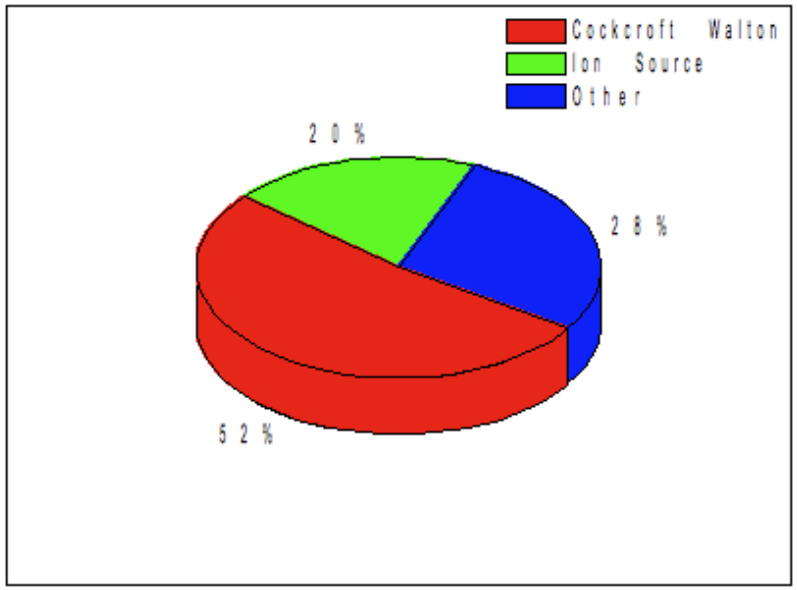
The H- Injector Upgrade

C.Y. Tan
02 Nov 2011

Why

- After a review of all systems of proton source in 2009, the Cockcroft-Walton was determined to be a liability.
  - I- column failed in early 2009. Repairs took nearly 1 year.
  - Retirement of critical personnel (end of 2008). Lost 82 years of experience.
  - C-W is aging, total down time is 300 hours over 9 years. Downtime dominated by C-W.



An Old Idea – RFQ Injector

- FNAL has considered using RFQ's
  - Late 1980's
    - BNL and FNAL worked with LBNL on an RFQ design
    - 200MHz built for BNL but FNAL cancelled order.
    - BNL has successfully operated an RFQ injector since the 1980s.
  - There has been other RFQ injector proposals but no engineering plans.

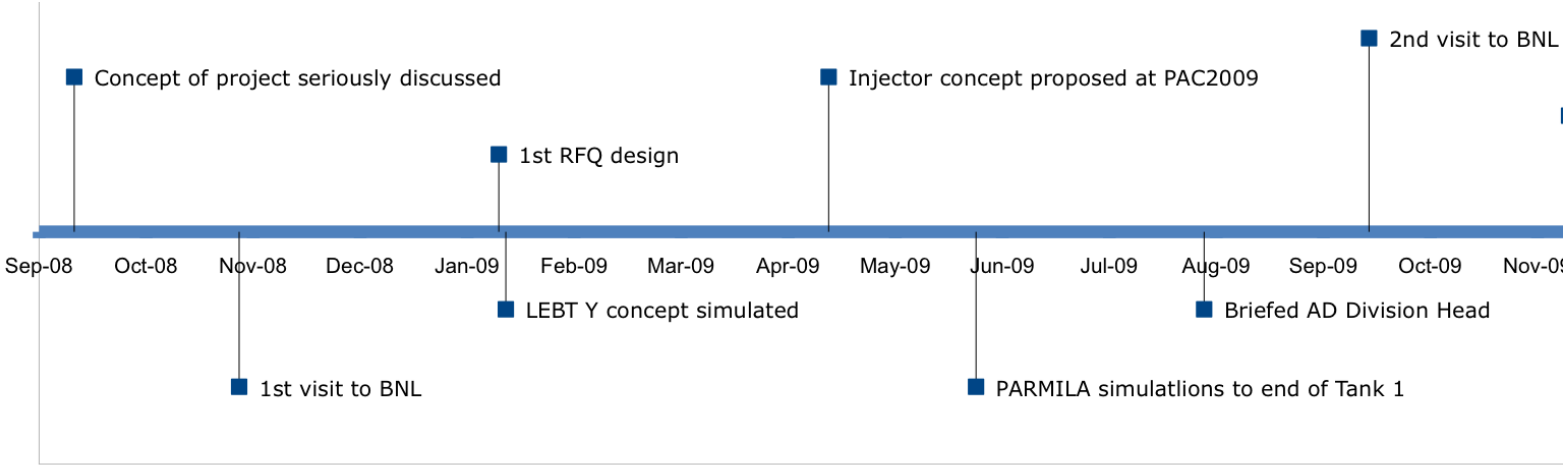
The New Injector (nearly the same as BNL)

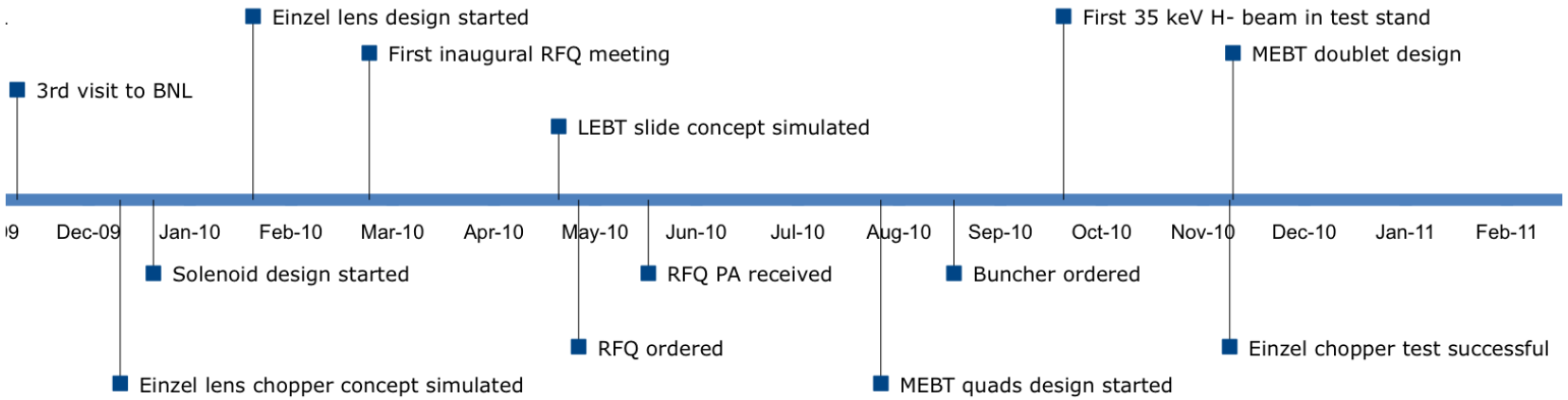
FNAL

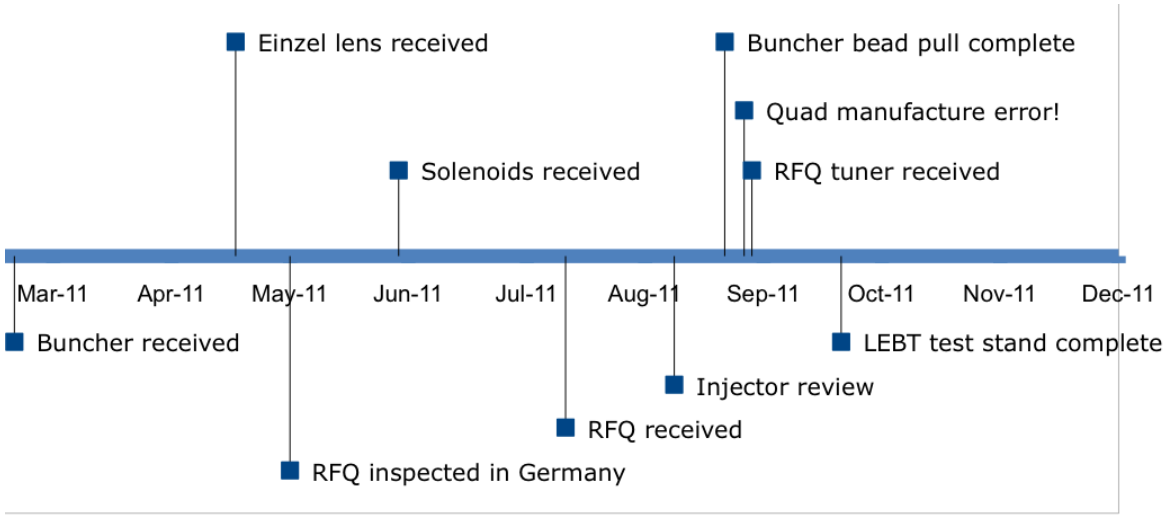
- 2 x 35 keV H- (round type) magnetron sources on a slide.
- Short LEBT (~118 cm)
  - 2 solenoids for focusing
  - Xe gas for neutralization
  - Einzel lens chopper
- RFQ (201.25 MHz) 1.2 m long
- Short MEBT (1 m)
  - 2 sets of doublets
  - 1 BNL style buncher

BNL (2009 line)

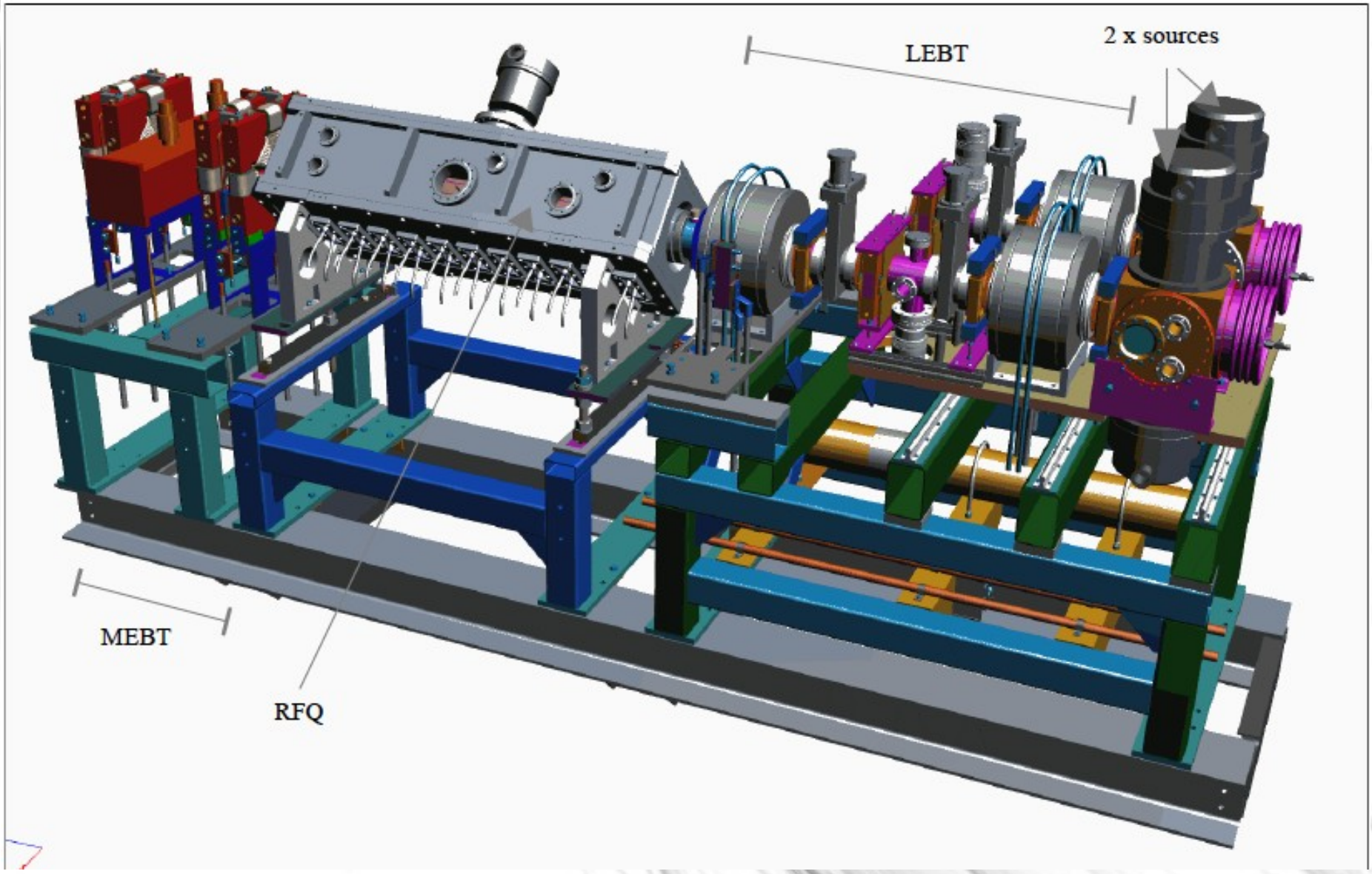
- 1 x 35 keV (round type) magnetron source.
- LEBT (~ 4 m)
  - 2 x solenoids
  - Xe gas for neutralization
  - 1 Einzel lens
  - 1 electrostatic chopper.
- RFQ (201.25 MHz) 1.5 m long
- Short MEBT (0.73 m)
  - 1 set triplets
  - 1 buncher


Concept of project seriously discussed
1st RFQ design
Injector concept proposed at PAC2009
2nd visit to BNL
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
LEBT Y concept simulated
Briefed AD Division Head
1st visit to BNL
PARMILA simulatlions to end of Tank 1


Einzel lens design started
First inaugural RFQ meeting
First 35 keV H- beam in test stand
MEBT doublet design
3rd visit to BNL
LEBT slide concept simulated
Dec-09
Jan-10
Feb-10
Mar-10
Apr-10
May-10
Jun-10
Jul-10
Aug-10
Sep-10
Oct-10
Nov-10
Dec-10
Jan-11
Feb-11
Solenoid design started
RFQ PA received
Buncher ordered
RFQ ordered
Einzel chopper test successful
Einzel lens chopper concept simulated
MEBT quads design started


Einzel lens received
Buncher bead pull complete
Quad manufacture error!
Solenoids received
RFQ tuner received
Mar-11
Apr-11
May-11
Jun-11
Jul-11
Aug-11
Sep-11
Oct-11
Nov-11
Dec-11
Buncher received
LEBT test stand complete
Injector review
RFQ received
RFQ inspected in Germany

The H- Injector

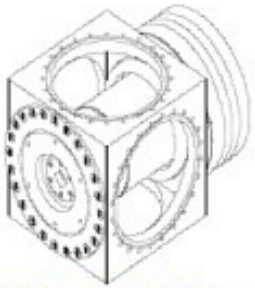


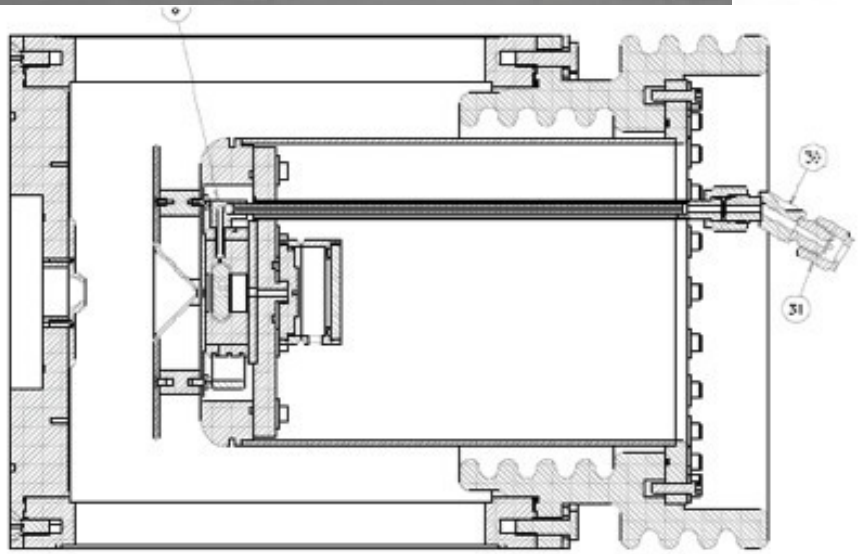
DANGER
HIGH VOLTAGE
DANGER
HIGH VOLTAGE
DANGER
ELECTRICAL SHOCK HAZARD
BURNS MACHINE CO.

H- Source

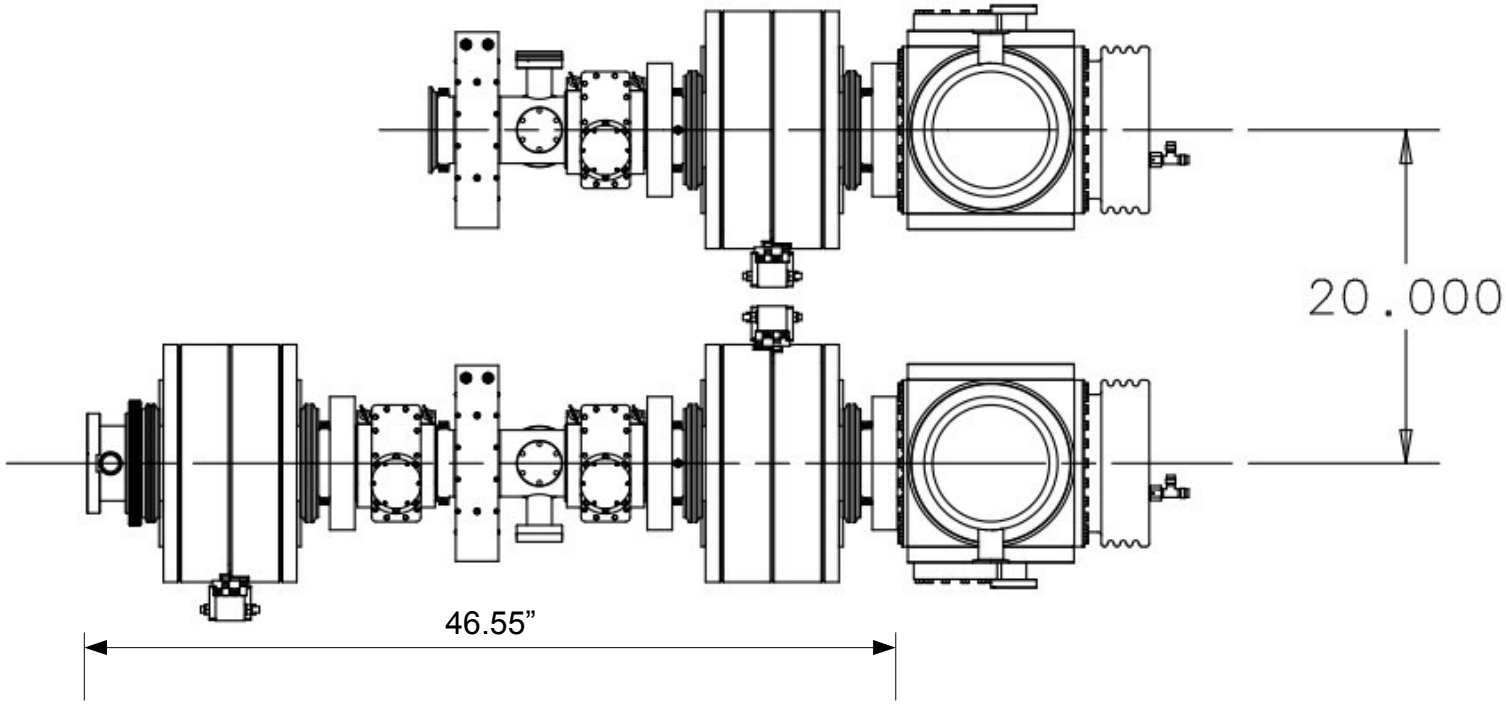
- BNL style round (dimpled) magnetron source
  - BNL has had very good experience with this type of source. Very reliable.
  - FNAL has a lot of experience with slit type magnetron sources. Easier transition.
  - FNAL can use the same hardware to work on the dimpled source.
- Even though it was a modification, it still took more than a year to get BNL type H- currents (~ 90 mA)

The H- source

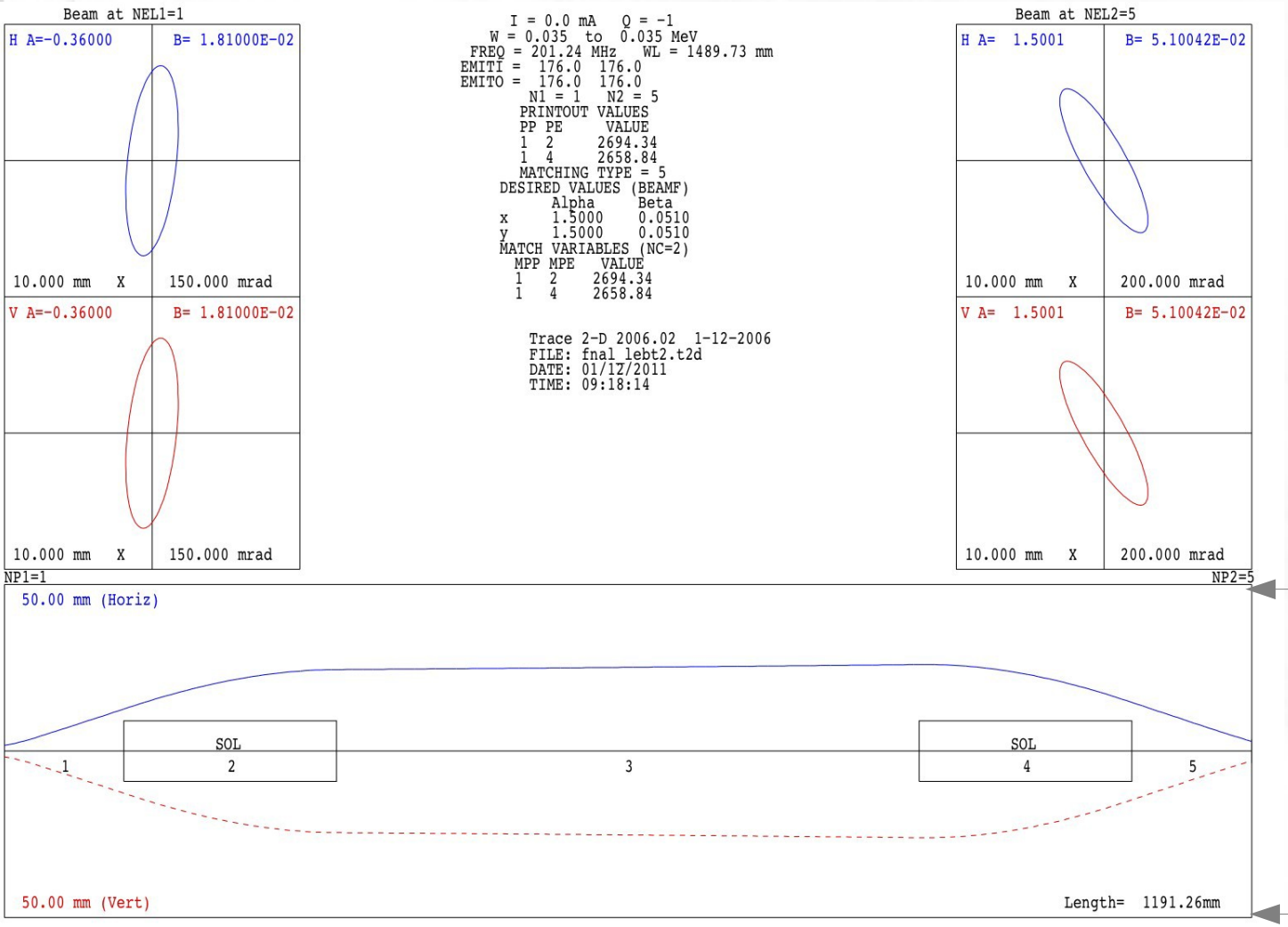




The LEBT



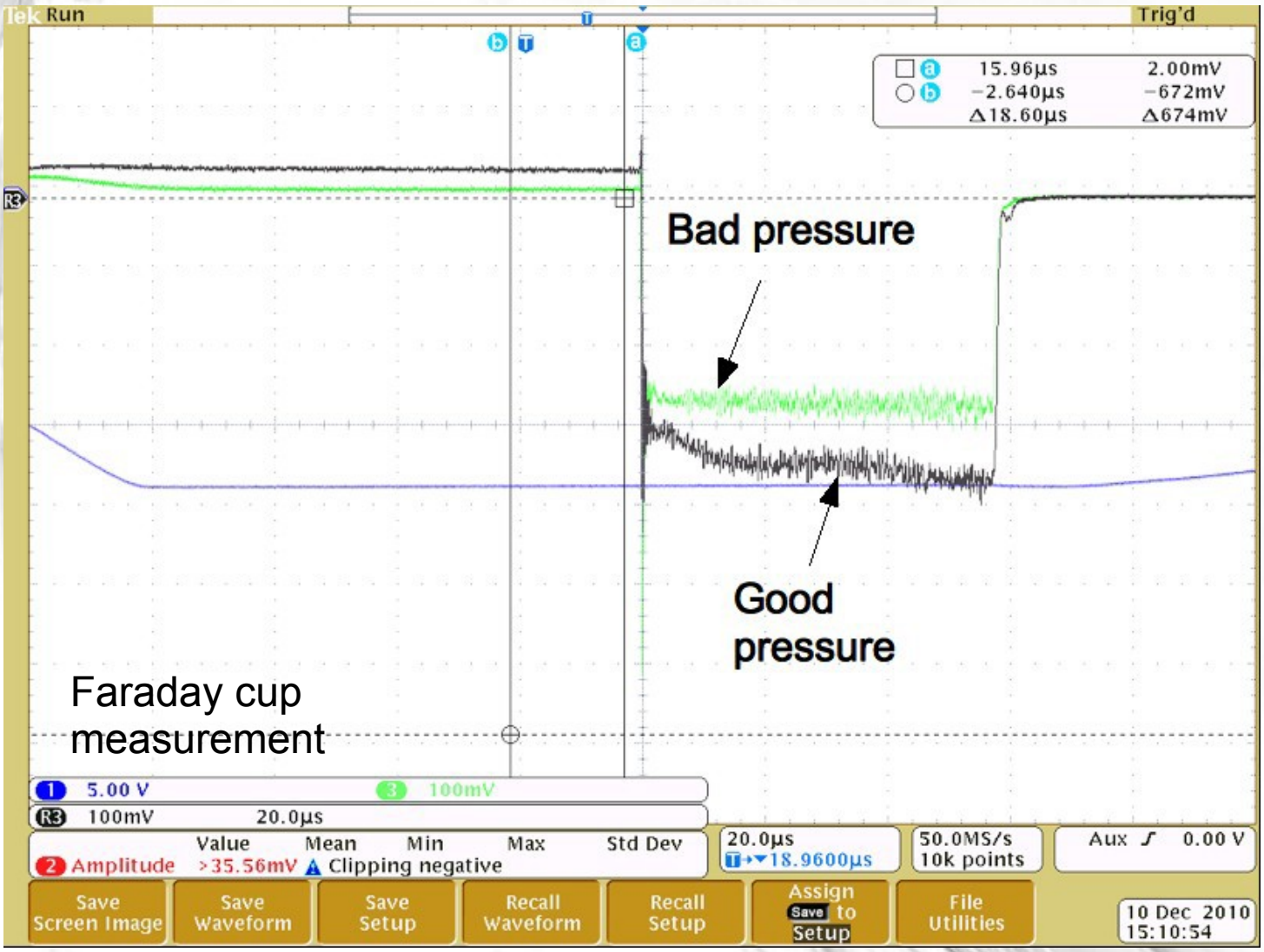
LEBT (con'td)



- BNL source emittance numbers
- RFQ input numbers from manufacturer
- Assume beam is neutralized.

Edge of beam pipe

Demonstration of neutralization



N2 used.

Good vacuum 1e-6 torr.

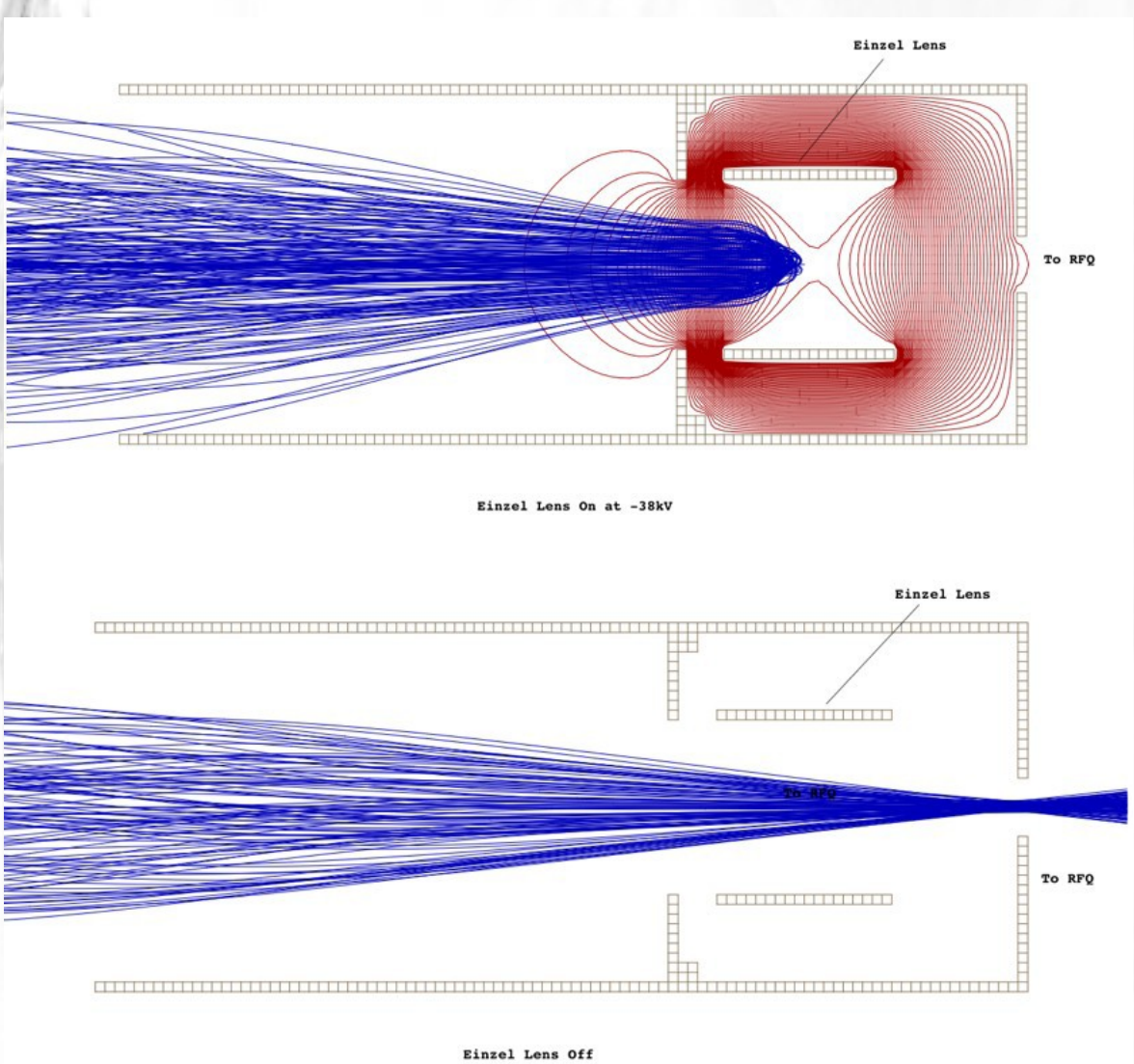
Bad vacuum 1e-4 torr.

Note: pressure gauge quite far from beam in test stand.

Chopper

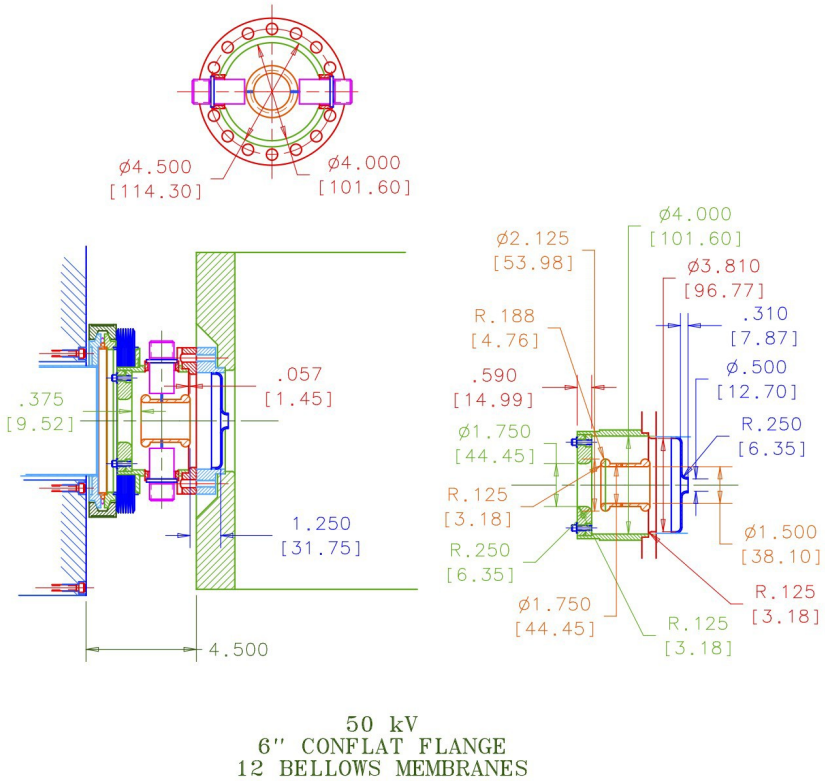
- Einzel lens will function as chopper
  - Suggested by D. Raparia
  - Lens placed close to the entrance of the RFQ
    - Keeps de-neutralization region small
    - Beam is already tightly focused here by the solenoid and so neutralization is probably at a minimum at this location.
- Einzel lens as chopper has been demonstrated to work **but** neutralization+chopper is **not**. Will be part of testing regimen.

Einzel lens as chopper

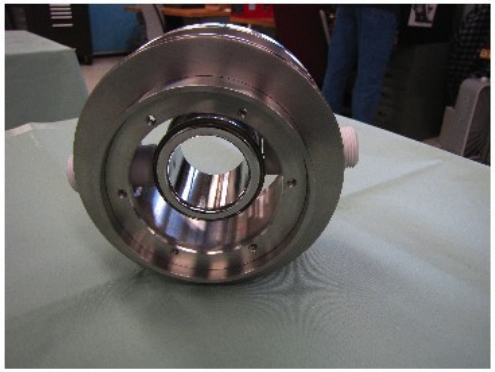


- Simulation using SIMION
- Optimized lens
  - 2” long
  - 1.75” diameter
  - -37 kV to stop 35keV beam.

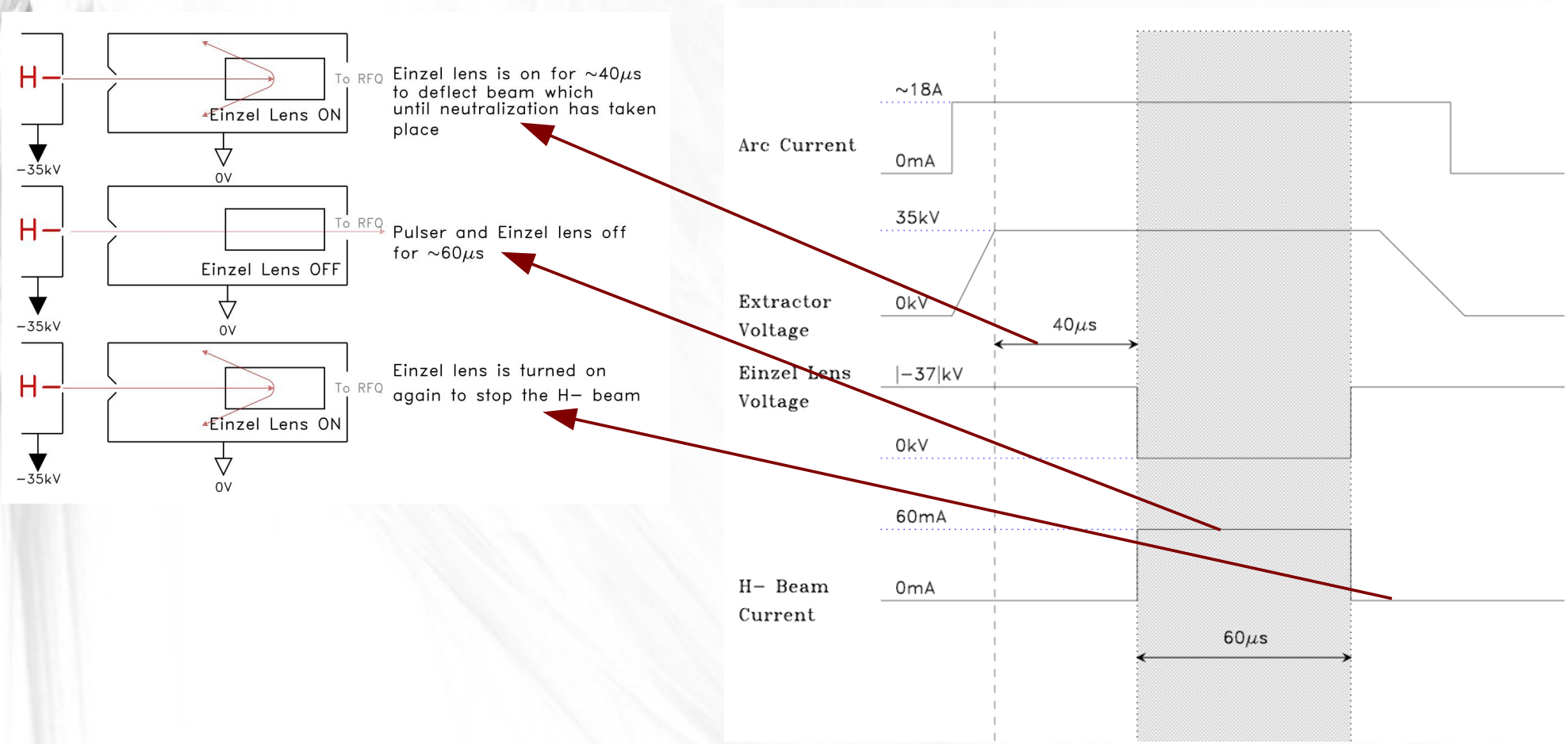
Einzel lens as built



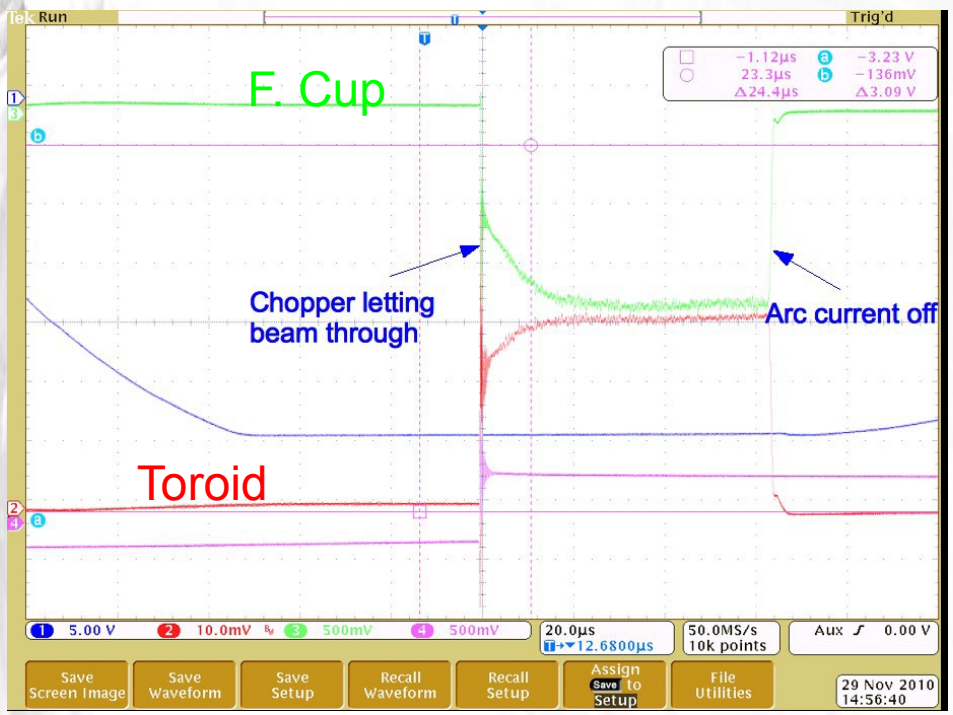
Designed by A. Makarov

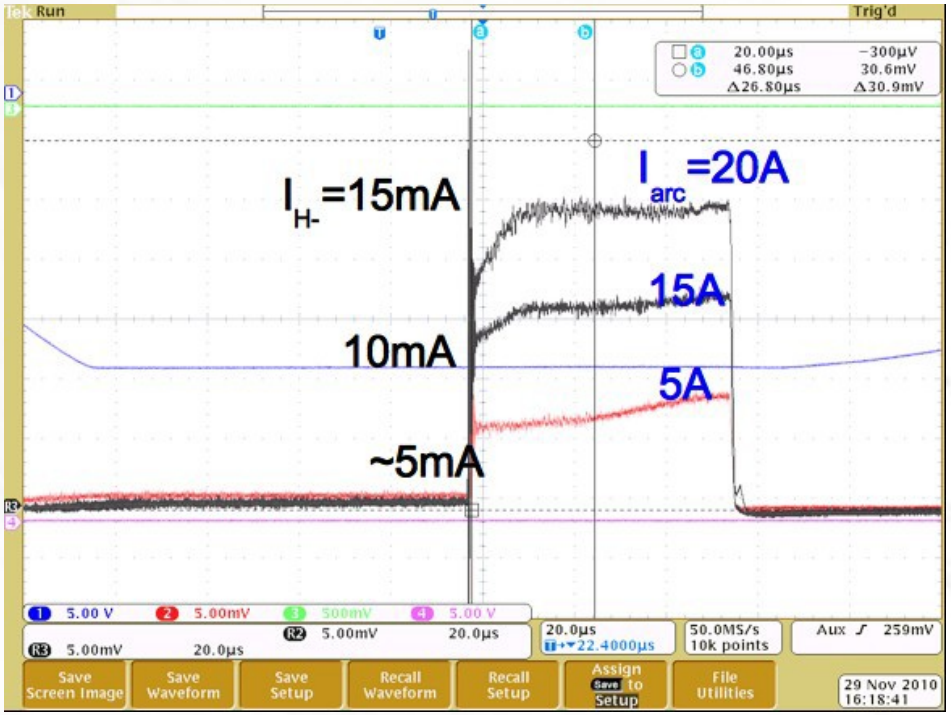


Chopper timings



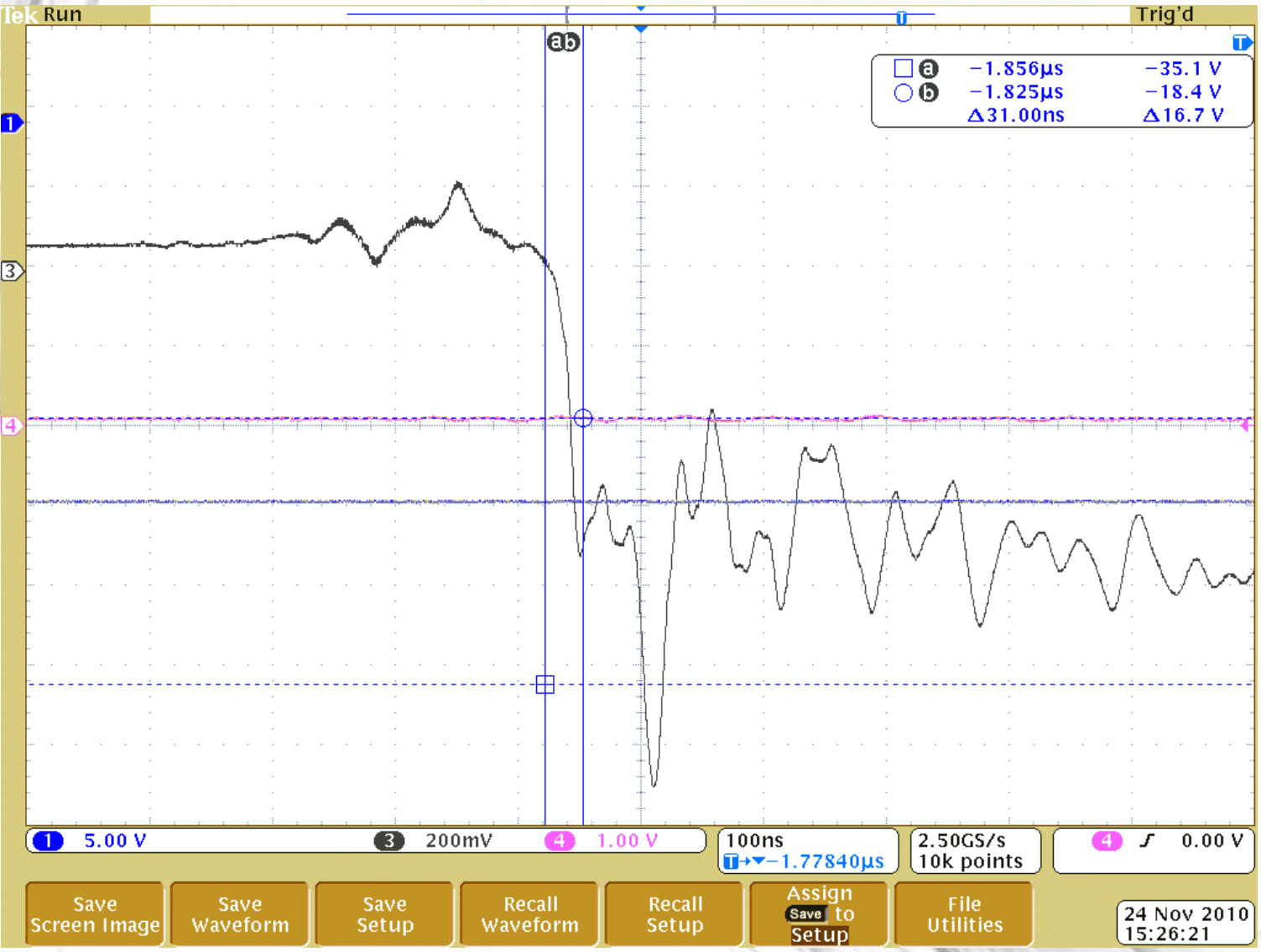
Einzel lens test





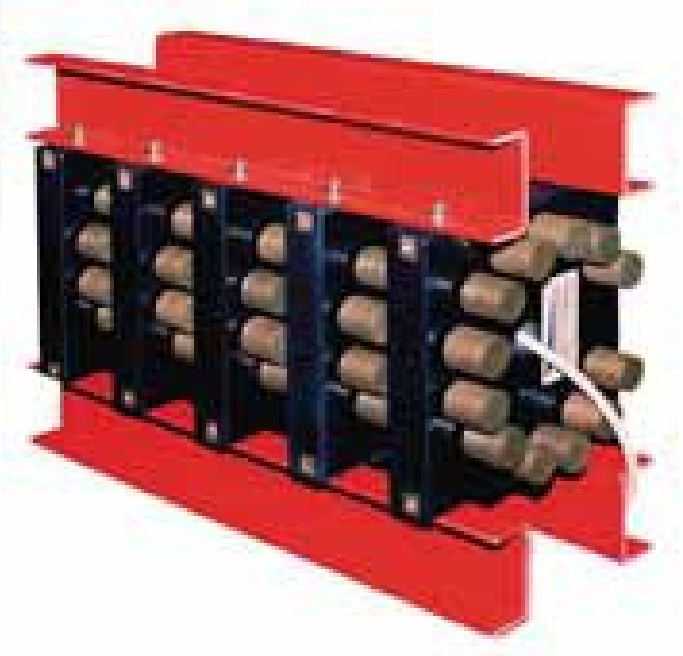
Note there is scraping and neutralization effects at the beginning of the pulse in the test stand.
This is a different Einzel lens than the one that we will be using.
This Einzel lens is 2” in diameter and 2.5” long.
Note: injector lens is 1.75” diameter and 2” long.

Einzel lens test (cont'd)



Rise time on Faraday cup is better than 50ns. Consistent with thyratron turn on of 35 ns. Ringing from finite bw of Faraday cup.

DTI Switches

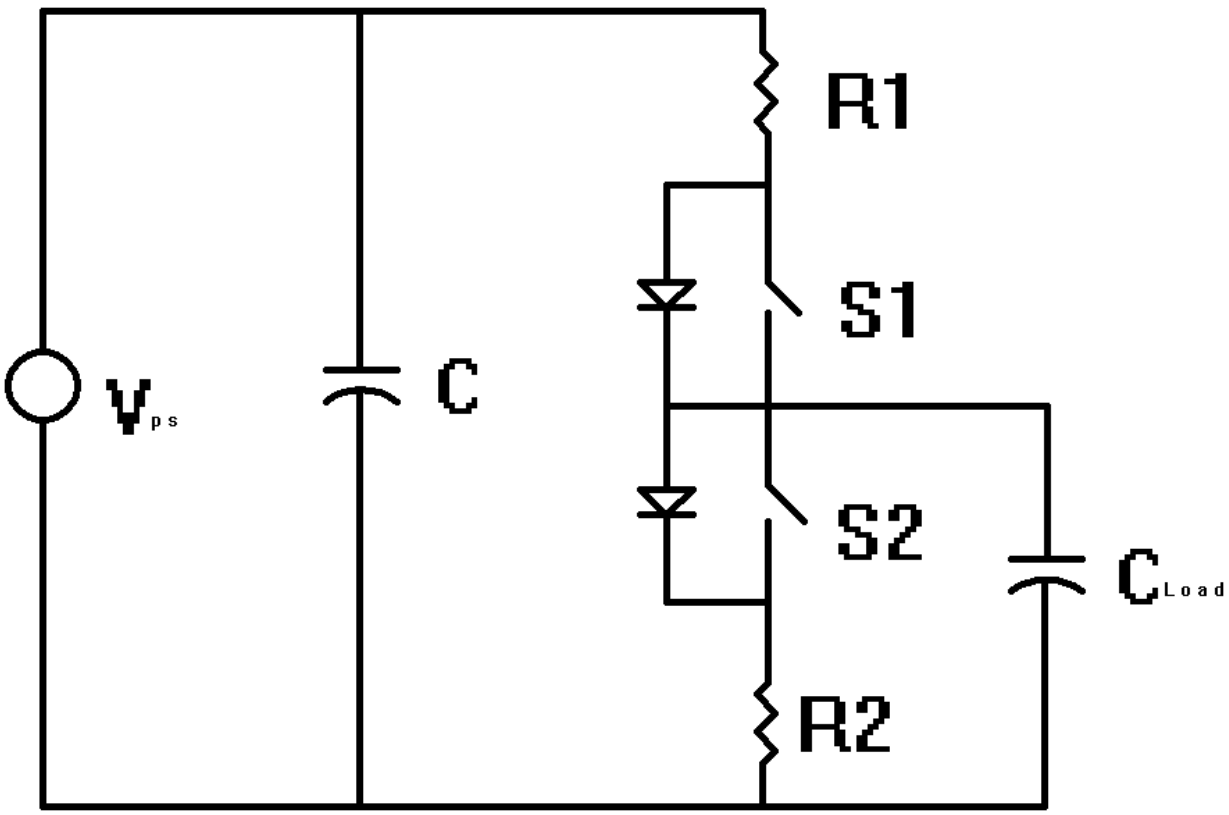


Switch module assemblies. Example: 45 kV, 30 A unit

Switch modules. Thee are rated 5 – 10 kV, 10 – 50 A.

Two 50kV/50A, 15Hz switches have been ordered. Delivery expected in 1st week of November.

Push-pull pulser circuit

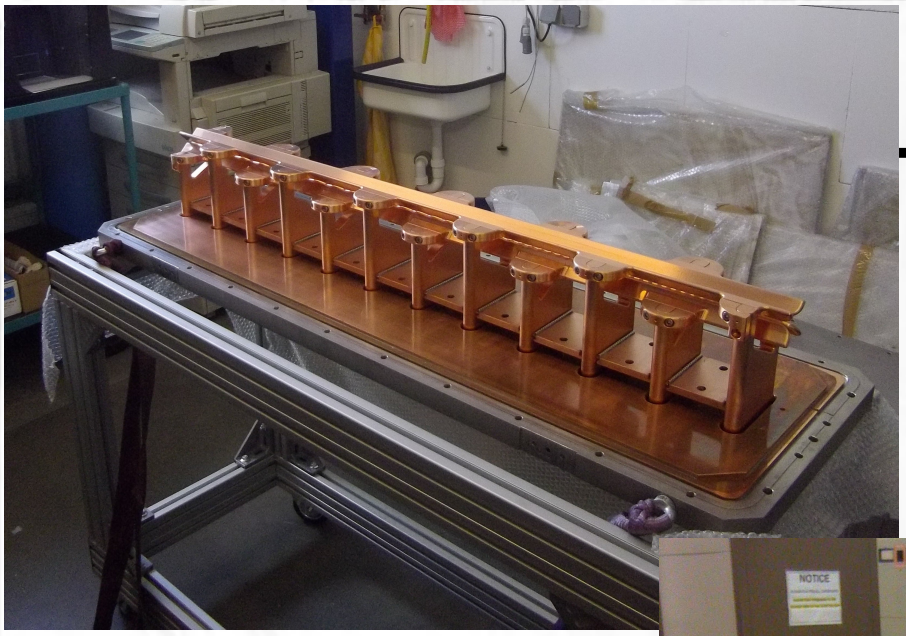


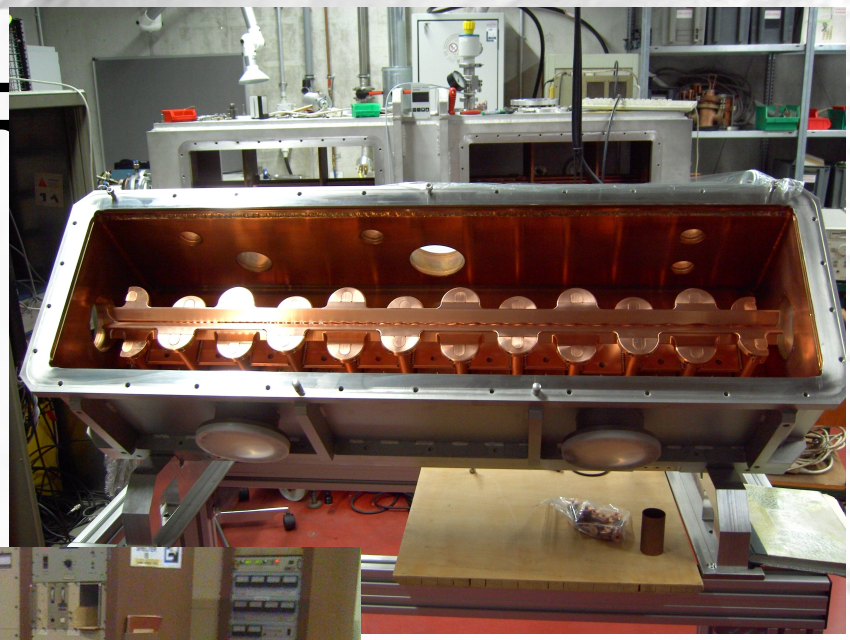
RFQ

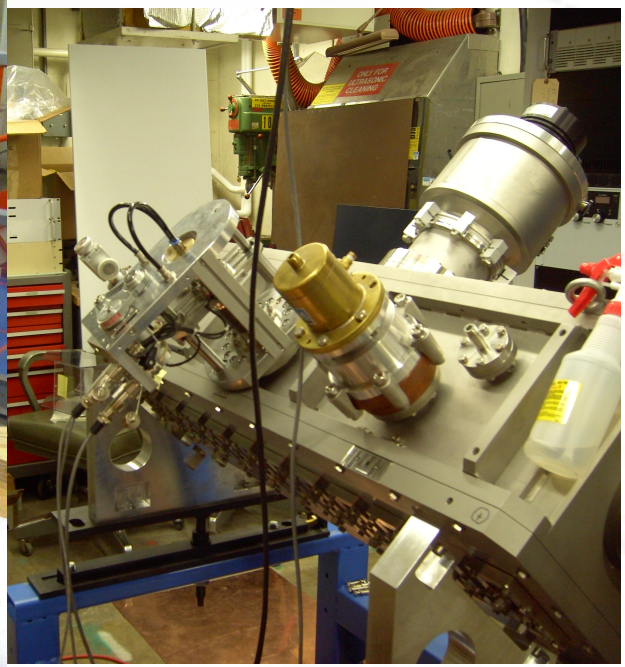
Parameter	Value	Units
Input energy	35	keV
Output energy	750	keV
Frequency	201.25	MHz
Number of cells	102	
Length	120	cm
Minimum radial aperture	0.3	cm
Maximum peak surface field	25.18	MV/m
Peak cavity power+beam power	< 100	kW
Duty factor (80 μs, 15 Hz)	0.12	%
Design current	60	mA
Modulation m	$1 \leq m \leq 1.95$	
Intervane voltage	72	kV
Transmission efficiency	> 98	%

Designed by A. Schempp.
Tuned by J. Schmidt and B. Koubek.

Rod type RFQ.

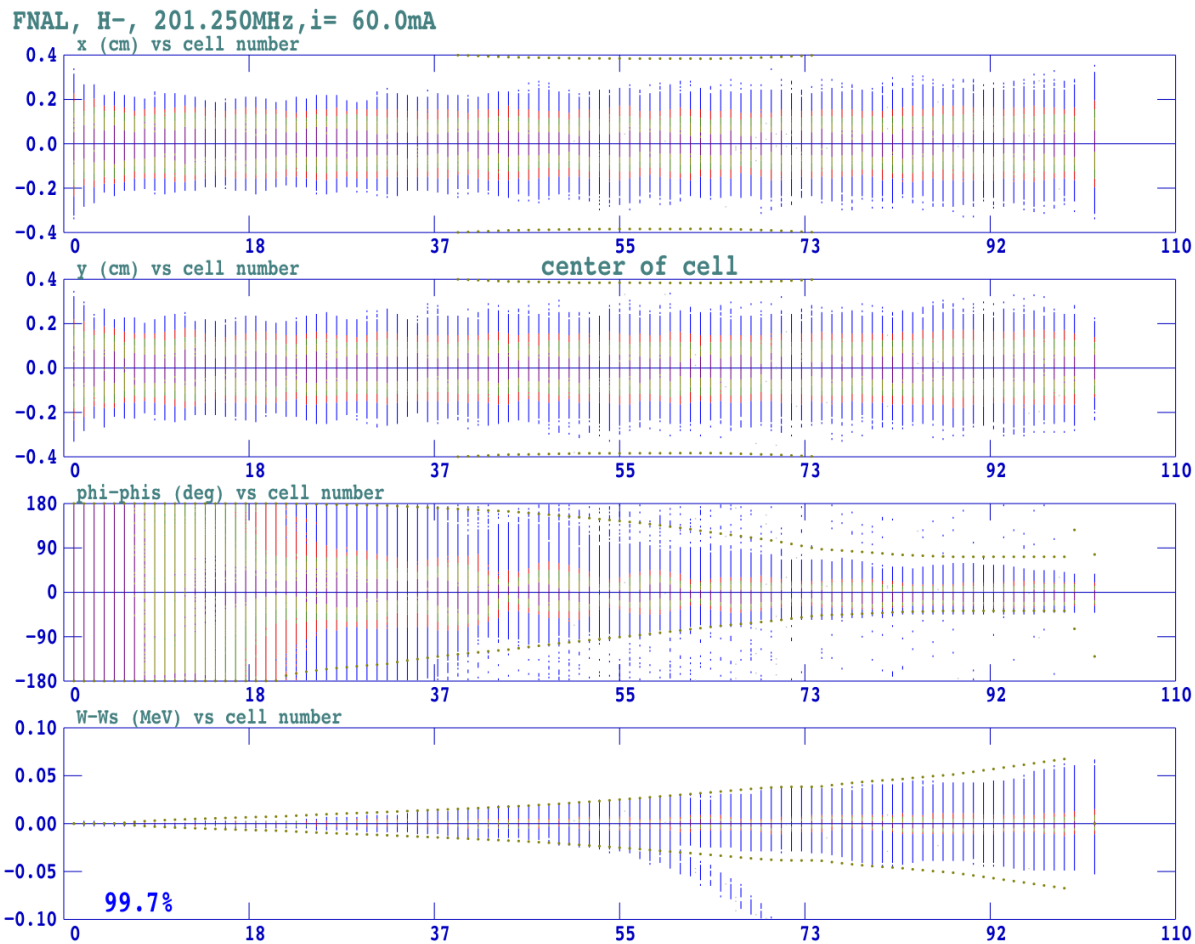






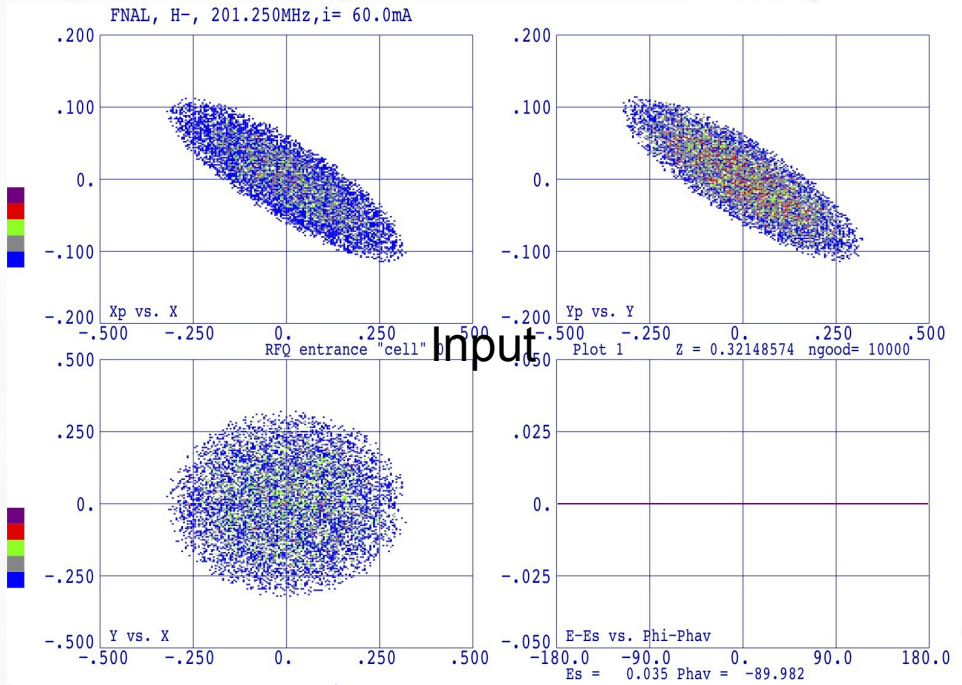
Low power measurements have started. Resonant frequency is too high. J. Schmidt will be here next week to retune.

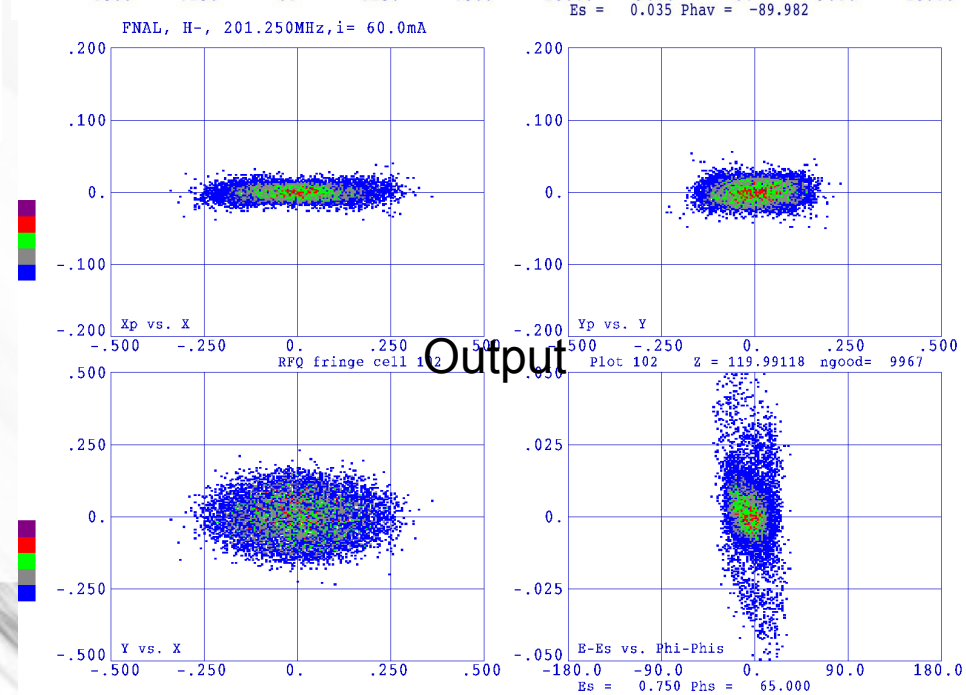
PARMTEQM simulations



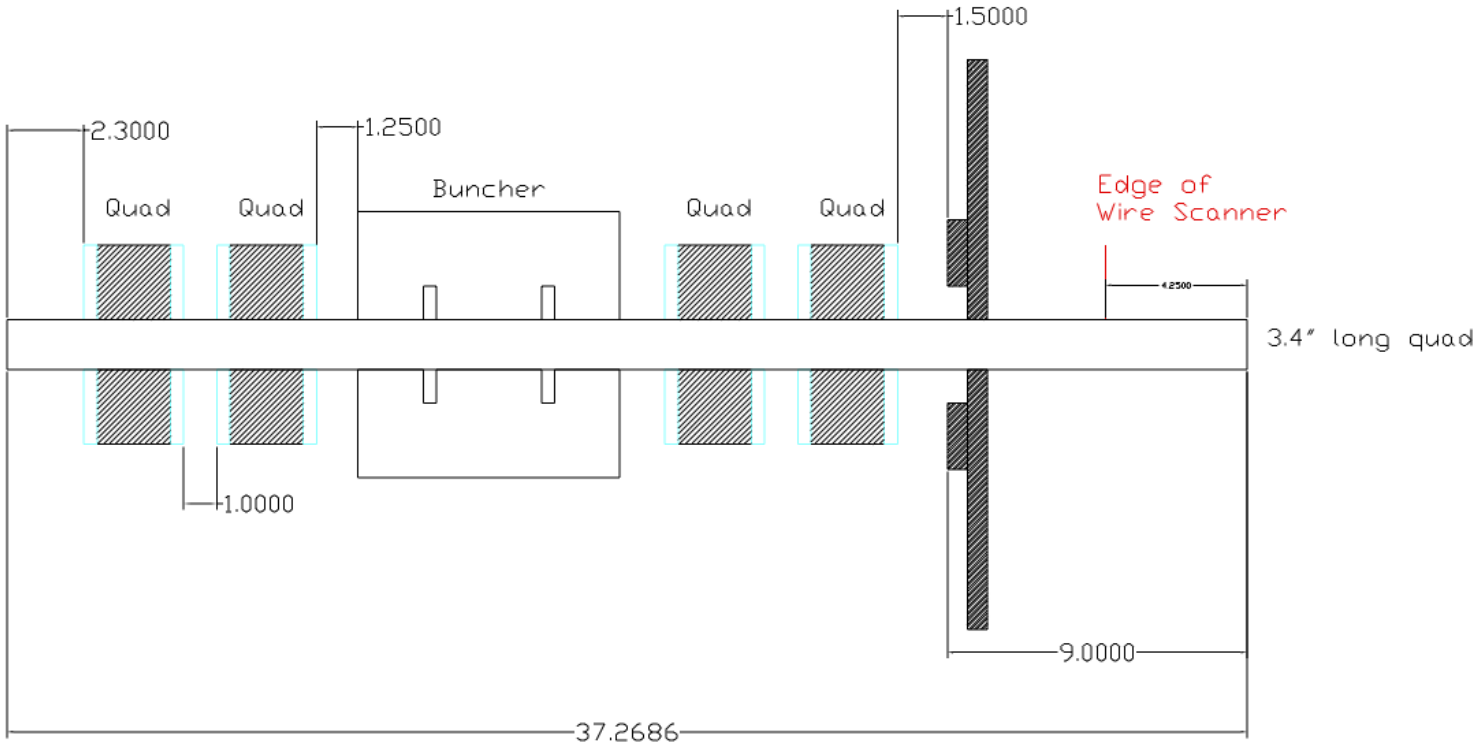
Transmission efficiency > 99% for 60mA beam.

Twiss Parameter	x		y		z	
	Manufacturer	FNAL	Manufacturer	FNAL	Manufacturer	FNAL
Input α	1.5	-	1.5	-	-	-
Input β	5.1 cm/rad	-	5.1 cm/rad	-	-	-
Input ϵ (1× rms)	0.30 π mm mrad norm.	-	0.30 π mm mrad norm.	-	-	-
Output α	−0.18	−0.039	0.07	−0.0813	0.21	0.25
Output β	12.5 cm/rad	12.7 cm/rad	5.5 cm/rad	5.6 cm/rad	1170° MeV	1110° MeV
Output ϵ (1× rms)	0.37 π mm mrad norm.	0.38 π mm mrad norm.	0.35 π mm mrad norm.	0.36 π mm mrad norm.	0.14 π MeV deg unnorm.	0.14 π MeV deg unnorm.



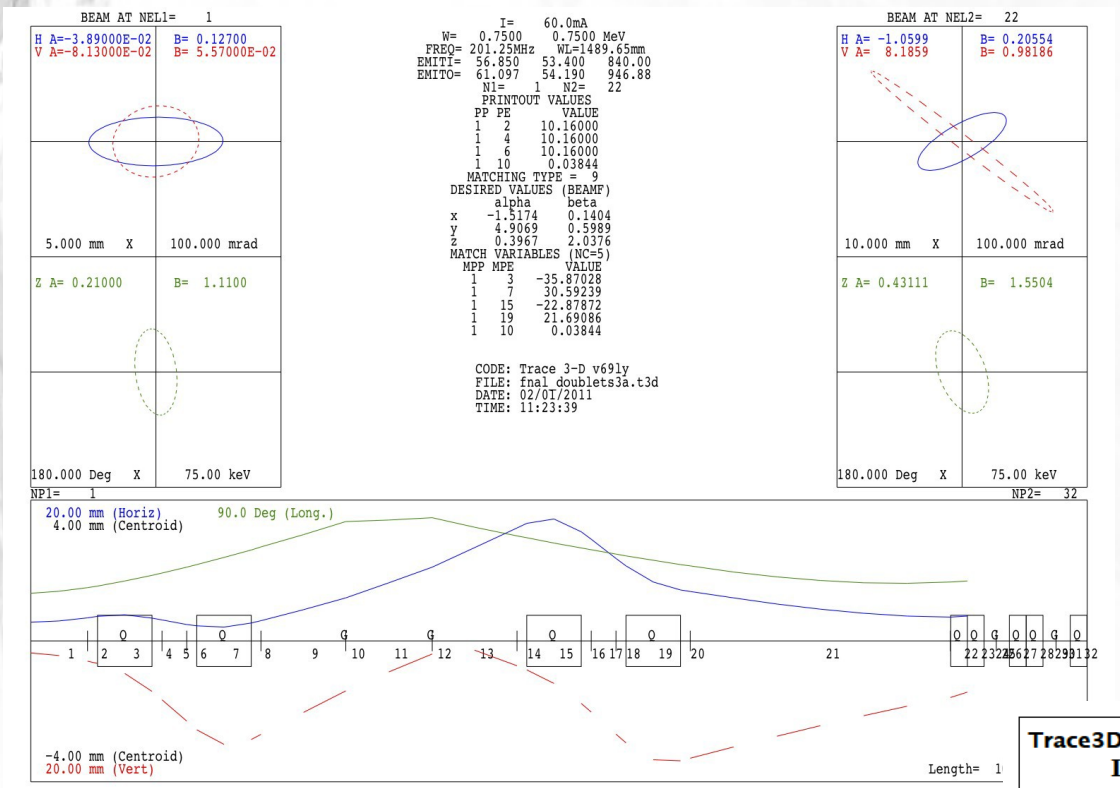


MEBT



Doublet – Buncher – Doublet (30 cm longer compared to BNL MEBT)

MEBT simulations

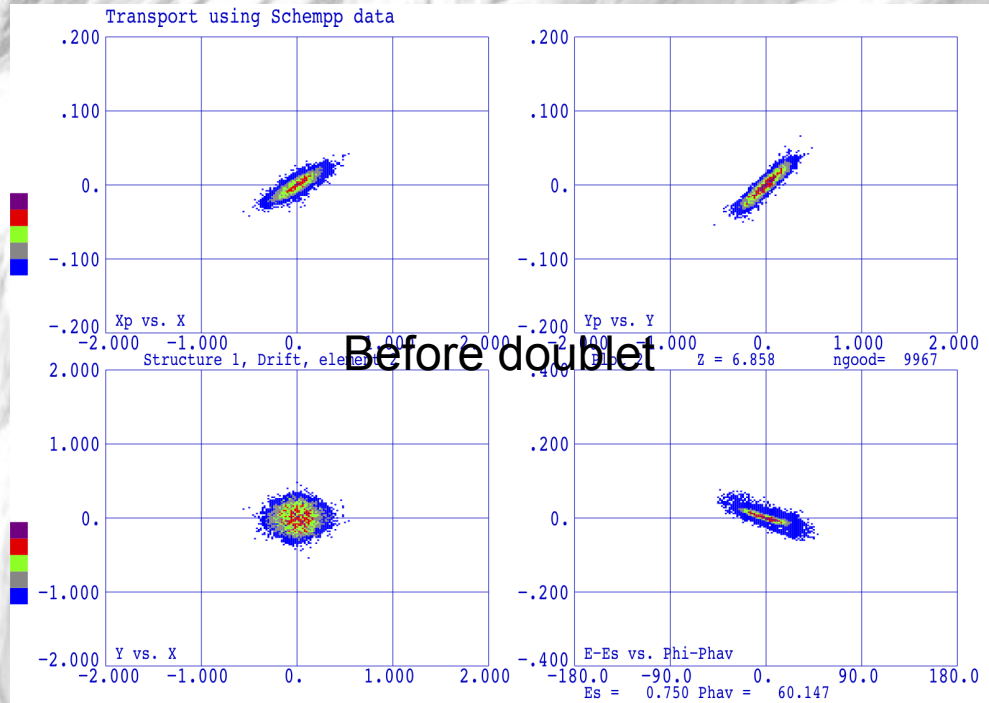


PARMILA shows 95.1% of the beam is captured at the end of DTL 1.

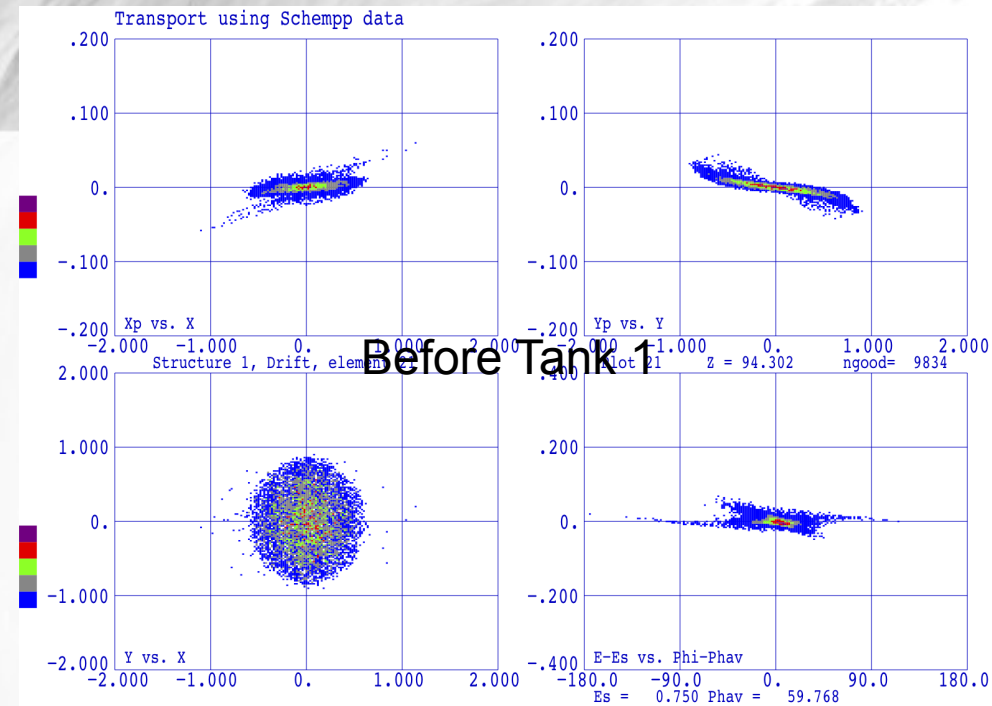
Note: Lattice of DTL not well understood! Using “as found” DTL lattice from M. Popovic.

Note: Quads are very strong

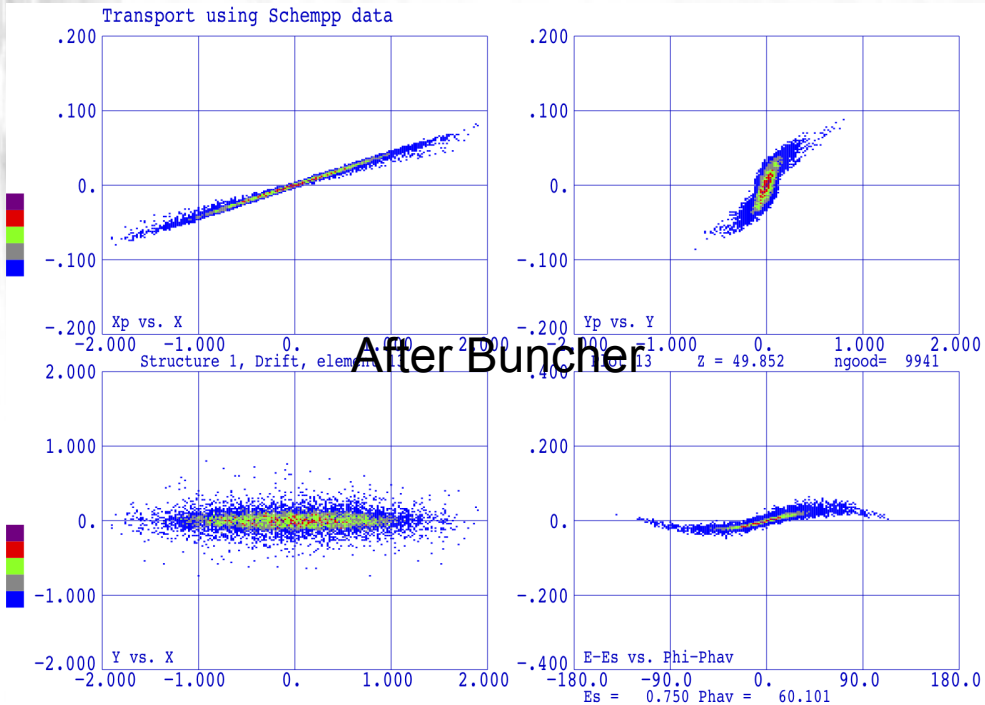
Trace3D Element ID	Element	Gradient (T/m)	Integrated Field (T)	Comments
3	Quadrupole	–35.9	–2.0	Doublet A
7	Quadrupole	30.6	1.7	
15	Quadrupole	–22.9	–1.3	Doublet B
19	Quadrupole	21.7	1.2	
		Gap Voltage (kV)		
15,17	Buncher	38.4 kV		Value is E_0TL. Buncher has two gaps.



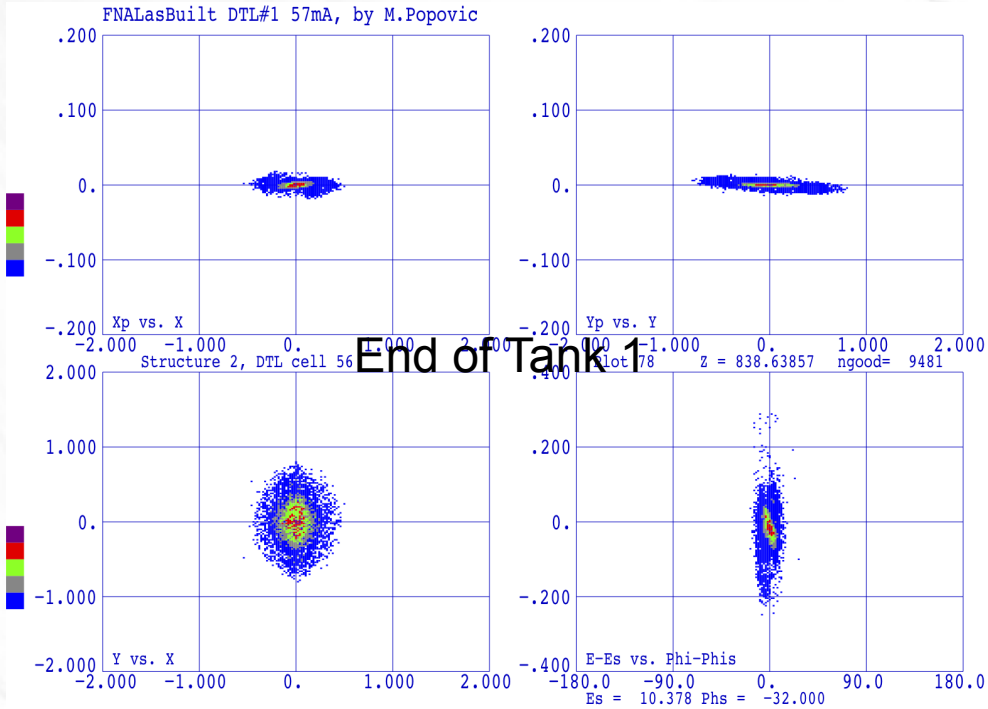
Before doublet



Before Tank 1

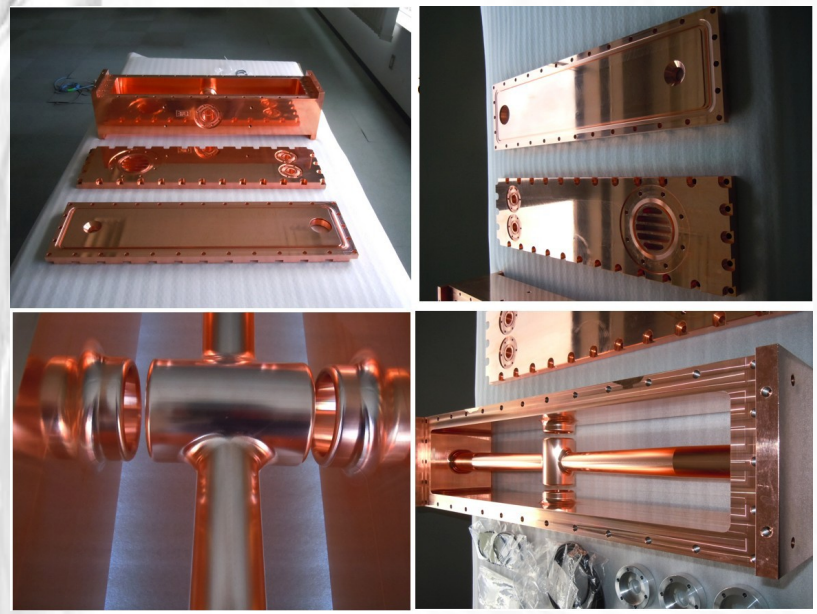


After Buncher



End of Tank 1

Buncher



Parameter	Value	Units
Resonant frequency	201.25	MHz @ 20°C
Resonant type	½ wave length	
Unloaded Q	> 4000	
Min. bore id	32	mm
Max. cavity length	200	mm
Dist. between voltage centers	89.2	mm
Max. input RF power[4]	3	kW
Gap length	10	mm
Induced total gap voltage	> 60	kV

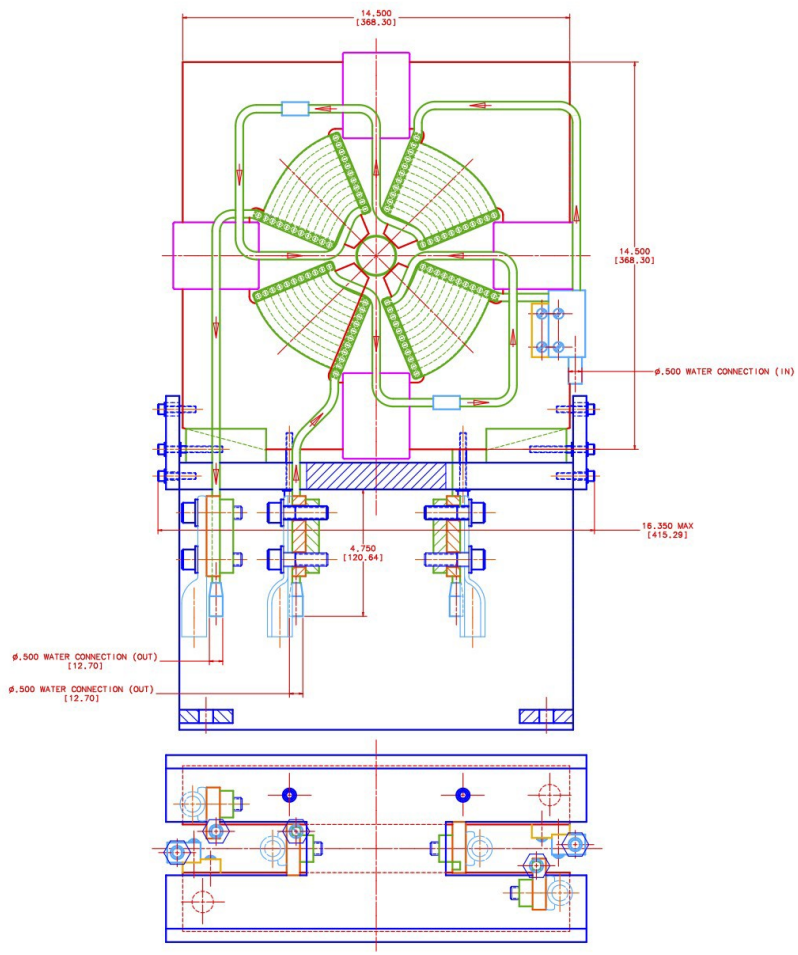
Same as BNL (except FNAL buncher is made of copper while BNL buncher is made of aluminium) Designed by M. Okamura.

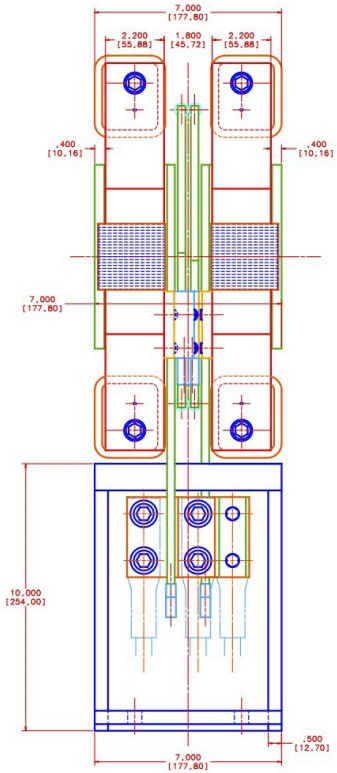
Must have grids to get transit time factor correct.

Low power test with and without grids are complete at FNAL.

Conditioning to be done soon.

Quad doublets with embedded dipole correctors





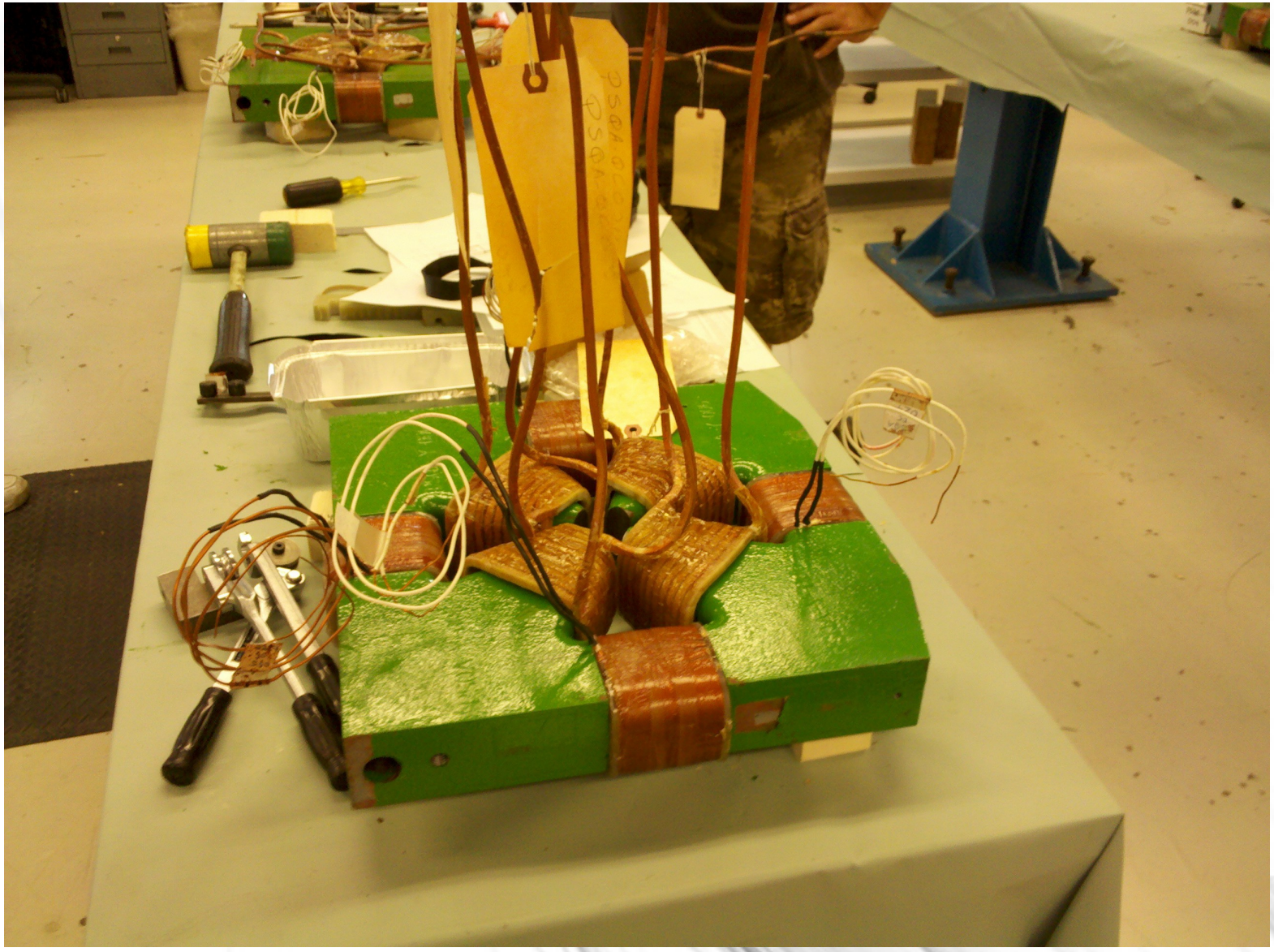
Quadrupole runs DC and water cooled.
Iron core.

Has embedded corrector dipoles.

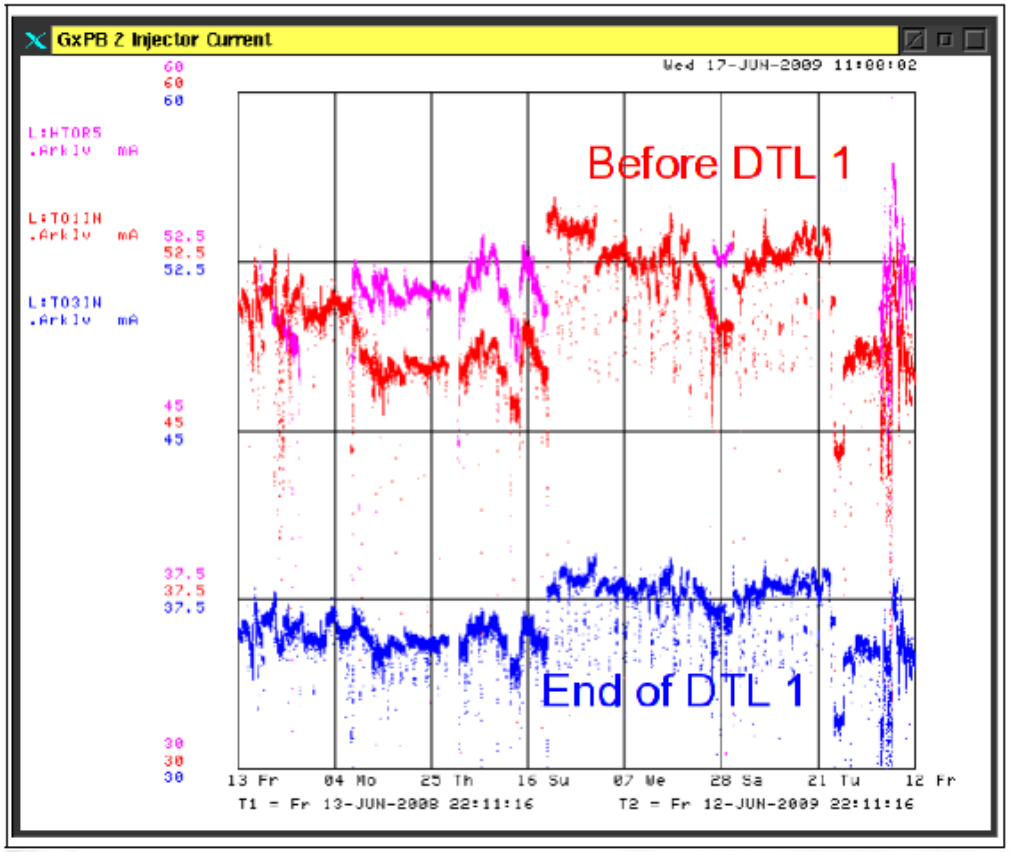
Overall length of doublet is 7”, 1.5” beam pipe.

Tests show that these quads have a large dodecapole component that can blow up transverse emittanace ~15% but we only lose about ~1% of the beam at the end of Tank 1 with no change in transverse emittance.

Quads being assembled.



Performance Goals



Location	Current[5] (mA)	% Transmission from previous location	Comments
Output of H- source	43.5	–	Source can operate up to 100mA. See ref. [2].
End of LEBT before RFQ	40	92	See section 4.2.1.
End of RFQ	39.5	99	See section 4.3.
End of DTL 1	37.5	95.5	See section 4.4.

Location	Current (mA)	ϵ_x (norm., 1σ, π·mm·mrad)	ϵ_y (norm., 1σ, π·mm·mrad)	Comments
Start of DTL 1	46	0.86	0.91	Taken on 3 Jun 2009

At minimum, must perform as well as present system.

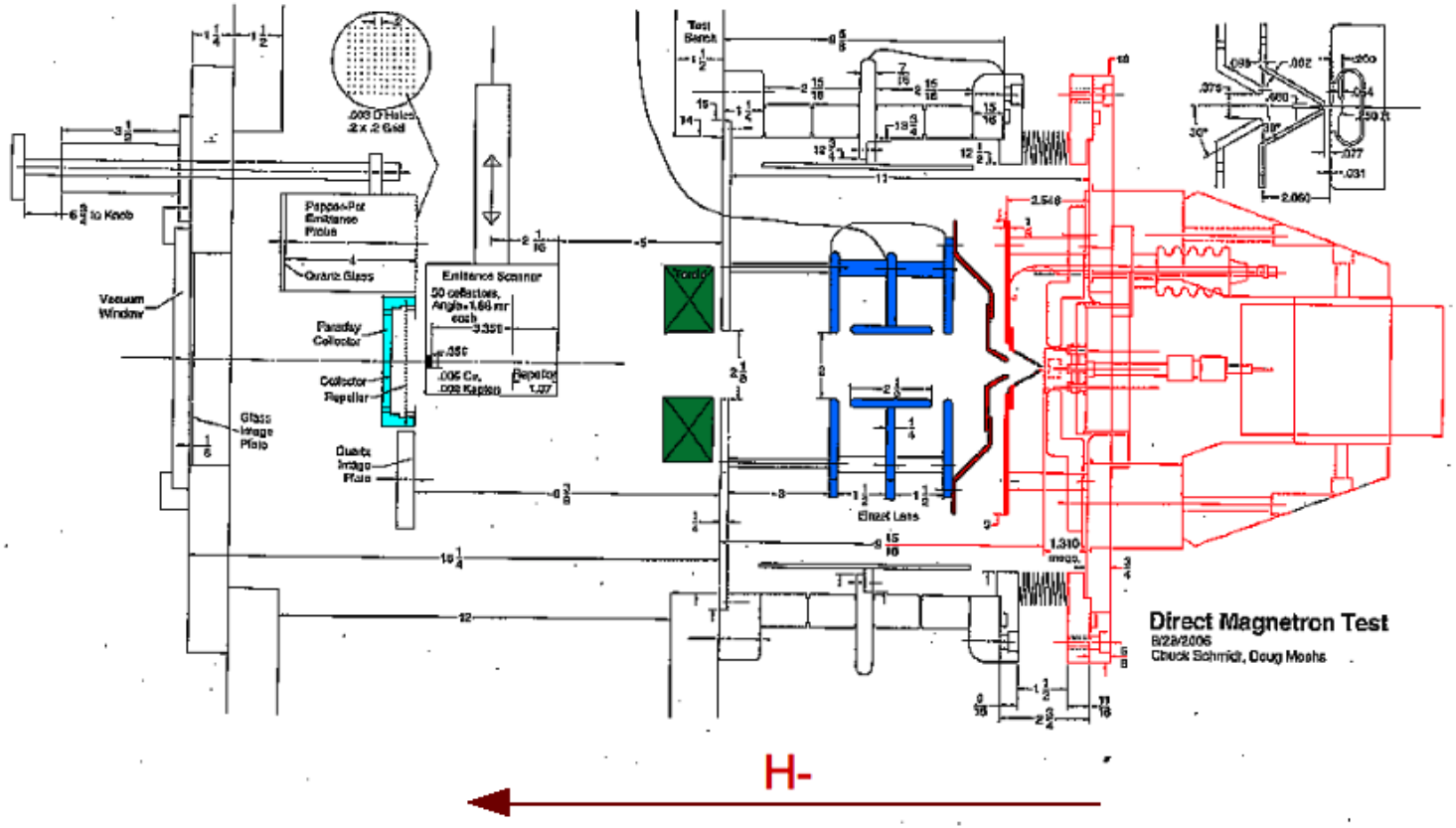
Status

- Beam soon!
  - Heaters are on. Takes about 6 hours to get H-.
- RFQ to be retuned.
  - Once this is done, pump down and RF conditioning.

Conclusion

- Nothing in the design is “cutting edge”
  - Not pushing any envelopes.
  - 01 Sep review “Overall, the project seems to be well thought out and conservative. There's every reason to believe it will succeed.”
  - Copying as much as possible the BNL injector has helped a lot!
- There will be a lot of work in the coming months to validate the design in the test set up. We will **not** install if it doesn't meet emittance and bunching criterion.

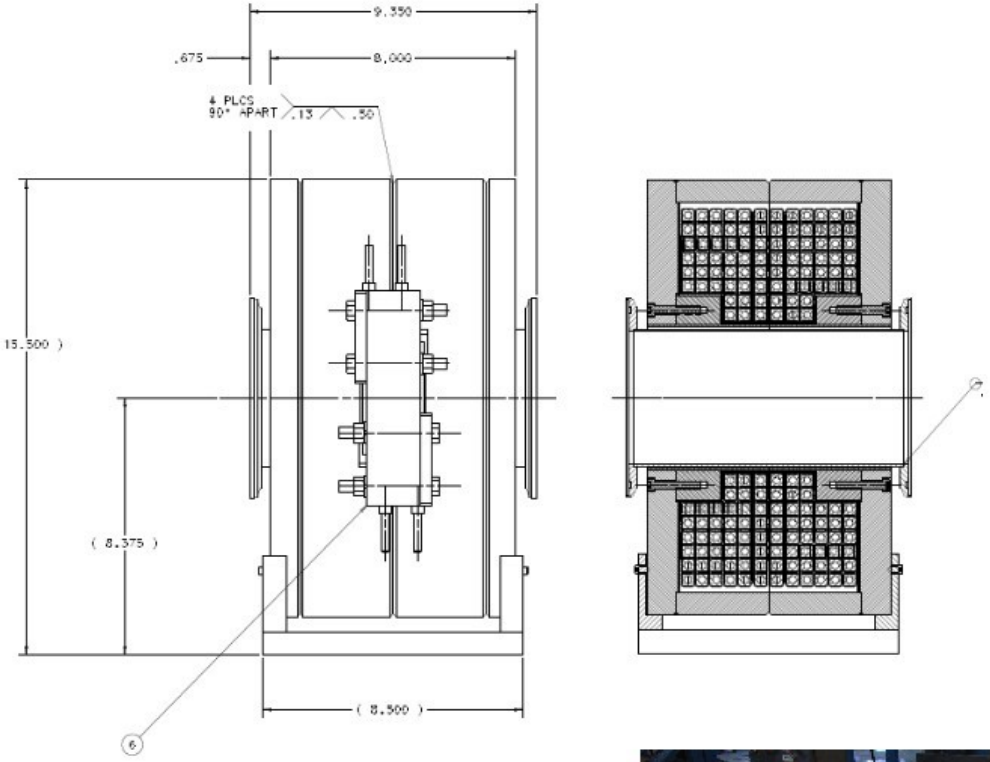
Test Stand

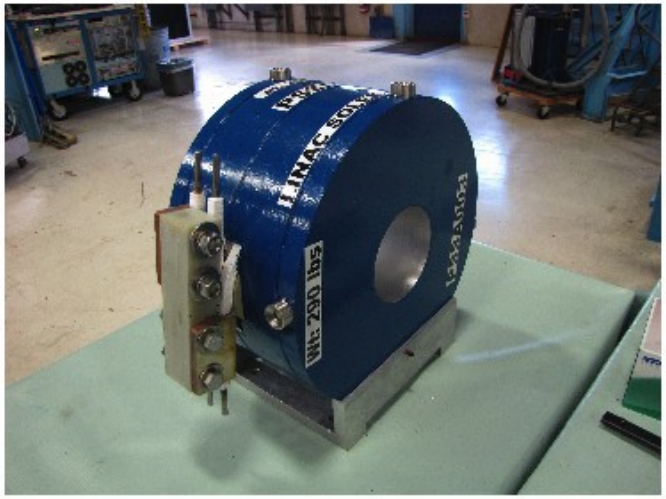


Einzel lens is 2” in diameter and 2.5” long.

Note: injector lens is 1.75” diameter and 2” long.

Solenoids



Solenoids run DC.
Water cooled.
Settings ~500A.

Designed by A. Makarov and V. Kashikhin.