Beam Loss Control on the ESS Accumulator Rings

Chris Warsop
Rutherford Appleton Laboratory, UK

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- Requirements for Ring Beam Loss Control
- Collimator Design
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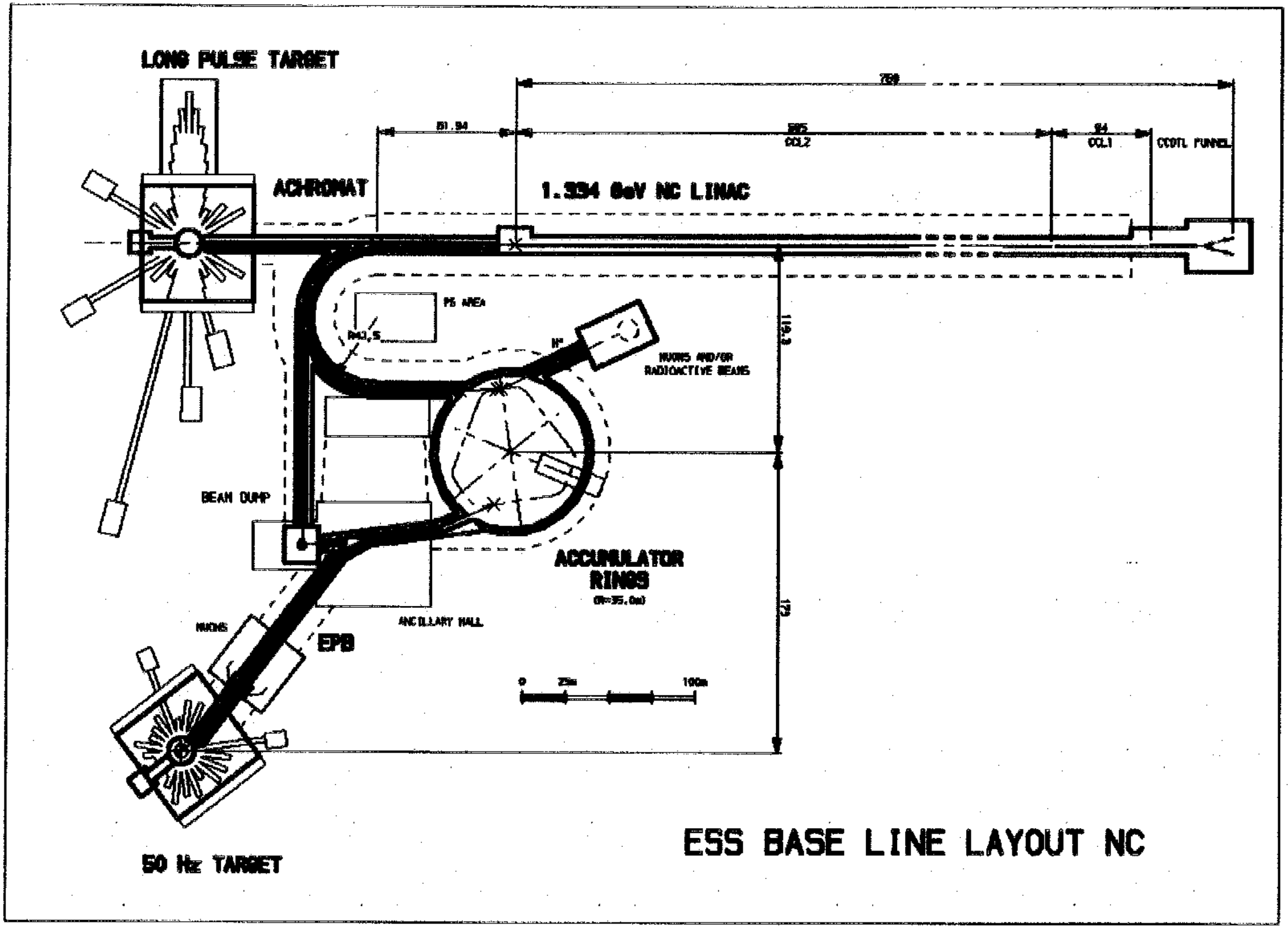
- Summary



LONG PULSE TARGET
ACHROMAT
1.334 GeV NC LINAC
CCL2
CCL1
CCDTL FUNNEL
PS AREA
MUONS AND/OR
RADIOACTIVE BEAMS
BEAM DUMP
ACCUMULATOR
RINGS
ANCILLARY HALL
MUONS
EPB
50 Hz TARGET
ESS BASE LINE LAYOUT NC

The ESS Accelerators

- Accumulator Rings Provide

~ 1 μs Pulses of 4.68×10^{14} ppp @ 50 Hz: Mean Power 5 MW

- Operation

1.334 GeV H^- Linac: Mean/Peak Current 80 mA/114 mA
Two Rings Operate in Parallel at 50 Hz
H^- Injection: Accumulate 2.34×10^{14} in each over 600 turns
Chopped at Ring Revolution Frequency 1.242 MHz
Captured in Ring DHRF System: Extraction Gap
Fast Extraction and Transport to Target

- Low Loss Design

Injection Line Achromat with 3 D Collimation of H^-
Highly Optimised Injection: H^-, H^0, e^- removal
3 D Painting
~ 1 foil recirculations

- Concern here is loss once protons enter the Rings

Uncontrolled Loss < 1 W/m
Total Uncontrolled Ring Loss ~ 0.01% (R=35 m)

Ring Beam Losses

- Regular Loss – 50 Hz during operational running

(i) Expected Losses: Foil Interactions 0.01 %

Transverse Emittance Growth
Momentum Tail

(ii) Possible Losses: Unexpected, Errors ? %

~ Allow for non-optimal conditions ~

- Severe Fault Loss – Diagnostics Turn Beam Off

~ 1 bad pulse lost before beam tripped off ~

- Main Aims of Collection System

Localise ~ 1 kW regular loss: keep uncontrolled loss < 1 W/m

Minimise loss at extraction

Control losses due to non ideal / severe fault conditions

- Ability to control loss may determine highest intensity

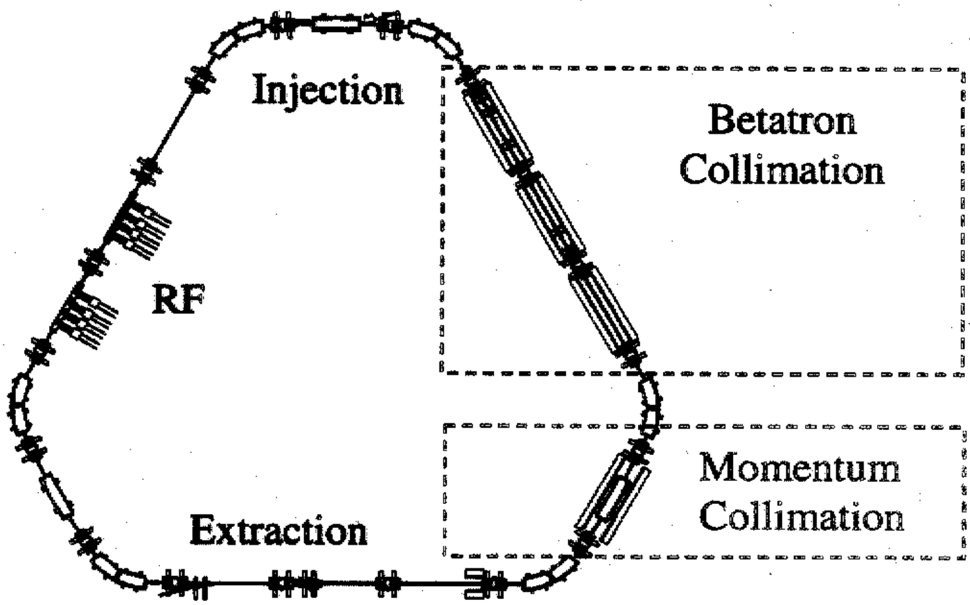
Ring Beam Loss Collection Systems

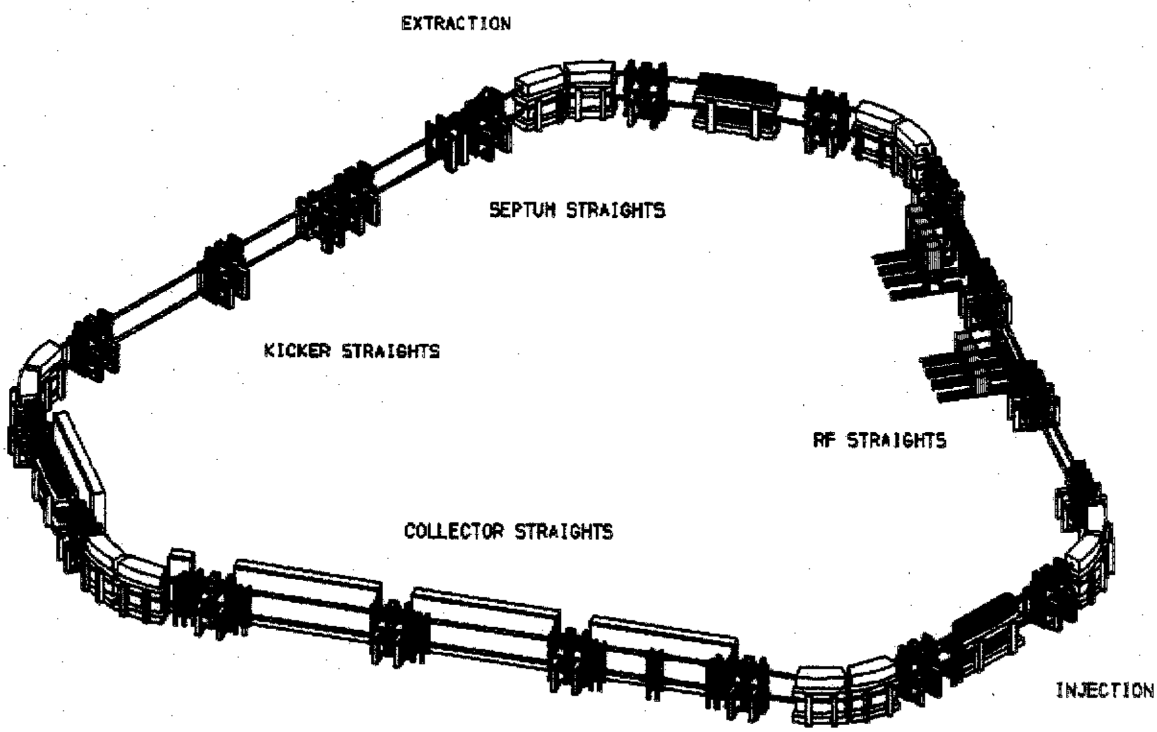
Machine Collimation Limits (π mm mr)	
Painted Beam Emittance	150
Primary Collimation	260
Secondary Collimation	285
Aperture	480
Extraction System	260-285
Momentum Collimation	$\lvert dp/p \rvert \geq 0.8\%$

(1) Betatron (and Momentum Tail) System	
Placement	Dedicated Dispersionless Straight
Importance	Most Expected and Possible Loss
Main Loss Effects	Foil Interactions, Emittance Growth
Expected Loss Levels	< 1 kW
Planes	Horizontal and Vertical
Number of Collectors	1 Prim. and 2 (+2) Secs. per Plane
Relative Betatron Phases	0°, 90°, 164° (also 20°, 32°)
Jaw Configuration	Both Sides of Beam (Double Jaws)

(2) General Momentum System	
Placement	Dispersion Max after Coll$^{\underline{n}}$ Straight
Importance	Precaution
Main Loss Effects	Leakage from Betatron System, Errors
Expected Loss Levels	< 10 W
Number of Collectors	1 Prim.

ESS Accumulator Rings





Practical Considerations

Combine Horizontal and Vertical Jaws into Box Construction

Minimal Number of Mechanical Units: Active Parts Enclosed

Provide Collimation of Secondary Particles: Protect Quads etc

Layout of Collimator Boxes

Jaw	Ideal Phase		Actual Phase		Relative Lattice Position (m)
	ϕ_h	ϕ_v	ϕ_h	ϕ_v	
Primary H&V	0	0	0	0	0.1
Protective	-	-	20	20	4.4
Protective	-	-	32	32	8.4
Secondary H&V	90	90	100	82	20.9
Secondary H	163	-	159	-	33.0
Secondary V	-	163	-	146	37.5

Finite Length Jaws Cover ~ 4° phase

Flat Rectangular Jaws: Options for Longt[l] Trans[y] Angles

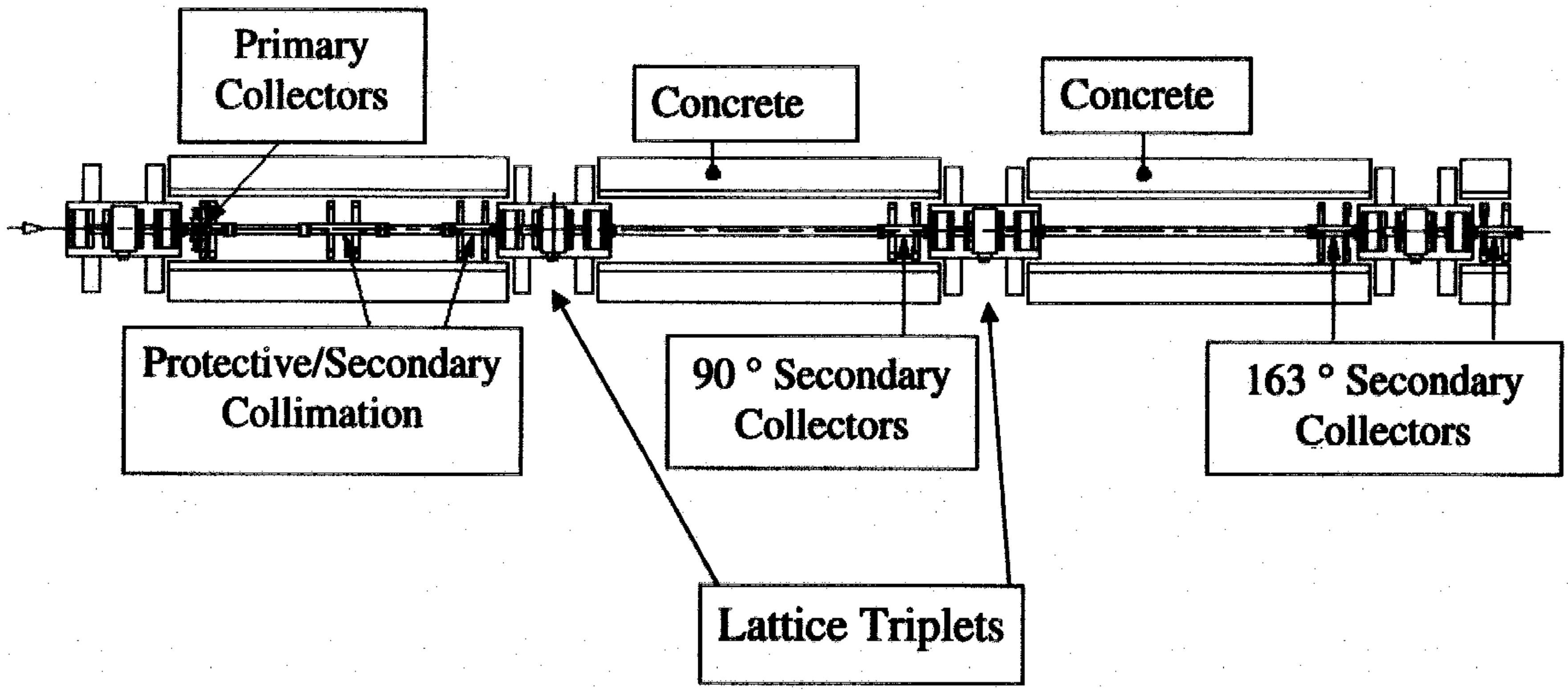
Copper Primary (0.5 m), Graphite Secondaries (1.0 m)

Straight Enclosed in Concrete Shielding

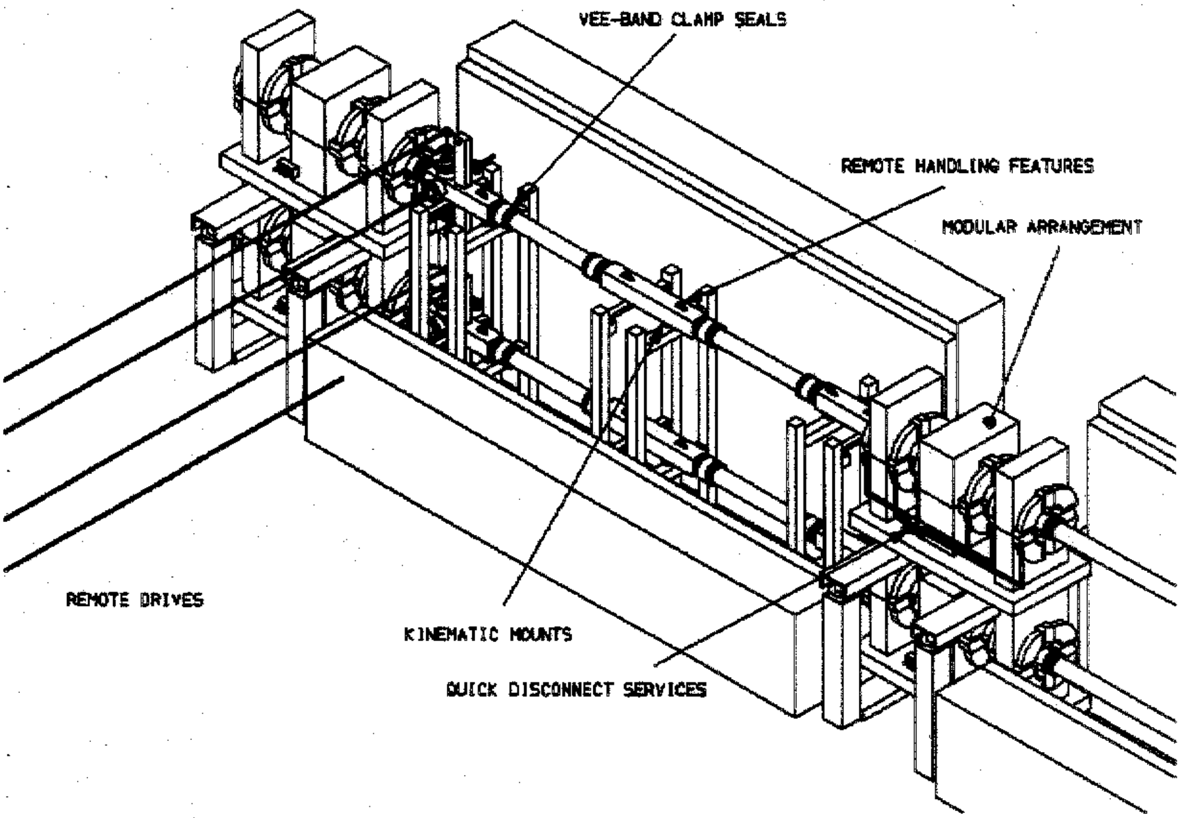
Active Handling Concepts: Quick Installation/Removal

Active Collimation: Beam in Gap Kicker, Dipole Steering

Collimator Straight Layout



Ring Collector Details



Monte Carlo Simulation

- Primary Protons Only
- All Important Processes

  Multiple Scattering (Moliere)
  Nuclear Inelastic/Elastic Scattering
  Ionisation Energy Loss/Straggling

- 3 D Model of Collector Jaws
- Detailed Model of ESS Rings and Apertures
- Treatment of Errors/Misalignments etc.

  Random Errors: Quads k ± 0.5%
  Alignment ± 1.5 mm, ± 1.0 mr

- Treat Many Loss Modes
- All code tested against published/experimental data

Used selected GEANT, CERN, ACCSIM routines/methods.

Basic Tests: Check Transverse Collimation

- Test Beam: ε_h & ε_v: 0-480 π mm mr (uniform)
  $\frac{\Delta P}{P}$: $\pm$ 0.6% (uniform)

- **Single Turn Results**

Loss Distribution

β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
59.6±0.8%	37.7±0.4%	2.4±0.1%	0.3±0.1% (0.4*)

** Very Small Variations due to Machine Errors*

Collimated Halo (π mm mr)

	90%	95%	99%
ε_h	275±2 (301*)	297±3 (334*)	344±3 (374*)
ε_v	270	288	331

** Worst Case Values with Machine Errors*

- **Multiple (10) Turn Results**

Loss Distribution

β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
67.0±0.8%	30.4±0.4%	2.3±0.1%	0.3±0.1% (0.4*)

** Very Small Variations due to Machine Errors*

Collimated Halo (π mm mr)

	90	95	99
ε_h	237±2 (243*)	251±3 (261*)	261±3 (281*)
ε_v	237	250	260

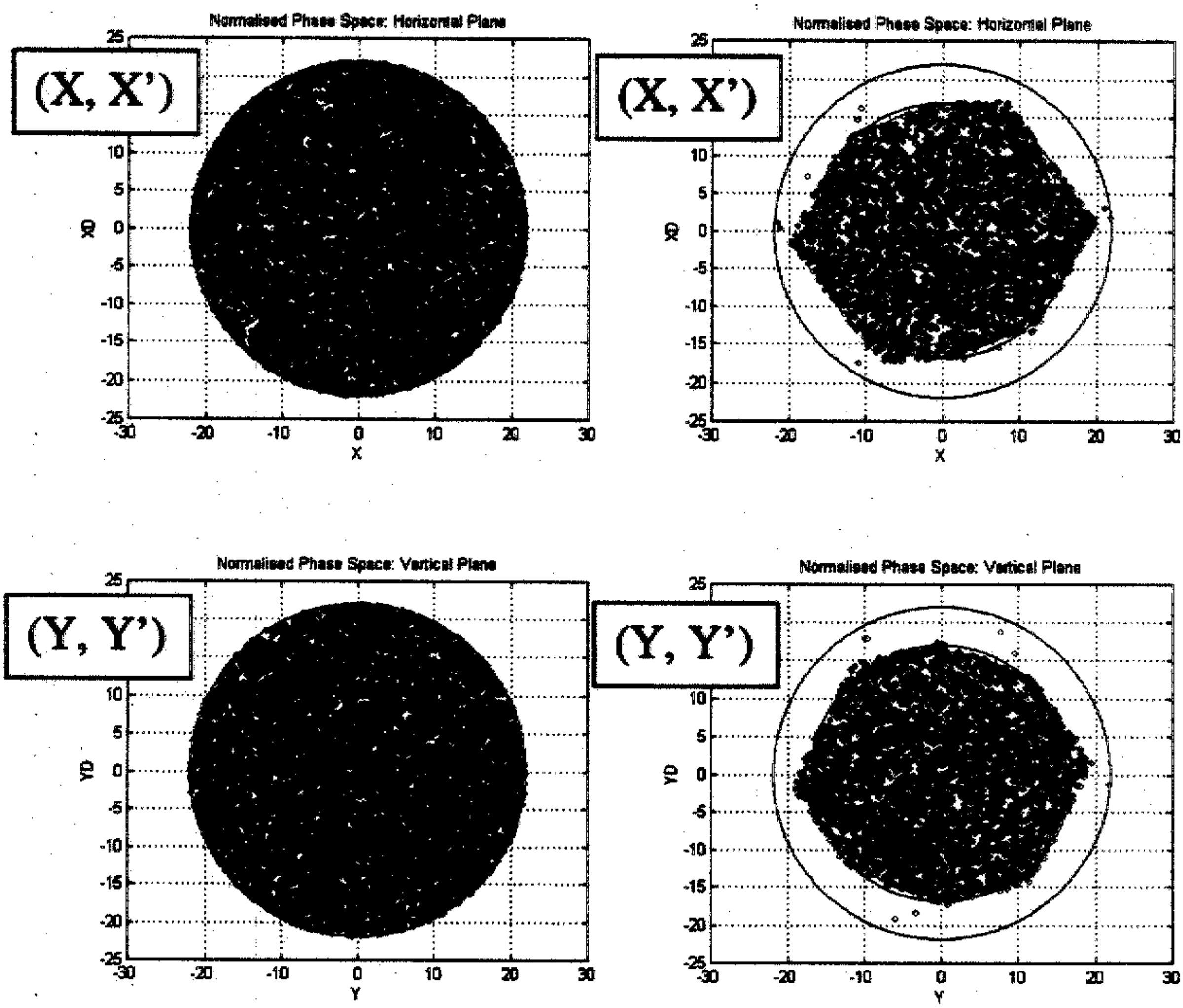
** Worst Case Values with Machine Errors*

Summary of Simulation Tests

- Basic Checks of Transverse Collimation
- Transverse Collimation as a Function of Growth Rate
- Collimation of Transverse Halo before Extraction
- Momentum Tail Collimation
- General Momentum Collimation
- Foil Induced Loss Levels
- Effect of Jaw Geometry on Collimation Efficiency
- Effect of Jaw Material on Collimation Efficiency
- Effects of Machine Errors and Q Shifts

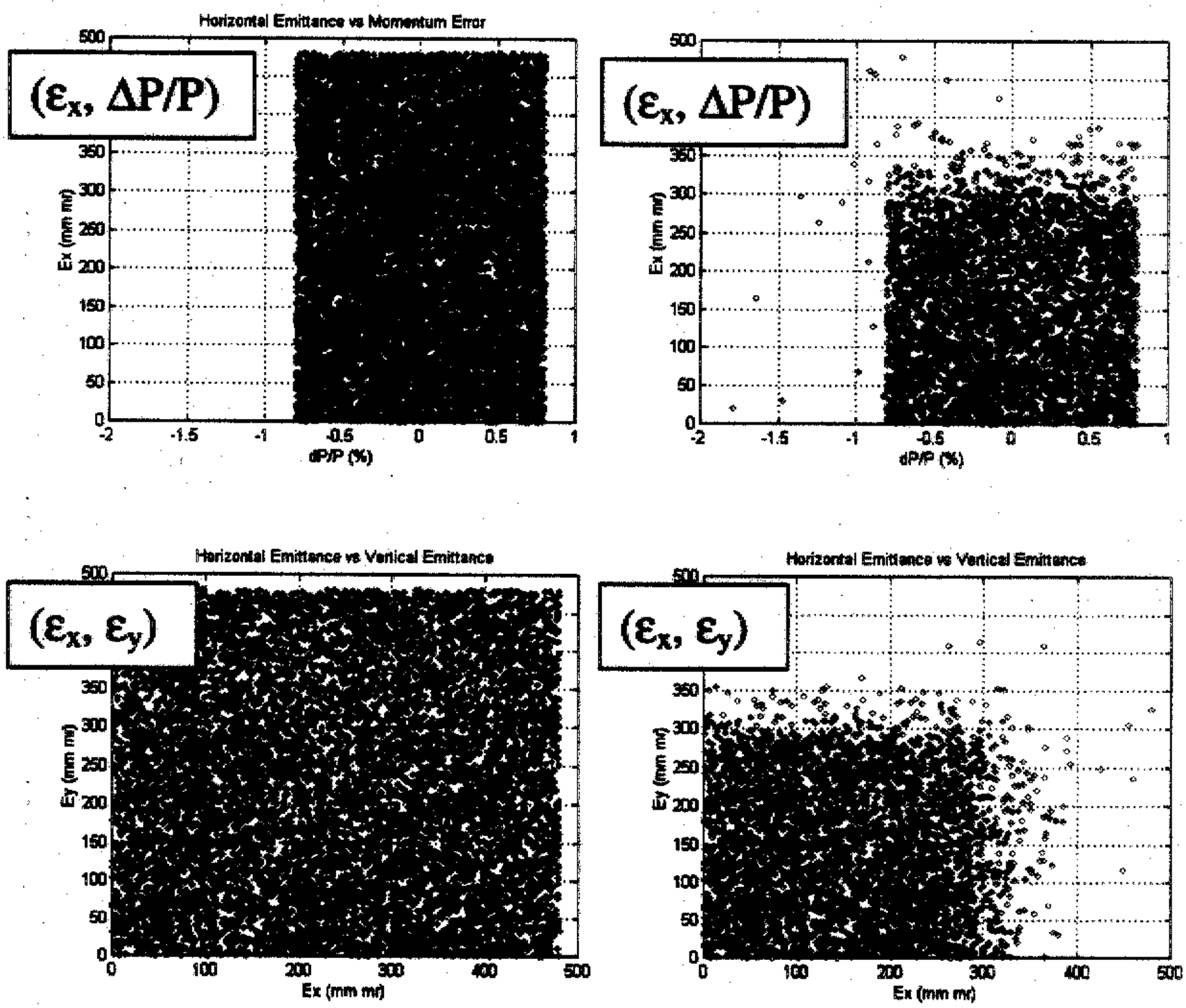
Basic Tests of Transverse Collimation
Single Turn

Input | **Collimated**



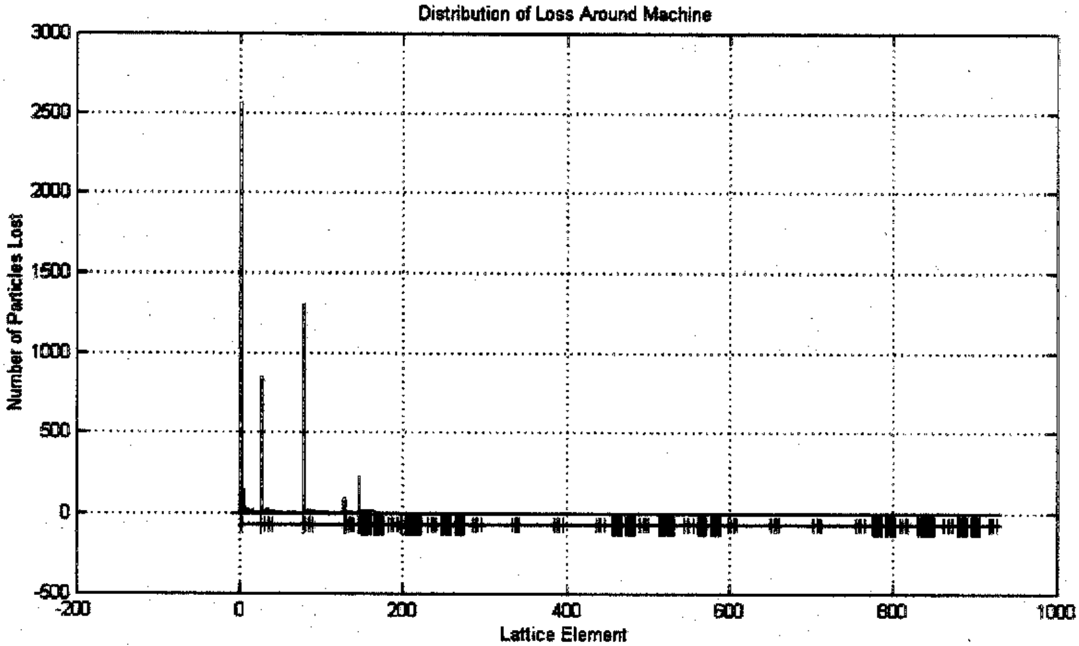
Basic Tests of Transverse Collimation
Single Turn

Input | **Collimated**



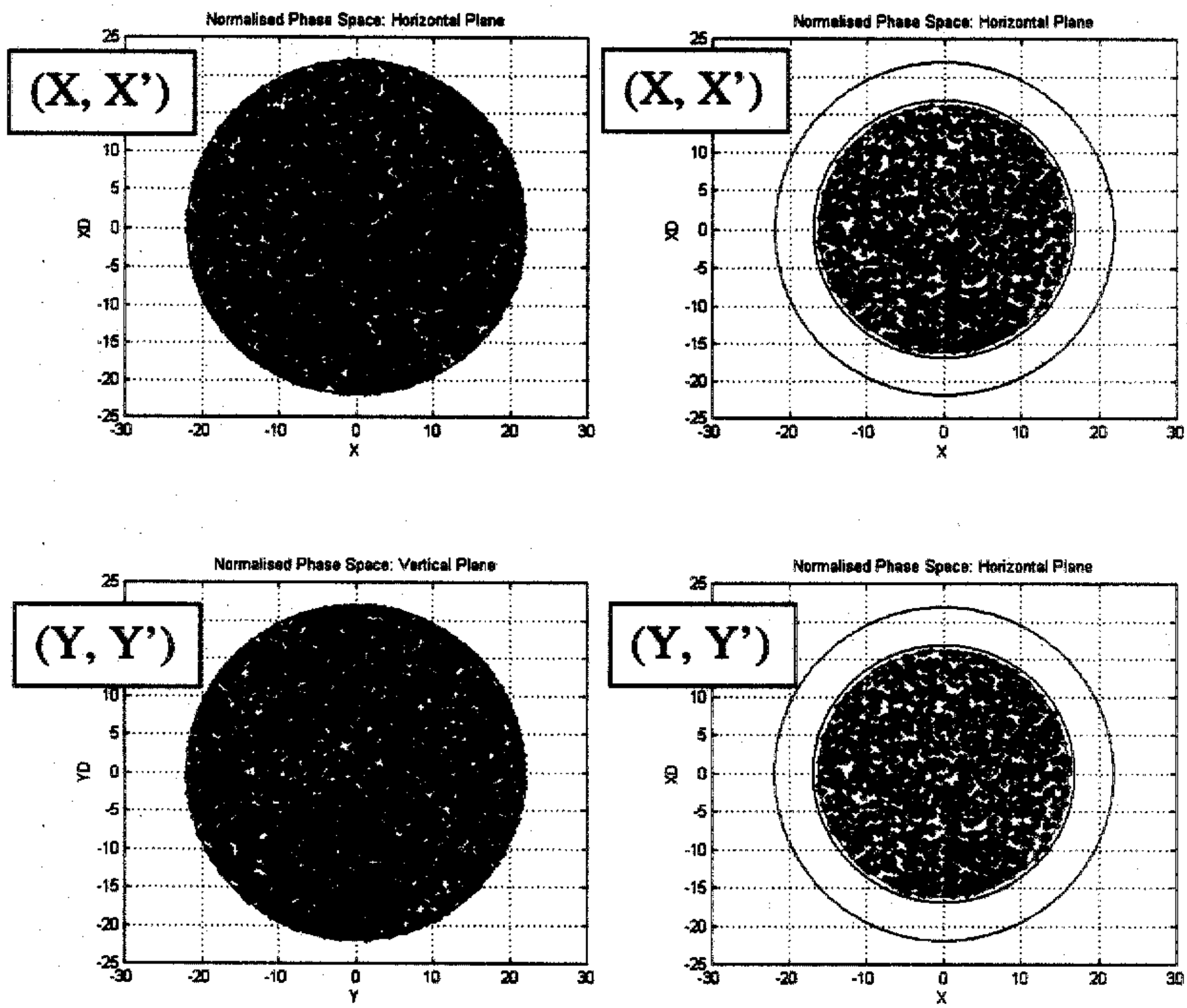
Basic Tests of Transverse Collimation
Single Turn

Loss Distribution around Machine



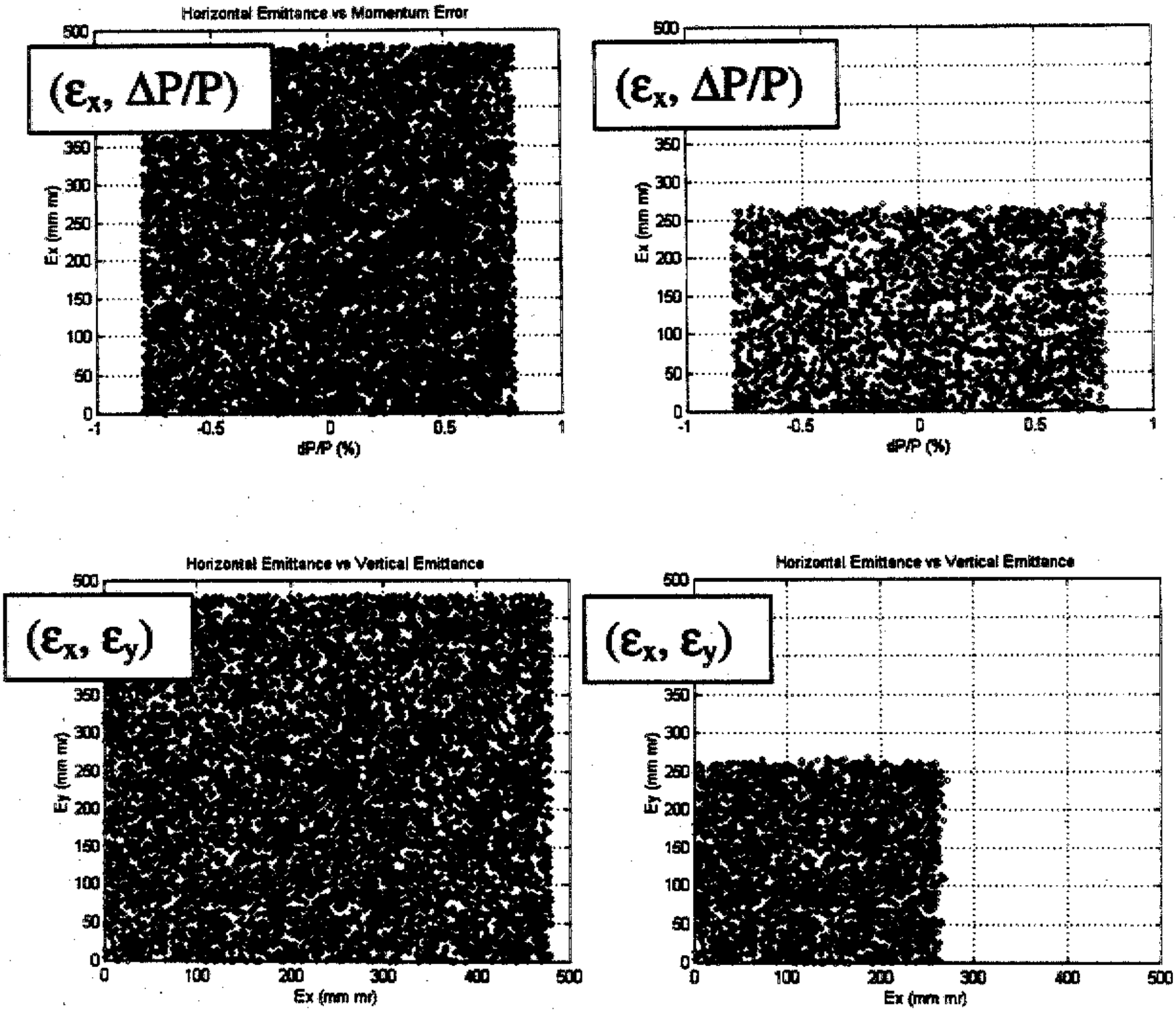
Basic Tests of Transverse Collimation
Multiple Turn

Input | Collimated



Basic Tests of Transverse Collimation
Multiple Turn

Input **Collimated**



Collimation as a Function of Transverse Growth Rate

- **Test Beam:** ε_v: Matched Contour with **GR**
  ε_h: 0-260 π mm mr
  $\frac{\Delta P}{P}$: $\pm 0.6\%$

Growth Rates (GR) at Primary 1, 10, 100, 1000 μm/turn

- **Results**

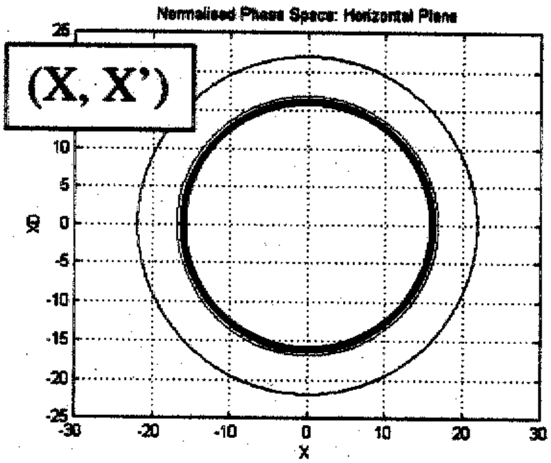
Loss Distribution

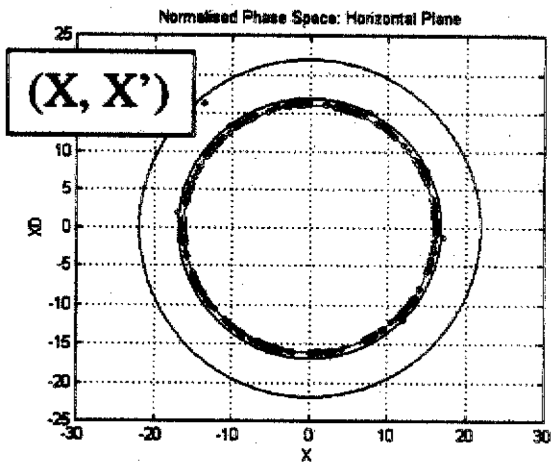
GR	β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
1	53.5 (40.3*)	43.3 (48.6*)	2.5 (6.5*)	0.7 (4.6*)
10	75.0 (85.1*)	25.0 (11.5*)	1.0 (2.0*)	0.4 (1.4*)
100	91.8	8.0	0.3	0.1 (1.5*)
1000	96.7	3.1	0.1	0.0 (1.5*)

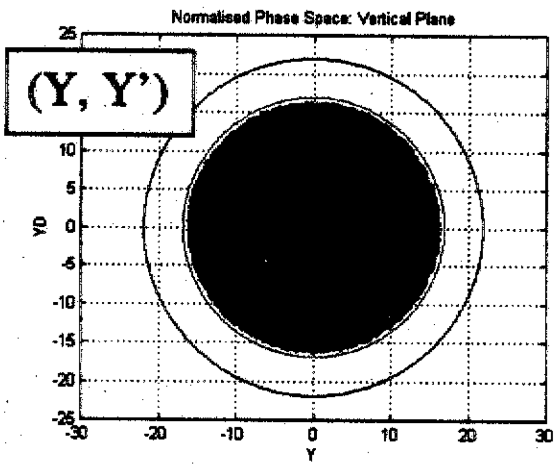
** Worst Case Values with Machine Errors*

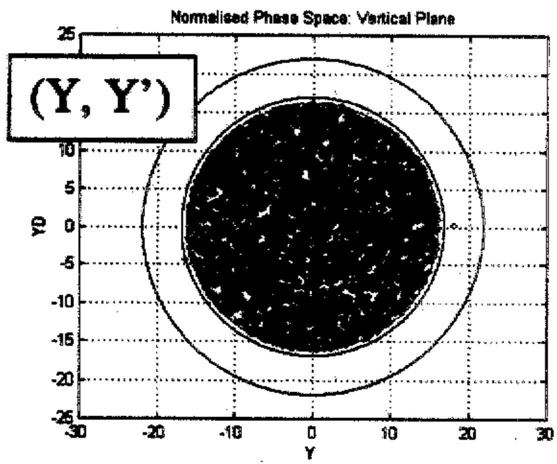
Tests of Transverse Collimation with Growth Rate
Multiple Turn

Input | Collimated





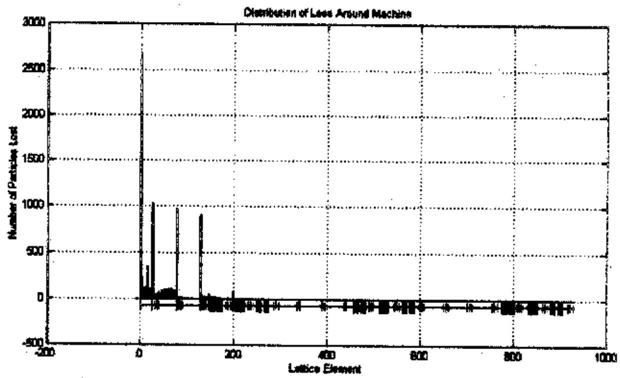




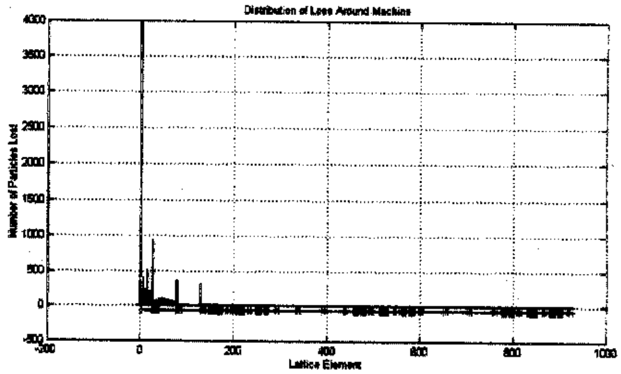
Tests of Transverse Collimation with Growth Rate
Multiple Turn

Loss Distribution around Machine

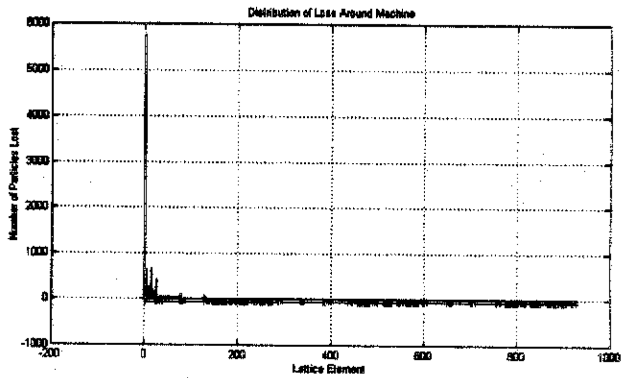
1 μm/turn



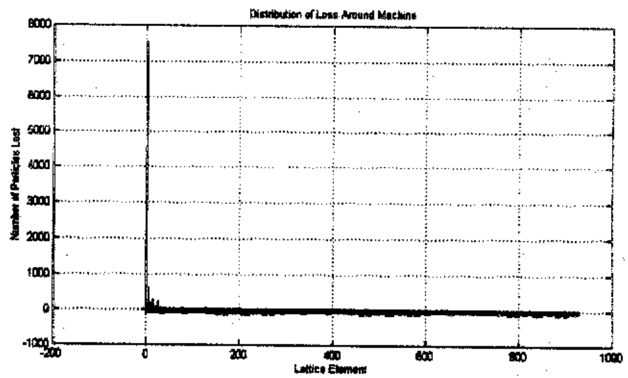
10 μm/turn



100 μm/turn



1000 μm/turn



Study of Collector Options (a)

Transverse Angle on Collector Jaw

~ *Enhance impact depth and efficiency?*

- **Test Beam:** ε_v: matched contour with GR=10 μm/turn
  ε_h: 0-260 π mm mr
  $\frac{\Delta P}{P}$: ± 0.6%

- **Results**

Loss Distribution

GR	β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
10° angle on primary				
10	87.0	12.1	0.5	0.4
no angles				
10	75.0	23.6	1.0	0.4

Longitudinal Angle

~ *Jaws parallel to beam envelope: enhance removal?*

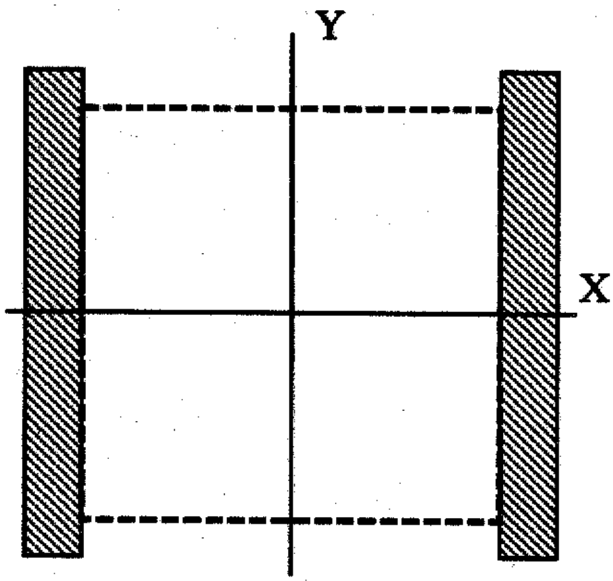
- **Test Beam: as above**

- **Results**

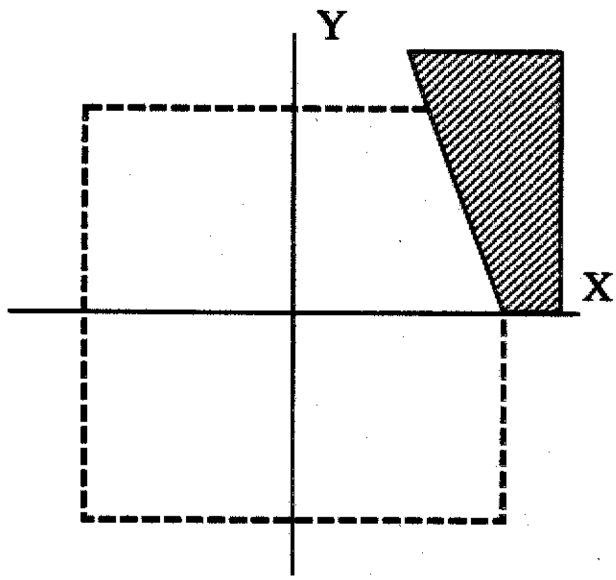
Loss Distribution

GR	β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
longitudinal angles on all				
10	77.8	21.6	0.5	0.1
no longitudinal angles				
10	75.0	23.6	1.0	0.4

Primary Jaw Shapes



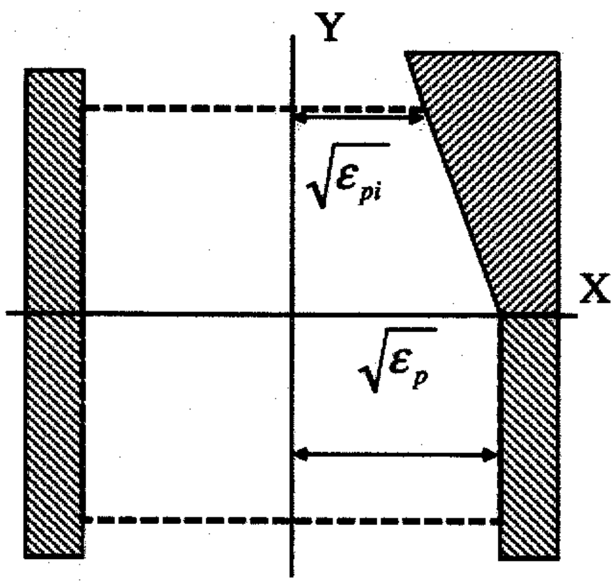
Double Jawed, Flat



Single Jawed, Angled

ε_{pi}=240 π mm mr

ε_{p}=260 π mm mr



Combination

Study of Collector Options (b)

- **Material for Primary Jaws**

~ *Relative advantage of high A materials?*

- **Test Beam: as above**

- **Results**

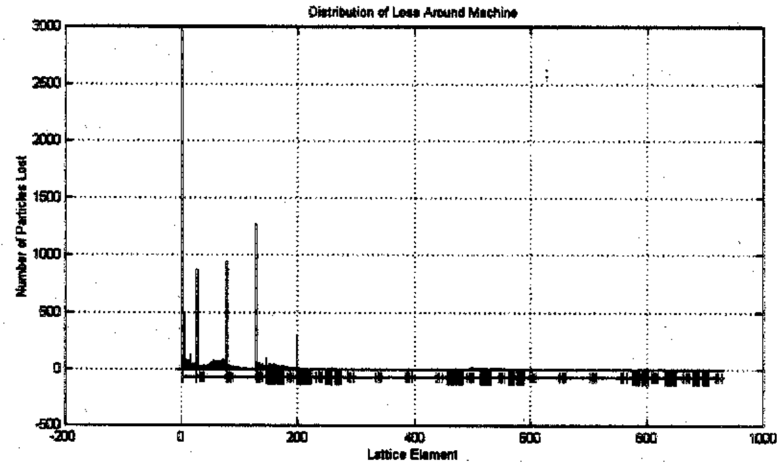
Loss Distribution

Material	β Cell 1	β Cell 2 & 3	P Coll	Rest of Machine
C	50.3	39.3	7.1	3.3
Cu	75.0	23.6	1.0	0.4
W	89.6	10.0	0.3	0.1
Pt	90.8	8.9	0.2	0.1

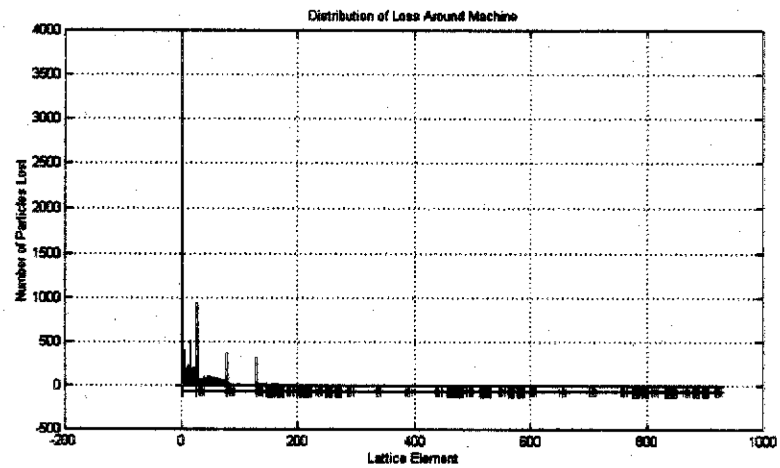
Notes: - **Geometry Identical in all cases**
- **Secondary Jaws Graphite in all cases**

Variation of Beam Loss Distribution with Primary Jaw Material

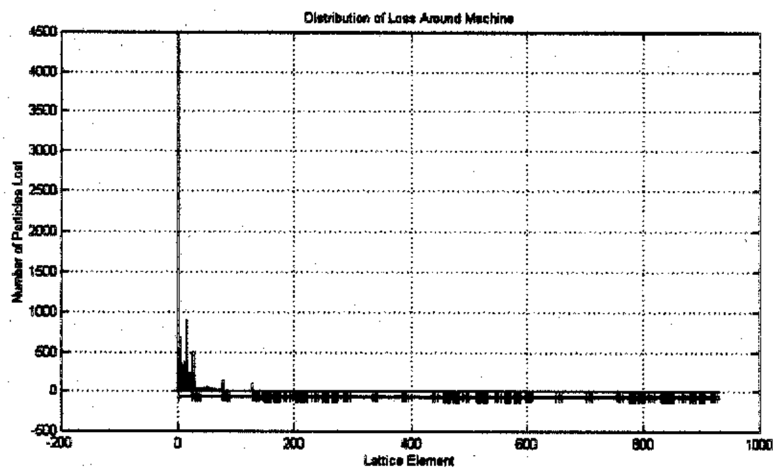
Graphite Primary



Copper Primary



Tungsten Primary



Loss Distributions

- Expected Loss Distributions

~ *Depend on type of loss*
~ *Real Distribution = Sum Over Loss Modes*

Use 'representative' 10 μm/turn Transverse GR

- Distribution around Machine

Loss Levels Peak at ~0.1 W/m for 1 kW Total Loss

- Distribution in/near Collimator Straight

Most loss is on Collimators

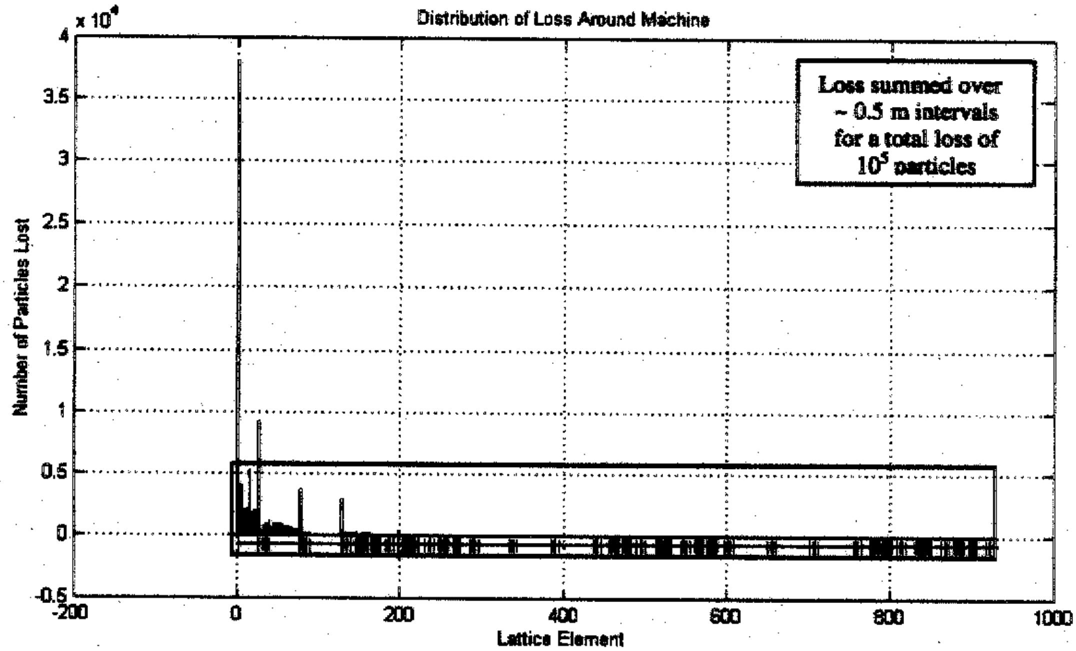
Loss Rates For 1 kW Total Loss

1st Quads/Cell	~20 W/m
Dipoles	~ 1 W/m

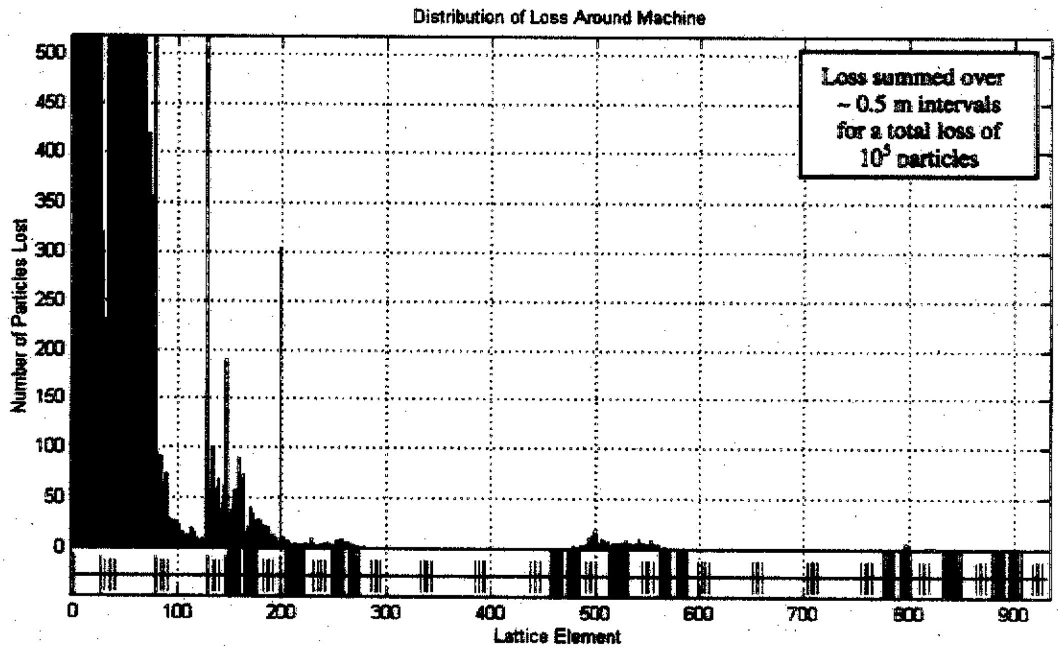
Is a Rough Guide ~ More Detailed Calculations Required for Dose Rates etc.

Expected Loss Distributions: Whole Machine

For 10μm/turn horizontal growth rate (no errors)



Loss around Whole Machine: Magnified Vertical Scale



Conclusions and Future Work

- **Summary**

Loss Control to 90-95% levels expected

Apertures selected work well

Main effect of errors is larger surviving halo

Simple design (approx. positions, flat jaws) works well

Transverse angles do improve efficiency with slow GR

Optimisation of design for loss/activation within collimator straight to be looked at

Verify code experimentally on ISIS