Space-Charge Challenges of MEIC

Alex Bogacz

Overview

- Collider design goals
- High-luminosity design strategy for MEIC
- Ion Complex: Space-charge issues and mitigation schemes:
  - Ion Linac: RMS beam envelope matching
  - Booster injection: transverse phase-space painting in two planes
  - Operating Ion Booster with large direct space-charge tune shift (> 0.3)
    - High Luminosity upgrade of the PS Booster – Laslett tune shift > 0.3
    - Resonance compensation in the presence of space-charge
    - Stop-band correction with sextupoles – anti-resonances
  - Proposed tracking studies: resonance crossing with space-charge
    - Modern space-charge tracking codes
- Conclusions

MEIC Electron-Ion Collider – Space-Charge Issues

Alex Bogacz

on behalf of MEIC Collaboration

MEIC Design Goals

Energy

- Full coverage of $\sqrt{s}$ from **15** to **65** GeV
- Electrons **3-10** GeV, protons **20-100** GeV, ions **12-40** GeV/u

Ion species

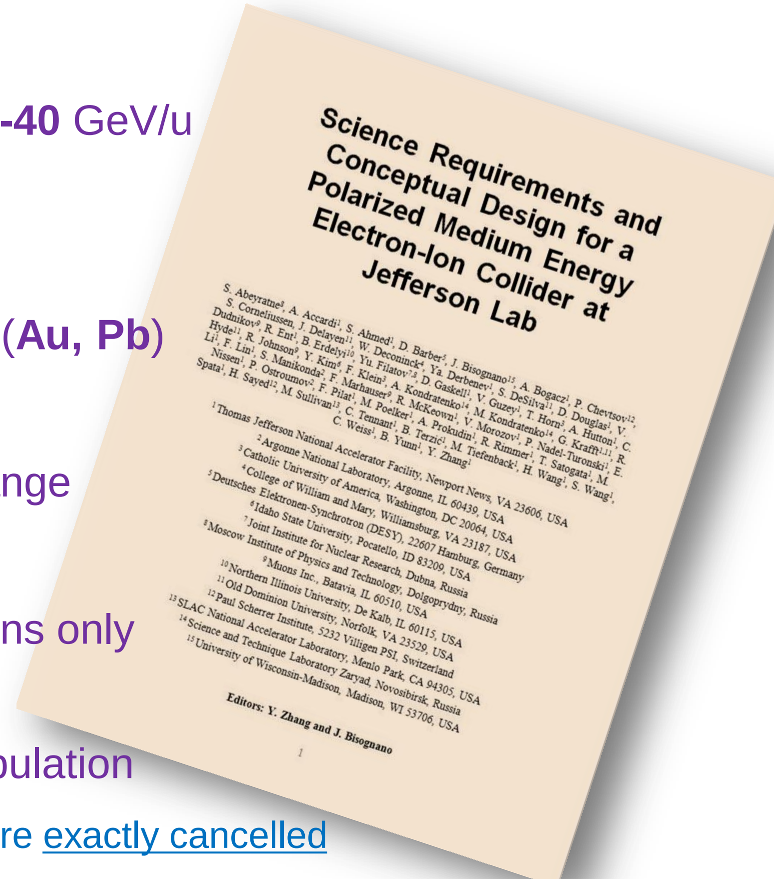
- Polarized light ions: **p**, **d**, **^{3}He**, and possibly **Li**
- Un-polarized light to heavy ions up to A above 200 (**Au, Pb**)

Luminosity

- **10^{33} to 10^{34}cm^{-2}s^{-1} per IP** in a broad CM energy range

Polarization

- At IP: longitudinal for both beams, transverse for ions only
- **All polarizations >70%**
- **Figure-8** topology for all rings – ease of spin manipulation
  - Spin precessions in the left & right parts of the ring are exactly cancelled
  - Net spin precession (***spin tune***) is zero, thus energy independent
  - Spin is easily controlled and stabilized by small solenoids, or other compact spin rotators



Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

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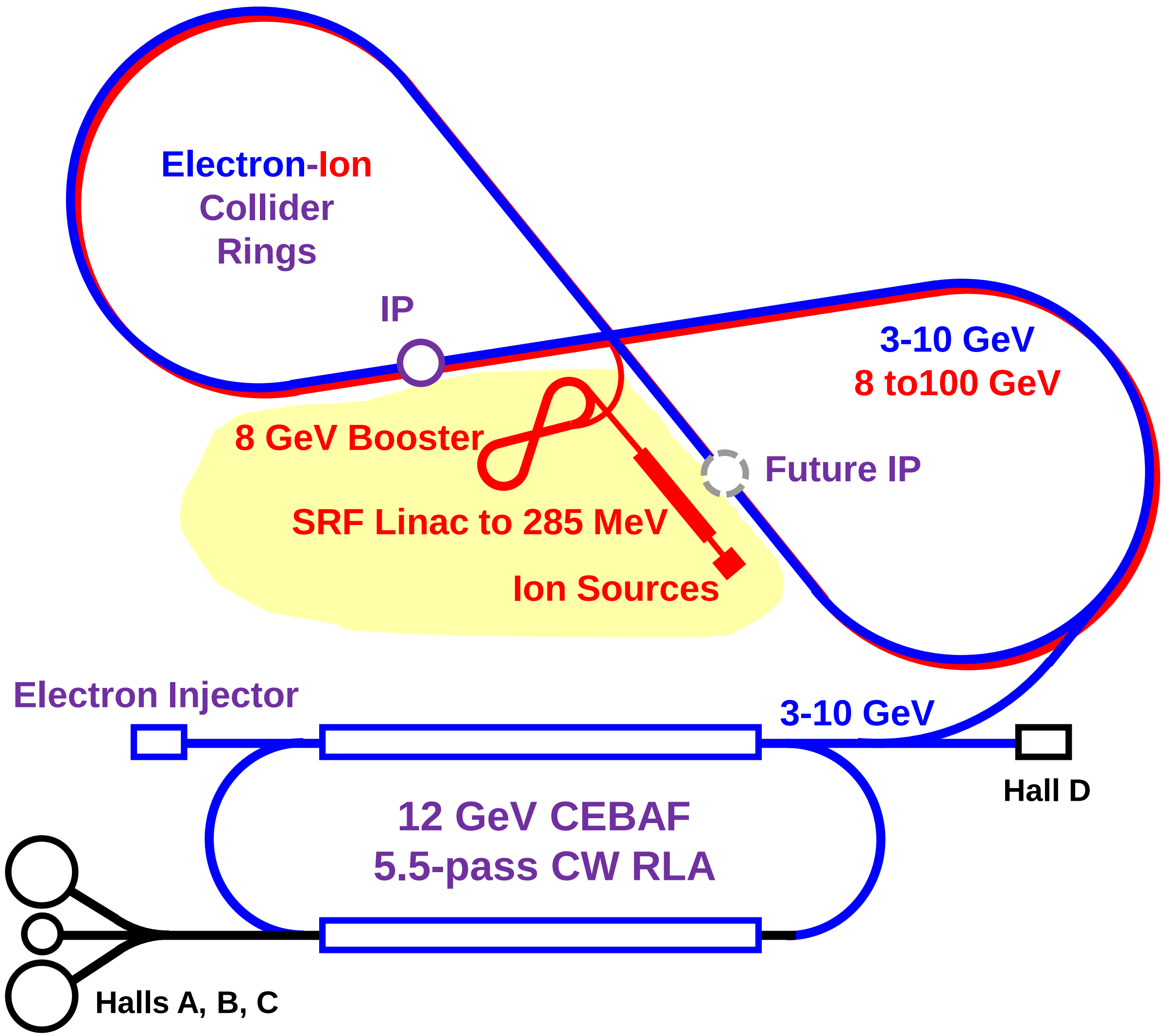
MEIC Complex – Baseline Layout



Jefferson Lab Campus Layout

MEIC Design Strategy for High Luminosity

High bunch repetition rate of CW colliding beams

$$L = f\,\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim 10^{34}\,cm^{-2}s^{-1}$$

MEIC Beam Design

- **Large** number of bunches
  (high collision frequency *f)*
- **Low** bunch charge (n_1 and n_2)
- **Short** bunches
- **Small** beta-star

"Traditional" Hadron Colliders

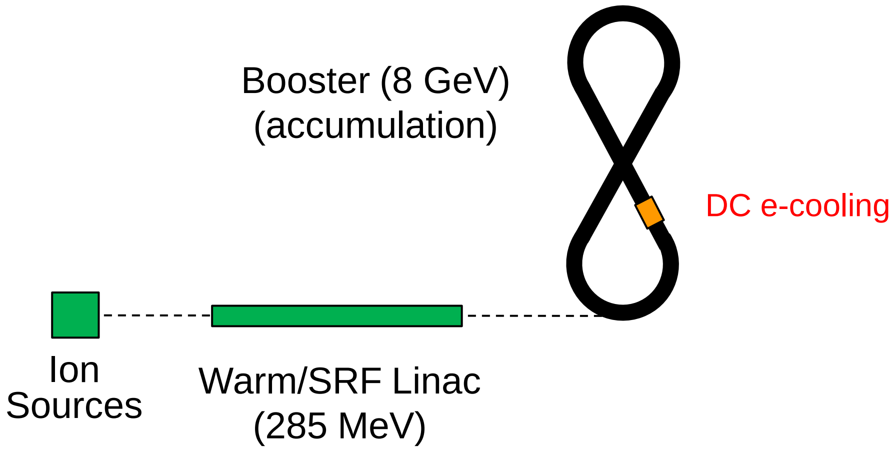
- **Small** number of bunches
  (low collision frequency *f)*
- **High** bunch charge (n_1 and n_2)
- **Long** bunches
- **Large** beta-star

MEIC Space-Charge Mitigation Strategy

- High bunch repetition rate (476 MHz)
  - Limits bunch charge, while allowing higher average current
  - Increased bunch length to store more charge in a bunch ⇨ hour glass luminosity reduction
- Superconducting linac with a warm front-end to provide fast acceleration of ion beams, with individual velocity profiles for multiple-charge, light and heavy ions ⇨ maximize individual injection energies of into the booster for variety of ion species:
  - 280 MeV for H^-
  - 100 MeV/u for Pb^{67+}
- Minimize direct space-charge effect (strongest for H^-) ⇨ improved current and emittance of the injected beam into the booster

$$\Delta\nu_{sc} = \frac{r_0 \lambda C}{4\pi\beta\gamma^2\varepsilon_n}\frac{Z^2}{A} = \frac{r_0 Q}{4\pi\beta\gamma^2\varepsilon_n}\boxed{\frac{Z}{A}}\,, \qquad Q = \lambda C Z$$

Ion Injector Complex – Overview



- Present status of the ion injector complex:
  - Relies on demonstrated technology for injectors and ion sources
  - Adopted an SRF linac design (al FRIB)
  - 8 GeV Booster design avoiding transition crossing with all ion species (configured with super-ferric magnets)

Evolution of Beam Parameters: Polarized Protons

	(units)	*ABPIS Source	Linac	Booster	
			Entrance	Injection	Extraction
Charge status		H^-	H^-	$H^- \rightarrow H^+$	H^+
Kinetic energy	MeV	~0	13.2	285	7062
γ				1.3	8.52
β				0.64	0.993
Pulse current	mA	2	2	2	
Pulse length	ms	0.5	0.5	0.22	
Charge per pulse	μC	1	1	0.44	
Protons per pulse	10^{12}	3.05	3.05	2.75	
Pulses				1	

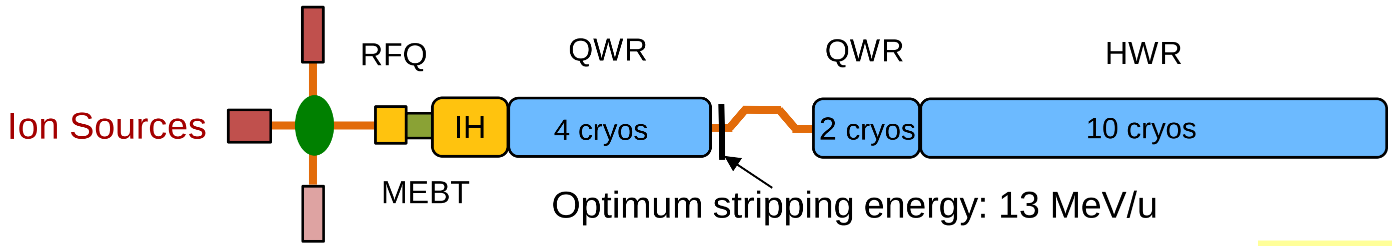
***ABPIS** – Atomic Beam Polarized Ion Source

Evolution of Beam Parameters: Ions (e.g. Pb)

	(units)	*EBIS Source	Linac	Booster	
			After stripper	Injection	After acceleration
Charge status		$^{208}Pb^{30+}$	$^{208}Pb^{67+}$	$^{208}Pb^{67+}$	$^{208}Pb^{67+}$
Kinetic energy	MeV/u	~0	13.2	100	670
γ				1.11	1.71
β				0.43	0.83
Pulse current	mA	1.3	0.1		
Pulse length	ms	0.01	0.01		
Charge per pulse	μC	0.075	0.015		
Ions per pulse	10^{10}	1.0	0.2		
Pulses				28	

*** EBIS** – Electron Beam Ion Source

Warm/Cold Ion Linac – Current Baseline



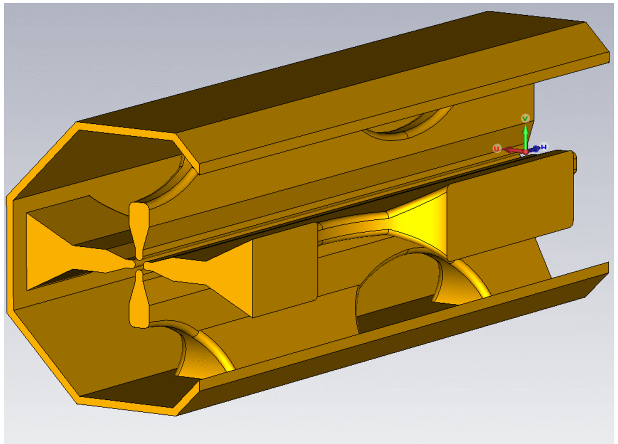
P. Ostroumov, ANL

- Linac design based on the ANL linac for FRIB
  - Pulsed linac capable of accelerating multiple charge ion species (H^- to Pb^{67+})
- Warm Linac Sections (115 MHz):
  - RFQ (3 m)
  - MEBT (3 m)
  - IH structure (9 m)
- Cold Linac Sections:
  - QWR + QWR (24 m + 12 m) 115 MHz
  - stripper, chicane (10 m) 115 MHz
  - HWR section (60 m) 230 MHz

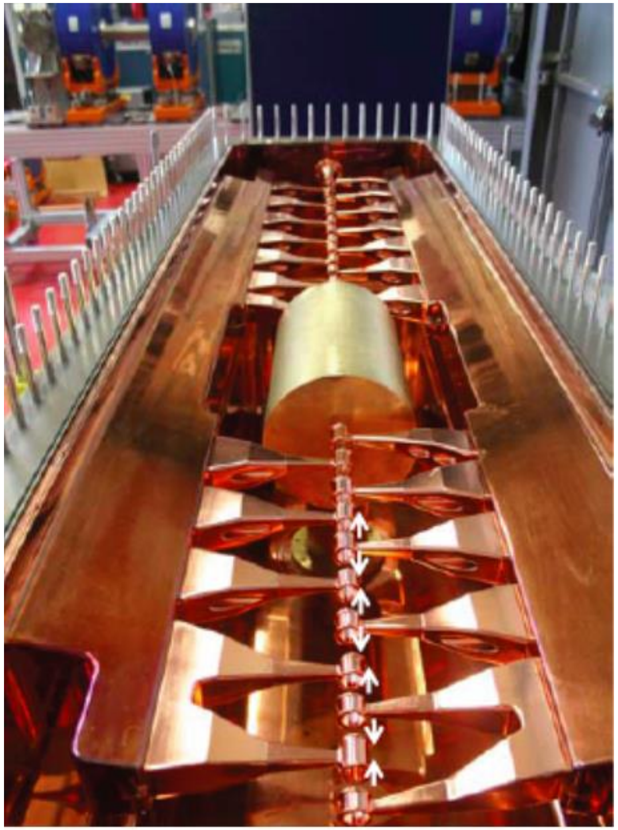
Ion species: p to Pb	
Ion species for the reference design	^{208}Pb
Kinetic energy (p, Pb)	285 MeV 100 MeV/u
Maximum pulse current: Light ions (A/Q<3) Heavy ions (A/Q>3)	2 mA 0.5 mA
Pulse repetition rate	up to 10 Hz
Pulse length: Light ions (A/Q<3) Heavy ions (A/Q>3)	0.50 ms 0.25 ms
Maximum beam pulsed power	680 kW
Fundamental frequency	115 MHz
Total length	121 m

Radio Frequency Components

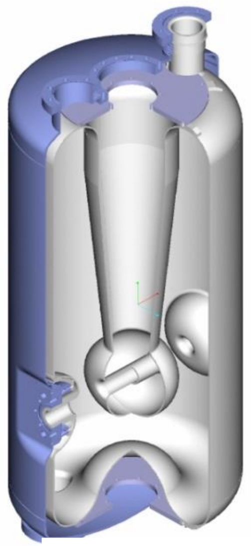
RFQ Segment



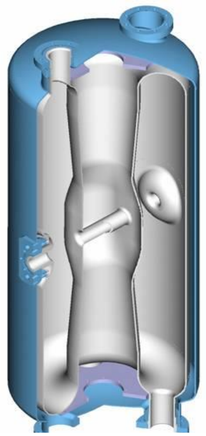
IH Structure



SRF Cavities



QWR



HWR

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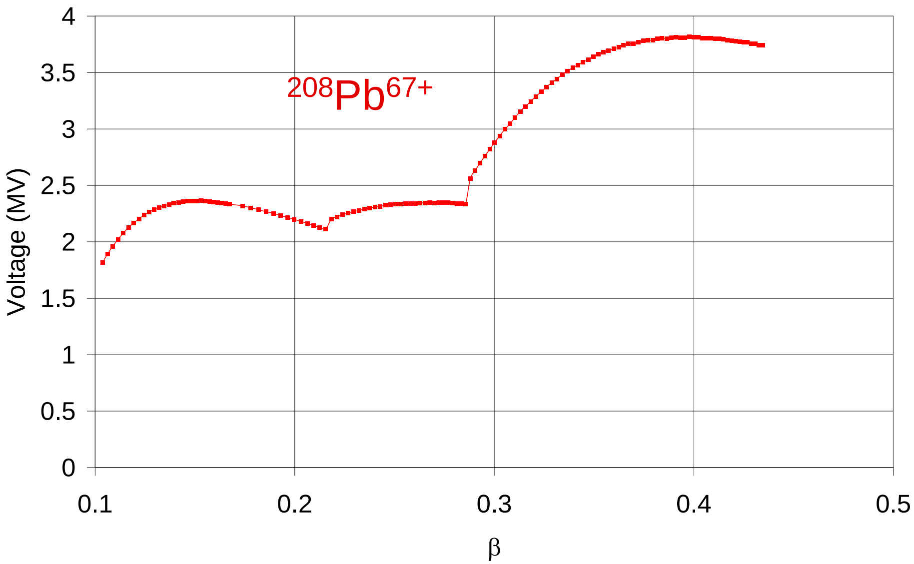
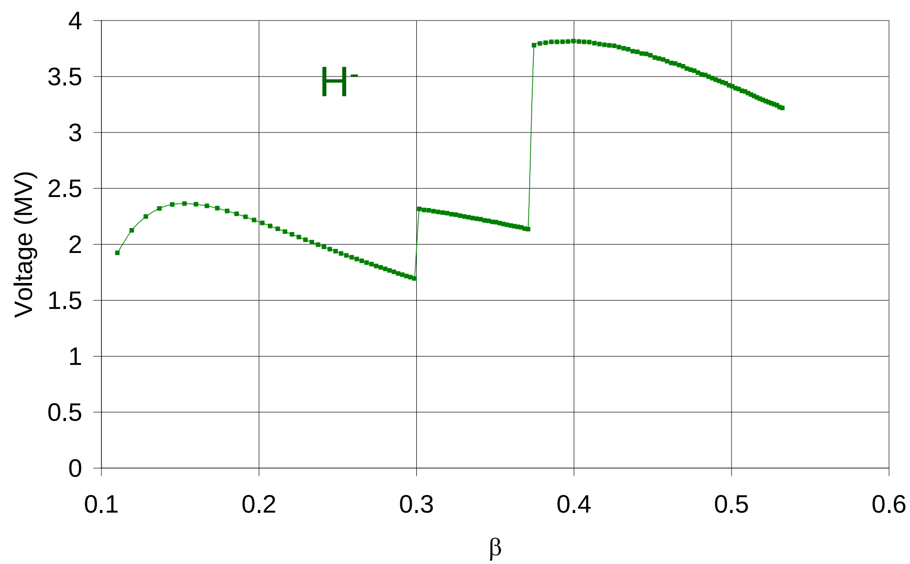
Superconducting Ion Linac

- SC linac provides superior flexibility to maximize energies for multiple charge ion beams (from H^- to $^{208}Pb^{67+}$).
  - SC linac can provide 100 MeV/u for lead ions.
  - In the same SC linac, an H^- beam can reach 280 MeV, which is high enough to suppress space-charge in the booster (space-charge is most severe for the lowest mass-to-charge ratio, i.e. H^-)
  - Single 2-gap SC cavity can provide significantly higher (factor of 10) voltage per cavity compared to room temperature cavities. High-Q (power ~ voltage^2) ⇨ much higher peak fields available with SC cavities.
- If one built a room temperature linac with standard technology for 100 MeV/u lead ions (the same total voltage as for SC linac), one could only get 100 MeV protons.

Voltage Gain per SC Cavity – Final Energies

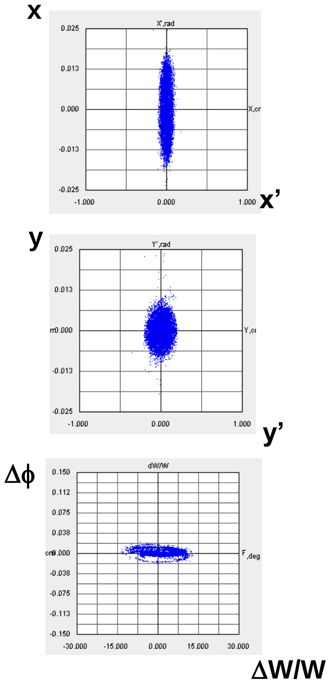


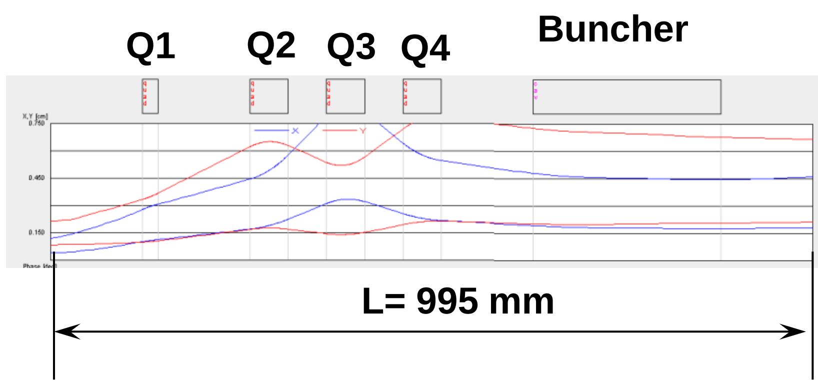


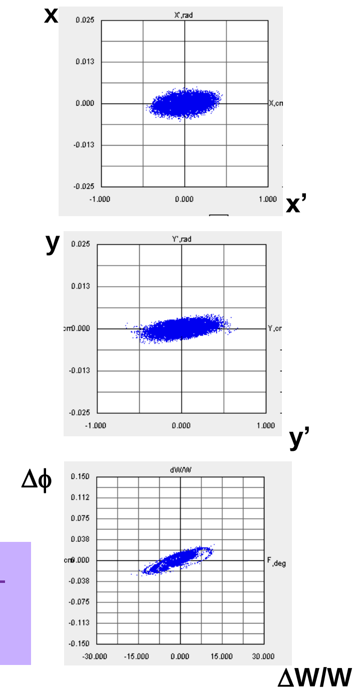
	Q ion source	Energy at the stripper MeV/u	Q after the stripper	Total energy MeV/u
Proton	1	55	1	285
Dueteron	1	32.8	1	169
^{40}Ar	12	22.4	18	150
^{132}Xe	26	16.5	48	120
^{208}Pb	30	13.2	67	102

P. Ostroumov, ANL

Medium Energy Beam Transport (MEBT)







Space-charge self focusing quite significant – rms beam envelope matching required

Quadrupole Parameters

	Eff. Length (mm)	Gradient (T/m)
Q1	20.0	23.0
Q2	50.0	-22.0
Q3	50.0	32.75
Q4	50.0	-16.5

Buncher Parameters

Cavity	Quarter Wave
Voltage	0.8 MV
Frequency	115 MHz
Length	340 mm

Ion Source/Linac – Space-Charge Issues

- The space-charge effects are quite significant in the injection beam-lines from the **ion sources**.
  - Emittance after both ABPIS and EBIS are not simple ellipses, beam **collimation** is required before transferring ions into the linac.
- Following the RFQ there are no significant space-charge effects
  - If EBIS is used for ion beam generation (peak current ~5 mA) one needs to compensate space-charge self-focussing with standard rms beam envelope matching technique.

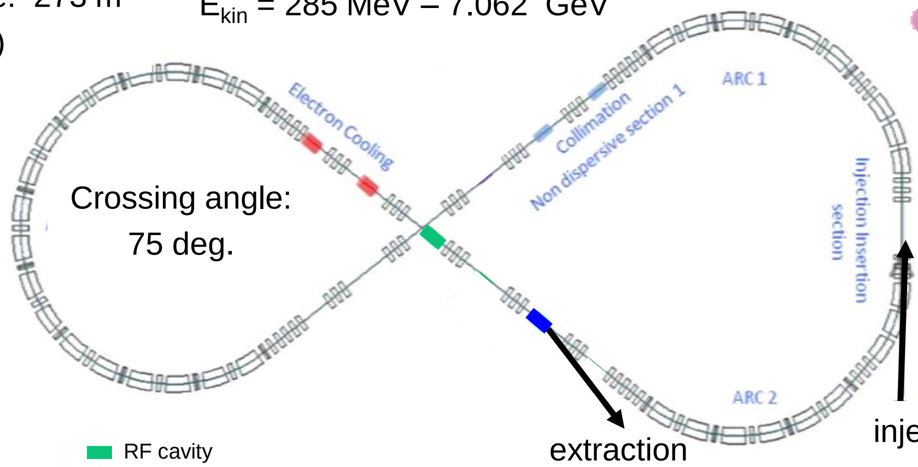
Booster (8 GeV, $\gamma_t = 10$)

Ring circumference: 273 m (≈ 2200/8)

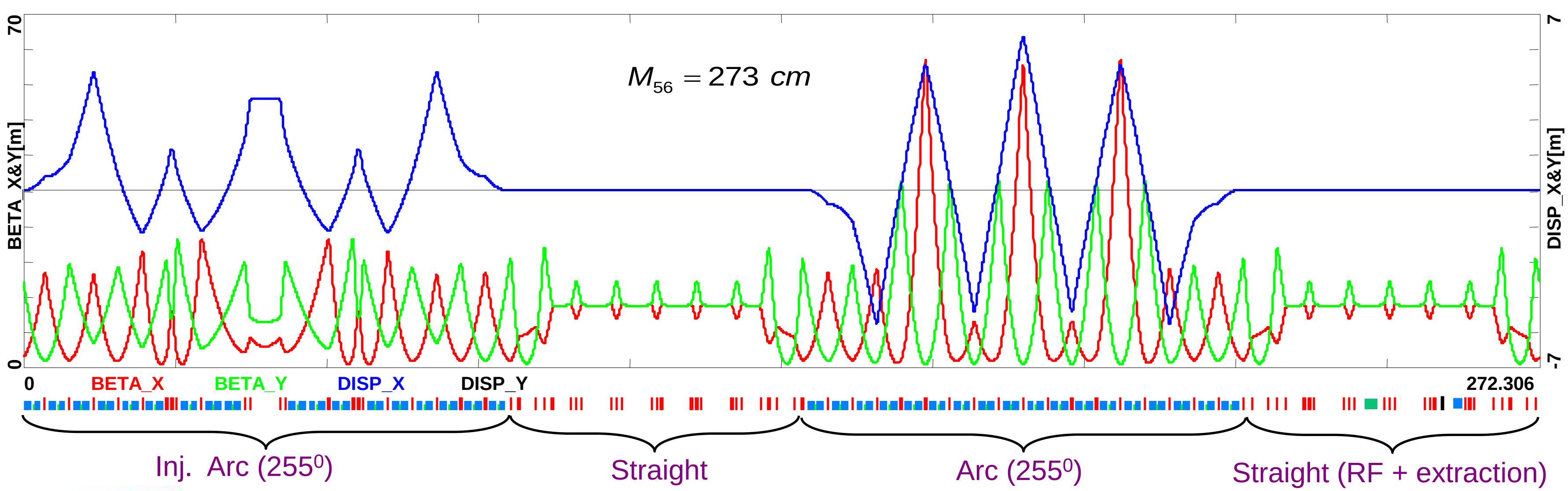
E_{kin} = 285 MeV – 7.062 GeV

$$\gamma_t = \sqrt{\frac{S}{M_{56}}}$$

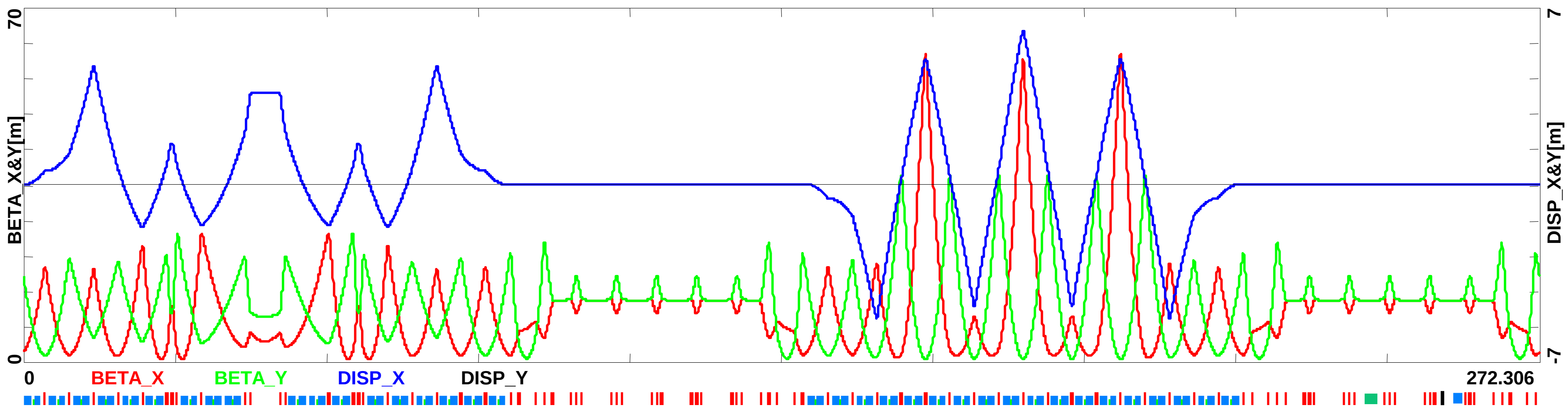
$$M_{56} = \oint \frac{D}{r} ds$$



- Injection: multi-turn 4D painting
  - 0.22-0.25 ms long pulses ~180 turns
  - Proton single pulse charge stripping at 285 MeV
  - Ion 28-pulse drag-and-cool stacking at ~100 MeV/u
  - Ion energies scaled by mas-to-charge ratio to preserve magnetic rigidity



Booster Lattice (8 GeV, $\gamma_t = 10$)



Proton beam energy (total)	GeV	1.2 - 8
Circumference	m	272.5
Arc length	m	86.9 / 77.9
Straight section length	m	53.8
Maximum hor. / ver. b functions	m	60 / 38
Maximum hor. dispersion	m	5.9
Hor. / ver. betatron tunes $n_{x,y}$		9.87 / 8.85
Hor. / ver. natural chromaticities $x_{x,y}$		-28 / -24
Momentum compaction factor a		10^{-2}
Hor. / ver. normalized emittance $e_{x,y}$	µm rad	2.7 / 2.7
Beam current	Amp	0.2
Laslett tune shift at injection (protons)		0.1

Arc Bends:

L_b = 120 cm
B = 2.73 Tesla
bend ang. = 7.08 deg.
Sagitta =1.8 cm

Arc Quadrupoles:

L_q = 40 cm
G = 12-58 Tesla/m

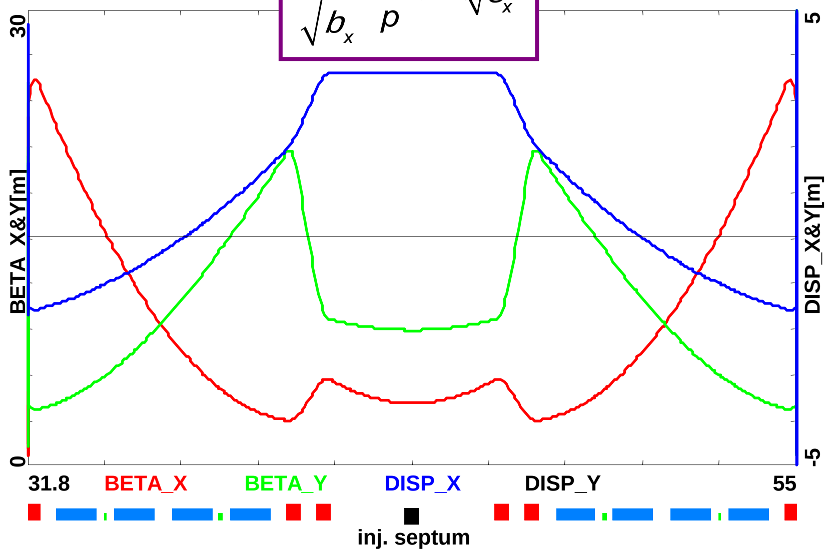
Straight Quads:

L_q = 40 cm
G_F = 12.57 Tesla/m
G_D = -24.52 Tesla/m
G_F = 12.57 Tesla/m

Lattice configured with super-ferric magnets

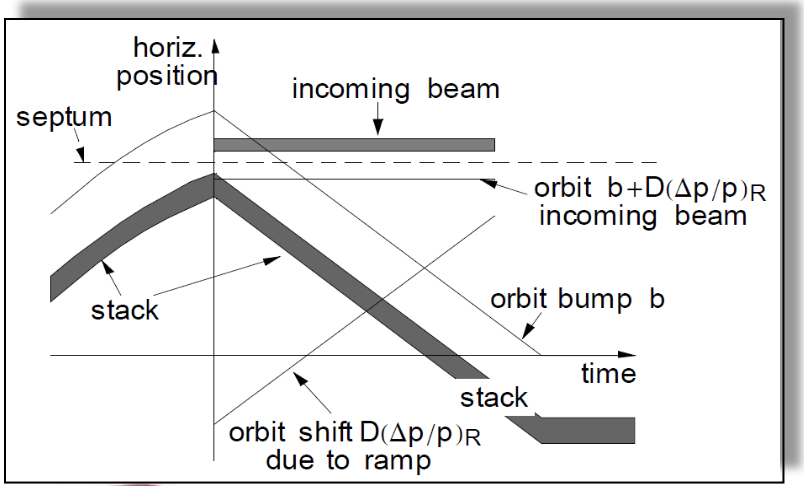
Ion Injection – Transverse Phase-space Painting

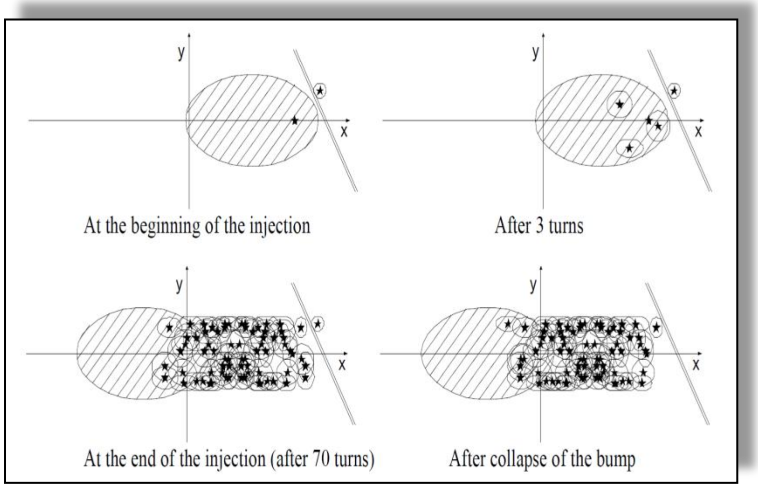
$$\frac{D_x}{\sqrt{\beta_x}}\frac{\Delta p}{p} >> \sqrt{\varepsilon_x}$$



➢ **Two-plane painting injection design**

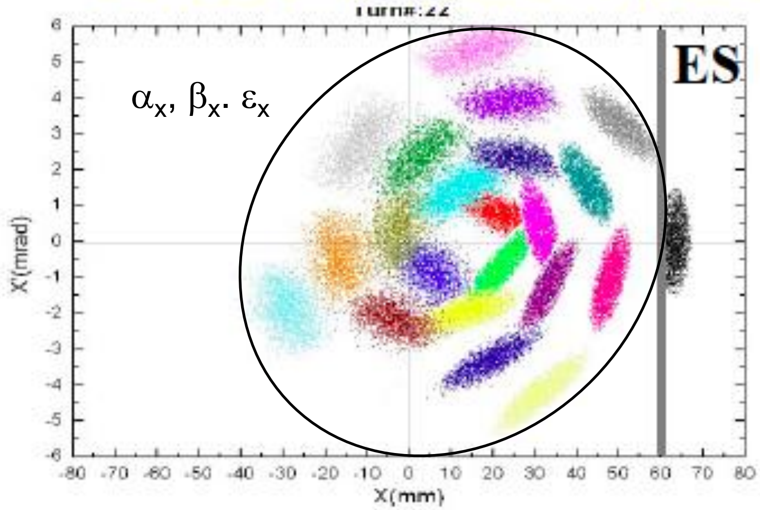
- **Tilted septum**
- **H+V painting simultaneously**
- **4~6 times of intensity gain compared with single-plane multiturn injection**
- **Two groups of orbit bump for both horizontal and vertical**



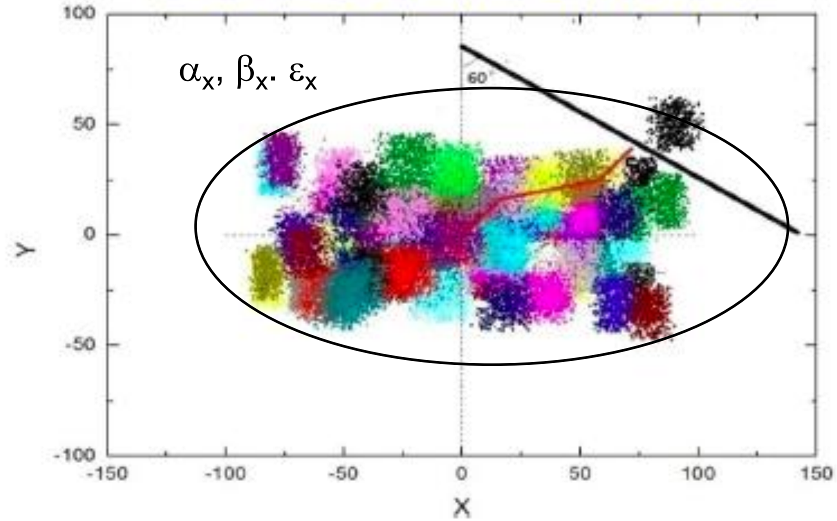


Two-plane painting injection

Conventional multiturn injection



Two-plane painting injection



Ions	Energy (MeV/u)	Injection current (pmA)	Plane	Injection turns	Single injection	Number of injection	intensity
			H	33	3.0×10^{10}	5	1.4×10^{11}
$^{238}U^{34+}$	25	0.028	V	16	1.5×10^{10}	10	1.4×10^{11}
			H+V	**150**	**1.5×10^{11}**	**1**	**1.4×10^{11}**

Space-charge induced Twiss parameter mismatch of the injected beam causes beam loss during the phase-space painting.

W. Chai , HIAF

Tune Diagram –'Tune Footprint'

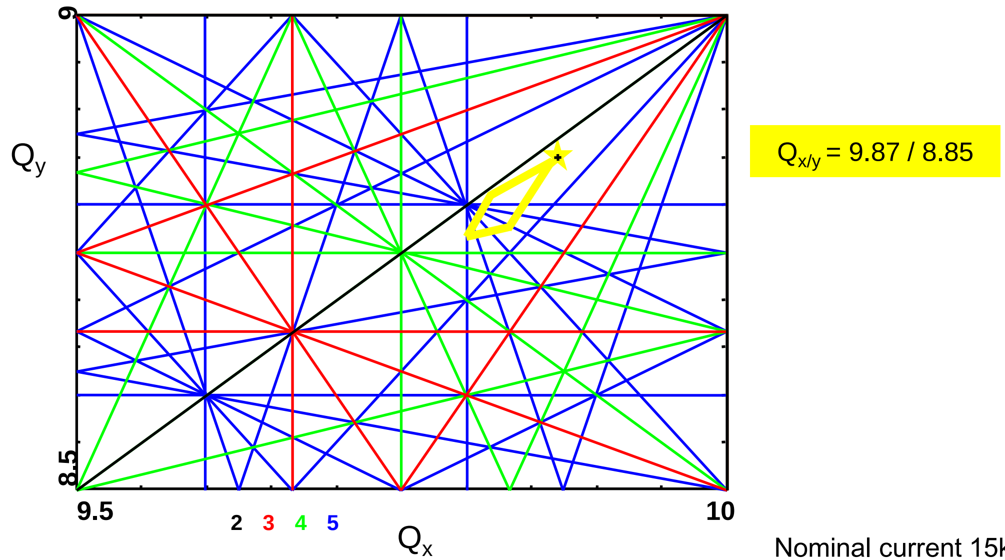


Table 1 Dipole, multipoles in units of 10^{-4}, reference radius at 1.5 cm

I_{scale}	b_0(T)	b_2	b_4	b_6	b_8	b_{mod}
0.1	-0.32176	0.08708	0.59582	-0.20929	-0.05253	0.44683
0.2	-0.6435	0.0803	0.59617	-0.20927	-0.05253	0.89361
0.3	-0.96518	0.07208	0.59682	-0.20924	-0.05253	1.34025
0.4	-1.28668	0.0619	0.59569	-0.20889	-0.05255	1.78582
0.5	-1.6071	0.0238	0.58361	-0.20639	-0.05266	2.22453
0.6	-1.91987	-0.28566	0.57678	-0.19833	-0.0531	2.63669
0.7	-2.21129	-0.93483	0.62211	-0.18461	-0.05412	3.0095
0.8	-2.48116	-1.31638	0.75232	-0.17323	-0.0554	3.35539
0.9	-2.72932	-0.94327	1.00524	-0.17088	-0.05669	3.6795
1	-2.95464	0.21439	1.27708	-0.17257	-0.05813	3.98352
1.1	-3.16415	1.7906	1.52332	-0.17535	-0.05968	4.27484

Nominal current 15kA (I_{scale}=1)

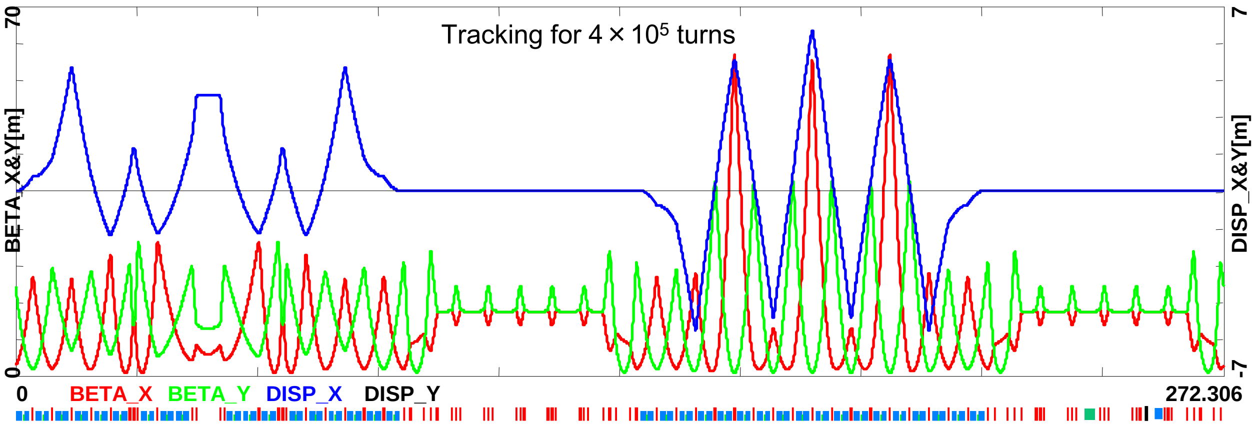
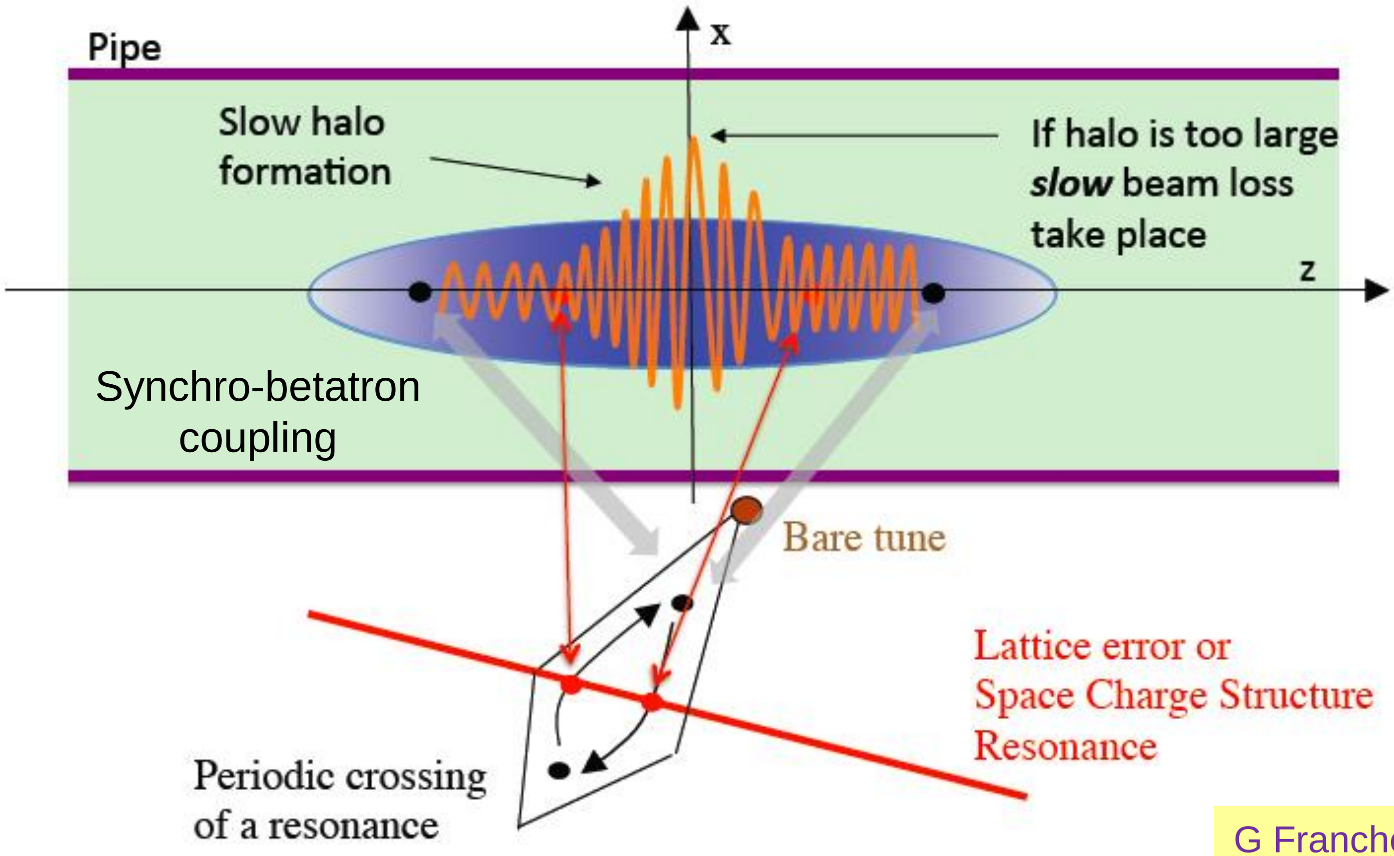


Table 2 Quad multipoles, reference radius 3 cm

I_{scale}	b_1(T/m)	b_5	b_9	B_{mod}
0.05	-10.21812	-0.78158	-0.1525	0.53951
0.1	-18.11761	-0.81085	-0.15758	0.96571
0.2	-25.81432	-1.06328	-0.18984	1.5147
0.3	-32.11643	-1.75817	-0.25051	2.08225
0.4	-37.24015	-3.20299	-0.31863	2.59426
0.5	-41.67083	-6.61844	-0.28676	3.07151
0.6	-45.60973	-9.07414	0.24837	3.53291
0.7	-49.17036	-5.91589	0.67629	3.99022
0.8	-52.54698	-0.26071	0.60584	4.4499
0.9	-55.8136	4.91642	0.43936	4.90185
1	-58.99089	9.33004	0.27043	5.34909
1.1	-62.07561	13.03944	0.11773	5.78807

Periodic crossing of resonances by high intensity beams



G Franchetti, GSI

Periodic resonance crossing – a high intensity bunch stored for a long time and the space-charge tune spread interacts with the resonance

‘Fast’ and ‘Slow’ resonance crossing

When the machine tunes cross a stable resonance, the dynamics of a particle may follow two distinct patterns:

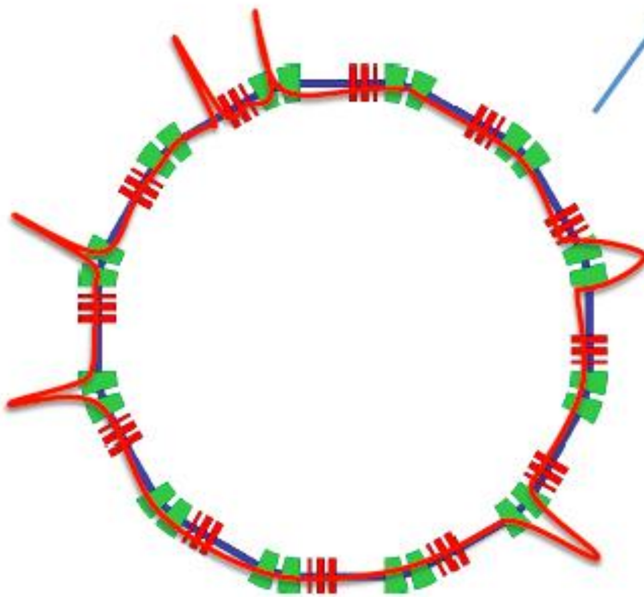
(1) If the tunes cross the resonance slow enough (adiabatically), the resonance captures the particle and stays ‘‘locked’’ to it. The consequence is that a particle gains large amplitudes leading to the halo formation.

(2) If the tunes cross the resonance fast enough, beam particles will receive a small kick by the stable islands and each single particle invariant will be ‘‘scattered’’, again leading to the halo formation.

Resonances - intro

$$x'' + k_x x = k_n(s) x^n$$

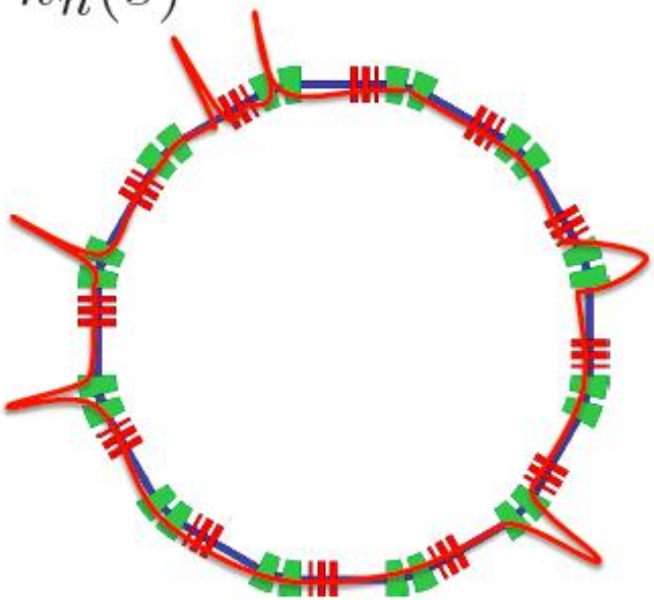
nonlinearity of order n



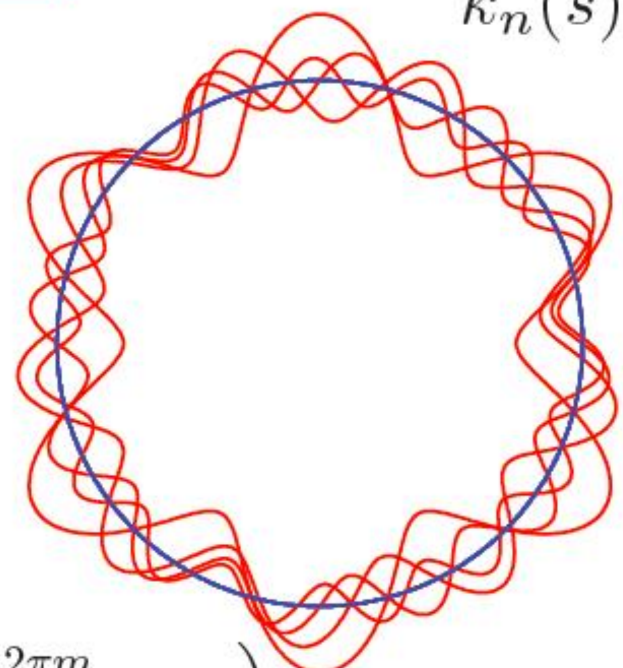
Harmonic decomposition

$$x'' + k_x x = \boxed{k_n(s)} x^n$$

$k_n(s)$



$k_n(s)$



$$\Lambda_{n,m} \cos\left(\frac{2\pi m}{L} s + \alpha_m\right)$$

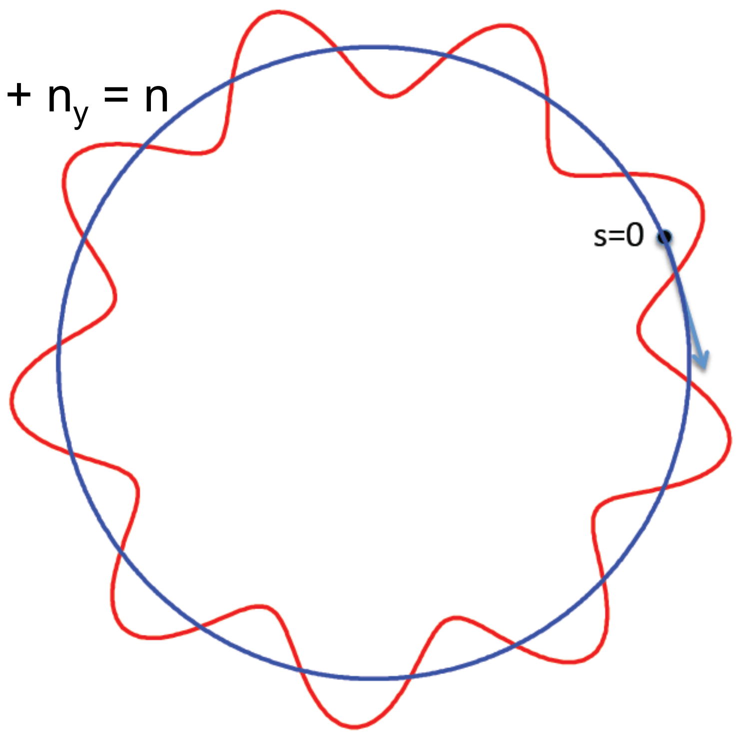
Parameters characterizing a resonance

N-th harmonics of a distribution of nonlinear errors
of n-th order excites the resonances:

$$\boxed{n_x Q_x + n_y Q_y = N}$$

$n_x + n_y = n$

Q_x, Q_y tunes



is excited by the harmonics
of order N

$$\Lambda_{n,N} \cos\left(\frac{2\pi N}{L}s + \alpha_N\right)$$

Each resonance depends on
2 parameters

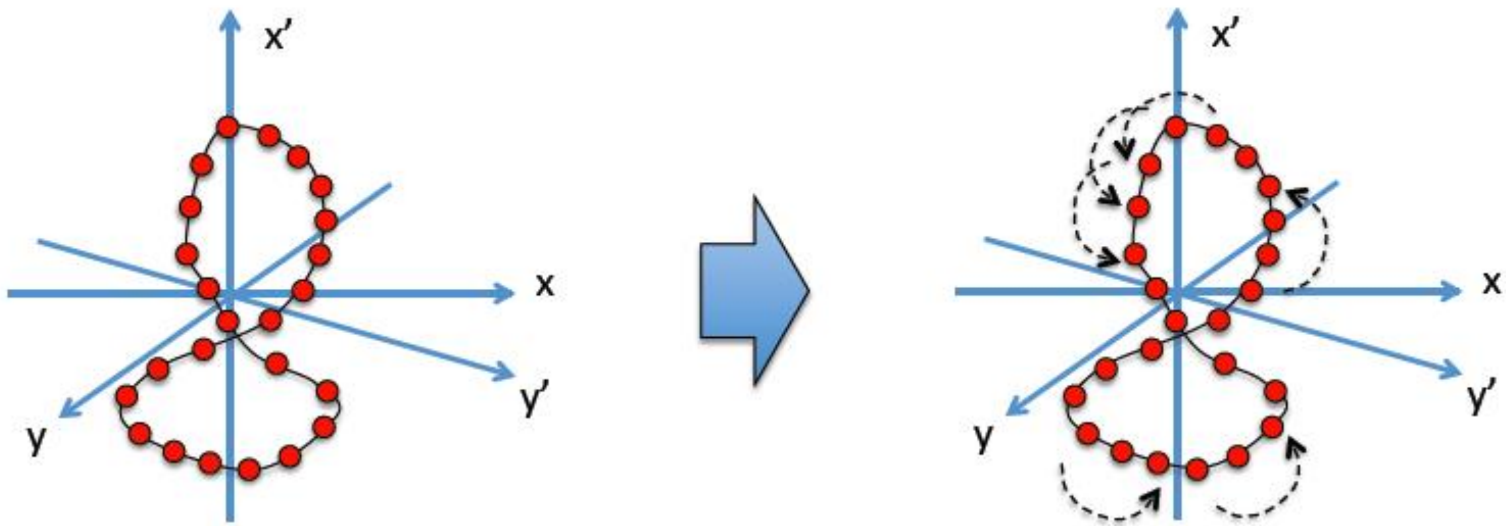
$$\Lambda_{n,N}, \quad \alpha_N$$

In 2D resonances → fix-lines

4D phase space

One turn

4D phase space



F. Schmidt

After one turn each point on the fix-line is mapped into the fix-line

Resonance Compensation

The fix-line is generated by the following Hamilton's equations of motion:

$$a'_x = -2\frac{\partial H_1}{\partial \varphi_x}$$

$$\varphi'_x = 2\frac{\partial H_1}{\partial a_x}$$

$$a'_y = -2\frac{\partial H_1}{\partial \varphi_y}$$

$$\varphi'_y = 2\frac{\partial H_1}{\partial a_y}$$

action-angle variables

$$H_1 = \Lambda_{1,2}\sqrt{a_x}a_y\cos[\ldots] + \ldots +$$ many harmonics

$\Lambda =$ is a special combination of the strength K_2 of all errors along the machine, including all beta functions beta_x, beta_y

Λ of the sextupolar error is responsible for creating a fix line

Therefore with corrector sextupoles we try to create an opposite driving term

G. Franchetti & F. Schmidt, submitted....

Driving term and beam loss

‘Stop-band’ correction with sextupoles

The pair

$$(\Lambda, \alpha)$$

one pair of sextupoles

$$(K_{2,1}, K_{2,2})$$

Effective driving term

$$\Lambda_{eff}^2 = \Lambda^2 + \Lambda_e^2 - 2\Lambda\Lambda_e \cos(\alpha - \alpha_e)$$

Reduction/cancellation of Λ_{eff} is equivalent reducing beam loss in the resonance crossing process

Space charge complicates the dynamics

Without the space-charge a driving term can be compensated cleanly with a well defined theoretical procedure... However, in the presence of the space charge change the driving term created by the errors along the machine by altering beta function, and phase advance

$$\Lambda_c = -\sum_j \frac{1}{8L} K_{2j} \sqrt{\beta_{xj}} \beta_{yj} \cos\left[2\pi \frac{s_j}{L} N + \mathscr{D}_x(s_j) + 2\mathscr{D}_y(s_j)\right]$$

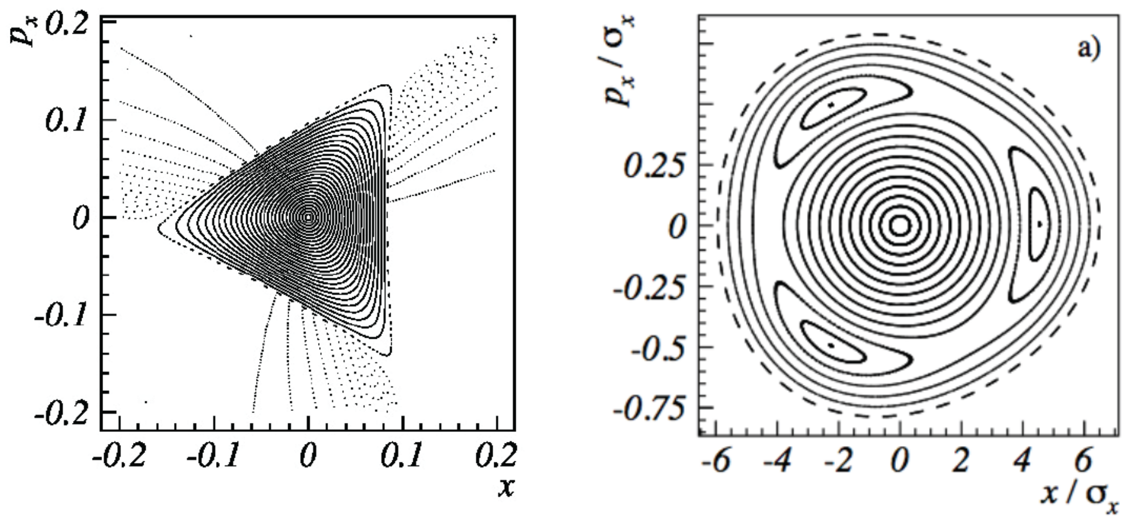
$$\Lambda_s = -\sum_j \frac{1}{8L} K_{2j} \sqrt{\beta_{xj}} \beta_{yj} \sin\left[2\pi \frac{s_j}{L} N + \mathscr{D}_x(s_j) + 2\mathscr{D}_y(s_j)\right]$$

In presence of space charge the resonance compensation is altered resulting in a "residual" excitation, which may play a detrimental role in mitigating beam loss

Effect of space charge on "resonances"

Space-charge creates a strong nonlinear dependence of betatron tune on the transverse amplitude (similar to the octupole), which drives the transverse islands much further out in the phase space than the chromaticity alone.

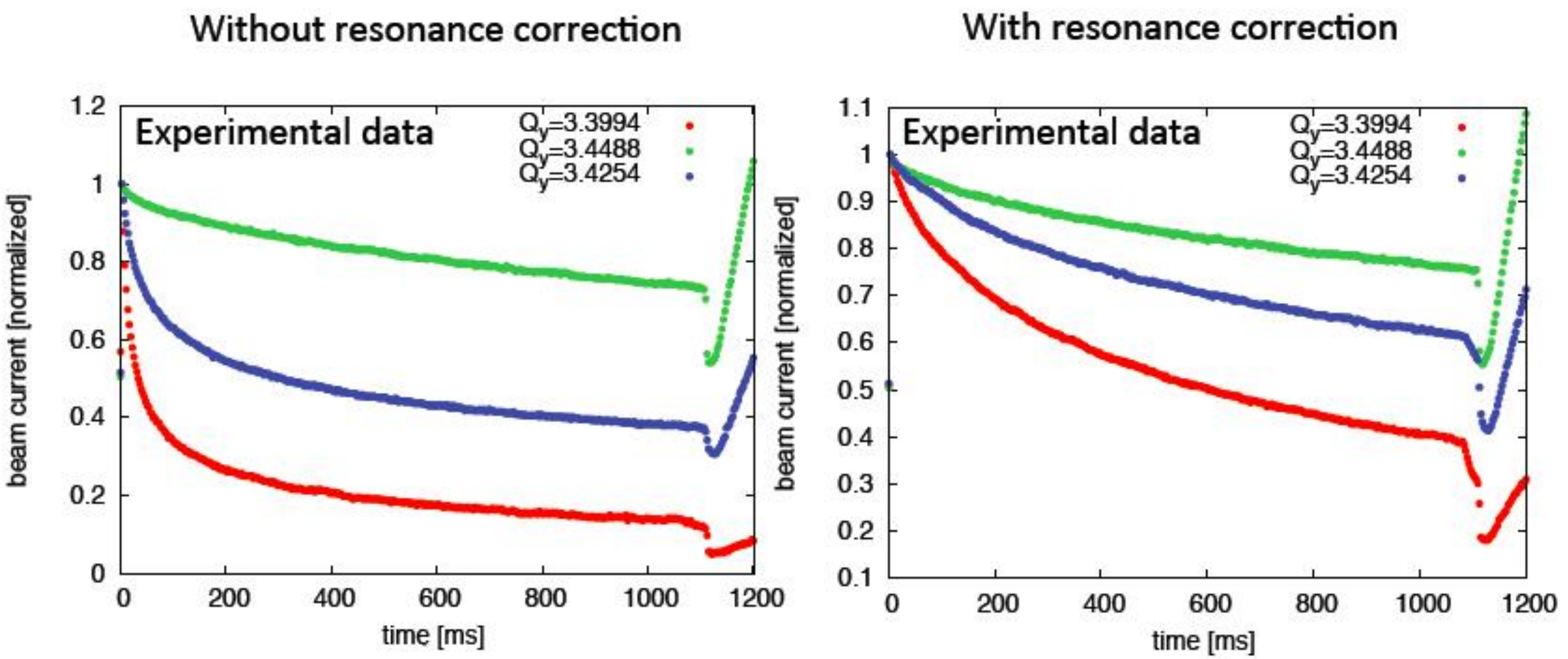
Space charge stabilizes unstable resonances.



unstable fix points are stabilized → stable islands creates scattering/trapping

Trapping of particles on islands leads to halo generation, eventually causing beam loss

Resonance Compensation – Experimental verification



U^{73+} bunched beam stored for 1 second in SIS18

Space Charge at injection (1.4 GeV - 2 GeV)
CERN PS Booster Study

Study to determine largest acceptable tune spread.

Today max acceptable: ΔQy ~|0.3| @ 1.4 GeV
HL-LHC max needed: ΔQy > |0.3| @ 2 GeV

Goal: demonstrate that possible to inject a beam with ΔQ>|0.3| with limited emittance blowup (max 5%)

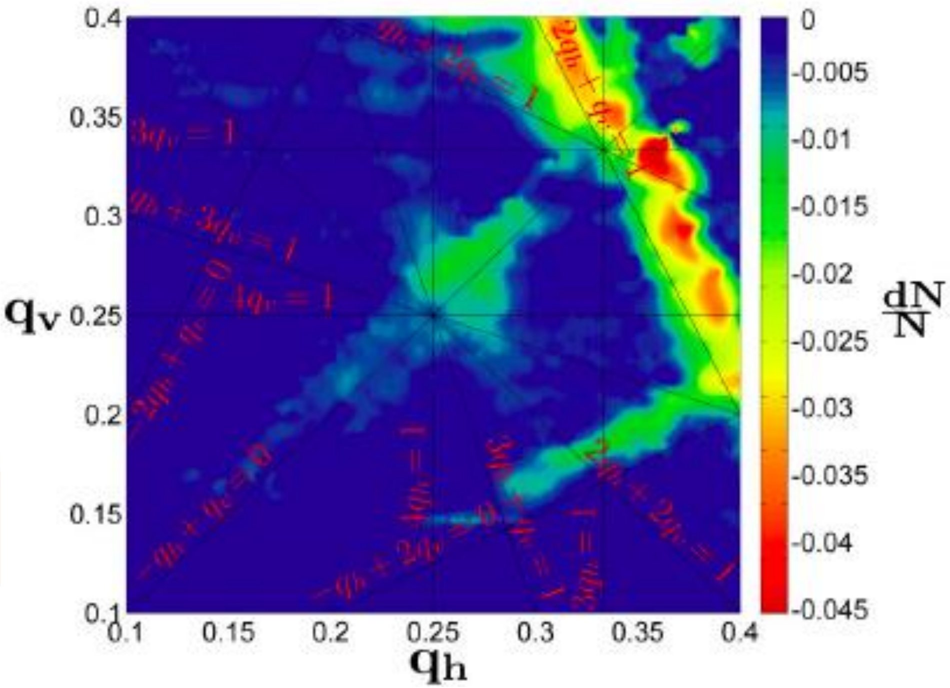
Experimental studies:

- ✓ Learn from operational beams experience. Current Laslett at about -0.28 with Qy<0.25
- ✓ Tune scan to identify via beam losses dangerous resonances
- ✓ *Driving terms measurements*
- ✓ Compensate resonances (as done already in 1975 with injection at 50 MeV)

Simulation studies:

- **PTC–Orbit(pyOrbit) simulations**
- **IMPACT – MADX-FZM simulations**
- ✓ Lack of good magnetic error model
  - No error tables from magnetic measurements (à la LHC) available from 1958
  - Opera©-based magnetic error simulations

measured beam-loss tune scan



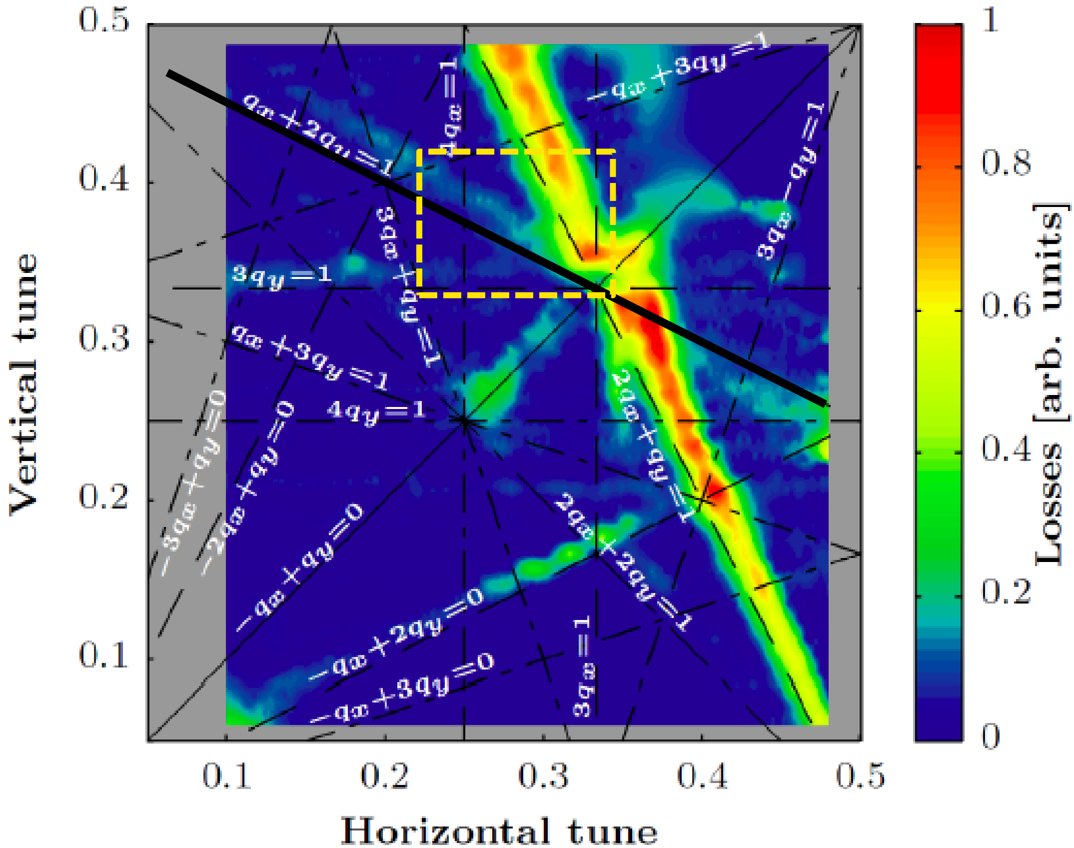
- Better understanding of integer resonance
- Better understanding of 4th (or 8th) order resonance

S. Gilardoni
CERN

CERN PS Experimental Study

- Coupled 3rd order resonance $q_x + 2q_y = 1$ was chosen
- Single bunch, low intensity beam (50x10^{10} p) with small tune spread (-0.06, -0.08) used
- Sextupole powered with 2 A to excite resonance

Tune diagram at 2 GeV

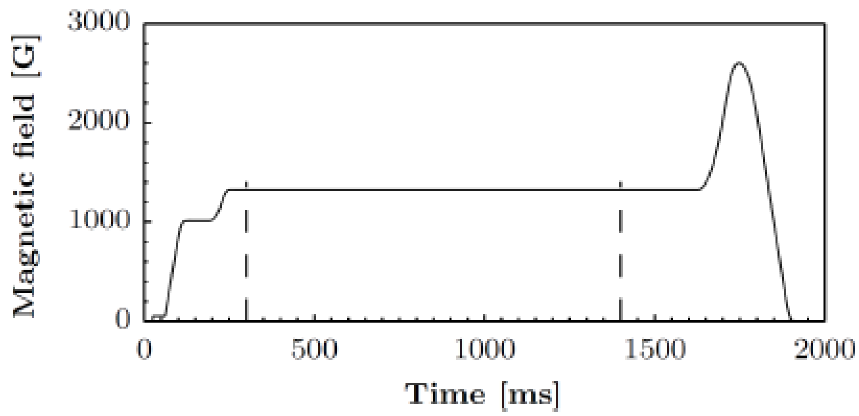


A. Huschauer, CERN

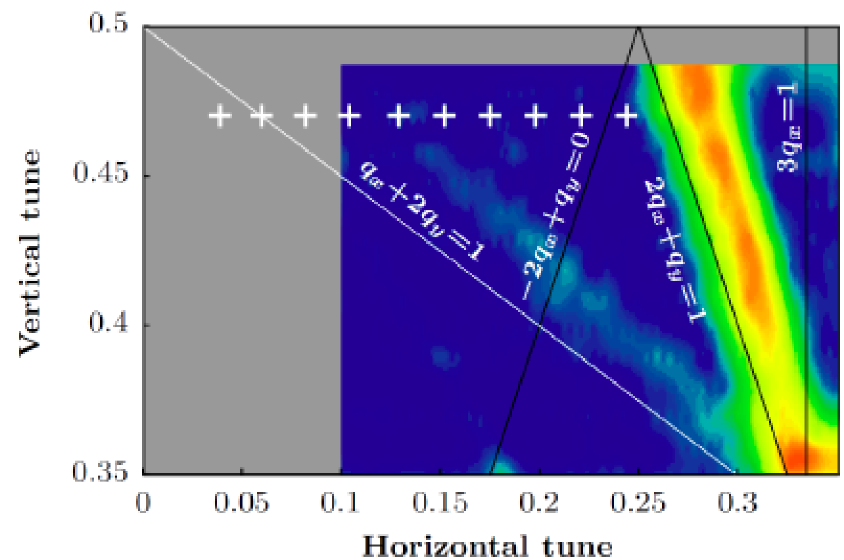
Measurement conditions
CERN PS

- Measurements conducted on the shown 2 GeV plateau
- Static working point, 10 different configurations ($q_y = 0.47$ programmed)
- Measurement duration: 1100 ms ≈ 480000 turns
- Initial and final profiles in both transverse planes recorded with wire scanners

Magnetic cycle



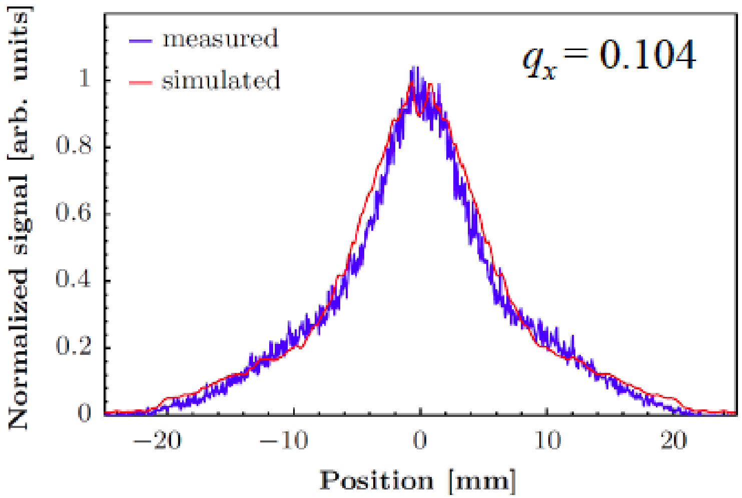
Detail of the tune diagram

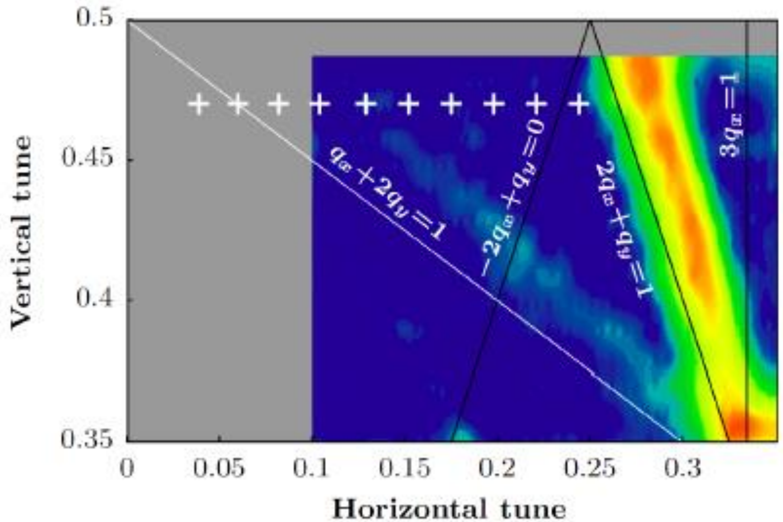


A. Huschauer, CERN

Simulations
CERN PS

- Same working points investigated as in the measurements
- 1152 space charge nodes inserted in the lattice
- Initial distributions generated based on measured initial emittance
- Only 1000 macro-particles used





A. Huschauer, CERN

Optimizing Booster for Large Laslett Tune (0.3)

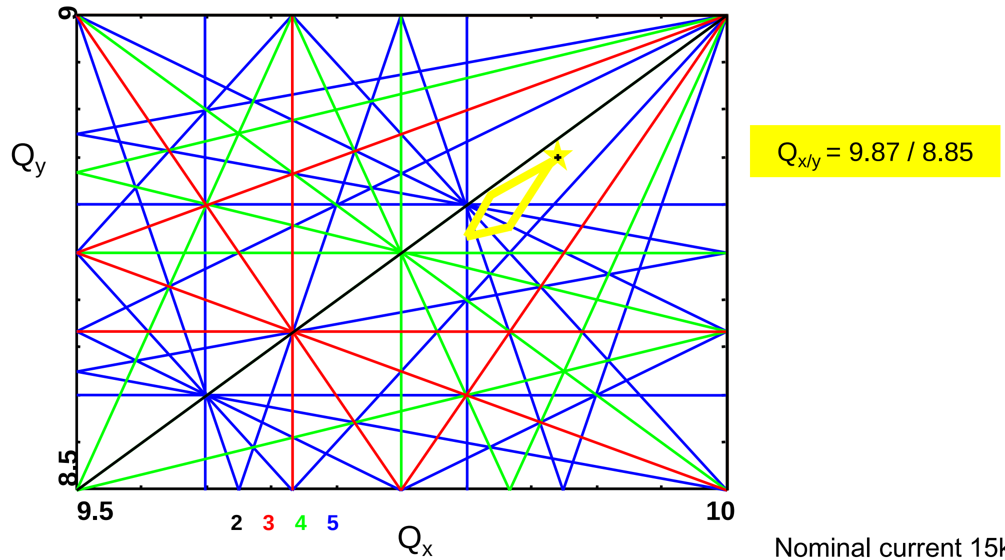


Table 1 Dipole, multipoles in units of 10^{-4}, reference radius at 1.5 cm

I_{scale}	b_0 (T)	b_2	b_4	b_6	b_8	b_{mod}
0.1	-0.32176	0.08708	0.59582	-0.20929	-0.05253	0.44683
0.2	-0.6435	0.0803	0.59617	-0.20927	-0.05253	0.89361
0.3	-0.96518	0.07208	0.59682	-0.20924	-0.05253	1.34025
0.4	-1.28668	0.0619	0.59569	-0.20889	-0.05255	1.78582
0.5	-1.6071	0.0238	0.58361	-0.20639	-0.05266	2.22453
0.6	-1.91987	-0.28566	0.57678	-0.19833	-0.0531	2.63669
0.7	-2.21129	-0.93483	0.62211	-0.18461	-0.05412	3.0095
0.8	-2.48116	-1.31638	0.75232	-0.17323	-0.0554	3.35539
0.9	-2.72932	-0.94327	1.00524	-0.17088	-0.05669	3.6795
1	-2.95464	0.21439	1.27708	-0.17257	-0.05813	3.98352
1.1	-3.16415	1.7906	1.52332	-0.17535	-0.05968	4.27484

Nominal current 15kA (I_{scale}=1)

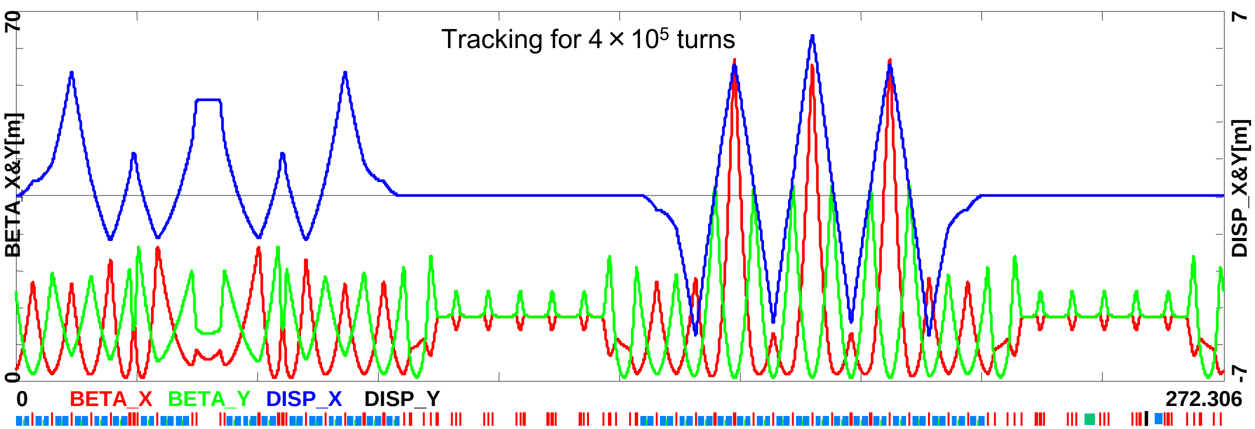
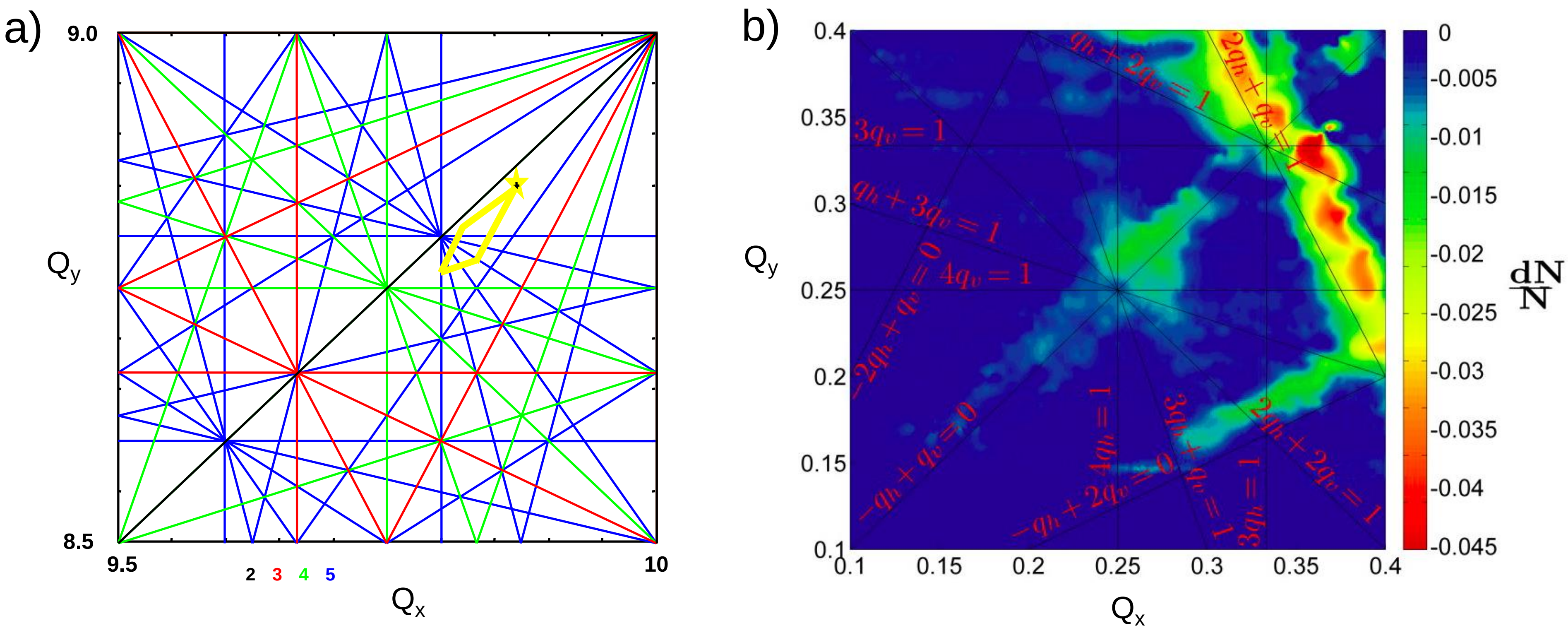


Table 2 Quad multipoles, reference radius 3 cm

I_{scale}	b_1 (T/m)	b_5	b_9	B_{mod}
0.05	-10.21812	-0.78158	-0.1525	0.53951
0.1	-18.11761	-0.81085	-0.15758	0.96571
0.2	-25.81432	-1.06328	-0.18984	1.5147
0.3	-32.11643	-1.75817	-0.25051	2.08225
0.4	-37.24015	-3.20299	-0.31863	2.59426
0.5	-41.67083	-6.61844	-0.28676	3.07151
0.6	-45.60973	-9.07414	0.24837	3.53291
0.7	-49.17036	-5.91589	0.67629	3.99022
0.8	-52.54698	-0.26071	0.60584	4.4499
0.9	-55.8136	4.91642	0.43936	4.90185
1	-58.99089	9.33004	0.27043	5.34909
1.1	-62.07561	13.03944	0.11773	5.78807

Optimizing Booster for Large Laslett Tune (0.3)



Spreadsheet of Space-Charge Codes I

Code	Language	Platform	GUI	Parallel	1D/2D/3D	Particles	linacs/rings
IMPACT	F90	Unix/Linux Mac, Windows	no	MPI	3D	$> 10^6$	linacs
ML-IMPACT	F90	Unix/Linux/Mac	no	MPI	3D	$> 10^6$	linacs/rings
PARMILA	F90	Windows	no	no	2D/3D	10^4-10^5	linacs/ transfer lines
GPT	C, C++	Windows	yes	MPI scans	3D	10^6	linacs/FEL/ transfer lines
BEST	F90	Unix/Linux	python/IDL	MPI/ OpenMP	3D	$> 10^6$	linacs/rings
VADOR	C++	Unix/Linux	no	MPI	2D	n/a	linacs
SPUNCH	F77	Linux	no		1D	10^4	LEBT
PATH	F90	Windows Mac	yes	no	3D	10^5	linacs/rings
TRACEWIN	C++	Windows	yes	no	2D/3D	$>10^5$	linacs
DYNAC	F77	Linux/Unix/ Windows	no	no	2D/3D	10^5	linacs
Synergia	F90/C++/ Python	Unix	no	MPI	3D	$> 10^6$	linacs/rings
WARP	Python/ F77/F90/C	Linux/Unix/ Windows/Mac	Under dev	MPI	3D/rz/xy	up to 10^8	linacs/rings

C. Prior, RAL

Science & Technology Facilities Council

Spreadsheet of Space-Charge Codes II

Code	Space Charge Solver	Boundaries/Images	Impedances	Field Maps	Integration order
IMPACT	spectral	open/periodic/ rectangular/circular	no	yes	2nd order in z
ML-IMPACT	spectral	elliptical/ polygon/lossy	yes	no	2nd in z 5th Runge-Kutta
PARMILA					
GPT	3D multigrid	open conductive rect. pipe, cathode	no	2D,3D	5th Runge-Kutta
BEST	spectral, FD	circular conducting wall	automatic/ external	no	user specified
VADOR	FFT	conductive wall any shape	no	no	2nd
SPUNCH	exact for disc-shaped particles	circular conducting wall	n/	n/a	1st
PATH	Schell, pt-to-pt	open	no	yes	?
TRACEWIN	Scheff/PICNIC/Gaussup	open	no	Yes	?
DYNAC	Scheff/Scherm/Hersc	open	no	yes	3rd analytical
Synergia	spectral (IMPACT)	open/periodic/ rectangular/circular	no	yes	2nd order in z
WARP	FFT, Cap matrix, multigrid, adaptive mesh, refined MG	square/round pipe, internal conductors, bent pipe, general	*ad hoc*	no	2nd order

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C. Prior, RAL

Synergia: What is it?

- Self-consistent 3D Particle-in-cell accelerator simulation code
- Specifically to simulate collective effects in accelerators
- Designed from the beginning to run on large parallel computing systems (but it doesn't have to)
- Simulations are python scripts

Collective effects:

- Space Charge (validated with GSI space charge benchmark)
- Impedance

Single Particle Optics

- Magnets, RF cavities, Drifts, Apertures, Septa

Combine most suitable algorithms in each area for a complete simulation.

Used to simulate all of Fermilab's circular machines

Developed by the Accelerator Simulation group within Fermilab's Scientific Computing Division: J. Amundson, P. Lebrun, A. Macridin, L. Michelotti, C.S. Park, P. Spentzouris, E. Stern

http://web.fnal.gov/sites/synergia

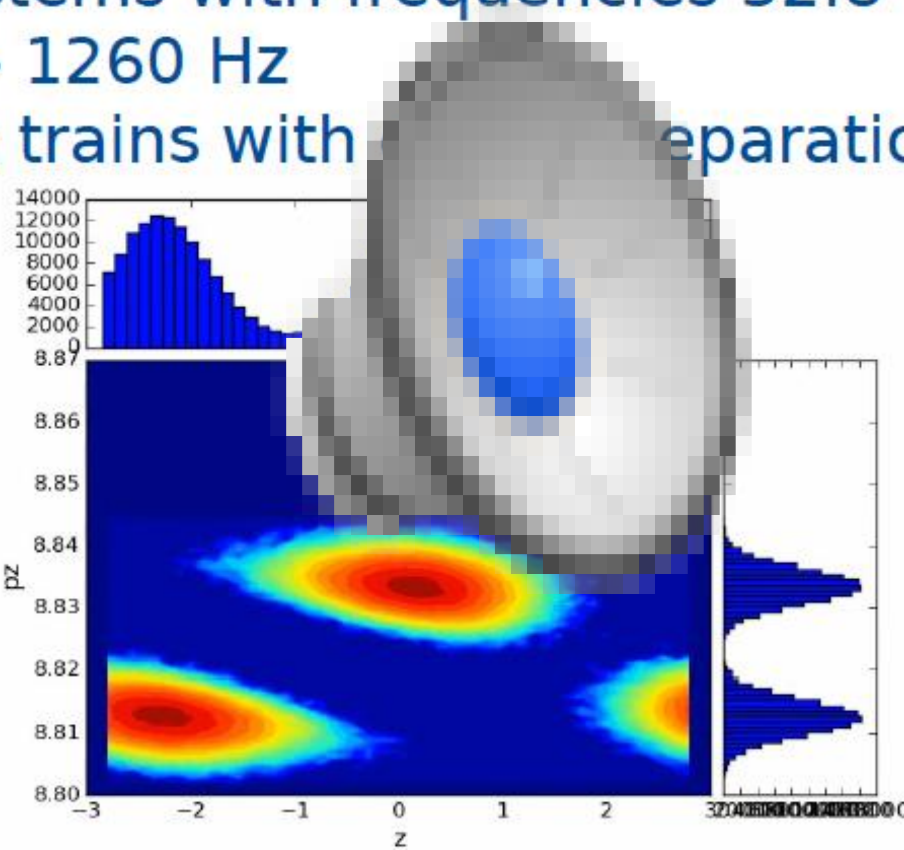
Fermilab

Anharmonic RF Cavities

Slip-stacking in the Fermilab Recycler

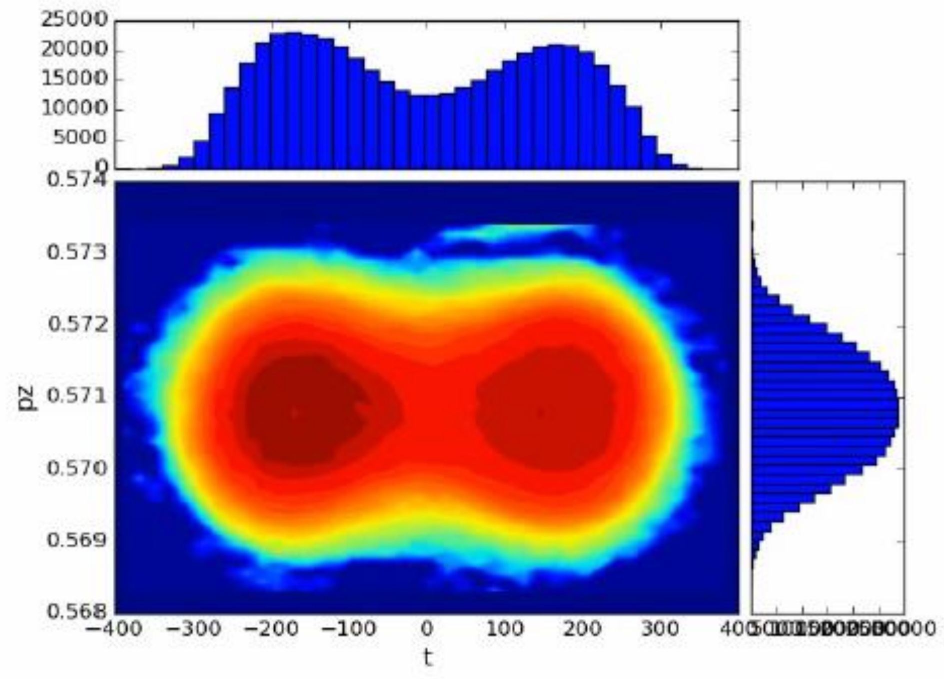
Using RF gymnastics to combine two bunches

- Two RF systems with frequencies 52.8 MHz, 52.8 MHz - 1260 Hz
- Two bunch trains with eparation of 24 MeV



Fermilab

PSB Double RF Longitudinal Phase Space



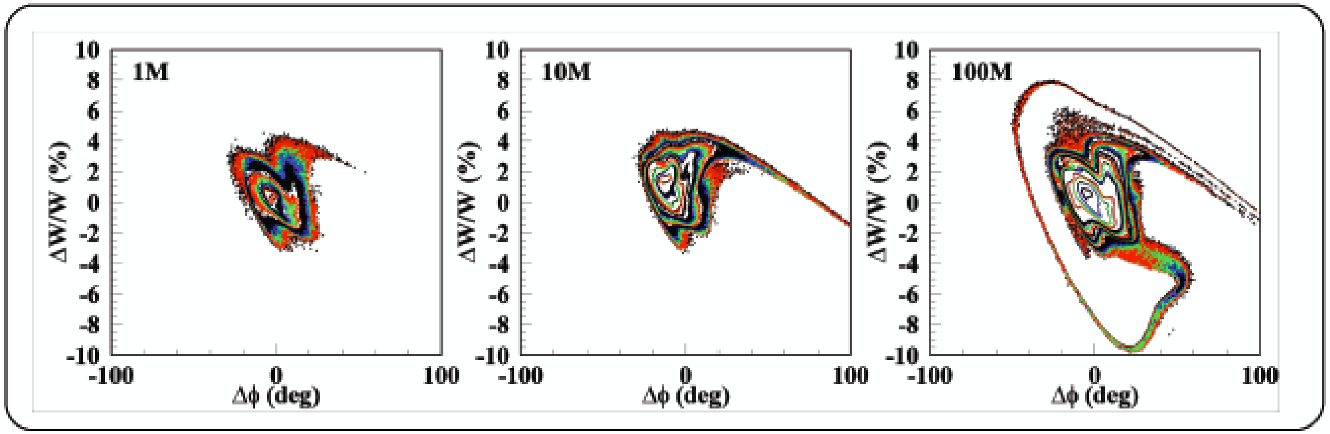
Longitudinal phase-space painting at injection

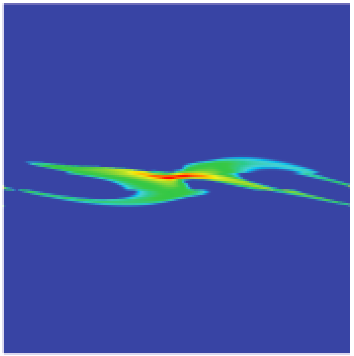
Simulation with ~10^9 Particles

With super-fast computers and parallel processors can now simulate a large number of particles: actual number if possible

- Suppress noise from the PIC method: enough particles/cell
- More detailed simulation: better statistics, better characterisation of beam halo

Longitudinal Tracking of the SNS RFQ





Phase space plots for 8.65×10^8 protons after 30 cells in the SNS RFQ.

C. Prior, RAL

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Ion Booster – Space-Charge Issues

- Injection Simulation of two-plane phase-space painting
- Operating Booster with large Laslett tune shift (> 0.3).
- Resonance crossing and stop-band correction
  - If the incoherent space-charge tune shift at injection is large, > 0.3, significant fraction of particles in the beam can move cross third-integer and quarter-integer resonance lines.
  - Properly placed quadrupoles and sextupoles could be used to correct the stop-band width of those resonances to minimize the amplitude growth and hence the beam loss.
  - Trapping of particles on space-charge induced islands leads to halo generation, eventually causing beam loss
- Tracking studies required to define Booster performance
  - Beam-loss tune scan, selection of the working point tunes

Summary

- Space-charge mitigation by design – MEIC high-luminosity strategy:
  - High bunch repetition rate of CW beams limits bunch charge
- Superconducting **Ion Linac** with warm front-end (based on FRIB design)
  - Following the RFQ and MEBT sections, where the rms matching technique is required, there are no sizable space-charge effects for the rest of the linac.
- 8 GeV **Booster** design avoiding transition crossing for all ion species
  - Simulation of two-plane phase-space painting required to optimize injection.
  - More aggressive operation with Laslett tune shift at injection > 0.3 considered
  - Study of resonance crossing in the presence of space–charge required.
  - Stop-band correction and other mitigation schemes need to be studied.
- Thorough space-charge studies required to optimize the present design
  - Define optimum injection energy, working point tunes, maximum current, acceptable halo and beam loss.

Thanks for your attention!

Backup Slides

Other Boosters – Tunes

SNS Accumulator:	5.82 / 5.80
SSC LEB:	11.65 / 11.60
SPS:	1.82 / 2.72
SPS Booster:	6.23 / 6.25
J-PARC RCS:	6.45 / 6.42
MEIC Booster:	**9.87 / 8.85**

Collider Luminosity Parameters

CM energy	GeV	21.9 **(low)**		44.7 **(medium)**		63.3 **(high)**	
		p	*e*	*p*	*e*	*p*	*e*
Beam energy	GeV	30	4	100	5	100	10
Collision frequency	MHz	476		476		159	
Particles per bunch	10^{10}	0.66	3.9	0.66	3.9	2.0	2.8
Beam current	A	0.5	3	0.5	3	0.5	0.72
Polarization	%	>70%	>70%	>70%	>70%	>70%	>70%
Bunch length, RMS	cm	2.5	1.2	1	1.2	2.5	1.2
Norm. emitt., vert./horz.	µm	0.5/0.5	74/74	1/0.5	144/72	1.2/0.6	1152/576
Horizontal and vertical β^*	cm	3	5	2/4	2.6/1.3	5/2.5	2.4/1.2
Laslett tune-shift		0.054	small	0.01	small	0.01	small
Hour-glass (HG) corr.		0.89		0.88		0.73	
Lumi./IP, w/HG corr.	$10^{33}cm^{-2}s^{1}$	**1.9**		**4.6**		**1.0**	

		e	*d*	$^{3}He^{++}$	$^{12}C^{6+}$	$^{40}Ca^{20+}$	$^{208}Pb^{82+}$
Beam energy	GeV	5	50	66.7	50	50	39.4
Particles/bunch	10^{10}	3.9	0.66	0.33	0.11	0.033	0.008
Beam current	A	3	0.5	0.5	0.5	0.5	0.5
Polarization		>70%	> 70%	> 70%	-	-	-
Bunch length, RMS	cm	1.2	1	1	1	1	1
Norm. emit., horz./vert.	µm	144/72	0.5/0.25	0.7/0.35	0.5/0.25	0.5/0.25	0.5/0.25
Laslett tune-shift			0.041	0.022	0.041	0.041	0.041
Lumi/IP/***nucleon***, w/HG corr.	$10^{33}\ cm^{-2}s^{-1}$		9.2	6.6	9.2	9.2	7.8

* Parameters are still evolving….

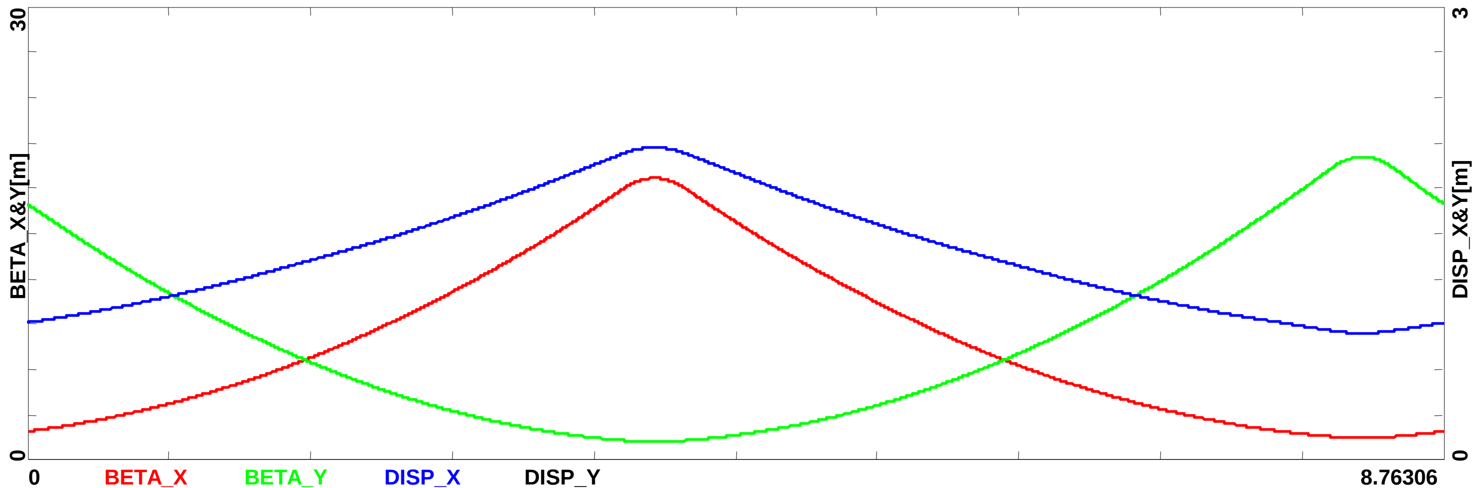
Beam Formation Cycle

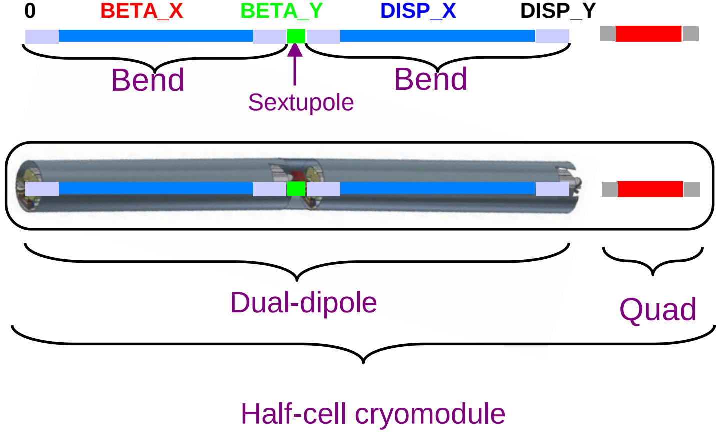
1. Eject the expanded beam from the collider ring, cycle the magnet
2. Injection from the ion linac to the booster
3. Ramp to 2 GeV (booster DC cooling energy)
4. DC electron cooling
5. Ramp to 8 GeV (booster ejection energy)
6. Inject the beam into the collider ring for stacking
7. The booster magnets cycle back for the next injection
8. Repeat step 1 to 6 for 8 times for stacking/filling the whole collider ring
9. Cooling during stacking in the collider ring
10. Ramp to the collision energy (20 to 100 GeV)
11. Coasting/re-bunching (or bunch splitting) to the designed bunch repetition rate

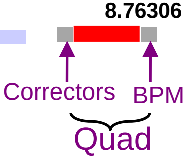
Total formation time: **30 min**

Y. Zhang, JLAB

Arc Cell – Super-ferric Magnets







Bend:

L_b = 120 cm (magnetic length)

Lead ends: 2 × 22 cm

B = 2.73 Tesla

bend ang. = 7.08 deg.

Sagitta =1.8 cm

Quadrupole:

L_q = 40 cm

G = 12-58 Tesla/m

Correctors (H/V): 10 cm

BPM can: 10 cm

Magnet aperture radius:

$6\sigma_{rms}$ = 42 mm

Sextupole:

L_s = 10 cm

S = 750 Tesla/m^2

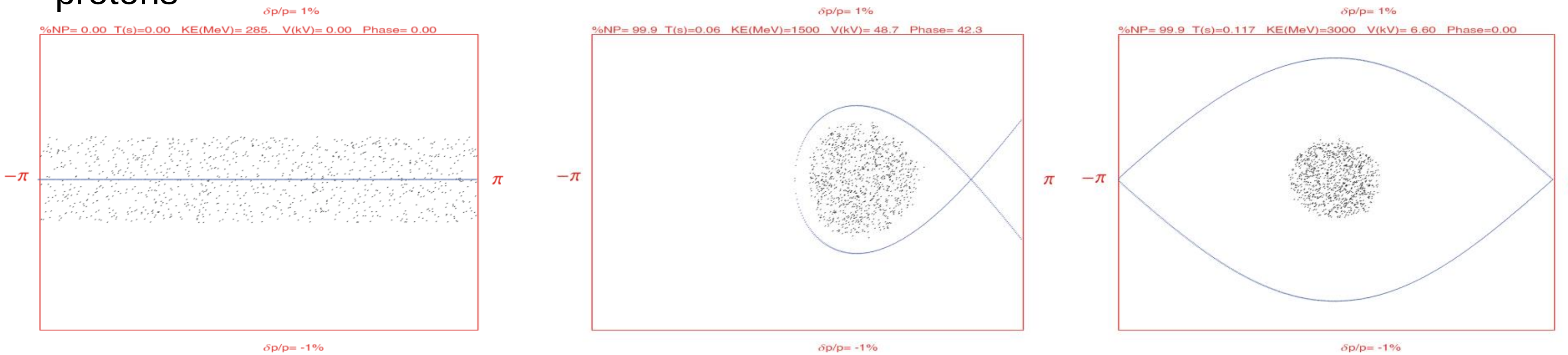
Booster Ring Parameters

Proton beam energy (total)	GeV	1.2 - 8
Circumference	m	272.5
Arc's net bend	deg	255
Straights' crossing angle	deg	75
Arc length	m	86.9 / 77.9
Straight section length	m	53.8
Maximum hor. / ver. β functions	m	60 / 38
Maximum hor. dispersion	m	5.9
Hor. / ver. betatron tunes $\nu_{x,y}$		9.87 / 8.85
Hor. / ver. natural chromaticities $\xi_{x,y}$		-28 / -24
Momentum compaction factor α		10^{-2}
Hor. / ver. normalized emittance $\varepsilon_{x,y}$	µm rad	2.7 / 2.7
Beam current	Amp	0.2
Laslett tune shift at injection (protons)		0.3 ?

Adiabatic Capture and Acceleration (h =1)

	H^+	$^{208}Pb^{67+}$	
Energy	0.28 – 8	0.112 – 3.2	GeV
RF Frequency Range	0.817 – 1.274	0.578 – 1.25	MHz
Ramping Time	0.396	0.56	sec

protons



lead ions