**Workshop on Hadron Beam Therapy of Cancer**

**Erice, Sicily, Italy**

**April 24, 2009 - May 1, 2009**

# POSTER ABSTRACTS on Display on TUESDAY, April 28, 2009

## Berkeley Experience – From Cyclotron to Cancer Treatment

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Lawrence Berkeley Laboratory has played a seminal role in the development of Nuclear Medicine. Ernest Lawrence was the inventor of the cyclotron placed strong emphasis on medical uses of his cyclotrons. Ernest's brother John Lawrence was the father of nuclear medicine. By 1993 several thousand patients had been treated at the laboratories 184inch cyclotron and the Bevatron. In this poster present a brief history of accelerator based cancer treatment at Lawrence Berkeley Laboratory.

## LBNL's Accelerator & Engineering Strategies for Ion Beam Cancer Therapy

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Ion-beam therapy of cancer has achieved remarkable clinical success worldwide, and research interest is expanding, but in many cases is based on outdated technologies. We have identified areas where LBNL has the capability to do just that, benefitting patients, hospitals, and society through more-effective treatment modalities; smaller, less costly accelerators; and better beam delivery and dosimetry systems. Here we describe several of the areas that we are under investigation.

## Various RF Methods for Non-Scaling FFAGs

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This is the first of four posters devoted to the subject of acceleration in a FFAG machine. These machines, simply because the magnetic field is fixed in time, can be rapidly cycled (perhaps at 1 kHz) and, therefore, are ideal for spot scanning. Furthermore, because one can have full-aperture kickers, the beam can be extracted over a range of energies (perhaps +-20%) and, therefore, are ideal for scanning a tumor in energy. In order to take advantage of the FFAG it is necessary to develop a suitable rf acceleration scheme as well as the appropriate hardware. It is to that end that these four posters are directed; two devoted to rf theory and two devoted to hardware.

In this first poster we study three different rf schemes: (1) Harmonic jumping, (2) Harmonic jumping with frequency modulation and (3) Fixed frequency with phase control. We also use a circuit model of an rf cavity to study the effect of rapid (less than 1 ns) variation of cavity drive frequency as well as cavity resonant frequency.

## Numerical Study of RF Schemes for Non-Scaling FFAGs

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Acknowledgement: A.M. Sessler, LBNL

In this poster, we numerically explore the rf schemes described in the previous poster. First, we derive the Hamiltonian describing longitudinal motion in an Non-scaling FFAG accelerator. Then, we employ this Hamiltonian in numerical simulations. Various parameter-dependences are explored for accelerating multi-bunches in the rf scheme of the harmonic jumping with frequency modulation.

## Acceleration in the non-scaling FFAG proton therapy machine

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Acknowledgement: A.M. Sessler, LBNL

We present a method of fast acceleration ~1000 turns by the non-scaling Fixed Field Alternating Gradient (FFAG) where after every turn the phase of the RF cavities is adjusted with negligible change of the frequency. The present example is made by a very reasonable, easy to built cavities, but with relatively low quality factor Q. Cavities are distributed around the 24 cell 26.88 meters long – radius of 4.27 m. The central frequency is 374 MHz and acceleration is possible from 22 MeV to 250 MeV with relativistic factor $0.24 < b < 0.61$. This example assumes very low quality factor Q~50. There are ~80 ns to change the cavity frequency within the beam gap. We have done detail simulation of the acceleration under different magnet settings and found very stable solutions with very small emittance blow-up.

## Rapidly Tunable RF Cavity* for FFAG Accelerators

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Acknowledgement: A.M. Sessler, LBNL and D. Trbojevic, BNL

An rf cavity has been designed, operating at 375 MHz, and using barium-strontium-titanate (BST) a ferroelectric material with dielectric constant of 600. The cavity is tunable over a range of 30 MHz in tens of nanoseconds. The cavity is 5.5 cm long, has a radius of only (about) 4.5 cm, and has entrance tubes of 4 cm diameter and a peak accelerating voltage of 30 keV. The electrical bias is up to 50 kV. Further R&D studies, that are required, are presented.

## A 30-250 MeV Compact, Achromatic Non-scaling FFAG with Long Insertions for Proton Therapy

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The drive for higher beam power, high duty cycle, reliability, and precisely controlled beams at reasonable cost has generated world-wide interest in Fixed-field Alternating Gradient accelerators (FFAGs). FFAGs have the potential to combine both the energy variability of the synchrotron with the high duty cycle of the cyclotron. A new concept in non-scaling FFAGs has been invented in which the machine tune is stable over an extended acceleration cycle, a factor of a 3-6, or more, in momentum. Fermilab Research Association (FRA) has elected to patent this concept and a strong collaborative design effort to optimize, simulate, and demonstrate the technical feasibility of this accelerator approach is underway to be followed by a commercial engineering design. Sophisticated simulation tools within the advanced accelerator simulation code, COSY INFINITY, have been developed to fully and accurately describe the FFAG's complex electromagnetic fields - including realistic edge-field effects and high-order dynamics. Predicted performance showed the promised tune stability, and a sustainable slow acceleration rate by a modest acceleration system. The 8-cell design is compact, achieves a 250-MeV extraction energy, and remains within a 5-m radius, and under 4T in poletip fields. The concept has been further extended to a recent "triplet" base structure that incorporates a single, meter-long straight per cell to facilitate injection and kicker-based or resonant extraction. In the broadest sense, this new nonscaling FFAG represents a generalized radial sector FFAG exploiting wedge-shaped magnets, strong, weak and edge focusing principles, but relaxing the scaling constraint of similar reference orbits.

## RFQ-Linear Accelerator for Hadron Beam Therapy

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IAP, Univ. Frankfurt, Germany

At IAP a RFQ for use in Hadron Beam Therapy has been build, tested is now operating at HIT. The alignment and tuning of industrial Therapy-RFQs has been done also. The design includes a combination of a 4-Rod-RFQ structure and drifttubes in one cavity, which has been developed in collaboration with GSI in Darmstadt, Germany.
This design and the properties of our Therapy-RFQ will be presented.

## RF HIGH POWER TESTS ON THE FIRST MODULE OF THE ACLIP LINAC

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ACLIP is a 3 GHz proton SCL linac designed as a booster for a 30 MeV commercial cyclotron. The final energy is 62 MeV well suitable for the therapy of ocular tumors or for further acceleration (up to 230 MeV) by a second linac in order to treat deep-seated tumours. The possibility of using magnetrons as the source of RF power, to reduce the overall cost of the machine, is one the more relevant features of this project and this investigation is carried out within the frame of a collaboration with e2v (Chelmsford, UK). ACLIP is formed by 5 modules coupled together. The first one (able to accelerate proton from 30 to 35 MeV) has been machined, completely brazed and in December 2008 full power RF tests have been performed. In this paper we will review the main features of the linac and discuss the results of the RF measurements carried out on this prototype.

## Low Energy High Power Side Coupled Linac Optimization

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The use of BBAC (Back-to-Back Accelerating Cavity) tiles in proton Side Coupled Linacs can be extended down to energies of the order of 20 MeV, keeping more than suitable shunt impedances and energy gradients. However, the considerable energy dissipation from the cavity noses may induce a remarkable increase in their temperature. This may cause both a strong duty-cycle-dependent detuning of the modules, and dangerous thermo-mechanical stress due to the non-uniform temperature distribution. An innovative shape of the BBAC tile is proposed, which allows to limit the temperature rise within a safe range, without introducing detrimental effects on the quality indices (shunt impedance, dissipated power). A protocol for the design of such a cavity will be presented.

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# Compact, Tunable RF Cavities

Charles Ankenbrandt[1], Alfred Moretti[1], Milorad Popovic[1], Ray Tomlin[1], Mohammad Alsharo'a[2], Ivan Entchevitch[2], James Griffin[2], Rolland P. Johnson[2], Sergey Korenev[2], Branko Popovic[2]
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Abstract
New developments in the design of fixed-field alternating gradient (FFAG) synchrotrons have sparked interest in their use as rapid cycling, high-intensity accelerators of ions, protons, and muons. Potential FFAG applications include medical accelerators of protons and light ions for cancer therapy, proton drivers for neutron or muon production, and rapid muon accelerators. The successful development of compact tunable RF cavities for these machines will establish/enhance the feasibility of FFAG machines for these purposes.

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**" Innovation in Research"**
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**Abstract**
Muons, Inc. was formed in 2002 to participate in SBIR-STTR programs to fund research on muon beam cooling and applications such as neutrino factories, muon colliders, and stopping muon beams.
Muons Inc. carries out innovative scientific research on topics of national and global interest, including development, design, and implementation.
We believe that muon accelerators and storage rings are inevitable, given the inherent advantages of muons over protons and electrons for collider applications and the fundamental interest in the muon itself.

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# A New Detector for Proton Imaging

Van McGary[b,c], Charles Ankenbrandt[b], Janet Conrad[c], Mary Anne Cummings[b], Milorad Popovic[a]

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**Abstract.** Proton therapy has come a long way since its initial conception in 1946. Today, there are more than two dozen proton treatment centers around the world, with over 60,000 patients having undergone proton therapy. Compared to conventional X-ray treatments, it offers a superior dose distribution, resulting in less damage to normal tissue. However, proton therapy still relies on X-ray images of cancerous areas to plan treatments. In this paper, we propose a new detector that will use the protons from the treatment accelerator itself to form *in situ* images of the areas to be treated. Computed tomography using protons could have at least two advantages: more frequent imaging to follow the progress of treatment, and avoidance of errors due to differences in the physical processes that x-rays and protons undergo during their passage through matter.

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**The MedAustron Project**

Adrian Fabich

MedAustron is a synchrotron based accelerator facility for cancer treatment with proton and carbon ion beams. In addition to the clinical application, the accelerator will also provide beams for non-clinical research, in the fields of medical radiation physics, radiation biology and experimental physics.

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**ARCHADE an EUROPEN ADVANCE RESSOURCE CENTER FOR HADRONTHERAPY**

Presented By Eric Baron

ARCHADE is a European research and development centre exclusively dedicated to hadrontherapy, it will located in Caen, Basse Normandie, France. Hadrontherapy is a new form of radiotherapy, which is more precise and effective in treating certain types of cancer. This promising new technology is in full expansion in Europe and worldwide. As a result, there is an important need for technical, biological and clinical research in this field. ARCHADE benefits from a network of leading scientific and clinical partners at both the regional and national level. Over time, these partners have developed distinctive expertise in areas well-suited to the field of hadrontherapy. The ARCHADE Centre was founded in close partner ship with IBA, the world leader in proton therapy, one modality of hadrontherapy. ARCHADE benefits, as well, from strong support from the Basse-Normandie Region, which anticipates growth in high technology research and economic activity from its investment in the centre

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# $^{12}$C fragmentation measurements for hadrontherapy @ GANIL

LPC Caen: G. Ban, B. Braunn, J. Colin, D. Cussol, J.M. Fontbonne, M. Labalme, F. R. Lecolley, C. Pautard.
IPN Lyon: M. Chevallier, D. Dauvergne, F. Le Foulher, C. Ray, E. Testa, M. Testa.
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CEA/IRFU/SPhN Saclay: M.D. Salsac

Hadrontherapy treatments require a very high precision on the location of the dose in order to keep the benefits of the precise ions' ballistic. The largest uncertainty on physical dose is due to ion fragmentation. Up to now, the simulation codes are not able to reproduce the fragmentation process with the required precision. The constraints on nuclear models and fragmentation cross sections between 30 and 100MeV/u are not sufficient.
To constraint the codes, we have performed an experiment on May 2008 at GANIL with a 95 MeV/u $^{12}$C beam. The goals were the measurement of the fluence, energy and angular distributions of the fragments coming from the nuclear reaction between $^{12}$C and water-like PMMA targets of different thicknesses : from 0.5 to 4cm. At 95MeV/u, the $^{12}$C Bragg Peak depth in PMMA is 2cm.
To detect the charged particles, the experimental set-up included five three stages $\Delta$E/E telescopes with two Si detectors (thicknesses: 80µm and 500µm) and one CsI scintillator (thickness: 7cm). These telescopes were mounted on rotating arms in order to cover angles from 0° to 60°. The setup also included four DE MON detectors to measure the neutrons at four different angles (15°, 25°, 45° and 70°).
Production rates, from proton to carbons, have been obtained at 10 different angles for the five different PMMA thicknesses. The figure below shows a $\Delta$E/E spectrum of charged fragments for incident $^{12}$C on a 1.5cm PMMA target. The $\alpha$ energy spectra at four different angles are also shown, with the same target.

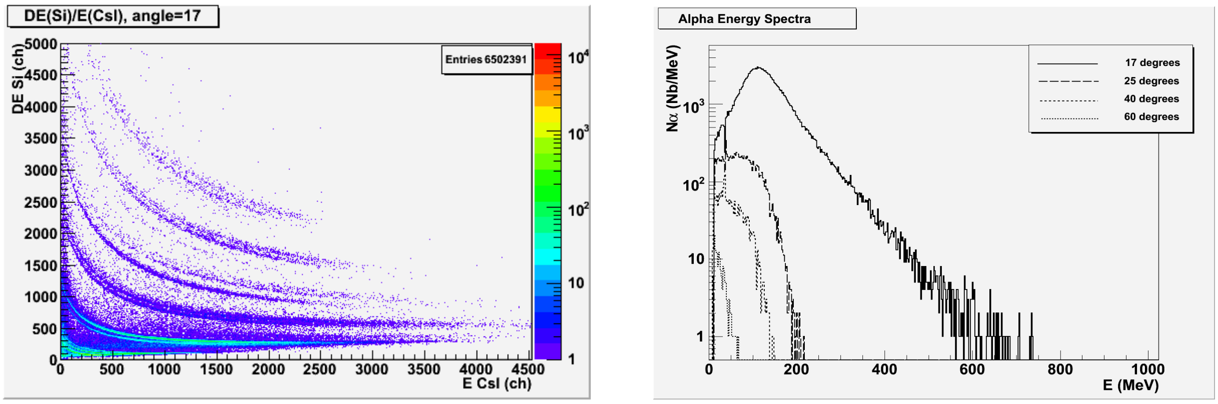


*Fig: $\Delta$E/E raw data at 17° and $\alpha$ energy spectra at four different angles for 95MeV/u incident $^{12}$C on a 1.5cm thickness PMMA target. Number of incident $^{12}$C=6.5.10$^{8}$*

Comparisons with Geant4 simulations have to be achieved in order to evaluate the accuracy of the models (eg. G4BinaryLightIonReaction, G4BinaryCascade…) included in GEANT4 for hadrontherapy purposes (light ion on light target; energy range: 80-400MeV/u).
A raw comparison between simulations and experimental data show some discrepancies. Thus, we will propose experiment on thin targets at GANIL (C-C, C-H, C-O, C-Ca… from 40 to 95 MeV/u). These double differential cross sections of charged fragments and neutrons are necessary to reach the precision required for a hadrontherapy reference simulation code.

**China High-Intensity Accelerator Technology Developments for Neutron Sources and Accelerator Driven Systems***

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Shinian Fu, Institute of High Energy Physics, CAS, China

During the recent years, there have been aggressive developments in China on the technology of high intensity hadron accelerators for the spallation neutron source, accelerator driven systems (ADS), and related programs including hadron therapy. For example, the China Spallation Neutron Source (CSNS) is a newly approved project to be constructed in Guangdong, China. The CSNS complex consists of an H- linear accelerator, a rapid cycling synchrotron accelerating the beam to 1.6 GeV, a solid tungsten target station, and five instruments for spallation neutron applications. The facility operates at 25 Hz repetition rate with an initial design beam power of 120 kW and upgradeable beam power of 500 kW. The primary challenge is to build a robust facility at a fraction of the "world standard" cost. Benefiting from a close collaboration with world leading institutes and facilities, tremendous efforts were made in China to develop domestic vendors to comprehend the technology for key systems of high intensity ion source, linear accelerators, and rapid cycling synchrotron. Goals of such facilities include spallation-neutron-based, muon-based, and proton-based platforms for multi-discipline science and industrial applications, fast-neutron-based platform for nuclear science and applications, and parasitic apparatus for medical therapy and ADS tests. This paper attempts to summarize the R&D efforts, key component prototyping and vendor development experience, and user development efforts during the past several

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**Recent hadron therapy proposals in China**

Jie Wei, Tsinghua University, China

Shinian Fu, Yi Jiao, and Sheng Wang, Institute of High Energy Physics, Chinese Academy of Sciences, China

Ruimei Ma, Memorial Sloan Kettering Cancer Center, USA

Steven Peggs and Todd Satogata, Brookhaven National Laboratory, USA

Precision 3D stereo-tactic radio-surgery, therapy, and imaging may be realized by proton or carbon beams generated from various types of accelerator techniques: cyclotrons with mechanically adjusted energy degrading films, slow cycling synchrotrons with slow-extraction programmable for variable energies, rapid cycling synchrotrons with extraction timing programmed to intended energies, FFAG's with wide energy acceptance and output range, and rapidly adjustable linear accelerators. In China, there have been increased interests in developing cyclotron and synchrotron based hadron therapy machines. In particular, along with the development of China Spallation Neutron Source project based on rapid cycling synchrotron technologies, an effort was made to develop the EMIT (Energy Modulating Ion Therapy) proton facility consisting of linac injector (50 keV hydrogen source, 2.5 MeV Radio-frequency Quadrupole linac, and 10 MeV Drift-tube linac), a rapid cycling synchrotron delivering the proton with energies variable from 6t0 to 250 MeV, and beam delivering systems. The facility is designed to deliver proton pulses for spot scanning at 25 to 50 Hz repetition rate with energy adjustment made within about 2 s, producing about 20 Gy/min. irradiation dose. This report summarizes recent hadron therapy interests and efforts in China including intended facilities to be established mostly with imported instruments and the EMIT program.

**Carbon and proton FFAG proton therapy accelerators**

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Abstract:
We present a complex of three non-scaling Fixed Field Alternating Gradient (FFAG) designed for proton/carbon therapy to be used at the same times. This is a strong focusing machine made of combined function magnets. For the carbon ions due their larger mass superconducting magnets are used. The acceleration is assumed to be with a relatively fixed frequency. After every turn the phase of the RF cavities is adjusted with negligible change of the frequency. Non-scaling FFAG rings for cancer hadron therapy offer reduced physical aperture and large dynamic aperture as compared with scaling FFAG's. The variation of tune with energy implies the crossing of resonances during acceleration. Our design avoids intrinsic resonances, although imperfection resonances must be crossed. We consider a system of three non-scaling FFAG rings for cancer therapy with 250 MeV protons and 400 MeV/u carbon ions. Hadrons are accelerated in a common RFQ and linear accelerator, and injected into the FFAG rings at v/c = 0.1294. $H^+/C^{6+}$ ions are accelerated in the two- smaller/larger rings to 31 and 250 MeV/68.8 and 400 MeV/u kinetic energy, respectively. The lattices consist of doublet cells with a straight section for RF cavities.