Ultra-Slow Muon Transport and Beam Characteristics

Patrick Strasser

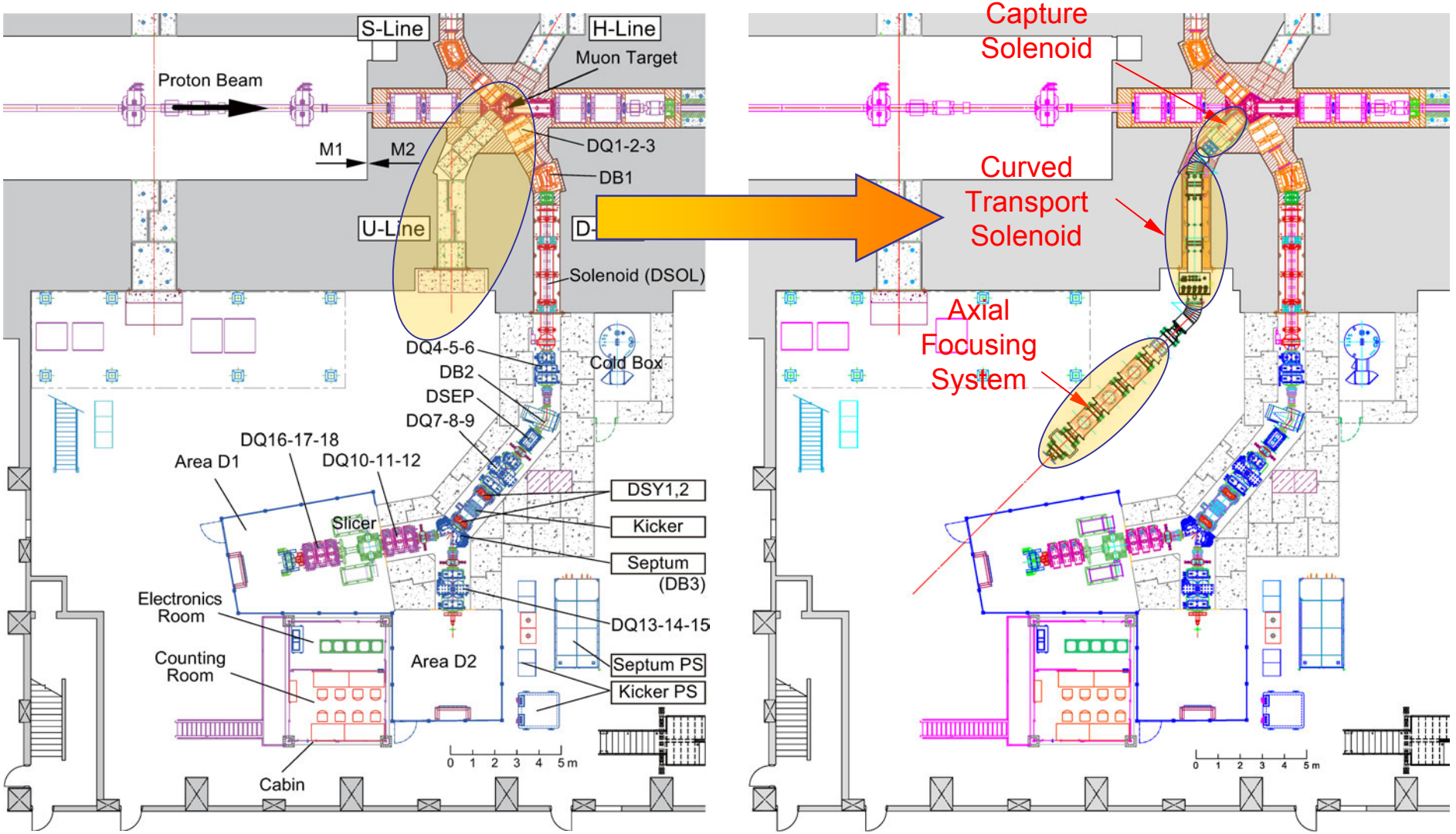
Muon Science Laboratory, KEK
&
Muon Section, Materials and Life Science Division, J-PARC Center

Collaborators: S. Makimura, Y. Ikedo, J. Nakamura, T. Nagatomo, R. Ohkubo, K. Nishiyama, K. Shimomura, A. Koda, N. Kawamura, H. Fujimori, W. Higemoto, R. Kadono, and Y. Miyake.

Contents:

KEK-TRIUMF Workshop on “Ultra-Slow Muons”
TRIUMF, Vancouver, Canada, March 8-9, 2012.

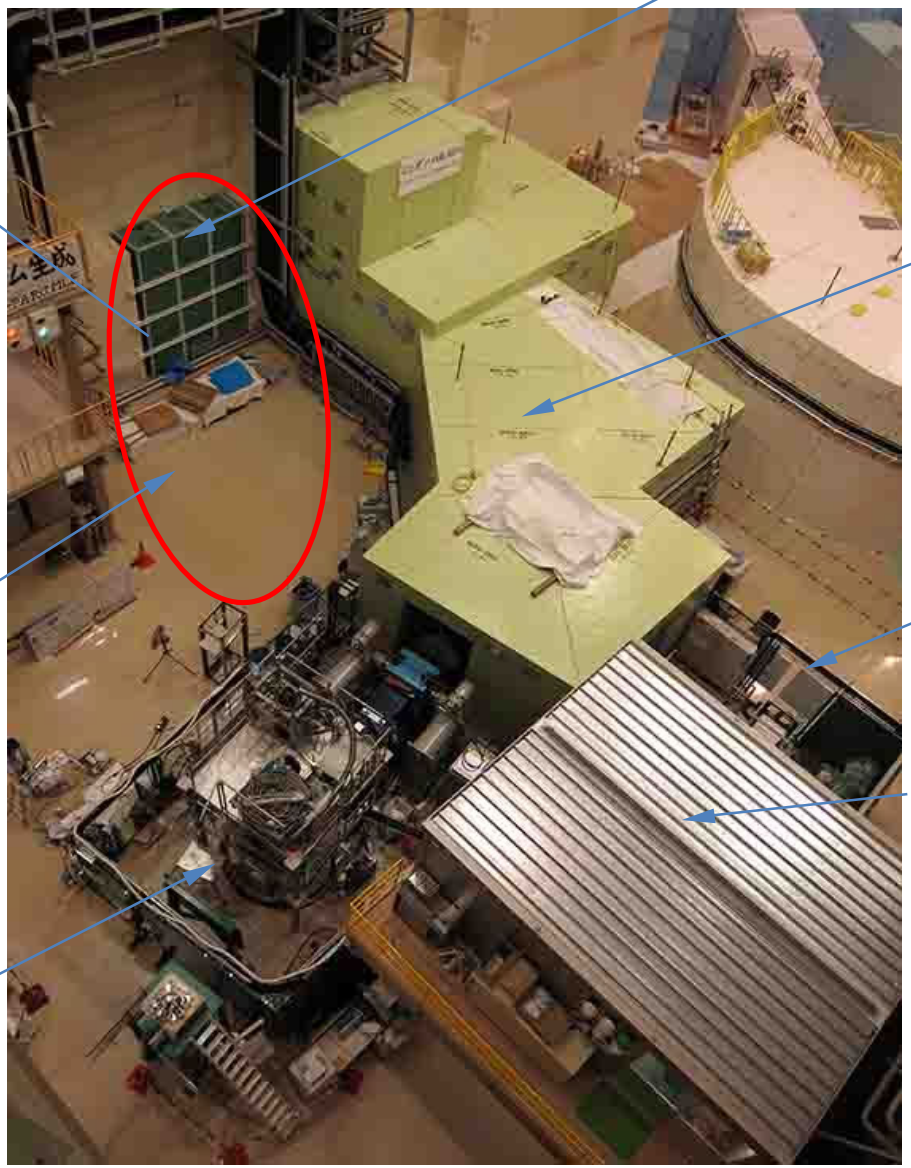
MLF Experimental Hall No.2: U-Line Layout



Experimental Hall No. 2 at MLF

U-Line New Concrete Shield

29 Sep. 2011



U-line Tunnel Exit

D-line

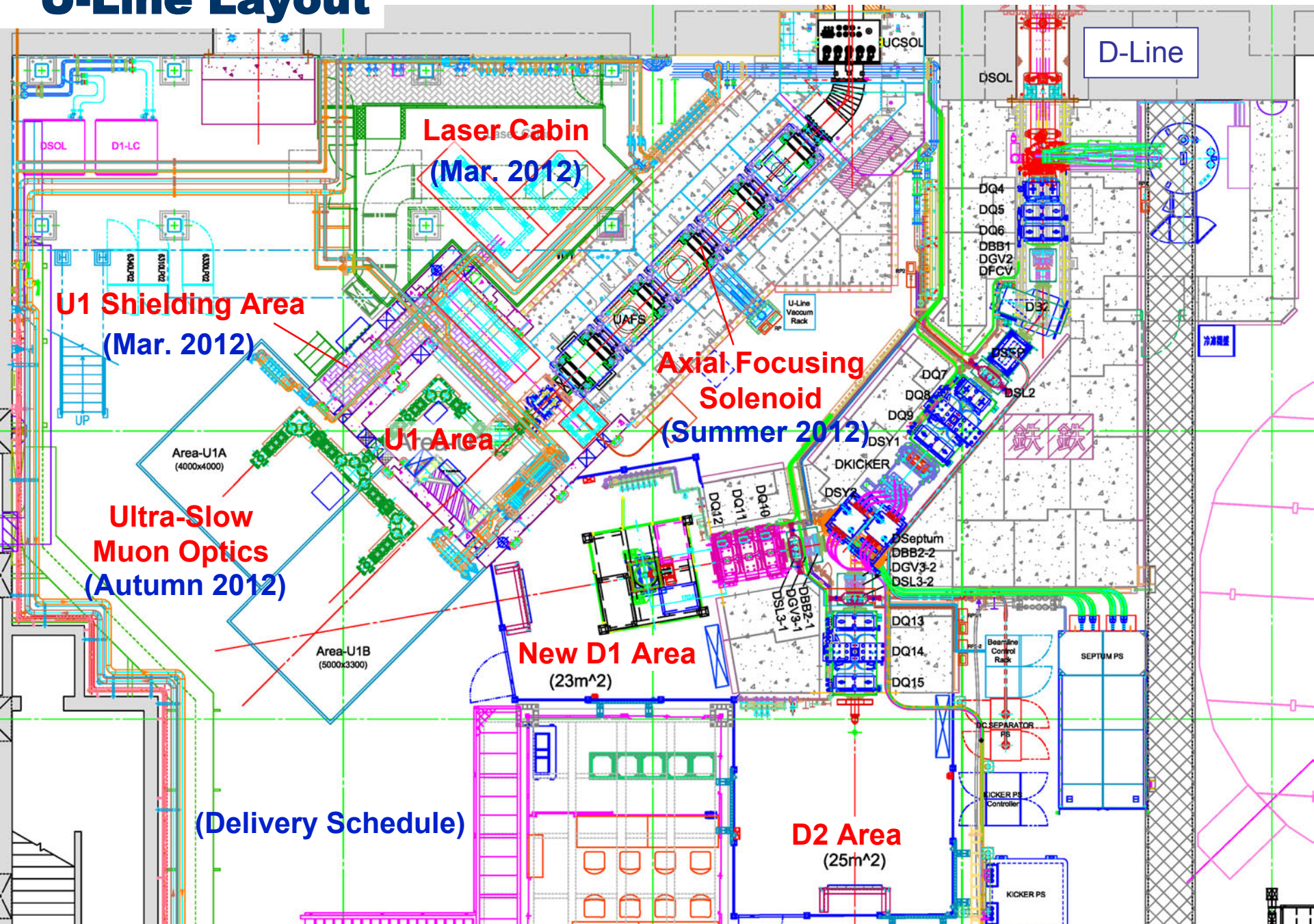
D2 port

Users' Cabin (Control and Counting room)

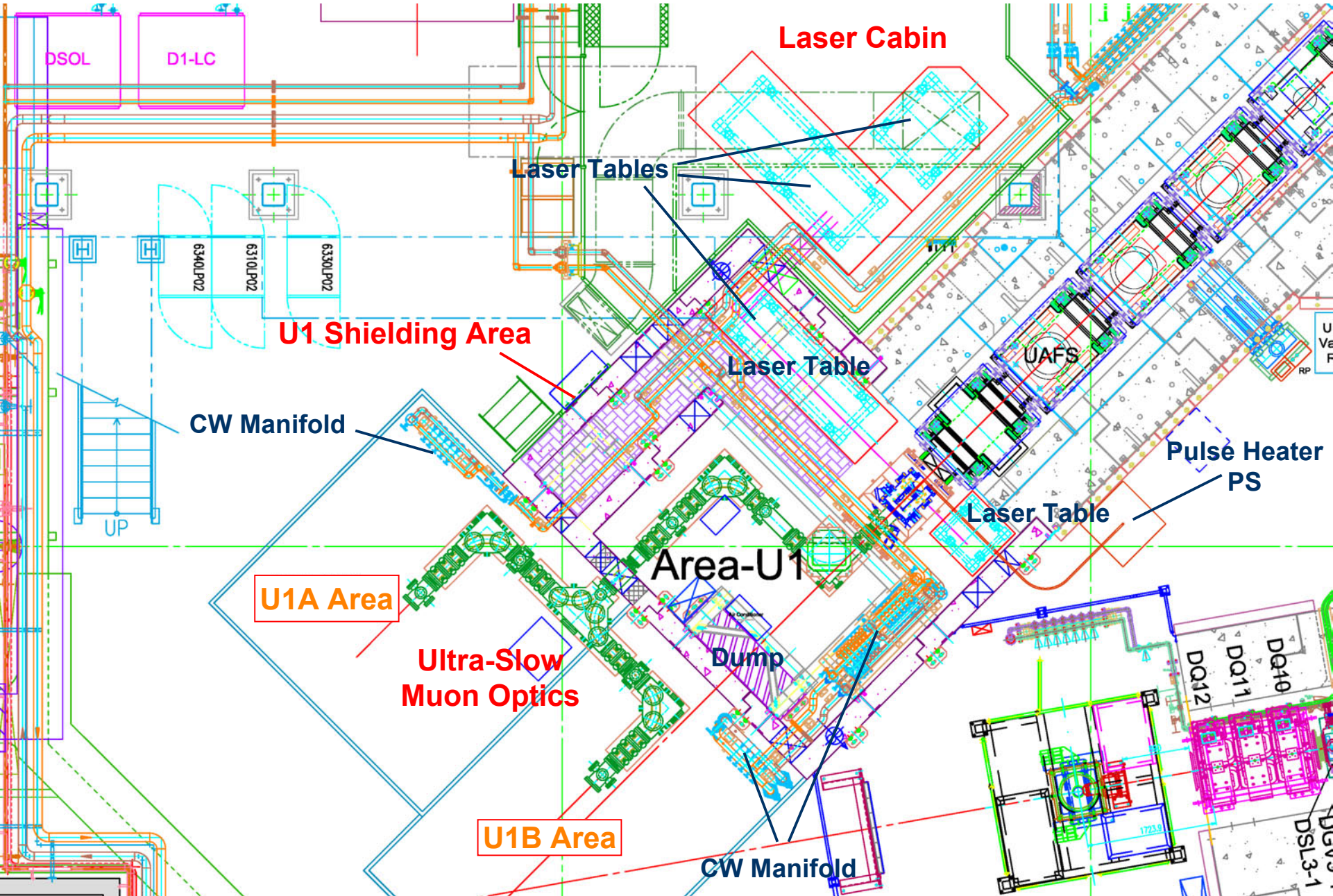
Superomega will soon be installed here.

D1 port

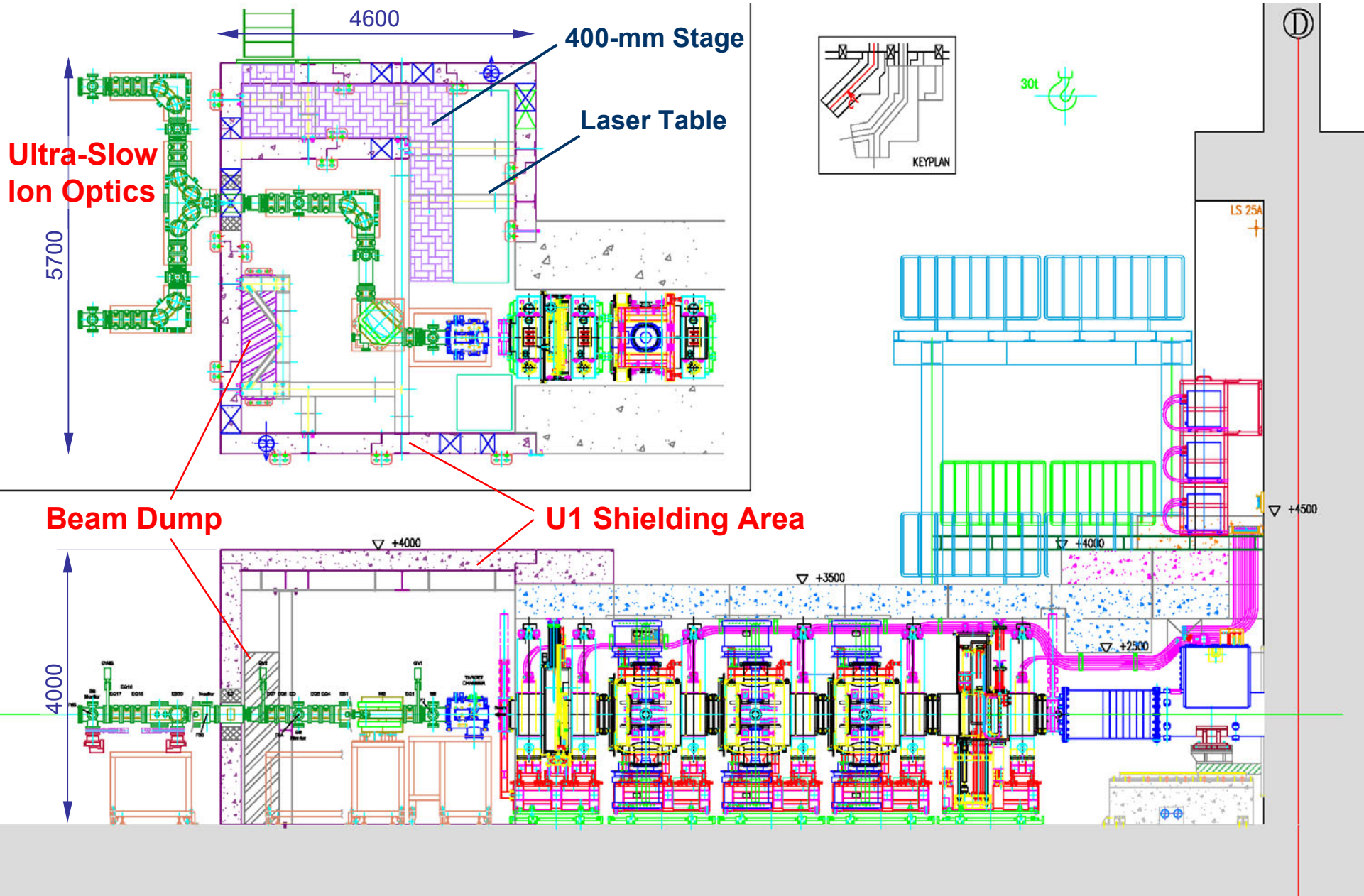
U-Line Layout



U1 Shielding Area Layout (1)

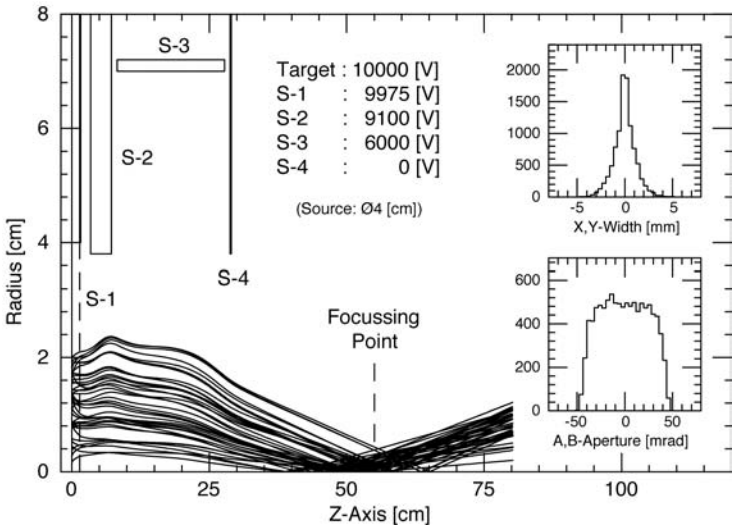


U1 Shielding Area Layout (2)

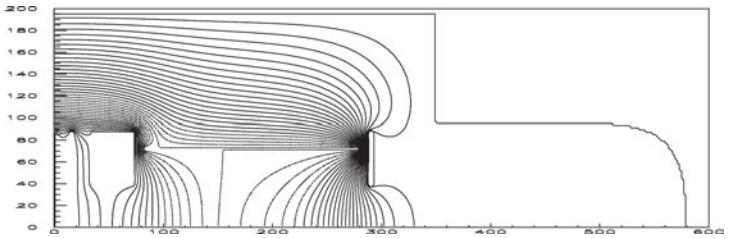


Slow Muon Setup 1999

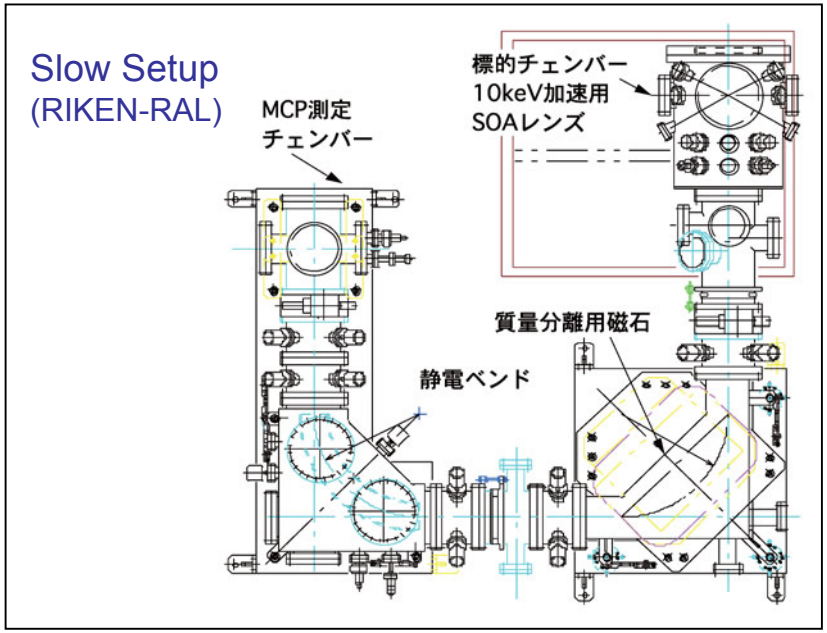
(1) Slow Muon Extraction (SOA Lens)



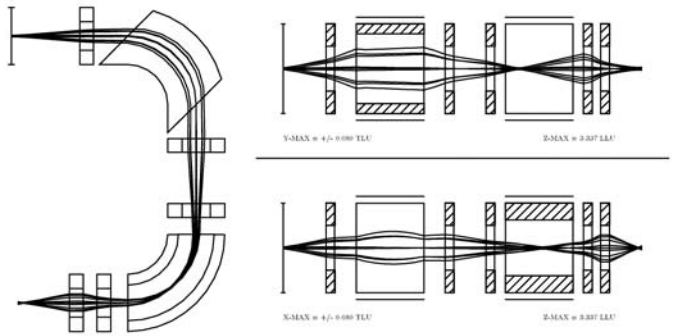
Relax3D Field Calculation

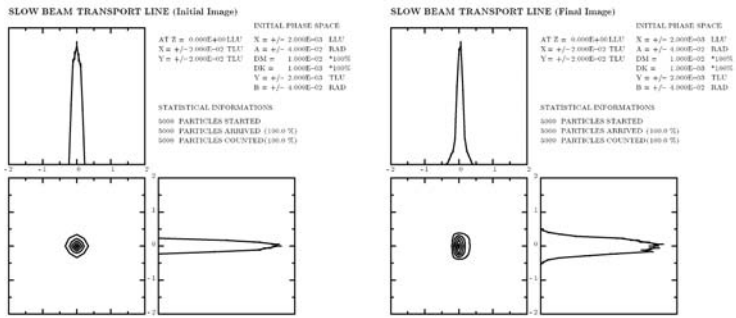


Slow Setup (RIKEN-RAL)



(2) Slow Beam Transport Line (GIOS)





Initial
X,Y = ±2 mm
A,B = ± 40 mrad

New Slow Optics Design Concept (1)

(1) Initial Acceleration and Focusing (SOA Lens)

- 10-30 keV
- Residual field by last Axial Focusing Magnet
- 50% spin polarization ➞ recovery to 100% by longitudinal field

(2) Transport Line

- 100% transmission efficiency
- Point to point focusing (F1→F2→F3), achromatic
- Short beamline ➞ μ^+ decay in flight (10 keV μ^+: velocity of ~ 4m/μs)

(3) Mass Separation

- First bend should be a magnetic bend at 90°!
- Remove e^+, select deuterium for tuning, μ^+ monitoring (F2), …
- 90° bend ➞ μ spin rotation, TF measurement (like at RAL and PSI) !
- Beam dump after magnet
- Good field stability (10 keV μ^+: B=120gauss, R=400mm)

(4) Optics Elements ➞ Electrical components

Transport Code (matrix element)	
• Electric Quadrupole (EQ), cylindrical Electric Bend (EB), …	✓
• Einzel Lens ➞ cylindrical aberration	✗
• Electric Mirror: transmission efficiency, mesh size, field uniformity, …	✗

New Slow Optics Design Concept (2)

(5) Beam Optics with Two Branches

Leading to two Ultra-Slow Muon Experimental Area

(A) Ultra-Slow Muon μSR (at PSI: LE-μSR)

(B) Microbeam μSR ➞ Reacceleration

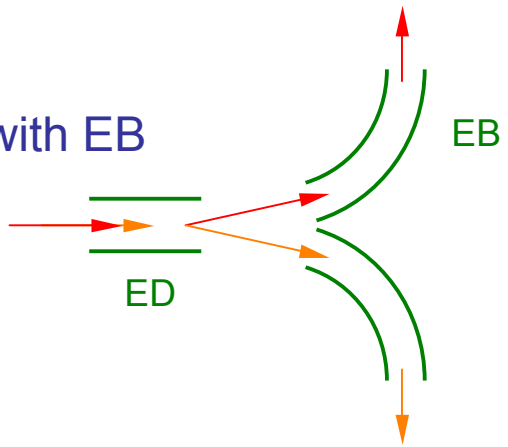
(RFQ: initial beam requirement/characteristics)

(i) Sector magnet

(ii) Electric Septum: Electric Deflector (ED) combined with EB

➞ Need simulation, entrance field mapping, …

➞ Pulsed ED at 12.5 Hz possible



(6) Radiation Shielding

- Beam dump (neutron)
- Concrete Housing around Mu production target (10^8 μ^+/s ➞ 10^8 e^+/s)

→ Extend slow optics outside for Slow Exp. Area (to reduce background)

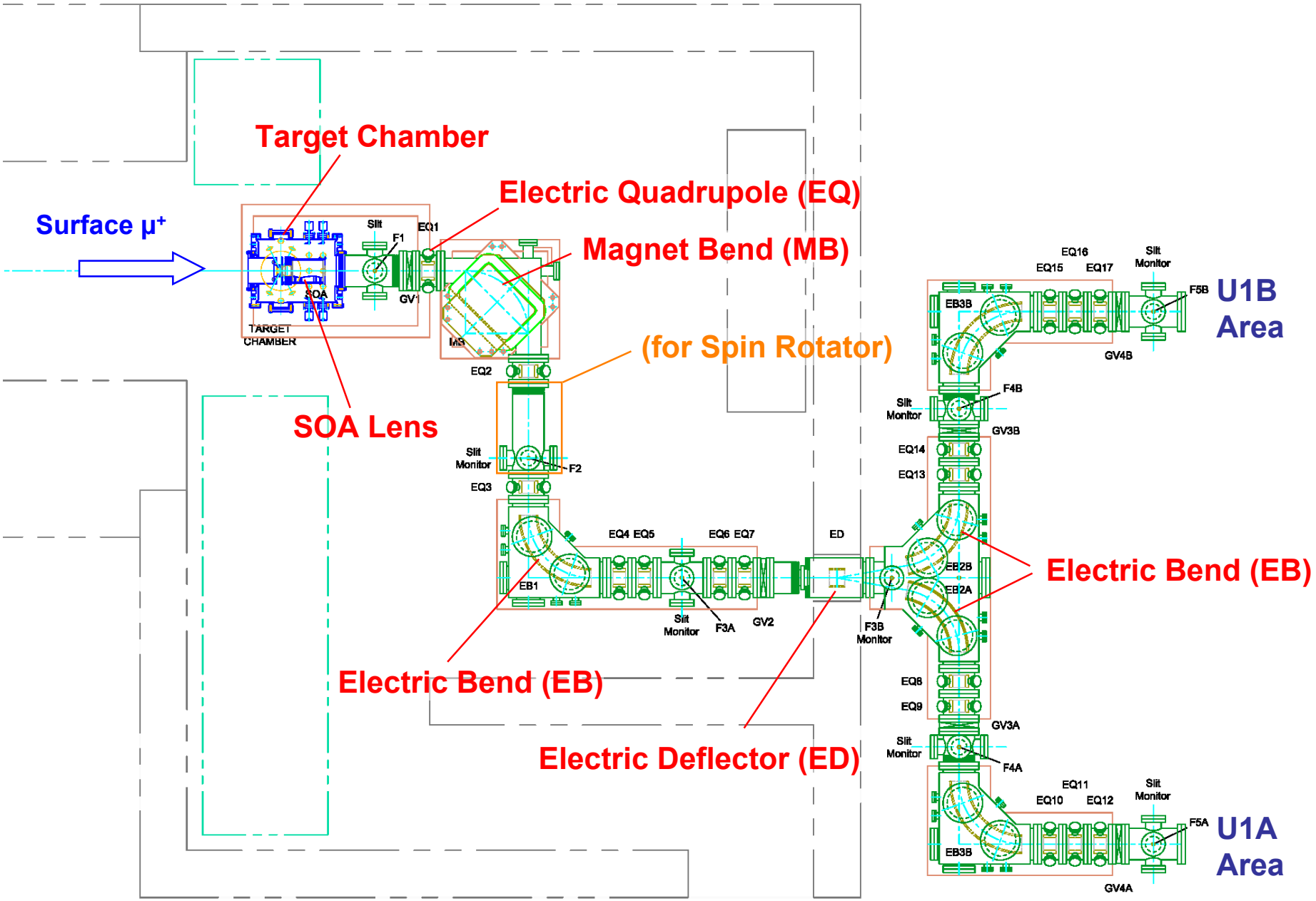
(7) Compact System

- MLF Experimental Hall No.2 space limitation

(8) Flexibility

- Modular: Target, Extraction, Spin rotator, … (for future improvements)
- U-Line extension (μ^+/μ^-) → Slow Setup moved downstream!

Ultra-Slow Muon Beamline Layout



SOA Lens

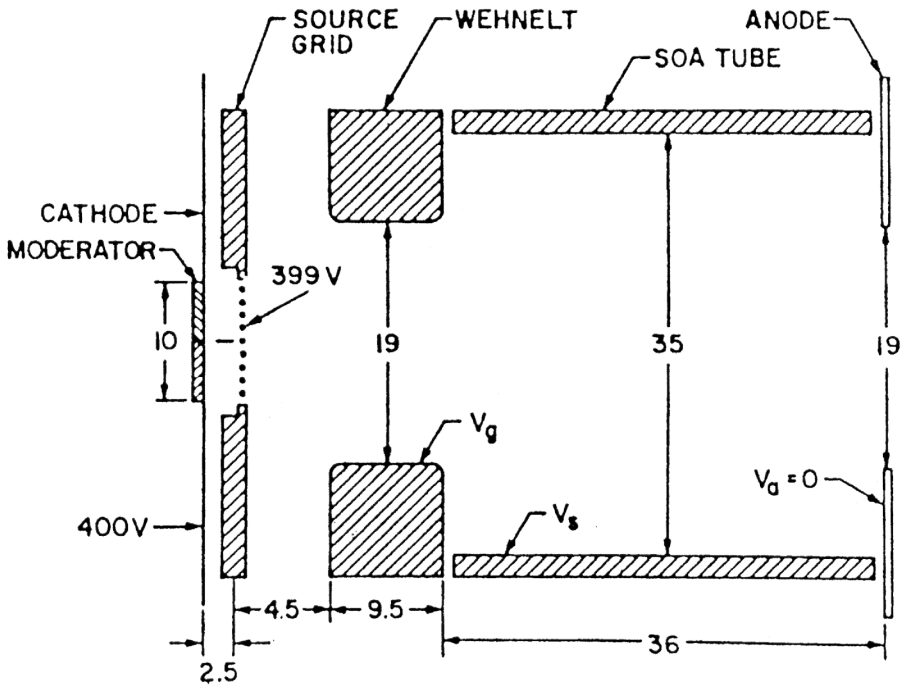


Fig. 1. Modified Soa gun. Dimensions are given in mm. The Wehnelt electrode has 1.5 mmradius rounded edges. A Co-58 source is mounted against the source grid and faces the moderator.

Modified Soa immersion lens positron gun geometry described by. Canter et al.

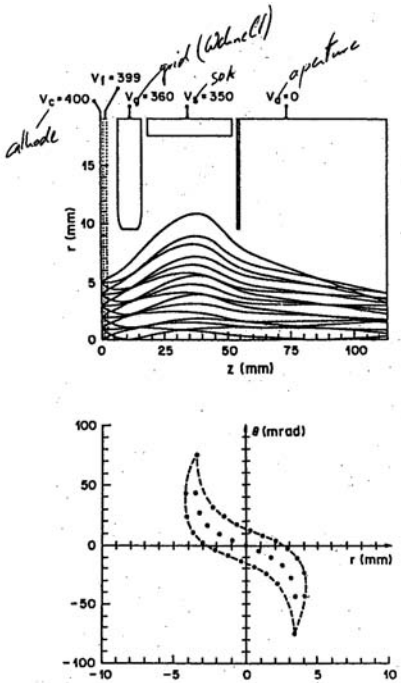


Fig. 2. a) Trajectories and b) Phase space for an electrostatic positron gun.

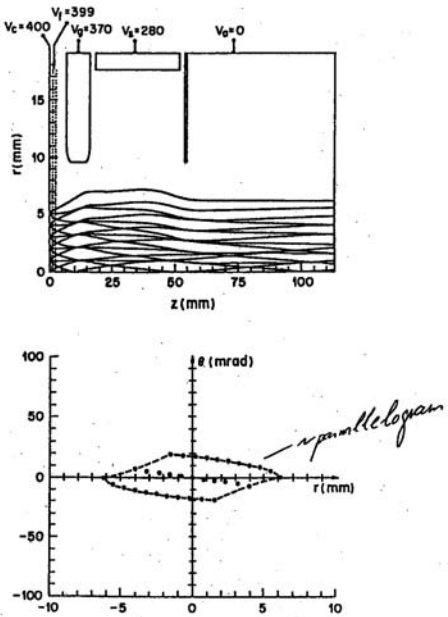
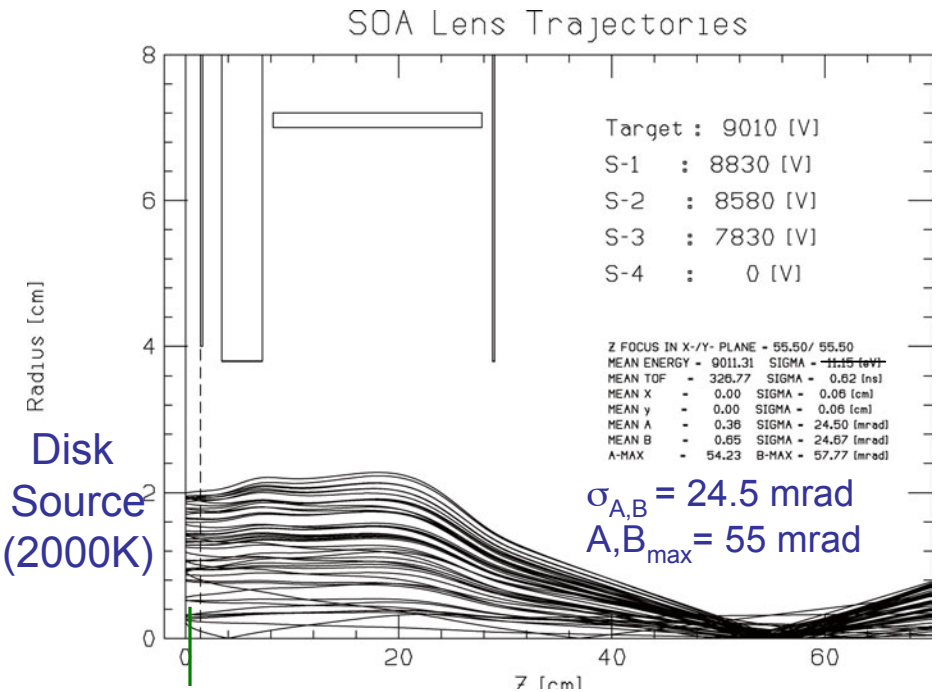


Fig. 3. Plots for a different tuning of the electrostatic gun in Fig. 2.

K. F. Canter, P. H. Lippel, W. S. Crane and A. P. Mills Jr., in "Positron Studies of Solids, Surfaces and Atoms", ed. by A. P. Mills Jr. et al., (World Scisntific 1986), pp. 199-206

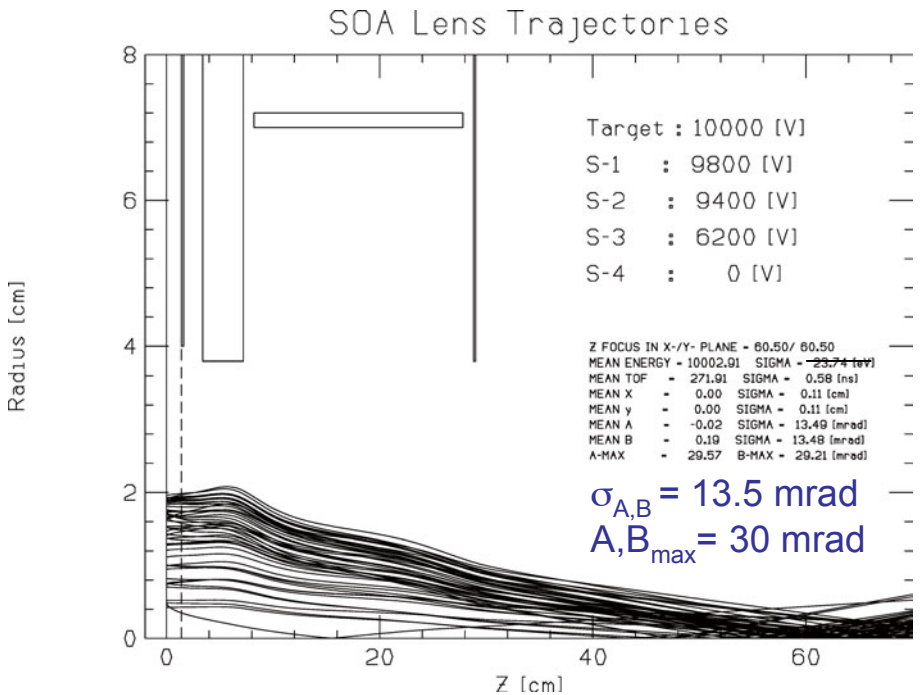
Initial Extraction/Acceleration: SOA Lens



Disk Source (2000K)

$\sigma_{A,B}$ = 24.5 mrad

A,B_{max} = 55 mrad



$\sigma_{A,B}$ = 13.5 mrad

A,B_{max} = 30 mrad

Ionization Volume

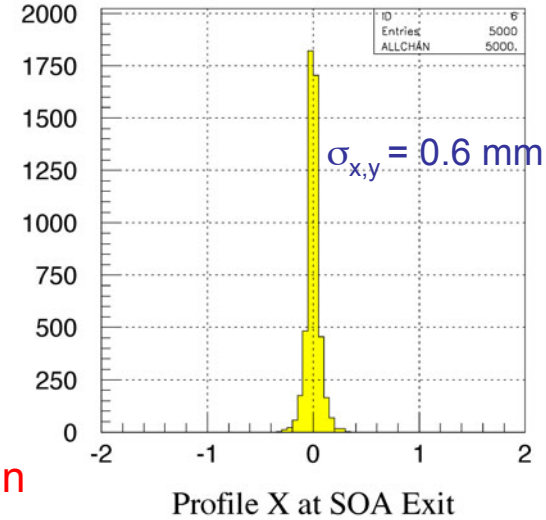
↓

Extraction Bias

↓

Δt vs. ΔE

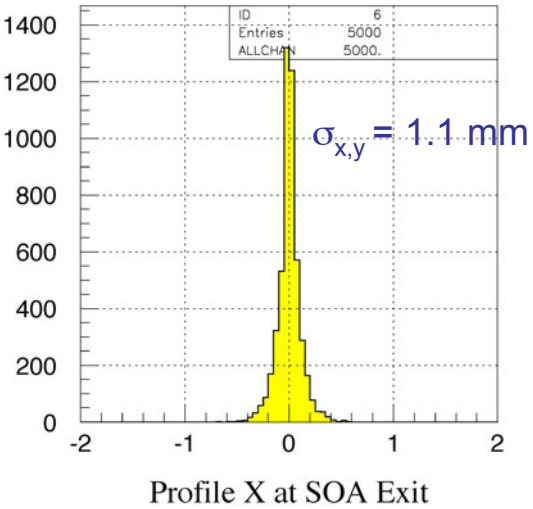
→ Pulsed Extraction



$\sigma_{x,y}$ = 0.6 mm

$\varepsilon(3\sigma) \sim 90$ mm•mrad

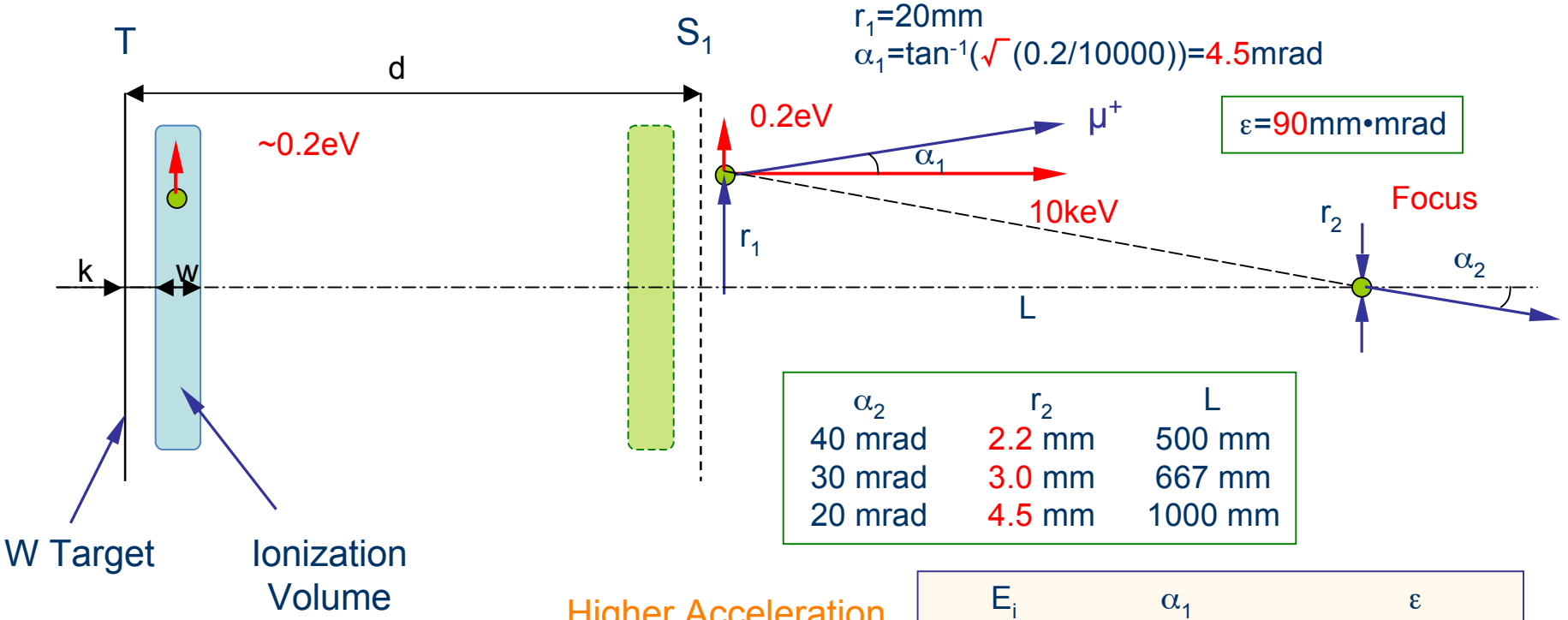
Old Simulation Code:
RELAX3D
+
Monte Carlo



$\sigma_{x,y}$ = 1.1 mm

Initial Acceleration

$$\varepsilon = \frac{p_r}{p_z} = \frac{\sqrt{E_{th}}}{\sqrt{E_i}}$$



ε=90mm•mrad

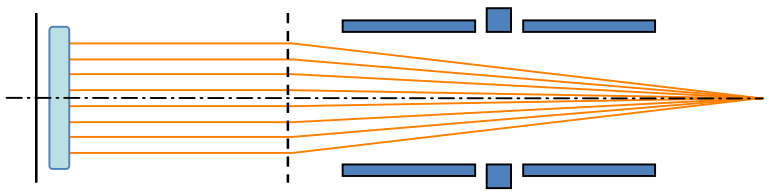
α_2	r_2	L
40 mrad	2.2 mm	500 mm
30 mrad	3.0 mm	667 mm
20 mrad	4.5 mm	1000 mm

Higher Acceleration Voltage

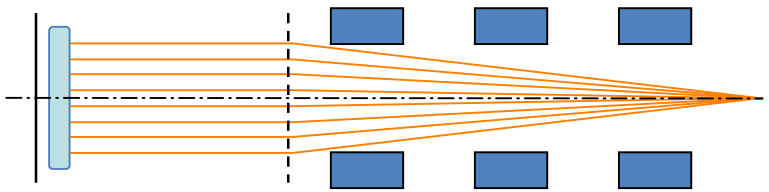
E_i	α_1	ε
10 kV	4.5 mrad	90 mm•mrad
20 kV	3.2 mrad	64 mm•mrad
30 kV	2.6 mrad	52 mm•mrad

Alternative Extraction Schemes:

Einzel Lens

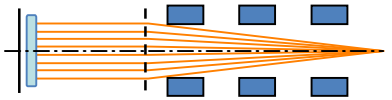


Electric Quadrupole Triplet

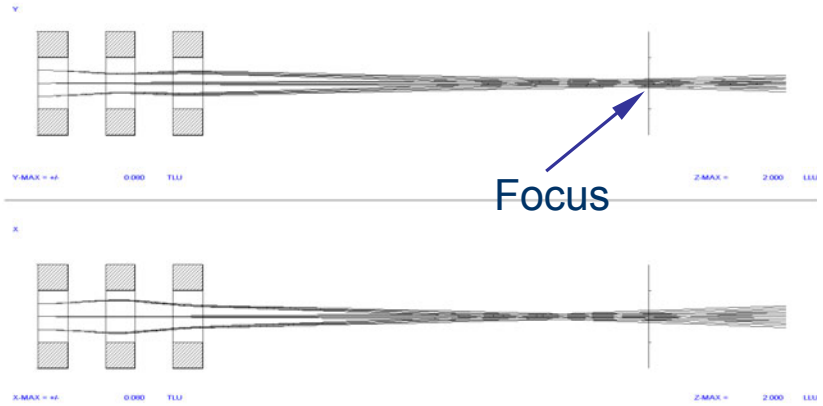


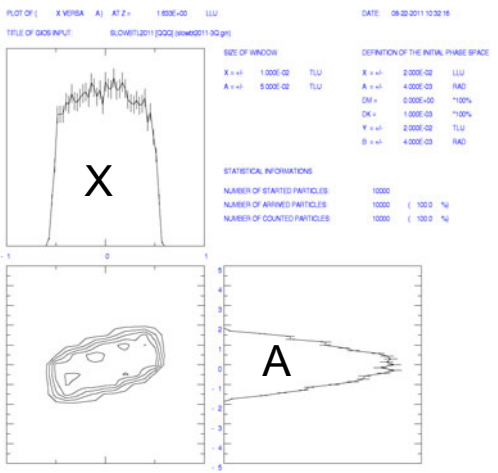
Initial Extraction: EQ Triplet

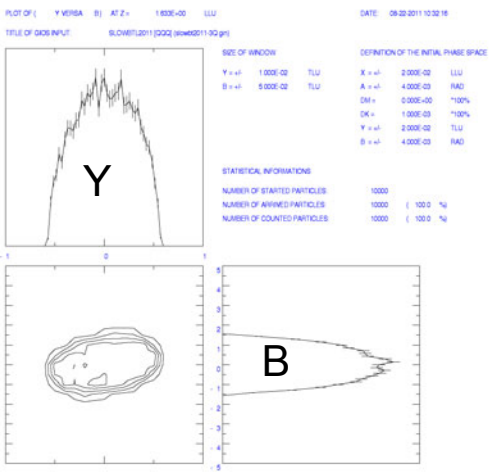
r_1=20mm
α_1=4mrad



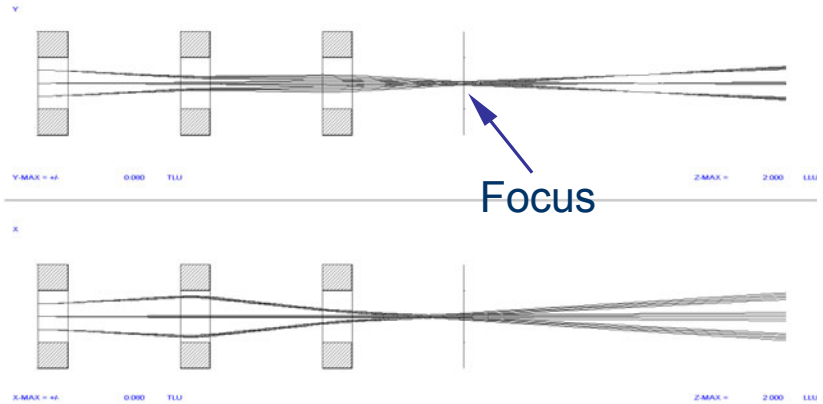
Distance between EQ: 100 mm

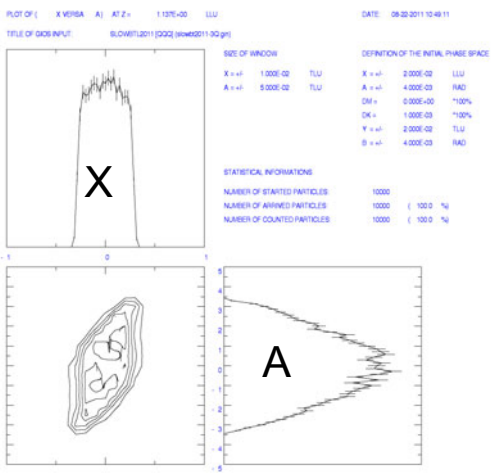


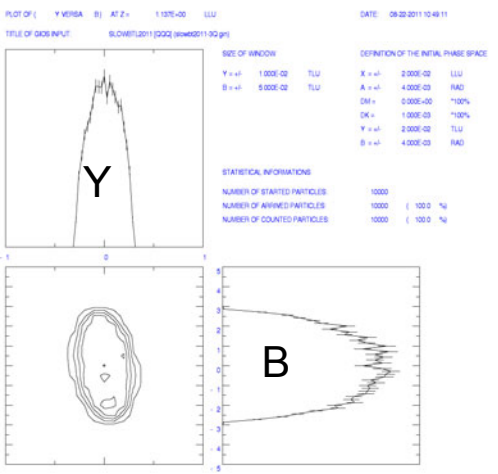




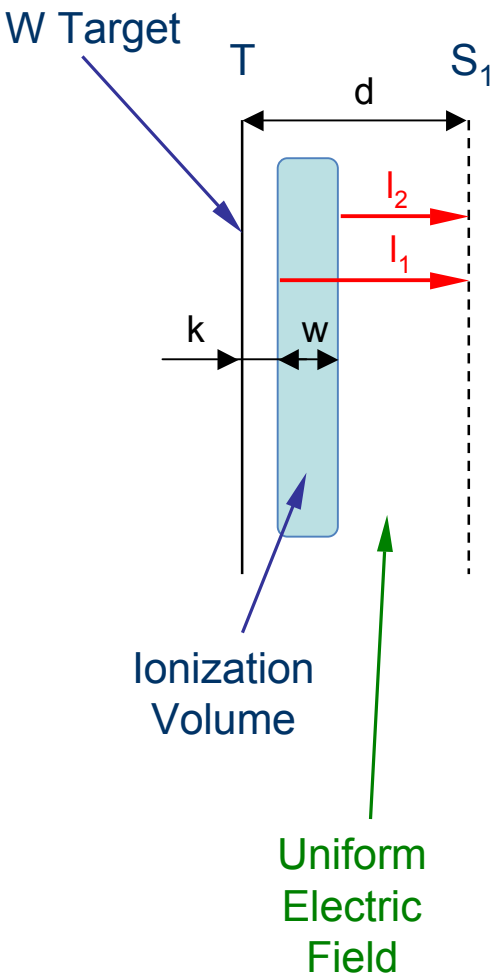
Distance between EQ: 300 mm







Initial Acceleration: Static



$U(T\text{-}S_1)$ =	140 V	140 V	140 V	1400 V
Electrode gap d =	14 mm	14 mm	14 mm	14 mm
Laser width w =	2 mm	1 mm	2 mm	2 mm
Laser distance k =	2 mm	2.5 mm	4 mm	2 mm

Energy Spread:

$dE = Uw/d$

20 V	10 V	20 V	200 V

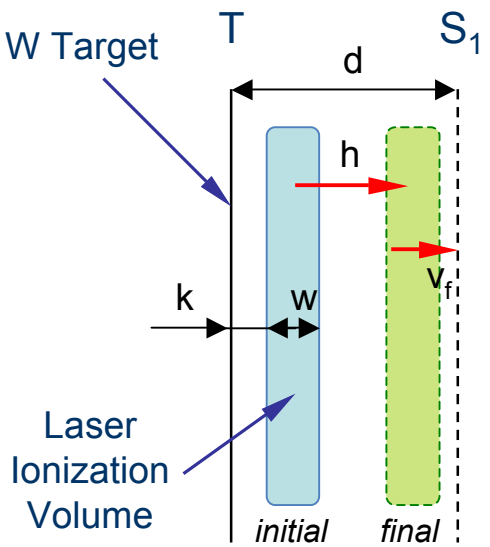
Time Jitter:

$dt = \sqrt{(2/a_o)}\,(\sqrt{I_1} - \sqrt{I_2})$

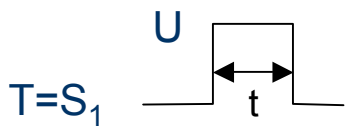
4.6 ns	2.3 ns	5.1 ns	1.5 ns

with $a_o = qU/d/m_\mu$

Initial Acceleration: Pulsed Extraction



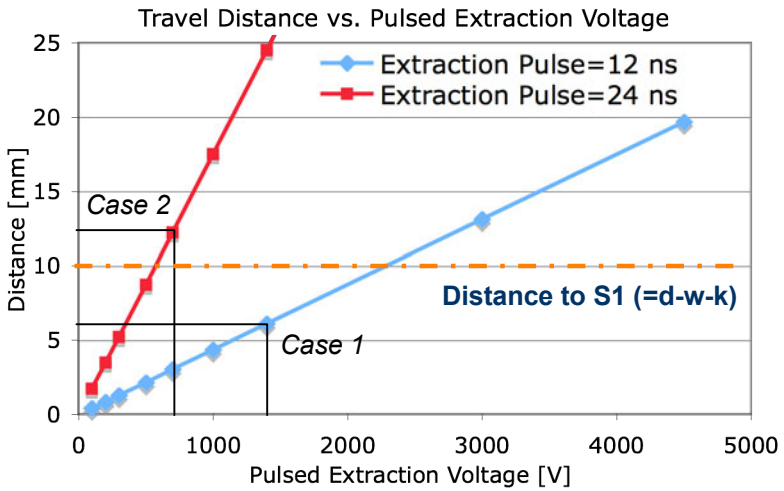
	-- Case 1 --	-- Case 2 --	-- Case 3 --
Pulsed Voltage, U =	1400 V	1400 V	700 V
Electrode gap, d =	14 mm	14 mm	14 mm
Laser width, w =	1 mm	2 mm	2 mm
Laser distance, k =	2.5 mm	2 mm	2 mm
Pulse duration, t =	12 ns	12 ns	24 ns
Final velocity, v_f =	1.0 mm/ns	1.0 mm/ns	1.0 mm/ns
Travel distance, h =	6.1 mm	6.1 mm	12.2 mm
Energy Spread =	0 V	0 V	0 V
Time Jitter, w/v_f =	1.0 ns	2.0 ns	2.0 ns

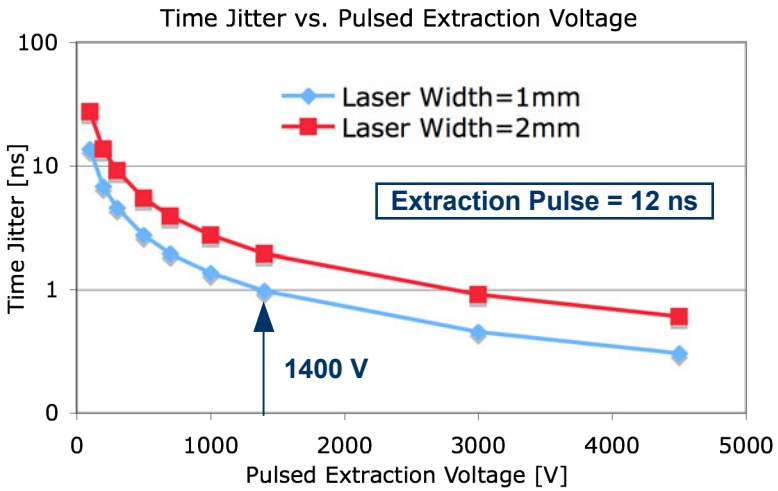


Pulsed Voltage between T and S_1

with $a_o = qU/d/m_\mu$
$v_f = a_o\, t$
$h = 0.5\, a_o\, t^2$

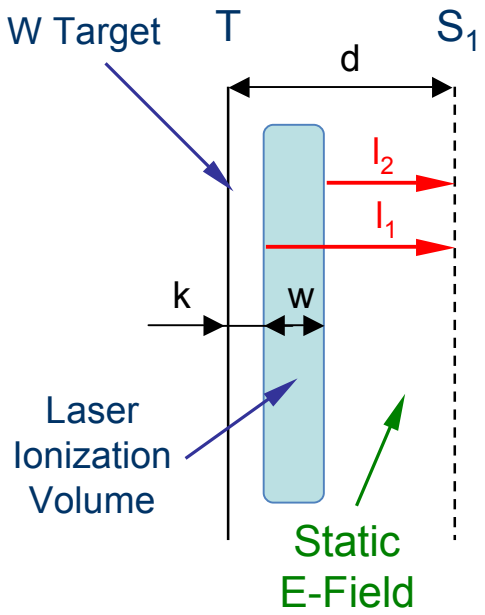
(laser center from W target = 3 mm, laser width = 1, 2 mm)

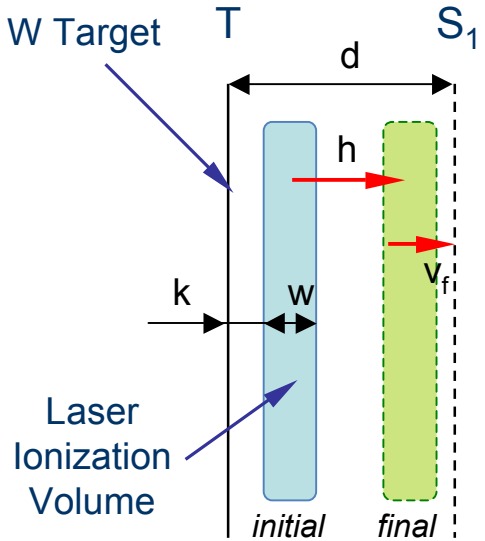




Initial Acceleration: Energy Spread

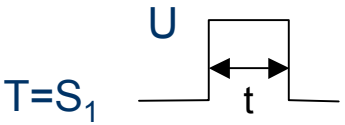
(laser center from target = 3 mm, laser width = 2 mm)





	- STATIC -	- PULSE -	- PULSE 2 -
Voltage, U =	140 V	1400 V	1400 V
Electrode gap, d =	14 mm	14 mm	**28 mm**
E-Field =	10 V/mm	100 V/mm	**50 V/mm**
Laser width, w =	2 mm	2 mm	2 mm
Laser distance, k =	2 mm	2 mm	2 mm
Pulse duration, t =	n/a	12 ns	24 ns
Travel dist., I_1, I_2,h =	10-12 mm	6.13 mm	12.26 mm
Final velocity, v_f =	0.17-0.20 mm/ns	1.02 mm/ns	1.02 mm/ns
Final Energy 1 =	100 eV	613 eV	613 eV
Final Energy 2 =	120 eV	613 eV	613 eV
Energy Spread =	20 V	0 V	0 V
Time-of-flight 1 =	48.5 ns	15.8 ns	35.5 ns
Time-of-flight 2 =	53.1 ns	17.8 ns	37.5 ns
Time Jitter =	4.6 ns	2.0 ns	2.0 ns
Error d (T/S_1):			
±0.5 mm (±3.6%)	±3.6 eV	±22 eV	±11 eV (±1.8%)
±0.1 mm (±0.7%)	±0.7 eV	±4.4 eV	±2.2 eV (±0.4%)
Error laser align.:			
±0.1 mm	±1 eV	± 0.1eV	± 0.1eV

Pulsed Voltage between T and S_1



with $a_o = qU/d/m_\mu$

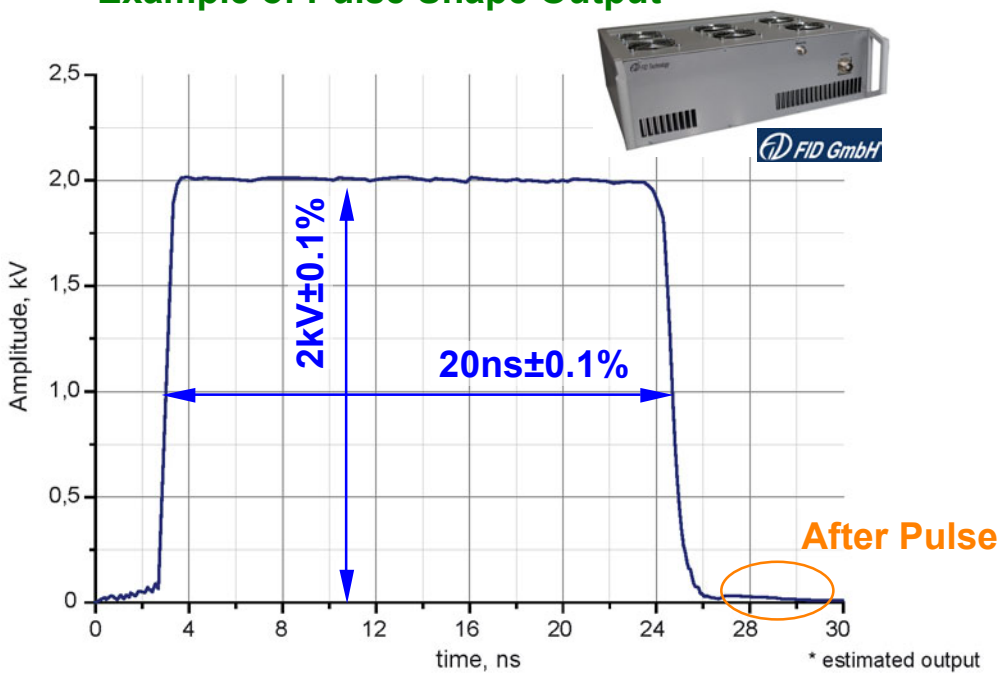
$v_f = a_o\, t$

$h = 0.5\, a_o\, t^2$

Pulsed HV Power Supply

Amplitude:	0 – 2kV ± 0.1%
Pulse duration:	2 – 20ns ± 20ps
Rise Time (10-90%):	≤ 2ns
Fall Time:	≤ 2ns
After pulse:	≤ ±0.1% (±2 V)
Jitter:	≤ 0.5ns
Trigger Frequency:	25 Hz
Operation:	> 5000 hours

Example of Pulse Shape Output



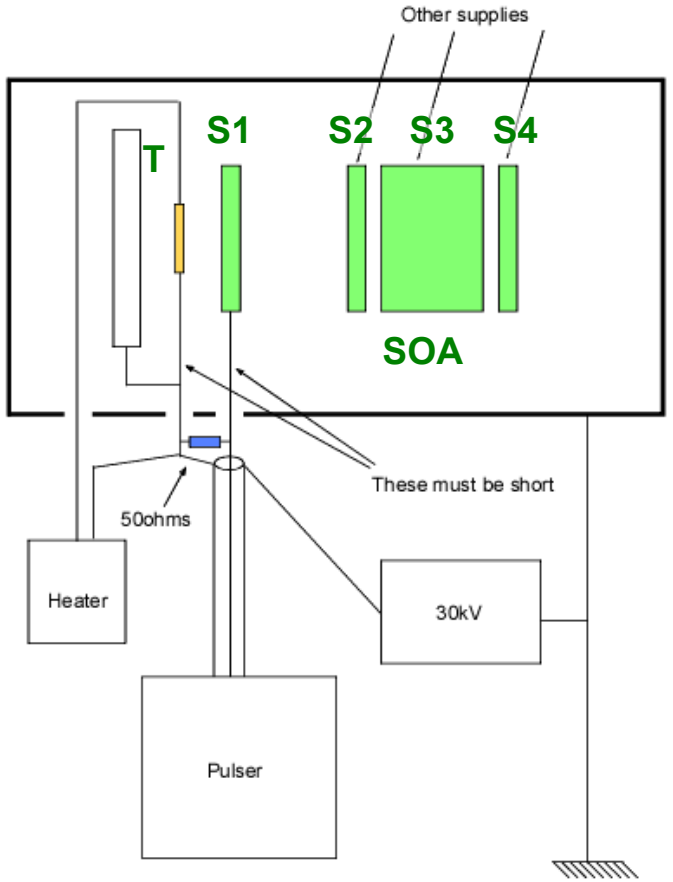
Error on the initial muon energy:

Pulse: 2kV, 8ns ⇒ ~600 eV μ^+ (v = 1mm/ns)

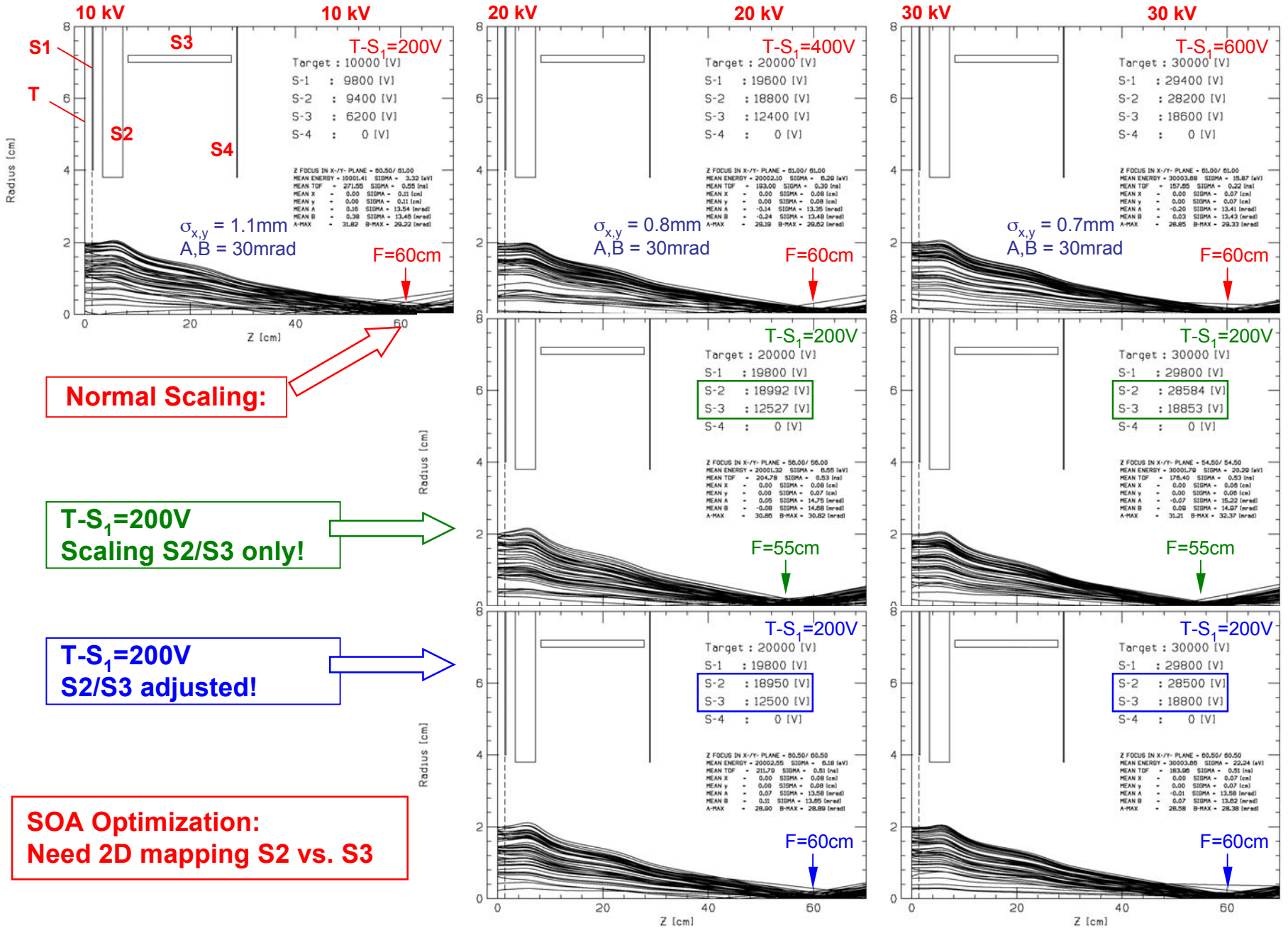
Amplitude: ± 0.1% ⇒ dE ~ 1 eV

Duration: ± 0.1% ⇒ dE ~ 1 eV

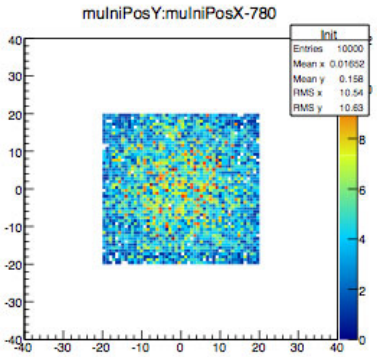
After pulse: (±2V) ⇒ dE ~ 2 eV

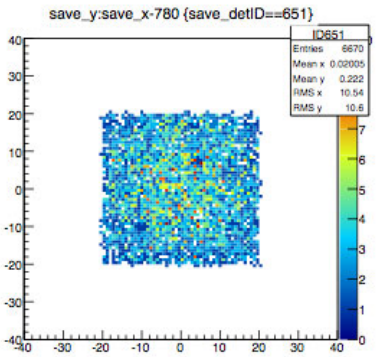


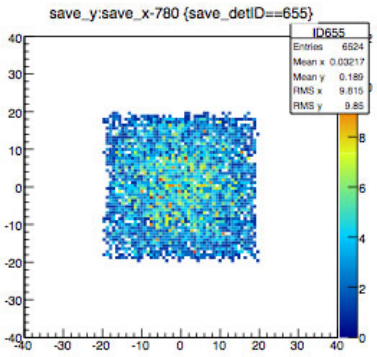
SOA Lens HV Settings

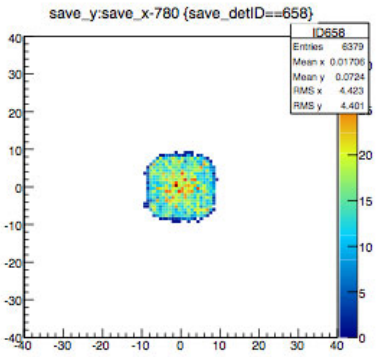


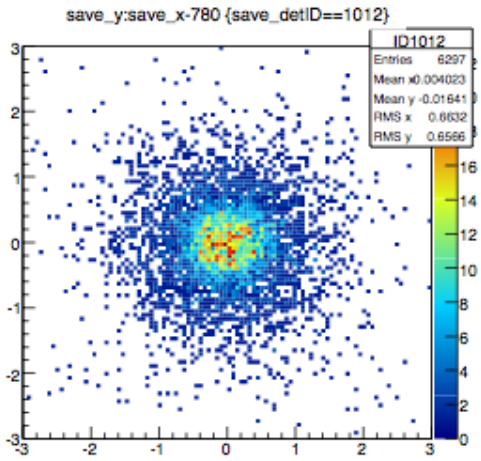
SOA Geant4 Simulation using PSI Package

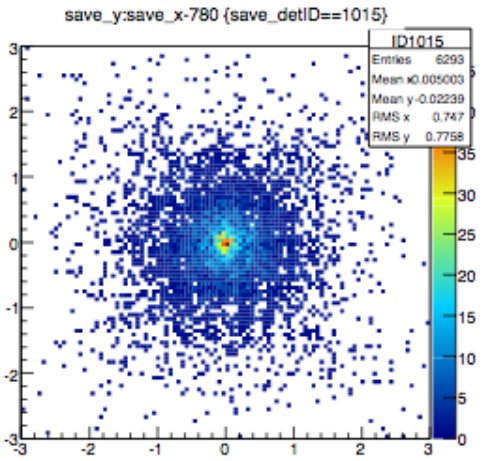


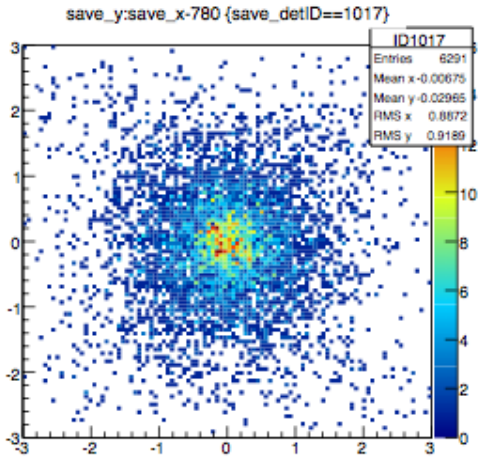


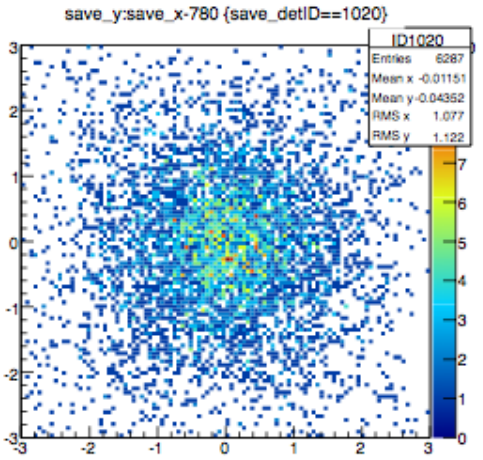




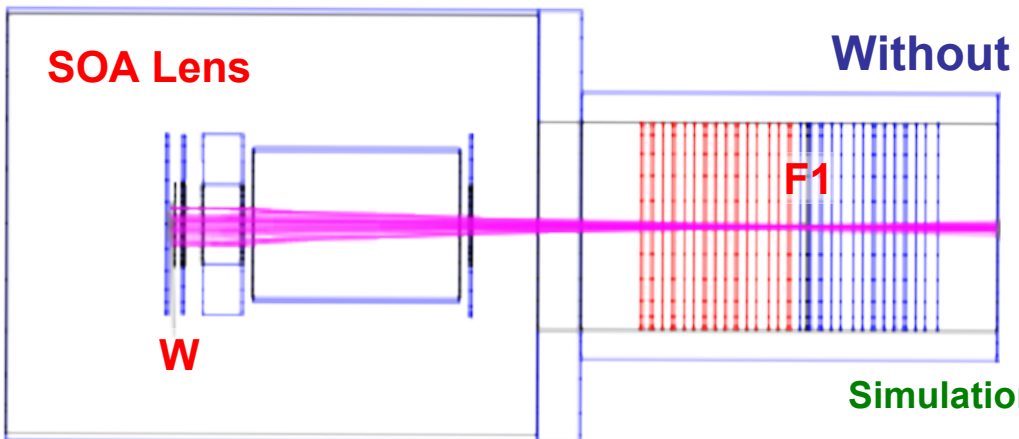








T : 30.00 kV
S1 : 29.80 kV
S2 : 28.50 kV
S3 : 18.80 kV

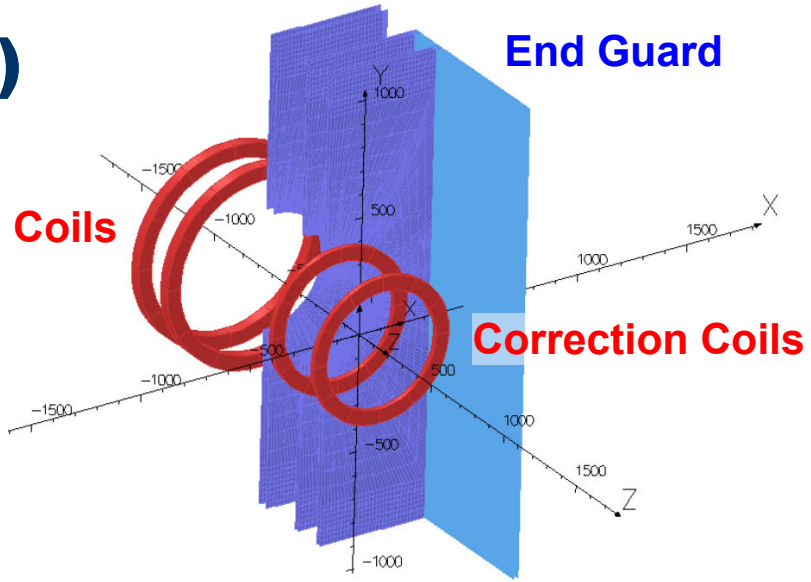


Without Fringe Field

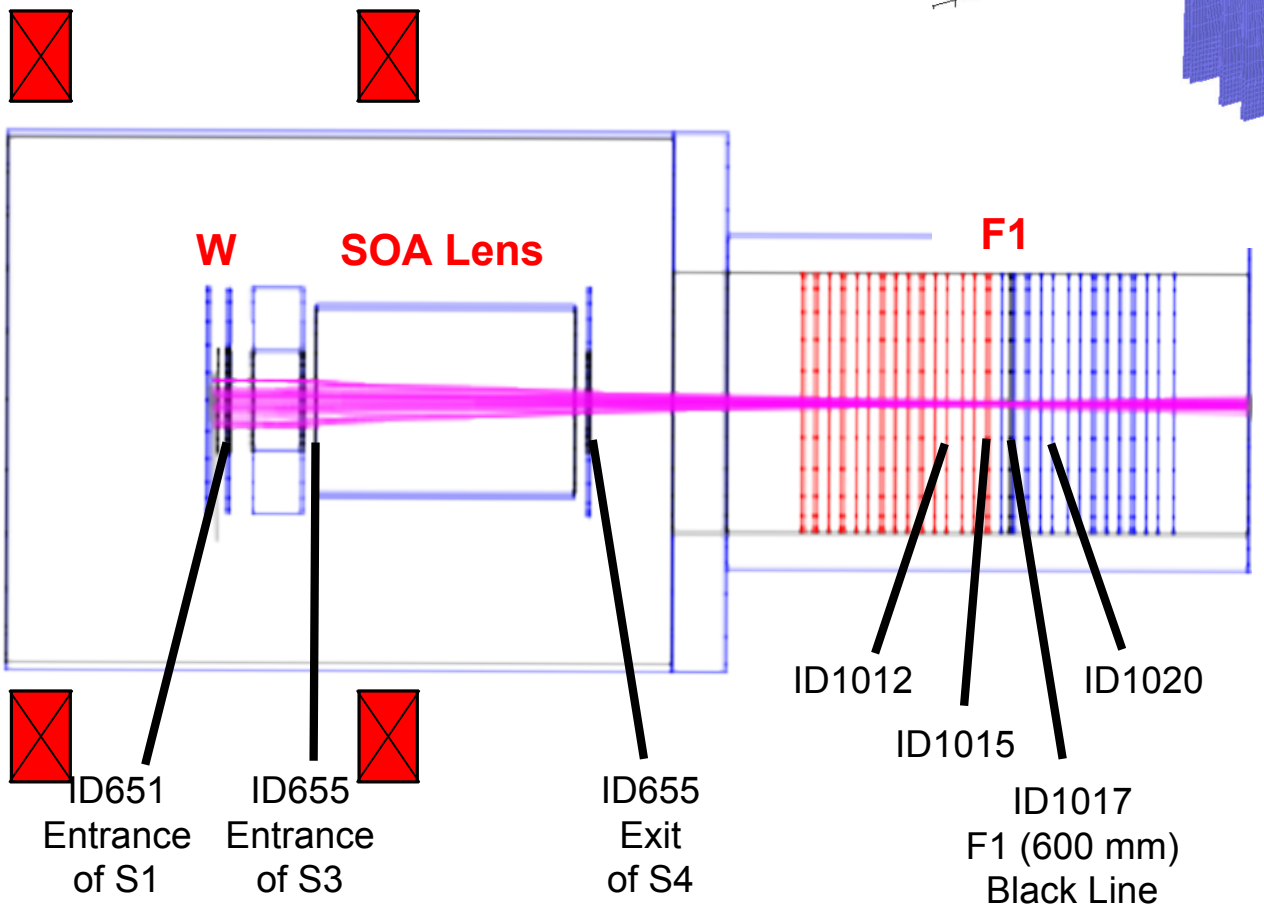
PRELIMINARY

Simulation by T. Nagatomo

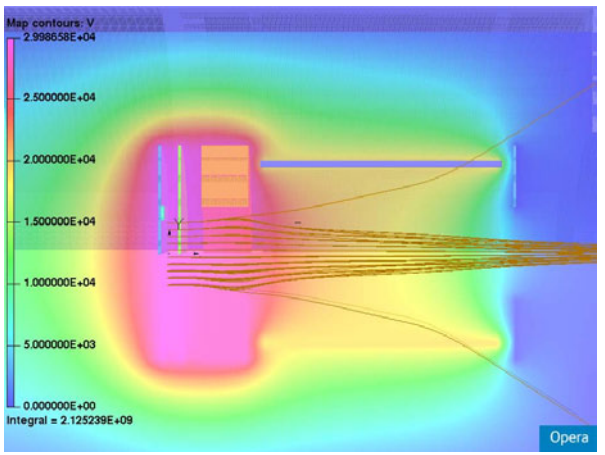
SOA Geant4 Simulation (2)



Correction Coils



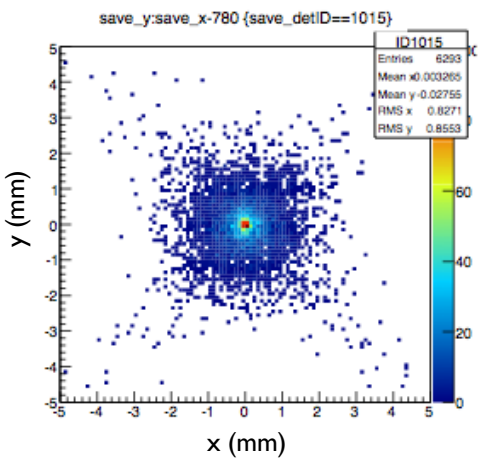
Opera

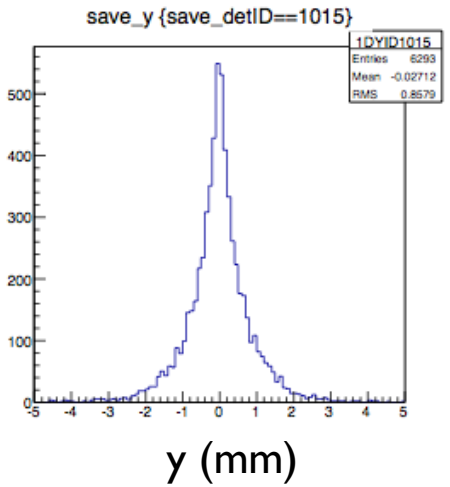


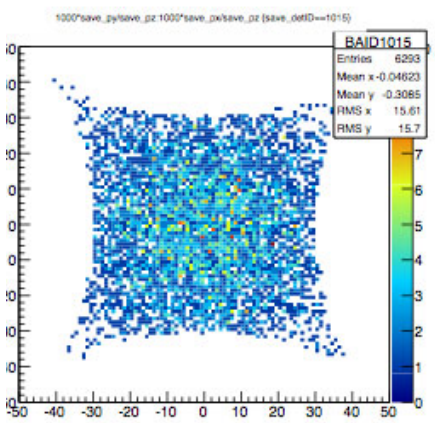
Simulation by T. Nagatomo

SOA Geant4 Simulation (3)

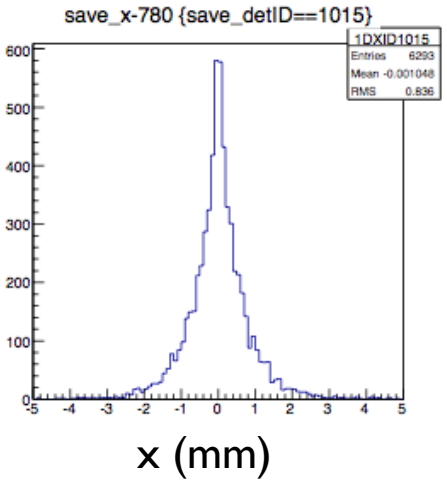
Without Fringe Field from Axial Focusing Solenoid !

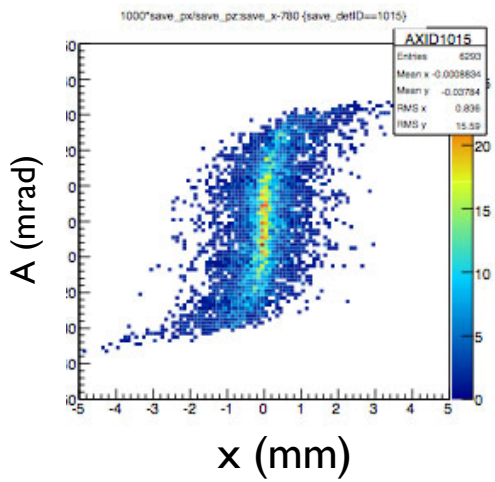


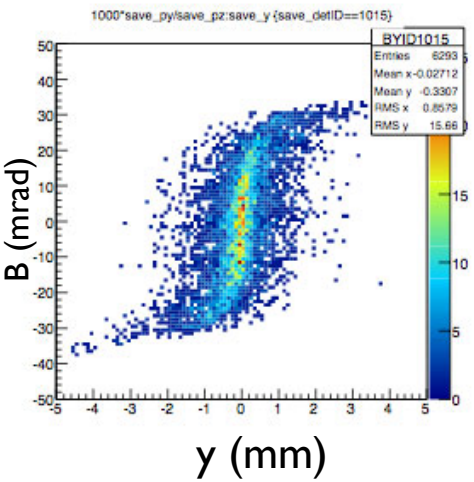




PRELIMINARY



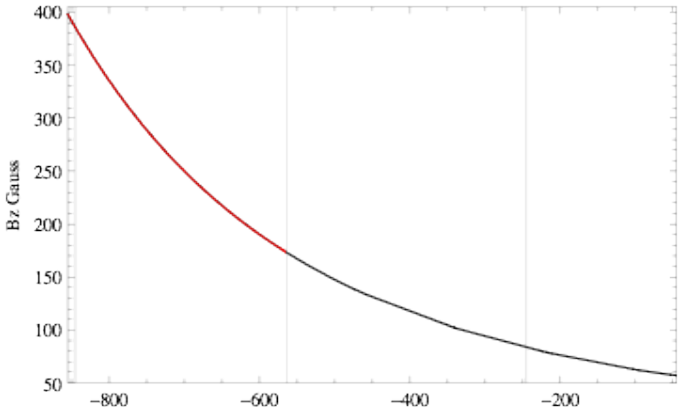


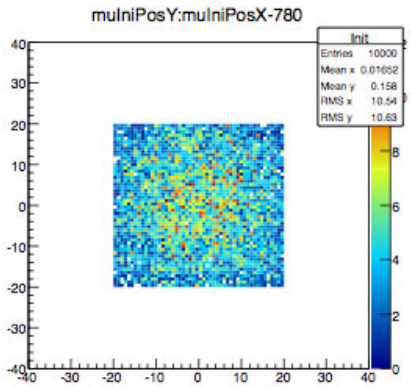


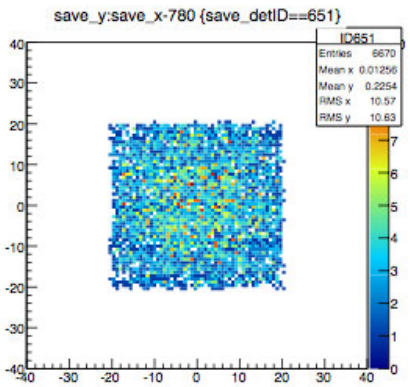
Simulation by T. Nagatomo

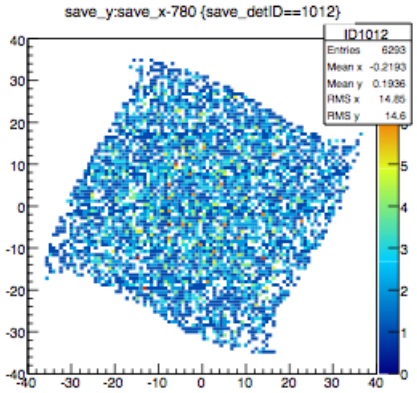
SOA Geant4 Simulation (4)

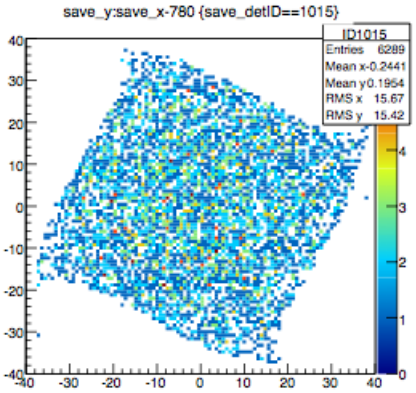
Fringe Field: YES
End Guard: NO
Correction Coil: NO

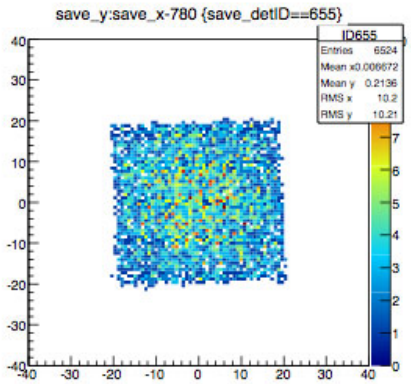


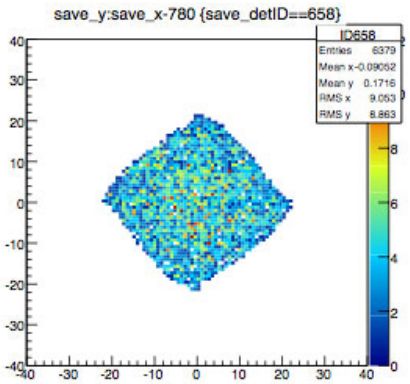


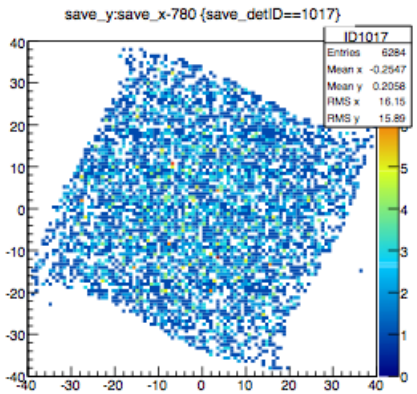


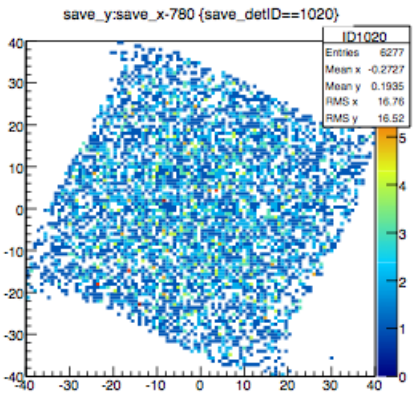








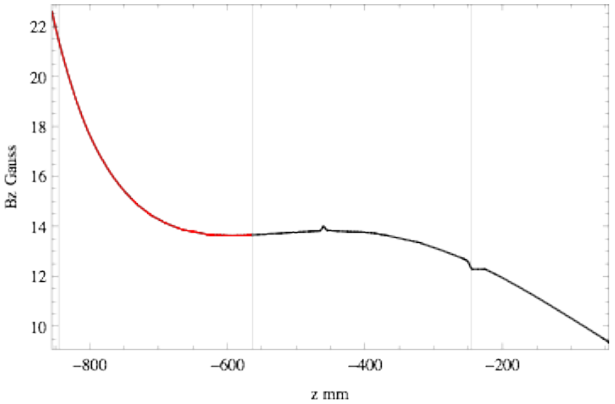


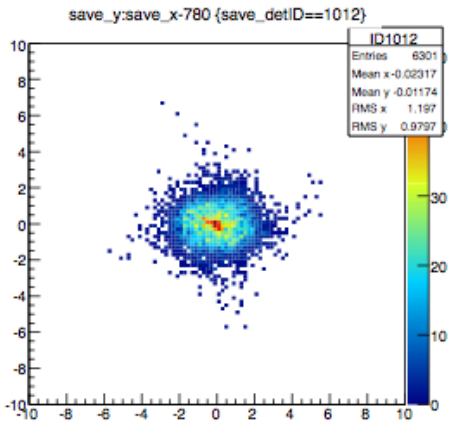


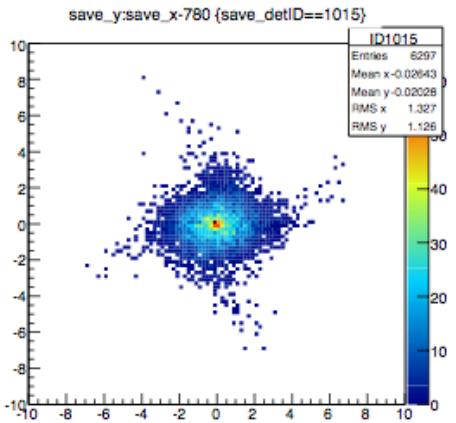
Simulation by T. Nagatomo

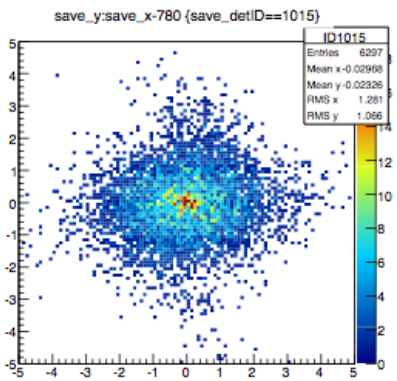
SOA Geant4 Simulation (5)

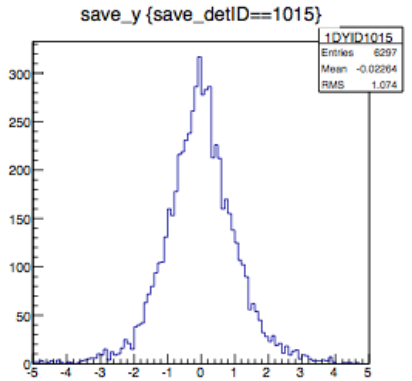
Fringe Field: YES
End Guard: YES
Correction Coil: NO

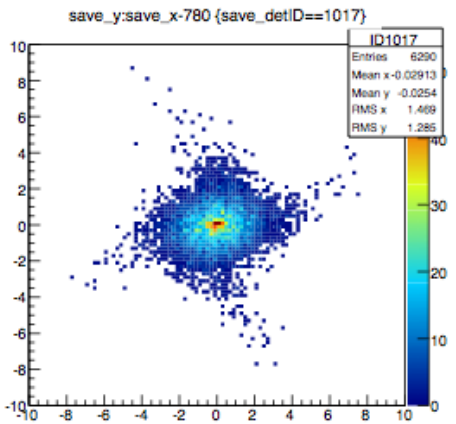


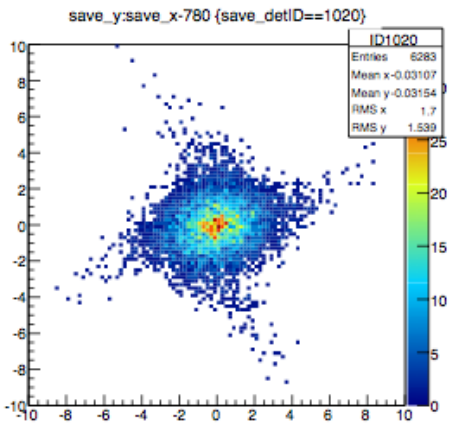


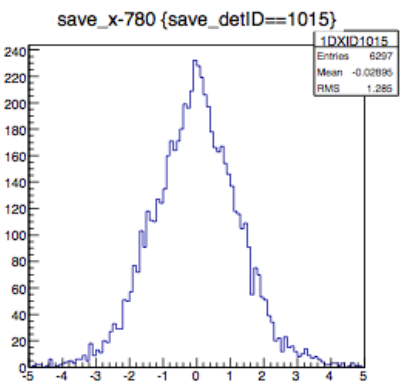












PRELIMINARY

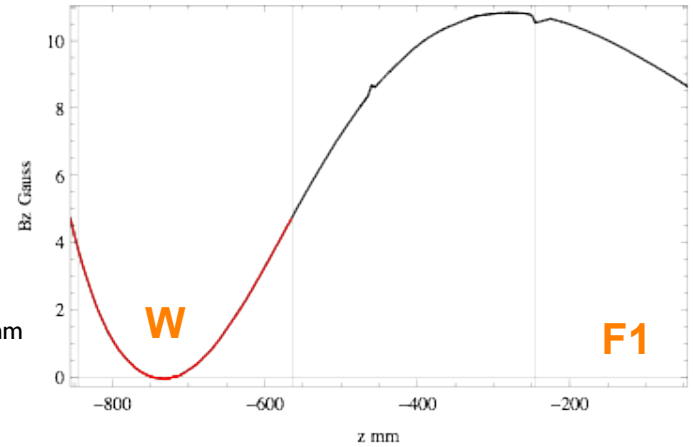
Simulation by T. Nagatomo

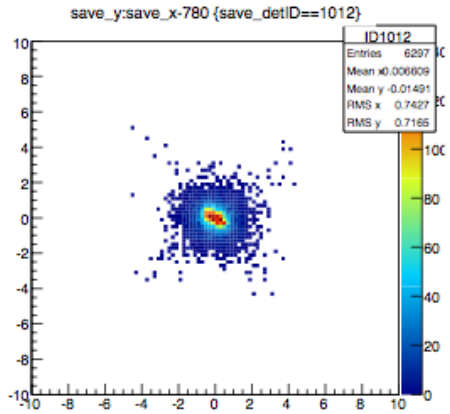
SOA Geant4 Simulation (6)

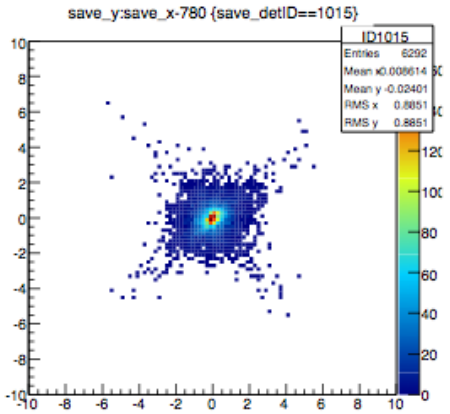
Fringe Field: YES
End Guard: YES
Correction Coil: YES

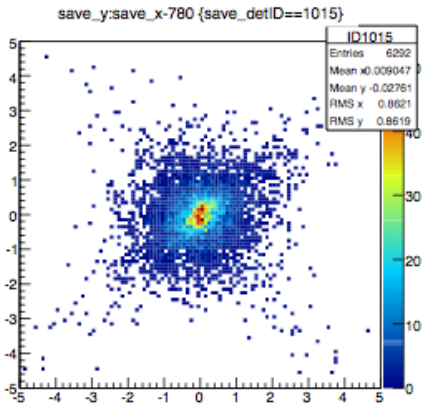
Sol. 1 : 20 A/mm^2
Sol. 2 : 60 A/mm^2
Corr. 1 : -0.45 A/mm^2
Corr 2 : -0.30 A/mm^2

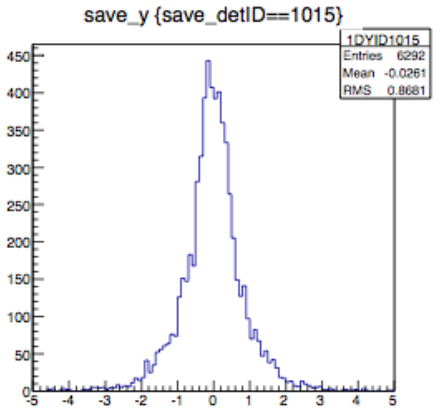
Corr. coil : 60 mm x 20 mm
I (Corr. 1) = -540 A

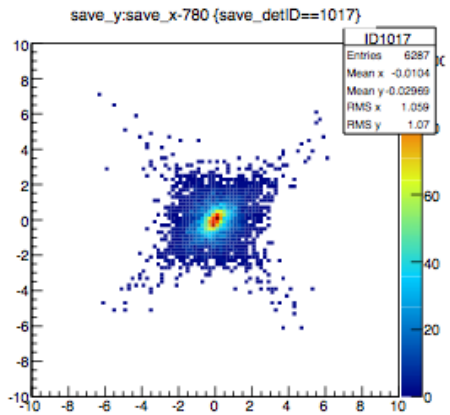


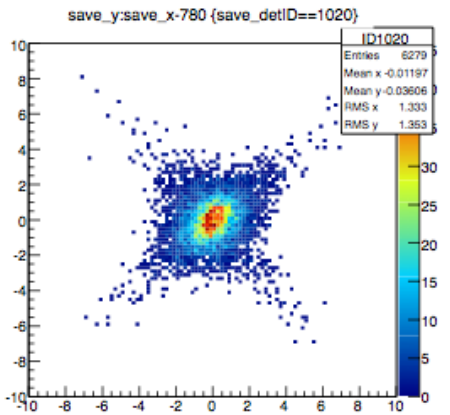


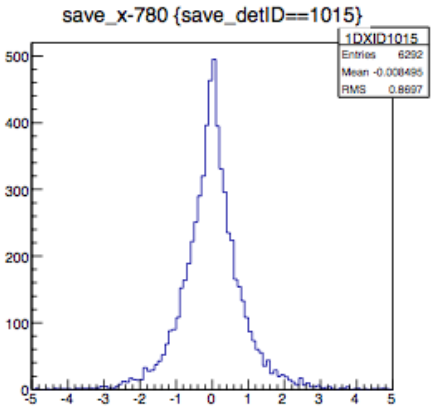










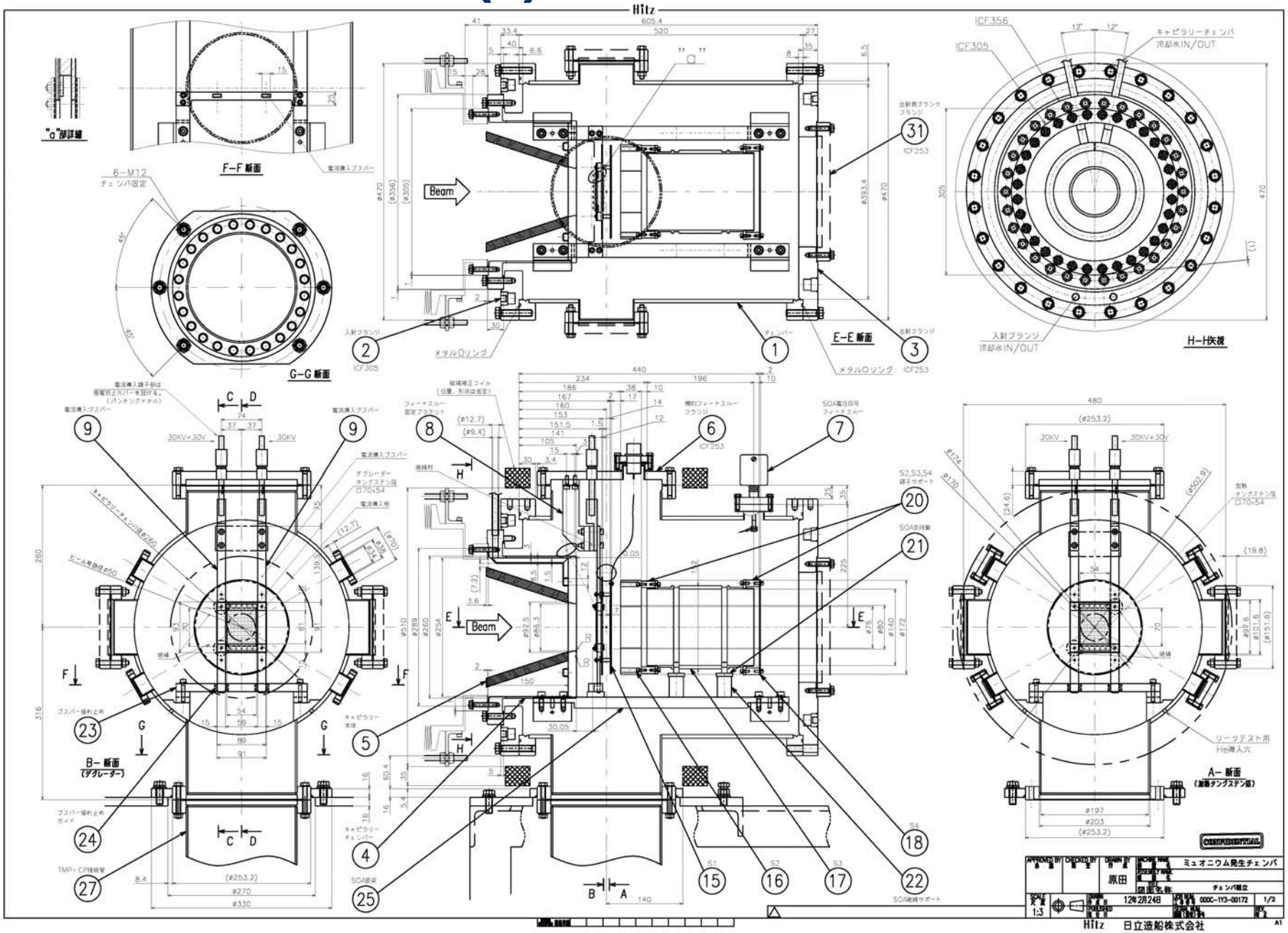


PRELIMINARY

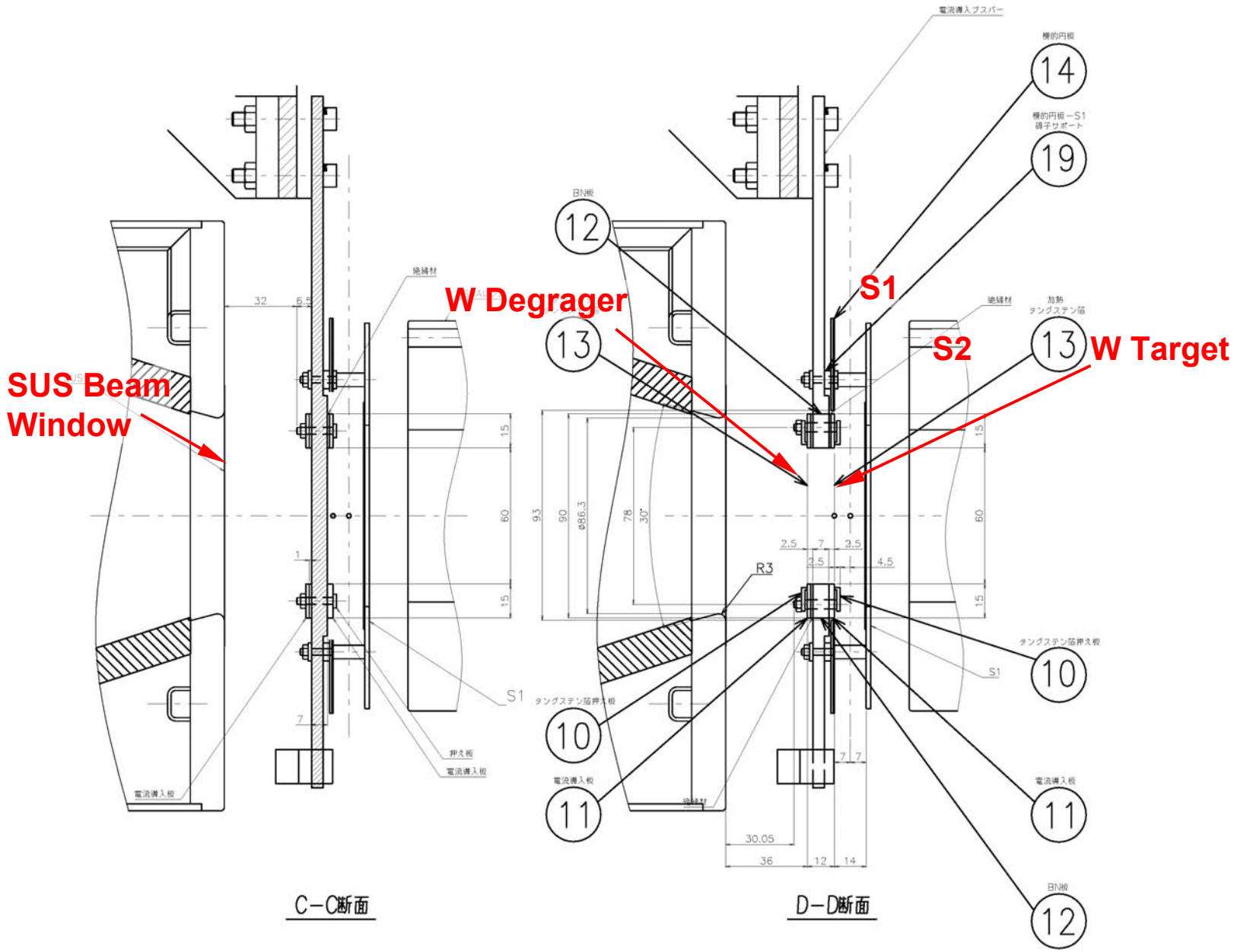
Simulation by T. Nagatomo

Muonium Chamber (1)

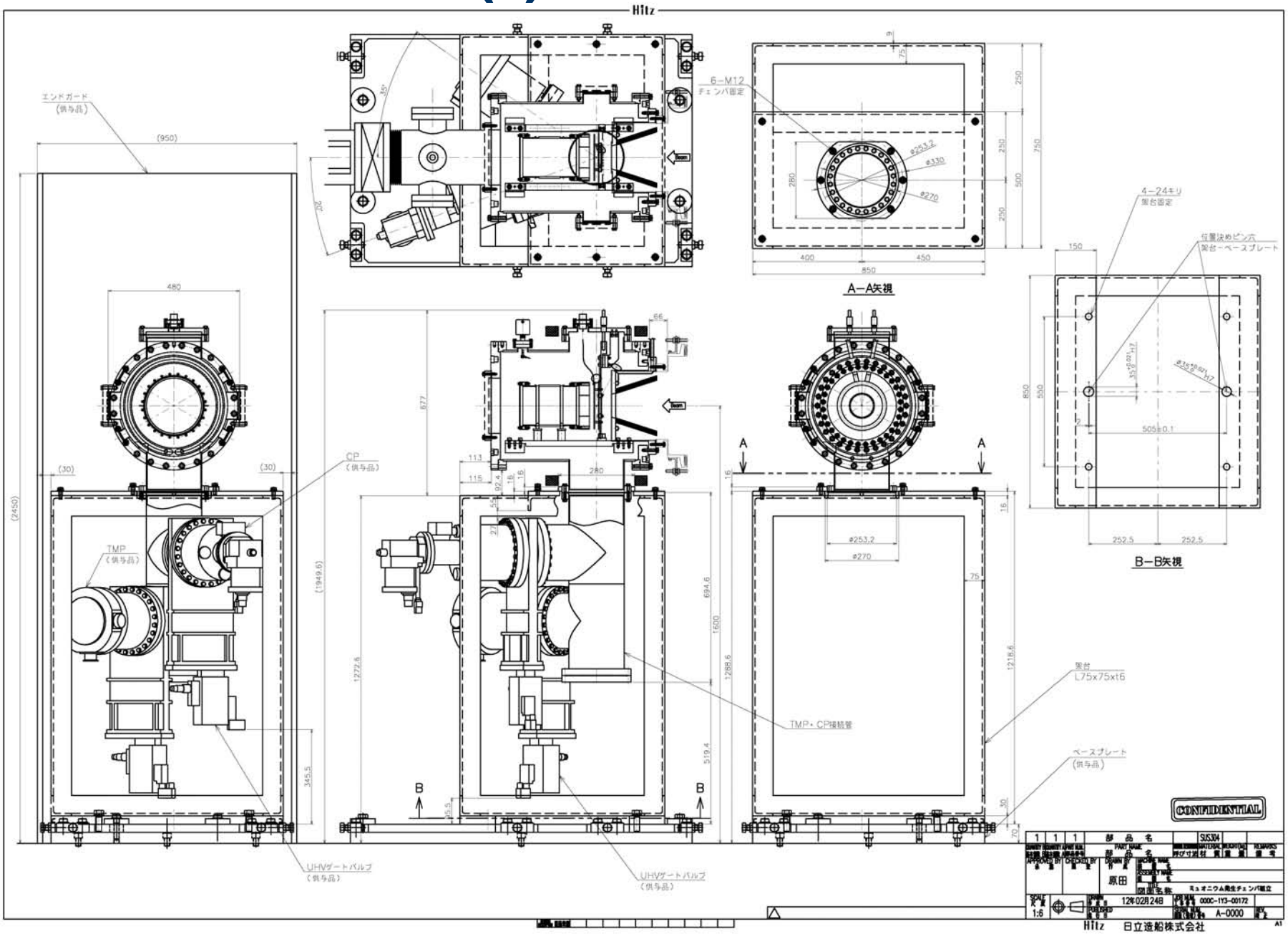
Under design and fabrication by Hitachizosen



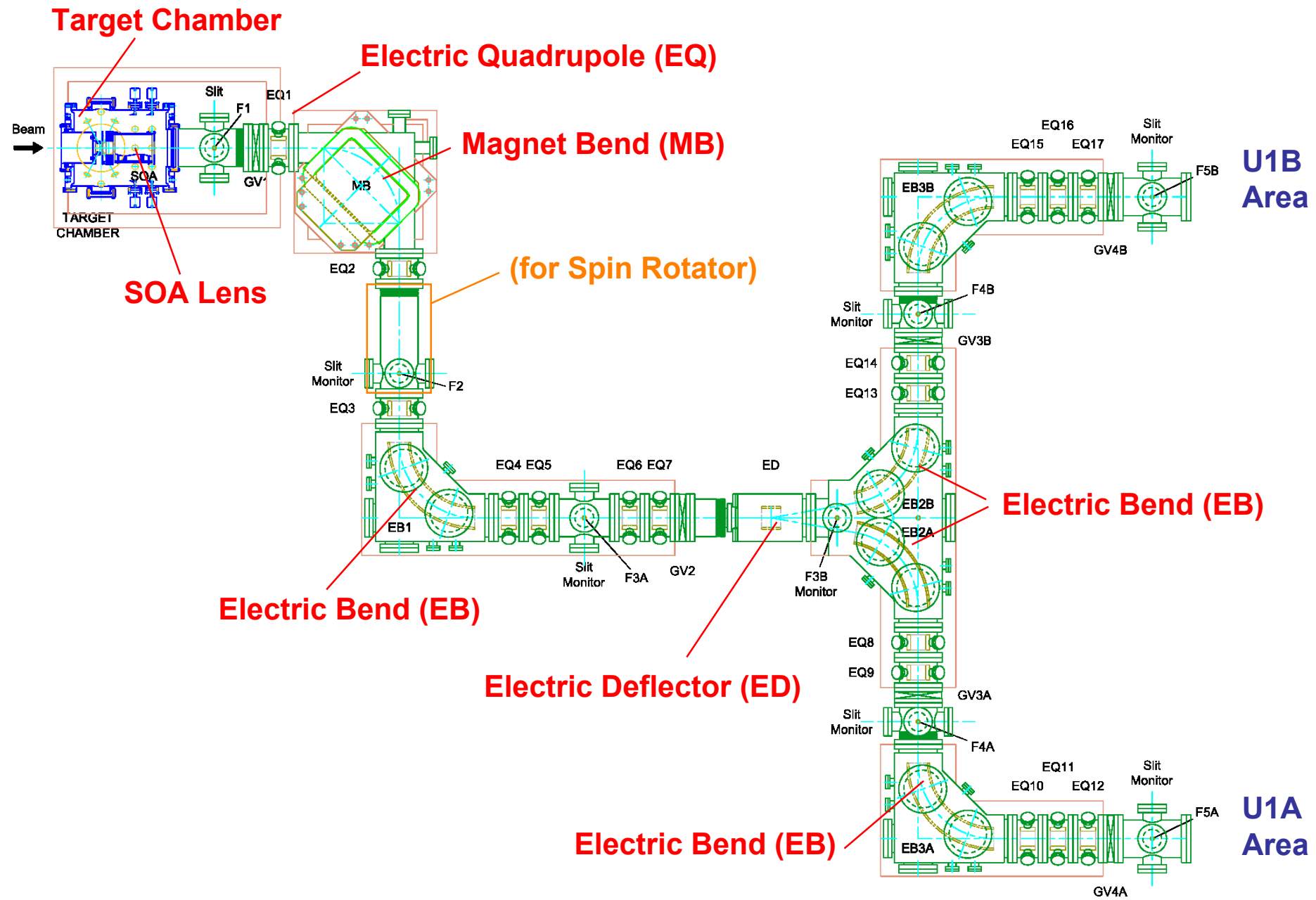
Muonium Chamber (2)



Muonium Chamber (3)

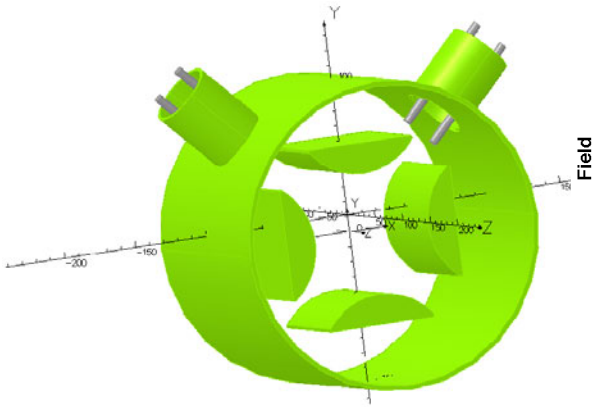


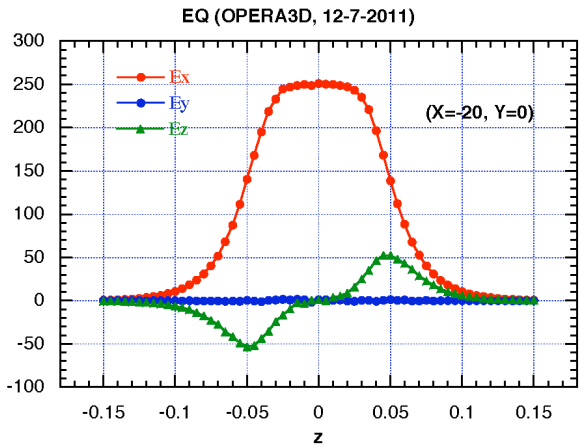
Ultra-Slow Muon Beamline Layout



Fringing Field Calculations

Electric Quadrupole (EQ)



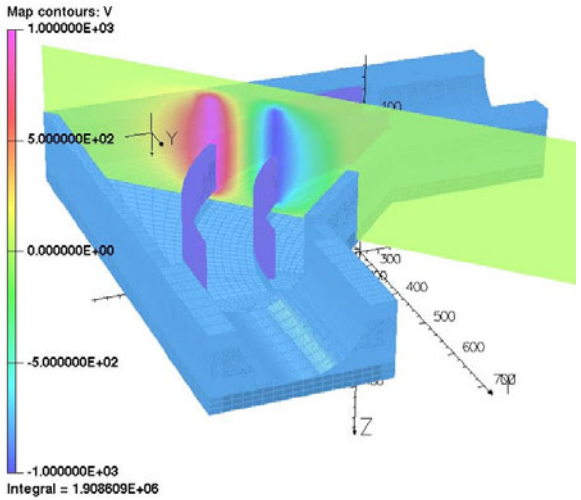


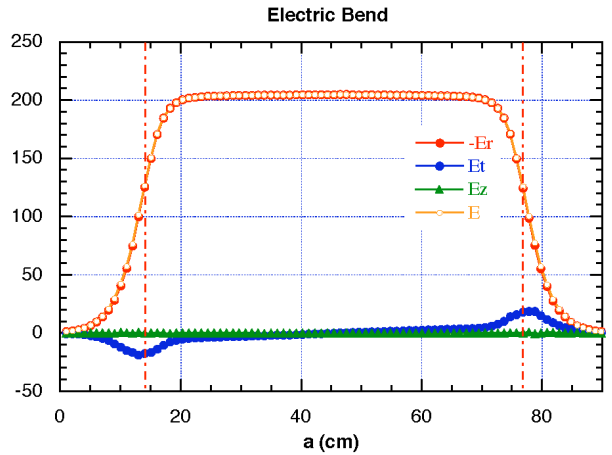
Opera

```
----------------------------------------
RESULTS:
  EFF. FIELDBOUNDARY        0.28789463
 I1A       0.07182710   I1B       0.06879283
 I2A       0.00264758   I2B      -0.02175483
 I3A       0.02298548   I3B       0.01898187
 I4A      -0.20563349   I4B      -0.31097021
 I5A       0.35501367   I5B       0.70629006
 I6A       0.25417266   I6B       0.01987549
 I7A       0.04004784   I7B       0.04979843
 I8A       0.06879283   I8B      -0.03540865
 I9       -0.03729295
 I10       0.14108427
 I11       0.00000000
 I14       1.52045111
 I11A      0.00263973   I11B      0.00681417
 I12A     -0.00343126   I12B      0.00090701
----------------------------------------
```

```
INTEGRALS FOR THE MAGNETIC AND ELECTRIC QUADRUPOLE
I1A,I2,I3A,I4A,I1B,I5B,I6B,I8,I11A,I11B,I12A,I12B
0.07183   0.00265   0.02299  -0.20563   0.06879   0.70629
0.01988  -0.03541   0.00264   0.00681  -0.00343   0.00091
```

Electric Bend (EB)





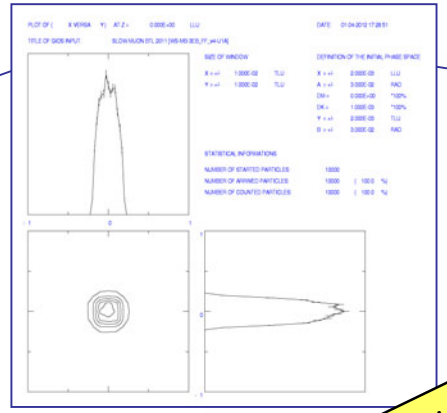
Opera

```
----------------------------------------
RESULTS:
  EFF. FIELDBOUNDARY        0.22159816
 I1A       0.33645213   I1B       0.31959760
 I2A       0.02799061   I2B      -0.37509225
 I3A       0.28263129   I3B       0.28946329
 I4A      -0.43550710   I4B      -0.64192124
 I5A      14.75124567   I5B       0.39120209
 I6A      55.18072787   I6B       0.02950822
 I7A       0.09871120   I7B       0.09304819
 I8A       0.31959760   I8B      -0.02901848
 I9       -0.18776009
 I10       0.15570313
 I11       0.00000000
 I14       0.26460509
 I11A      0.05103149   I11B      0.41801289
 I12A     -0.86043145   I12B      0.71775549
----------------------------------------
```

```
INTEGRALS FOR THE ELECTRIC SECTOR
I1A,I1B,I4A,I4B,I5,I6,I7,I3A,I3B
0.33645   0.31960  -0.43551  -0.64192   0.39120   0.02951
0.09871   0.28263   0.28946
```

New Optics Calculation

WinGIOS2

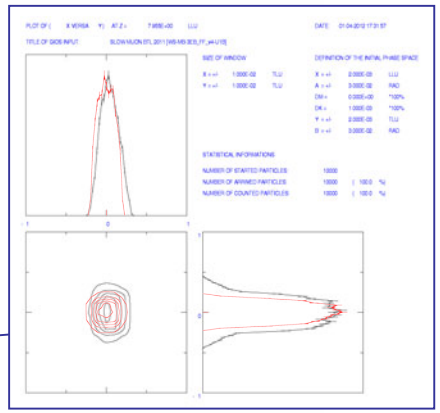


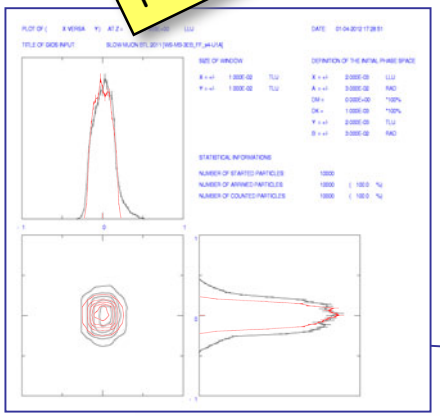
Initial
X,Y = ±2 mm
A,B = ± 30 mrad

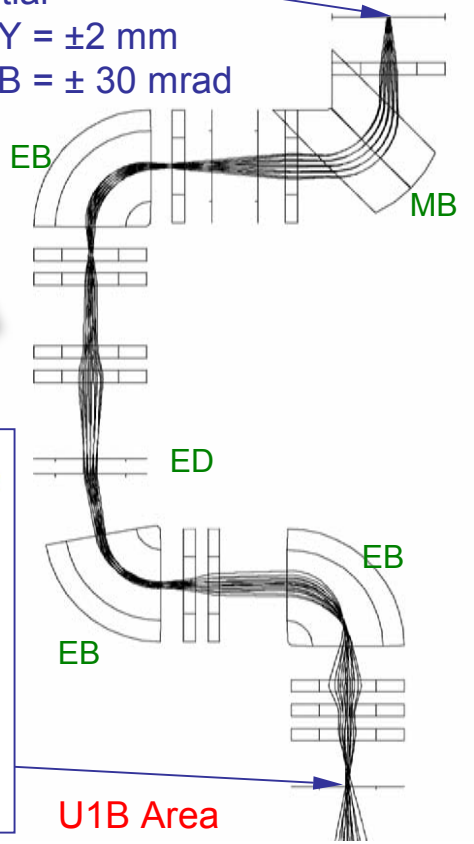
3rd order transport calculation

PRELIMINARY

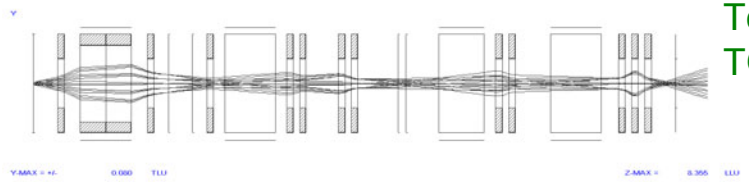
Final Focus

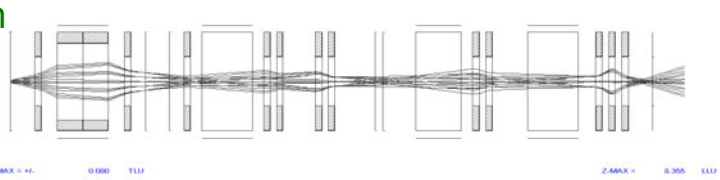


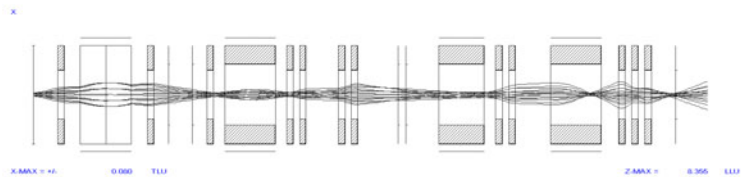


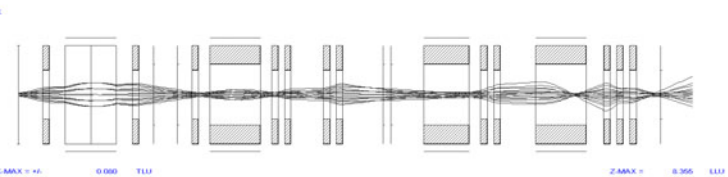


Total Length = 7955 mm
TOF = 1361 ns (20keV)
1112 ns (30keV)





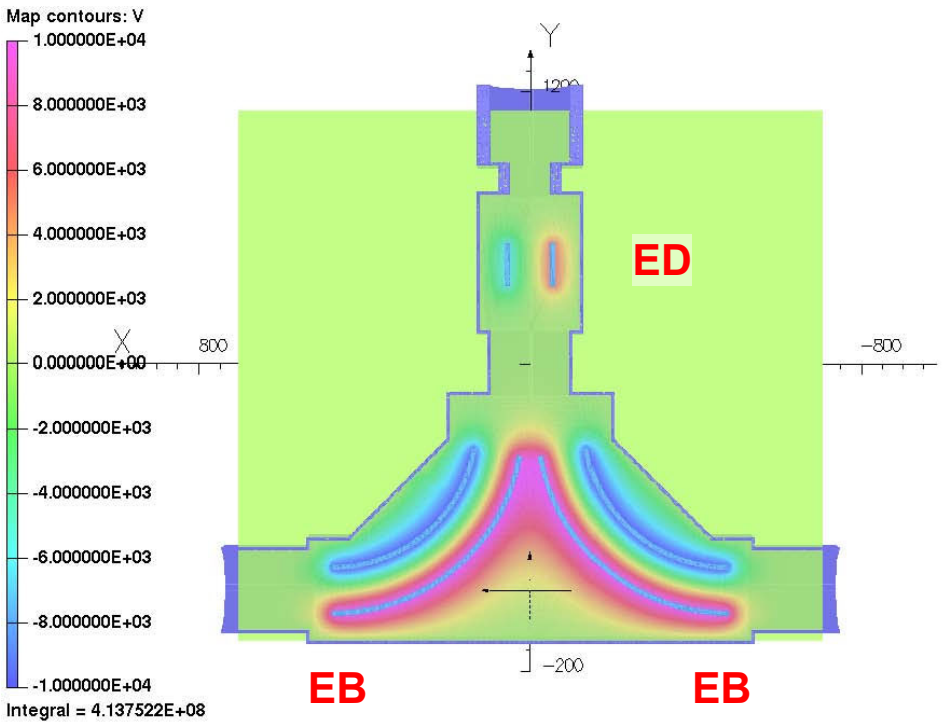




Next Step: Full Beamline Geant4 Simulation

W Target → SOA Lens → Beam Transport → μSR Target

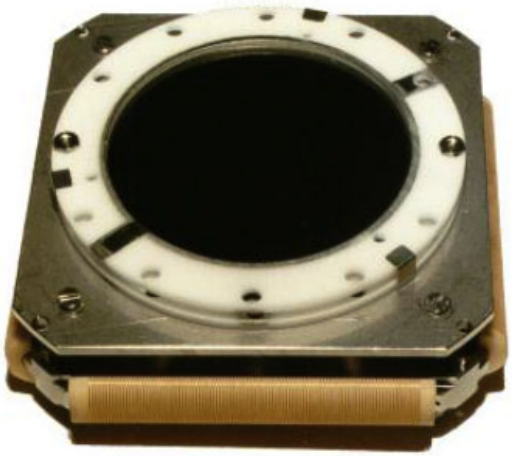
Electric Deflector:



Beam Monitoring

Two-dimensional MCP

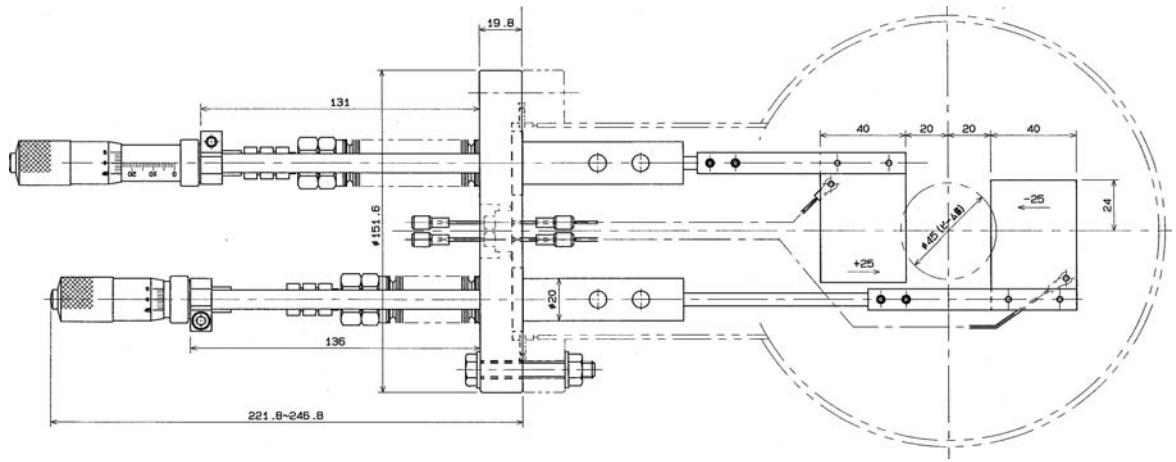
RoentDek
Handels GmbH



MCP Delay Line Detector: model DLD40

Diameter: 40 mm

Slit X/Y



Summary

- The design of the slow muon optics is in progress.
- Basic concept similar to the RIKEN-RAL Slow Setup.
- Improve energy spread of the initial extraction/acceleration as good as technically feasible.
- Optimize SOA Lens.
- Improve slow muon transport parameters.
- Full Geant4 beamline transport simulation in progress.