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Delivery Ring Extraction for Mu2e – Optics Design

Steve Werkema

Mu2e Beamline, Controls and Instrumentation Technical Design Review

6 October 2015

Outline

1. Delivery Ring Extraction Requirements
2. Overview – Extraction Equipment layout
3. Extraction optics and trajectory
4. Calculation of M4 beamline starting parameters

Delivery Ring Extraction Section Requirements

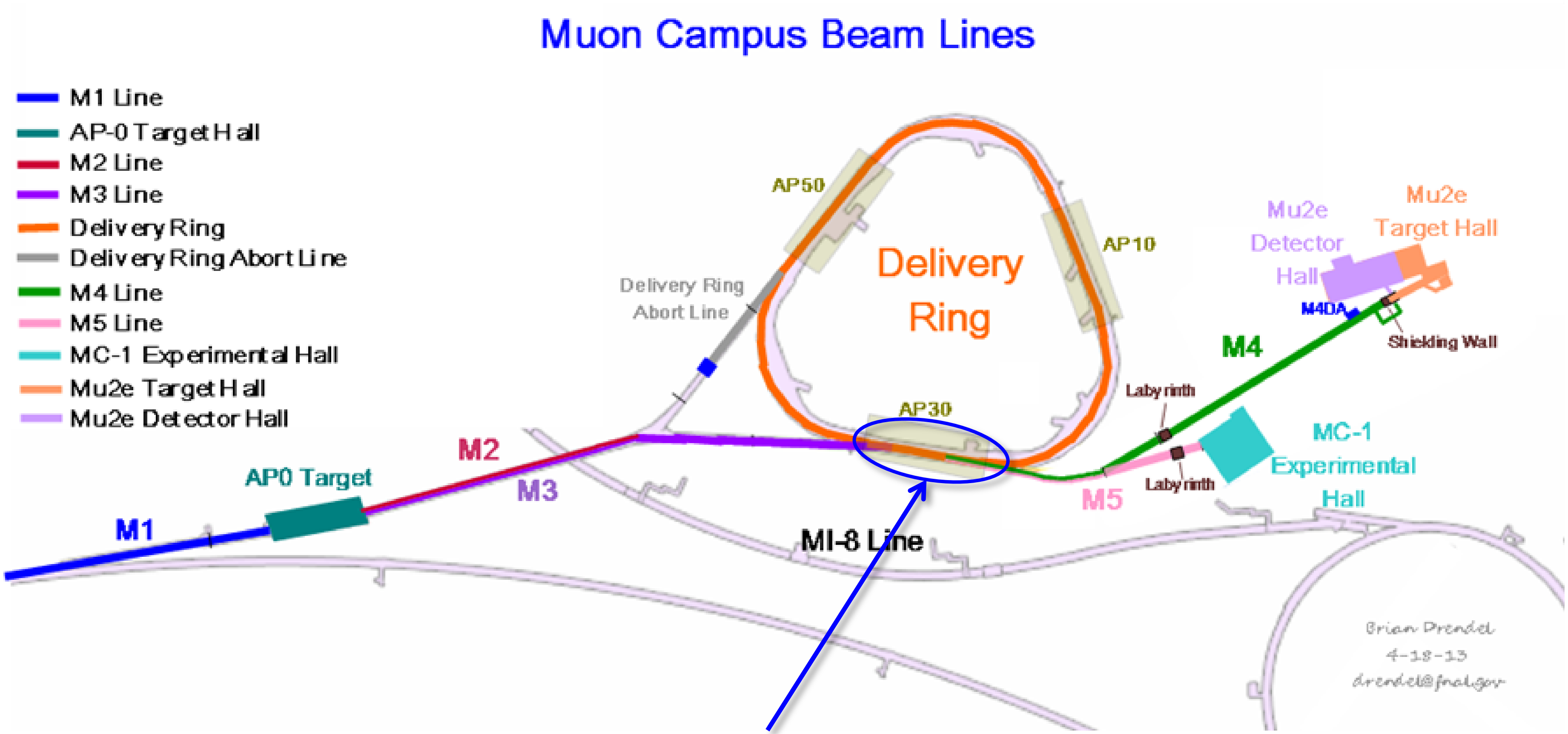
1. Transport resonantly extracted 8.9 GeV/c proton beam from the Delivery Ring electro-static septum extraction channel to the upstream end of the C-magnet downstream of quadrupole D2Q5
2. Maintain – to the extent possible – the Delivery Ring extraction layout used for extraction of 3.1 GeV/c muons to the g-2 experiment*
3. Efficiently extract beam to minimize losses such that prompt and residual radiation dose rates are as low as possible –
   - *MARS tracking models show ~98% efficiency*
   - *Gives acceptable radiation dose rates*

* A significant exception to this is noted in a later slide

Overview of Delivery Ring Extraction

- Equipment layout
- Resonant extraction overview (not in scope of this review)

Muon Campus Layout



Proton injection and extraction is located in the D30 straight section

Brian Drendel

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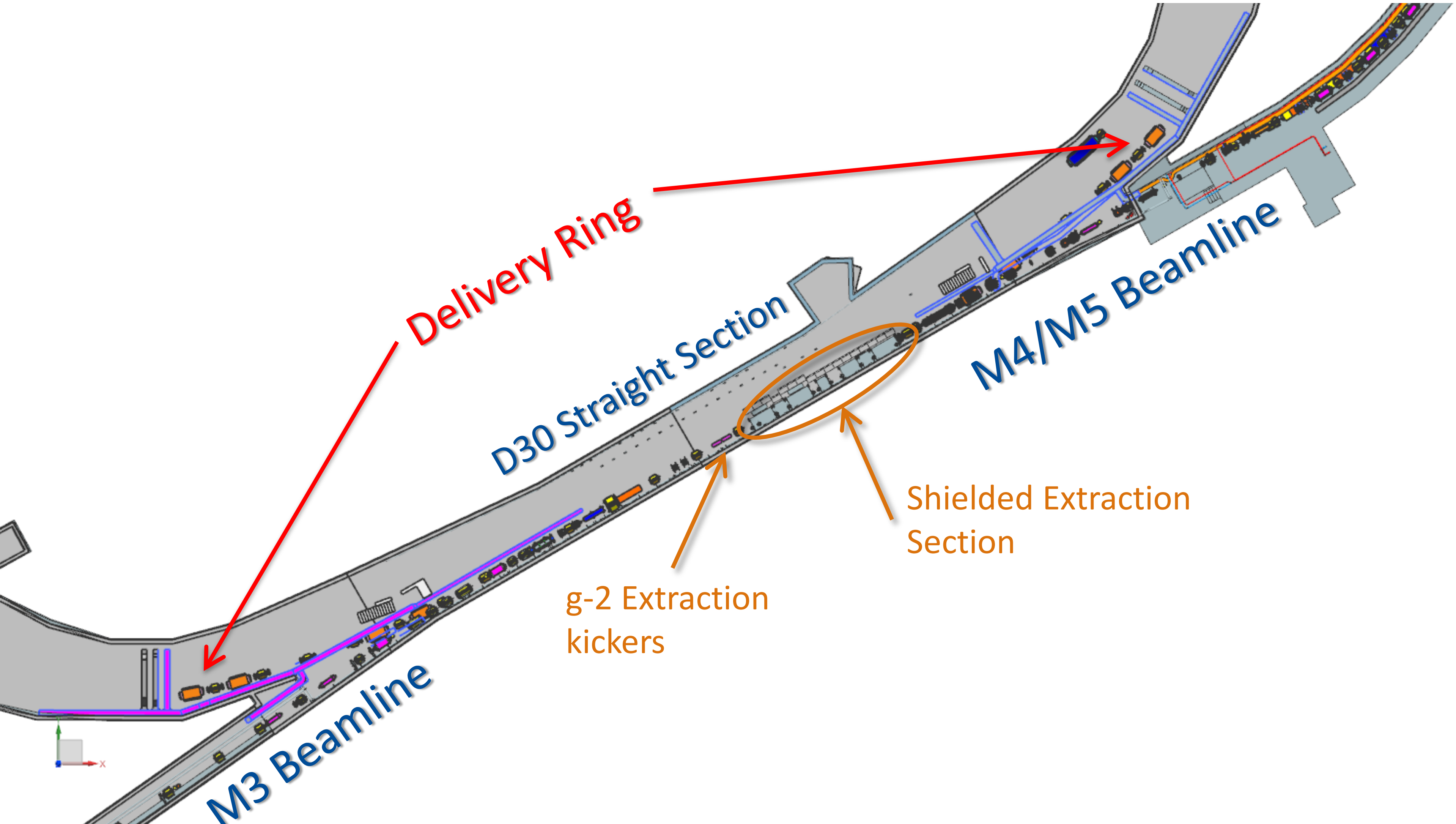
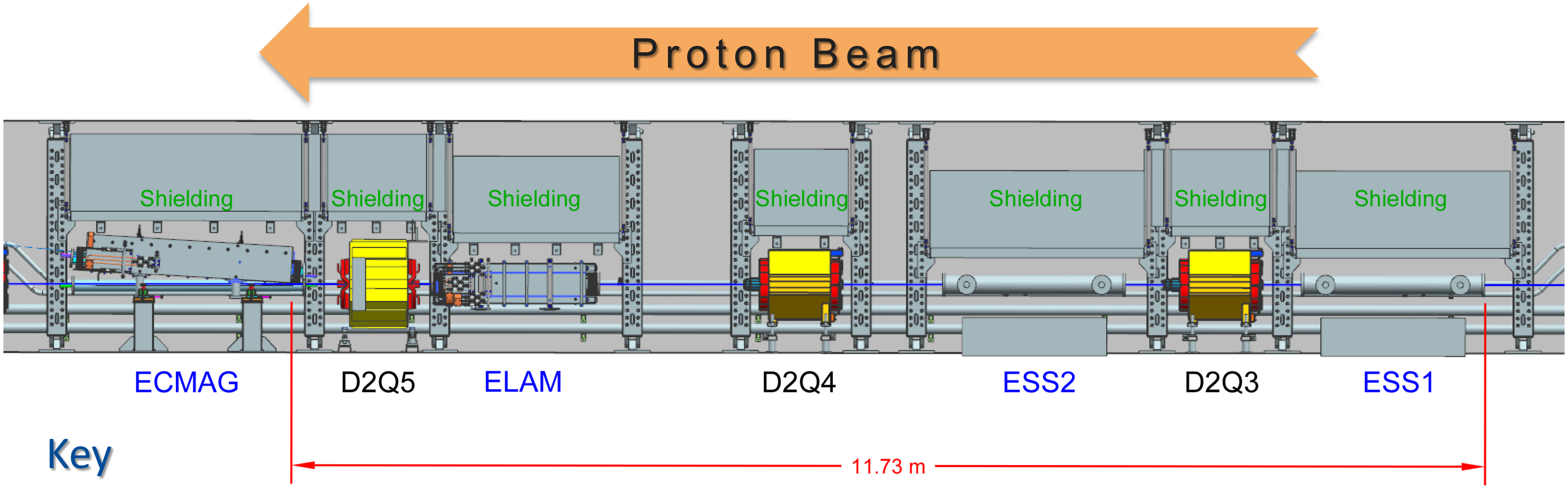
Delivery Ring D30 Straight Section



Delivery Ring Extraction Equipment Layout for Mu2e

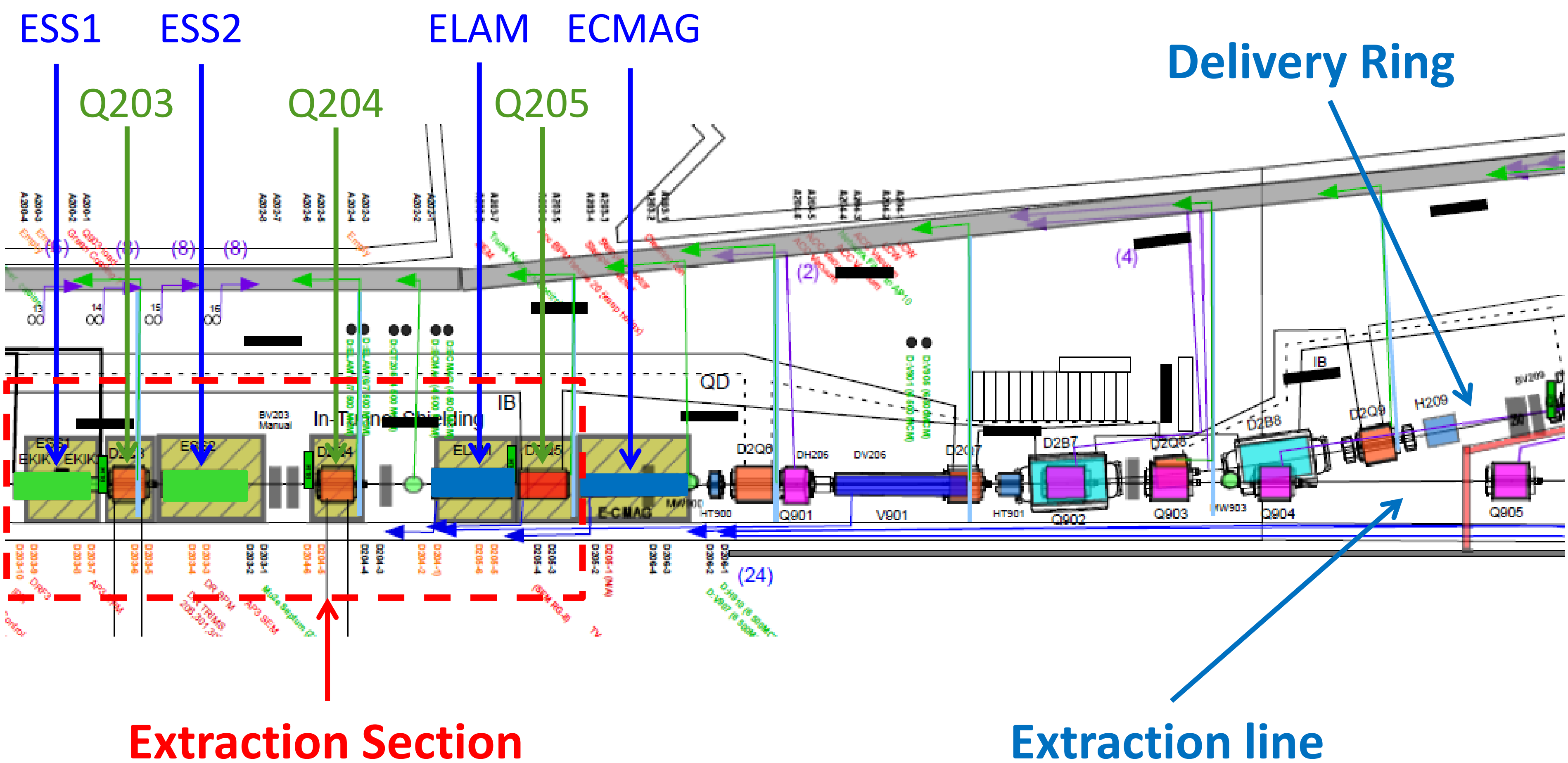


Key

ESS1	Electro-static Septum Module 1	(Kick: 0.8 mrad, Horizontal inward)
ESS2	Electro-static Septum Module 2	(Kick: 1.2 mrad, Horizontal inward)
ELAM	Extraction Lambertson Magnet	(Kick: 40.0 mrad, Vertical upward)
ECMAG	Extraction C- Magnet	
DsQn	n^{th} Delivery Ring Quadrupole in sector s (n = 0 at center of straight)	

- *Starting point of Delivery Ring extraction model is upstream end of ESS1*
- *Starting point of M4 beamline model is the upstream end of ECMAG*

Extraction Section – Plan View



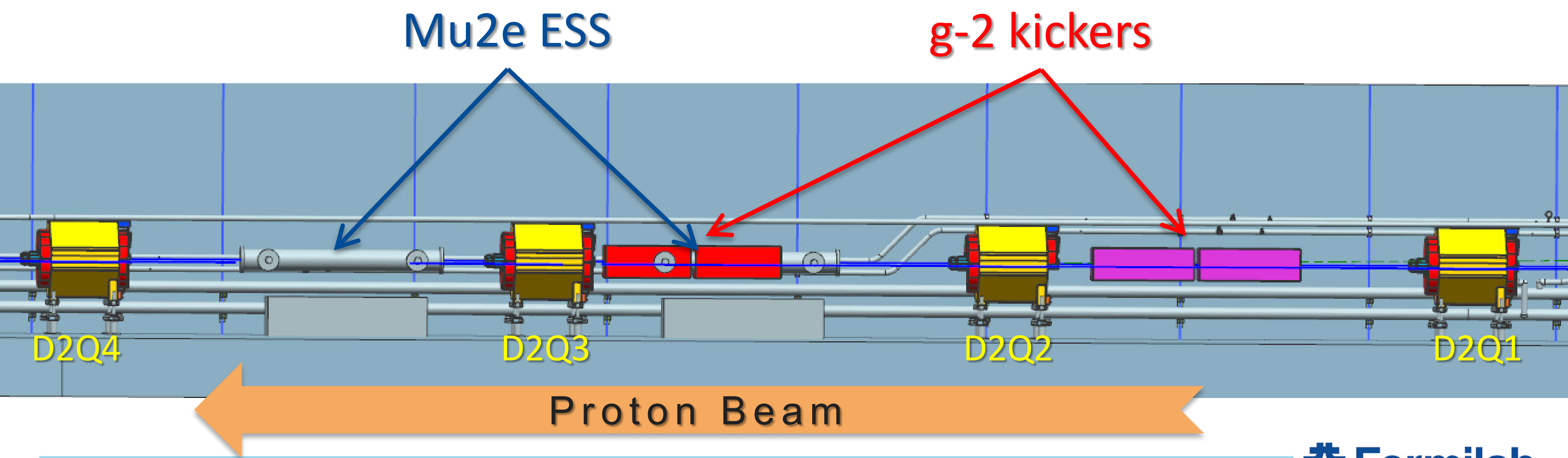
Compatibility of Mu2e & g-2 Extraction

The downstream g-2 extraction kicker modules must be removed prior to installation of ESS1.

Implications:

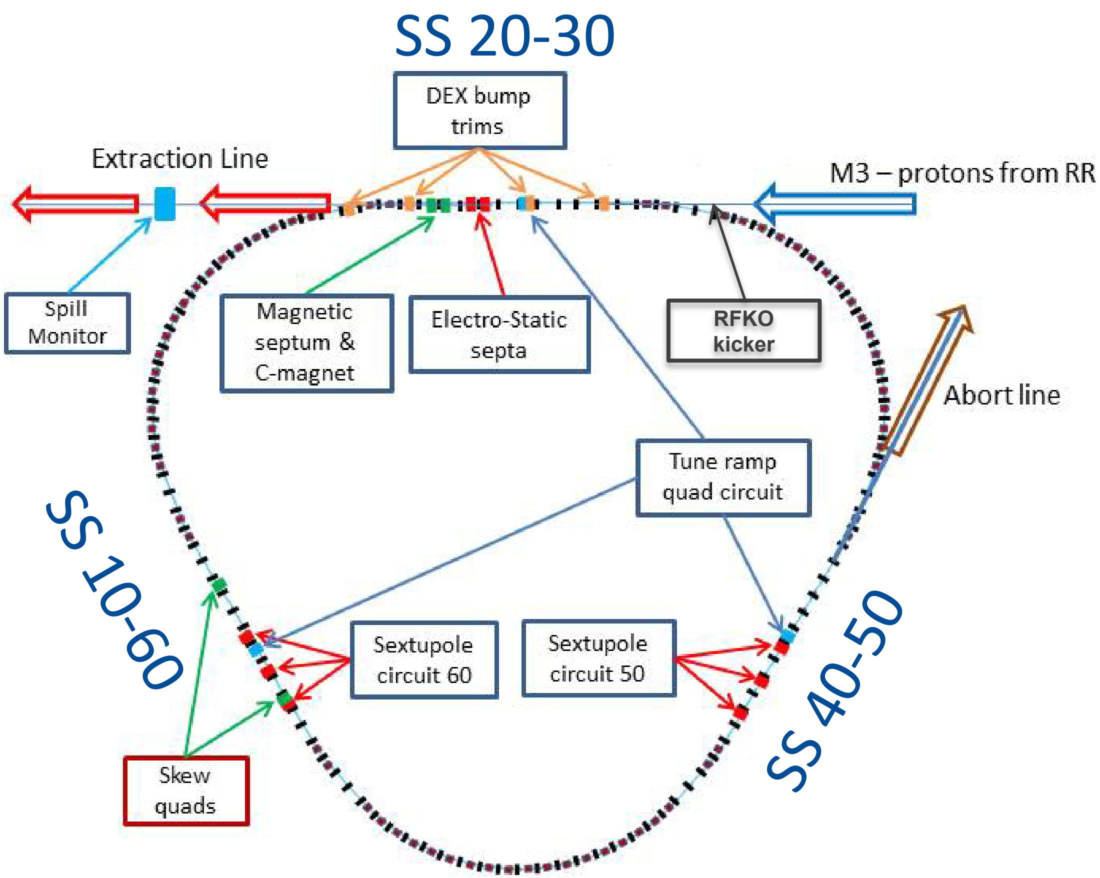
- Single turn proton extraction at 8 GeV not possible with only one kicker
- g-2 3.1 GeV/c operation still possible with one kicker with slightly reduced efficiency

⇒ Must have M4 line commissioned up to diagnostic absorber before installing ESS1



Implementation of Resonant Extraction in the Delivery Ring

- New injection point
- Extraction in SS 20-30
- Electro-static septa
- 2 families of harmonic Sextupoles
- A family of tune Quadrupoles
- Extraction Lambertson
- Dynamic orbit control
- Abort line
- RFKO system
- Spill monitoring
- Spill regulation



- ○ Horizontal 3rd Integer resonance
- ○ Q_x / Q_y=9.650 / 9.735

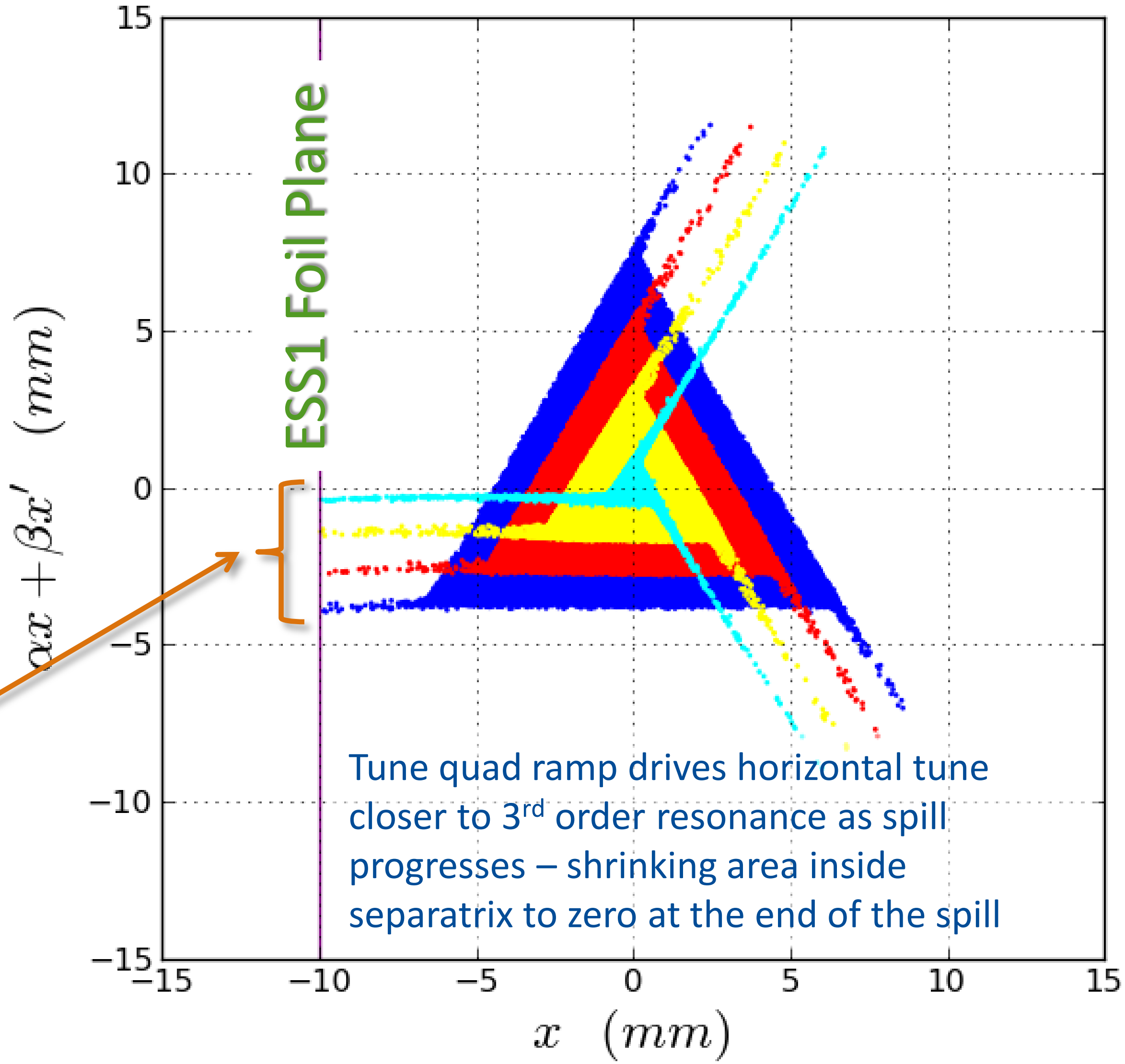
Vladimir Nagaslaev

Resonant Extraction Horizontal Phase Space

Horizontal phase space distribution of circulating beam at the upstream end of ESS1

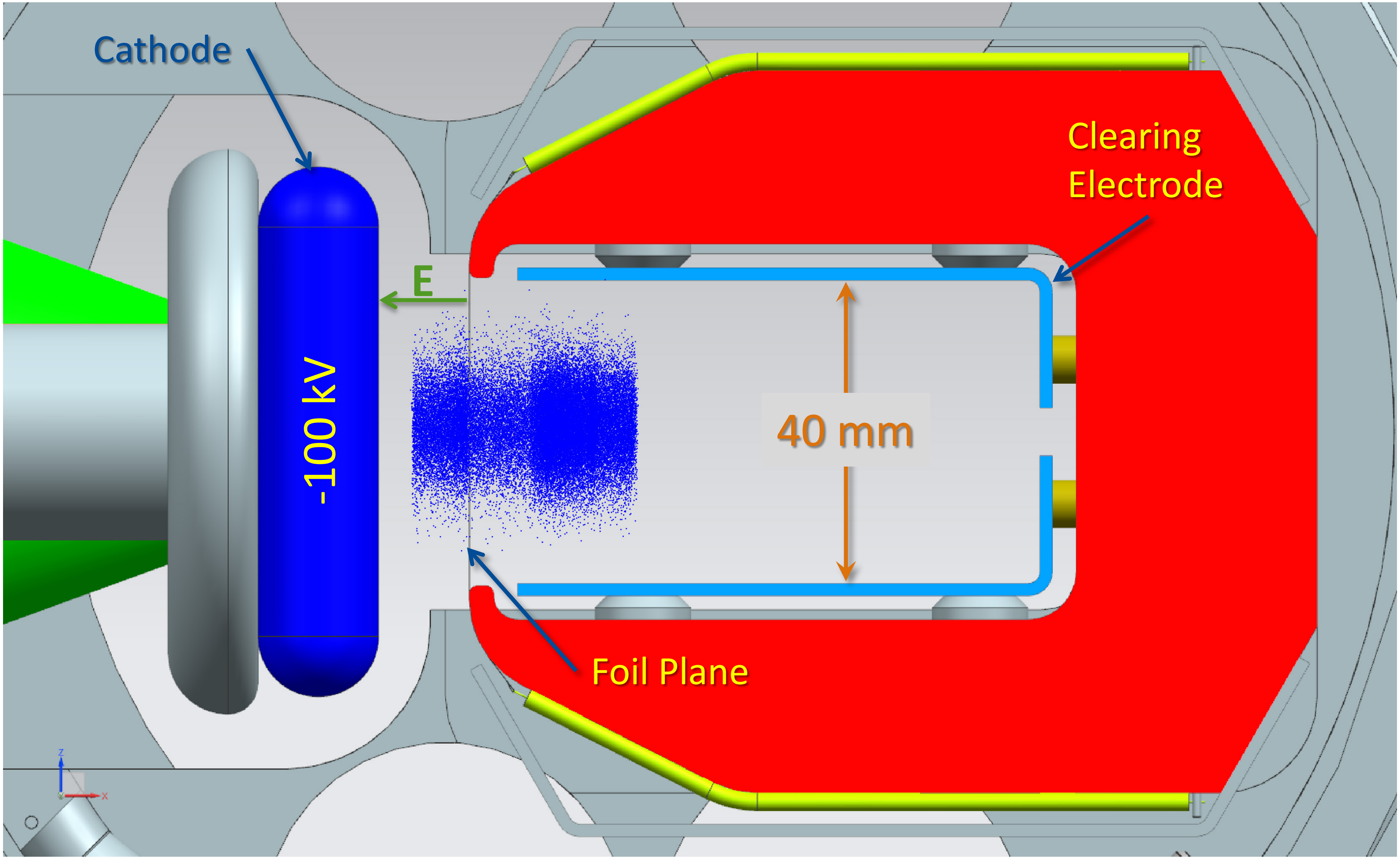
- Blue – beginning of spill
- Red – early in spill
- Yellow – late in spill
- Cyan – end of spill

Note: x' at the foil plane changes throughout spill – compensated by DEX bump

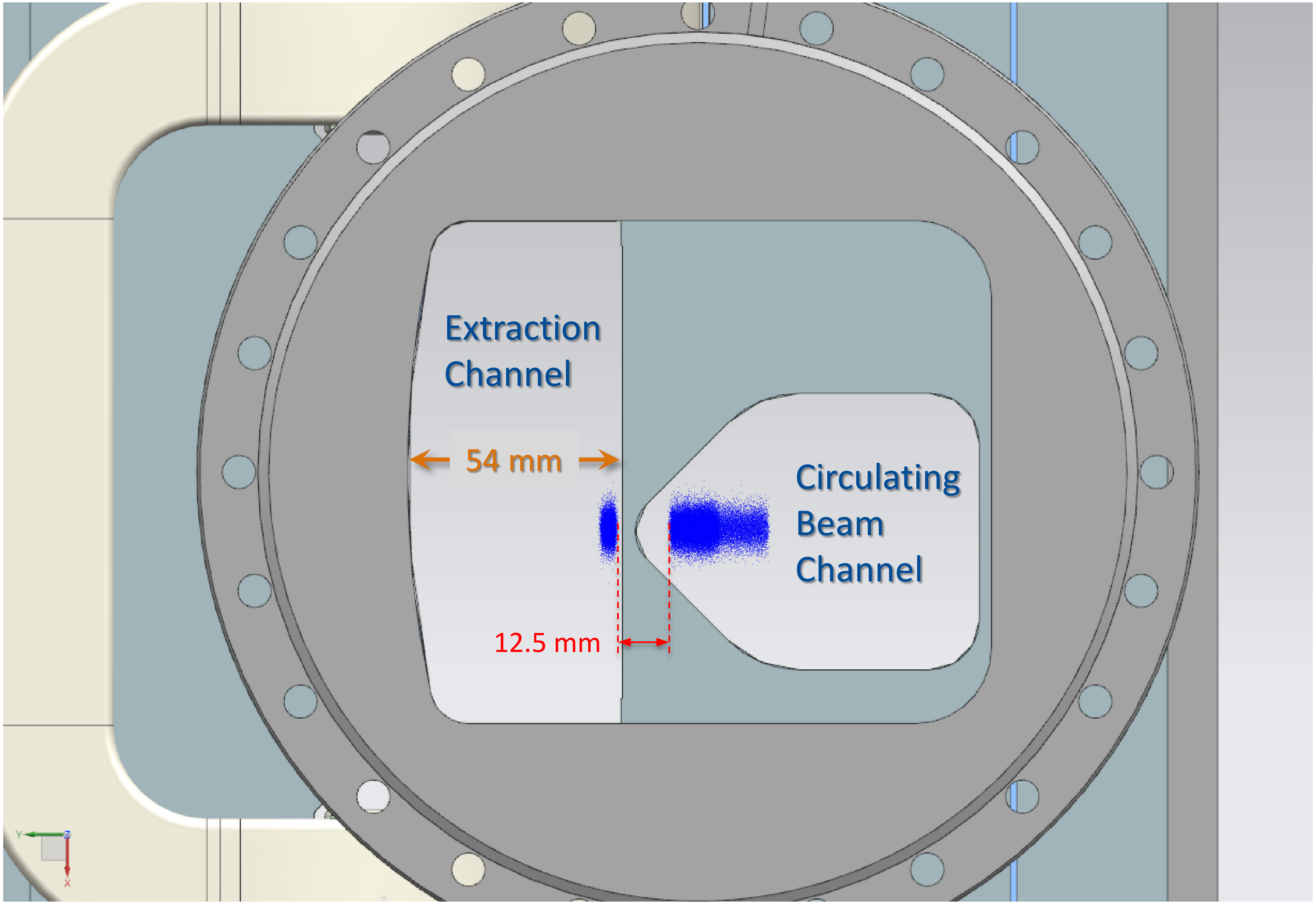


Synergia model
Chong Shik Park

Circulating and Extracted Beam at Upstream End of ESS1



Extraction Lambertson – Upstream End (8.6 m downstream of ESS1)



Delivery Ring Extraction Model

Delivery Ring Extraction Models

Several models of Delivery Ring extraction for Mu2e have been constructed

- Optics Models
  - Original Concept: hand calculation of trajectories (Jim Morgan)
  - Original Model in MAD 8 (Carol Johnstone)
  - Present Model in MAD X (Steve Werkema) ⇐ Focus of next few slides
  - Model independently checked in OptiM (Vladimir Nagaslaev)
- Resonant extraction studies
  - MARS model (Vladimir Nagaslaev)
  - Optimize resonant extraction parameters to minimize losses
  - Provide beam distributions for tracking models of M4 beamline for extinction and targeting studies
- Radiation dose rate/shielding studies
  - MARS model that includes shielding (Tony Leveling)
  - sky shine, direct dose rate, and residual activation studies

Delivery Ring Extraction Optics Model

Two pass process:

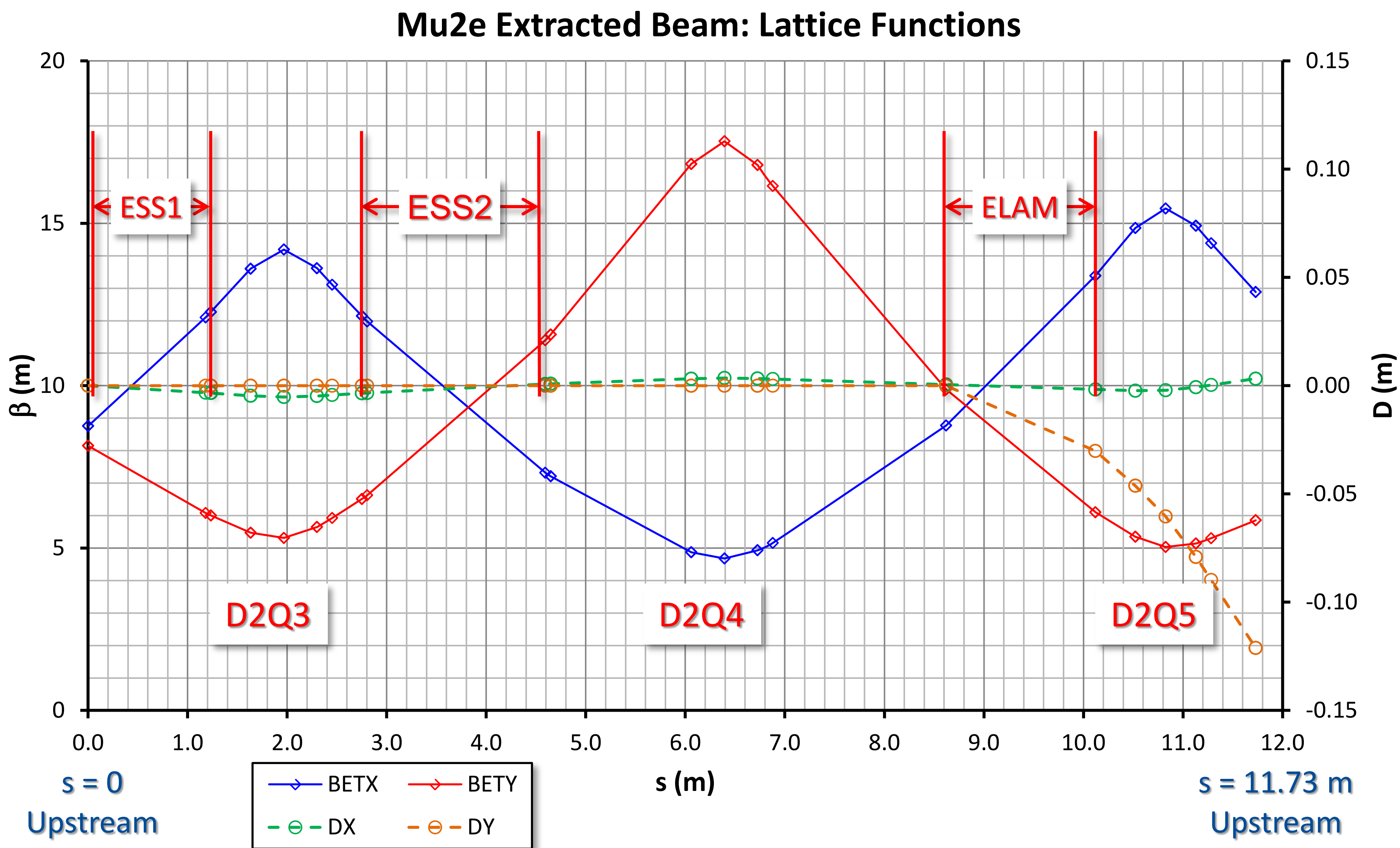
1) First Run:

- Model ESS1, ESS2, and ELAM as correction dipoles (doesn't change survey trajectory)
- **Starting survey coordinates** = coordinates of circulating beam at upstream end of ESS1
- **Starting x *and* x'** = center of extracted beam at the upstream end of ESS1
- **Final coordinates** at the upstream end of ECMAG are calculated from the survey coordinates of the circulating beam, and the bearing, pitch, x, x', y, and y' of the extracted beam
- **Final Dispersion (D and D')** at upstream end of ECMAG is calculated from change in in x and y for a 1% change in $\Delta p/p$

2) Second Run:

- Model ESS1, ESS2, and ELAM as RBENDs
- **Starting survey coordinates** = coordinates of extracted beam at upstream end of ESS1
- Model kicks from off-center passage through quads by embedding short (10 mm) RBENDs in quads with kicks determined from quad $\Delta x'$ and $\Delta y'$ from first run.
- β_x, α_x, β_y, and α_y at upstream end of ECMAG determined by this run

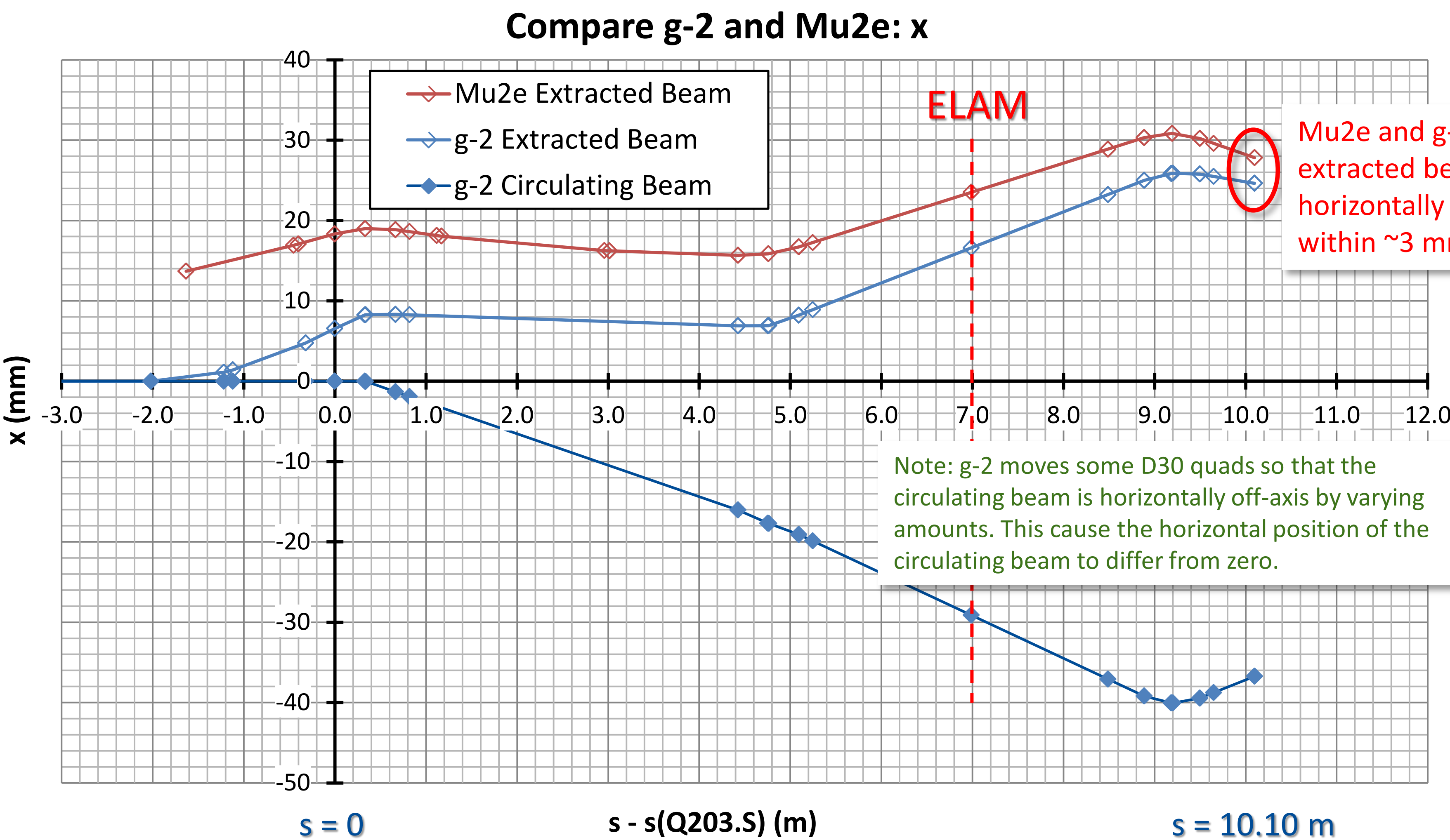
Extracted Beam Lattice Functions



s = 0
Upstream
end ESS1

s = 11.73 m
Upstream
end ECMAG

Extracted Beam Horizontal Trajectory: Mu2e and g-2



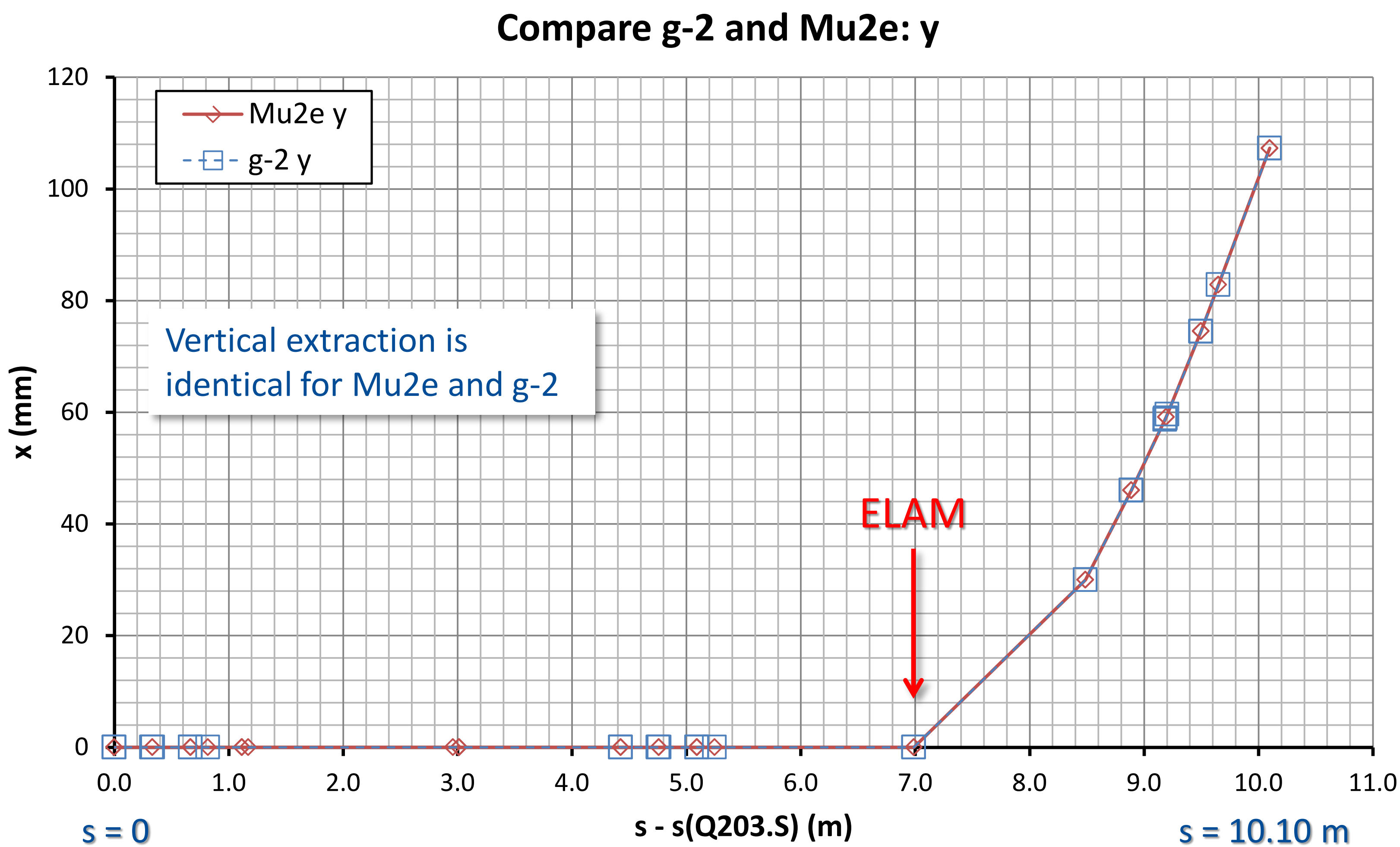
Mu2e and g-2 extracted beam horizontally within ~3 mm

Note: g-2 moves some D30 quads so that the circulating beam is horizontally off-axis by varying amounts. This cause the horizontal position of the circulating beam to differ from zero.

s = 0
Upstream end D2Q3

s = 10.10 m
Upstream end ECMAG

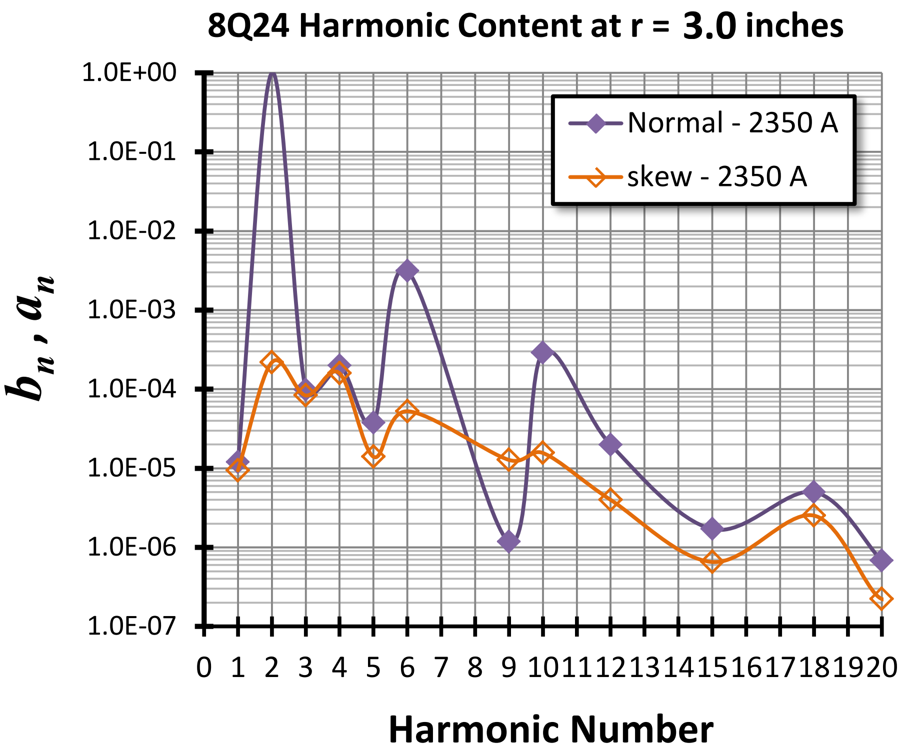
Extracted Beam Vertical Trajectory: Mu2e and g-2

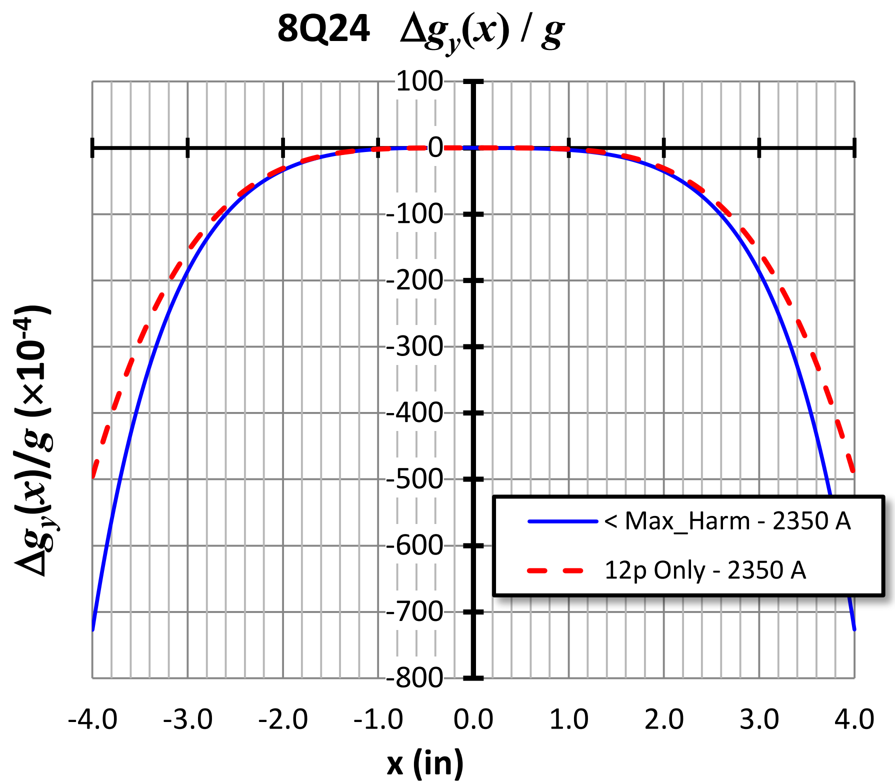


s = 0
Upstream
end D2Q3

s = 10.10 m
Upstream
end ECMAG

Possible problem: D2Q5 Field Non-Uniformity





8Q24 Quadrupole: measured normal (b_n) and skew (a_n) harmonic strengths.

Measurements show unusually strong 12- pole (n = 6) and 20-pole (n = 10) components.

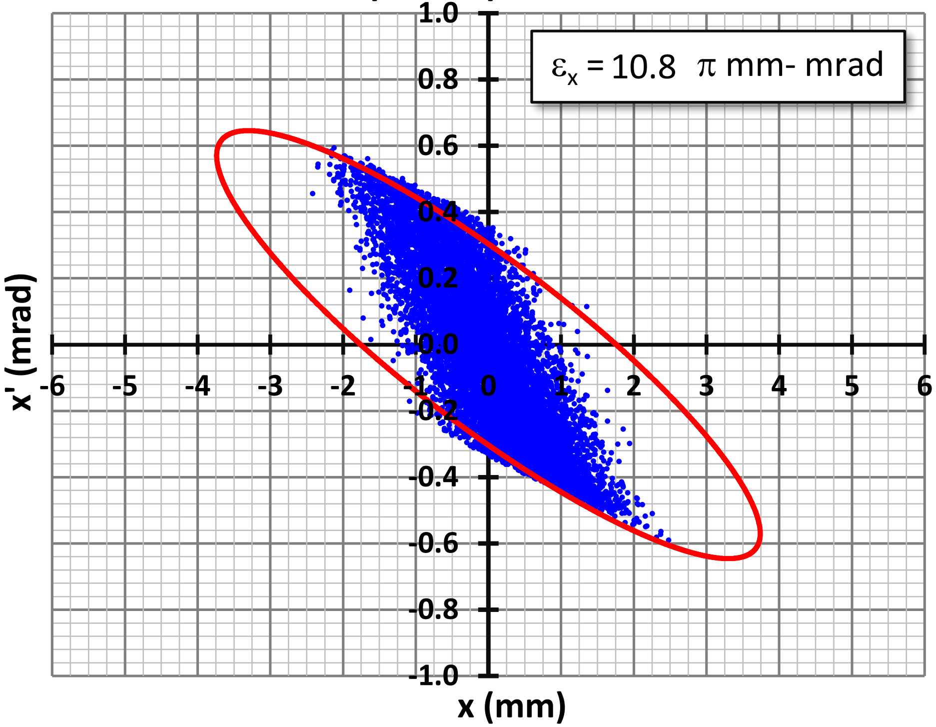
- 2% deviation in gradient at 3” (where we intend to send beam)
- There were some measurement problems – an 8Q24 is now on a MTF test stand undergoing a new round of measurements

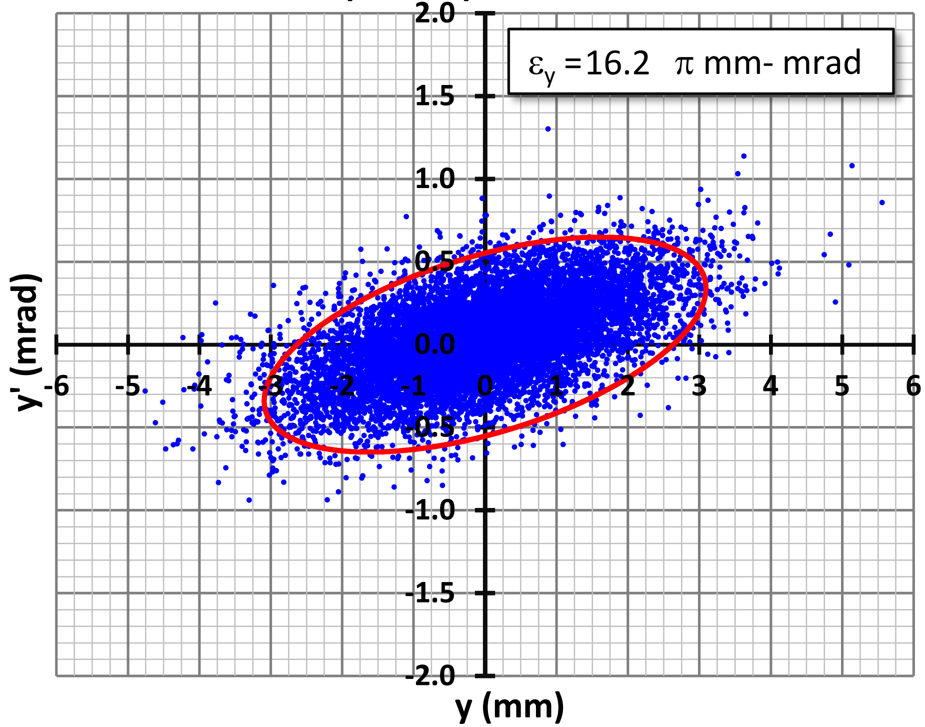
M4 Beamline Starting Parameters

Starting Position and Lattice for M4 line

	Quantity	Value	Units	Description
Starting Coordinates	X_0	30071.579381	m	Site North
	Y_0	222.112319	m	Elevation
	Z_0	30446.932635	m	Site East
	θ_0	2.090508	rad	Bearing
	φ_0	0.054674	rad	Pitch
Starting Lattice Functions	β_x	12.316	m	
	α_x	1.877		
	D_x	0.027	m	
	D_x'	0.004		
	β_y	5.600	m	
	α_y	-0.616		
	D_y	-0.119	m	
	D_y'	-0.069		

M4 Starting Phase Space





Horizontal transverse phase space distribution is determined by DR extraction optics

- ε_x = 11 π mm-mrad
- Not matched to lattice

* There is a small vertical dispersion (-12 cm) from the vertical bend in ELAM.

Vertical transverse phase space distribution is relatively un-affected* by extraction. Thus, vertical phase space distribution is approximately that coming from the Recycler.

- ε_y = 16 π mm-mrad
- Matched to the lattice

Conclusions

- The design of the extraction optics for extraction from the Delivery Ring to Mu2e is very nearly complete
- The design delivers extracted beam to the same position at the upstream end of ECMAG as g-2 extraction
  – Mu2e extraction requires replacement of downstream g-2 extraction kickers with ESS1
- Work remaining: incorporate the impact of the D2Q5 gradient non-uniformity into the model

Backup Slides

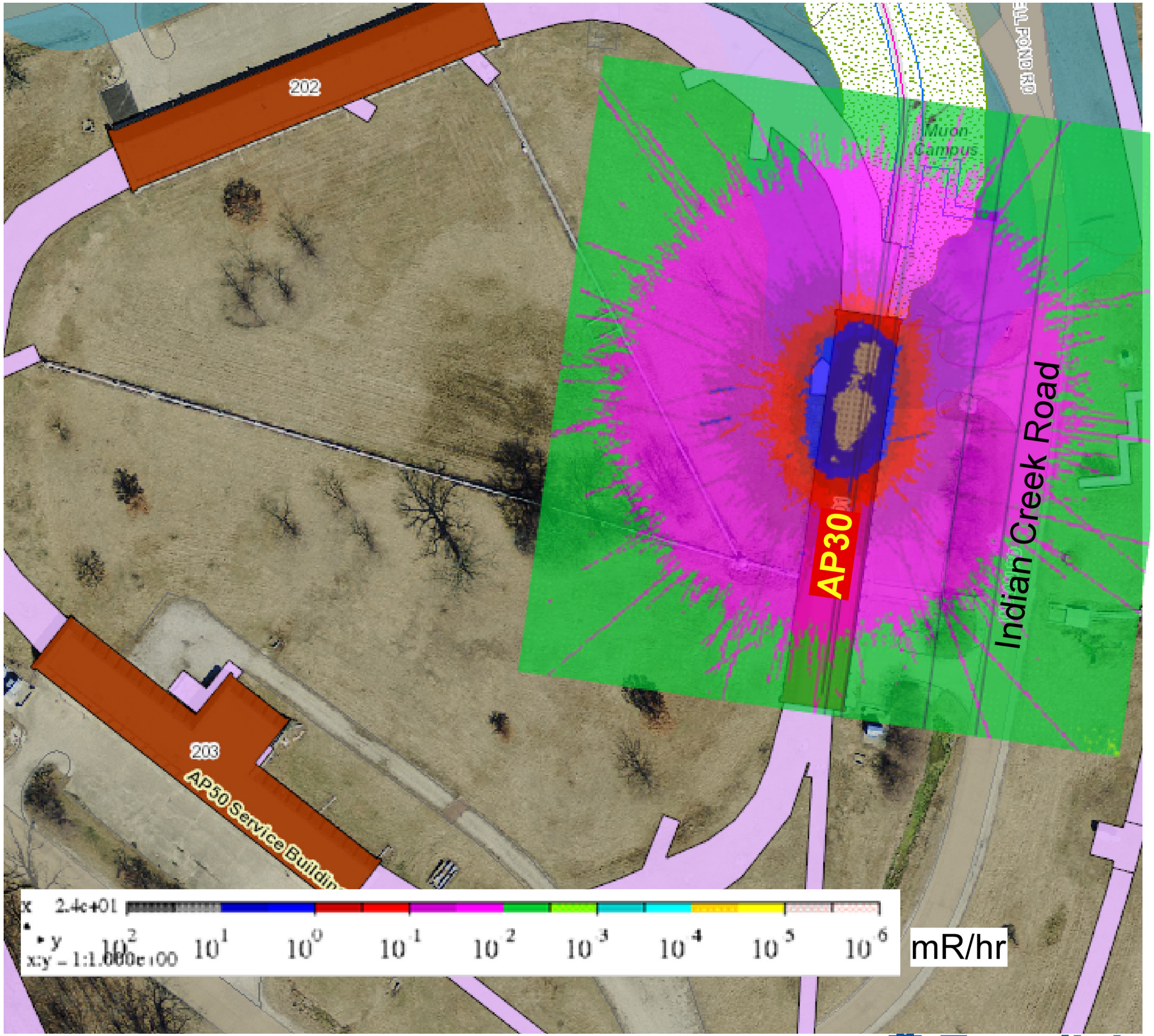
Surface Level Dose Rates at AP30 during Mu2e Beam Operation

MARS simulation of direct and sky shine dose rates during Mu2e operation at design beam power.

Assumptions:

- Design Beam Power (8kW)
- 98% Extraction Efficiency

Peak dose rate: 24 mR/hr inside AP30 service building



Tony Leveling

Calculation of Coordinates at Upstream End of ESS1

Coordinates and direction of beam at the upstream end of ESS1 Cathode

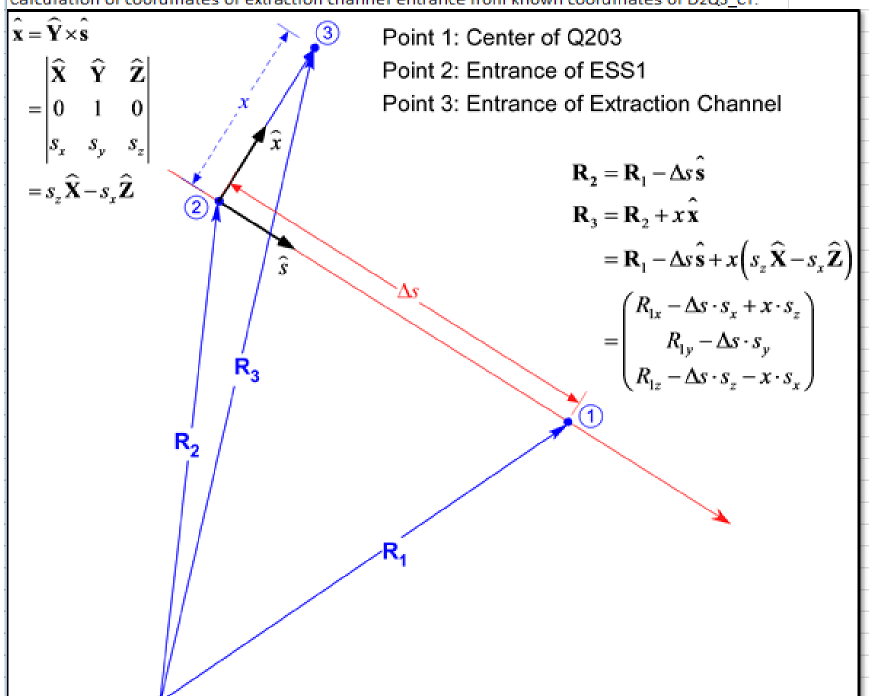
Updated:	Steve Werkema	9/24/2015

Parameters	Value	units	
Center of Extr. Chan. relative to quad axis (x):	13.687	mm	positive is toward inside of DR
Beam Angle w/resp. to D30 axis at u/s end of ESS1:	2.341	mrad	positive is toward inside of DR
Dist. from D2Q3 Center (Δs):	1.9669	m	Entrance to ESS1

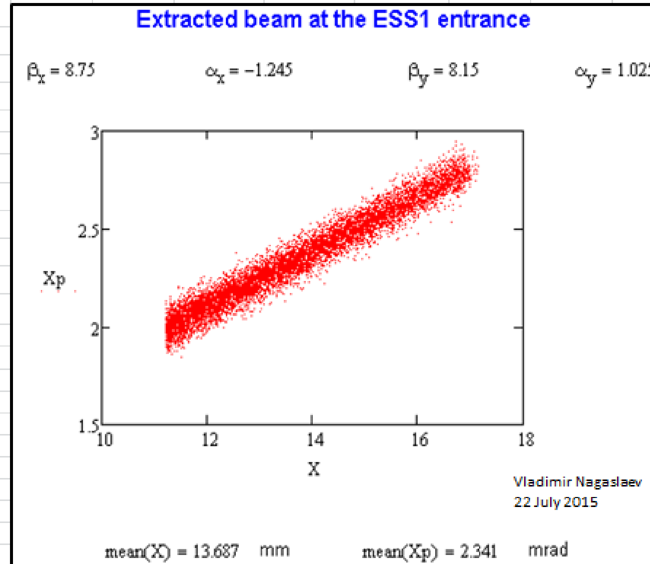
MAD Coordinates of Upstream end of ESS1 Extraction Channel:

	X(m) - Northing	Y(m) - Elevation	Z(m) - Easting	θ (rad)	φ (rad)
$\mathbf{R}_1$ (Center of D2Q3) =	30063.137949	222.005015	30451.839361	2.094478	0.000000
$\mathbf{R}_2$ (Circ. Beam at Upstream end of ESS1) =	30061.434612	222.005015	30452.822971	2.094478	0.000000
$\hat{\mathbf{x}}$ (Beam horizontal) =	-0.500072	0.000000	-0.865984	3.665274	0.000000
$\mathbf{R}_3$ (Extracted Beam at ESS1.S) =	**30061.427767**	**222.005015**	**30452.811118**	**2.096819**	**0.000000**

Calculation of coordinates of extraction channel entrance from known coordinates of D2Q3_CT:



Extracted beam horizontal phase space at entrance to ESS1:



Tests

	$R_3 - R_2$	$R_2 - R_1$	$R_3 - R_1$	Q202.C - R_2		
Δs =	0.000	-1966.938	-1966.938	-2468.393	mm	4435.331
Δx =	13.687	0.000	13.687	-0.149	mm	
ΔY =	0.000	0.000	0.000	0.084	mm	

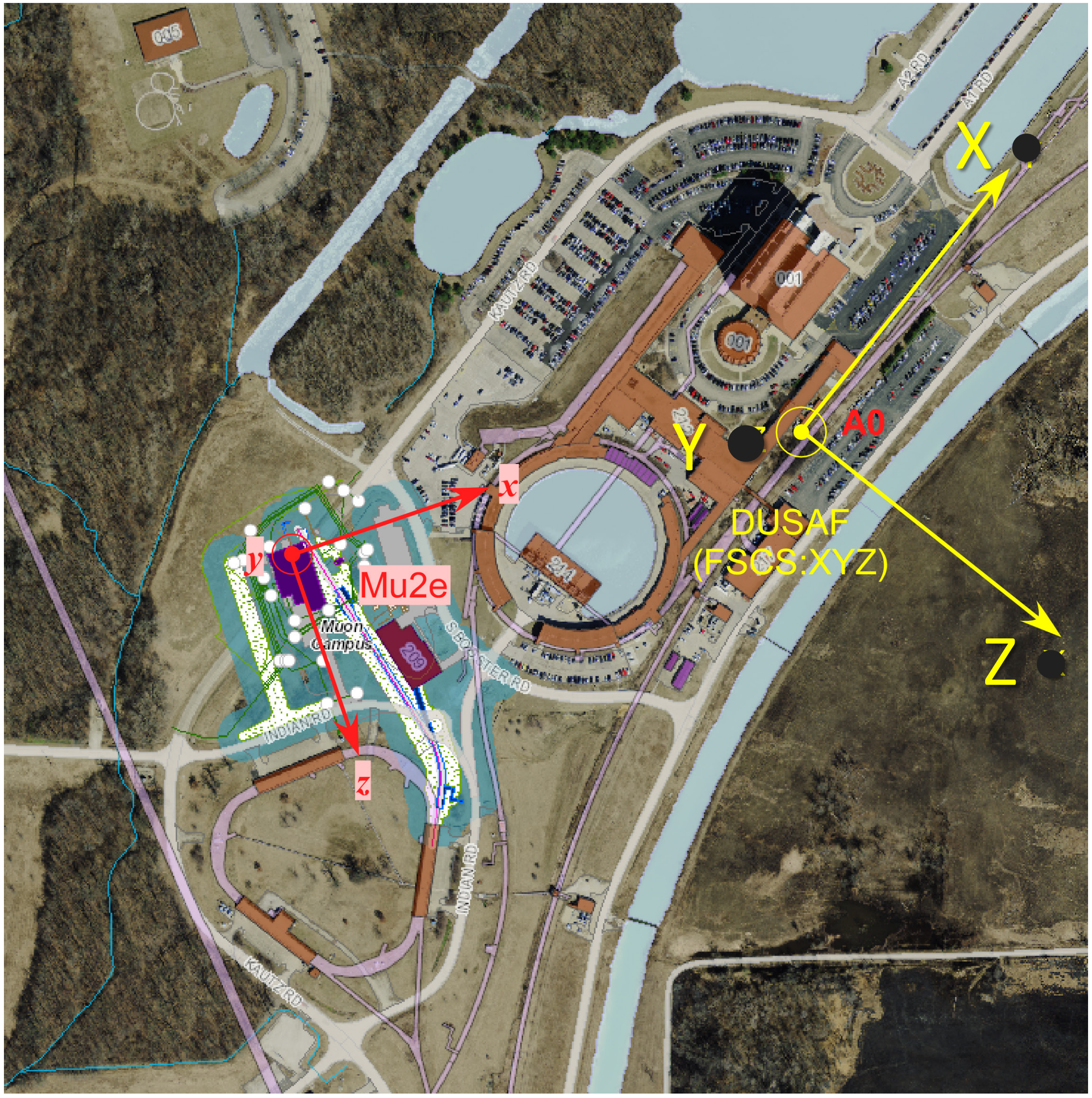
Emulating kicks from beam offsets in quadrupoles

```
! Build quads that include the quad kicks as bending elements that DO affect the survey trajectory:
ELSEIF (Quad_Bends == ON) {
    ! Emulate quad kicks by L = L_Kick RBENDs at the center of each quad.
    ! The strength of these RBENDS is determined from a run with Calc_Quad_Kicks = YES

    ! Cancel the non-zero PSI
    Psi205 = 0.0 ;                                          ! (rad)
    IF (ZERO_PSI == YES ) { Psi205  = -0.000301296 ; }  ! (rad) value of -psi205x from a run with ZERO_PSI = NO

    IF (Quads_as_RBENDs == NO) {
        Q203 :  SEQUENCE, REFER = ENTRY, L = L_Q203_Comp  ;
                        QFS203,     at = 0.0 ;
            Q203.C   :  MARKER,     at = L_Q203 ;
            xKick203:   RBEND,      at = L_Q203,                    ANGLE = -HKICK_Q203,  L = L_Kick ;
                        QFS203,     at = L_Q203_Comp - L_Q203 ;
        ENDSEQUENCE ;

        Q204 :  SEQUENCE, REFER = ENTRY, L = L_Q204_Comp ;
                        QDS204,     at = 0.0 ;
            Q204.C   :  MARKER,     at = L_Q204 ;
            xKick204:   RBEND,      at = L_Q204,                    ANGLE = -HKICK_Q204,  L = L_Kick ;
                        QDS204,     at = L_Q204_Comp - L_Q204 ;
        ENDSEQUENCE ;

        Q205 :  SEQUENCE, REFER = ENTRY, L = L_Q205_Comp ;
                        QFS205a,    at = 0.0 ;
            xKick205:   RBEND,      at = L_Q205a,                   ANGLE = -HKICK_Q205,  L = L_Kick ;
            Srot205  :  SROTATION,  at = L_Q205a + L_Kick*f_Q205_H, ANGLE = Psi205 ;
            Q205.C   :  MARKER,     at = L_Q205a + L_Kick*f_Q205_H ;
            yKick205:   RBEND,      at = L_Q205a + L_Kick*f_Q205_H, ANGLE = -VKICK_Q205,  L = L_Kick,   TILT = PI/2 ;
                        QFS205b,    at = L_Q205_Comp - L_Q205b ;
        ENDSEQUENCE ;
    }
```

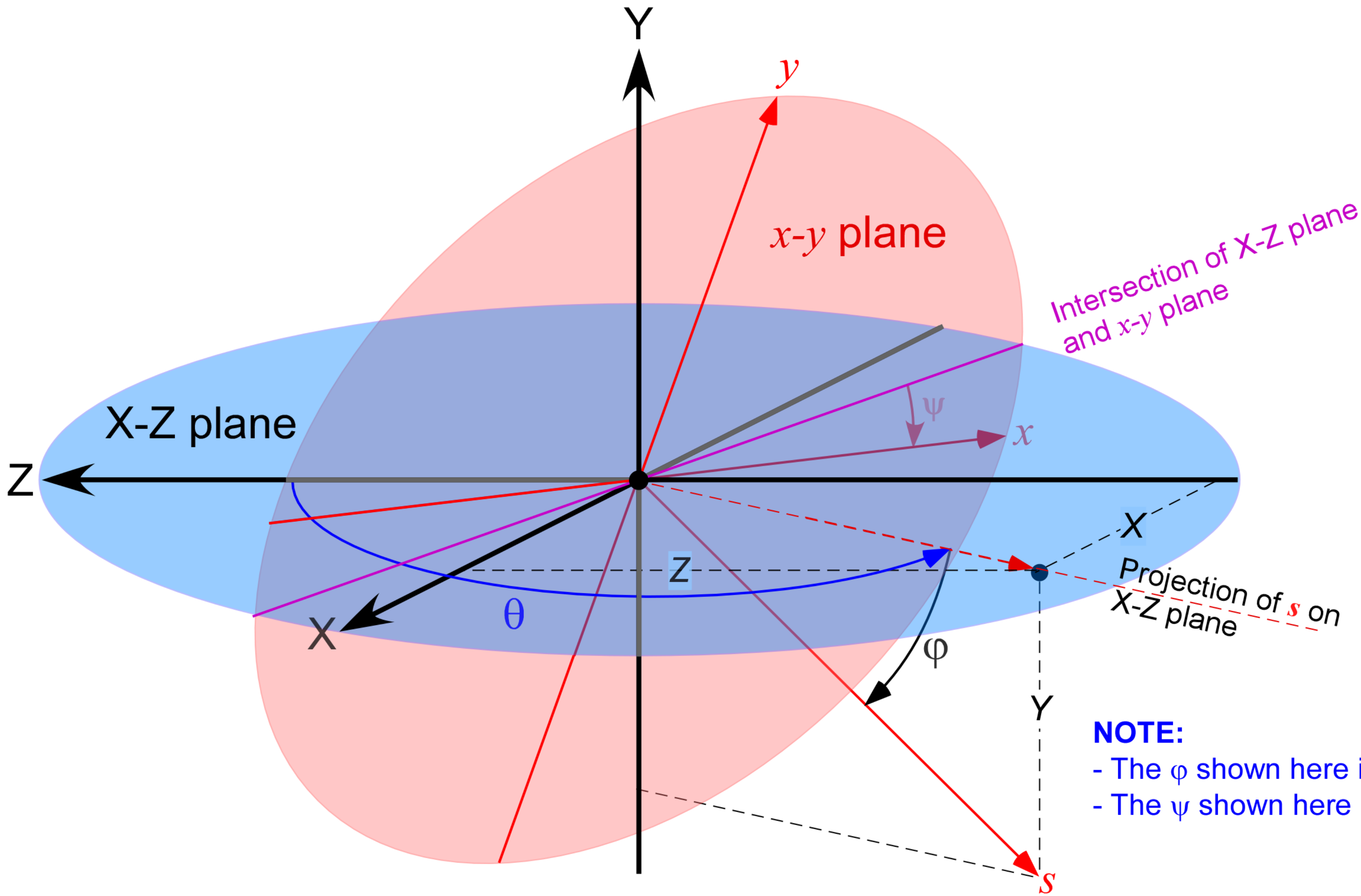
MAD Global Coordinates

MAD Coordinates:

- Axis directions are those of the DUSAF (FSCS:XYZ) system except:
  - X is site North (not East)
  - Y is Up (not North)
  - Z is site East (not Up)
- Gives a system where Y is up (as in most accelerator coordinate systems) and X,Y,Z is right handed.



MAD Global and Local Coordinates



NOTE:
- The φ shown here is negative
- The ψ shown here is negative