PRESENTATION FOR DoE-NP SBIR/STTR EXCHANGE MEETING, OCT. 24-25, 2011

# MULTI-CAVITY PROTON CYCLOTRON ACCELERATOR*

Report based on work supported by US DoE-NP
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Outline of talk:

- brief description of Omega-P, Inc.
- uses in NP and elsewhere for intense <GeV-scale proton beams
- operating mechanism for multi-cavity proton cyclotron accelerator
- electron counterpart multi-cavity cyclotron accelerator
- summary

*Work reported here is supported by a sub-grant from Omega-P to Yale (MAL, Yale PI).

**Collaborators: J.L. Hirshfield (PI, Omega-P), S. Shchelkunov (Yale), V. Yakovlev (FNAL).

# Description of Omega-P:

## *A small R&D company in New Haven, CT specializing in advanced accelerator concepts, RF sources and RF accelerator structures*

• Typically, a dozen full- and part-time employees & consultants.

• Enjoys collaborations with SLAC, BNL, FNAL, ANL, NRL, IAP, BINP, Columbia Univ., and Yale Univ. (JL Hirshfield is adjunct professor of physics at Yale).

• Awarded 73 SBIR/STTR grants since 1992 (mostly DoE-HEP), 38 of which advanced to Phase II. Currently, 2 Phase I's and 6 Phase II's are active.

• Published on average about 12 archival research papers annually.

• Current main funded research activities include:

- multi-cavity proton (and electron) cyclotron acceleration;
- two-channel dielectric wake field electron acceleration;
- multi-mode detuned cavity structures for high-gradient electron acceleration;
- two-beam collinear accelerator structures;
- active elements (plasmas, e-beams, ferroelectrics) for high-power RF phase shifting, switching, and RF pulse compression;
- RF source development, e.g, low-voltage (60 kV) 10-MW L-band multi-beam klystrons for ILC and Project X, and multi-MW harmonic converters;
- RF breakdown studies on CVD diamond, on alloys, and on Cu structures with thin insulating coatings, for possibly increasing breakdown thresholds.

# Why the present interest in new proton accelerators?

See *Accelerators for America's Future,* W. Henning and C. Shank, eds., DoE report, June 2010.

The iconic prototype (1999) is LANL's LEDA (100 mA, 6.7 MeV, CW 8-m RFQ), originally to be the front-end for a 600 MeV proton driver for APT.

New compact, efficient proton accelerators are needed for:

- energy (nuclear waste transmutation, sub-critical reactors);
- medicine (proton therapy, radioisotope production);
- industry (ion implantation, materials development);
- discovery science (neutrons, muons, neutrinos, support for Project-X at FNAL: e.g., beam stability/transport < 1nA/1W interception/m).

In order to address some of these topics, Prof. O.K. Baker, the Director of Yale's Wright Nuclear Structure Lab, is considering plans for a low-energy, high-current, proton beam facility; to replace the tandem Van de-Graaff long used for basic nuclear structure studies. Omega-P is providing Prof. Baker with informal advice on accelerator-related issues.

# Omega-P and Yale have a long history with **C**yclotron **A**uto-**R**esonant **A**cceleration **CARA**

VOLUME 76, NUMBER 15 PHYSICAL REVIEW LETTERS 8 APRIL 1996

**Experimental Demonstration of High Efficiency Electron Cyclotron Autoresonance Acceleration**

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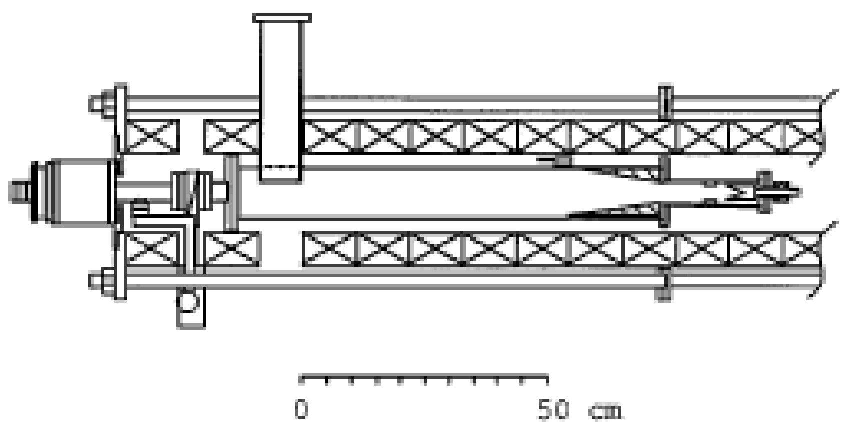
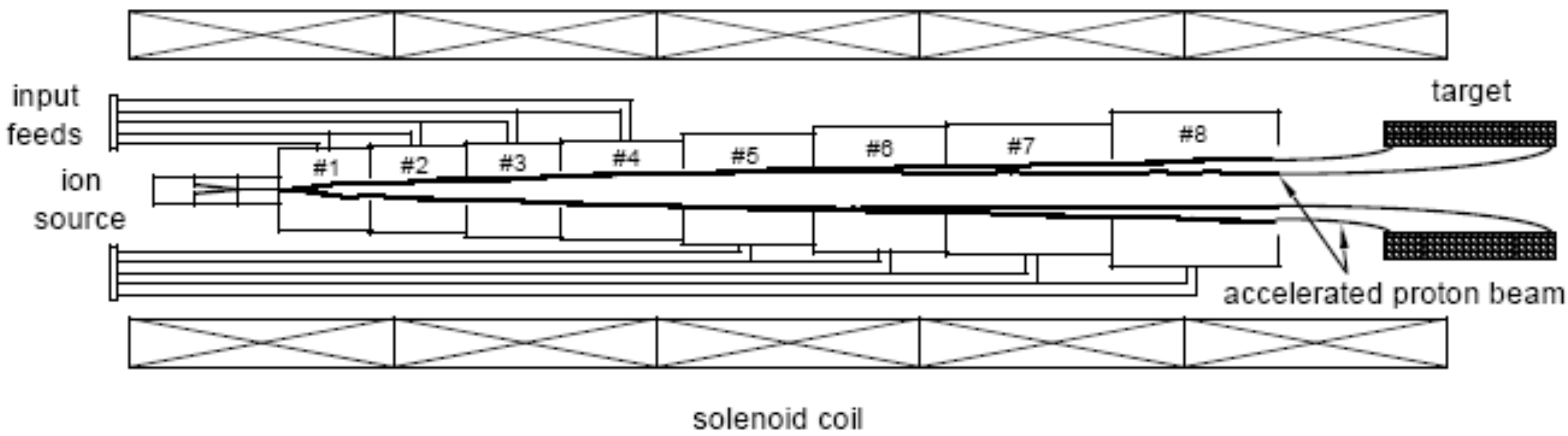
(Received 23 October 1995)

First experimental results are reported on the operation of a multimegawatt 2.856 GHz cyclotron autoresonance accelerator (CARA). A 90–100 kV, 2–3 MW linear electron beam has had up to 6.6 MW added to it in CARA, with an rf-to-beam power efficiency of up to 96%. This efficiency level is larger than that reported for any fast-wave interaction between radiation and electrons, and also larger than that in normal conducting rf linear accelerators. The results obtained are in good agreement with theoretical predictions.



CARA has an upper energy limit [Wang and Hirshfield, *Phys.Rev.E* **51**, 2456 (1995)] so a multi-cavity, multi-frequency structure would be needed to reach, say, 1 GeV for protons.




- High effective (axial) acceleration gradient;
- High average current;
- Low RF electric fields on cavity walls;
- Large apertures to guard against higher-order mode excitation;
- Solenoid focusing is adequate;
- Uses room temperature cavities.
- *BUT IT REQUIRES A STRONG-FIELD LARGE SC SOLENOID!!*

# Four Cavity Electron Counterpart

Parameters to mimic proton accelerator

Proton $E_f$ = 952 MeV ($\gamma$=2) $I_{inj}$=1 MeV, 122 mA ($\beta$=0.04)

RF power: 174 MW Final Beam Power: 116 MW

Electron $E_f$ = 500 keV ($\gamma$=2), $I_{inj}$=1 keV, 10 $\mu$A ($\beta$=0.06)

RF power: 1.4 MW Final Beam Power: 5 W

No high intensity electron beam intended as this experiment is to study the multi-cavity, multi-frequency mechanism.

Mechanisms to be tested include:

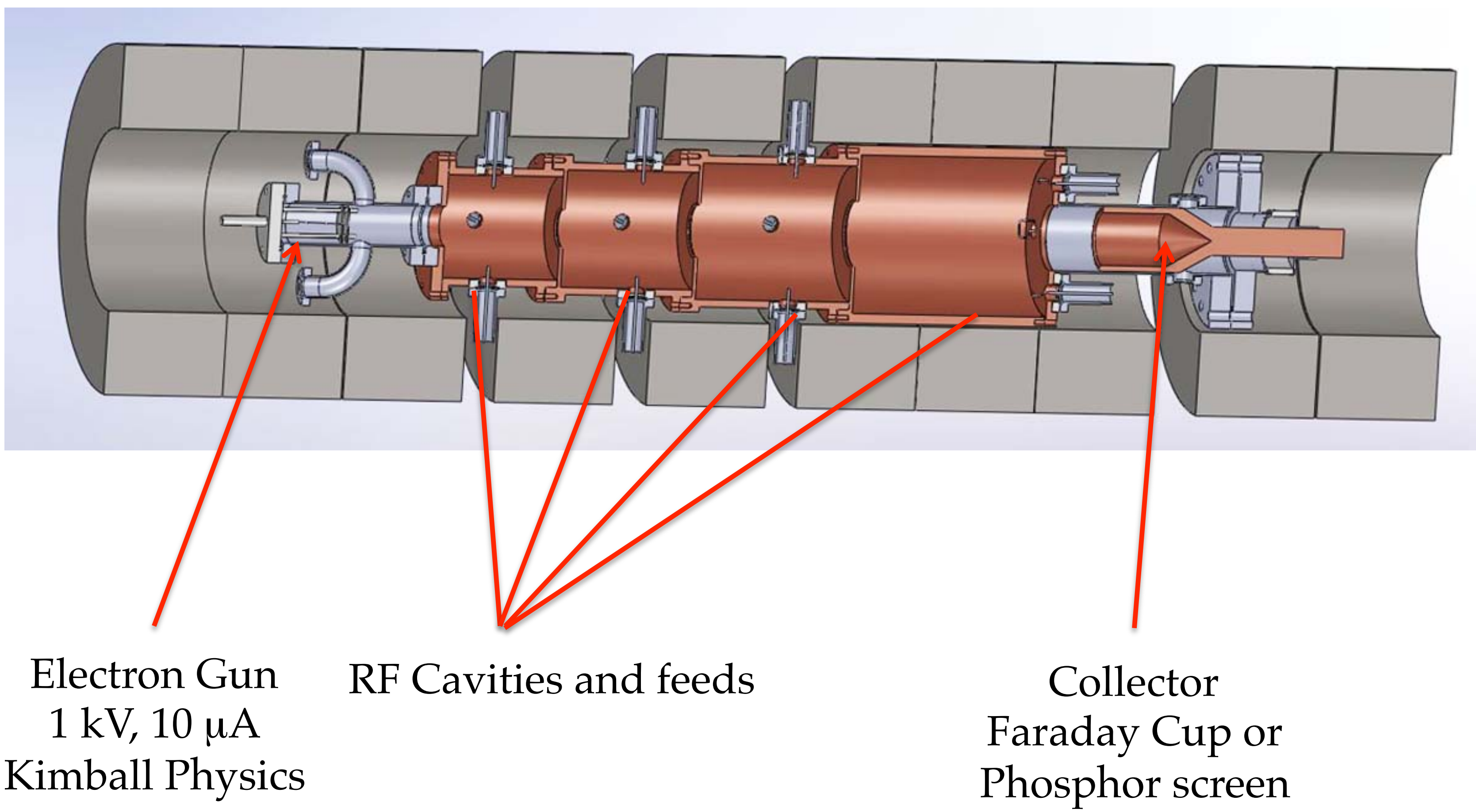
Multi frequency gain mechanism to maintain synchronism

Phase acceptance

Energy spread and growth

Emittance growth

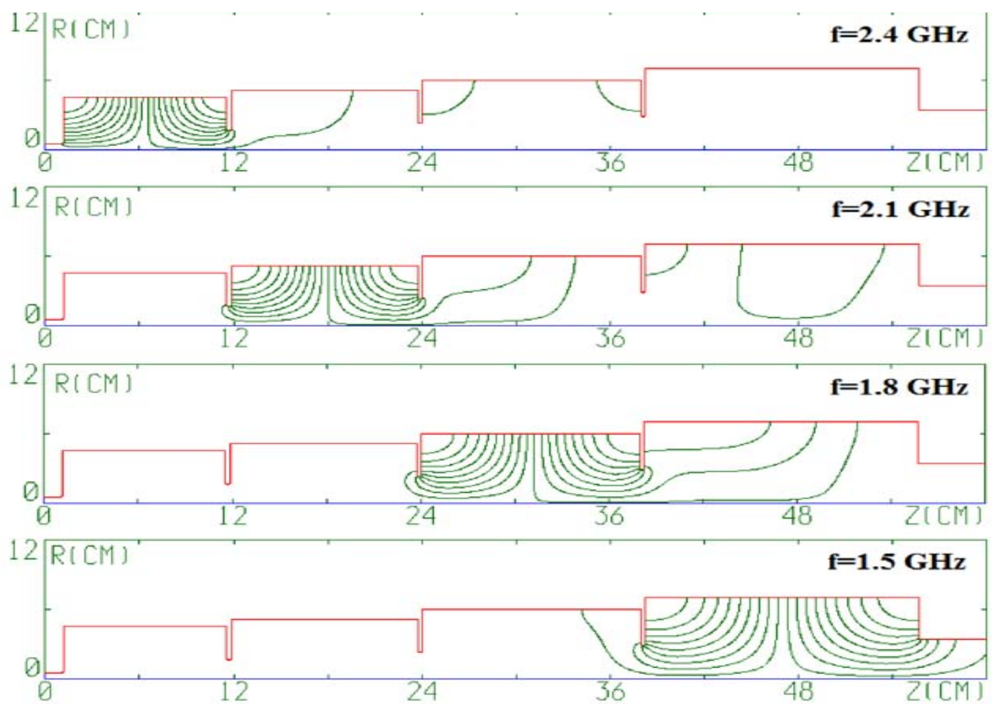
4-cavity electron counterpart to test acceptance/emittance trade-offs. $f = 2.4, 2.1, 1.8, 1.5$ GHz; $B = 1.6$ kG.




Operating mode for cavities is $TE_{111}$ rotating. Solenoid coils to provide ~1600 Gauss field

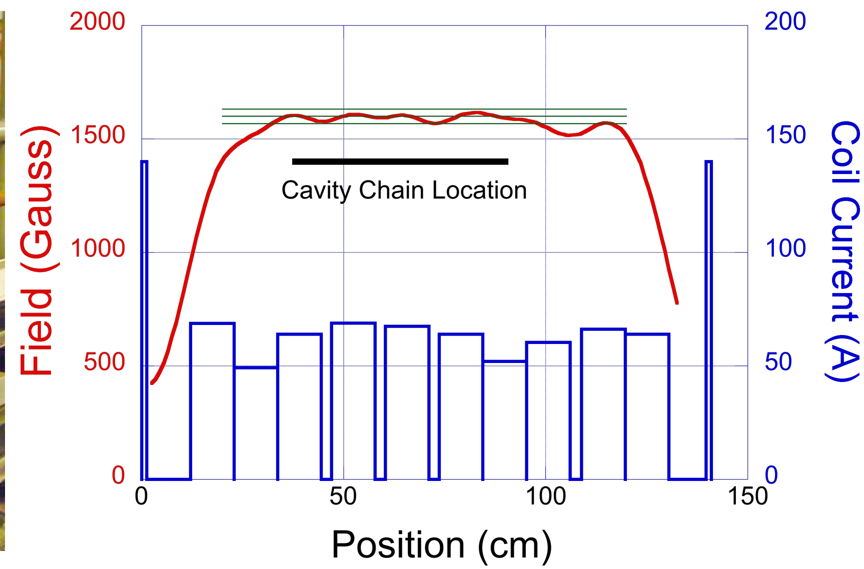
# Parameters for 4-cavity electron counterpart

| Cavity | $f_{TE111}$, GHz | $R$ mm | $L$ mm | $A$ mm | $Q$ | $P$ $W$ | $dU$ $kev$ |
|---|---|---|---|---|---|---|---|
| 1 | 2.4 | 45.37 | 104 | 16.3 | 24300 | 207 | 119 |
| 2 | 2.1 | 51.21 | 119 | 22.8 | 26000 | 420 | 123 |
| 3 | 1.8 | 59.24 | 139 | 28.4 | 28500 | 367 | 105 |
| 4 | 1.5 | 70.05 | 174 | 33.6 | 30800 | 426 | 147 |
| Total | | | 536 | | | 1420 | 494 |



# Status of the Four Cavity Experiment: Magnetic system

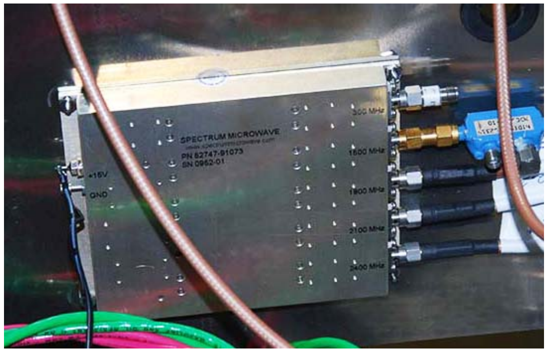
Magnet System is assembled and ready for installation of experiment. Each coil is powered by an individual independently controlled power supply.

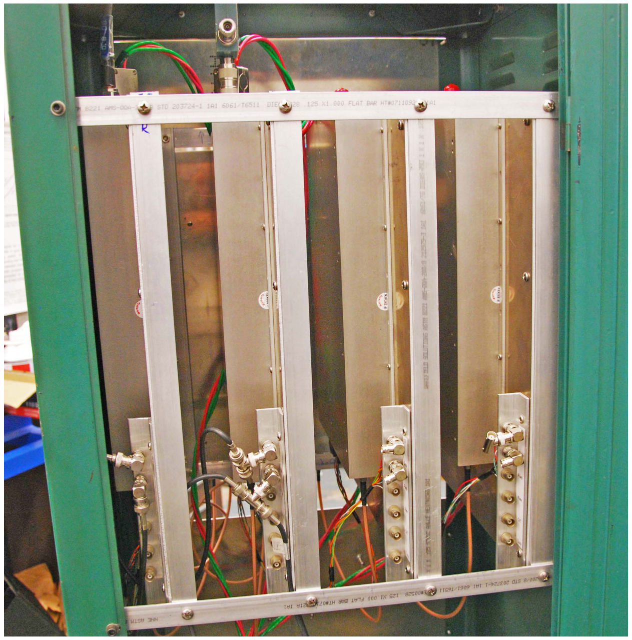


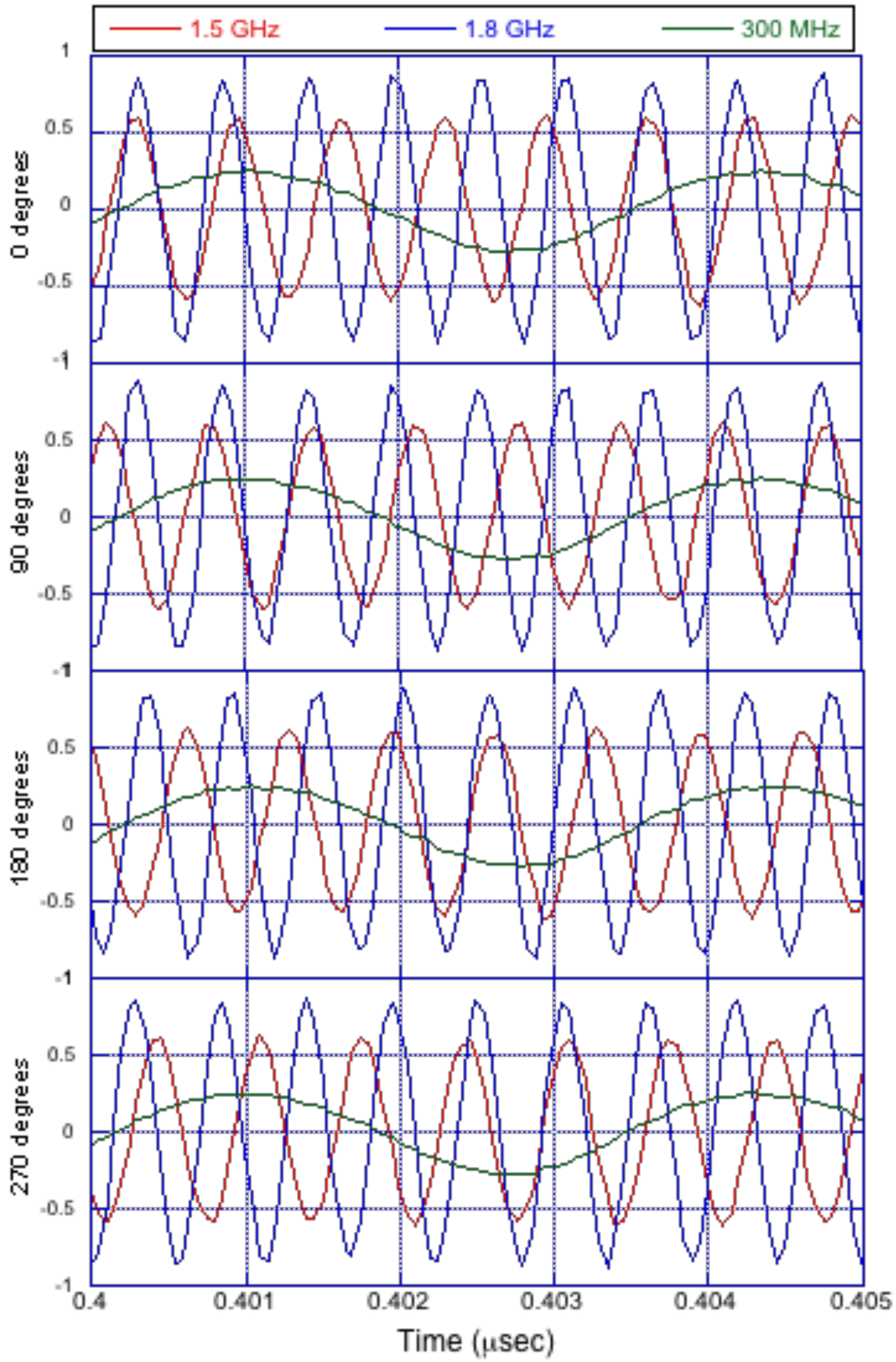

The magnet system was tested at the operating field and achieved the 1.6 kGauss over the interaction region. Ripple due to the necessary gaps in the solenoids is less than 2% over the interaction region for all four cavities, and can be reduced.

# Status of the Four Cavity Experiment: RF System

Four Solid State pulsed amplifiers operating at 1.5, 1.8, 2.1, and 2.4 GHz.
Each is capable of 500 W at a maximum duty cycle of 1 %.
RF source is a Spectrum Microwave custom harmonic converter.
Four frequencies generated from a 300 MHz master.
Ensures the phase coherence between the four frequencies.
Amplitude/phase controlled by ARRA microwave attenuators and phase shifters.






This data set shows the relative phase between the 300 MHz source (low level ~5 dBm) and the sampled high power output from the 1.5 GHz (red) and 1.8 GHz (blue) solid state amplifiers.

The phase shifter for the 1.5 GHz amplifier was adjusted through 270 degrees as shown by the red traces. The phase shifters have 0.15 degree resolution and estimated 0.5 degree repeatability.

Measurements of the phase stability will be performed next.

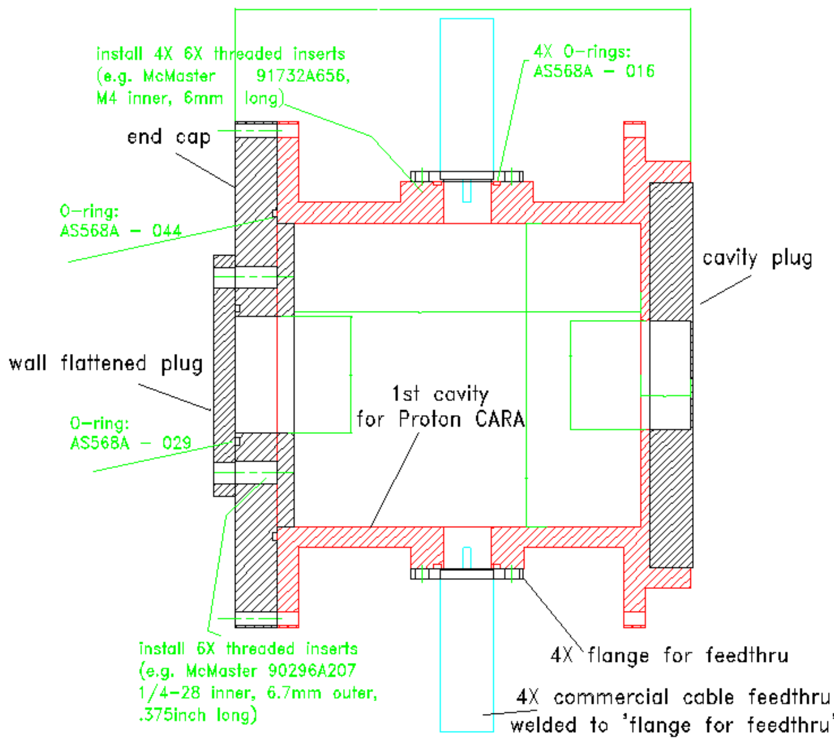
# Status of the Four Cavity Experiment: Cavity Structure

The 2.4 GHz cavity is being manufactured by Gen-El-Mec Associates, Bridgeport, CT.

Cold testing will be performed to determine final tuning of cavity.

Optimization of antenna coupling for both drive and sample ports will be done.

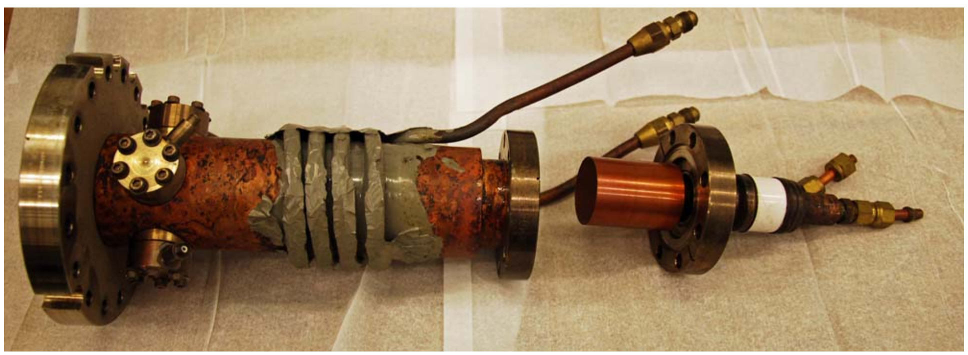
Engineering drawings for the 2.1, 1.8 and 1.5 GHz cavities will be done after we gain experience with this cavity.



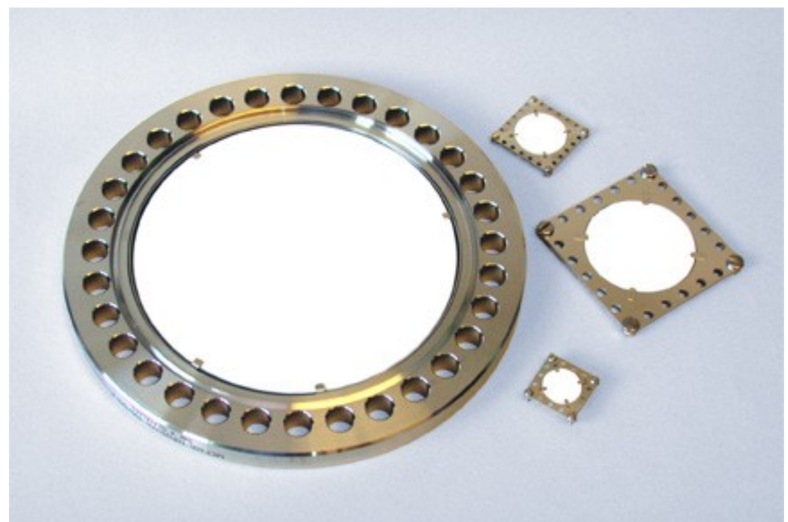
# Status of the Four Cavity Experiment: Diagnostics

Beam Diagnostics: Faraday cup/calorimeter (Beam current & energy)
Phosphor Screen (Beam imaging, emittance?)

RF Diagnostics: Directional couplers on RF feeds (F & R power)
Sample RF ports on cavities (cavity diagnostic)



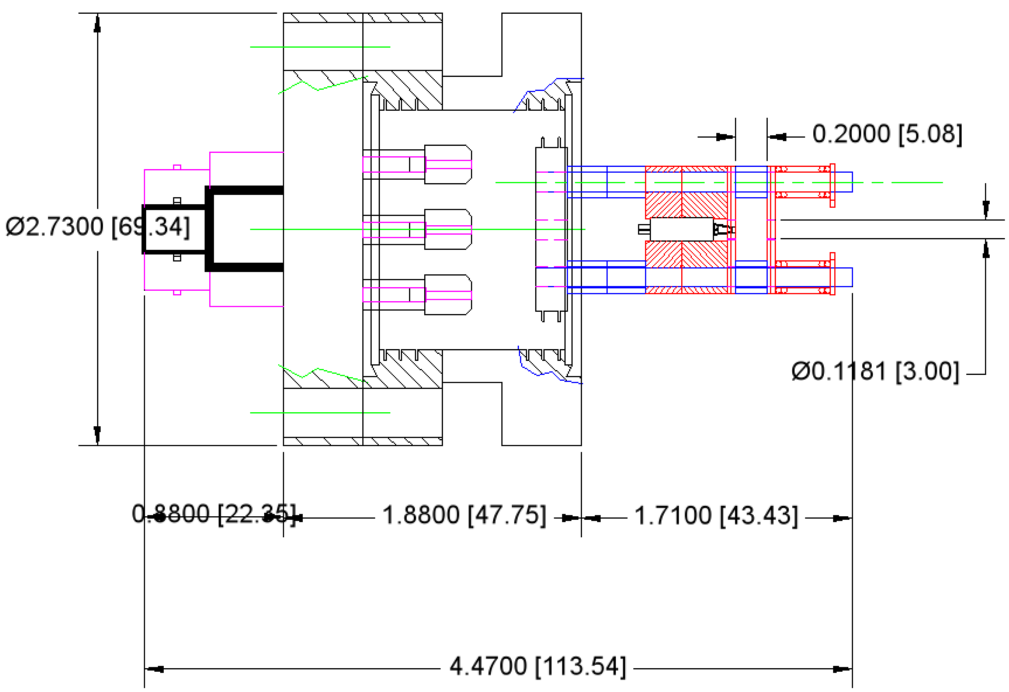
Existing Faraday Cup/ Calorimeter



Kimball Physics phosphor screens

# Status of the Four Cavity Experiment: Electron Gun

Design is based on a Kimball Physics model ES-015 BaO disc cathode.
All commercial parts are in house.
Custom parts (cathode holder and focusing electrode) are being built by the Gibbs Machine shop at Yale.




Operating Parameters

$V_i = 1$ kV

$I_c = 10\ \mu$A

Initally pulsed ~10 µsec

Future chopped at 300 MHz

# Summary for proton cyclotron CARA and multi-cavity cyclotron accelerators

•CARA: full phase acceptance (i.e., cw), high efficiency; and with a waveguide with up-tapered radius ($n \rightarrow 1$, i.e. group velocity $\rightarrow c$), there is no energy upper limit, but acceleration gradient falls rapidly as energy grows.

•Multi-cavity: limited phase acceptance *vs* emittance (i.e., pulsed), but has an upper energy limit dictated by practical solenoid radius and field strength; requires multiple frequency RF sources.

•Electron counterpart: may help to understand practical limits, and to identify applications for a proton CARA or multi-cavity cyclotron.

# SUMMARY

• CARA and multi-cavity cyclotron accelerator are under study as possible future high intensity proton accelerators. Parameters are strongly governed by realistic limits for large-diameter high-field solenoids.

• Electron counterpart experiments are expected to deepen understanding of the acceptance/emittance tradeoff, and how this influences efficiency and beam transport after acceleration.

• Costs and complexities should be compared between very large SC solenoids necessary for the Multi Cavity Proton Accelerator and SC RF which is now the preferred technology for future high intensity proton accelerators (e.g., Project X).