Fermilab

Fermilab Accelerator Science and Technology (FAST) Facility

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Fermilab

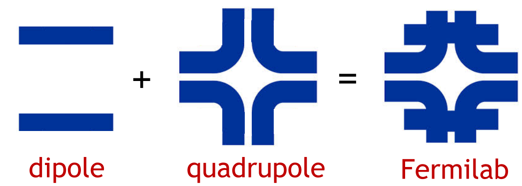
A Brief History of Fermilab (evolving slide)

- 1968: construction begins
- 1972: first beams
  - 200➔400 GeV proton beams
  - Highest energy lab ~~ever since~~ until recently
- ~1985:
  - “Tevatron”: first superconducting synchrotron.
  - 900GeV x 900 GeV p-pBar collisions
- Upgraded in 1997
  - Main Injector-> more intensity
  - 980 GeV x 980 GeV p-pBar collisions
  - Intense neutrino program
- For awhile ~~Soon the *second* most powerful collider~~

- Fermilab is now the only remaining US High Energy Physics Lab
- With the LHC now the highest energy collider, the lab must focus on different types of physics.

Fermilab

Fermilab Firsts and Records



- Firsts:
  - First separated function synchrotron:
    - Main Ring, 1972
  - First superconducting synchrotron/collider
    - Tevatron, 1983 (first collisions in 1986)
  - First permanent magnet storage ring
    - Recycler, 2000
- Records:
  - Highest energy proton beam
    - Main Ring, 1972 (breaks AGS record)➔1983 (broken by Tevatron)
    - Tevatron, 1983-2008 (broken by LHC)
  - Highest energy hadron collider
    - Tevatron, 1986 (breaks SppS record)➔2009 (broken by LHC)
  - Highest hadronic luminosity
    - Tevatron, 2005 (broke ISR *p-p* record!) ➔ 2011 (broken by LHC)
  - Highest energy p-pbar collider
    - Tevatron, 1986 (breaks SppS record)➔ present
  - Highest p-pbar luminosity
    - Tevatron, 1992 (broke SppS record)➔ present

Context: P5 Report

- The "Particle Physics Project Prioritization Panel" (P5) advises the DOE Office of High Energy Physics on research funding priorities in high energy physics
- After a lengthy process, the panel released a report in May, 2014. Top priorities for Fermilab:
  - Support the LHC and its planned luminosity upgrades
  - Pursue the g-2 and Mu2e muon programs*
  - Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.
    - "Flagship" activity
    - Will ultimately require a "multi-megawatt" beam at 60-120 GeV
  - Continue at least R&D toward a future linear e^+e^- collider (ILC)

FAST supports these

*E. Prebys, UCD Colloquium, March 28, 2016

ILC-Related R&D

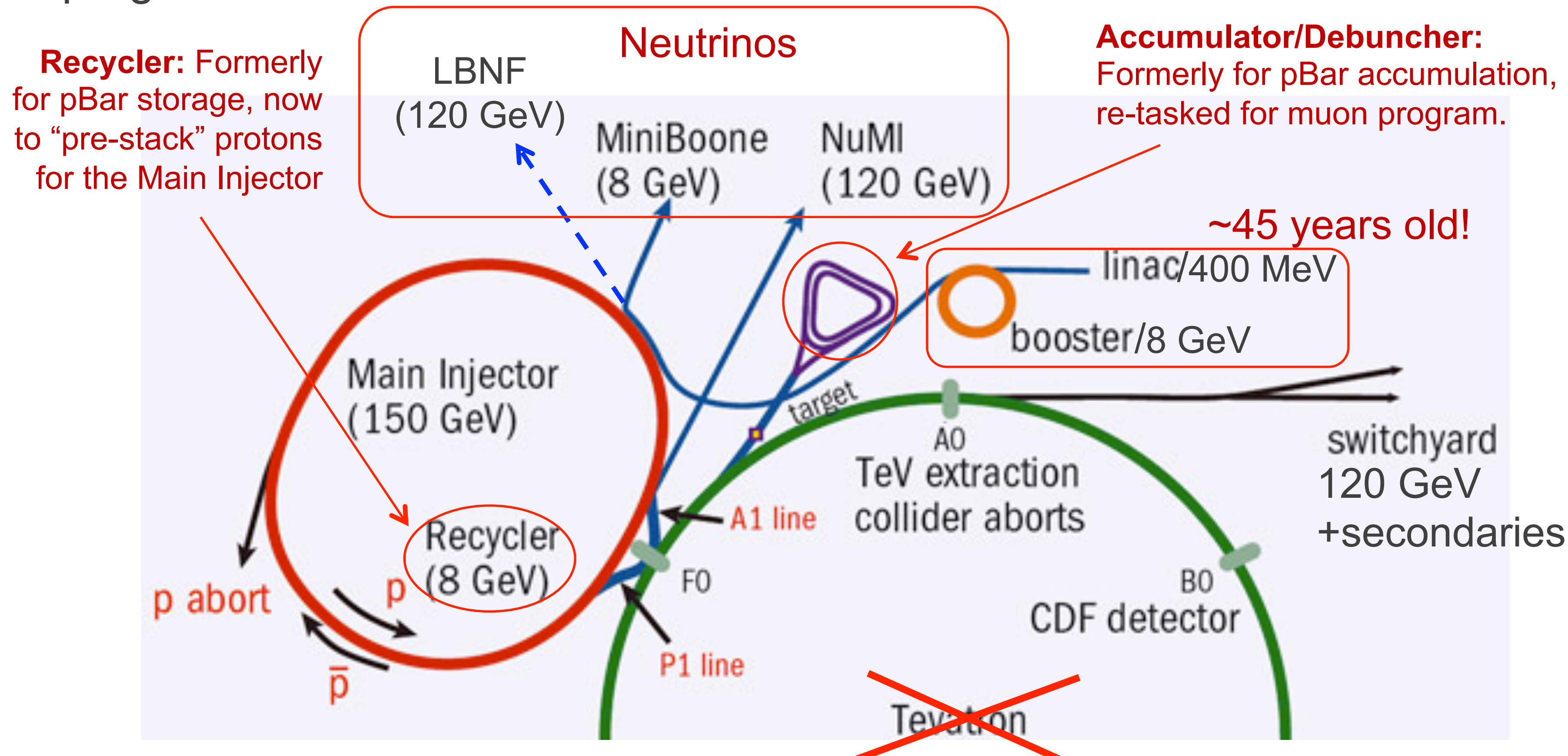
- This is the easy one…
- Over the last ~15 years, Fermilab has gone from having no SRF program to becoming one of the world leaders.
- Fermilab areas of interest include
  - Increasing gradient and high-gradient-Q of cavities
  - Source/LEBT/RFQ/MEBT development
  - Bunch manipulation
  - Systems and integration issues.

FAST program

- This work is largely orthogonal to the rest of the Fermilab program
- Understanding the rest of the program requires some understanding of the lab's long term plans…

Orientation: Accelerator Complex

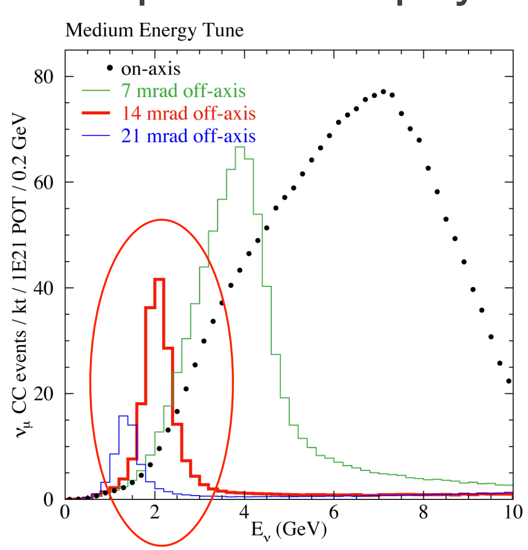
- Following the LHC turn-on, FNAL has transitioned to an intensity based program

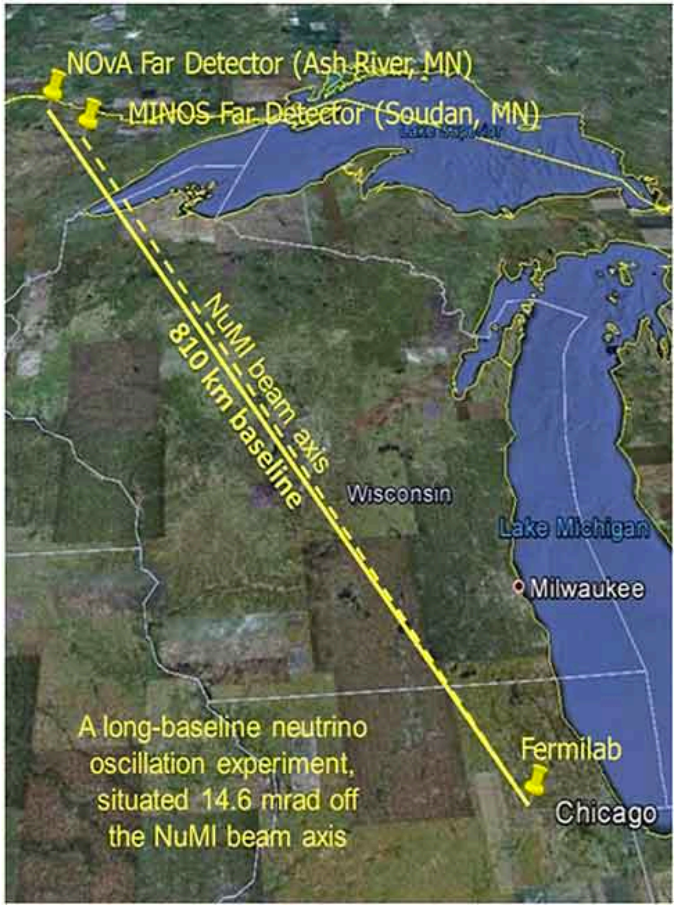


- Intensities are limited by the 8 GeV proton source, which is still largely original.

Current Long Baseline ν Program

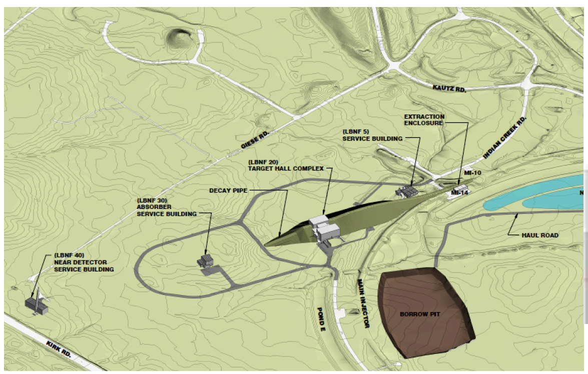
- The "Neutrinos from the Main Injector" (NuMI) line uses 120 GeV neutrinos from the Main Injector to produce neutrinos, which are detected in
  - MINOS: 725 km away
  - NOνA: 810 km, 14.6 mrad off axis
    - Produces narrower energy spread, which is important for physics goals

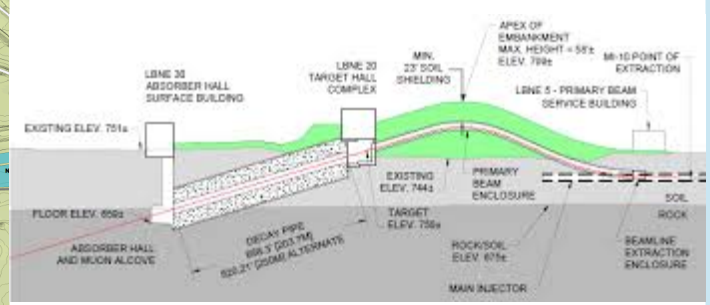




Future ν Program: LBNF→DUNE

- Fermilab will construct a new new “Long Baseline Neutrino Facility” (LBNF) beam line to produce neutrinos for the “Deep Underground Neutrino Experiment” (DUNE), located at the “Sanford Underground Research Facility” (SURF) in Lead, SD, 1300 km away.





- Truly international effort, including 150 institutions in 27 countries.
- Physics program extends 20-30 years.

Critical Issue: Space Charge Limit

- The maximum useful injected charge into the Booster is limited by the space charge tune-shift, which can drive harmonic instabilities.

total protons

"Bunch factor" = I_{peak}/I_{ave}
(Reduce with higher RF harmonics)

$$\Delta\nu \approx \frac{N r_0}{2\pi \epsilon_N \beta\gamma^2} F B \lesssim .2$$

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

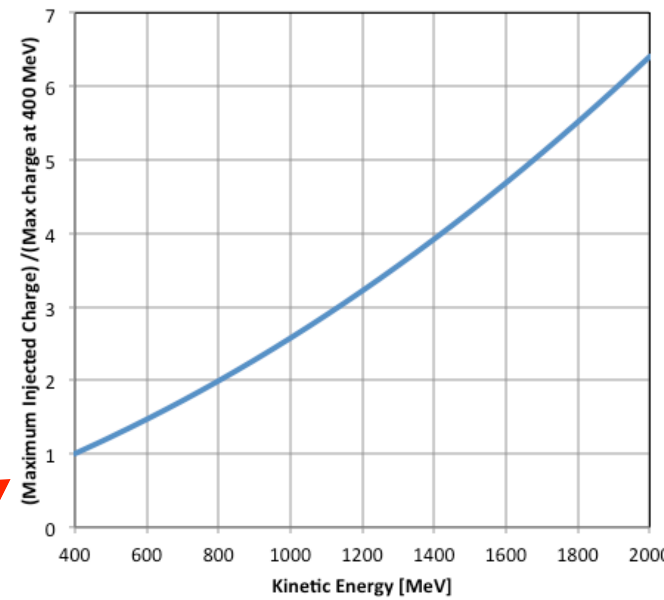
normalized emittance

$$\epsilon_N = \epsilon\beta\gamma = \text{constant}$$

- So the maximum accelerated charge grows rapidly with increasing energy

$$N_{max} \propto \beta\gamma^2$$

- Could gain an additional factor of βγ if we were not constrained by the MI admittance



doesn't include improvement of going to uniform distribution with painting

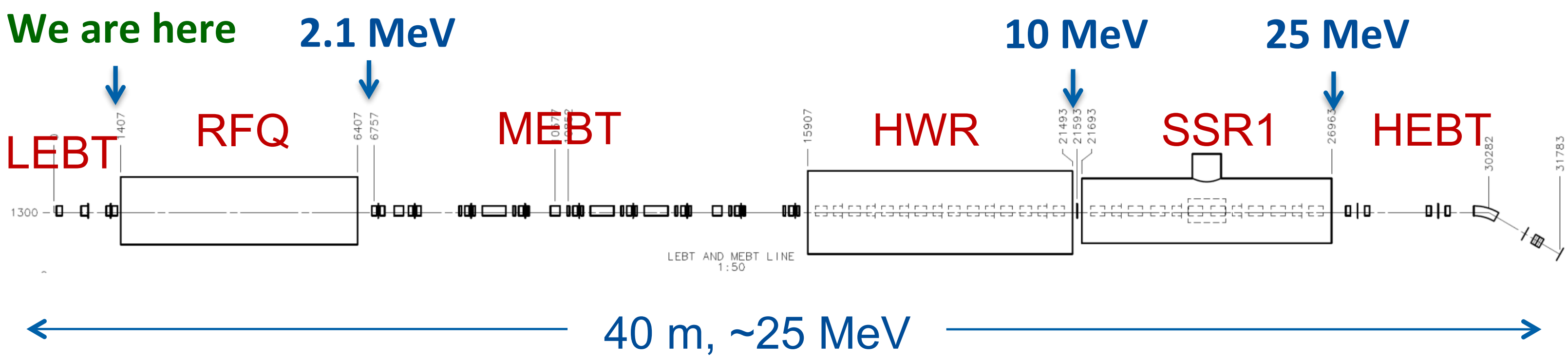
Staged Plan to Increase Intensity

- Proton Improvement Plan (PIP) (ongoing)
  - Numerous improvements to maximize potential of existing complex.
  - Provide 700 kW to NuMI + 30 kW to 8 GeV program
- PIP-II (CD-0)
  - Keep existing Booster, but increase cycle rate from 15 to 20 Hz
  - Replace existing 400 MeV linac with 800 MeV superconducting linac that has CW capability
  - Deliver 1.2 MW to NuMI or LBNF
  - Support 8 GeV program and 800 MeV program
    - (eg. 100kW 800 MeV beam to Mu2e-II)
- PIP-III (conceptual)
  - Keep PIP-II linac
  - Replace Booster with "something"
  - Deliver 2.5 MW to LBNF + ??

Rapid Cycling Synchrotron (RCS) or pulsed linac?

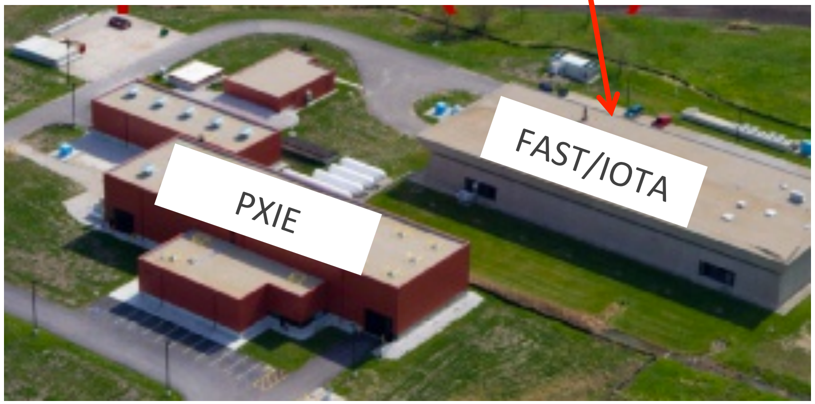
PIP-II R&D

- The PIP-II Injector Experiment (PXIE) is designed to test the technology needed for the PIP-II Linac



- Among other things, PXIE will investigate
  - Low Energy Beam Transport (LEBT) pre-chopping.
  - Validation of chopper performance
  - Bunch extinction
  - Operation of Half Wave Resonator (HWR) in close proximity to 10 kW absorber
  - Emittance preservation

What I'll be talking about



Beyond PIP-II: Linac vs. RCS

- The linac option would provide more beam at 8 GeV or lower energies, which could support a very diverse physics program, however
- Unless there is a major breakthrough in SRF technology, it would cost significantly more than the RCS option.
- The strong feedback from the DOE is that we should pursue the most cost effective way to deliver high power beam to LBNF/DUNE, with no specific mandate for a lower energy program. Therefore…
- We are pursuing the rapid cycling synchrotron as the primary option, with the linac as backup
  - There might be a breakthrough in SRF technology
  - Priorities have been known to change

PIP-III Straw Man Parameters*

	PIP-II		PIP-III (RCS, no Recycler)		units
MI/Recycler					
Beam Energy	120	60	120	60	GeV
Cycle Time	1.2	0.8	1.45	0.95	sec
Protons per pulse (extracted)	7.50E+13	7.50E+13	1.89E+14	1.98E+14	ppp
Slip Stacking Efficiency	97	97	99	99	%
Injection Turns	1	1	1	1	
Beam Power	1.2	0.9	2.5	2	MW
Proton Source					
Injection Energy (Kinetic)	0.8	0.8	0.8-2.0	0.8-2.0	GeV
Extraction Energy (Kinetic)	8.0	8.0	8.0	8.0	GeV
Circumference	474	474	474	474	m
RF Frequency (extraction)	52.8	52.8	52.8	52.8	MHz
Cycles to Recycler	12	12	6	6	
Cycle Rate	20	20	20	20	Hz
Beam Cycle Rate to MI	10	15	4.14	6.32	Hz
Protons per Pulse (extracted)	6.44E+12	6.44E+12	3.18E+13	3.33E+13	
Protons per Pulse (injected)	6.63E+12	6.63E+12	3.22E+13	3.37E+13	
Beam Power to Recycler/MI	82	124	168	269	kW
Beam Power to 8 GeV Program	82	41	645	584	kW

~6x record Booster protons per pulse

~4x record Main Injector protons per pulse

*P. Derwent

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Mitigating Space Charge in Synchrotron

- Recall:

$$N_{max} \propto \epsilon_N \left(\beta\gamma^2\right)$$

Can paint beam to increase emittance, but limited by Main Injector aperture (~20-25 π-mm-mr)

Can increase injection energy (costly)

- Other ways?
  - This is where FAST comes in!

RCS Comparisons

2.5 MW @ 60 GeV

	Booster (now)	Booster (PIP-II)	PIP-III RCS (800 MeV)	PIP-III RCS (2 GeV)	JPARC RCS
Circumference [m]	474	474	474	474	348
Injection Energy [MeV]	400	800	800	2000	400
Extraction Energy [MeV]	8000	8000	8000	8000	3000
Injection Current [mA]	30	4	5	5	50
RF Harmonic	84	84	84	84	2
Emittance (normalized) [pi-mm-mr]	15	15	20	20	102
Protons/batch [1e12]	4.2	6.6	34	34	84
Bunching Factor	3.0	3.0	3.0	3.0	2.0
Gaussian factor	3.0	1.0	1.0	1.0	1.0
Tune Shift Parameter	-0.43	-0.11	-0.43	-0.13	-0.28
Frequency [Hz]	15	20	20	20	25
Output power, max [kW]	80.64	168.96	870.4	870.4	1008

Too big for "ordinary" synchrotron. Can FAST help?

We'd rather not build the expensive linac extension if we don't have to

What are "Nonlinear Integrable Optics"?

- All accelerators today are based on physics worked out in the 1950s

PHYSICAL REVIEW VOLUME 88, NUMBER 5 DECEMBER 1, 1952

The Strong-Focusing Synchroton—A New High Energy Accelerator*

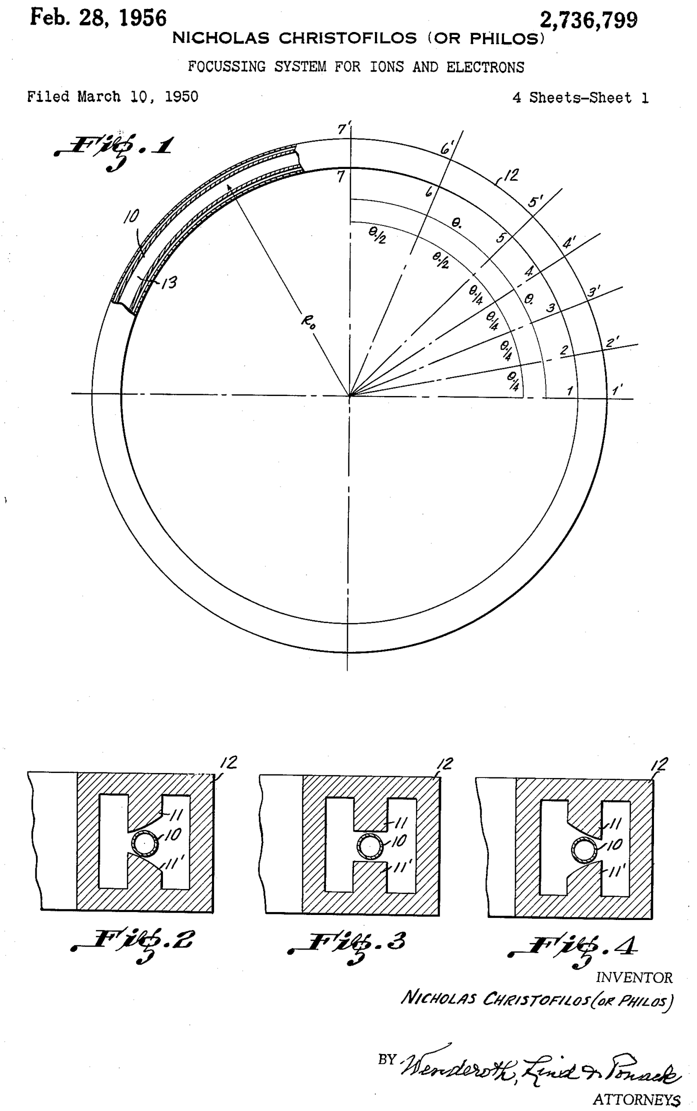
Ernest D. Courant, M. Stanley Livingston,† and Hartland S. Snyder
Brookhaven National Laboratory, Upton, New York
(Received August 21, 1952)

  - Stable orbits based on "linear" optics
    - The defining magnetic lattice contains only dipole and quadrupole terms.
    - The result is a system in which particles experience a transverse force which depends linearly on their deviation from a reference orbit. Described in general by a "Hill's Equation"

$$x'' + K(s)x = 0; \quad K(s+C) = K(s)$$

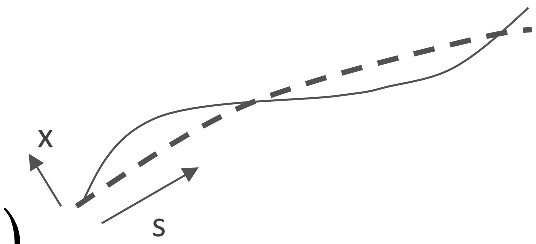
Interesting Footnote

- Strong focusing was actually previously invented by a Greek elevator engineer named Nicholas Christofilos, who applied for a patent in 1950.
- After they became aware of if, Courant and Snyder recognized the priority of Christofilos' work in their 1958 paper, *which lays the groundwork for all synchrotrons built to this day.*



All the Accelerator Physics U Need 2 Know

- We can describe (strongly focused) particle motion in terms of initial conditions and a "beta function" β(s), which is only a function of location along the nominal path, and follows the periodicity of the machine.



$\beta(s)$

Lateral deviation in one plane

$$x(s) = A\sqrt{\beta(s)}\cos\left(\psi(s)+\delta\right)$$

Phase advance

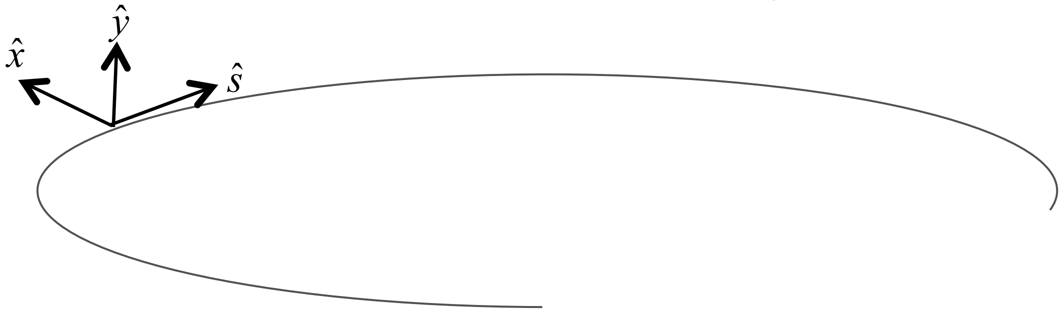
$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

The "betatron function" $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.

- In other words, particles undergo "pseudo-harmonic" motion about the nominal trajectory, with a variable wavelength.
- Note: β has units of [length], so the amplitude has units of $[\text{length}]^{1/2}$

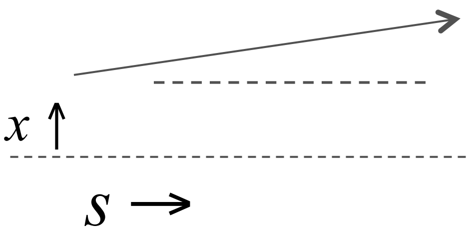
Formalism: Coordinates and Conventions

- We generally work in a right-handed coordinate system with *x* horizontal, *y* vertical, and *s* along the *nominal* trajectory (x=y=0).

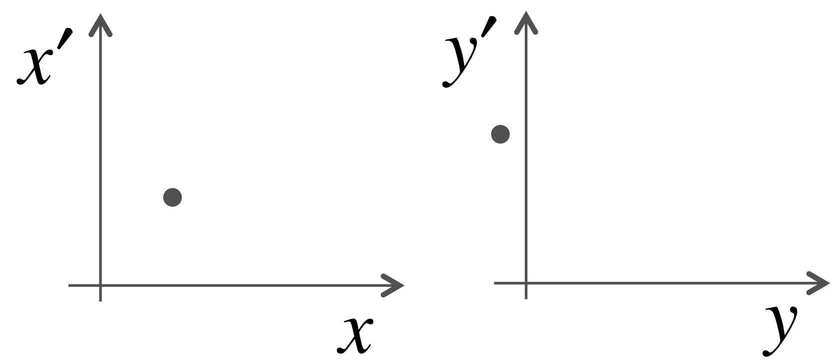


Note: *s* (rather than *t)* is the independent variable

Particle trajectory defined at any point in *s* by location in *x,x'* or *y,y'* "phase space"



$$\frac{dx}{ds} \equiv x' \approx \theta$$



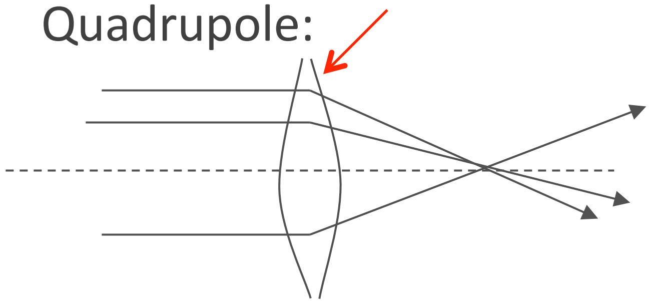
unique initial phase space point ➔ unique trajectory

Transfer Matrices

- Dipoles *define* the trajectory, so the simplest magnetic "lattice" consists of quadrupoles and the spaces in between them (drifts). We can express each of these as a linear operation in phase space.

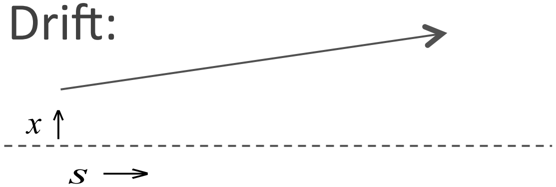
$$\Delta\theta = \Delta x' = -\frac{x}{f}$$

Quadrupole:



$$x = x(0)$$
$$x' = x'(0) - \frac{1}{f}x(0)$$
$$\Rightarrow \begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}$$

Drift:



$$x(s) = x(0) + s x'(0)$$
$$x'(s) = x'(0)$$
$$\Rightarrow \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}$$

- By combining these elements, we can represent an arbitrarily complex ring or line as the product of matrices.

$$\mathbf{M} = \mathbf{M}_N \ldots \mathbf{M}_2 \mathbf{M}_1$$

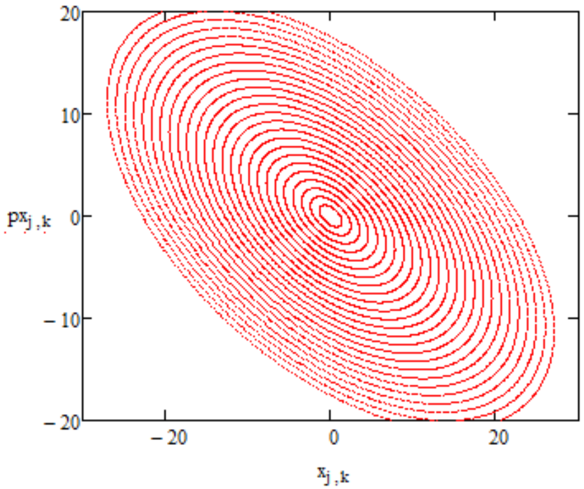
Hamiltonian Treatment of Accelerators

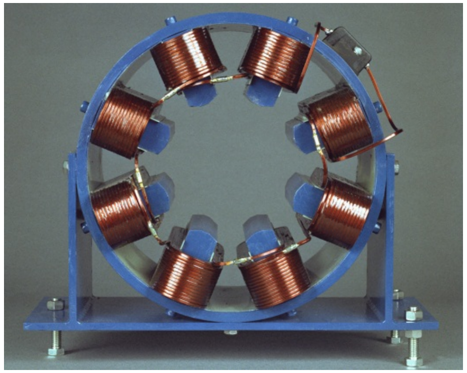
- Like other mechanical systems, accelerators are treated with Hamiltonian formalism. For a simple system, the Hamiltonian I given by:

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right)$$

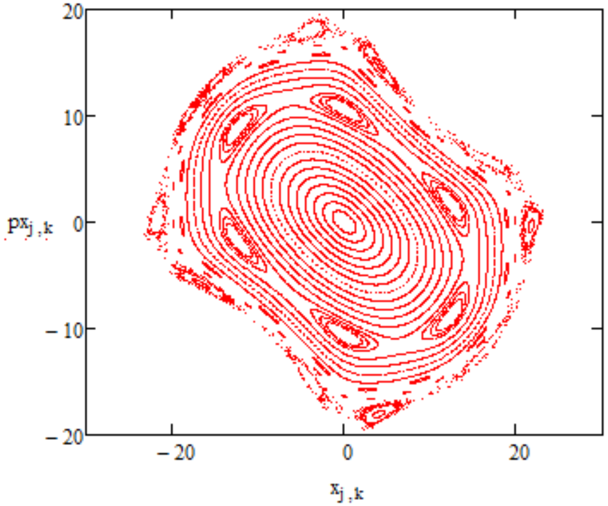
Motion in a Linear System

- Properties of linear lattices
  - Explicit solution
  - In the paraxial approximation (sinθ~tanθ~θ), particles undergo a fixed number of oscillations per orbit ("tune") which is independent of amplitude.
- Nonlinear terms are dealt with perturbatively, and generally lead to chaotic instability at high amplitudes

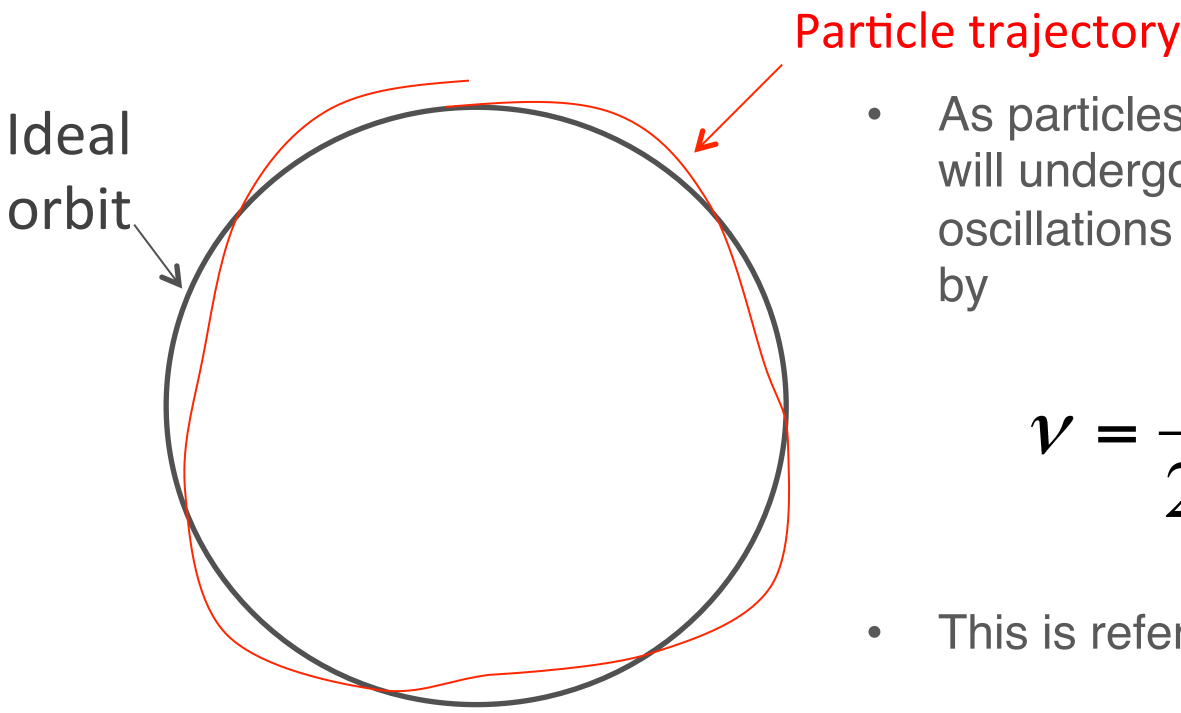




octupole



Betatron Tune



- As particles go around a ring, they will undergo a number of betatrons oscillations *v* (sometimes *Q*) given by

$$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

- This is referred to as the "tune"

- We can generally think of the tune in two parts:

Integer : magnet/ aperture optimization → 6.7 ← Fraction: Beam Stability

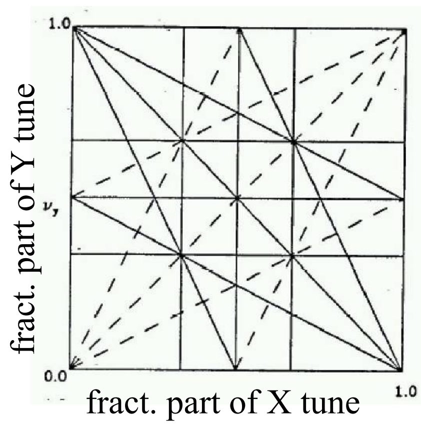
Instabilities In Linear Systems

- A unique tune leads to inherent instabilities
  - Tune spread➔"Landau Damping"
- Lattice imperfections lead to harmonic instabilities

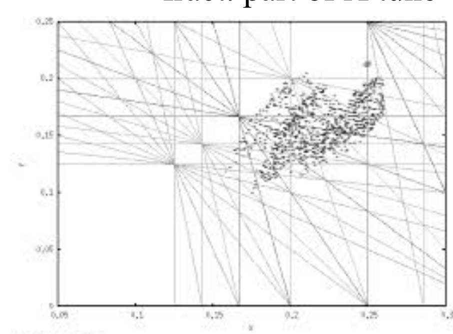
$$k_x \nu_x \pm k_y \nu_y = \text{integer} \Rightarrow \text{(resonant instability)}$$

"small" integers

➔Avoid lines in the "tune plane"



- In particular, space charge can shift the tune onto an instability
  - Space charge limit



Do Accelerators Need to be Linear?

- Motion will be stable if we can identify conserved integrals of motion➔"Integrable"
- There has been a long search for integrable nonlinear systems.
- Early work
  - Orlov (1963)
  - McMillan (1967) – 1D solution
  - ✓ Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams. **Require non-Laplacian potentials to realize**

2D Generalization of McMillan Mapping

SOME THOUGHTS ON STABILITY
IN NONLINEAR PERIODIC FOCUSING SYSTEMS

Edwin M. McMillan

September 5, 1967

- 1D – thin lens kick

$$x_i = p_{i-1}$$
$$p_i = -x_{i-1} + f(x_i)$$

$$f(x) = -\frac{Bx^2 + Dx}{Ax^2 + Bx + C}$$

$$Ax^2p^2 + B\left(x^2p + xp^2\right) + C\left(x^2 + p^2\right) + Dxp = \text{const}$$

- 2D – a thin lens solution can be carried over to 2D case in axially symmetric system (non-Laplacian!)

1. The ring with transfer matrix

$$\begin{pmatrix} cI & sI \\ -sI & cI \end{pmatrix} \begin{pmatrix} 0 & \beta & 0 & 0 \\ -\frac{1}{\beta} & 0 & 0 & 0 \\ 0 & 0 & 0 & \beta \\ 0 & 0 & -\frac{1}{\beta} & 0 \end{pmatrix}$$

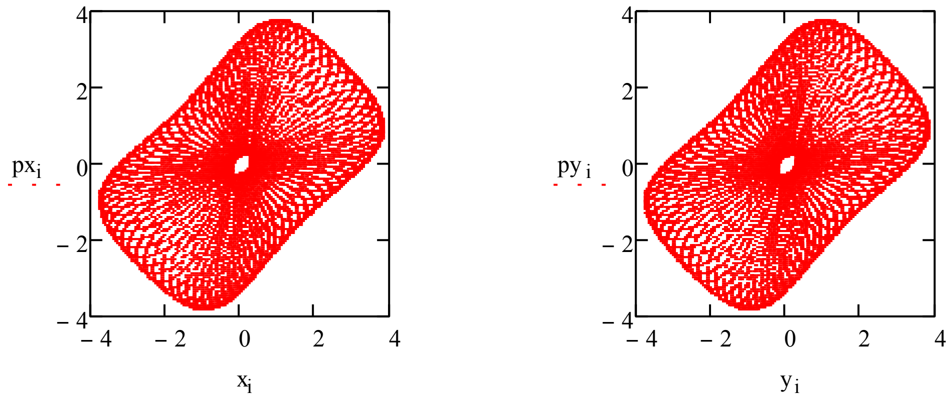
$$c = \cos(\phi)$$
$$s = \sin(\phi)$$
$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

2. Axially-symmetric thin kick

$$\theta(r) = \frac{kr}{ar^2 + 1}$$

2D Generalization of McMillan Mapping

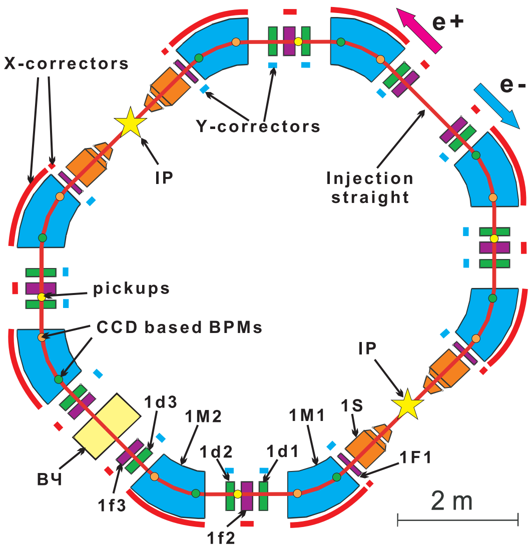
- The system is integrable. Two integrals of motion (transverse):
  – Angular momentum: $xp_y - yp_x = const$
  – McMillan-type integral, quadratic in momentum



- For large amplitudes, the fractional tune is 0.25
- For small amplitude, the electron (defocusing) lens can give a **tune shift of ~ –0.3 per cell !**
- Potentially, can cross an integer resonance

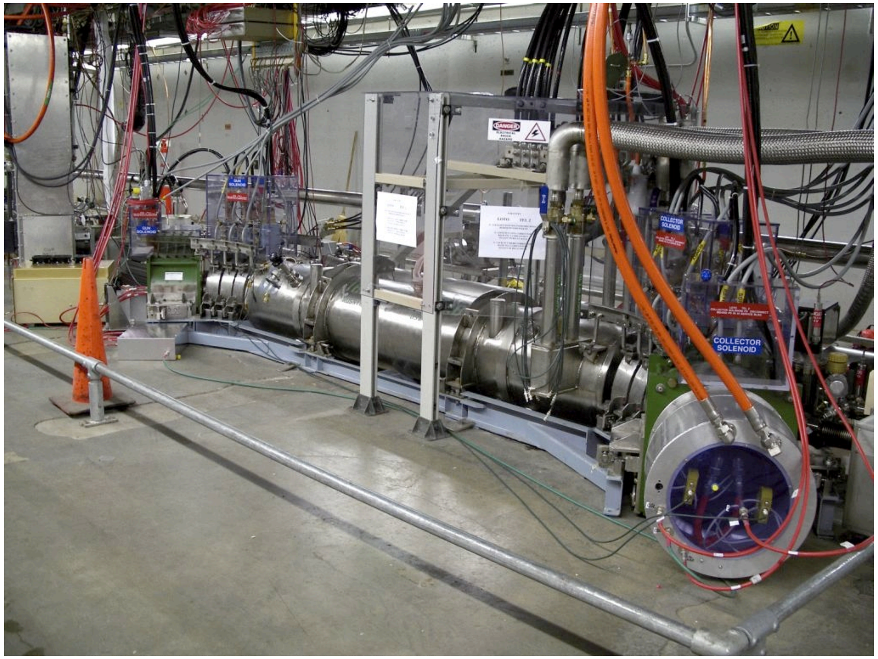
Verification: VEPP-2000

- Danilov and Perevedentsev's "round colliding beams"
  - equal beta functions, tunes, and emittances
  - no coupling
- Under these conditions
  - longitudinal component of angular momentum is conserved
  - dynamics is "quasi integrable"
- This was demonstrated experimentally at the BINP VEPP-2000 e+ e- collider, which achieved record tune spread of 0.25 (Romanov, NA-PAC13)
- Solution would be fully integrable if beams had "McMillan distribution"
  - Can also be achieved with electron lenses!

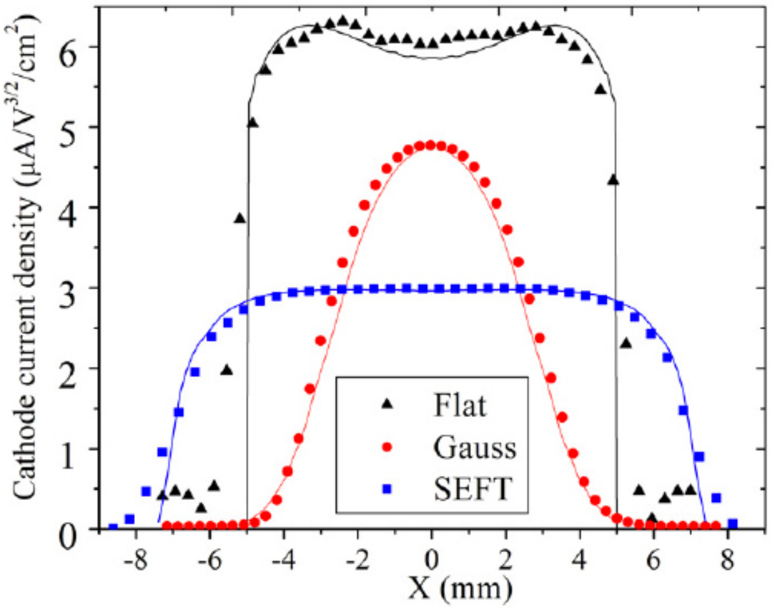


We can test this: IOTA Electron Lens

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components



Arbitrary current profile



Laplacian Solution*

- Start with a Hamiltonian

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right) + V(x, y, s)$$

- Choose s-dependence of the nonlinear potential such that *H* is time-independent in normalized variables

$$z_N = \frac{z}{\sqrt{\beta(s)}},$$

$$p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}},$$

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(\psi)V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right)$$

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N, \psi)$$

- This results in *H* being the integral of motion
- Note: there is no requirement on *V* – can be made with any conventional magnets, i.e. octupoles

*Danilov and Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002 (2010) (2010)

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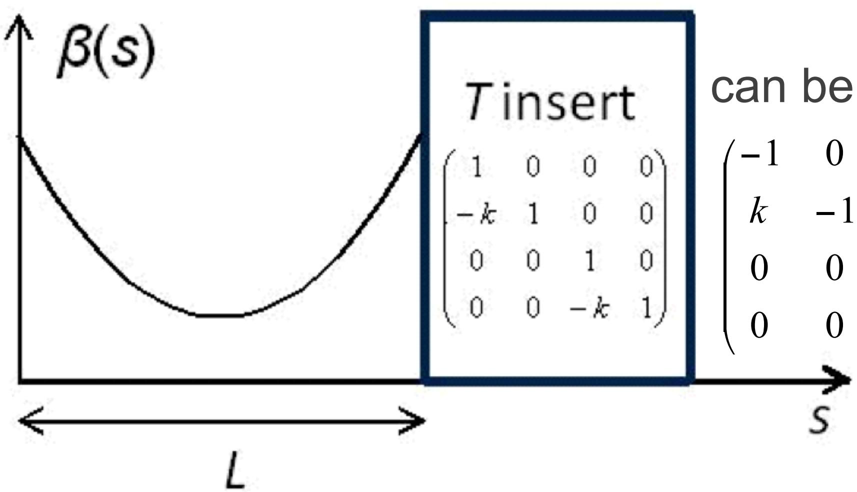
Nonlinear Integrable Optics with Laplacian Potential*

1. Start with a round axially-symmetric *linear* lattice (FOFO) with the element of periodicity consisting of
   a. Drift L
   b. Axially-symmetric focusing block "T-insert" with phase advance n×π



can be also

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ k & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & k & -1 \end{pmatrix}$$

2. Add special nonlinear potential *V(x,y,s)* in the drift such that

$$\Delta V(x,y,s) \approx \Delta V(x,y) = 0$$

Stability of Nonlinear Lattices

Nonlinear systems can be more stable!

- 1D systems: non-linear (unharmonic) oscillations can remain stable under the influence of periodic external force perturbation. Example: $\ddot{z} + \omega_0^2 \sin(z) = a \sin(\omega_0 t)$

- 2D: The resonant conditions $k\omega_1(J_1, J_2) + l\omega_2(J_1, J_2) = m$

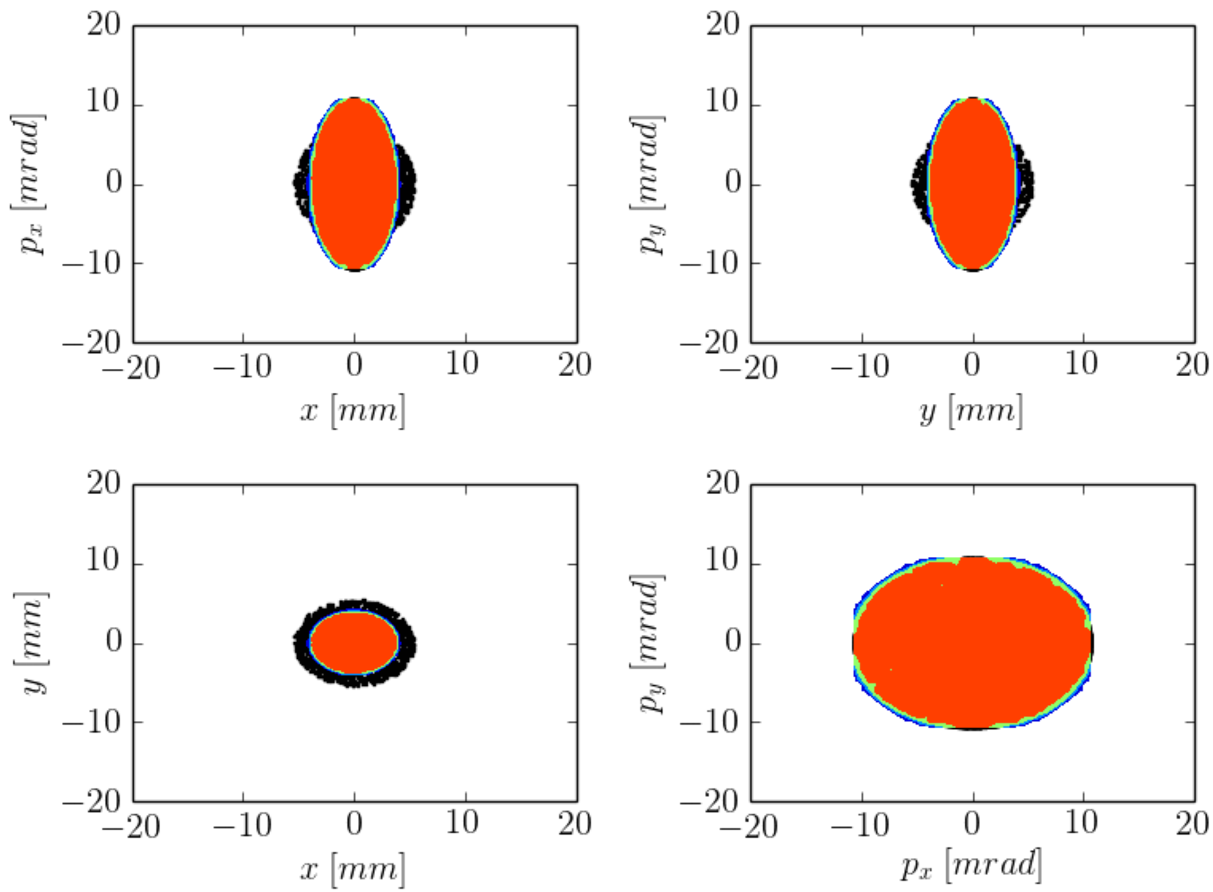
  are valid only for certain amplitudes; i.e.
  the tune depends on the initial conditions!

- Nekhoroshev's condition guaranties detuning from resonance and, thus, stability.
  - *An Exponential Estimate of the Time of Stability of Nearly-Integrable Hamiltonian Systems*. Russian Math. Surveys 32:6 (1977) from Uspekhi Mat. Nauk 32:6 (1977)

Space Charge in Linear Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

$\Delta Q_{sc} \sim -0.7$



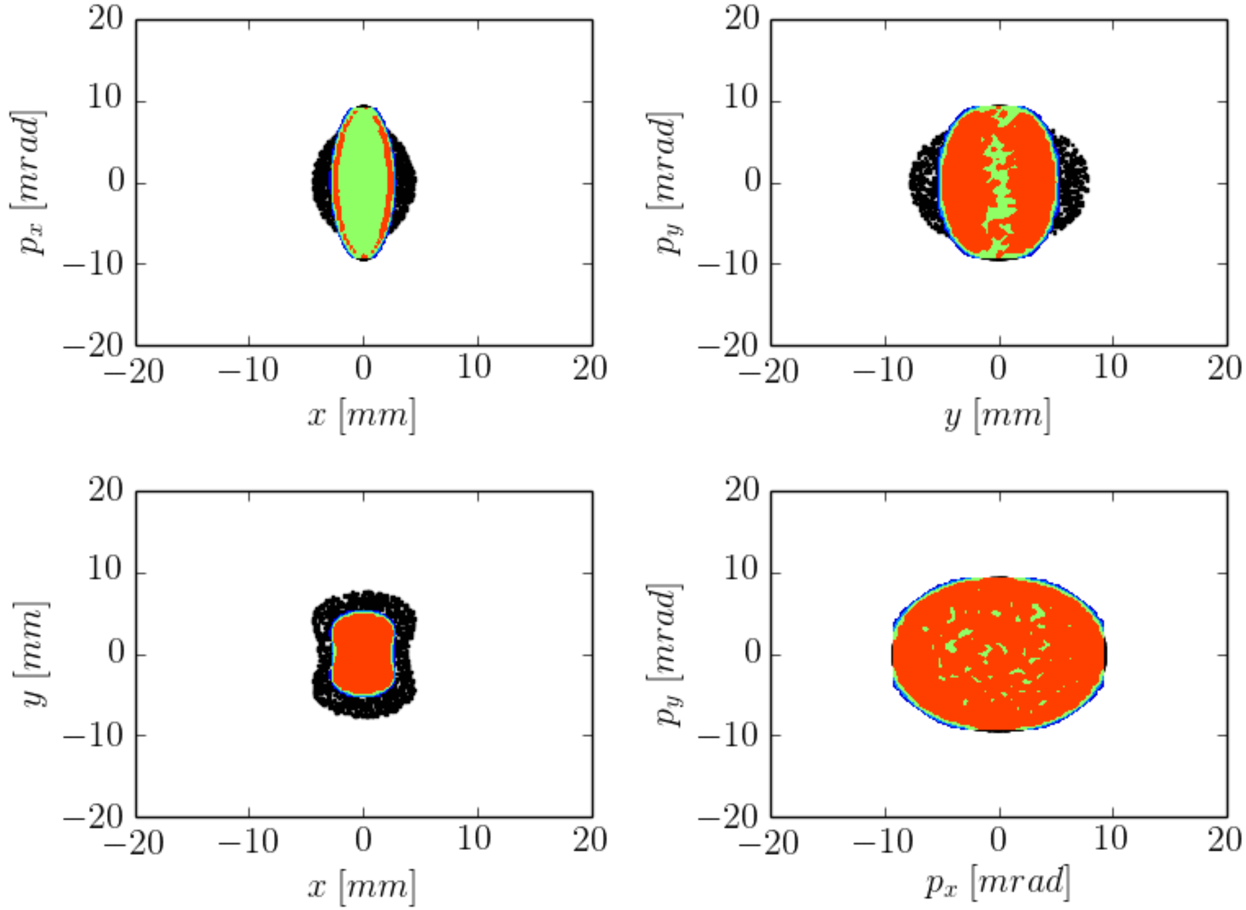
Tech-X, RadiaSoft simulation

Fermilab

Space Charge in NL Integrable Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: nonlinear decoherence suppresses halo

ΔQ_{sc} ~ –0.7



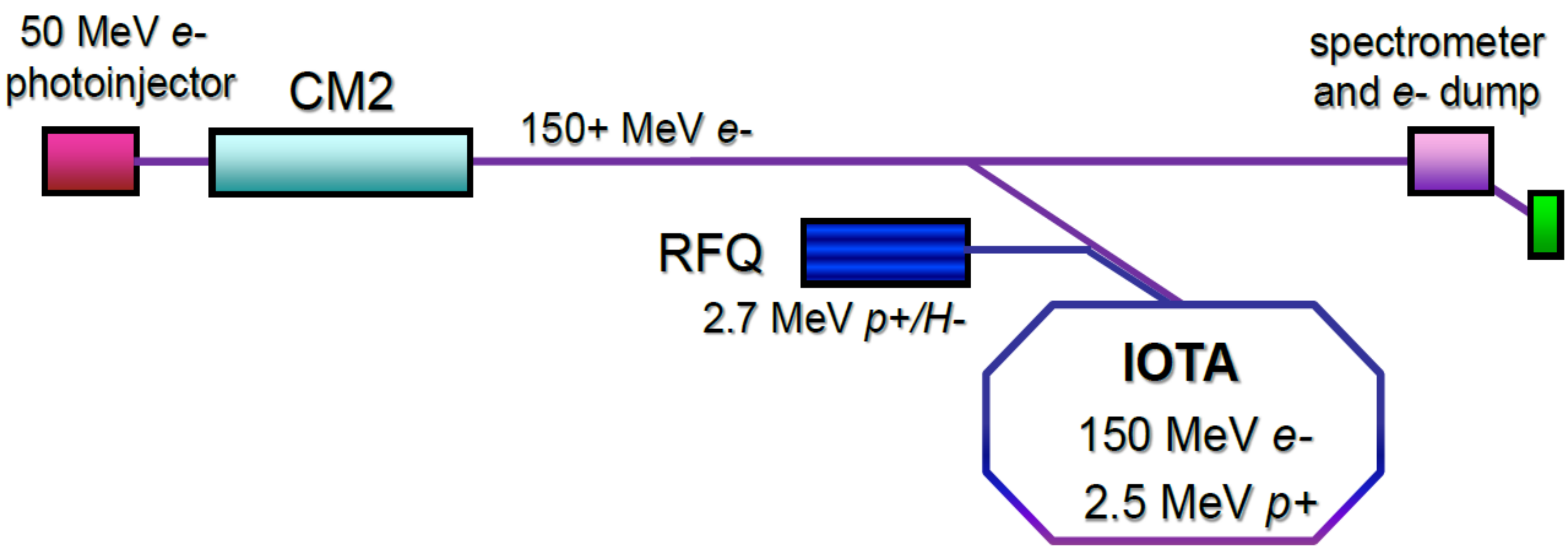
Tech-X, RadiaSoft simulation

Studies at Fermilab: FAST/IOTA

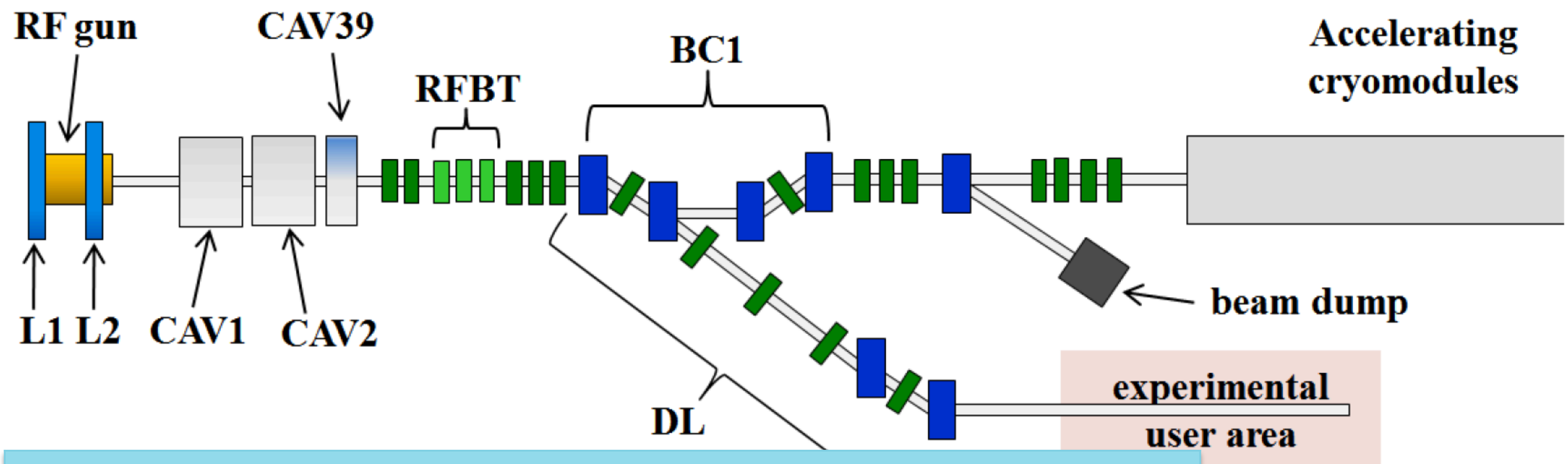
- The former New Muon Lab (NML) was originally being developed as an R&D facility for the ILC.
  - Original plan was for three ILC cryomodules.
- This evolved into a plan for an electron-based study program.
- DOE reviews concluded that there are numerous electron-based facilities in the country, but that the IOTA portion was unique.
- On their recommendation, the priorities of the facility were modified to focus on the IOTA ring.
  - Primary purpose for the electron beam is as an injector
  - Will also support an ancillary R&D program.

Current Plan for FAST/IOTA

- Because the emphasis of the facility has changed, so has had the name: ASTA/IOTA➔Fermilab Accelerator Science and Technology (FAST) Facility
  - Reduce cryomodules from three to one
  - Primary mission is as an injector for IOTA



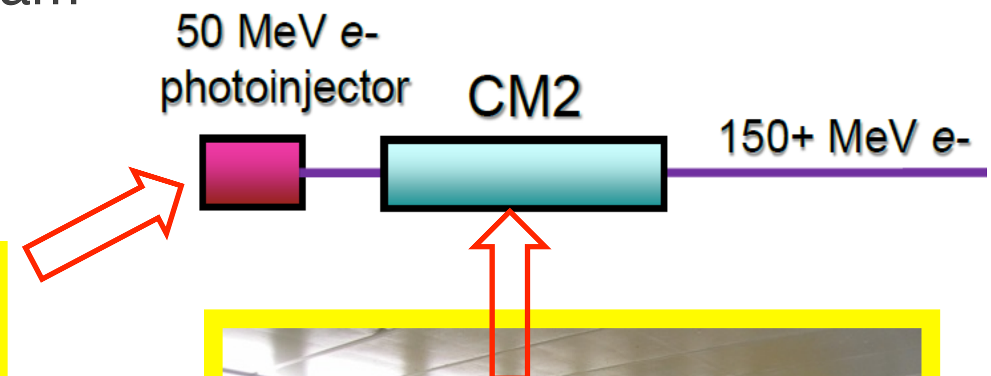
e⁻ Injector

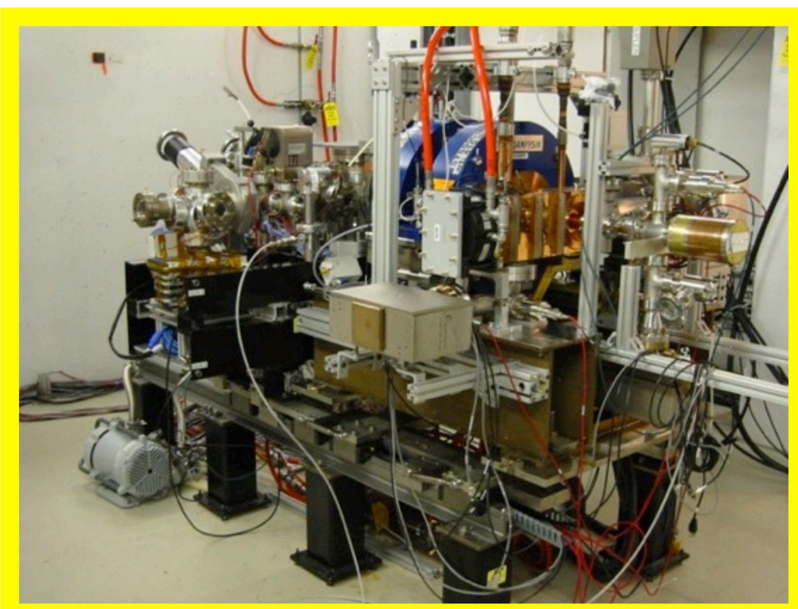


Parameter	ILC nominal	Range
Bunch charge	3.2 nC	10pC to > 20 nC
Bunch spacing	333 ns	<10 ns to 10 s
Bunch train	1 ms	1 bunch to 1 ms
Train rep. rate	5 Hz	0.1 Hz to 5 Hz
Transverse emit.	25 mm-mrad	1 to 100 mm-mrad
r.m.s. bunch length	1 ps	10fs to 10ps
Beam energy	300 MeV	50-300 MeV

ASTA

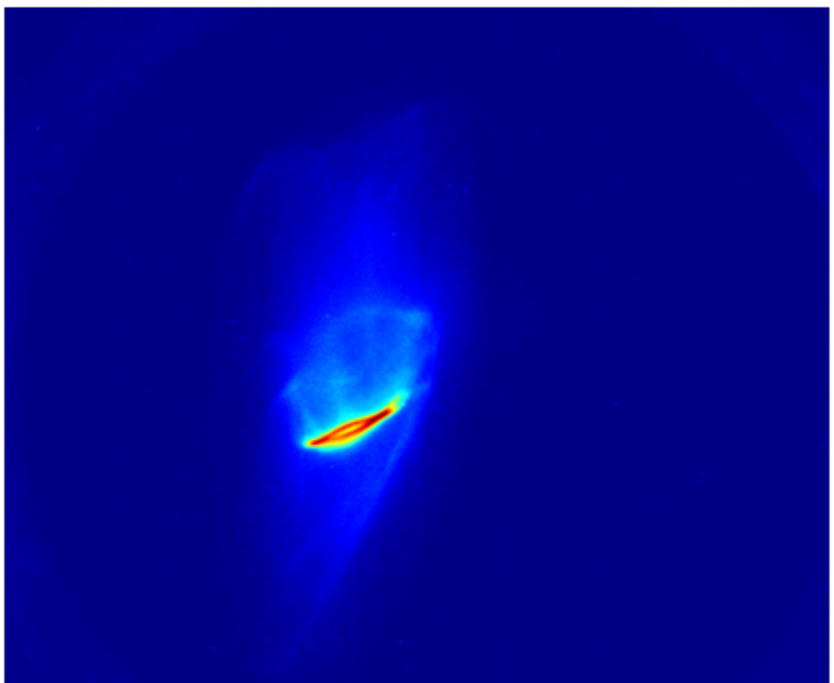
- Progress
  - Electron source and cryomodule are in place
  - First 50 MeV electron beam





First Electrons Through Photoinjector!

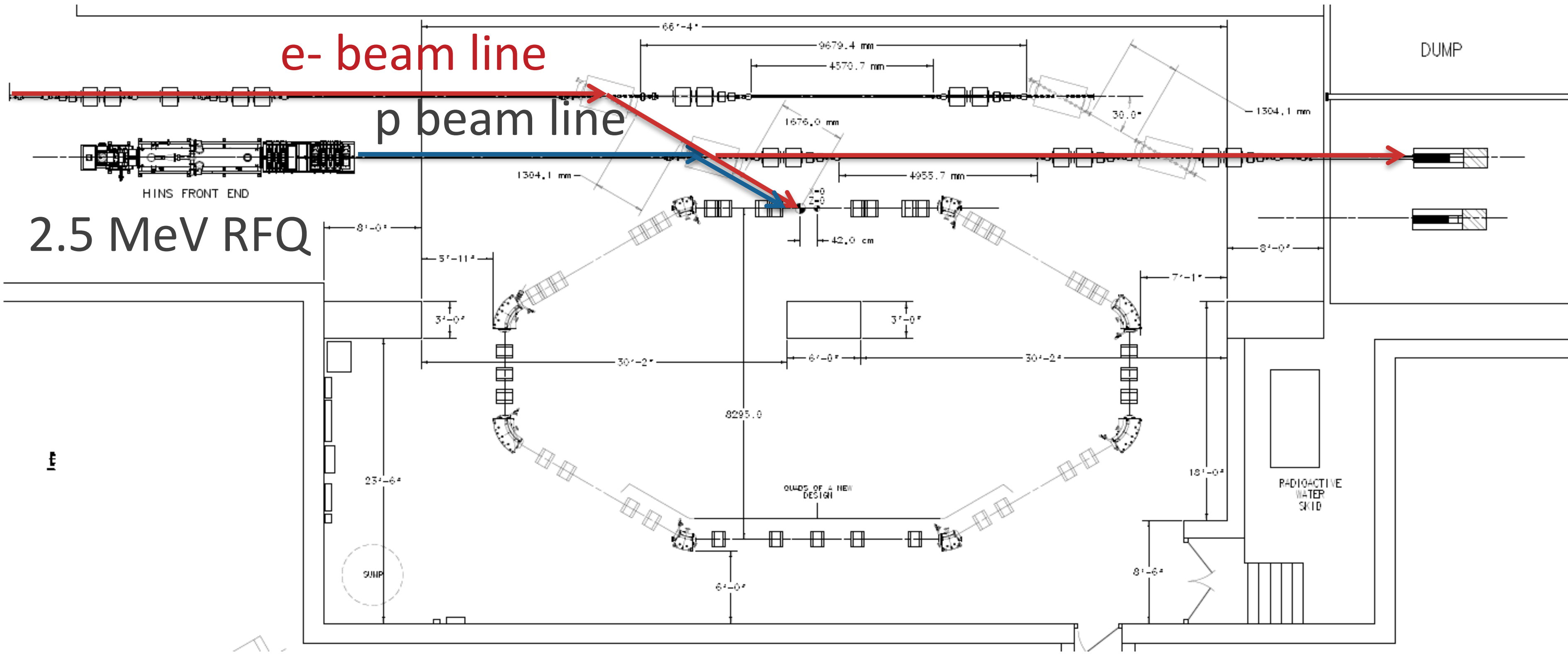
- Sign-offs Wednesday, 25 March, 2015
- Electrons beyond the gun - Wednesday, 25 March
- Beam after CC2, towards end of line – Thursday, 26 March
- Electrons seen at low energy beam absorber (~20 MeV) – Friday morning, 27 March



Validating Nonlinear Optics

- Both electron lenses and nonlinear magnetic elements involve discrete insertions in an otherwise conventional lattice.
  - Albeit a lattice with strict control over lattice functions!
- This allows for the design of a fairly simple “test bed” to evaluate the efficacy of these solutions.

Integrable Optics Test Accelerator (IOTA)



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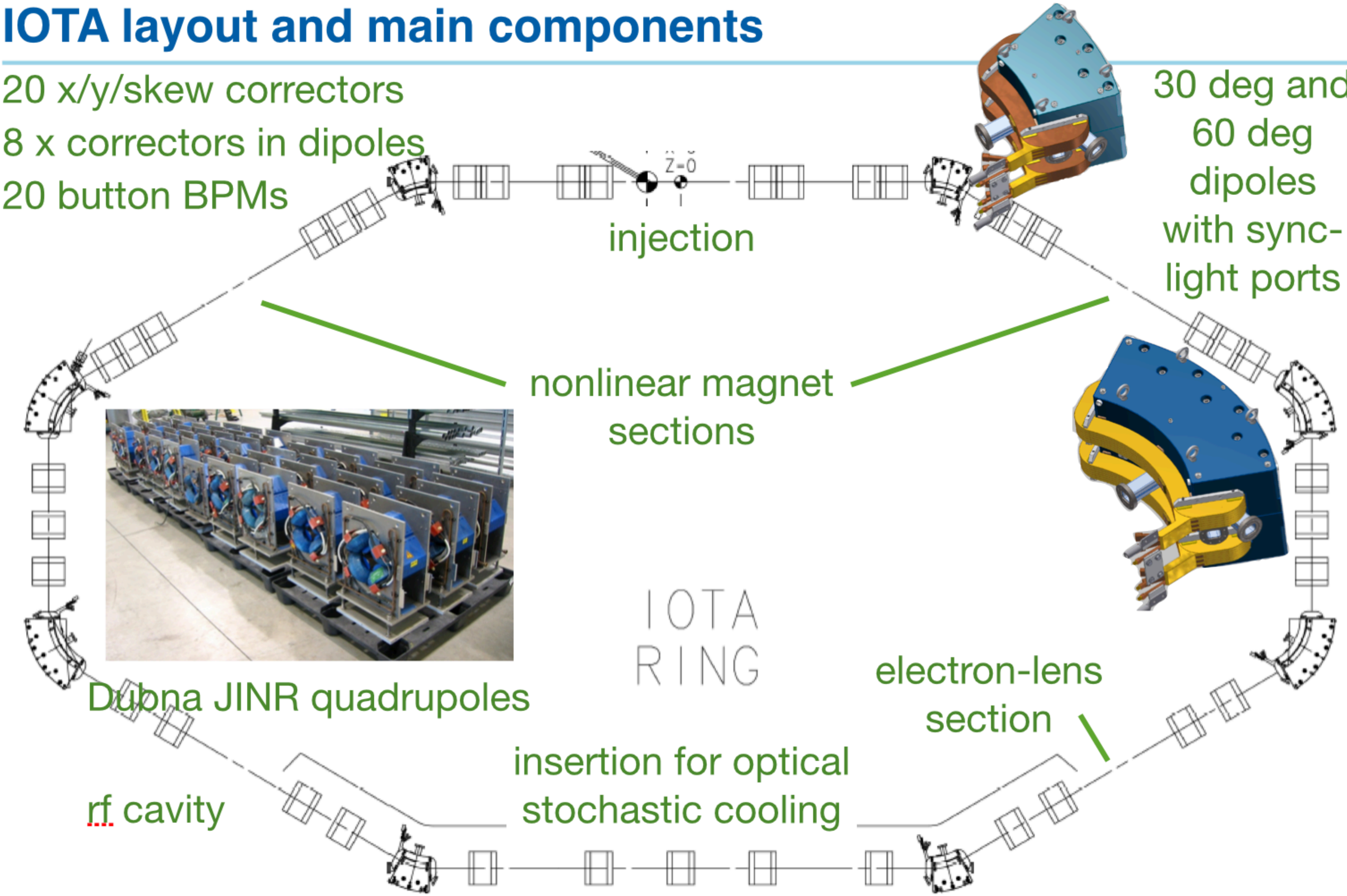
IOTA layout and main components

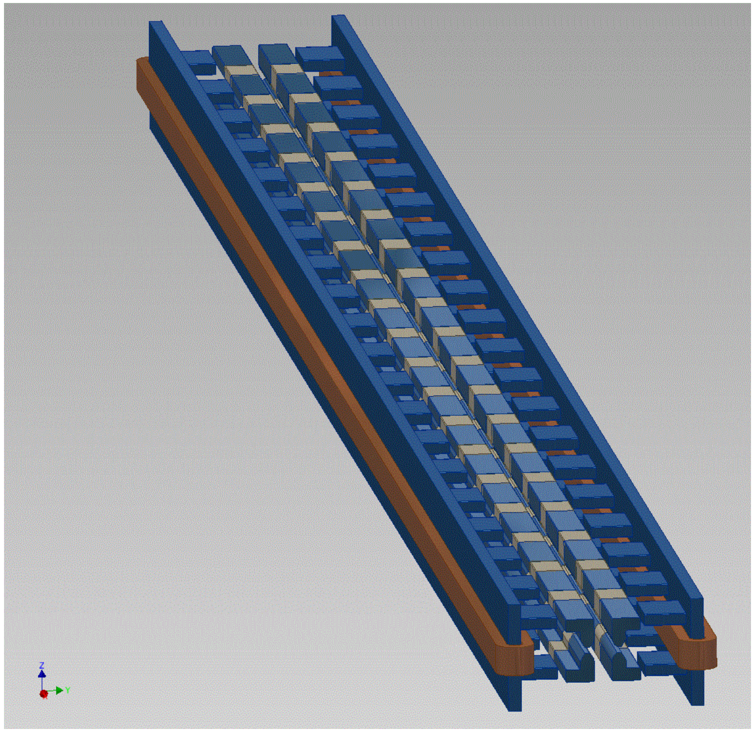


IOTA Parameters (Electrons)

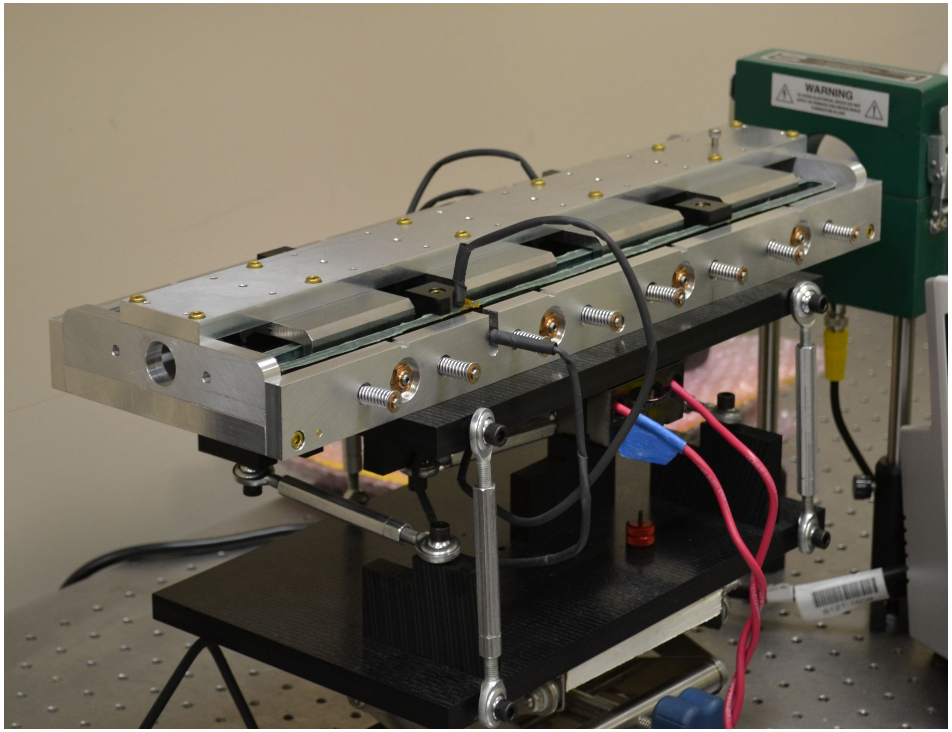
Nominal kinetic energy	e^-: 150 MeV
Nominal intensity	e^-: 1×10^9
Circumference	40 m
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 - 0.1
Betatron tune (integer)	3 - 5
Natural chromaticity	-5 - -10
Transverse emittance r.m.s.	0.04 μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,h	1 kV, 30 MHz, 4
Synchrotron tune	0.002 - 0.005
Bunch length, momentum spread	12 cm, 1.4×10^{-4}

Nonlinear Magnet

- Joint effort with RadiaBeam Technologies (Phase I and II SBIR)



FNAL Concept: 2-m long nonlinear magnet



RadiaBeam short prototype. The full 2-m magnet will be designed, fabricated and delivered to IOTA in Phase II

IOTA Goals for Integrable Optics

The IOTA experiment has the **goal to demonstrate the possibility to implement nonlinear integrable optics** with a large betatron frequency spread $\Delta Q>1$ and stable particle motion **in a realistic accelerator design**

Benefits of nonlinear integrable optics include

- Increased Landau damping
- Improved stability to perturbations
- Resonance detuning

Integrable Optics Test Accelerator (IOTA)

- **Unique features**:
  - Can operate with either electrons or protons (up to 150 MeV/c momentum)
  - Large aperture
  - Significant flexibility of the lattice
  - Precise control of the optics quality and stability
  - Set up for very high intensity operation (with protons)
- **Based on conventional technology** (magnets, RF)
- **Cost-effective solution**
  - Balance between low energy (low cost) and discovery potential

IOTA Staging – Phase I

Phase I will concentrate on the academic aspect of single-particle motion stability using e-beams

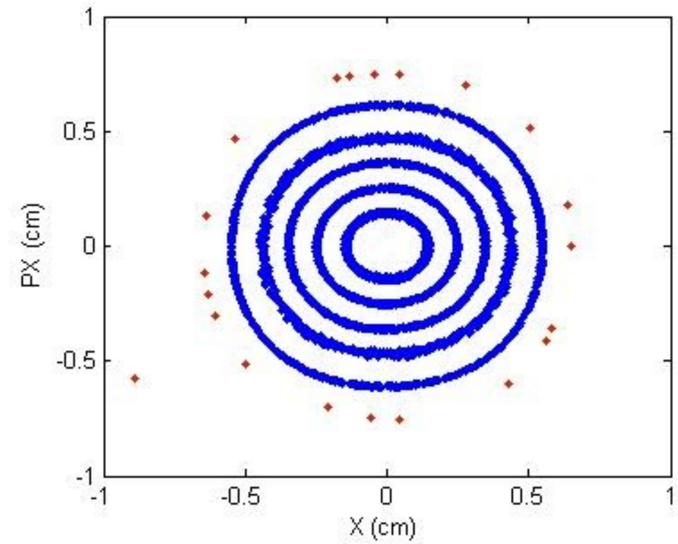
- **Achieve large nonlinear tune shift/spread** without degradation of dynamic aperture **by "painting"** the accelerator aperture **with a "pencil" beam**
- Suppress strong lattice resonances = cross the integer resonance by part of the beam without intensity loss
- Investigate stability of nonlinear systems to perturbations, develop practical designs of nonlinear magnets
- The measure of success will be the achievement of high nonlinear tune shift = 0.25

IOTA Staging – Phase I

- The magnet quality, optics stability, instrumentation system and optics measurement techniques must be of highest standards in order to meet the requirements for integrable optics
  - 1% or better measurement and control of β-function, and 0.001 or better control of betatron phase
- This is why **Phase I needs pencil e^- beams** as such optics parameters are not immediately reachable in a small ring operating with protons

Experimental Procedure

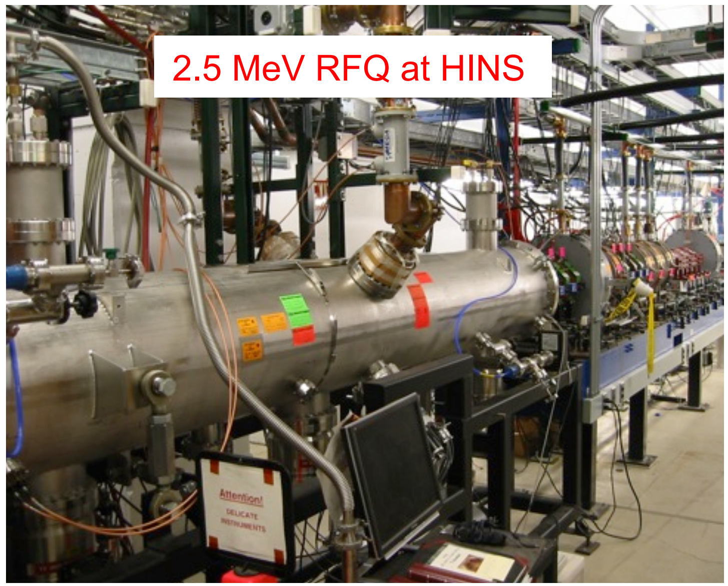
- Two kickers, horizontal and vertical, place particles at arbitrary points in phase space
- Measure beam position on every turn to create a Poincare map



- As electrons lose energy due to synchrotron radiation, they will cover all available phase space
- Can control the strength on the nonlinearity
- Final goal – measure dependence of betatron frequency on amplitude

Phase II: Proton Injection

- Luckily, we have an extra RFQ just lying around…
- The HINS ("High Intensity Neutrino Source") was developed as the front end of a pulsed "Project X" 8 GeV proton linac



- Because of cooling problems, it never reached its design pulse rate
- ProjectX (now PIP-II) specification was changed to a CW front end
  - HINS->PXIE
- HINS RFQ available for our use

IOTA Proton Injector Parameters

Table 1: HINS Parameters for IOTA

Parameter	**Value**	**Unit**
Particle type	proton	-
Kinetic Energy	2.5	MeV
Momentum	68.5	MeV/c
β	.073	-
Rigidity	.23	T-m
RF structure	325	MHz
Current	8	mA
Circumference	39.97	m
Total Protons	9.1×10^{10}	-
RMS Emittance (un-normalized)	4	π-mm-mrad
Tune shift	$-.51\times B$	-
Pulse rate	<1	Hz
Pulse length	1.77	μsec

$\sim \frac{1}{2} p_e$ (Momentum)

Phase II (cont'd)

After the IOTA commissioning, we will move the existing 2.5 MeV proton/H- RFQ into the FAST hall to inject protons into the IOTA ring.

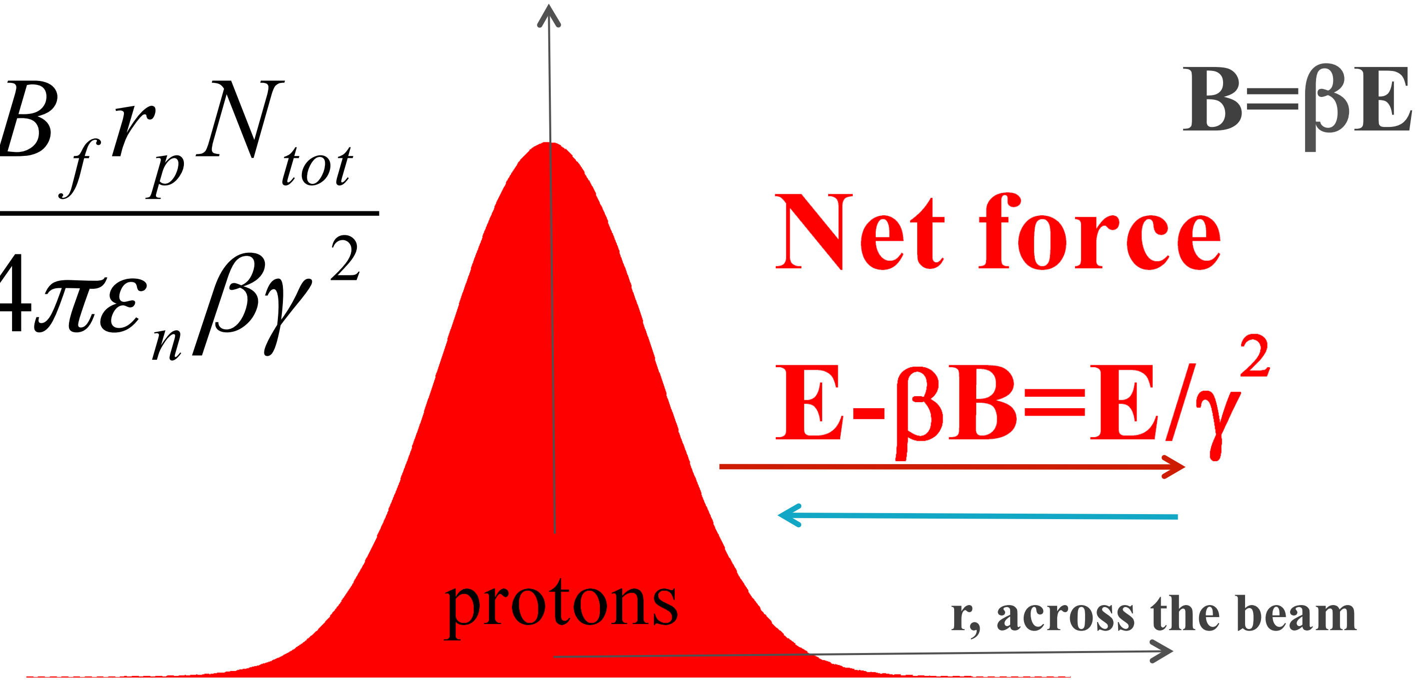
ΔQ_{SC} =0.5 for one-turn injection

*multi-turn injection possible

- Allows tests of Integrable Optics with protons and realistic space charge beam dynamics studies
- **Allows space charge compensation experiments**
- Unique capability

Space Charge Compensation

$$\xi_{SC} = \frac{B_f r_p N_{tot}}{4\pi\varepsilon_n \beta\gamma^2}$$



A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

Plan of Activities and Status

Phase 1: FY15-17

1. Construction of main elements of the FAST/IOTA facility:
   a) electron injector based on existing FAST electron linac
      - Low energy injector operational. HE beamline construction in FY15. Connect CM2 and send beam down HE beamline in FY16
   b) IOTA ring
      - Most components procured. Begin assembly in FY16
   c) proton injector based on existing HINS proton source in situ
      - Resurrecting the ion source in FY15, RFQ in FY16
   d) special equipment for AARD experiments.
2. Commissioning of the IOTA ring with electron beam – FY17
3. Study of single-particle dynamics in integrable optics with electron beams.

Plan of Activities – Outlook

Phase 2: FY18-20

1. Commission IOTA operation with proton beams.
2. Carry out space-charge compensation experiments with nonlinear optics and electron lenses.

Phase 3: FY21 and beyond

1. Study the application of space-charge compensation techniques to next generation high intensity machines.
2. Expand the program beyond these high priority goals to allow Fermilab scientists and a broader accelerator HEP community to utilize unique proton and electron beam capabilities of the FAST/IOTA facility

Open Questions

- Instrumentation:
  - Loss monitors:
    - Protons don't get out of beam pipe!
    - Tentatively chosen diamond-based loss monitors in vacuum
  - Transverse proton development
    - Ionization Profile Monitor?
    - Gas jet?
    - Electron Deflection?
    - One of these plus retractable loss monitors for tails
- Experimental program:
  - Fermilab has R&D has always been very "mission-oriented"
  - No real experience with a general purpose accelerator physics facility

Collaboration

- A lot of interest to participate in IOTA from the accelerator community
  – 2 annual Collaboration Meetings, ~60 participants
  – 'IOTA Focused Workshop'
- Significant intellectual and in-kind contributions, expressions of interest
  – **NIU, UMD, RadiaSoft, CERN, ORNL, BINP, Colorado State, Univ. Mexico** – integrable optics, space charge effects, phase space manipulation
  – **LBNL, ANL** – optical stochastic cooling demonstration
  – **UMD** – multi-pickup beam profile monitor for IOTA
  – **JINR** – integrable optics and space charge, contributed quadrupole magnets for IOTA
  – **Univ. Frankfurt** – electron lens

International *Space Charge Collaboration* at IOTA

- Collaborating institutions (at present): **Fermilab, ORNL, CERN, RadiaSoft, UMD**
- Work on the scientific case, hardware development, simulations, planning and execution of space charge compensation experiments with protons in IOTA
- Major topics
  - Operation of IOTA with protons, injection, and space charge measurements
  - Space charge compensation in nonlinear integrable lattice
  - Special magnets
  - Electron lens
  - Space charge compensation with electron columns
  - Space charge suppression with circular modes **– for FCC**

Training and University Collaboration

- Excellent connection to the university community through the Joint Fermilab/University PhD program
  - Already 9 graduate students doing thesis research at FAST/IOTA
    - 7 NIU, 1 U.Chicago, 1 IIT, 2 more to join soon
- Partnership with university groups
  - NIU – DOE GARD grant on OSC
  - Univ. of Maryland – NSF grant for IOTA-related work
  - Univ. Frankfurt – IOTA electron lens
  - Univ. Mexico – ASTA linac commissioning
  - Colorado State – ASTA gun stability
  - Interest from: UC Berkeley, MIT, Oxford

Summary

- Experimental accelerator R&D at **IOTA is one of the cornerstones of the proposed national R&D thrust** "Multi-MW Beams and Targets", and is well aligned with P5 priorities
- IOTA offers a **unique scientific program** aiming at breakthrough research to allow for x**3-5 increase of beam intensity in future proton rings**
  - IOTA augments the US program lacking ring facilities for accelerator research and training
- IOTA experiments are a great opportunity to explore something **truly novel with circular accelerators**
- IOTA will be a strong **driver of national and international collaboration and training**

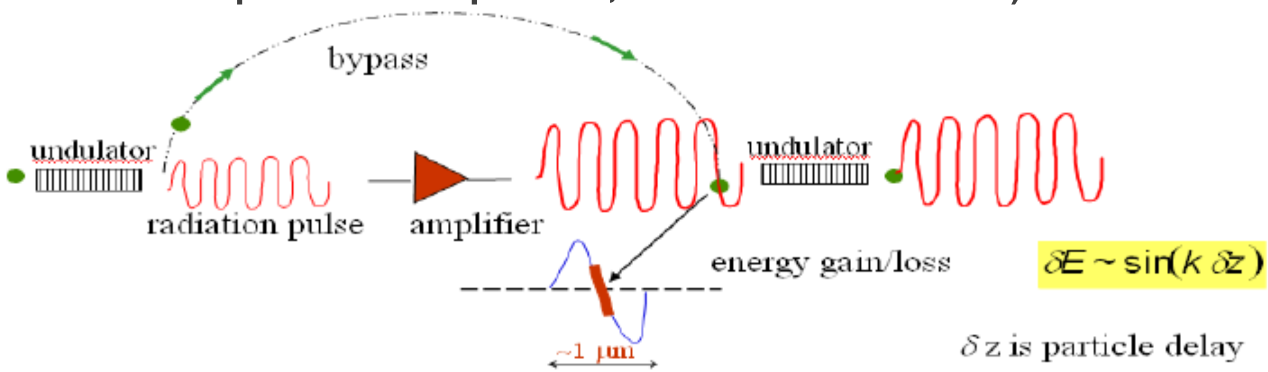
Acknowledgments

- A.Burov, K.Carlson, A.Didenko, N.Eddy, V.Kashikhin, V.Lebedev, J.Leibfritz, M.McGee, S.Nagaitsev, L.Nobrega, H.Piekarz, A.Romanov, G.Romanov, V.Shiltsev, R.Thurman-Keup, A.Valishev, S.Wesseln, D.Wolff (FNAL)
- D.Shatilov (BINP)
- G. Kafka (IIT)
- S. Danilov (ORNL),
- S. Antipov (U of Chicago)
- J. Cary (Tech-X)
- D. Bruhwiler, S. Webb (RadiaSoft)
- F.O'Shea, A.Murokh (RadiaBeam)
- R.Kishek, K.Ruisard (UMD)
- JINR, Dubna

- Backups

Optical Stochastic Cooling Demonstration

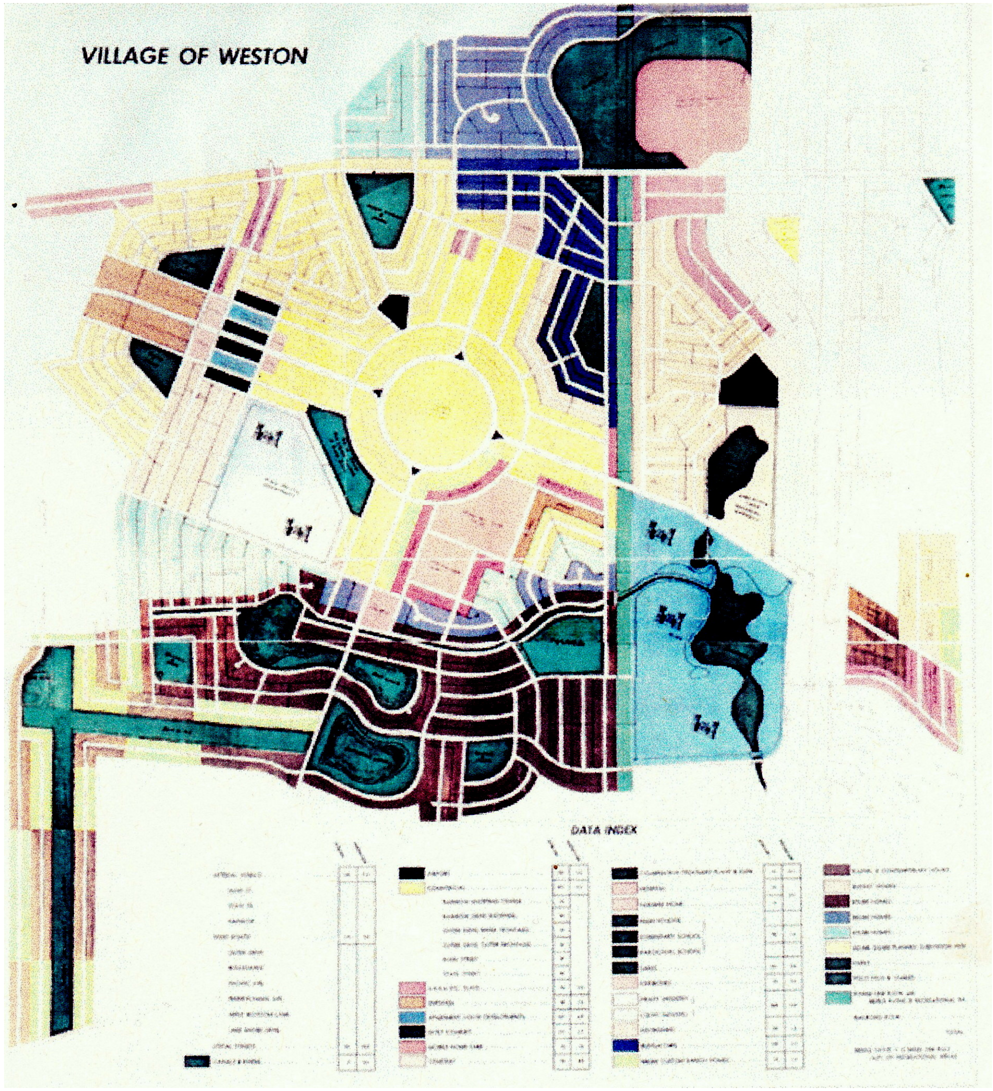
- Goal:
  - Experimental demonstration of the optical stochastic cooling technique (1st – no optical amplifier, then with OPA)



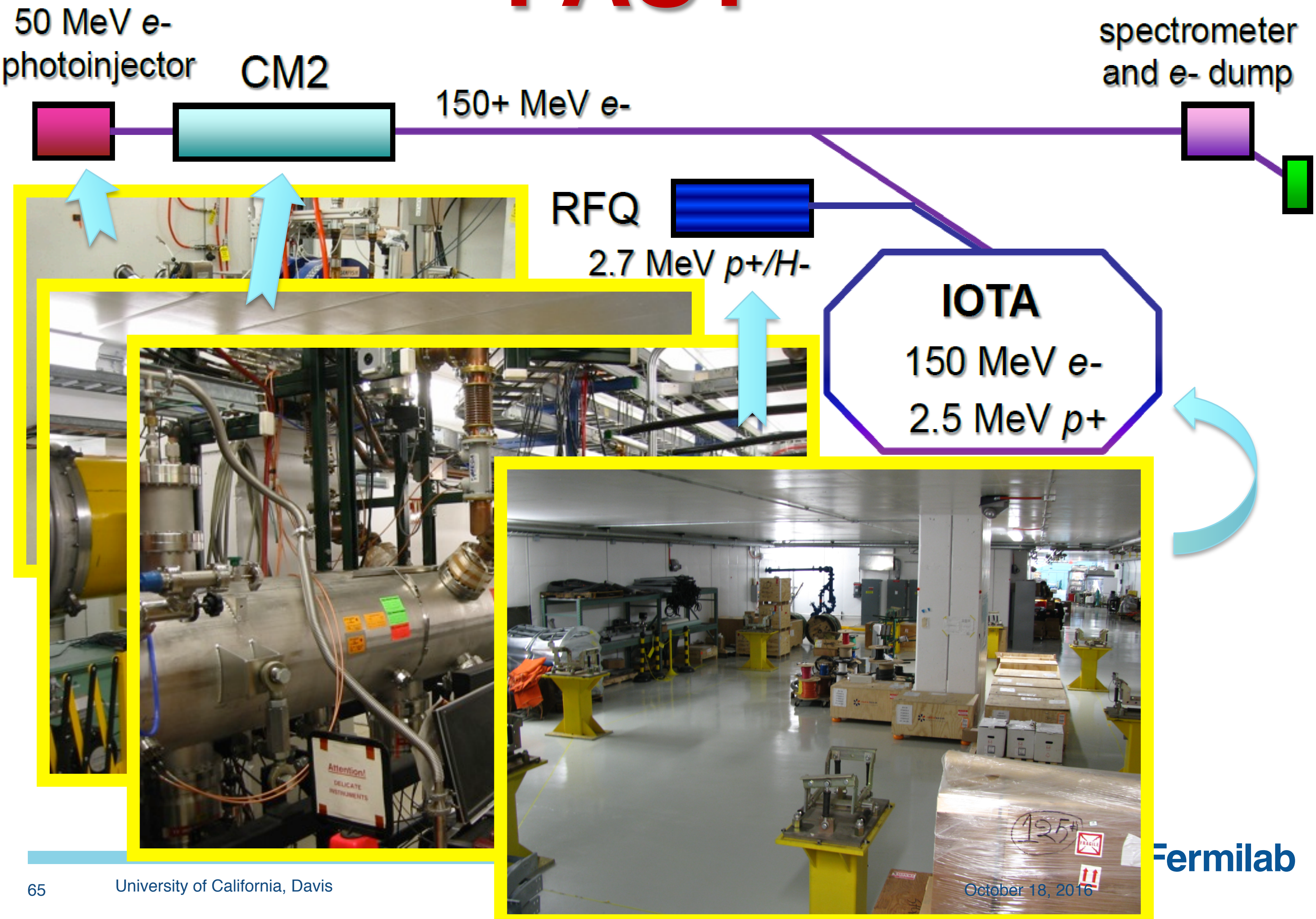
- Why IOTA:
  - Need IOTA – low energy (~100 MeV – minimal synchrotron radiation damping) flexible lattice e- storage ring
- Motivation:
  - Beam cooling for high energy accelerators

Backstory: Weston Illinois

- The footprint of what is now Fermilab started out as a planned community called "Weston". Developer William Riley promised homes, apartments, shopping centers, parks, etc
- After a very small part was built, the project went bankrupt
- Riley disappeared (possibly into witness protection).
- The local mayors convinced the state to offer up the land to the government to site the proposed N.A.L.
- The remains of Weston became "The Village", which now houses visitors to the lab.



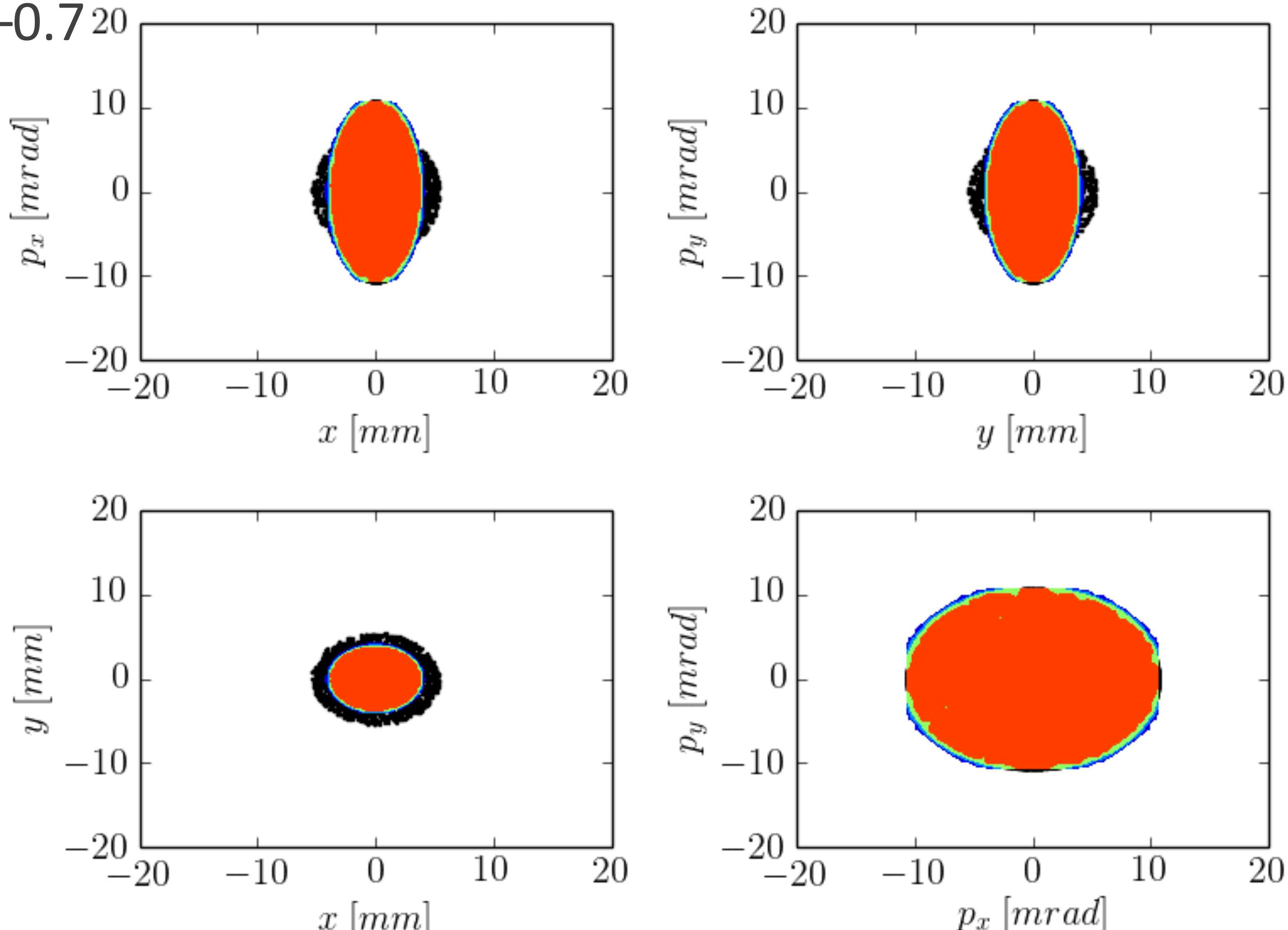
FAST


50 MeV e-
photoinjector
CM2
150+ MeV e-
spectrometer
and e- dump
RFQ
2.7 MeV p+/H-
IOTA
150 MeV e-
2.5 MeV p+
Attention!
DELICATE
INSTRUMENTS

Space Charge in Linear Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

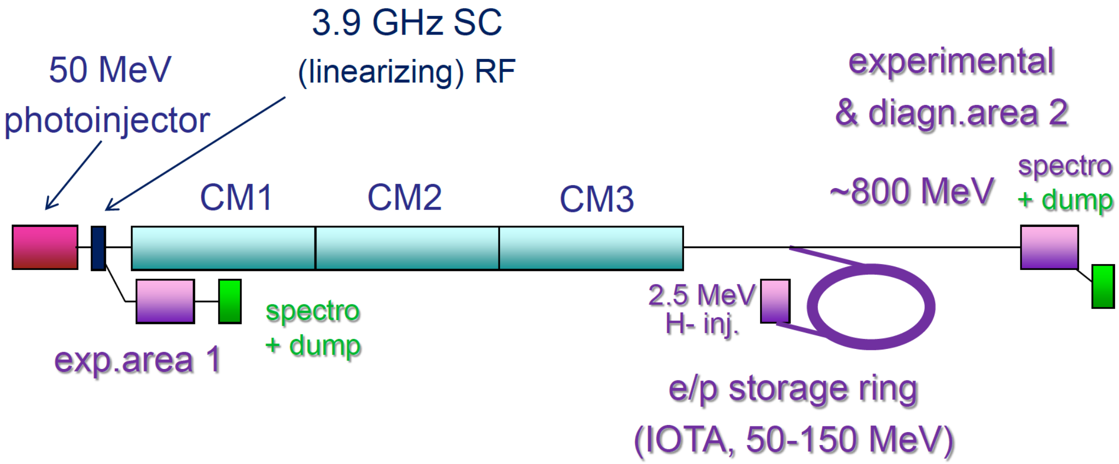
$\Delta Q_{sc} \sim -0.7$



Tech-X, RadiaSoft simulation

ASTA/IOTA: Original Proposal

- This facility began life as the “Advanced Superconducting Test Accelerator (ASTA)”, designed as a test bed for ILC technology
  – Front end + 3 cryomodules = ~800 MeV electron
  – Designed an electron-based experimental program around this facility
- Tacked on the “Integrable Optics Test Accelerator (IOTA)” to test non-linear integrable optics.



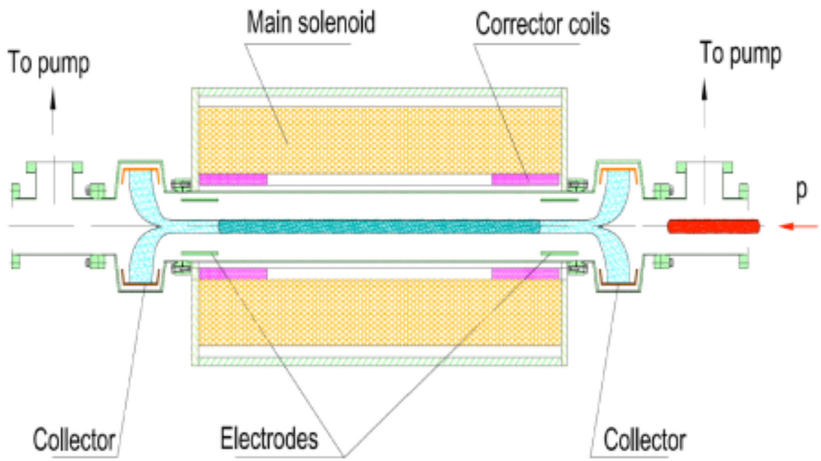
Fermilab

Existing Infrastructure

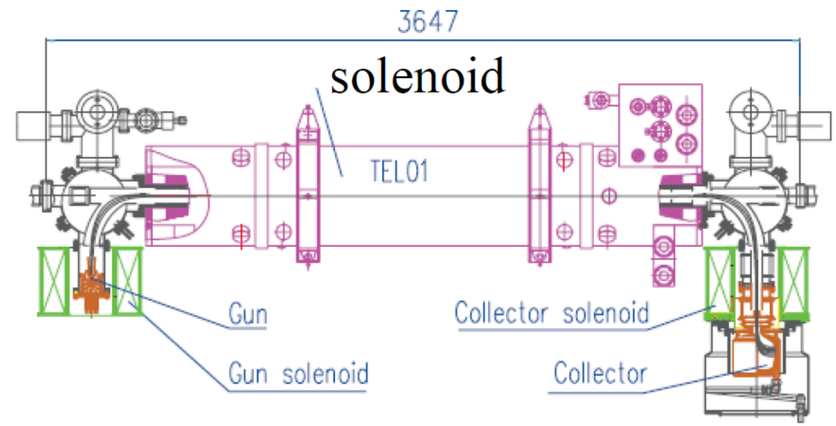
- **IOTA capitalizes on the investments** made by OHEP for highly successful ILC/SRF R&D Program.
- Construction of ASTA (formerly NML) began in 2006 as part of the ILC/SRF R&D Program and later American Recovery and Reinvestment Act (ARRA). The facility was motivated by the goal of building, testing and operating a complete ILC RF unit.
- **Multi-million (>$90M) investment** resulted in the successful commissioning of 1.3 GHz SRF cryomodule (CM2).
  - Beam through low-energy photo injector
  - Facility nears completion
- The **addition of IOTA expands scope** to host high-intensity accelerator research.

Possible Implementations

E-column concept



E-lens concept



1. The impact of electrons is equal to the total impact of space-charge over the ring

$$\left|\Delta\nu_{sc}\right| = \frac{N_{b,tot} r_{cb}}{2\pi\beta_b^2\gamma_b^3\varepsilon}\frac{\hat{I}}{\bar{I}} = \Delta\nu_e = \frac{N_e r_{cb}}{2\pi\beta_b^2\gamma\varepsilon} \qquad \frac{N_e}{N_{b,tot}(\hat{I}/\bar{I})} = \frac{1}{\gamma_b^2} = \eta_0\frac{N_{ec}L_{ec}}{C}$$

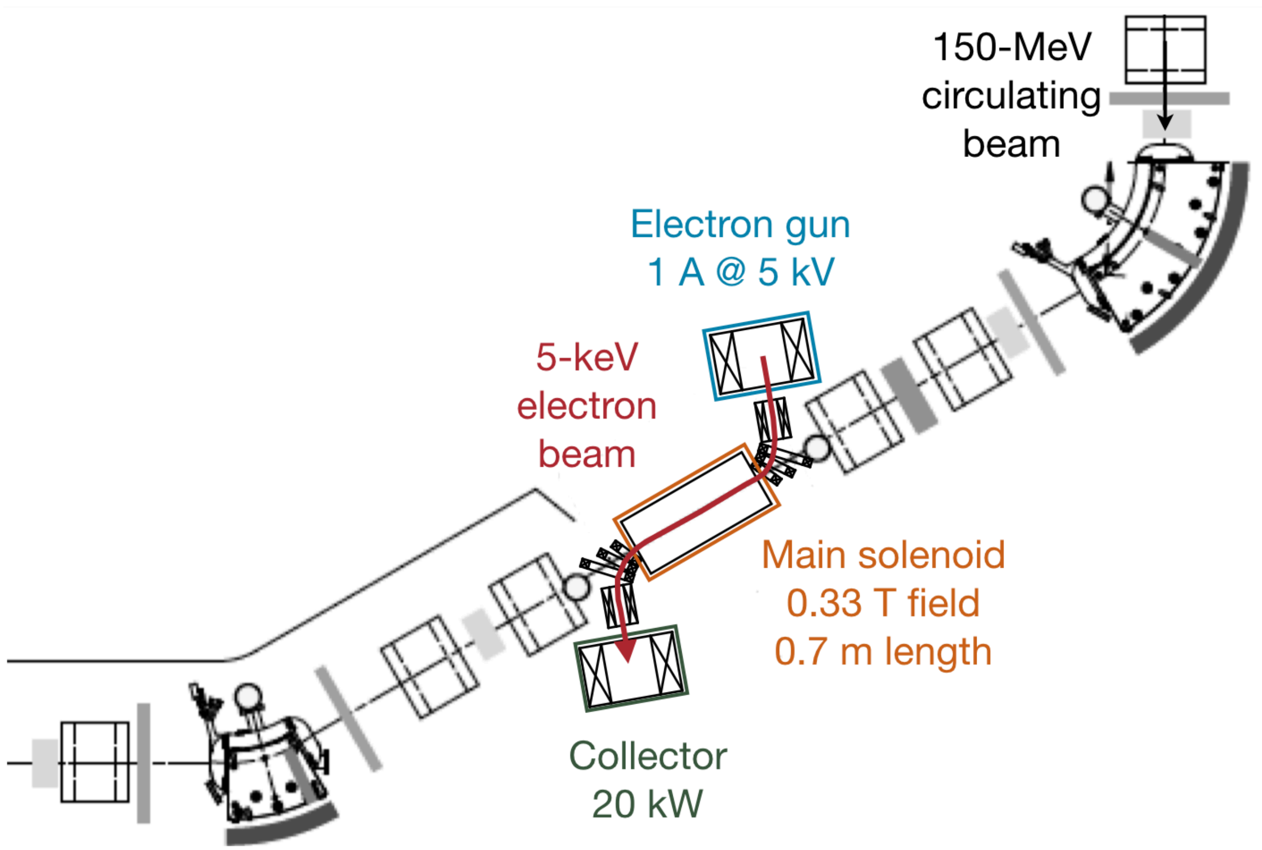
2. The transverse profile of the electron is made the same as that of the proton beam

→ use of solenoid

3. The system of magnetized electrons and protons is now dynamically stable

IOTA Electron Lens

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components



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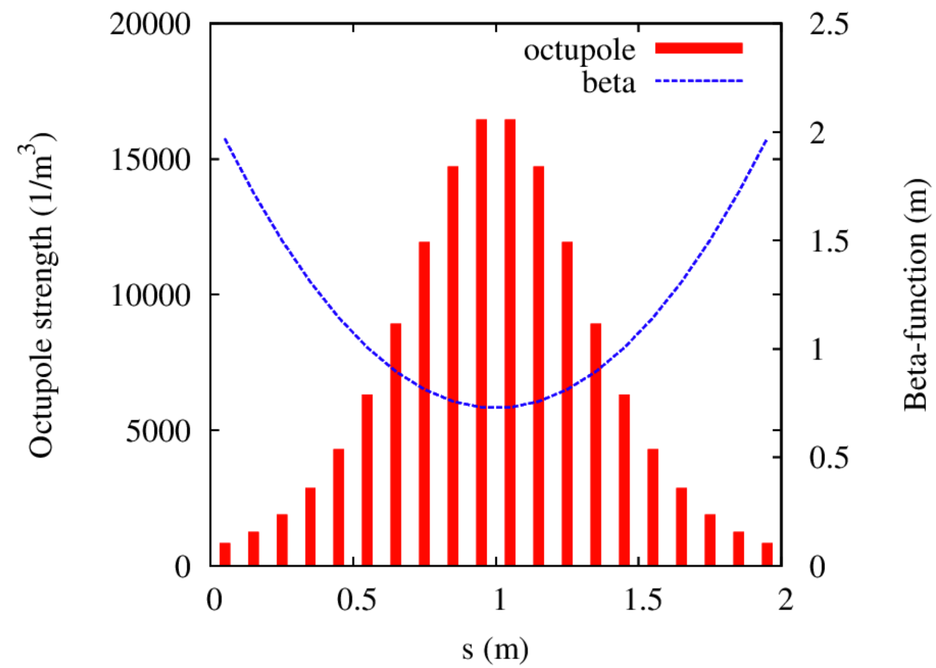
Quasi-Integrable System

- Build *V* with Octupoles

$$V(x,y,s)=\frac{\kappa}{\beta(s)^3}\left(\frac{x^4}{4}+\frac{y^4}{4}-\frac{3x^2y^2}{2}\right)$$

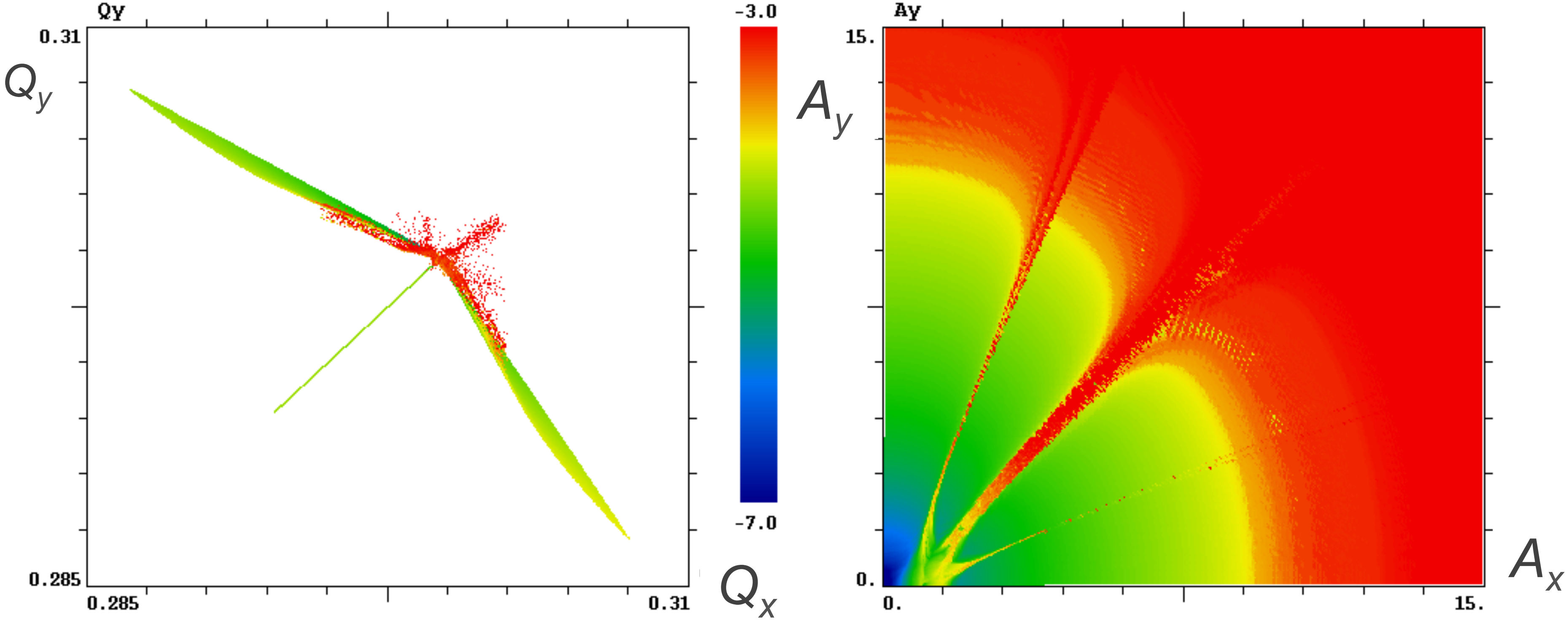
$$U=\kappa\left(\frac{x_N^4}{4}+\frac{y_N^4}{4}-\frac{3y_N^2x_N^2}{2}\right)$$



$$H=\frac{1}{2}(p_x^2+p_y^2)+\frac{1}{2}(x^2+y^2)+\frac{k}{4}\left(x^4+y^4-6x^2y^2\right)$$

- Only one integral of motion – *H*
- Tune spread limited to ~12% of Q_0

Quasi-Integrable System with Octupoles



- While dynamic aperture is limited, the attainable tune spread is large

Special Potential – Second Integral of Motion

- Find potentials that result in the Hamiltonian having a second integral of motion quadratic in momentum
  - All such potentials are separable in some variables (cartesian, polar, elliptic, parabolic)
  - First comprehensive study by Gaston Darboux (1901)

$$I = Ap_x^2 + Bp_x p_y + Cp_y^2 + D(x,y) \qquad A = ay^2 + c^2, B = -2axy, C = ax^2$$

- Darboux equation

$$xy\left(U_{xx} - U_{yy}\right) + \left(y^2 - x^2 + c^2\right)U_{xy} + 3yU_x - 3xU_y = 0$$

  - General solution in elliptic variables ξ, η, with f and g arbitrary

$$U(x,y) = \frac{x^2}{2} + \frac{y^2}{2} + \frac{f_2(\xi) + g_2(\eta)}{\xi^2 - \eta^2}$$

  - Solution that satisfies the Laplace equation

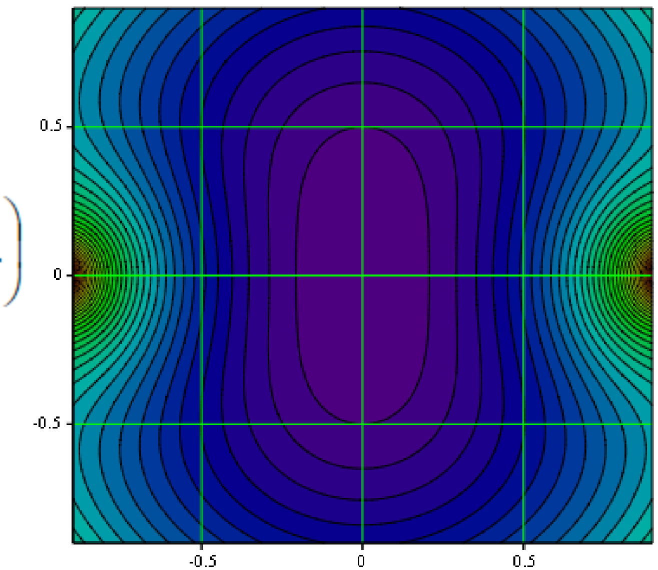
$$f_2(\xi) = \xi\sqrt{\xi^2 - 1}\left(d + t\,\mathrm{acosh}\left(\xi\right)\right) \quad g_2(\eta) = \eta\sqrt{1 - \eta^2}\left(q + t\,\mathrm{acos}\left(\eta\right)\right)$$

Maximum Tune Shift

- Multipole expansion of *U*:

$$U(x,y) \approx \frac{x^2}{2} + \frac{y^2}{2}$$

$$+\,t\,\mathrm{Re}\left((x+iy)^2 + \frac{2}{3}(x+iy)^4 + \frac{8}{15}(x+iy)^6 + \frac{16}{35}(x+iy)^8 + \ldots\right)$$

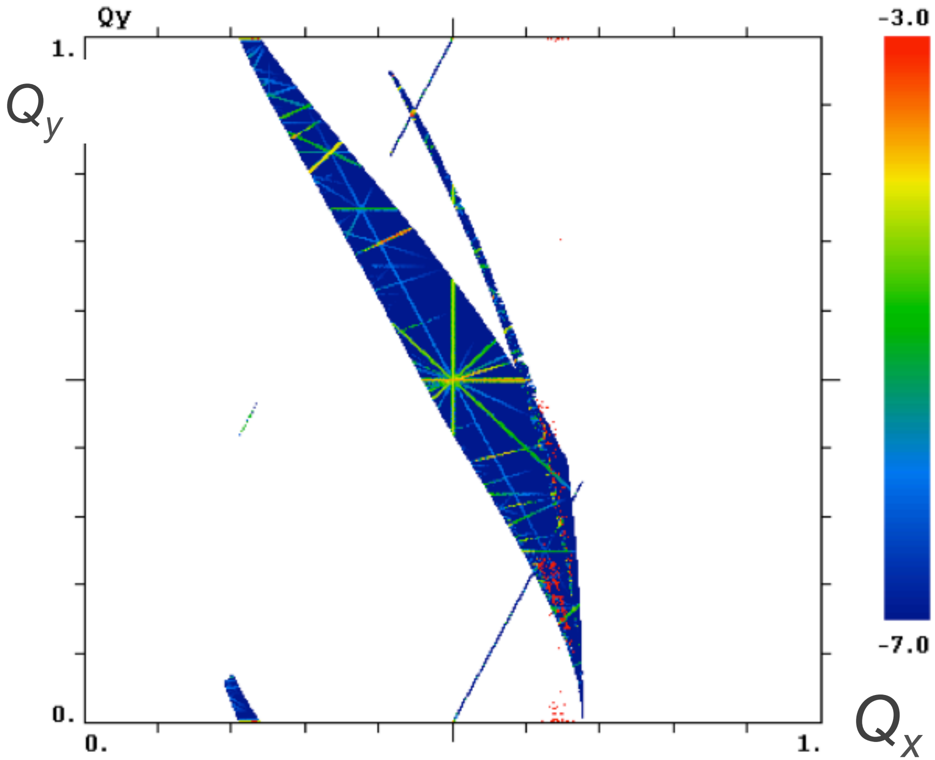


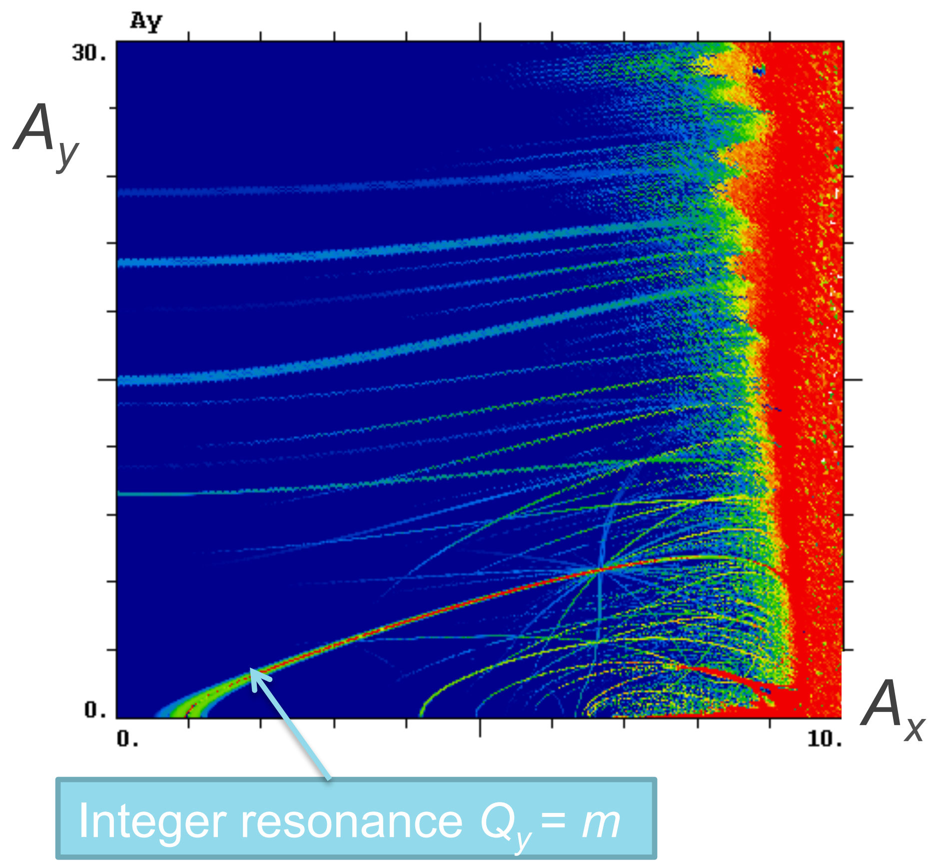
- For small-amplitude motion to be stable*, $t<0.5$

$$\nu_1 = \nu_0\sqrt{1+2t} \qquad \nu_2 = \nu_0\sqrt{1-2t}$$

- Theoretical maximum nonlinear tune shift per cell is
  - 0.5 for mode 1, **or 50% per cell**
  - 0.25 for mode 2, **or 25% per cell**

Single Particle Dynamics in Integrable Optics





Fermilab

Novel Ways to Mitigate Space Charge

- Non-linear integrable optics
  - All synchrotrons ever built are based on linear optics (magnetic quadrupoles). Non-linearities are handled perturbatively, and eventually lead to instabilities.
  - Is has been shown* that non-linear magnetic fields that satisfy a very particular set of conditions can result in stable orbits, but without a unique tune
    - Extremely insensitive to harmonic instabilities
    - Stable up to space charge tune shifts of order unity!
- Electron lens
  - A beam of electrons can be used to cancel the space charge effects of the protons
  - Demonstrated in the Tevatron
  - Used operationally at RHIC

*Danilov, Nagaitsev, PRSTAB 2010