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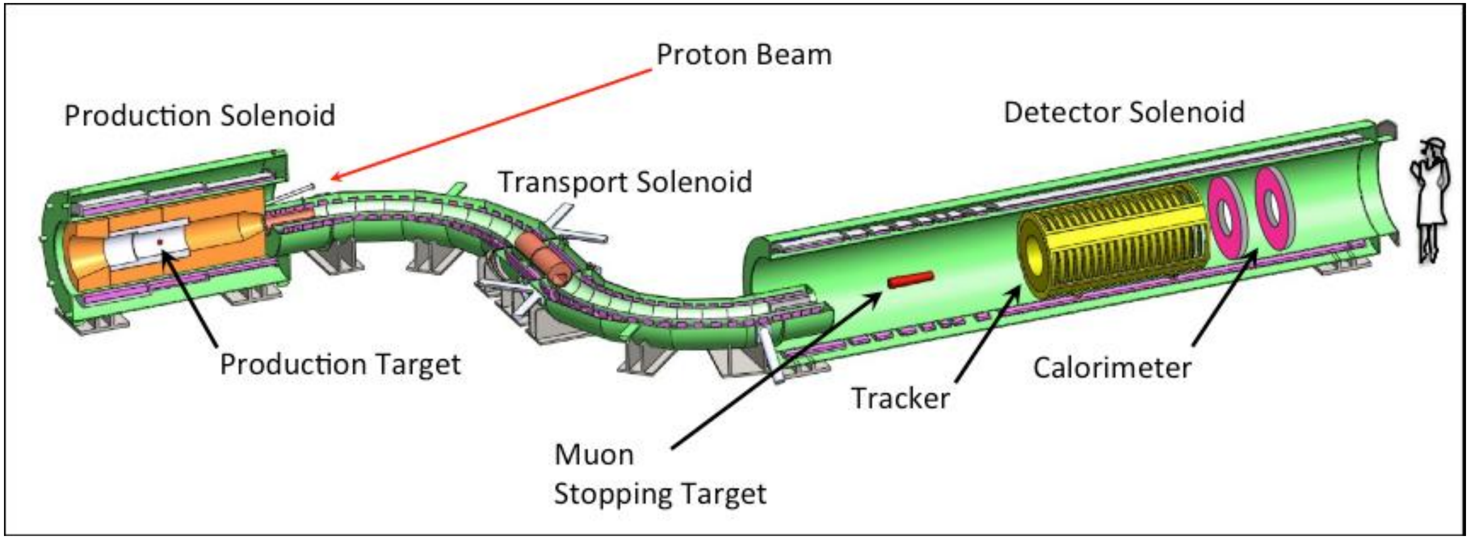
Slow Extraction for the Mu2e Experiment at Fermilab

Vladimir Nagaslaev, FNAL

Slow Extraction Workshop, Darmstadt

1 June, 2016

The Mu2e Experiment

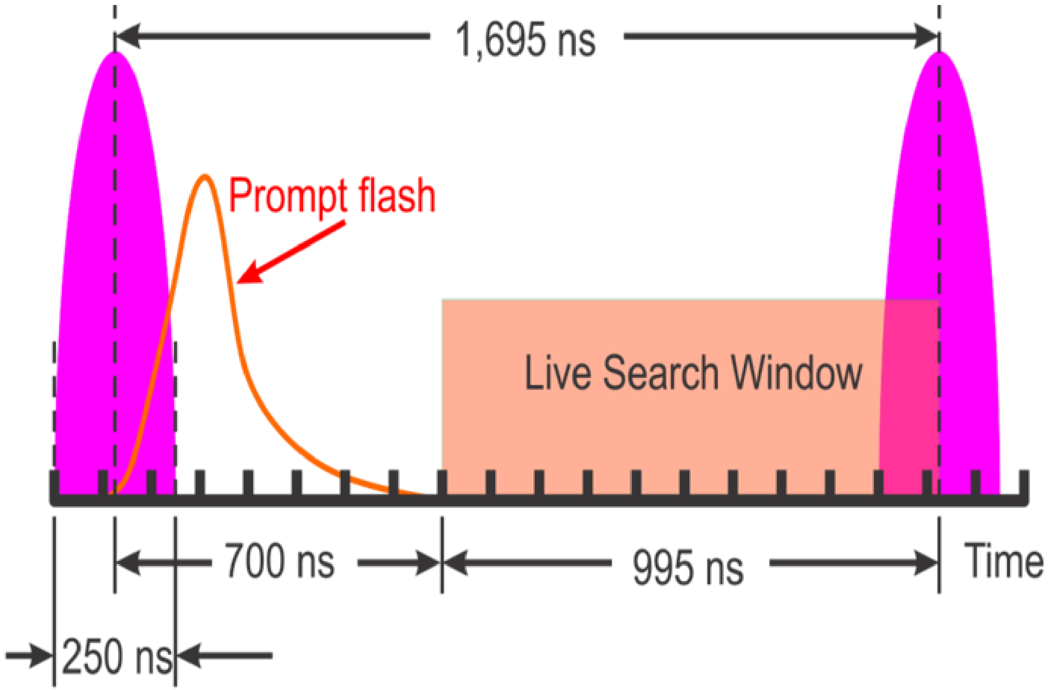


$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)},$$ SES ~ 3e-17 *New physics if >0*

Mu2e proposes to measure the ratio of the rate of the neutrinoless, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus:

Mu2e TDR, arXiv:1501.05241

Beam Structure Requirements



Pulsed beam

Detector dead time - 700ns

Detector Live time - 995ns

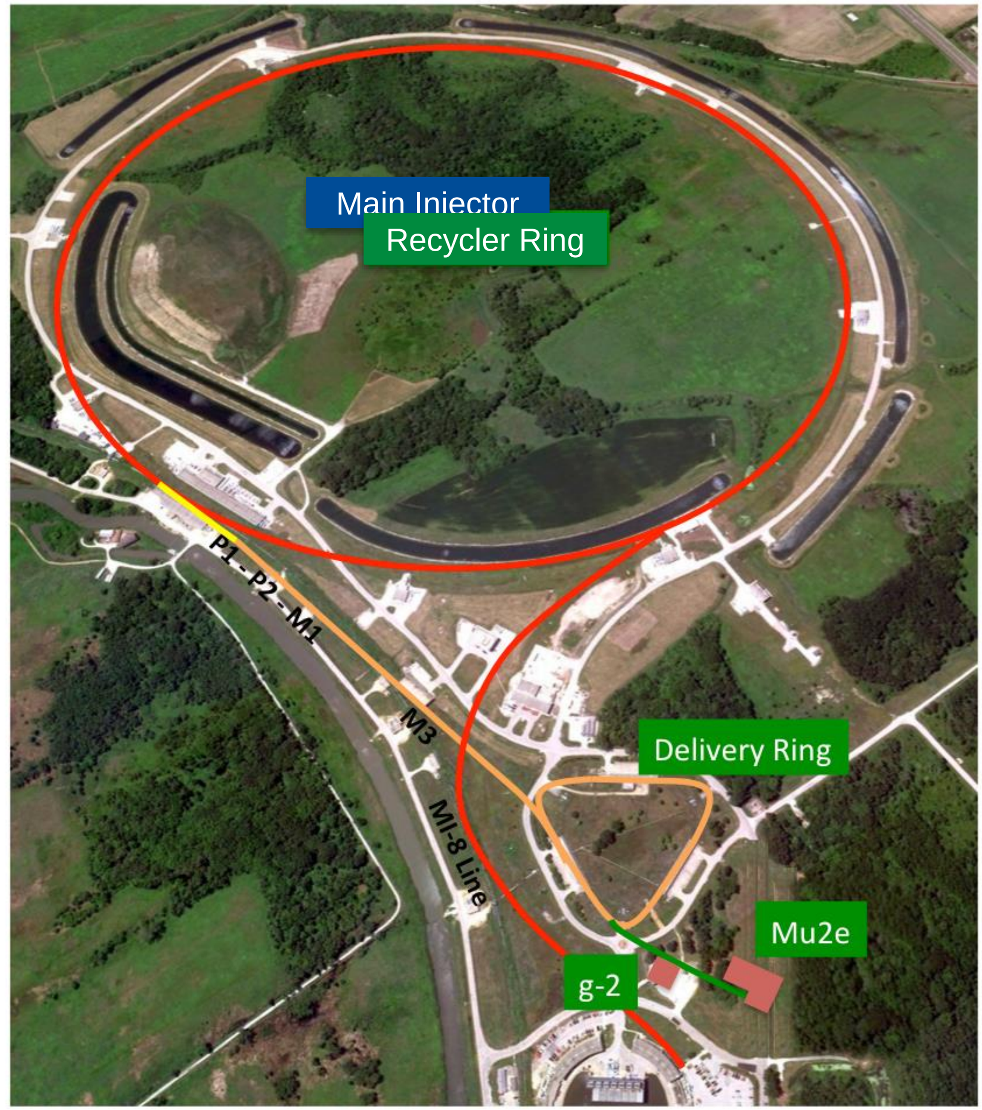
Extinction level - $< 10^{-10}$ relative to the pulse intensity

Beam Delivery

- Enhancement of the FNAL Accelerator complex, 500kW
- Repurposing the FNAL Anti-Proton source as the Muon Campus
- **Mu2e upgrades**
  - Recycler RF
  - Transport to DR
  - Delivery Ring RF
  - Resonant Extraction
  - External Beam line
  - Extinction System
  - Extinction Monitoring
  - Target Station

Going live in FY2021

Production starts this year



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Beam Parameters

Parameter	Value
Main Injector (MI) Cycle time	1.333 sec
Number of spills per MI cycle	8
Number of protons per micro-pulse	3.9×10^{7} protons
Maximum DR Beam Intensity	1.0×10^{12} protons
Beam-On Duty Factor	28 %
Duration of each spill	43 msec
Reset time gap between spills	5 msec
Spill rate variations	±50 %
Extraction efficiency	>98 %

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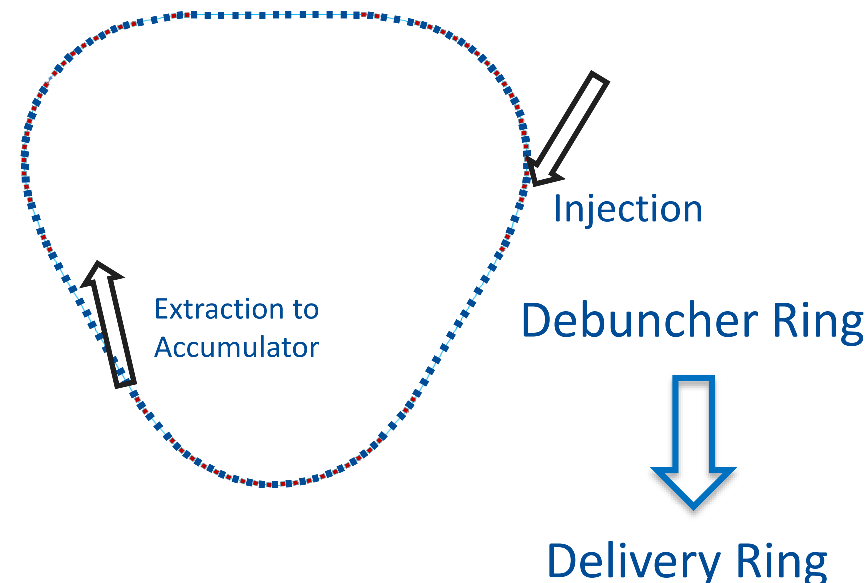
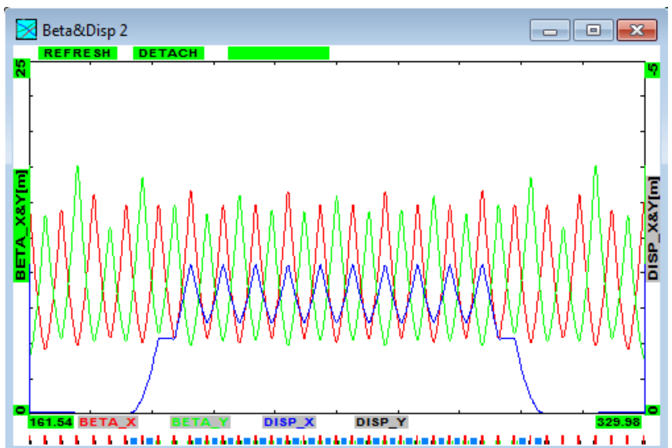
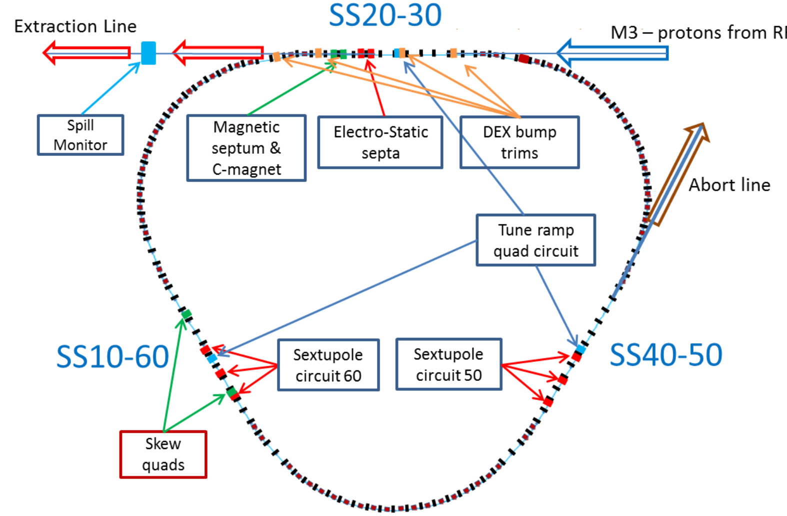
Legacy Debuncher Ring

Parameter	Value	New Value
Circumference	505m	
# of FODO cells	57	
Max beta	15m	
Operating point	9.763/ 9.769	9.650/ 9.735
Max Intensity	3e8 $\overline{p}$	1e12 p
Acceptance (unnorm.)	36 $\pi\mu$	





Lattice functions in 1/3 of the Debuncher
(original design)



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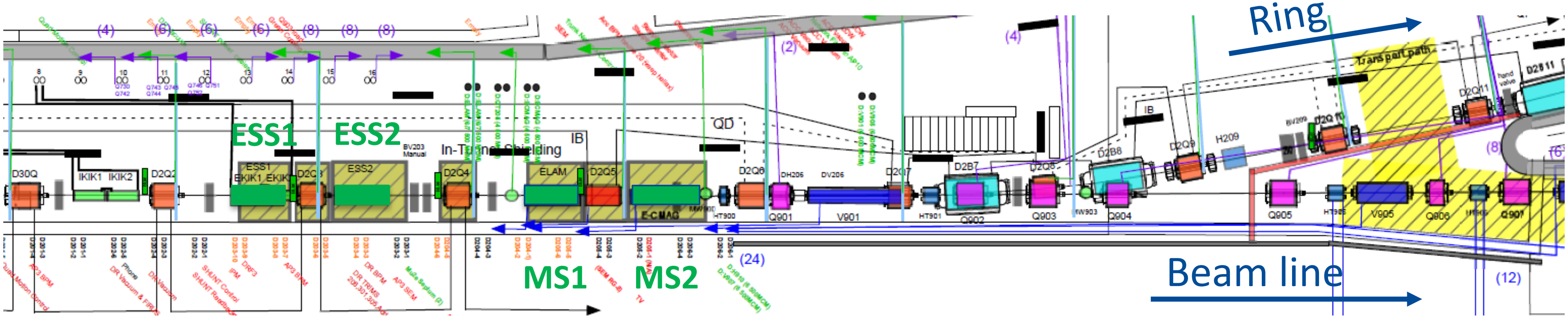
Specifics of the Delivery Ring

Delivery Ring legacy design features:

1. Strong focusing, space constraints
2. Max beta = 15m
3. Machine acceptance = 36 π-mm-mr
4. Light enclosure shielding
5. Vacuum > 1e-8 Torr



Tunnel works in progress

AP30 SS in Collider Run

AP30 SS in June 2015

Scheduled to resume operations in 2017 for g-2 experiment

AP30 SS in June 2016

Performance Calculation

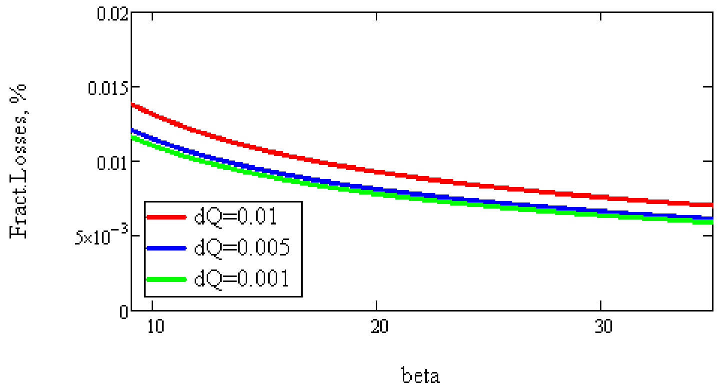
Semi-analytical extension of the perturbation model:

V.Nagaslaev, L.Michelotti: FERMILAB-FN-0974-AD-APC-CD

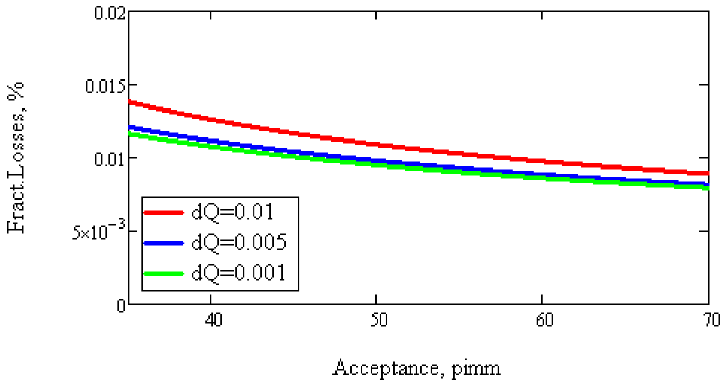
$$\mathrm{inEff}(Xs, Xa, X_0, w) := \frac{\ln\left[\frac{(Xs + w - X_0)\cdot(Xs + X_0)}{(Xs + w + X_0)\cdot(Xs - X_0)}\right]}{\ln\left[\frac{(Xa - X_0)\cdot(Xs + X_0)}{(Xa + X_0)\cdot(Xs - X_0)}\right]} \quad \Rightarrow \quad R_L = \frac{d_w}{X_S^2 - X_0^2}\,\frac{2X_0}{\ln\left(\frac{X_{\max} - X_0}{X_{\max} + X_0}\,\frac{X_S + X_0}{X_S - X_0}\right)}$$

$\Downarrow$

Septum plane position is constrained $\Rightarrow$ $R_L = R(t, \beta, \varepsilon, Ap)$



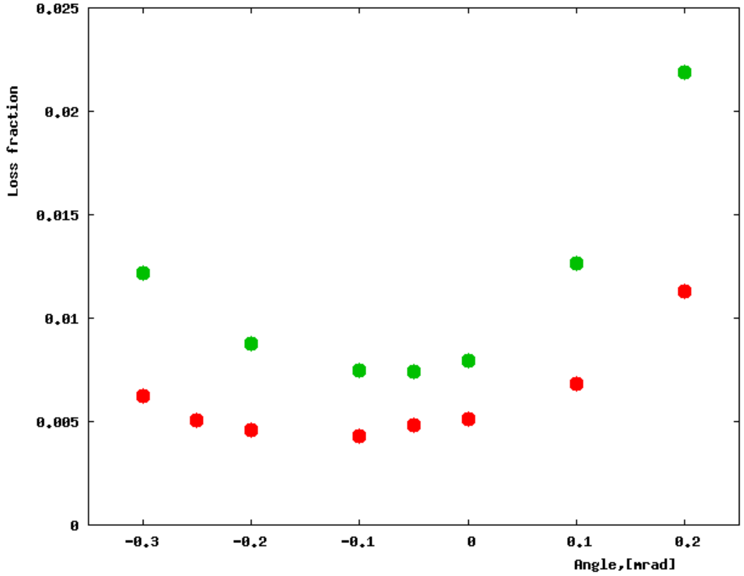
Geometrical losses vs beta-function at ESS



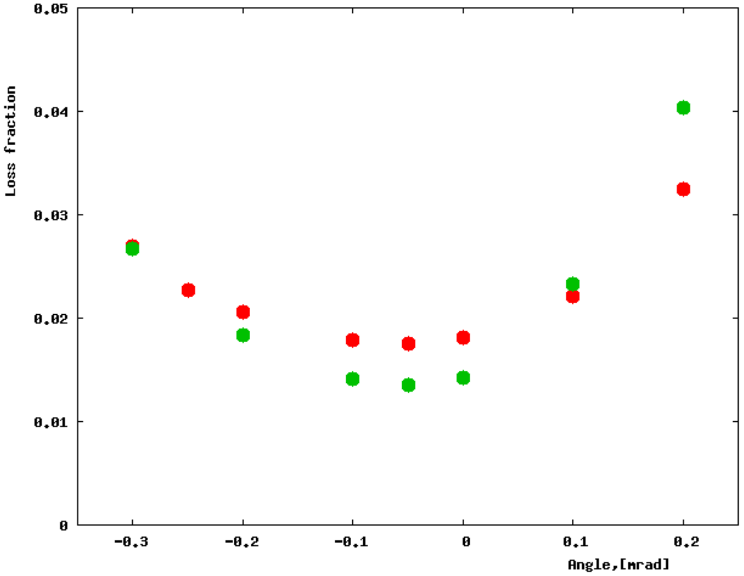
Geometrical losses vs machine acceptance

MARS Simulations and Geometry Choices

Local losses vs beam angle.



Total losses vs beam angle.



Red- 100μ wires; Green- 50μ foils

Note different scale!

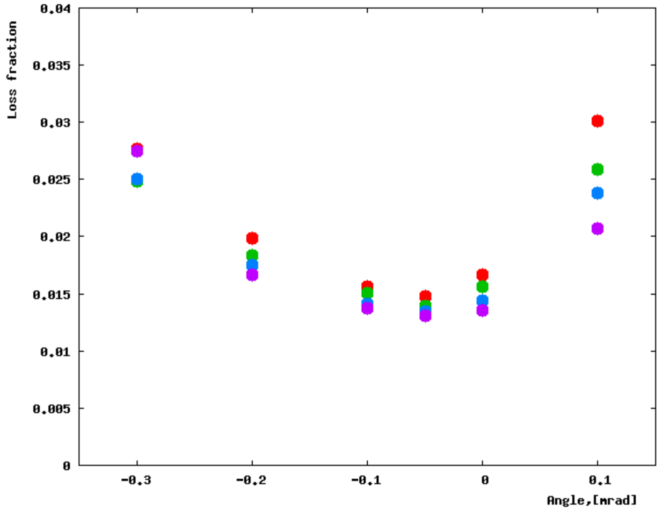
The choice between wires or foils is not trivial. Our choice for foils is made based on previous experience with SE in Main Injector at FNAL.

MARS Simulations and Geometry Choices

Septa lengths:

- ✓ Losses are most significant in ESS1
- ✓ Losses grow with ESS1 length due to the beam angle spread
- ✓ Performance can be improved by making L1 < L2

MARS:
Total losses vs beam angle.

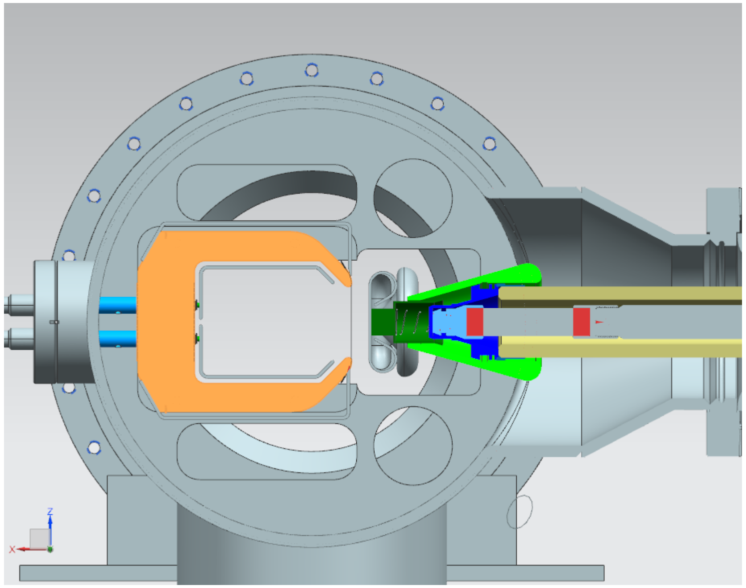


ESS1/ESS2 length ratio:
Purple-0.5m/2.5m; Blue-0.7m/2.3m; Green-1m/2m; Red-1.5m/1.5m

Practical choice: L1=1.25m (+0.5m diffuser) and L2=1.75m leads to equal total vessel lengths. This makes design of two septa fully interchangeable.

Electrostatic Septum

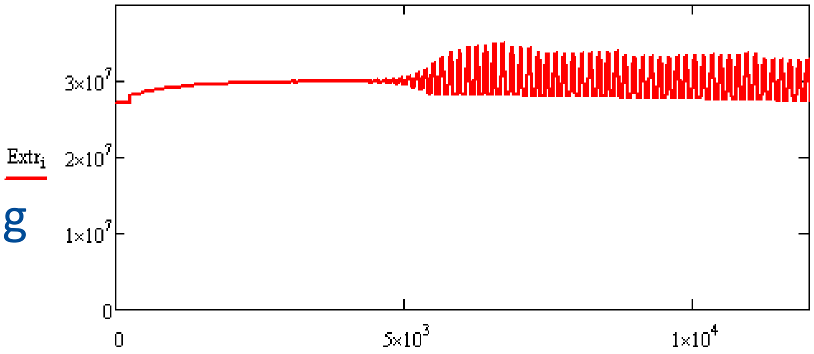
- Asymmetric/Symmetric
- Frame (yoke) not movable
- Foils
  - W25Re, 25u X 1mm
  - Spacing 2.5mm
  - Tension + Retraction > 1 kg
  - Foils coupling
- Retraction concept
  - Single spring
  - Retraction time ~2ms
- Diffuser
  - Ti (grade 2) foils

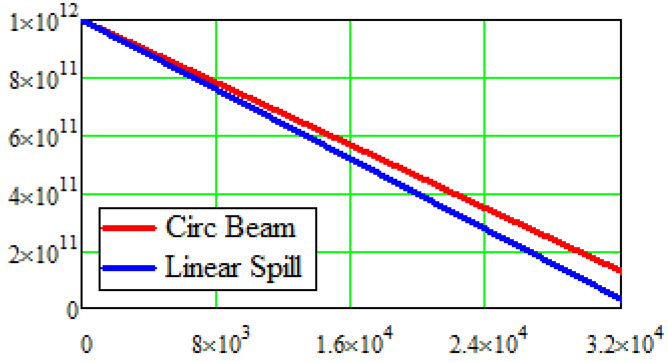


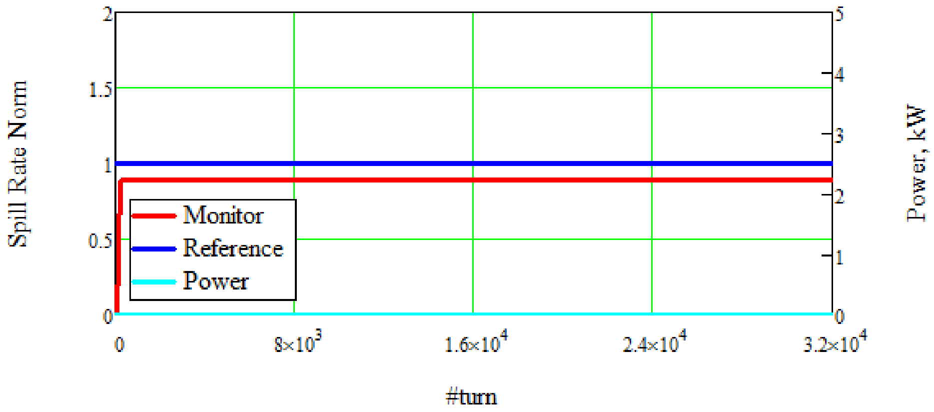
RF Knock Out

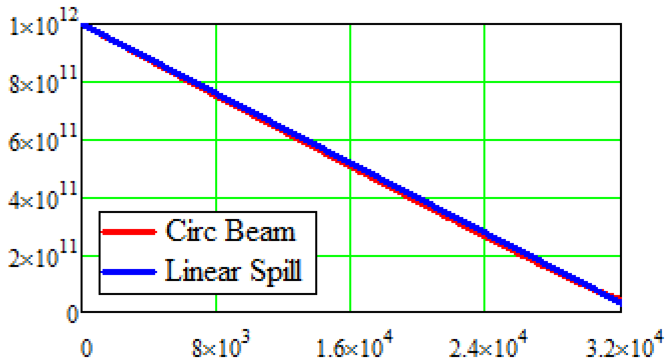
RFKO Emittance Growth Rate simulations (*FERMILAB-CONF-11-475-AD*):

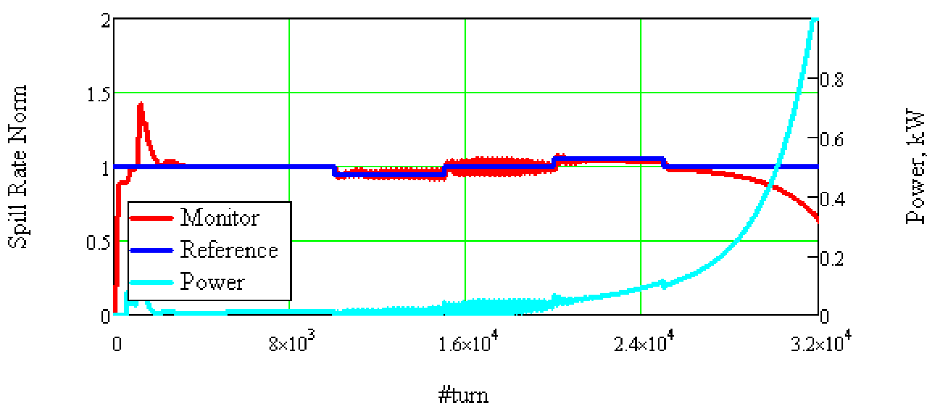
1. Growth rate: $$\frac{d\varepsilon_{95}}{dt} = k\frac{\theta_0{}^2\beta_x}{2\Delta f}\cdot f_0{}^2\cdot F(f,\Delta f,\Delta Q),\qquad k\approx 1$$
2. Works only for chromatic beam tune spread (not SC)
3. High tune spread also leads to the extracted beam angle spread, which affects extraction efficiency
4. In our case the trade-off is at C_X=1
5. Difficult to model regulation with tracking codes
6. Tried to use semi-analytical tracking

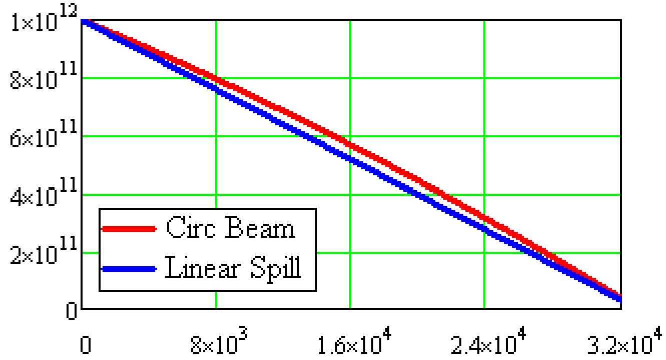



1×10^12
8×10^11
6×10^11
4×10^11
2×10^11
0
Circ Beam
Linear Spill
0
8×10^3
1.6×10^4
2.4×10^4
3.2×10^4


Spill Rate Norm
Power, kW
Monitor
Reference
Power
#turn


Circ Beam
Linear Spill


Spill Rate Norm
Power, kW
Monitor
Reference
Power
#turn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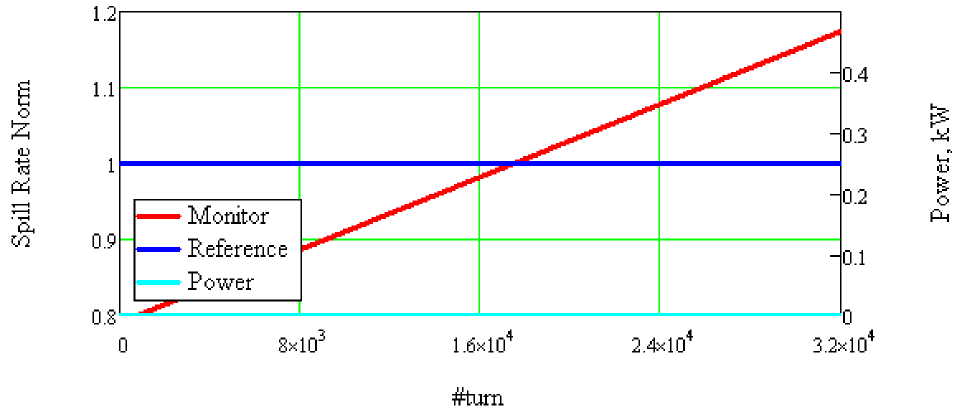
Circ Beam
Linear Spill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1.1
1
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0.8
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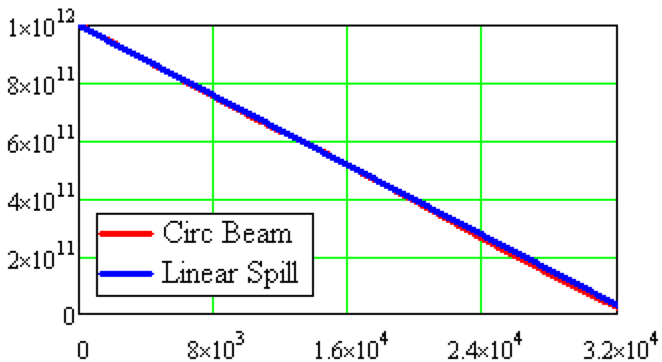
1.6×10^4
2.4×10^4
3.2×10^4
0.4
0.3
0.2
0.1
0
Spill Rate Norm
Power, kW
#turn
Monitor
Reference
Power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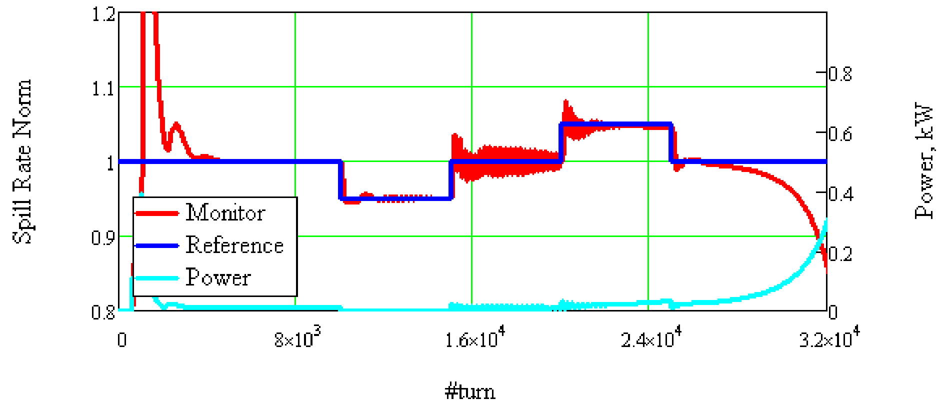
Circ Beam
Linear Spill


1.2
1.1
1
0.9
0.8
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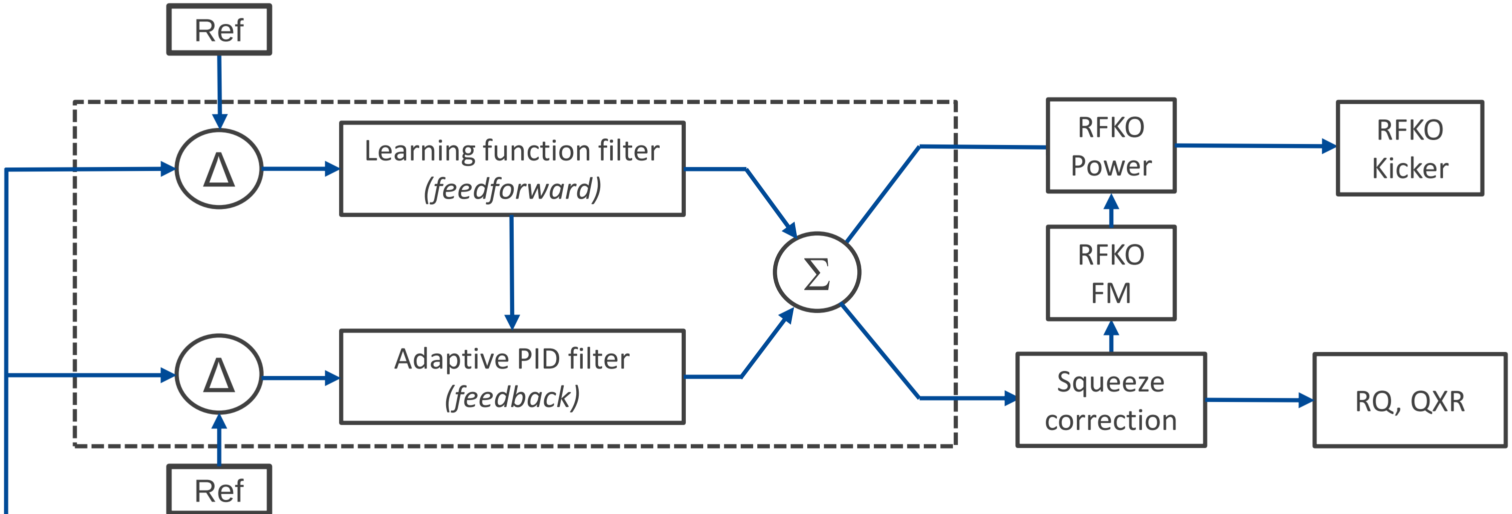
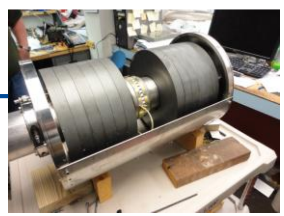
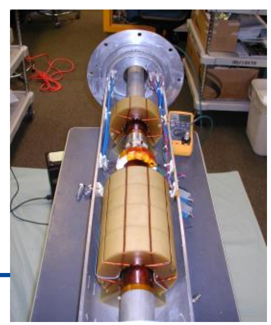
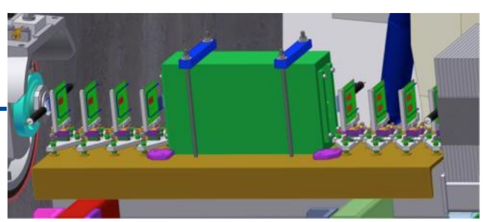
8×10^3
1.6×10^4
2.4×10^4
3.2×10^4
0.8
0.6
0.4
0.2
0
Spill Rate Norm
Power, kW
#turn
Monitor
Reference
Power

Spill Regulation









- Realized in MVME5500 and FPGA
- Slow learning and fast adaptive PID filters
- Regulation to both RFKO and quads
- Possible addition of "bucker" quads
- Important low noise monitoring
- Additional line of monitoring from ExtMon

Summary

1. Slow Extraction for the Mu2e goes live in FY2021
2. Production starts late this year
3. Number of challenging requirements:
   a. High extraction efficiency
   b. Low spill variations
   c. Short spill duration
4. Discussions are greatly appreciated!