr	($t_{1/2}$=3.3 d)
^{63}Cu(n,2n) ⇒ ^{62}Cu	($t_{1/2}$=9.74 m)
^{12}C(n,2n) ⇒ ^{11}C	($t_{1/2}$=20 m)

LLNL Nuclear Counting Facility in B151

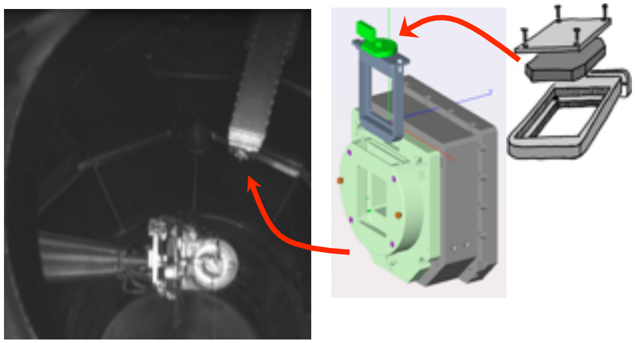


The six "flavors" of Neutron Activation

DIM-NAD (DD)

In

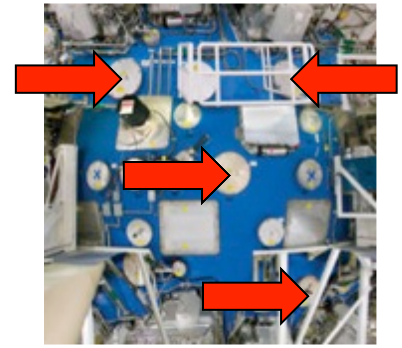
$t_{1/2}$=4.5h



Flange-NAD (DT)

Zr

$t_{1/2}$=3.3d

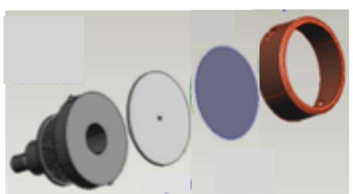


(not actual locations)

Snout-NAD (DD)

In

$t_{1/2}$=4.5h

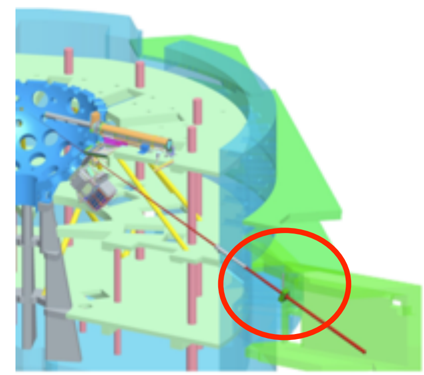


NAD20 (DT)

Cu Zr

$t_{1/2}$=9.7m

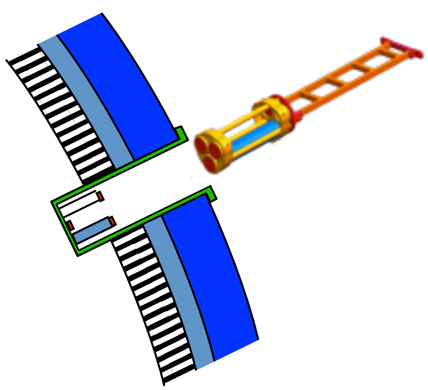
$t_{1/2}$=3.3d



Well-NAD (DT)

Zr

$t_{1/2}$=3.3d



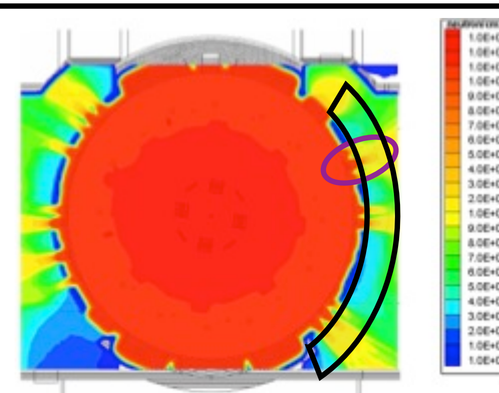
Background model validation (DT)

In Al Zr

$t_{1/2}$=4.5h

$t_{1/2}$=15h

$t_{1/2}$=3.3d

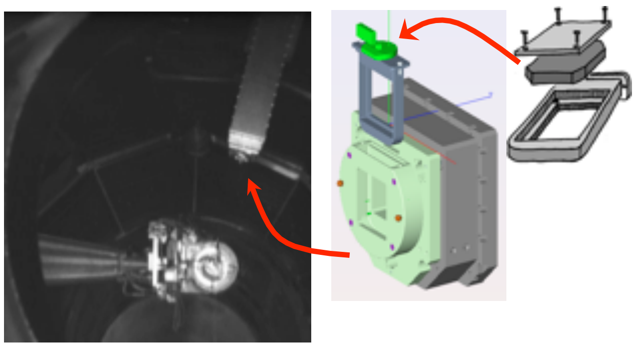


The six "flavors" of Neutron Activation

DIM-NAD (DD)

In

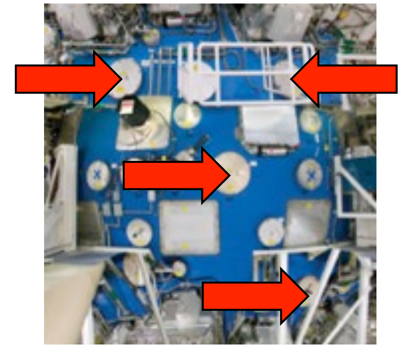
$t_{1/2}$=4.5h



Flange-NAD (DT)

Zr

$t_{1/2}$=3.3d

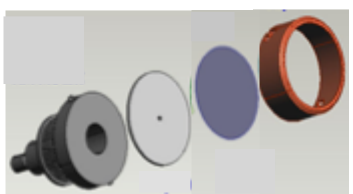


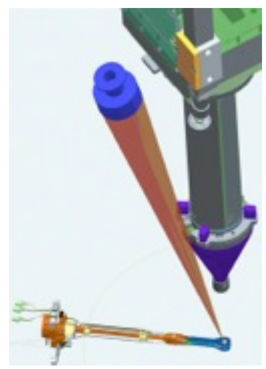
(not actual locations)

Snout-NAD (DD)

In

$t_{1/2}$=4.5h



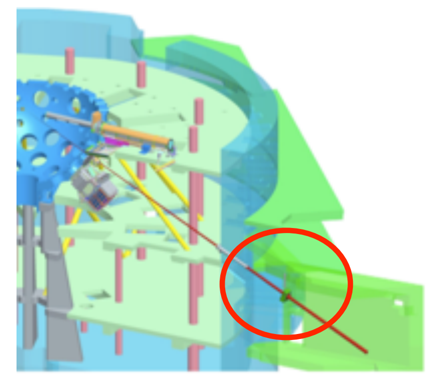


NAD20 (DT)

Cu Zr

$t_{1/2}$=9.7m

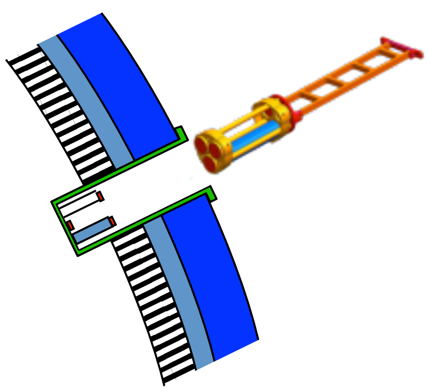
$t_{1/2}$=3.3d



Well-NAD (DT)

Zr

$t_{1/2}$=3.3d



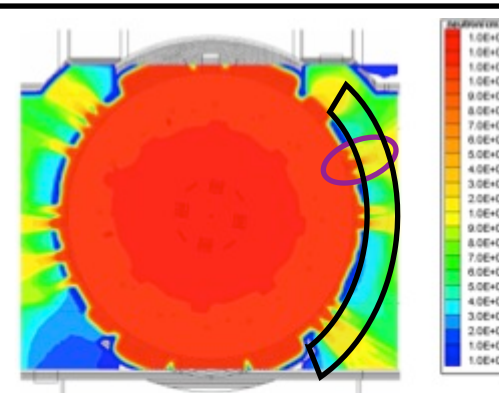
Background model validation (DT)

In Al Zr

$t_{1/2}$=4.5h

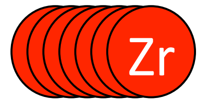
$t_{1/2}$=15h

$t_{1/2}$=3.3d

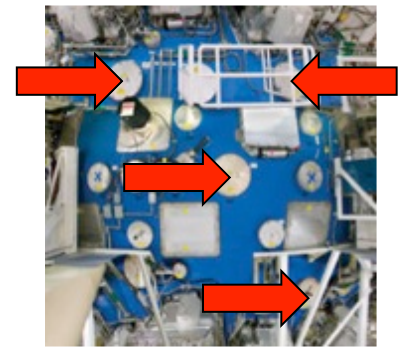


The six "flavors" of Neutron Activation

Flange-NAD (DT)



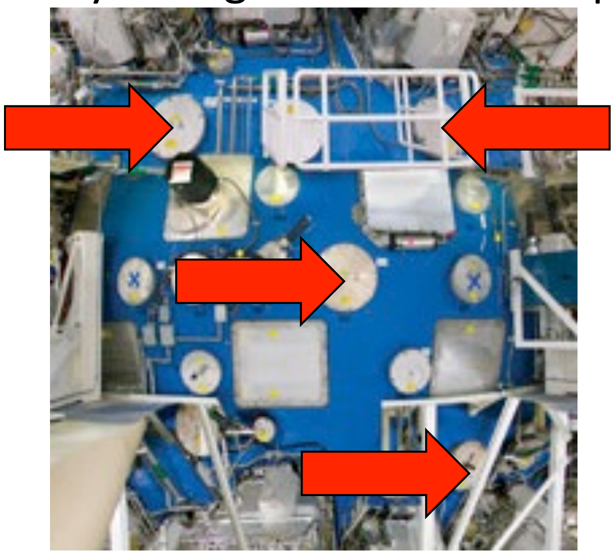
$t_{1/2}$=3.3d



(not actual locations)

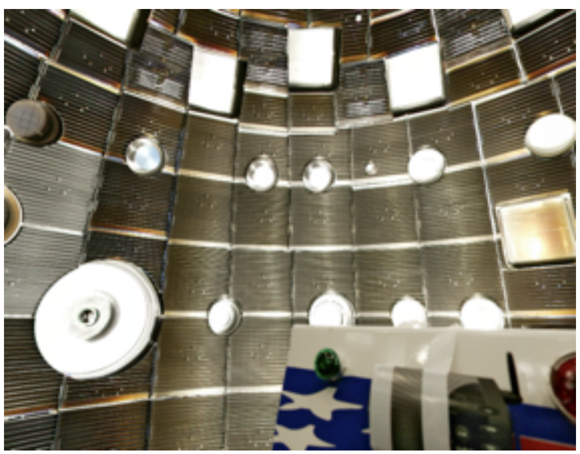
Flange-NAD Overview

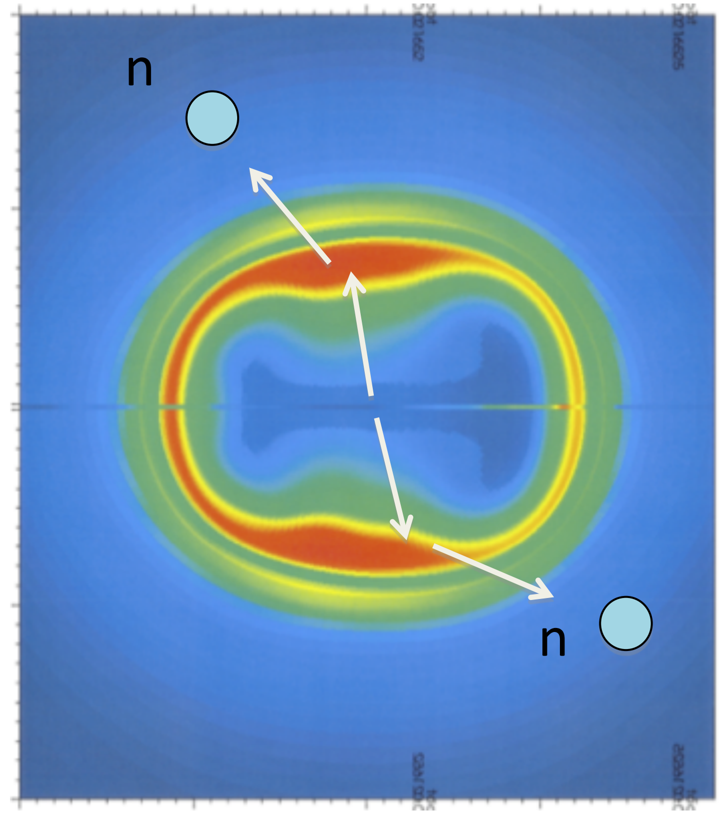
- Zirconium samples mounted outside 9-16 ports around target chamber.
- Intention is to measure yield anisotropy to <2-5% precision by taking in ratio to isotropic shot.

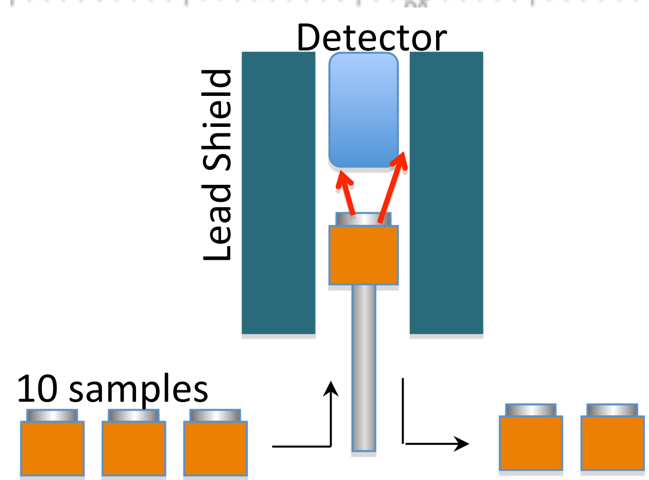


(not actual locations)

$$R_Y(\Omega) = \left(\frac{m_{W1} m_{F2}}{m_{W2} m_{F1}}\right)\left(\frac{A_{W2}^{\ 0}}{A_{W1}^{\ 0}}\right)\left(\frac{A_{F1}^{\ 0}}{A_{F2}^{\ 0}}\right) - 1$$

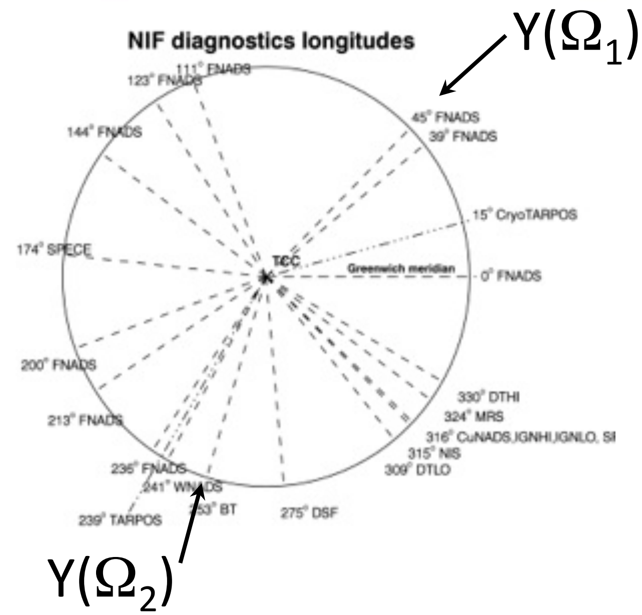






Double ratio to minimize uncertainties

$$Y_n = A^0 \frac{4\pi R^2 A}{\lambda m f_{BR} f_a N_A \varepsilon_{irr} \varepsilon_{det} < \sigma >}$$



Shot A:
"layered"

Shot B:
"exploding pusher"
(isotropic)

$$R_{SA} = \frac{Y_A(\Omega_1)/Y_A(\Omega_2)}{Y_B(\Omega_1)/Y_B(\Omega_2)} = \left(\frac{m_{A2}m_{B2}}{m_{A1}m_{B1}}\right)\left(\frac{A^0_{A1}}{A^0_{A2}}\right)\left(\frac{A^0_{B2}}{A^0_{B1}}\right)$$

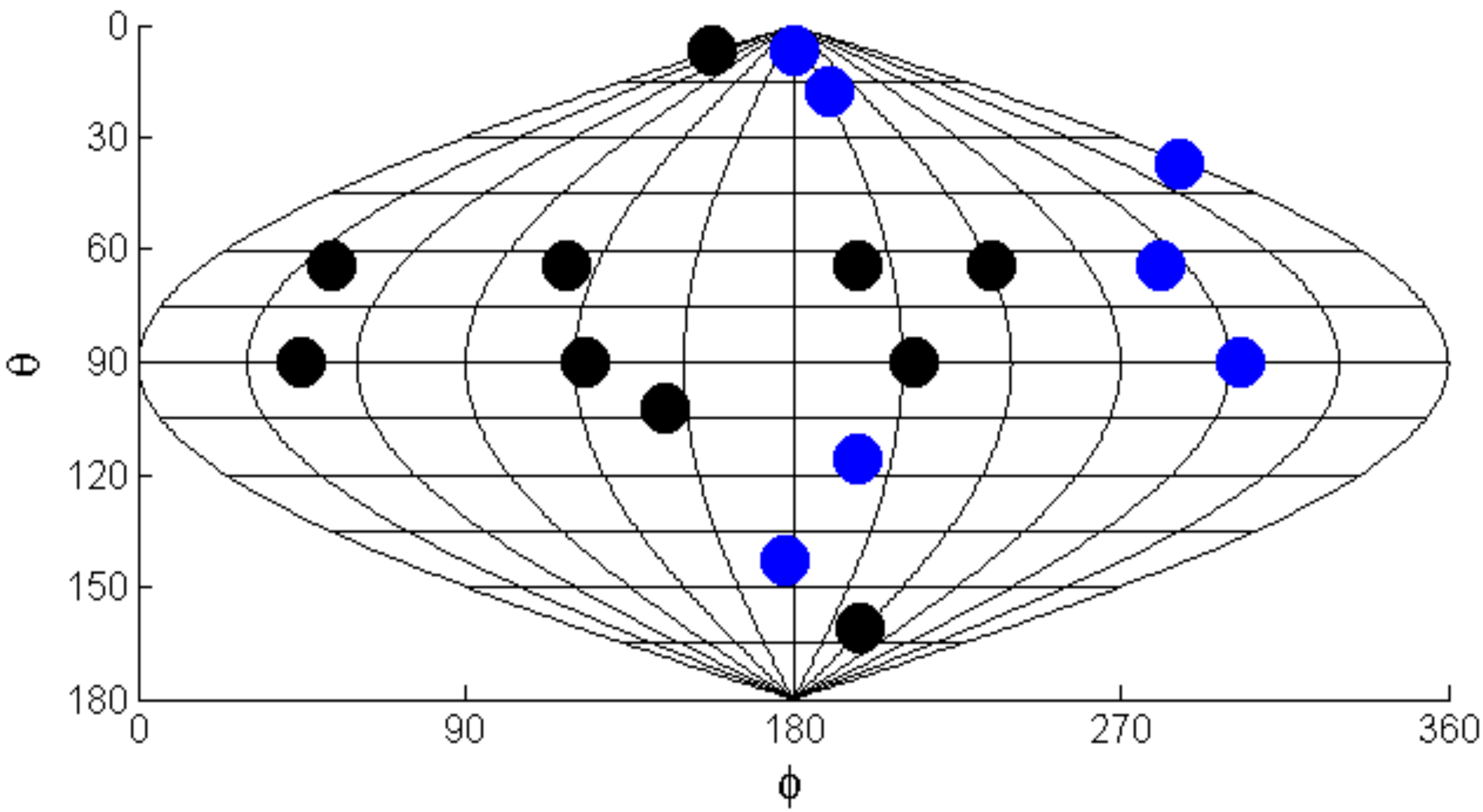
Take ratio of one flange position to another (Well-NAD) and normalize to an isotropic shot (exploding pusher). All systematic errors are eliminated.

$$\Delta\rho R = -\frac{A_{DT}}{\sigma_{scatter}} \ln\left(R_{SA}\right)$$

This "double ratio" of specific activities is related to the areal density *differences* of the fuel.

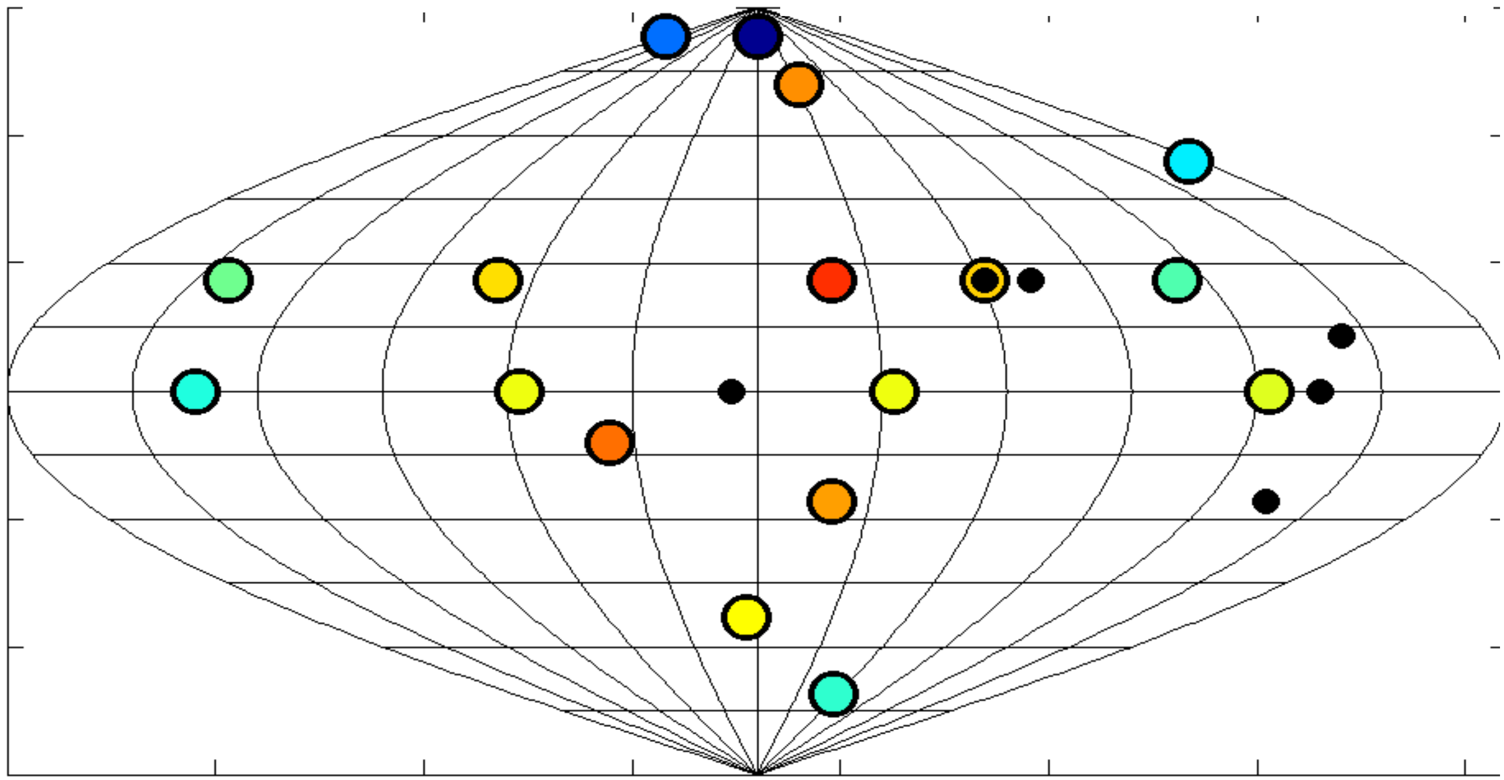
Note: <σ> does not cancel in the case of a "bulk fuel velocity."

Flange-NAD locations



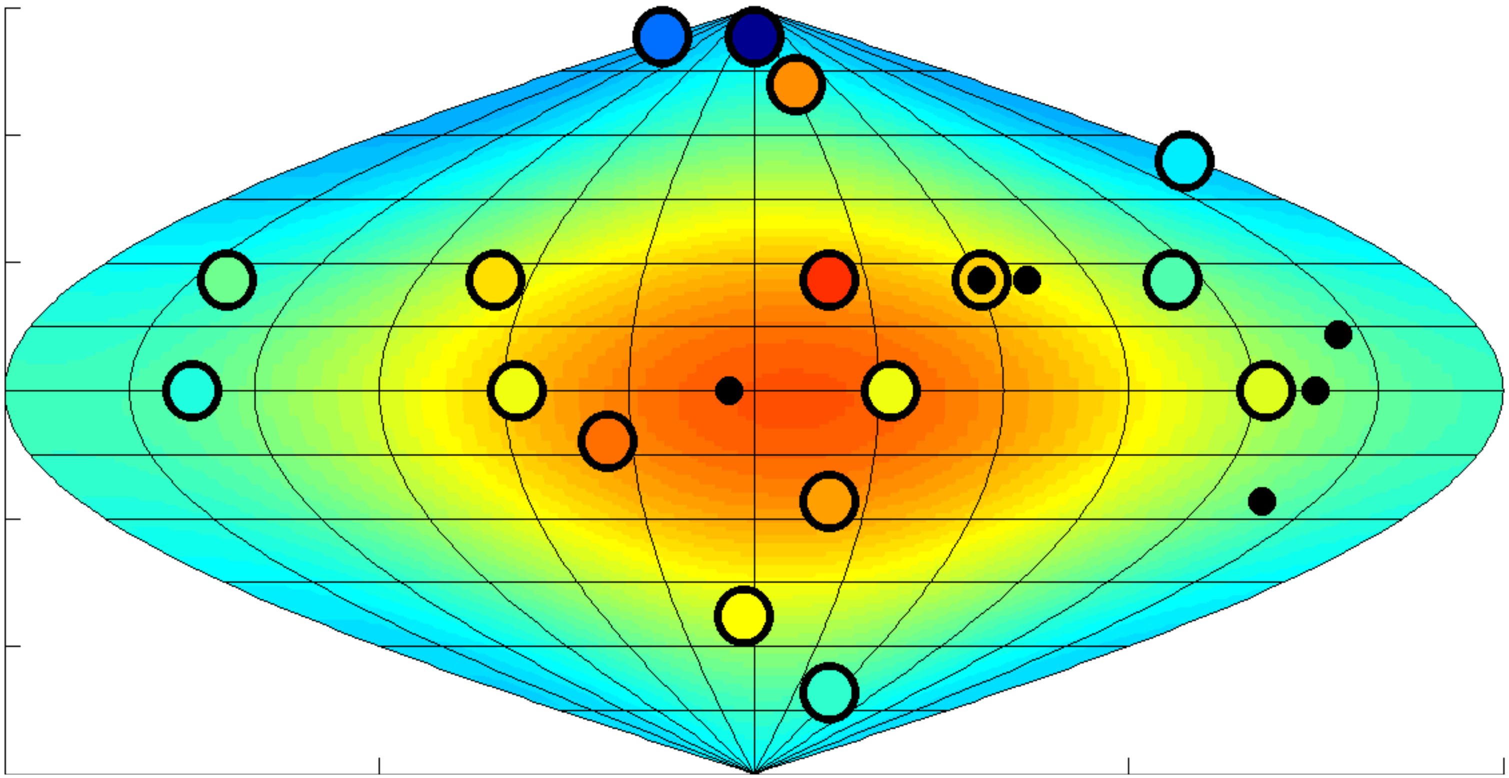
New FNAD locations (blue) were added after Feb 2012.

Flange-NAD locations



Activity ratios measured at 17 locations

Flange-NAD locations

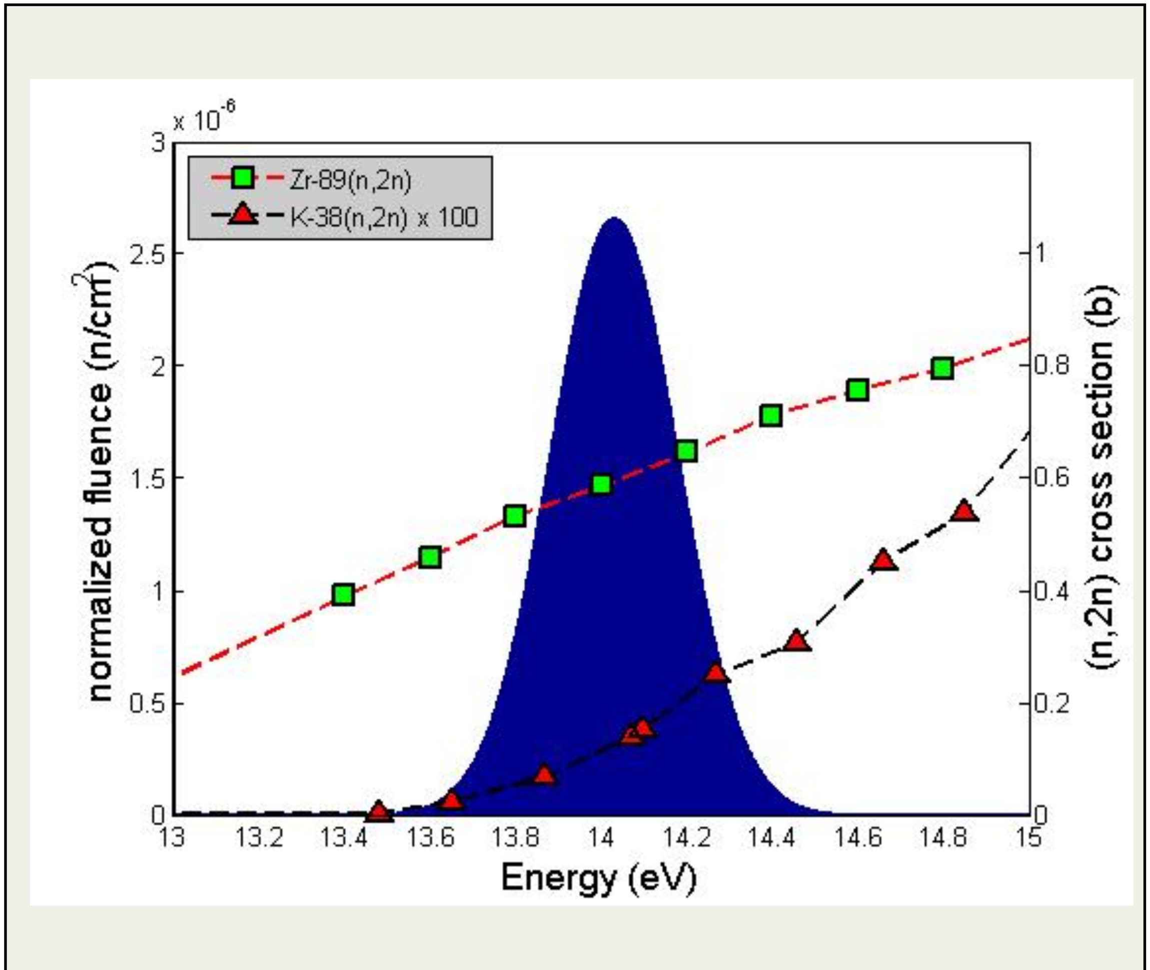


Activity ratios measured at 17 locations

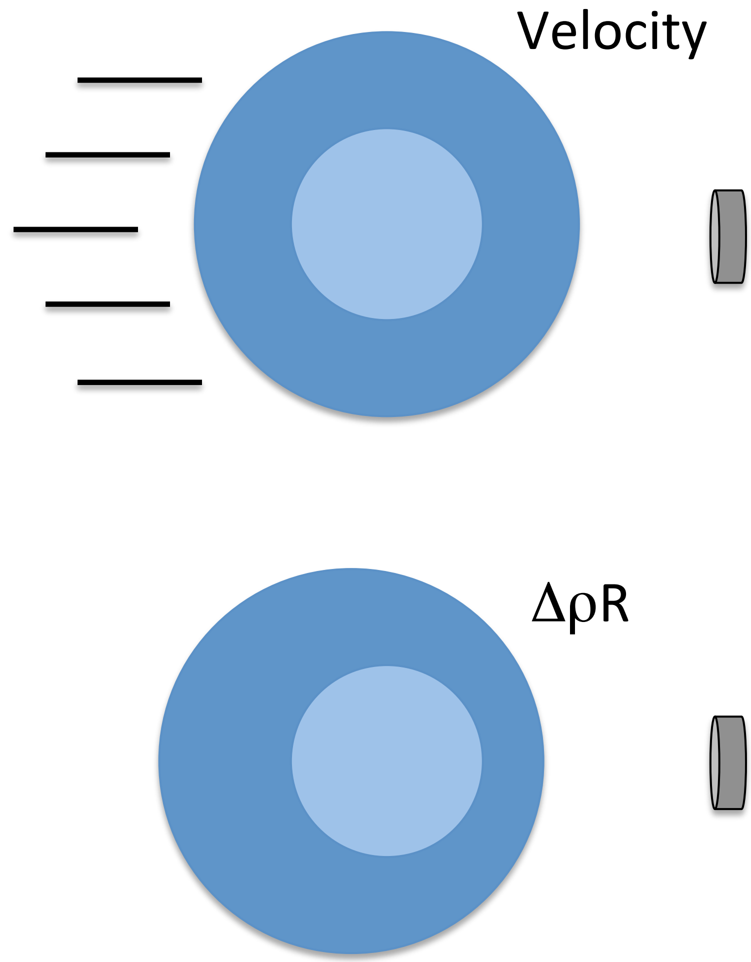
Fit to low-order spherical harmonics

Flange-NAD is sensitive to both ρR and core velocity along a given line of sight.

^{90}Zr and ^{39}K σ-(n,2n)



μ_0=14.07 MeV, σ=0.150 MeV



nToF and MRS yields are independent of velocity. Peak shift independently measures velocity.

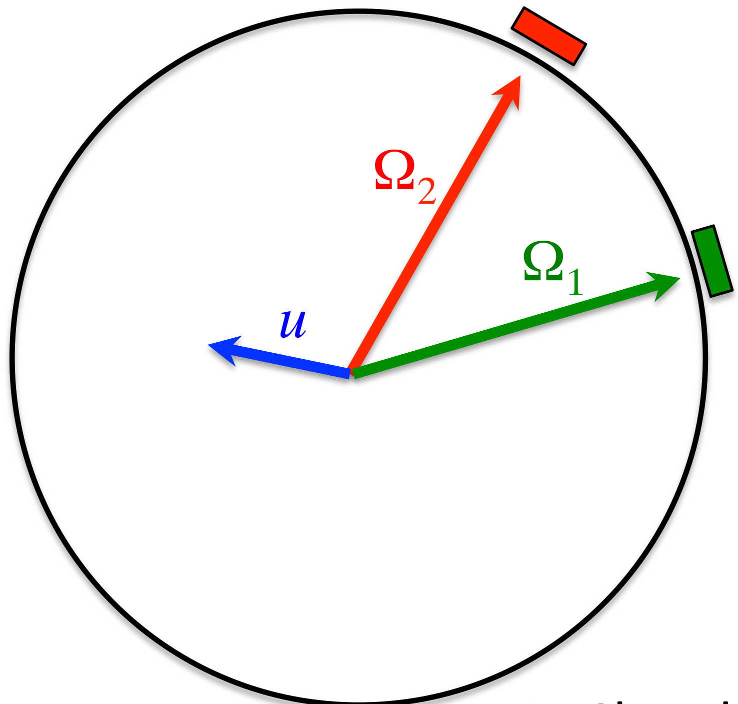
How to calibrate when the measurements are on the "calibration" shots?

$$Y_n = A^0 \frac{4\pi R^2 A}{\lambda m f_{BR} f_a N_A \varepsilon_{irr} \varepsilon_{det} < \sigma >}$$

$$R_{SA} = \frac{Y_A(\Omega_1)/Y_A(\Omega_2)}{Y_B(\Omega_1)/Y_B(\Omega_2)} = \left(\frac{m_{A2} m_{B2}}{m_{A1} m_{B1}}\right)\left(\frac{A^0_{A1}}{A^0_{A2}}\right)\left(\frac{A^0_{B2}}{A^0_{B1}}\right)$$

Assumed isotropic!

$$\frac{A^0_2}{A^0_1} = \frac{\varepsilon_2}{\varepsilon_1}\left(\frac{1+\alpha\vec{u}\cdot\hat{\Omega}_2}{1+\alpha\vec{u}\cdot\hat{\Omega}_1}\right) \qquad \alpha = \frac{3.2\%}{100 km/s}$$



NIF Chamber

In principle…

- 12 calibration (Expl. Push.) shots
- x 17 zirconium activation measurements
- = 204 datapoints

- 17 irradiation efficiencies
- + 3 velocity vectors x 12 shots
- = 53 unknowns

Can a *global* fit to all calibration shots give us the efficiencies despite velocity effects?

How to calibrate when the measurements are on the "calibration" shots?

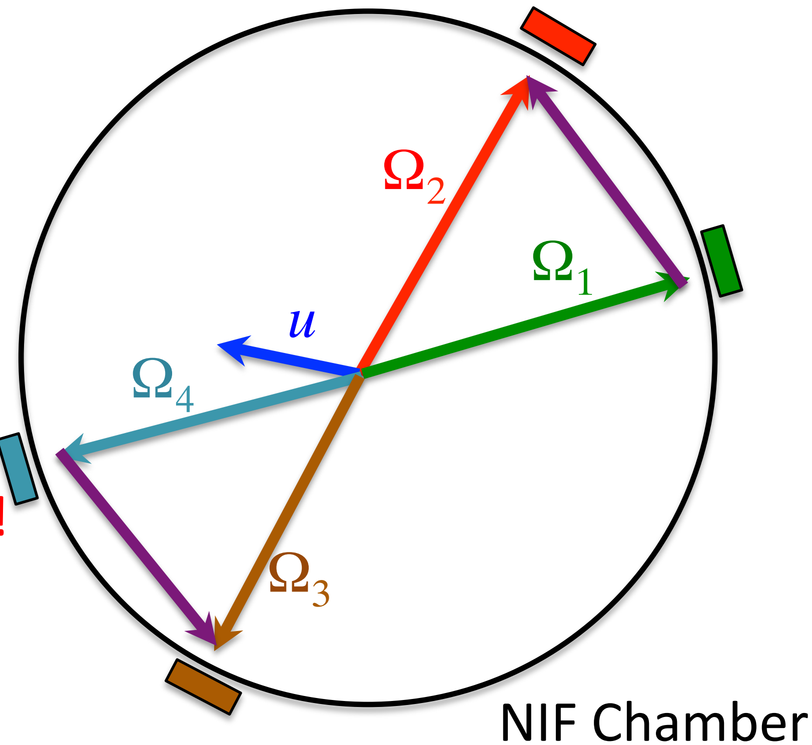
NIC

$$Y_n = A^0 \frac{4\pi R^2 A}{\lambda m f_{BR} f_a N_A \varepsilon_{irr} \varepsilon_{det} < \sigma >}$$

$$R_{SA} = \frac{Y_A(\Omega_1)/Y_A(\Omega_2)}{Y_B(\Omega_1)/Y_B(\Omega_2)} = \left(\frac{m_{A2} m_{B2}}{m_{A1} m_{B1}}\right)\left(\frac{A^0_{A1}}{A^0_{A2}}\right)\left(\frac{A^0_{B2}}{A^0_{B1}}\right)$$

Assumed isotropic!

$$\frac{A^0_2}{A^0_1} = \frac{\varepsilon_2}{\varepsilon_1}\left(\frac{1+\alpha\vec{u}\cdot\hat{\Omega}_2}{1+\alpha\vec{u}\cdot\hat{\Omega}_1}\right)$$



If we get clever…

$$\frac{A^0_2}{A^0_1} = \frac{\varepsilon_2}{\varepsilon_1}\left(1+\alpha\vec{u}\cdot\left(\hat{\Omega}_2-\hat{\Omega}_1\right)+O(\alpha^2)\right)$$

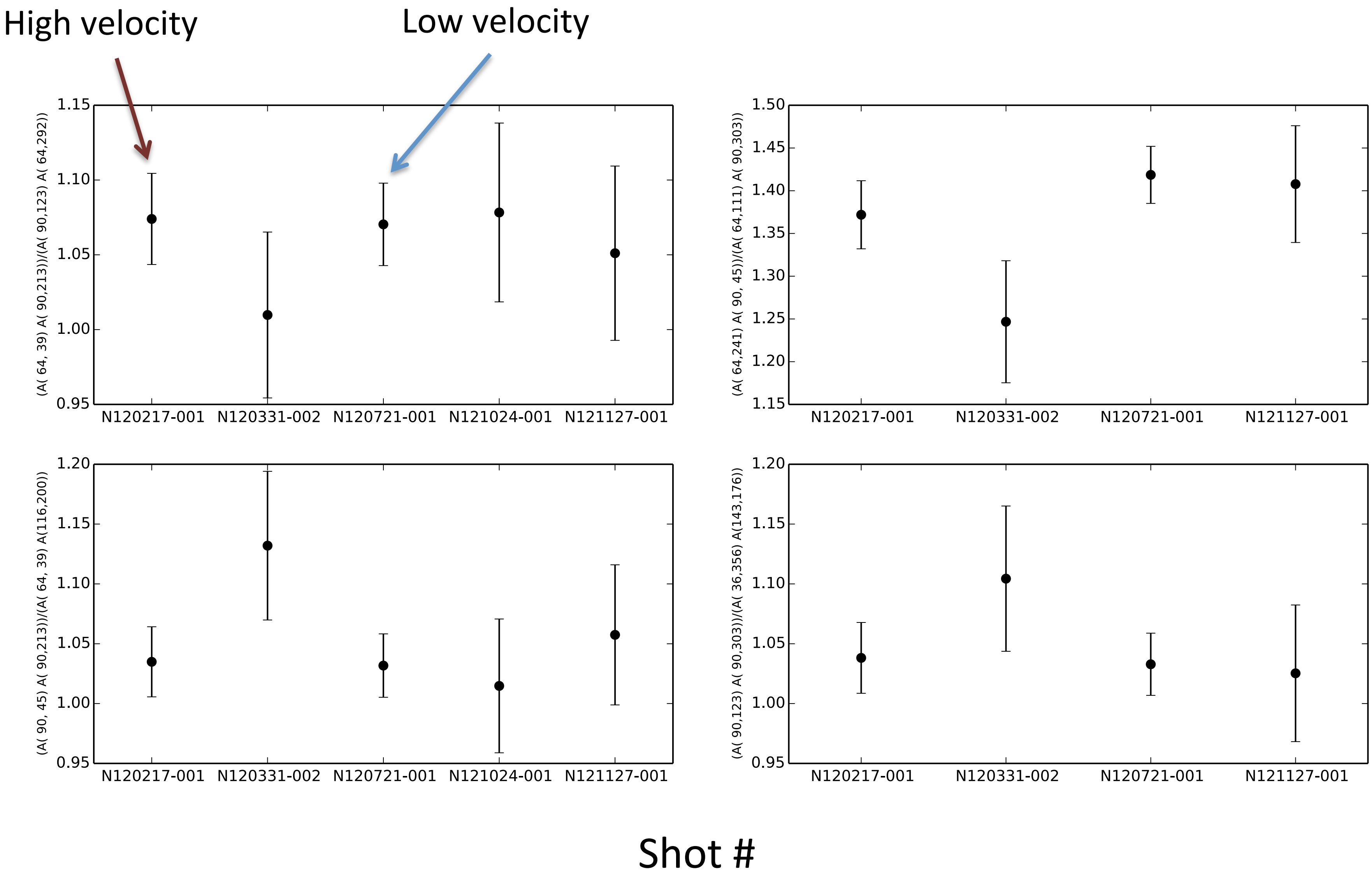
$$\frac{A^0_2 A^0_4}{A^0_1 A^0_3} = \frac{\varepsilon_2\varepsilon_4}{\varepsilon_1\varepsilon_3}\left(1+\alpha\vec{u}\cdot\left(\hat{\Omega}_2-\hat{\Omega}_1+\hat{\Omega}_4-\hat{\Omega}_3\right)+O(\alpha^2)\right)$$

We found six four-vector combinations which sum to <10%, including every FNAD location.

Six constraints were added to our global fit, eliminating velocity bias.

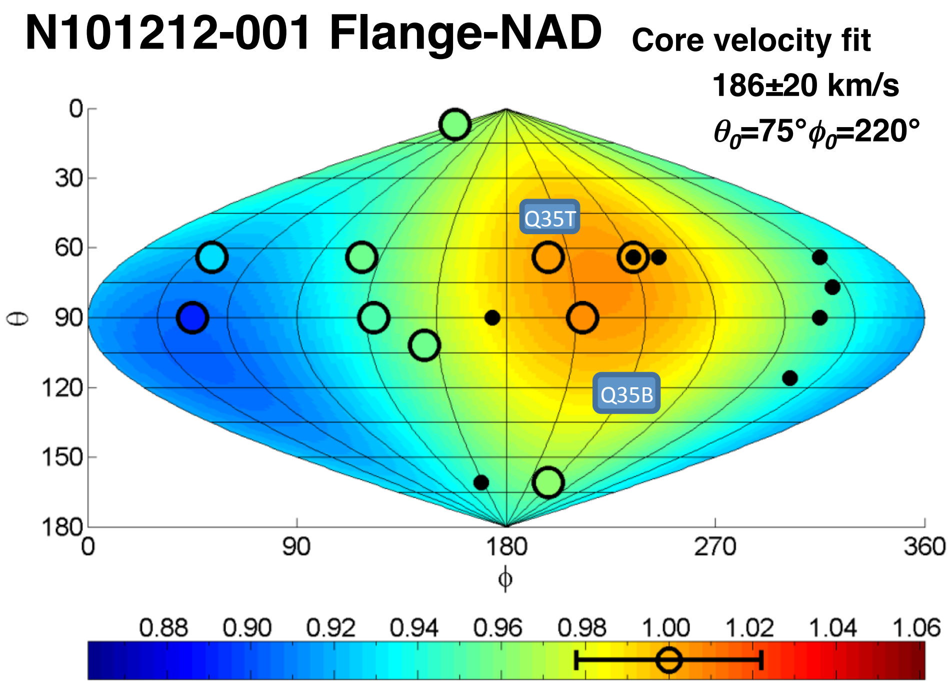
How to calibrate when the measurements are on the “calibration” shots?

$$\frac{A_2^0 A_4^0}{A_1^0 A_3^0} = \frac{\varepsilon_2 \varepsilon_4}{\varepsilon_1 \varepsilon_3}$$

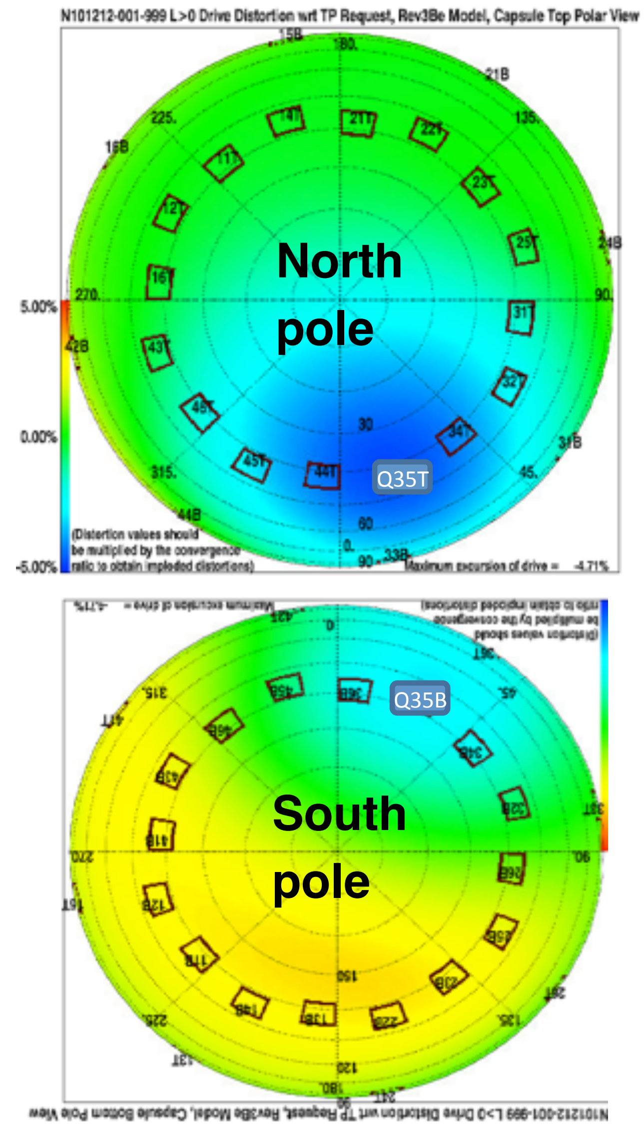


Core Velocity Correlates Strongly with Drive Asymmetry

N101212-001 exploding pusher (direct drive)



Drive distortion (Hydra postshot)

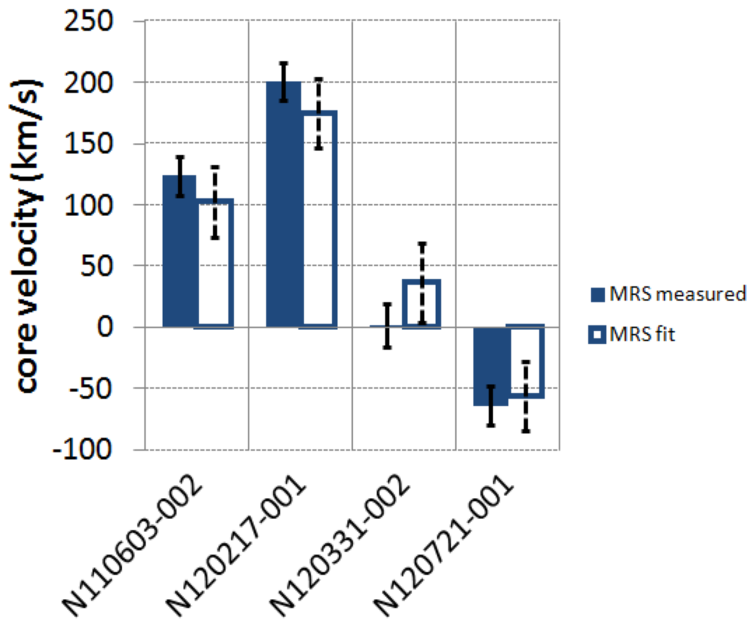


Core fuel velocity correlates with drive distortion, Doppler-shifting neutron spectrum, increasing activation along velocity axis.

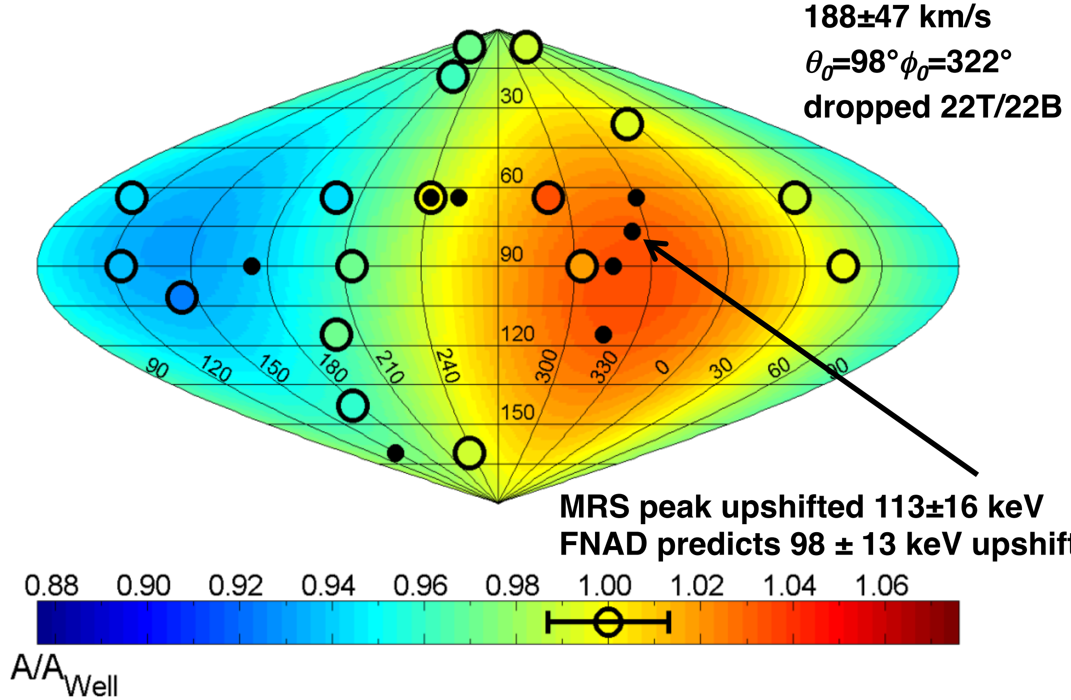
N120217-001 Flange-NAD

example of MRS peak shift prediction from FNAD data set

MRS has measured the DT peak energy shift predicted from the FNAD fit to within the known errors on every exploding pusher where MRS ran in medium-resolution mode and yield was sufficient for FNAD performance.

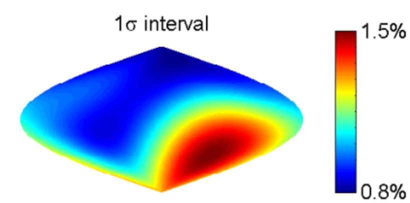


N120217-001 Flange-NAD normalized to globalExPu results fit



Coefficients:
apx=0.081759
apy=-0.066036
apz=-0.01403
as=3.4845

Fit values:
Well-NAD: 0.98791
MRS: 1.0314
nToF BT: 0.99719
SpecA: 1.0319
SpecE: 0.93985
NI: 1.034
DT HI: 1.0255
SPBT: 0.97281



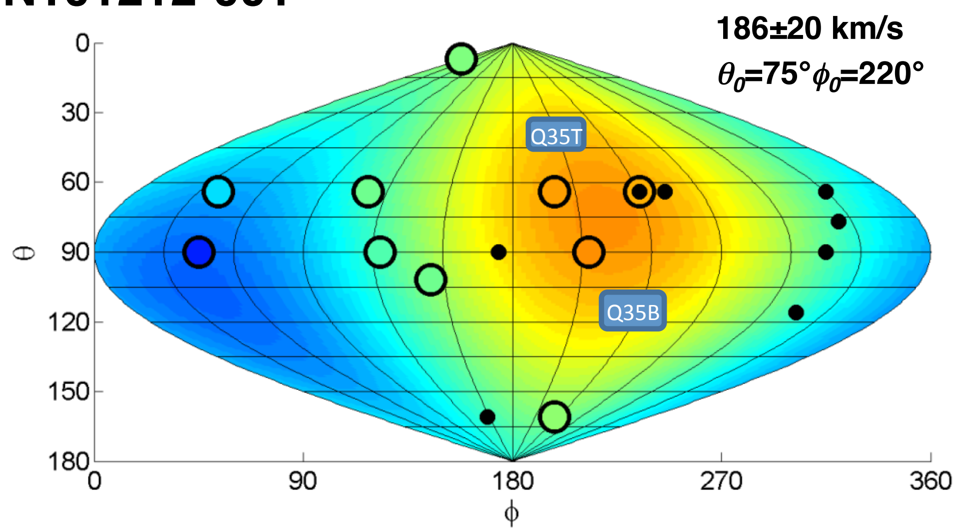
plot generated 12-Nov-2012 12:02:47

χ^2: 9.20 (ν=13)
p-value: 0.24

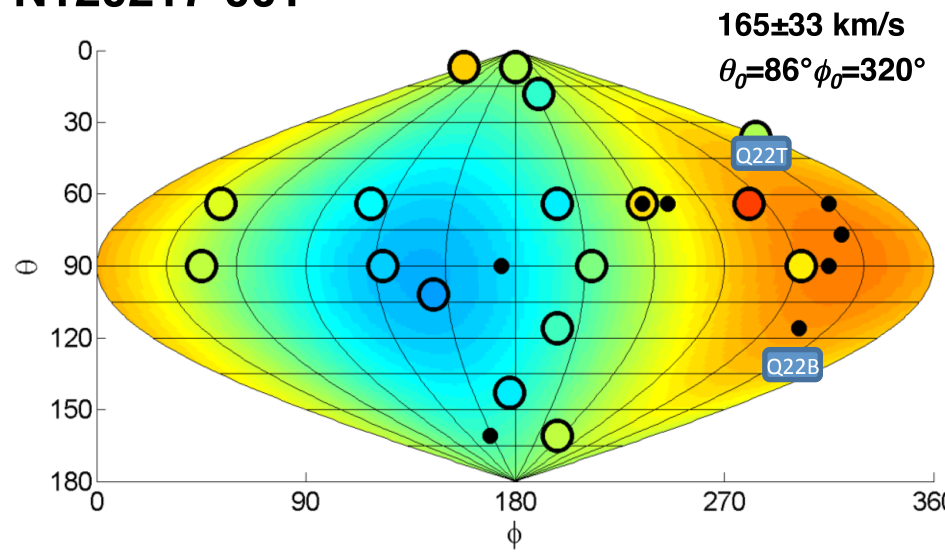
Flange-NAD Measured Core Velocities
Exploding Pushers with Drive Asymmetries

normalized to N120721-001 (velocity corrected)

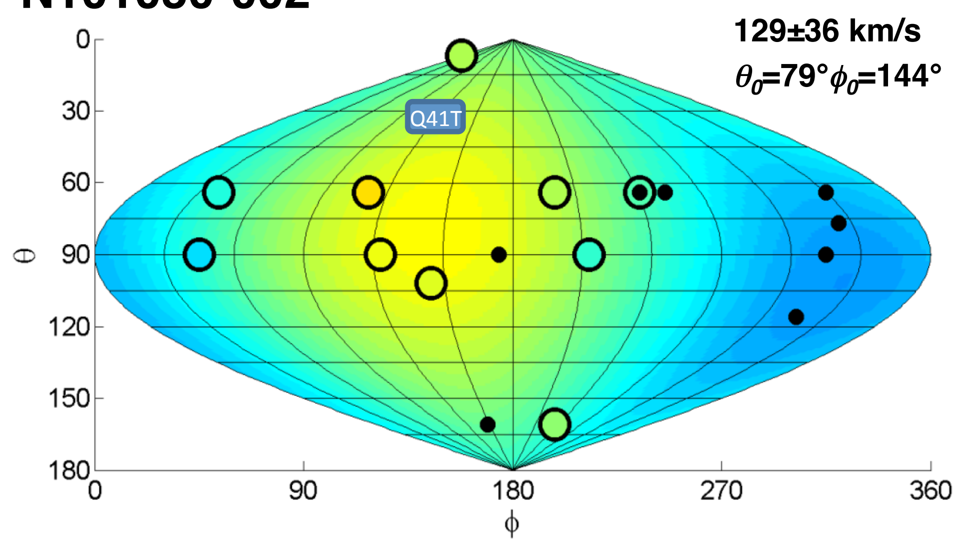
N101212-001



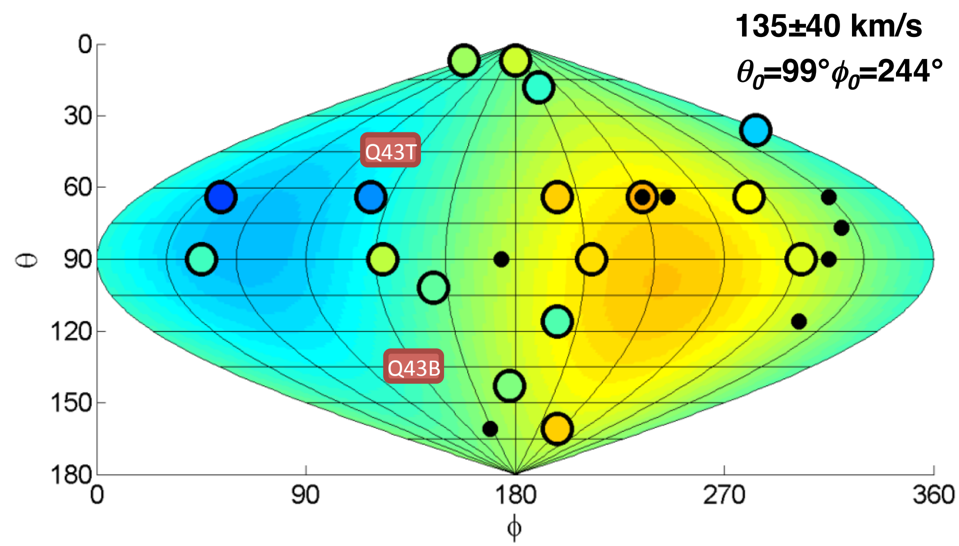
N120217-001



N101030-002

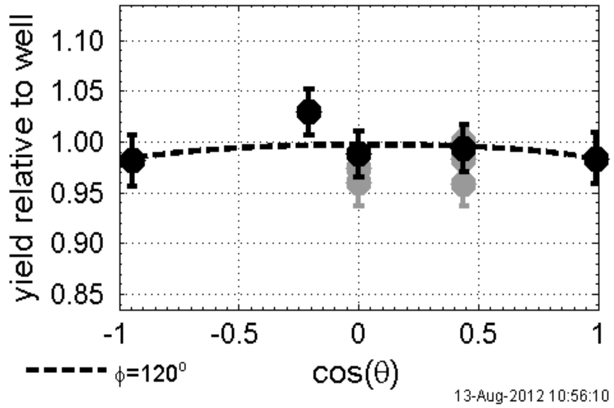


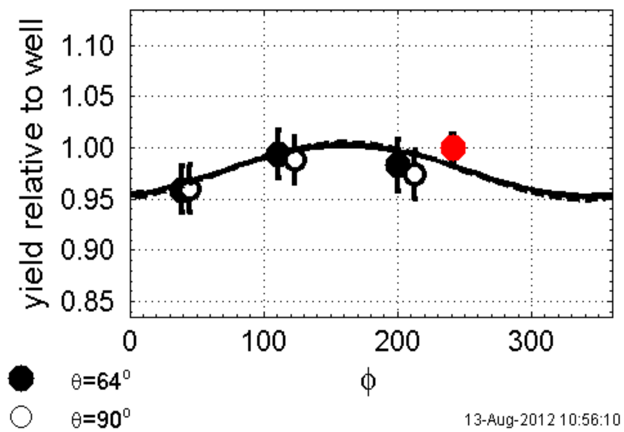
N120331-002

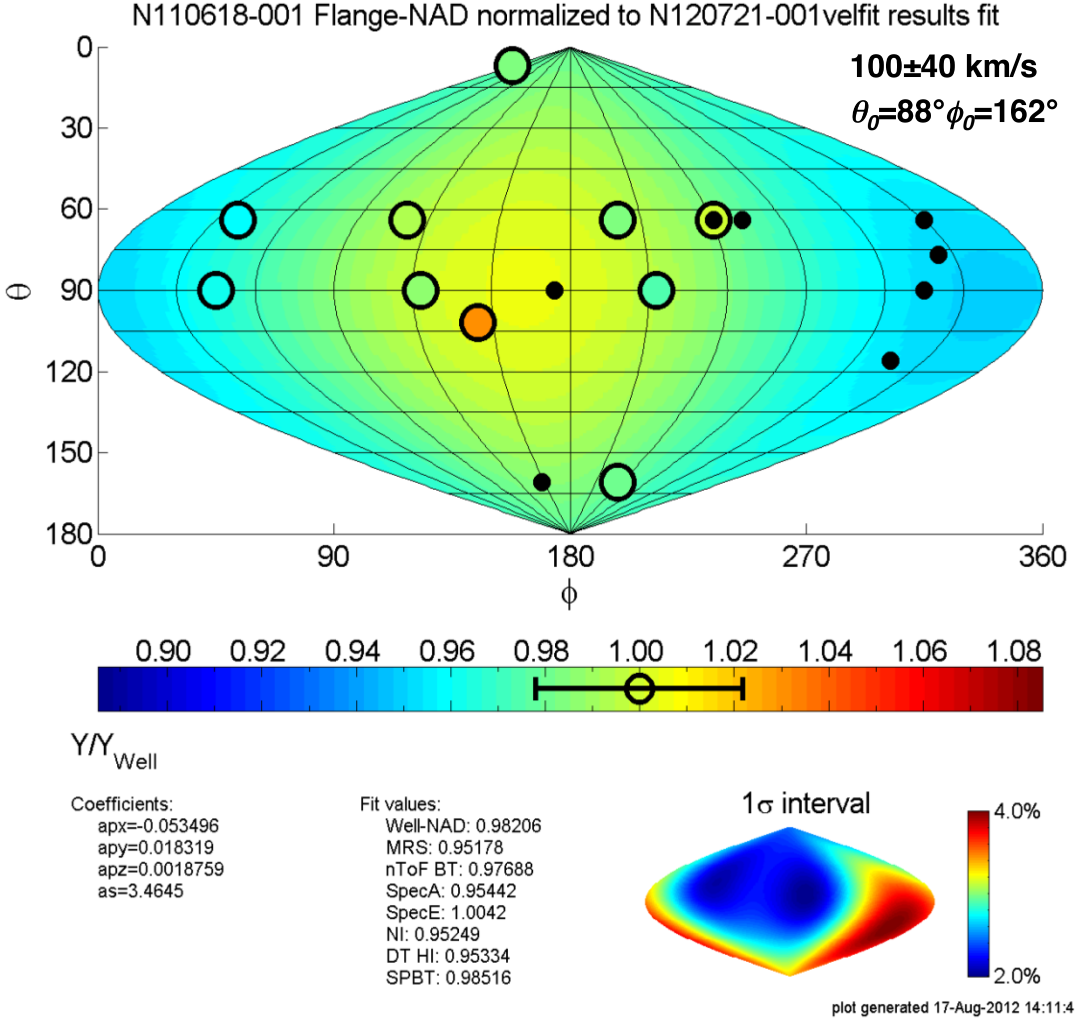


Flange-NAD Measured Core Velocities
Exploding Pushers with Target Alignment Problems

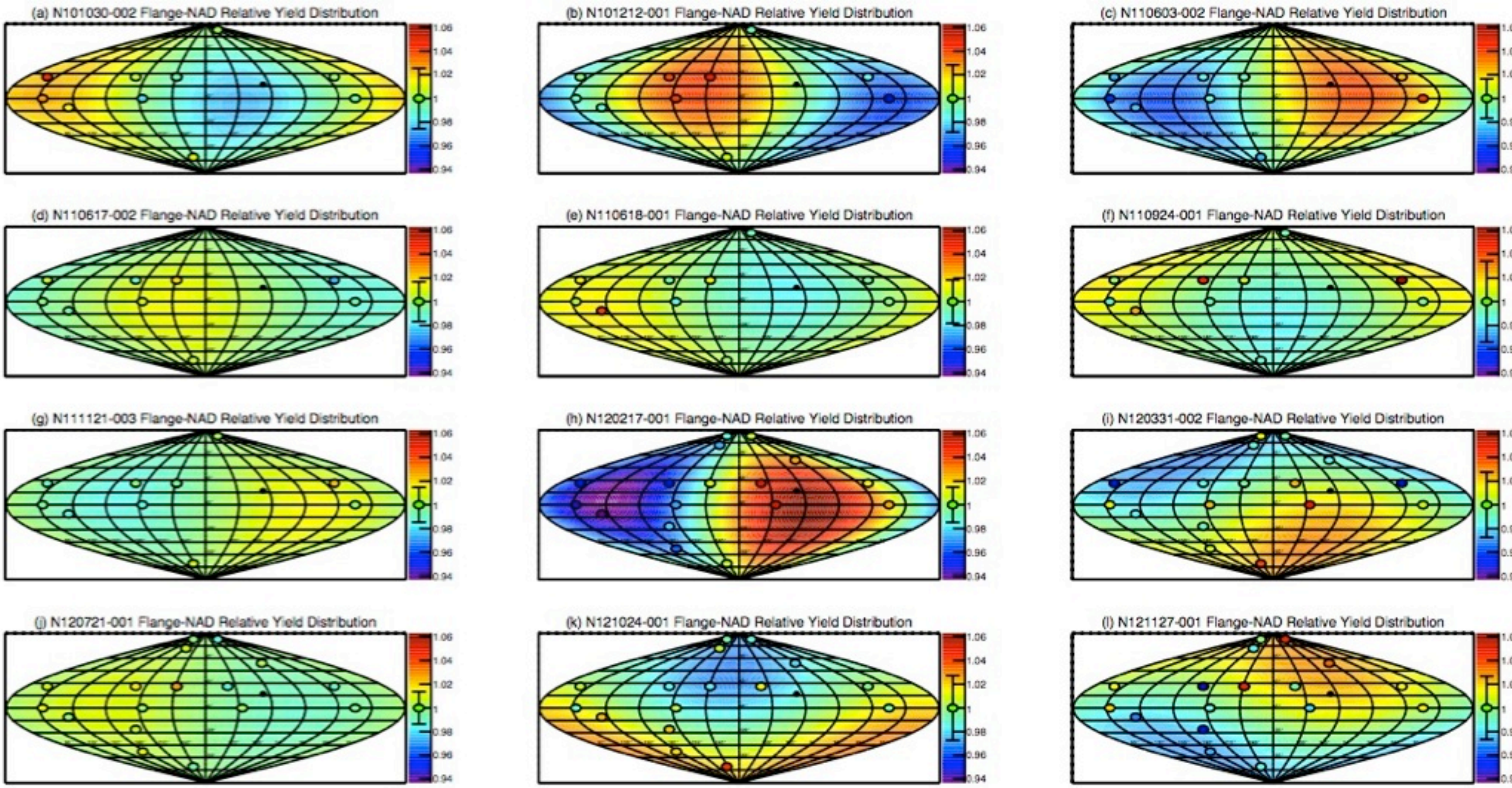
normalized to N120721-001 (velocity corrected)







Observed velocities on all twelve exploding pusher shots



Conclusions

- Activation provides an accurate DT yield measurement at the NIF.
- Flange-NAD can provide a high-precision measure of yield anisotropy and bulk velocity.
- Making a measurement on a calibration shot is tricky, but not impossible when you have clever post-docs.
- Measured bulk fuel velocities are as high as 200 km/s, correlating with laser drive asymmetries and misaligned capsules.

LLNL

- Lee Bernstein
- Rich Bionta
- Jac Caggiano
- Charlie Cerjan
- Owen Drury
- Chris Hagmann
- Ed Hartouni
- Robert Hatarik
- Steve Hatchett
- Hesham Khater
- Joe Kilkenny
- Kenn Knittel
- Sebastien Le Pape
- Andy Mackinnon
- Jim McNaney
- Ken Moody
- Mike Moran
- Dave Munro
- Dieter Schneider
- Dawn Shaughnessy
- Charles Yeamans
- Rich Zacharias

UCB

- Brian Daub
- Bethany Goldblum

NIC

LLE

- Tim Duffy
- Vladimir Glebov
- Jim Knauer
- Craig Sangster

OHIO

- Carl Brune

SNL

- Gary Cooper
- Ray Leeper
- Carlos Ruiz

LLNL NCF:

- Bryan Bandong
- Cindy Conrado
- Phil Torretto
- Todd Wooddy

MIT

- Dan Casey
- Johan Frenje
- Maria Gatu Johnson

SUNY-Geneseo

- Cassie Brown
- Steve Padalino

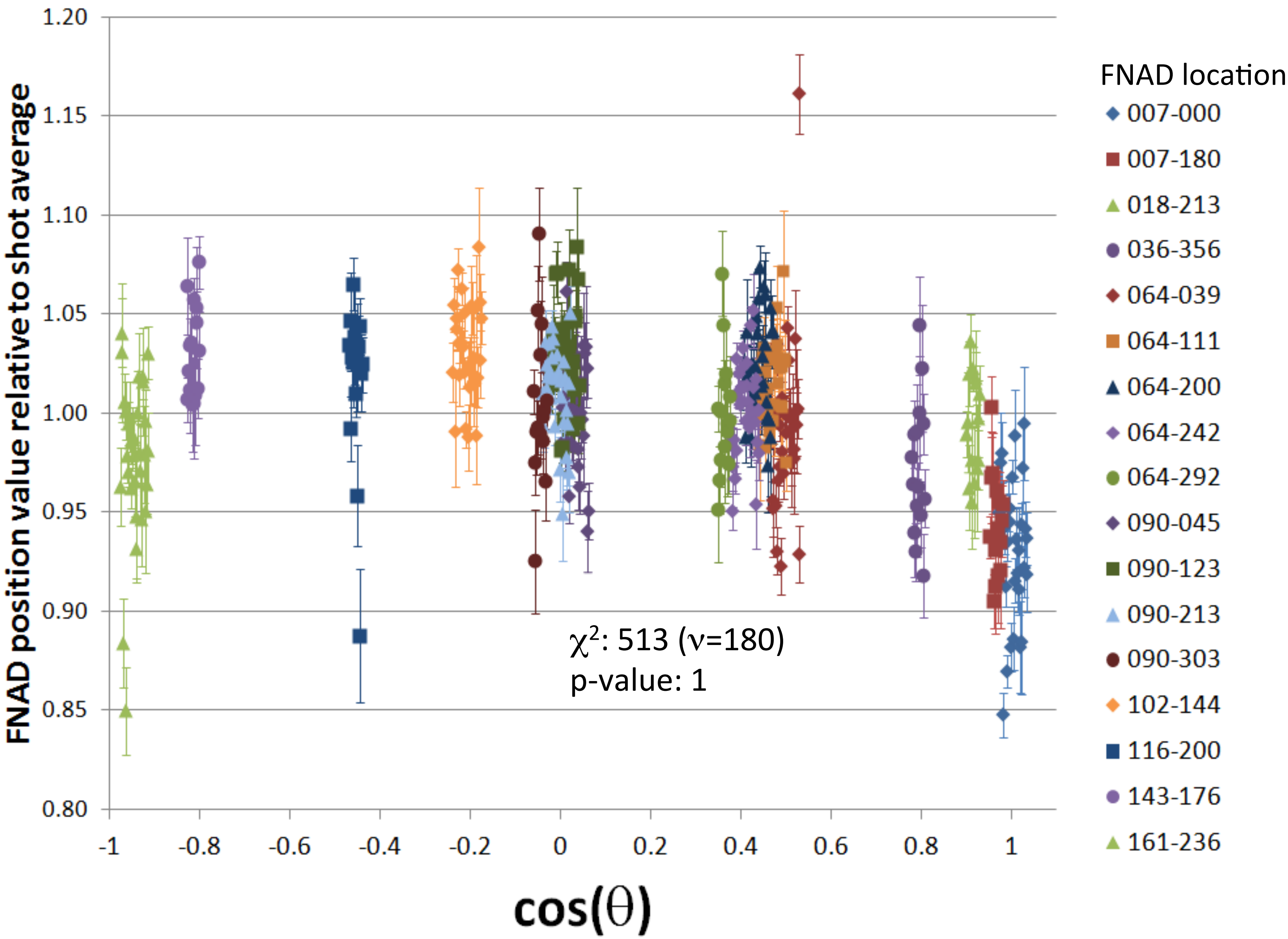
LMJ

- Jean-Luc Bourgade

Extra Slides

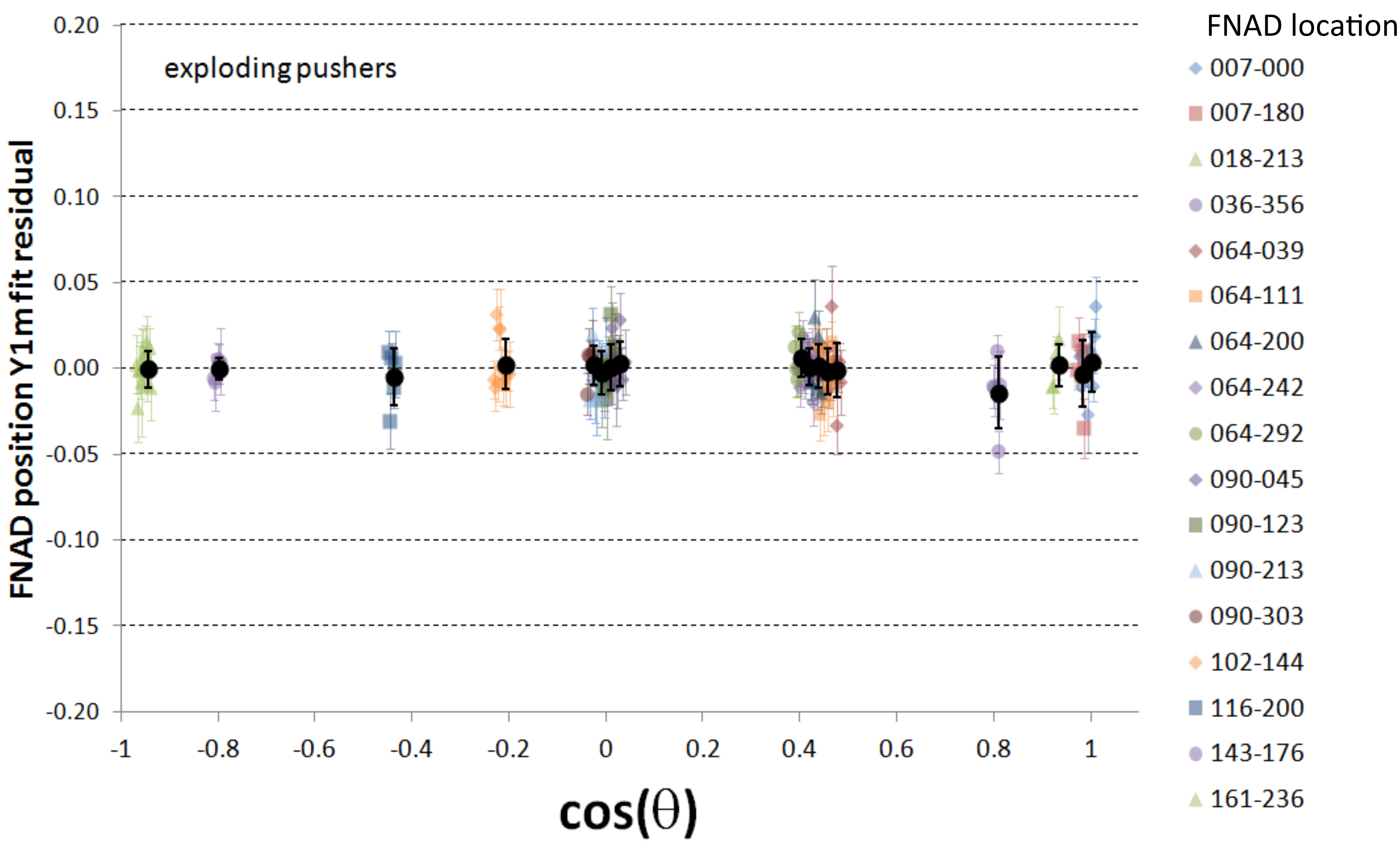
Are the variations in layered cryo shots real or statistical?

minimum yield 3e13 and Flange-NAD diagnostic success required



Exploding Pusher Shots, velocity-corrected

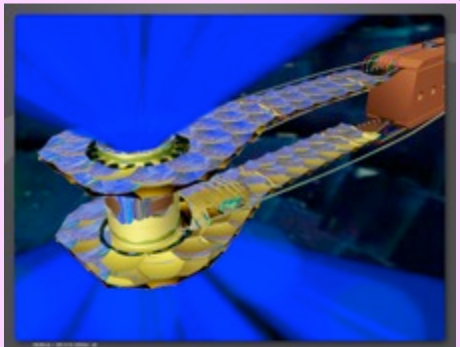
minimum yield 3e13 and Flange-NAD diagnostic success required



152 data points, p=0.52. Instrument response is demonstrated.

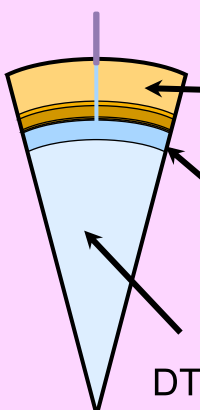
"Layered-cryo" w/ hohlraum (indirect drive) vs. "Exploding pusher" (direct drive)

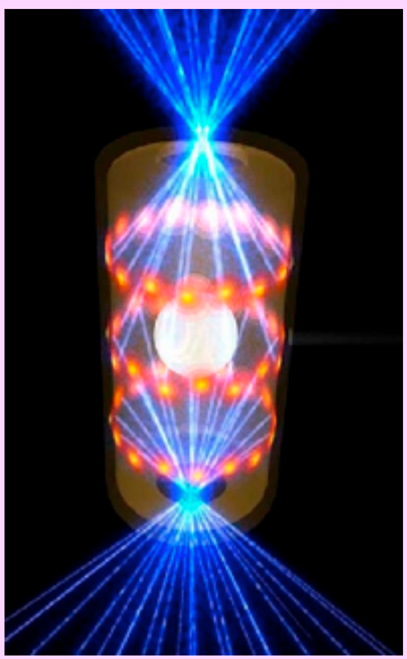
"Layered-Cryo"



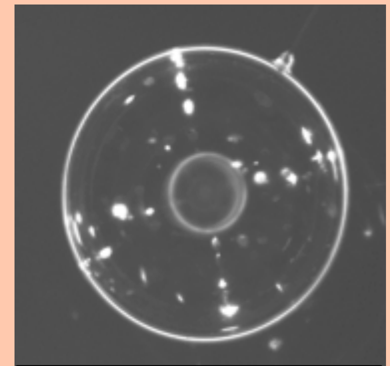
Cryogenic, x-ray driven, layered targets

- Laser energy produces ~300 eV x-rays in hohlraum "can," heating CH or Be capsule wall
- Cryogenic DT "layered" fuel shell with gas interior
- "Hot spot" ignites high ρR layer burn
- Yield up to 10^{19} n



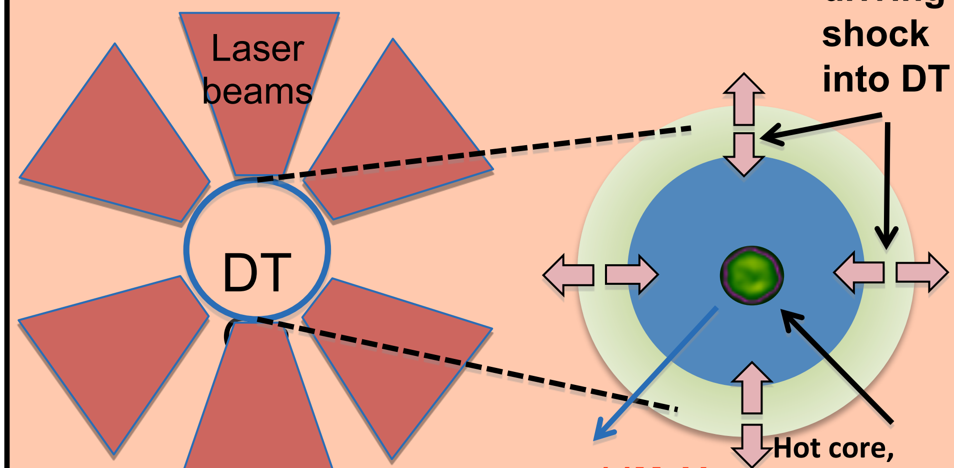


"Exploding Pusher"

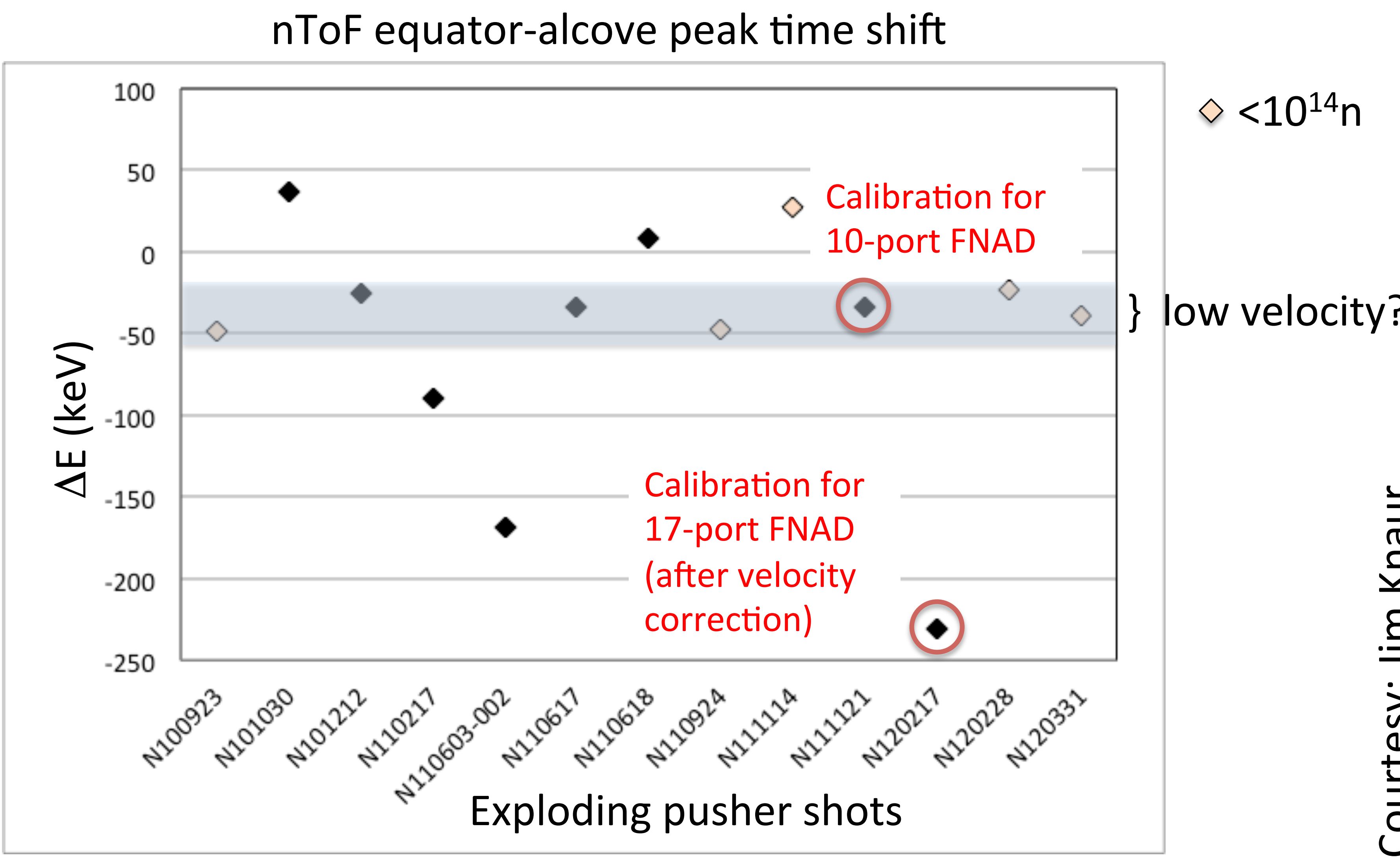


Simple direct drive targets

- Laser energy produces ~ 10 keV electrons: heats thin Si capsule wall
- Low ρR (no n scatter)
- Isotropic
- Yield up to $5x10^{15}$ n



Flange-NAD needs calibration to <u>low-velocity</u>, high-yield exploding pusher

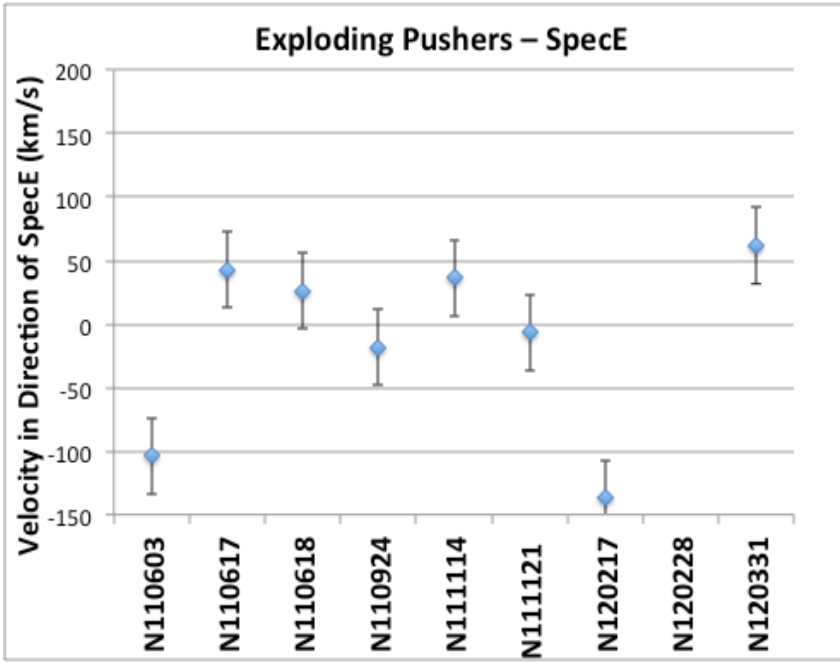


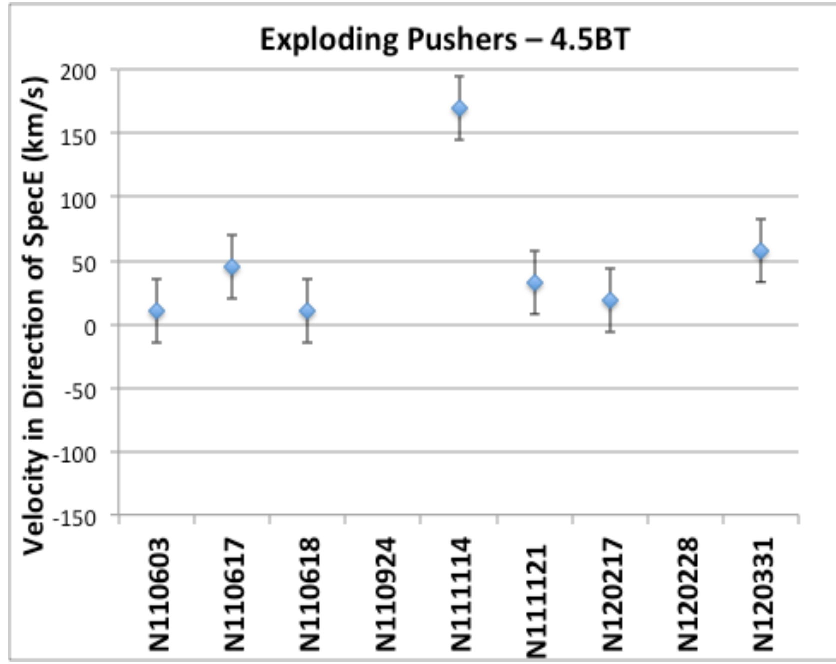
Courtesy: Jim Knaur

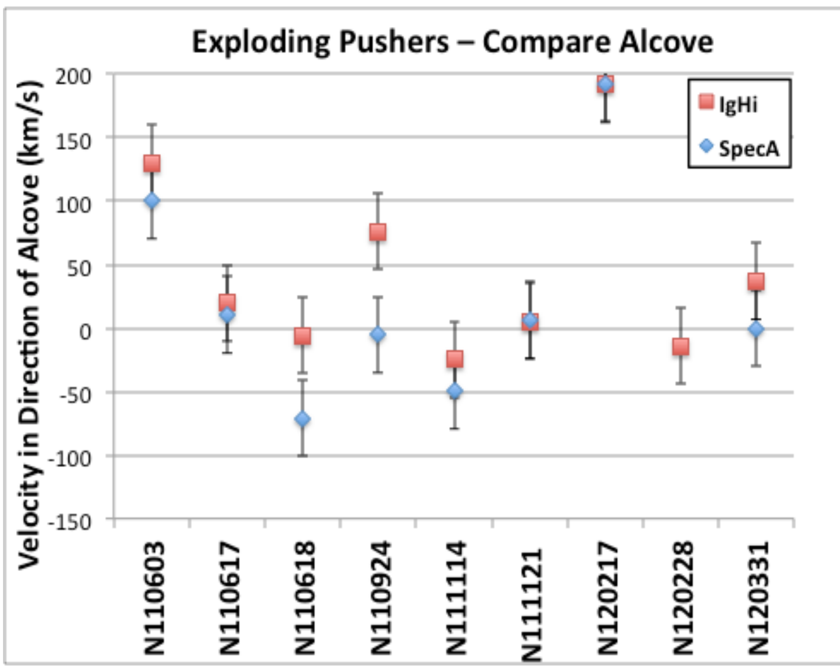
Most low-velocity shots are low yield.
N111121 used as calibration for 10-location FNAD.

Core velocities for nTOF LOS

Courtesy: Jim Macnaney







Derived core velocity vectors for exploding pushers

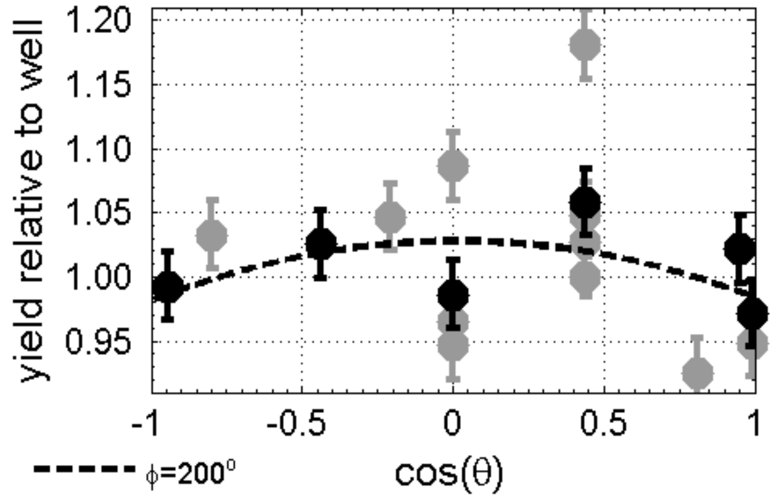
Shot	Core Velocity Magnitude (km/s)	Polar angle (°)	Azimuthal angle (°)
N110603	132	115	324
N110617	82	116	229
N110618	31	111	200
N111114	187	40	247
N111121	39	39	281
N120217	193	120	319
N120331	129	123	229

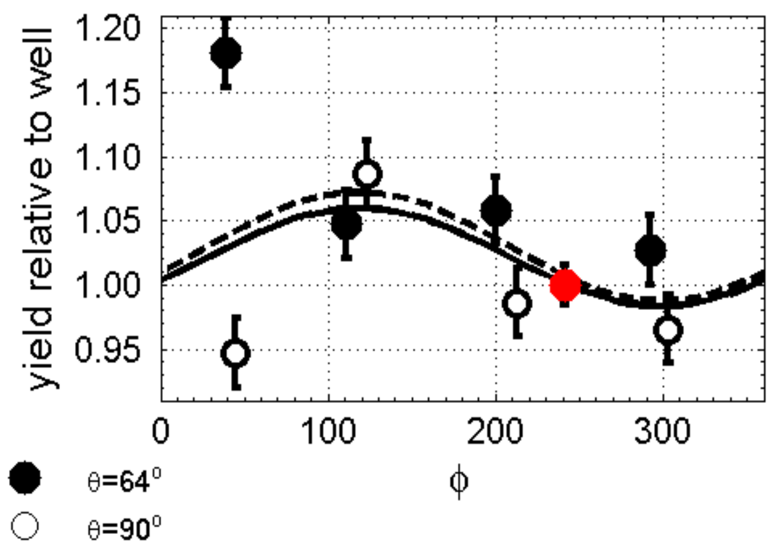
FNADS
165km/s
(86, 319)

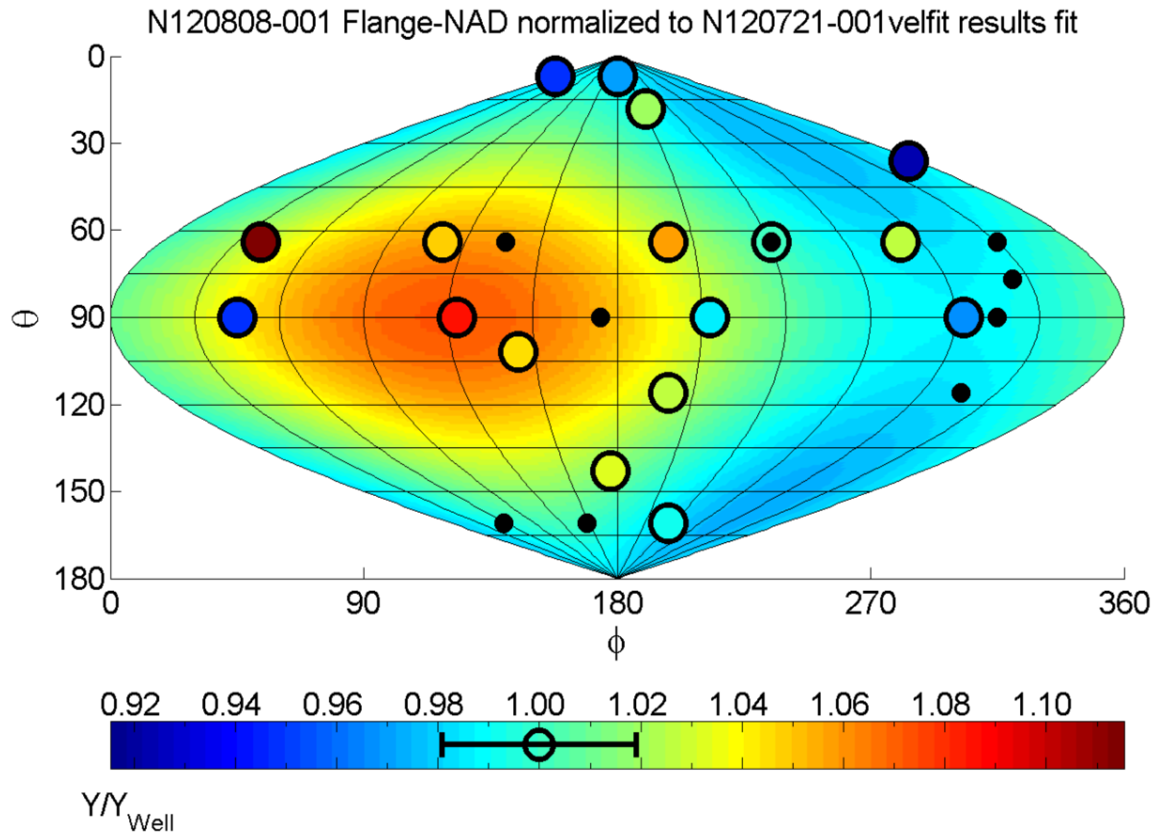
162km/s
(112, 227)

Flange-NAD results N120808-001

normalized to N120721-001 velocity-corrected

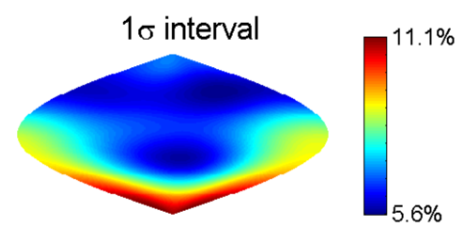






Coefficients:
adz2=-0.04867
apx=-0.041012
apy=0.076477
apz=0.0027626
as=3.5964

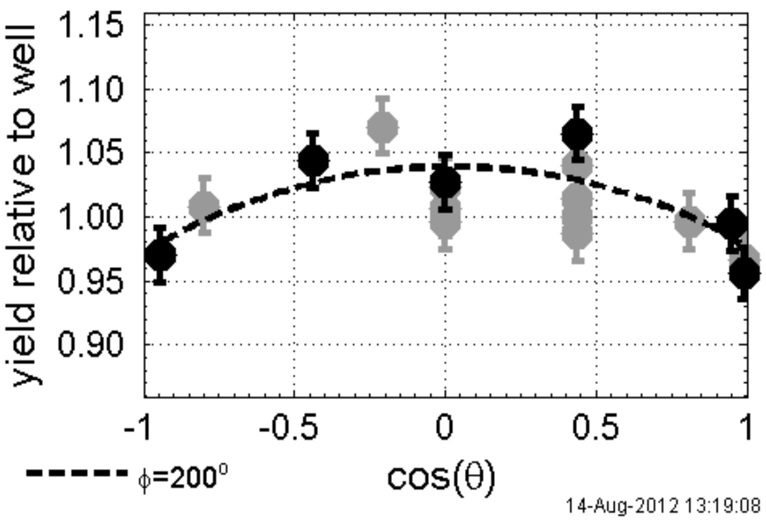
Fit values:
Well-NAD: 1.001
MRS: 0.99065
nToF BT: 1.0579
SpecA: 0.98415
SpecE: 1.0537
NI: 0.98929
DT HI: 0.98923
SpecSP: 0.99387
SPBT: 0.99953

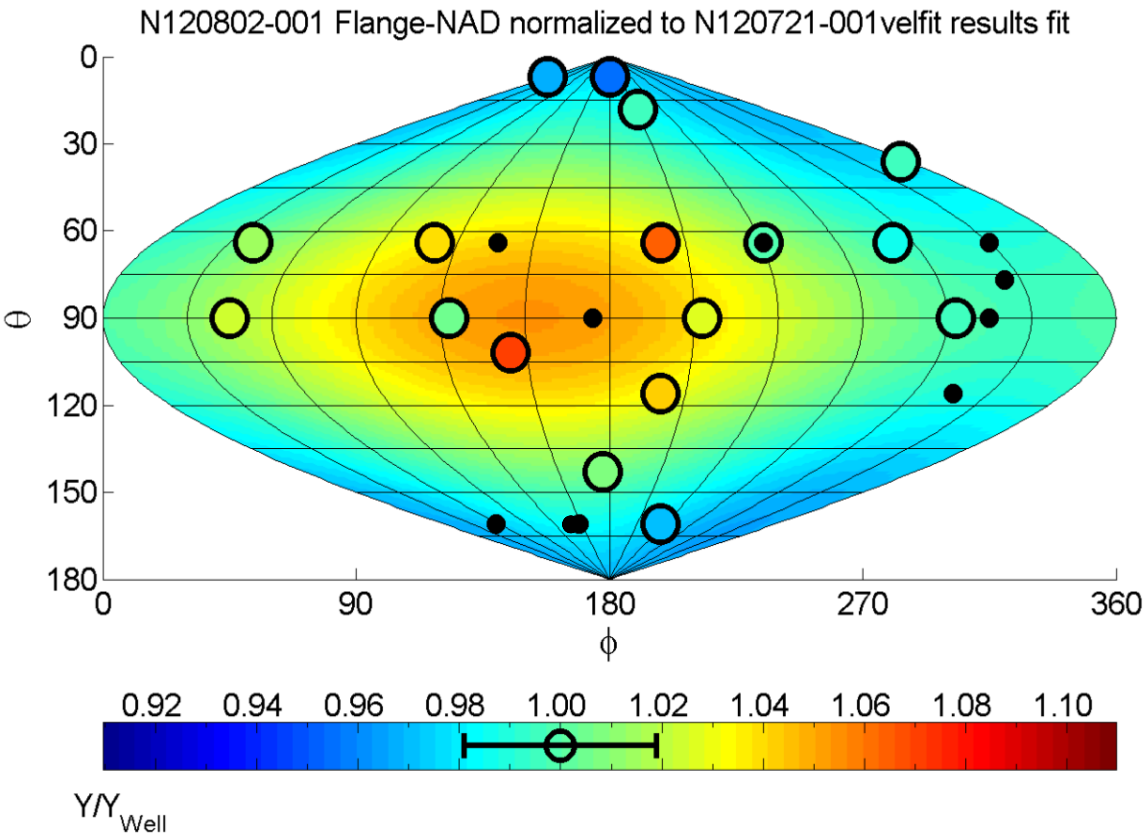


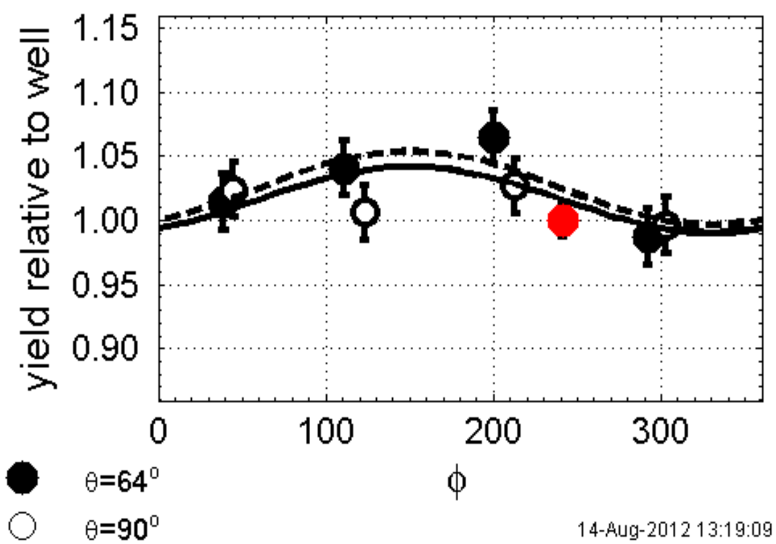
plot generated 14-Aug-2012 19:44:0

N120802-001

normalized to N120721-001 velocity-corrected

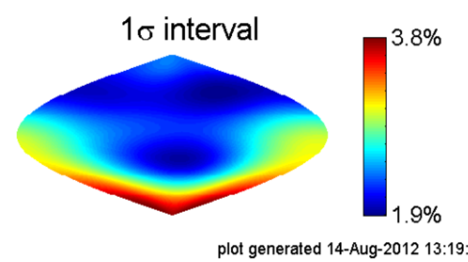






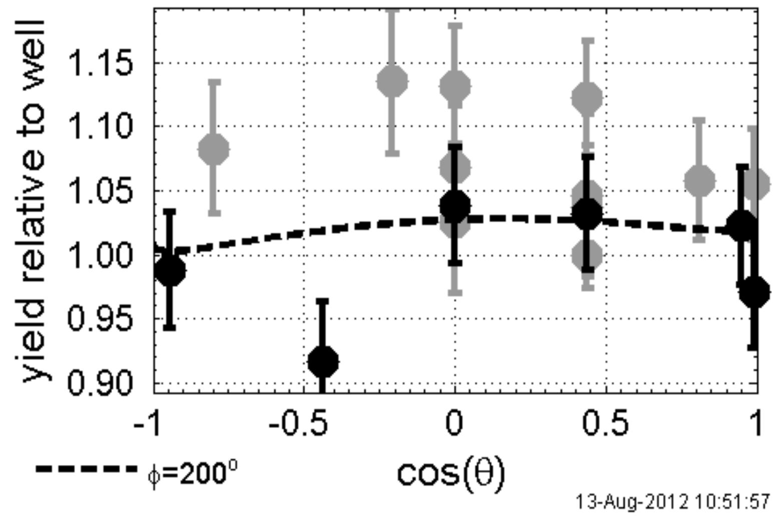
Coefficients:
adz2=-0.056647
apx=-0.051223
apy=0.029225
apz=0.005365
as=3.5707

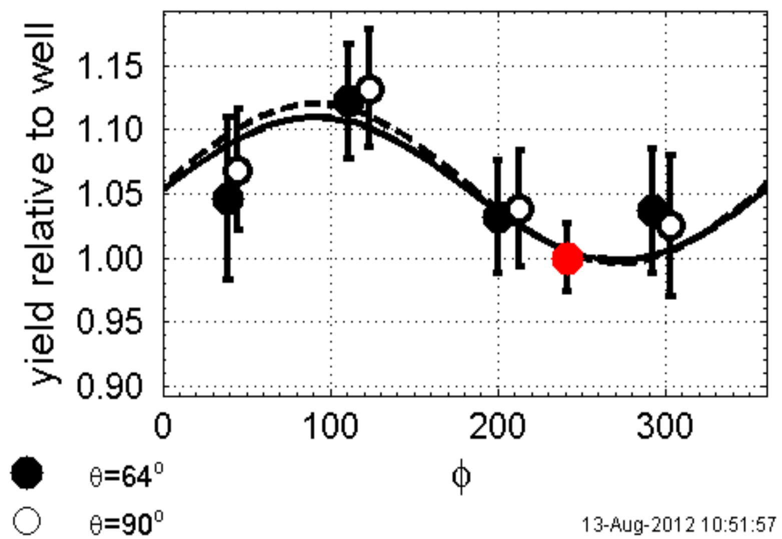
Fit values:
Well-NAD: 1.0157
MRS: 0.99512
nToF BT: 1.0411
SpecA: 0.98861
SpecE: 1.0515
NI: 0.99736
DT HI: 0.9901
SpecSP: 0.97405
SPBT: 0.98412

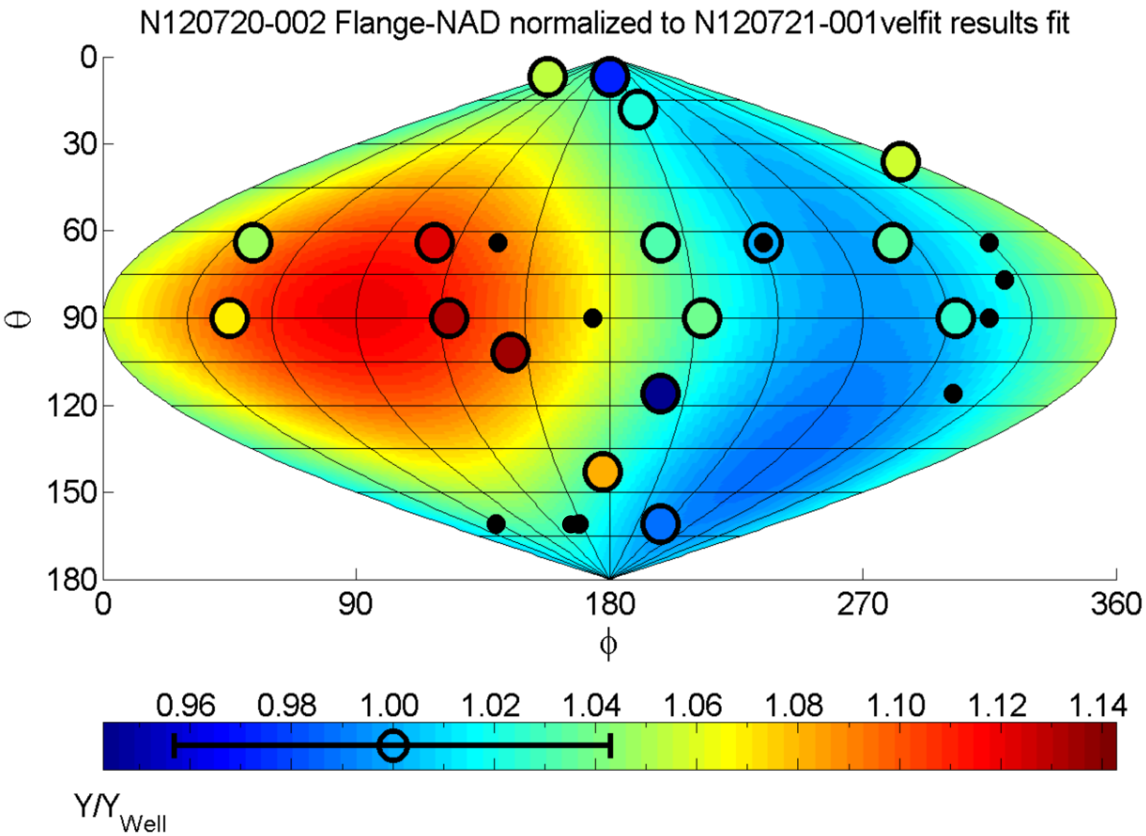


N120720-002

normalized to N120721-001 velocity-corrected

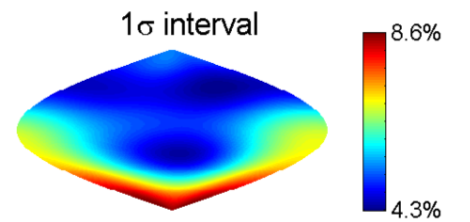






Coefficients:
adz2=-0.043349
apx=-0.0027155
apy=0.12692
apz=0.017785
as=3.7012

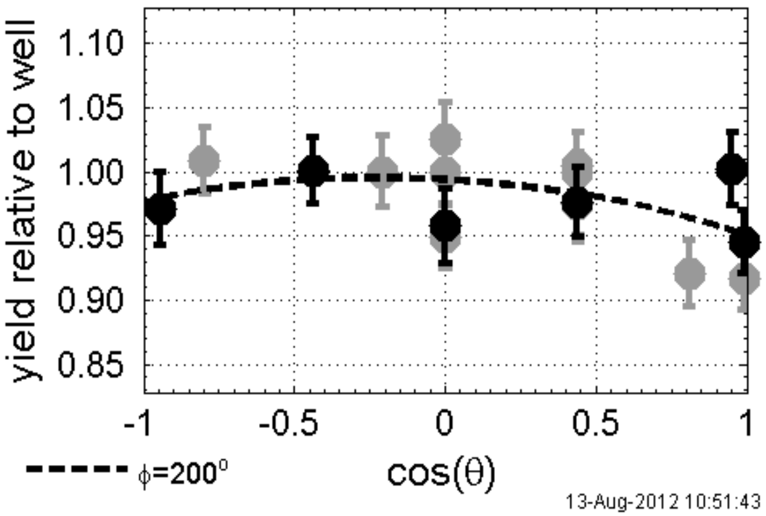
Fit values:
Well-NAD: 1.0055
MRS: 1.0211
nToF BT: 1.0933
SpecA: 1.0065
SpecE: 1.0656
NI: 1.013
DT HI: 1.0248
SpecSP: 1.0294
SPBT: 1.0242

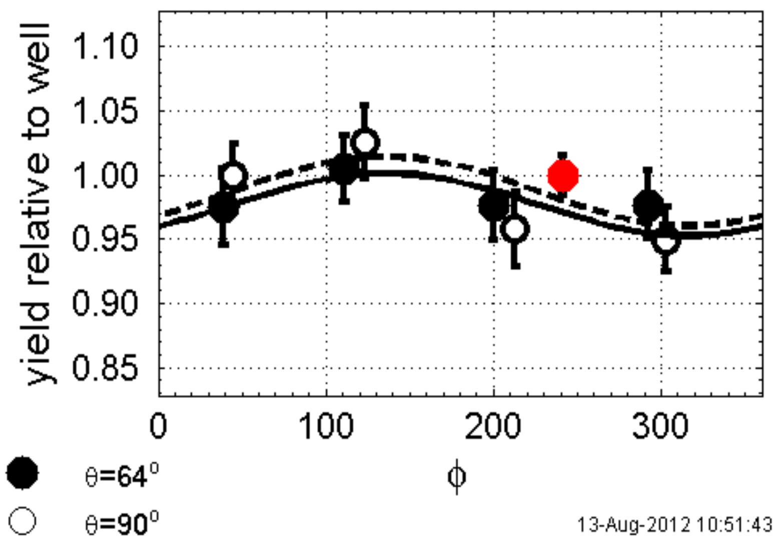


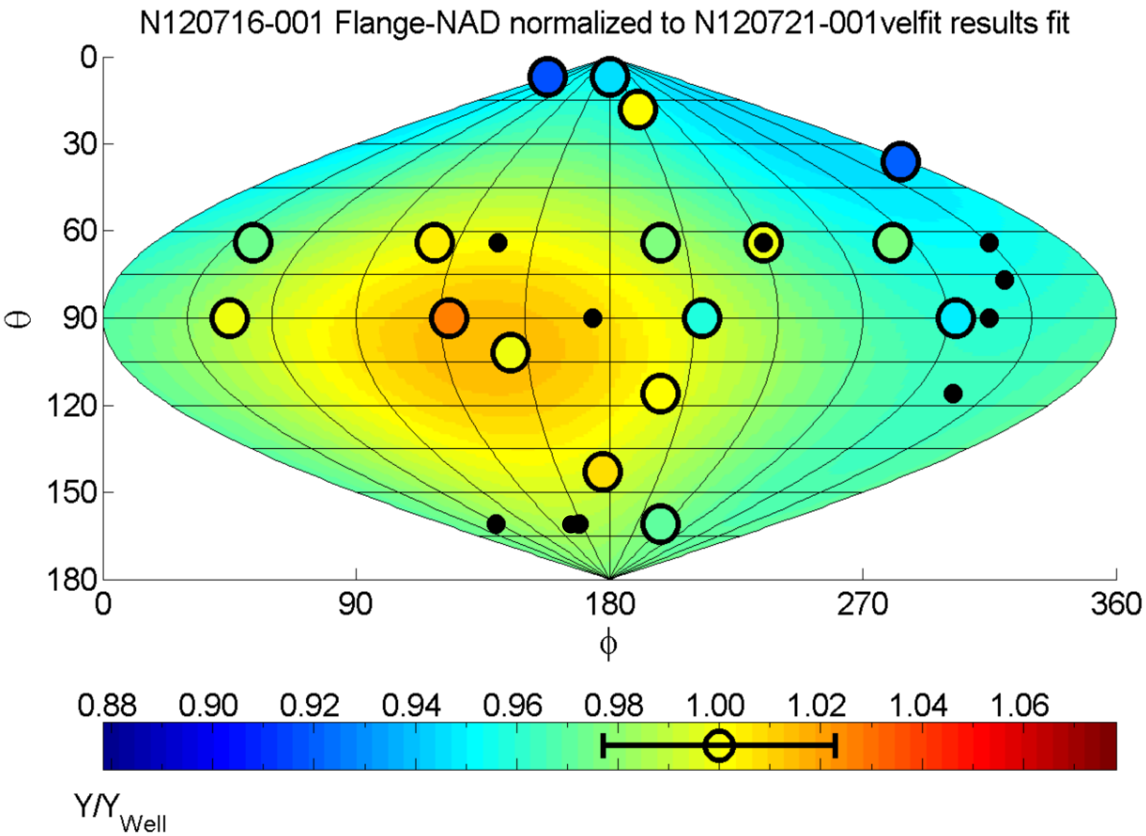
plot generated 13-Aug-2012 10:51:5

N120716-001

normalized to N120721-001 velocity-corrected

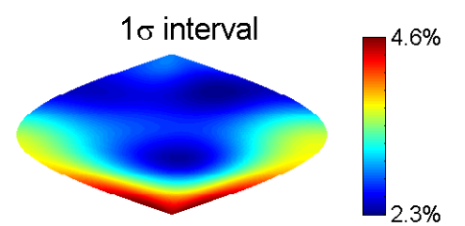






Coefficients:
adz2=-0.026036
apx=-0.039523
apy=0.038882
apz=-0.026336
as=3.4714

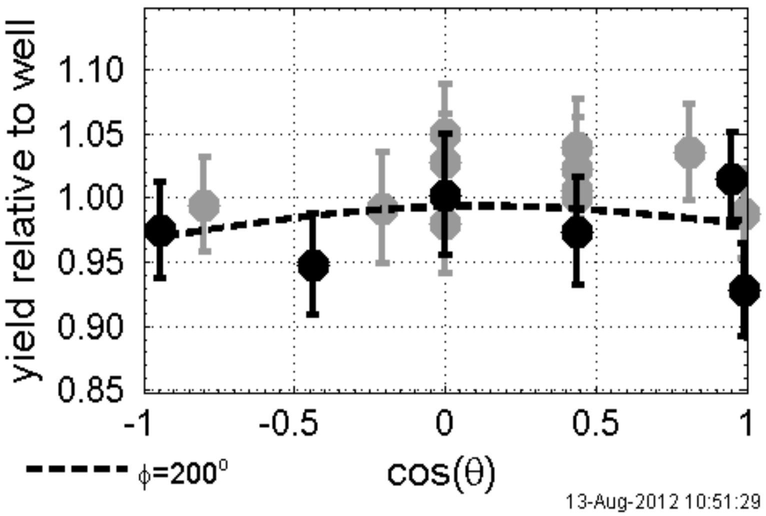
Fit values:
Well-NAD: 0.97058
MRS: 0.95723
nToF BT: 1.0014
SpecA: 0.96404
SpecE: 1.0087
NI: 0.96039
DT HI: 0.95353
SpecSP: 0.97923
SPBT: 0.98626

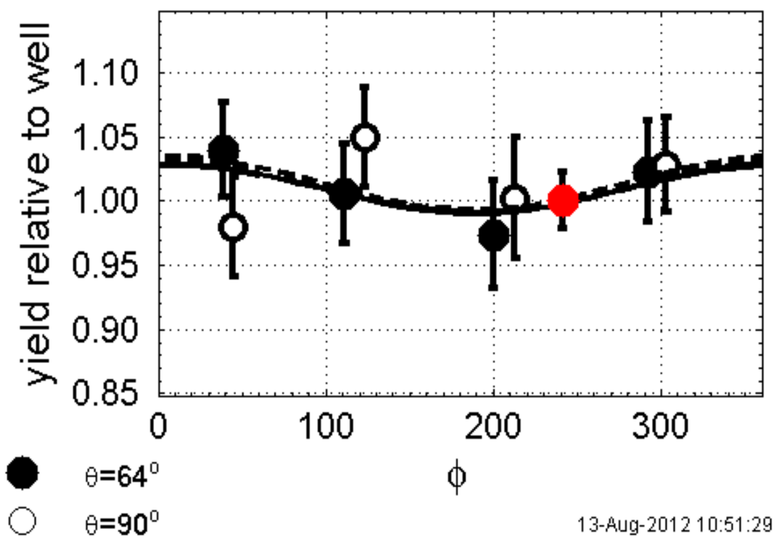


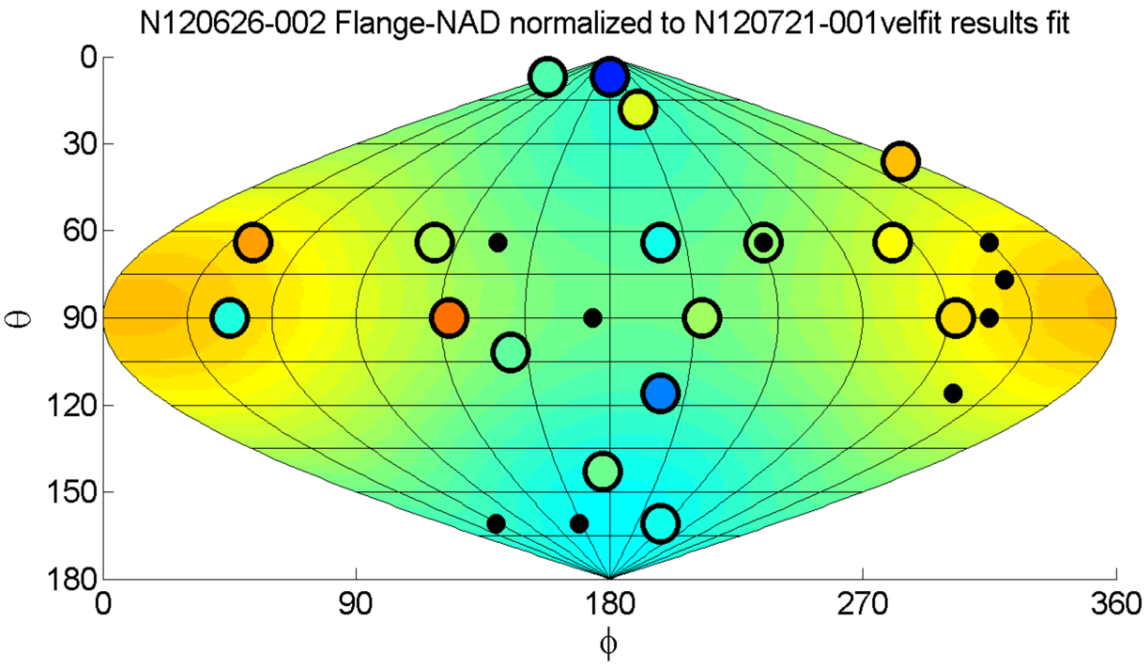
plot generated 14-Aug-2012 13:18:4

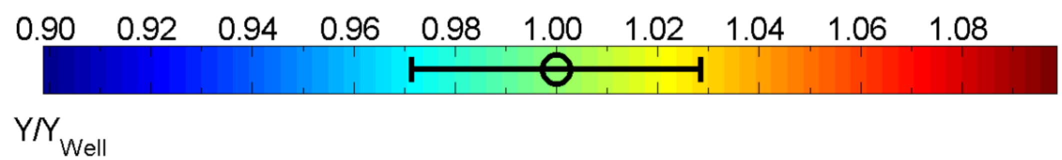
N120626-002

normalized to N120721-001 velocity-corrected



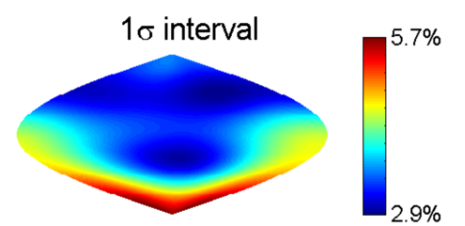






Coefficients:
adz2=-0.035732
apx=0.04206
apy=0.0064607
apz=0.012296
as=3.5522

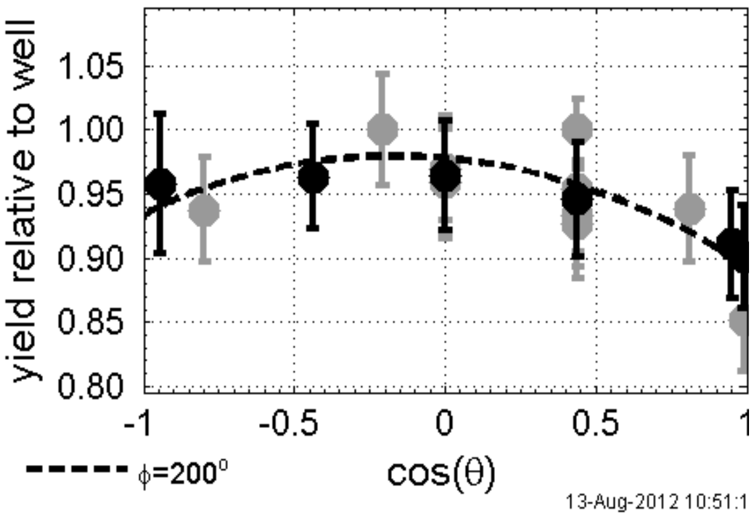
Fit values:
Well-NAD: 0.99802
MRS: 1.0274
nToF BT: 0.99814
SpecA: 1.0155
SpecE: 0.99322
NI: 1.0256
DT HI: 1.024
SpecSP: 0.98201
SPBT: 0.97237

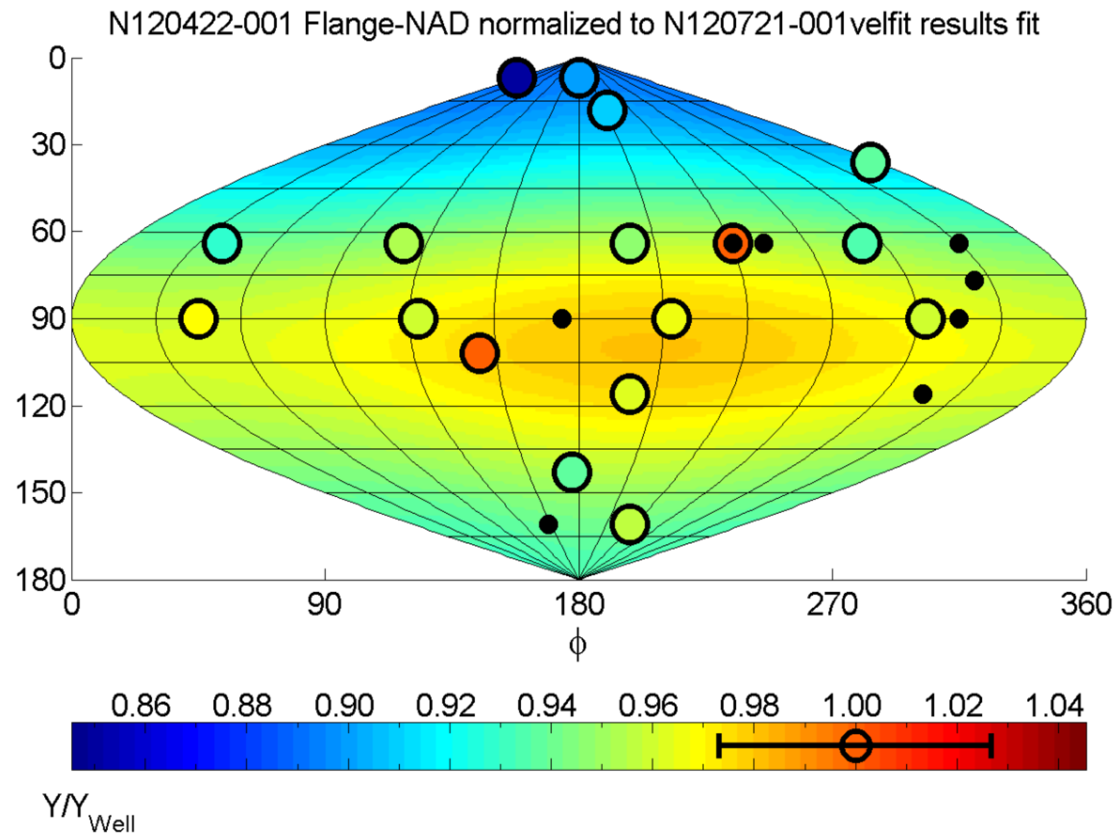


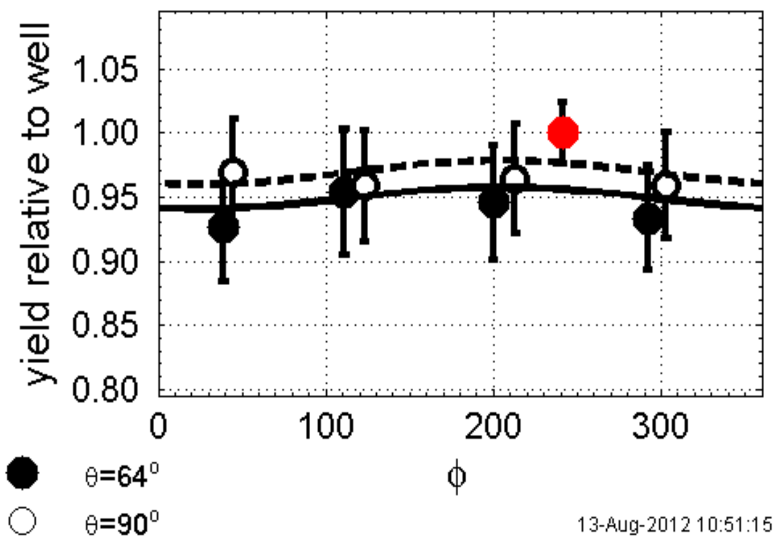
plot generated 13-Aug-2012 10:51:2

N120422-002

normalized to N120721-001 velocity-corrected

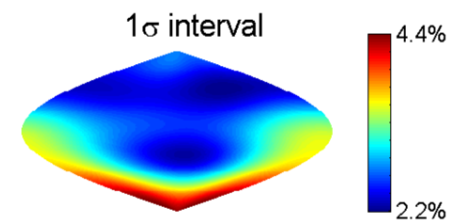






Coefficients:
- adz2=-0.060209
- apx=-0.017468
- apy=-0.0079766
- apz=-0.042197
- as=3.3683

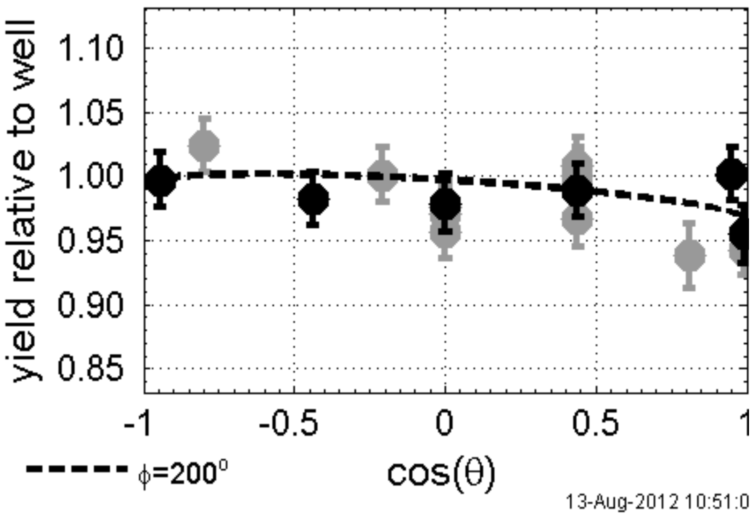
Fit values:
- Well-NAD: 0.95597
- MRS: 0.95716
- nToF BT: 0.95478
- SpecA: 0.96418
- SpecE: 0.97726
- NI: 0.9659
- DT HI: 0.9443
- SPBT: 0.93938

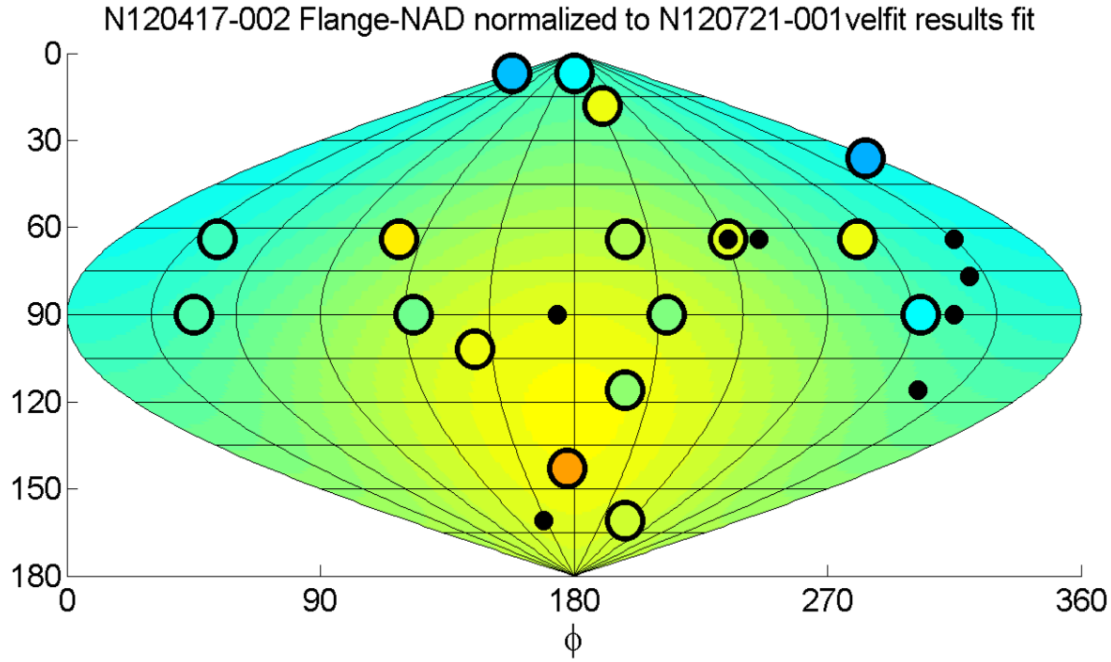


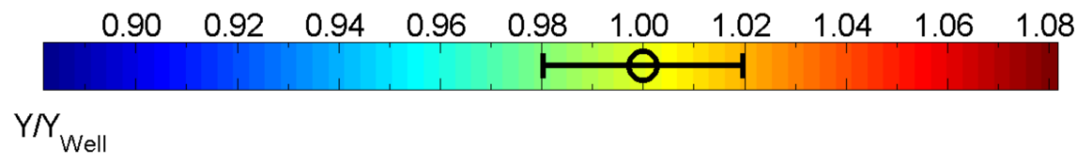
plot generated 13-Aug-2012 10:51:1

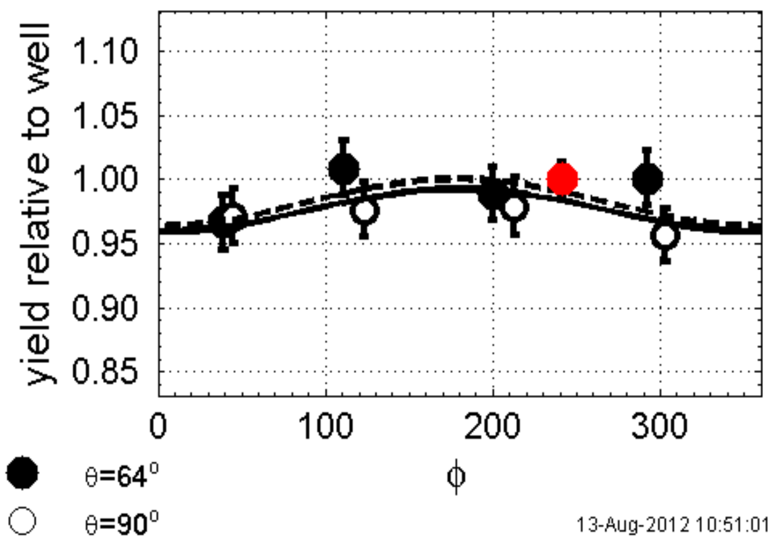
N120417-002

normalized to N120721-001 velocity-corrected



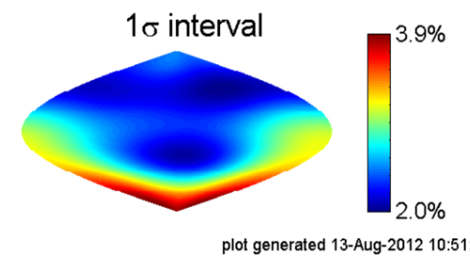






Coefficients:
adz2=-0.0014711
apx=-0.037903
apy=0.00077998
apz=-0.028073
as=3.4795

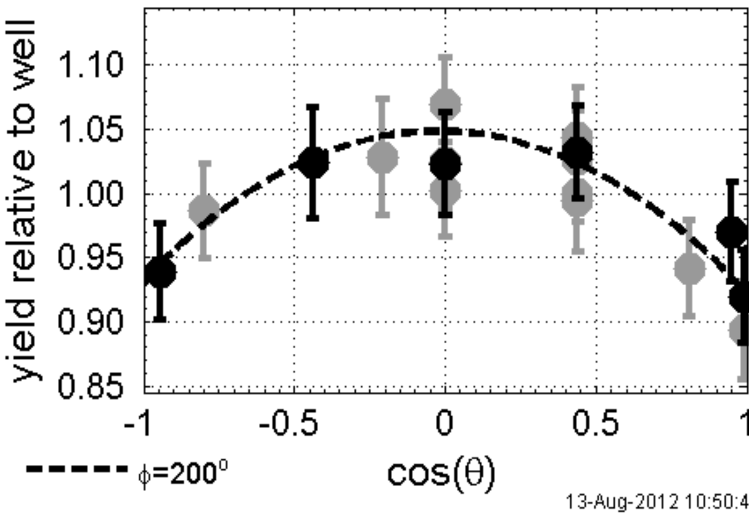
Fit values:
Well-NAD: 0.9835
MRS: 0.96403
nToF BT: 0.98026
SpecA: 0.97554
SpecE: 1.0005
NI: 0.96864
DT HI: 0.96114
SPBT: 0.99886

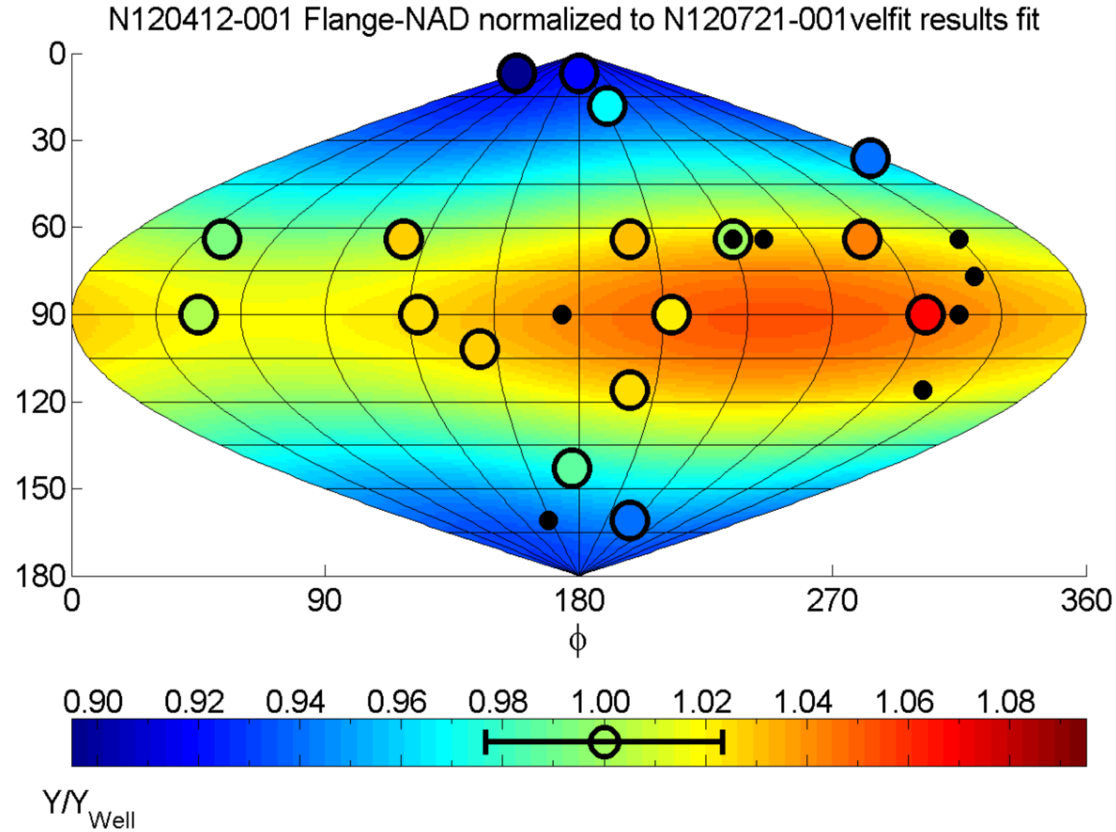


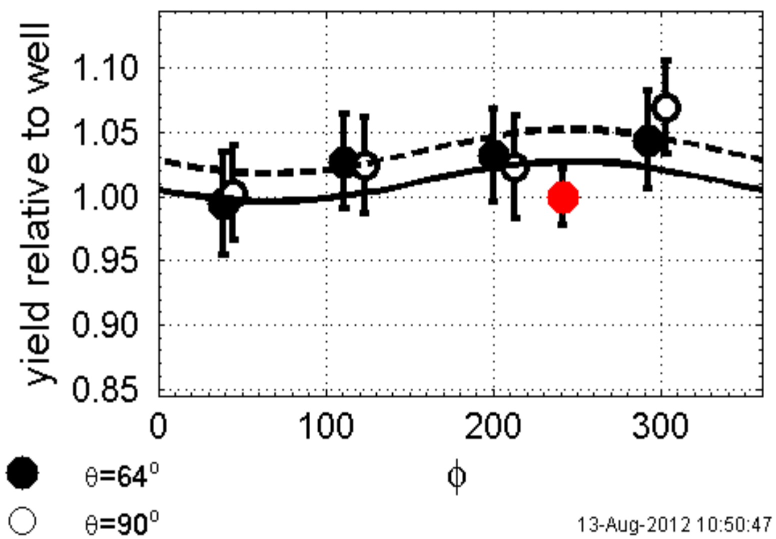
plot generated 13-Aug-2012 10:51:0

N120412-001

normalized to N120721-001 velocity-corrected

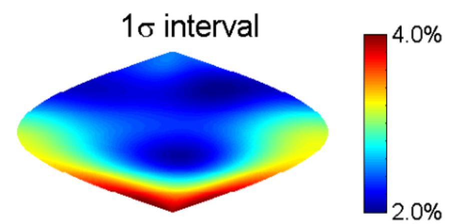






Coefficients:
- adz2=-0.11714
- apx=-0.013837
- apy=-0.032678
- apz=-0.010144
- as=3.5388

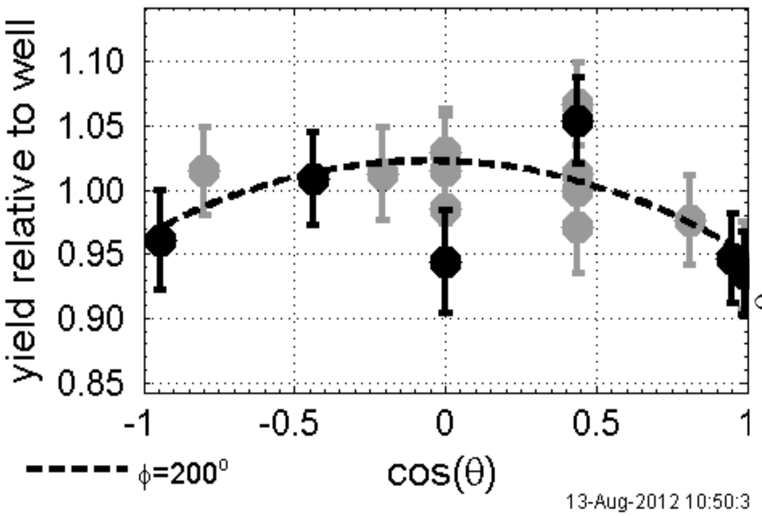
Fit values:
- Well-NAD: 1.0272
- MRS: 1.0323
- nToF BT: 1.0273
- SpecA: 1.0217
- SpecE: 1.0403
- NI: 1.0417
- DT HI: 1.0137
- SPBT: 0.93984

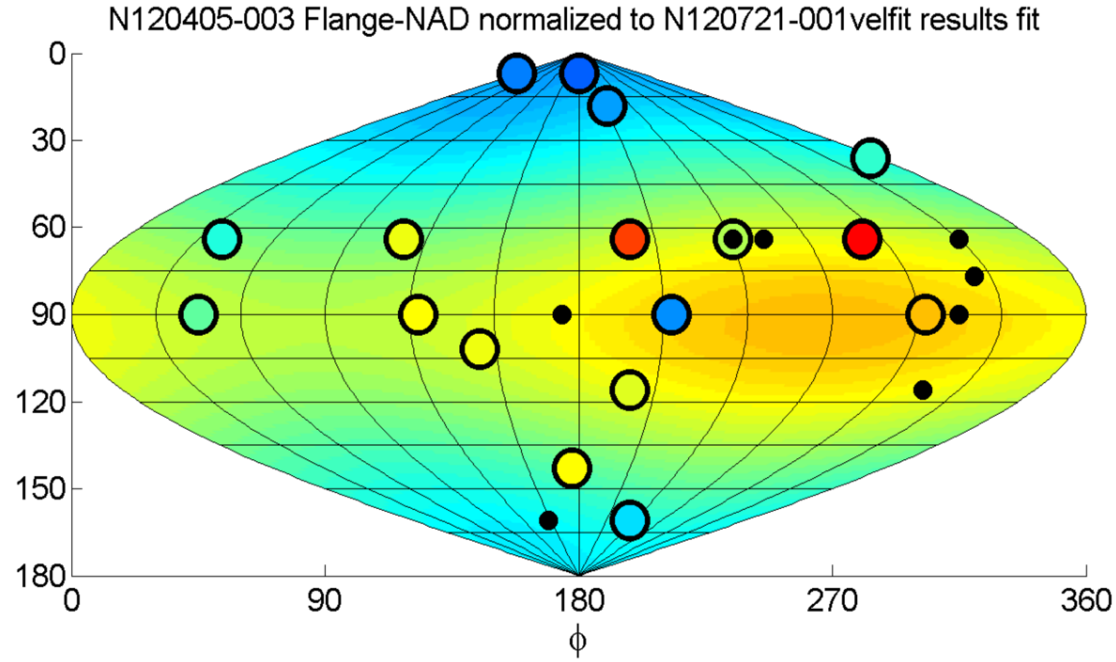


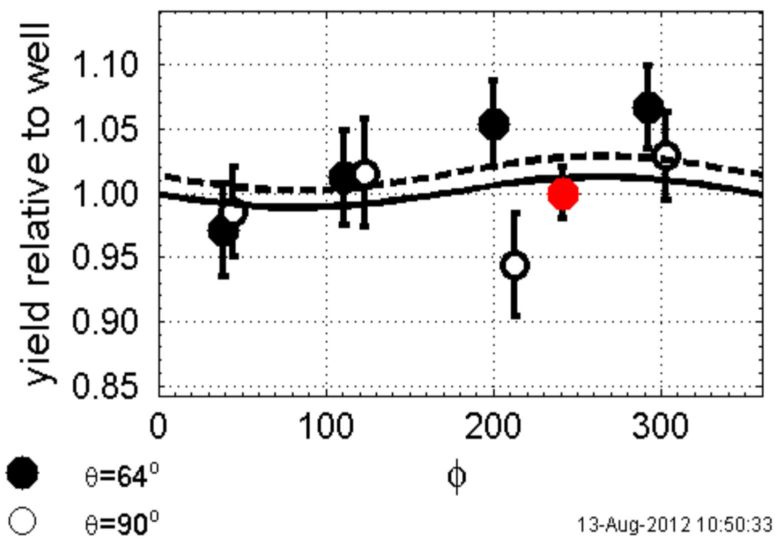
plot generated 13-Aug-2012 10:50:4

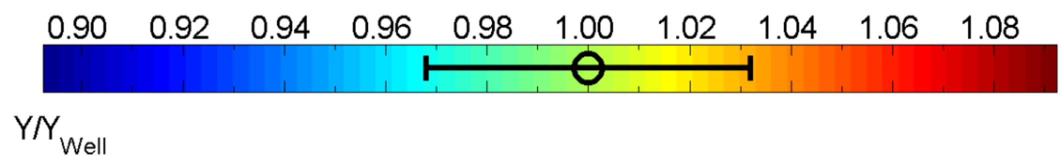
N120405-003

normalized to N120721-001 velocity-corrected



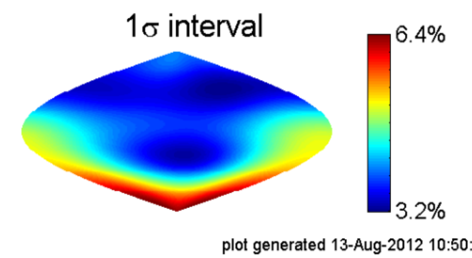






Coefficients:
adz2=-0.063676
apx=-0.0028629
apy=-0.027161
apz=-0.014747
as=3.5283

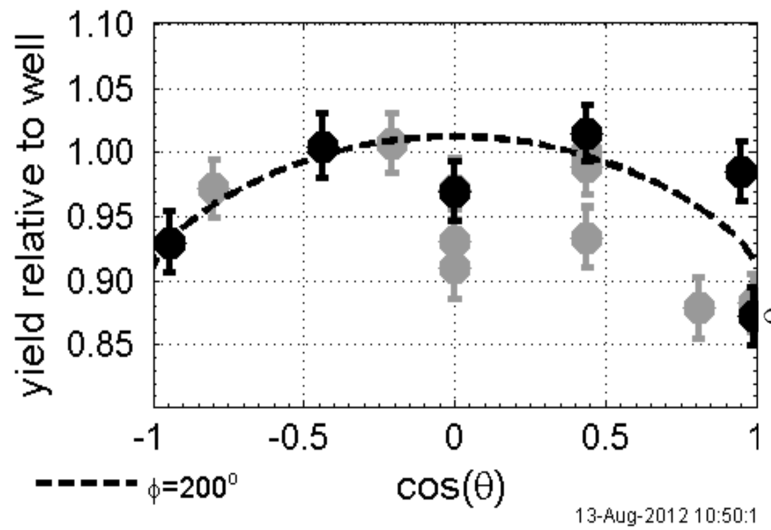
Fit values:
Well-NAD: 1.0117
MRS: 1.0172
nToF BT: 1.0124
SpecA: 1.0144
SpecE: 1.0154
NI: 1.0238
DT HI: 1.0055
SPBT: 0.96638

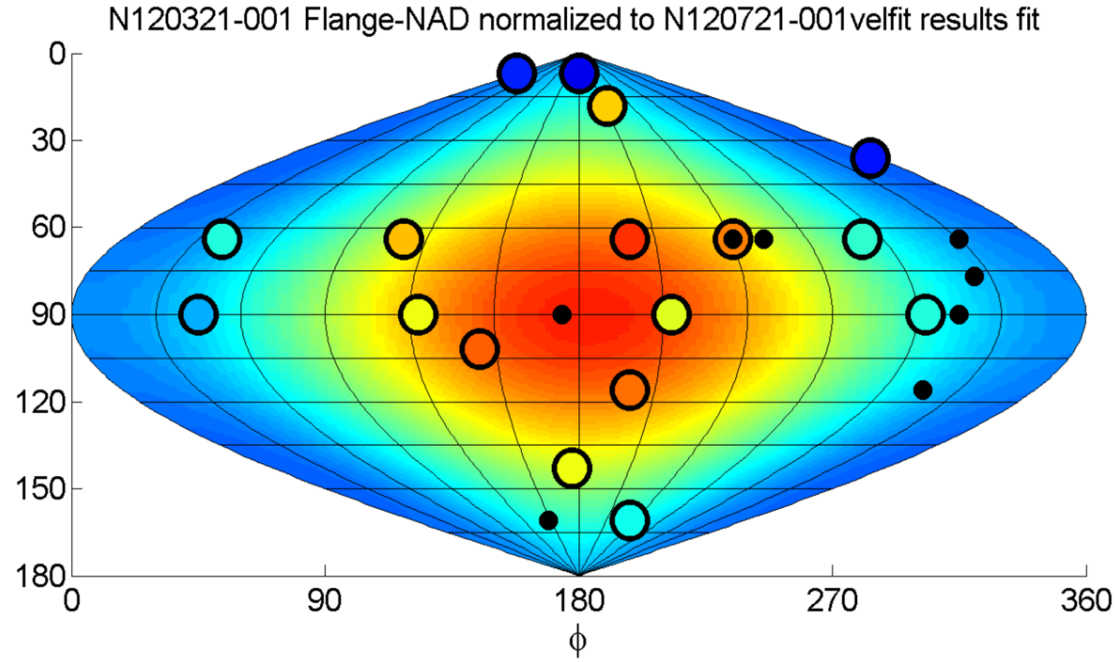


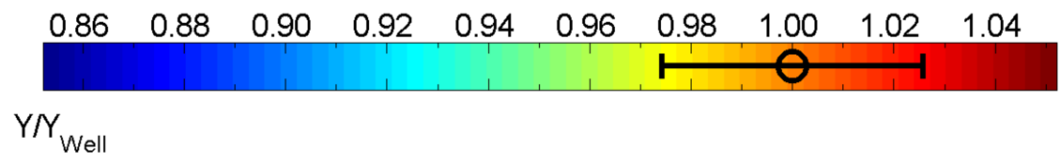
plot generated 13-Aug-2012 10:50:3

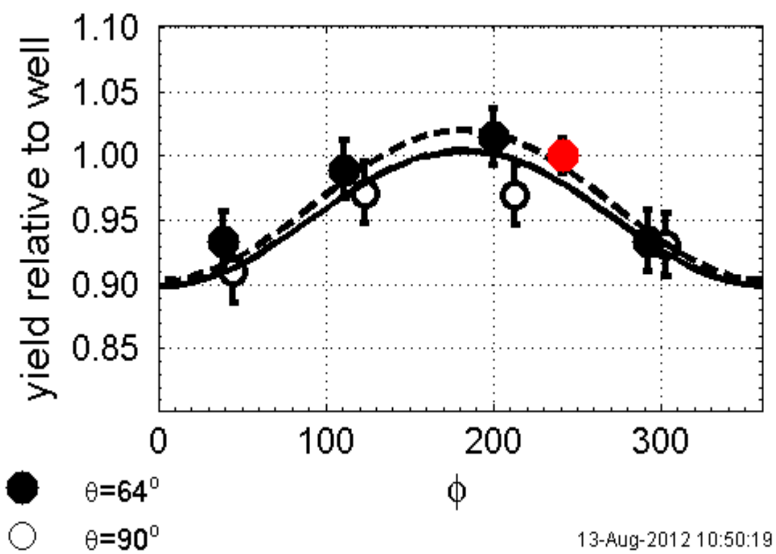
N120321-001

normalized to N120721-001 velocity-corrected



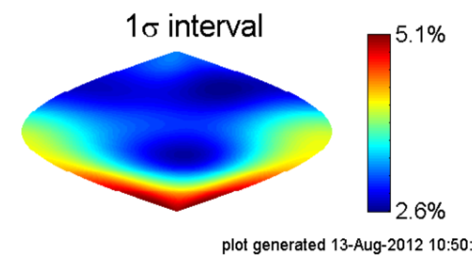






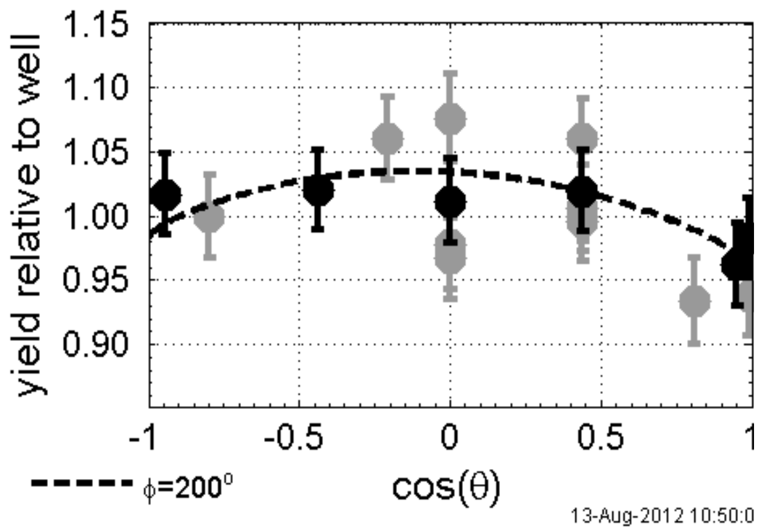
Coefficients:
- adz2=-0.054754
- apx=-0.11985
- apy=-0.0040114
- apz=-0.00068449
- as=3.3474

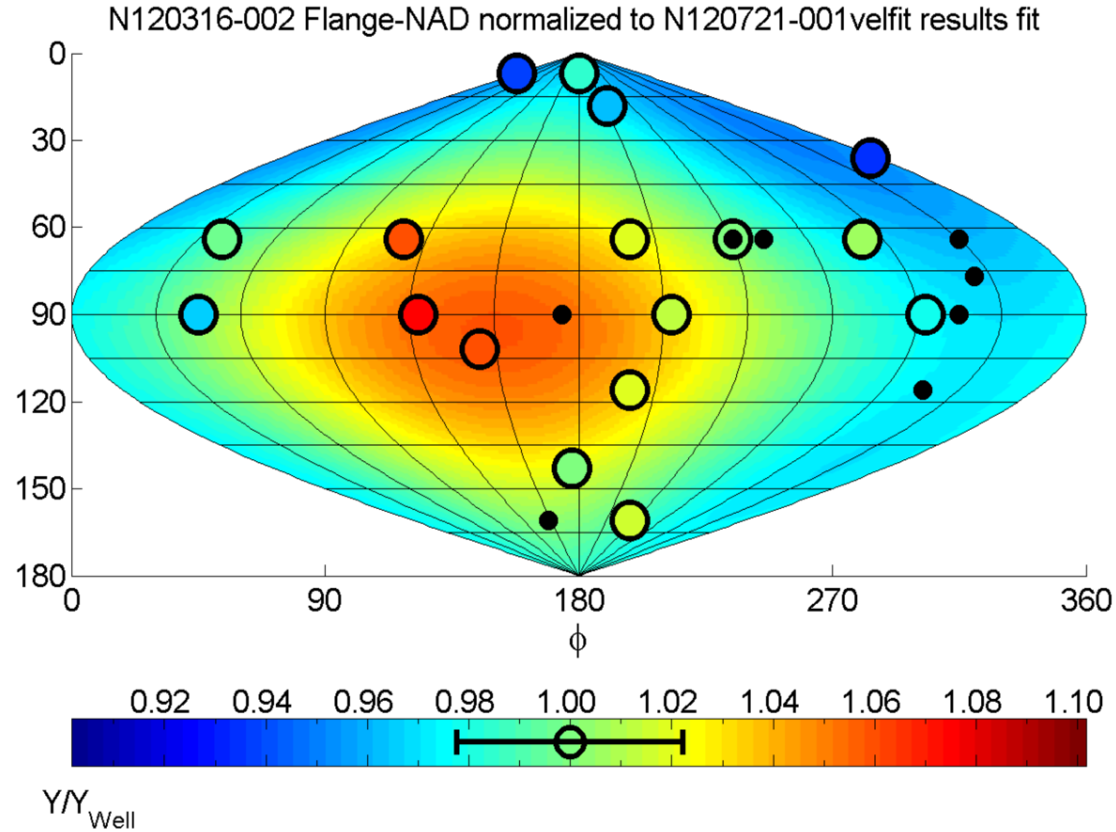
Fit values:
- Well-NAD: 0.97852
- MRS: 0.91383
- nToF BT: 0.96854
- SpecA: 0.91512
- SpecE: 1.0196
- NI: 0.92154
- DT HI: 0.90676
- SPBT: 0.93121

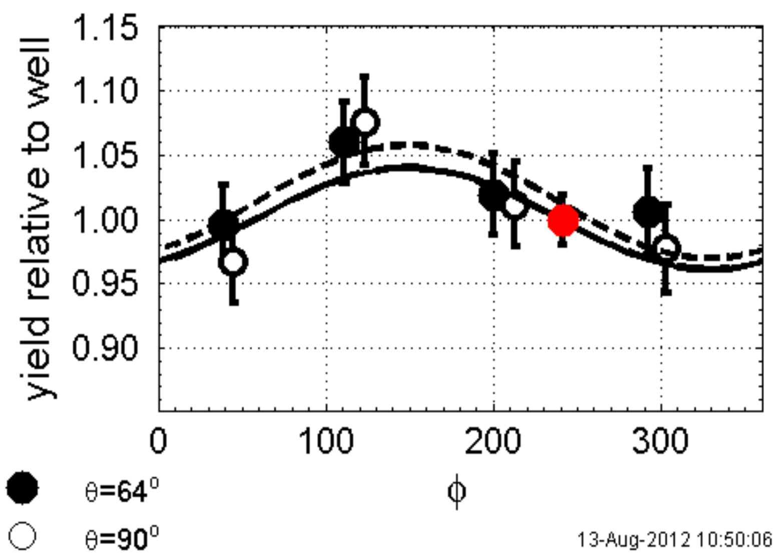


N120316-002

normalized to N120721-001 velocity-corrected

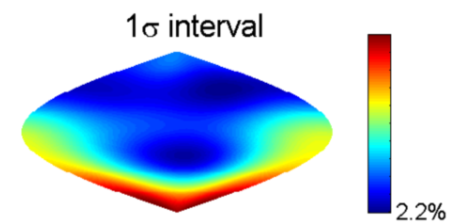






Coefficients:
adz2=-0.044305
apx=-0.077064
apy=0.04695
apz=-0.024138
as=3.5453

Fit values:
Well-NAD: 0.99922
MRS: 0.96648
nToF BT: 0.99103
SpecA: 0.97252
SpecE: 1.0539
NI: 0.97123
DT HI: 0.96123
SPBT: 1.0021



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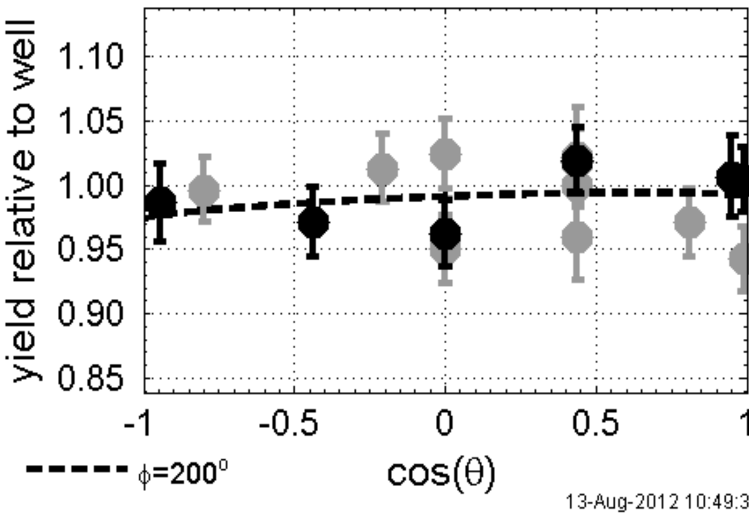
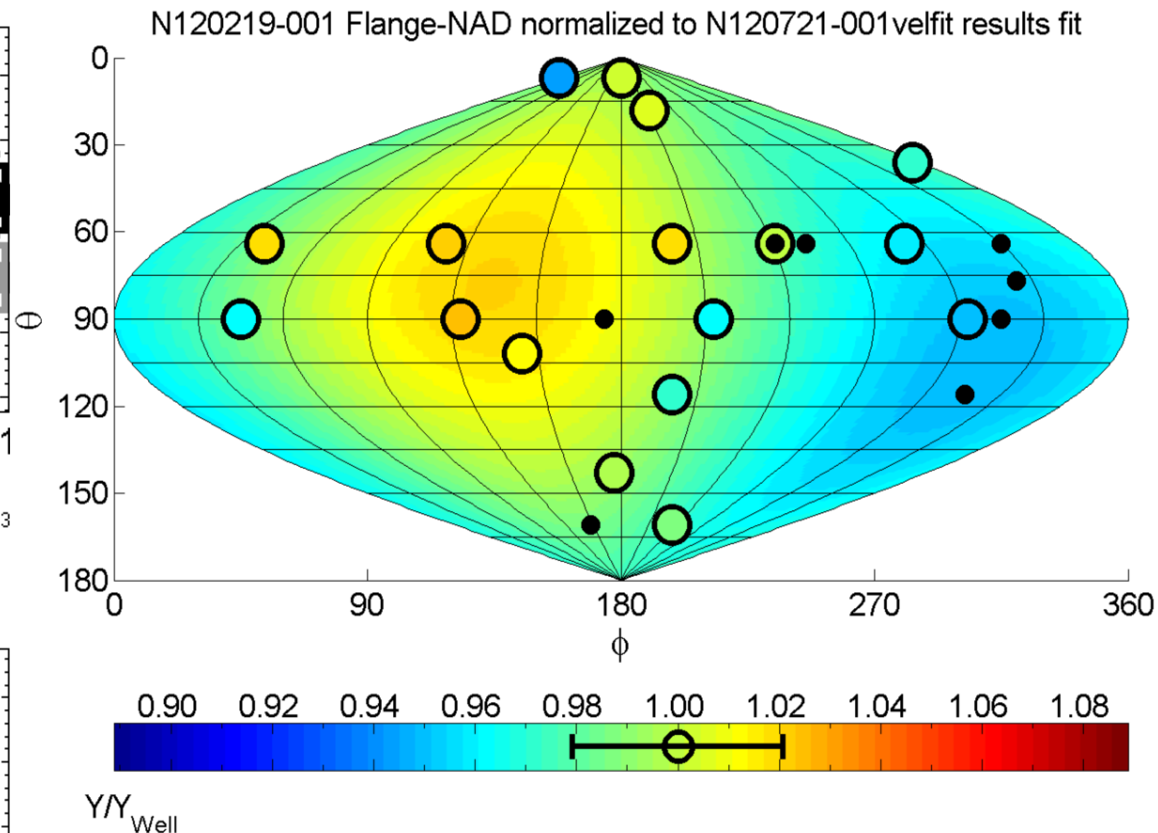
N120219-001

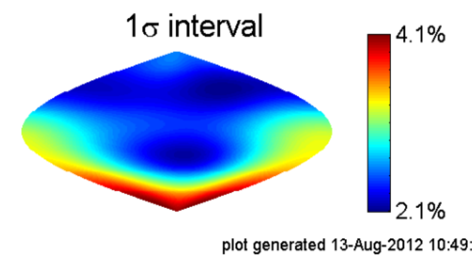
normalized to N120721-001 velocity-corrected





Coefficients:
adz2=-0.0019983
apx=-0.04814
apy=0.052935
apz=0.017646
as=3.4881

Fit values:
Well-NAD: 0.97793
MRS: 0.95309
nToF BT: 0.97196
SpecA: 0.9491
SpecE: 1.0107
NI: 0.94968
DT HI: 0.95808
SPBT: 0.98576



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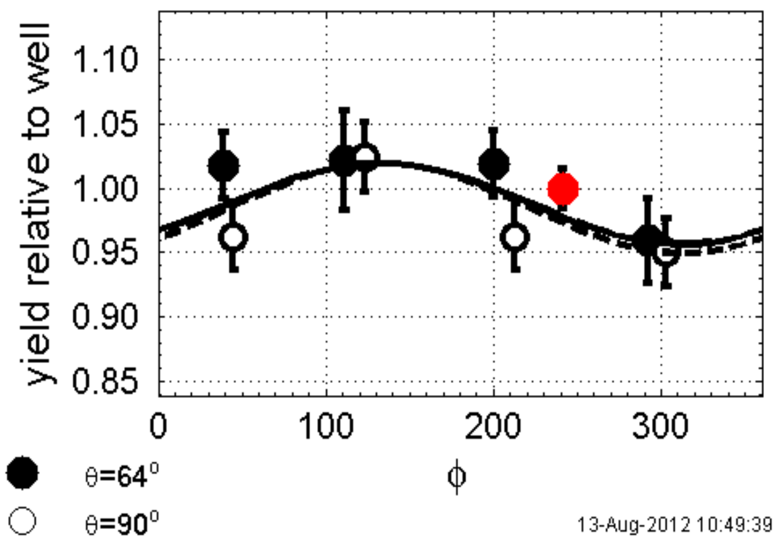
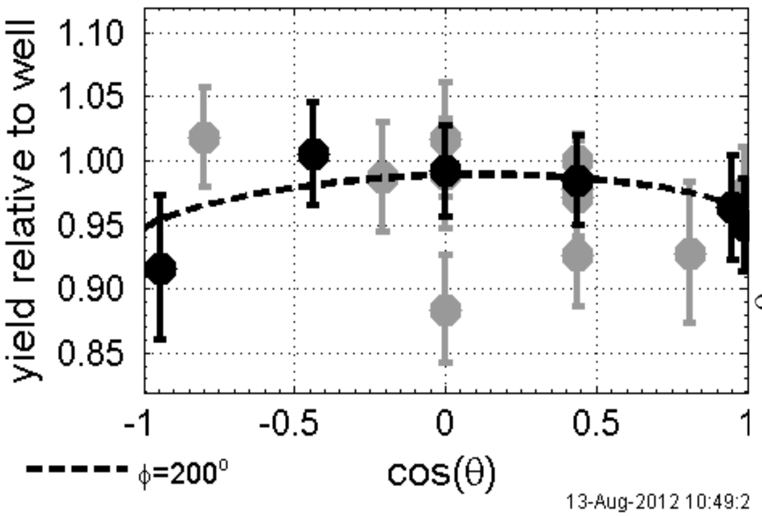
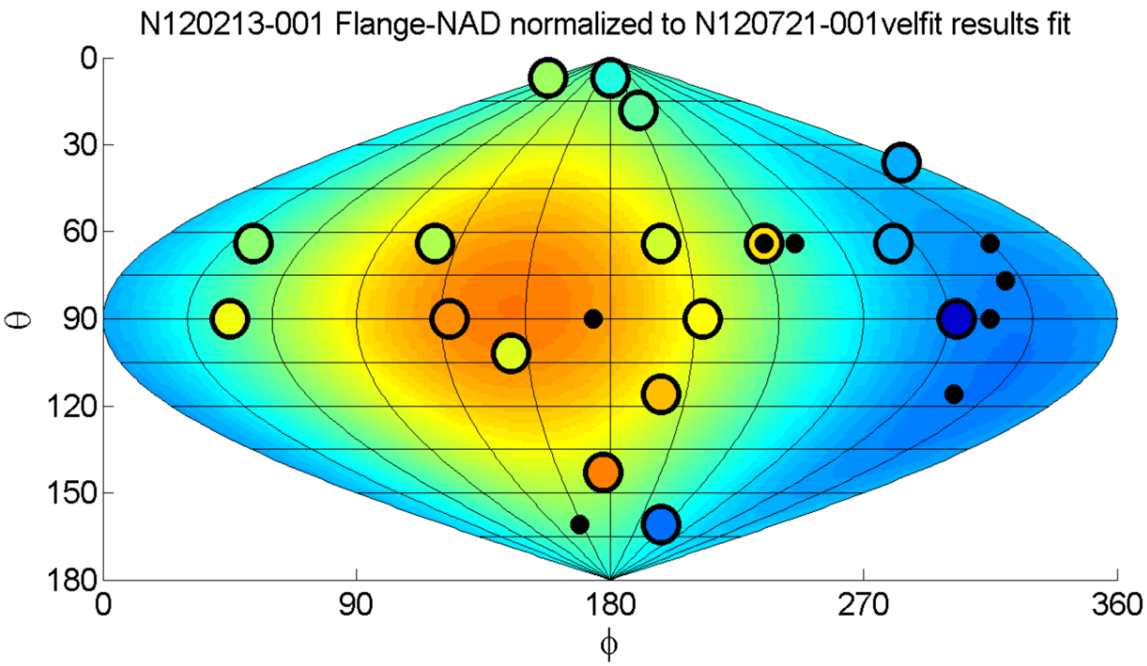
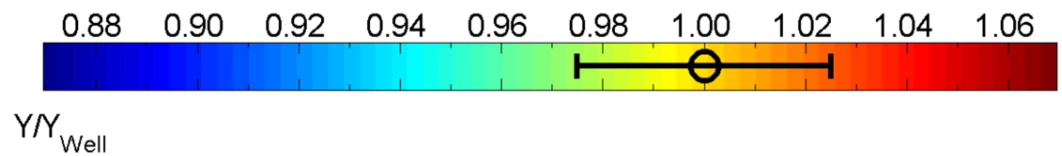


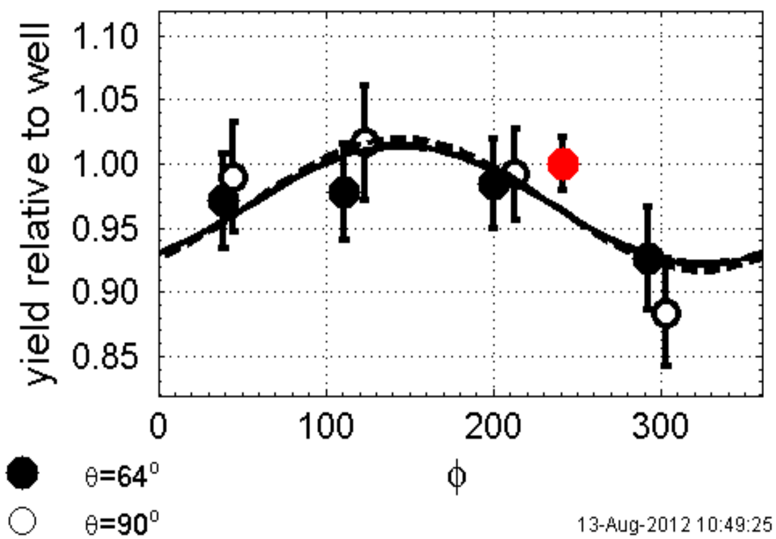
N120213-001

normalized to N120721-001 velocity-corrected



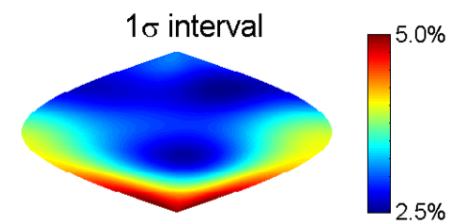






Coefficients:
- adz2=-0.016983
- apx=-0.08565
- apy=0.060839
- apz=0.013092
- as=3.413

Fit values:
- Well-NAD: 0.96273
- MRS: 0.91876
- nToF BT: 0.95331
- SpecA: 0.91664
- SpecE: 1.0129
- NI: 0.91754
- DT HI: 0.92193
- SPBT: 0.96443



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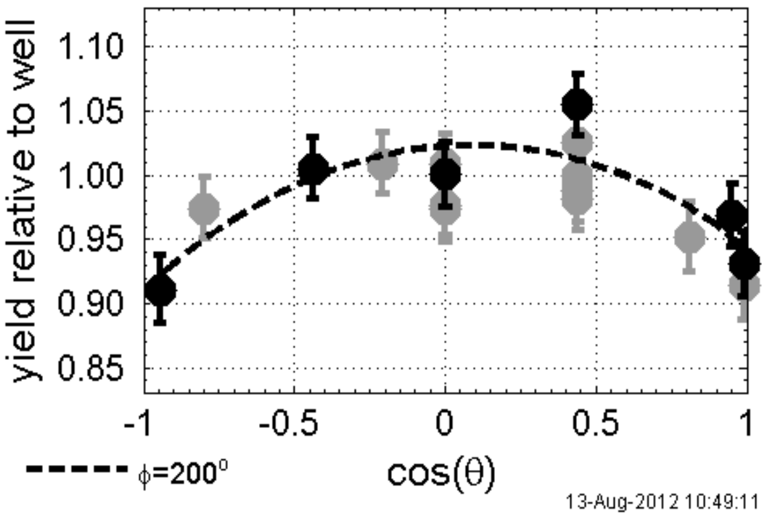
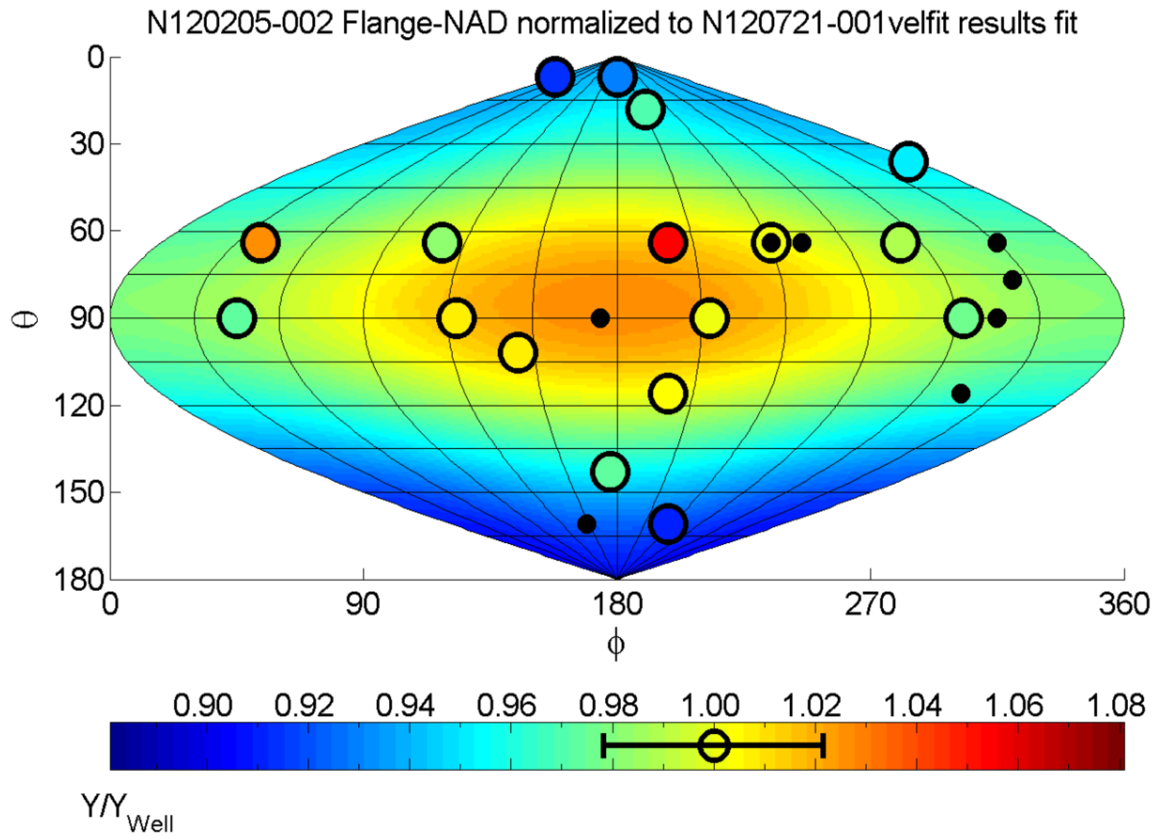
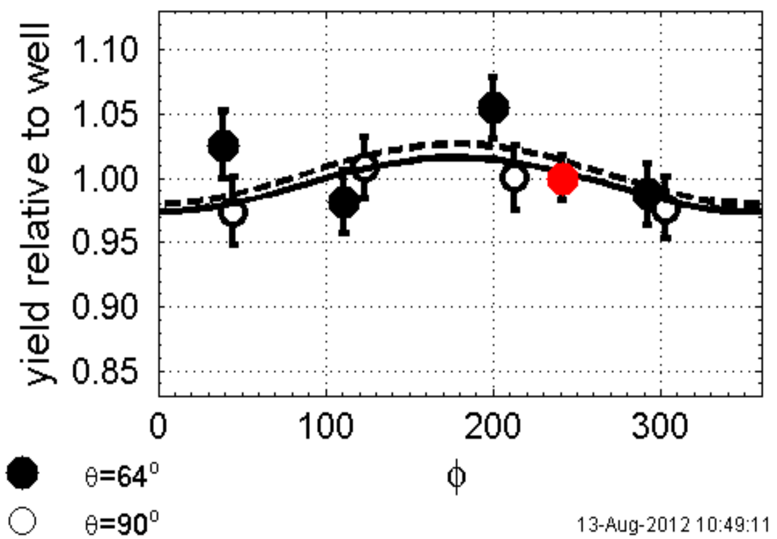
N120205-002

normalized to N120721-001 velocity-corrected

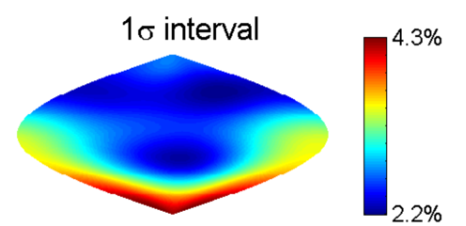






Coefficients:
adz2=-0.085364
apx=-0.04815
apy=0.0018169
apz=0.033652
as=3.4613

Fit values:
Well-NAD: 1.0046
MRS: 0.9839
nToF BT: 1.0004
SpecA: 0.96485
SpecE: 1.0268
NI: 0.98608
DT HI: 0.97632
SPBT: 0.92217



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