Parameters of Proton Operations in IOTA

Goals

- Create technical memo/physics note containing parameters of proton operations in IOTA. – Draft ready.

Parameters of proton operations at the Integrable Optics Test Accelerator

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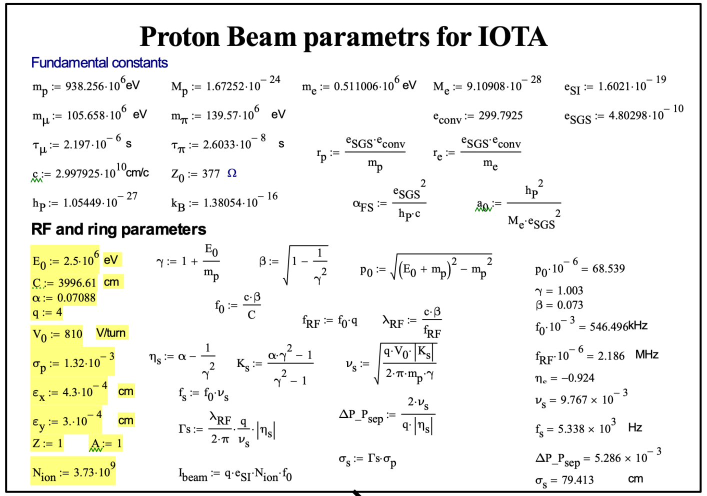
- Cite primary sources for all injector parameters. – Mostly.
- Make reasonable assumptions and calculate parameters in IOTA. – Done.
- Summarize values in data tables. - Done

Injector parameters

Single turn injection from the IOTA proton injector.

- Bunch length: 0.3 ns -> 6.6 mm
- Assuming 7 mA beam from injector, maximum intensity is $\frac{I_{src}T_{rev}}{e} = 8.16\times10^{10}$



Proton Beam parametrs for IOTA

Fundamental constants

$m_p := 938.256\cdot10^{6}\,\text{eV}$ $M_p := 1.67252\cdot10^{-24}$ $m_e := 0.511006\cdot10^{6}\,\text{eV}$ $M_e := 9.10908\cdot10^{-28}$ $e_{SI} := 1.6021\cdot10^{-19}$

$m_\mu := 105.658\cdot10^{6}\,\text{eV}$ $m_\pi := 139.57\cdot10^{6}\,\text{eV}$ $e_{conv} := 299.7925$ $e_{SGS} := 4.80298\cdot10^{-10}$

$\tau_\mu := 2.197\cdot10^{-6}\,\text{s}$ $\tau_\pi := 2.6033\cdot10^{-8}\,\text{s}$ $r_p := \frac{e_{SGS}\cdot e_{conv}}{m_p}$ $r_e := \frac{e_{SGS}\cdot e_{conv}}{m_e}$

$c := 2.997925\cdot10^{10}\,\text{cm/c}$ $Z_0 := 377\ \Omega$

$h_P := 1.05449\cdot10^{-27}$ $k_B := 1.38054\cdot10^{-16}$ $\alpha_{FS} := \frac{e_{SGS}^{2}}{h_P\cdot c}$ $a_0 := \frac{h_P^{2}}{M_e\cdot e_{SGS}^{2}}$

RF and ring parameters

$E_0 := 2.5\cdot10^{6}\,\text{eV}$ $\gamma := 1 + \frac{E_0}{m_p}$ $\beta := \sqrt{1-\frac{1}{\gamma^2}}$ $p_0 := \sqrt{(E_0+m_p)^2 - m_p^{2}}$ $p_0\cdot10^{-6} = 68.539$

$C := 3996.61\,\text{cm}$ $\gamma = 1.003$

$\alpha := 0.07088$ $\beta = 0.073$

$q := 4$ $f_0 := \frac{c\cdot\beta}{C}$ $f_{RF} := f_0\cdot q$ $\lambda_{RF} := \frac{c\cdot\beta}{f_{RF}}$ $f_0\cdot10^{-3} = 546.496\,\text{kHz}$

$V_0 := 810\ \text{V/turn}$

$\sigma_p := 1.32\cdot10^{-3}$ $\eta_s := \alpha - \frac{1}{\gamma^2}$ $K_s := \frac{\alpha\cdot\gamma^2 - 1}{\gamma^2 - 1}$ $\nu_s := \sqrt{\frac{q\cdot V_0\cdot|K_s|}{2\cdot\pi\cdot m_p\cdot\gamma}}$ $f_{RF}\cdot10^{-6} = 2.186\ \text{MHz}$

$\eta_s = -0.924$

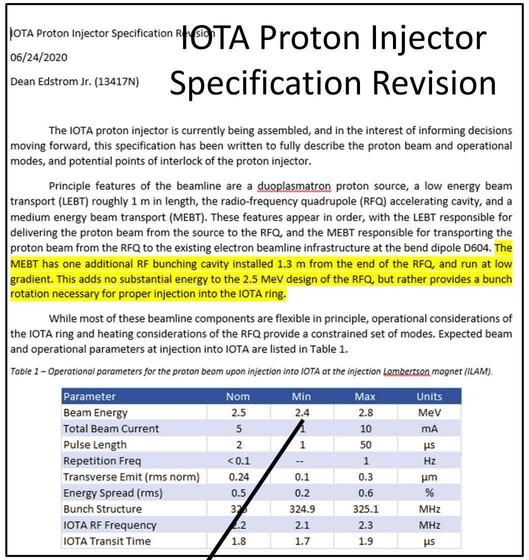
$\varepsilon_x := 4.3\cdot10^{-4}\,\text{cm}$ $f_s := f_0\cdot\nu_s$ $\nu_s = 9.767\times10^{-3}$

$\varepsilon_y := 3.\cdot10^{-4}\,\text{cm}$ $\Gamma s := \frac{\lambda_{RF}}{2\cdot\pi}\cdot\frac{q}{\nu_s}\cdot|\eta_s|$ $\Delta P\_P_{sep} := \frac{2\cdot\nu_s}{q\cdot|\eta_s|}$ $f_s = 5.338\times10^{3}\ \text{Hz}$

$Z := 1$ $A := 1$

$\sigma_s := \Gamma s\cdot\sigma_p$ $\Delta P\_P_{sep} = 5.286\times10^{-3}$

$N_{ion} := 3.73\cdot10^{9}$ $I_{beam} := q\cdot e_{SI}\cdot N_{ion}\cdot f_0$ $\sigma_s = 79.413\ \text{cm}$



IOTA Proton Injector Specification Revision

06/24/2020

Dean Edstrom Jr. (13417N)

IOTA Proton Injector Specification Revision

The IOTA proton injector is currently being assembled, and in the interest of informing decisions moving forward, this specification has been written to fully describe the proton beam and operational modes, and potential points of interlock of the proton injector.

Principle features of the beamline are a duoplasmatron proton source, a low energy beam transport (LEBT) roughly 1 m in length, the radio-frequency quadrupole (RFQ) accelerating cavity, and a medium energy beam transport (MEBT). These features appear in order, with the LEBT responsible for delivering the proton beam from the source to the RFQ, and the MEBT responsible for transporting the proton beam from the RFQ to the existing electron beamline infrastructure at the bend dipole D604. The MEBT has one additional RF bunching cavity installed 1.3 m from the end of the RFQ, and run at low gradient. This adds no substantial energy to the 2.5 MeV design of the RFQ, but rather provides a bunch rotation necessary for proper injection into the IOTA ring.

While most of these beamline components are flexible in principle, operational considerations of the IOTA ring and heating considerations of the RFQ provide a constrained set of modes. Expected beam and operational parameters at injection into IOTA are listed in Table 1.

Table 1 – Operational parameters for the proton beam upon injection into IOTA at the injection Lambertson magnet (ILAM).

Parameter	Nom	Min	Max	Units
Beam Energy	2.5	2.4	2.8	MeV
Total Beam Current	5	1	10	mA
Pulse Length	2	1	50	µs
Repetition Freq	< 0.1	--	1	Hz
Transverse Emit (rms norm)	0.24	0.1	0.3	µm
Energy Spread (rms)	0.5	0.2	0.6	%
Bunch Structure	325	324.9	325.1	MHz
IOTA RF Frequency	2.2	2.1	2.3	MHz
IOTA Transit Time	1.8	1.7	1.9	µs

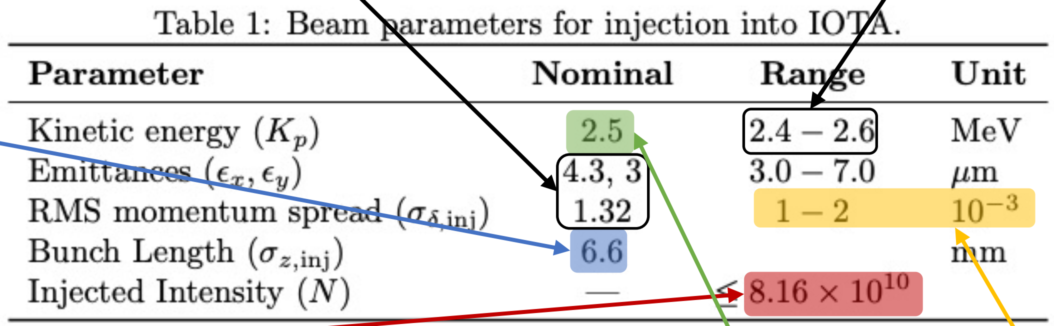


Table 1: Beam parameters for injection into IOTA.

Parameter	Nominal	Range	Unit
Kinetic energy (K_p)	2.5	2.4 – 2.6	MeV
Emittances (ϵ_x, ϵ_y)	4.3, 3	3.0 – 7.0	μm
RMS momentum spread ($\sigma_{\delta,\text{inj}}$)	1.32	1 – 2	10^{-3}
Bunch Length ($\sigma_{z,\text{inj}}$)	6.6		mm
Injected Intensity (N)	—	8.16×10^{10}	

Cite-able References:

[1] E. Prebys, “RF Capture of Protons in the IOTA Ring”, Beams Document 4837-v1, Fermilab, 2015.

[2] P. N. Ostroumov, V. N. Aseev, and A. A. Kolomiets, “Application of a new procedure for design of 325 MHz RFQ”, JINST vol. 1, no.04, P04002, 2006.

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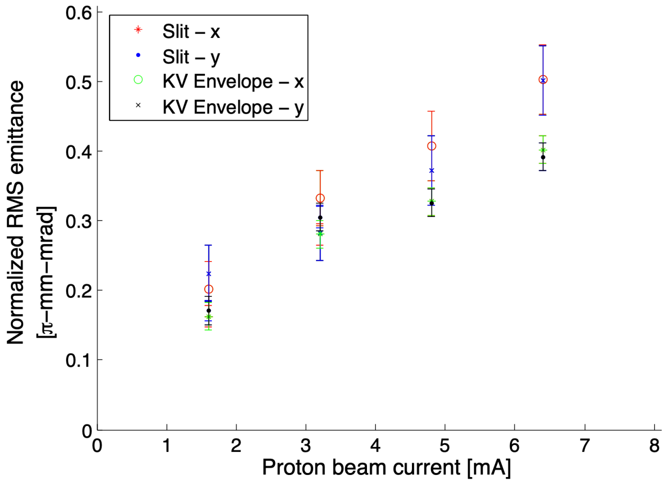
Transverse rms emittance

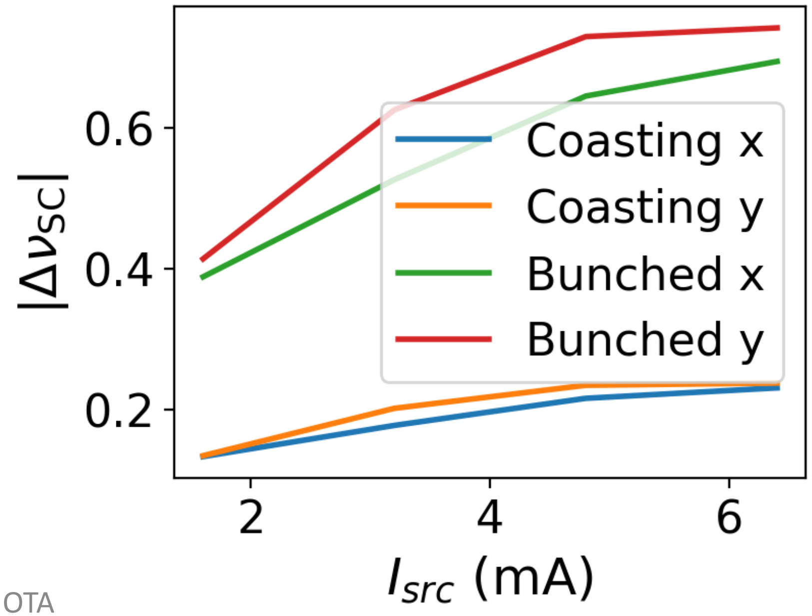
Mostly depends on duoplasmatron source with less than 10% increase inside the RFQ.

1. The maximum incoherent tune shift due to space-charge for coasting beam seems to saturate around 0.25.
2. We can reach tune shifts above 0.5 for bunched beam.

High rf voltages will allow realization of high tune shifts even if source yield is low. – Relevant for proposed bunch compression experiment.

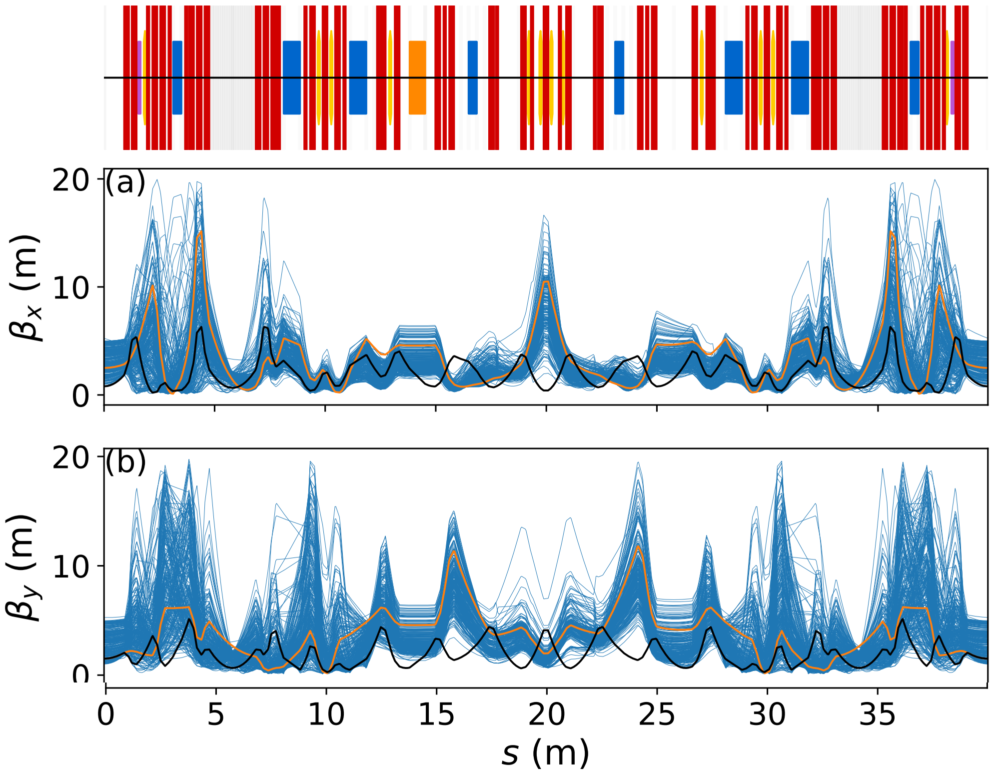


W. M. Tam, "Characterization of the proton ion source beam for the high intensity neutrino source at Fermilab", PhD Thesis, Indiana University, Bloomington, 2010.



Lattices for proton operations

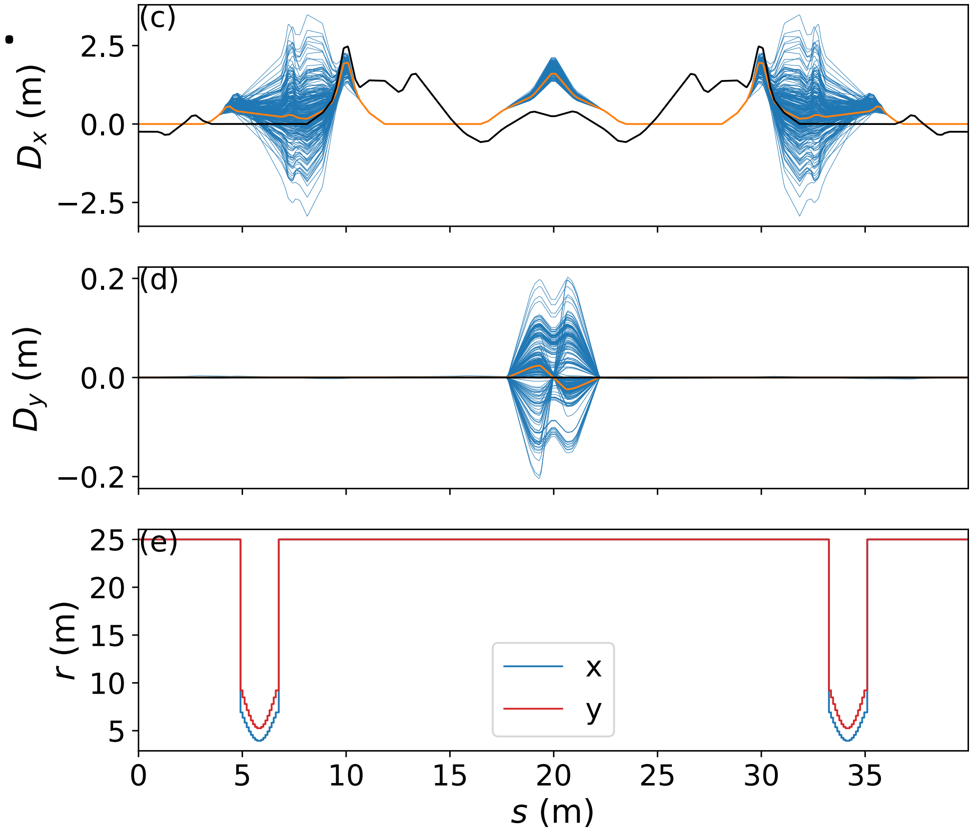
I assume that the lattice with the Danilov-Nagaitsev non-linear magnet will be used to commission protons in IOTA.



- 1IO

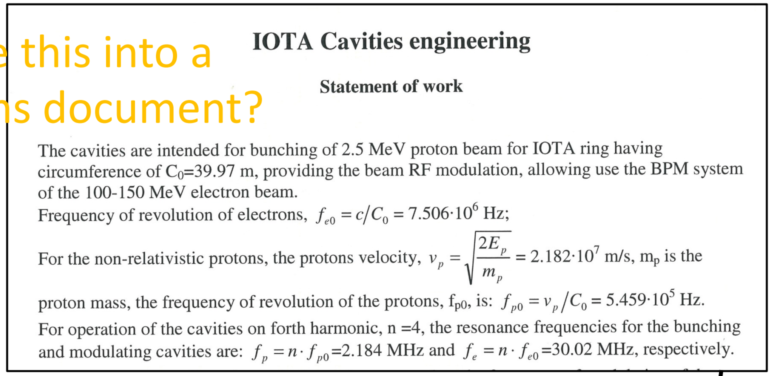
- ECool ensemble

- ECool reference



Longitudinal dynamics in IOTA

Make this into a Beams document?



IOTA Cavities engineering

Statement of work

The cavities are intended for bunching of 2.5 MeV proton beam for IOTA ring having circumference of C_0=39.97 m, providing the beam RF modulation, allowing use the BPM system of the 100-150 MeV electron beam.

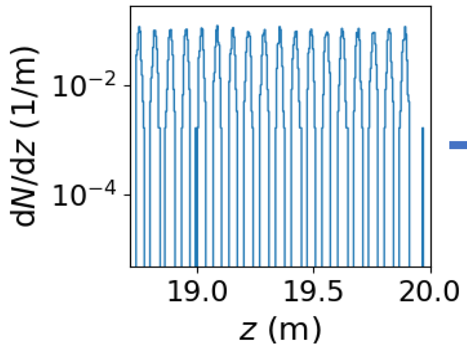
Frequency of revolution of electrons, $f_{e0} = c/C_0 = 7.506\cdot 10^6$ Hz;

For the non-relativistic protons, the protons velocity, $v_p = \sqrt{\frac{2E_p}{m_p}} = 2.182\cdot 10^7$ m/s, m_p is the proton mass, the frequency of revolution of the protons, f_{p0}, is: $f_{p0} = v_p/C_0 = 5.459\cdot 10^5$ Hz.

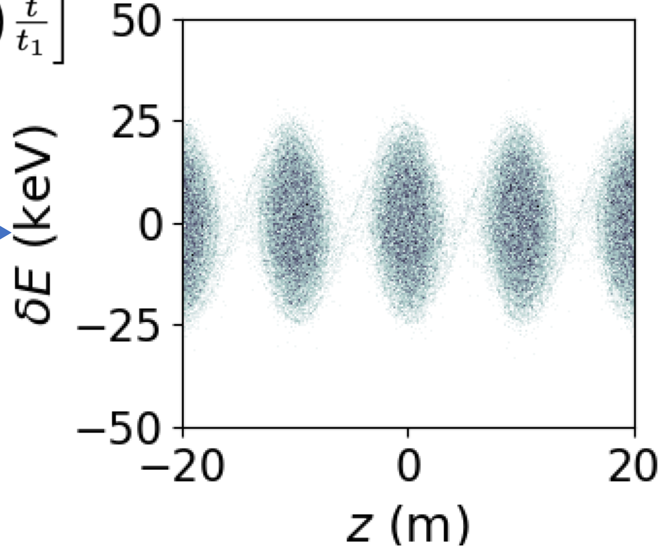
For operation of the cavities on forth harmonic, n =4, the resonance frequencies for the bunching and modulating cavities are: $f_p = n\cdot f_{p0}$=2.184 MHz and $f_e = n\cdot f_{e0}$=30.02 MHz, respectively.

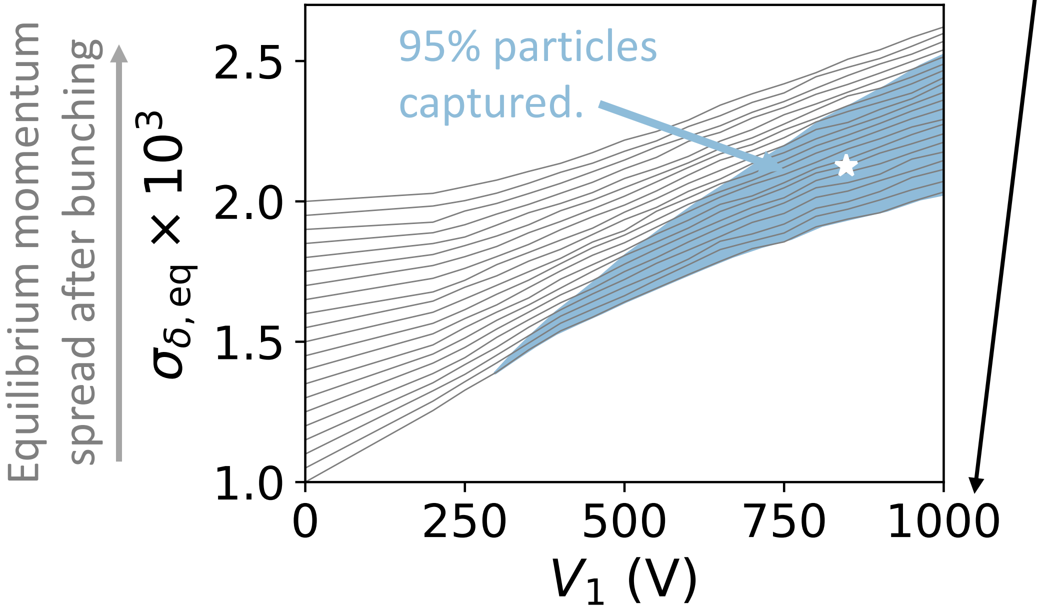
Start with bunches with rms length of 0.3 ns, and separation 3.08 ns.

$$V(t) = \frac{V_0}{\left[1 - \left(1 - \sqrt{\frac{V_0}{V_1}}\right)\frac{t}{t_1}\right]^2}$$



1000 turns





95% particles captured.

Equilibrium momentum spread after bunching

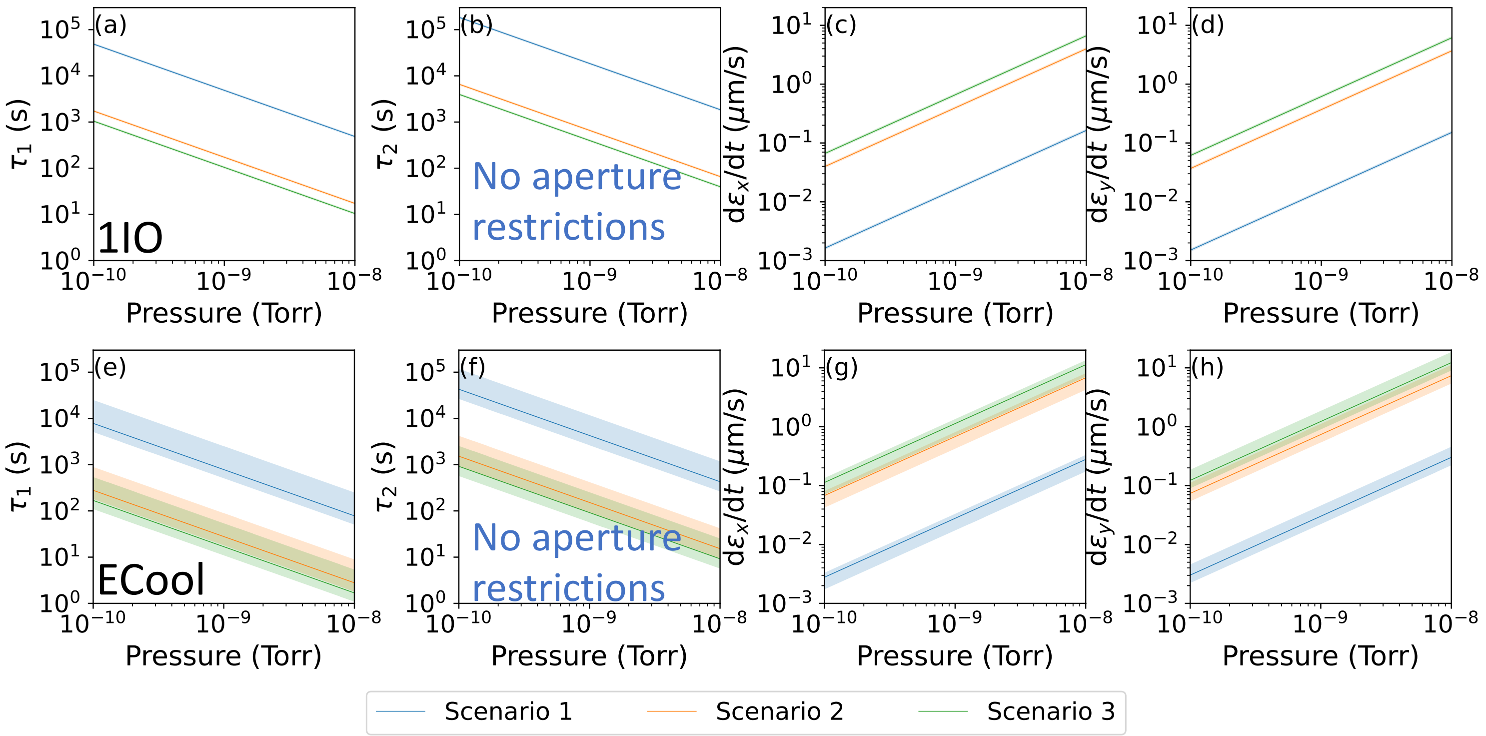
h=4 Cavity voltage

E. Prebys, "RF Capture of Protons in the IOTA Ring", Beams Document 4837-v1, Fermilab, 2015.
K. Y. Ng, "Continuous multiple injections at the Fermilab Main Injector", Phys. Rev. ST Accel. Beams vol. 5, 061002, 2002.

Residual gas scattering depends on pressure

- Single scattering events lead to a finite lifetime. 8 mins @ 4.2 x 10^{-8} Torr measured in atomic hydrogen equivalents.
- Multiple scattering events lead to emittance growth independent of intensity. 20-30 seconds @ 4.2 x 10^{-8} Torr

Baking can reduce residual pressure and increase lifetime.



V. Lebedev et al., “Report on Single and Multiple Intrabeam Scattering Measurements in IOTA Ring in Fermilab”, Beams Document 8837-v1, Fermilab, 2020.

V. Lebedev and S. Nagaitsev, “Particle Scattering in the Residual Gas”, Beams Document 8859-v1, Fermilab, 2020.

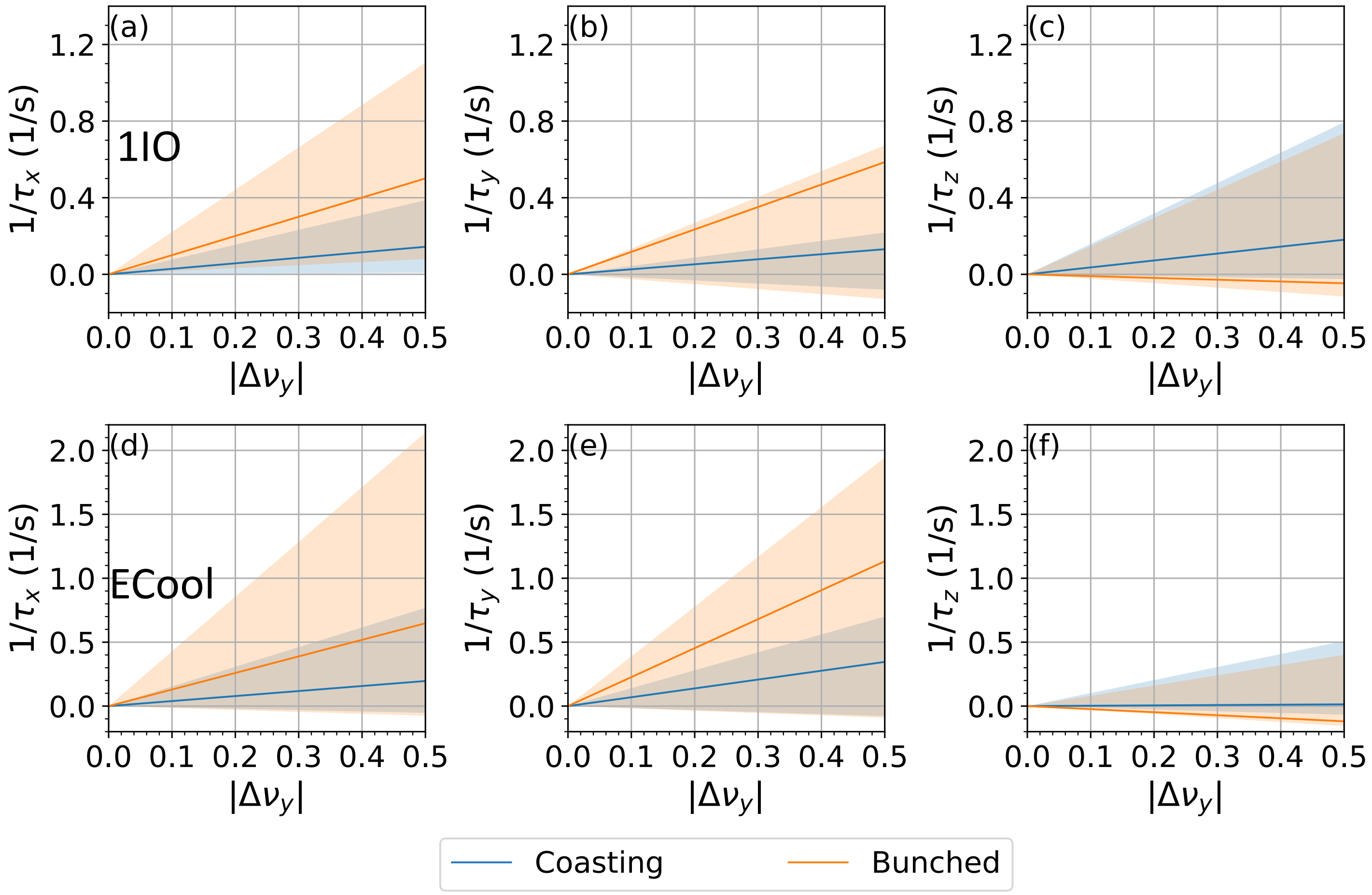
Intra-Beam Scattering depends on intensity

We calculate ranges of emittance growth rates due to IBS for the entire range of energies, emittances, momentum spread, rf voltage and intensity.

$$z = \frac{\sigma_\delta^2}{\gamma^2 \theta_\perp^2}$$

Longitudinal

Transverse



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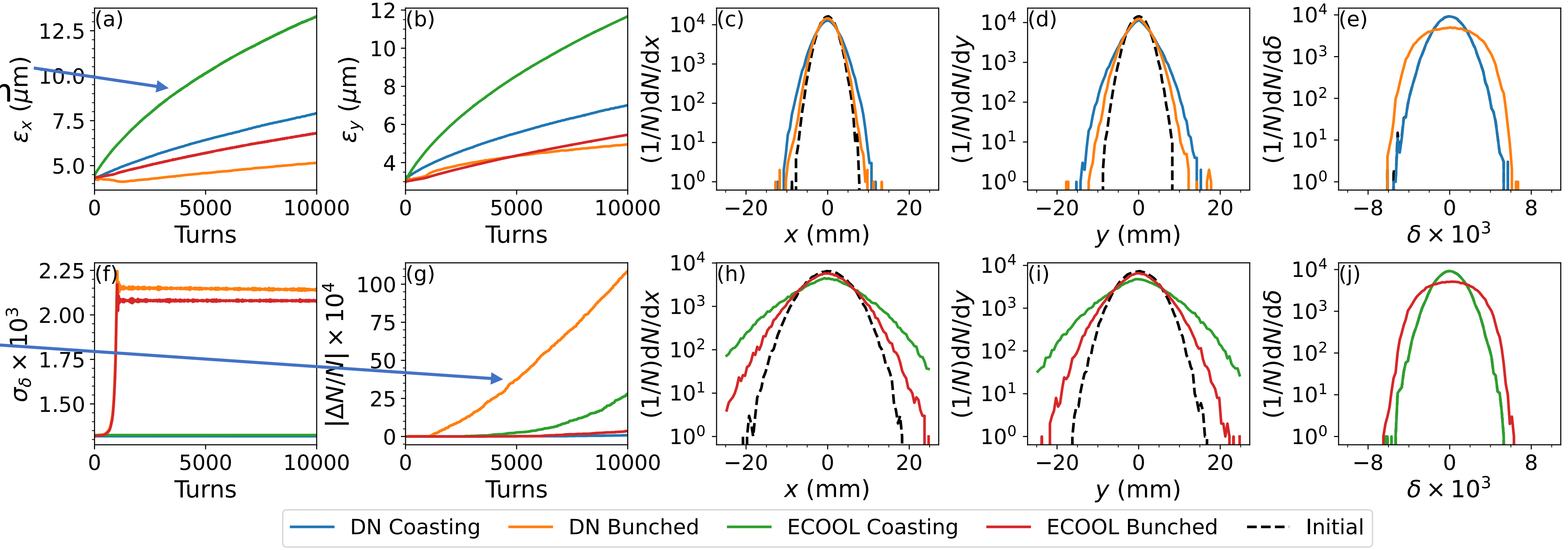
Space-charge dynamics with realistic injection

Simulated 10000 turns after proton injection using the 2.5 D space-charge model in PyORBIT. $|\delta\nu_{y,\mathrm{SC}}| \sim 0.1$



Transverse Emittance growth

Beam Loss

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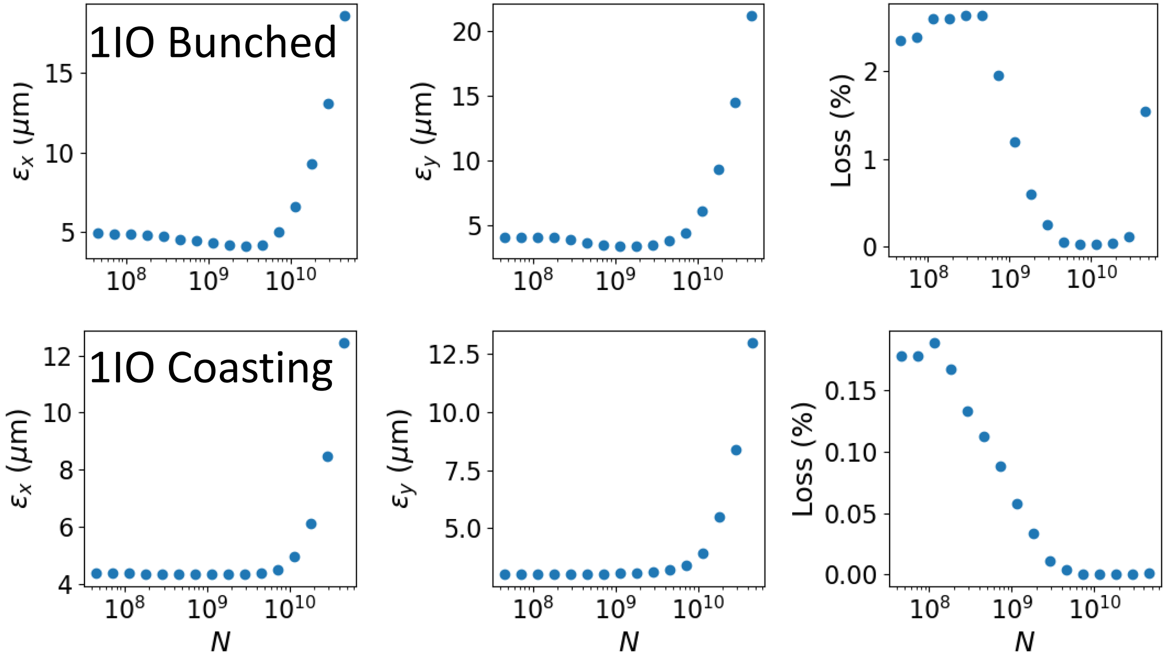
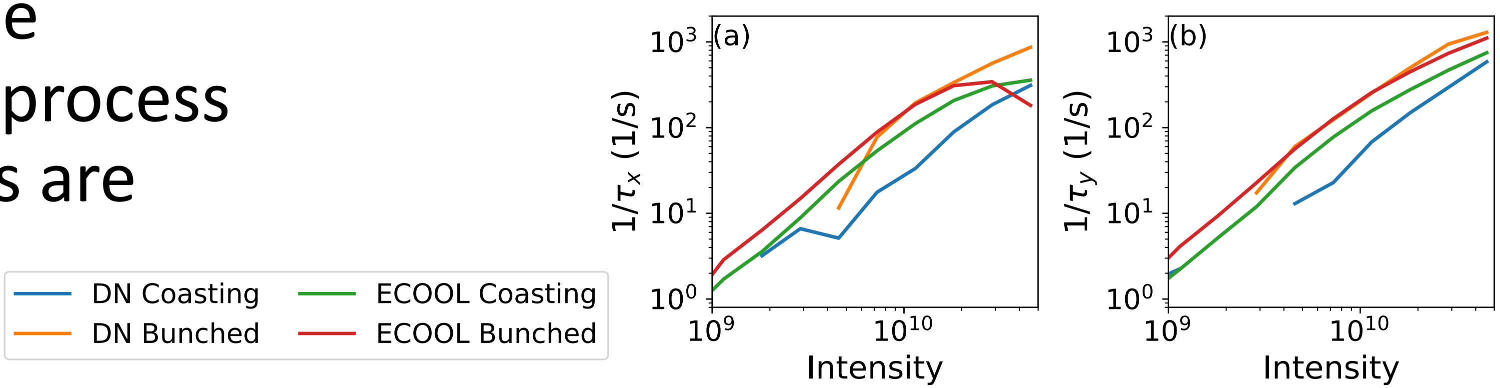
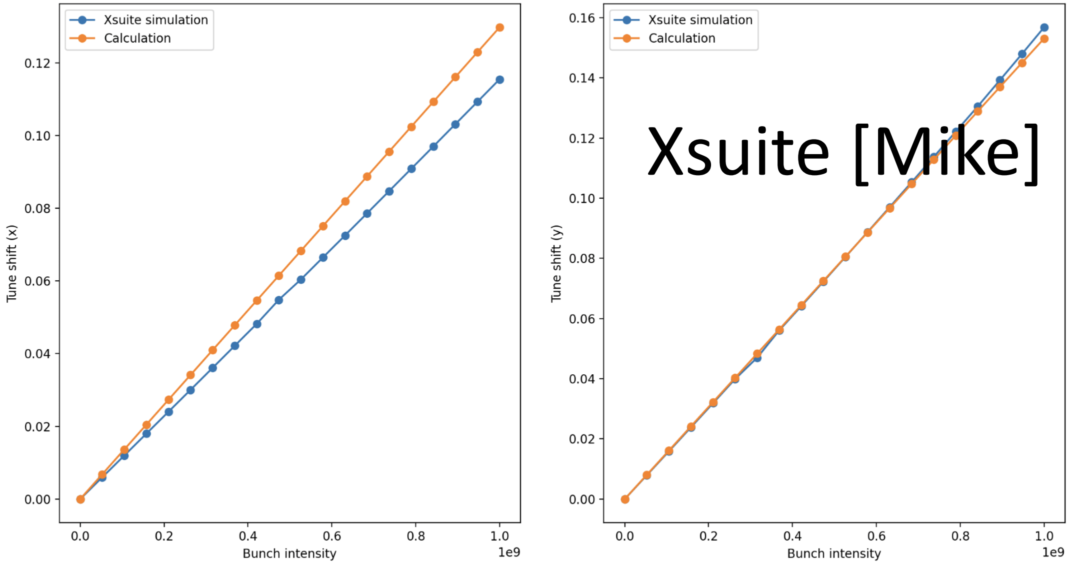
Space-charge effects as a function of intensity

- Transverse emittance growth rates and final values after 2000 turns depend on intensity.
- More loss at intermediate intensities. Why?
- More loss during the adiabatic bunching process since some particles are not captured.

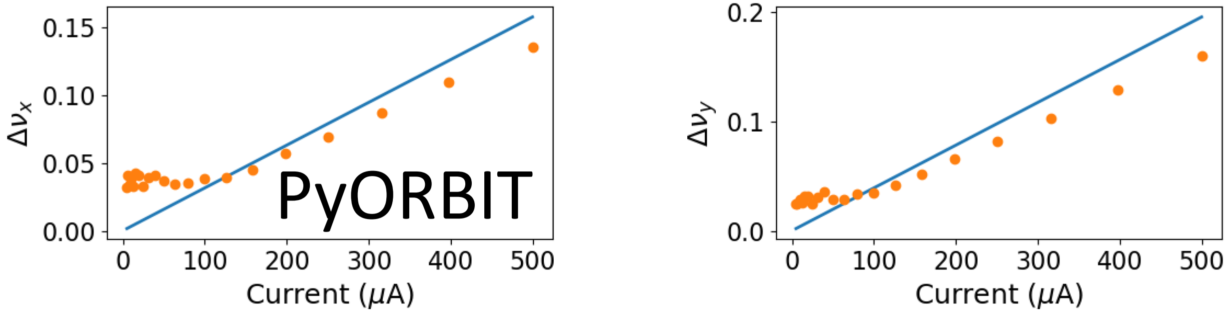




Space-charge simulations in multiple codes

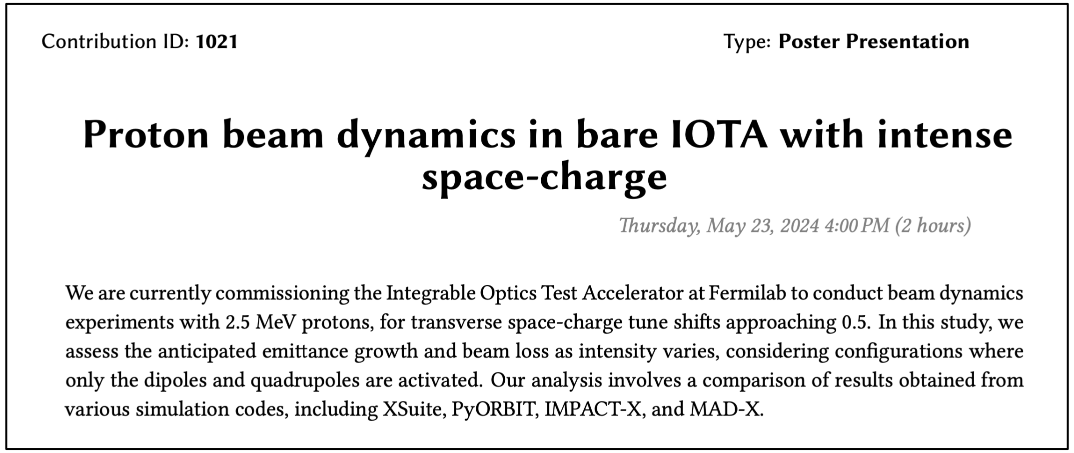


Xsuite [Mike]



PyORBIT

Also, IMPACT-X [John], MAD-X [Ben]



Contribution ID: **1021**

Type: **Poster Presentation**

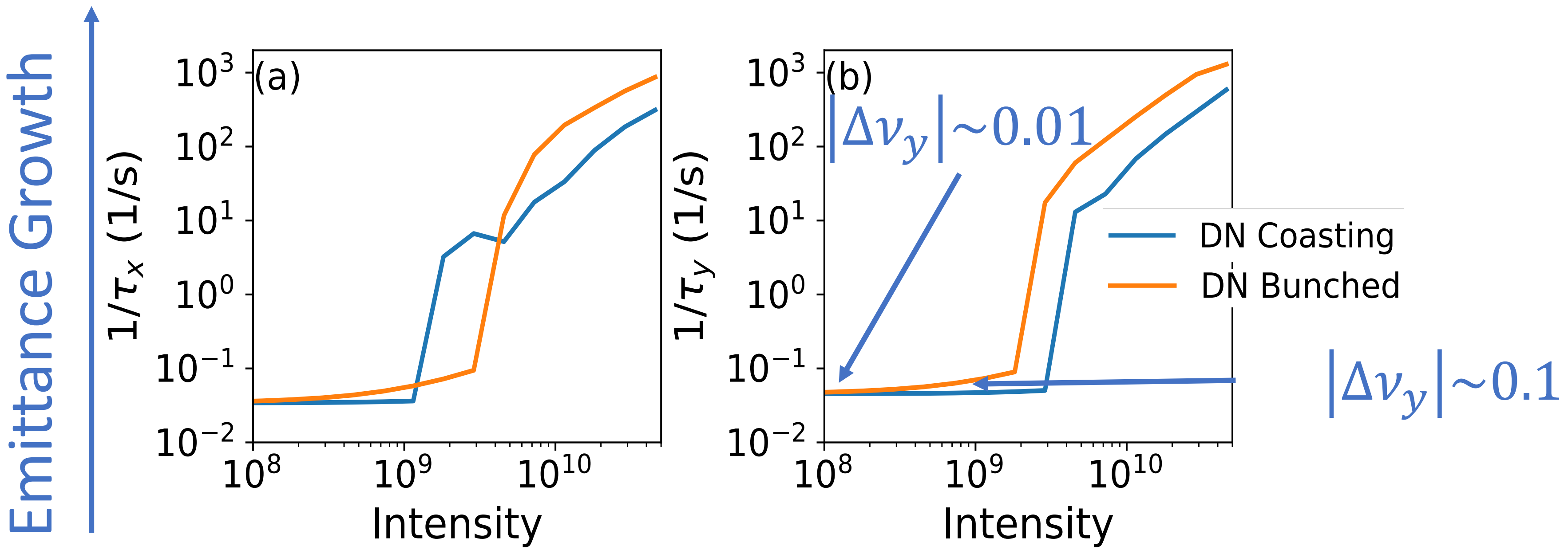
Proton beam dynamics in bare IOTA with intense space-charge

Thursday, May 23, 2024 4:00 PM (2 hours)

We are currently commissioning the Integrable Optics Test Accelerator at Fermilab to conduct beam dynamics experiments with 2.5 MeV protons, for transverse space-charge tune shifts approaching 0.5. In this study, we assess the anticipated emittance growth and beam loss as intensity varies, considering configurations where only the dipoles and quadrupoles are activated. Our analysis involves a comparison of results obtained from various simulation codes, including XSuite, PyORBIT, IMPACT-X, and MAD-X.

Cumulative emittance growth rates

RGS dominates at low intensities, IBS at intermediate and SC at high intensities.



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Tables are all you need

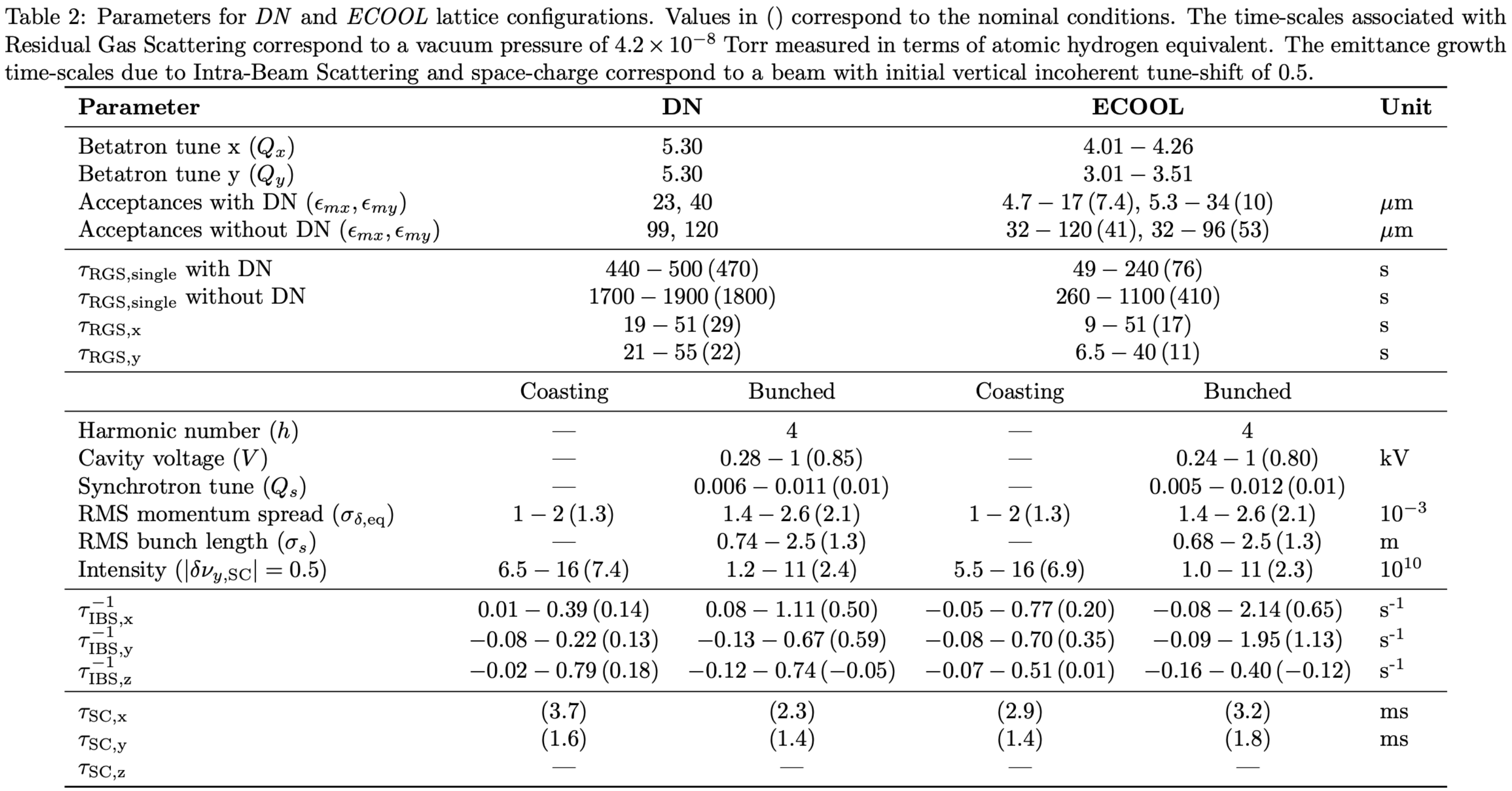

Table 2: Parameters for *DN* and *ECOOL* lattice configurations. Values in () correspond to the nominal conditions. The time-scales associated with Residual Gas Scattering correspond to a vacuum pressure of 4.2×10^{-8} Torr measured in terms of atomic hydrogen equivalent. The emittance growth time-scales due to Intra-Beam Scattering and space-charge correspond to a beam with initial vertical incoherent tune-shift of 0.5.

Parameter	**DN**		**ECOOL**		**Unit**
Betatron tune x (Q_x)	5.30		$4.01 - 4.26$		
Betatron tune y (Q_y)	5.30		$3.01 - 3.51$		
Acceptances with DN ($\epsilon_{mx}, \epsilon_{my}$)	23, 40		$4.7 - 17\,(7.4)$, $5.3 - 34\,(10)$		μm
Acceptances without DN ($\epsilon_{mx}, \epsilon_{my}$)	99, 120		$32 - 120\,(41)$, $32 - 96\,(53)$		μm
$\tau_{\mathrm{RGS,single}}$ with DN	$440 - 500\,(470)$		$49 - 240\,(76)$		s
$\tau_{\mathrm{RGS,single}}$ without DN	$1700 - 1900\,(1800)$		$260 - 1100\,(410)$		s
$\tau_{\mathrm{RGS,x}}$	$19 - 51\,(29)$		$9 - 51\,(17)$		s
$\tau_{\mathrm{RGS,y}}$	$21 - 55\,(22)$		$6.5 - 40\,(11)$		s
	Coasting	Bunched	Coasting	Bunched	
Harmonic number (h)	—	4	—	4	
Cavity voltage (V)	—	$0.28 - 1\,(0.85)$	—	$0.24 - 1\,(0.80)$	kV
Synchrotron tune (Q_s)	—	$0.006 - 0.011\,(0.01)$	—	$0.005 - 0.012\,(0.01)$	
RMS momentum spread ($\sigma_{\delta,\mathrm{eq}}$)	$1 - 2\,(1.3)$	$1.4 - 2.6\,(2.1)$	$1 - 2\,(1.3)$	$1.4 - 2.6\,(2.1)$	10^{-3}
RMS bunch length (σ_s)	—	$0.74 - 2.5\,(1.3)$	—	$0.68 - 2.5\,(1.3)$	m
Intensity ($\lvert\delta\nu_{y,\mathrm{SC}}\rvert = 0.5$)	$6.5 - 16\,(7.4)$	$1.2 - 11\,(2.4)$	$5.5 - 16\,(6.9)$	$1.0 - 11\,(2.3)$	10^{10}
$\tau^{-1}_{\mathrm{IBS,x}}$	$0.01 - 0.39\,(0.14)$	$0.08 - 1.11\,(0.50)$	$-0.05 - 0.77\,(0.20)$	$-0.08 - 2.14\,(0.65)$	s^{-1}
$\tau^{-1}_{\mathrm{IBS,y}}$	$-0.08 - 0.22\,(0.13)$	$-0.13 - 0.67\,(0.59)$	$-0.08 - 0.70\,(0.35)$	$-0.09 - 1.95\,(1.13)$	s^{-1}
$\tau^{-1}_{\mathrm{IBS,z}}$	$-0.02 - 0.79\,(0.18)$	$-0.12 - 0.74\,(-0.05)$	$-0.07 - 0.51\,(0.01)$	$-0.16 - 0.40\,(-0.12)$	s^{-1}
$\tau_{\mathrm{SC,x}}$	(3.7)	(2.3)	(2.9)	(3.2)	ms
$\tau_{\mathrm{SC,y}}$	(1.6)	(1.4)	(1.4)	(1.8)	ms
$\tau_{\mathrm{SC,z}}$	—	—	—	—	

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Next Steps

- Trace the source of loss and explain the dependence on intensity.
- Add anything missing. Feedback welcome!
- Publish report as technical memo/physics note.
- Write similar report for electron cooling. – In progress.

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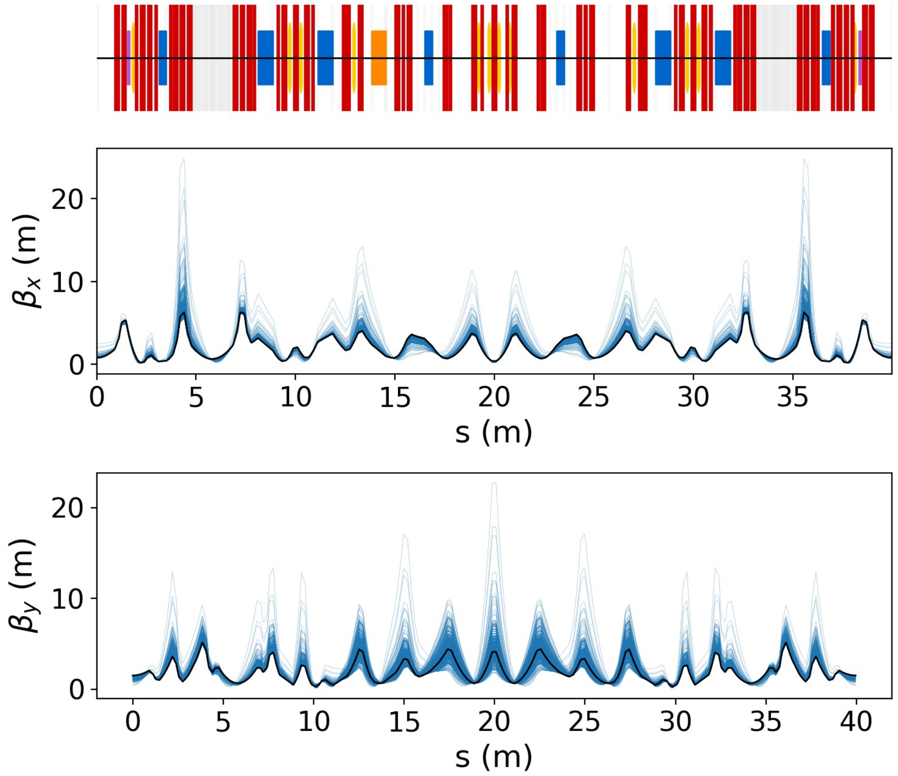
Appendix: Un-corrected linear lattice perturbations

A. L. Romanov, G. T. Kafka, S. Nagaitsev, and A. Valishev, “Lattice Correction Modeling for Fermilab IOTA Ring”, in Proc. IPAC'14, Dresden, Germany, Jun. 2014, pp. 1165-1167.

Tolerances in position: 0.1 mm, angle: 1 mrad and quad field: 1%



Not considered in parameter range calculations.