RING PHYSICS ISSUES

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Contributors

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Sources of Beam Loss

- Primary concern: radio-activation
  - – 100 – 200 m rem / h average activation (30 cm, 4h down)
  - – 1 – 2 W / m average beam power loss ↦ 0.01% of the total intensity @ 1GeV (actual record 0.3% in PSR)
- Sources of beam loss
  - – Space charge: large tune-shift, crossing of resonances
  - – Injection loss: Premature H^- and H^0 stripping, foil hits
  - – Magnet errors: eddy-current & saturation, fringe fields
  - – Instabilities: Head-tail, microwave, coupled bunch, electron cloud
  - – Accidental loss: Ion source and linac malfunction, extraction kicker failure

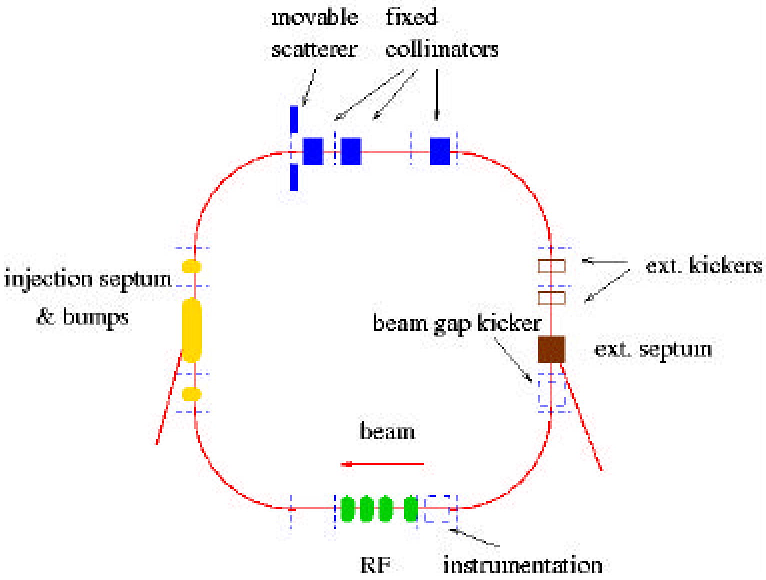
Low-loss Design Philosophy

(Wei et al., PRST-AB, 2000)

- Maximize acceptance (matching)
- Optimize injection process (stripping loss, foil hits, foil survival)
- Design a robust extraction system (two stages fast extraction)
- Improve magnet quality (multipole compensation), provide correction (chromaticity, amplitude detuning, resonances)
- Reduce space charge tune shift (painting)
- Control impedance & instabilities (chromatic sextupoles, energy spreader, tapering, TiN coating)
- Localize beam losses with collimators & Beam-In-Gap kicker
- Engineering issues (hardware shielding for an average 10^{-2} beam loss and up to two full pulses, quick removal of devices)
- Operational flexibility (tuning, painting schemes, adjustable collimation, interchangeable RF cavities)
- Off-normal condition protection (device failures, ground motion)

Ring Optics Design

(J. Wei et al.)

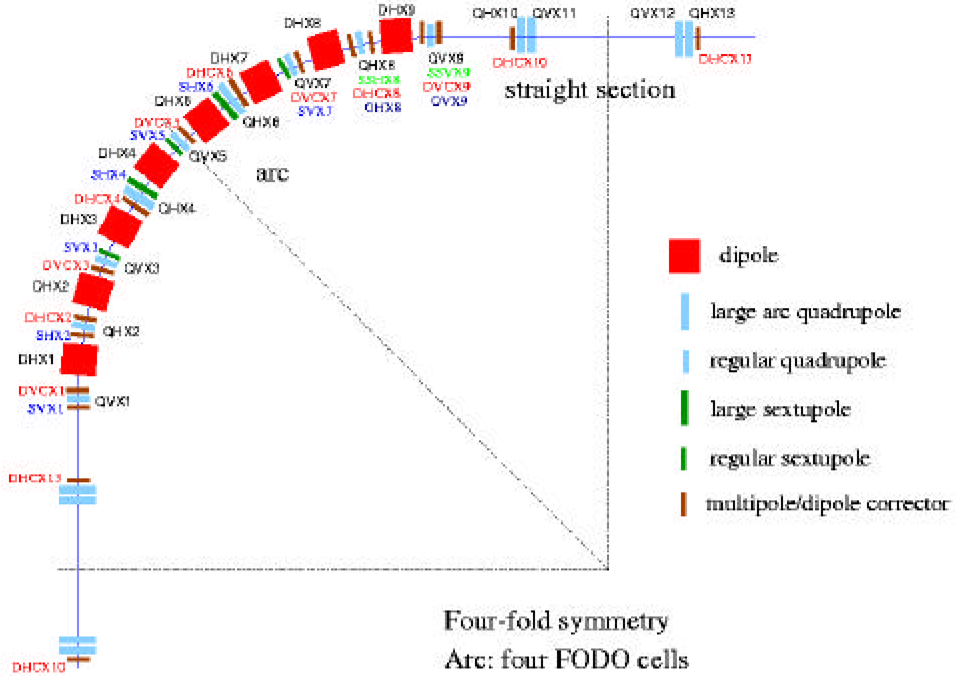


- Separate-function magnets for robustness
- Split tune to suppress coupling (space charge + systematic skew quad errors)
- Avoid structure resonances

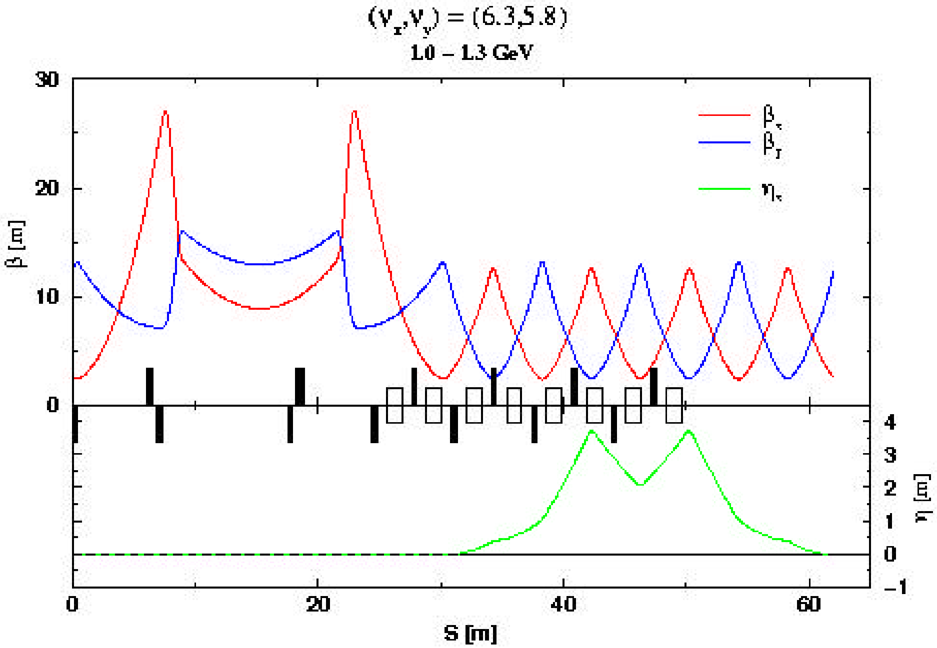
- FODO
  - Modest quad strength
  - Easy for correction (alternating β functions)
- Doublet/triplet:
  - Long uninterrupted straights
  - Less joints, bellows, vacuum chambers
- Four straights with separate functions
  - Injection modules
  - Two-stage collimation
  - Extraction & Beam-in-gap kickers
  - 3(h=1)&1(h=2) interchangeable RF cavities

Ring Lattice and Optics Functions

(J. Wei et al.)



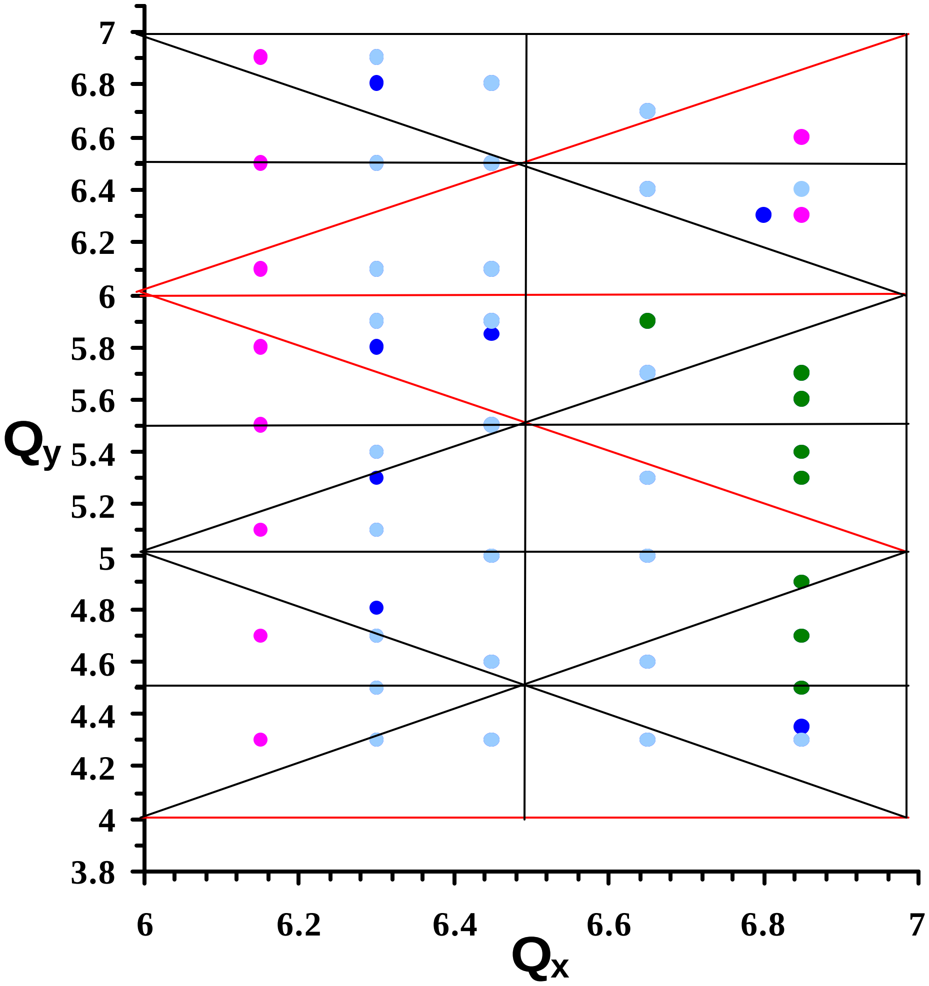
Four-fold symmetry
Arc: four FODO cells
S.S.: doublets



- Perfect matching
- Arc achromats
- Zero dispersion in straights
- Chromatic correction with arc sextupoles
- Resonance correction with correctors in the straights

Tune Survey (cont'd)

(J. Holmes et al.)



Tunability: 1 unit in horizontal, 2 units in vertical

–1st-2nd order structural resonances

–1st-2nd order non-structural resonances

- Excessive maximum b_x
- Excessive maximum b_y

- All constraints satisfied
- All constraints satisfied (preferred)

Injection Beam Loss

(J. Beebe-Wang)

Major sources of beam loss that go to the injection dump:

- Foil Inefficiency (FI)

  Foil 400~200μg/cm^2

  FI = 2~10%

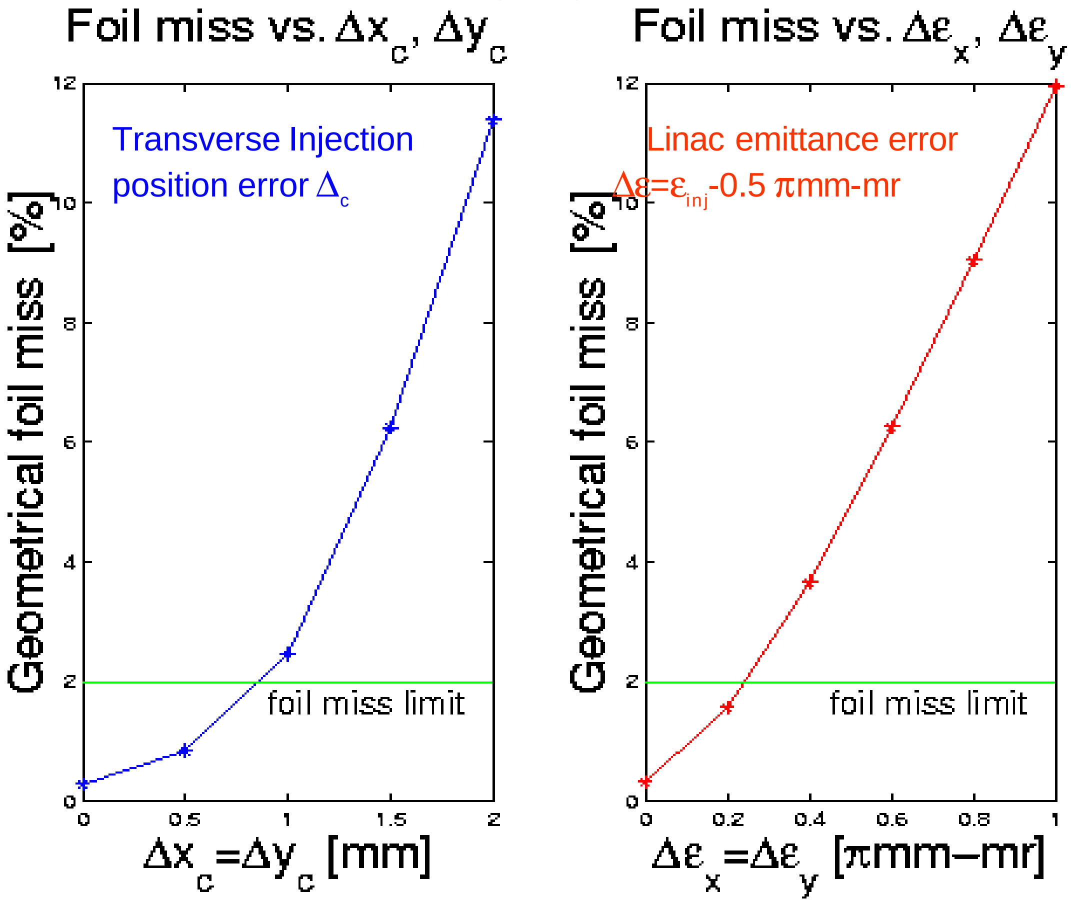
- Foil miss (FM)

  (see figures)

Injection dump limit:

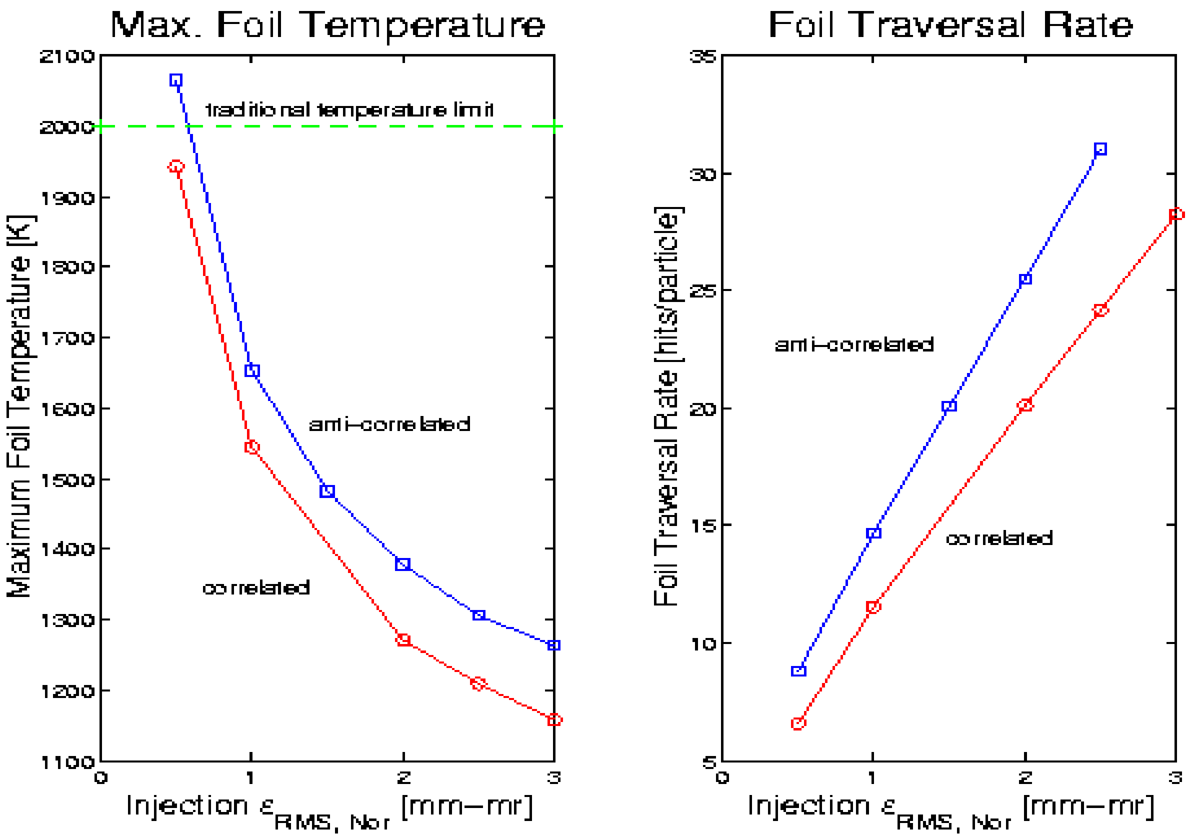
FM + FI ≤ 10%

Beam loss caused by injection errors:



Foil Heating & Scattering

(J. Beebe-Wang)



Emittance optimization (foil life-time, uncontrolled loss)

Beam Loss Due to Foil Traversal

(J. Beebe-Wang et al.)

Beam loss as a consequence of foil traversal through the following mechanism:

(1GeV proton, foil = 300µg/cm^2, foil traversal rate = 7hits/particle)

- Nuclear Scattering

  estimated fractional loss = $3\text{x}10^{-5}$

- Particle loss in gap due to energy straggling

  estimated fractional loss = $3\text{x}10^{-6}$

- Transverse emittance growth due to multiple scattering

  estimated $\Delta\varepsilon$ = $4\text{x}10^{-2}$ πmm-mr

Basic Painting Schemes

(J. Beebe-Wang et al.)

painting scenarios	correlated	anti-correlated
Beam shape without SC	Rectangular	Oval
Beam emittance evolution	Small to large	~ constant
Final emit. $\varepsilon_x+\varepsilon_y$($\pi$mm-mr)	120+120	160
Foil-hit rate (11 linac dist.)	6.1 ~ 8.3	8.0 ~ 10.5
Max foil temp. (K) (11 linac dist.)	2113 ~ 2273	2248 ~ 2376
Horizontal aperture (Δ_H)	1:1	1:1
Vertical aperture (Δ_V)	1:1	1:1.5
Susceptible to coupling	Yes	No
Capable for KV painting	No	Yes
Paint over halo	Yes	No
Horizontal halo/tail	Normal	Normal
Vertical halo/tail	Normal	Large
Satisfy target requirements	Likely	Not likely
Bump function candidates for optimization	Square root; exp(-t/0.3ms); Combination	Square root; exp(±t/0.6ms); Sinusoidal

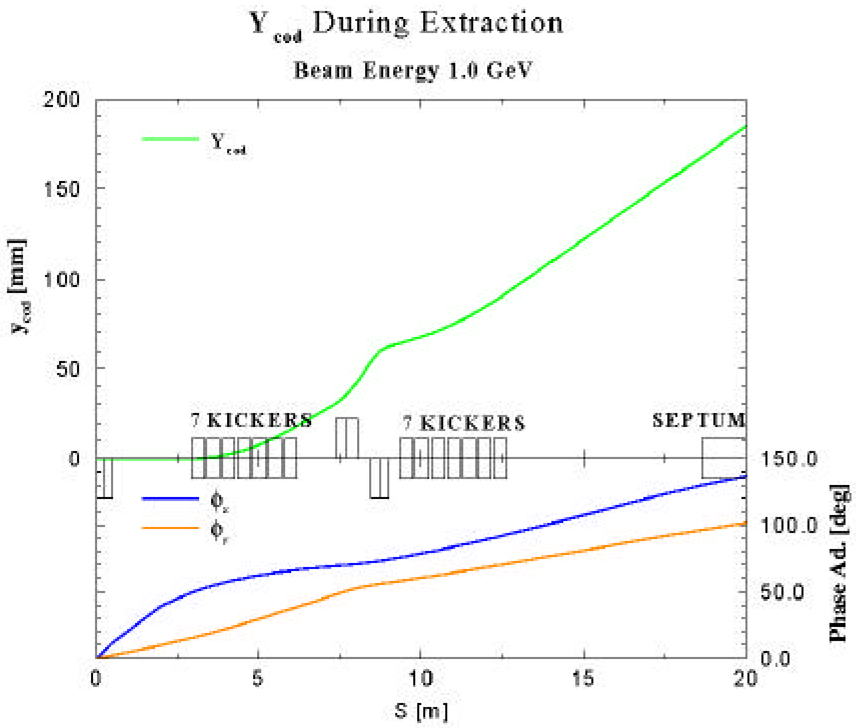
Injection Bump Optimization

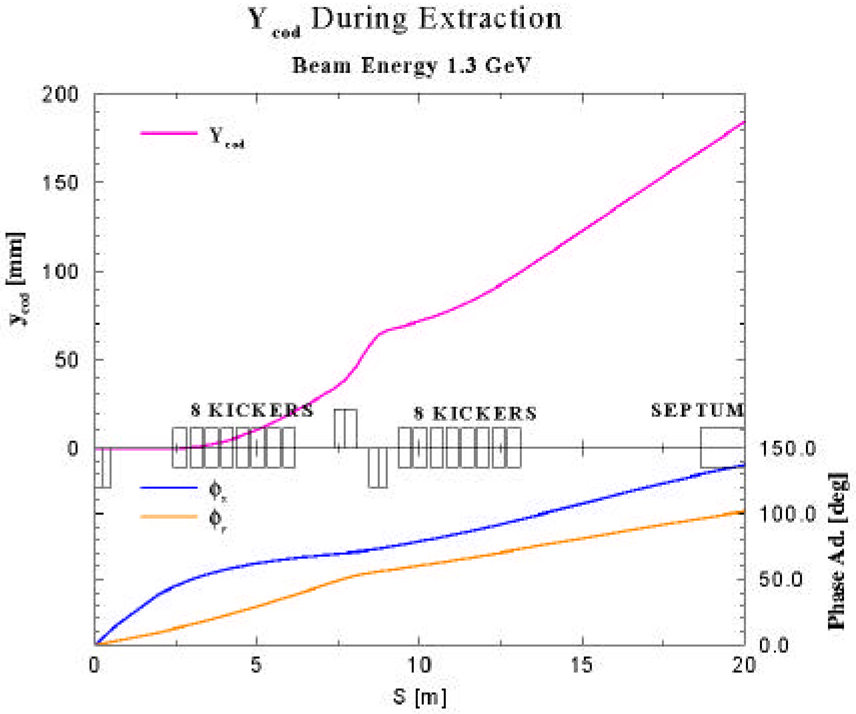
(J. Beebe-Wang et al.)

Work is in progress in developing injection bumps that optimize between the goals:

Extraction Zone Design

(N. Tsoupas, YY. Lee et al.)





- **Two stage extraction**
  - **7+7 fast kickers (8+8 for 1.3GeV)**
  - **Septum Lambertson type magnet**
- **Robust to 1 kicker failure**

- **Magnetic field simulations finalized**
- **Impedance studies performed**
- **PFN moved out of the ring**

Magnetic Imperfections

(Y. Papaphilippou et al.)

Fringe Fields

- Scaling law for relative impact of fringe fields for any multipole: $(e{\wedge}a_{max})/L_{mag}$ (10^{-2} level for SNS)
- Dipole fringe fields are negligible (sextupole-like)
- Quadrupole fringe fields are dominant (octupole-like). Tune-shift can be corrected with 3 families of octupoles
- Higher order fringe fields are negligible (scaling law confirmed)
- 5th order fringe-field maps implemented in UAL; inclusion of correction elements in progress

Magnet errors

- 3D Tosca modeling (W. Meng) showed that sextupole and decapole errors in dipoles and dodecapole in quadrupoles are high (large tune-shifts)
- Local compensation provided
- 1GeV dipole, quadrupole measured and achieved a 10^{-4} level in all field errors (J.Jackson and P.Wanderer)
- Measurements of 1.3 GeV magnets are under way
- Magnet measurement analysis and error table data-base is under construction

Expected tune-spreads

Mechanism	**Tune-spread**
Space Charge (2MW beam)	0.15
Chromaticity (2% mom.spread)	±0.15
Fringe-field	0.025
Uncompensated magnet errors	±0.02
Compensated magnet errors	±0.002
Chromatic Sextupoles	±0.002
Fixed injection chicane	0.004
Injection painting bump	0.001

Correction packages

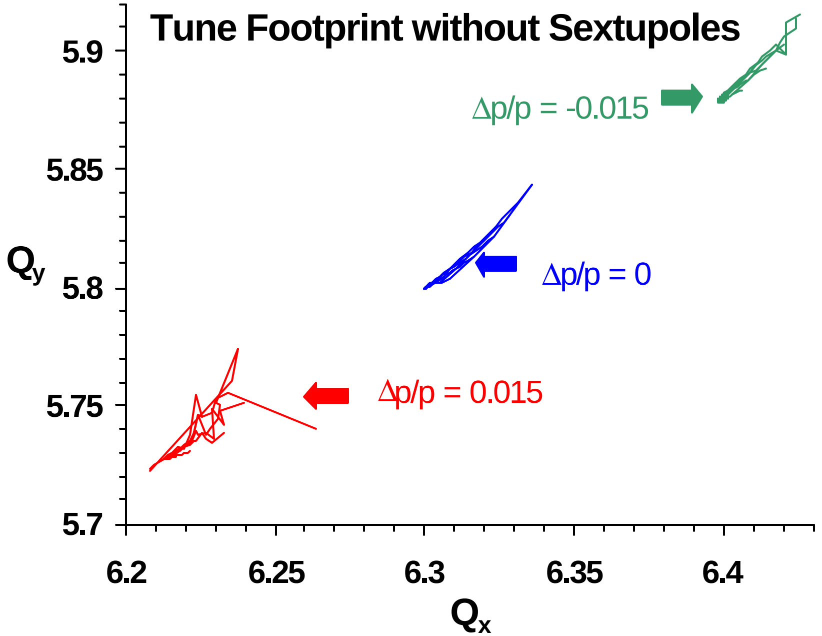
(Y. Papaphilippou et al.)

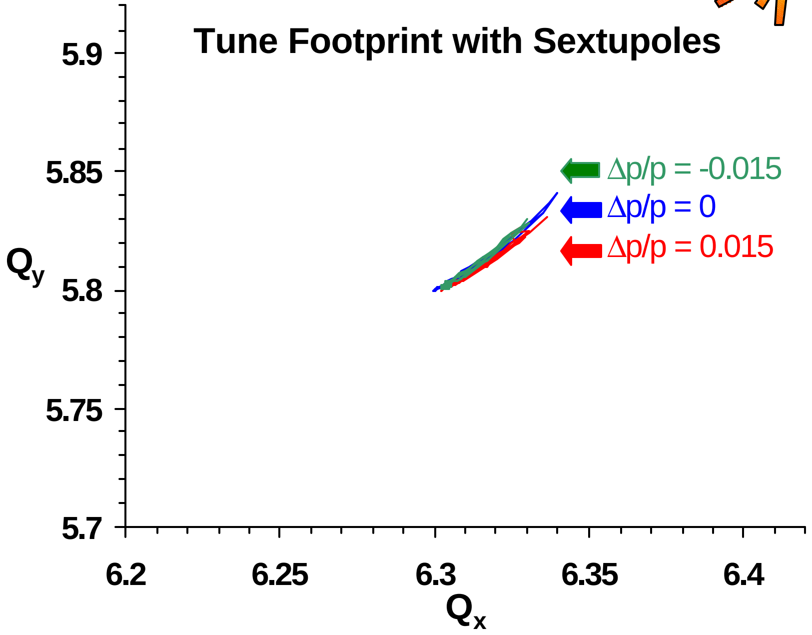
Effects	**Correctors**	**Quantity**	**Powering**
Closed orbit distortion	Dipole	52	Individual
Quadrupole perturbation	TRIM Quadrupole strings	52	Individual
Fast tune variation	"Pulsed" Quadrupoles	8	2 families
Coupling	Skew Quadrupoles	16	Individual
Chromaticity correction	High-Field Sextupoles	20	4 families
Normal sextupole resonances	Normal Sextupoles	8	Individual
Skew sextupole resonances	Skew Sextupoles	16	8 families
Tune-shift with amplitude	Octupoles	8 (+4)	2 (+1) families

- In the baseline
- Required
- Under study

Chromatic Sextupoles

(N. Tsoupas and Y. Papaphilippou)





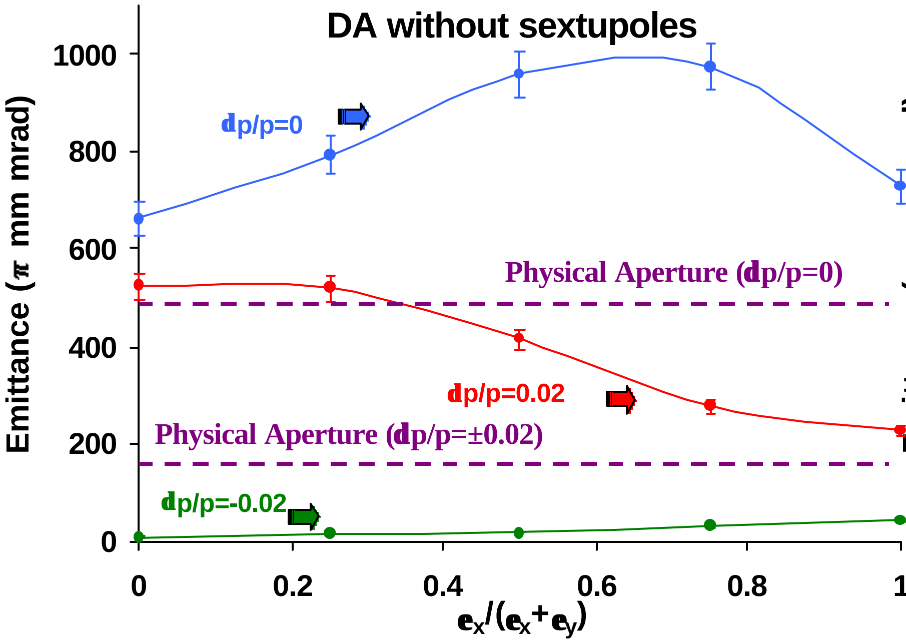
Item	Mom. Aperture
Momentum spread (99%)	± 0.007
RF acceptance(40kV, h=1)	± 0.01
Ring momentum acceptance	± 0.02

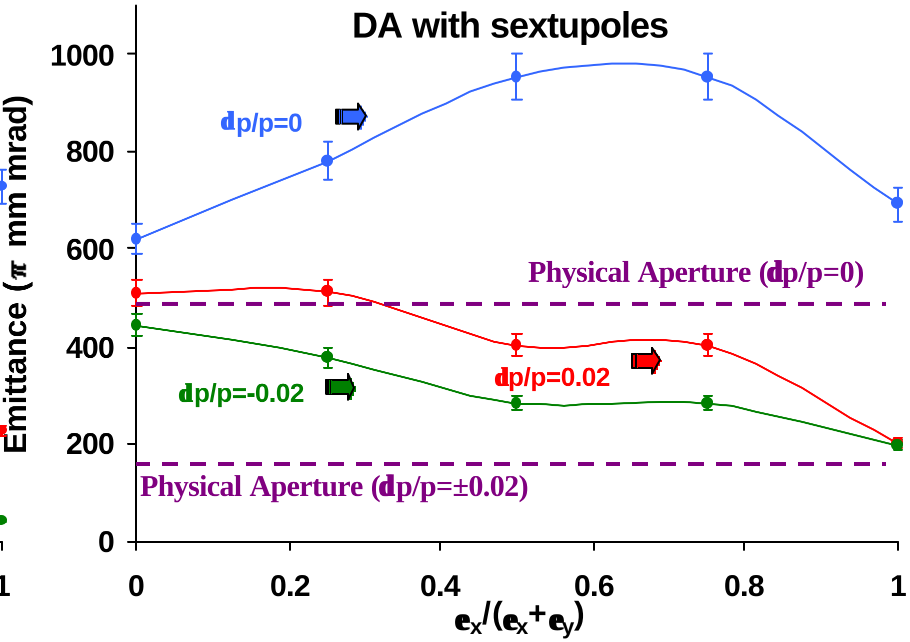
- **Chromaticities ($\mathbf{x}_x$,$\mathbf{x}_y$) =(-7.7,-6.4)**
- **For Dp/p = ±2% ® Dn = ± 0.15**

- **Huge tune-spread without chromatic correction (resonance crossing)**
- **Small non-linear effect of chromatic sextupoles (tune-shift 1/10 of quad. fringe-fields)**

Chromatic Sextupoles (cont’d)

(N. Tsoupas and Y. Papaphilippou)





- **Dynamic aperture tracking without (left) and with (right) chromatic sextupoles**
- **Unacceptable drop of the DA without chromatic sextupoles for Dp/p=-0.02 due to the half integer resonance**
- **Smaller drop for Dp/p=+0.02.**

Space Charge & Halo Formation

(A. Fedotov et al.)

Study of various mechanisms that can lead to beam tail growth

- Other mechanisms may be more important for halo development than the parametric halo
- Combined effect of space charge and machine resonances is very important
- A less restrictive space-charge limit is expected due to the effective ("coherent") tune shift
- Painting schemes and bump optimization is needed to prevent excessive halo
- Space-charge induced resonances are under study
- Comparison of simulation results with different beam profiles are in progress

Space-charge Simulations

(A. Fedotov, N. Malitsky et al.)

New SNS package based on Unified Accelerator Libraries (UAL) was successfully benchmarked for space-charge studies.

We now perform simulations with the space charge and exact treatment of non-linear equations of motion (TEAPOT approach).

- Major effects included in simulations:
  - **Multi-turn painting**
  - **Magnet field errors and misalignments**
  - **Fringe fields (up to 5th order maps)**
  - **Space charge**

Systematic study of space-charge effects in the presence of magnet field errors for various working points is in progress.

Working Points and Space Charge

(A. Fedotov et al.)

- $(Q_x,Q_y)=(5.82,5.8)$ – we earlier concluded that this leads to non-linear space-charge driven resonance $2Q_x - 2Q_y = 0$. Due to the fact that this is a difference resonance such coupling would not lead to significant emittance growth. However, for our case of correlated painting which results in a square shape beam and very strict beam loss requirements it leads to excessive halo.
- $(Q_x,Q_y)=(6.3,5.8)$ – leads to sum resonance in the presence of skew-quadrupole errors and space charge. This resonance can be corrected using the conventional schemes. However, due to a very large space-charge tune shift we will need very precise correction of the skew-quadrupole terms.
- Other working points are under study.

Ring RF System

(M. Blaskiewicz, J.M. Brennan, J.Delong, M. Meth, A. Zaltsman)

System Requirements

- Charge exchange injection (1ms) followed by 1 turn extraction with clean ~ 250 ns gap
- Minimize peak current to keep space charge forces small
- Maximize frequency spread to prevent instabilities
- Large beam currents imply heavy beam loading

System Chosen

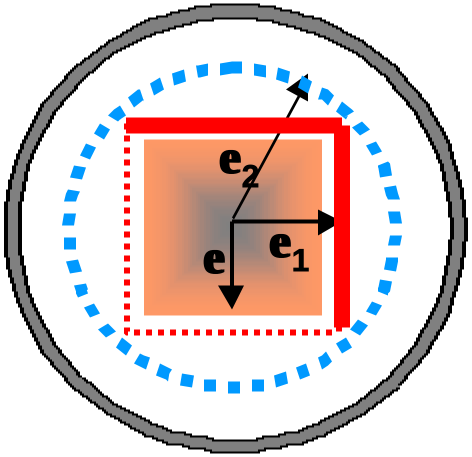
- Dual harmonic with 40 kV on h=1 and 20 kV on h=2
- Median synchrotron frequency ~ 1kHz, (entire cycle is a transient in longitudinal phase space)

Progress

- Time domain analysis for both RF and beam dynamics in progress (simulations described in EPAC 2000)
- First cavity should be finished in June 2001
- First power amplifier and beam simulation will be ready sooner
- Rigorous system test including simulated beam current and beam response function planned for winter 2001
- Realistic integrated test of High and Low level system well before installation

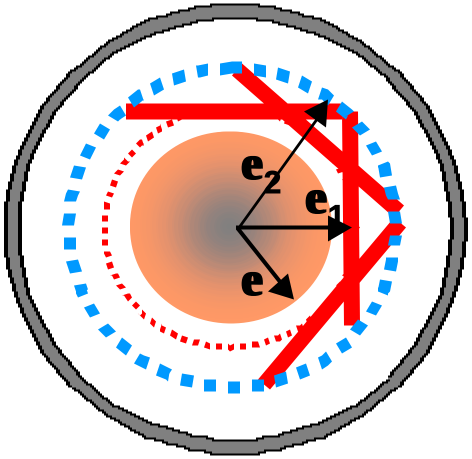
Collimation schemes for the 248m accumulator ring (N. Catalan-Lasheras et al.)

Correlated painting



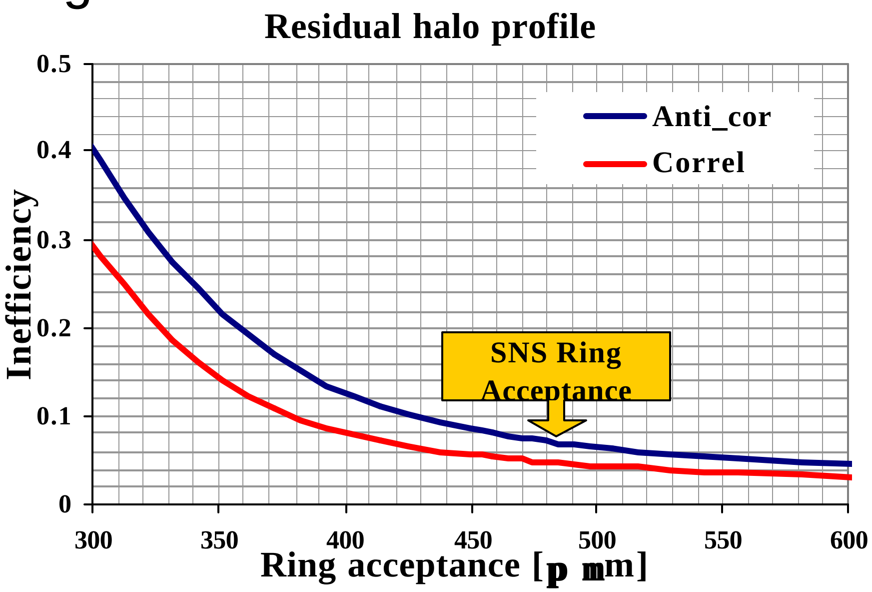
$\varepsilon_1 > \varepsilon = 120; \varepsilon_2 > 2\varepsilon_1$

Anti-correlated painting



$\varepsilon_1 > \varepsilon = 160; \varepsilon_2 > \varepsilon_1$

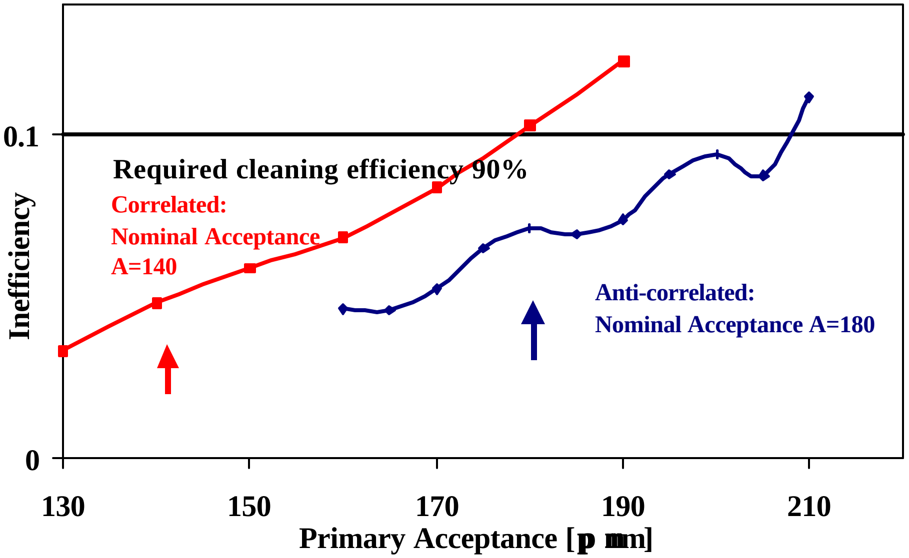
$e_1=140; e_1=180; e_2=300$


Residual halo profile

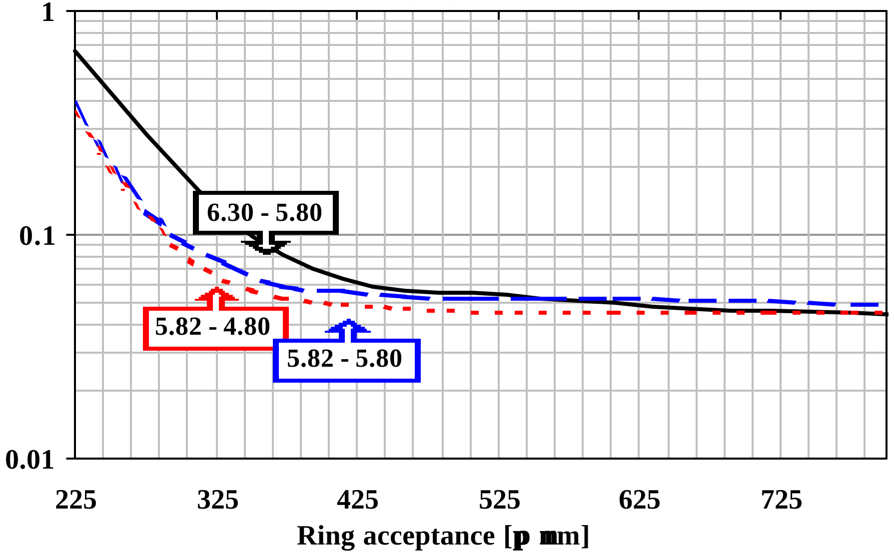
- Flexible collimation for housing correlated and anti-correlated painting schemes
- Cleaning efficiency over 95%

Cleaning efficiency against change in nominal conditions (N. Catalan-Lasheras et al.)

Changing the primary aperture



Changing the tune

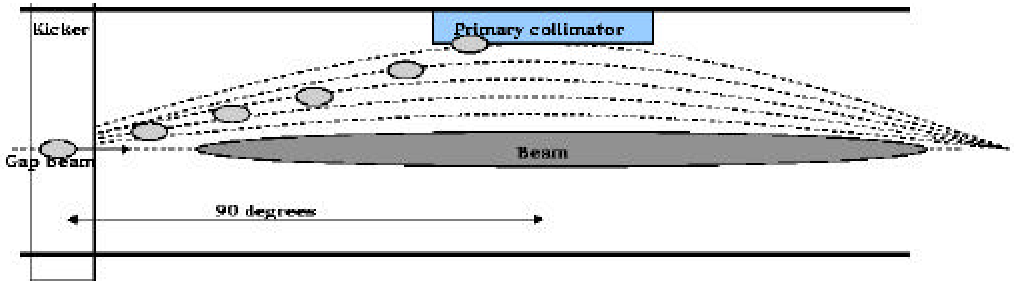


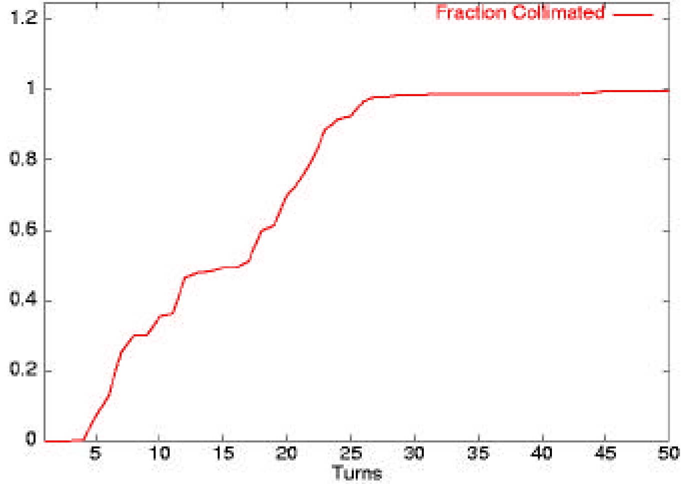
- Cleaning efficiency studied vs. working points and primary aperture
- Robust against closed orbit deviation and misalignment errors
- Two stage system efficiency shows no variation against emittance growth changes within three orders of magnitude

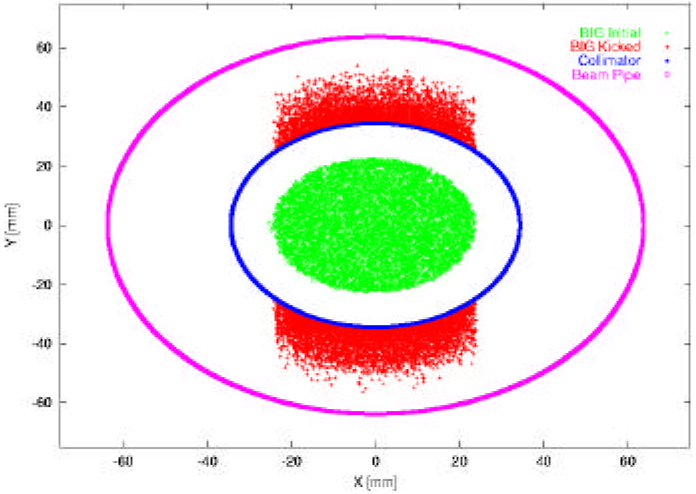
Longitudinal collimation
Beam-In-Gap kicker (S. Cousineau and J. Holmes)

- Kick the beam-in-gap vertically and drive it into the primary collimator

"Unbunched beam cleaning in HERA-p"
C.Montag, J.Klute (EPAC'00)



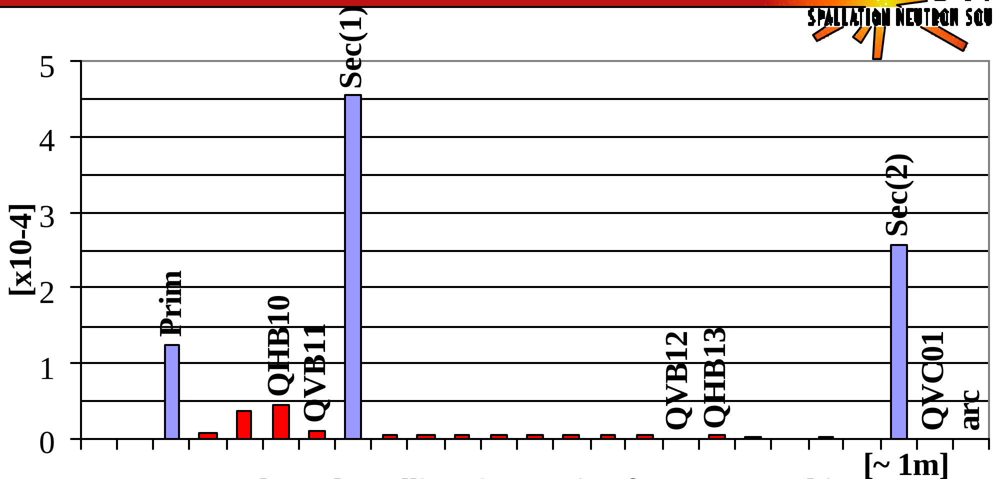




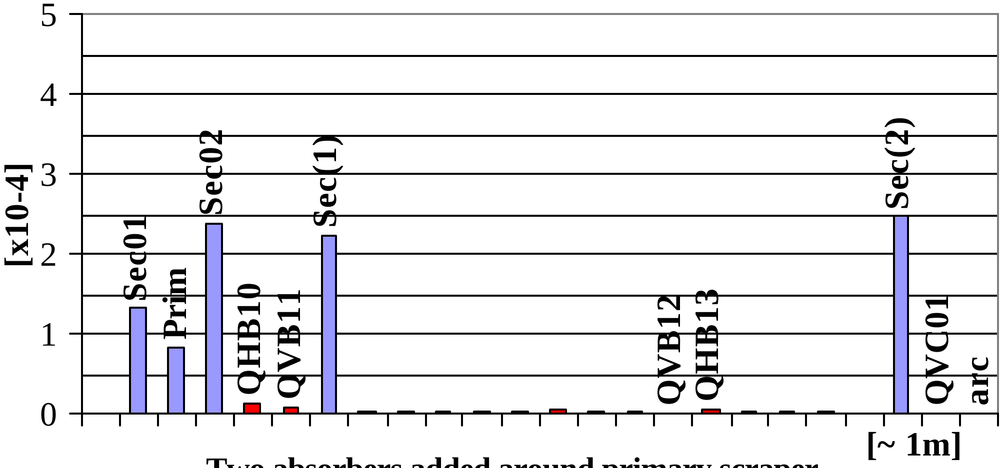
- Five fast kicker modules after the extraction channel
- Operate at the revolution frequency
- Same strength, polarity changes according to the tune
- Simulated with ORBIT

Loss distribution along the collimation section (N. Catalan-Lasheras)

- Simulation results assuming 0.001 fractional loss
- Two absorbers added around the scraper reduce direct losses in downstream quadrupoles (~1/4)
- Residual radiation also reduced in a factor 2 to 4
- Cleaning straight section designed as a hot area



Losses along the collimation section for 248m machine



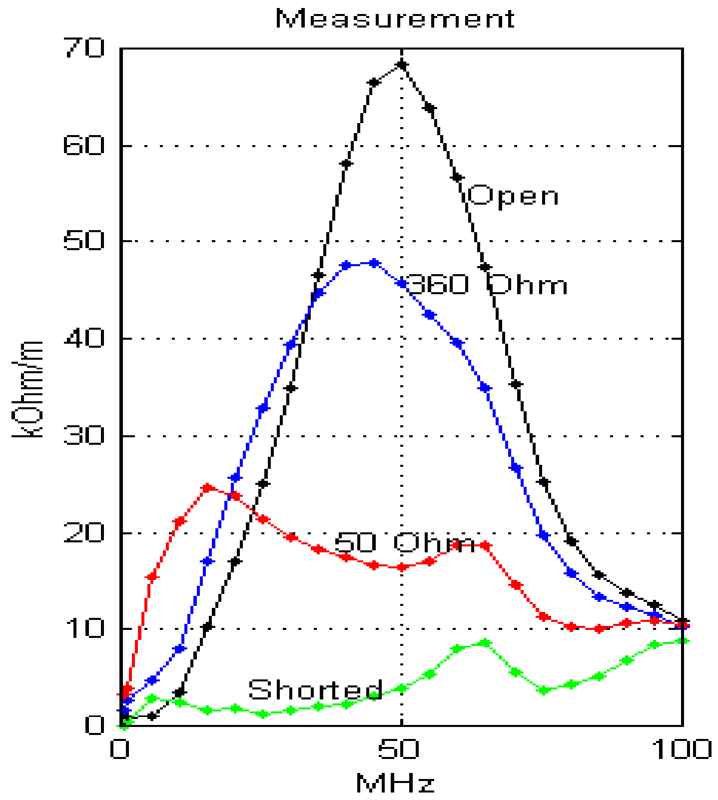
Two absorbers added around primary scraper

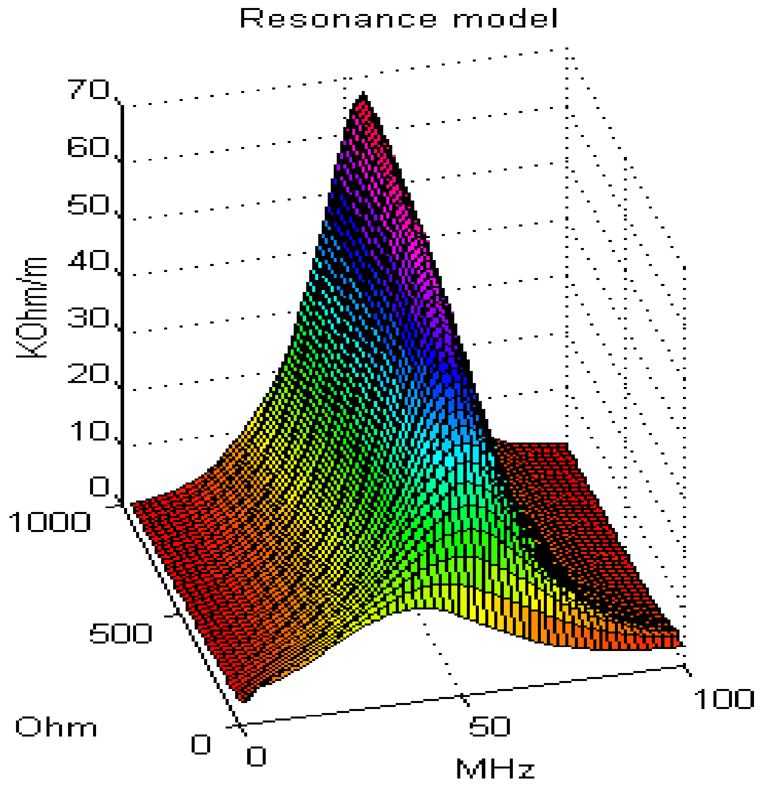
Ring Impedance Development

(S.Y. Zhang, S. Danilov et al.)

- Detailed study of collimator impedance has shown that it will not be a problem.
- Potential problem of the shielding contact leads to the discussion of not shielding the bellows.
- Extraction kicker.
  - Window frame kicker impedance has been measured and the results have been studied.
  - The kicker impedance needs to be reduced for the 2 MW machine.
  - It is decided to move PFN out of the ring.
  - New design of the extraction kicker system has been proposed. The impedance, reflection modes and image current effect have been studied.
  - Design optimization in progress

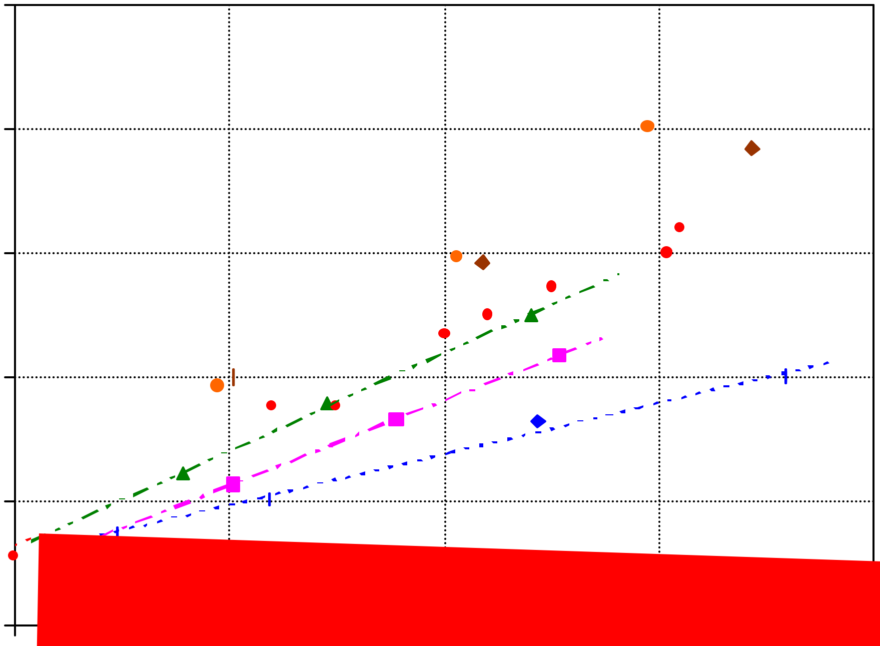
Extraction Kicker Impedance Measurement & Model (S.Y. Zhang, J.G. Wang et al.)





- Left: Kicker transverse impedance measurement.
- Right: Simulation with different termination resistance.

- PSR threshold intensity scales linearly with RF voltage, for fixed bunch length
- Electron flux decreases with conditioning
- Strong indications that:
  - **instability is E-P**
  - **electrons are produced by secondary emission**
  - **secondary emission yield is reduced by scrubbing**
- For the SNS, TiN coating of the vacuum chamber should suppress the instability for design currents



Summary

- The design of the ring is solid and frozen
- It is considered as a reference for other projects (spallation sources, muon collider, multi-function facilities)
- Challenging physics issues are treated
  - Multi-turn injection
  - Phase space painting
  - Fast extraction
  - Magnet fringe-fields
  - Space-charge effects
  - Instabilities (E-P)
  - Collimation, radio-activation
- Long to-do list, especially on commissioning plans