PROGRAM FOR THE JOINT ACCELERATOR SCHOOL

Radio Frequency Engineering for Particle Accelerators

9-18 September 1996, Japan

Course Description

This course will provide an elementary introduction to the principles of rf engineering for accelerators. Commencing with the fundamentals of microwave electronics, the morning lecturers will cover the principles of modulators, klystrons, and accelerating structures. Students will be exposed as well to the practical issues of cavity design, fabrication & conditioning.

In the afternoon, students may choose from a selection of mini-tutorials on: Low-Level RF & Feedback, Microwave Measurements, Beam Measurements & Beam Dynamics, or Electron Linear Accelerators. Seminars in the evening will round out the historical and cultural context of the field. The latter part of the course will include a series of practical exercises at KEK.

Morning Lectures

8:30-10:15 & 10:45-12:30

Monday, 9 September

1. Microwave Electronics 1: **Maxwell's Equations & Modes in a Guide** --- *D.Whittum, SLAC* Maxwell's equations, Lorentz force law, conservation of energy (Poynting flux, energy density), skin-depth & wall-losses. Maxwell's equations in uniform guide, orthogonal modes, propagation constant, cut-off wavelength, group velocity, phase velocity.

2. Microwave Electronics 2: **Equivalent Circuit Representation for Modes in a Guide**--- *K. Takata, KEK* Examples of waveguide modes, including rectangular guide TE10, coaxial line TEM, circular guide TM01. Field expansion in terms of modes in a guide, notions of voltage, current, reflection coefficient, VSWR (Voltage Standing Wave Ratio), impedance, Smith Chart, transformation of impedance through a length of guide.

3. Microwave Electronics 3: **Modes of a Cavity** --- *K. Takata, KEK* Maxwell's Equations in a cavity with conducting and open boundaries with dielectric loading and specified current and charge (free sources). Pillbox cavity as the simplest accelerating cavity. Coupled cavity chain, circuit analysis, analysis in terms of fields, alternating periodic structure.

4. **Cavity Design** --- *E. Nelson, LANL* Finite difference and finite element methods. Time domain, frequency domain and eigenmode solvers. Variational form of Maxwell's equations in an eigenmode problem. Capabilities and limitations of cavity design codes: MAFIA, HFSS, SUPERFISH, YAP.

Tuesday, 10 September

5. Microwave Electronics 4: **Cavity with a Port & External Q** --- *Y.Y. Lau, University of Michigan* Cavities, Coupling of cavities by probe, loop and hole, Q and external Q, Equivalent circuit and Foster form, Examples.

6. Microwave Electronics 5: **Microwave Networks** --- *W. Pirkl, CERN*
- Tuning of a cavity with a short-circuit plunger at an external port (tuning curve, plane of detuned short)
- Measurement of the properties of a resonance (Easy part: *f*, *Q* ; difficult part: *R/Q*, *R* ...)
- Scattering parameters and S-matrix (unitarity, symmetry, impedance transform through a two-port, bilinear function)
- Examples of twoports and fourports (reciprocal vs. nonreciprocal, active vs.passive, 3-dB-coupler)
- RF distribution networks (canonical structure with 3-dB-couplers vs. in-line structure with variable coupling factors)
- HW example with worked-out solution on 3-dB coupler will be distributed.

7. Microwave Electronics 6: **Slater's Perturbation Theorem** --- *Y. Yamazaki, KEK*

8. **Superconducting Cavities** --- *W. Weingarten, CERN*
The main advantages of superconducting (sc) cavities are a lower power dissipation and a lower impedance compared to copper cavities. The first item opens up the possibility of high gradients in CW operation, the second one allows high intensity beams. Fundamental and practical limits of sc cavities are discussed (surface resistance, critical field, anomalous losses), and sc materials being studied are presented. Technological achievements and applications show the state of the art.

Wednesday, 11 September

9. **Beam-Cavity Interaction, Beam-Loading** --- *M. Karliner, INP*
- Excitation of modes of oscillations in a cavity by beam current and generator.
- Equivalent circuit for a cavity loaded by a beam.
- Conditions for equilibrium acceleration for an intense beam. Vector diagram for currents and voltages.
- Power consumed from a generator by beam-loaded cavity.

10. **Klystron 1- Space-Charge Limited Flow, Guns** --- *S. Isagawa, KEK*
Thermionic emission, Cathode as an e- emitter, Space-charge limited effect and 3/2 power law, Perveance, Beam spread due to space charge, Pierce guns, Magnetically immersed guns, Method of gun design, including simulations, Examples, mainly treating of E3786 which will be operated by attendees above 1MW-cw in practical exercise course at KEK.

11. **Structure 1-Standing-Wave** --- *E. Kozyrev, INP*
- As the simplest example of standing wave structure a pill-box cavity is dealt with. The field components of E010 mode for this cavity are presented and concepts of a transit time factor, quality factor and shunt impedance are introduced.
- The mathematical model of coupled cavity chain is briefly expounded. Examples of structures, developed at various accelerator centers (DESY, CERN, BINP, KEK) operating at PI and PI/2 oscillation modes as well as DAW (Disk and Washer) structure features are presented.

12. **RF Pulse Compression** --- *I. Syrachev, Serpukhov*
RF pulse compression is a method to exchange the long low- power rf pulse for the short pulse of higher peak power. This is essential for the future linear collider, where required peak power about 100 MW per meter of accelerator can not be produced with conventional rf sources. The most advanced methods of the rf pulse compression are described. Short theory and the specific features of them are presented. The different schemes are illustrated with their certain design and compared for the particular
collider configurations.

Thursday, 12 September

13. **Wakefields 1: Fundamentals** --- *K. Ko, SLAC*
Basic concepts of wakefields and impedances: longitudinal and transverse, Panofsky-Wenzel theorem. loss parameter and transverse kick, resistive wall, short- and long-range wakes, narrow- and broad-band impedance due to lumped discontinuities, inductive versus capacitive, impedance budget.

14. **Klystron 2 - Bunching, Space-Charge** --- *B. Carlsten, LANL*
Definition of harmonic current, power transfer from the electron beam to an rf structure including definition of induced current, beam/cavity circuit model for beam-loaded admittance, ballistic and space-charge dominated bunching, and idler, penultimate and output cavities in a klystron.

15. **Structure 2-Travelling Wave** --- *D. Boussard, CERN*
As an introduction,the dispersion relation in a smooth waveguide is recalled,together with the notions of phase and group velocity.Periodically loaded waveguides will be treated analytically (as thin obstacles in a smooth waveguide and as a chain of coupled resonators) to introduce the notion of passband (forward and backward).A few examples will be presented to illustrate.The specific features of travelling wave structures under strong beam loading will then be examined.As an illustration the use of travelling wave structures in the CERN SPS to accelerate heavy ions in a non integer harmonic number mode will be briefly described.

16. **Ferrite Loaded Cavities** 1 --- *S. Ninomiya, KEK*
The principle of ferrite loaded cavities for proton synchrotrons is explained from the view point of its operation. After introducing transfer function methods, the automatic tuning system of the cavity which is the most important technology for this type of cavities is explained by the use of tranfer functions.

Friday, 13 September

17. **Wakefields 2: SW & TW Structures** --- *E. Haebel, CERN*
Wakefields can be decomposed into the fields of modes, both propagating and non-propagating, the latter remaining confined to cavities. For accelerating cavities it is reasonable to differentiate further between the fundamental mode which, since coupled to a RF generator, can be controlled by active means, and the other "higher order" modes for which we have to rely on passive methods, damping and detuning. In this context damper design will be explained in some detail using coaxial constructions as a paradigm. Also different ways of estimating external Q-values with the help of cavity codes will be discussed. Finally background information needed to follow the present developments of the detuning approach shall be given: dipole-mode field patterns in multi-cell cavities, model building and the stability of modal field patterns in the presence of detuned cells.

18. **Klystron 3 - Simulation** --- *T. Shintake, KEK*

19. **Structure 3-Fabrication and Conditioning** --- *T. Higo, KEK*
lExamples: Standing-Wave (the TRISTAN ring cavity--biperiodic structure and/or disk and washer) Travelling-Wave (linac structure of JLC-X, detuned)
lFabrication: tolerances, frequency, *Q*, tuning, mechanical design to meet the electrical design
lConditioning: breakdown, dark current, & multi-pactoring.

20. **Structure 4 - High Gradient Operation of Structures** --- *J.W. Wang, SLAC*
Field emission and Fowler-Nordheim plots, experimental methods for accelerators at very high gradient, studies of dark current and related phenomena, vacuum breakdown and discussion of various breakdown models, surface condition and rf processing.

Saturday, 14 September

21. **Wakefields 3: Other Sources of Impedance** --- *Y. Chin, KEK*
In this lecture, we expand the concept of wake fields and wake potentials to the configurations which need more elaborate techniques to compute them than a simple method based on their definitions. Several advanced cases and their numerical examples are reviewed.

22. **Other RF Sources** --- *G. Kurkin, INP*
Triode tube, main static and dynamic characteristics, equivalent schematic of amplifying stage, conditions for stable operation. Requirements for operation of of triode stage loaded with accelerating cavity. Influence of parameters of the output stage and transmission line length on output impedance of RF system for the beam. Typical design of power output stage.
lMagnetron, the principle of operation, main parameters. Magnetron loaded with the cavity of microtron, methods of coupling, requirement for stable operation.
lTraveling wave tube, the principle of operation, main parameters, application in the accelerating technique.
lMagnicon - BHF generator with circular deflection of electron beam, principle of work, results of development.

23. **High Gradients in Superconducting Cavities** --- *H. Padamsee, Cornell University*
lBenefits of high gradient sc cavities for future accelerators
lWhat is the theoretically expected gradient in sc cavities made from Nb, Nb3Sn and other materials
lCompare the theoretical expectations to the values achieved in test cavities and accelerating structures
lPhysics of the limiting phenomena
- o thermal breakdown of superconductivity
- o field emission

lApproaches and techniques developed to overcome the limitations
lSuccesses and prospects for the future

24. **Modulators** --- *S. Humphries, University of New Mexico*
Many high-power RF systems operate in pulses at low duty cycle. The main motivations are economy of operation and limits on the power-handling capabilities in accelerator

structures. The lecture describes devices to generate short electrical pulses with controlled characteristics, covering the following topics.
- The theory of transmission lines and pulse-forming networks.
- Modelling pulsed power devices with SPICE.
- Charging HV modulators with resonant transformers.
- High-power switches, including thyratrons, spark gaps, hard tubes, and saturable-core magnetic switches.

Sunday, 15 September

25. **Windows & High-Power Transmission** --- *H. Matsumoto, KEK*

26. **Ferrite Loaded Cavities 2** --- *M. Brennan, BNL*
- Some Fundamentals - Why put ferrites in cavities? Magnetic field and one-gap cavities. Tuning or reactance control. Ferrite properties; magnetic, electric, and mechanical. Electrically short cavities and lumped circuit equivalents.
- Methods of Applying Bias - Figures of eight techniques. Using the cavity body for a one-turn loop. Quadrupole bias external to the cavity. Tuning circuits, equivalent circuits, feedback principles.
- Impedance Issues - *R/Q* and gap capacitance. Ferrite losses, linear and anomalous. Coupling the power stage to the gap. Loading at the gap. RF feedback, stability issues.

27. **Design for System Stability - Heavy Beam Loading** --- *D. Boussard, CERN*
Beam disturbances,in particular the excitation of longitudinal dipole or quadrupole mode oscillations should be reduced as much as possible,especially in hadron machines with no natural damping.As a consequence the architecture of the RF system must be conceived to achieve this goal.The techniques in use for low and high intensity beams will be reviewed ,their performance and limitations presented.The case of strong periodic beam loading will be examined at the end.

Afternoon Tutorials

14:30-16:30

Monday 9 September - Saturday 14 September
(except Thursday)

Low-Level RF and Feedback --- *E. Ezura, KEK and R. Garoby, CERN* This course will provide students with a theoretical grasp of high-level concepts such as gap voltage regulation, beam loading and beam loading compensation, linac phasing, bunch-by-bunch feedback. Practical RF systems for particle accelerators include a number of feedback loops to reliably achieve the required level of performance. The first part of these tutorials will remind the basics of linear controls and signal modulation and apply them to the typical servo-loops used in RF systems (gap-voltage and tuning regulation, I/Q feedback, beam controls). The perturbation introduced by beam-loading will be investigated and the known cures described.

Microwave Measurements --- *J. Byrd, LBNL and F. Caspers, CERN* Introduction to modern VNA (vector networkanalyzers 30 KHz -3GHz) with time-domain display; practical measurements on: one ports (lumped element R,L,C, detector diodes), two ports (attenuators , cables, filters, amplifiers) ,three ports (power splitters, circulators), 4- ports (90 and 180 deg hybrids, directional couplers) and 5- ports (power splitters, frequency multiplexer); waveguide components; VNA calibration techniques; RF cavity mode meas, higher order modes of a pillbox, Q measurement,adjust coupling (beta) to fundamental mode; beadpull on TM110 mode (frequency shift) ,calculate impedance; Beam impedance (wire method) on stripline pair, transfer impedance, Sum and Difference mode. Characteristics of low level RF amplifiers: gain, noise figure, 1dB compression point, 2nd+3rd order intercept point.

Beam Measurements & Beam Dynamics --- *A. Hofmann, CERN and G. Jackson, FNAL* The longitudinal beam dynamics in a ring is summarized for coasting and bunched beams. A fast beam position/intensity monitor and RF-fields are the main tools to measure the longitudinal machine parameters and beam parameters like dispersion, momentum compaction, synchronous phase angle,energy loss, and energy distribution. These methods are then used to investigate coupled and single bunch instabilities. Special attention will be given to beam measurements with synchrotron radiation and to energy calibration.

Electron Linear Accelerators --- *T. Shintake, KEK and D. Whittum, SLAC* This will course will provide an elementary treatment of modulators, klystrons, pulse compression, and accelerating structures. The following topics will be covered, with emphasis complementary to the morning lectures.

- Microwave Electronics notions of voltage, current, impedance. Reflection from an iris. Properties of periodically loaded waveguide, Brillouin curve. Coupling of a waveguide to a cavity.
- Interaction of a beam with a cavity, transit angle, R/Q, loss factor. Constant impedance and constant gradient accelerating structures.
- Single bunch & multibunch beam-loading. Longitudinal wakefield, transverse wakefield, transport in a FODO lattice, preservation of beam quality.
- Choke mode accelerating strucuture.
- Coupled-cavity model for disk-loaded structure, pulse response of a structure and tuning.
- RF-Pulse compression and the "PM-AM" method.
- Frequency scaling of structures, klystrons and modulators and the example of C-band.

Seminars

17:00-18:15

Monday - **The Story of RFQ's: A Technology that Changed a Field** - *A. Schempp, Universität Frankfurt*
Tuesday - **History of Development of Linear Colliders** - *V. Balakin, Serpukhov*
Wednesday - **Early History of Electromagnetic Engineering in Japan** - *J. Nishizama, Tohoku University*
Friday - **Future Directions of Advanced Accelerator Research** - *R. Siemann, SLAC*
Saturday - **Round Table on the Future of Accelerators**- *Chair: N. Dikansky, INP*

Practical Exercises at KEK

17 Sept.Tuesday - All Day

Station ‹ Bead-pull measurement of a model cavity
Station › Surface analysis of cavity walls, windows, etc. via Auger-spectrometer
Station ﬁ Measurement and calculation of HOM damping via Al model of the KEKB superconducting cavity
Station ﬂ Introduction to an electron linac RF system
Station Introduction to the ferrite loaded cavities of PS
Station – Introduction to the crab cavity system for KEKB
Station † Operation of 1 MW klystron at TRISTAN