New High-efficiency Slow Extraction Concepts

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Introduction

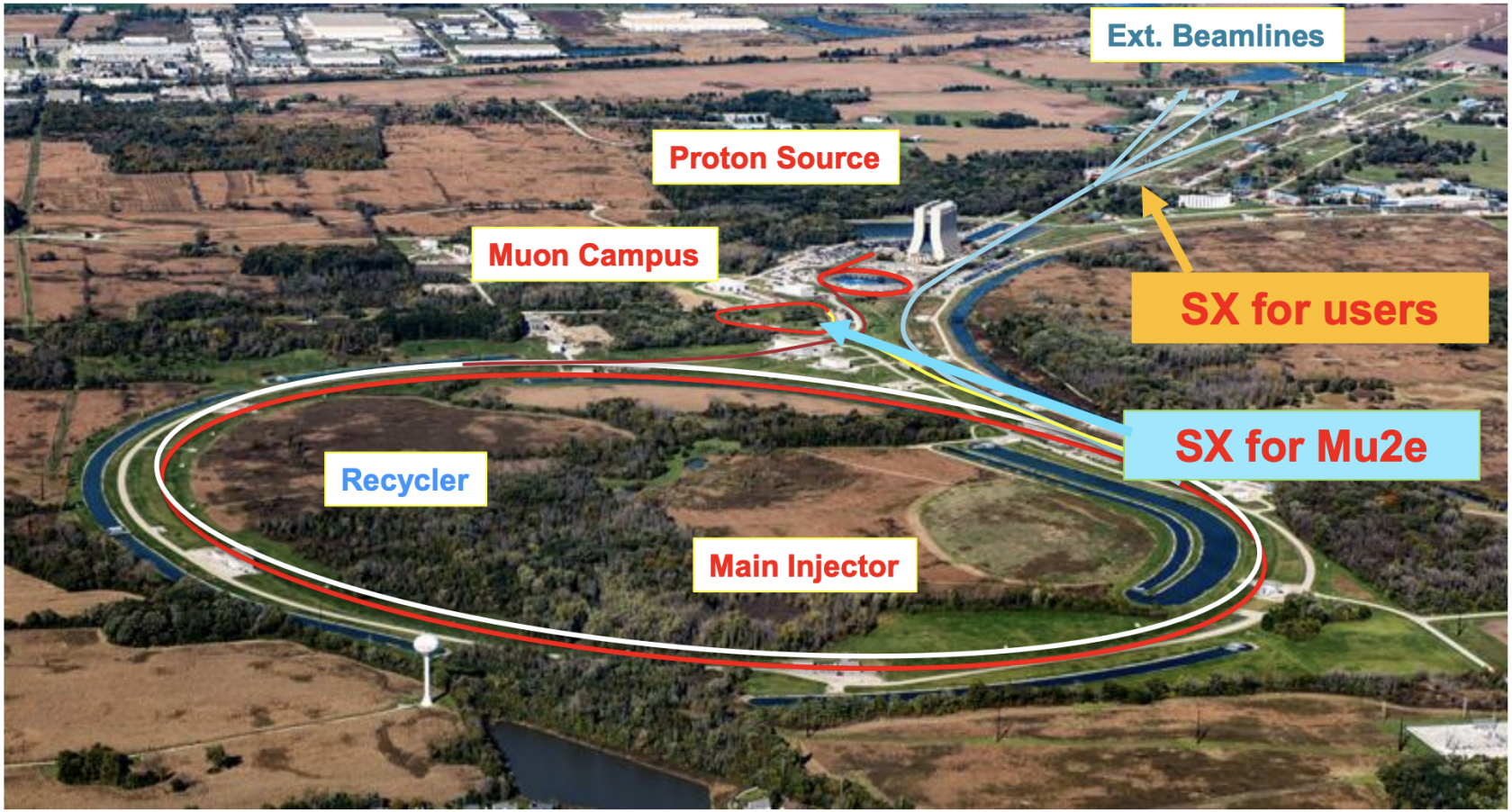
The slow resonant extraction of a beam in a storage ring is a very well-established technique used by several high-energy physics accelerator facilities around the world. At the same time, the demand for beam power is constantly growing, extraction efficiency in many cases is becoming a limiting factor. A low beam loss (high extraction efficiency) operation is required to reduce the machine damage and radiation exposure during hands-on maintenance.

Existing facilities

Slow extraction facilities for HEP

Lab	Facility	Particles/spill	Spill duration (sec)	Efficiency	Notes
CERN	SPS	4e13	4.0	97%	Highest energy 450GeV
J-PARC	Main Ring	4.8e13	2.1	99.5%	Highest efficiency
FNAL	Main Injector Mu2e (design)	1e13 1e12	4 0.043	96% 98.5%	- Shortest spill
IHEP	U70	(2-10)e12	1.35	90-94%	
GSI	SIS18	1.4e6	1.55		Ions
BNL	AGS (stopped)	7.6e13	2.4	98%	SX discontinued

Fermilab


Ext. Beamlines
Proton Source
Muon Campus
SX for users
SX for Mu2e
Recycler
Main Injector

State of art in slow extraction

JPARC

- Large apperture (e.g. FNAL ring is desing for antiprotons which is smaller)
- $\approx$ 50m beta function vs. $\approx$ 15m at FNAL
- Bigger budget
- Ti septum
- 0.5% losses vs 1.5% FNAL

Milestone: beat the efficiency record

Shadowing

- Crystal channeling
  [demonstrated at SPS — would this be effective at 8-30 GeV]
- Diffusers
  [was not effective at SPS, should be more effective at J-PARC, FNAL]

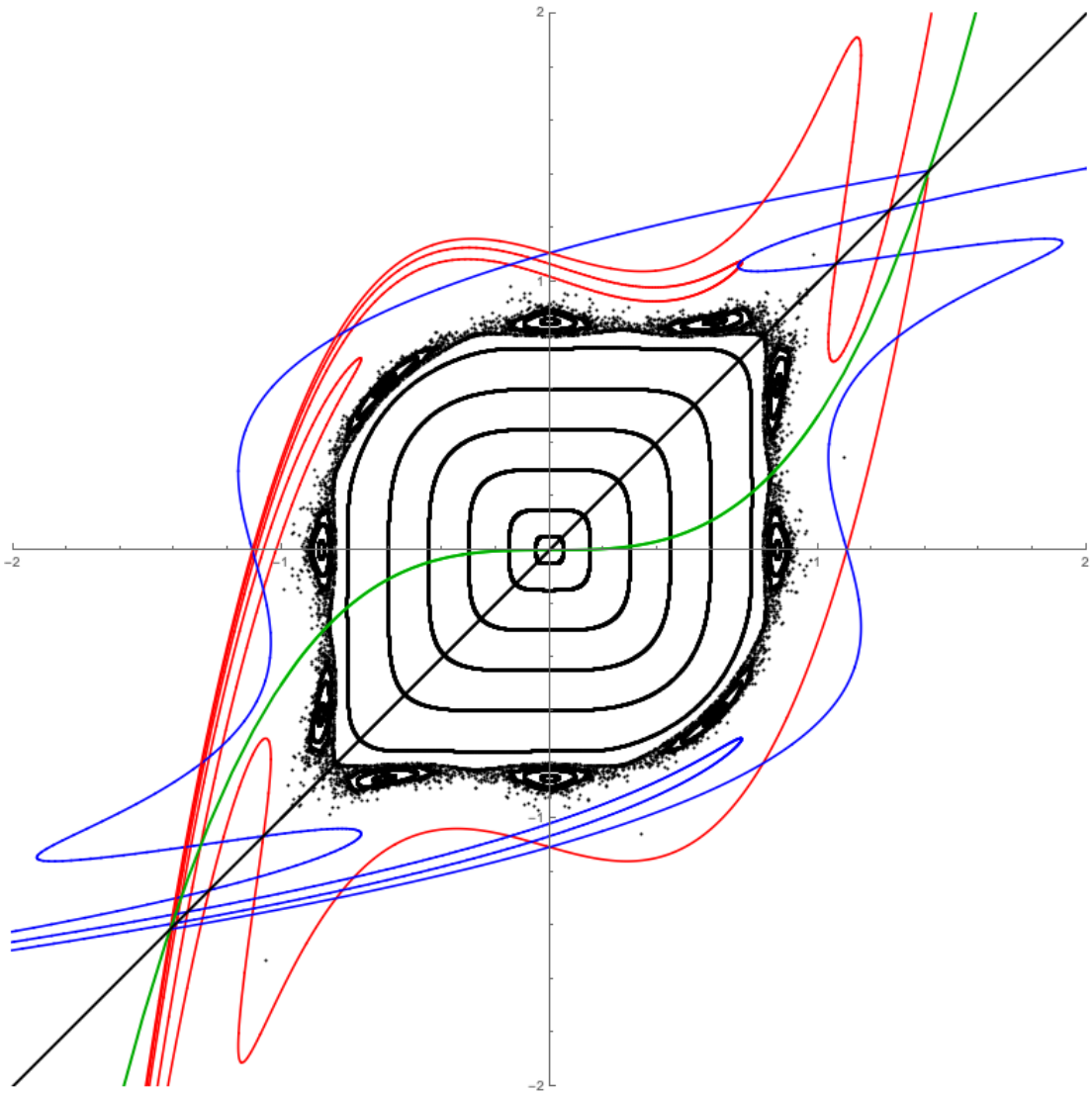
Using novel low-Z materials

- Using Carbon Nano-Tubes (CNT) wire as septum

Phase space manipulation

- Higher multipoles
  [demonstrated at SPS]

Phase space manipulation

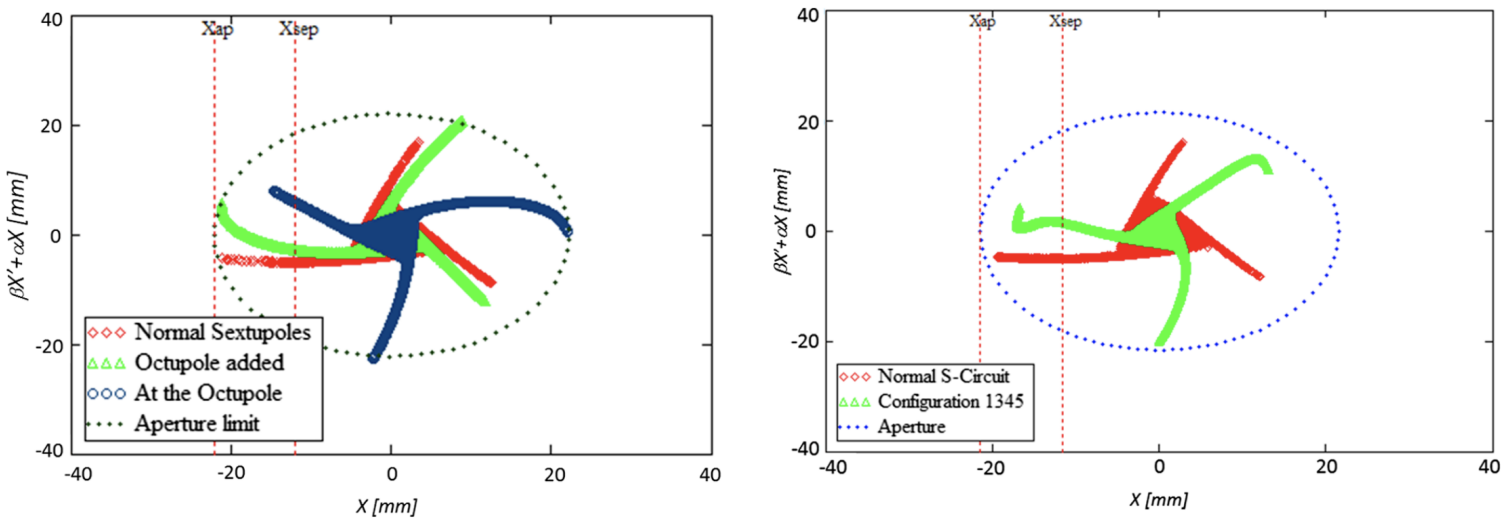


Phase space manipulation

Some questions

- Demonstrated at SPS, but do we fully understand why?
- Unstable flow bend vs wiggle?
- Can we use higher multipoles? Will the effect be mitigated by physical aperture?
- How the wiggle of separatrix changes our "naive" idea that losses are proportional to the ration of septum width to the one step on separatrix?
- Can we use higher order resonances (4-th, 5-th, etc.)?
- Can we use the concept of integrable optics?

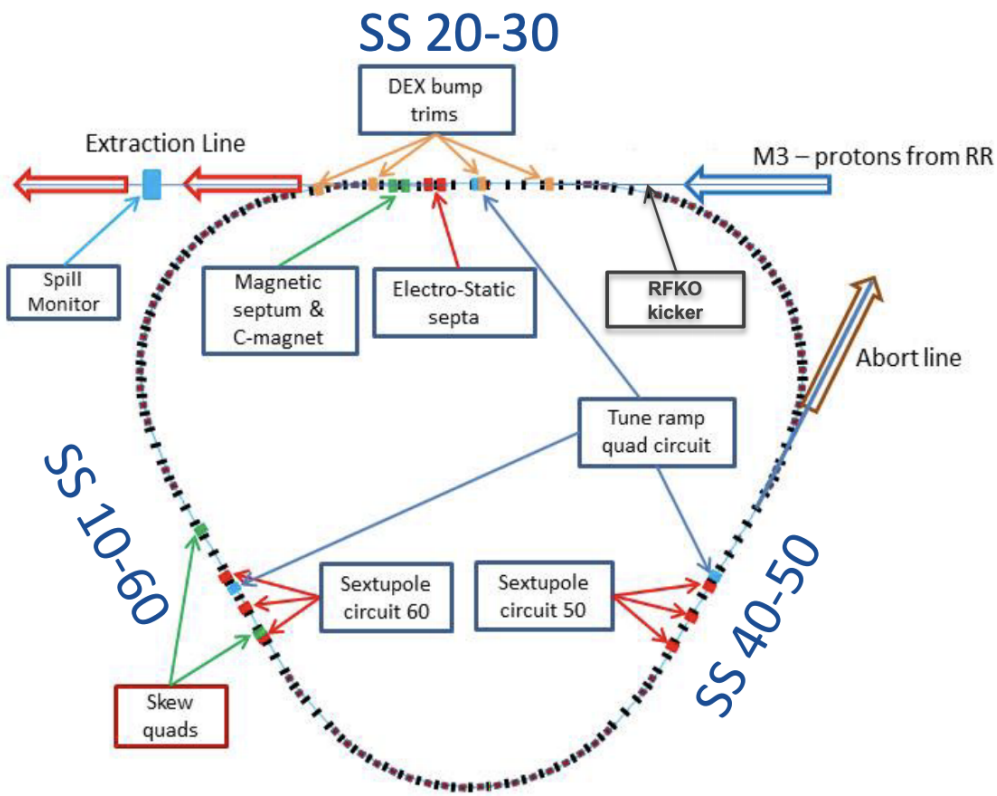
Unstable flow bend vs wiggle



[V. Nagaslaev PhysRevAccelBeams.22.043501]

Implementation of Resonant Extraction in the Delivery Ring for Mu2e

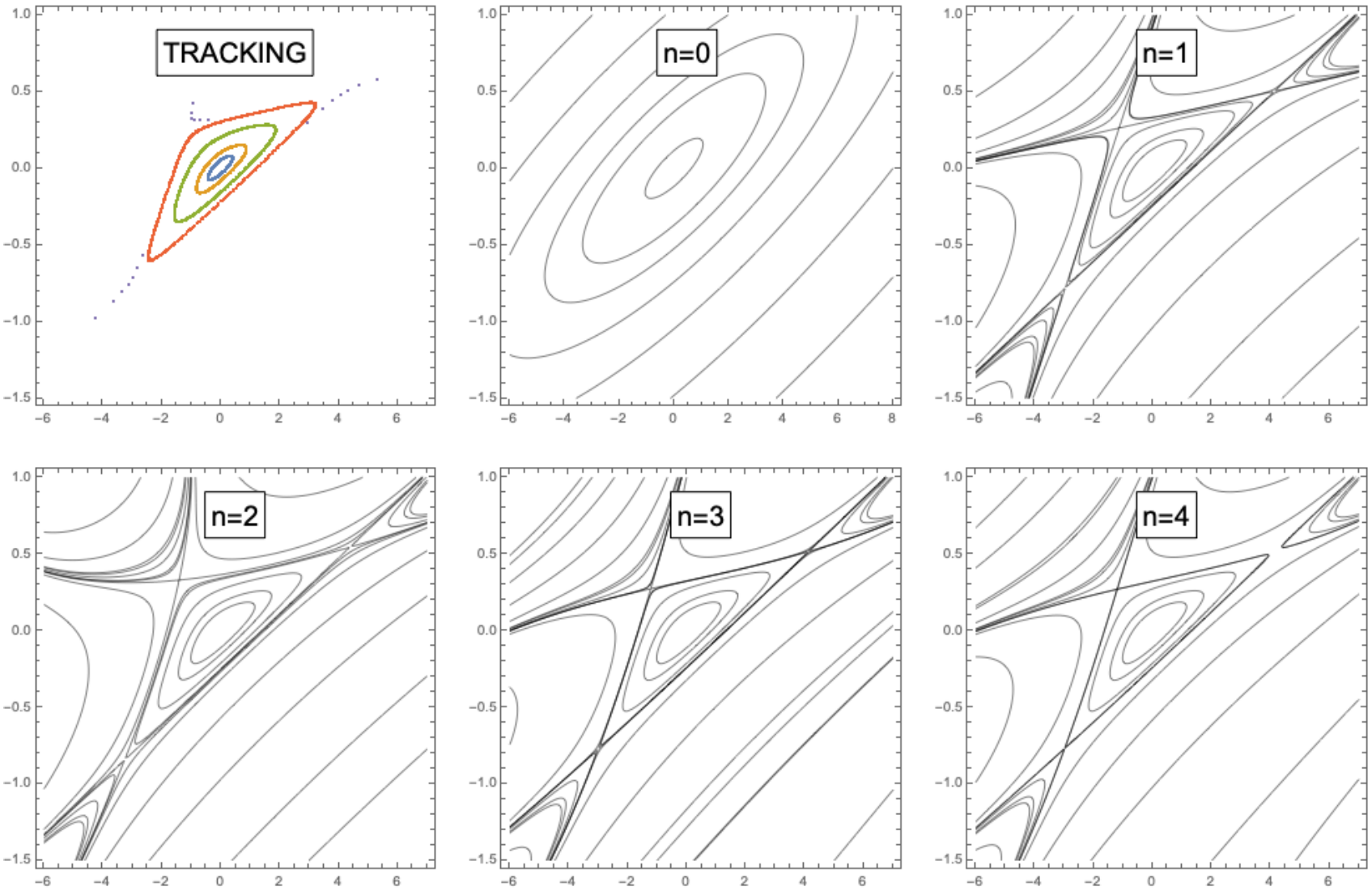
- New injection point
- Extraction in SS 20-30
- Electro-static septa
- 2 families of harmonic Sextupoles
- A family of tune Quadrupoles
- Extraction Lambertson
- Dynamic orbit control
- Abort line
- RFKO system
- Spill monitoring
- Spill regulation



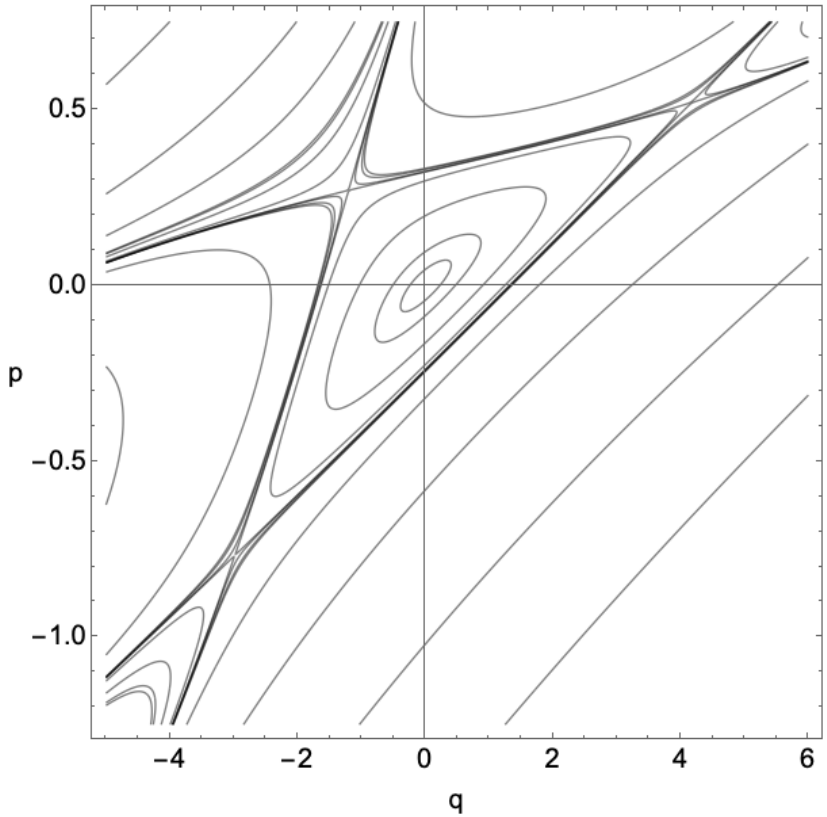
- Horizontal 3rd Integer resonance
- Q_x / Q_y=9.650 / 9.735

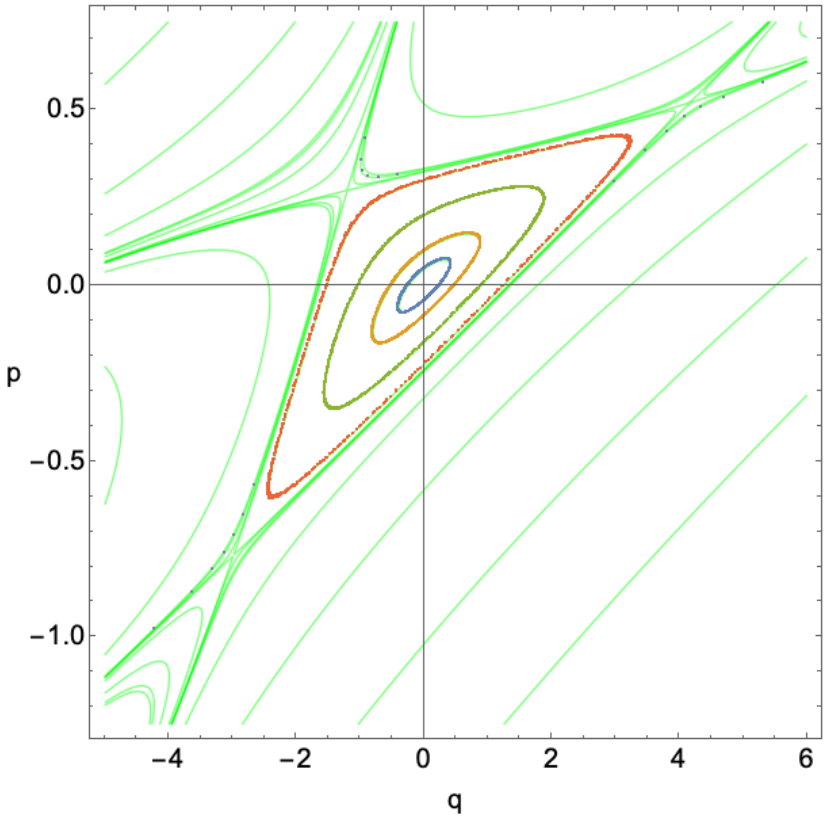
Vladimir Nagaslaev

0-th — 4-th order approximated invariants, $\mathcal{K}^{(n)}(p, q)$

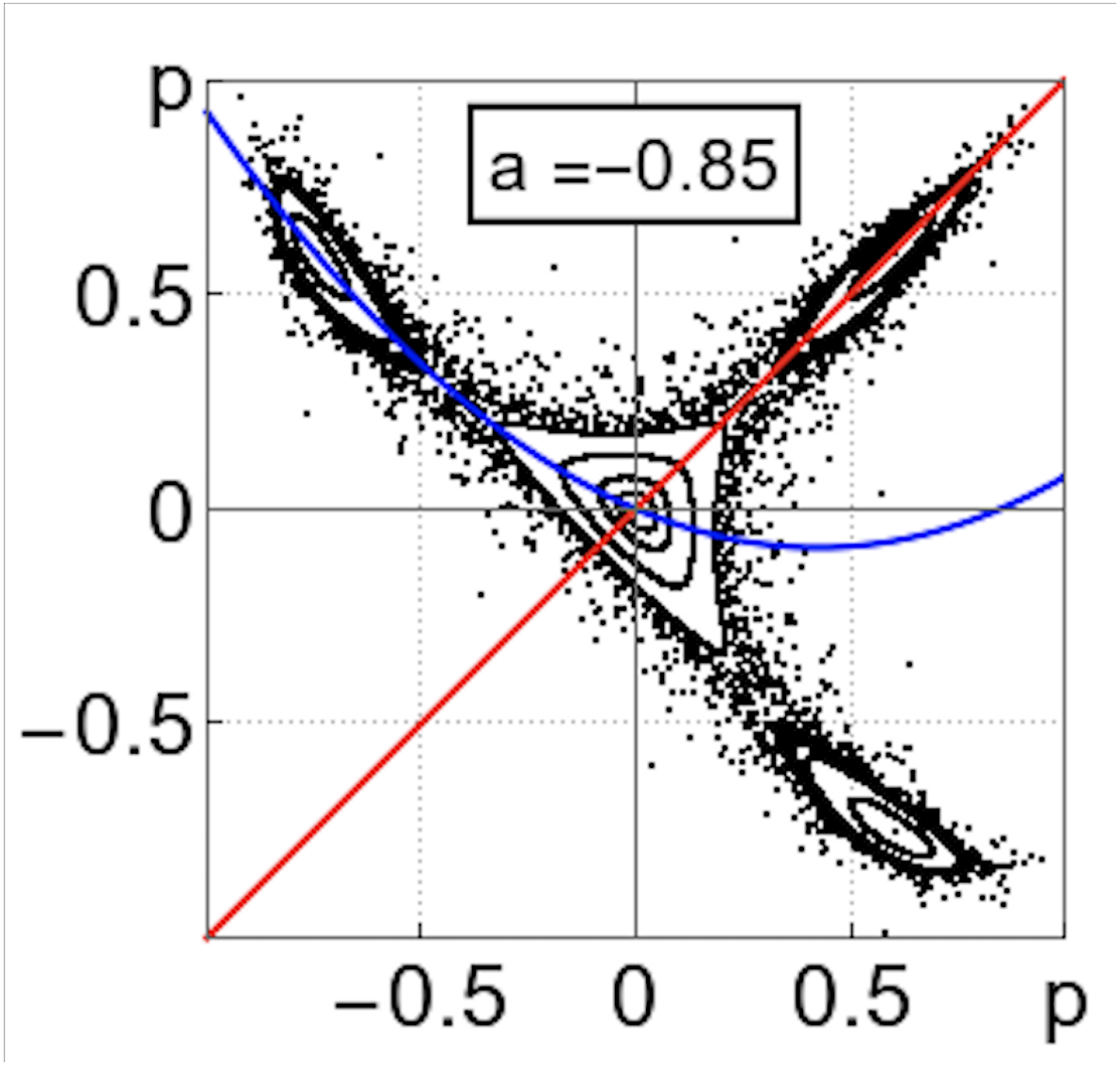


4-th order vs. tracking



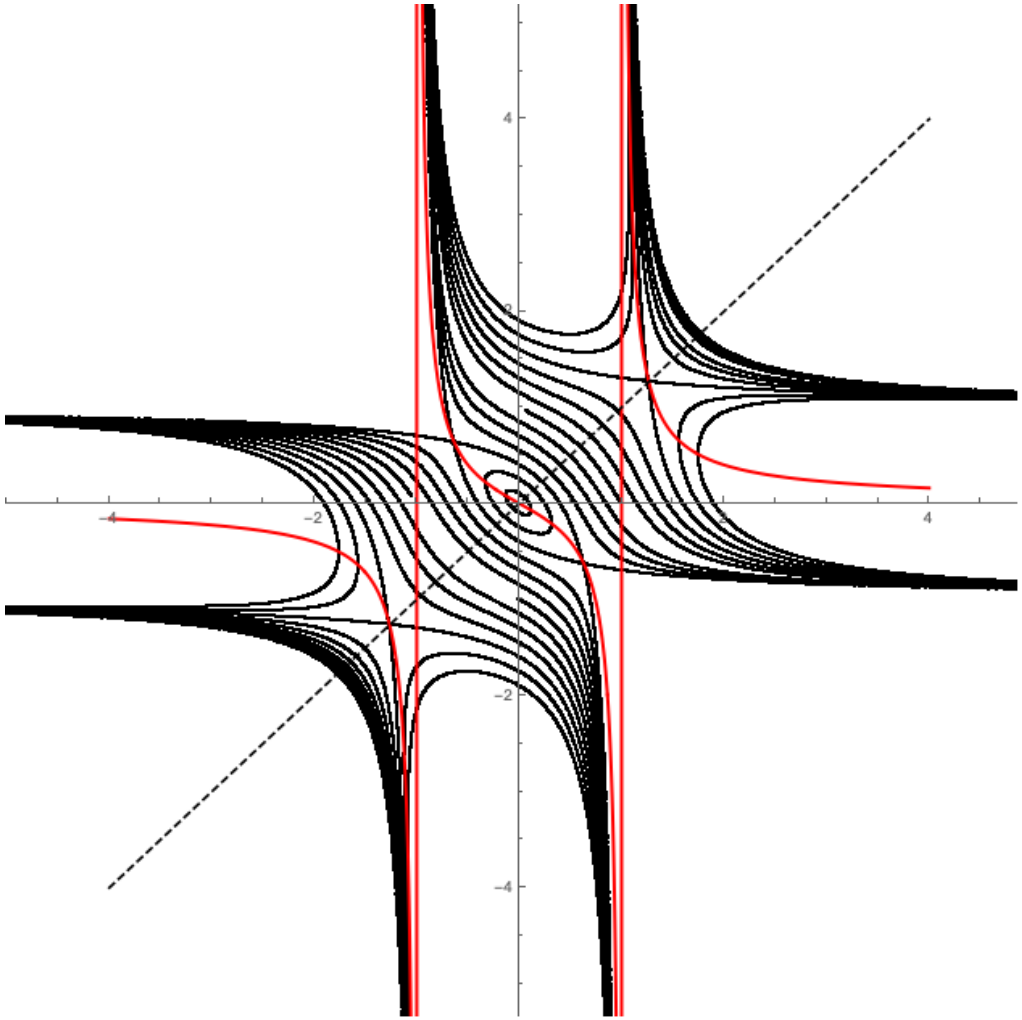


Can we use the concept of integrable optics?



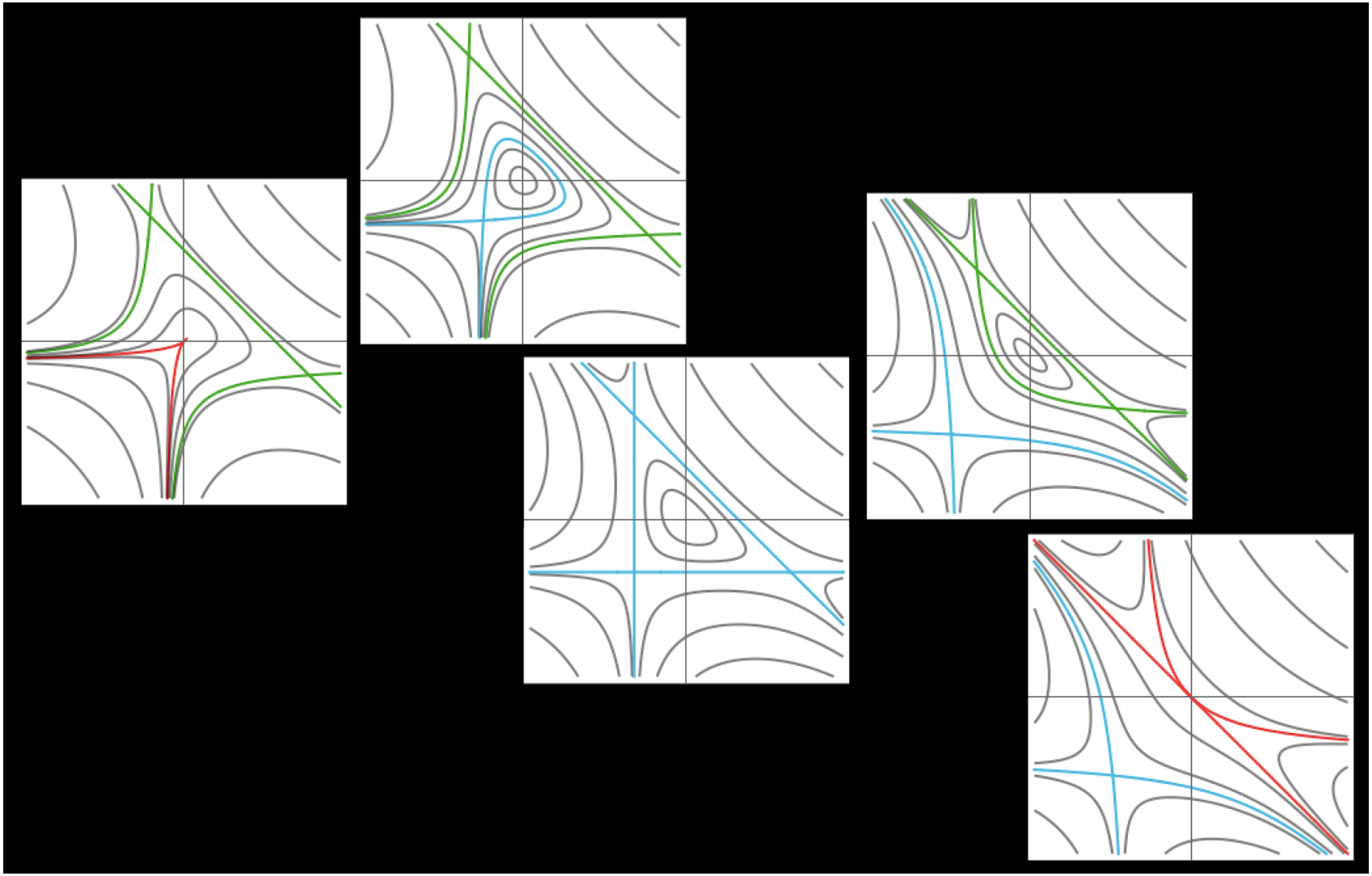
Example 1: Octupole McMillan map, $f(q) = -\frac{2\,\epsilon\,q}{q^2+\Gamma}$

$$\mathcal{K}(q,p) = p^2\,q^2 + \Gamma\,(p^2+q^2) + 2\,\epsilon\,p\,q$$



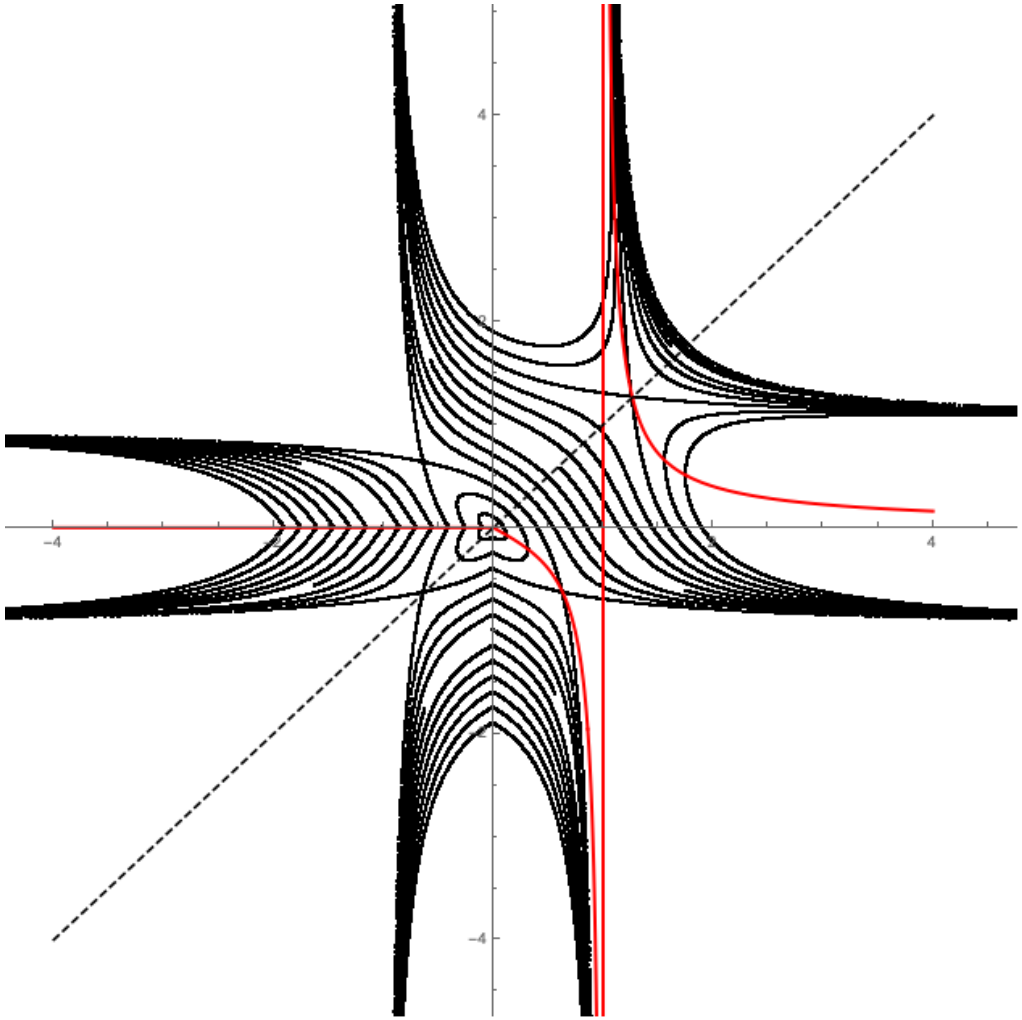
Example 2: Sextupole McMillan map, $f(q) = -\frac{q\,(q+2\,\epsilon)}{q+\Gamma}$

$$\mathcal{K}(q,p) = p^2\,q + p\,q^2 + \Gamma\,(p^2+q^2) + 2\,\epsilon\,p\,q$$



Example 3: Picewise McMillan map, $f(q > 0) = -\frac{2\,\epsilon\,q}{q^2+\Gamma}$

$$\mathcal{K}(q,p) = p^2\,q^2 + \Gamma\,(p^2+q^2) \pm 2\,\epsilon\,p\,q$$



Summary

Road map for slow extraction

- New low-Z materials, crystal channeling, diffusers
- Better understanding of chaotic unstable flow
- Better understanding of potential of integrable latices
- Development of analytical tools for dynamics analysis

Many thanks to V. Nagaslaev and S. Nagaitsev.