

PRESENTATION FOR DoE-NP SBIR/STTR EXCHANGE MEETING, SEPT. 13-14,2010

MULTI-CAVITY PROTON CYCLOTRON ACCELERATOR*

Report based on work supported by US DoE-NP
under SBIR grant DE-FG02-07 ER 84862

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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
- predicted performance for a 200-MeV proton cavity cyclotron accelerator
- electron counterpart multi-cavity cyclotron accelerator
- two-beam proton accelerator - an alternative approach
- summary

*US patent 6,914,396 B1; Symons, Hirshfield, & Wang, July 5, 2005.

**Collaborators: M. LaPointe, S. Shchelkunov, V. Yakovlev

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 71 SBIR/STTR grants since 1992 (mostly DoE-HEP), 36 of which advanced to Phase II. Currently, 4 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 new 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 has a long history with Cyclotron Auto-Resonant Acceleration CARA

VOLUME 76, NUMBER 15

PHYSICAL REVIEW LETTERS

8 APRIL 1996

Experimental Demonstration of High Efficiency Electron Cyclotron Autoresonance Acceleration

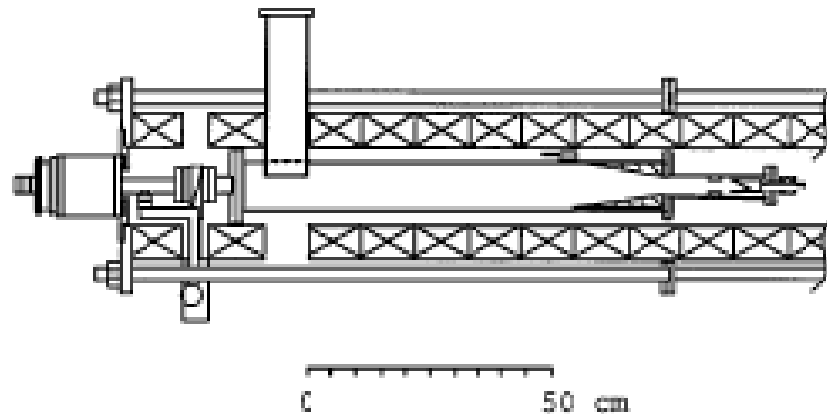
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(Received 23 October 1995)

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.

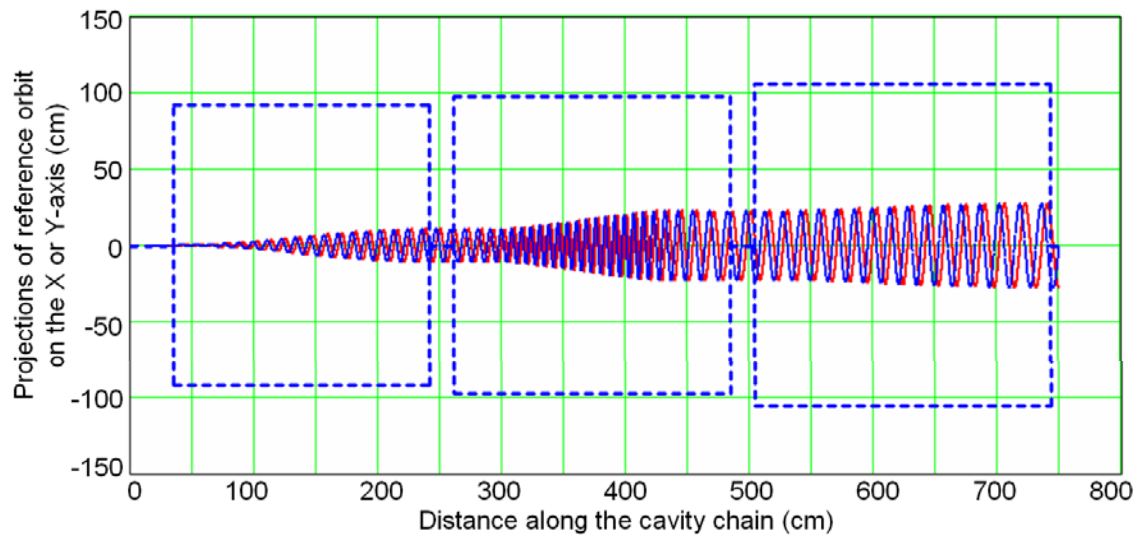
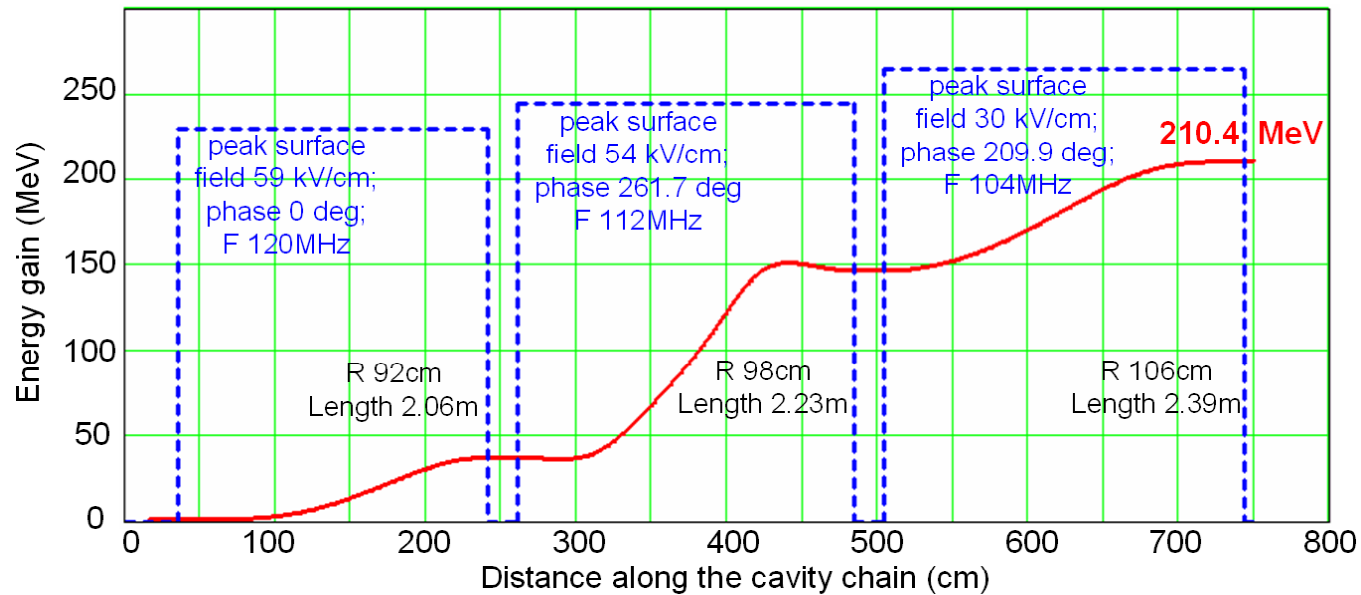


CARA has an upper energy limit [Wang and Hirshfield, *Phys.Rev.E* 51, 2456 (1995)] so a multi-cavity, multi-frequency structure would be needed to reach, say, 1 GeV for protons.

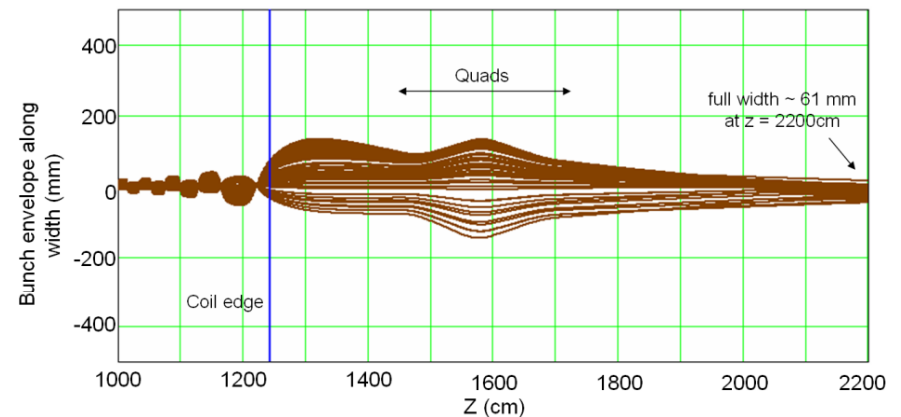
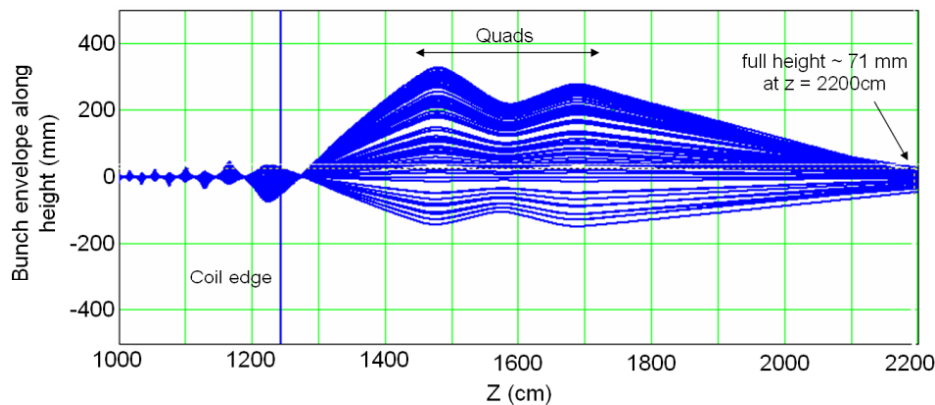
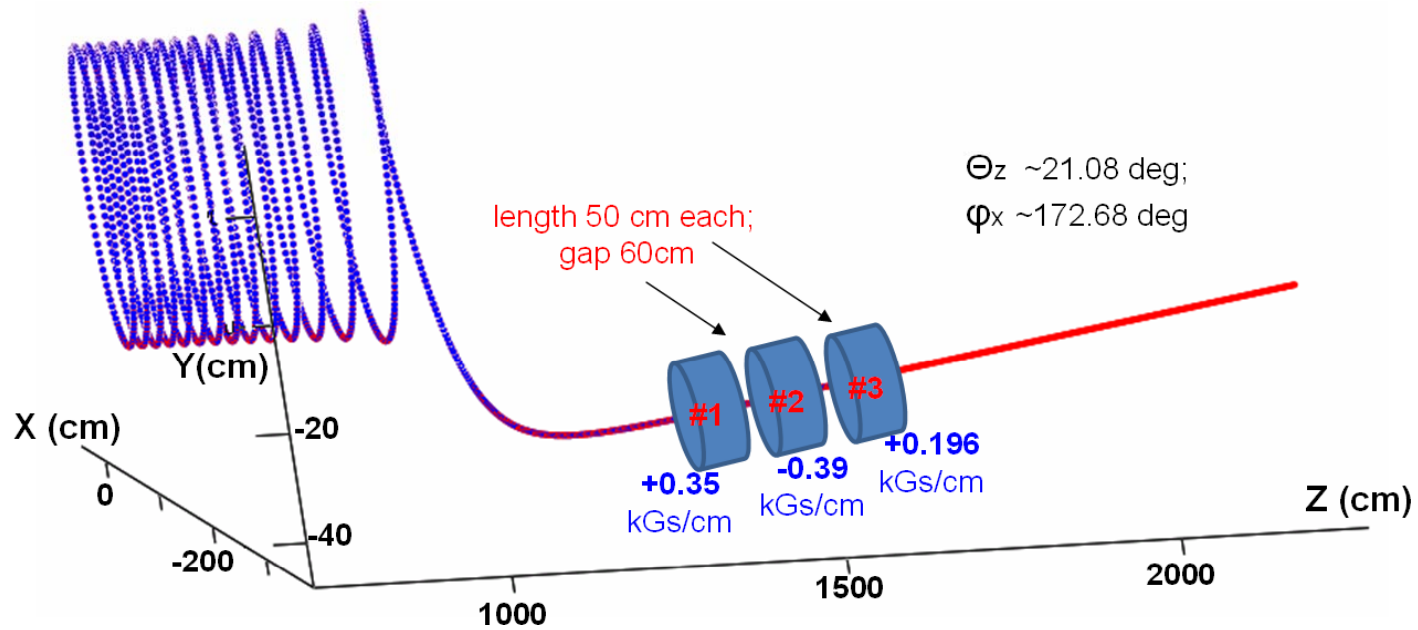


- High effective (axial) acceleration gradient;
- High average current;
- Low RF electric fields on cavity walls;
- Large apertures to guard against higher-order mode excitation;
- Solenoid focusing is adequate;
- Uses room temperature cavities.
- ***BUT IT REQUIRES A STRONG-FIELD LARGE SC SOLENOID!!***

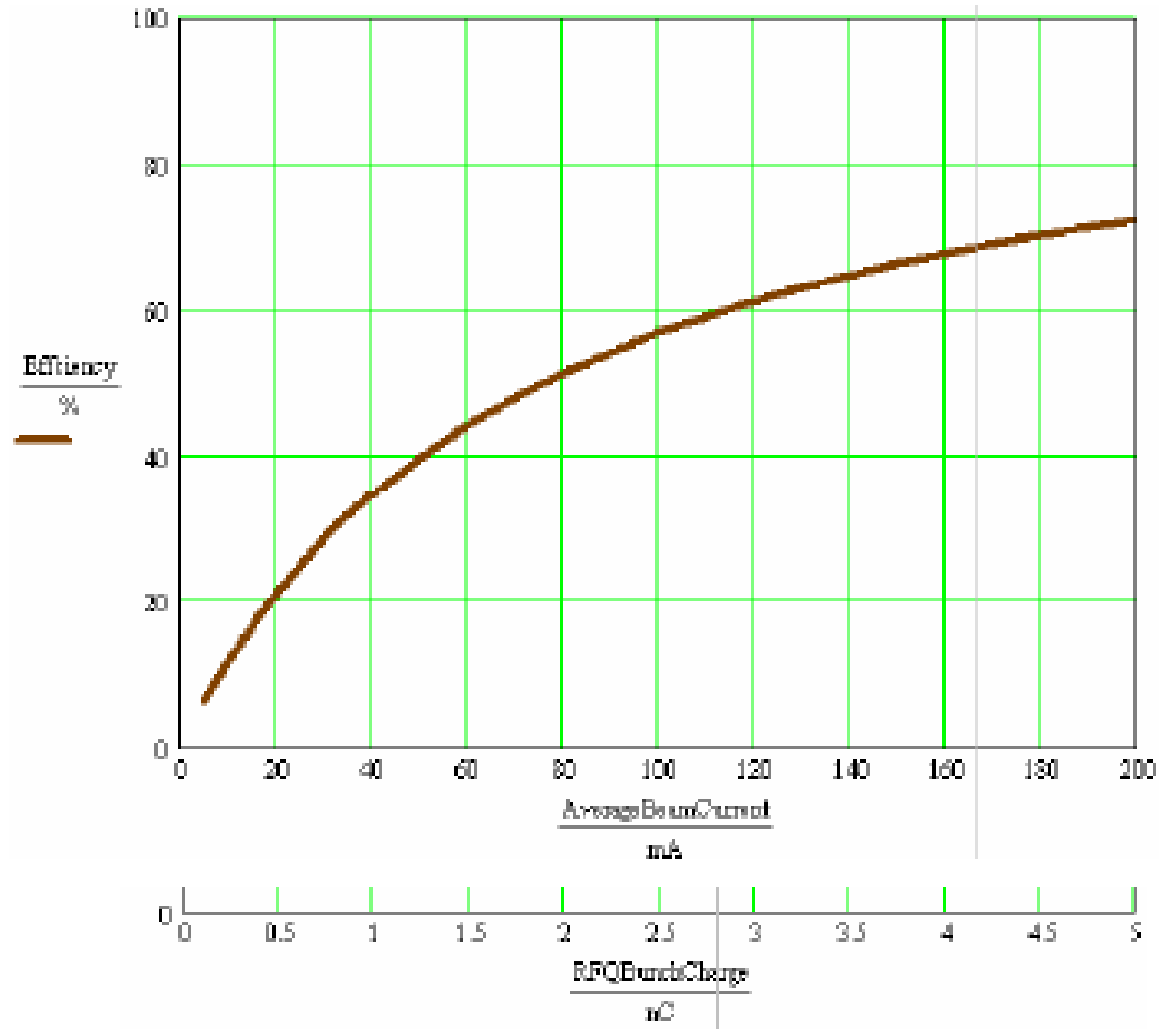
Example of a 3-cavity 210 MeV proton cyclotron: $B = 8T$.
 Along axis, $G = 28$ MeV/m in 7.5 m; or along orbit $G = 3.4$ MeV/m in 63 m.



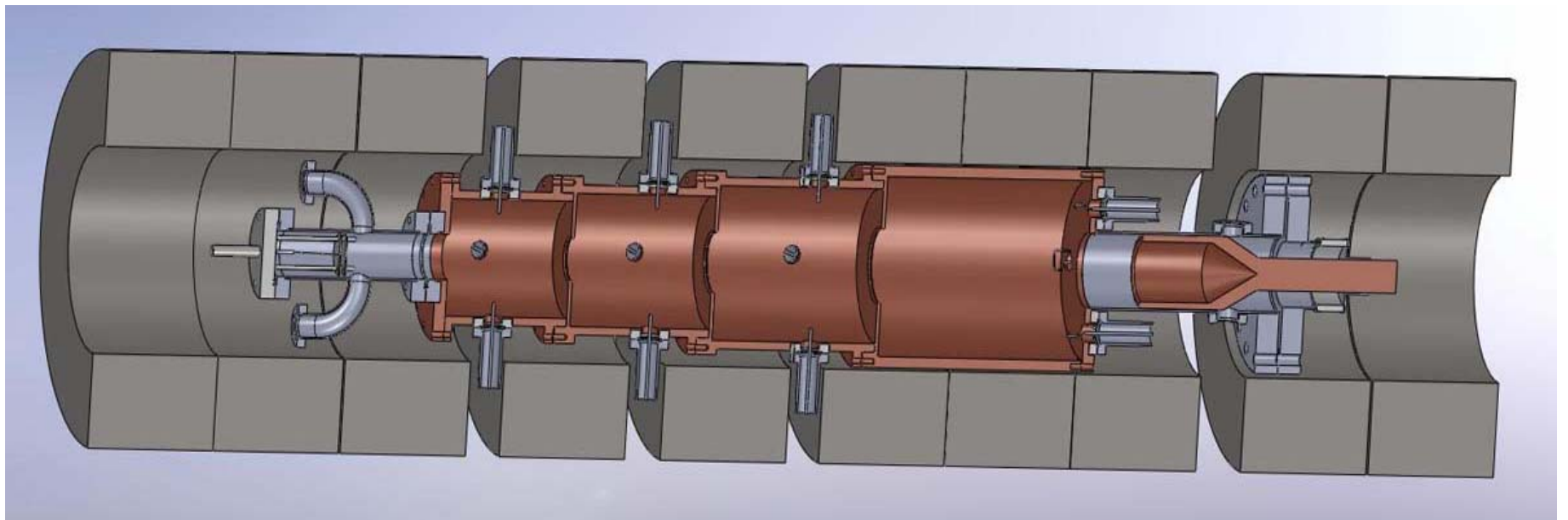
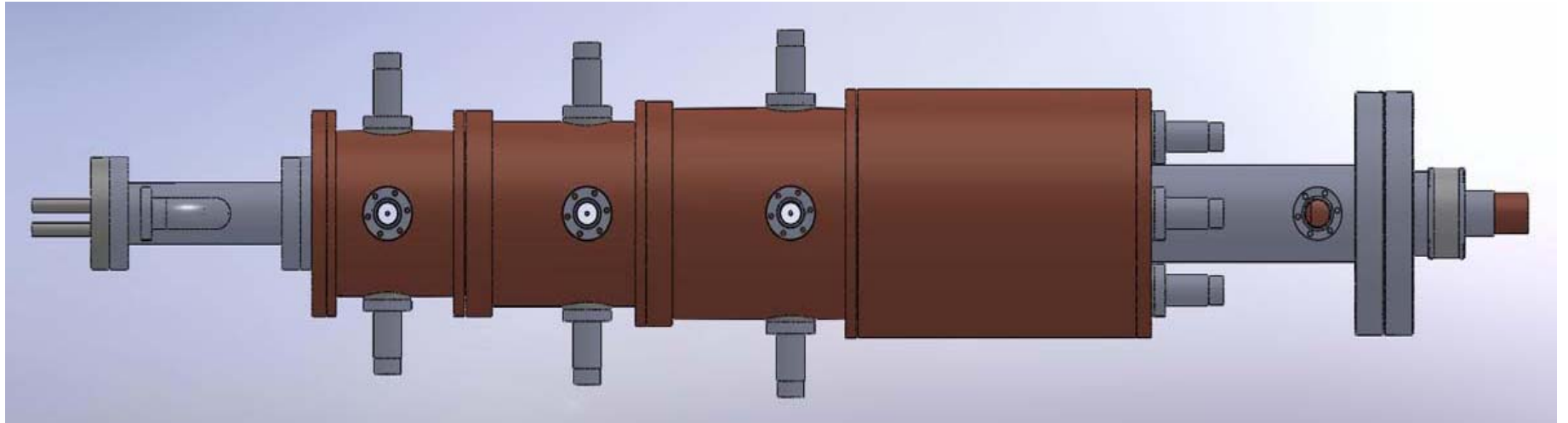
Example of extraction and focussing from proton cavity cyclotron of 210 MeV beam with longitudinal emittance of 52 nsec-keV



Efficiency for 3-cavity 200-MeV proton cavity cyclotron (five 5-MeV RFQ bunches/pulse. 8 MHz prf, ϵ -long = 52 ns-keV)

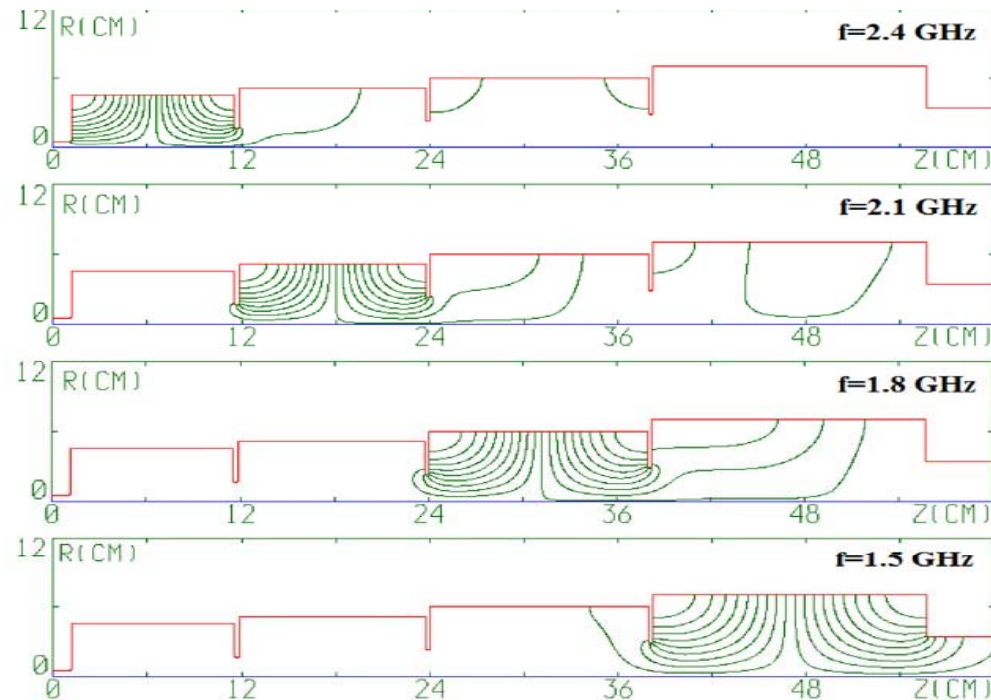


4-cavity electron counterpart to test acceptance/emittance trade-offs. $f = 2.4, 2.1, 1.8, 1.5$ GHz; $B = 2$ kG.



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



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.
- Either, for protons, requires a 10's-m long, 1-2 m diam 8-16 T solenoid. But for a 1 GeV - 100 MW proton driver for ADS, magnet complexity and cost should be compared with the ~250 m SC linac now contemplated.
- Thus, one asks: Is there any other novel approach on the horizon for a compact, efficient, high-current GeV-scale proton accelerator?

NEXT SLIDE PLEASE---

Alternative approach: collinear 2-beam proton accelerator using a high-current electron drive beam, and alternating detuned cavities with varying gaps

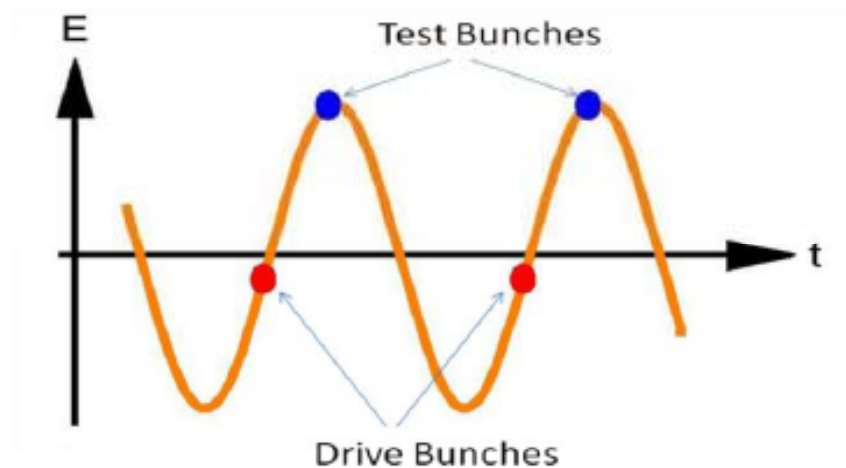
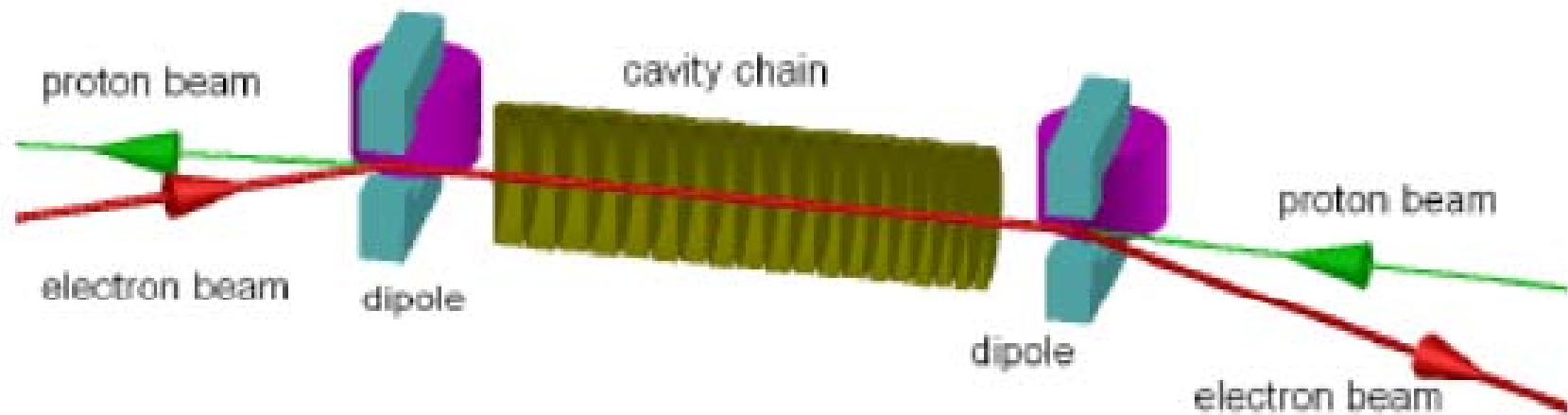
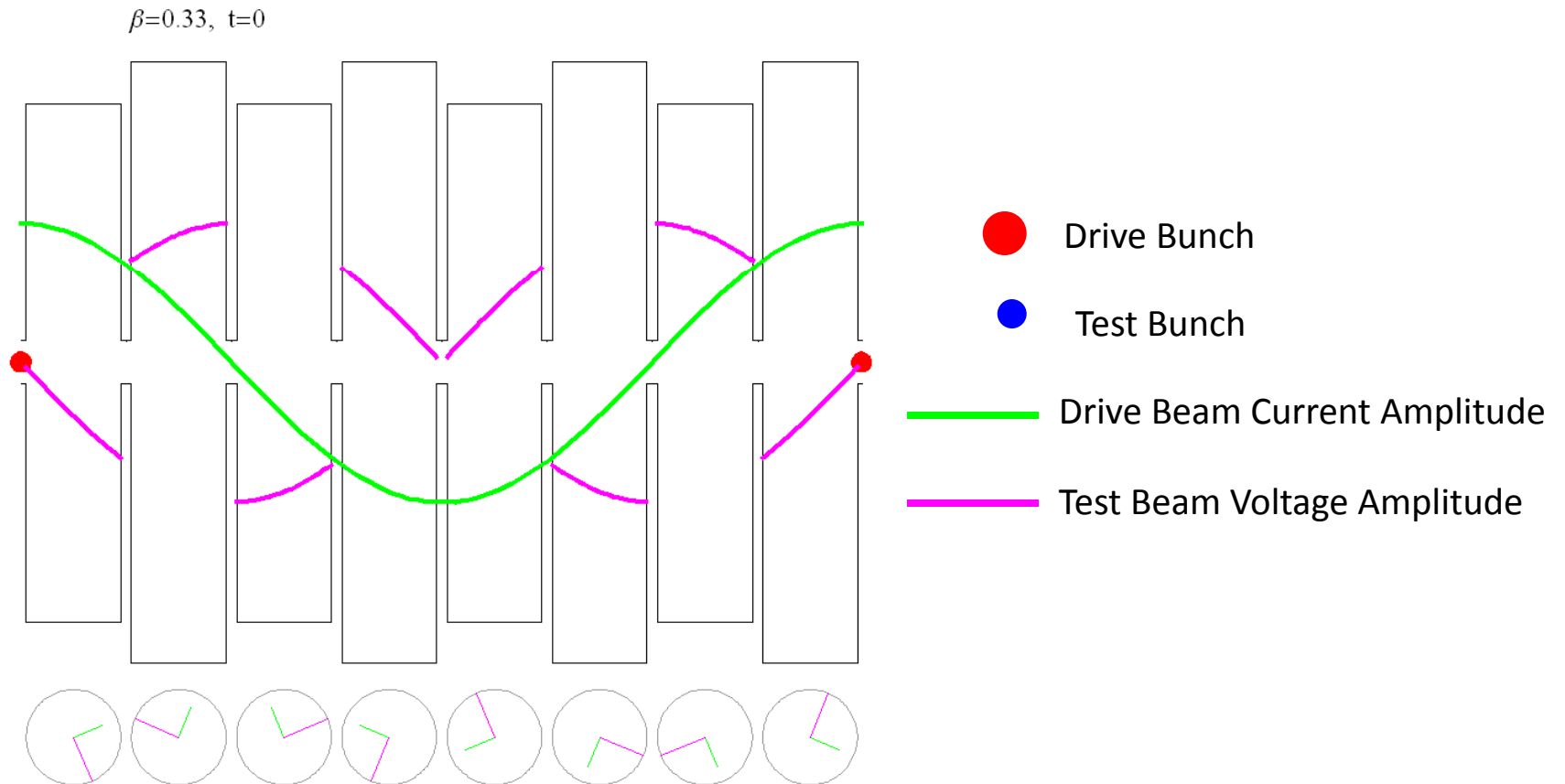


Fig. 3. Accelerating protons (blue dots) moving to the right ($q\mathbf{E}\cdot\mathbf{v} > 0$), while decelerating drive beam electrons (red dots) moving to the left ($-q\mathbf{E}\cdot\mathbf{v} < 0$), in a structure consisting of alternating detuned cavities. Note large transformer ratio.

Synchronization: Example

$$\beta_T = \frac{\beta_D}{3} \quad \lambda = 8\Lambda$$



Parameters for a 2-beam 1-GeV proton accelerator that uses alternating detuned cavities with varying gaps.

See Kazikov, Kuzikov, Jiang, Hirshfield, *PRST-AB* 13, 071303 (2010).

β	proton energy (MeV)	cavity gap (cm)	beam-to-beam eff. (%)	gradient (MV/m)	transformer ratio T	peak E field (MV/m)	average wall loss (W/cm^2)
0.30	45.3	1.05	69	19	8.8	27	7.6
0.40	85.4	1.33	73	20	9.1	27	7.6
0.50	145.1	1.57	76	20	9.1	26	7.1
0.60	234.5	1.77	78	20	9.1	26	7.1
0.70	375.5	1.96	80	21	9.0	26	7.1
0.80	625.3	2.12	81	21	8.9	25	6.7
0.90	1,213.9	2.27	82	21	8.8	25	6.7
1.0	-	2.40	83	21	8.7	25	6.7

Table III. Parameters for a two-beam one stage proton accelerator with alternate cavity detunings of $\Delta\omega/\omega = 3.0 \times 10^{-3}$. With $T \approx 9.0$, the drive beam energy would be about 110 MeV. With an average acceleration gradient of about 20 MV/m, the active machine length would be ~ 50 m.

APPARENT VIRTUES OF A 2-BEAM COLLINEAR PROTON ACCELERATOR THAT EMPLOYES ALTERNATELY DETUNED CAVITIES WITH VARYING GAPS

- there is no need for a large cryogenic plant, as with competing superconducting designs;
- there is a high acceleration gradient, resulting in a small required real estate footprint;
- there is but one (tapered) accelerator section consisting of a cascade of simple cavities;
- there is no need for an RF power transmission system along the accelerator;
- there is no need for couplers and windows to introduce RF power to the structure;
- there is pulsed rather than cw operation, that may allow flexibility in design and in making rapid proton beam power adjustments.

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 to be compared between very large SC solenoids and SC RF which is now the preferred technology for future high intensity proton accelerators (e.g., Project X).
- A novel alternative (2-beam collinear proton accelerator) may be attractive, but this concept is still in its infancy. A proposal from Yale to support its further study is pending with DoE-NP.