My summary

Space Charge 2015

23-27 March 2015

Trinity College, Oxford
Space-charge induced Tune Shift

\[ \Delta \nu_{y,\text{inc}} = - \frac{N r_0 R}{\pi \nu_y \beta^2 \gamma} \left( \frac{\beta^2 \epsilon_1}{\hbar^2} + \frac{\beta^2 \epsilon_2}{g^2} + \frac{F/B}{\gamma^2 b(a+b)} \right) \]

\[ = -2.25 \times 10^{-5} \text{ m}^{-2} \times (4. \text{ m}^2 + 3. \text{ m}^2 + 14004. \text{ m}^2) \]

\[ = -0.315 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>(3.12 \times 10^{11})</td>
</tr>
<tr>
<td>(r_0)</td>
<td>(1.53 \times 10^{-18}) proton</td>
</tr>
<tr>
<td>(R_0)</td>
<td>(4.54 \text{ m}) average radius of injection orbit</td>
</tr>
<tr>
<td>(\beta, \gamma)</td>
<td>(0.147, 1.011) 11 MeV</td>
</tr>
<tr>
<td>(\nu_x, \nu_y)</td>
<td>((3.7, 1.4))</td>
</tr>
<tr>
<td>((a, b))</td>
<td>((20, 15)) mm</td>
</tr>
<tr>
<td>(B_f)</td>
<td>(1/5)</td>
</tr>
<tr>
<td>(F)</td>
<td>(1.5)</td>
</tr>
<tr>
<td>(h)</td>
<td>(32.5 \text{ mm}) half gap of the vacuum chamber</td>
</tr>
<tr>
<td>(g)</td>
<td>(37.9 \text{ mm}) half gap of the magnet</td>
</tr>
</tbody>
</table>

Rep. rate: 100 ~ 200 Hz
Average current: 5uA

Y. Ishi, FFAG’14
A linear Paul Trap used to simulate a focussing channel in an accelerator, including space charge: **S-POD** (Simulator of Particle Orbit Dynamics)

- Ar⁺ gas ionised by electron gun
- Trapped in a potential well
- 1 MHz confinement wave applied to quadrupole rods
- Add a perturbation wave (dipole)

LIU-PSB Activities – Finemet®

Installation of 10 Finemet® modules in PSB Ring 4:

5-cells open cavity

Beam accelerated up to 8e12 with Finemet®

Finemet® on a cooling ring

From Simone Gilardoni’s talk
LEAR: beam loss not understood

Main scheme limitation: LEIR maximum intensity

LEIR maximum extracted intensity limited to \(\sim 5.5 \times 10^8\) charges probably due to:
1. Working point too close to 4th order resonance (space charge)
2. Transverse instability at RF capture
3. Positive chromaticity in the vertical plane
4. Beam loss associated to RF-capture rather than mag. Ramp

From Simone Gilardoni’s talk
**HIAF: Layout and composition**

**CRing: Compression ring**  
Circumference: 804 m  
Rigidity: 43 Tm  
Barrier bucket stacking  
Beam compression  
Beam acceleration  
In-beam experiment

**ERL: Energy Recovery Linac**  
electron machine

**SRing: Spectrometer ring**  
Circumference: 188.7m  
Rigidity: 15 Tm  
Electron/Stochastic cooling  
Two TOF detectors  
Three operation modes

**BRing: Booster ring**  
Circumference: 402 m  
Rigidity: 34 Tm  
Beam accumulation  
Beam cooling  
Beam acceleration

**iLinac: Superconducting linac**  
Length: 180 m  
Energy: 25MeV/u(U^{34+})

1. Nuclear structure spectrometer  
2. Low energy irradiation target  
3. RIBs beam line  
4. High precision spectrometer ring  
5. External target station  
6. Electron-ion recombination spectroscopy  
7. Electron-Nucleus Collision (ENC)  
8. High energy irradiation target  
9. High Energy Density Physics target

From Weiping Chai’s talk
HIAF: building super-ferric dipoles

HIAF technical R&D-4

Super-ferric dipole with warm iron yoke
BRing and SRing

Features and design proposal:
- Big gap — Superconducting coil
- Big good field region — Warm yoke
- Fast-cycling rate (small inductance) — large operation current, liquid helium inner cooling superconducting cable
- Type of cooling — Forced flow cooling with super-critical helium/two-phase helium

- Superconducting solenoids: 3T, 5T, 7T for Penning trap
- The superconducting dipole prototype for the super-FRS has been manufactured and tested at IMP, and it has been already transferred to GSI

From Weiping Chai’s talk
J-PARC 3GeV RCS reaches 1MW

From Hideaki Hotchi’s talk

Present output beam power for the routine user program: 400 kW

High intensity beam tests of up to 573 kW for both injection energies of 181 MeV and 400 MeV

1-MW beam tests from October 2014

On this process of the high intensity beam tests, we had several beam loss issues mainly caused by the space charge and its combined effect with machine imperfections. But they were well solved with the aid of the numerical simulation.
Numerical simulation for the RCS

Simpsons (developed by Dr. Shinji Machida)
- PIC,
- 3-D motion of beam particles including space-charge and realistic injection process

Machine imperfections included:

◆ Time independent imperfections
  - Multipole field components for all the main magnets:
    BM (K_{1-6}), QM (K_{5,9}), and SM (K_8) obtained from field measurements
  - Measured field and alignment errors

◆ Time dependent imperfections
  - Static leakage fields from the extraction beam line:
    K_{0,1} and SK_{0,1} estimated from measured COD and optical functions
  - Edge focus of the injection bump magnets:  
    K_{1} estimated from measured optical functions
  - BM-QM field tracking errors
    estimated from measured tune variation over acceleration
  - 1-kHz BM ripple
    estimated from measured orbit variation
  - 100-kHz ripple induced by injection bump magnets
    estimated from turn-by-turn BPM data . . . etc.

◆ Foil scattering:
  Coulomb & nuclear scattering angle distribution calculated with GEANT

✓ Now the numerical simulation gets a good agreement with measurements and plays a vital role in solving the beam loss issues in the RCS.
J-PARC 3GeV RCS reaches 1MW

Intensity dependence of beam loss

BLM signals @ collimator over the first 3 ms in the low energy region

Calculations

Number of lost particles/turn

Loss power (W)

Intensity (x 10^{13})

The intensity dependence of beam loss almost had a linear response up to the 429-kW beam intensity.

But the extra beam loss increase was observed for the 573-kW beam intensity.

Making use of the numerical simulation result, a possible cause of the extra beam loss was investigated.

From Hideaki Hotchi’s talk
Space Charge Studies on the ISIS Ring

From Christopher Warsop’s talk

Outline of ISIS

- Injector
  - H⁺ Penning Ion Source
  - 665 keV RFQ
  - 70 MeV DTL Linac

- Ring
  - 70 - 800 MeV RCS

- Target Stations
  - TS1 40 Hz
  - TS2 10 Hz

- Mean beam power ~ 200 kW
Space Charge Studies on the ISIS Ring

2.3 ISIS II: 1-10 MW machine - FFAG route

- FFAGs now a serious option
  Studies of ASTeC/IB at RAL

- Designs now being developed
  EG G H Rees 0.8-3 GeV FFAG design

- Intensity limits → losses?

- New R&D into intensity limits of FFAG
  Experimental work KURRI with ASTeC/IB
  SPOD at RAL (plasma trap)
  Ideas for new research ring on FETS

- Understand relative merits FFAG & RCS
  Important overlap in RCS-FFAG studies

D Kelliher, S Machida, C R Prior, G H Rees, S Sheehy, et al ASTeC/IB

From Christopher Warsop’s talk
A NON-DESTRUCTIVE PROFILE MONITOR FOR HIGH INTENSITY BEAMS

W. Blokland and S. Cousineau, ORNL *, Oak Ridge, TN 37831, U.S.A

Abstract

A non-destructive profile monitor has been installed and commissioned in the accumulator ring of Spallation Neutron Source (SNS). The SNS Ring accumulates during a 1 ns cycle high intensity proton bunches of up to 1.5e14 protons with a typical peak current of over 50 A and a bunch length of about 0.7 μs.

The profile monitor consists of two systems, one for each plane, with electron guns, correctors, deflectors, and quadrupole magnets to produce pulsed electron beams that scan through the proton bunch. The electric and magnetic fields of the proton bunch alter the trajectory of the electrons and their projection on a fluorescent screen. The projection is analyzed to determine the transverse profile of the proton bunch. Because the duration of the electron scan is very short compared to the bunch length, the longitudinal profile can be obtained by making multiple scans while varying the time delay relative to the proton bunch.

This paper describes the theory, the hardware and software, analysis, and results of, as well as improvements made to the electron scanners. The results include a comparison of wire scanner profiles of extracted ring beam with the profiles of ring beam from the electron scanner.

INTRODUCTION

\[
\frac{d\theta}{dx} = \int L \frac{e}{mv^2} \cdot \frac{\delta(x,y)}{e_0} dy
\]

where \( e \) is the electron charge, \( m \) is the electron mass, \( v \) is the velocity, \( \delta(x,y) \) is the proton beam density distribution, and \( \theta \) is the electron deflection angle. The formula states that the profile can be reconstructed by taking the derivative of the projected curve.

Figure 1: The deflection of a diagonal line of electrons.

While the electrons are similarly deflected if the scan is aligned vertically, one can no longer uniquely associate
Fix-Point Structures in 1D Phase Space
- Example: SPS 1 strong Sextupole

It is interesting to note that in this case the chaotic layer around the 1D un-stable fix-point is so thin that it cannot be detected via simulations! This is typical in 1D.
CERN PS: space charge driven $8
\nu_y = 10 \ (40\nu_y = 50)$ resonance

Space Charge at injection (1.4 GeV)

- Current injection energy: 1.4 GeV
- Typical tune-spread of current operational beam ~ (0.2 ; ~0.3)
- LHC double batch injection:
  Long flat bottom: 1.2s
- HL-LHC beams requirement: tune-spread > 0.3
- LIU Budgets: 5% losses, 5% emittance growth

Importance of the study of present resonances and their influence on the beam.

From Remond Wasef’s talk
CERN PS: space charge driven $8\nu_y = 10 \ (40\nu_y = 50)$ resonance

The beam tune-spread is trapped between the $Q_v=6.25$ and the integer resonances.

- If one increases the vertical tune to avoid growth due to the integer, the losses increase because of the $Q_v=6.25$ resonance
- There are less losses with higher tune-spread because the proton population becomes smaller on the $Q_v=6.25$ after compression.
- The choice of the working point is a compromise between losses and emittance blow-up

From Remond Wasef’s talk
Space charge effect in multi-turn extraction at CERN

From Shinji Machida’s talk, referring to work from S. Gilardoni & M. Giovannozzi
First observations of intensity-dependent effects for transversely split beams during multturn extraction studies at the CERN Proton Synchrotron

Simone Gilardoni* and Massimo Giovannozzi†
CERN, CH 1211 Geneva 23, Switzerland

Cédric Hernalsteens‡
CERN, CH 1211 Geneva 23, Switzerland
and EPFL, CH 1015 Lausanne, Switzerland

(Received 26 April 2012; revised manuscript received 2 April 2013; published 17 May 2013)

During the commissioning of the CERN Proton Synchrotron multturn extraction, tests with different beam intensities were performed in order to probe the behavior of resonance crossing in the presence of possible space charge effects. The initial beam intensity before transverse splitting was varied and the properties of the five beamlets obtained by crossing the fourth-order horizontal resonance were studied. A clear dependence of the beamlets’ parameters on the total beam intensity was found, which is the first direct observation of intensity-dependent effects for such a peculiar beam type. The experimental results are presented and discussed in detail in this paper.

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PACS numbers: 29.20.–c, 29.27.Bd

I. INTRODUCTION

The multturn extraction (MTE) [1,2] has been proposed as a new beam manipulation in the transverse plane. The idea is to cross a resonance exhibiting stable islands. The beam will be eventually trapped in the islands as they move through the phase space area occupied by the charged particles. As a result of this manipulation the beam will be split in the transverse plane. In the case of a stable resonance, two structures will be generated: one representing the beam trapped in the islands, with an effective length corresponding

It should be emphasized that such an extraction method is aimed at providing the most uniform filling of a receiving machine with a circumference length different from that of the extracting machine. At CERN, this is the case for the Proton Synchrotron (PS) transfer to the Super Proton Synchrotron (SPS) for fixed target physics. The current extraction method, the so-called continuous transfer [3] is being gradually replaced by MTE in its PS implementation [4] (see Refs. [5,6] for the accounts of the experimental results and Ref. [7] for a report on the commissioning).

The splitting process is performed on the 14 GeV/c
FIG. 7. Superposition of the horizontal beam profiles measured after splitting for various beam intensities. The displacement of the four outermost beamlets due to the change in the total beam intensity is clearly visible. The raw data are fitted here with splines to improve the visibility of the different profiles. The results shown in Figs. 9 and 11 have been obtained by fitting the raw data with the function of Eq. (6).

From S. Gilardoni & M. Giovannozzi's paper
Shift of the islands depends on momentum.

From Shinji Machida’s talk
Continuum Models for Space Charge Instabilities in Fixed-Field Rings

Shear Inviscid Instability

Unzoomed

Zoomed

From Antoine Cerfon’s talk
Continuum Models for Space Charge Instabilities in isochronous Rings

**Shear Inviscid Instability**

![Image of shear inviscid instability](image)

Figure: Linear and nonlinear instability of a compressible shear layer described by the Navier Stokes equation\(^4\)


From Antoine Cerfon’s talk
Continuum Models for Space Charge Instabilities in isochronous Rings

From Antoine Cerfon’s talk
Historical remarks on space charge

1963 High Energy Accelerator Conference (Dubna)
   - L. Smith (LBL): envelope modeling of gradient errors (→ higher intensity
due to coherent force – quadrupolar resonance not determined by s.p. Q!)

1960’s: MURA (Midwestern Universities Research Association, 1953-
64) hosted many ground-breaking developments on high intensity with
planned FFAG – failed “politically” 1964
   - D.C. Morin (MURA-report, 1962): Integer resonance not at Q, but at Q₀!

1976 ... 1990’s: strong boost of space charge studies by heavy ion
inertial fusion (HIF)
   - 1978 Rutherford SNS-workshop on space charge issues for HIF

1998 Coming of SNS (Shelter Island Workshop in 1998) – many early
concerns – partly unjustified, partly not well understood

Beyond 2000: SNS + JPARC worked, FAIR, LHC + upgrade
   - to-date: tremendous increase in understanding!!

From Ingo Hofmann’s talk
PIC noise study

From Ingo Hofmann’s talk

\[ \epsilon_{6d} \sim S \text{ (entropy)} \]

in equilibrium beam

Minimizing rms entropy growth → determine optimum grid/particle resolution

\[ \frac{\Delta \epsilon}{\epsilon} \]

optimum

grid dominated
- not resolving Gaussian profile -

collision dominated
- charge \( \sim 1/N \) -

Propagation of numerical noise in PIC tracking

Tracking of a coasting beam in a constant focusing channel.

From Frederik Kesting’s talk

Basic idea of maps:

\[
\begin{pmatrix}
  x'_i \\
  x'_f
\end{pmatrix} \rightarrow \begin{pmatrix}
  x'_f \\
  x'_f
\end{pmatrix} = M(s_i, s_f) \begin{pmatrix}
  x_i \\
  x_i
\end{pmatrix}
\]

Space charge can be modeled by kicks:

\[
x'_i \rightarrow x'_f = x'_f + \Delta s \frac{g_{Ex}(x_i, y_i)}{y_0 p_0}
\]

From Frederik Kesting’s talk
Propagation of numerical noise in PIC tracking

Space charge simulation for the SIS100 at FAIR

Emittance: $\varepsilon_x = \varepsilon_y = 30 \text{ mm mrad}$
Current: $I = 30 mA$

grid: $128 \times 128$
macro-particles: 1000 resp. 5000

1000 macro - particles

5000 macro-particles

From Frederik Kesting’s talk
Propagating numerical noise in PIC tracking

Correlated in Numerical Noise - Simulation

Stochastic resonances (SR) in particle-in-cell tracking!
(constant focusing channel with strong space charge)

\[ \Delta s = L \quad \Rightarrow \quad \Delta \Phi = Q_y \]

Condition for SR:

\[ n \Delta \Phi \in \mathbb{N} \]

From Frederik Kesting's talk
$N_b = 0.16 \times 10^{12}$ \hspace{2cm} $N_b = 0.8 \times 10^{12}$ \hspace{2cm} $N_b = 1.6 \times 10^{12}$ \hspace{2cm} $N_b = 3.2 \times 10^{12}$

From Adrian Oeftiger’s talk
Space charge simulation of Injector II cyclotron (OPAL)

From Anna Kolano’s talk

Courtesy: Richard Kan, PSI
Space charge simulation of Injector II cyclotron (OPAL)

From Anna Kolano’s talk—last turn

Collimators → rectangular “boxes”
Space charge simulation of Injector II cyclotron (OPAL)

From Anna Kolano’s talk—last turn