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Proceedings of the Third ICFA Mini-Workshop on
High Intensity, High Brightness Hadron Accelerators

T. Roser, et. al.

May 7-9, 1997

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Brookhaven National Laboratory
Associated Universities, Inc.
Upton, Long Island, New York 11973

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Preface

The 3rd mini-workshop on high intensity, high brightness hadron accelerators was held at Brookhaven National Laboratory on May 7-9, 1997 and had about 30 participants.

The workshop focused on rf and longitudinal dynamics issues relevant to intense and/or bright hadron synchrotrons. A plenary session was followed by four sessions on particular topics. This document contains copies of the viewgraphs used as well as summaries written by the session chairs.

M. Blaskiewicz
Scientific Secretary
**Contents**

<table>
<thead>
<tr>
<th>Author/Speaker</th>
<th>Topic/Session</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Roser</td>
<td>Summary of Plenary Session</td>
<td>1</td>
</tr>
<tr>
<td>J.M. Brennan</td>
<td>AGS/RHIC Status and Plans</td>
<td>3</td>
</tr>
<tr>
<td>R. Garoby</td>
<td>CERN Status and Plans</td>
<td>25</td>
</tr>
<tr>
<td>D. Wildman</td>
<td>FNAL Status and Plans</td>
<td>38</td>
</tr>
<tr>
<td>C. Ohmori</td>
<td>KEK Status and Plans</td>
<td>61</td>
</tr>
<tr>
<td>A. Thiessen</td>
<td>LANL Status and Plans</td>
<td>75</td>
</tr>
<tr>
<td>M. Blaskiewicz</td>
<td>Summary of Barrier Cavity Session</td>
<td>93</td>
</tr>
<tr>
<td>M. Yoshii</td>
<td>AGS Barrier Cavity Upgrade</td>
<td>94</td>
</tr>
<tr>
<td>C. Ohmori</td>
<td>KEK Barrier Cavity Results and Plans</td>
<td>107</td>
</tr>
<tr>
<td>R. Garoby</td>
<td>Summary of Longitudinal Emittance Control Session</td>
<td>123</td>
</tr>
<tr>
<td>S. Hancock</td>
<td>CERN Experiences</td>
<td>125</td>
</tr>
<tr>
<td>E. Jensen</td>
<td>LHC Issues</td>
<td>131</td>
</tr>
<tr>
<td>J.M. Brennan</td>
<td>High Brightness in RHIC</td>
<td>137</td>
</tr>
<tr>
<td>K.Y. Ng</td>
<td>Space Charge Effects and Ferrite Compensation</td>
<td>142</td>
</tr>
<tr>
<td>J. Wei</td>
<td>RHIC Operation with Increased Bunch Area (I)</td>
<td>160</td>
</tr>
<tr>
<td>J. Kewisch</td>
<td>RHIC Operation with Increased Bunch Area (II)</td>
<td>169</td>
</tr>
<tr>
<td>K.Y. Ng</td>
<td>Summary of Longitudinal Instabilities Session</td>
<td>175</td>
</tr>
<tr>
<td>Y.H. Chin and H. Tsutsui</td>
<td>Longitudinal Instabilities in a Barrier Rf System</td>
<td>176</td>
</tr>
<tr>
<td>M. Blaskiewicz</td>
<td>Fast Particle-Particle Update Schemes</td>
<td>191</td>
</tr>
<tr>
<td>J. Rose</td>
<td>Stability in RHIC</td>
<td>195</td>
</tr>
<tr>
<td>J.M. Brennan</td>
<td>Summary of Beam Loading and Rf Stability Session</td>
<td>203</td>
</tr>
<tr>
<td>E. Onillon</td>
<td>State Vector Techniques</td>
<td>205</td>
</tr>
<tr>
<td>M. Blaskiewicz</td>
<td>The NSNS Rf System</td>
<td>223</td>
</tr>
<tr>
<td>R. Garoby</td>
<td>PS Phase Measurement System</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td>List of Participants</td>
<td>231</td>
</tr>
</tbody>
</table>
Plenary Session

T. Roser

During the plenary session summary and status talks from the four organizing laboratories (BNL, CERN, FNAL, and KEK) and also from LANL were presented.

Mike Brennan reported on the various high intensity and high brightness efforts at BNL. In preparation for RHIC operation the AGS needs to produce very bright Gold beams with $10^9$ ions per bunch and a bunch area of $0.2 \, eV \, s / u$. The present performance has reached already $0.4 \times 10^9$ ions per bunch with a bunch area of $0.6 \, eV \, s / u$. This intensity was achieved by merging 8 bunches into one which is most effectively done early in the acceleration cycle.

High intensity proton beams are accelerated in the Booster and AGS. With second harmonic cavities more than $2 \times 10^{13}$ protons on two bunches each with a bunch area of about $1.5 \, eV \, s$ were accelerated in the Booster. The beak performance is very sensitive to the relative phase of the first and second harmonic rf system. Four Booster beam batches are accumulated in the AGS for a maximum intensity of $6 \times 10^{12}$ protons. Stability during accumulation can only be achieved by diluting the bunches to about $4 \, eV \, s$ using a high frequency cavity.

To avoid excessive blow-up and also to allow for the accumulation of more than four Booster batches a Barrier bucket system is being developed. With such isolated sine waves gaps in the debunched beam can be manipulated in such a way as to stack successive loads from the Booster. So far with two $12 \, kV$ cavities an intensity of $3 \times 10^{13}$ protons was achieved by stacking six Booster loads. The development goal is to build $80 \, kV$ cavities to produce $125 \, ns$ long sine waves.

The development and upgrade plans for the CERN PS and PS Booster in the LHC era were presented by Roland Garoby. With only one bunch accelerated per Booster ring two Booster loads can be accumulated in the PS. Before extraction to the SPS the beam will be debunched and rebunched into 84 bunches with a new $140 \, MHz$ rf system. Each bunch will have to contain $10^{11}$ protons in a bunch area of $0.3 \, eV \, s$. The goal is to send nominal LHC beam to the SPS in 1998.

The status and plans for high intensity beams at FNAL was summarized by David Wildman. The next Tevatron collider run will make use of the new Main Injector with increased production and stacking rate for antiprotons. High proton intensity will also be required for the long baseline neutrino experiment and in the future for even higher Tevatron luminosity. Presently longitudinal coupled
bunch instabilities driven by higher order modes of the rf cavities in the Booster, Main Ring, and Tevatron are limiting intensity unless a number of active and passive dampers are used. A permanent magnet 8 GeV Recycler ring has recently been made part of the Main Injector project. This ring will be used to store and cool anti-protons both remaining from the previous store and directly from the Antiproton Accumulator ring. Wide band ferrite loaded barrier cavities with a peak voltage of 2 kV will be used to manipulate the antiprotons in the Recycler.

Chihiro Ohmori reported on the plans for the Japanese Hadron Facility. It will consist of a 200 MeV Linac, a 3 GeV Booster accelerating $5 \times 10^{13}$ protons at $25 \, Hz$ and a 50 GeV Main ring accelerating $2 \times 10^{14}$ protons. The Main ring lattice will be transition-free. A development program is underway to use Finemet (Fine-Crystal High $\mu$ Metal) in the main ring cavities. This material has high permeability, a low Q factor ($Q < 1$) and performs well even for large rf fields. These cavities will be used for acceleration as well as Barrier Cavities.

Arch Thiessen gave an overview of the LANSCE PSR status and upgrade plans. The intensity at 800 MeV is limited to $4 \times 10^{13}$ protons by a fast transverse instability which is believed to be caused by electrons. Clearing gaps in the beam help suppress this instability and an upgrade of the rf system including a second harmonic system is underway to improve the situation. Potential well distortion from space charge is typically overcome by using much larger rf gap voltage. Alternatively the vacuum pipe impedance could be modified to cancel the space charge effects. A test is planned this year at the PSR of such an impedance tuner.
Workshop on High Intensity-High Brightness Beams: RF Issues

BOOSTER/AGS/RHIC

J. M. Brennan

- High Brightness for RHIC
  J. Rose - Stability
  E. Onillon - Beam Control

- High Intensity Protons
  M. Blackkawer - NSNS

- Barrier Cavity, Development
  M. Yoshi

Issues for Discussion

- Phase modulation for emittance blow-up

- Higher brightness for...e.g. g-2 experiment

- Very high brightness for a proton driver

- More accumulation for higher average current
  ➤ Barrier Cavities
High Brightness for RHIC
\((^{179}\text{Au}^{+79}, \gamma=12)\)

I. Specifications
- Bunch Intensity = \(10^9\) ions
- Longitudinal Emittance = 0.2 eVs/u

II. Performance to date (Jan. 97)
- Bunch Intensity = \(0.4 \times 10^8\) ions
- Longitudinal Emittance = 0.6 eVs/u

III. Operating Mode
- Bunch merging, 2 x 2 x 2
- Accumulation in AGS at 430 MeV/c/u

Motivations

Gold Acceleration at the AGS

4 Booster Cycles:
\(^{35+}: 40 \ldots 430\) MeV/c/nuc
\(h = 8 \rightarrow 4\) by bunch stacking 60% Stripping Efficiency:

\[^{79+}: 0.43 \ldots 11.6\) GeV/c/nuc

\(h_{\text{Int}} = 16\)
\(h_{\text{Ext}}(\text{FEB}) = 4\)
\(h_{\text{Ext}}(\text{SEB}) = 12\)

Source Tandem

Au\(^{1-}\) Au\(^{12+}\)
1. Luminosity formula

\[ L = \frac{3}{2} f_{\text{rev}} B (\beta \gamma)^2 \frac{N_0^2}{\epsilon_n \beta^*} \]

*Intensity per bunch is paramount*

2. Transverse emittance must be low

3. Longitudinal emittance is not in the formula,
   i. Chromatic non-linearities at transition, growth
   ii. Leakage into adjacent buckets at re-bucketing to 197 MHz
   d. Filling time, IBS at low energy, blows up longitudinal emittance

\[ h: \quad 8 \quad 16 \quad 8 \quad 4 \]

\[ \beta: \quad 0.04 \rightarrow 0.4 \quad 0.4 \rightarrow 0.996 \]

\[ q: \quad +32 \quad +77 \quad +79 \]
The loss rate was a surprise!

Same rate with rf on or off.

Vacuum?
- not predicted
- capture? Au^{+77}
- problem for RHIC? Au^{+79}
Longitudinal Emittance
After Three Bunch Mergings

\[ \sqrt{v_{rf}} = 220 \text{ kV} \]
\[ \delta = 0, \quad \lambda = 8 \]
\[ l = 28 \text{ ms} \]
\[ \Rightarrow \varepsilon = 0.60 \text{ eV s/\mu} \]

The Booster Emittance is Small Enough.

- If we put all the Booster beam into one RHIC bunch, we still have a factor of two head room.
- There is 100% growth in the Booster
\[ \delta \left( -\frac{B}{V_{\text{th}}} \right) \text{ is large and fast!} \]
Mismatch at AGS Injection

- Momentum Error

- Bucket shape mismatch, need more Vrf for ΔE

- New batch perturbs old batch via phase loop
  - Batch-by-batch phase loop, bunch shape damper
With odd number of bunches, phase of $\phi = 8$ is not equal to phase of $\phi = 16$. This causes transient ($\phi < 16$) in phase loop during $16 \rightarrow 8$ merge.
At top energy ($\gamma=12$) $^{133}Ba^{68}$, when the bunch area is small compared to the bucket area, the merge $b=8 \rightarrow b=4$ causes much emittance growth.

2048 times per trace  \[ T_{rej} = 2.7 \mu s \]
Issues for Discussion

- Preserving the phase feedback during merge
- "Vacuum loss"?
- Using larger emittance in RHIC
- Bunch stability in RHIC
- RF Noise during 10 hour store

Booster
(200 Mev to 1.9 GeV, $2 \times 10^{13}$ ppp)

I. Parameters

1. Frequency range: 1.6 to 2.8 MHz, $h=2$

2. Voltage:
   - $2 \times 45$ kV, $h=2$
   - $2 \times 15$ kV, $h=4$

3. Beam Current: 8 - 10 Amps, rf

4. Power: $h=2$
   - $2 \times 120$ kW to beam
   - $2 \times 60$ kW to ferrite
   - $2 \times 120$ kW tetrodes

II. Current transformer plot

III. Second harmonic
   1. Bucket area
   2. Bunching factor
Booster Beam Current
$2.1 \times 10^3$ ppp

Complete cycle

Early loss
2 ms - stop bands
10 ms - bucket area

RF "capture" loss
200 μs
$V_{max} = \pm 8 \text{kV}$

$V_{max} = 19 \%V_{max}$

$V_{max} = 9.1 \%V_{max}$

$V_{max} = 8 \text{kV}$

7-Jun-95
18:12:04

Main Menu

- $-2 \text{ ms} \ 20 \text{ mV}$

Channel 1
- $0.2 \mu s \ 10 \text{ mV}$

EXT 0.05 V DC

CH1 10 mV
CH2 20 mV
CH3 5 V
CH4 10 mV

T/div 0.2 μs

7-Jun-95
18:11:29

Main Menu

- $-2 \text{ ms} \ 50 \text{ mV}$

Channel 1
- $0.2 \mu s \ 1 \text{ V}$

EXT 0.05 V DC

CH1 1 V
CH2 50 mV
CH3 5 V
CH4 10 mV

T/div 0.2 μs
Issues for Discussion

- Near Beam-loading limit
  1. Rf feedback
  2. Feedforward compensation
  3. Low-level drive feedback

- Optimize use of second harmonic
  1. Programing the phase $h=4/h=2$
  2. Stability in double rf bucket

AGS
(1.9 GeV to 23 GeV, $6 \times 10^{13}$ ppp)

I. Parameters

1. Frequency range: 2.8 to 2.9 MHz, $h=8$

2. Voltage: $10 \times 40$ kV (4 gaps each)

3. Beam Current: 5 to 7 Amps, rf

4. Power: $10 \times 60$ kW to beam
   $10 \times 50$ kW to ferrite
   $10 \times 190$ kW in tetrode

II. Description of cycle

1. Four batches, 450 ms accumulation
2. Low voltage at injection, transition, and de-bunching for slow spill
3. Power booster at key points
4. Emittance blow-up via “VHF”, 93 MHz
Bunch Flattopping at Injection in AGS.

- Bunch Injected off-center
- Bunch after dilution

Parameters:
- $h=8$, $V_{rf}=136$ kV
- $h=279$, $V_{rf}=20$ kV
Barrier Cavity Development

I. Motivation
1. Slow loss during accumulation, AGS
2. Accumulate more than 4 loads
3. Prospects for a dedicated accumulator

II. Our approach
1. Isolated sine waves
2. High-Q cavities
3. Two cavities, two barriers

III. Development goals
1. 80 kV per cavity
2. 250 ns sine wave, 3 µs rep. rate
An accumulator could be added to the AGS tunnel.
Time Domain Stacking with Barrier Bucket Cavity

\[ I(t) = \frac{V_0}{R} + C \frac{dV}{dt} + \frac{1}{2} \int V(t') dt' \]

\[ V(t) = V_0 \sin(\omega t) \quad 0 < \omega t < 2\pi \]

\[ I(t) = \frac{V_0}{R} \sin(\omega t) + \frac{V_0}{\omega L} + V_0 \cos(\omega t \left( \omega c - \frac{1}{\omega L} \right) \right) \]

RF Waveform for Barrier Bucket (below transition)

Cavity Voltage and Current for \( Q = 25 \)

Ring Circumference \([0 .. 360^\circ]\)
Barrier Buckets (12kV each)

24-Apr-95
17:02:14

Main Menu

Chann 1
1 μs 1 V
Chann 2
1 μs 1 V
Chann 3
1 μs 1 V

21-Apr-95
16:40:40

Main Menu

3 x 10 protons

100 MHz
beam

Beam Pickup
well current
monitor

current
transformer

Chann 1
0.0 eV
Chann 3
0 eV
Chann 4
0 eV

At 0 sec
No Matt

Trslv 2 e
1. INTRODUCTION

The big picture …

The Injectors' complex

This talk analyzes issues in the PS complex

2. REMINDER

The injectors' chain for protons

Operations in the longitudinal phase plane

Conclusion no. 1: the transverse emittance budget is tight

Conclusion no. 2: the longitudinal emittance budget is also tight
The LHC injection complex

LHC 7 TeV p-p

LEP 100 GeV e⁺-e⁻

SPS (450 GeV)

LHC
- Protons
- Heavy Ions

LEP
- Positrons
- Electrons

Booster (1.4 GeV)

PS (26 GeV)

Ion Accumulator (LEAR)

Protons, Ions
50 MeV LINACS

LIL e⁺e⁻ LINACS
LONGITUDINAL LIMITATIONS OF THE PS FOR THE LHC PROTON BEAM

1. NOMINAL OPERATING SCHEME ([1, 2] and R. Cappi at LHC96)

<table>
<thead>
<tr>
<th>Id.</th>
<th>DESCRIPTION</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 bunch / ring in the PSB, reduction of peak line density with second harmonic cavity</td>
<td>~ OK (under test)</td>
</tr>
<tr>
<td>2</td>
<td>Controlled blow-up of longitudinal emittance during acceleration in the PSB: aim for hollow particle distribution</td>
<td>~ OK (under test)</td>
</tr>
<tr>
<td>3</td>
<td>Bunch to bucket transfer PSB to PS of 2 PSB batches</td>
<td>OK</td>
</tr>
<tr>
<td>4</td>
<td>Bunch splitting in the PS (8 $\rightarrow$ 16 bunches) at low energy</td>
<td>OK</td>
</tr>
<tr>
<td>5</td>
<td>Controlled longitudinal blow-ups during PS flat-tops</td>
<td>OK</td>
</tr>
<tr>
<td>6</td>
<td>Acceleration up to 26 GeV</td>
<td>OK</td>
</tr>
<tr>
<td>7</td>
<td>Debunching (h=16) &amp; rebunching (h=84)</td>
<td>MARGINAL</td>
</tr>
<tr>
<td>8</td>
<td>Fast ejection</td>
<td>MARGINAL</td>
</tr>
</tbody>
</table>
2. DELICATE PROCESSES (items 1, 2, 7 and 8)

2.1 Dual harmonic operation in the PSB (1)

- Lots of experience with $h=5$ & 10 in the PSB since > 10 years
- Thoughts and experiments with $h=1$ & 2 presented by F. Pedersen at this workshop

2.2 Blow-up during acceleration in the PSB (2)

- The defocusing $h=2$ spoils the "normal" operation of the blow-up process.
  Understood after the test in 12/93 but experimental demonstration is still to be done.
  (Presented at EPAC94 [3])
2.3 Debunching (h=16) and rebunching (h=84) at 26 GeV in the PS

- Tight longitudinal emittance budget (following figures from low intensity simulation):
  - Total initial beam emittance (h=16): 36 eVs
  - Emittance of debunched beam: 26 eVs
  - Emittance of compressed bunches: 30 eVs

- Bunch dimensions (l_b, D_p) marginally satisfying for capture and stability in SPS, although with an already very large voltage for the PS

- Non-adiabatic beam gymnastics prior to ejection (⇒ phase and energy drift of the beam w.r.t. reference)

2.4 Fast ejection at 26 GeV from the PS

- Kicker rise-time longer than distance between bunches:
  - 3 bunches will be lost in the PS extraction system,
  - 1 (2 ?) bunch(es) will be incorrectly deflected and will end up with a tail at large transverse amplitudes
3. RECENT RESULTS

3.1 Hardware

- Prototype 40 MHz system for the PS ("C40"):
  - built and ready on time for first installation in the PS (week 40 / 1996)
  - Nominal performance achieved (V range: 3 to 300 kV pulsed, V rise-time < 20 μs, Closed loop bandwidth: ~ 400 kHz, Gap short-circuit active, H.O.M. dampers installed)

- Prototype 0.6 – 1.8 MHz system for the PSB ("C02"):  
  - built and tested on bench in 1996
  - Nominal performance achieved (V range: up to 8 kV CW, Open loop gain of fast feedback: ~ 20 dB)
  - installed on ring 3 during the 96 winter shut-down

- 1.2 – 3.6 MHz systems for the PSB ("C04"):  
  - operationally available (modification of present C08 systems)
Le synchrotron va prouver le CERN apprend de nouveaux tours

CERN's Proton Synchrotron learns new tricks

A picture showing the new 40 MHz cavity installed in the PS. The cavity is shown in the lower left corner. The new cavity will be used to accelerate protons in the PS and will be part of a new experiment to test the performance of the PS and its capabilities.

La procédure des collas- sions entre les premiers faisceaux de protons en 2005, sous le nom de LHC, est un événement majeur au CERN. Mais auparavant, il faudra encore beaucoup de travail, et pour être prêt à temps il faut commencer dès maintenant. Le LHC bénéficiera d'une nouvelle structure de synchronisation avec une fréquence d'impulsion plus élevée que la précédente. Le 40 MHz, qui a déjà prouvé sa fiabilité, sera utilisé pour synchroniser les cycles de travail.

Y Cette nouvelle cavité est installée au PS. L'amplificateur qui alimente le cordon de l'interconnecteur est installé à la première pile.

Le PS est le berceau des protéines. Les accélérateurs du PS sont les premiers à faire face à ce défi. Le LHC, le plus grand d'entre eux, sera la voie d'accès au monde des particules. Pour améliorer leurs systèmes d'acquisition de données, les scientifiques du CERN travaillent intensivement sur l'optimisation des systèmes de mesure et de traitement des données. Leurs efforts visent à améliorer la qualité et l'efficacité des mesures pour pouvoir tirer le meilleur parti des données collectées.

Dans la chaîne des accélérateurs qui composent le complexe du LHC, le PS est la première étape pour les particules. Il amplifie les faisceaux de particules pour les propulser vers le LHC, utilisant une cavité de 40 MHz. Cette cavité est essentielle pour le fonctionnement correct du PS et pour assurer la stabilité des faisceaux de particules. La valeur critique de cette cavité est de 40 MHz, ce qui correspond exactement à la fréquence d'impulsion des faisceaux de particules. La cavité de 40 MHz est un outil délicat mais essentiel pour assurer la performance du PS et des expériences entreprises à ce niveau.

Le PS est le berceau des protéines. Les accélérateurs du PS sont les premiers à faire face à ce défi. Le LHC, le plus grand d'entre eux, sera la voie d'accès au monde des particules. Pour améliorer leurs systèmes d'acquisition de données, les scientifiques du CERN travaillent intensivement sur l'optimisation des systèmes de mesure et de traitement des données. Leurs efforts visent à améliorer la qualité et l'efficacité des mesures pour pouvoir tirer le meilleur parti des données collectées.
I?

Q

I

I

I

2.12

(b) Single bunch compression in the PS (497)

Knob 16

Knob 15

Knob 14

Knob 13

Knob 12

Knob 11

Knob 10

Knob 9

Knob 8

Knob 7

Knob 6

Knob 5

Knob 4

Knob 3

Knob 2

Knob 1

Knob 0

Re-run experiments

R. Calow
4/97/50
40 MHz bunches in the PS
Vrf = 300 kV  11/12/96

BUNCH with V(h=84)=300 kV
BUNCH with V(h=20)=200 kV
4. WORK PLAN

4.1 Short term aims (till end 97)

- Build and test the hardware required for the 97-98 shut-down (4 CO2 RF systems for the PSB, 2 C80 RF systems for the PS, low level RF and beam controls for all new modes of operation, specification of control’s software for 98)
- As far as reasonably achievable (bnl internal joke), test prototypes and check all modes of operation during 97
- Beam studies (analysis of longitudinal instabilities, understanding of controlled blow-up mechanism with dual harmonics RF system in the PSB, minimization of longitudinal emittance in the PS, etc.)
- Provide test beams to SPS
- Feasibility study for a 2 GeV Supraconductive Linac
- Define & begin work for the Anti-proton Decelerator (“AD”)

4.2 Medium term aims (till end 98)

- Resume operation for physics for the start-up in March 98
- Provide nominal LHC proton beam to SPS for the summer 98
- Build / modify hardware and begin beam studies for the AD

4.3 Long term aims (after 98)

- Start & run the AD
- Implement modifications (if any) for proper handling of the nominal LHC beam in the SPS
- Design and implement a technique to create a void of a few bunches in the PS 40 MHz bunch train
- Prepare ions injectors’ complex for LHC
- Define (implement?) a scheme to attain the ultimate luminosity in LHC...
PREPARATION OF THE PS COMPLEX FOR THE LHC-ERA IN 1997:

RF AND LONGITUDINAL PHASE PLANE STUDIES

1. PSB (ring 3)

<table>
<thead>
<tr>
<th>LHC H⁺</th>
<th>SFTPRO</th>
<th>SFTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Acceleration on h=1 &amp; 2 in ppm, Synchronisation 1 GeV, Longitudinal blow-up (h=10)</td>
<td>• High beam intensity acceleration on h=1 &amp; 2, Analysis &amp; damping (1) of instabilities, Splitting @ 1 GeV, Synchro. after splitting</td>
<td>• Acceleration on h=4 using C02 &amp; C04 (0.72 to 3.86 MHz)</td>
</tr>
<tr>
<td>Weeks 16-26: Apr.-Jun.</td>
<td>Weeks 36-40: Sept.</td>
<td>Weeks 35: beam (1 bunch) to the PS</td>
</tr>
<tr>
<td>Weeks 36-40: (Sept.)</td>
<td>Weeks 17-40: Apr.-Sept.</td>
<td>Week 40: beam (2 bunches) to the PS</td>
</tr>
<tr>
<td>Week 47: beam (4 bunches) to the PS</td>
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</tbody>
</table>
2. PS

<table>
<thead>
<tr>
<th>SPS test beams</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td><strong>SPS</strong></td>
<td><strong>Test beams</strong></td>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>1 to 20 bunches on h=20 @ 26 GeV with freq synchron. on SPS</td>
<td></td>
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<tr>
<td>Recaptured beam on h=84 @ 26 GeV (10^{13} ppp, 0.4 eVs, 9.5 ns)</td>
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<tr>
<td>1 bunch on h=84 (from 1 bunch on h=20) (5 to 15x10^{13}ppb, 0.14 eVs, 3.8 ns)</td>
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<tr>
<td><strong>LHC H+</strong></td>
<td><strong>Cavities</strong></td>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>Capture on h=8</td>
<td></td>
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<tr>
<td>Splitting on h=16</td>
<td></td>
<td></td>
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<tr>
<td>Blow-up and acceleration on h=16</td>
<td></td>
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<tr>
<td><strong>SPS</strong></td>
<td><strong>Parameters</strong></td>
<td><strong>Actions</strong></td>
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<tr>
<td><strong>Domain</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>PS longitudinal parameters</strong></td>
<td></td>
<td>- increase ν_{BP}</td>
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<tr>
<td><strong>Gap in the beam</strong></td>
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<td>- &quot;killer&quot; kicker</td>
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<td>- bunch splitting</td>
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<td><strong>SPS longitudinal parameters</strong></td>
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<td>- reduce β_{al}</td>
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<tr>
<td><strong>New PS</strong> (&quot;PS-XXI&quot;)</td>
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<tr>
<td></td>
<td></td>
<td>- increase injection energy</td>
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<td><strong>High energy Linac</strong> (&quot;SPL&quot;)</td>
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<tr>
<td></td>
<td></td>
<td>- increased injection energy in the PS (2 GeV)</td>
</tr>
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</table>

3. OTHER TASKS ON THE MACHINES

- Test of new 200 MHz blow-up hardware (200 MHz phase-shifter with digital control by GFAS)
- Check phase stabilisation loop for 40 MHz system
- Build and test 40 MHz phase loop
- Set-up and exercise tuning loop for the 40 MHz cavity
- Monitor effects induced by the 40 MHz cavity on the beam, track evolution of multipactor levels.
Intensity Related RF Issues at Fermilab

Acknowledgments

Joe Dey
Kathy Harkay
Gerry Jackson
Ioannis Kourbanis
Dave McGinnis
Jim Steimel

Future Plans Requiring Higher Intensities

Collider Run II (1999)
Increase number of colliding bunches from 6x6 to 36x36
Multi-Batch Coalescing
Increase Pbar production and stacking rate
Higher Main Injector Intensity of 6e10 ppb
Recycler Ring Barrier Bucket RF system

Tev 33 (before LHC)
Increase Collider luminosity to 1e33
Slip stacking ?
Additional Main Injector RF ?
A higher frequency RF system for the Tevatron ?

NUMI = NeUtrinos at the Main Injector(2000+)
High intensity fixed target experiments to detect neutrino oscillations

Muon Collider (?)
A fast cycling high intensity proton driver
Three Topics for Discussion

Longitudinal Coupled Bunch Instabilities
Multi-Batch Coalescing (transient beam loading)
Wideband Recycler Ring RF (barrier buckets)

Figure 1.1 Time Evolution of the Bunch Phase (Mountain Range Plots) Through a Portion of the Booster Cycle. Growing dipole oscillations indicative of the coupled-bunch instability are clearly seen. The beam intensity is $1.5 \times 10^{10}$ protons per bunch, the transon pump system is off, and the RF cavity dampers are out. The horizontal scale is 2 ns per division. (Ref. 43)
Figure 5.9  Excitation of RF Cavity Mode B (833 MHz).  Shown are time-beam intensities: (a) 0.5x10^10, (b) 1.5x10^10, and (c) 2.5x10^10 protons per bunch.

Figure 5.8  Correspondence of RF Cavity HOM Impedance and Compton-Effect Modes. Spectrum before HOM Dampers. The RF harmonics are marked with a filled "O", mode 16 with an "X", and mode 48 with an open "O". (R12)
Booster RF Cavity

Figure 2.6  Cut-Away Drawing of RF Cavity. (Ref. 5)

Booster Cavity

Figure 5.12  RF Cavity Showing Installation of HOM Dampers. Depicted are the (a) nominal and (b) modified cavities.
Booster

Booster - with passive dampers

Figure 5.7 Frequency Spectra Showing the Complete-Bunch Mode Signal before and After RF Cavity ROM Damping. In (a), the bunch intensity is 1.5E9 photons per指导 (ROM dampers out) and so (b). In (a), 1.5E12 photons per bunch (ROM dampers in). In each case, the RF stations are on and the data correspond to 35 ms in the cycle. Mode 60 has been completely suppressed and only 49 oscillations occur, the intensity is greatly reduced (b).

Figure 5.17 Correspondence of RF cavity ROM impedance and Complete-Bunch Mode Spectrum After ROM Dampers. The RF harmonics are marked with a filled "O" and mode 50 with an open "O". (ECR)
Damping of Booster Mode 36 with an Active Damper

J. Steimel & D. McGinniss, 1993 PAC

For More Information on Active Dampers:
http://adwww.fnal.gov/proton/other/index.html
Main Ring Cavity

Rshunt vs Frequency at Full Bias

Center 125,000 MHz  Span 20,000 MHz

CH1 A/R  log MAC  10 dB/ REF -110 dB

Average 114
Channel 1 Scale 100 mV/div Offset -300.0 mV Input 50 Ohms
Time base Scale 2.10 ns/div Position 31.200000 ns Reference center
Trigger Mode edge Source trigger & Hysteresis normal Holdoff 60 ns
Level 999 mV Slope Pos
Measurement
DCRms cycle(1) 37.746 mV
Marker V X
1(FT)-20 mV 126.14 MHz
2(FT)-20 mV 126.14 MHz
Delta -20 mV 13.30 MHz
1/V/N = 75.19 ns
FFT fft magnitude channel 1
Scale 3.00 dBm/div Offset -52.8400 dBm
Scale 6.00 MHz/div Position 105.700000 Hz

Channel 1 Scale 100 mV/div Offset -300.0 mV Input 50 Ohms
Time base Scale 2.10 ns/div Position 31.200000 ns Reference center
Trigger Mode edge Source trigger & Hysteresis normal Holdoff 60 ns
Level 999 mV Slope Pos
Measurement
DCRms cycle(1) 37.746 mV
Marker V X
1(FT)-20 mV 126.14 MHz
2(FT)-20 mV 126.14 MHz
Delta -20 mV 13.30 MHz
1/V/N = 75.19 ns
FFT fft magnitude channel 1
Scale 3.00 dBm/div Offset -52.8400 dBm
Scale 6.00 MHz/div Position 105.700000 Hz

2.84 sec or 21
Start of plottop
Longitudinal Coupled Bunch Instabilities

Booster h=84

mode #16 (3rd & 5th harmonic of RF cavities)
  passive dampers
mode #36 (fixed frequency drift tube mode)
  passive and active dampers

Main Ring h=1113

mode #457 (3rd harmonic of RF cavity)
  passive dampers
mode #327 (5th harmonic of RF cavity)
  passive damper

Tevatron h=1113

mode #40 (3rd harmonic of RF cavity/transmission line)
  passive damper
Coalescing Protons in the Main Ring (single batch)

20 ns/div
4 ms/trace
Coalescing in Main Ring

13.000 μs

Channel 1 Scale 20 mV/div Offset 0.00 Input ac 50 Ohms
Channel 2 Scale 500 mV/div Offset 0.00 Input dc 50 Ohms
Time base Scale 500 ns/div Time Position 301.670 ns Reference center
Window scale 5.00 ns/div Window position -368.000 ns
Trigger Mode Exact Source Trigger 2 Hysteresis normal Holdoff 50 ns
Level 178 mV Slope Pos

Measurement

Current peak1 47.9240 μA peak2 1.9569 μA rise 371.1300 ns fall 917.900 ns
Width peak1 9.4297 ns peak2 381.1400 ns

Marker

Y 1(3) = 1.450 V 2(3) = -375 V
X 178 μV 381.1400 ns Delta = -1.755 V 754.2780 ns 1/ΔX = 1.32577 MHz

Main Ring

Ro6 η/α off

5% and 10 ηA faulted
Multi-batch Coalescing (Adiabatic)

Cavity Sheets In

Cavity Sheets Out

Multi-batch Coalescing

Feedback on RF Cavity phase
Feedback off

5X10" 12 batches, 12 MV at 150 GdV

3.49 sec on 2B

502/div
Multi-Batch Coalescing

Feedforward Off
RF Cavity phase 9°/div

Feedforward On
RF Cavity phase 9°/div

Multi-Batch

3 BT NO BLC ~ 6.2E12

Acquired: 27 Nov 1996 15:25:00.10
Printed: 27 Nov 1996 15:25:10

Acquired: 27 Nov 1996 16:08:12.20
Printed: 27 Nov 1996 16:08:12

3 BT Tun. BLC ON (+3db) (-0.5ms)

With Feedforward Compensation
Recycler Ring

An 8 GeV permanent magnet Pbar storage ring

Located above the Main Injector Ring

Dual Purpose: Store and Cool Pbars directly
from the Accumulator
Store and Cool Pbars recycled from
the Tevatron Collider

Uses Wideband RF system to generate Barrier
Buckets for injecting and extracting Pbars

Figure 2.1.23: Full ring phase space sketches of the initial stage of
antiproton recycling in the Recycler. In the top drawing (a) the cooled
beam starts off basically unbounded (unless an additional gap is necessary
for beam clearing reasons). In the bottom drawing (d) a rectangular
barrier voltage system, adiabatically squeezes the beam into a fraction
of the circumference.

Figure 2.1.25: Recycling of antiproton bunches from the Main Injector.
The leftmost charge distribution is always the cooled antiprotons. The
shown Recycler injection kicker waveform has a rise-time and fall-time of
1 usec. The recycling process never requires more than 3 years of barrier
voltage pulses.
Scope

4 ferrite loaded, 50 ohm RF cavities with a peak accelerating voltage of 2 kV

4 wideband amplifiers, 2500 watts CW, 10 kHz to 100 MHz

Low level RF system to generate barrier bucket pulses
Solid-State Amp

3000A100 TYPICAL POWER OUTPUT

WATTS

0 600 1200 1800 2400 3000 3600 4200

FREQUENCY (MHz)

0.001 0.01 0.1 1 10 100 1000
Accelerator Complex of Japan Hadron Facility

Chihiro Ohmori
KEK-Tanashi

Accelerator Complex

• 200-MeV linac high brightness
  accelerated particle H⁺ ion
  peak beam current >30(50) mA (25Hz, 400μs)
  structures RFQ + DTL + ACS

• 3-GeV booster rapid cycling
  intensity 5 x 10¹³ ppp
  repetition rate 25Hz
  beam power 0.6 MW
  RF frequency 1.99-3.43MHz
  RF voltage 220kV
  circumference 339.4m (KEK-PS tunnel)

• 90-GeV main ring transition free(negative α)
  intensity 2 x 10¹⁴ ppp
  acceleration cycle 0.3Hz
  RF frequency 3.43-3.51MHz
  RF voltage 270kV
  momentum compaction ~ -10⁻³
  circumference 1442m (north site of KEK)
ACCELERATION ENERGY (GeV)

Beam intensities of high-intensity proton synchrotrons.
50-GeV, 10 μA

16 bunches (h=17)
0.3Hz
2x10^{14} ppp

3GeV, 200μA

h=4
25Hz
5x10^{13} ppp

50-GeV, 10 μA

2x10^{10} ppp

slow extraction
T=0.7sec, 2x10^{10} ppp

fast extraction
bunch length: ~50ns

3GeV, 200μA

fast extraction
bunch length: ~100ns

200MeV, 30mA

50-GeV, 10 μA

P1-P2: 0.12s
P2-P3: 1.9s
P3-P4: 0.7s
P4-P5: 0.7s

Main Ring Cycle: 3.42 sec

P1-P2: 0.12
P2-P3: 1.9
P3-P4: 0.7
P4-P5: 0.7

h=17, # of bunches: 16
BEAM INTENSITY: 2x10^{14} ppp
flat top duty factor: 0.21
Design Issues

50-GeV Main Ring

* Transition-free ring
  Imaginary \( \gamma_i \) lattice: \( \alpha \approx 10^{-3} \)
* Free from instabilities
  Low impedance ring
* Large dynamic aperture

3-GeV booster

* Tunability \((v_{x,y})\)
* Small emittance growth
  Space charge, Coupling \((x:y:z)\)
* Beam scraping

Imaginary \( \gamma_i \) lattice

"4-6-3 lattice"

(1) Stability of linear optics

* Selection of phase advance
* Beam size
* \( \alpha \) vs dispersion and tunes
* \( \alpha \) vs space charge (Umstatter effects)

(2) Dynamic apertures (DA)

* Chromaticity
* Synchrontron oscillation amplitudes
* Space charge

(3) COD correction

* Dry run
\[ \sqrt{\beta_x} \sqrt{\beta_y} (\text{m}) \]

\[ \Phi_p = 0.00132 \]

\[ \Phi = 300 \]

\[ \beta_x : \text{small} \]

4-6-3

Super periodicity module cell

23:00:04 Tuesday 29-Apr-96
Maximum Apertures of the 50 GeV Main Ring

apertures
\[ A_x = \sqrt{\beta_x \varepsilon_x + \eta_x \left( \frac{\Delta p}{p} \right)} + \text{COD} + \text{sagitta} \]
\[ A_y = \sqrt{\beta_y \varepsilon_y + \text{COD}} \]

\[ \varepsilon_{x,y} = \frac{53.9 \text{ mm.mrad}}{5} \]
\[ \frac{\Delta p}{p} = 0.5\% \]
\[ \text{COD} = 5 \text{ mm} \]

<table>
<thead>
<tr>
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<th>vertical</th>
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<tbody>
<tr>
<td>B magnet</td>
<td>47 mm</td>
</tr>
<tr>
<td>Q magnet (max)</td>
<td>53 mm</td>
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</table>

summary of Lattice “4-6-3”

* \( \alpha \sim -10^{-3} \)

(1) Linear optics stability
* stable operating point O.K.
* beam size \(~50\text{ mm}\) O.K.
* tunability
  \[ Q_{x,y} \eta \] vs. \( \alpha \) O.K.
* space charge O.K.

(2) Non-linear optics (Dynamic apertures)
* \( \xi \) O.K.
* \( \Delta p/p \) O.K.
* space charge O.K.
* error fields need optimization

(3) Corrections COD etc. (O.K.)
**”Dry run”**
Maximum apertures of the 3 GeV booster

apertures

\[ A_x = \sqrt{\beta_x \epsilon_x + \eta_x \left( \frac{\Delta p}{p} \right)} + COD + (\text{sagitta}) \]

\[ A_y = \sqrt{\beta_y \epsilon_y} + COD \]

\[ \epsilon_{x,y} = 340 \text{mm.mrad} \]

\[ \frac{\Delta p}{p} = 0.5\% \]

COD = 5 mm

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<tr>
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<tbody>
<tr>
<td>B magnet</td>
<td>93 mm</td>
<td>95 mm</td>
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<tr>
<td>Q magnet</td>
<td>106 mm</td>
<td>107 mm</td>
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</table>

\[ H' \hat{y} V' \hat{z} \quad (N_x = 5 \hat{z} \quad N_y = 3 \hat{y}) \]
Space Charge Limit

\[
N_{\text{inc}} = \frac{\pi \beta^2 \gamma^3 (1 + \frac{e_i e}{e_H f}) e_i \Delta \nu B}{r_F \rho}
\]

\[
N_{\text{coh}} = \frac{\pi Q_0 h^3 \beta^2 \gamma^3 B \Delta \nu}{r_F \rho}
\]

\[
\Delta \nu = -0.25
\]

<table>
<thead>
<tr>
<th>Incoherent</th>
<th>Coherent</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 GeV Booster</td>
<td>$5.6 \times 10^{13}$ ppp</td>
</tr>
<tr>
<td>50 GeV Main Ring</td>
<td>$4.7 \times 10^{14}$ ppp</td>
</tr>
</tbody>
</table>

Summary 3-GeV Lab

| $\sqrt{\beta_{\text{max}}}$ | 5 | 4.6 | 6.2 |
| $\gamma_{\text{max}}$ | $3.6_m(\alpha_k)$ | $3.8_m(\alpha_l)$ | $2.6_m(\alpha_l)$ |
| $\gamma_c$ | -15 | -6 | -6 |
| $A(\psi)$ | Large | Large | Small |
| $A(\phi)$ | Large | Large | Small |
| Injection (Scrapers...) | $\bigcirc$ | $\bigtriangleup$ | $\bigtriangleup$ |
| Extraction (1 cell lag 8.5) | $\bigcirc$ | $\bigtriangleup(\psi)$ | $\bigcirc$ |
| Long, matching with MR | $\bigcirc$ | $\bigtriangleup$ | $\bigtriangleup$ |
b) Narrow Band

Longitudinal Coupled-Bunch

RF cavity parasitic mode: \( f_p/f_c = \frac{1}{3B'} \) (R. Baartman)

booster (injection): \( R_s < 900 \Omega (Q \geq 5, f_p \sim \text{MHz}) \)

main ring (injection): \( R_s < 700 \Omega (Q \geq 5, f_p \sim 15 \text{MHz}) \)

"active damper", "Q<1 cavity?"

c) Resistive Wall

Transverse Coupled-Bunch

booster: < 0.14MΩ/m

main ring: < 1.4MΩ/m

---

Collective Effect

a) Broad Band

Space Charge, Inductive Wall

[1] Microwave Instability

Main ring

3 GeV (injection) \( |Z| \leq 20 \Omega \) @ \( \varepsilon_L = 1 \text{eV} \cdot \text{sec} \)

space charge impedance \( \approx 55 \Omega \) : \( \varepsilon_L \approx 3 \text{eV} \cdot \text{sec} \)

booster: no problem


Inductive wall: \(- \Im \frac{Z}{n} \leq 3 \Omega \) @ \( \varepsilon_L = 3 \text{eV} \cdot \text{sec} \)

space charge: no problem—capacitive, \( c<0 \) (right lattice)
1997  New Organization

1998  Construction Start

1999  Neutrino Oscillation Experiment at 12-GeV PS

2000

2001  3-GeV Ring Installation into the 12-GeV PS Tunnel

2002  50-GeV Ring completion, First Beam

1. RF Cavity
   (Fine-Crystal High-
   * 1 Metal)

2. Ceramic Beam Duct

3. Main Ring
   *Main Ring
   106mm(gap) x 1.5m

4. Booster Magnet Power Supply
   Resonant Network System

Q  = 1
RF Cavity

Heavy Beam Loading
(1) Beam Power > Cavity Power
(2) Robinson Stability Criterion 
   $Rs \sim$ small ($1k\Omega/m$)
(3) Coupled Bunch Instability
   $Q \sim$ small ($Q<5$)

Ferrite (problems)
* nonlinear behavior at large RF field
* low Curie temperature

New Material
“Fine-crystal High-$\mu$ Metal”
* high permeability
* $Rs \sim$ constant for larger RF field
* $Q \sim 1$

BEAM DUCT

Requirements
(1) Eddy current 
   25Hz (3GeV) 
   0.3Hz (50GeV)
(2) Impedance 
   RT<1.4M$\Omega$/m @ 50GeV 
   RT<0.14M$\Omega$/m @ 3GeV
(3) Thermal shock 
   Beam hitting
(4) No magnetization
(5) Ease of fabrication
(6) Small maintenance residual activities
(7) Cost

3-GeV Booster >> Ceramic duct

50-GeV MR >> INCONEL duct
>> Ceramic duct
Control of Resonant Network Systems

テスト電源-ブロックダイアグラム

\[ \Delta \phi = \phi_1 - \phi_2 < 8.28 \mu s \text{ for } \Delta Q = 0.01 @ 25 \text{ Hz} \]
Overview from Los Alamos:
Current Thinking on RF Upgrade Issues

- PSR Upgrades in Progress
- Space Charge Compensating Inductor
- Barrier Bucket RF
- PSR Instability
  - by Arch Thiessen
  - 8 May, 1997

PSR Upgrades in Progress
PSR parameter list

- Beam energy: 797 MeV ($\gamma = 1.85$, $\beta = 0.84$)
- Circumference: 90.2 m
- Bunch length: 250 ns
- Number of bunches: 1
- Revolution period: 357 ns
- Betatron tunes: $v_x = 3.18$, $v_y = 2.14$
- Transition gamma: 3.1
- Maximum rf voltage: 12.5 – 14 kV
- Chromaticity, horizontal: $-1.26 \pm 0.06$
- Chromaticity, vertical: $-0.8 \pm 0.2$
- Momentum spread from linac: 0.05%
- Momentum spread in PSR: 0.5%

---

PSR parameter list (cont.)

- Typical injection time: 600 $\mu$s
- Typical storage time: 10 $\mu$s
- Max bunched-beam charge stored: $6.4 \mu$C ($4 \times 10^{13}$ ppp)
- Max coasting-beam charge stored: $2 \mu$C ($1.3 \times 10^{13}$ ppp)
- Synchrotron period: 720 $\mu$s for 10 kV buncher
- Coherent tune shift: 0.008
PSR Upgrade Programs In Progress

- LANSCE Reliability Improvement Program (LRIP) Phase I (complete!)
  - Improved Beam Availability from ~65% to ~85%
- LRIP Phase II
  - Goal is 100 µA @ 20 Hz
  - Direct H- Injection
    - Construction Starts 1 Aug, '97, Complete 1 March '98
- Short Pulse Spallation Source Enhancement (SPSS)
  - Goal is 200 µA @ 30 Hz, 4x10^{13} protons per pulse
    - New H+ Ion Source
      - 1.5-2x Existing Current at Smaller Emittance
        - Collaboration with K-C Leung, BNL
    - New RF System
      - Phase I (1997-1998) - New Driver for Existing 2.8 MHz Cavity
        - Needed both for Beam Dynamics and Reliability Improvement
      - Phase II (1999-2000) - New Cavity and RF Driver - Sum 12 KV @ 2.8 MHz, -6 KV @ 5.6 MHz
    - Building, Cooling Water, and Utilities

Voltage Waveforms Considered

![PSR RF Waveforms](image)

- 10.5 kV 2.8 MHz
- 12 kV 2.8 MHz, -15 kV 5.6 MHz
- 13 kV 2.8 MHz, -15 kV 5.6 MHz, 4 kV 5.6 MHz

LANSCE

5/08/97 5

5/08/97 6
PSR before Upgrade

- Foil Hits 307
- Losses
- 0.15%
- 0.10%
- 0.03%

PSR with 2 Harmonics
Space Charge Compensation with Inductor

Longitudinal Space Charge Control

- Maximum Value is ~1/2 of Applied Voltage after upgrades
  - Up to Now, Propose Control by "Brute Force"
    - Make Sure $V_s > V_{sc}$
    - And Test by Tracking with ACCSIM or other code
  - For $g=3$ - inductance required in PSR is about 11 microHenries
  - Actual value of $g$ not well known
    - at present $g=3.9$
    - After LRIP $g=3.6$
    - After SPSS $g=3.3$
  - In Process of Tracking Code (ACCSIM) Modification
    - for any longitudinal impedance
    - variation of $g$ with Courant/Snyder invariant
A Test of Space Charge Compensator

- For Space Charge Compensator Test, ~5 microHenries Max
  - Less than 1/2 Amount Needed for Full Compensation
    - Idea is to see effect
      - bias off vs on
      - beam in gap?
      - Stability threshold?
    - Look for other problems caused by inductor
      - change in instability threshold
      - good ideas for effects to look at?
- Two Days with Access for Installation July 31, 1 Aug
- One 24 hr Day for Tests with Beam
  - Tentatively Scheduled for 2/3 August, 1997

Barrier Bucket at PSR
Barrier Bucket at PSR

- Study Just Getting Underway
  - Tracking Code Not Yet Adapted for Barrier Bucket
- Tradeoff between Injection Time and Voltage
  - Both Are Problems at PSR
    - Present injection time 250 ns is too long for clean gap
    - Voltage Available on One-Cavity, ~10 kV is Low
      - \( h=1.5 \) to 10 kV ok, but bunching factor low
      - \( h=2.5 \) requires 30 kV for full height bucket
    - How Does PSR Work Now?
      - Not many particles at high \( dp/p \) at end of bunch
      - Reasonable options are \( h=1.5 \), \( h=2 \), \( h=2.5 \), \( h=3 \) barriers
        - \( h \) integer ok if Cathode Follower Driver
- Want to Compare with a Traditional 2-Harmonic System

5/08/97 13
PRESENT OPERATION

EXTREME PARTICLES, 230 nS WAVELENGTH

GAP

I

II

III

2 HARMONICS
EXAMPLE

TIME

NORMALIZED GAP VOLTAGE

SOME HALF SINUSOIDS

(NOTE: These are appropriate for "high impedance" drivers. With cathode followers, any harmonic is O.K.)

NORMALIZED GAP VOLTAGE

\[ L = 3.5 \ (22 \text{ kHz}) \]

\[ L = 3.5 \ (7 \text{ kHz}) \]

\[ L = 1.5 \ (4.2 \text{ kHz}) \]
SINUSOID GENERATION IDEAS

1. ISOLATED SINUSOID

\[ I(t) \rightarrow V(t) \rightarrow I_0 \]

\[ I(t) \rightarrow V(t) \rightarrow I_0 \]

2. ISOLATED HALF-SINUSOIDS

\[ I(t) \rightarrow V(t) \rightarrow I_0 \]

\[ I(t) \rightarrow V(t) \rightarrow I_0 \]

Note: 5% D.F. MAX. EXISTING CATHODE FOLLOWER

(Also: \( I_0 \text{ OFF} \approx 3 \))
Coasting beam instability signals

23-Feb-97 20:24:02

End of injection

3.0 μC injected
(2.0 μC before instab.)
925 μs injection
250 ns PW
rf off
-1900 V opp. elec.

Bunched beam instability signals

23-Feb-97 20:35:36

rf off

3.0 μC
925 μs injection
250 ns PW
6 kV rf
-1900 V opp. elec.
Stable Peak Intensity vs. Buncher Voltage

Peak Stored Charge vs. Bunch Length
Instability from PSR RF System Problems?

- Measured Phase and Amplitude Jump at Extraction
  - Phase Change <5°
  - Amplitude Change <5%
    - These Result in Tiny Changes in Beam Dynamics
- See Also Arch's Experiment
  - With Open Circuit Drive of Cavity

Logbook - Arch's Test:
With Open Circuit Buncher Drive
Instability from Beam in Gap?

![Graph showing peak buncher voltage versus duration of beam injected into gap (μs).]

Duration of beam injected into gap (μs)

- Bunch length = 220 ns
- Bunch length = 150 ns

Logbook - Beam in Gap

5/08/97 22
Signal power vs. time

- Signal power at $t$, $t + 60$ μs, and $t + 160$ μs from wide band stripline beam position monitor.
- Power begins at about 175 MHz, then spreads in width and amplitude.

$$f = \frac{1}{2\pi} \sqrt{\frac{2Nc^2(1-\eta_e)}{\pi b(a+b)R}}$$

Data from SRW414V, 4/7/97.
WM41VD.012

5/08/97 24

Peak frequency vs. intensity

- The peak in the signal spectrum depends on the beam intensity.
- Top spectrum is twice the intensity of the bottom spectrum.
- Beam conditions for the top and bottom spectra are the same except for the beam intensity and the buncher voltage.

$$f = \frac{1}{2\pi} \sqrt{\frac{2Nc^2(1-\eta_e)}{\pi b(a+b)R}}$$

SRW414V from 13Apl97 data.
WM41VD.4C, SRW414V.4F

5/08/97 25
Where Vertical Instability Grows:
2nd Half of Bunch

- CERN BPM Vertical Difference
  - three traces at different times

Vertical oscillations and beam density

- WM41VD.4B
- WC41.4B
- Data taken Apr. 14, 1997
- Data at t, t+115 μs, t+230 μs, t+345 μs
Transverse oscillation $\lambda$ correlated with $\rho$

![Graph showing oscillations](image)

SRM41 (top)
SRWM41 $\Delta V$ (Bot)
Data from 22/Feb/97

Sources of electrons

For each injected proton, we have:

- "Convoy" electrons 1
- SEM from stripper foil from convoy electrons 0.1 - 1
- Knock-on electrons from stripper foil 1.3
- SEM from foil from circulating protons 6
- Thermionic emission from foil <0.02

- SEM from beam loss 0.01 - 1
  (2 to 200 electrons created per proton lost)
- Residual gas ionization 0.0001
- Electron multiplication from electron osc. ?
Conclusions

+ Study of Inductor for Space Charge Compensation Underway
  - An Experiment Planned for August
    - If logistics work out
+ Studying Barrier Bucket for PSR Underway
  - No Results Yet
+ PSR Instability is e-p
  - Frequency Dependence
  - Starts in 2nd Half of Bunch
    - But Source of Electrons
    - And Mechanism for Growth
      - Not Yet Understood

LANSCE

5/08/97 30
Session on Barrier Cavity Issues

M. Blaskiewicz

The working group on barrier cavity issues included two presentations. Masahito Yoshii presented plans for the AGS barrier cavity upgrade and Chihiro Ohmori presented plans for the JHF.

Plans for the AGS barrier cavity upgrade included cavity design and materials as well as drive considerations. The system will produce two single period sine wave pulses of amplitude 80 kV and period 250 ns (1/4 MHz) at a rep rate of 350 kHz. There will be one rf station for each pulse. Since the cavity is run in a non-resonant mode the cavity voltage $V$ and generator current $I$ are related via $V \approx IR/Q$ where $R/Q$ is the ratio of shunt impedance to cavity $Q$ for the resonant mode at 4 MHz.

Yoshii stressed the need for a high inductance and a low capacitance so that the necessary waveform could be obtained with minimum generator current. The AGS philosophy is to use a fairly low loss ferrite (Philips 4B2 or 4L2) to obtain the high inductance and to control the shape of the voltage waveform by careful adjustment of the generator. This technique minimizes the peak generator current required for a given gap voltage and cavity $R/Q$. The generator supplies current in one direction only, which reduces cost.

The total voltage of 80 kV is obtained using 8 gaps with 10 kV per gap. Such a design does not require high voltage feedthroughs and a prototype of a single cell using Philips 4L2 has achieved the necessary voltage.

The JHF design included an upgrade of the KEK Booster as well as the new high energy JHF. Accelerating voltages of 10 kV/meter are required. The KEK design differs from the AGS design mainly in the choice high permeability material. Ohmori agreed that large inductance with small capacitance was needed, but is more inclined toward the very high permeability and lossy FINEMET. For a truly isolated voltage pulse the system requires a push-pull current drive, but the voltage waveform from a half sine wave current pulse was not far from ideal. The low $Q$ leads to large power dissipation in the cavity, but FINEMET has a 600 C Curie temperature. Additionally, the low quality factor reduces the shunt impedance of parasitic modes which should reduce instability problems. A prototype cavity has been built and has achieved 11 kV/ meter. Studies of feedback and beam loading are underway.
AGS Barrier Cavity

M. Yoshii (KEK)
M. Meth (BNL)
R. Spitz (BNL)

May 7 1997
Barkner Hall Room B
BNL, Upton NY, USA

AGS Barrier Requirements

- 80 kV per each station
- Two Barrier Stations
  the length of station should be
  less than 102 inches (2.6m)
- 4 MHz
  cf. the revolution frequency at AGS
  Injection is 357 kHz

CONTENTS

✓ AGS Barrier Requirements
✓ Design Principles
  ✓ permeability : \( \mu \)
  ✓ \( \mu Q \)-product : \( \mu Q \)
  ✓ capacitance : \( C \)
✓ Ferrites
  ✓ \( \mu (r) \) measurement
  ✓ sample measurement
✓ Cavity Capacitance
✓ New AGS Barrier Cavity
  ✓ design
  ✓ 1/8 model
  ✓ drive circuit
✓ Summary
Design Principles

✓ to minimize the drive-tube current
✓ high cavity inductance
✓ square current waveform
✓ simple structure

The total current required for the barrier gap voltages is,

\[ I(t) = \omega C v_0 \left( 1 + \frac{\sin(\omega t)}{Q} \right) + v_0 \cos(\omega t) \left( \omega C - \frac{1}{\omega L} \right) \]

And, the peak current on resonance is,

\[ I_p = \omega C v_0 \left( 1 + \frac{1}{Q} \right) \]

Therefore, following three basic parameters for the cavity; \( \mu \), \( \mu Q \)-product and total \( C \) are chosen in order to minimize total tube current.

✓ Capacitance per gap < 200 pF
  - to keep the average rf-current as low as possible

✓ \( \mu Q \)-product > 2000
  - to keep the peak rf-current as low as possible

✓ \( \mu \) > 500:
  - to get a high gap voltage, \( v' = L \frac{dl}{dt} \)
  - also, to make a cavity short
Radial Dependence of Ferrite $\mu$ and Magnetic Flux

G. Rakowsky (BNL) "RF Accelerating Cavity For AGS Conversion"

$\mu(r)$, $B(r)$ distributions under biasing conditions

For a given I_{dc},

- $\mu$ increases with radius
- $H_r$ decrease as radius

$\Rightarrow$ Magnetic Flux becomes uniform

---

I_{dc} = 0 or weekly biased

- $\mu$ is uniform in a ferrite

$\Rightarrow$ Magnetic Flux has radial dependence.

\[
\frac{\pi}{\alpha R^2} = \tau
\]

where

\[
\frac{V}{\alpha R^2} = \tau
\]

\[
\frac{I_1}{\alpha R^2} = \tau
\]

Magnetic Flux

Measurement of Permeability and Flux Distribution

- 412 $\phi_{500} \times 2000 \times 22.4 \text{mm}$
- 30 Turns of pick-up coil (6 positions along the radial direction)
- 100 turns of primary winding for biasing

MAY 7-97
M. Yoshii
Mini-workshop
An induced voltage at each pick-up is
\[
e^{n, \alpha} = -\frac{d \phi^{n, \alpha}}{dt} \text{ (volts)},
\]
where \( N \) is the turn-number of pick-up coil, \( \phi \) is a magnetic flux through the coil and a suffix (n) denotes the pick-up position.

As a flux \( \phi^{n, \alpha} = \int \overline{B}^{n, \alpha} dS^{\alpha} \), \( \phi = \frac{d \phi^{n, \alpha}}{dS^{\alpha}} \text{ flux n-th pick-up crosssectional area} \).

The time-integration of eq.(2) gives
\[
\phi^{\alpha}(t) = \frac{1}{N^{\alpha}} \int_{t_0}^{t} \phi^{\alpha}(t) dt
\]
(4).

From (3) and (4), then, the average flux density \( B_n \) at n-th pick-up is given by
\[
\overline{B}^{\alpha}(t) = \frac{1}{N^{\alpha} S^{\alpha}} \int_{t_0}^{t} \phi^{\alpha}(t) dt
\]
(5).

In the measurements all data are discretely sampled. So, Integration in eq.(5) must be re-written by,
\[
\overline{B}^{\alpha}(t) = \frac{\Delta t}{N^{\alpha} S^{\alpha}} \sum_{n=1}^{N^{\alpha}} \phi^{\alpha}(n) \Delta t
\]
(6).

for example, in our case,
\( N = 30 \) turns, \( S = 763 \times 10^{-6} \text{ m}^2 \), \( \Delta t = 200 \mu \text{sec} \)
\[
\overline{B}^{\alpha} = 8.75 \times 10^{-3} \int_{t_0}^{t} \phi^{\alpha} \text{ (volts \cdot sec/meter)}
\]
Sample measurements

The Ferrite materials are required at 4MHz

<table>
<thead>
<tr>
<th>μ</th>
<th>μQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 500</td>
<td>&gt; 2000</td>
</tr>
</tbody>
</table>

Philips: 4A11 4B3 4L2
TDK: L6H

Ceramic Magnetics: CMD10 CMD5005

Bias Current: 100 - 1100 A

Differential $\mu_s = \frac{\Delta B}{\Delta H}$

Relative $\mu(0)$

$\mu(0)$ inside $\mu(0)$ outside

$\mu(0)$ product

$\mu(0)$=$\mu(0)$, $\mu(0)$=$\mu(0)$, $\mu(0)$=$\mu(0)$

MAY 7-97
M. Yoshii
Mini-workshop
Table - 1. List of dimensional parameters of tested samples

<table>
<thead>
<tr>
<th>Name</th>
<th>Maker</th>
<th>I.D (mm)</th>
<th>O.D (mm)</th>
<th>t (mm)</th>
<th>AL/μp (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H3</td>
<td>Philips</td>
<td>20.</td>
<td>30.</td>
<td>8.</td>
<td>640.</td>
</tr>
<tr>
<td>L6H</td>
<td>TDK</td>
<td>15.</td>
<td>25.</td>
<td>8.</td>
<td>770.</td>
</tr>
<tr>
<td>CMD10</td>
<td>CH</td>
<td>23.</td>
<td>27.</td>
<td>15.</td>
<td>600.</td>
</tr>
<tr>
<td>CMD5005</td>
<td>CH</td>
<td>38.</td>
<td>25.</td>
<td>15.</td>
<td>986.</td>
</tr>
</tbody>
</table>

Measurements

- conditions: 4 turns winding for measuring 4A11, 4H3, 4L2, CMD10 and CMD5005
  5 turns for L6H
- instruments: HP8751A Network Analyzer with HP87612A Transmission/Reflection Test Set for 4A11, 4H3, 4L2 and L6H measurements
  HP8753A Network Analyzer with HP85044A Transmission/Reflection Test Set for CMD10 and CMD5005 measurements
- frequency range: 100kHz to 10 MHz or 300 kHz to 10 MHz
Capacitance Measurement:

\[ f^2 = \frac{L}{C_{\text{ext}}} : C_{\text{ext}} \text{ unknown} \]
\[ f^2 = L(C_{\text{net}} + C_{\text{m}}) : C_{\text{net}} \text{ known} \]

\[ C_{\text{st}} \rightarrow x \]

![Typical plot](image-url)

**FIGURE 2:** Typical plot

Cavity Capacitance

- \( C_{\text{net}} \): net capacitance
- \( C_{\text{ext}} \): external capacitance
- \( C_{\text{m}} \): stray capacitance
- \( C_{\text{gap}} \): gap capacitance
- \( n \): number of gaps
- \( n \): resonant condition

\[
\left( \frac{f}{2\pi} \right)^2 = \left( \frac{C_{\text{net}} + C_{\text{ext}} + C_{\text{gap}}}{n} \right)
\]

Contribution of \( C_{\text{net}}, C_{\text{ext}}, \) and \( C_{\text{gap}} \) to \( C_{\text{st}} \) becomes less with \( n \).
FIGURE 6 Superfish Field Plots:
Electric field lines in the ferrite loaded cavities with the cooling plates (a), and without the plates (b) are displayed. Each cross-sectional view shows a half of the cavity.
<table>
<thead>
<tr>
<th>Name</th>
<th>&lt;φ&gt;</th>
<th>dφ</th>
<th>Lp(V)/gap</th>
<th>CT (pF)</th>
<th>Cext (pF)</th>
<th>Total kV</th>
<th>ksh</th>
<th>Pw/ring (kW)</th>
<th>Pw density (W/cm²)</th>
<th>P (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8-Gap Cavity</td>
<td></td>
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<td></td>
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<td>3</td>
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<td>4</td>
<td>ID = 200 mm</td>
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<tr>
<td>5</td>
<td>t = 28.1 mm</td>
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<tr>
<td>6</td>
<td>k = 50 pF</td>
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<tr>
<td>8</td>
<td>N = 6</td>
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<tr>
<td>9</td>
<td>8 gaps</td>
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</tr>
<tr>
<td>12</td>
<td>η = 11</td>
<td>490</td>
<td>1.2</td>
<td>25.7</td>
<td>61.7</td>
<td>-28.3</td>
<td>227</td>
<td>97</td>
<td>11</td>
<td>8.6378</td>
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<td>13</td>
<td>445</td>
<td>370</td>
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<td>318</td>
<td>211</td>
<td>5</td>
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<td>14</td>
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<td>3.0</td>
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<td>213.3</td>
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<td>15</td>
<td>LGH</td>
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<td>1.3</td>
<td>32.0</td>
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<td>178</td>
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<td>8</td>
<td>4.9319</td>
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<td>16</td>
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<td>740</td>
<td>1.4</td>
<td>39.4</td>
<td>42.5</td>
<td>-252.0</td>
<td>150</td>
<td>180</td>
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<td>905</td>
<td>0.7</td>
<td>47.4</td>
<td>33.4</td>
<td>-313.1</td>
<td>193</td>
<td>104</td>
<td>10</td>
<td>6.1710</td>
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<tr>
<td>18</td>
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<tr>
<td>20</td>
<td>&lt; Brf &gt;</td>
<td>157</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>B max @ r = r1</td>
<td>250</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>22</td>
<td>Vgap total (kV)</td>
<td>10.9</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>23</td>
<td>Frequency (MHz)</td>
<td>4.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
N = \frac{H}{2R} \pm \frac{\sqrt{L_n}}{\sqrt{V_n}} \left(1 + \frac{1}{Q^2}\right)
\]

New Cavity Design

1. 8 gaps
2. 10 kV/gap
3. Ferrite: 500 x 200 x 28
4. Cooling plates, electrically floated
5. \(N_f = 6\)
The AGS barrier cavity consists of 8 cells of a re-entrant ferrite loaded cavity. Total gap voltage is required to be 80kV at 4MHz. And, the cavity is going to be driven by one TH 558 power tetrod (500kW).

1. Ferrite disc: 6x200 x 250 x 128 (mm), 6 per cell
2. Cooling Plate: 1/4" thick, 7 plates per cell
3. Accelerating Ceramic Gap: max. 10kV gap voltage at 4MHz
4. Beam Pipe: bore should be as same as a present pipe
5. Outer Conductor of the Cavity
6. RF Power Feed Line
7. Bus Bar Cell Connection

March 26, 1997
M. YOSHI
Kenny's cavity (1/8 model)

Results of High Power Test

6 x 4L2 Ferrites

Vgap
(10kV/div)

Vgrid
(100V/div)

Irf
(40A/div)

\[ V_g = -375 \text{ V, } f = 3.8 \text{ MHz} \]
**4B3 x 2 discs**

- \( f = 3.7 \, \text{MHz} \)
- \( Q = 2 \)
- \( V_{\text{peak}} = 2.8 \, \text{kV} \)
- \( I_{\text{ave}} = 44 \, \text{A} \)
- \( \omega L = 59 \)

**SUMMARY**

In order to minimize the driving current: <400A

- # N dependence of gap capacitance and the effect of cooling plates have been studied
  \[ C_{\text{eq}} = \text{const.} \times \frac{C}{N} \]
  - >> cooling plates must be electrically isolated

Experimental results explained G.Rakovsky's representations about \( \mu \) and flux distribution in a ferrite

(as far as major magnetizing process)

**Sample measurements**

- # there were only two interesting ferrite found.

**New design**

- # 8 gap, 80 kV per station, six rings per gap
- # basic design has been done

**1/8 model cavity**

- # 10 kV gap voltage with 6 x 4L2 was achieved
  - (2.2 kV II per ring with one 4L2)
- # new grid drive circuit has been test well

As a minor problem,

- # no satisfied ferrite material yet
- # fast grid circuit needs some improvements
- # to need dumping the ringing on the plate current
R&D Works for RF System of JHF

Chihiro Ohmori
KEK-Tanashi

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Booster</th>
<th>Main Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF VOLTAGE</td>
<td>~450 kV</td>
<td>270 kV</td>
</tr>
<tr>
<td>RF FREQUENCY</td>
<td>1.99-3.43 MHz</td>
<td>3.43-3.51 MHz</td>
</tr>
<tr>
<td>REPETITION RATE</td>
<td>25Hz(50Hz)</td>
<td>0.3 Hz</td>
</tr>
<tr>
<td>CIRCULATING CURRENT</td>
<td>4 - 7 A</td>
<td>6.4 - 6.6 A</td>
</tr>
<tr>
<td>I_b</td>
<td>8 - 14 A</td>
<td>12.8 - 13.2 A</td>
</tr>
</tbody>
</table>
REQUIREMENTS FOR RF SYSTEMS

NEED HIGH VOLTAGE

SPACE IN BOOSTER IS LIMITED
(24*6m STRAIGHT SECTION).

50 Hz OPERATION NEEDS 800~900 kV

~40 kV/CAVITY/3~4M
>10 kV /m  (>13 kV/m)

10 Hz OPERATION FOR MAIN RING (in future)

>10 kV /m

September 18, 1996

REQUIREMENTS FOR RF SYSTEMS

STABILITY FOR BEAM LOADING

CIRCULATING CURRENT  4 - 7 A

IB  ~14 A

Y (=IB/I0)  < 1.4

I0  10 A

To handle Beam without direct feedback.

September 18, 1996
ASSUME .20 CORES PER METER
2.5 cm thickness

V > 500 V

R > 100 Ω

SUMMARY OF MAGNETIC CORE MEASUREMENTS

<table>
<thead>
<tr>
<th>CORE FOR BOOSTER</th>
<th>CORE FOR MAIN RING</th>
</tr>
</thead>
<tbody>
<tr>
<td>HITACHI NSC</td>
<td>NOT GOOD</td>
</tr>
<tr>
<td>PHILIPS 4M2</td>
<td>OK</td>
</tr>
<tr>
<td>TDK SY2</td>
<td>NOT GOOD</td>
</tr>
<tr>
<td>FINEMET FT3</td>
<td>PROBABLY OK</td>
</tr>
<tr>
<td></td>
<td>—— NEED BIG CORE</td>
</tr>
<tr>
<td></td>
<td>NOT GOOD (HIGH LOSS EFFECT)</td>
</tr>
<tr>
<td></td>
<td>NEED BIG CORE</td>
</tr>
<tr>
<td></td>
<td>OK</td>
</tr>
</tbody>
</table>

September 18, 1996
What is FINEMET?

Soft Magnetic Material with very fine crystallized structure.

High Permeability \(1931 \text{@} 3.3 \text{MHz}\)
Low Quality factor \(0.63 \text{@} 3.3 \text{MHz}\)
R \(76 \ \Omega \text{@} 3.3 \text{MHz}\)
R~100 \(\Omega\) for new core as O.D. is large (67cm).

Very High Curie Temperature \(~600\ \text{deg.C}\)

Very Stable for Temperature and RF Power

Very thin tape, Easy to make a big core

Not Saturated @ 10 A
FINEMET CAVITY

Suitable for Barrier Bucket RF

Easy to make an isolated pulse

Many possibility for RF gymnastics

To store more particles
To change RF frequency
To make empty bucket

Decrease Peak intensity

To flatten Bunch shape

September 18, 1996
Barrier Bucket

JHP synchrotrons: very high intensity machines.

To reduce beam loss is important issue.

Stable operation @ high intensity

Reduction of S.C. tune shift.

To change Beam distribution

To store more particles in rings

Barrier Bucket is very attractive !!!
FINEMET CAVITY

Dump wake field quickly

Good for instabilities,
Coupled bunch as $H=4$ for Booster
as $H=17$ for Main Ring

September 18, 1996
\[ Q = \frac{R}{\omega L} = \frac{\mu''}{\mu'' + \frac{\sigma}{\mu}} \]

FT3: \( f \) vs \( \mu', \mu'', Q \)

Diagram showing a graph with frequency on the x-axis and \( \mu', \mu'', Q \) on the y-axis.
The aim of the 30 kW test cavity is to prove the following:

- The required accelerating voltage of 10 kV/m can be obtained.
- The isolated pulse for the barrier bucket can be generated.
- The frequency of the parasitic resonance is very high and/or the quality factor is low enough to avoid the dangerous growths of the instabilities.
- The beam loading and transient beam loading effects are controllable.
The typical RF voltage signal in the class AB operation.

The RF voltage signal for the frequency sweep of the range of 2 to 3.4 MHz. The repetition is 1 Hz.
The typical voltage signal in the class AB operation for the barrier bucket.

Beam Loading

RF system does not include the tuning loop. \(\rightarrow\) Simpler

for Fundamental Frequency

Y=1.4 was chosen for stable operation.

If no tuning system, compensation technique is required.

Ex.: feed-forward
Beam Loading

Electron Gun will be ready in summer. About 200 keV, 7 A, 1µs

![Diagram showing the setup of the beamloading system]

Aims:
- Beam Loading Effects
- Fundamental, Higher Order (Distortion of RF Bucket)
- Transient Beam Loading
- Compensation Techniques.

For 2nd(3rd) harmonics:
- Component in the beam current is about 30% (for half-sine) of the fundamental component.
- Impedance is also about 30% of that at the RF frequency.
- Effects are about 10% of those by RF frequency components.

It may be possible to compensate by feedback and/or feed-forward techniques.
Transient Beam Loading

As Q-value is low, effects excited by other bunches have been damped, automatically.
Because of fast response, compensation is applicable.

CONCLUSIONS
The test cavity using a new material has been developed.

The voltage more than the designed value has been obtained. In order to achieve the higher voltage, a new material is being developed.

The impedance measurement shows that the cavity has no dangerous parasitic resonance.

An isolated pulse for the barrier bucket was generated and the maximum voltage of 11.3 kV was obtained.

However, the distortion of RF voltage was not small because of the class B operation of the single tube. It is expected that the distortion will be improved by the planned modification of the amplifier to a push-pull amplifier.
Session on Longitudinal Emittance Control

R. Garoby

On the issue of emittance control, representatives of Brookhaven and CERN have presented their aims and worries for achieving the level of performance ultimately needed by their respective future high energy machines. One step further in the future, the issue of longitudinal space-charge effects and possible cure in the 3 GeV proton driver for the proposed muon collider was described.

1. For RHIC at Brookhaven the gymnastics taking place in the AGS are the dominant source of longitudinal emittance blow-up (J.M. Brennan). Recent results have been shown, where the final bunch emittance approaches 0.7 eVs/u, for an initial design goal of 0.2 eVs/u. Two directions are pursued for solving the problem: a) improvement of the gymnastics in the AGS. Many of the reported imperfections are attributed to the lay-out and adjustment of the low level RF hardware, and solutions are being designed (J.M. Brennan). b) increase to 0.5 eVs/u of the nominal emittance accepted by RHIC. A larger emittance is beneficial at injection energy because it reduces intra-beam scattering. The first bottleneck used to be at transition because RHIC ramping rate is limited by the superconducting magnets, and transition is crossed slowly. But thanks to the newly agreed transition jump scheme, bunches of 0.5 eVs/u can now be accelerated with less than 10 for the second bottleneck due to the rebucketing (bunch transfer from a 28 MHz into a 196 MHz bucket), but improvement is possible doing it slightly above transition energy, where acceptance is largest (J. Kewisch).

2. For LHC at CERN most longitudinal beam characteristics are established in the PS. Specifications result from SPS characteristics (RF frequency and single bunch beam stability at injection) and LHC requirements (25 ns bunch spacing and number of protons per bunch), and the overall emittance budget is tight (E. Jensen). The undergoing LHC injectors project is implementing the most economical means to approach the nominal performance. Results will be obtained already in 1998. The hope is that the combination of these improvements with the planned SPS upgrade programme will help achieve the full beam performance needed at injection in LHC. Controlled longitudinal blow-up is a necessary ingredient and future plans include the use of a new method to generate flat-topped bunches corresponding to hollow distribution (S. Hancock). A promising technique for tomography in the longitudinal phase plane is under investigation for monitoring beam characteristics, even in the presence of non-linearities and/or time-varying potential.
3. Space-charge in the proton driver rings of the muon collider dangerously reduces the longitudinal focusing given by RF (K.Y. Ng). Compensation by an inductive impedance is a tempting challenge, which is under investigation. The design presented is based on a 2.4 m ferrite cylinder surrounding the beam with perpendicular bias by a solenoidal field to follow the variation of potential well distortion between 1 and 3 GeV. Tests are planned in the PSR ring at Los Alamos which suffers from similar effects.

Third ICFA Mini-Workshop on High Intensity, High Brightness Hadron Accelerators Brookhaven National Laboratory May 7-9, 1997
Controlled Longitudinal Blow-ups

As the name suggests, the purpose of a blow-up is to increase the longitudinal emittance of the beam in a reproducible fashion. This reduces the peak beam current and hence the so-called Laslett tune shift, which is important at low energy. It also increases beam stability by increasing the spread of synchrotron frequencies of particles in a bunch.

In the special case of a stationary bucket, the synchrotron frequency, $f_s$, may be expressed in terms of the complete elliptic integral of the first kind.

$$f_s = \frac{1}{2\pi} \frac{1}{B_1} \int_0^\pi \sin^2 \phi d\phi = \frac{1}{2\pi} \int_0^\pi \frac{1}{1 + \frac{1}{2} \sin^2 \phi} d\phi$$

$$B_1 = \frac{1}{2\pi} \int_0^\pi \frac{1}{1 + \frac{1}{2} \sin^2 \phi} d\phi$$

Plot[
  {x, 0, 1}, {y, 0, 1},
  AxesLabel -> Map[FontForm[#, 10] &] &
  
  (* Evaluate *)
  
  perturbedTune[r_] := tune[r] + (1 - r^2)

  For VRFratio < 0.3 and integer bratio. The SFT/PRO cycle, for example, typically has VRF/ratio = 6V/455V, bratio = 47/10, Anod = PI for BU1 and VRF/ratio = 10V/455V, bratio = 43/10, Anod = PI for BU2.

  However, whatever the frequency ratio of the two RF systems, the underlying principle of blow-ups is the same: phase space dilation occurs when particles at a certain amplitude have a synchrotron frequency which is resonant with the frequency of the phase modulation. This results in non-zero delta for these particles.

  Experiments, with both integer and non-integer bratio, support the theory. See CERNPES 91-40 (RF).
H.SENS,EXT, 30 dB, GAIN-BE; 2 Dec 1992 02:49
MD 249 + 1 RF/h + 1115 ns
$4\Sigma\text{Sigma} = 56.7 \text{nS OF} = 0.78$
$\text{NB} = 26.6 \text{ E10}$

$\text{Fitting NH}$
$4\Sigma\text{Sigma} = 48 \text{nS}$
$\text{To} = 46.5 \text{nS}$
$\text{NB} = 33.1 \text{ E10}$
$\text{Sigma0} = 11 \text{nS}$

$10 \text{nS/div}$

$4\Sigma\text{Sigma} = 74.4 \text{nS}$
$\text{To} = 47.7 \text{nS}$
$\text{NB} = 33.9 \text{ E10}$
$\text{Sigma0} = 17.1 \text{nS}$

$10 \text{nS/div}$

$Q_f = \frac{\text{Mean (over } \pm 3\sigma_{\text{rms}}) \text{ line charge density}}{\text{Peak line charge density}}$

$p(t) = \text{Rectangular} \rightarrow Q_f = 100\%$
$p(t) = \text{Parabolic} \rightarrow Q_f = 80\%$
$p(t) = \text{Gaussian} \rightarrow Q_f = 66\%$

**COMPLEX PICTURE CAN BE RECONSTRUCTED** with a photographic analogue of the summation method derived by S.E. Vineale of the Institute of Crystallography in Moscow. The projection of the picture is made by moving a sheet of film across it so the film is exposed to light. The result is a "stress picture", a set of parallel lines whose density depends on the total density of the original picture along each line. A series of such projections can be made at various angles. The reconstruction is obtained by superposing the stress pictures photographically. Reconstruction is right was made with 16 projections spaced at intervals of 10 degrees.
Advantages of the New Algorithm

- Large-amplitude motion is correctly treated.
- The constraint on trigger rate (re-arm deadline) is relaxed.
- Computational investment in the maps benefits repeated use with different data - as in optimization.
- Replacement of the Runge-Kutta integration by full-blown tracking would permit the reconstruction of:
  - arbitrarily complex (even no) RP;
  - non-adiabatic processes;
  - self fields
  - particles outside the bucket (but NB normalization).

Question Marks

- How fast can it be made to run?
- Minimum number of profiles required.
- "Free" parameters: n, gain.
- Influence of the phase loop.
### LHC beam $\varepsilon_{long}$ “budget”

<table>
<thead>
<tr>
<th>Machine &amp; process</th>
<th>$\varepsilon_{max}$</th>
<th>$p$</th>
<th>$\varepsilon_{beamlet}^{(bunch)}$</th>
<th>$\varepsilon_{beamlet}^{(LHC bunch)}$</th>
<th>bunch length</th>
<th>$\Delta p / p_{max}$</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC in capture</td>
<td>0.05</td>
<td>0.31</td>
<td>(0.55)</td>
<td>0.06</td>
<td>1600</td>
<td>4.8</td>
<td>0.8</td>
</tr>
<tr>
<td>acc + contr. bu?</td>
<td>1.40</td>
<td>2.14</td>
<td>1.45</td>
<td>0.14</td>
<td>1900</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>CPS injection</td>
<td>1.40</td>
<td>2.14</td>
<td>1.45</td>
<td>0.14</td>
<td>1900</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>acc.</td>
<td>2.74</td>
<td>3.56</td>
<td>1.00</td>
<td>0.14</td>
<td>46</td>
<td>4</td>
<td>7.38</td>
</tr>
<tr>
<td>b split + contr. bu (200 MHz)</td>
<td>2.74</td>
<td>3.56</td>
<td>1.00</td>
<td>0.19</td>
<td>24</td>
<td>1</td>
<td>7.6</td>
</tr>
<tr>
<td>acc.</td>
<td>25.5</td>
<td>26.4</td>
<td>1.00</td>
<td>0.19</td>
<td>12</td>
<td>0.7</td>
<td>40</td>
</tr>
<tr>
<td>adiabatic debunching</td>
<td>25.5</td>
<td>26.4</td>
<td>(0.25)</td>
<td>0.25</td>
<td>40</td>
<td>4</td>
<td>2.2</td>
</tr>
<tr>
<td>adiabatic rebunching</td>
<td>25.5</td>
<td>26.4</td>
<td>0.36</td>
<td>84</td>
<td>40</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>bunch rotation</td>
<td>25.5</td>
<td>26.4</td>
<td>0.36</td>
<td>84</td>
<td>40</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>SPS injection</td>
<td>25.5</td>
<td>26.4</td>
<td>0.36</td>
<td>84</td>
<td>40</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>acc. + contr. bu (600 MHz)</td>
<td>450</td>
<td>451</td>
<td>1</td>
<td>35460</td>
<td>1</td>
<td>0.9</td>
<td>400</td>
</tr>
<tr>
<td>bunch compression</td>
<td>450</td>
<td>451</td>
<td>1</td>
<td>92960</td>
<td>1</td>
<td>0.9</td>
<td>400</td>
</tr>
<tr>
<td>LHC injection</td>
<td>450</td>
<td>451</td>
<td>1</td>
<td>35460</td>
<td>1</td>
<td>0.9</td>
<td>400</td>
</tr>
</tbody>
</table>

1. Phase space area attributed to one LHC bunch, or total CPS longitudinal emittance/84 or (PSB bunch emittance)/10.5.

2. Bunch half height. For upright elliptical bunch, $\varepsilon_{beamlet} = (\chi^2 - 1) \Delta W / (\chi \sigma)^2$.

---

### bunch parameter limitations

$10^{11}$ protons/bunch

- Max. emittance @ LHC injection
- 400 MHz BL
- SPS TMC
- 200 MHz BL
- Transfer line momentum acceptance
- SPS m-wave instability
- PS n-wave instability

---

May 7-9, 1997  4th MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLIDERS

132
the most stringent bunch parameter limitations

- **SPS microwave instability**
  "Keil-Schnell-Boussard", \( Z/n = 10 \Omega \) assumed.
  \( \eta \): 23 \( \Omega \) 19 (decreases also capture voltage)?

- **TMC (transverse mode coupling)**
  \( Z_c = 23 \text{ M} \Omega /\text{m} \), \( Q=1 \) @ 1.3 GHz assumed.

- **200 MHz periodic transient beam loading (BL)**
  \( Z_{\text{cav}} = 360 \text{ k} \Omega \) assumed.

- **400 MHz BL**
  300 kW installed power assumed.

- **Transfer line momentum acceptance**
  \( 6 \times 10^{-3} \) total assumed.

---

Quasi-adiabatic compression

on \( h=84 \) to 600 kV (!)

40 MHz cavity

First 40 MHz bunches

40 MHz bunches in the PS
Vrf = 300 kV 11/12/96

May 7-9, 1997
Bunch rotation test

May 29, 1997
3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS

Synchroplisation jitter

May 29, 1997
3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS
SEB mode

\[ \begin{align*}
    & h = 8 & 5.0 \text{ MHz} & 4.5 \text{ MHz} \\
    & 0.55 \text{ MHz} & 1.87 \text{ MHz} & h = 12
\end{align*} \]

RHIC mode

\[ \begin{align*}
    & h = 8 & h = 16 & h = 8 & h = 4 \\
    & 5.0 & E \times K & 4.0 & 2.96 \\
    & 2.6 & 4 \text{ Booster Cycles} & 1.5 & 2.0 \\
    & 1.48 & F-Bank & P-Bank & \text{Flatop}
\end{align*} \]

\[ \begin{align*}
    & t \\
    & \dot{B} = 0.3 \text{ T/S} & 2.5 \text{ T/S} & 0.0 \\
    & \text{Booster} & \text{AGS}
\end{align*} \]

MountainRange.jmb
Last modified on 1/20/97 at 6:34 AM

2048 turns per trace \[ T_{eq} = 2.7 \mu s \]
Mismatch at AGS Injection

- Momentum Error
- Bucket shape mismatch, need more Vrf for ΔE
- New batch perturbs old batch via phase loop
  - Batch-by-batch phase loop, bunch shape damper

\[ \delta \left( \frac{B}{Vrf} \right) \text{ is large and fast!} \]
Space-Charge Effects and Ferrite Compensation

K.Y. Ng and Z. Qian

(May 7, 1997)

I INTRODUCTION
II TRANSVERSE TUNE SPREADS
III MICROWAVE INSTABILITIES
IV POTENTIAL-WELL DISTORTION
V FERRITE COMPENSATION
VI FERRITE-LOADED WAVEGUIDE
VII HIGH TRANSVERSE DC BIAS
VIII CONCLUSIONS
I INTRODUCTION

- C. Ankenbrandt suggested 2 rings for the proton driver.
- We concentrate on the first ring where space-charge is more important.

<table>
<thead>
<tr>
<th>Kinetic Energy</th>
<th>1 GeV injection, $\gamma = 2.06579, \beta = 0.87503$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 GeV extraction</td>
<td></td>
</tr>
<tr>
<td>Cycle rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Circumference, $C$</td>
<td>237.10 m</td>
</tr>
<tr>
<td>Rf harmonic, $h$</td>
<td>2 or 4 for 2 or 4 bunches</td>
</tr>
<tr>
<td>Transition, $\gamma_t$</td>
<td>7</td>
</tr>
<tr>
<td>Bunching factor, $B$</td>
<td>0.25</td>
</tr>
<tr>
<td>No. per bunch, $N_B$</td>
<td>$2.53 \times 10^{13}$</td>
</tr>
<tr>
<td>95% bunch area, $A$</td>
<td>1 eV-s</td>
</tr>
<tr>
<td>95% emittance, $\epsilon_{N95}$</td>
<td>$200 \times 10^{-6} \pi$ m</td>
</tr>
</tbody>
</table>
II TRANSVERSE TUNE SPREADS

- Laslett tune shift at injection

\[ \Delta \nu = -\frac{3N_{\text{total}} \tau_p}{2 \gamma^2 \beta \epsilon_{N95} B} = \begin{cases} -0.199 & \text{2 bunches, good} \\ -0.397 & \text{4 bunches, manageable} \end{cases} \]

This is an incoherent effect and cannot be compensated by ferrite.

III MICROWAVE INSTABILITIES

- For parabolic bunch, \( B = 0.25 \Rightarrow \)

\[ \begin{align*} \hat{\tau} & = 84.73 \text{ ns or } \hat{\ell} = 22.23 \text{ m for } h = 2 \\ \hat{\tau} & = 42.37 \text{ ns or } \hat{\ell} = 11.12 \text{ m for } h = 4 \end{align*} \]

\( \downarrow \)

\( \hat{\delta} \)

\[ \approx 5.49 \times 10^{-2} \]

\( \approx 1.098 \times 10^{-1} \)

- Using Krinsky-Wang criterion and a bunch area of 1 eV-s,

\[ \left| \frac{Z_{||}}{n} \right| < \frac{2 \pi E |\eta|}{e \beta^2 I_p} \left( \frac{\sigma_E}{E} \right)^2 = \begin{cases} 71.27 \text{ } \Omega \text{ for } h = 2 \\ 142.5 \text{ } \Omega \text{ for } h = 4 \end{cases} \]

Note: If the Boussard-modified Keil-Schnell criterion is used, these limits will be 1.67 times larger.
• Space-charge impedance:

With $\epsilon_{N95} = 2 \times 10^{-4} \pi \text{ m}$, bunch area 1 eV-s, and assuming a momentum dispersion of $\sim 2 \text{ m}$, $< \beta > = 7.28 \text{ m}$

beam radius is $a = 3.35 \text{ cm}$ and $3.85 \text{ cm}$ for $h = 2$ and 4.

Using a 5 cm radius beam pipe,

$$\frac{Z_{\parallel}}{n}_{spch} = i \frac{Z_0}{2\gamma^2 \beta} \left( 1 + 2 \ln \frac{b}{a} \right) = \begin{cases} i91.1 \Omega & \text{for } h = 2 \\ i76.8 \Omega & \text{for } h = 4 \end{cases}$$

Note: Same size as the stability limit. However, we are below transition, hopefully, microwave instability will not develop.

• Assume pipe radius of 5 cm. Cutoff freq is 2.30 GHz, or harmonic $n_{cutoff} = 2074$. Tunes: $\nu_x = \nu_y = 5.18$.

$$|Z_{\perp}| < \frac{4\nu \beta}{eRI_{peak}} (\Delta E)_{FWHM} |(n - \nu)\eta + \nu \xi| = 31.56 \text{ M}\Omega/\text{m}$$

• With $b = 5 \text{ cm}$, $a = 3.35, 3.85 \text{ cm}$ for $h = 2, 4$,

$$Z_{\perp}_{spch} = i \frac{RZ_0}{\beta^2 \gamma^2} \left( \frac{1}{a^2} - \frac{1}{b^2} \right) = \begin{cases} i2.21 \text{ M}\Omega/\text{m} & h = 2 \\ i1.23 \text{ M}\Omega/\text{m} & h = 4 \end{cases}$$

Therefore transverse microwave instability will not happen.
IV POTENTIAL-WELL DISTORTION

- A particle at distance $s$ from bunch center sees a longitudinal space-charge $E_{zsp \ ch}$ field and a potential drop per turn:

\[
E_{zsp \ ch} = -\frac{e g_0}{4\pi \varepsilon_0 \gamma^2} \frac{d\lambda}{ds}, \quad g_0 = 1 + 2 \ln \frac{b}{a}
\]

\[
V_{sp \ ch} = E_{zsp \ ch} C = -\left(\frac{3\pi I_{av} Z_0 g_0}{4\gamma^2 \beta}\right) \left(\frac{R}{\ell}\right) \frac{s}{\ell} = \begin{cases} 
11.1 \frac{s}{\ell} \text{kV} & \text{for } h = 2 \\
37.4 \frac{s}{\ell} \text{kV} & \text{for } h = 4
\end{cases}
\]

- On the other hand, neglecting space charge, the synchrotron tune and required rf are

\[
\nu_s = \frac{|\eta| \hat{\sigma}}{\omega_0 \hat{r}} = \begin{cases} 
0.000919 & V_{rf} \cos \phi_0 = \frac{2\pi \beta^2 E}{|\eta| h} \nu_s^2 = \begin{cases} 
18.41 \text{kV} & \text{for } h = 2 \\
147.3 \text{kV} & \text{for } h = 4
\end{cases}
\end{cases}
\]

- For $\phi_0 = 0$, rf voltage seen by end particle of bunch is

\[
V = V_{rf} \sin \frac{\hbar_0 \ell}{\beta c} = V_{rf} \sin \frac{3\pi B}{2} = 0.924 V_{rf}
\]

- The potential-well distortion is large compared with rf voltage required if there is no space-charge, especially for $h = 2$.

- We wish to compensate this distortion by ferrite. The frequency is roughly is at $\sim 2.2$ MHz and $\sim 4.4$ MHz for $h = 2$ and 4.

\[
to \frac{2}{2} \times 2.2 = 2.2 \text{MHz} \quad to \ \frac{146}{4} \times 4.4 \text{MHz} = 14.4 \text{MHz}
\]
V FERRITE COMPENSATION

The voltage drop per turn due to space charge can be written as

\[ V_{\text{sp ch}} = \left( \frac{3\pi I_{av}}{2} \right) \frac{Z_{||}}{n_{\text{sp ch}}} \left( \frac{R}{\ell} \right)^2 \frac{s}{\ell} \]

Thus, it can be canceled by adding an inductance.

Consider using a hollow cylinder of ferrite of inner and outer radii \( b \) and \( d \) and length \( \ell \). Impedance introduced is

\[ \frac{Z_{||}}{n_{\text{ferrite}}} = -\frac{iZ_0\omega_0}{2\pi c} \mu' \ell \ln \frac{d}{b} \]

For example, with \( \mu' = 1000, d = 5.5 \) cm, \( b = 5 \) cm, to cancel a space-charge \( Z/n \) of \( \sim 100 \) \( \Omega \), a length of \( \ell = 63 \) cm will be enough.
\section*{V.1 Loss}

- One way to include loss is to write

\[ \mu = \mu' + i \mu'' \quad \text{and} \quad Q = \frac{\mu'}{\mu''} \]

\[ Z_\parallel = \left\{ \frac{1}{Q} - i \right\} |Z_\parallel|_{\text{spch}} \]

- We want material with large $\mu'$. However, $\mu''$ will be large as well.

- Since the real part is proportional to frequency, we need to sum many harmonics to compute the total loss. For each bunch,

Current: \quad I(t) = I_{av} + \sum_{n=1}^{\infty} I_n \cos n\omega_0 t

Power: \quad P = \frac{1}{2} \sum_{n=1}^{\infty} n^2 I_n^2 |Z_\parallel/n|_{\text{spch}} / Q
\[ \tau \omega_0 = 0.589 \]

\[ n \frac{I_n^2}{I_{av}^2} \quad I_n/I_{av} \]

Revolution Harmonics \( n \)
• If we assume Gaussian distribution, the summation can be approximated by integration to give, \( \hat{r} = \sqrt{5}\sigma_r \),

\[
P = \frac{I_{av}^2 |Z_{||}/n|_{spch}}{Q(\sigma_r\omega_0)^2}.
\]

For \( h = 2 \), \( |Z_{||}/n|_{spch} = 100 \, \Omega \), and \( Q = 1 \), the power loss is \( P = 25.6 \, \text{kw} \), parabolic, (29.2 kw by above formula).

Need to sum up to at least \( n \sim 4/(\sigma_r\omega_0) = 7 \) for \( h = 2 \).

For \( h = 4 \), need to sum to at least \( n = 14 \), and loss per bunch is 102.2 kw, 4 times larger.

\[\text{Average}\]

• Loss per particle per turn is 6.5 kV.

Worst of all, because of the short wake (small \( Q \)), center of bunch loses much more than the ends.

Such position-dependent loss is hard to compensate.

• There are other problems like (1) high frequency response of ferrite, (2) effect of electric permittivity \( \epsilon \), (3) transverse effects.

• If loss is small (see below), the problem can be solved analytically.
VI FERRITE-LOADED WAVEGUIDE

- Here, the assumptions are (a) a perfectly conducting medium outside ferrite and (b) the ferrite insertion is infinitely long.


- The transverse and longitudinal wakes of the $m$-th azimuthal is

$$ W_m(z) = \frac{Z_0 c \ell}{2\pi m d^{2m+1}} \sum_{\lambda=1}^{\infty} \tilde{F}_{rm\lambda}(x_{m\lambda}) \sin \frac{x_{m\lambda} z}{d \sqrt{\varepsilon \mu - 1}} $$

$$ W'_m(z) = \frac{Z_0 c \ell}{2\pi (1 + \delta_{0m}) d^{2m+2}} \sum_{\lambda=1}^{\infty} \tilde{F}_{zm\lambda}(x_{m\lambda}) \cos \frac{x_{m\lambda} z}{d \sqrt{\varepsilon \mu - 1}} $$

where $x_{m\lambda}$ is the $\lambda$-th zero of some combinations of modified Bessel functions of order $m$.

- The above are just summations of sharp resonances.

There are analytic expressions if the ferrite layer is thin.

$$ Z_n(\omega) \sim \int W_n'(z) e^{-i \omega \frac{z}{c}} d\left(\frac{z}{c}\right) $$

$$ Z_1(\omega) \sim \int W_1'(z) e^{-i \omega \frac{z}{c}} d\left(\frac{z}{c}\right) $$
Monopole \((m = 0)\)

- If \(\delta = \frac{t}{b} \ll 1\), \(x_{01} = \sqrt{\frac{2\epsilon}{\delta}}\), and \(\tilde{F}_{x01} = 4\).

Resonance frequency is

\[
\omega_{01} = \frac{x_{01}c}{d\sqrt{\epsilon\mu - 1}} = \frac{c}{d} \sqrt{\frac{2\epsilon}{\delta(\epsilon\mu - 1)}} \quad \rightarrow \quad \frac{c}{d} \sqrt{\frac{2}{\mu\delta}}
\]

when \(\epsilon\mu \gg 1\)

\[
\frac{Z_\parallel}{n} = -i\frac{\omega_0 Z_0}{2\pi c} \left(\mu - \frac{1}{\epsilon}\right) \ell \delta
\]

- Result is \(\epsilon\) independent when \(\epsilon\mu \gg 1\).

- For \(\mu = 1000\), \(\delta = 0.1\), \(d = 5.05\) cm, \(\ell = 63\) cm,

\[
f_{01} = 840\text{ MHz}, \quad \frac{Z_\parallel}{n} = -i100\ \Omega
\]

But if loss is included as perturbation, loss is \(\sim 76.8\) kV per turn near bunch center and almost zero at both ends.

- For the low-loss Yttrium-iron garnet, \(\mu = 3, \epsilon = 8, \ell = 63\) cm,

\[
f_{01} = 15.3\text{ GHz} \quad \frac{Z_\parallel}{n} = -i3\ \Omega
\]
VII HIGH TRANSVERSE DC BIAS

- From KE 1 GeV injection to KE 3 GeV, the space charge impedance will be reduced by a factor of 4.58. We would like the inductance of the ferrite to decrease by the same factor.

- This can be accomplished by passing a DC bias field through the ferrite. To reduce loss, we suggest the bias field \( \perp \) field due to the bunch particles. This can be done by putting a solenoid outside the ferrite.

- Use a dc biased field \( H_c \) in \( z \)-direction, so high that the magnetization \( \vec{M} \) inside the ferrite is saturated and becomes \( \hat{z}M_s \).

- The ac field \( \vec{H}_1 \) from beam particles is in the \( x-y \) plane. This ac field causes the magnetization to precess about \( H_c \), or creating an ac magnetization \( \vec{M}_1 \) in the \( x-y \) plane.

- Thus, we have

\[
\vec{H} = \hat{z}H_c + \vec{H}_1, \quad \vec{M} = \hat{z}M_s + \vec{M}_1
\]
When $|\vec{H}_1| \ll H_c$, the equation of motion is

$$\frac{d\vec{M}}{dt} = \gamma (\hat{z}M_s \times \vec{H}_1 + \hat{z}\vec{M} \times H_c)$$

where $\gamma = 2.80 \times 2\pi$ MHz/Oersted is the gyromagnetic ratio of the electron. Defining the magnetic susceptibility tensor $\hat{\chi}_r$ as $\vec{M}_1 = \hat{\chi}_r \vec{H}_1$, the solution is

$\hat{\chi}_r = \begin{pmatrix} \chi & -j\kappa & 0 \\ j\kappa & \chi & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$\mu_r = 1 + \frac{\hat{\chi}_r}{\mu_0}$

where

$$\frac{\chi}{\mu_0} = \frac{\omega_c \omega_m}{\omega_c^2 - \omega^2}, \quad \frac{\kappa}{\mu_0} = \frac{\omega_m}{\omega_c^2 - \omega^2} = \frac{\chi}{\mu_0} \frac{\omega}{\omega_c}$$

and

$$\omega_c = \gamma H_c, \quad \omega_m = \gamma \frac{M_s}{\mu_0}$$

There is a resonance at the gyromagnetic resonant frequency

$$\omega_c = \gamma H_c$$

which is proportional to the dc $H_c$. This explains why we want $H_c$ to be large so that the resonance effect can be avoided.
• Loss can be included by letting \( \omega_c \rightarrow \omega_c - i \omega \alpha \), giving

\[
\frac{\chi'}{\mu_0} = \frac{(\frac{\omega_m}{\omega})(\frac{\omega}{\omega}) \left[ (\frac{\omega}{\omega})^2 - 1 + \alpha^2 \right]}{\left[ (\frac{\omega}{\omega})^2 - 1 - \alpha^2 \right]^2 + 4 (\frac{\omega}{\omega})^2 \alpha^2}
\]

\[
\frac{\chi''}{\mu_0} = \frac{(\frac{\omega_m}{\omega}) \alpha \left[ (\frac{\omega}{\omega})^2 + 1 + \alpha^2 \right]}{\left[ (\frac{\omega}{\omega})^2 - 1 - \alpha^2 \right]^2 + 4 (\frac{\omega}{\omega})^2 \alpha^2}
\]

Note that, actually the above depend on only \( M_s \) and \( \alpha \).

• Usually the ac field comes from a cavity. Then, \( \omega \) will not be changed by very much and can be considered fixed except very near to the resonance. Therefore, \( \chi \) is plotted as a function of \( H_c \). This explains why the formulas have been written as a function of \( \omega_c / \omega \).

• In our application, the ac field comes from the beam particles. So \( \omega \) has the range of the bunch spectrum. For \( h = 2 \), \( \omega / (2\pi) \) varies up to \( \sim 2.2 \) MHz, and for \( h = 4 \), up to \( \sim 4.4 \) MHz, \( \sim 15 \) MHz,
or \( 7.7 \) MHz.

• The merit of this application is the low loss, because the ferrite is saturated, there will not be hysteresis loss. The only loss is due to spin wave which is small. The disadvantage is \( \mu' \) is usually small.
Application

- Choose Ferramic Q-1, which has saturated flux density of 3300 Gauss at 25 Oersted.

- Thus, \( M_s = 3300 - 25 = 3275 \) Gauss.

- Choose \( H_c = 25 \) Oe.

  This gives resonant frequency \( \omega_c/(2\pi) = \gamma H_c = 70 \text{ MHz} \).

  Up to 10 MHz, \( \mu' \sim M_s/H_c = 131 \).

- With ferrite thickness \( t = 1 \text{ cm} \), to cancel \( |Z_{\parallel}/\nu|_{\text{sp}} = 100 \Omega \), we need a length of \( \ell = 2.4 \text{ m} \) of ferrite is required.

- At extraction, want \( \mu' \) to be reduced to \( 131/4.58 = 28.6 \).

  The biased field should be raised to \( H_c = M_s/\mu' = 114.5 \) Oe.

- At low frequencies, the loss is \( \mu'' \rightarrow \frac{\alpha \omega \omega_m}{\omega^2_c} \).

- Take a typical value of \( \alpha = 0.05 \), we find \( \mu'' \) varies linearly from 0 and reaches 0.5 at 5 MHz when \( H_c = 25 \) Oe at injection, and is reduced by a factor of \( 4.58^2 = 21.0 \) when \( H_c = 114.5 \) Oe at extraction.
VIII CONCLUSIONS

1. The most serious space-charge effect Laslett tune shift for $h = 4$.

2. Longitudinal microwave instability seems to be safe.

3. Potential-well distortion needs ferrite compensation.

4. Ordinary compensation without DC bias field gives large $\mu'$ and also large $\mu''$ of the order of 1000. The loss is about 100 kV per turn and is position dependent along the bunch.

5. Large transverse DC bias beyond saturation eliminate hysteresis loss. Only loss is due to spin wave and is tiny.

6. However, large transverse DC bias gives small $\mu'$, but is still good enough. Total ferrite length of 2.4 m is required if thickness is 1 cm.

7. From injection energy of 1 GeV to extraction energy of 3 GeV, the DC bias field need to be increased quadratically with energy from 25 Oe to 114.5 Oe. Hopefully, this can be accomplished by using a solenoid.
RHIC Operation with Increased Longitudinal Bunch Area (I)

Jie Wei, Brookhaven National Laboratory

I. Introduction

II. Intrabeam Scattering at Injection

III. Transition Crossing

IV. Storage and Luminosity

V. Conclusions

Results of 1997 Sextant Test:

- Intensity: typical $2 \times 10^8$, up to $4 \times 10^8$ /bunch
- Bunch area: typical $S = 0.5 \pm 0.1$ eV s/u

Au$^{79+}$ beam during 1997 sextant test
Figure 1: Au²⁺ beam exhibiting dipole motion in an AGS RF bucket

Figure 2: Two distinct glows of damage of Au²⁺ due to imperfect tuning rotating in an AGS RF bucket (110 degrees)
**Longitudinal phase-space reconstruction:**

Figure 5: Longitudinal phase space of a Au$^{11+}$ beam in AGS reconstructed with RADON on (a) Dec. 15, 1996 and (b) Jan. 12, 1997, showing improvement of merging at bunch coalescing.

**Possible problems with increased bunch area:**

* • emittance growth and particle loss at transition;
  (Johnson) chromatic nonlinear effect
• re-bucketing (28 MHz → 196 MHz);
  to be discussed by Jörg
• consequences in intrabeam scattering (injection & storage).

  IBS @ injection
  Luminosity performance & IBS @ storage

V. Mane, et al.
II. Intrabeam Scattering at Injection

Quasi-equilibrium condition: "equal temperature"
(below transition)

\[
\frac{\sigma_x}{\beta_x} \approx \frac{\sigma_y}{\beta_y} \approx \frac{\sigma_p}{\gamma}, \quad \gamma \ll \gamma_T.
\]  

(1)

\[
\sqrt{\text{For} \quad \frac{\sigma_{xy}}{\beta_{xy}} \gg \frac{\sigma_p}{\gamma}} \quad \text{(low longitudinal temperature)}
\]

\[
\left[ \frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \right] \sim 42.4 L_c \sigma_p^2 E_0 \frac{Z^4 N}{A^2 \gamma_{ee} S} \left[ \frac{\gamma \sigma_x}{\beta \sigma_p} \frac{\beta \sigma_p}{2 \gamma \sigma_x} \right]
\]

(2)

\[
\text{For} \quad \frac{\sigma_{xy}}{\beta_{xy}} \ll \frac{\sigma_p}{\gamma} \quad \text{(high longitudinal temperature)}
\]

\[
\left[ \frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \right] \sim 27 L_c \ln x r_b^2 E_0 \frac{Z^4 N}{A^2 \gamma_{ee} S} \left[ \frac{-\gamma^2 \sigma_x^2}{\beta^2 \sigma_p^2} \frac{1}{2} \right]
\]

(3)

* strong dependence on energy
* proportional to 6-d phase space density
* \( \sim \frac{E}{A^4} \), problem for \( \text{Au}^{79+} \)

IBS growth at RHIC injection:

- mainly occurs in longitudinal direction;
  lower longitudinal temperature
- with \( S = 0.2 \text{ eV·s/u} \), the growth time is about \( \text{3 minutes} \);
- the growth rate can be reduced by increasing \( \sigma_p \) (rf voltage);
- with \( S = 0.5 \text{ eV·s/u} \), the growth time is about \( \text{20 minutes} \).
III. Transition Crossing

Figure 2: Effects of chromatic nonlinearities and self fields at transition.

Recent progress in transition design:

- a "first-order, matched" γγ-jump lattice,
  \[ \alpha_1 = -0.6 \text{ remains almost constant during the jump;} \]
  \[ \alpha_1 = +0.6 \text{ } \rightarrow \text{ } \alpha_1 = -0.6 \text{ } (\text{new}) \]

- two quadrupole corrector families, one for γγ-jump, the other for optical optimization;

- chromatic nonlinear effects greatly reduced.

\[ \frac{\Delta \phi}{\phi} \sim (\nu + 1.5) \cdot \sigma_p \]

\[ V_{rf} = 300 \text{ kV} \]
- low enough to have a smaller \( \sigma_p \)
- high enough to compensate beam induced fields, especially in storage cavities.
Figure 1: Transition is crossed almost 10 times faster with the nominal RHIC bipolar transition jump than without. Not to scale.

\[ \Delta T = 4T_{\text{base}} = 516 \text{ msec} \]
\[ \frac{dy}{dt} = 1.6 \text{ (sec)} \]

\[ \gamma_T \text{ jump and } \alpha_1 \text{ variation:} \]

\[ I(\gamma_T) = -2 \gamma_1 \]
\[ \Delta \gamma_T \approx 0.4 \]

\[ \alpha_1 = \gamma_1 \]

RHIC 92, rev. 06 Lattice; MAD Result

1997.4.10, \( K_0 = 0.008 \text{ m}^2, K_\phi = 0.007 \text{ m}^2 \)

\[ I(\gamma_T) = +2 \gamma_1 \]
\[ \Delta \gamma_T \approx -0.4 \]

\[ \alpha_1 = -0.5 \]
emittance growth after transition:

RHIC Transition Crossing, TIBETAN

$\alpha_1 = -0.6$

(new)

negligible growth

RHIC Transition Crossing, TIBETAN

$\alpha_1 = +0.6$

(old)

considerable growth
IV. Storage and Luminosity

**Intrabeam Scattering growth at storage:**

- growth occur in both transverse and longitudinal directions with similar rates;
- there exists no equilibrium state (negative-mass regime) (above transition)

\[
\frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \sim 34.6 L_0 \frac{e^2 E_0}{A^2 \gamma \epsilon_x \epsilon_y S} \frac{Z^4 N}{S_0},
\]

\[
\frac{1}{\sigma_x} \frac{d\sigma_x}{dt}
\]

* always grows
* weak dependence on energy
* proportional to 6-D phase space density
* \( \sim \frac{Z^4}{A^2} \) problem for \( Au \)
V. Conclusions

With an increased longitudinal emittance:

- intrabeam scattering growth at injection will be reduced;
- Current γτ-jump scheme is adequate for efficient transition crossing;
- No significant change is expected in luminosity performance during collision.
- Re-bucketing process will be discussed by Jorg.
Rebucketing in RHIC

Motivation:
Short bunches (rms < 20 cm) are required for optimum detector design. (20 cm rms = 50 cm 95%)

Question:
If the requirement for the longitudinal bucket area is relaxed from 0.2 eV sec/µ to 0.45 eV sec/µ, how does that effect the particle loss during rebucketing.
Conclusion

Particles are captured up to (sigma):

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>at storage 0.2 eV sec/u</td>
<td>8.3</td>
</tr>
<tr>
<td>at storage 0.45 eV sec/u</td>
<td>3.75</td>
</tr>
<tr>
<td>after transition 0.45 eV sec/u</td>
<td>5.4</td>
</tr>
<tr>
<td>after transition 0.45 eV sec/u, V=800kV</td>
<td>5.9</td>
</tr>
</tbody>
</table>

To do:

- Extend tracking program to simulate rebucketing while ramping

- ???
Session on Longitudinal Instabilities

K.Y. Ng

There were 3 talks in this session. The first talk was by Y.H. Chin and H. Tsutsui on “Microwave Instability in a Barrier Cavity”. A bunch inside a barrier bucket behaves like a coasting beam because the bunch particles drift most of the time. However, it is also a bunch because of its finite length, and therefore we can talk about bunch modes. Chin and Tsutsui demonstrated the equivalence between mode-crossing instability and the Boussard-Keil-Schnell microwave instability. Although this equivalence had been demonstrated for a resonant impedance by many authors, they were the first to demonstrate mode-crossing instability for a pure inductive impedance below transition, which is predicted by the Boussard-Keil-Schnell theory. They expanded the bunch modes in terms of orthogonal functions and compute the eigen-modes as a function of bunch current. They also wrote a code to track the bunch particles in the longitudinal phase space, and verified that the onsets of instability agree with theory. The code is a tracking in the time domain and approximates a bunch as a series of triangular bunches.

The second talk by M. Blaskiewicz is on “Fast Particle-Particle Update Scheme” in tracking. When tracking \( N \) particles involving binary interaction, the number of steps per turn is usually \( \mathcal{O}(N^2) \), which rises sharply when more particles are required. First, the time-order of the particles are sorted, which takes \( \mathcal{O}(N \ln N) \) steps. Once the ordering is known, the positions of the particles can be updated using a recurrence relation, which takes \( \mathcal{O}(N) \). Thus, for each turn, the number of steps is reduced from \( \mathcal{O}(N^2) \) to \( \mathcal{O}(N \ln N) \), and the saving in time is very significant.

The third talk by J. Rose is on “Stability in RHIC” against longitudinal coupled-bunch instability. ZAP and analytic formula computations for bunches passing through the the 28 MHz cavity shows instabilities driven by only the first few higher-harmonic modes (HOM). This is because the form factor falls off as the inverse of both the HOM frequency and the square of the bunch length. Since the bunches in RHIC will be long, the form factor is less than 0.6. Note that this is rather conservative; for a Gaussian bunch distribution, the form factor will fall off very much faster. Some passive de-Qing had been performed on these offensive modes, so that the growth rates for the unstable modes will be within the range of the injection damper rate of 10 sec\(^{-1}\). From the MAFIA computation of the HOM dampers, it appears that there should not be any problem concerning longitudinal coupled-mode instability.
Longitudinal Bunched-Beam Instabilities in a Barrier RF System

KEK
Yong Ho Chin and Hiroshi Tsutsui

1997 Particle Accelerator Conference
Vancouver, Canada
May 13, 1997

Introduction

- Barrier RF System

![](image)

Relative position of particle in a beam

- Characteristics of a barrier RF system
  - A very flat bunch \(\rightarrow\) A smaller peak current
  - A variable bunch length
  - A small synchrotron frequency \((v_{\text{rms}}=17\text{Hz at JHF})\)
  - Synchrotron frequency proportional to the energy deviation \(\rightarrow\) A spread is comparable to the frequency itself
  - A strong Landau damping effect
Collective stability of a bunched-beam in a barrier bucket

- Keil-Schnell-Boussard criterion would give a reasonable estimate, IF
  - the wave length of beam density modulation is much shorter than the bunch length
  - the instability growth is much faster than the synchrotron motion.

How do we know without calculation?

If not, or no way to know if the coasting approximation is good or not, what should replace Keil-Schnell-Boussard criterion?

A need to develop a theory proper to a bunched-beam
Main framework of the newly developed theory

- No coasting beam approximation
- Vlasov equation for evolution of phase space distribution
- Synchrotron and energy mode expansion
- Action-angle variables to describe the squarish particle trajectory in phase space
- A Gaussian energy distribution
- A full inclusion of Landau damping effect

A simulation code ECLIPS (Evaluation Code for Longitudinal Instabilities in a Proton Synchrotron) was also developed.

- Their application to JHF 50 GeV proton synchrotron at injection show good agreements.
- We will demonstrate (as Sacherer predicted)

Coasting Beam Mode Number "n"
Vlasov analysis

Square model

\[ W = \frac{\Delta E}{\omega_0} \quad f(\omega, \phi, \theta) \]

Since the particle trajectory is a complicated function of \( w \) and \( \phi \), let us introduce the action-angle variables.

Action = area in \( \square \)

Angle = phase of motion

Synchrotron frequency proportional to \( I \) (or \( \Delta \phi_{\text{max}} \))

Vlasov eq. for the phase space distribution \( f(l, \psi, \theta) \)

\[ \frac{\partial f}{\partial \theta} + \psi \frac{\partial f}{\partial \psi} + r \frac{\partial f}{\partial l} = 0 \]
Perturbation method + separate factorization with respect to $l$ and $\psi$ + Fourier expansion

\[ f(x, \theta) = f_0(\theta) + \sum_{m=-\infty}^{\infty} f_m(x) \exp(i\psi) \exp(-i\Omega) \]

Line charge density $p(\phi)$

- $m = \text{odd}$
- $m = \text{even}$

Corresponds to $n = 1$ constituent beam mode when $\phi_{max} = \pi$

$\phi_{max}$

Particle

Beam

Ring
Using impedance $Z(\omega / \omega_0)$ and Fourier transform of $p(\phi), \tilde{p}(\nu)$

\[ l' = -e^2 N \frac{\phi_{\text{max}}}{\pi^2} \text{sgn}(\nu) \sum_{p=-\infty}^{\infty} Z(p + \Omega) \tilde{p}(p + \Omega) \times \exp(-i(p + \Omega)\phi - i\Omega \theta) \]

\[ \psi' = v_s(I) \]

- Vlasov eq. becomes an integral eq. for $f_m(l)$:

\[ \mathbf{a} - \mathbf{N} \mathbf{a} = \mathbf{M} \mathbf{a} \]

where $I_b$ = circulating current and

\[ \frac{\phi_{\text{max}}}{\pi^2} \sum_{p=-\infty}^{\infty} Z(p + \Omega) \tilde{p}(p + \Omega) \times \exp(-i(p + \Omega)\phi - i\Omega \theta) \]

- The integral eq. for unknown $f_m(l)$ can be solved by expanding $f_m(l)$ with a set of orthogonal polynomials.

- For a Gaussian energy distribution $f_0(l)$, the best choice is the Laguerre polynomials $L_k(x)$.

- Finally, we get a matrix eigenvalue eq. for $\Omega$:

\[ N_{mk} = -m \frac{\pi \eta}{\sqrt{2} \phi_{\text{max}} \beta^2} \frac{\Delta E}{E_0} \delta_{mn} L_m \]

\[ L_m = \int \sqrt{x^2 - L_k(x) L_m(x)} dx \]
Numerical examples

Main parameters of JHF 50 GeV proton synchrotron at injection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy, $E_i$</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Circumference, $C$</td>
<td>1442 m</td>
</tr>
<tr>
<td>Design circulating current, $I_0$</td>
<td>6.65 A</td>
</tr>
<tr>
<td>Slippage factor, $\eta$</td>
<td>-0.05</td>
</tr>
<tr>
<td>Half bunch length in angle, $\alpha_{max}$</td>
<td>150 degree</td>
</tr>
<tr>
<td>RMS energy spread, $(\Delta E/E)$, $I_{rms}$</td>
<td>0.212%</td>
</tr>
<tr>
<td>RMS synchrotron frequency, $\Omega_0/2\pi$</td>
<td>16.97 Hz</td>
</tr>
<tr>
<td>Impedance of the ring, $R_s$</td>
<td>10 kΩ</td>
</tr>
<tr>
<td>Resonant frequency, $f_r$</td>
<td>3.4 MHz</td>
</tr>
<tr>
<td>$Q$-value</td>
<td>1</td>
</tr>
</tbody>
</table>

- Two impedance cases to be studied by the theory and simulations:
  - Resonator impedance
  - Pure inductive impedance
    - The strength chosen to be equal to that of the resonator impedance at low frequency

Resonator impedance

![Analytical result](image)

Fig. 1: Coherent synchrotron mode frequencies ($f / \Omega_0$) and the growth rate as a function of circulating current.

Barrier Buckets at $\pm 150^\circ$, $\Omega_0$ = 1.005849e+01 / sec

GAUSSIAN, $\alpha_{0}$ = 0.012%, $R$ = 10 kΩ, $\Omega_0$ = 3.4 MHz, $\text{Imax} = 29$, $\text{numax} = 10$
Fig. 2: Time evolution of the rms energy spread at 5A for various initial energy spreads.
Resonator Impedance

TURN = 15000
Energy = 5 GeV
Icroc = 0 A
TO = 0 usec
NSPERX = 6000
divwsks = 0.01 usec
divpr = 0.1 usec
taigm = 1.8 usec
spgmnmt = 0.0005
ther = 0.0790929 usec
taigm = 1.1944 usec
spqbr = 0.000929061
spgmnmt = 0.0008129

95msec (5.25)

After Wakes On

Resonator Impedance

TURN = 100000
Energy = 5 GeV
Icroc = 0 A
TO = 0 usec
NSPERX = 6000
divwsks = 0.01 usec
divpr = 0.1 usec
taigm = 1.8 usec
spgmnmt = 0.0005
ther = 0.019089 usec
taigm = 1.18515 usec
spqbr = 0.00004946
spgmnmt = 0.0008128

500msec (9.34)

After Wakes On
• The simulation for 5A shows that the energy distribution stops to blow up at the initial spread of about 0.20%, in good agreement with the analytical result.

• The phase space plots show a uniform particle density after the blow-up the energy spread.

A signature of the microwave instability

Inductive Impedance

• The coasting beam theory predicts the excitation of the negative mass instability.

Analytical result

Fig.4: Coherent synchrotron mode frequencies ($\sqrt{\omega_0}$) and the growth rate as a function of circulating current.
Negative Mass Instability

Simulation result

Fig. 5: Time evolution of the rms energy spread at 9A for various initial energy spreads.
Fig. 7: Overshooting of the energy spread. The final spread versus the initial spread.

Fig. 6: Phase space distribution after the instability ceased for the initial energy spread of 0.05%.
- The simulation at 9A shows that the energy distribution stops to blow up at the initial spread of about 0.21%, in good agreement with the analytical result again.

- Strong concentration of particles can be observed in the phase space after the instability ceased.

An evidence of the negative mass instability

- The negative mass instability has the same threshold for all coasting beam mode"n" for an inductive impedance:

\[
\left| \frac{Z_n}{n} \right| \leq \frac{\epsilon B^2 n}{\epsilon l_p} \left( \frac{\Delta p}{p} \right)^2 \tag{Kell-Schnell-Boussard criterion}
\]

This behavior agrees with the simultaneous onset of mode-coupling instabilities of all synchrotron modes.
TRIANGULAR, $\sigma = 0.204\%$, $L = 468.103\mu H$, $l_{\text{max}} = 29$, $m_{\text{max}} = 10$

Barrier Buckets at $\pm 150^\circ$, $\Omega_r = 9.991650e+01 / \text{sec}$
Fast P-P Update Schemes

Motivation: Allows for smooth symplectic modeling of the space charge force in reasonable time.

\( \gamma_k \) = arrival time of particle \( k \), \( k = 1, 2, \ldots, N \)

\( \delta_k \) = momentum deviation

\[ \hat{V}(\delta, \bar{x}) = \frac{\xi}{\gamma_k} \lambda(\bar{x} - \bar{x}_k) \]

\[ F = -\sum_k \bar{x}_k \delta_k + \hat{V}(\delta, \bar{x}) \]

Canonical Transformation

Goldstein 

\[ \gamma_i = -\frac{dF}{d\delta_i} = \bar{\gamma} \]

\[ \delta_i = -\frac{dF}{d\gamma_i} = \delta_i - \frac{dV}{d\gamma_i} \]

\[ \lambda(\gamma) = (1 + \alpha_1 |\gamma|) e^{-\alpha_1 |\gamma|} \]

Continuously with continuous 1st and 2nd derivatives

\[ \lambda(\gamma) = -\alpha^2 \gamma e^{-\alpha_1 |\gamma|} \]

\[ \delta_k = \delta_k + K \frac{N}{\gamma_k} (\bar{\gamma}_k - \gamma) \]

The pairwise sum for all \( N \) particles can be done in \( O(N \log N) \) operations for appropriate \( \lambda(\gamma) \).

\[ \delta_k = \delta_k + K \sum_{j=1}^{N} (\gamma_k - \gamma_j) \]

\[ \delta_k = \delta_k + K \sum_{j=1}^{N} (\gamma_k - \gamma_j) e^{-\alpha_1 |\gamma_k - \gamma_j|} \]

\[ \frac{\delta \rightarrow \bar{\gamma}_k}{(\bar{\gamma}_k - \gamma_j)(\bar{\gamma}_k - \gamma_j)} \]
\[ F_k = \sum_{j=1}^{N} (Y_k - Y_j) e^{-\alpha(Y_k - Y_j)} \]

The Trick:
Sort \( Y_j \leq Y_{j+1} \), which is \( O(N \log N) \) with Heapsort or Quicksort.

\[ F_k = \sum_{j=1}^{k} (Y_k - Y_j) e^{-\alpha(Y_k - Y_j)} + \sum_{j=k+1}^{N} (Y_k - Y_j) e^{-\alpha(Y_k - Y_j)} \]

\[ = Y_k (S^{-1}_k + S^{-1}_k) - (S^{-2}_k + S^{-2}_k) \]

\[ S^{-2}_k = \sum_{j=1}^{k} Y_j e^{\alpha(Y_j - Y_k)} \]

\[ = Y_k + \sum_{j=1}^{k} Y_j e^{\alpha(Y_k - Y_j)} = Y_k + e^{\alpha(Y_k - Y_k)} S^{-1}_{k-1} \]

Since \( Y_k \geq Y_{k-1} \), \( e^{\alpha(Y_k - Y_k)} \leq 1 \)
and the recurrence relation is stable

\[ S^{-}_k = \sum_{j=k+1}^{N} Y_j e^{\alpha(Y_k - Y_j)} \]

\[ = (S^{-}_k + Y_k) e^{\alpha(Y_k - Y_{k+1})} \]
again stable

So, start with \( S^{-}_0 = 0 \), \( S^{+}_0 = 0 \)
and use

\[ S^{-}_{n+1} = 1 + e^{\alpha(Y_n - Y_{n+1})} S^{-}_n \]
\[ S^{+}_{n+1} = Y_n + e^{\alpha(Y_n - Y_{n+1})} S^{+}_n \]

\[ S^{-}_{n-1} = (1 + S^{+}_n) e^{\alpha(Y_{n-1} - Y_n)} \]
\[ S^{+}_{n-1} = (Y_n + S^{+}_n) e^{\alpha(Y_{n-1} - Y_n)} \]

Recurrence is \( O(N) \) so: \( O(N \log N) \) total
HOM Dampers for RHIC 28.1 MHz
Accelerating Cavity:

Stability in RHIC?

RF Workshop @BNL
May 8, 1997

Jim Rose, RHIC rf

SUPERFISH Output for 28 MHz
Cavity (150 kHz low to allow final
tuning after manufacture)

<table>
<thead>
<tr>
<th>Beta</th>
<th>T</th>
<th>Tp</th>
<th>S</th>
<th>Sp</th>
<th>q/L</th>
<th>L/L</th>
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<td>0.02374</td>
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<table>
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<th>rbeg</th>
<th>send</th>
<th>send</th>
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<td>17.4500</td>
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<td>21.7000</td>
<td>20.0000</td>
<td>2.5558</td>
<td>3239.1914</td>
<td>0.0000</td>
<td>0.9598</td>
<td>0.0000</td>
</tr>
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<td>21.7000</td>
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<td>0.0000</td>
<td>0.9598</td>
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</tr>
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<td>21.7000</td>
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<td>0.0000</td>
</tr>
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<td>21.7000</td>
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<td>3239.1914</td>
<td>0.0000</td>
<td>0.9598</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Wall---------------------------| Total = 77675.5078 | Wall---------------------------
Longitudinal Coupled Bunch Instabilities

Higher Order Modes (HOM's) in the rf cavities have been calculated with the code URMEL and agree with measured values of shunt impedance and Q.

Growth rates have been calculated both with the code ZAP and analytically with the expression

\[ \frac{1}{\tau} \frac{\omega}{r_s V_{\text{cos}},.} \]

Where \( F_m \) is a form factor less than 0.6 and which falls off as the inverse of both the HOM frequency and the square of the bunch length. Because of the long bunch length in RHIC, only the first few HOM's contribute to instabilities.

<table>
<thead>
<tr>
<th>HOM Frequency</th>
<th>Growth Rate (sec (^{-1}))</th>
<th>Stable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>103 MHz</td>
<td>12</td>
<td>U</td>
</tr>
<tr>
<td>192 MHz</td>
<td>3.7</td>
<td>U</td>
</tr>
</tbody>
</table>

Modest amounts of passive damping (factor of 10) will bring these within the range of the injection damper rate of 10 sec\(^{-1}\). Damping experiments have confirmed this de- Qing on the Proof of Principle (PoP) 26.7 MHz cavity.
Form Factors for Degenerate case (Σ azimuthal modes)

Impedance limit for growth rates of 2 sec\(^{-1}\) with undamped (lines) and damped (x’s) HOM impedances superimposed.

\[
F_{i}(l_{a}) = \frac{\gamma_{p}(p+2)}{\gamma_{p}} \frac{2^{(l+1)}}{l!} \frac{(m_{p} + 2k + p)!}{(n_{p} + k + l)!} \frac{(m_{p} + k + p)!}{(n_{p} + k + l)!} \text{J}_{n}(\eta_{p}, \theta)
\]

Distribution \( \psi(r) = k \left[ 1 - \left( \frac{r}{r_{p}} \right)^{\nu} \right]^{\nu_{m}} \quad \nu_{m} = 1 \)
Impedance limit for \( \frac{1}{\tau} = 2 \text{s}^{-1} \)
and various bunch lengths and gap volts:

\[
\chi = \frac{\omega_{cs}}{\omega_{rf}} \hat{\phi} \quad \hat{\phi} = \text{bunch half length in radians} \quad \omega_{rf}
\]

\[
\frac{1}{\tau} = \frac{\omega_{rf}}{\hat{\phi}} \frac{I_0 R_{se}}{V_T \cos \phi_T}
\]

HOM damper performances (two damping loop-longitudinal modes only). MAFIA results.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>F(MHz)</th>
<th>(R_d(\text{k}\Omega))</th>
<th>(Q[-])</th>
<th>(\sqrt{Q})[(\Omega)]</th>
<th>(R_w(\text{k}\Omega))</th>
<th>(\frac{R_w}{R_c})</th>
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</thead>
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<tr>
<td>1</td>
<td>27.7</td>
<td>1120</td>
<td>17900</td>
<td>17900</td>
<td>62.6</td>
<td>1120</td>
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<tr>
<td>2</td>
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<td>166</td>
<td>29250</td>
<td>5.7</td>
<td>1.3</td>
<td>123</td>
</tr>
<tr>
<td>3</td>
<td>197.9</td>
<td>34</td>
<td>22800</td>
<td>2.4</td>
<td>1.4</td>
<td>38.6</td>
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<tr>
<td>4</td>
<td>269.2</td>
<td>86.3</td>
<td>21400</td>
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<td>7.0</td>
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<td>10.4</td>
</tr>
<tr>
<td>6</td>
<td>324.3</td>
<td>342.5</td>
<td>31400</td>
<td>10.3</td>
<td>14.5</td>
<td>22.6</td>
</tr>
</tbody>
</table>
Prototype HOM Damper Notch Filter

"Folded" Quarter wave resonator creates open circuit at fundamental rf frequency; similar to parallel L-C notch filter.

Dimensions of 370 mm long by 150 mm diameter.

Bench test:
Notch depth of -49 dB, 2\textsuperscript{nd} notch at 368 MHz, 3\textsuperscript{rd} at 422 MHz.

\[ V_m = 10.7 \text{ kV} \text{ at 400kV gap volts} \]
\[ R_{\text{dissip}} = 81 \text{ k}\Omega \text{ at 700 Watts} \]

\[ -325 \text{ mm long \times 300 mm diameter} \]
5-Element Chebyshev High Pass Filter. Resitive losses less than 40W for Ug=400kV.
Fundamental frequency attenuation > 60dB.

**HIGH PASS FILTER MODE DAMPER ASSEMBLY**

- Standard 6 inch coax outer conductor
- Commercial ceramic vacuum feedthrough
- Water feed tube and return
### Table 3

**MAFIA RESULTS (NO KOM INSTALLED)**

<table>
<thead>
<tr>
<th>No.</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>Ra(h)[k]</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
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<td>122</td>
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<td></td>
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### Table 2

**POP CAVITY - MAFIA RESULTS**

<table>
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<th>No.</th>
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<th>Ra(h)[k]</th>
<th>$\mathcal{E}(\mu g)$</th>
<th>$\mathcal{E}(\mu g)$</th>
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<td>402.2</td>
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<td>1.1</td>
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</tbody>
</table>

**Table 3**

*Stability diagram for beams with parabolic line density.*
Session on Beam Loading and rf System Stability

J.M. Brennan

Emmanuel Onillon of Brookhaven gave a lecture on state variable techniques for feedback system analysis and design. He presented a pedagogical summary of the state variable formulation of the analysis of dynamical systems, with frequent references to the classical transfer function technique. For feedback systems used in accelerator applications the state variable technique is attractive because it provides a means for optimizing the performance of complex systems where many loops operate simultaneously. Two techniques were described which allow the designer to find the best set of settings of loop parameters in multi-loop feedback systems such as frequently occur in rf systems.

The two techniques, pole placement and LQR (linear quadratic regulator) were developed in some detail and shown to be complementary. Pole placement is a convenient technique when one wants to obtain analytic formulae for feedback gains in the presence of a changing system parameter, such as, synchrotron frequency or beam energy. LQR is a technique that obtains the optimum set of gains that maximize some performance criterion. Typically the criterion is a weighted sum of output accuracy plus a measure of the control effort.

Onillon showed that in the design of the RHIC beam control system the two techniques were used together. First LQR was used to produce a set of feedback gains and the system poles were obtained. Then analytic relations were found for the gains as functions of beam and rf parameters by pole placement. These analytic relations will be imbedded in the digital signal processing (DSP) algorithms for the RHIC rf beam control system. The benefit is that the system dynamics, bandwidth and tracking error, for example, will be independent of beam energy or rf voltage.

M. Blaskiewicz of Brookhaven presented a description of the rf system for the US National Spallation Neutron Source (NSNS) project. Although the rf system does not accelerate the beam because the ring is only an accumulator it is a high power system because of very high beam loading. At $2 \times 10^{14}$ protons in the ring the rf beam current will approach 80 A. Making the assumption that the cavity will be essentially uncompensated because the injection period (1ms) is shorter than ferrite response time requires full reactive beam current from the power amplifier. The system employs high power tetrodes (600 kW) which are capable of 300 A peak current. Results of a detailed analysis of the tetrodes capabilities based on the constant-current characteristics published by the manufacturer were presented.
Results from particle tracking calculations which included space charge were presented that showed the benefit of tailoring the rf waveform to increase the bunching factor. Addition of a second harmonic voltage improved the bunching factor by 25%, while using a isolated sinewave for a barrier bucket could give an even greater improvement of 35% in intensity will ultimately be limited by space charge driven tune spread any improvement in bunching factor will likely translate into increased intensity.

System stability was analyzed according to the conventional considerations used for synchrotrons even though the NSNS ring will not accelerate. Blaskiewicz pointed out that although these considerations are sufficient they may not be necessary and that further work is called for in analyzing the accumulator problem.

Roland Garoby of CERN/PS presented a brief description of a newly commissioned diagnostic system at the PS that measures the phase turn-by-turn of each bunch in the PS. The system is based on a commercial DSP board and commercial constant-fraction timing discriminators. Some typical results were shown that showed how the system can reveal coherent dipole oscillations from injection phase errors from one ring of the PS Booster. The main role of the new system will be in detecting and analyzing longitudinal coherent instabilities in the PS.
STATE VARIABLE ANALYSIS

E. Onillon

Concept introduced in control science in the 50's.

Powerful method, can be used for the study of numerous systems, linear or not, stationary or not, continuous or discrete.

Naturally leads to the idea of optimum control.

Associated with the idea of a prescribed trajectory the system has to follow with a minimum error and at a minimum cost (power for instance).

State vector $\dot{x}(t) = \text{minimum set of variables (information on the past) sufficient to calculate the future evolution of the system when we know for } t \geq t_0 \text{ the inputs and its internal physical laws}$

State vector $\dot{x}(t) = \text{minimum set of variables (information on the past) sufficient to calculate the future evolution of the system when we know for } t \geq t_0 \text{ the inputs and its internal physical laws}$

\[
\begin{align*}
\dot{i}(t) &= -\frac{(R_1 + R_2)}{L} i(t) - \frac{1}{L} v(t) + \left[ \frac{1}{C} \right] e(t) \\
\dot{v}(t) &= \left[ \frac{1}{L} \right] e(t)
\end{align*}
\]

$s = [R_2 \begin{bmatrix} 1 \\ v \end{bmatrix}]$

$F = M \dot{x}$

$x(0), v(0)$

$x(t), v(t)$
State vector $\dot{X}(t) = [x_i(t)]_i^{T}$ is the order of the system.

Input vector $U(t) = [u_j(t)]_j^{T}$.

Output vector $Y(t) = [y_k(t)]_k^{T}$.

**STATE AND OBSERVATION EQUATIONS**

Linear and stationary system:

\[
\begin{align*}
\dot{X}(t) &= AX(t) + BU(t) \quad \text{state} \\
Y(t) &= CX(t) + DU(t) \quad \text{observation}
\end{align*}
\]

For a discrete system:

\[
\begin{align*}
X_{n+1} &= A_d X_n + B_d U_n \\
Y_n &= C_d X_n + D_d U_n
\end{align*}
\]

Resolution of the state space equation:

Look for a linear solution

\[
X(t_0) \rightarrow \Phi(t, t_0) = e^{A(t-t_0)} \rightarrow X(t)
\]

State space representation / Transfer function:

\[
\begin{align*}
\dot{X}(t) &= AX(t) + BU(t) \quad \Rightarrow \quad sX(s) - X(0) = AX(s) + BU(s) \\
Y(t) &= CX(t) + DU(t) \quad \Rightarrow \quad Y(s) = CX(s) + DU(s)
\end{align*}
\]

\[
Y(s) = C(sI - A)^{-1} X(0) + \left(D + C(sI - A)^{-1} B\right) U(s)
\]

\[
H(s) = \frac{Y(s)}{U(s)} = D + C(sI - A)^{-1} B
\]

Poles = eigenvalues of A
Example

\[
A = \begin{bmatrix} -7 & -12 \\ 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad C = [1, 2], \quad D = 0
\]

\[
(sI - A) = \begin{bmatrix} s+7 & 12 \\ 1 & s \end{bmatrix}, \quad (sI - A)^{-1} = \frac{1}{s(s+7)+12} \begin{bmatrix} s & -12 \\ 1 & s+7 \end{bmatrix}, \quad H(s) = \frac{s+2}{s^2+7s+12}
\]

Passage transfer function / state: introduce a new variable

\[
\frac{Y(s)}{U(s)} = \frac{X_1}{s(s+7)+12} \Rightarrow Y = sX_1 + 2X_1 \quad \text{and} \quad X_1 = \frac{1}{s^2+7s+12} U(s)
\]

or with \( X_2 = X_1 \), (successive derivative)

\[
Y = X_2 + 2X_1 \quad \text{and} \quad X_1 = -7X_2 - 12X_1 + U
\]

Discrete state space representation

\[
\begin{align*}
\dot{X}(t) &= AX(t) + BU(t) \\
Y(t) &= CX(t) + DU(t)
\end{align*}
\]

POLE PLACEMENT, LQR

System: \( \dot{X} = AX + BU \)

\( Y = CX + DU \)

Commandability

\[
X(t_0) \xrightarrow{U(t)} t_0 \xrightarrow{t} X_f
\]

rank \([B \quad AB \quad \ldots \quad A^{n-1}B]\) = number of commandable states

Observability

\[
Y(t) \xrightarrow{U(t)} t_0 \xrightarrow{t} X(t_0)
\]

rank \([C^T \quad A^TC^T \quad \ldots \quad A^{n-1}C^T]\) = how many states we can reconstruct

Discrete state space representation

\[
\begin{align*}
X_{k+1} &= e^{AT}X_k + \sum_{i=k}^{T} e^{A(T-i)}BU(i) \\
Y_k &= CX_k + DU_k
\end{align*}
\]

\[
X_{k+1} = e^{AT}X_k + \sum_{i=0}^{T} e^{A(T-i)}BU_k \\
Y_k = CX_k + DU_k
\]
POLE PLACEMENT

Specify the poles you want the system to have

\[
\begin{align*}
    x &= Ax + Bu \\
    y &= Cx + Du
\end{align*}
\]

\[U = -LX + e \Rightarrow X = (A - BL)X + Be\]

(A, B) must be controllable.

Choice of the eigenvalues (poles of the system)

\[\text{Re}(\lambda_i) < 0 \text{ and if } \lambda_i, \lambda_i^\ast\]

The further the \(\lambda_i\) are from the eigenvalues of A, the bigger the command effort is.

If \(\lambda_i = s_i + jb_i \rightarrow e^{s_i t} \sin b_i t, e^{s_i t} \cos b_i t\) The bigger \(|s_i|\), the faster the system is.

With \(|\lambda_i| = \omega_0\) and \(\lambda_i + \lambda_i^\ast = \omega_0 = |\sin \theta|\omega_0\)

\[
\begin{array}{c}
\text{Minimum} \\
\text{damping}
\end{array}
\]

\[
\begin{array}{c}
\text{Minimum} \\
\text{speed}
\end{array}
\]

Determination of L

\[
\det(\lambda I - (A - BL)) = (\lambda - \lambda_1)(\lambda - \lambda_n)
\]
Discrete Systems

\[ U_k = -L_d X_k + e_k \Rightarrow X_{k+1} = (A_d - B_d L_d)X_k + B_d e_k \]

\[
\begin{aligned}
\det(\lambda I - (A_d - B_d L_d)) = (\lambda - \lambda_1) \ldots (\lambda - \lambda_n)
\end{aligned}
\]

discrete pole = \( e^{\text{continuous pole} \cdot T_d} \)

Numerically, \( R = 10 \Omega, J = 5 \times 10^{-5} \text{ kg m}^2, \Phi_o = 0.1 \text{ USl}, T = 5 \text{ms} \)

\[
\begin{aligned}
d\Omega &= -20\Omega(t) + 200U(t) \\
\Omega(k + 1) &= -0.952\Omega(k) + 0.952U(k)
\end{aligned}
\]

Continuous system: eigenvalue -20 (50ms)

Divide it by 2

\[ e^{-40T} = 0.819 \]

\[
\begin{aligned}
\Omega(k + 1) &= (-0.905 - 0.9521L)\Omega(k) \\
L &= 0.090
\end{aligned}
\]
LINEAR QUADRATIC REGULATOR (L.Q.R.)

Linear system
\[ \begin{align*}
X(t) &= AX(t) + BU(t) \\
X(0) &= X_0
\end{align*} \]

Goal: bring the state back to zero (regulator) while minimizing cost

\[ J = \frac{1}{2} \int \left( X^T(t)QX(t) + U^T(t)RU(t) \right) dt \]

Optimal command 
\[ U_{opt}(t) = -LX(t) = -R^{-1}B^TPX(t) \]

where \( P \) satisfies the algebraic Riccati equation:

\[ PA + A^TP - PBR^{-1}B^TP + Q = 0 \]

Optimal cost
\[ J_{opt} = X_0^TPX_0 \]

To find an optimal command 
- choose \( Q \) and \( R \)
- solve the Ricatti equation to find \( L \)
- command = linear combination of the state variables, the new poles being the eigenvalues of \( A-B* L \)

(A,B) has to be commandable

Choice of \( Q \) and \( R \):

Choose diagonal matrices

\[ Q_y = \begin{bmatrix}
q_1 & 0 & 0 \\
0 & \ddots & 0 \\
0 & 0 & q_p
\end{bmatrix}, \quad R_y = \begin{bmatrix}
r_1 & 0 & 0 \\
0 & \ddots & 0 \\
0 & 0 & r_j
\end{bmatrix} \]

In that case:
\[ J = \frac{1}{2} \int \left( \sum (q_i y_i^2) + \sum (r_j u_j^2) \right) dt \]

\( q_i \) and \( r_j \) represent the relative importance of the variables toward each other

- If \( R \rightarrow kR \) with \( k > 1 \), the command will be less strong, the closed system will be slower.
- If \( Q_y \rightarrow kQ_y \) with \( k > 1 \), closed loop faster, stronger command

\( (A,B) \) has to be commandable
**RHIC CASE**

Choice of Q and R

done at injection

requirement: loop response time

modify Q and R to reach that target

limit the phase excursion by having a stronger coefficient on the phase
Command frequency error sent to a DDS: limit the input by minimizing R

Compromise between speed/amplitude of the command and phase excursion

Several iterations before finding Q and R

Just a set of gains could not do it (compromise loop response/stability)

Discrete systems

\[
\begin{align*}
X_{k+1} &= A_d X_k + B_d Y_k \\
X_{k=0} &= X_0
\end{align*}
\]

\[
J = \frac{1}{2} \sum_{k=0}^{m} \left( X_{k+1}^T Q X_{k+1} + U_k^T R U_k \right)
\]

Solution:

\[
U_k = -L X_k \text{ with } L = B_d^T P^{-1} B_d + R^{-1}
\]

where P satisfies the discrete Ricatti equation:

\[
P = A_d^T PA_d - A_d^T PB_d \left( B_d^T PB_d + R \right)^{-1} B_d^T PA_d + QA_d
\]

Example:

\[
\dot{x}(t) + 2\xi \omega_n x(t) + \omega_n^2 x(t) = K u(t)
\]

\[
\omega_n = (2\pi), \xi = 0.1, K = \frac{1}{(2\pi)^2}
\]

\[
x_1 = x \text{ and } x_2 = \dot{x}
\]

\[
\gamma = 2\xi \omega_n
\]

\[
T_s = \frac{T_e}{6}
\]

\[
A = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -\gamma \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = K \begin{bmatrix} 1 & 0 \end{bmatrix}, D = 0
\]

\[
A_d = \begin{bmatrix} 0.5325 & 0.7815 \\ -0.7815 & 0.3762 \end{bmatrix}, B_d = \begin{bmatrix} 0.4675 \\ 0.7815 \end{bmatrix}, C_d = C, D_d = D
\]
Integral action

If one wants \( y = y_0 \)

\[
\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} A & B \\ \begin{bmatrix} C & 0 \end{bmatrix} & D \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ -y_0 \end{bmatrix}
\]

New state variable \( z = \int_0^t (y(t) - y_0) \, dt \)

\[
\frac{d}{dt} \begin{bmatrix} x \\ z \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ -y_0 \end{bmatrix}
\]

Discrete case

\( z_{k+1} = z_k + (y_k - y_0) \)
Variables

Beam transfer functions

THE PHASE AND RADIAL LOOP

Two state variables:

\[
\begin{align*}
    x_1 &= \frac{R}{b} = \frac{k_0}{s^2 + \omega_n^2} U \\
    x_2 &= \phi = \frac{0}{1} x_1 + \frac{0}{k_0} U
\end{align*}
\]

Third state variable:

\[
    x_3 = z = \int (R - R_0) dt \Rightarrow x_3 = R - R_0 = \frac{1}{b} x_1 - R_0.
\]

\[
b = \frac{ceV_{rf} \cos \varphi}{2nF_{rf} \beta} \quad \text{and} \quad \omega_n = f_n \sqrt{\frac{2nF_{rf} \cos \varphi}{E}}.
\]
Final state space representation:

\[
\begin{align*}
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} &=
\begin{bmatrix}
0 & 1 & 0 \\
-\omega_1^2 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
k_0 \\
0
\end{bmatrix}
U + 
\begin{bmatrix}
0 \\
-1 \\
0
\end{bmatrix}
R
\end{align*}
\]

\[
\begin{bmatrix}
\Phi_0 \\
\Phi_1 \\
\Phi_2
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix}
\]

\[
\text{rank}[B_{qR} A_{qR} B_{qR} A_{qR}^2 B_{qR}] = 3 \Rightarrow \text{Feedback using pole placement}
\]

\[
\begin{align*}
k_R &= \frac{(l_1 l_2 + l_1 l_3 + l_2 l_3 - \omega_\phi^2)}{b k_0} \\
k_\phi &= \frac{-(l_1 l_2 + l_1 l_3)}{k_0} \\
k_f &= \frac{-(l_1 l_2 l_3)}{b k_0}
\end{align*}
\]

Use of the phase integral: \( k_R \rightarrow -k_R \) if use of the radius. Transient Simulations: desired poles: \(-139 + j*139\), \(-139 - j*139\), \(-28283\). Reference: 1 mm radius step.
THE SYNCHRONIZATION LOOP

\[
X_s = \begin{bmatrix} \dot{x}_4 = \varphi_b \\ \dot{x}_5 = \omega_b \\ \dot{x}_6 = \varphi \end{bmatrix}, \quad Y_s = \begin{bmatrix} x_4 = \varphi_b \\ x_5 = \omega_b \\ x_6 = \varphi \end{bmatrix}.
\]

Evolution:
\[
\begin{bmatrix} \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \omega_b^2 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ k_\varphi \varphi_{sync} \end{bmatrix}.
\]

State space representation:
\[
\begin{bmatrix} \dot{X}_s \\ \dot{Y}_s \end{bmatrix} = \begin{bmatrix} A_s & B_s \\ 0 & 0 \end{bmatrix} \begin{bmatrix} X_s \\ \varphi_{sync} \end{bmatrix}
\]

\[
\text{rank} \begin{bmatrix} B_s & A_s B_s & A_s^2 B_s \end{bmatrix} = 3 \Rightarrow \text{Pole placement}
\]

\[
k_{\varphi_b} = \frac{1}{1 + \frac{1}{k_0} \varphi_b}, \quad k_{\varphi_{sync}} = \frac{1}{1 + \frac{1}{k_0} \varphi_{sync}}.
\]

Desired poles: -99638, -1202 + j*1047, -1202 - j*1047 during acceleration and -2203, -1469, -9442 during storage.

Step response of the synchronization loop

V_{tr}=170 kV, \gamma=12.6 \quad V_{tr}=300 kV, \gamma=108.4 \quad V_{tr}=6000 kV, \gamma=108.4

Rise time roughly 20 ms. Phase margin 80°, amplitude margin 20 dB and the cut off frequency 1.5 kHz.

Open loop Bode plots
PHASE ERROR FOR A GIVEN FREQUENCY ERROR

Phase measurements errors

System excited by a white noise (90° amplitude, bandwidth 5000 Hz)

Noise attenuated by a factor of 40.

Effects of the tuner on the phase and radial loop.

Tuner effect = rf phase steps.

The same simulation has been performed by using real RF phase measurements.

Step on the rf phase ⇒ the feedback tries to bring the phase to zero. The radius integers the step ⇒ the phase deviates.

\[
(\varphi_{rf} \rightarrow R) = b \int (\varphi_{rf} \rightarrow \varphi) \Rightarrow a(t) = \int_{0}^{1} \varphi(u)du = k*R
\]

Perturbations due to the tuner can be seen as radius steps.
DISCRETE REALIZATION OF THE LOOPS

Previous analog representation is sampled at the revolution frequency to get a discrete representation which includes the delay.

The phase and radial loop

Original state space representation with no integral:

\[
\begin{align*}
    x(n+1) &= a_d x(n) + b_d U(n) \\
    Y(n+1) &= c_d x(n) + d_d U(n)
\end{align*}
\]

where \( R(n+1) = C_a x(n) \)

\[
x(n) = \begin{pmatrix} R(n) \\ b \\ \psi(n) \\ U(n-1) \end{pmatrix}
\]

complete state space representation

\[
\begin{pmatrix}
    x(n+1) \\
    z(n+1) \\
    X(n+1) \\
    Y(n+1)
\end{pmatrix} =
\begin{pmatrix}
    a_d & 0 & (b_d) & 0 \\
    c_d & 2 & 0 & (−R_o) \\
    0 & 0 & 1 & 0 \\
    c_d & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    x(n) \\
    z(n) \\
    X(n) \\
    Y(n)
\end{pmatrix} +
\begin{pmatrix}
    0 \\
    0 \\
    0 \\
    0
\end{pmatrix} U(n)
\]

discrete pole = \( e^{\text{continuous pole} \cdot T_d} \)

Radius reference: 1mm step.

\[
\begin{align*}
    V_{ref} &= 170 \text{ kV, } \gamma = 12.6 \\
    V_{ref} &= 300 \text{ kV, } \gamma = 108.4 \\
    V_{ref} &= 60000 \text{ kV, } \gamma = 108.4
\end{align*}
\]

Radius response

\[
\begin{align*}
    V_{ref} &= 170 \text{ kV, } \gamma = 12.6 \\
    V_{ref} &= 300 \text{ kV, } \gamma = 108.4 \\
    V_{ref} &= 60000 \text{ kV, } \gamma = 108.4
\end{align*}
\]

Open loop Bode plots

Phase margin is 70°, amplitude margin 15 dB, cut off frequency 3.2 kHz.

Same response at transition (rise time \( \approx 20 \text{ ms} \))

phase margin 80°, amplitude margin 10 dB, cut off frequency 3 kHz

Loop behavior at transition (step response and Bode plot)

Phase comes back to zero in less than 100ms.
The synchronization loop

Discrete state vector: $X(n) = (\varphi_b, \omega_b, \varphi, U(n-1))^T$.

Step response

Rise time 20 ms.
Open loop Bode plots

Phase margin 80°, amplitude margin 20 dB, cut off frequency 1.5 kHz.

V_{RF}=170 \text{ kV}, \gamma=12.6
V_{RF}=300 \text{ kV}, \gamma=108.4
V_{RF}=6000 \text{ kV}, \gamma=108.4
Practical realization

Use of a VME DSP board

Store the feedback gains in a table (RAM), as a function of energy
Access the gain table as a function of the energy

 rtidl Com port

digital inputs (VSB)

Gains
200 sets (RAM)

DSP
Calculate gains
Ferror

f_{error} (updated at 78 kHz)

Specify for gain table calculation

f_{error} (updated at 78 kHz)

\( l_1, l_2, l_3, l_4 \) phase/rad

\( l_1, l_2, l_3, l_4 \) synchro

Ackermann's formula

Updated according to the loop response needed

VME Bus

Gain table

Phase and radial loop

<table>
<thead>
<tr>
<th>( V_{tr} )</th>
<th>( \gamma )</th>
<th>( k_{\text{phase}} )</th>
<th>( k_{\text{phase}} )</th>
<th>( k_{\text{delay}} )</th>
<th>( k_{\text{radius}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 kV, ( \gamma = 12.6 )</td>
<td>0.0242 ( 10^6 )</td>
<td>6.249 ( 10^6 )</td>
<td>0.291</td>
<td>0.0208 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>300 kV, ( \gamma = 108.4 )</td>
<td>0.0243 ( 10^6 )</td>
<td>6.671 ( 10^6 )</td>
<td>0.291</td>
<td>0.1014 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>6000 kV, ( \gamma = 108.4 )</td>
<td>0.0242 ( 10^6 )</td>
<td>1.13 ( 10^6 )</td>
<td>0.290</td>
<td>0.005 ( 10^6 )</td>
<td></td>
</tr>
</tbody>
</table>

Only \( k_{\text{radius}} \) changes during acceleration

<table>
<thead>
<tr>
<th>( V_{tr} )</th>
<th>( \gamma )</th>
<th>( k_{\text{radius}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 kV, ( \gamma = 12.6 )</td>
<td>0.0208 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>170 kV, ( \gamma = 108.4 )</td>
<td>0.1796 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>300 kV, ( \gamma = 12.6 )</td>
<td>0.0017 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>300 kV, ( \gamma = 108.4 )</td>
<td>0.0101 ( 10^6 )</td>
<td></td>
</tr>
</tbody>
</table>

Range: 0.0017 \( 10^6 \) to 0.1796 \( 10^6 \)
200 points: \( \Delta \text{gain} = 1000 \)

Triggers: VSB interrupts, corresponding to a different part of the DSP code

1 mm step: 1° phase jump

5 mm step: 7° phase jump
Synchronization loop

<table>
<thead>
<tr>
<th>$V_r$, kV</th>
<th>$\gamma$</th>
<th>$k_{phb}$</th>
<th>$k_{ph}$</th>
<th>$k_{delay}$</th>
<th>$k_{ob}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>12.6</td>
<td>$9.6386 \times 10^3$</td>
<td>$9.6447 \times 10^3$</td>
<td>$0.0001 \times 10^3$</td>
<td>$0.0728 \times 10^3$</td>
</tr>
<tr>
<td>300</td>
<td>108.4</td>
<td>$10.614 \times 10^3$</td>
<td>$0.6617 \times 10^3$</td>
<td>$0.0001 \times 10^3$</td>
<td>$0.0024 \times 10^3$</td>
</tr>
</tbody>
</table>

Only $k_{ph}$ and $k_{ob}$ change during acceleration.

Range:
- $k_{ph}$ from $0.6653 \times 10^3$ to $7.7186 \times 10^3$ 20 points $\Delta\gamma = 0.35$
- $k_{ob}$ from $0.0052 \times 10^2$ to $0.0728 \times 10^2$ 20 points $\Delta\gamma = 0.33$

No noticeable effect.
The NSNS rf System
M. Blaskiewicz, J.M. Brennan, A. Zaltsman

charge exchange injection for 1 ms then extract in one turn
60 Hz repetition rate
2 × 10¹⁴ 1 GeV kinetic energy protons at extraction
less than 10⁻⁴ uncontrolled losses
keep peak current small

Dual Harmonic system:

\[ V_{rf}(t) = 40kV \sin(\omega_0 t) + 20kV \sin(2\omega_0 t) \]

\[ \frac{Z_{sc}}{n} = 120\Omega, \quad R_{wall} = 20\Omega \]

\[ |E - E_0| \leq 5.6\text{MeV in Linac, } 9.4\text{MeV in Ring} \]
\[ T_{res} = 841\text{ns, } \tau_{chap} = 480\text{ns} \]

Cavity and Amplifier Design

\[ h = 1, \quad f = 1.26 \text{ MHz} \]
\[ h = 2, \quad f = 2.52 \text{ MHz} \]

±5% variability built in.
Need 40kV at \( h = 1 \) and 20kV at \( h = 2 \)
Want to retain the option of zero detuning angle \( \omega_r = \omega_0 \)
so full beam current must be compensated.
≤ 10kV per gap. Direct coupling to ~ AGS cavity.

Beam current

\[ I_s(t) \approx I_s(t) [1 + a_1 \cos(\omega_0 t) + a_2 \cos(2\omega_0 t)] \]
\[ a_1 = 1.3, \quad a_2 = .1, \quad \text{and } I_s(t) = 40t \text{ Amp ms}^{-1}. \]

\[ a_1 I_{max} = 52 \text{ Amps} \gg a_2 I_{max} = 4 \text{ Amps} \]

Equivalent Circuit
assume blocking capacitor and plate choke are very large gap voltage

\[ V_g(t) = V_a(t) - V_p \]

generator current across gap

\[ I_a(t) = -I_a(t) + I_p \]
anode current

\[ I_a = I_a(V_a, V_d) \]

\[ I_p(t) = -I_a(V_g(t) + V_p, V_d(t)) + I_p \]

power amplifier supplying \( n_g \) accelerating gaps in parallel

\[ V_g(t) = \int_0^\infty W(\tau)(I_b(t-\tau) + I_g(t-\tau)/n_g) d\tau \]

\( W(\tau) \) is the wake potential of the unloaded cavity

\[ W(\tau) = \frac{1}{2\pi} \int d\omega Z(\omega)e^{-i\omega\tau} \]

\[ Z(\omega) = \frac{R_{sh}}{1 + iQ(\omega_r/\omega - \omega/\omega_r)} \]

\( R_{sh} \) is the shunt impedance per gap of the unloaded cavity

\( \omega_r \) is its resonant frequency

\( Q \) is the unloaded quality factor.

Grid drive voltage

\[ V_d(t) = V_d + \Delta V_d \sin(\omega t + \phi_d) \]

Anode Voltage

\[ V_a(t) = V_a + \Delta V_a \sin(\omega t) \]

\( \Delta V_a = V_a \) for direct coupling Current through tetrode

\[ I_a(t) = I_0 - aI \cos(\omega t) + I_0 \sin(\omega t) + \text{higher harmonics} \]

\(-aI \) compensates the beam current

\( I_0 \) drives the cavity

For the \( \omega = \omega_r \) case \( I_0 = \Delta V_a / R_{sh} \)

\[ R_{sh} \approx 10k\Omega \rightarrow I_0 = 1 \text{ Amp} \]
irrelevant compared

\[ a_1 \bar{I} = 52 \text{ Amp} \]

Take

\[ n_g = 2 \rightarrow I_g = 104 \text{ Amp} \]

Anode Voltage, 6 gaps at \( h = 1 \)

\[ V_a(\omega t) = 9kV + 7kV \sin(\omega t) \]

Grid drive voltage

\[ V_d(\omega t) = -500V + 450V \cos(\omega t) - 53V \sin(\omega t) \]

Screen grid voltage = 2kV.

Load Line for \( h = 1 \), TH558 tetrode

For \( V_a > 2kV \)

\[ \frac{V_a}{1000} + (0.132 \pm 0.002) V_d = \text{constant} \]

So \( I_a = I_a( V_a + 132V_d ) \)

in region of interest \( \rightarrow 1 \) dimensional interpolation

\[ < I_a V_a >= 585 \text{ kW} \leq 600 \text{ kW} \text{ manufacturers spec} \]

How far can we push it?

For \( h = 2 \) two gaps, one tetrode, 20kV/gap, \( \approx 100 \text{ kW} \)

Anode Current and its Fourier Reconstruction, \( h = 1 \)
Dynamic tuning of the cavity resonant frequency
steady state first

gap volts \( V_g(t) = V_g \exp(i\omega_0 t) \)

beam current \( I_b(t) = I_b \exp(i\omega_0 t) \)

generator current \( I_g(t) = I_g \exp(i\omega_0 t) \)

\[ \dot{V}_g = Z_c(I_b + I_g) \]

relative phase of \( \dot{V}_g \) and \( \dot{I}_b \) is \( \approx 90^\circ \), \( (R_{wall}) \)

tune the cavity resonant frequency by biasing the ferrite, for minimum current

\[ I_g = V_g / R_{sh} \]

Where \( R_{sh} \sim 10k\Omega \) is the unloaded cavity impedance

Problem is now beam stability (Pederson 1975)

Have Robinson’s criteria for single harmonic

Dual harmonic rule of thumb?
took \( Y = I_b R_t / V_g \leq 3 \)

\( R_t \) = effective resistance of cavity and tetrode in parallel.

Calculating \( R_t \)

\[ I_g = I_p - I_e(V_d, V_a) \]

\[ \delta I_g = -\delta V_a \frac{\partial I_a}{\partial V_a} |_{V_d} \]

\[ \delta I_g + \delta I_b = \frac{\delta V_g}{R_{sh}} + \frac{1}{L} \int \delta V(t') dt' + C \frac{d\delta V_g}{dt} \]

\[ \delta V_g = \delta V_a \]

\[ \delta I_b = \delta V_g \left[ \frac{1}{R_{sh}} + Y_a \right] + \frac{1}{L} \int \delta V_g(t') dt' + C \frac{d\delta V_g}{dt} \]

where

\[ Y_a = \frac{\partial I_a}{\partial V_a} |_{V_d} \geq 0 \]

So

\[ \frac{1}{R_t} = \frac{1}{R_{sh}} + \left( \frac{\partial I_a}{\partial V_a} |_{V_d} \right) \]
Using $<Y_a>_r=1/375\Omega$ and 2 gaps per tetrode $R_t \approx 750\Omega$

$Y = 5.6$ without rf feedback

Use one turn feedback to reduce $R_t$ by a factor of 3.

Barrier cavity upgrade
Use same tetrodes, but drive with a pulse
reduce gap capacitance

$f_r = 2.33MHz > 2f_0$ for no debunching

$<I_0V_o>=1.8MW$ over one fill

$<I_0V_o>=220kW$ over many cycles
References


5.1 Sensitivity

The Mode Measurement System must be a highly sensitive tool in order to pin-point the birth and duration of beam instabilities. Proof of the sensitivity can be seen in Figure 33.

![Graph showing beam sensitivity](image)

**Figure 33** Evidence that bunches are oscillating at $f_n$ proves high sensitivity.

This plot was taken at C215 just before injection. Given that the small amplitude synchrotron frequency $f_n$, is approximately 1.6 kHz on this beam at injection energy, the graph should be able to confirm this statement.

Closer inspection reveals that the period of the signal in Figure 33 is approximately 600 µs. The frequency is thus given by

$$f = \frac{1}{T} = \frac{1}{600 \times 10^{-6}} = 1.67 \text{ kHz} = f_n$$

With the knowledge that synchrotron oscillations can successfully be observed, it is true to say that the system sensitivity is of a high quality.

5.2 Analysis of Beam Instabilities

The results of beam instability analysis were the key to completion of the project specification. If coherent longitudinal dipole instabilities could be identified, then RF specialists would be able to better isolate the source(s) of impedance driving the instability.

The first stage in this process - identification of the birth and nature of an instability - was successfully completed during the MD sessions.

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3 The small amplitude synchrotron frequency describes the motion of particles which are extremely close to the synchronous point whilst still performing synchrotron oscillations.
## Participants

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