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Beam Dynamics Challenges in High Energy Physics Accelerators

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Acknowledgments

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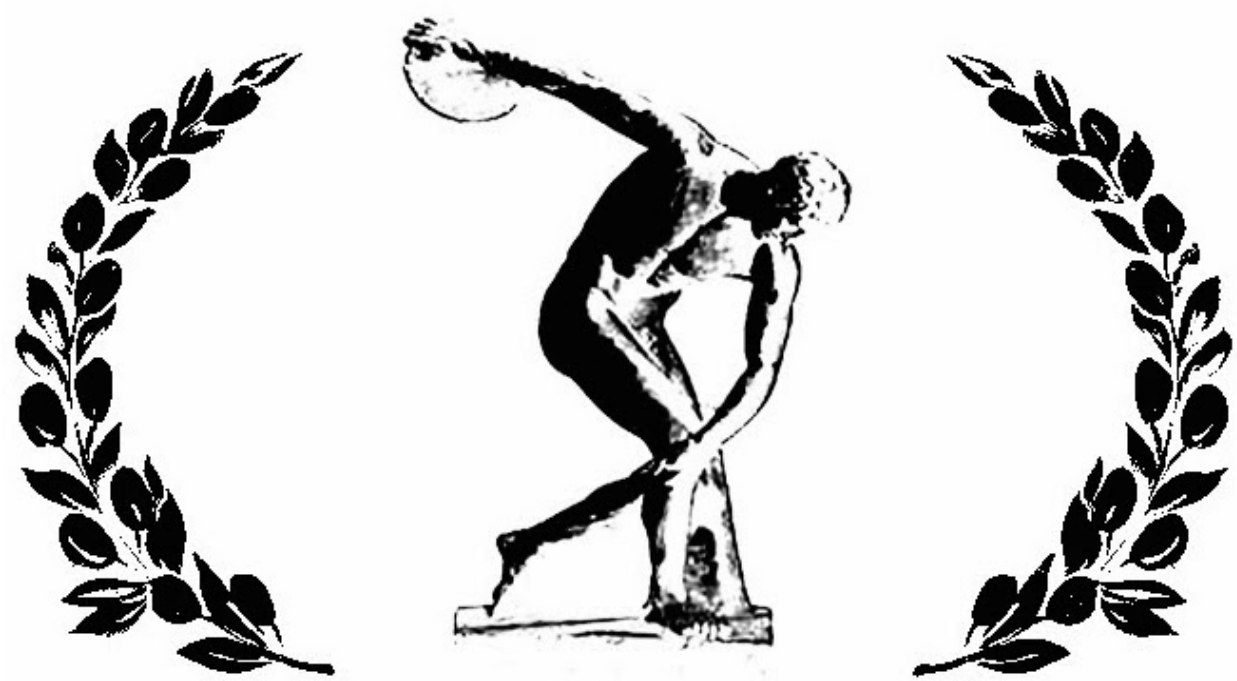
The Olympic Motto for Accelerators



CITIUS · ALTIUS · FORTIUS

MORE ENERGY INTENSITY BRIGHTNESS

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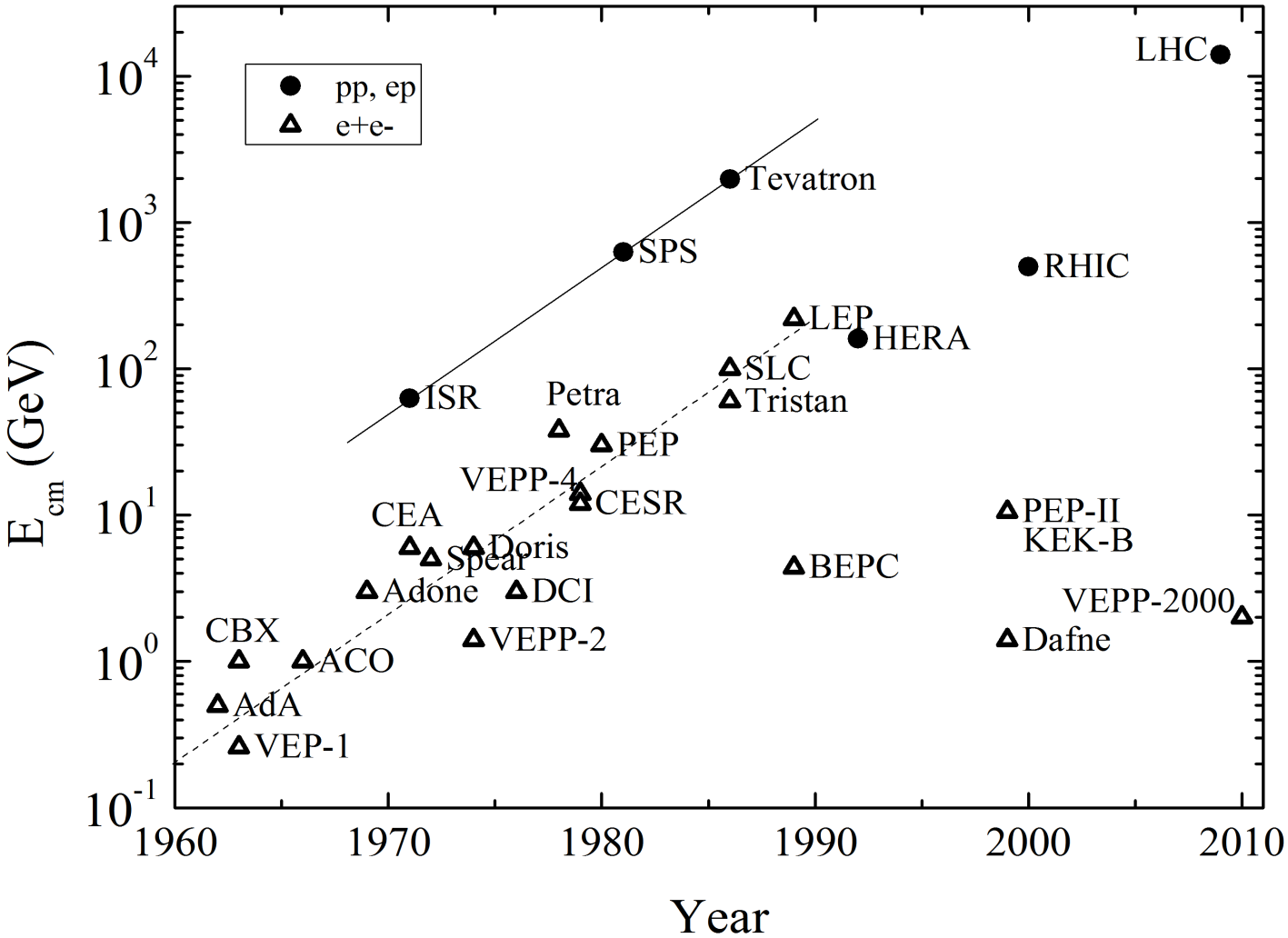
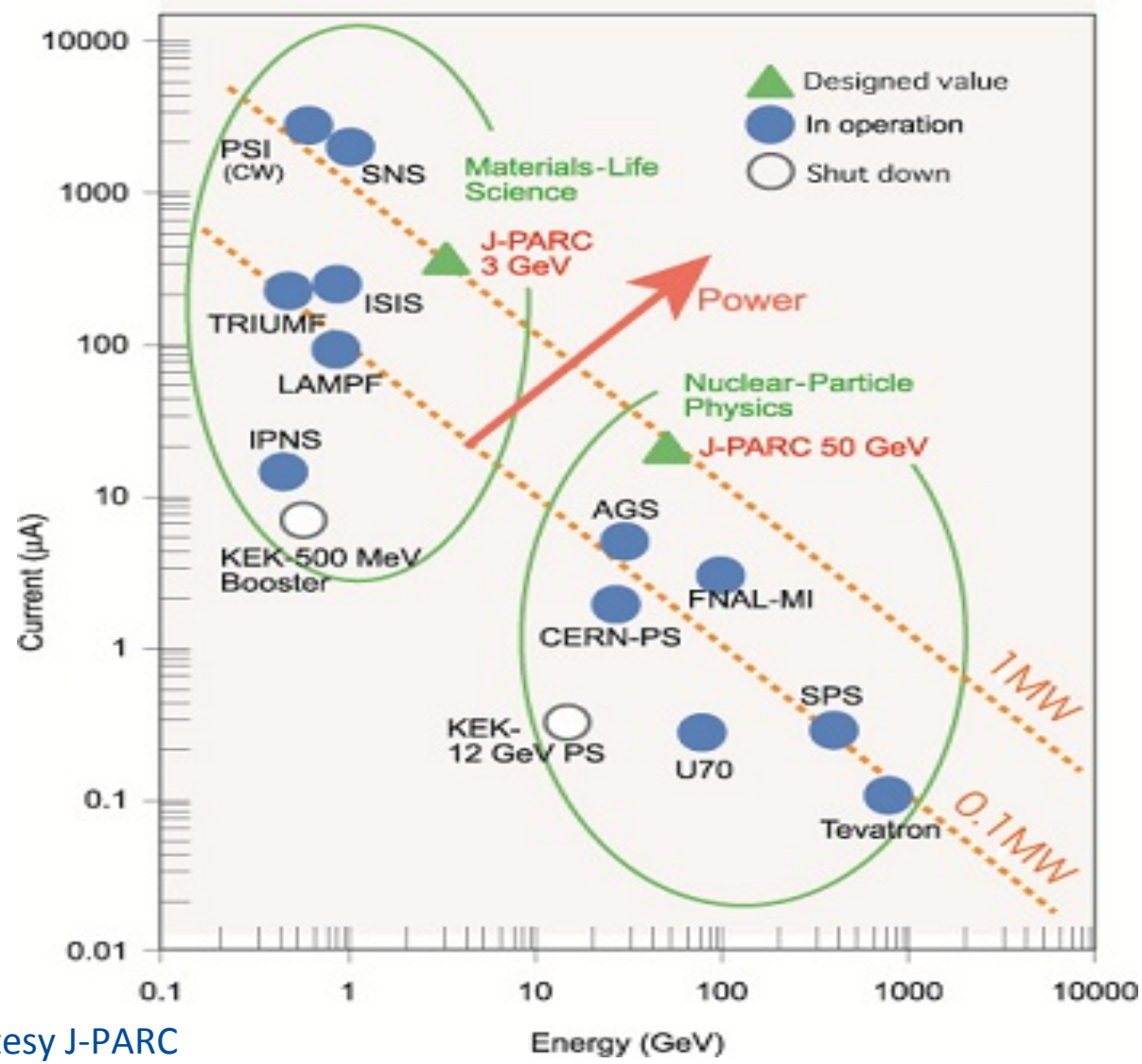
Energy Frontier – the Past of Colliders

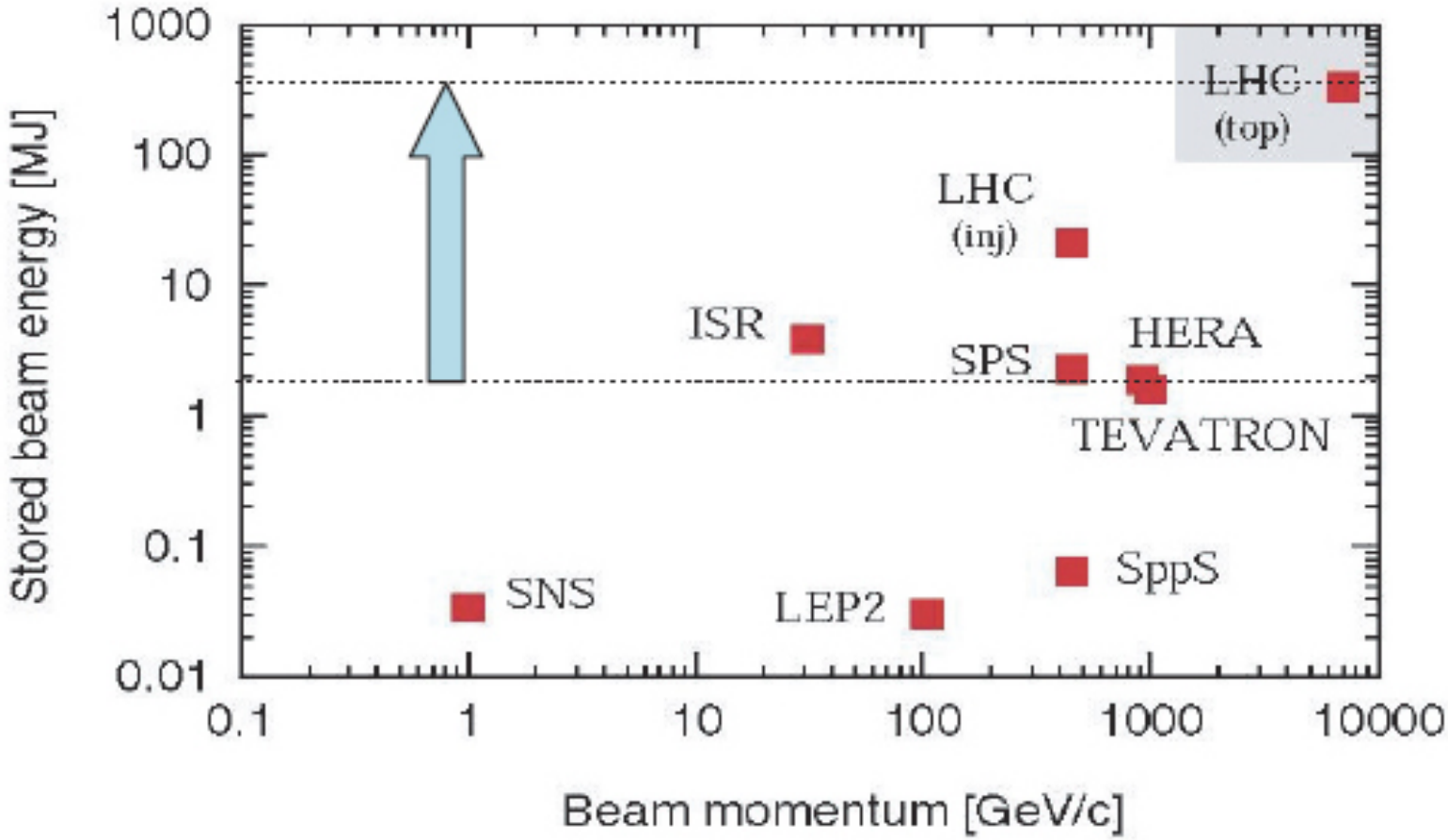


Intensity Frontier – High Power



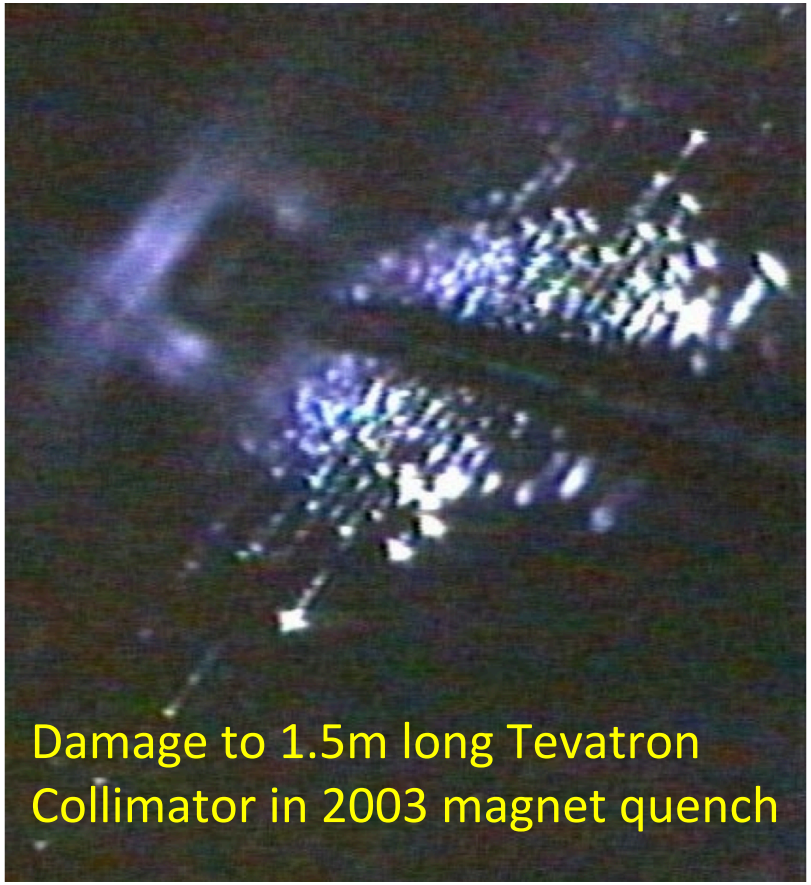
graphic courtesy J-PARC

Stored Beam Energy



graphic LHC Design Report

Beam Energy/Intensity – Consequences


Damage to 1.5m long Tevatron Collimator in 2003 magnet quench

Tevatron Run II	2 MJ
LHC Run I	140 MJ
LHC Design	360 MJ
HL-LHC	675 MJ

Particle losses lead to
- activation of machine components
- quenches of superconducting components
- damage to collimators, etc.

The Challenges

- **Modern machines are designed for *precise control* of the beam in the process of capturing, acceleration, and storage** with the goals to:
  - Avoid beam halo formation and related particle losses
  - Preserve beam quality (brightness)
  - Ensure long-term stability

  These can be achieved by a variety of ways…

This Talk is About

Selected novel methods of designing focusing lattices of circular accelerators with improved particle stability. The discussed methods are based upon a common physical principle – reduction of chaos in betatron oscillations and on improved "integrability"

Two major topics that will be discussed

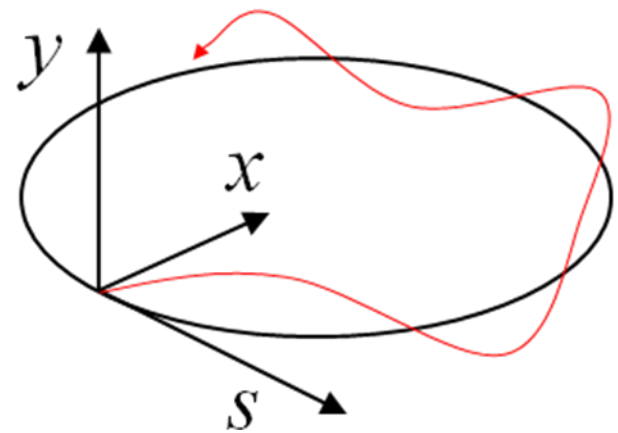
1. Beam-Beam effects
2. Novel nonlinear integrable focusing lattices

Particle Confinement in Rings

Charged particles are kept moving around a circular orbit with the use of static transverse magnetic fields.

$$\vec{F} = e\vec{v} \times \vec{B}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$



$$K_{x,y}(s+C) = K_{x,y}(s)$$

Linear focusing – dipole and quadrupole magnets

x,y motion – betatron oscillations

Longitudinally the beam is kept bunched with time-varying electrical field. s-motion is usually weekly coupled to x-y

Linear Focusing

In the case of linear focusing the system possesses two integrals of motion (Courant-Snyder invariants)

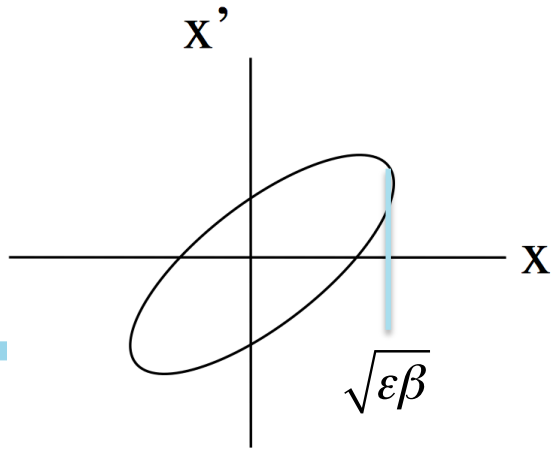
$$I_{x,y} = \frac{1}{2\beta_{x,y}(s)}\left((x,y)^2 + \left(\frac{\beta'_{x,y}(s)}{2}(x,y) - \beta_{x,y}(s)(x,y)'\right)^2\right)$$

β(s) is a periodic function (referred to as amplitude function).

$$\left(\sqrt{\beta}\right)'' + K(s)\sqrt{\beta} = \frac{1}{\sqrt{\beta^3}}$$

All particles in the beam have equal oscillation frequencies (tunes). Phase space trajectories (Poincare sections) are ellipses

$$\psi = 2\pi\nu = \oint \frac{ds}{\beta}$$



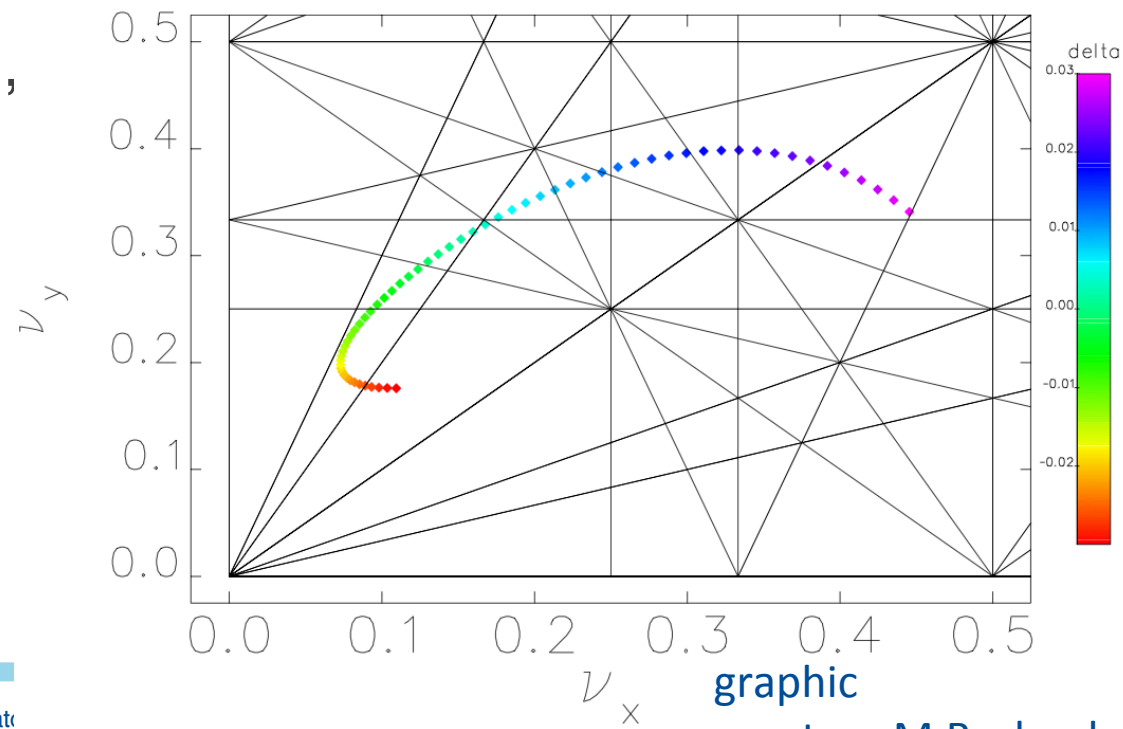
Nonlinear Aberrations

The particle beams are usually non-monochromatic (typical momentum spread $\Delta p/p$ is $10^{-4} \div 10^{-2}$). Focusing with electromagnets depends on particle's momentum. For quadrupole:

$$K = \frac{e}{pc} L \frac{\partial B_y}{\partial x} \approx \frac{e}{p_0 c} L \frac{\partial B_y}{\partial x} \left(1 - \frac{\Delta p}{p}\right)$$

Due to chromatic focusing, tunes now have a spread

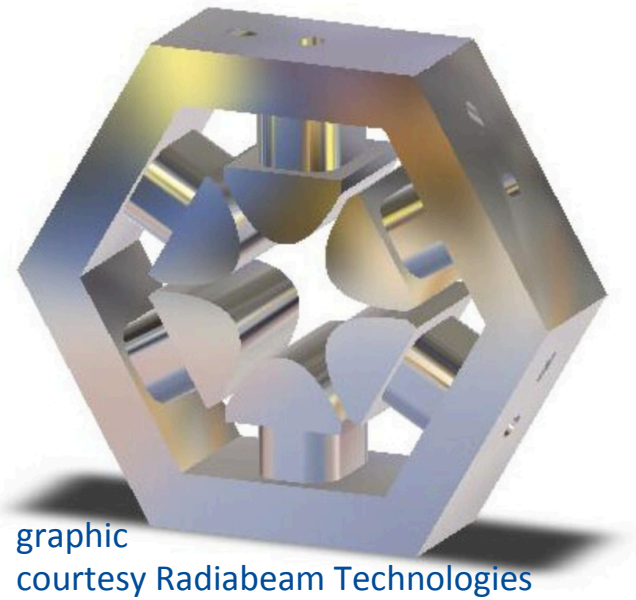
When tune reaches integer, focusing stability is lost



graphic courtesy M.Borland

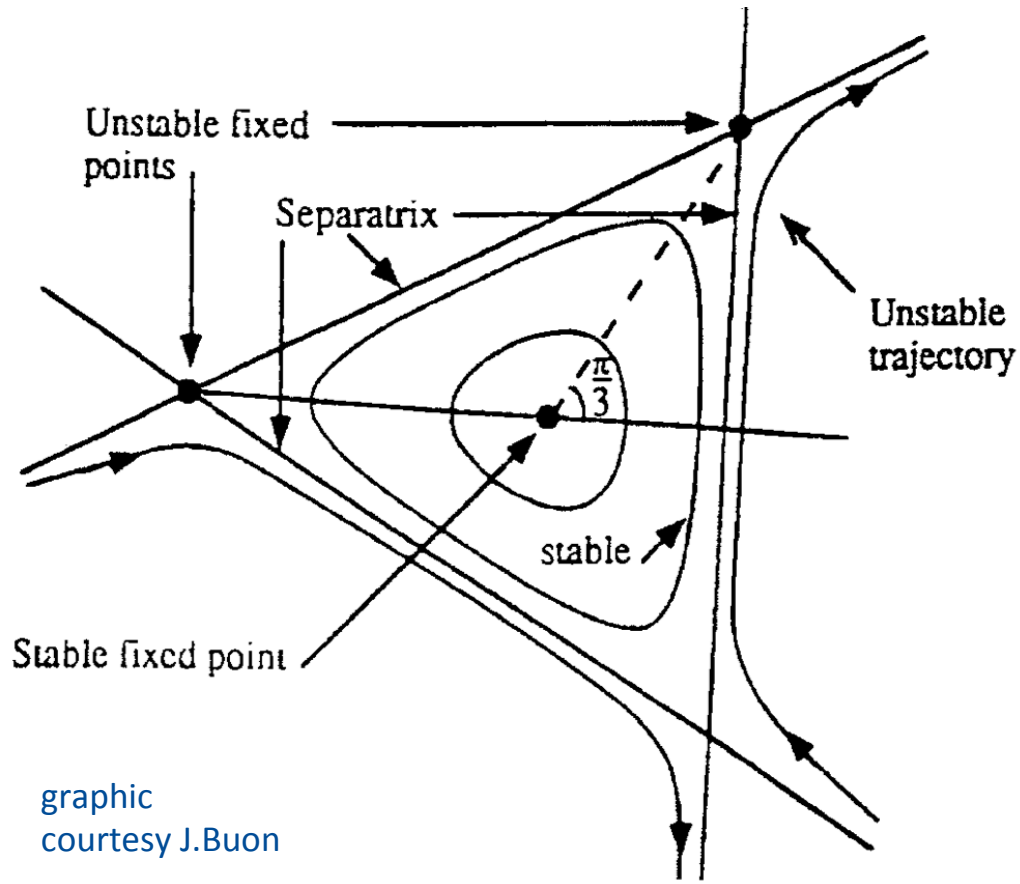
Chromaticity Correction

The chromaticity is corrected with sextupole magnets.



graphic
courtesy Radiabeam Technologies

$$\begin{cases} x'' + K_x(s)x = S(s)(x^2 - y^2) \\ y'' + K_y(s)y = -S(s)2xy \end{cases}$$

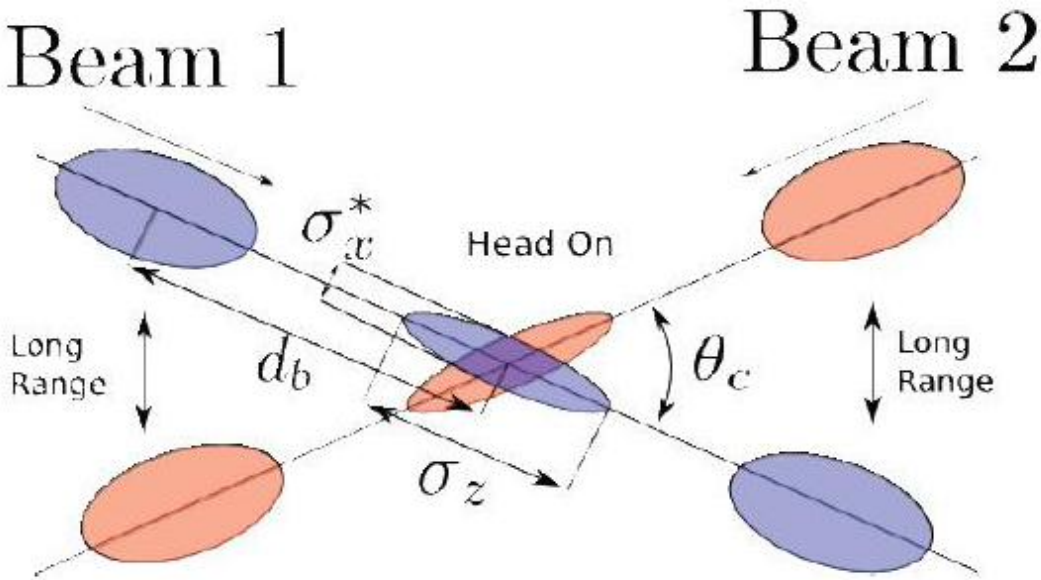


graphic
courtesy J.Buon

The motion is no longer integrable, chaotic at certain amplitudes (loss of stability = Dynamic Aperture)

Beam-Beam Interactions

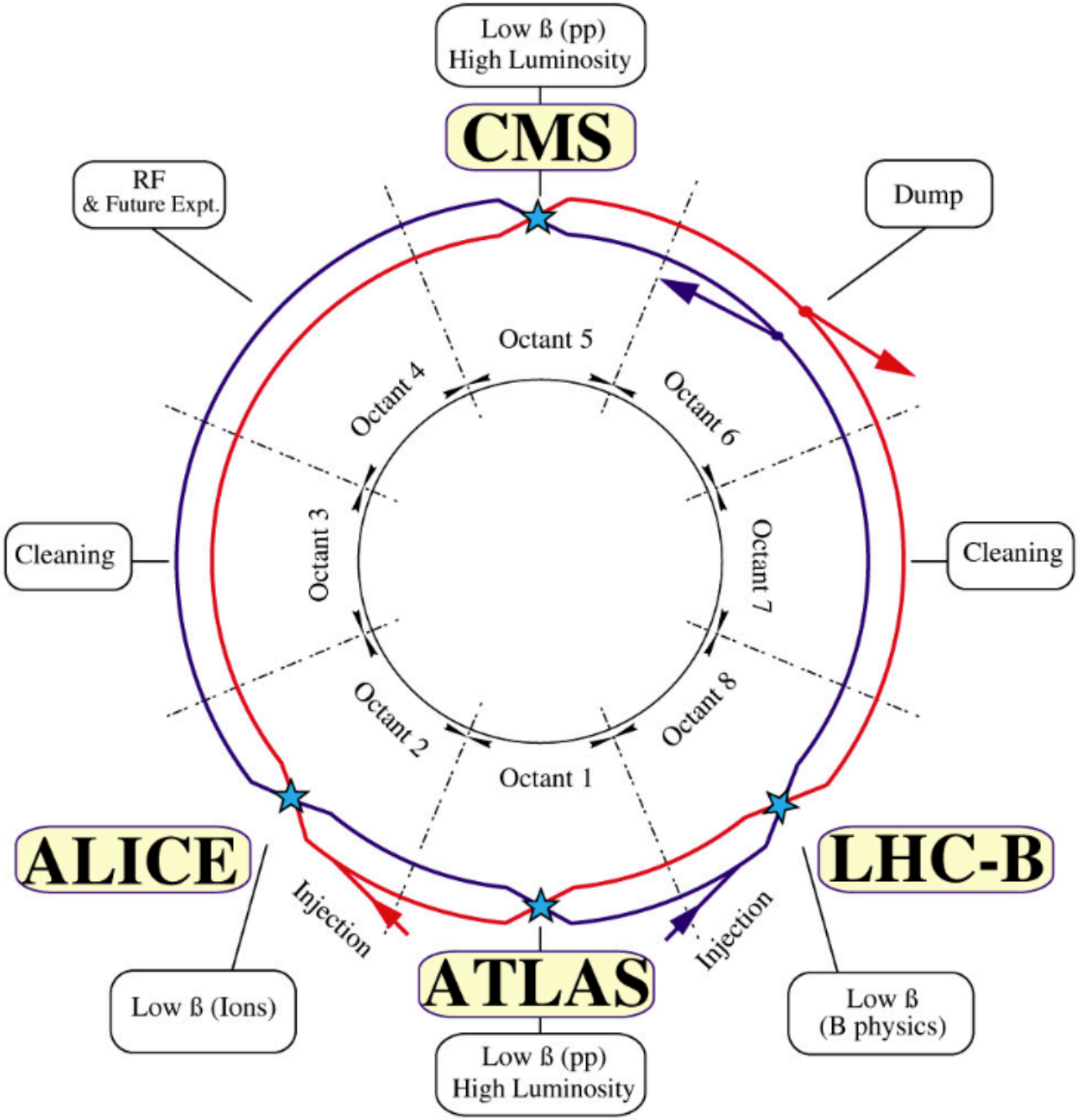
In colliders in addition to the focusing magnets, particles experience interactions with electromagnetic field of counter-rotating beam.



$$F \propto \Delta\nu_{BB} \frac{1}{r}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$

$$\Delta\nu_{BB} = \xi = \frac{N r_0 \beta}{4\pi\gamma\sigma^2}$$

Even though beam-beam adds relatively little to focusing – typical tune shift for LHC is 0.02 at lattice tune of 60, the beam-beam force is strongly nonlinear and localized in time



In proton operation:

3 head-on collisions (CMS, ATLAS, LHC-B)

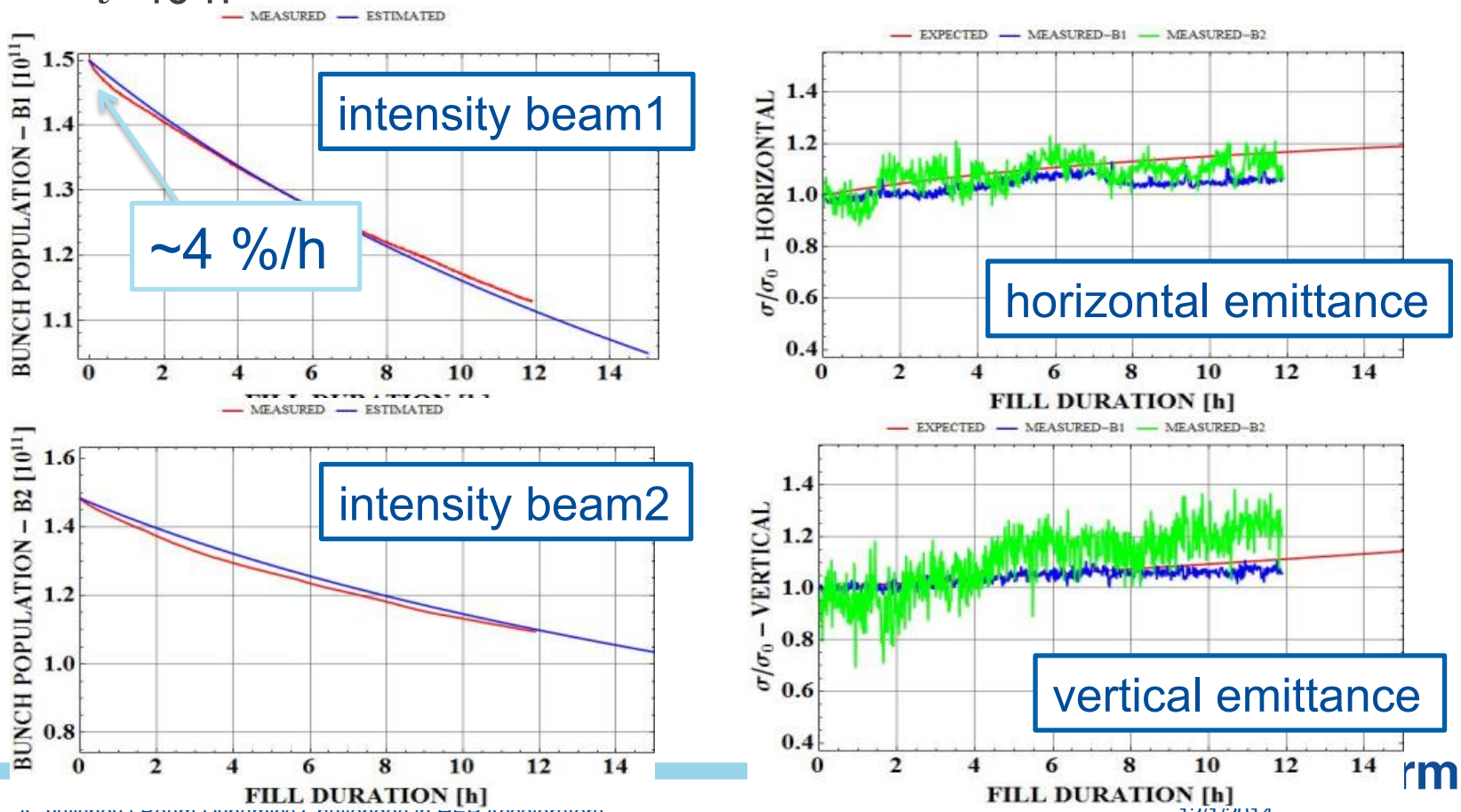
about 100 long-range at ~9σ separation

LHC operation in 2012

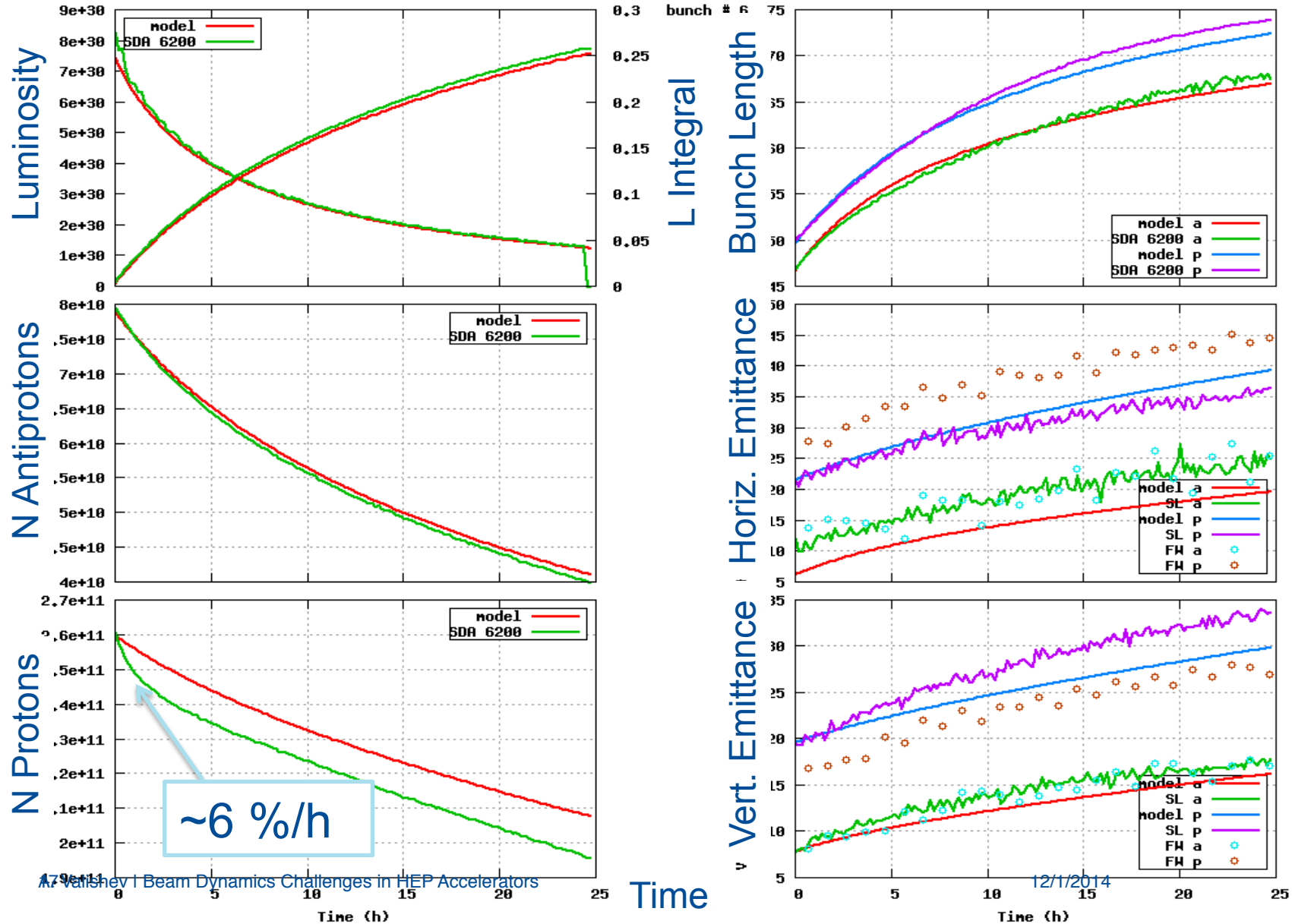
G.Arduini

Luminosity evolution for fill 2728 compared to model including

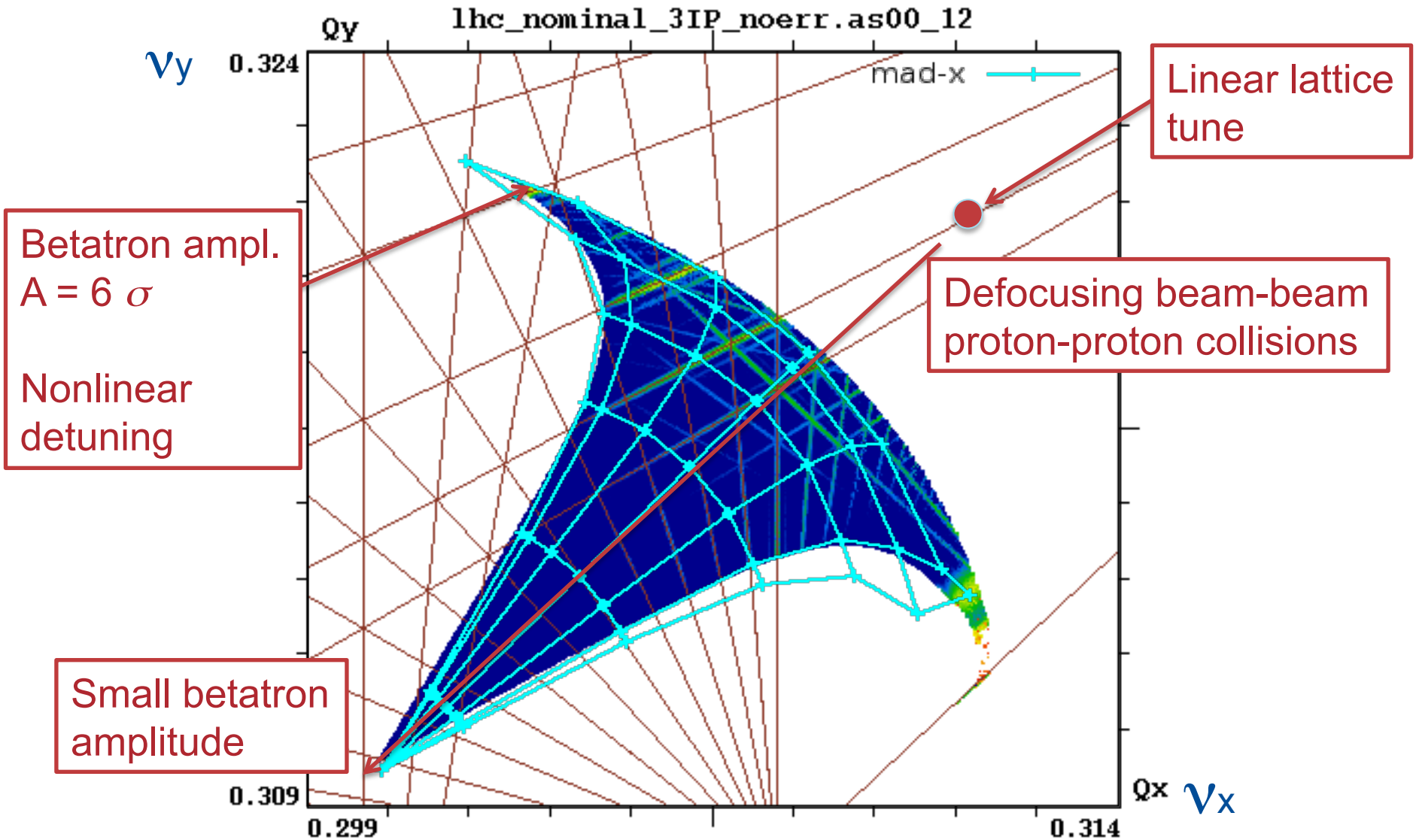
- Particle losses due to luminosity and unknown source τ=200 h
- Emittance growth due to IBS, SR damping and unknown growth with τ=40 h



Tevatron store 6200, L_0=2.95x10^{32}



Tune Footprint



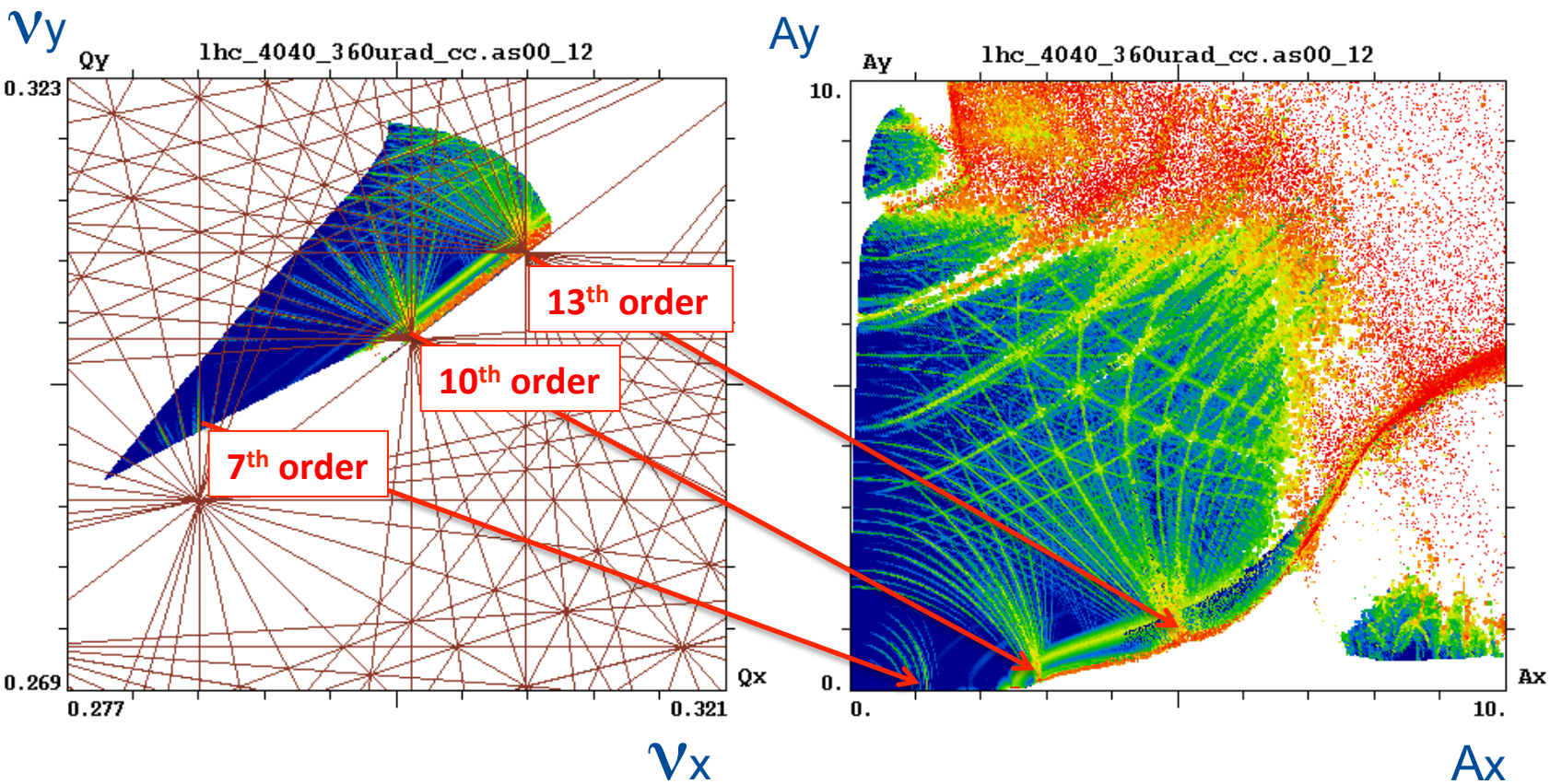
Frequency Map Analysis

J. Laskar, Icarus 88, 266-291 (1990) "The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones"

- Based on precise tune determination from FFT of turn-by-turn particle coordinate (2D tracking)
- Evaluate tune jitter in sliding time window ➔ resonances
- When the dynamic system is (or very close to) integrable, nonlinear resonances disappear – this must be clearly seen in FMA plot
- Imperfections violate integrability. Then FMA easily allows to determine the regular and stochastic areas in phase space

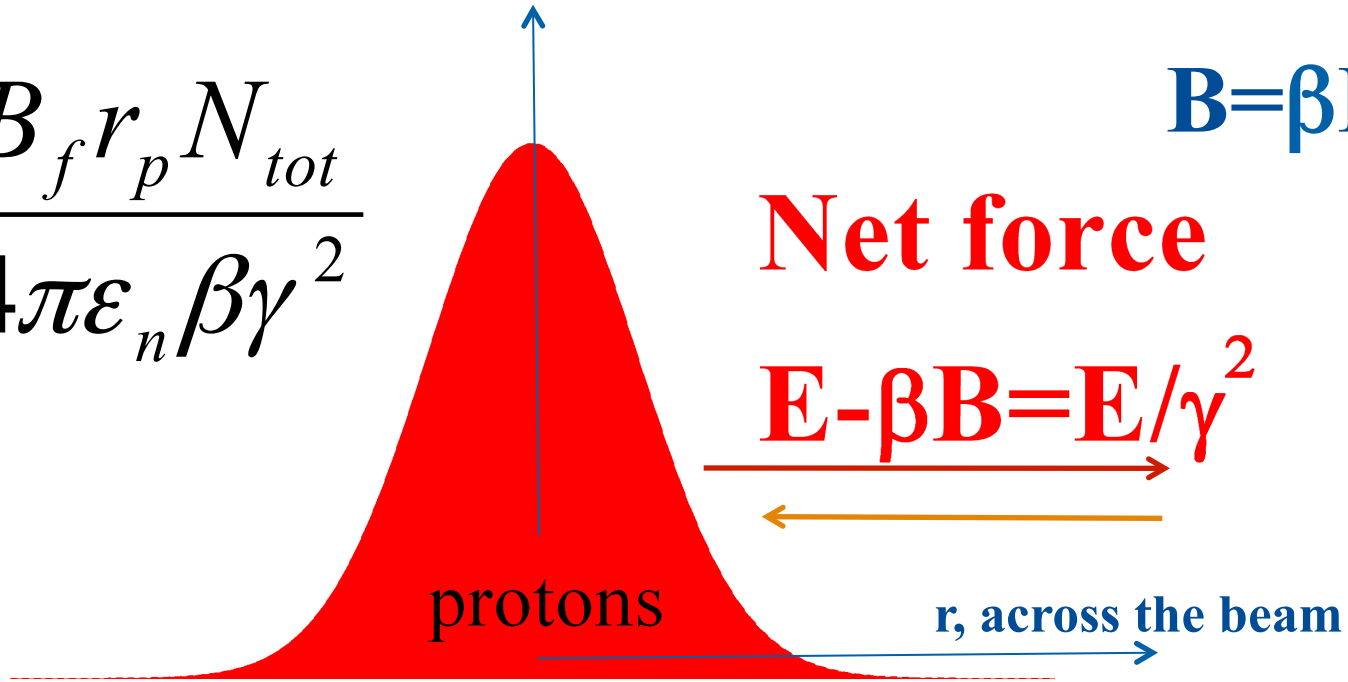
Frequency Map Analysis

ξ=0.03



Space Charge Effect

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



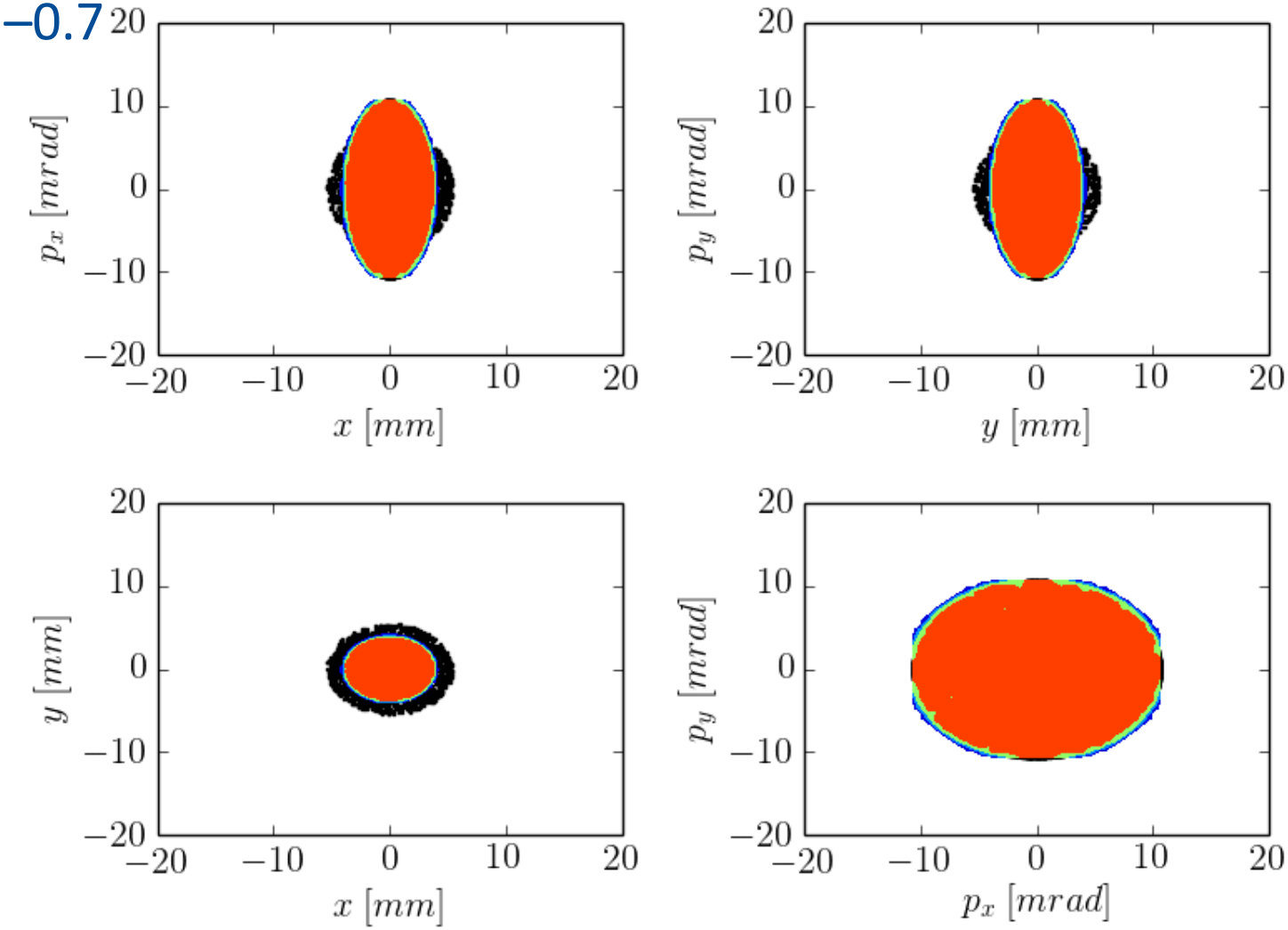
Self space-charge is modulated in time due to the bunch size variation along the accelerator

- Leads to effects similar to beam-beam
- Limits maximum current in high-intensity low energy machines

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

Intermediate Conclusions

- Linear accelerator lattices are stable by design. There are two non-commuting invariants of motion. All particles have equal oscillation frequencies (independent of amplitude).
- Nonlinear aberrations of the focusing are unavoidable (due to chromaticity), and some are introduced intentionally (e.g. sextupoles for chromaticity correction).
- Additional significant sources of nonlinearities are beam-beam interaction in colliders or self space charge in high intensity machines.
- Nonlinearities lead to unstable and chaotic motion
  - Nonlinearities shift tunes with amplitude
  - Time-dependence results in resonant conditions

Do Accelerators Need to be Linear?

Search for solutions that are strongly nonlinear yet stable

Additional invariants of motion improve stability

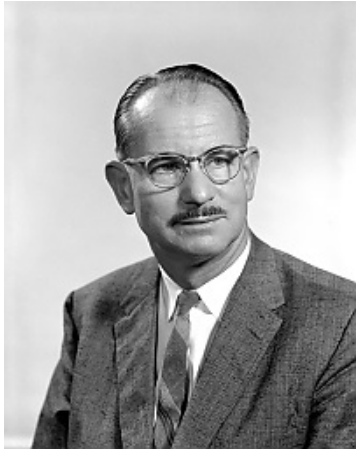
- Orlov (1963)
- McMillan (1967) – 1D solution
- ✓ Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams.
  - Round colliding beams possess 1 invariant – VEPP-2000 at BINP (Novosibirsk, Russia) commissioned in 2006. Record-high beam-beam tune shift ~0.25 attained in 2013
- Chow, Cary (1994)
- ✓ Nonlinear Integrable Optics: Danilov and Nagaitsev solution for nonlinear lattice with 2 invariants of motion that **can be implemented with Laplacian potential**, i.e. with special magnets – *Phys. Rev. ST Accel. Beams 13, 084002 (2010)*

2D Generalization of McMillan Mapping 1

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

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

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

Can be created with electron lens

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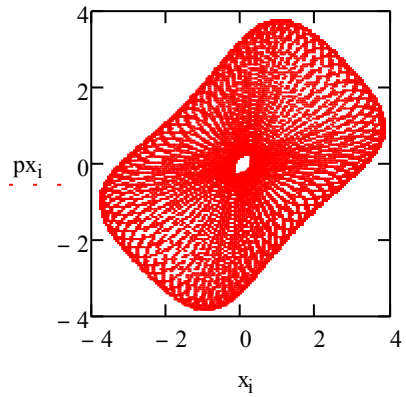
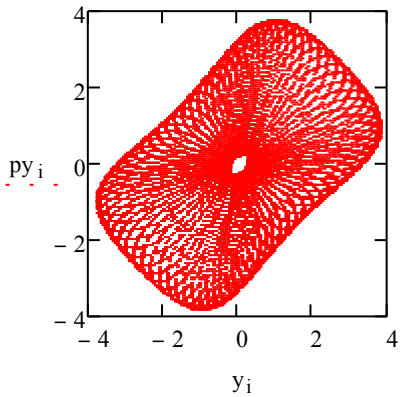
2D Generalization of McMillan Mapping 2

- 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
- Potentially, can cross an integer resonance

Round Colliding Beams

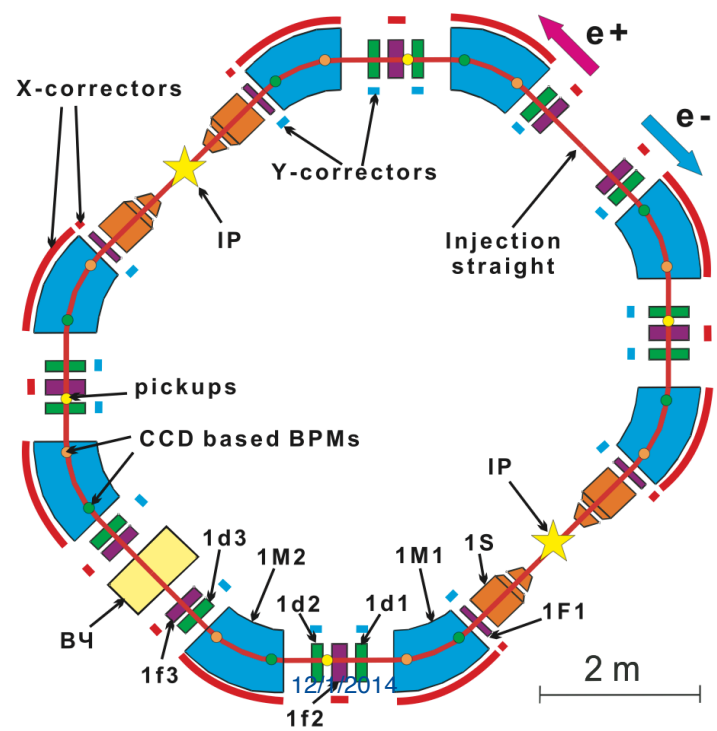
- McMillan mapping requires special shape of the nonlinear lens. Colliding beams are usually 3D Gaussian. Will one integral of motion improve stability?
  - Yes! Reducing 2D system to 1D eliminates coupling resonances
  - VEPP-2000 collider at BINP (Novosibirsk, Russia)
    - e+e- collider at ϕ-meson energy
    - Axially symetric linear focusing in arcs
    - Round beams at IPs

    - World record beam-beam tune shift

    ξ=0.25 in 2013

    A.Romanov et al., NA-PAC'13

graphic courtesy BINP



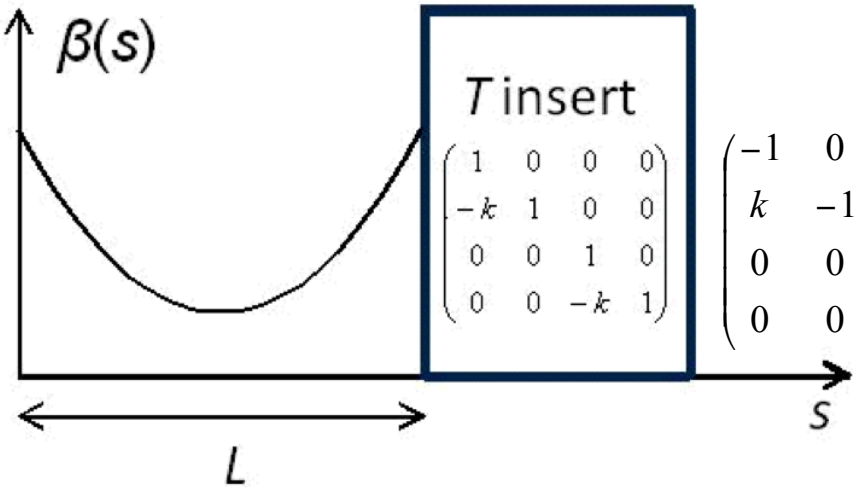
Round Colliding Beams – Next Step

Further, the system can be made *close to 2D integrable* through proper longitudinal shaping of the colliding bunches.

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



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

2. Shape bunch density λ(s)

1. *Ideal* distribution

2. Gaussian with $\sigma_z \sim \sqrt{2}\,\beta^*$

$$\lambda(s) \propto \frac{1}{\beta(s)} = \frac{1}{1+(s/2\beta^*)^2}$$

$$\lambda(s) \propto e^{-s^2/2\sigma_z^2} \approx 1 - s^2/2\sigma_z^2$$

Time-Independent Hamiltonian

- The Hamiltonian is

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

- For ideal λ(s) *H* is time-independent in normalized variables

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

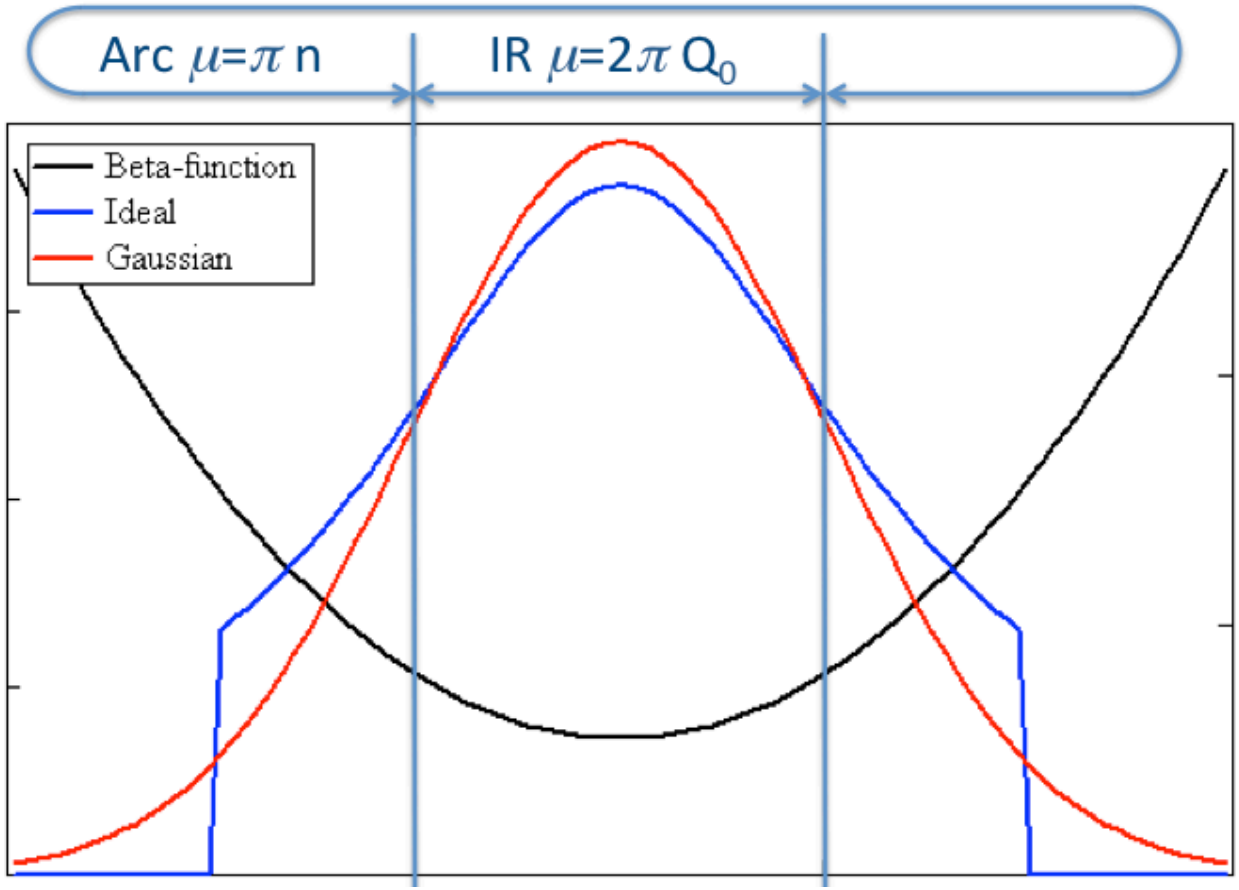
$$p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}},$$

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

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

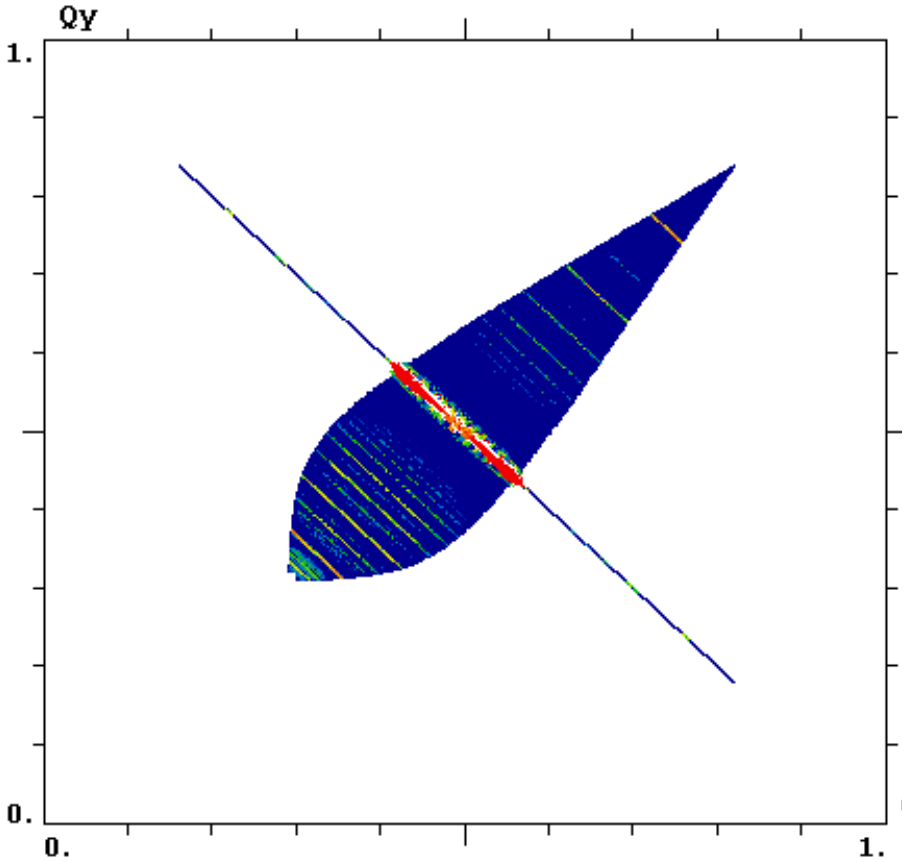
- This results in *H* being the integral of motion
- The Gaussian beam may be *close* to integrable

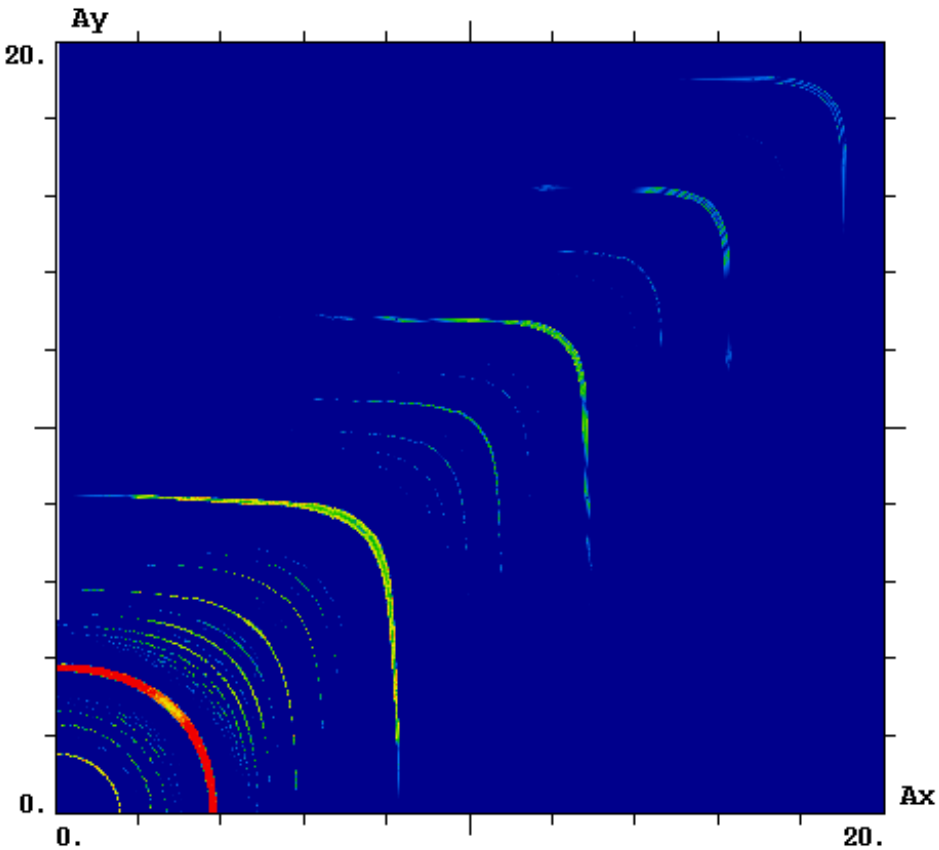
Model Lattice



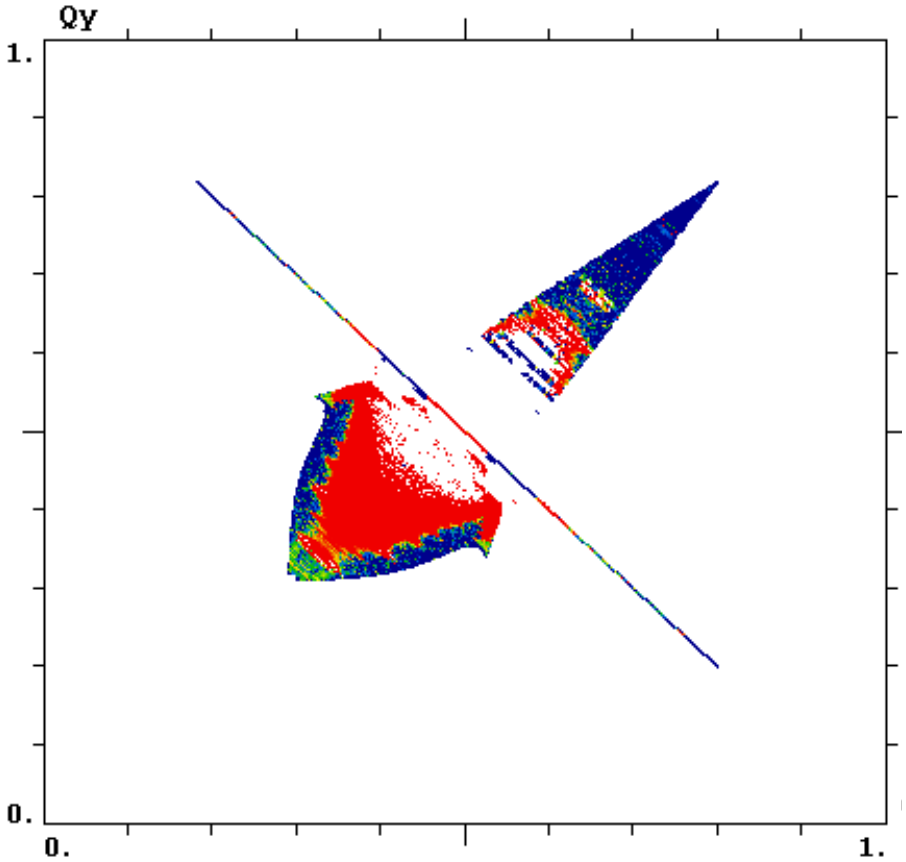
- Machine tune does not need to be close to integer or half-integer, $Q=n/2+Q_0$!

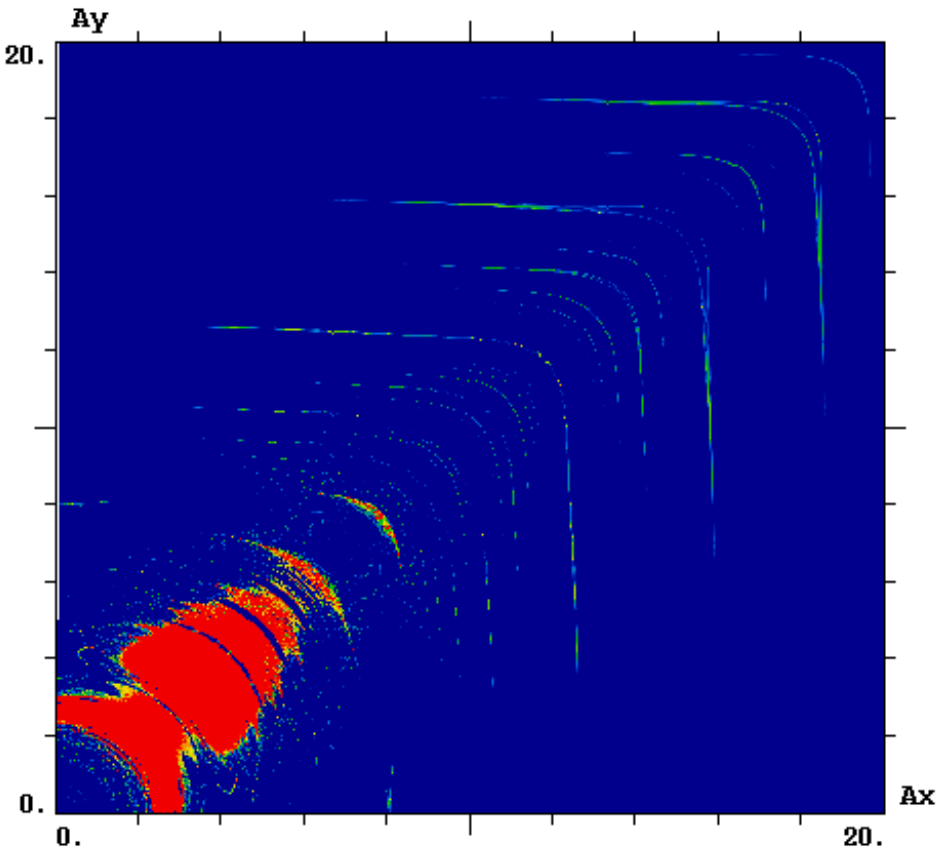
Ideal distribution Q = 0.3, ξ = 1





Gaussian distribution $\sigma=\sqrt{2}\beta$, $\xi=1$





Intermediate Conclusions 2

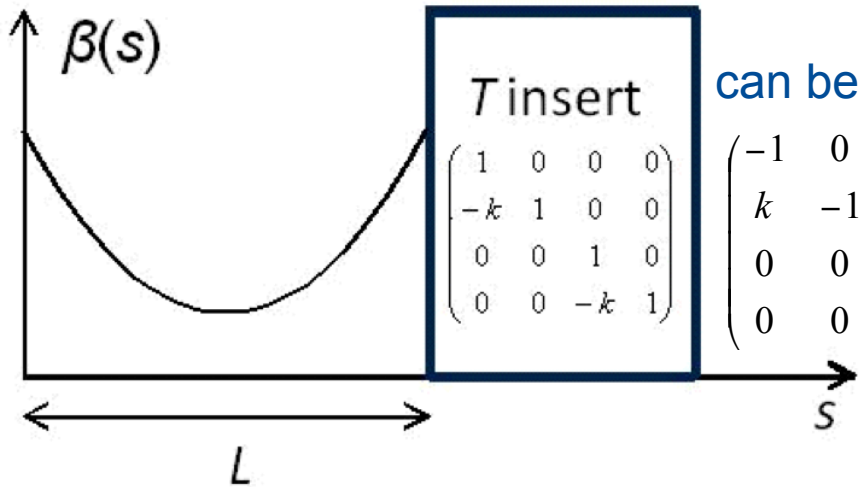
- Constructing nonlinear systems with 1 or 2 integrals of motion is possible with the use of non-Laplacian potential (e.g. beam-beam force)
- Compared to non-integrable systems, dynamics in nonlinear accelerator lattices with some degree of integrability is more stable
  - Nekhoroshev's condition guaranties 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)
  - Demonstrated with round colliding beams at VEPP-2000
- Can integrable systems be constructed with Laplacian potentials (conventional magnets)?

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

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

Time-Independent Hamiltonian

- 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

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

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

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

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

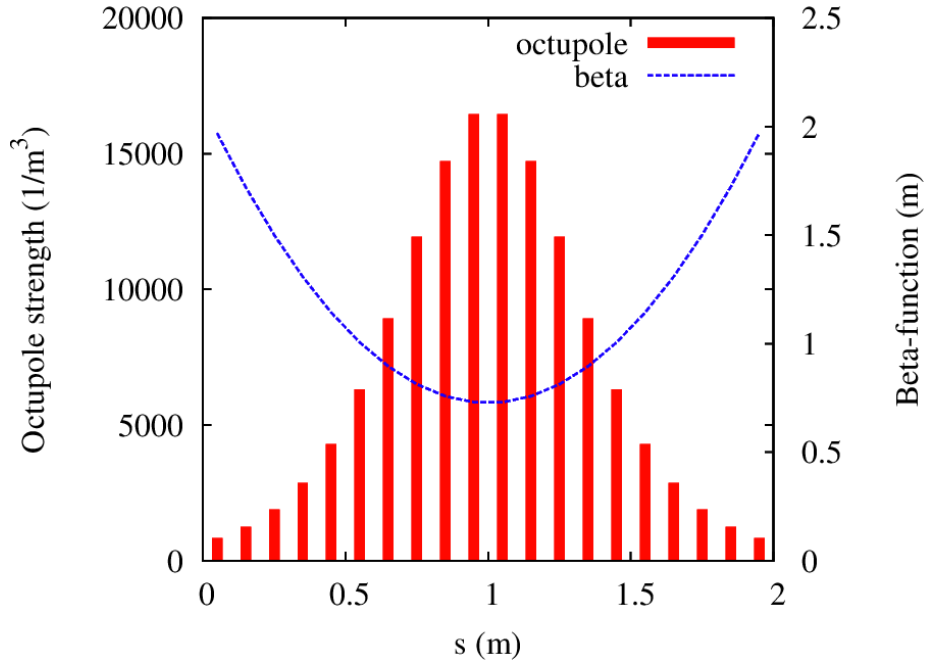
- This results in *H* being the integral of motion
- Note there was no requirement on *V* – can be made with any conventional magnets, i.e. octupoles

Quasi-Integrable System

- Build *V* with Octupoles

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

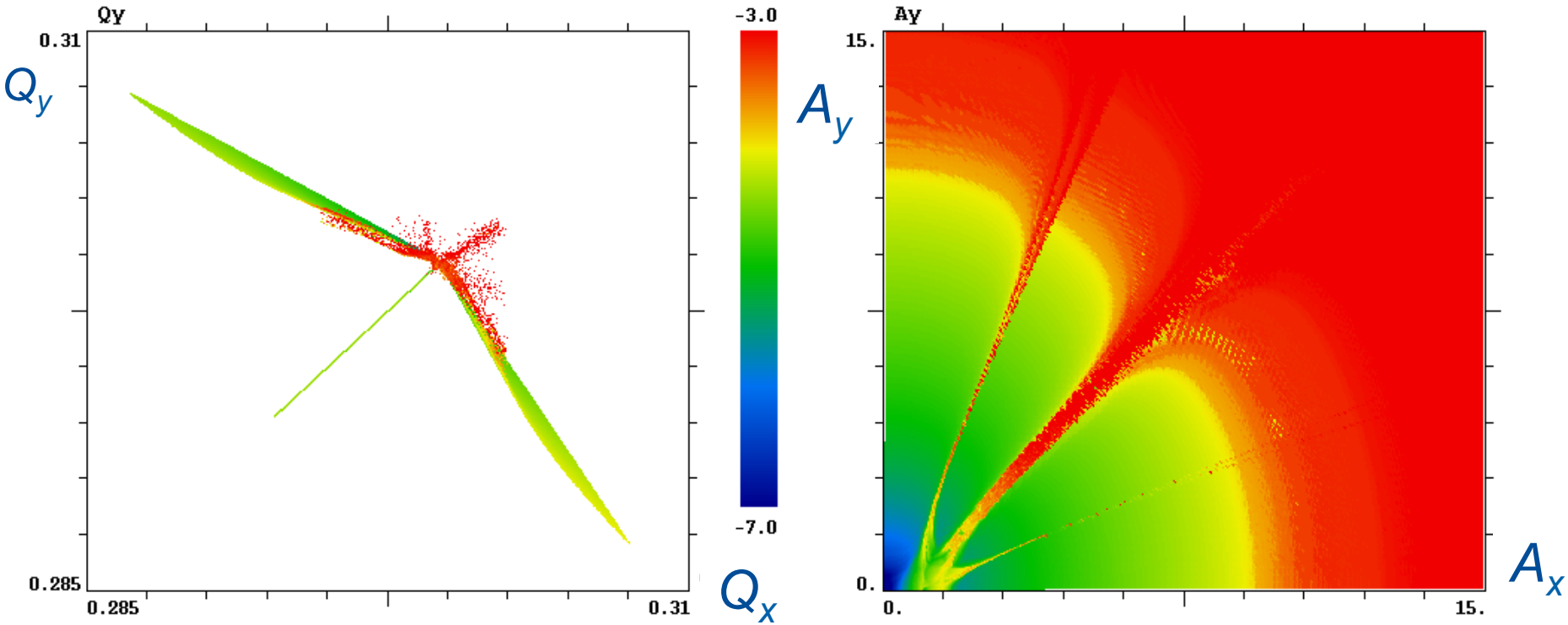
$$U = \kappa\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3y_N^2x_N^2}{2}\right)$$



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

- 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

Joint work with S.Antipov of Univ. Chicago

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

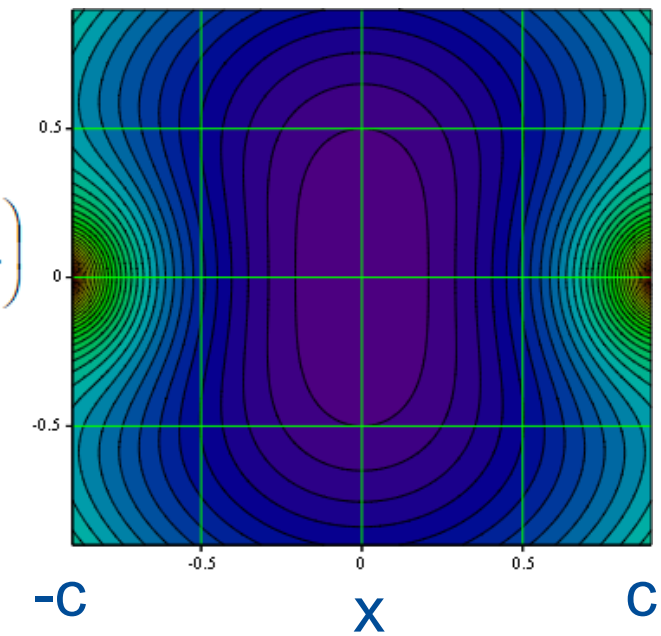
$$f_2(\xi) = \xi\sqrt{\xi^2 - 1}\left(d + t\,\mathrm{acosh}(\xi)\right) \quad g_2(\eta) = \eta\sqrt{1 - \eta^2}\left(q + t\,\mathrm{acos}(\eta)\right)$$

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

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

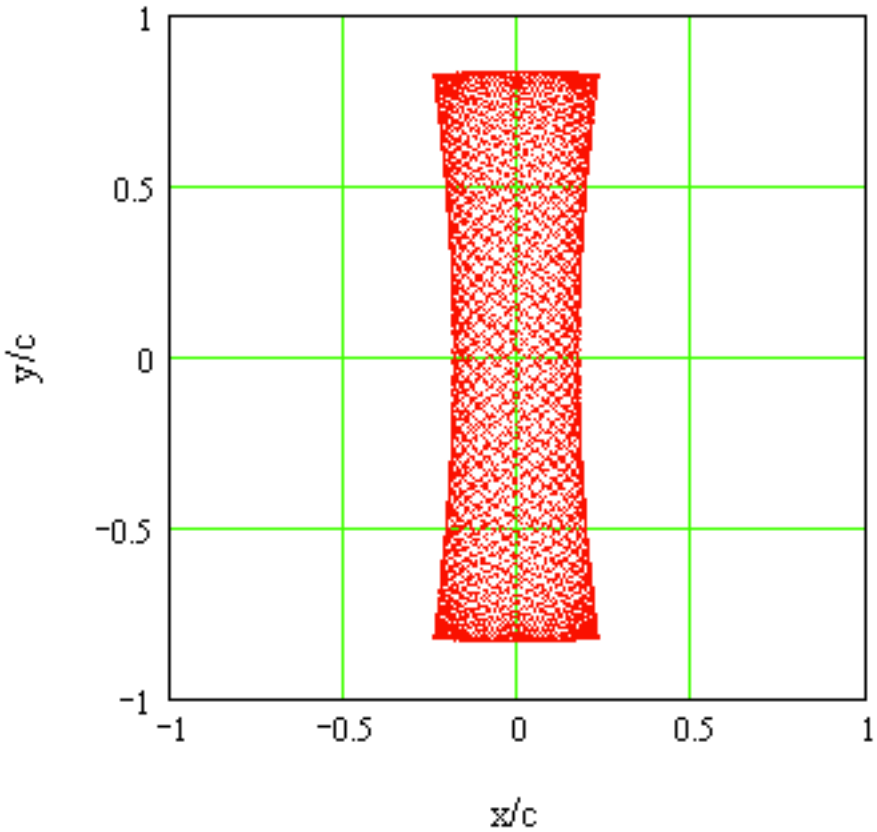
- Theoretical maximum nonlinear tune shift per cell is
  - 0.5 for mode 1, **or 50% per cell**
  - 0.25 for mode 2, **or 25% per cell**

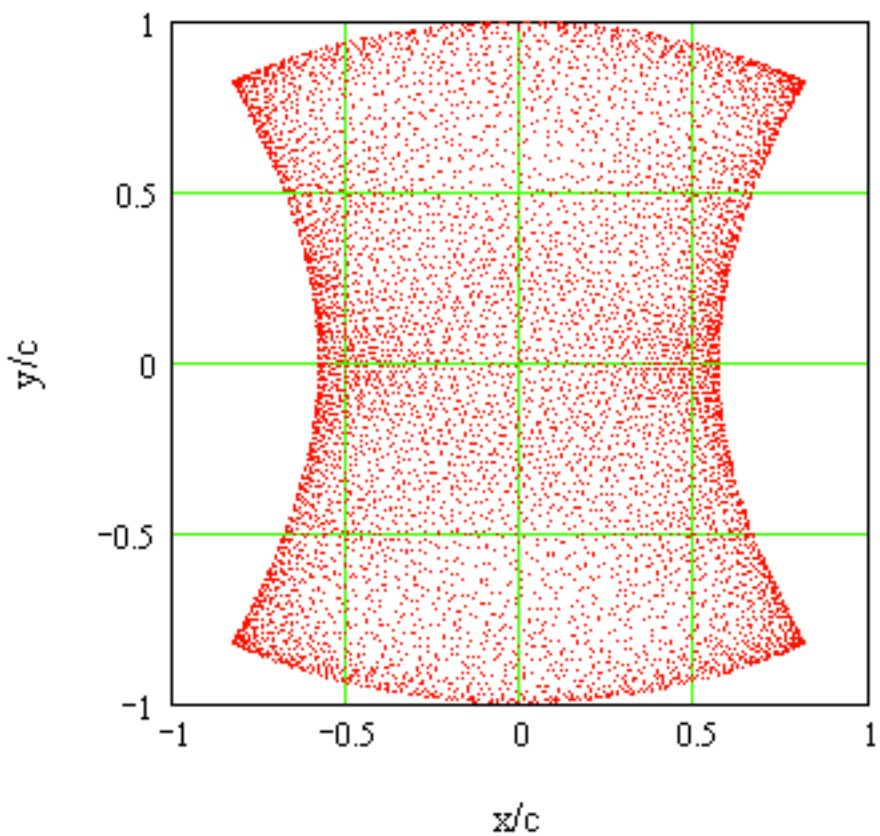
What is Unique About These Solutions?

- One can **add the special potential to a drift of a conventional accelerator** (albeit specially designed and carefully controlled) and make the lattice integrable.
  - **Does not require new technology for the significant portion of accelerator circumference – same cost!**

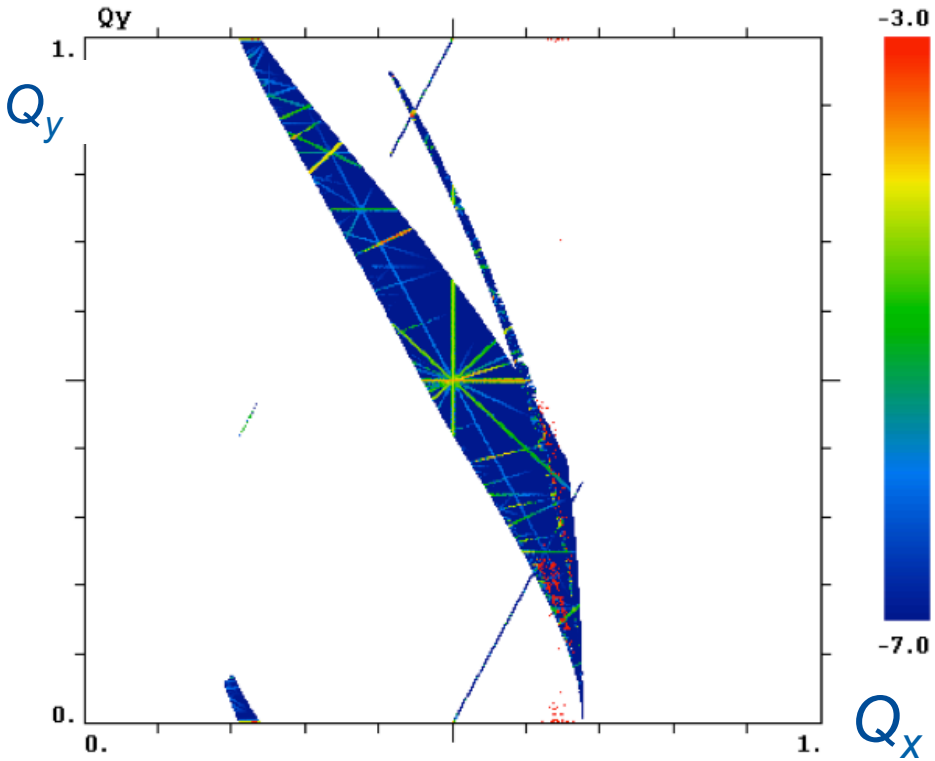
Single Particle Dynamics in Integrable Optics

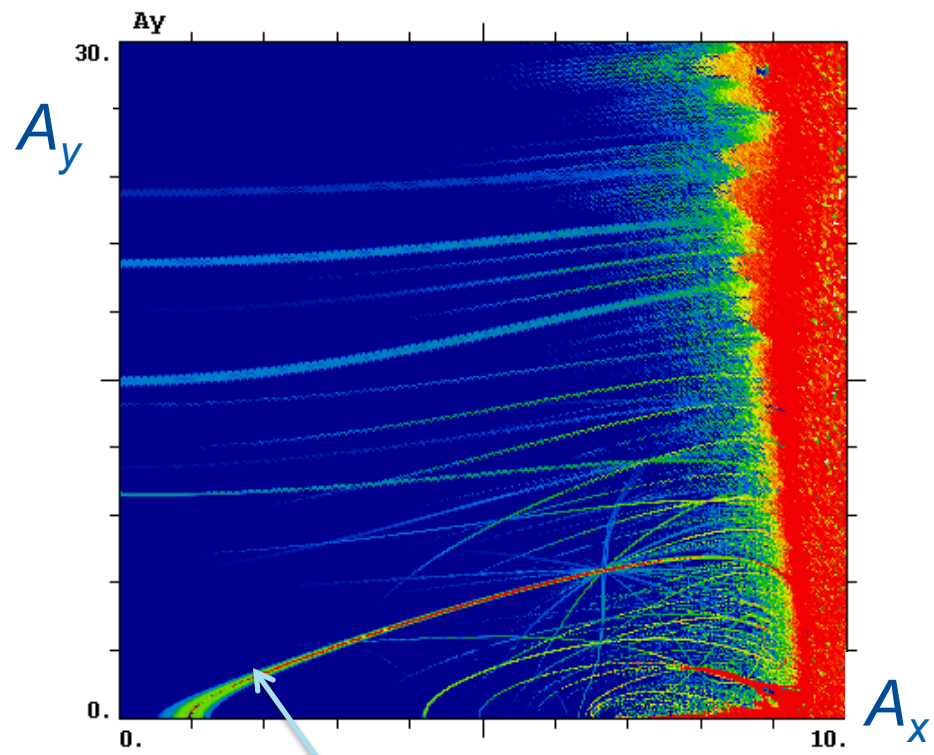
Example trajectories





Single Particle Dynamics in Integrable Optics





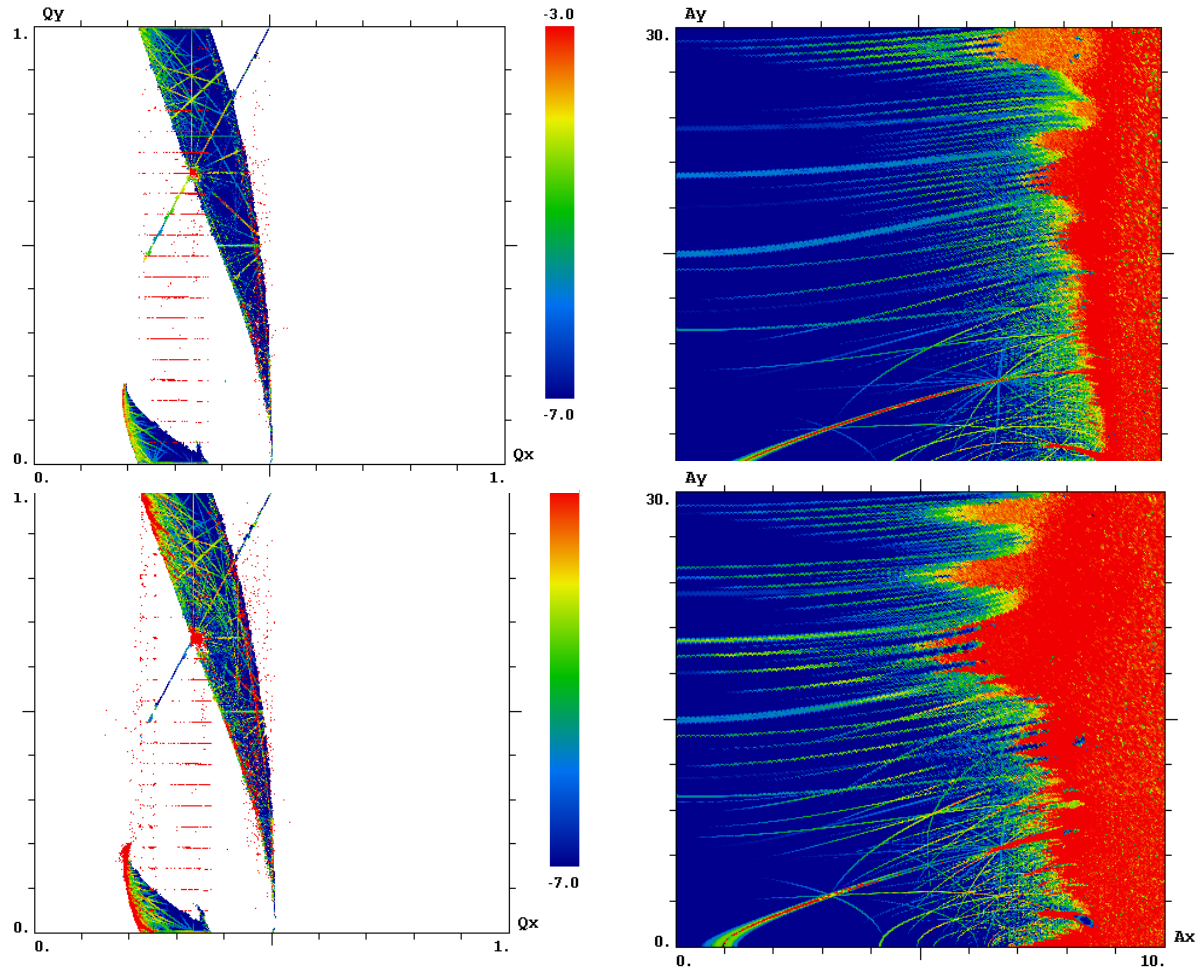
Integer resonance $Q_y = m$

Effects of Imperfect Implementation

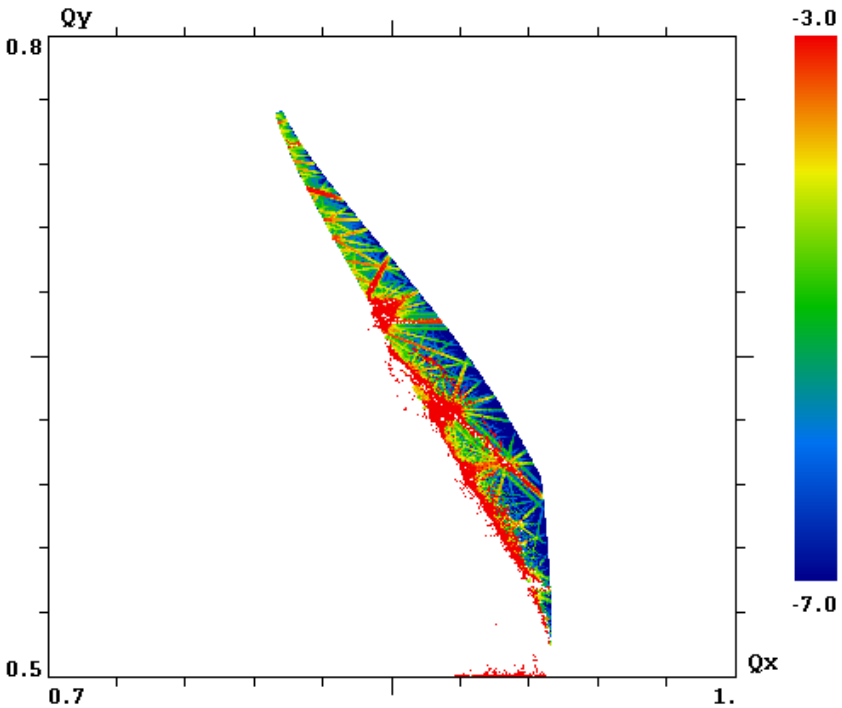
Approximation of continuously varying potential with finite (~20) number of elements

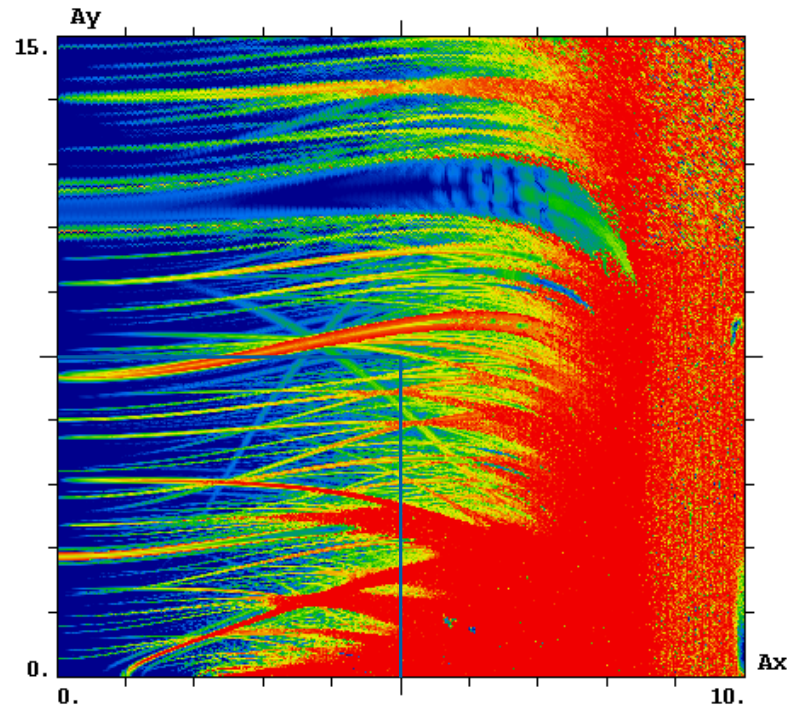
N = 20

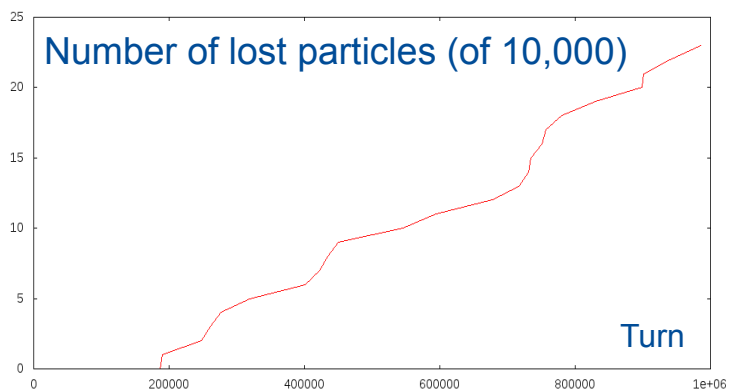
N = 10



Effects of Imperfect Implementation – all errors combined





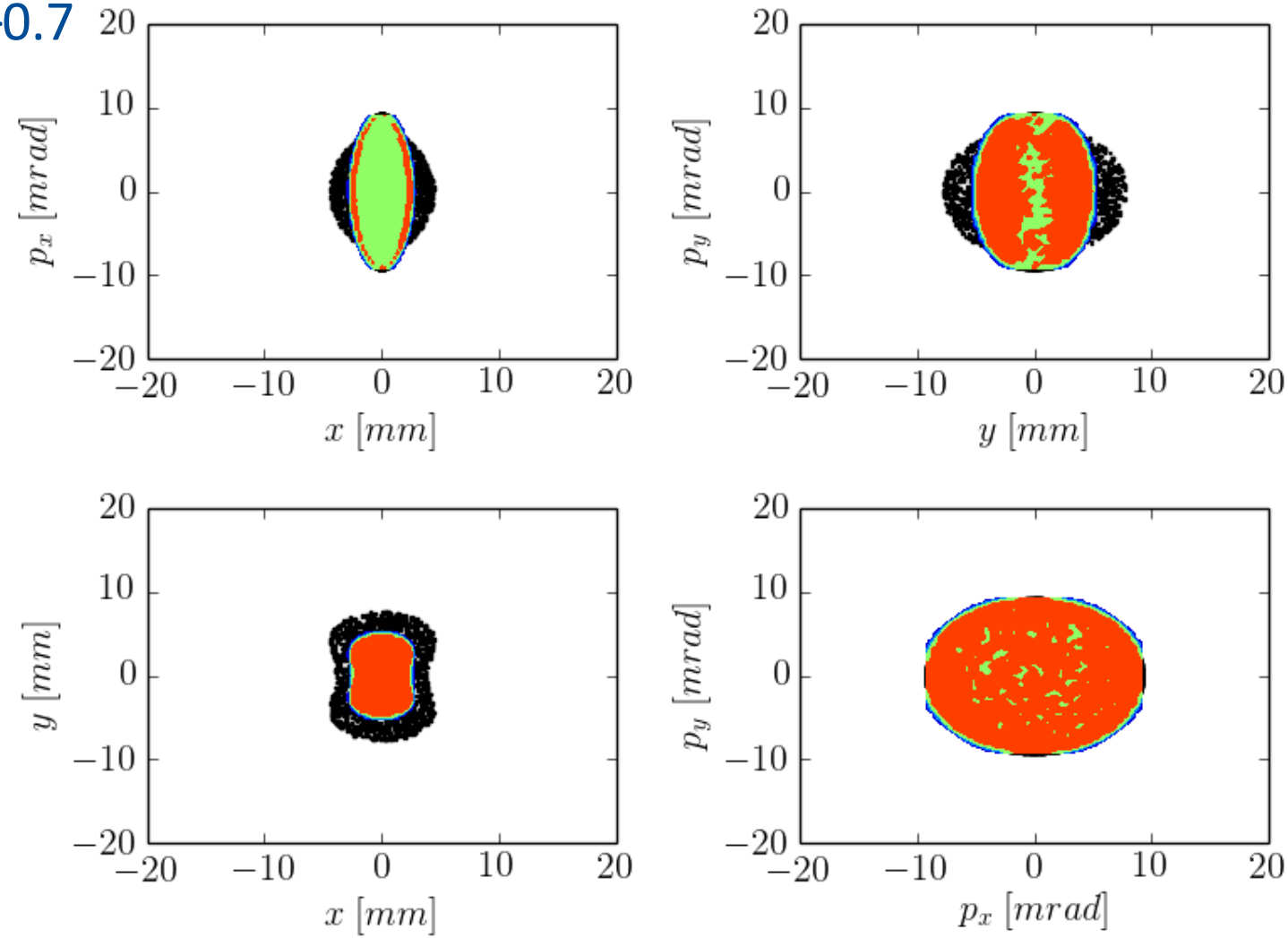


Simulations predict the tune shift / spread of 0.2 to be achievable with one nonlinear lens

Space Charge in NL Integrable Optics

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

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



Tech-X, RadiaSoft simulation

Fermilab's Accelerator R&D Program

- **There is a lack of dedicated ring-based accelerator test facilities** in the US for high intensity research
  - This hampers the training of next generation of accelerator scientists for HEP
  - At present, the only machine to study SC effects is UMER at University of Maryland with very low (10keV) electrons
- We started a **transformational Accelerator R&D program centered at Fermilab's ASTA/IOTA** – Advanced Superconducting Test Accelerator / Integrable Optics Test Accelerator
- ASTA/IOTA will become a unique machine for revolutionary proof-of-principle R&D towards future high intensity machines
  - push performance limits of rings by 3-5 times to enable multi-MW beam power – ΔQ_{SC}>1, lower losses, stable beams
  - become the focal point for collaboration and training

ASTA/IOTA Roadmap

I. **Construct and commission the Integrable Optics Test Accelerator (IOTA)** storage ring and its proton and electron injectors, and establish reliable and time-effective operation of the facility for accelerator research program.

II. **Carry out transformative beam dynamics experiments**

   a. Integrable optics with non-linear magnets and with electron lenses.

   b. Space charge compensation with electron lenses and electron columns.

   c. Optical stochastic cooling demonstration

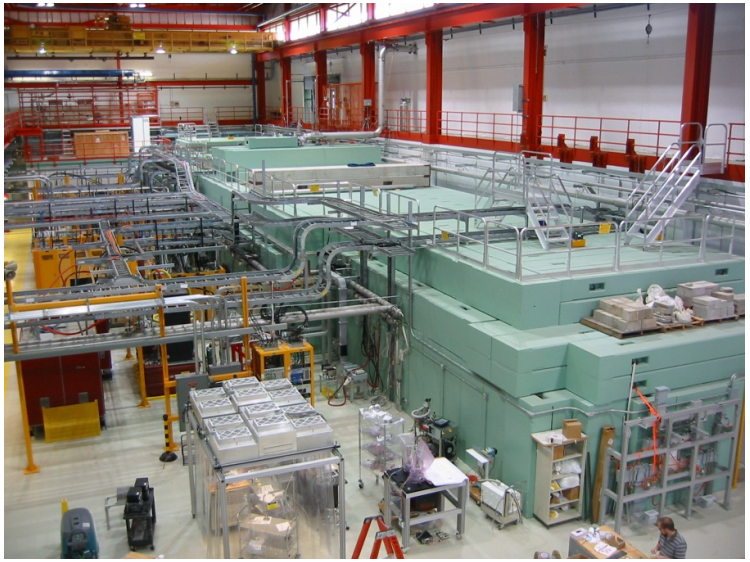
III. **Open new opportunities for training** young researchers

All in collaboration with national and international partners on corresponding modeling, design, and analysis efforts

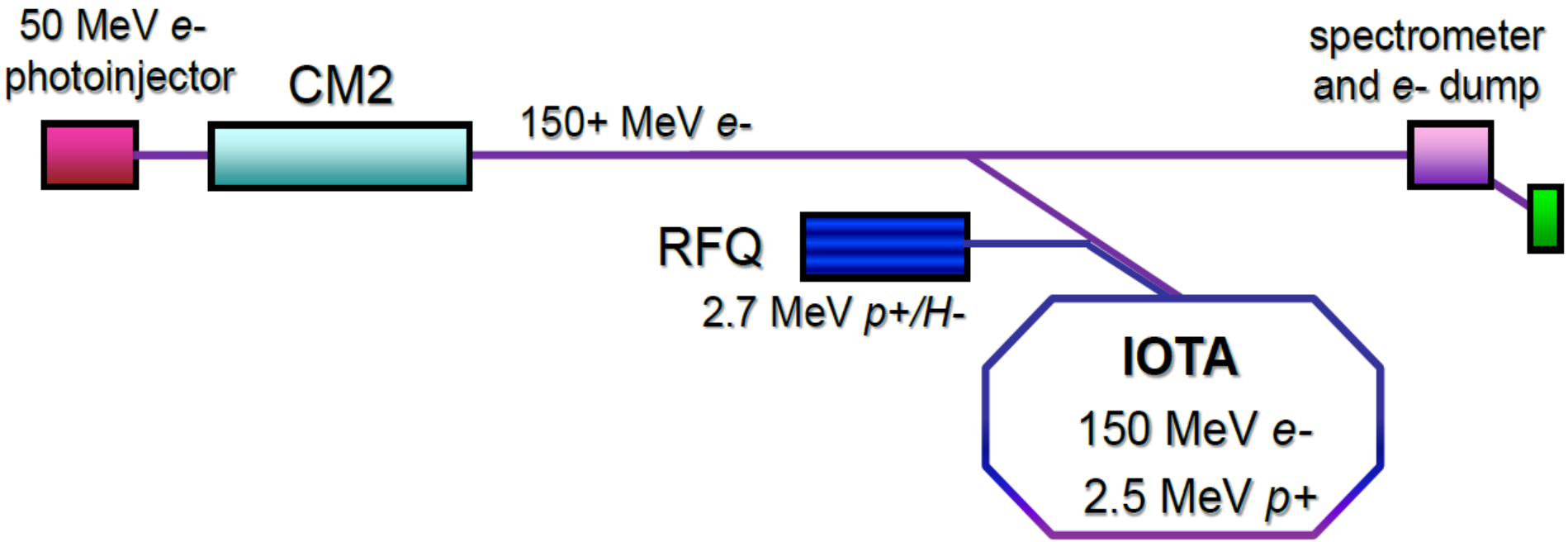
Existing Infrastructure

- **ASTA/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.

ASTA Facility



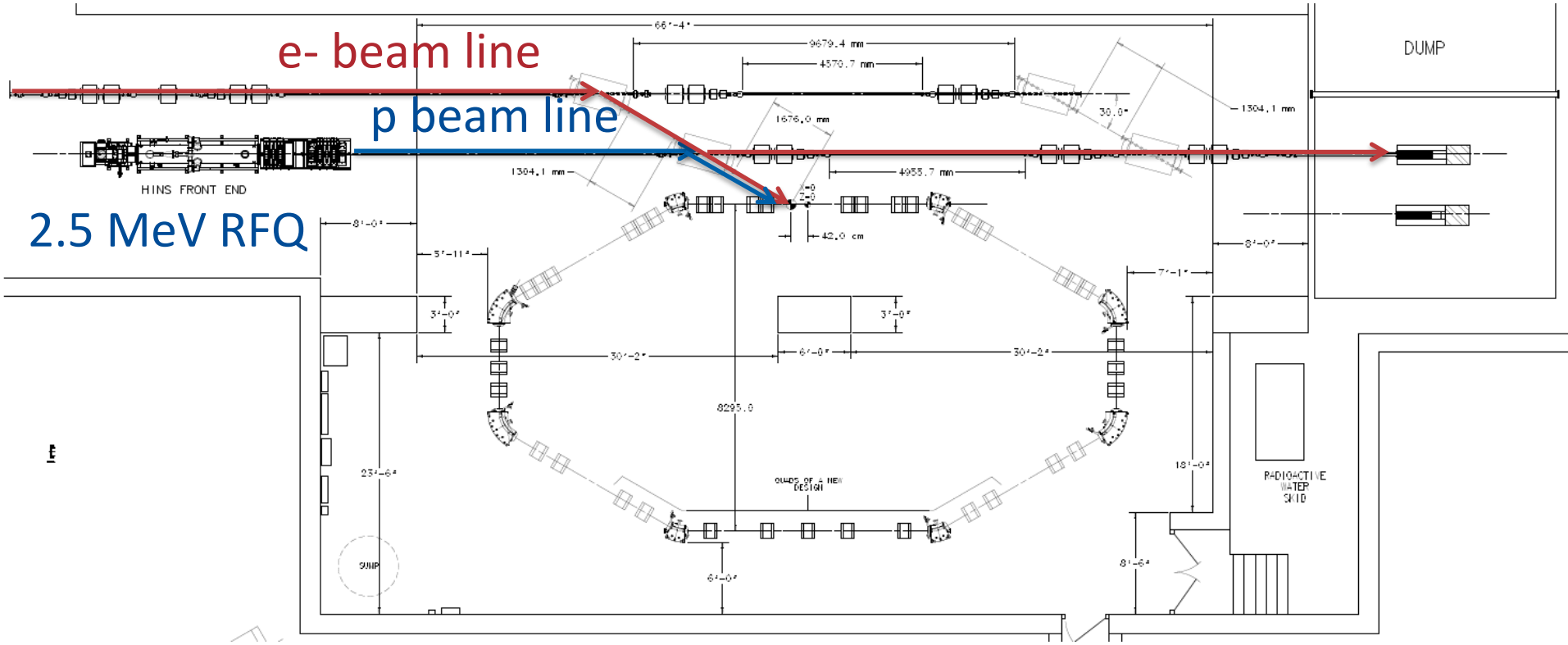
ASTA Schematic



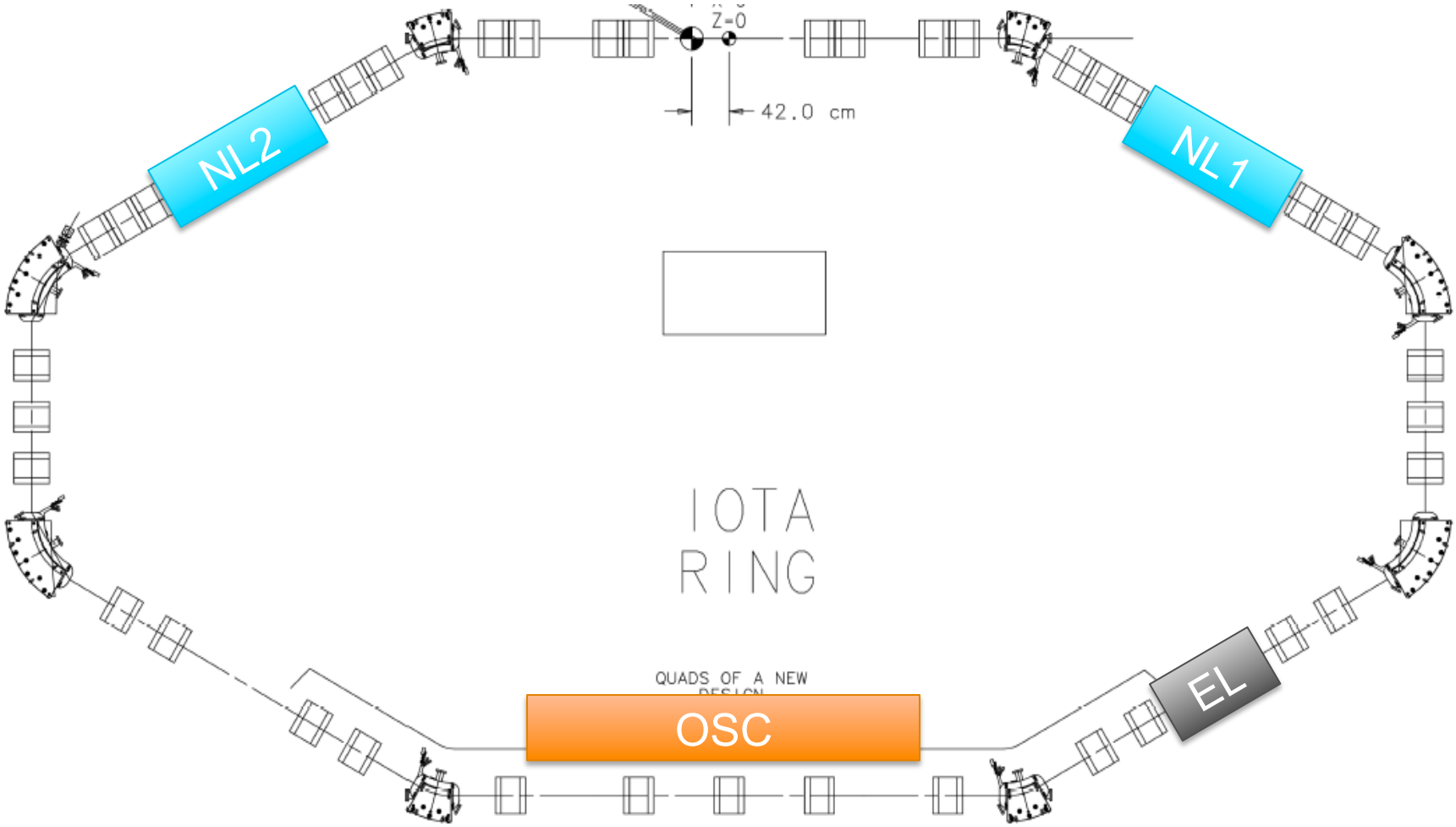
Integrable Optics Test Accelerator

- **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 Ring


e- beam line
p beam line
2.5 MeV RFQ
HINS FRONT END
DUMP
RADIOACTIVE WATER SKID
SUMP

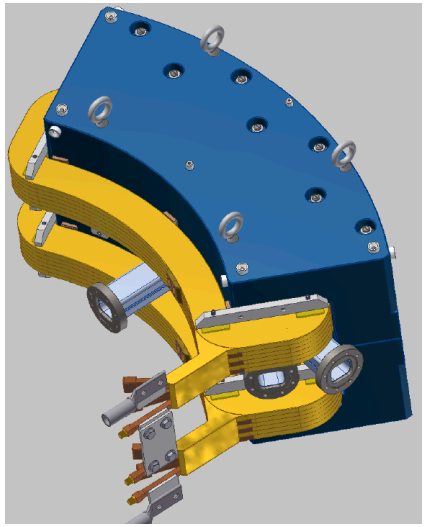
IOTA Layout

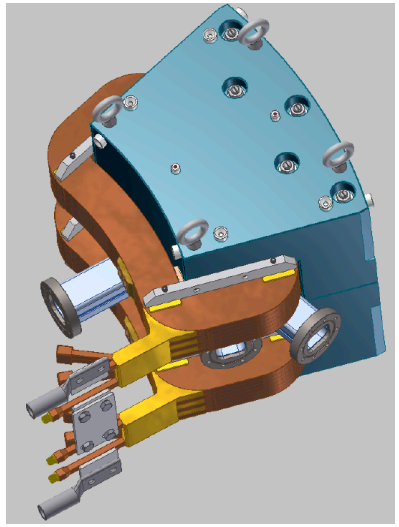


IOTA Parameters

Nominal kinetic energy	e^-: 150 MeV, p+: 2.5 MeV
Nominal intensity	e^-: 1×10^9, p+: 1×10^{11}
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.	e^-: 0.1 μm, p+: 2μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,q	e^-: 1 kV, 30 MHz, 4
Synchrotron tune	e^-: 0.002 ÷ 0.005
Bunch length, momentum spread	e^-: 2 cm, 1.4×10^{-4}

Ring Elements in Hand

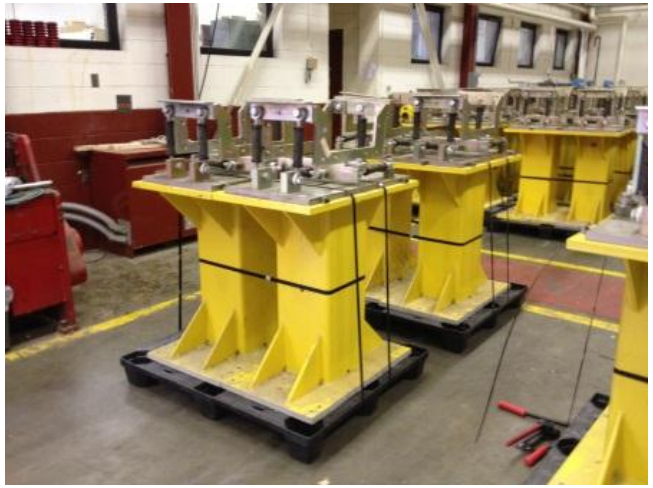




Dipole magnets (ordered)

32 quads from **JINR (Dubna)** received

Vacuum chambers
for dipoles (received)



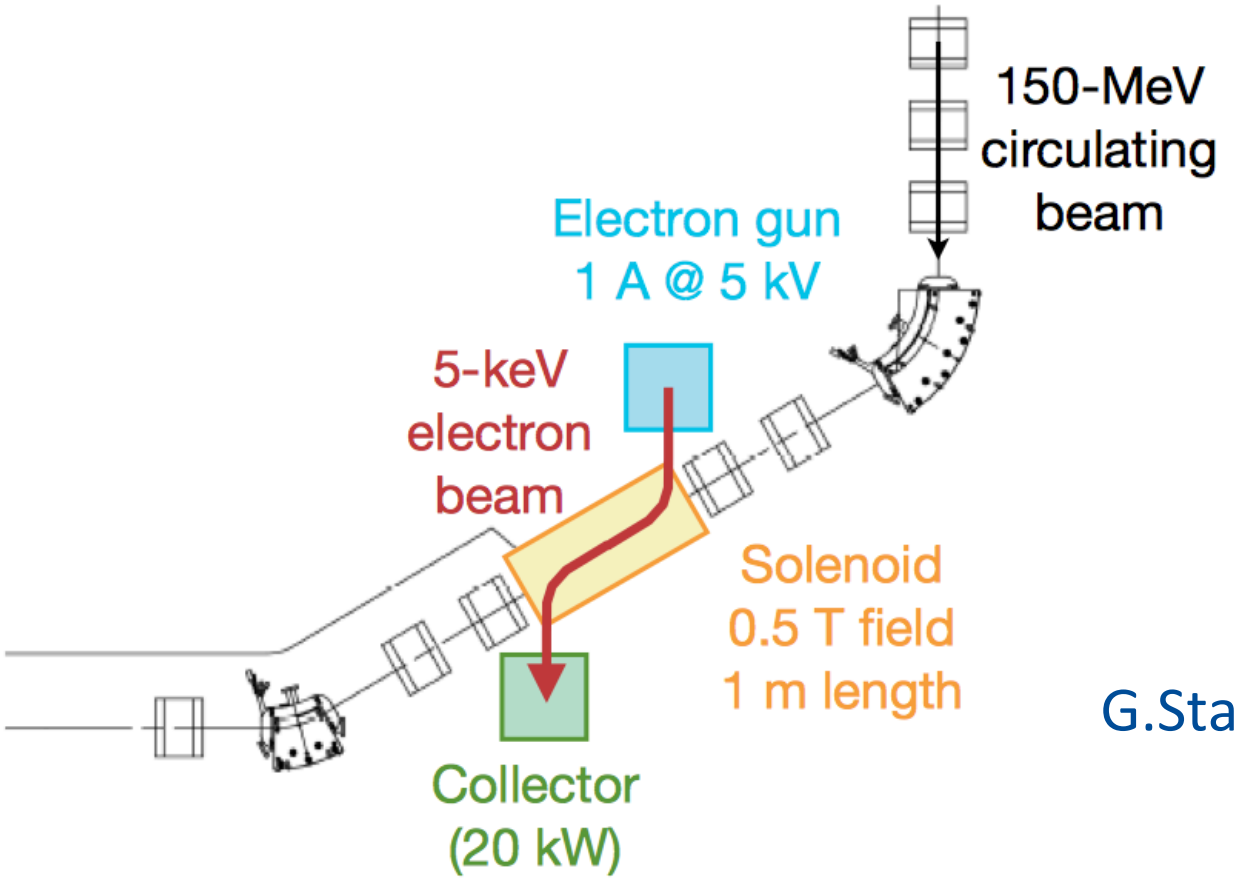
Magnet support stands
from **MIT** (received)

Also:

BPM bodies and electronics
Vacuum system
Dipole power supply
Corrector power supplies

IOTA Electron Lens

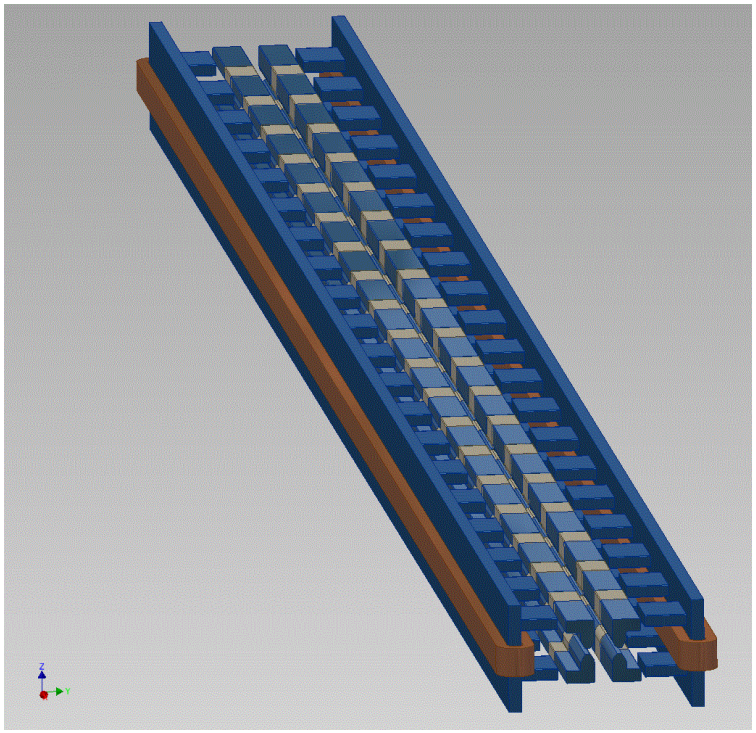
- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components



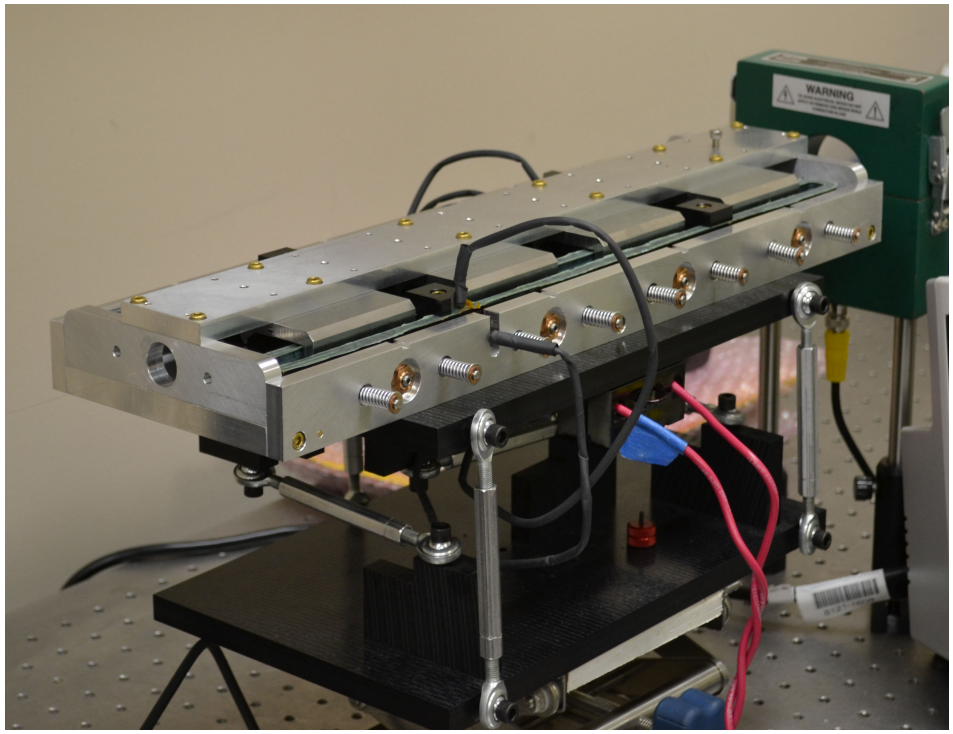
G.Stancari

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 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

IOTA Staging – Phase II

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

ΔQ_{SC} =0.6 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

Roadmap to High-Intensity Rings

- Theory and modeling to develop basis for high intensity circular machines
- Proof-of-principle experiments at ASTA/IOTA
- Ultimately, **develop a recipe for a new generation rapid cycling synchrotron for super-high beam intensity (× 3-5 present)**
  - Self-consistent or compensated space-charge
  - Strong non-linearity (for Landau damping) to suppress instabilities
  - Stable particle motion at large amplitudes

Collaboration

participants of the 2nd ASTA Collaboration Meeting, June 2014

Collaboration

- A lot of interest to participate in ASTA/IOTA from the accelerator community
  - 2 annual Collaboration Meetings, ~60 participants
- Significant intellectual and in-kind contributions, expressions of interest
  - **NIU, UMD, RadiaSoft, CERN, ORNL, BINP, U.Chicago** – 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

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

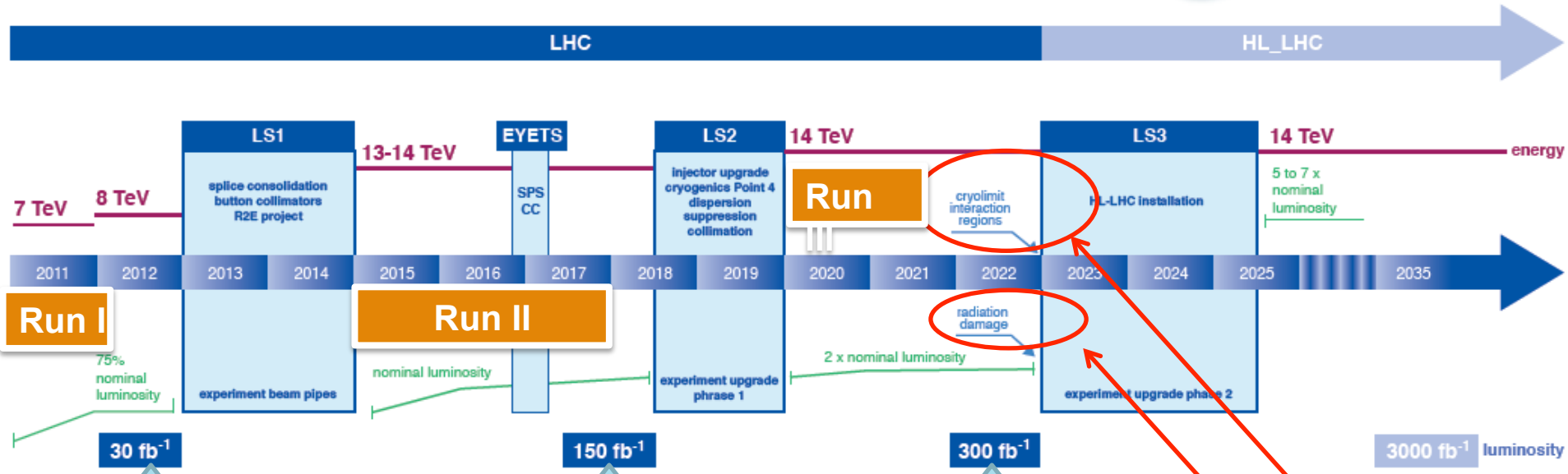
Training

- Excellent connection to the university community through the Joint Fermilab/University PhD program
  - Already 9 graduate students doing thesis research at ASTA/IOTA
    - 7 NIU
    - 1 U.Chicago
    - 1 IIT
  - 2 more to join soon
  - (see S. Cousineau's talk)
- Partnership with university groups
  - Univ. of Maryland – NSF grant for IOTA-related work

Summary

- Despite 50 years long history, beam dynamics in accelerators is still a lively field with many open questions requiring innovative solutions
- The physics of beams has synergies with other branches – mechanics, plasma, etc.
- Fermilab's ASTA/IOTA offers a **unique scientific program** aiming at breakthrough research to allow for x**3-5 increase of beam intensity in future proton rings**
- ASTA/IOTA experiments are a great opportunity to explore something **truly novel with circular accelerators**
- ASTA/IOTA will be a strong **driver of national and international collaboration and training**

LHC / HL-LHC Plan



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.7 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~45

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

50 ⇒ 25 ns

Lumi saturation
&
Technical
bottlenecks:

Plan approved by CERN management upon preparation in HL-LHC Coord Group and RLIUP
See deliverable D1.7 Common LHC time plan