# g-2 Ring Hardware

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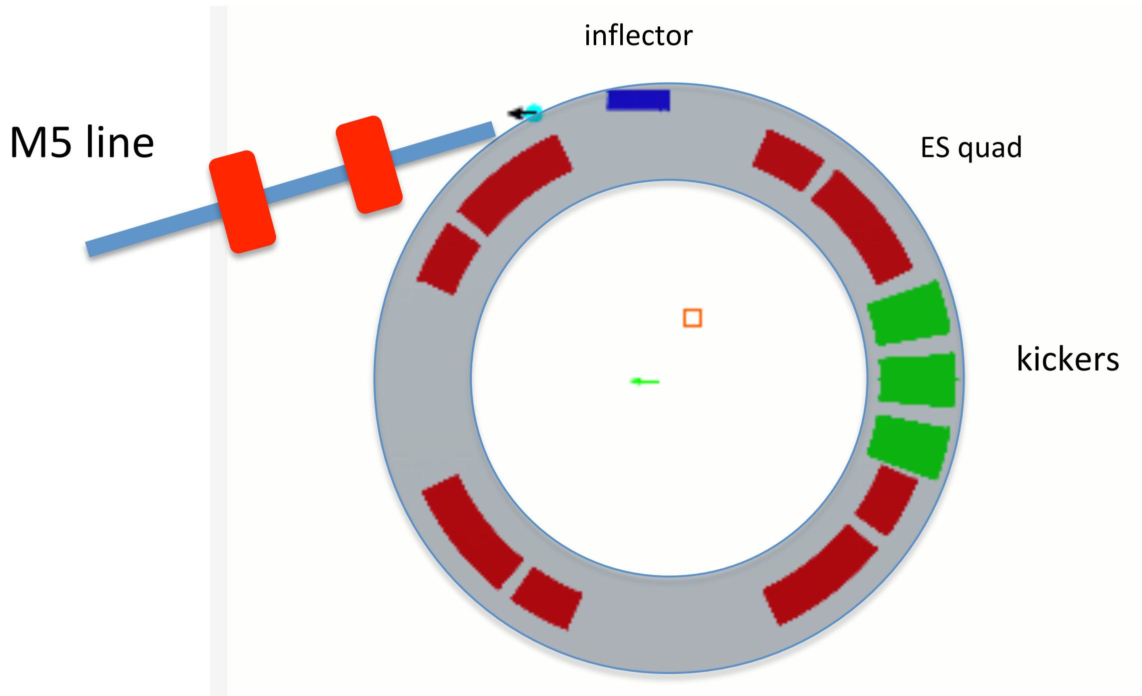
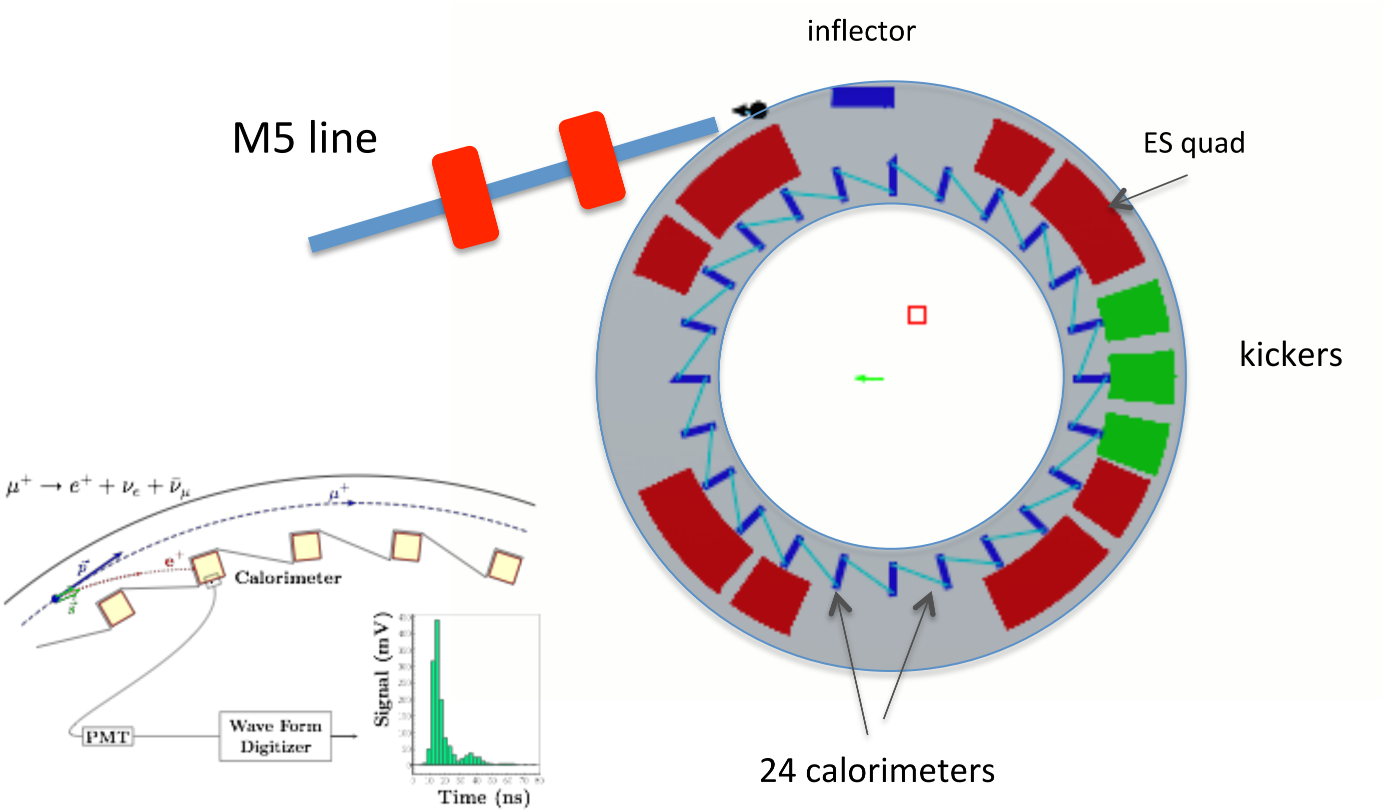
USPAS
January 2019

# Muon Storage Ring

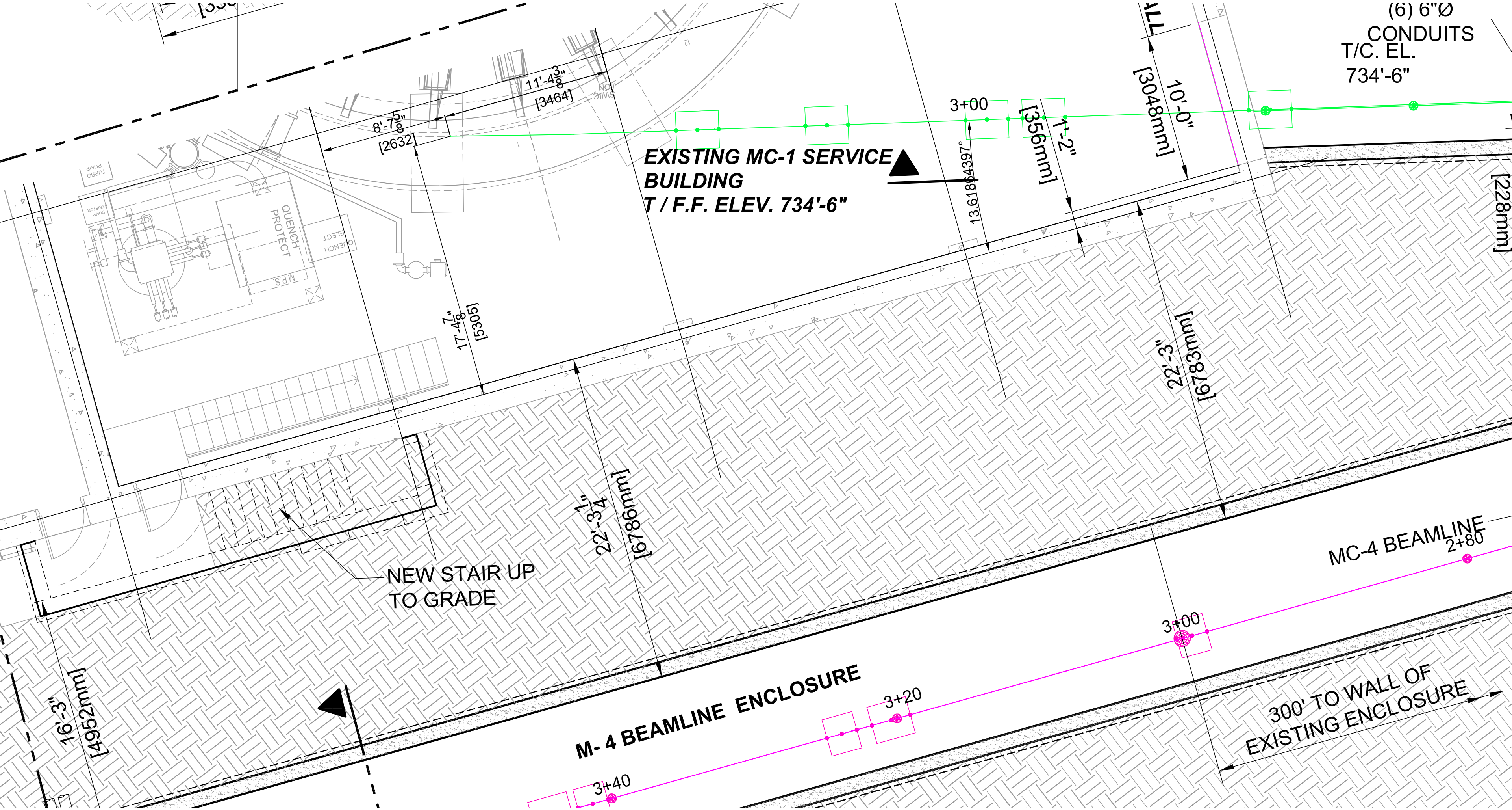


# g-2 Measurement

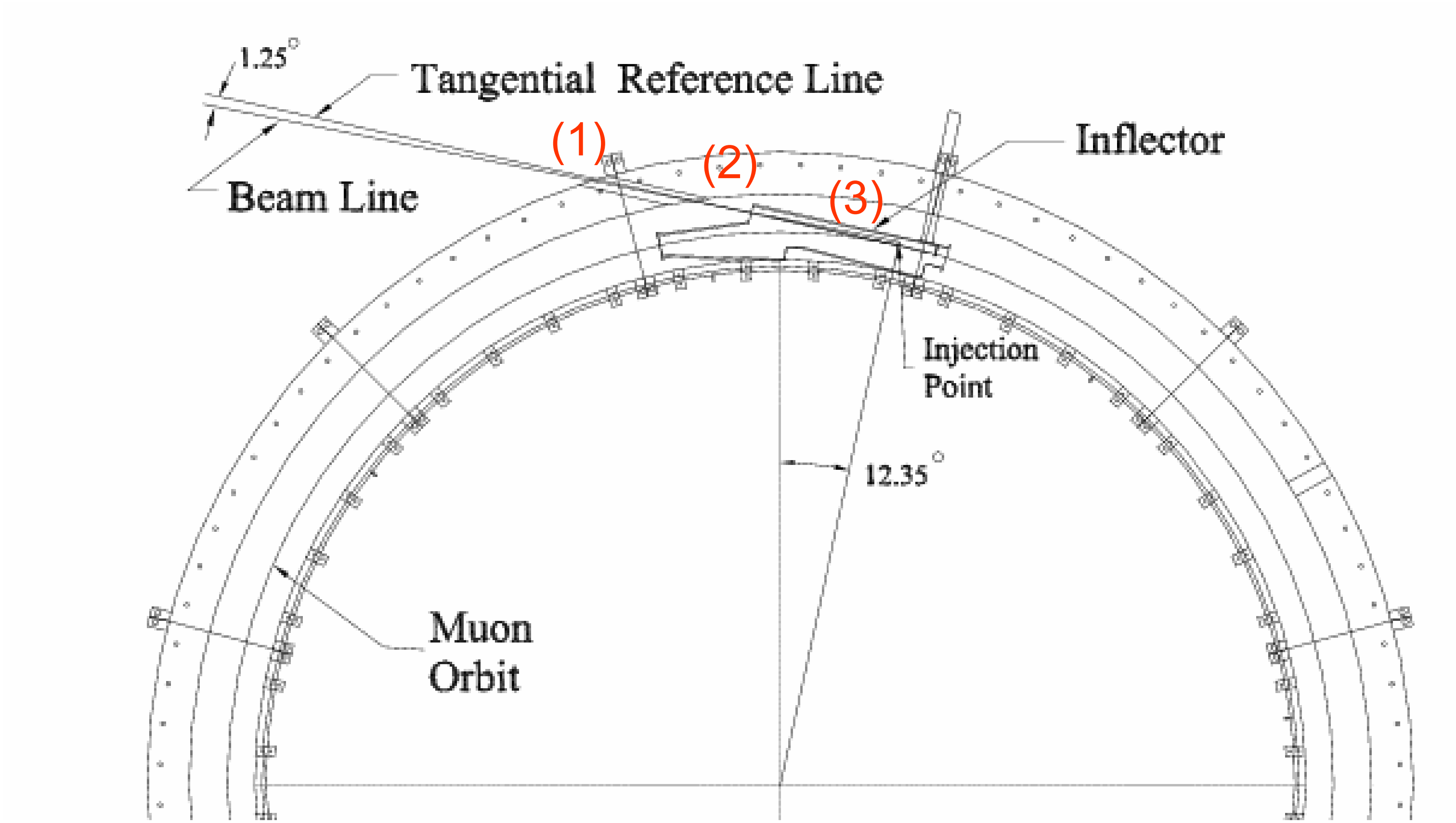



g-2 measurement

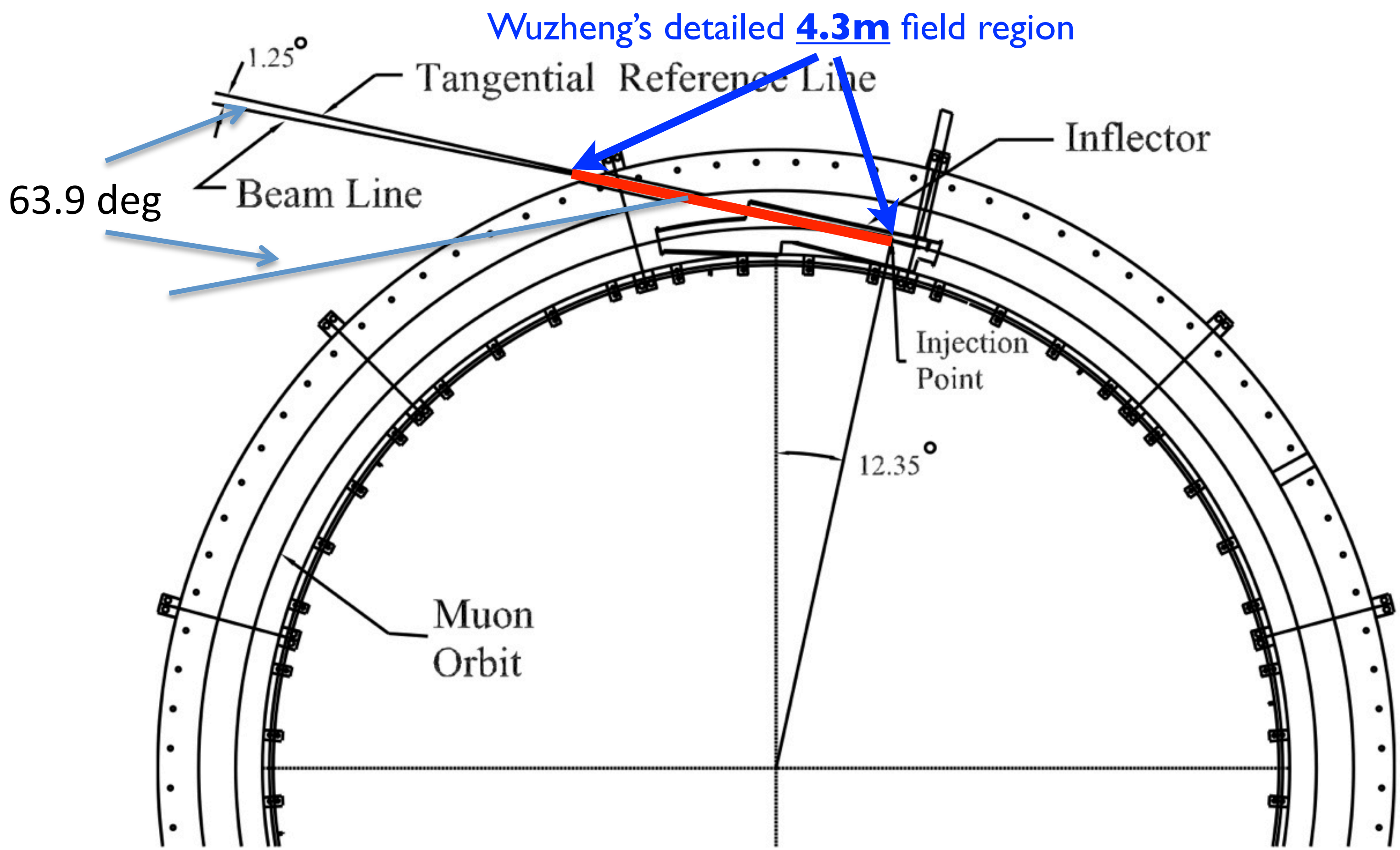
Time histogram of number of positrons with E> $0.58E_{max}$


(6) 6"Ø
CONDUITS
T/C. EL.
734'-6"
11'-4 3/8"
[3464]
8'-7 5/8"
[2632]
3+00
10'-0"
[3048mm]
1'-2"
[356mm]
EXISTING MC-1 SERVICE
BUILDING
T / F.F. ELEV. 734'-6"
13.61864397°
QUENCH PROTECT
MPS
17'-4 7/8"
[5305]
[228mm]
22'-3"
[6783mm]
22'-3 1/4"
[6786mm]
NEW STAIR UP
TO GRADE
MC-4 BEAMLINE
2+80
3+00
M- 4 BEAMLINE ENCLOSURE
3+20
3+40
300' TO WALL OF
EXISTING ENCLOSURE
16'-3"
[4952mm]

How do twiss parameters propagate through iron, cryostat, inflector into ring

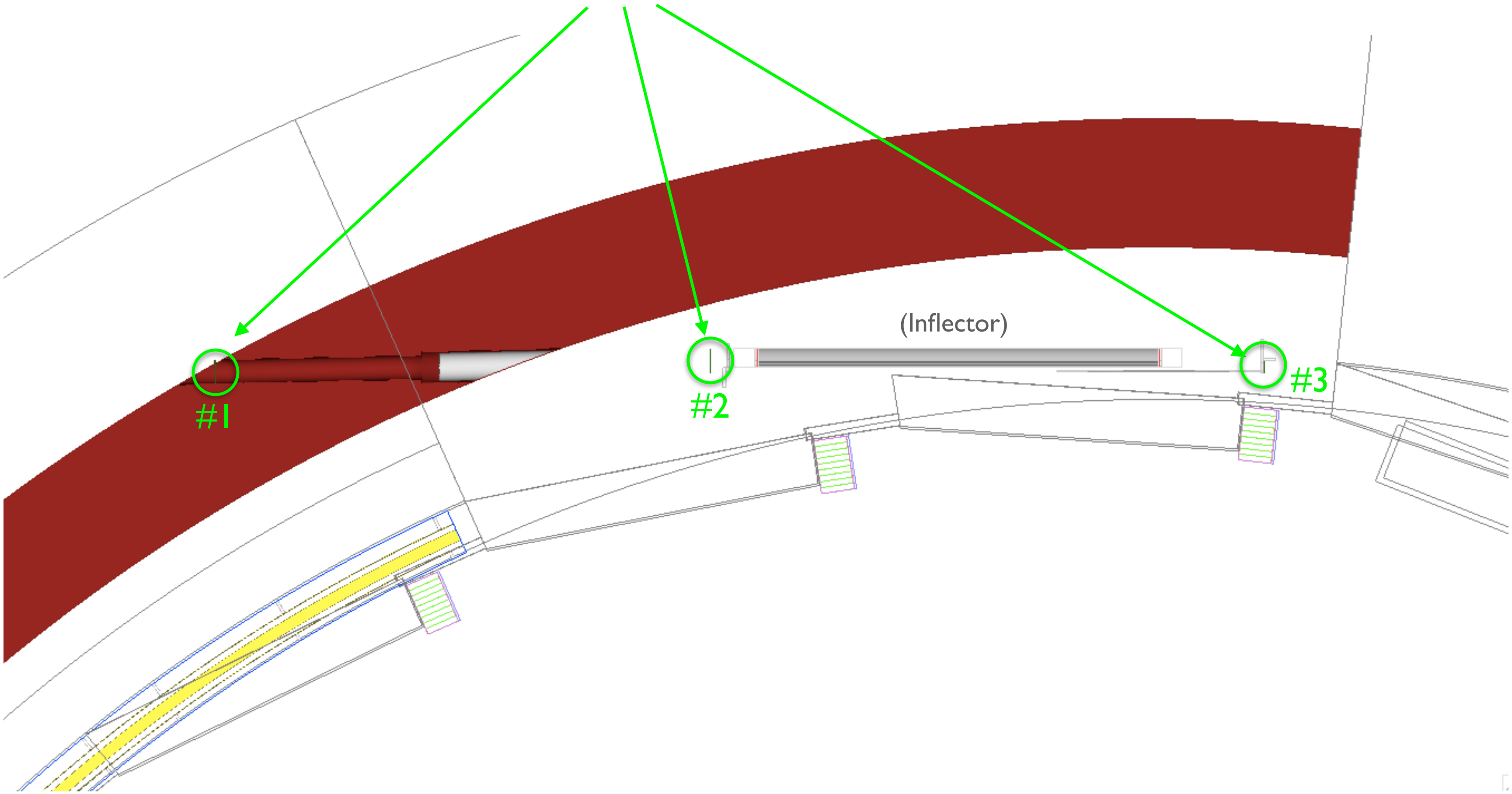


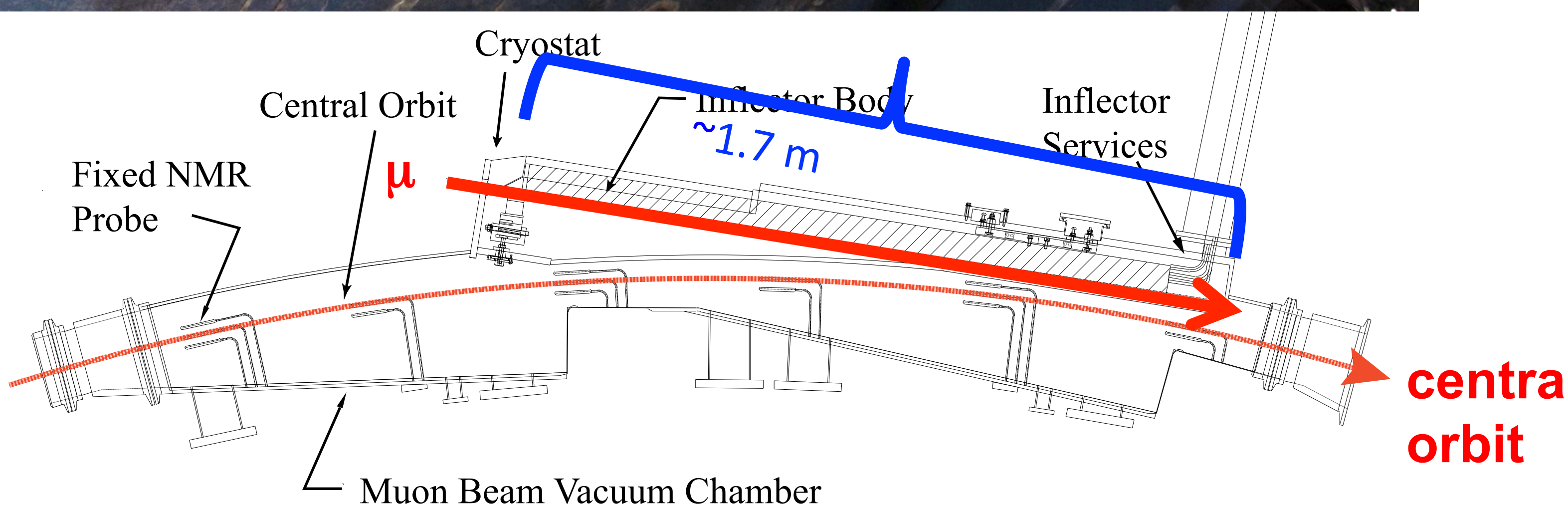

(1) hole in back leg, (2) storage ring fringe field, (3) inflector channel

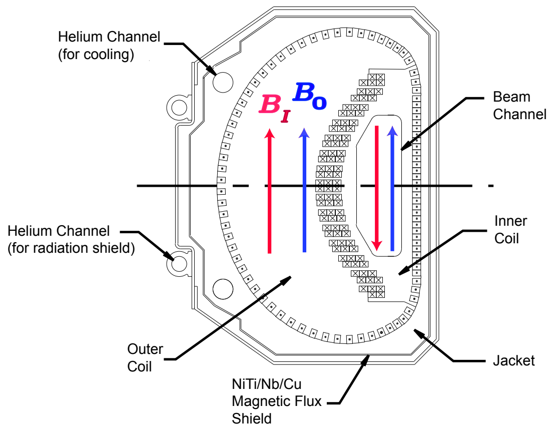


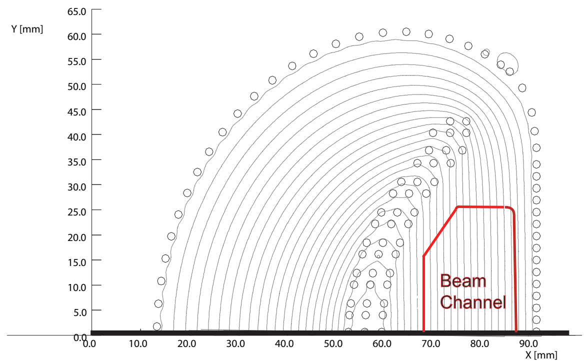

Effective gradient $G \approx (1+\cos(63.9))/2\ (\Delta B_y/\Delta R)$

IBMS: A system of 3 detectors to monitor the beam during injection

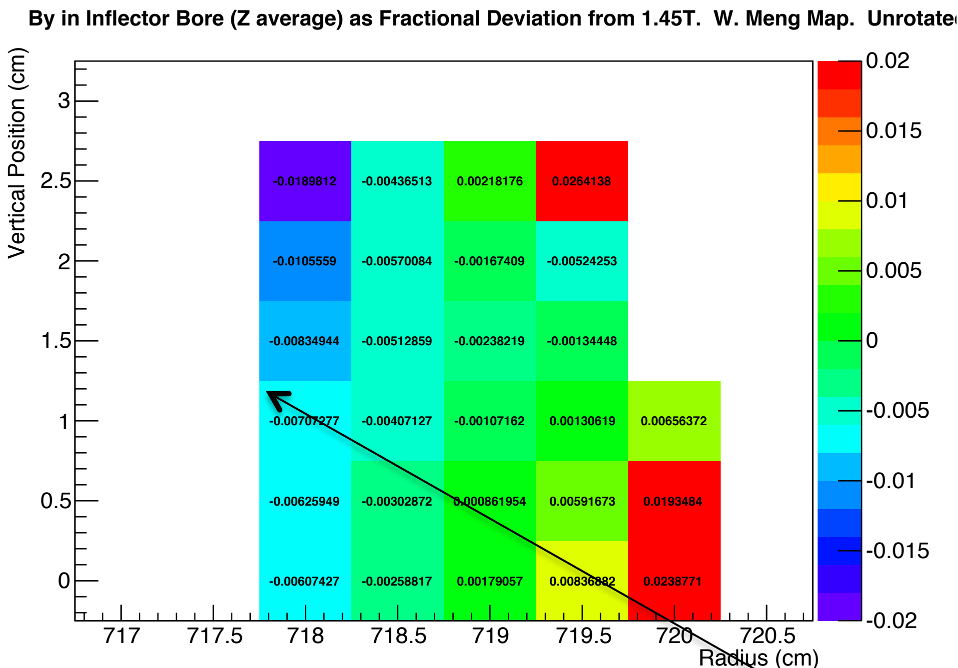



Cryostat
Central Orbit
Inflector Body
~1.7 m
Inflector
Services
μ
Fixed NMR
Probe
central
orbit
Muon Beam Vacuum Chamber


Helium Channel
(for cooling)
Beam
Channel
Inner
Coil
Helium Channel
(for radiation shield)
Outer
Coil
Jacket
NiTi/Nb/Cu
Magnetic Flux
Shield


Y [mm]
X [mm]
Beam
Channel

# Inflector field gradient




Inflector field map

$$\frac{\Delta B_y}{\Delta x} \sim 0.02 \left( \frac{1.45\text{T}}{0.018\text{m}} \right) = 1.6\text{T/m}$$

$$\rightarrow k \sim -0.16\text{m}^{-2}$$

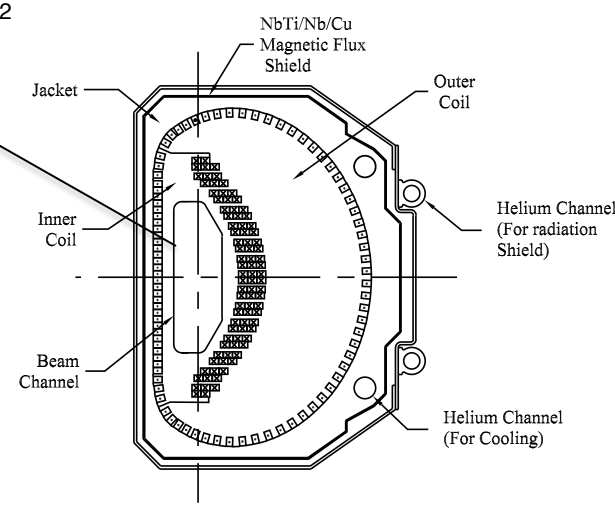
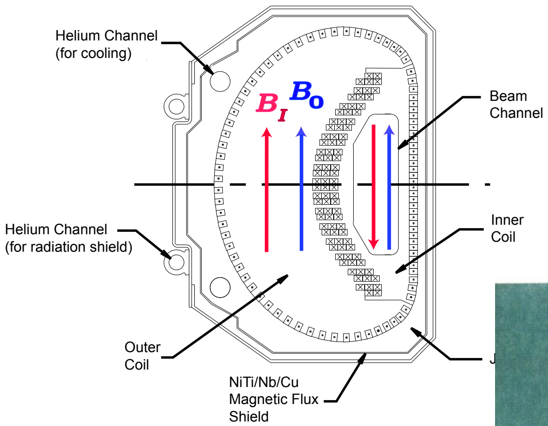
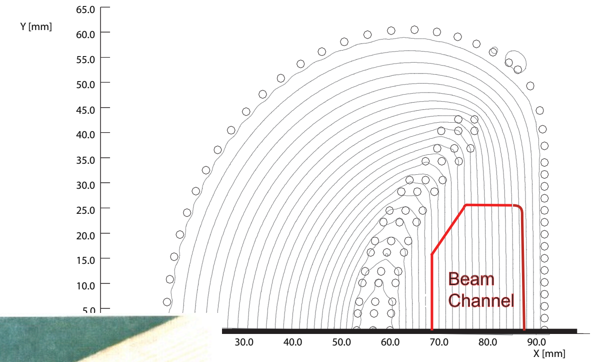
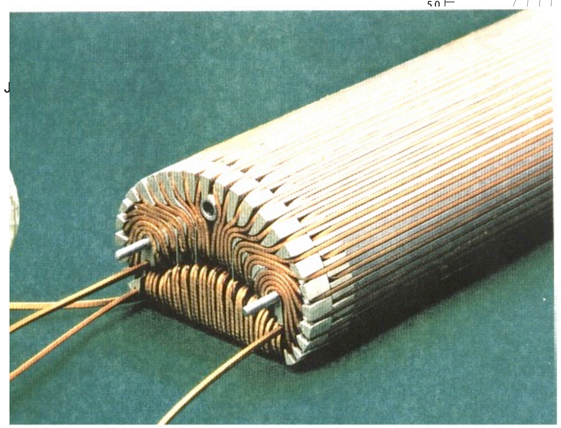



Fig. 7. Inflector cross-section.

*There is some uncertainty regarding magnitude of the gradient in the inflector : maintain flexibility*



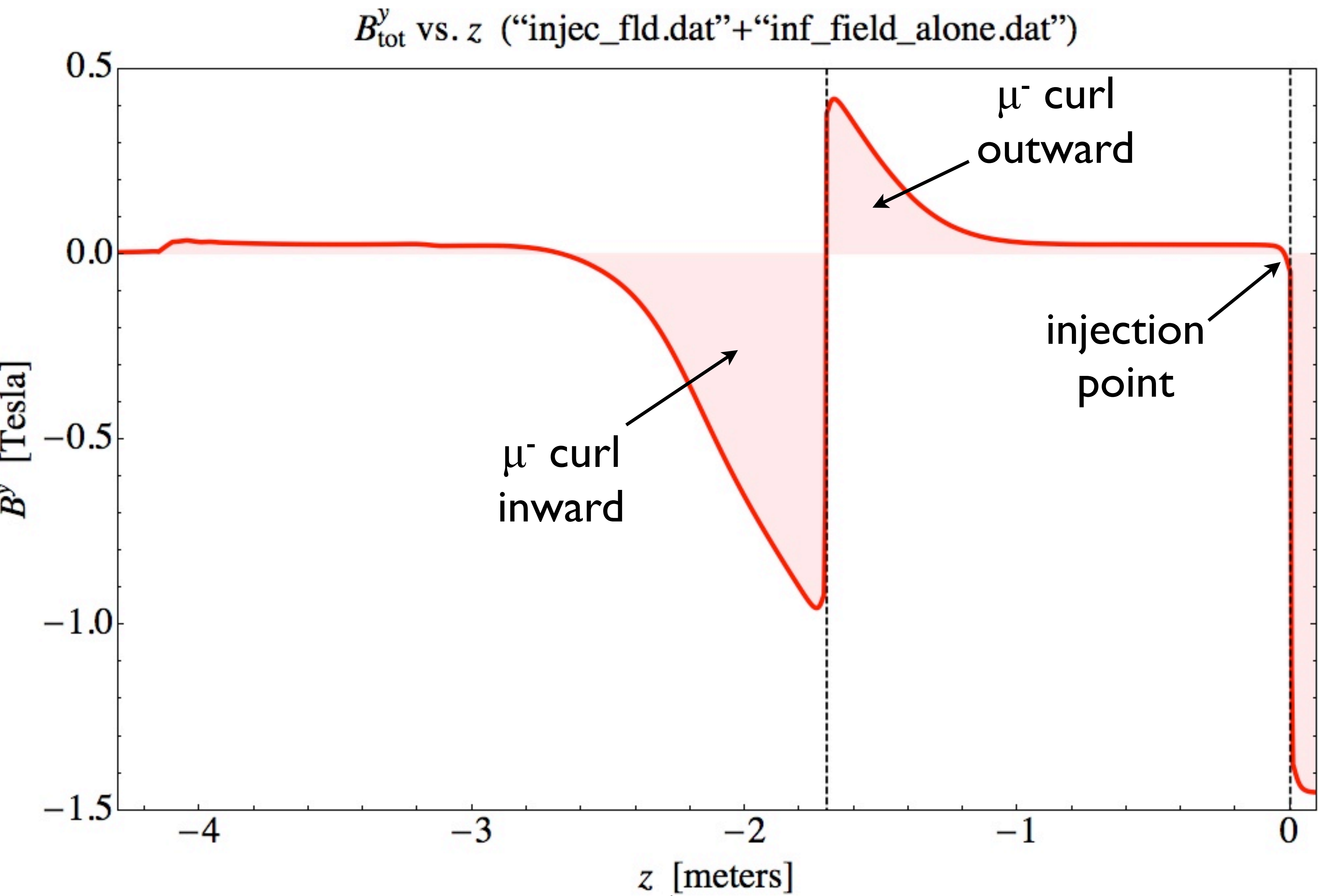



Cool storage ring magnet and power

Flux penetrates shield − Type II 0.009 T threshold

Cool shield-inflector − main field penetrates and is trapped

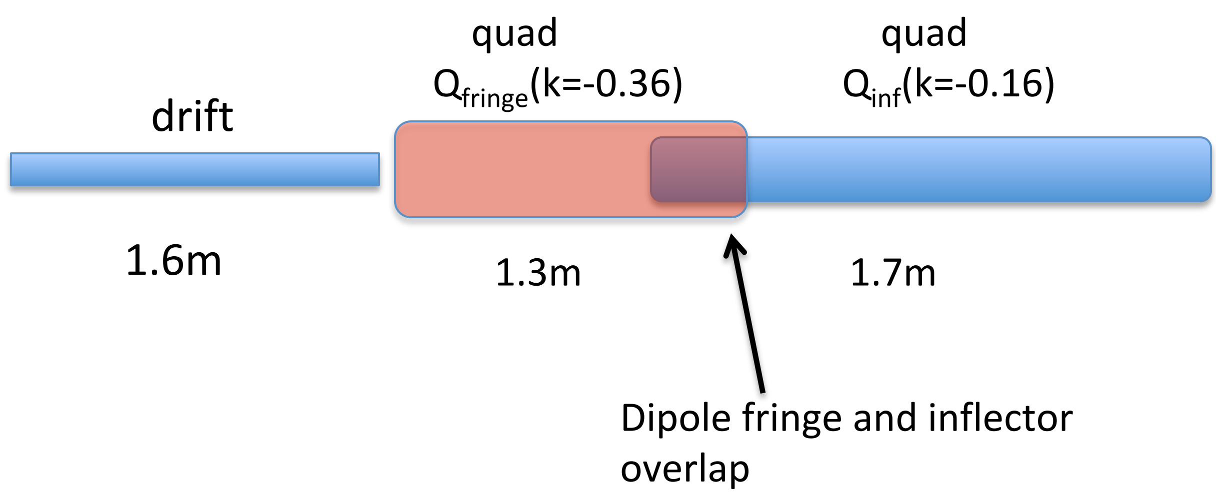
Power inflector − shield acts like perfect paramagnet



$B^y_{tot}$ vs. $z$ ("injec_fld.dat"+"inf_field_alone.dat")
0.5
0.0
−0.5
−1.0
−1.5
$B^y$ [Tesla]
−4
−3
−2
−1
0
$z$ [meters]
μ- curl outward
μ- curl inward
injection point

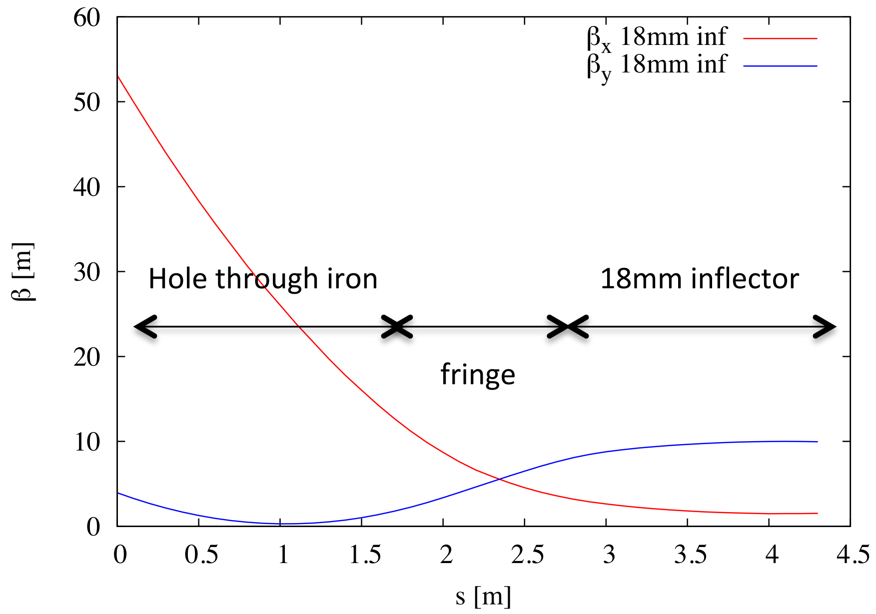
# Injection channel defocusing

The 4.3m injection channel can be modeled as follows




*Or we can compute the transfer maps numerically by tracking*

Propagation through injection channel



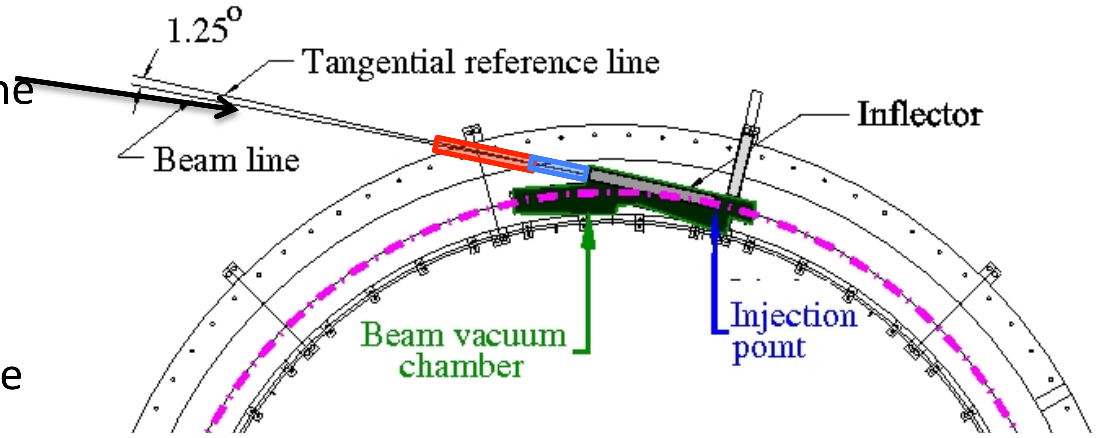

$\beta_x$ =1.5m, $\beta_y$ =10m at inflector exit

# Injection Channel

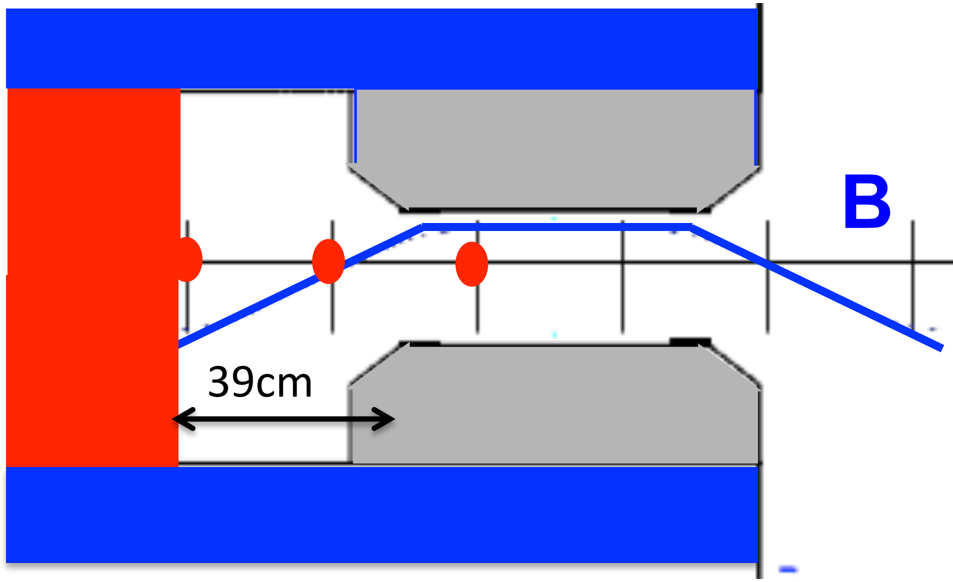
Muons come to the end of the M5 line and then propagate through:

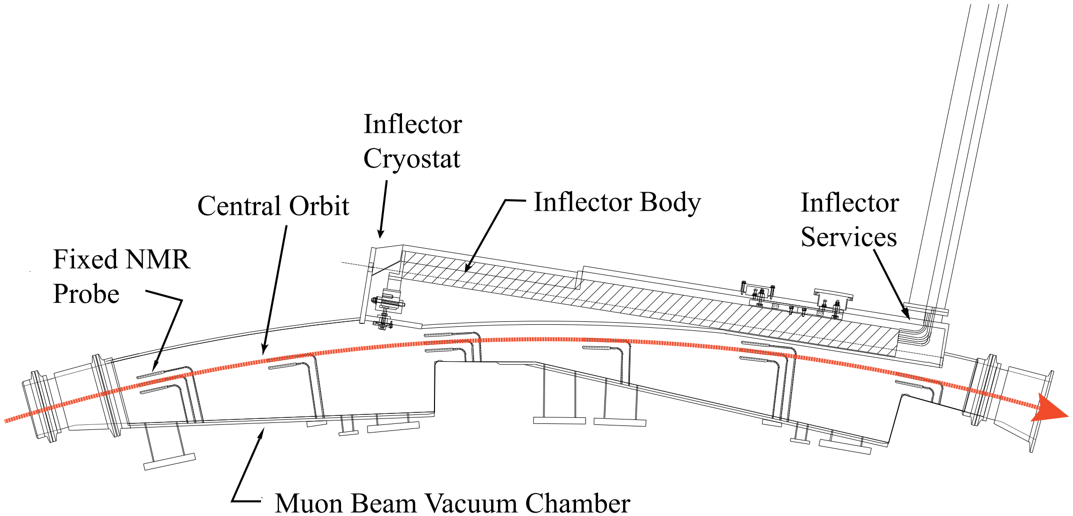
- Hole in magnet yoke
- Dipole fringe field
- Inflector

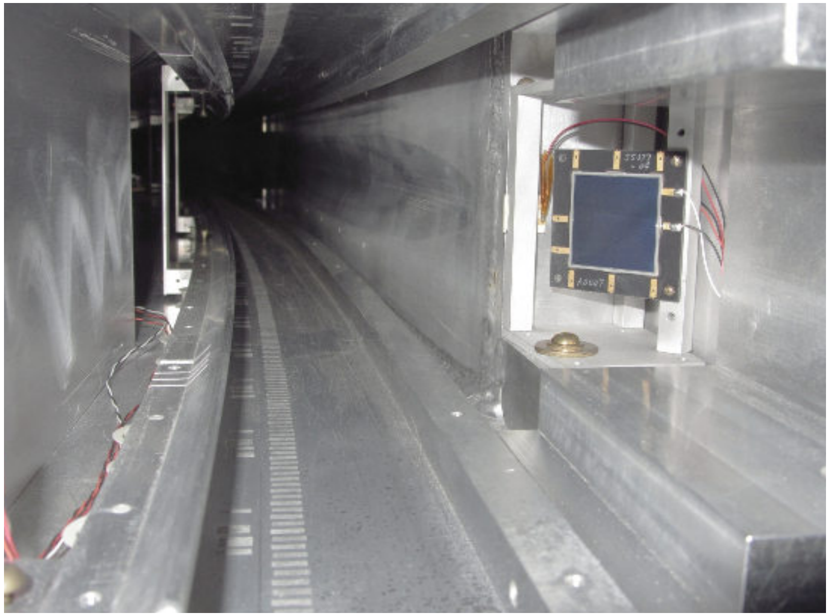
And exit the inflector 77 mm from the center of the dipole aperture

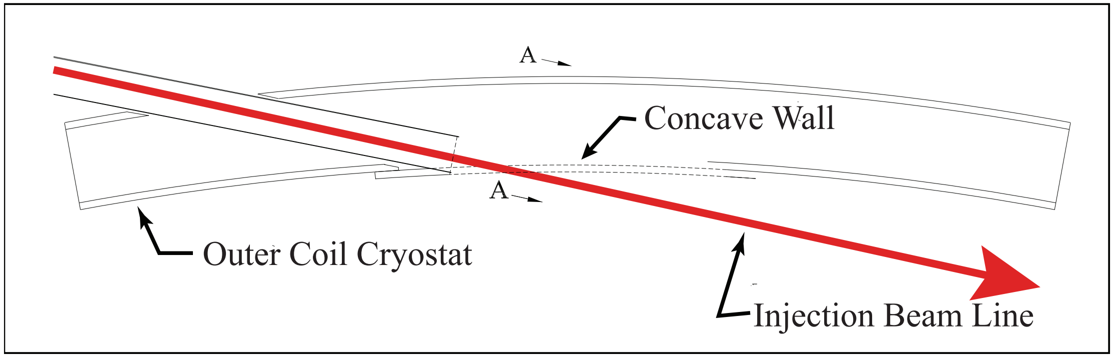



The magnetic field is near zero at the inner surface of the yoke, and rises to 1.45T between the magnet poles, over a distance of ~39cm

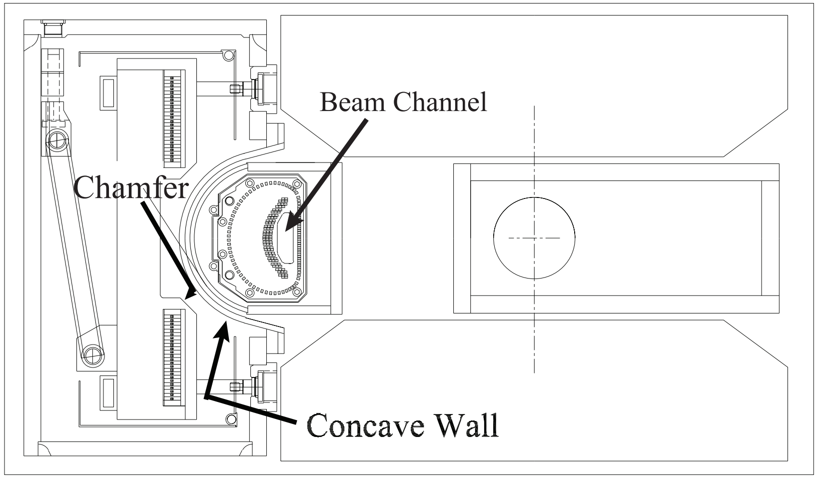



Inflector
Cryostat
Inflector Body
Central Orbit
Inflector
Services
Fixed NMR
Probe
Muon Beam Vacuum Chamber

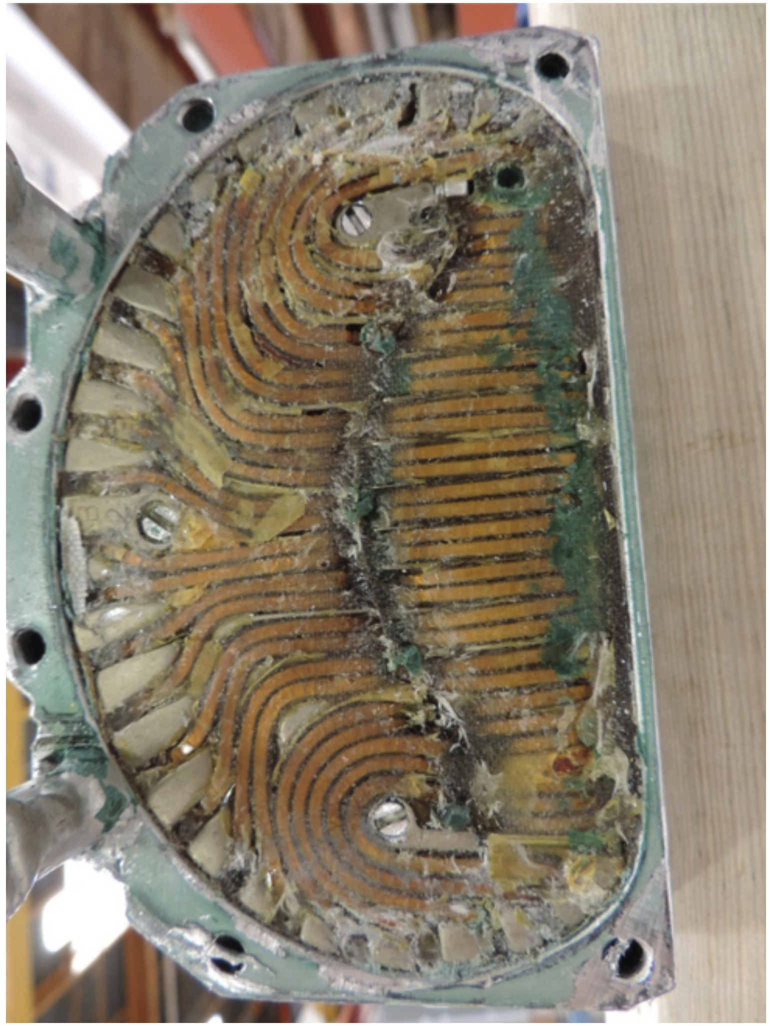


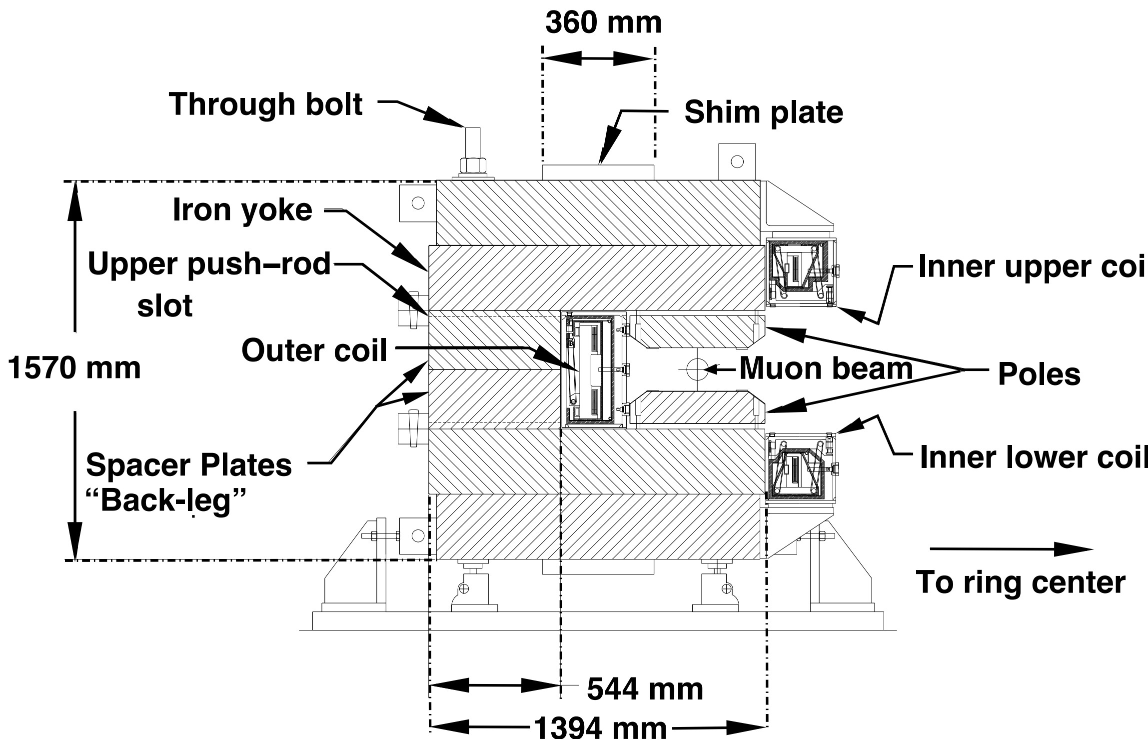


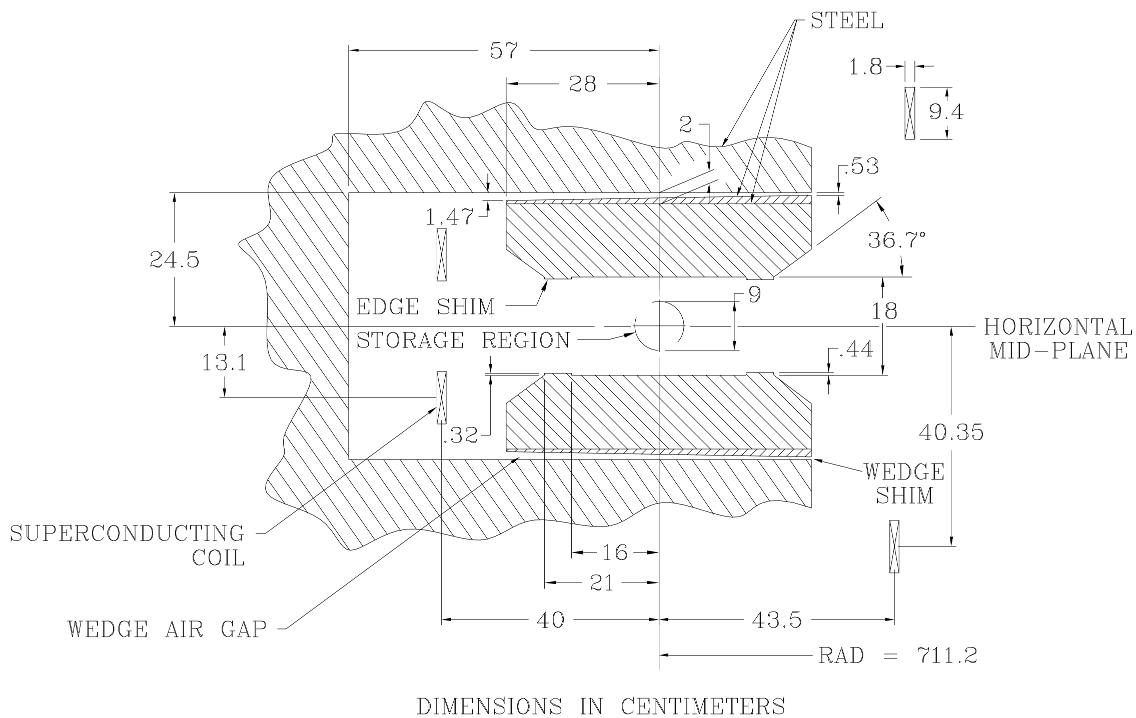
A
Concave Wall
A
Outer Coil Cryostat
Injection Beam Line

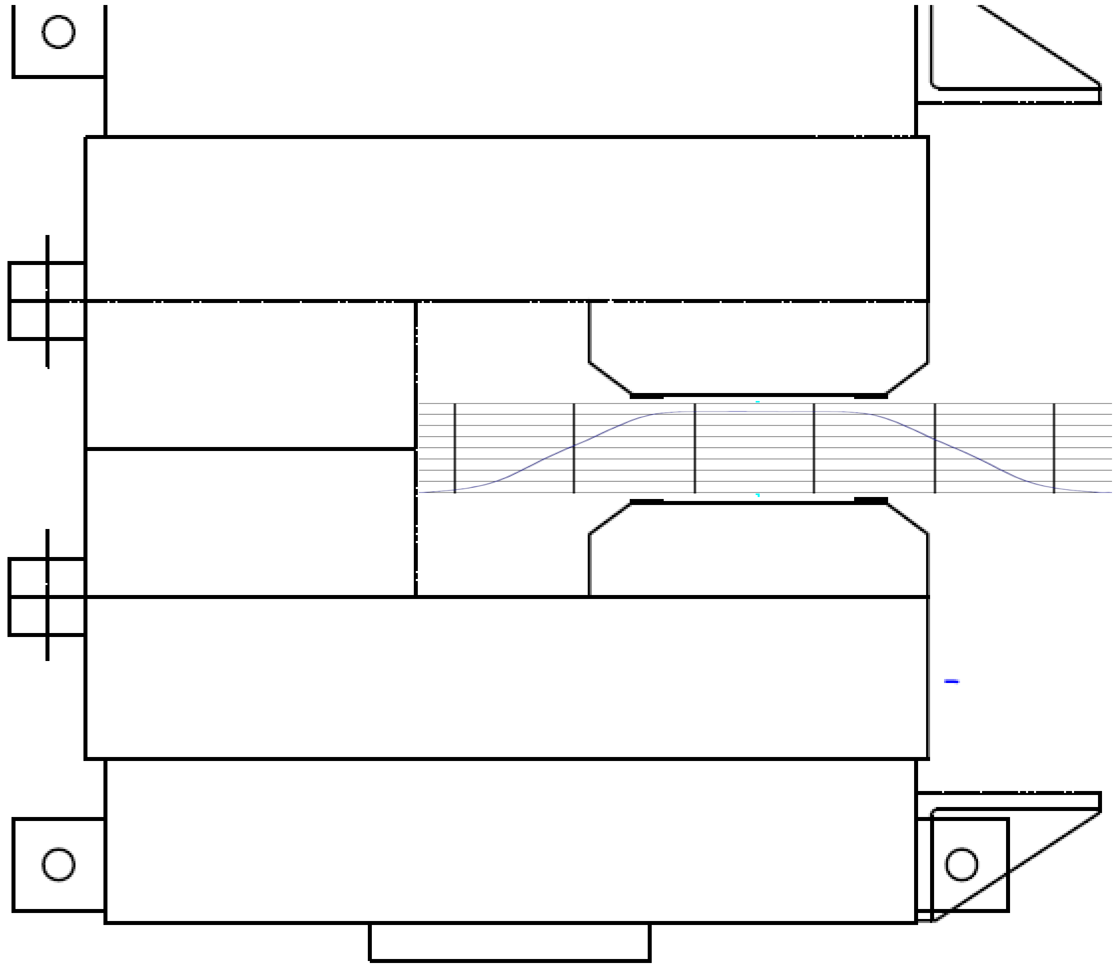
Beam Channel
Chamfer
Concave Wall



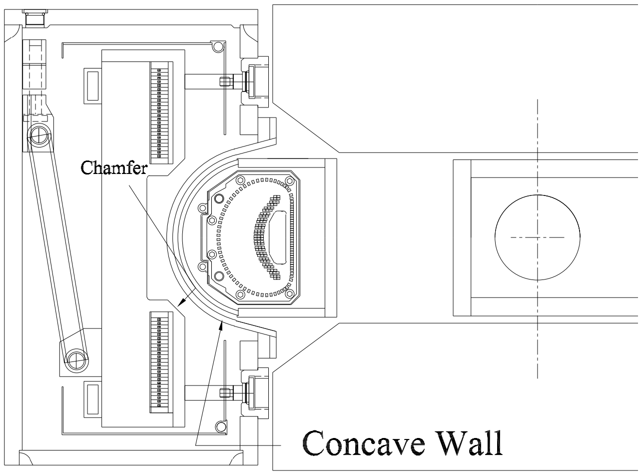

360 mm
Through bolt
Shim plate
Iron yoke
Upper push–rod slot
Inner upper coil
Outer coil
Muon beam
Poles
1570 mm
Spacer Plates "Back-leg"
Inner lower coil
To ring center
544 mm
1394 mm

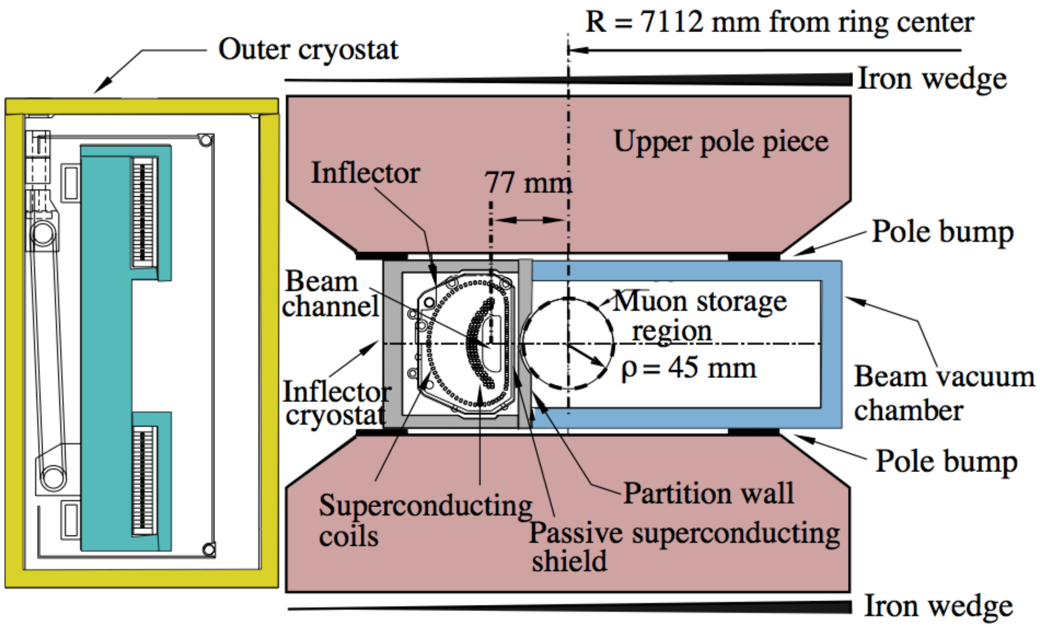

STEEL
57
28
1.8
9.4
2
.53
1.47
36.7°
24.5
EDGE SHIM
9
18
STORAGE REGION
HORIZONTAL
MID-PLANE
.44
13.1
.32
40.35
WEDGE
SHIM
SUPERCONDUCTING
COIL
16
21
WEDGE AIR GAP
40
43.5
RAD = 711.2
DIMENSIONS IN CENTIMETERS

# Cross Section of Storage Ring and Magnetic Field

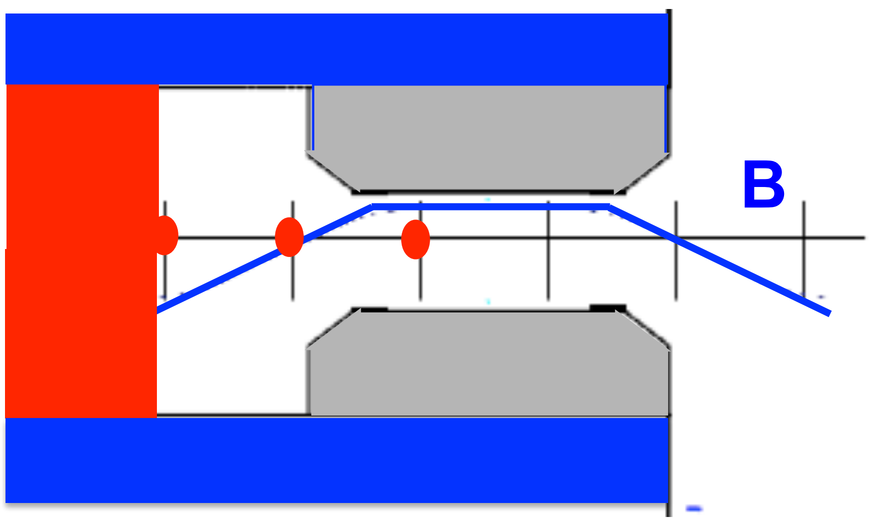


# Radial beam motion

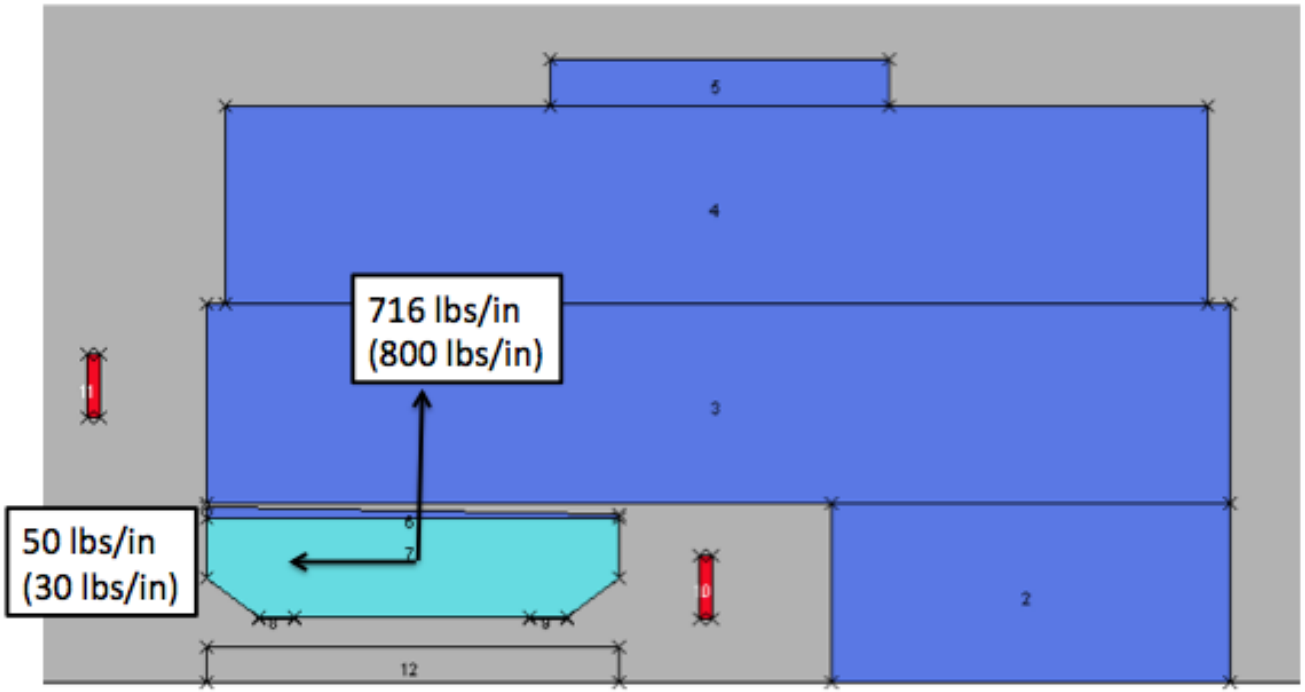


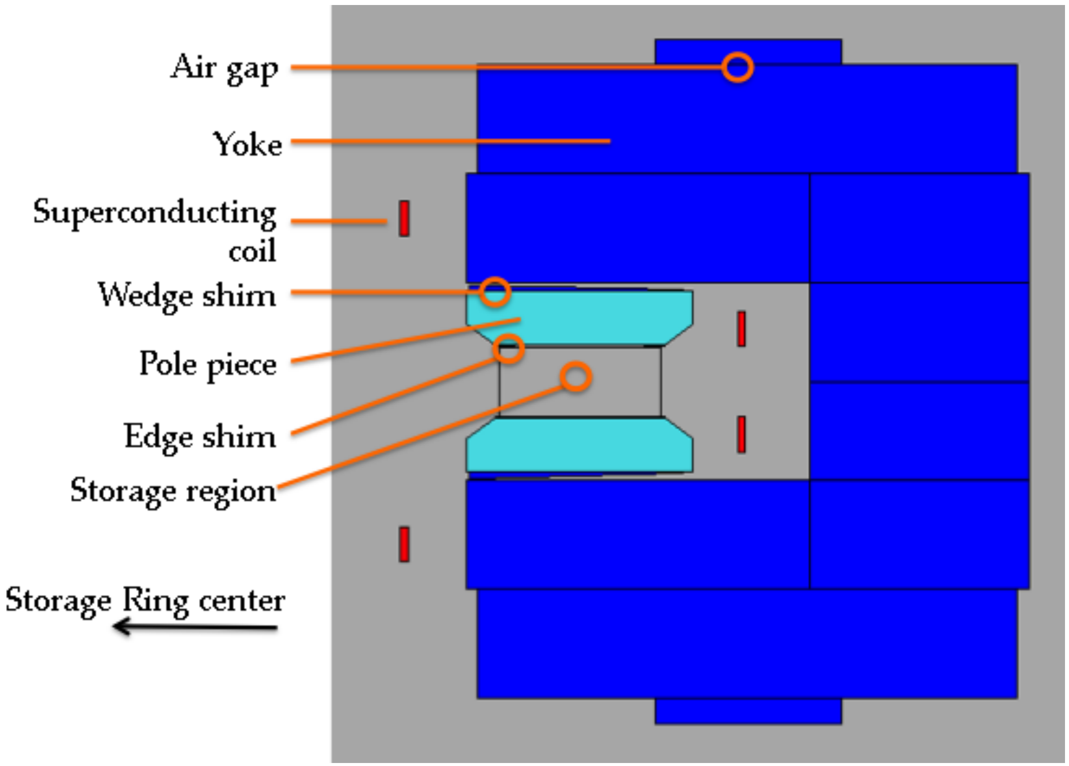




- Beam exits yoke
- Beam through outer coil
- Beam through Inflector
- Beam kicked onto orbit

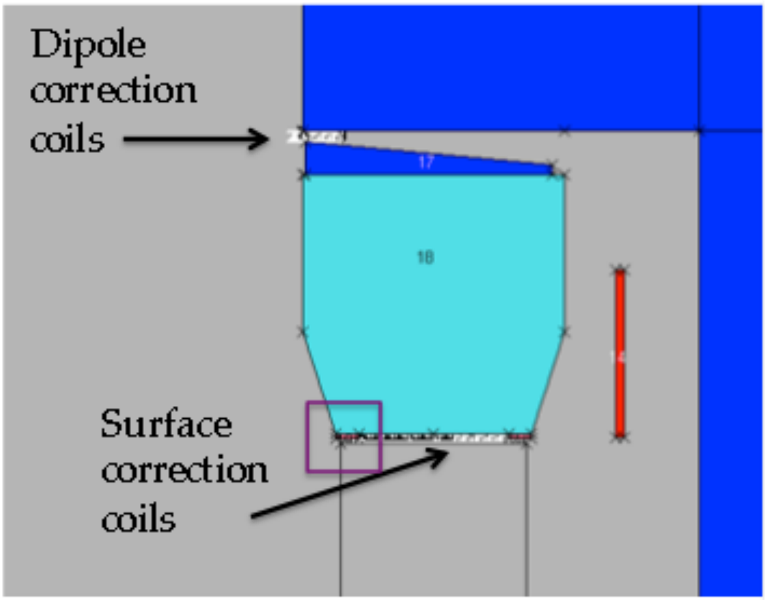


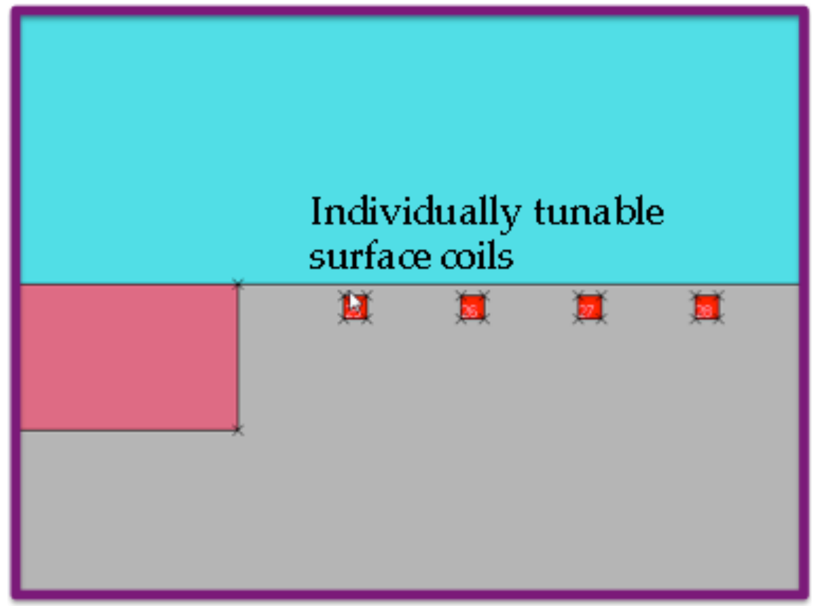
## Net Magnetic Force on an exact Pole

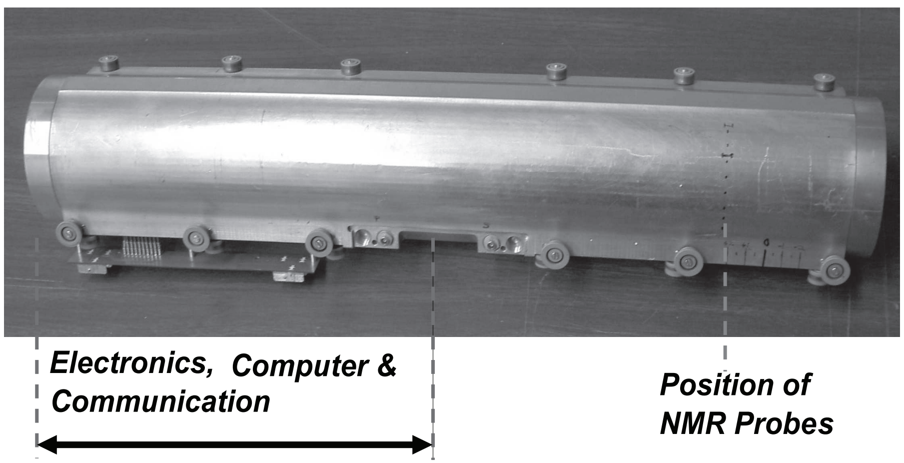




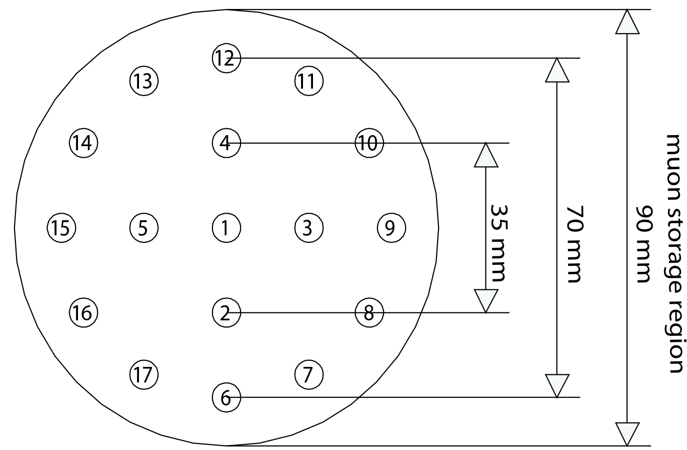
Air gap
Yoke
Superconducting coil
Wedge shim
Pole piece
Edge shim
Storage region
Storage Ring center


Dipole
correction
coils
Surface
correction
coils


Individually tunable
surface coils




(a) NMR Trolley



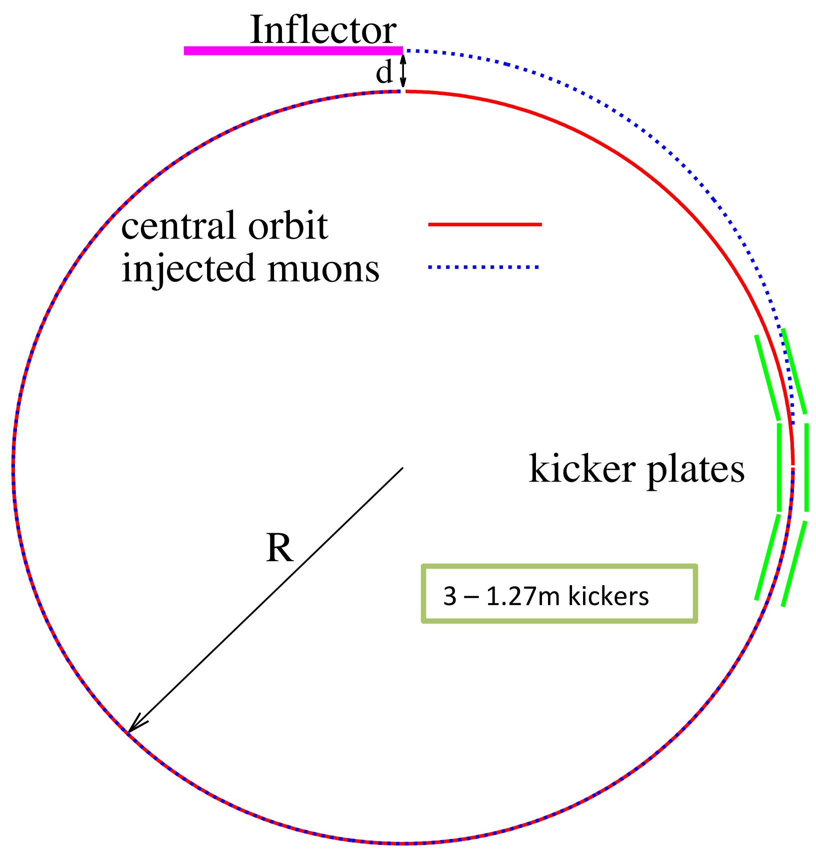

(b) Distribution of NMR probes

# Kickers

Kicker fields scale with displacement *d*

With larger aperture inflector
  d = 77mm => 91mm

Kick angle ~ 10.8 to 12.8 mrad
Integrated B-field ~ 1.11 to 1.31 kG-m




$\tau_{rev}$ = 149 ns

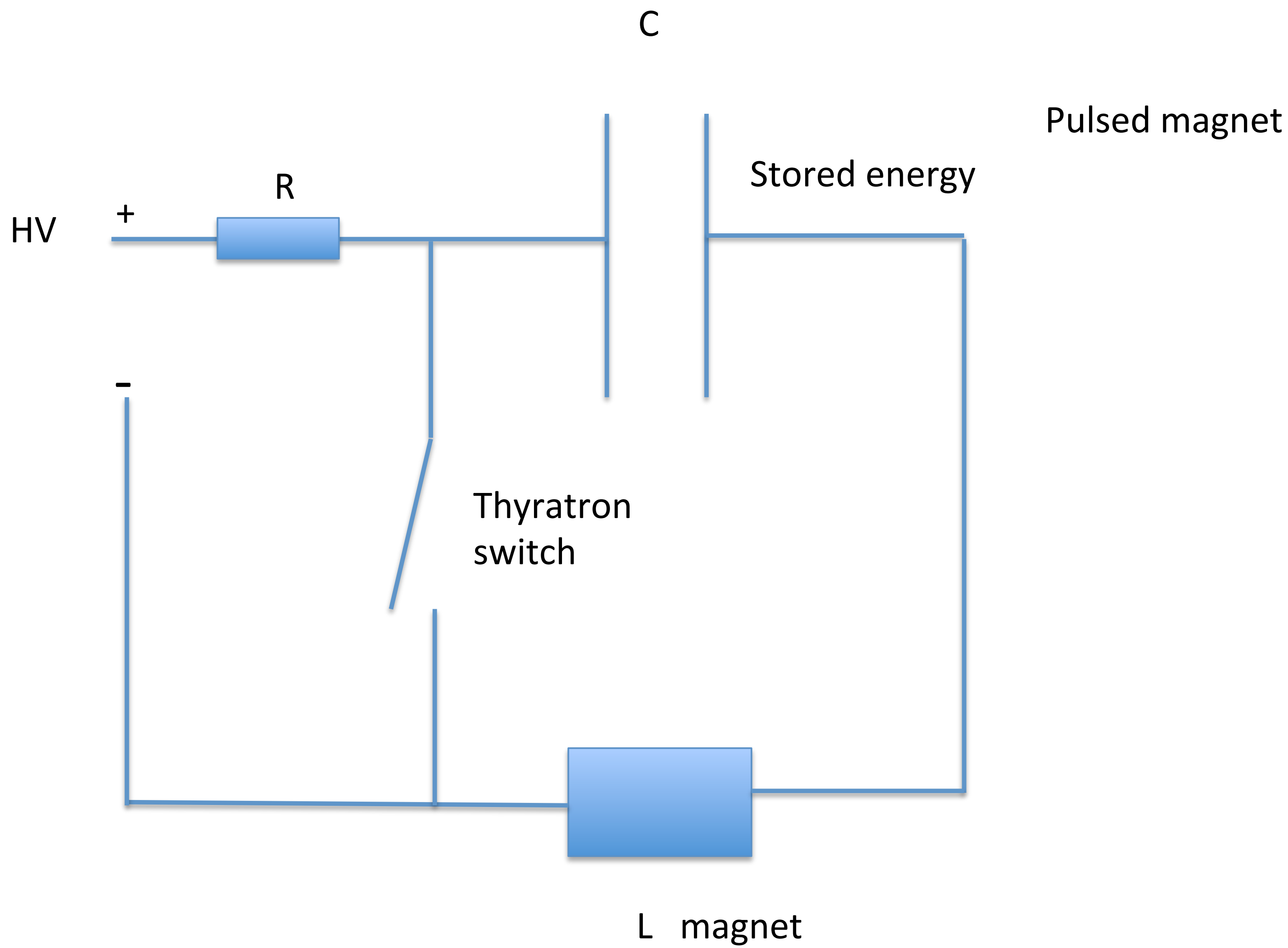
# Kicker Magnet

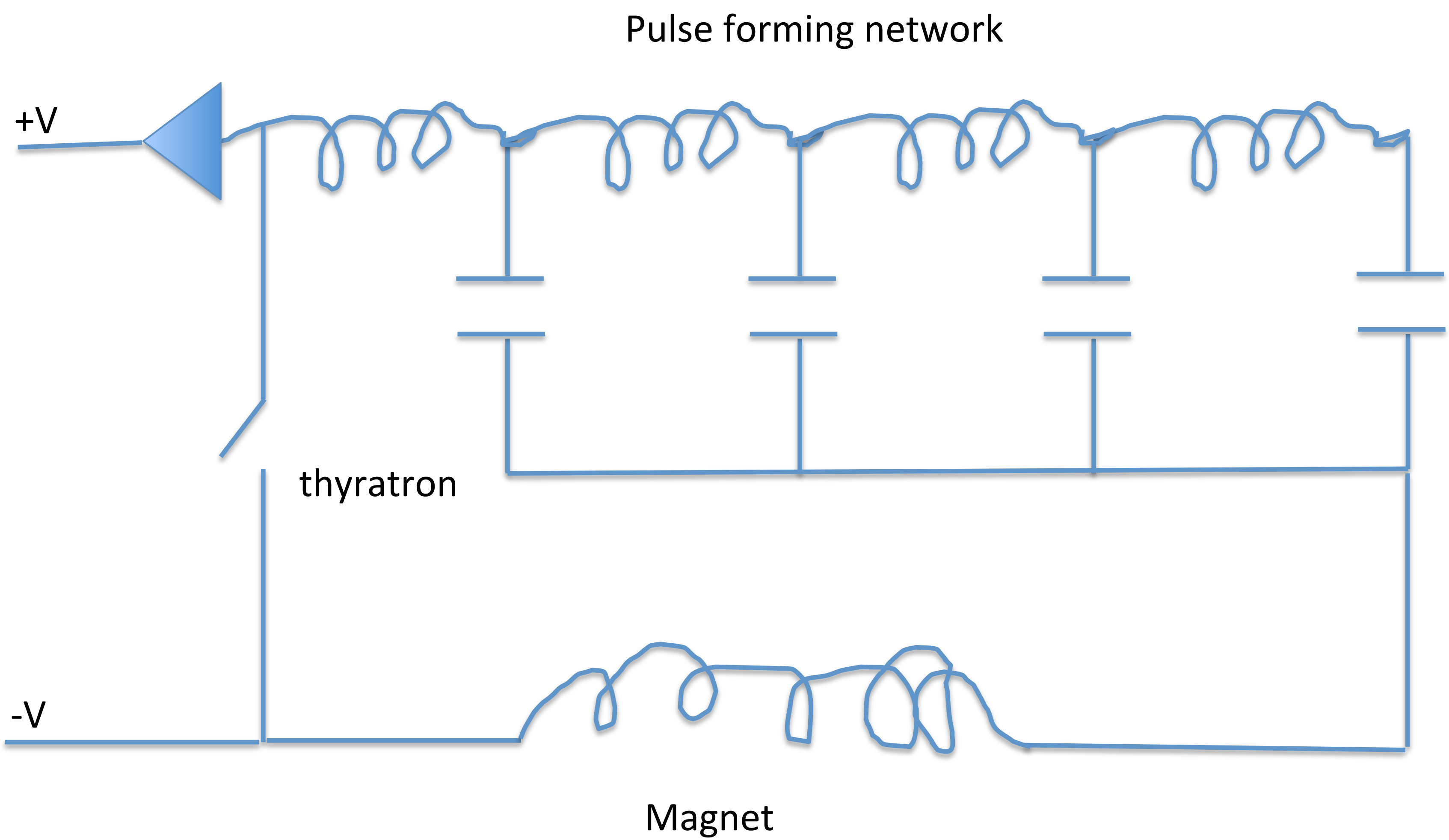
- 10.8 mrad kick corresponds to 1114 kg-m
  - 292 G for each of 3 - 1.27m long kicker magnets
  - 5000 A

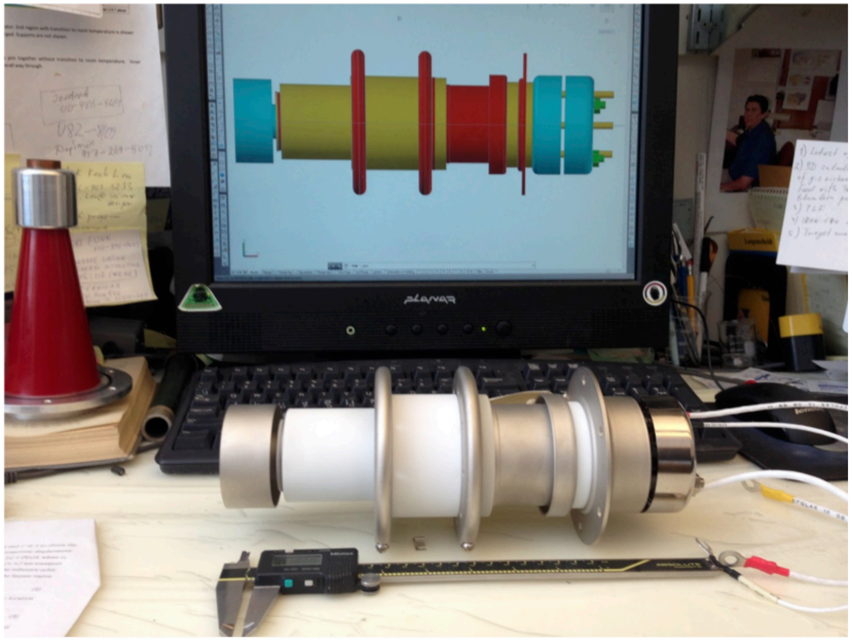
$$V = L\frac{dI}{dt}$$

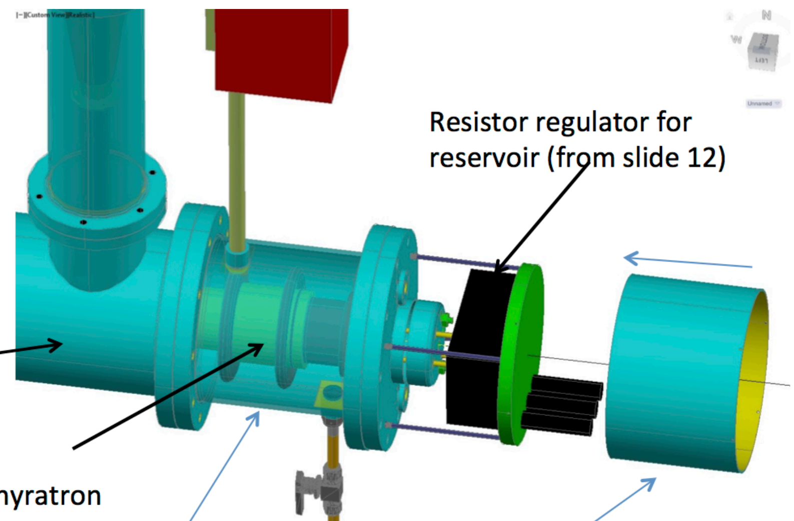
Fast pulse => high voltage

dt = 10 ns, dI = 5kA, L~ 1 micro-H => V = 100kV


C
Pulsed magnet
Stored energy
R
HV
+
-
Thyratron
switch
L magnet


Pulse forming network
+V
thyratron
-V
Magnet

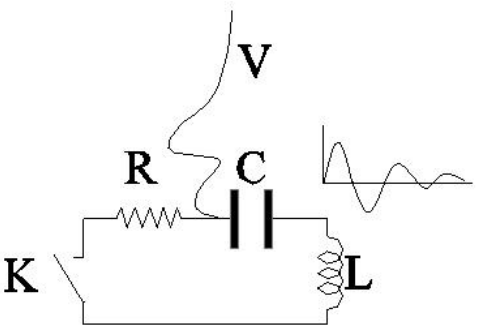




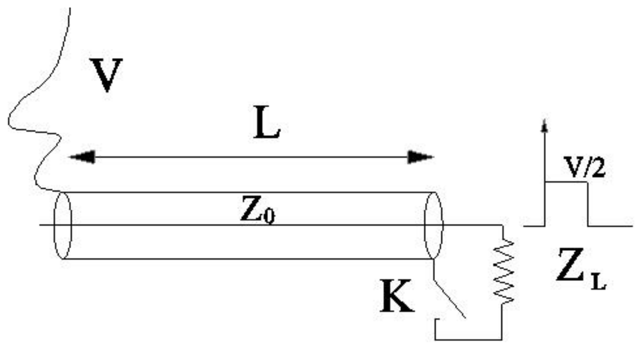

Deuterium gas filled thyratron switch

# Thyratron switch

# TO THE CHOICE OF HV PULSER SCHEME/TYPE



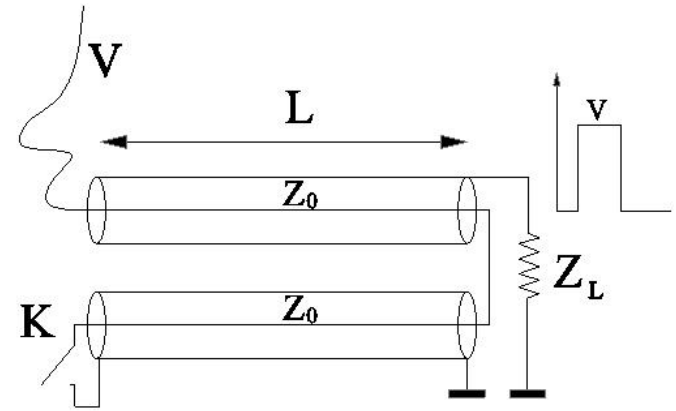

Present (old) one




Matched line

$$T = \frac{2L\sqrt{\mu_r \varepsilon_r}}{c}$$

$$V_{out} = V_{charge} \frac{Z_L}{Z_L + Z_0}$$

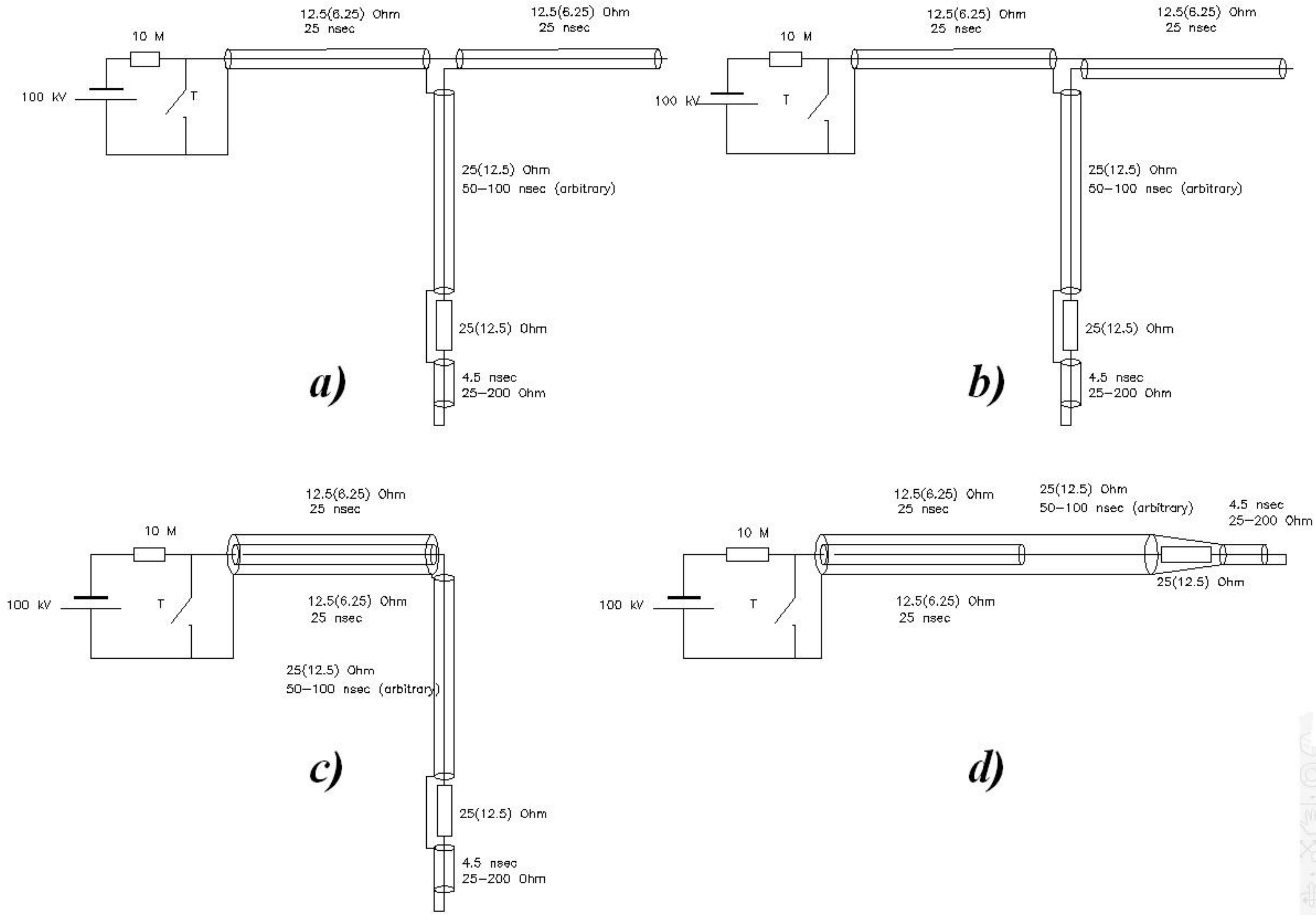



Blumline transmission line

**Double impedance**
**Double voltage**

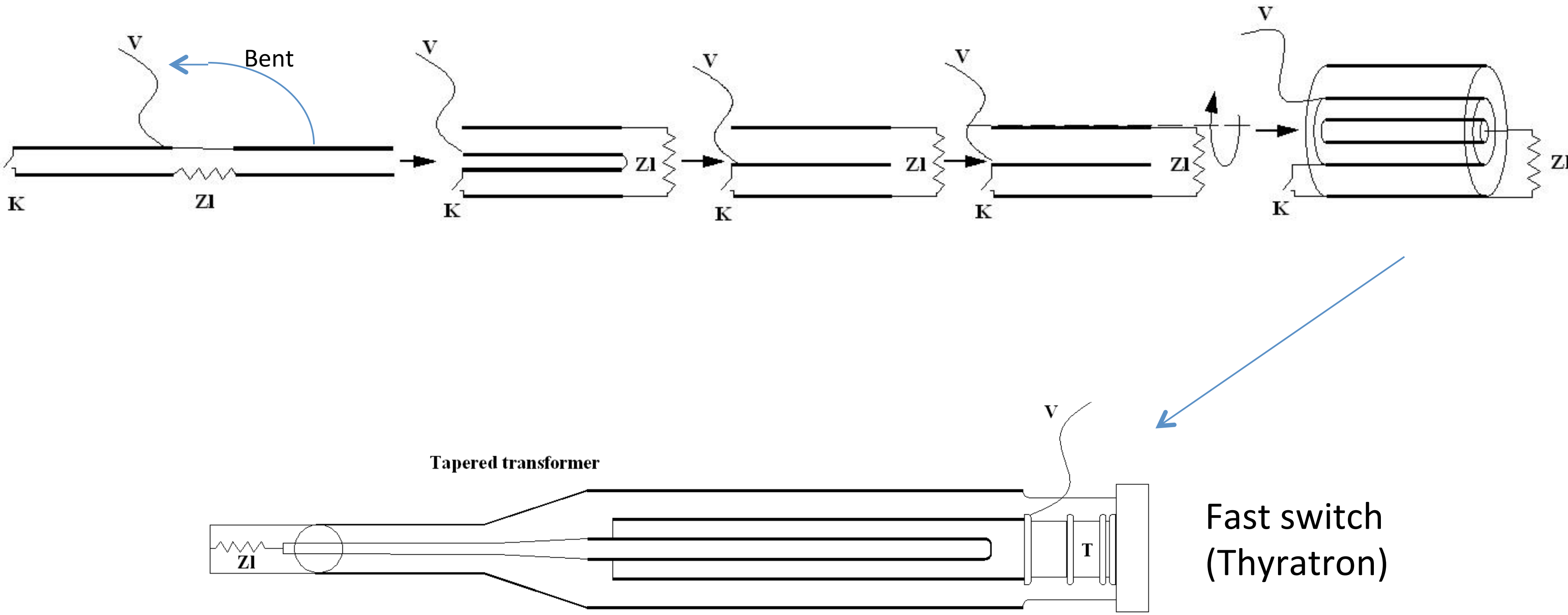
$$V_{out} = 2V_{charge} \frac{Z_L}{Z_L + 2Z_0}$$

# For modeling with PSPICE (Cadence)



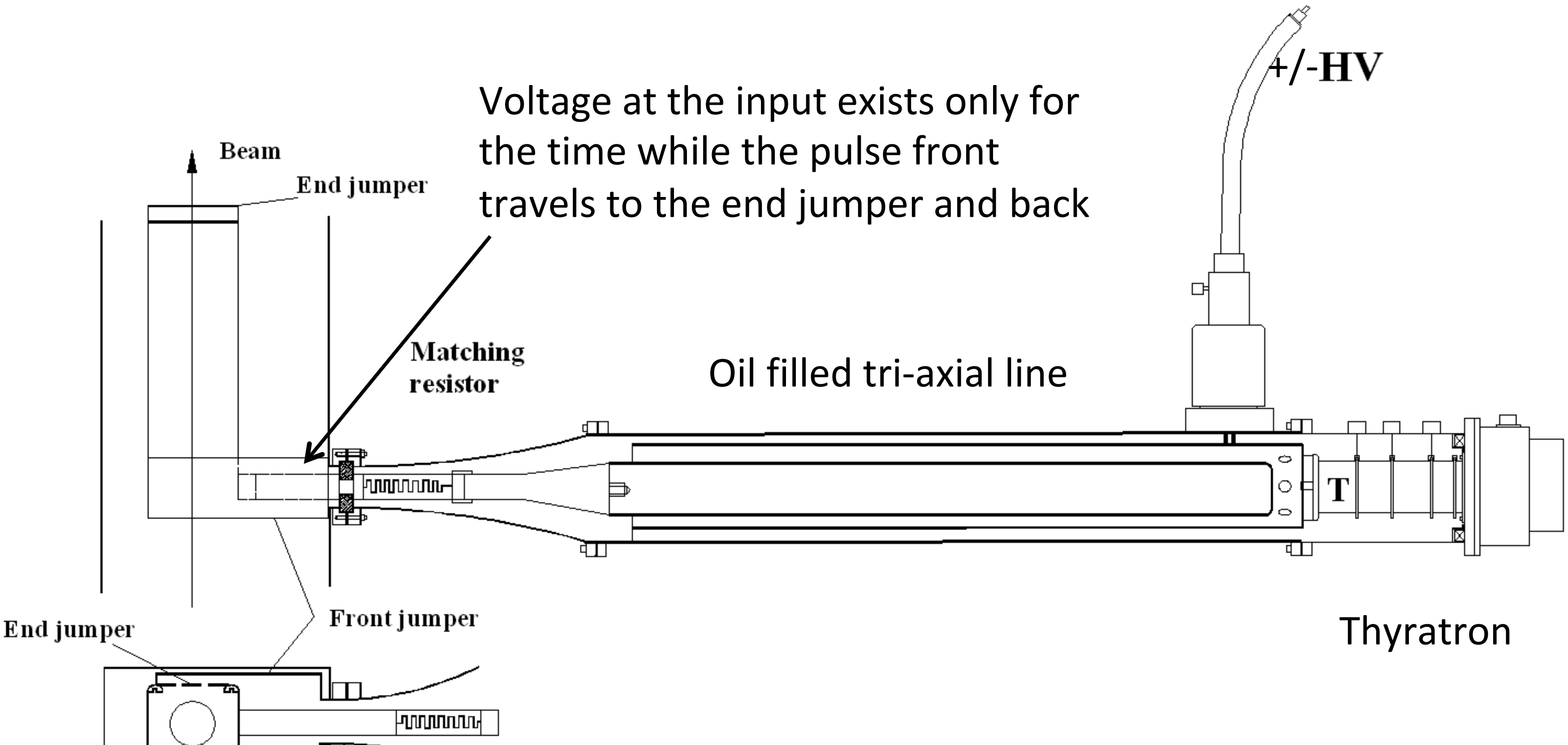

*a)* Original Blumlein scheme;
*b)* In a second coaxial the conductors are switched, so the potential of inner left coaxial is the same as the potential of outer right coaxial;
*c)* Right coaxial inserted into the left one. For this purposes its radiuses increased accordingly.
*d)* Final scheme.

# Topological transformation of Blumline scheme

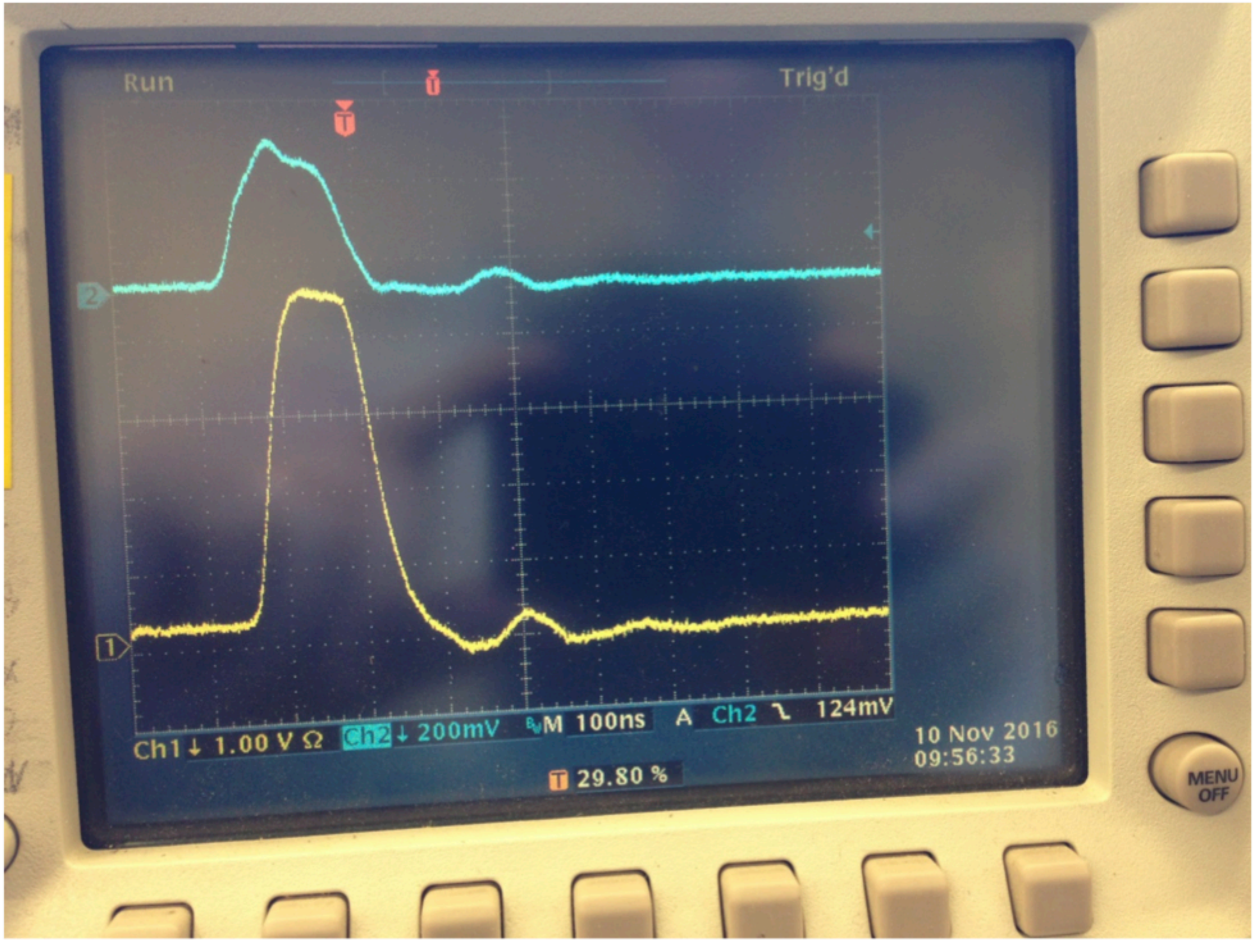



**Alan Dower Blumlein** (29 June 1903 – 7 June 1942) was a British electronics engineer, notable for his many inventions in telecommunications, sound recording, stereo, television and radar. He received 128 patents and was considered as one of the most significant engineers and inventors of his time (Wikipedia).

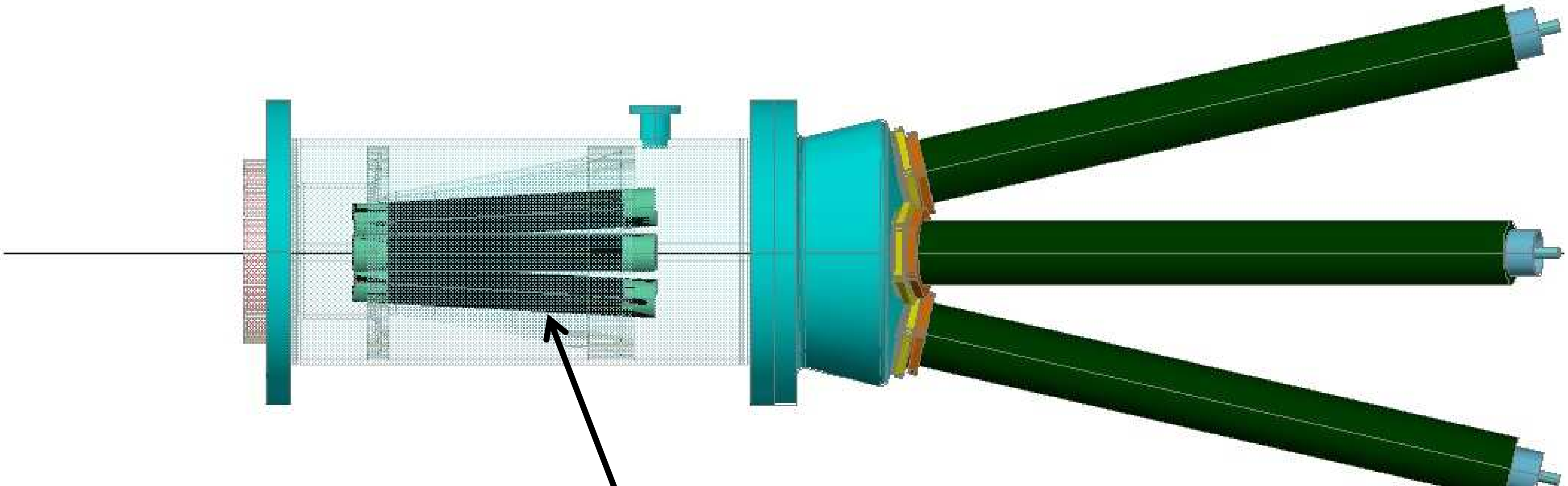
# Scheme recommended for the future




While using a ***bi-polar thyratron***, one can control the HV out-polarity

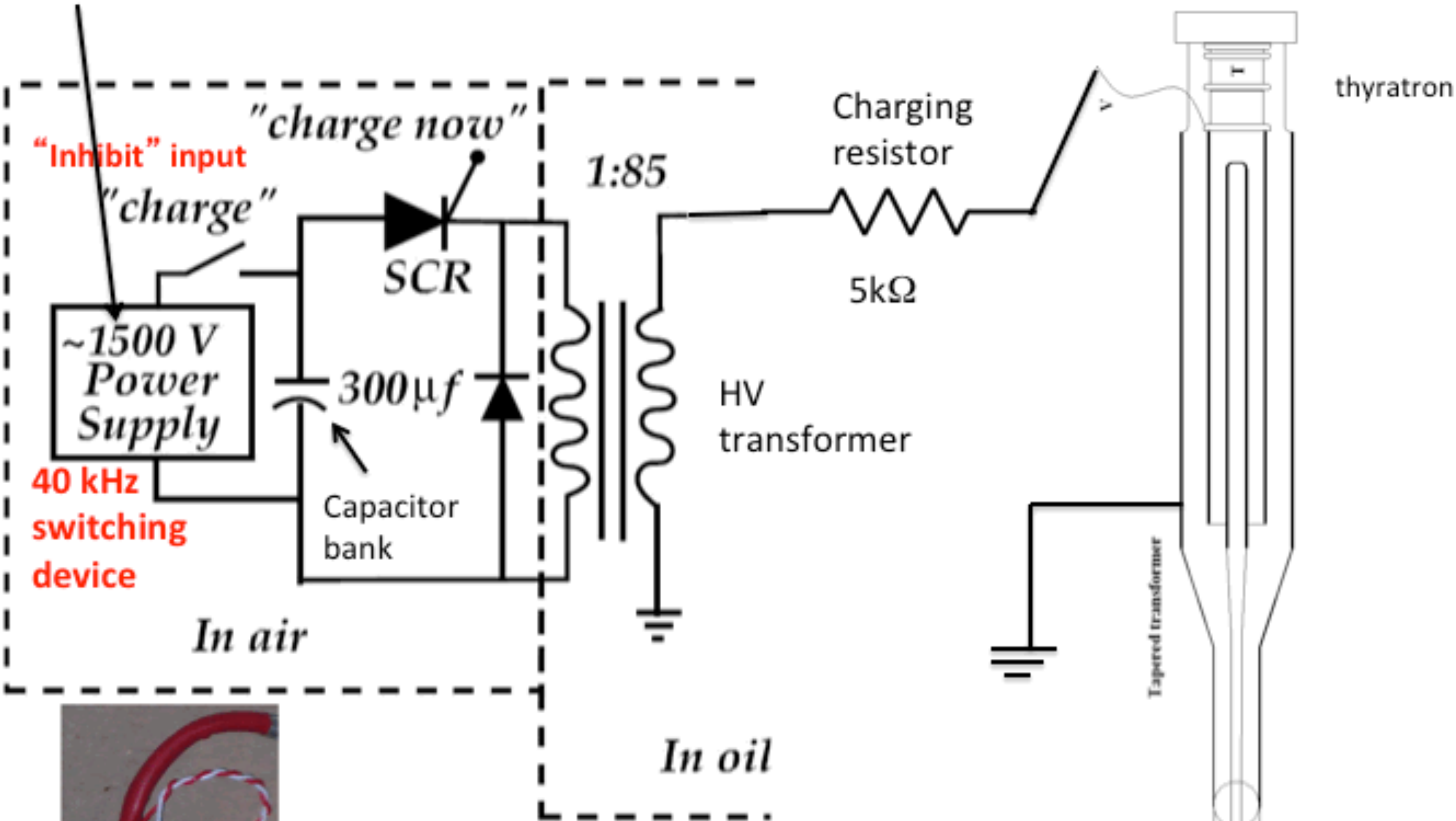

Run
Trig'd
Ch1 1.00 V Ω
Ch2 200mV
M 100ns
A Ch2 124mV
10 Nov 2016
09:56:33
29.80 %
MENU
OFF

Individual load for each cable (50Ω)



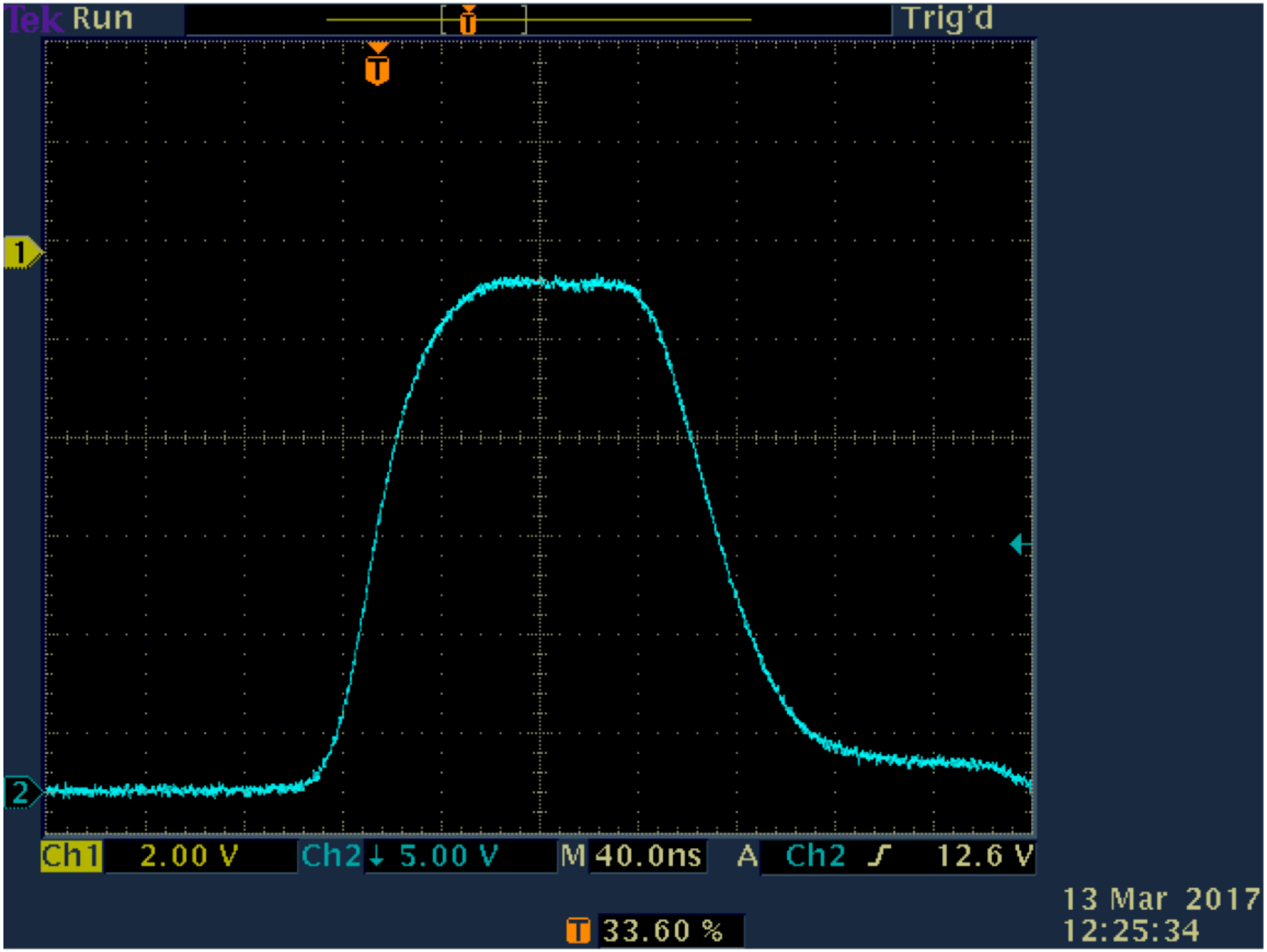
KANTHAL© resistors; 1” OD; 8” long

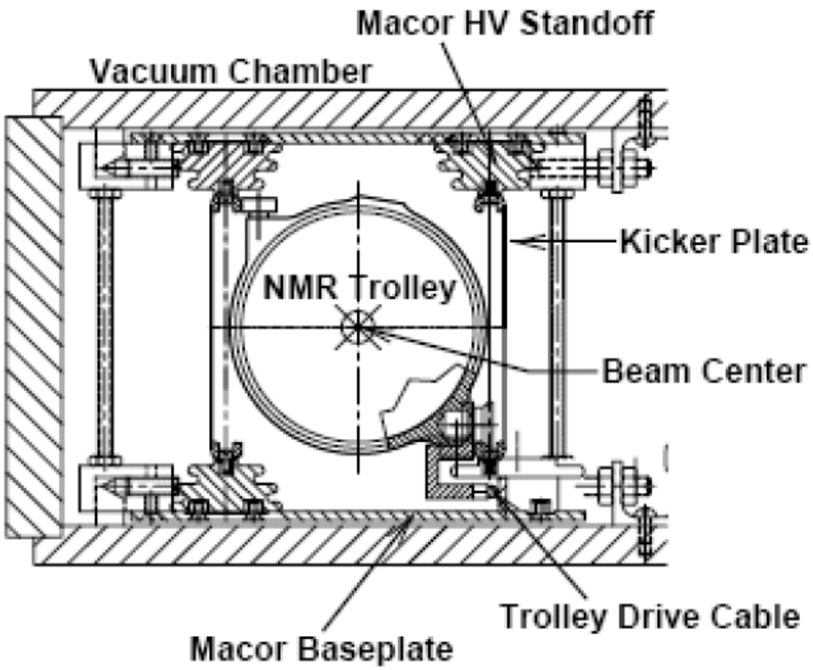
# Charging Circuit




SCR — Silicon Controlled Rectifier -Thyristor

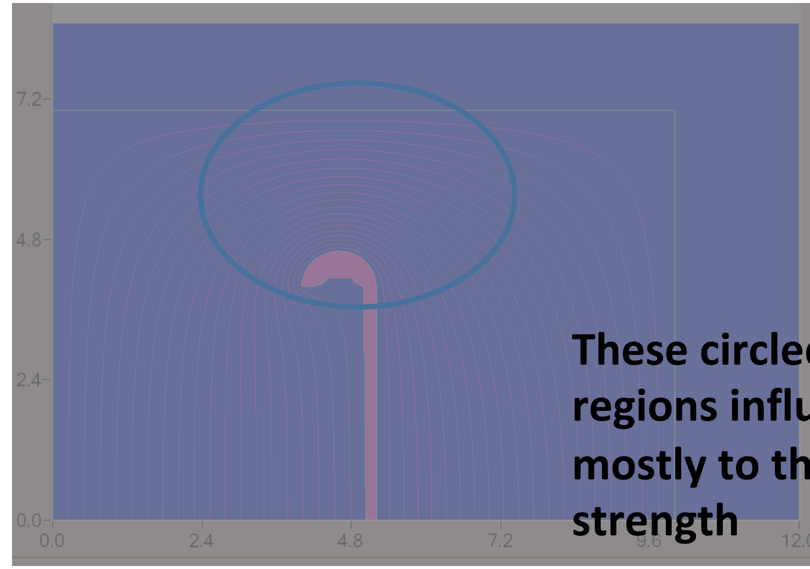
The time between "charge now" and the thyratron triggering ~ 2 ms


Tek Run
Trig'd
1
2
Ch1 2.00 V
Ch2 ↓ 5.00 V
M 40.0ns
A Ch2 ∫ 12.6 V
13 Mar 2017
12:25:34
33.60 %



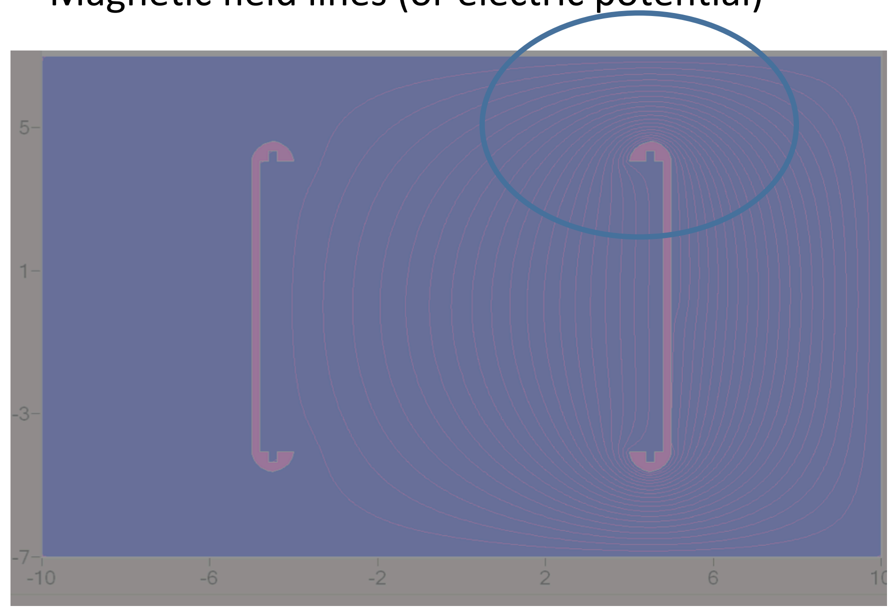

Kicker has 3 identical sections of 1.76 m-long each

Each section feed by its individual HV pulser



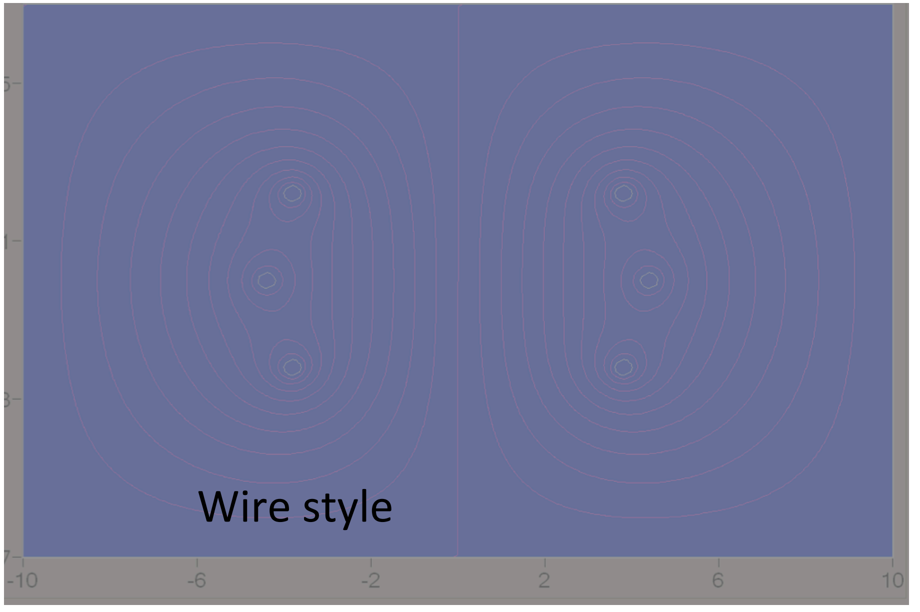

**These circled regions influence mostly to the field strength**

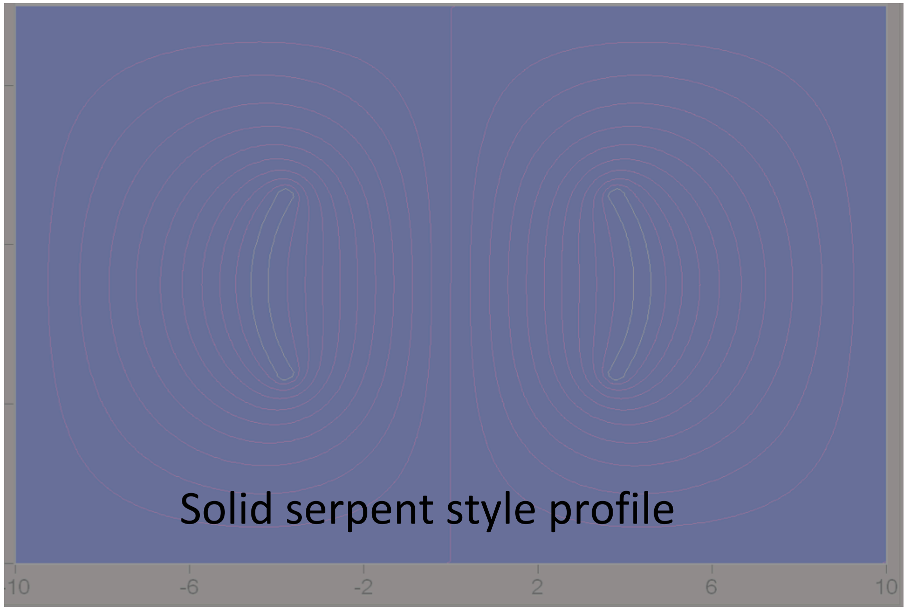
Magnetic field lines (or electric potential)




Field distribution in transient moments

# Some profiles of kicker electrodes and guidelines




L.Roberts, “Kicker R&D Work Plan: Options and Time Estimates”, New Muon (g-2) Technical Note #003, August 14, 2008.

***Make the impedance of the stripline kicker as low as possible;***
Lower impedance yields lower voltage for a given current that runs in the plates.

***Make the field distribution either more homogenous*** or with appropriate dependence on the transverse coordinate, if necessary by injection.

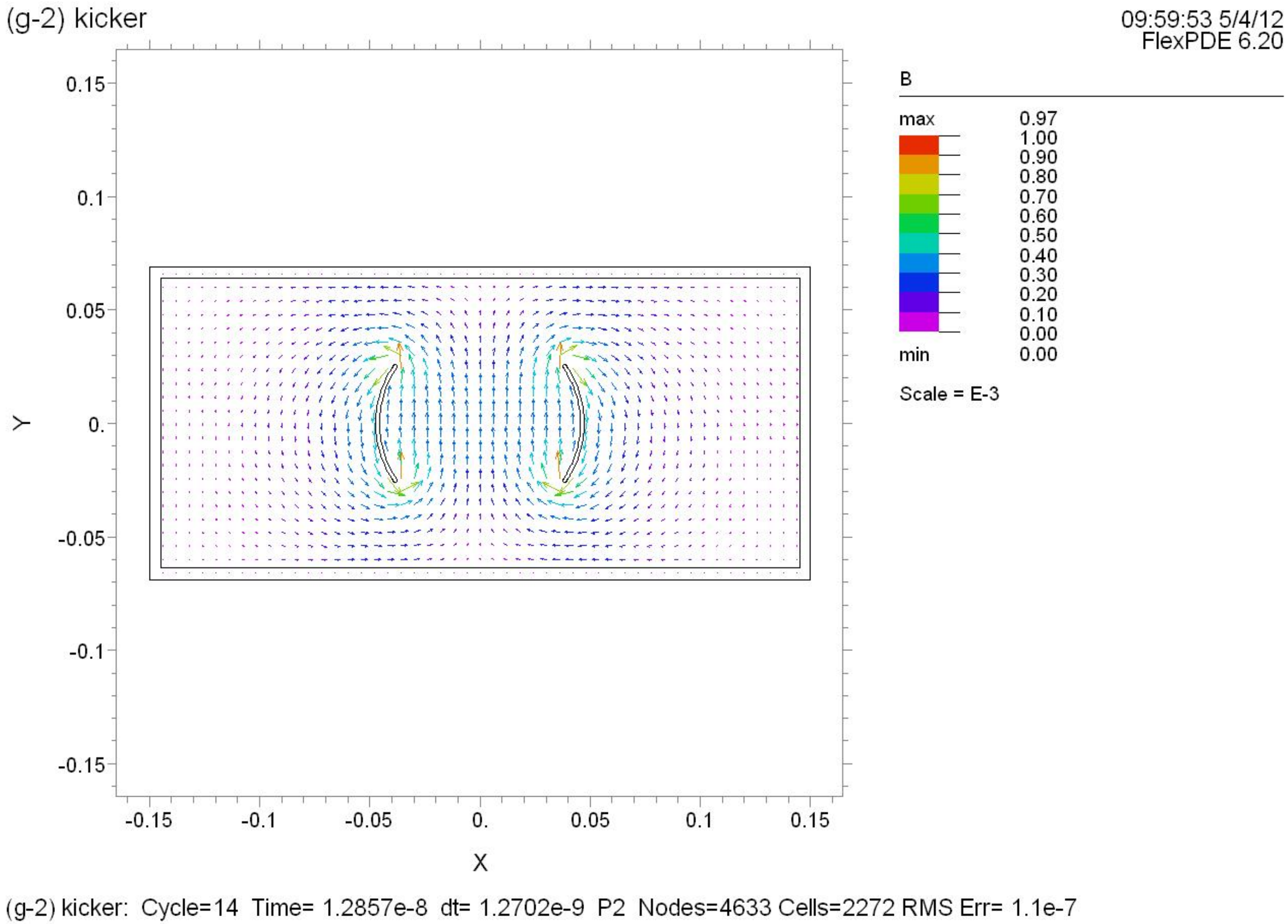
***Choice of materials*** should be done carefully, taking into account nonzero susceptibility.

***Stray fields in surroundings are another subject for research.*** Good conductors allow reduction of the fields capture in a skin layer, but circulation time for the currents captured in a skin-layer becomes longer, so careful analyses required here.

**Profile of electrodes will be chosen with appropriate 3D modeling**

**3D field calculation is in progress with FlexPDE**

Plans to do this with HFSS and CTS studio (License granted)




Field distribution in a transverse plane

Picture from “Final report on the Muon E821 Anomalous Magnetic Moment Measurement at BNL” (arXiv:hep-ex/0602035v1 20 Feb 2006)

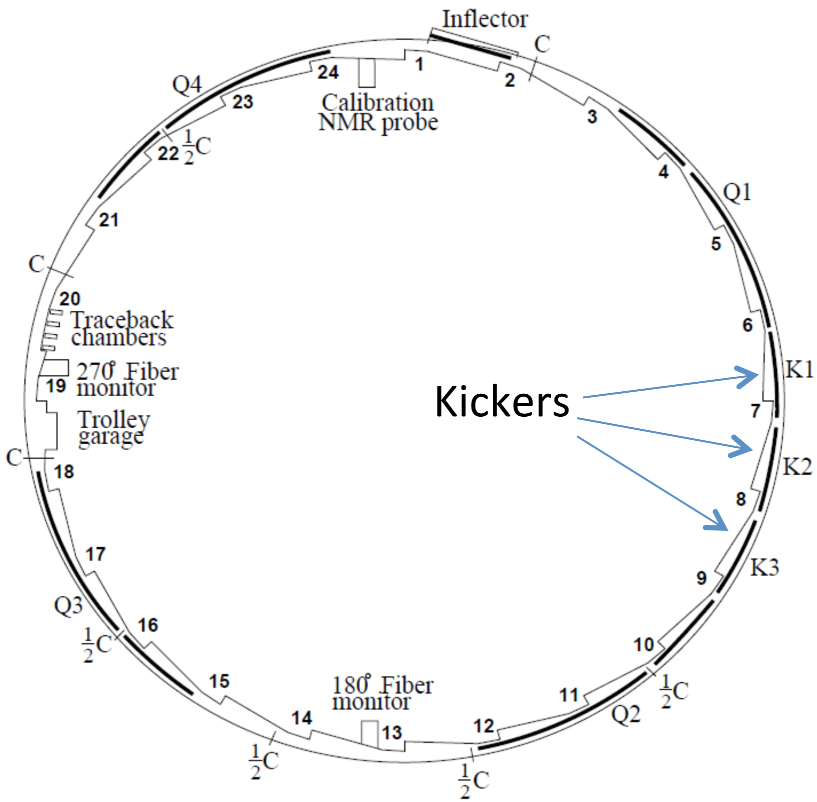



FIG. 8: The $(g-2)$ storage ring layout. The 24 numbers represent the locations of the calorimeters immediately downstream of the scalloped vacuum chamber subsections. Inside the vacuum are four quadrupole sections (Q1-Q4), three kicker plates (K1-K3) and full-aperture (C) and half-aperture ($\frac{1}{2}$C) collimators. The traceback chambers follow a truncated scalloped vacuum chamber subsection.

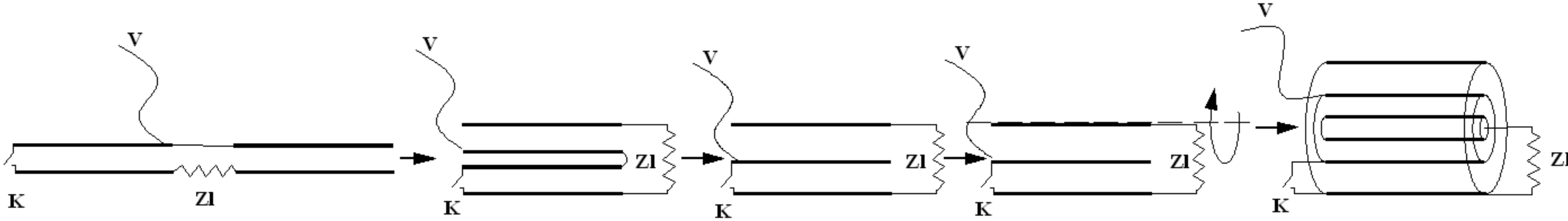
Selected muon storage ring parameters

| Parameter | Value |
|---|---|
| Nominal magnetic field | 1.4513 T |
| Nominal current | 5200 A |
| Equilibrium orbit radius | 7.112 m |
| Muon storage region diameter | 90 mm |
| Magnet gap | 180 mm |
| Stored energy | 6 MJ |

# Current Generator

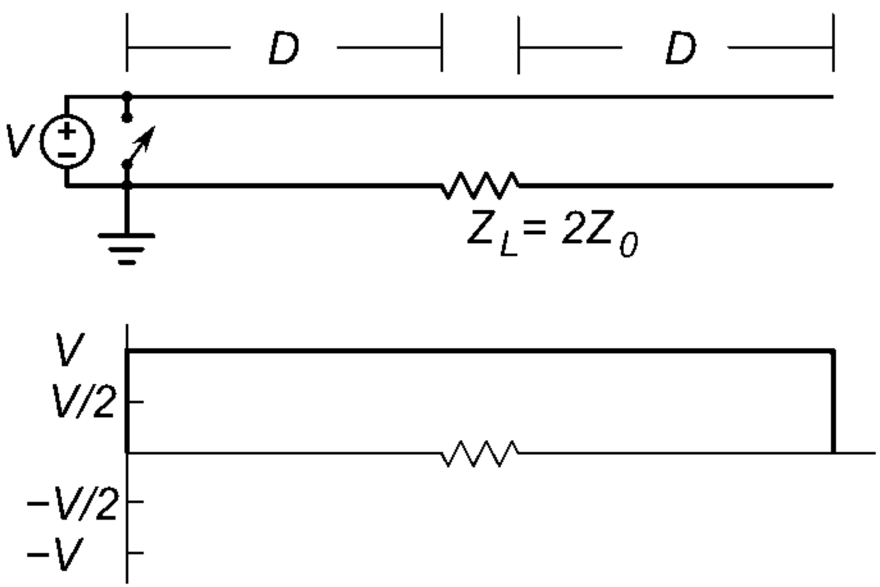
- 12.5 Ω Blumlein triaxial transmission line
- Assembled from 6 – 60 inch sections (20 ns/section) (30 ft long)
- Filled with Castor oil, ε=4.7, (pulse length τ α √ε) *(as compared to Corning 561 silicon oil, ε=2.7)*
- Concentric tubes are separated with teflon standoffs (we plan to replace with macor)
- Two grid(fast) thyratron – rated for up 70kV – 15kA (7.5 kA in load)
- Coupled via 4 parallel 50Ω coaxial cables and resistors (12.5 Ω equivalent) to the kicker magnet

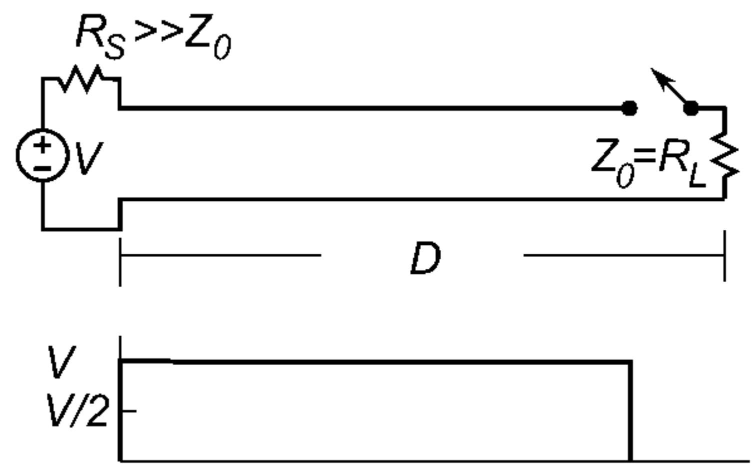
# Blumlein Pulse Forming Network




Blumlein
- voltage at load is equal to charging voltage
- Base of switch (thyratron) at ground

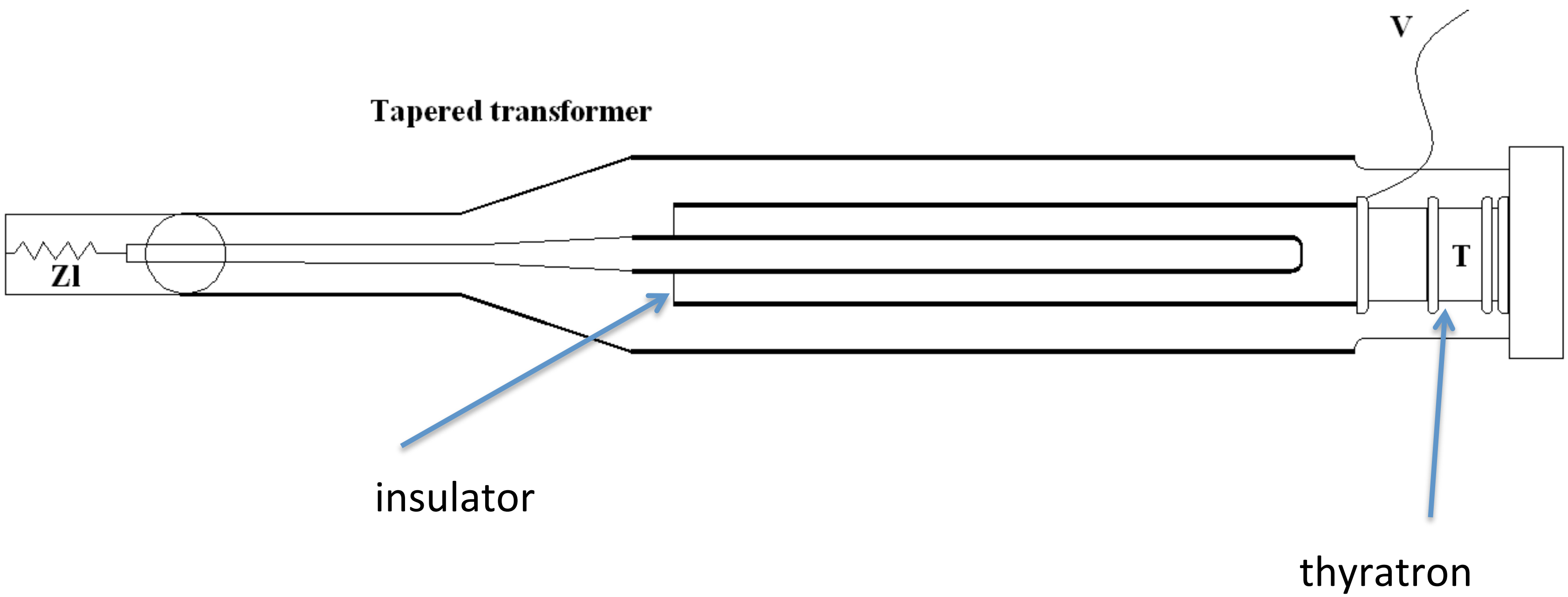
Simple transmission line
- voltage at load is ½ charging voltage
- Base of switch floats




Pulse length $$\tau = \frac{2D}{v} = 2D\frac{\sqrt{\mu\epsilon}}{c}$$

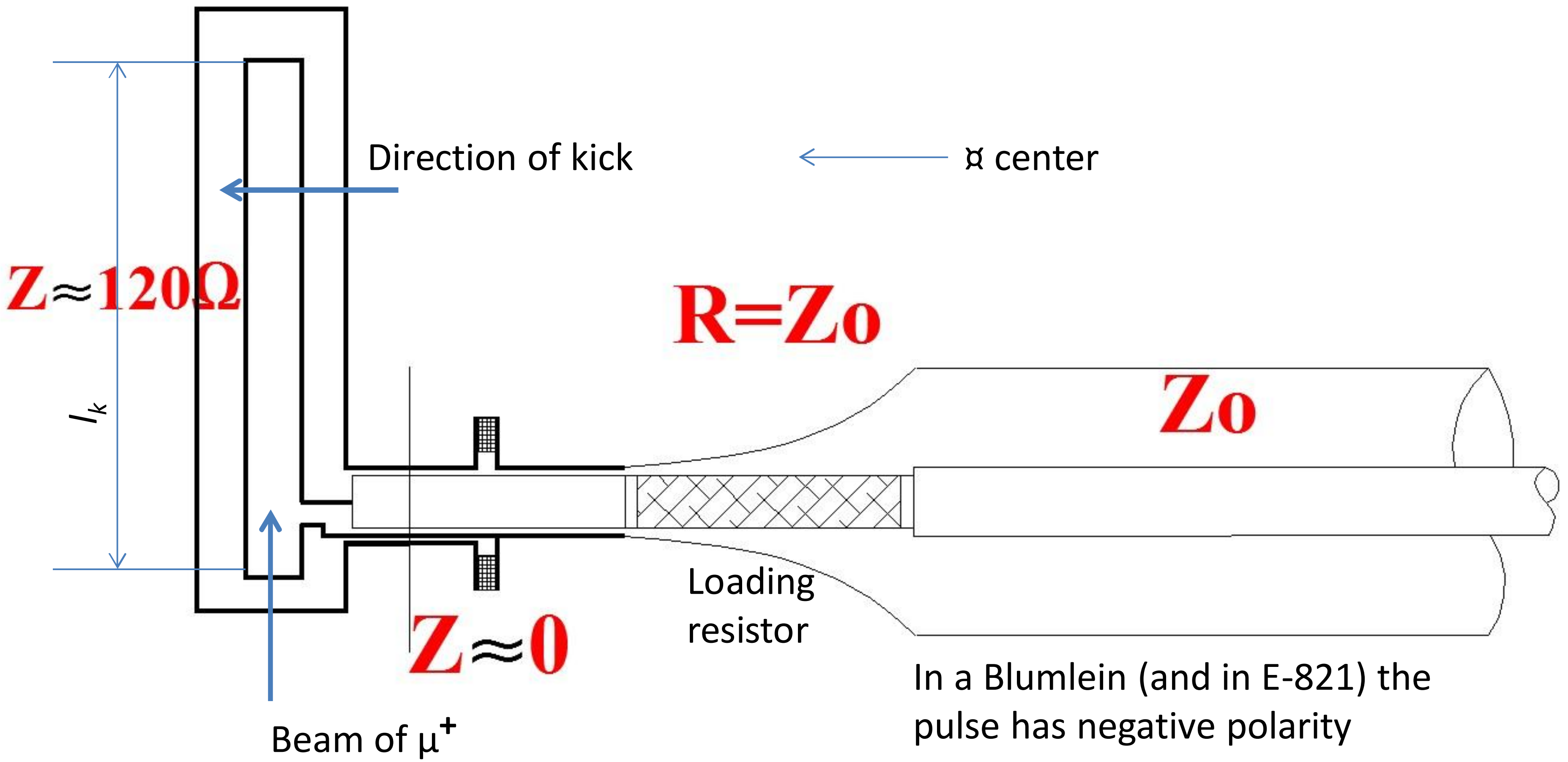
# Blumlein Pulse Forming Network




$$\tau = \frac{2D}{v} = 2D\frac{\sqrt{\mu\epsilon}}{c}$$

D = 9m
ε = 4.7 (Castor oil)
=> τ = 120ns

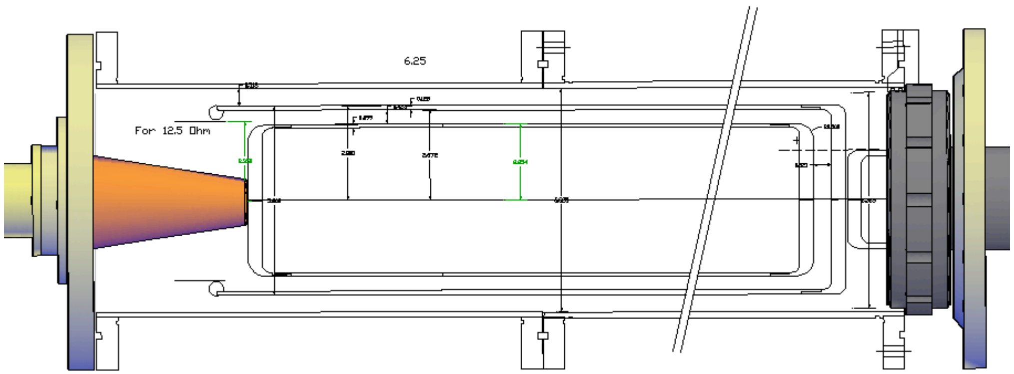
# Blumlein – matched load - magnet

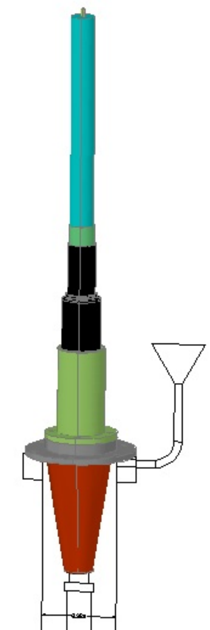



In a Blumlein (and in E-821) the pulse has negative polarity

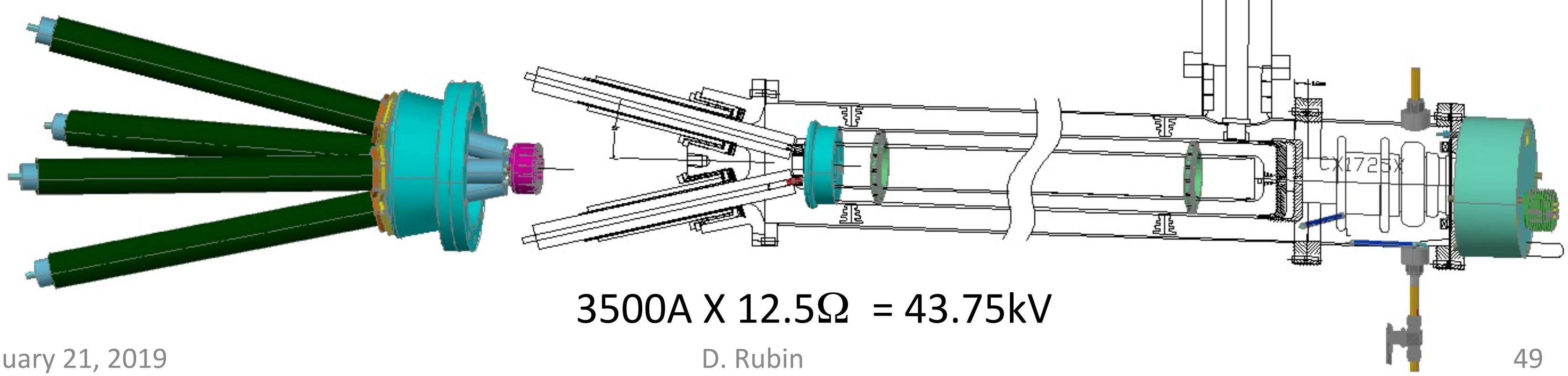
# Blumlein schematic

12.5 Ohm Blumlein



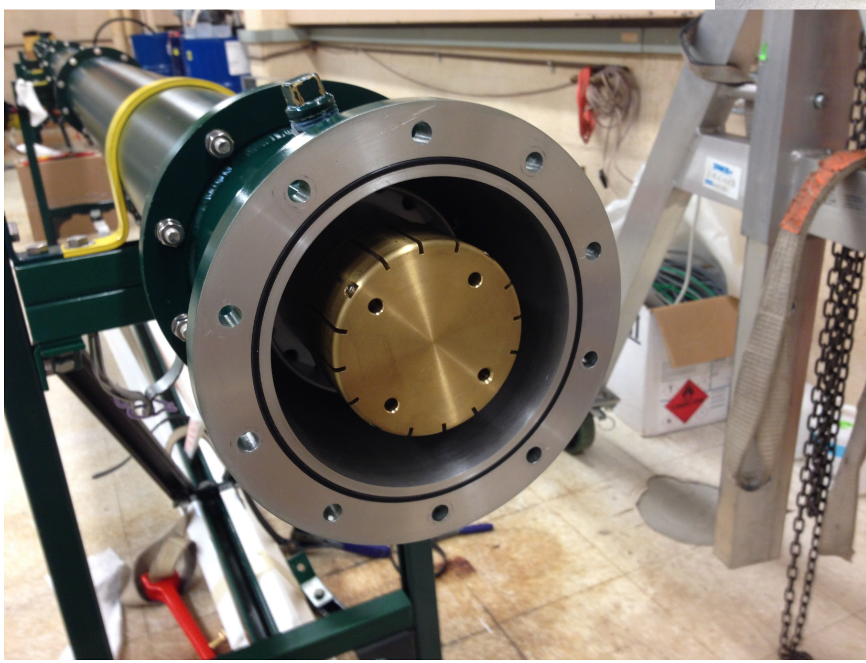



Four parallel 50 Ω coaxial cables couple 12.5Ω Blumlein to load

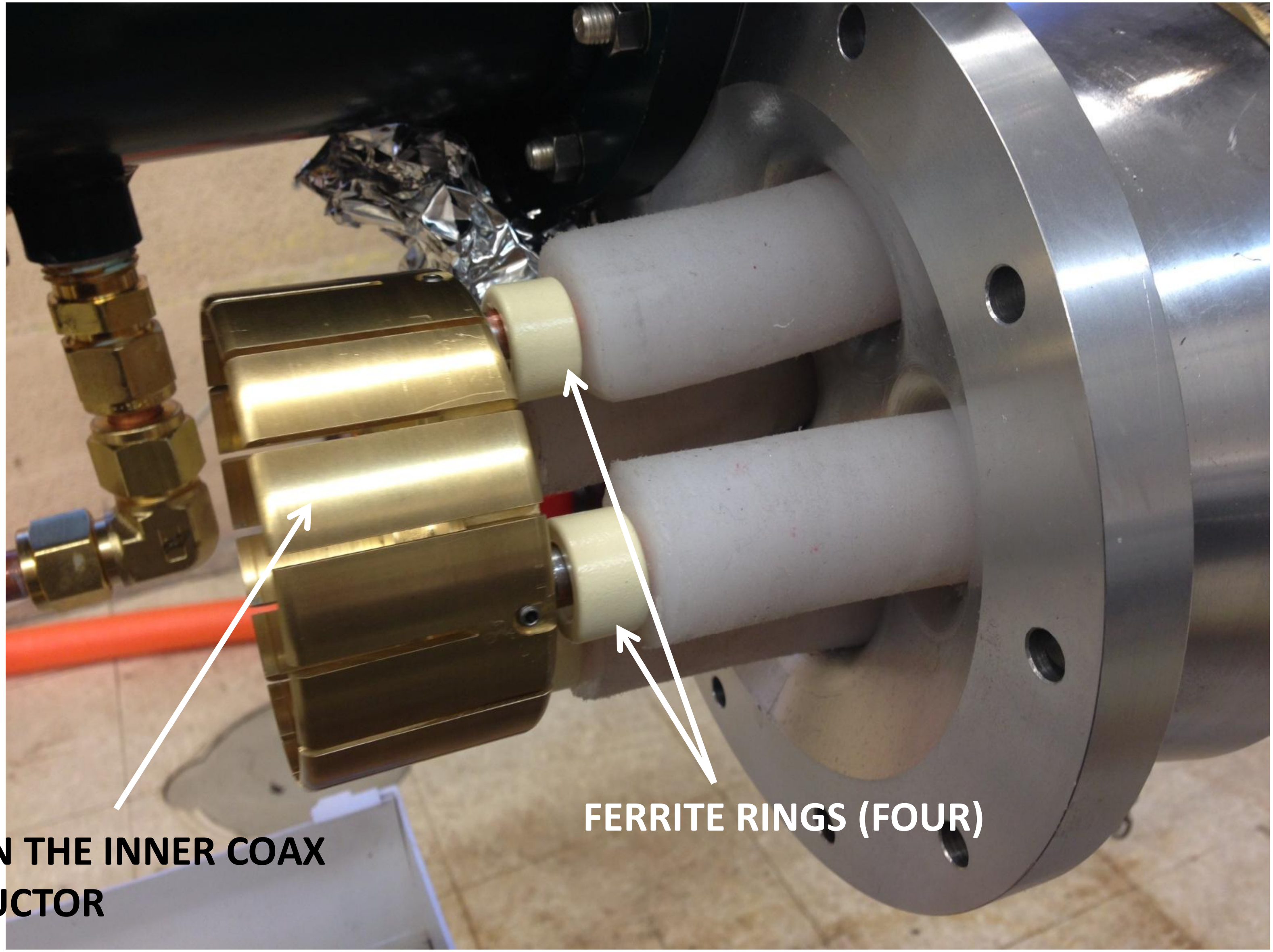



3500A X 12.5Ω = 43.75kV

Blumlein business end

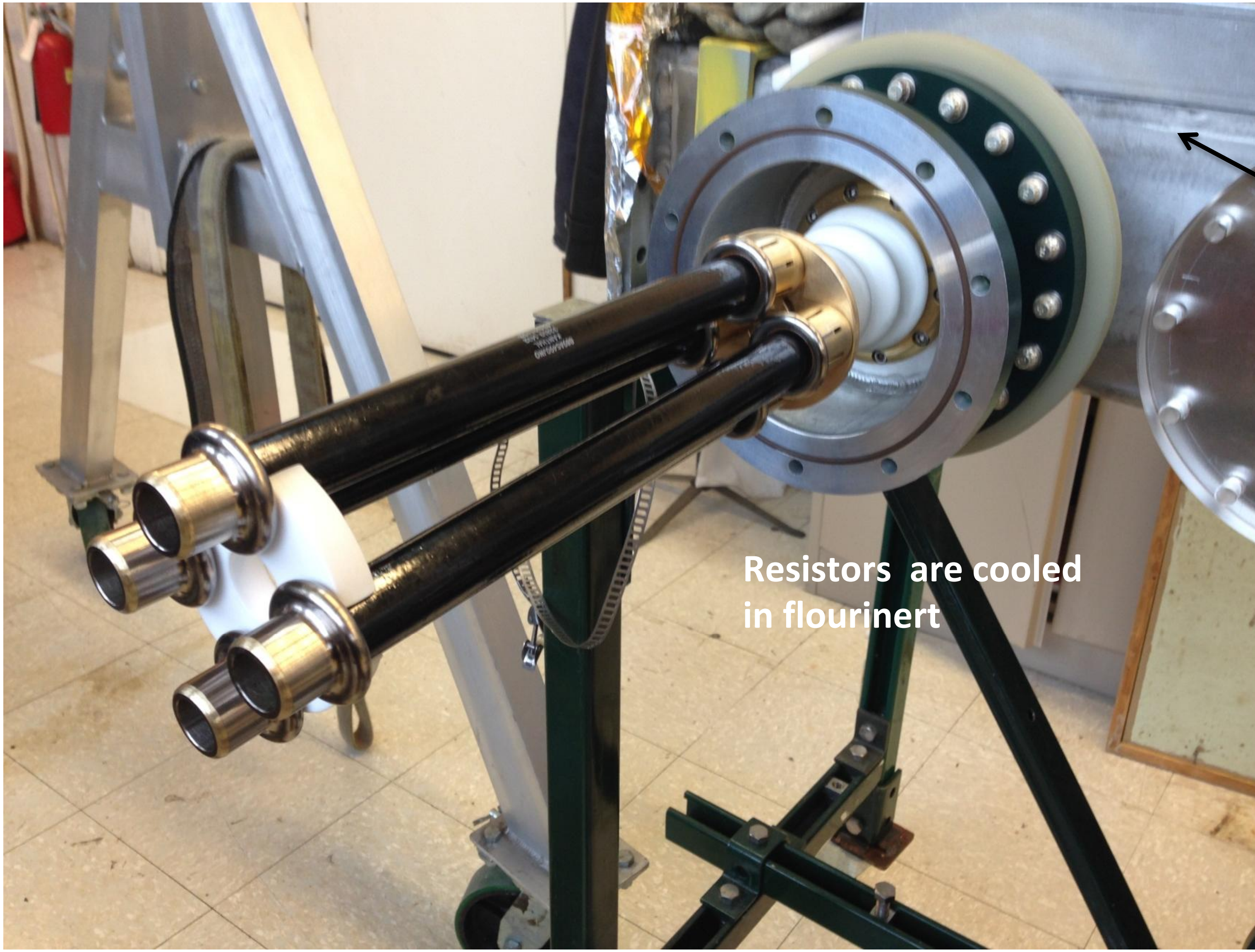


# CABLES AT THE BLUMLEIN END



# 4 –parallel coax to load

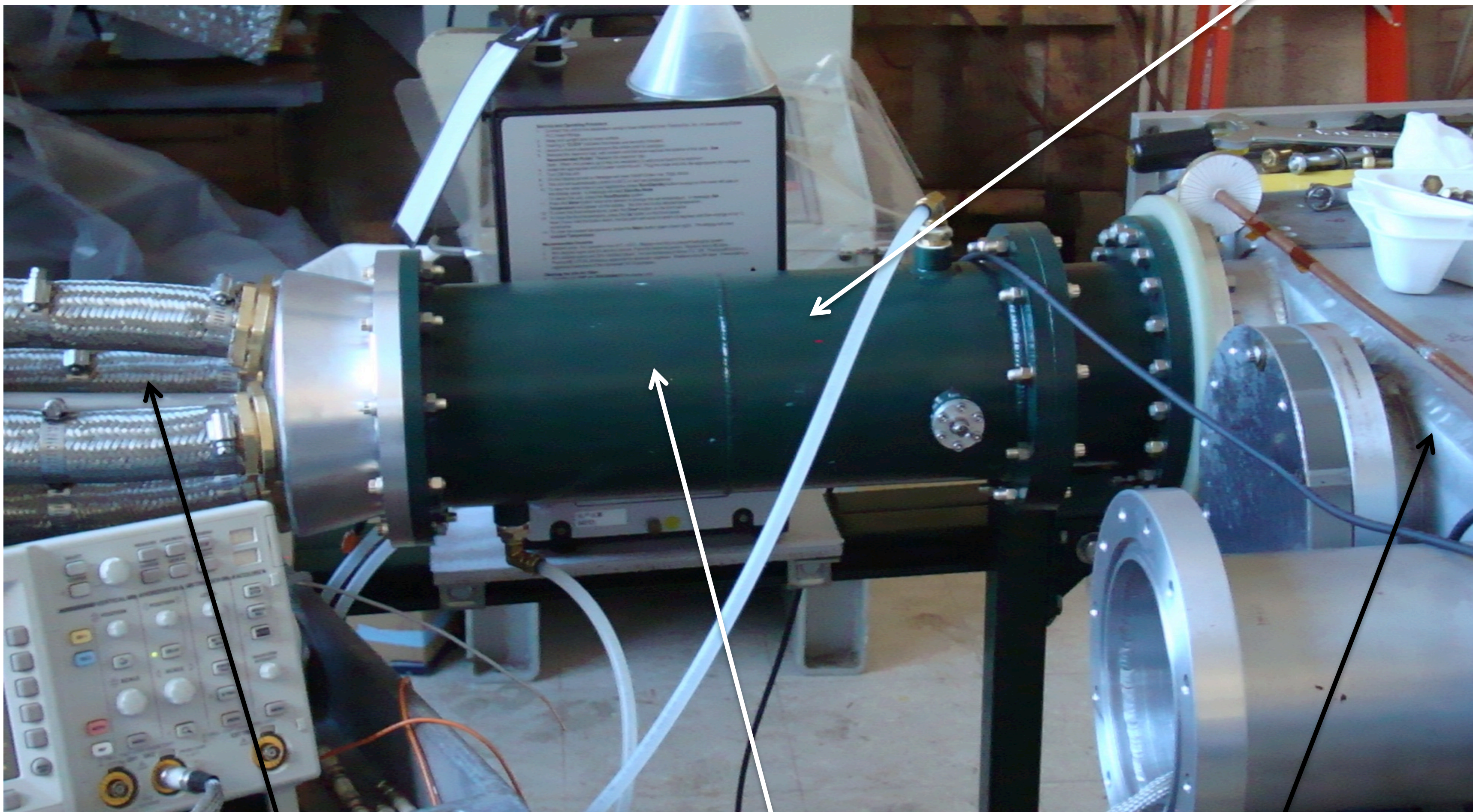
## RESISTORS AT THE INPUT OF KICKER




**EACH 50 Ω CABLE LOADED TO 50 Ω RESISTOR**

# Coupling to magnet

flourinert

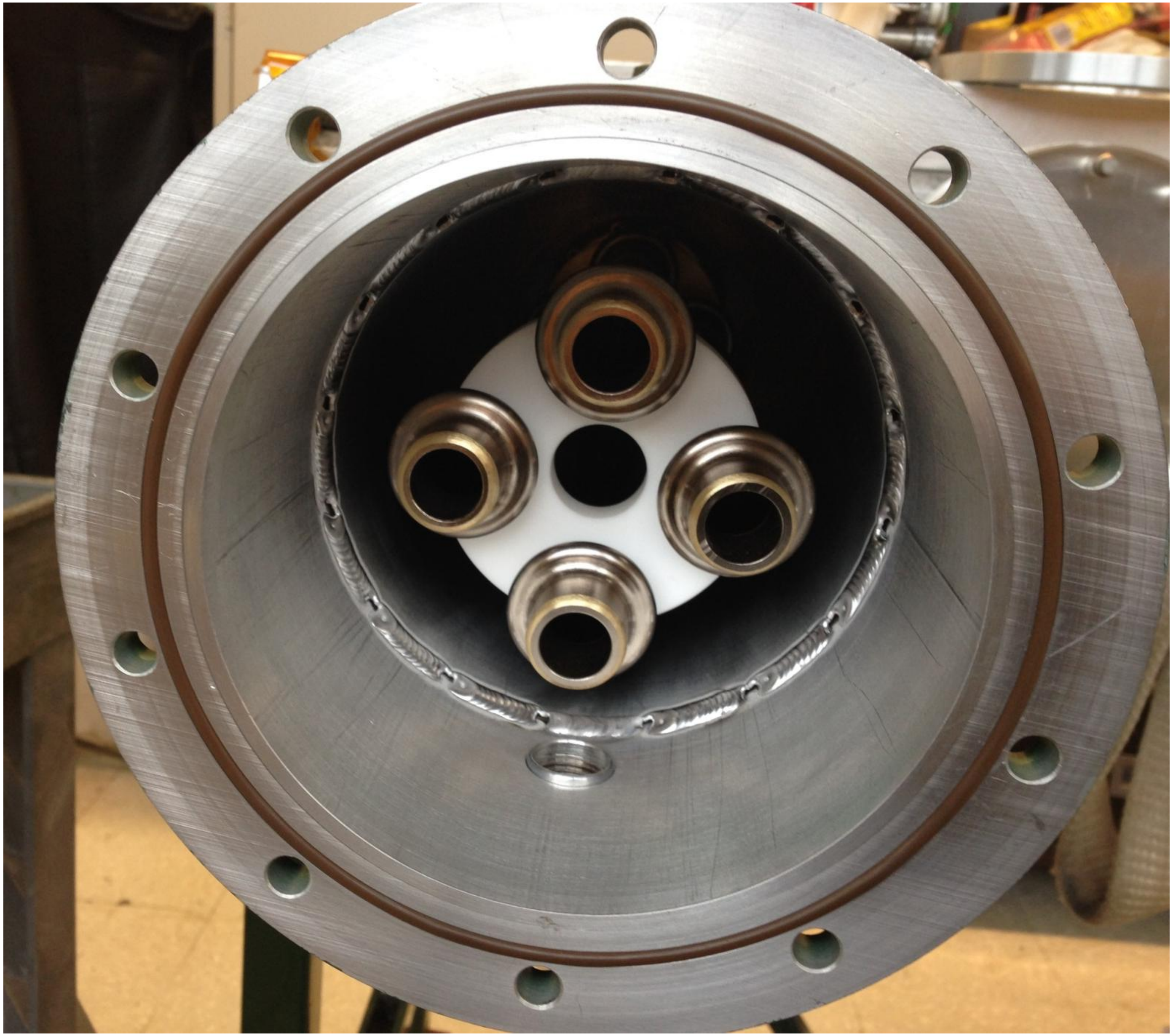


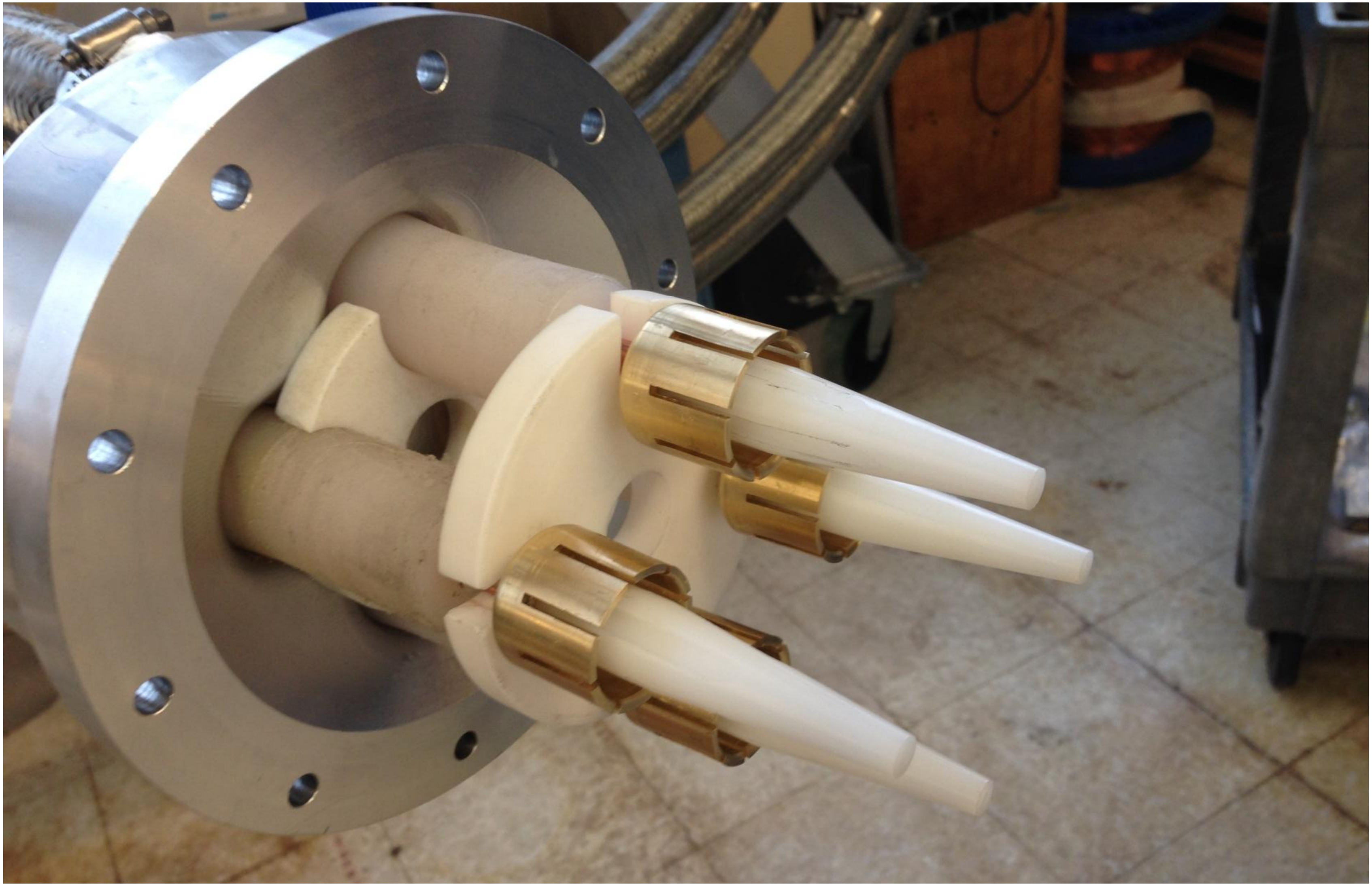
4 50Ω  coaxial cables

4 load resistors

Vacuum chamber

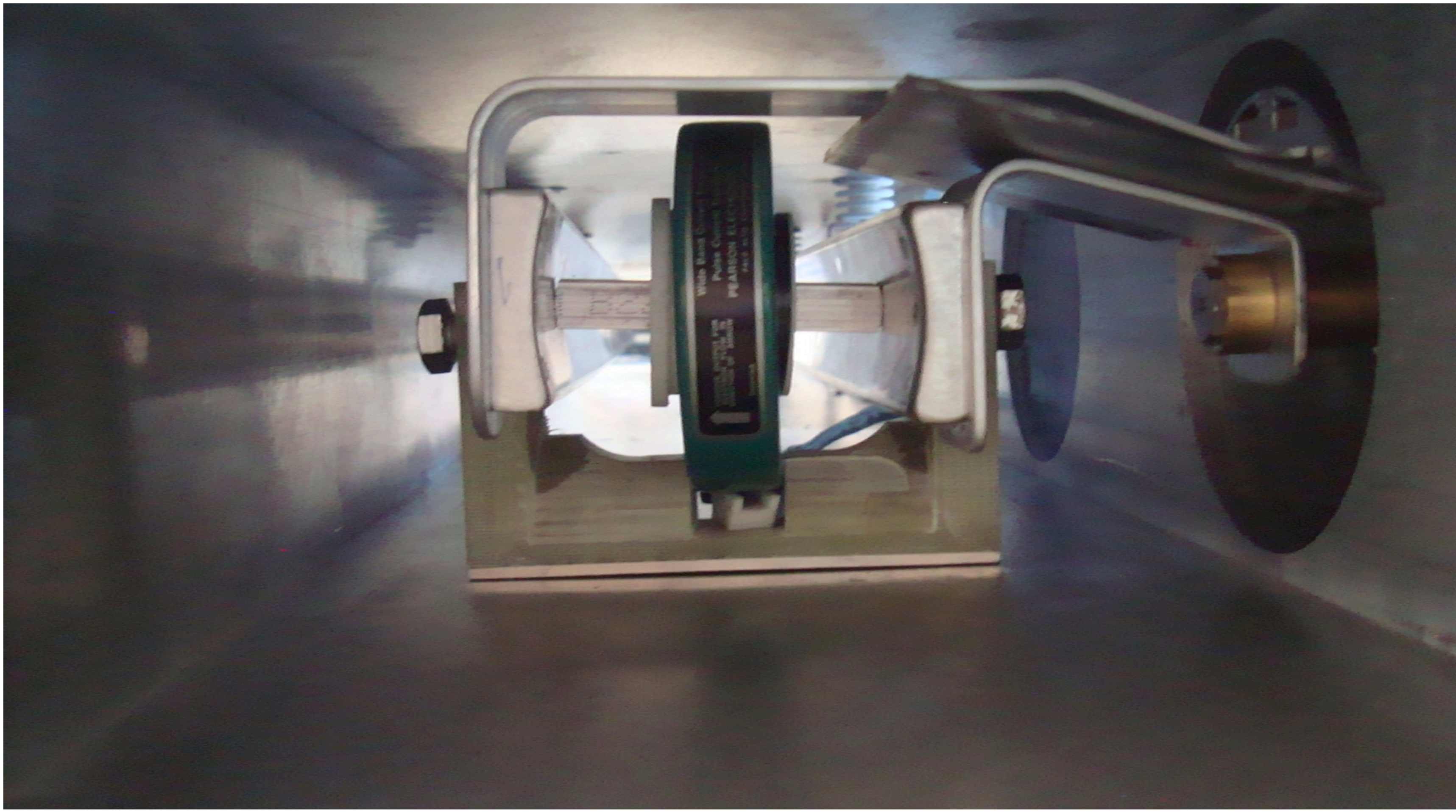
Load resistors
cooled in flourinert



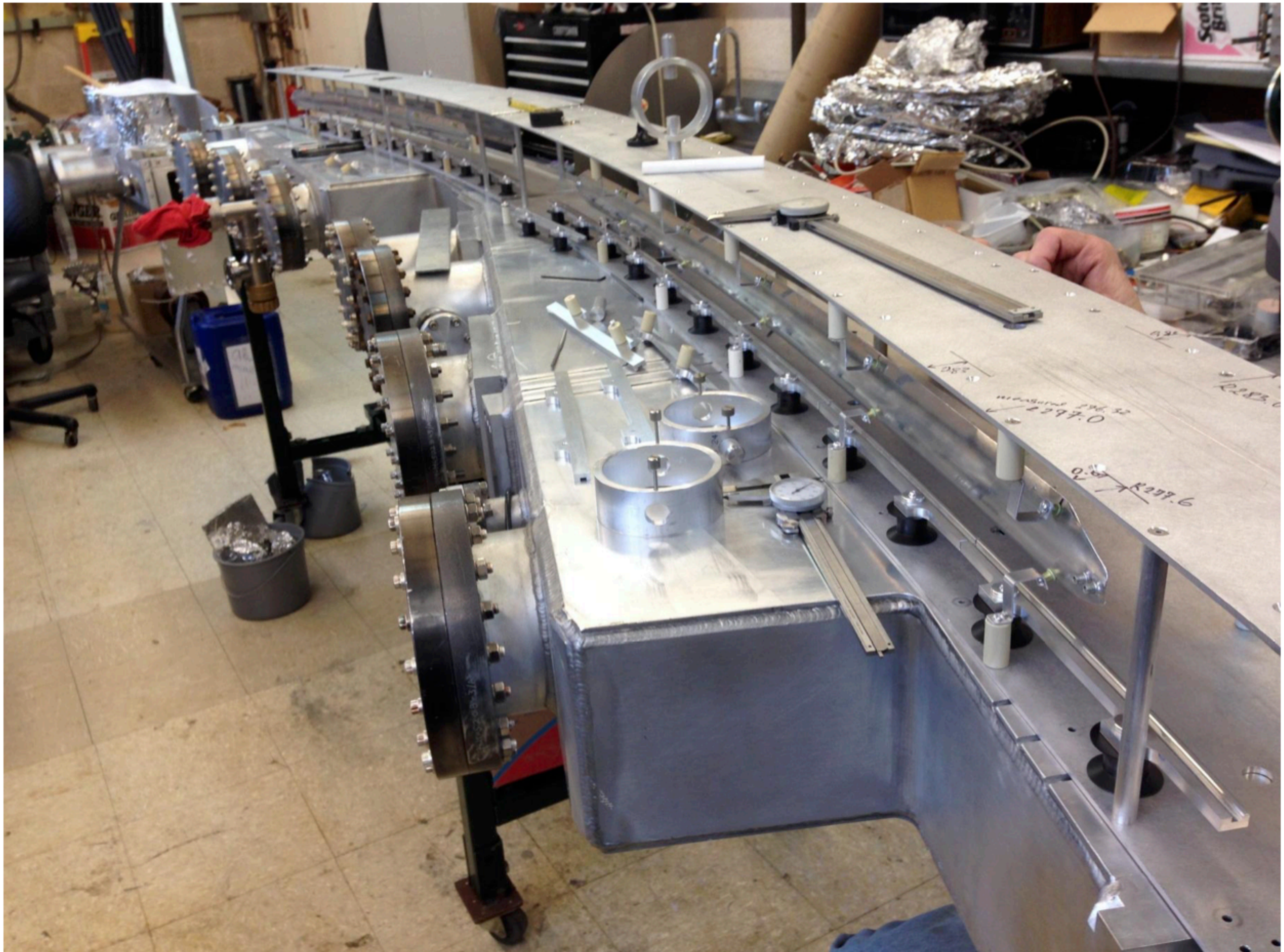


**CABLES AT RESISTOR SIDE; EACH CONE CAPTURES IT’S RESISTOR**

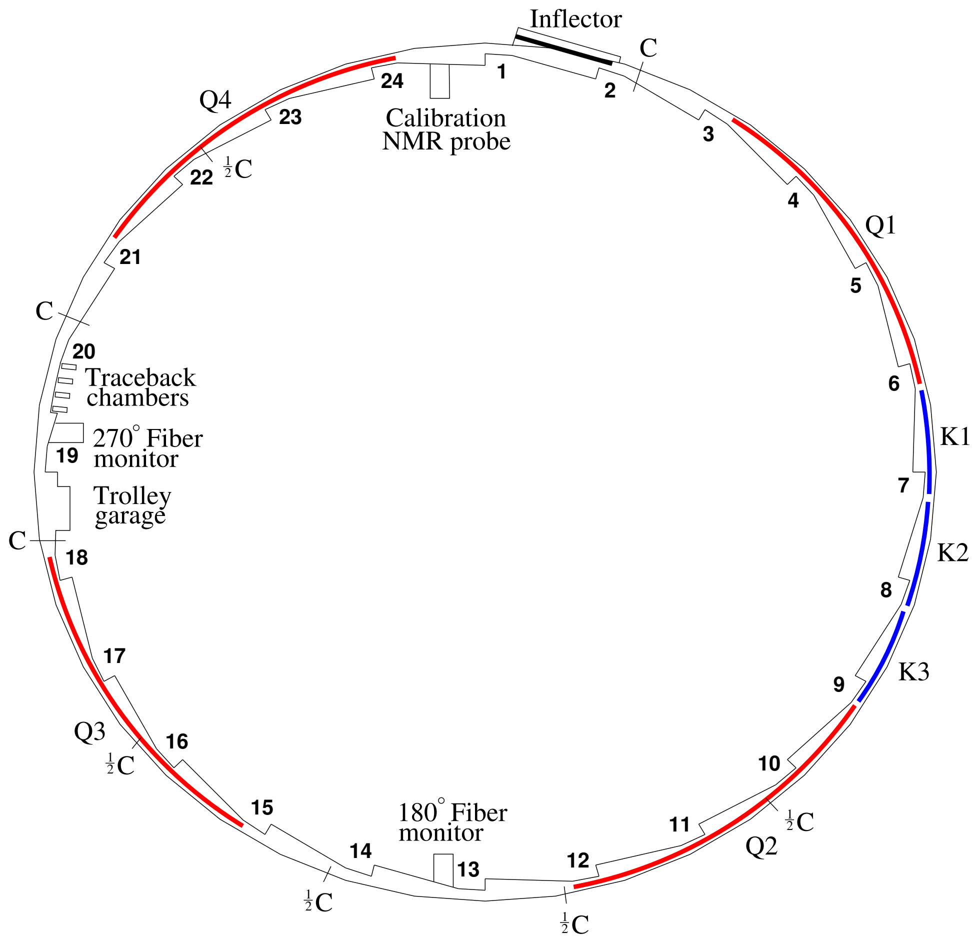
# Current transformer and shorted kicker

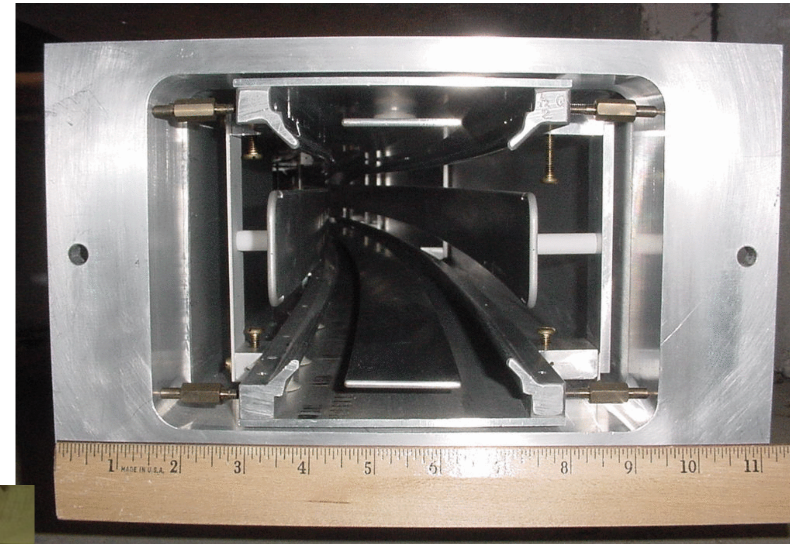


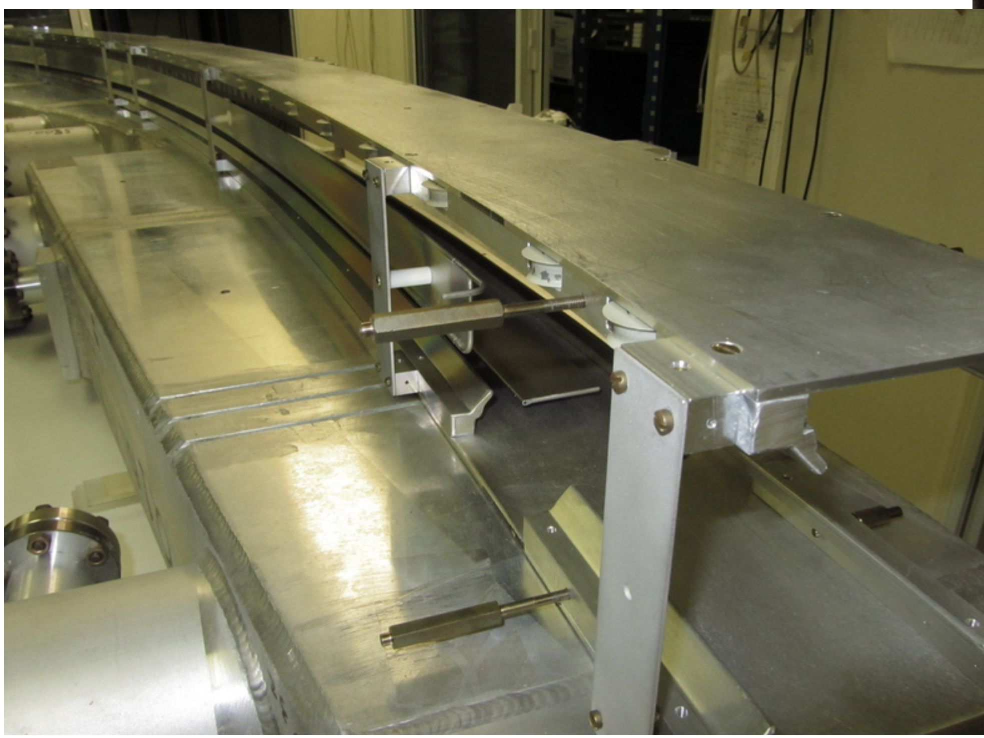

04/08/2018

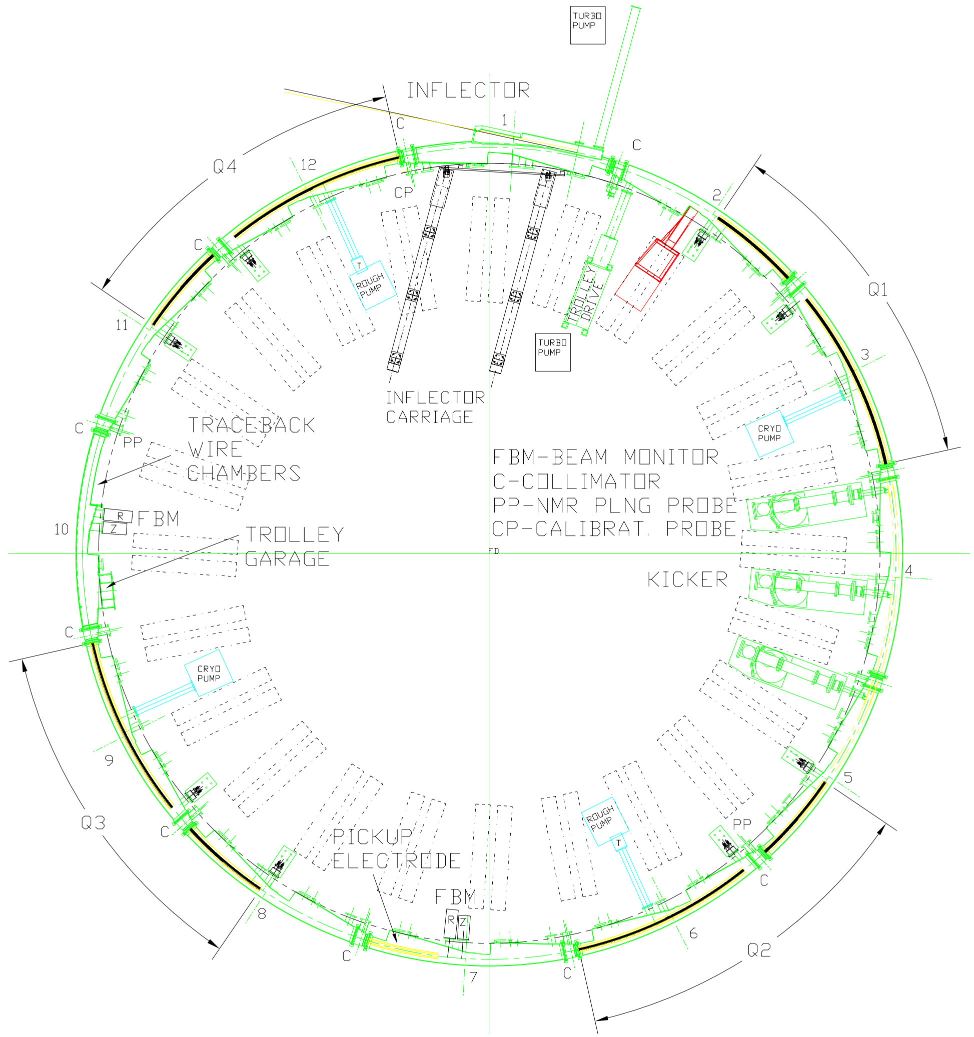


# Inflector – Kickers - Quadrupoles

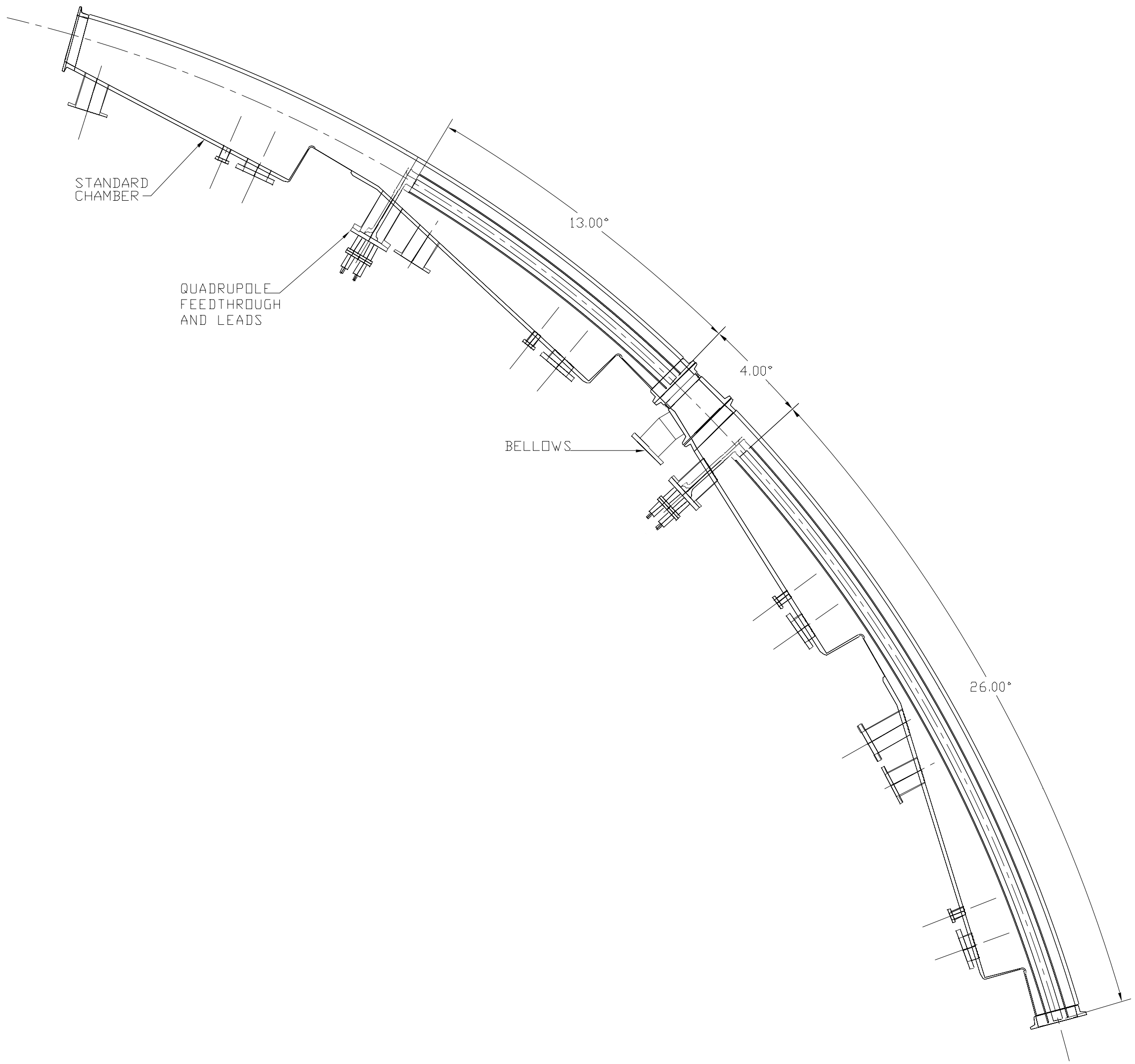


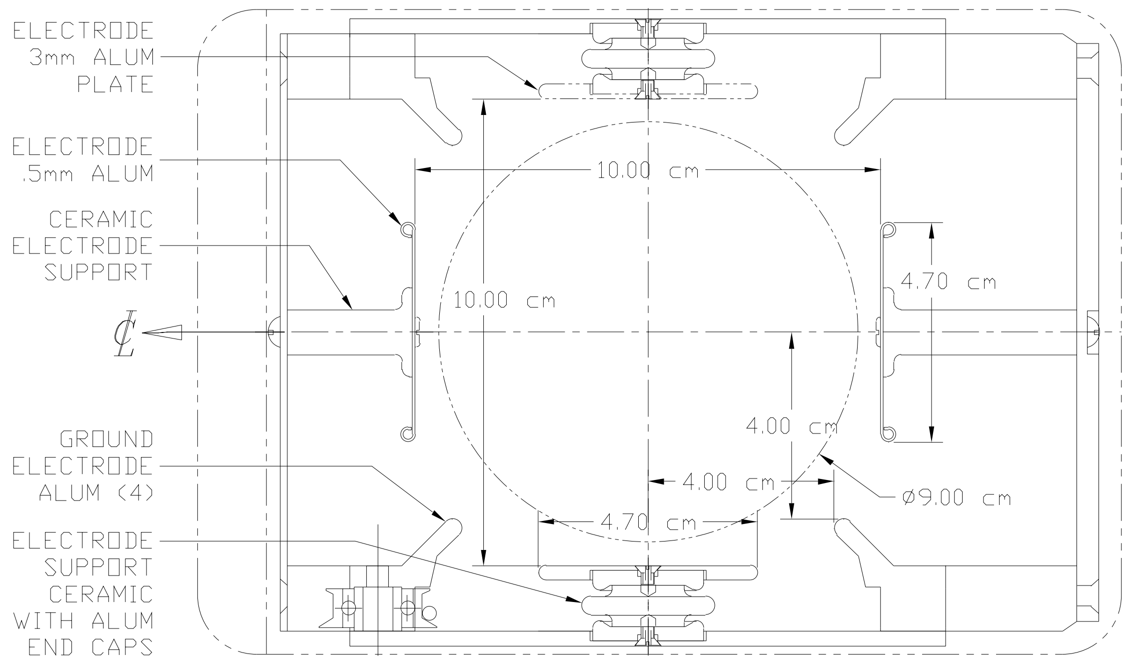

1 MADE IN U.S.A. 2 3 4 5 6 7 8 9 10 11

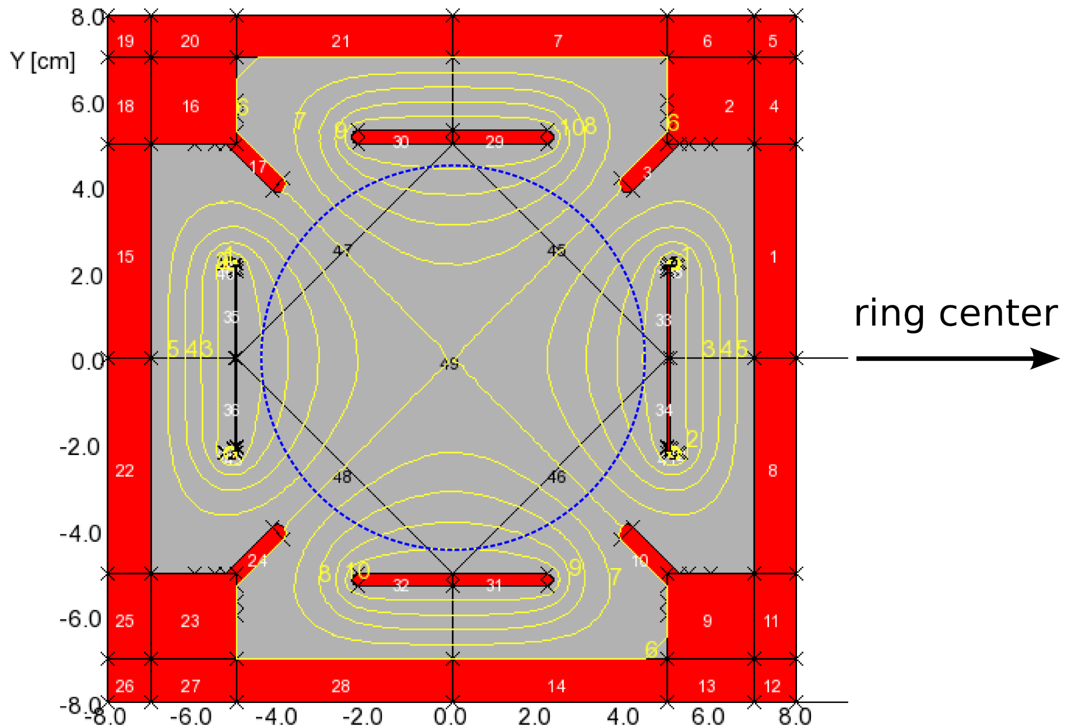




TURBO PUMP
INFLECTOR
Q4
Q1
Q2
Q3
C
CP
PP
ROUGH PUMP
TROLLEY DRIVE
TURBO PUMP
INFLECTOR CARRIAGE
TRACEBACK WIRE CHAMBERS
FBM-BEAM MONITOR
C-COLLIMATOR
PP-NMR PLNG PROBE
CP-CALIBRAT. PROBE
CRYO PUMP
R
Z
FBM
TROLLEY GARAGE
KICKER
PICKUP ELECTRODE
FBM
1
2
3
4
5
6
7
8
9
10
11
12


STANDARD CHAMBER
QUADRUPOLE FEEDTHROUGH AND LEADS
13.00°
4.00°
BELLOWS
26.00°


ELECTRODE
3mm ALUM
PLATE
ELECTRODE
.5mm ALUM
CERAMIC
ELECTRODE
SUPPORT
GROUND
ELECTRODE
ALUM (4)
ELECTRODE
SUPPORT
CERAMIC
WITH ALUM
END CAPS
10.00 cm
10.00 cm
4.70 cm
4.00 cm
4.00 cm
ø9.00 cm
4.70 cm


Y [cm]
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
ring center

# Nominal field configuration