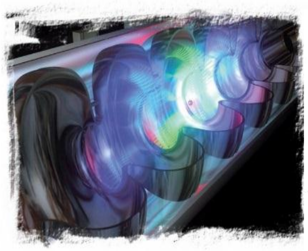
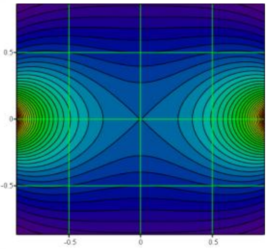
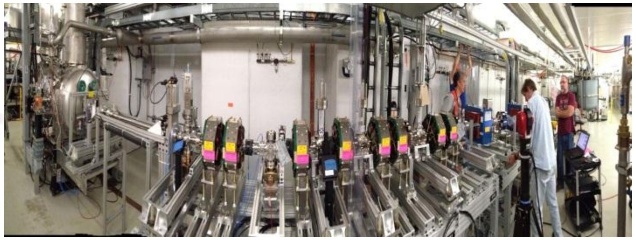
Accelerator Science Program in the FAST/IOTA Complex at Fermilab

Prof. Swapan Chattopadhyay

Joint Seminar
John Adams Institute and Particle Physics
Dennis Sciama Lecture Theatre
University of Oxford
June 2, 2016

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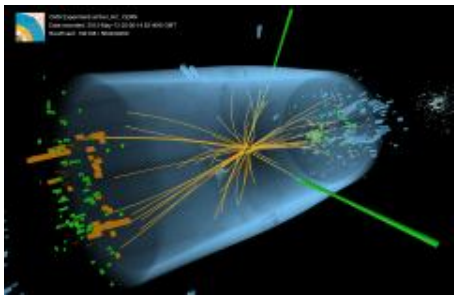
OUTLINE

- **Prologue**
- **Accelerator Science Motivation:**
  Neutrino science and DUNE experiment: Deep Underground Neutrino Experiment at Sanford Lab, South Dakota (~2026-2035)
- **Fermilab accelerators in support of neutrinos: PIP, PIP-II, Post-PIP-II**
- **Accelerator Science R&D for High Intensity Neutrinos and Fundamental Nonlinear Dynamics**
- **FAST/IOTA: A test-bed for high intensity accelerators and beyond**
- **Rudiments of an initial Accelerator Science Program in FAST/IOTA**
- **Partners and Collaborations**
- **Outlook**

SCALES of FUTURE POSSIBILITIES IN PARTICLE PHYSICS: *Time, Effort, Cost*

LHC HIGGS?



v Programme **I**
(~ $1B)

Muons **I**
(< $ 1 B)

Even Larger Circular Colliders (FCC) **E (I)**
100 TeV pp / 400 GeV e+e-
(~$ 10 B - 40 B)
→ Other Colliders?

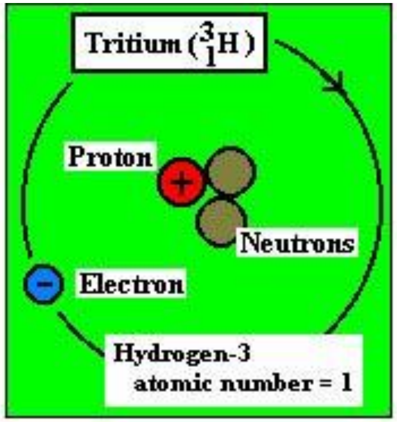
Brighter LHC (<$1B) **I, E**

2010 2020 2030 2040 2050

Linear e+e- Collider **E (I)**
Options Higgs factory”
(~400 GeV)
(~ $10 B - $30 B)

******I will focus on the Neutrino Program******

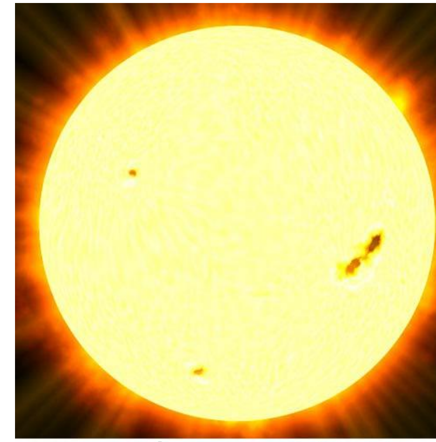
Ubiquitous Neutrinos



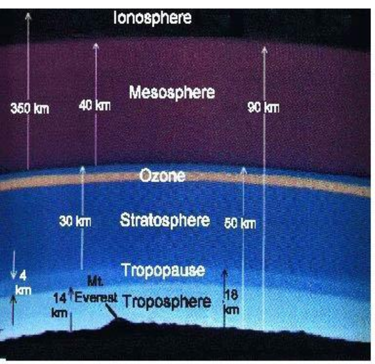
From radioactivity ~ MeV

From reactors - ~MeV

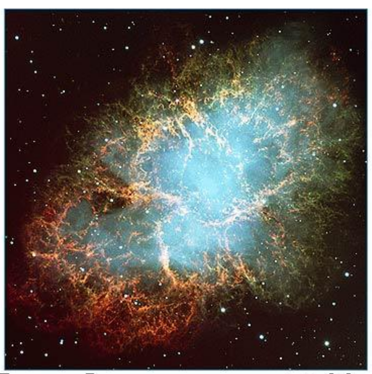
From accelerator - ~GeV



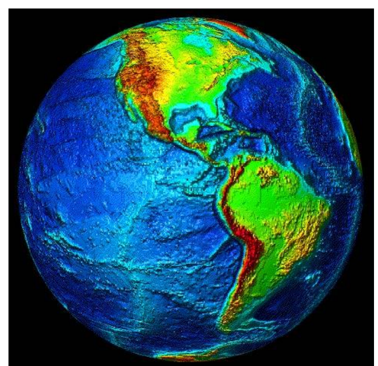
From the sun ~ MeV



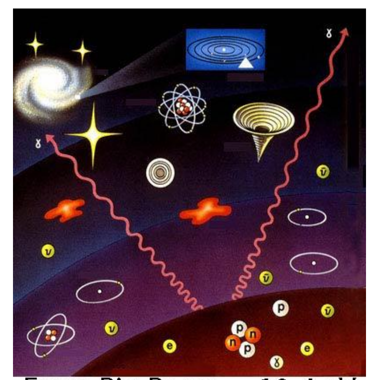
From atmosphere ~GeV



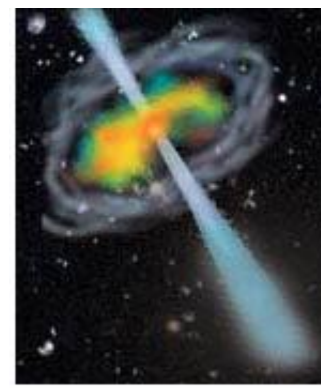
From Supernova ~ 10 MeV



From the earth ~ MeV



From Big Bang - ~10-4 eV



Extragalactic - ~TeV

Don’t miss!!!

The intriguing story of Neutrinos and Bruno Pontecervo

told by

Prof. Frank Close

right after my seminar in the same lecture hall!!!

Understanding Neutrinos: Fermilab Plans

Multi-MW proton beams from superconducting accelerator complex at Fermilab will impinge on targets producing unstable particles which will decay into intense and precise neutrino beams via magnetic horn techniques, directed towards an underground detector 1400 kms away in Sanford laboratory, within an abandoned mine in South Dakota, USA for short- and long-baseline neutrino experiments.

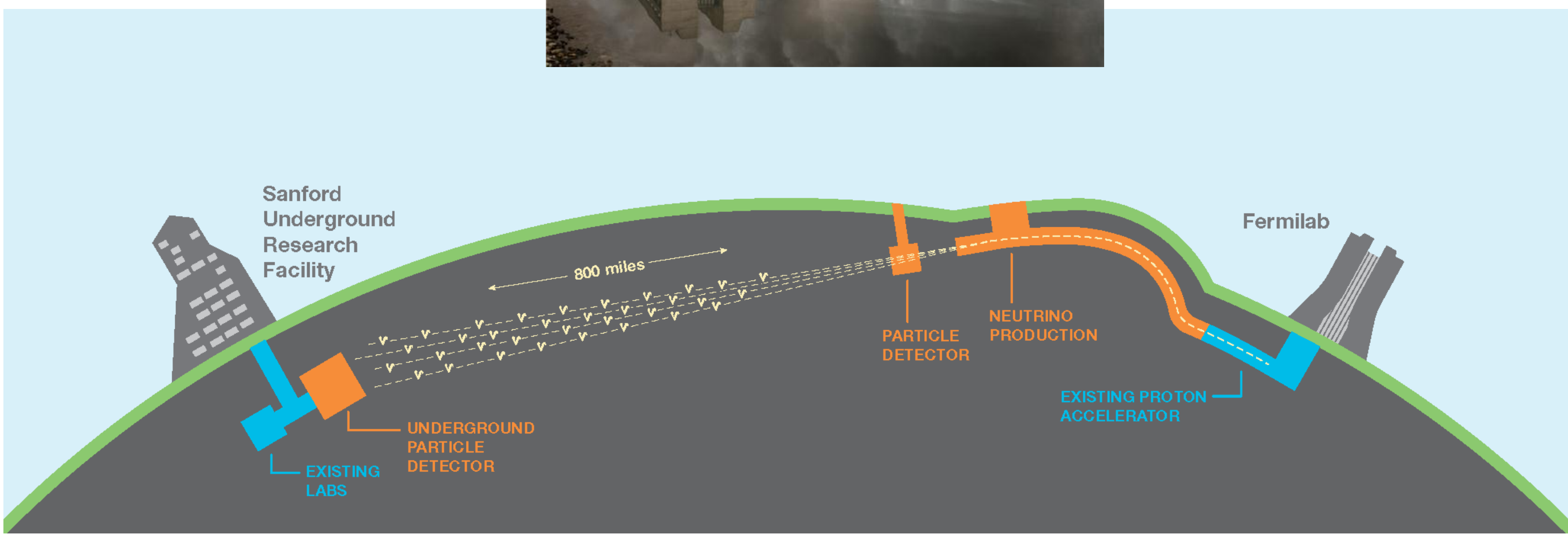
Figure-of-merit: (Mass of detector)x (Beam Power) x (Duration)

Goal for the first 10 years: 100 kT-MW-year to be achieved by 10 kT target, >1 MW beam from a superconducting linear accelerators observed over 10 years. This is the PIP-II scenario.

The Deep Underground Neutrino Experiment (DUNE) will be an international collaboration and unique in its scientific reach. Spokespersons: Andre Rubbia (ETH Zurich) and Mark Thomson (Univ. of Cambridge, UK)

Mid-term strategy for > 2 MW beam power after PIP-II depends on various choices.

LBNF-DUNE @ Fermilab

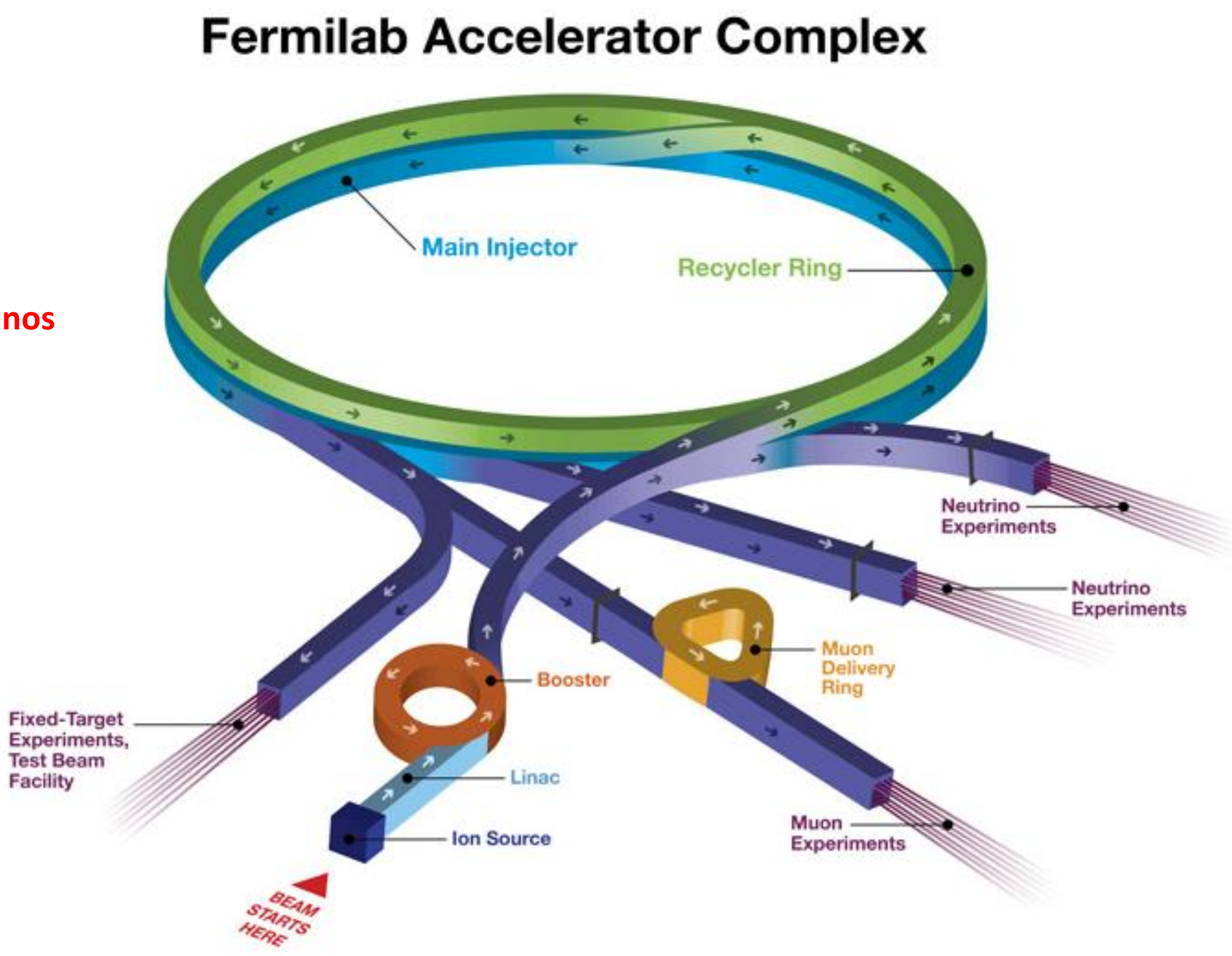


Evolution of Fermilab Campus

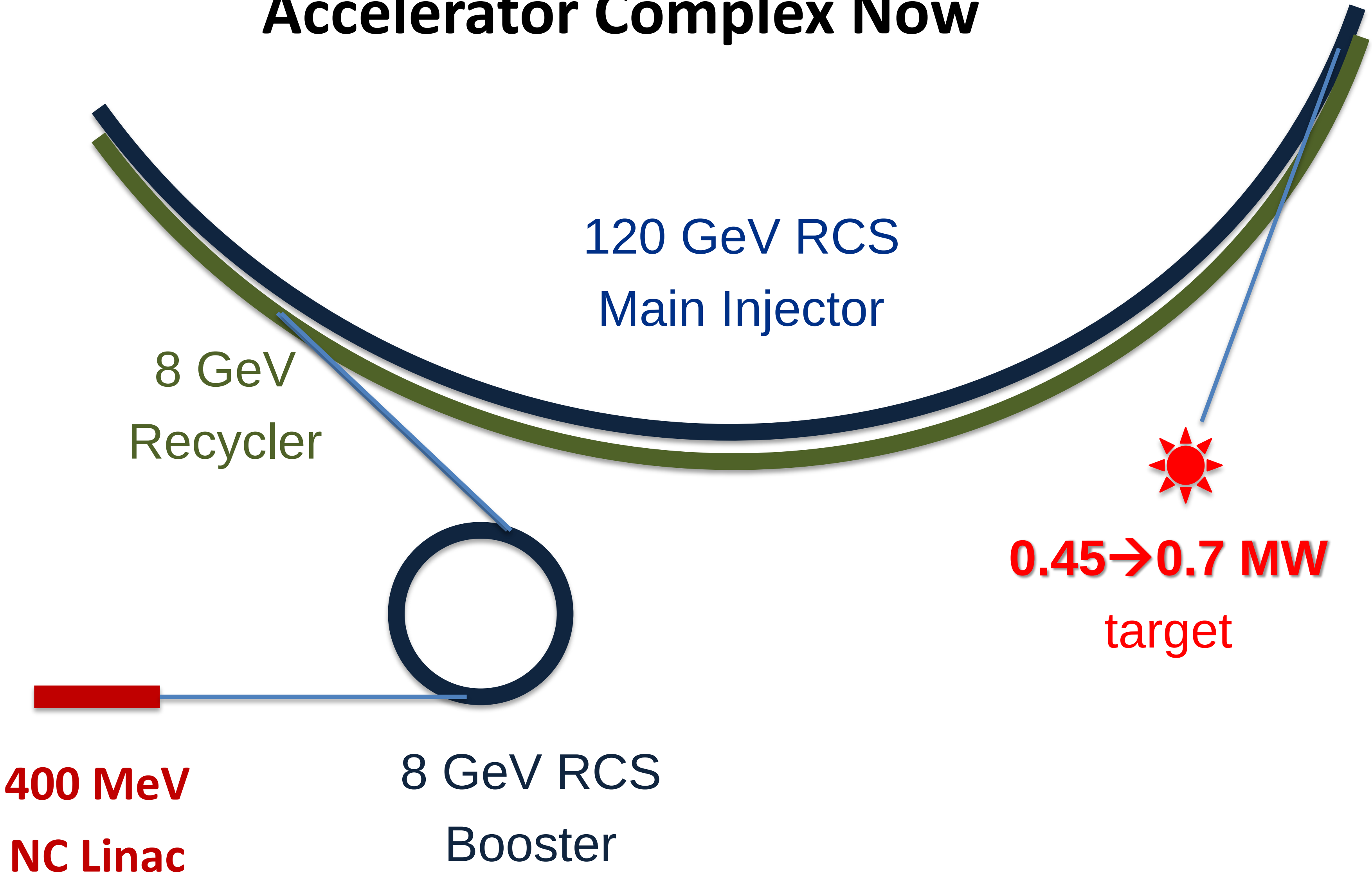
Linac: MTA
BNB: MicroBooNE
NuMI: MINOS+, MINERvA, NOvA
Fixed Target: SeaQuest, Test Beam Facility, M-Center
Muon: g-2, Mu2e (future)
DUNE: Short- and Long-baseline Neutrinos
PIP, PIP-II, PIP-III (future)

Also, test and R&D facilities:

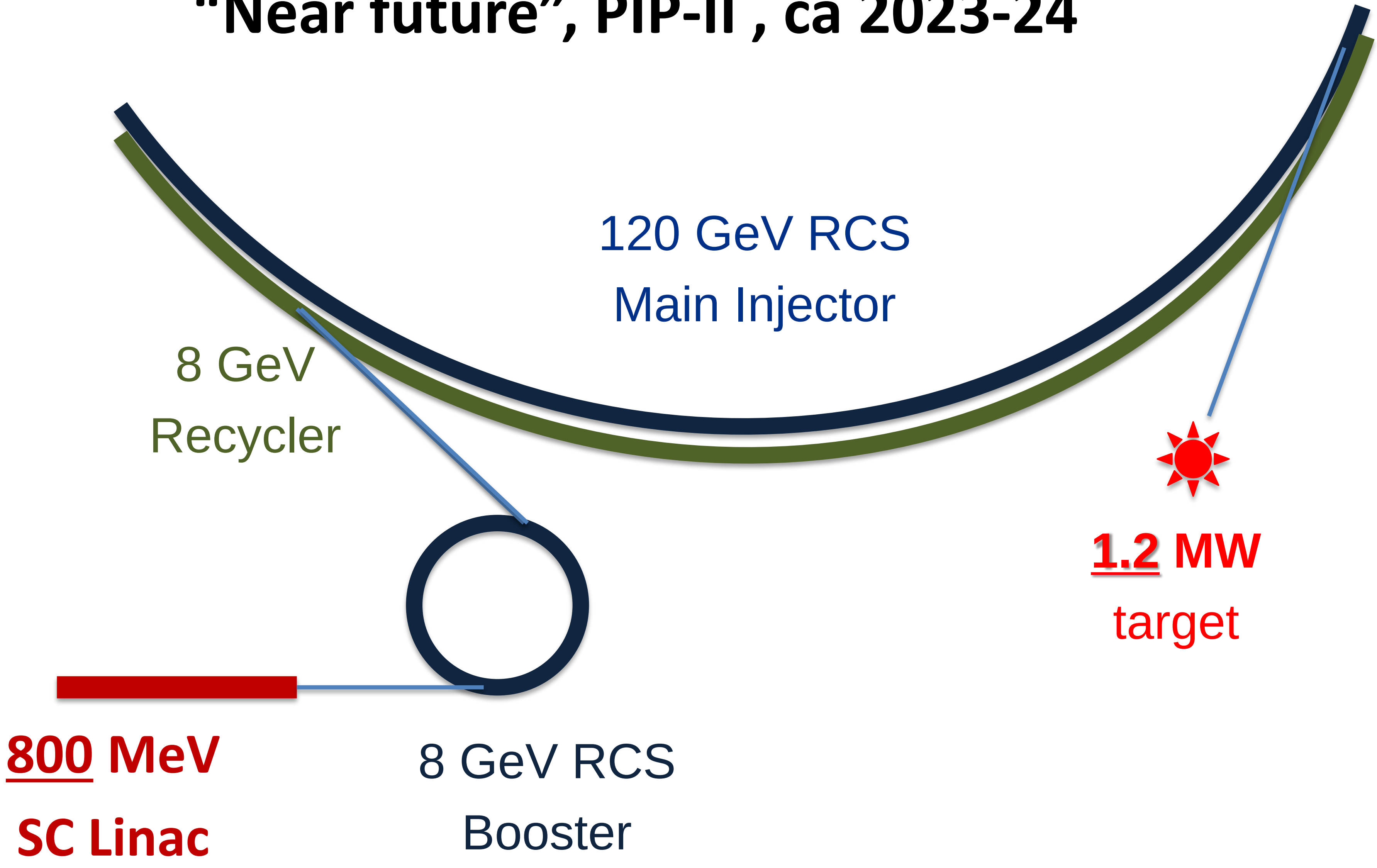
ILC Cryomodule
IOTA
SRF
Cryo
PXIE



Accelerator Complex Now



“Near future”, PIP-II , ca 2023-24

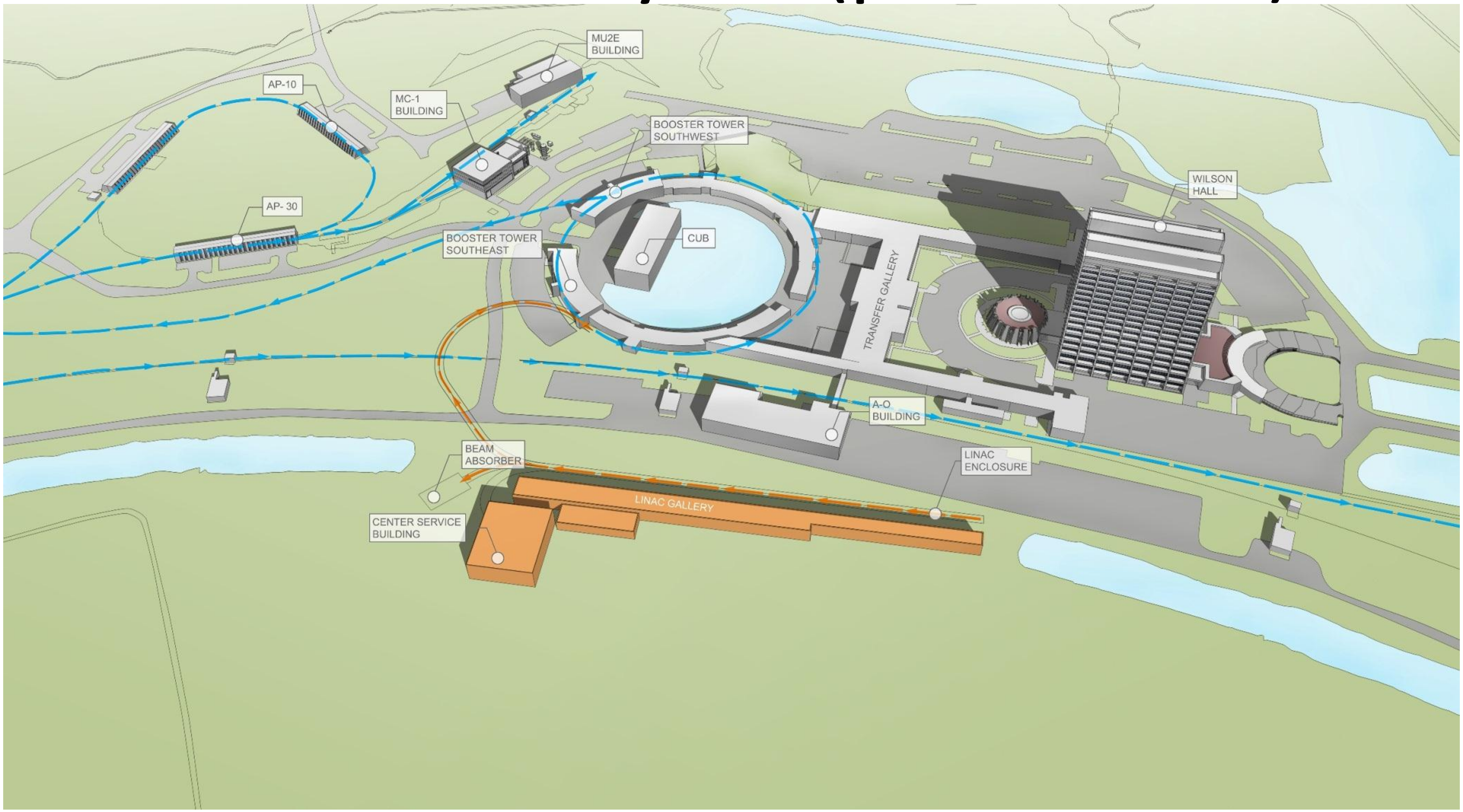


PIP-II Performance Goals

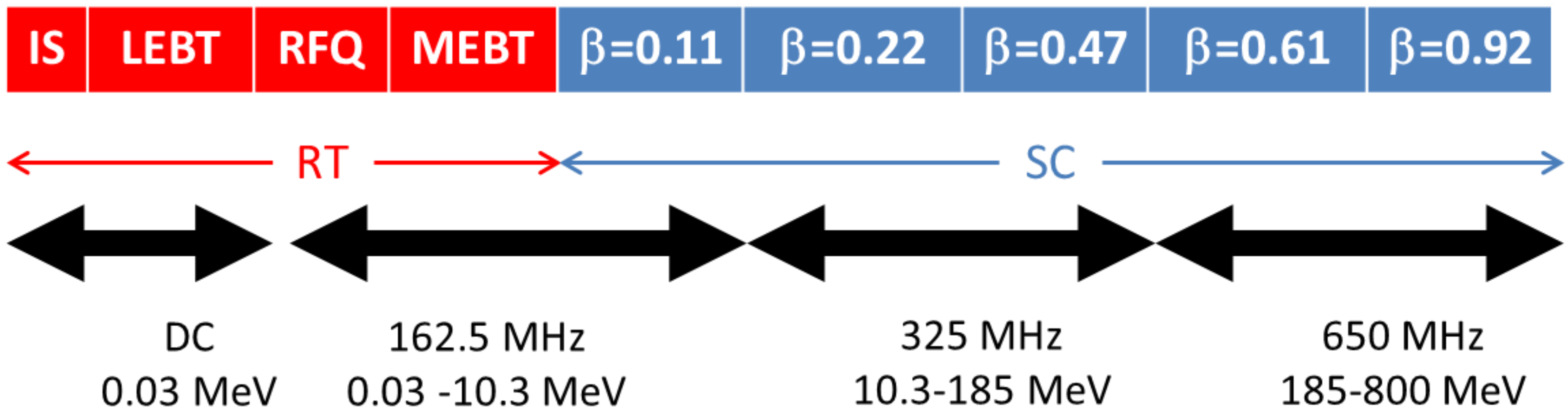
Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.6	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7*	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*NOvA operations at 120 GeV

PIP-II Site Layout (provisional)



PIP-II Technology Map

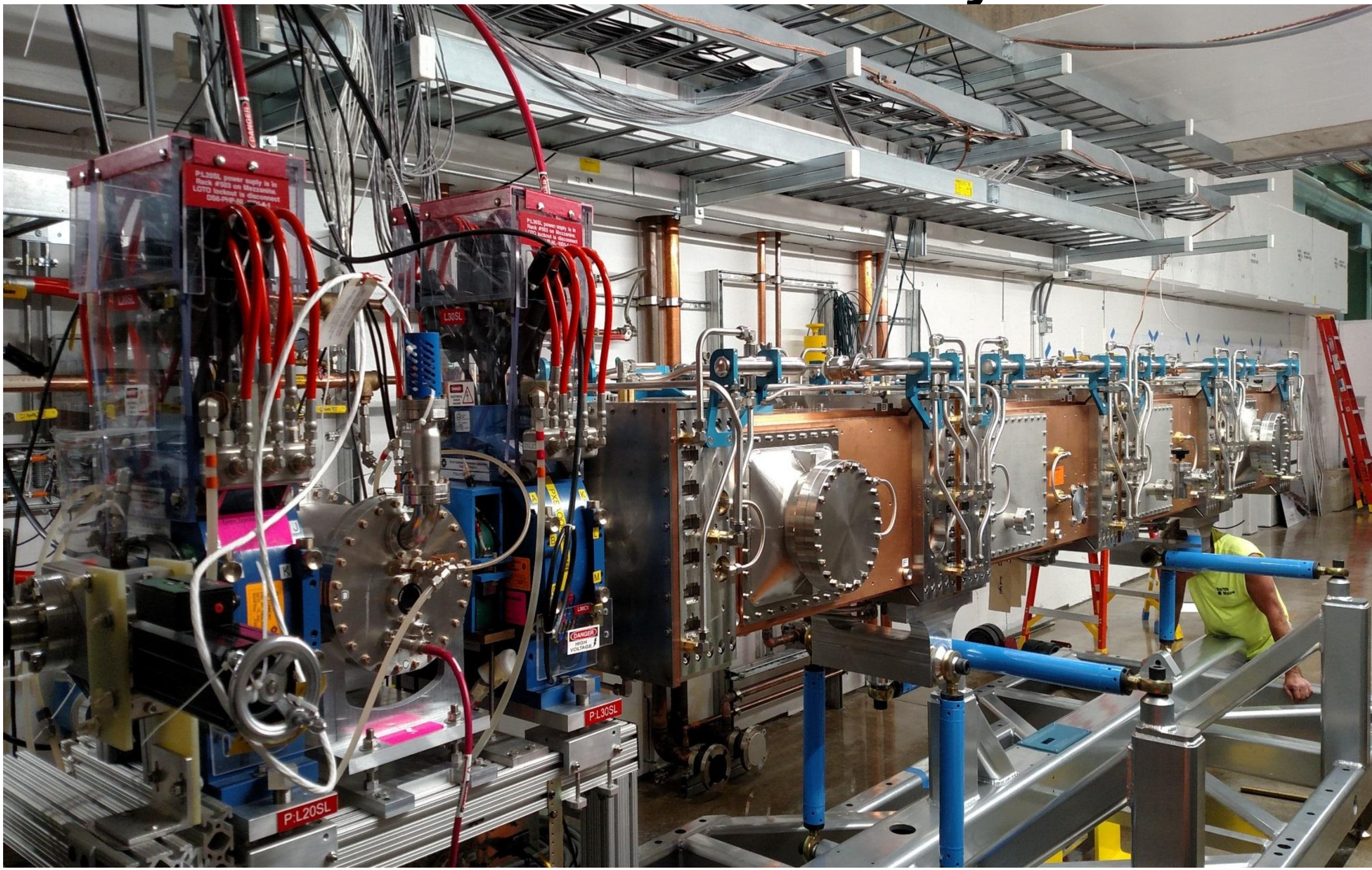


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_{g}=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_{g}=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

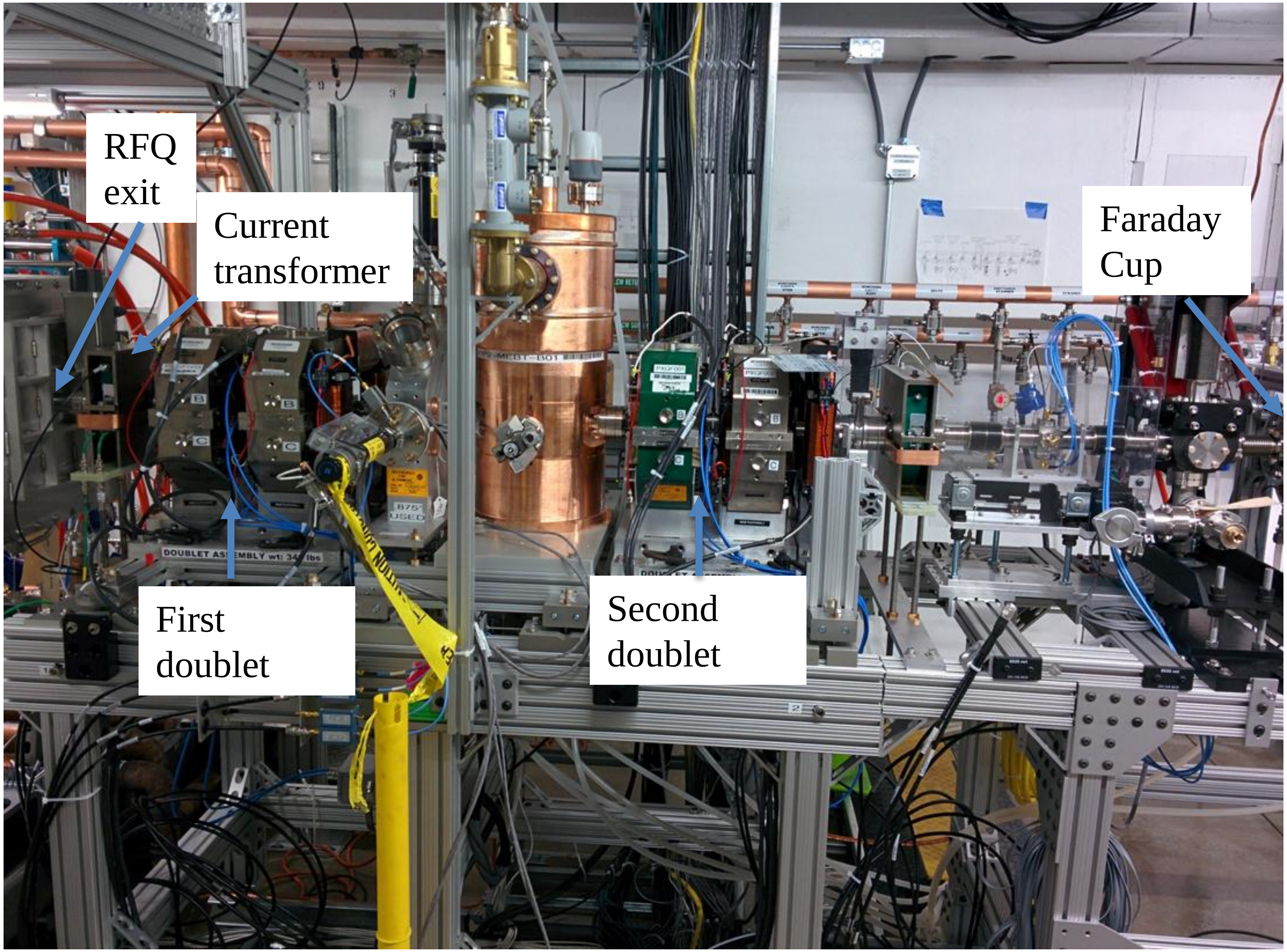
*Warm doublets external to cryomodules

All components CW-capable

PIP-II R&D: Proton Injector



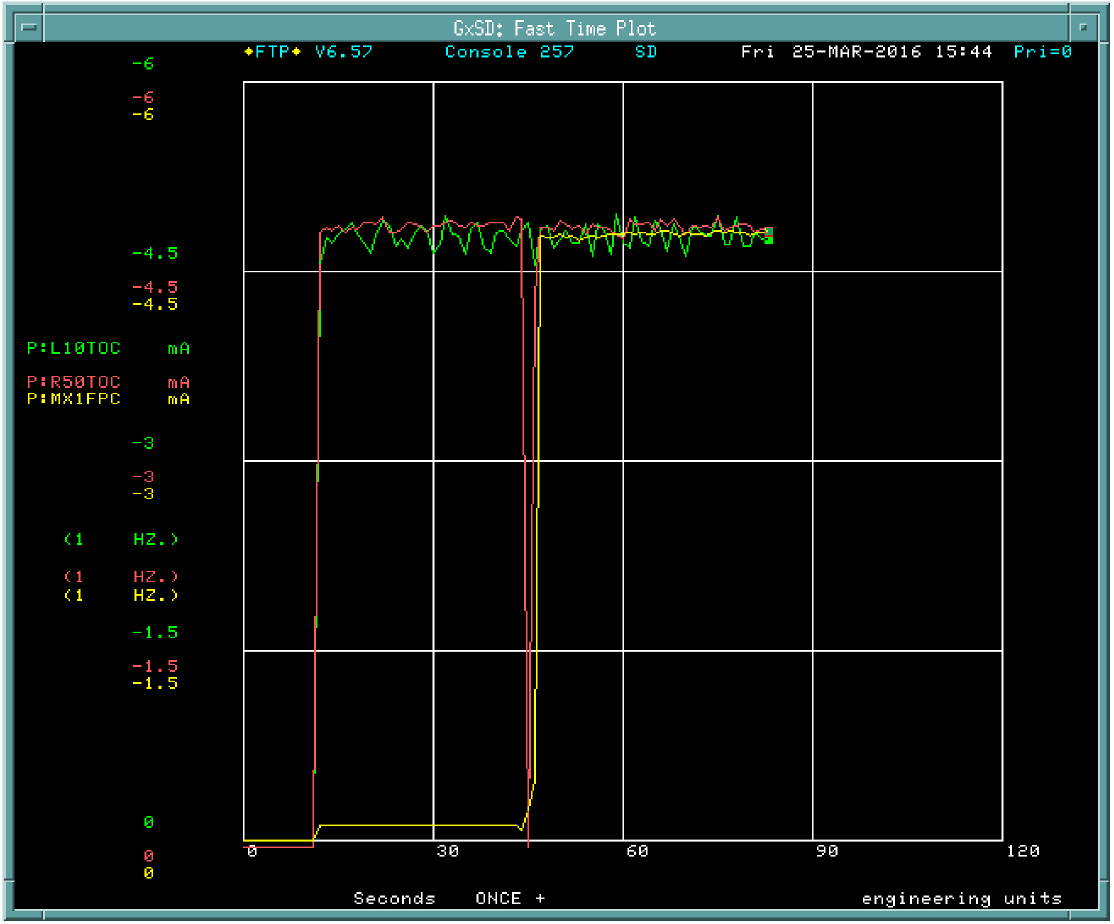
Proton Injector MEBT-1.1 beam line



Proton Injector RFQ beam transmission

Transmission > 95%

Beam Energy = 2.087±0.02 MeV



The MEBT magnets turned on at T=45 sec.

Red – beam current at the entrance of RFQ.

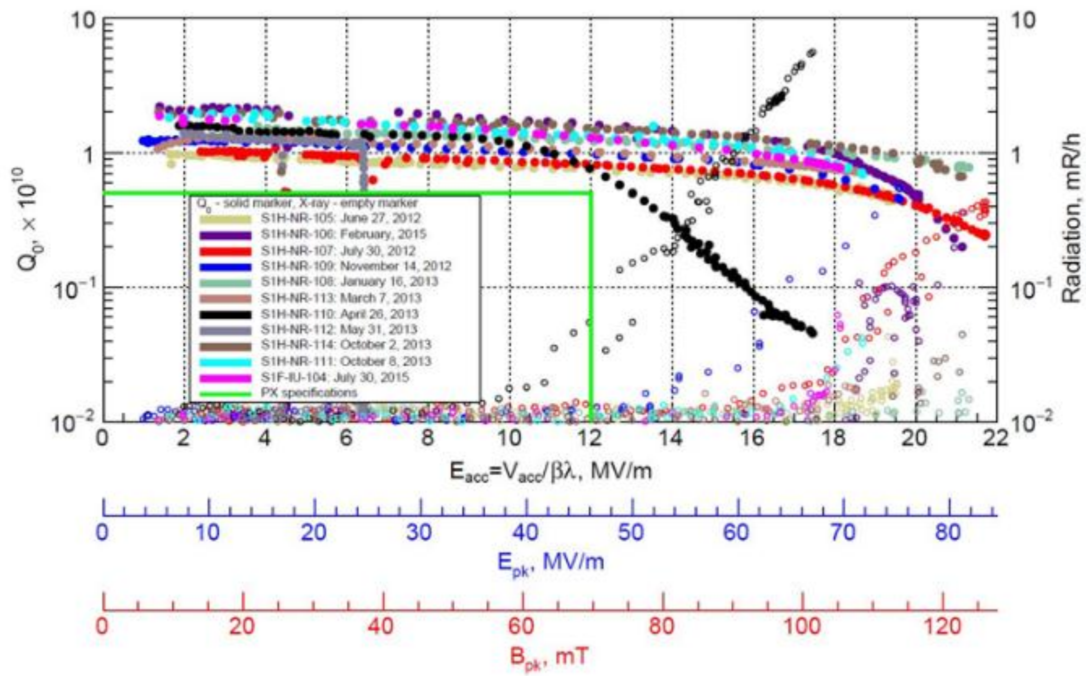
Green - beam current at the exit of RFQ.

Yellow – beam current in the Faraday Cup.

Vertical axis – beam current, 1.5 mA/div.

Horizontal axis – time, 30 sec/div.

PIP-II SRF: SSR1



Beyond PIP-II

PIP-II / Beyond PIP-II (mid-term)

	1st 10 years	2nd 10 years		
To Achieve :	100 kT-MW-year	500 kT-MW-year		
We combine :		Option 1	Option 2	Option 3
Mass	10 kT	50 kT	20 kT	10 kT
Power	1 MW	1 MW	2.5 MW	5 MW

– Mid-term strategy after PIP-II depends on the technical feasibility of each option and the analysis of costs/kiloton versus costs/MW

– Superconducting linear accelerators and high power targets are expensive --- need cost-effective solutions!!!

Intensity Frontier HEP Accelerators

300+ kW JPARC (Japan)

400+ kW CNGS (CERN)

600+ kW Fermilab's Main In

Challenges → need
R&D @ Beam Facilities

EVOLUTION OF INTENSITY FRONTIER AC ATORS

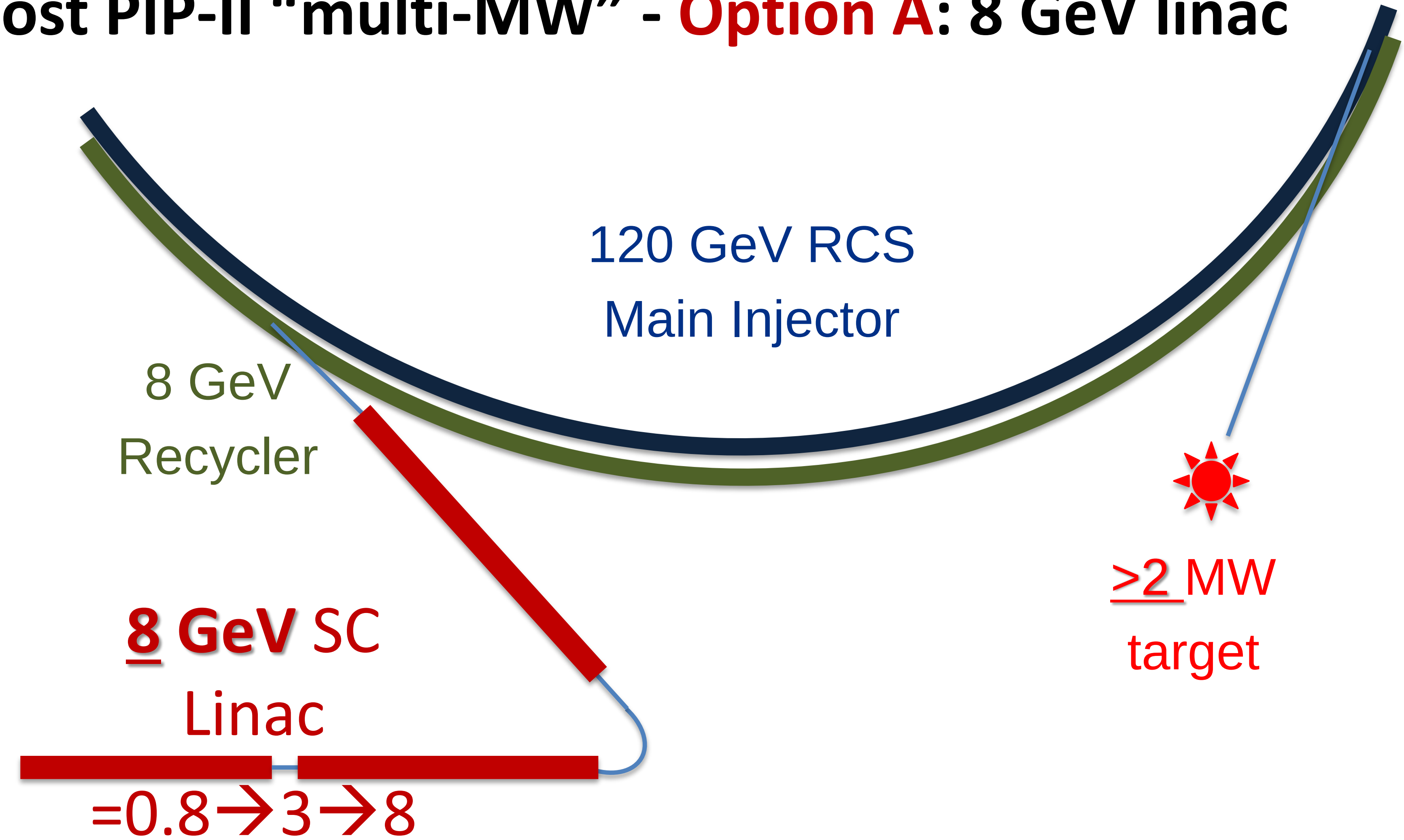
700+ kW Proton Improven nt Plan (PIP, 2016)

1.2+ MW Proton Improvement Plan-II (ca 2025)

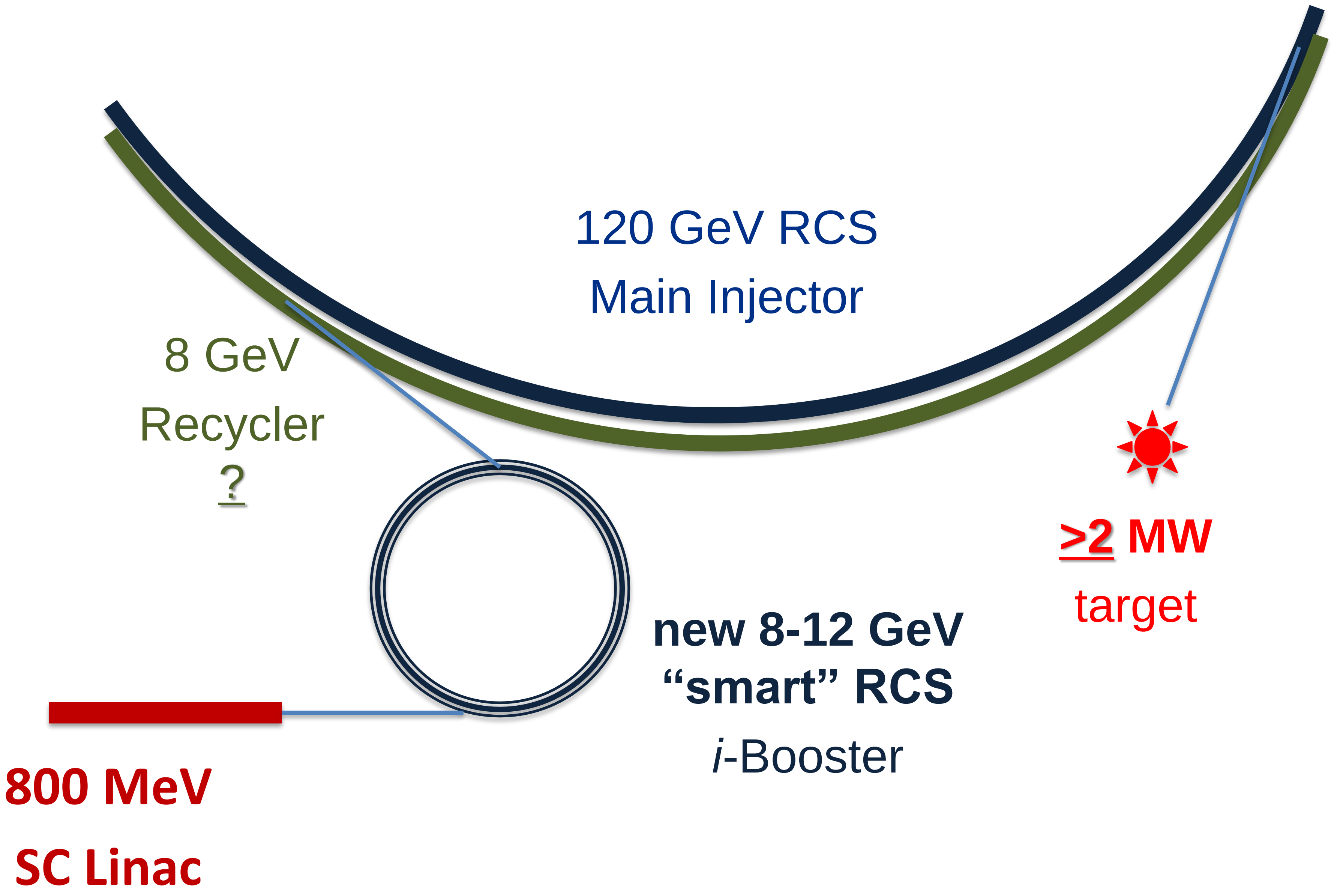
2.5 MW 5 MW?

Post Plan-II multi-MW Upgrade (under study)

Post PIP-II “multi-MW” - Option A: 8 GeV linac



Post PIP-II “multi-MW”- Option B: 8+ GeV smart RCS



Post PIP-II: Intelligent choice requires analysis and R&D

- Either increase performance of the synchrotrons by a **factor of 3-4**:
  - E.g. ***dQ_sc >1*** → need R&D
  - Instabilities/losses/RF/injection/collimation
  - IOTA/ASTA is being built to study new methods

- Or reduce cost of the **SRF / GeV** by a **factor of 3-4**:
  - Several opportunities → need R&D
  - (comprehensive program proposed by TD)

- And – in any scenario – develop **multi-MW** targets:
  - They do not exist now → extensive R&D needed

Alternative: Rapid Cycling "Smart Booster"

- **Increase performance of the synchrotrons by a factor of 3-4:**
  - Stable and rapid acceleration of severely space-charge Coulomb-field dominated beams → **Need R&D**
  - Instabilities/losses/RF/vacuum/collimation
  - Concept of Integrable Optics Test Accelerator (IOTA) → R&D program
  - Major focus of Accelerator Science R&D at Fermilab → how to produce, accelerate and deliver 5MW class intense proton beams

FAST/IOTA : Overarching Motivation – R&D on Intensity Frontier Accelerators for HEP

- To enable multi-MW beam power, losses must be kept well <0.1% at the record high intensity:
  - Need <0.06% for the post PIP-II ~2.5 MW upgrade
  - Present level ~3-5% in Booster and MI synchrotrons
  - (Very challenging after 50 years of development)
- Need to develop tools for
  - Coulomb Self-force "Space-charge" countermeasures
  - Beam "halo" control
  - Single-particle and coherent "beam stability"

What are the fundamental Physics and Scientific questions

A beam is a collection of nonlinear 3-D oscillators moving in the electromagnetic fields of the accelerating and focussing channel and its own Coulomb self-field

- →*Integrability and Nonintegrability*
- →*Hamiltonian Diffusion*
- →*Nonlinear Resonances and Chaos*
- →*Resonance "Hopping", Resonance "Streaming", Arnold Diffusion,…*
- →*Particle loss, beam growth in phase space, beam halo formation, loss of beam from focusing channel*

Integrablity

- **Look for second integrals of motion quadratic in momentum**
  - **First comprehensive study by Gaston Darboux (1901)**
- **Example in 2-D: we are looking for integrable potentials**

$$H = \frac{p_x^2 + p_y^2}{2} + \frac{x^2 + y^2}{2} + U(x, y)$$

Second integral: $$I = Ap_x^2 + Bp_x p_y + Cp_y^2 + D(x, y)$$

$$A = ay^2 + c^2,$$

$$B = -2axy,$$

$$C = ax^2,$$

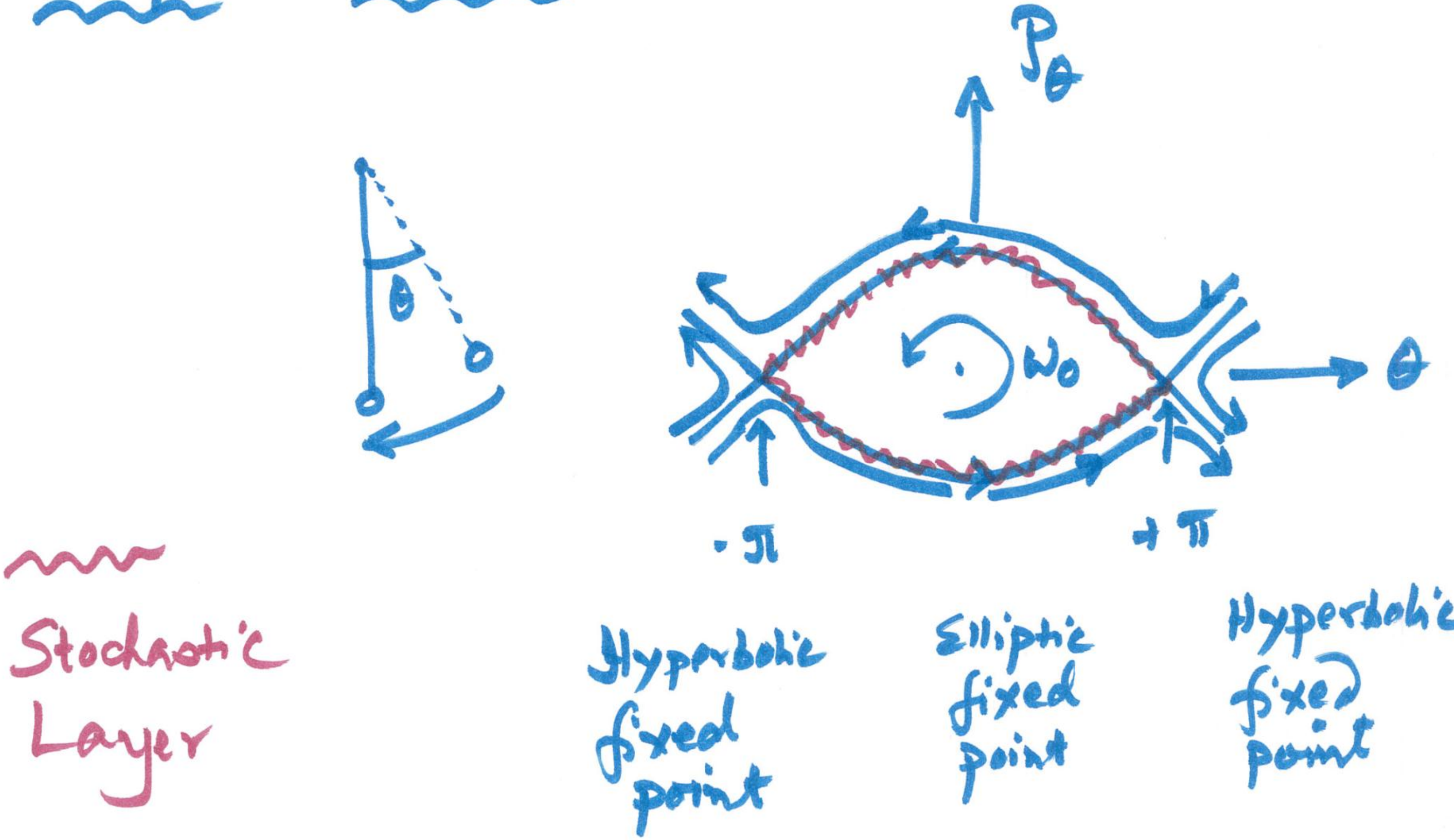
Integrablity with Coulomb Self-force and Nonlinear Focusing

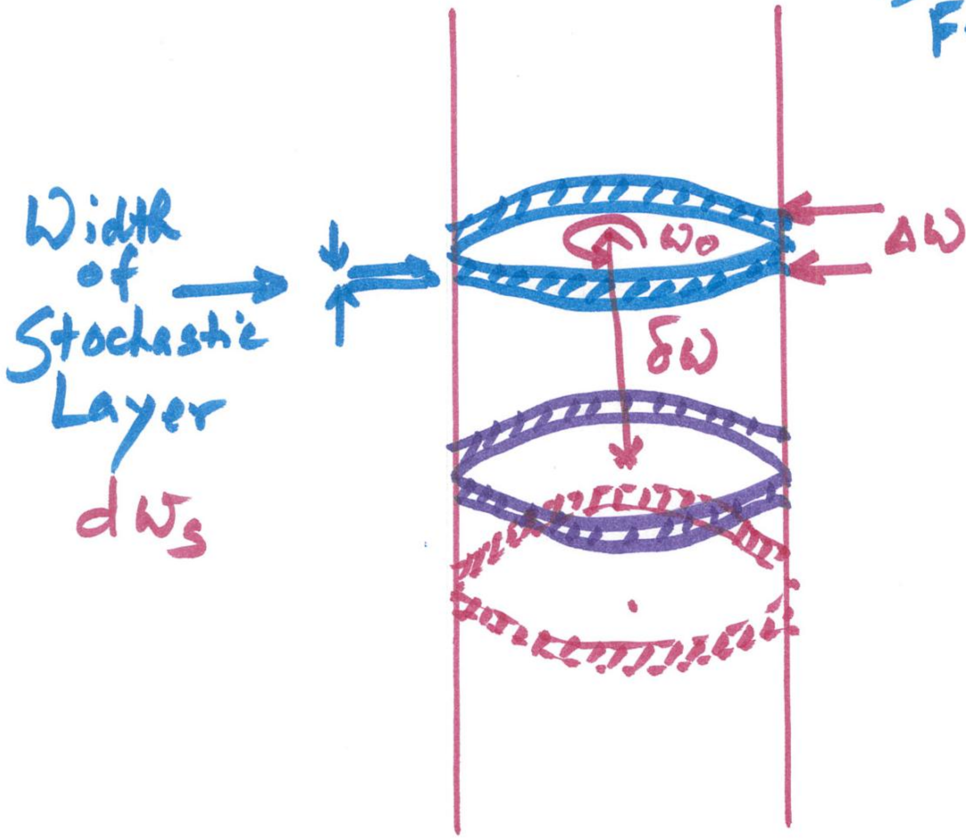
- **One particle motion integrable.**
  Two particles interacting via inverse-square law force also integrable.
  But three "interacting" particles break integrability already :
  → famous "3-body problem"!
  And we have 100 billion particles per bunch!!!

- **Then, we add the macroscopic "average" self-consistent Coulomb self-force !!**

→ A Brief Album of Resonance Dynamics

Simple Oscillator





Resonance Frequency → ω_0

Resonance Separation → $\delta\omega$

Resonance Width → $\Delta\omega$

$\omega_0, \ \Delta\omega, \ \delta\omega$

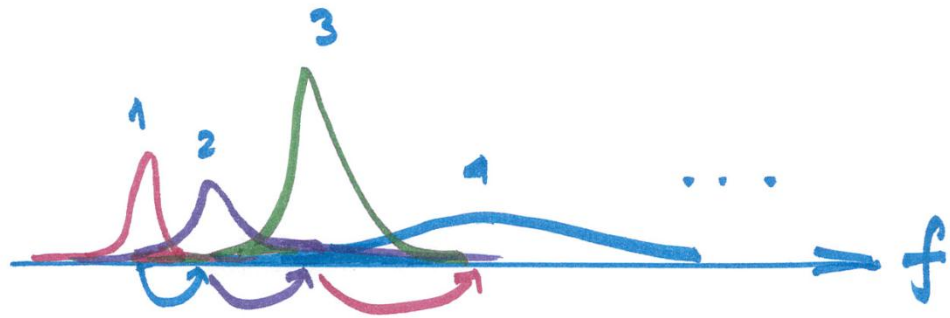
$$\frac{\delta\omega}{\Delta\omega} \sim 1 + d\omega_s$$

— DYNAMICAL CHAOS
STOCHASTICITY

CHIRIKOV

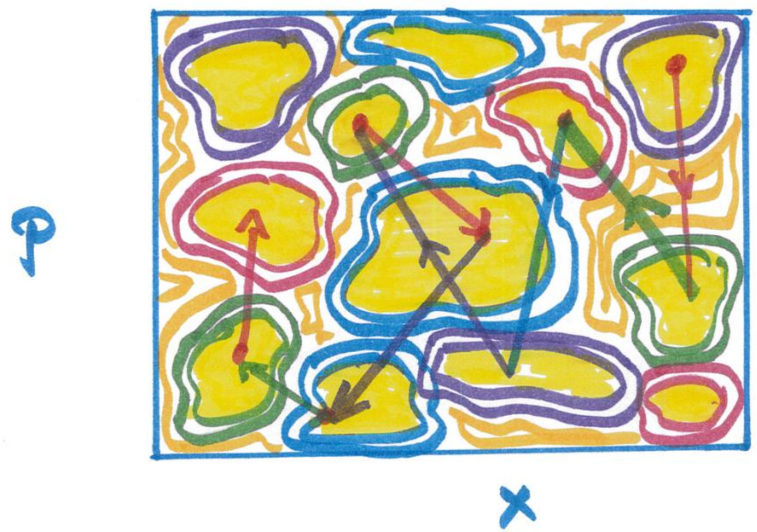
CRITEREON

(Boris Chirikov, 1976)



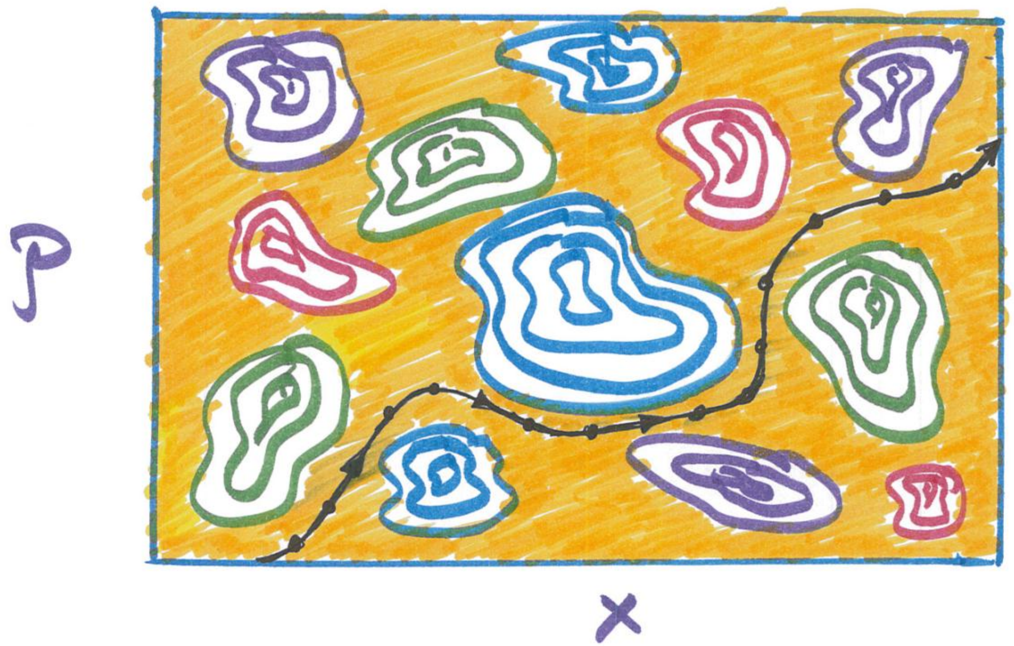
RESONANCE

"HOPPING"



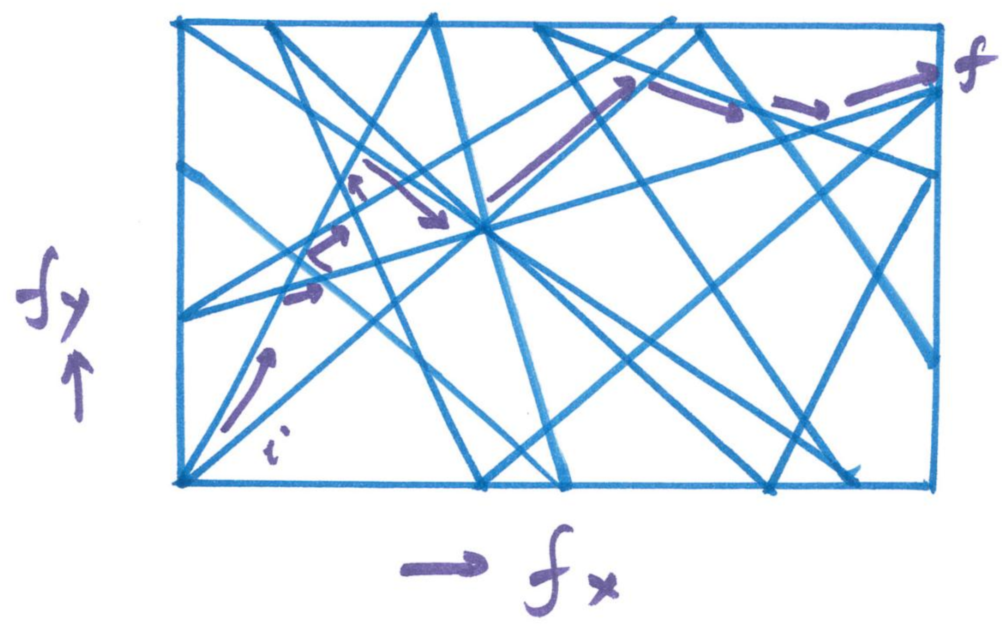
RESONANCE

"STREAMING"



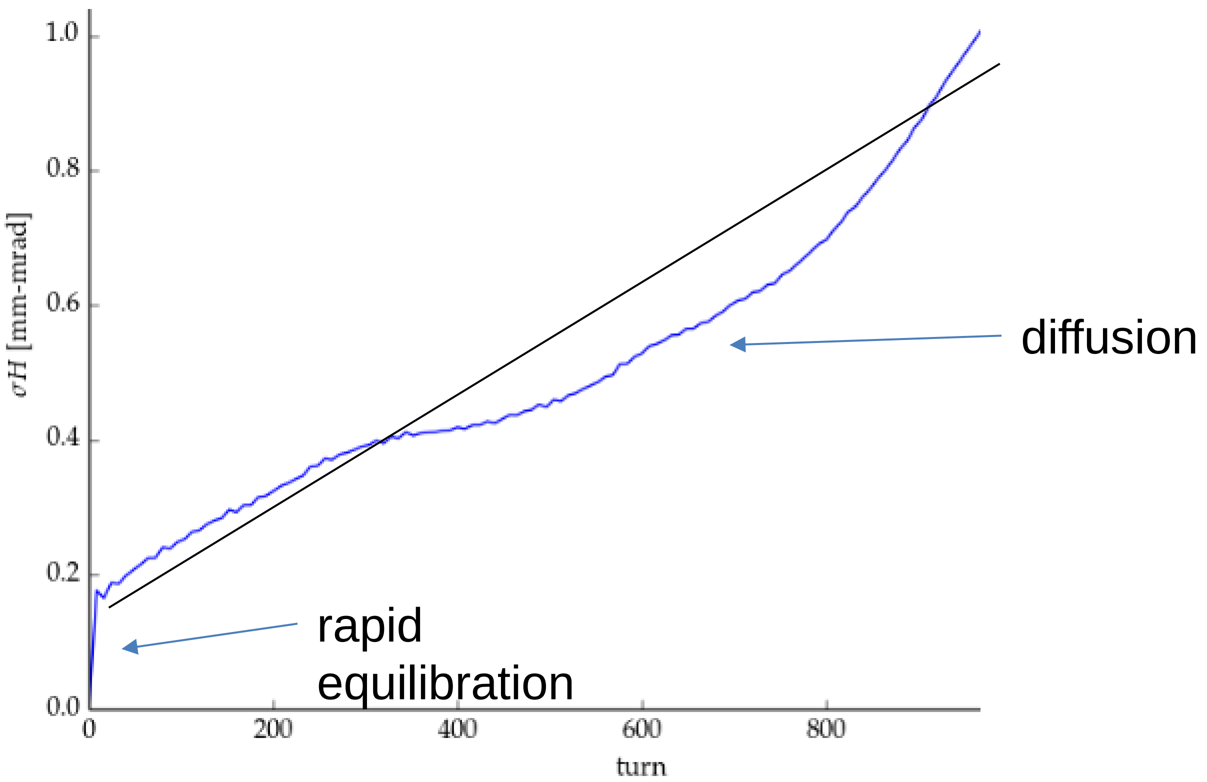
ARNOLD'S WEB

ARNOLD Diffusion

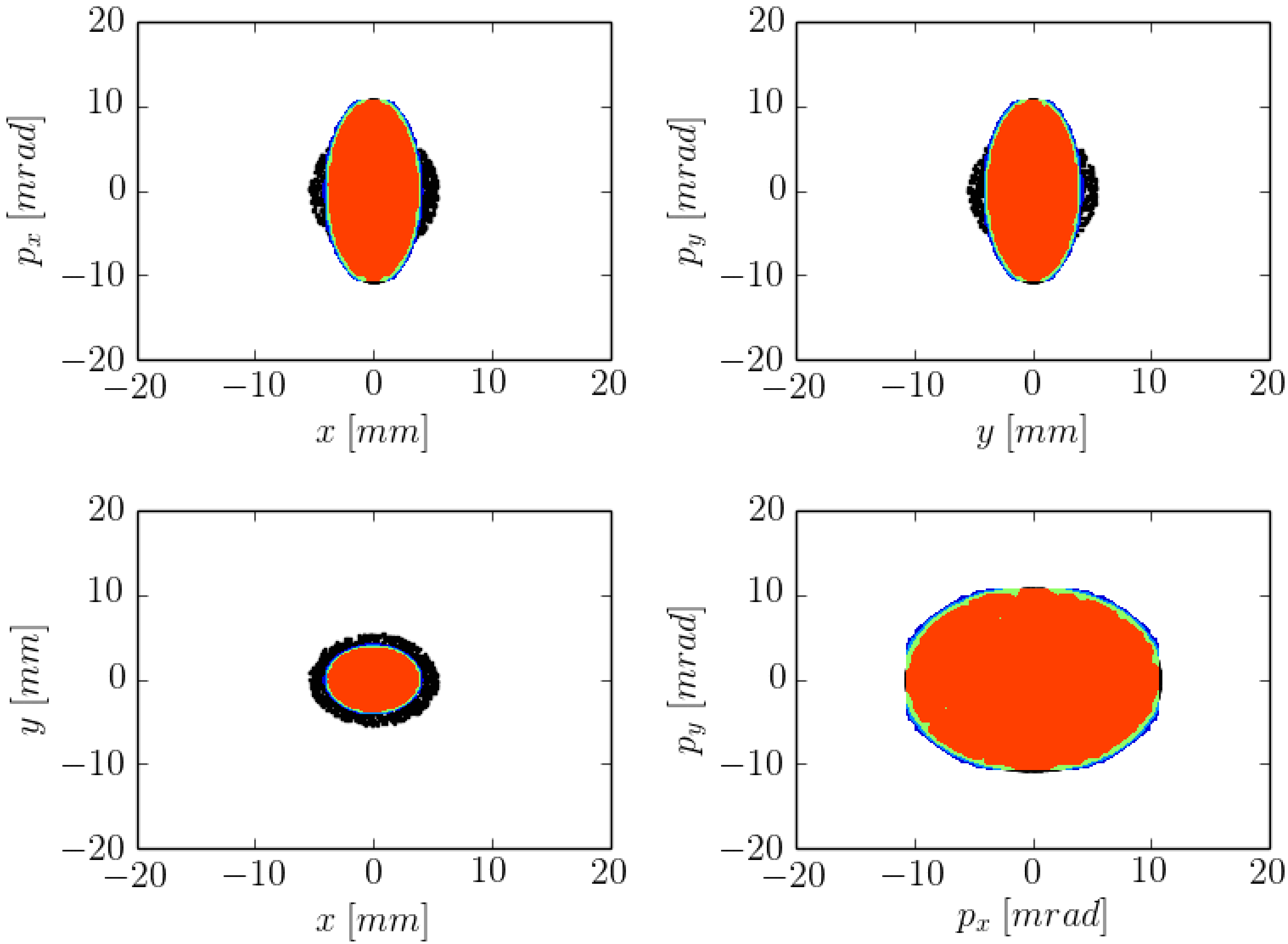


Diffusion of the Invariants on Intermediate Time Scale

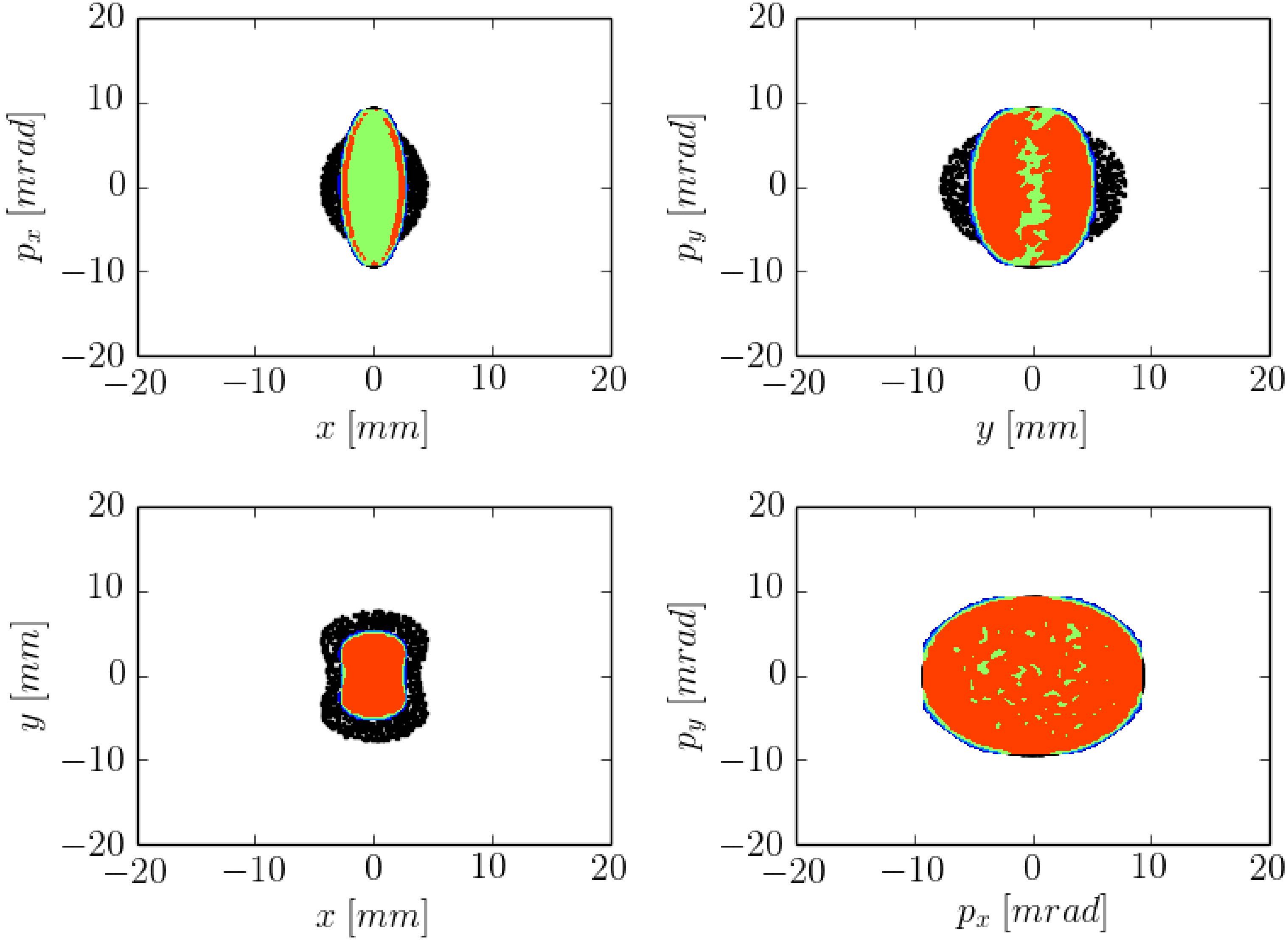
- *Nonlinear space charge forces break integrability*
  - ***Vlasov quasi-equilibria are evolving over time – show movie***
  - ***invariants of the motion show signs of diffusion***



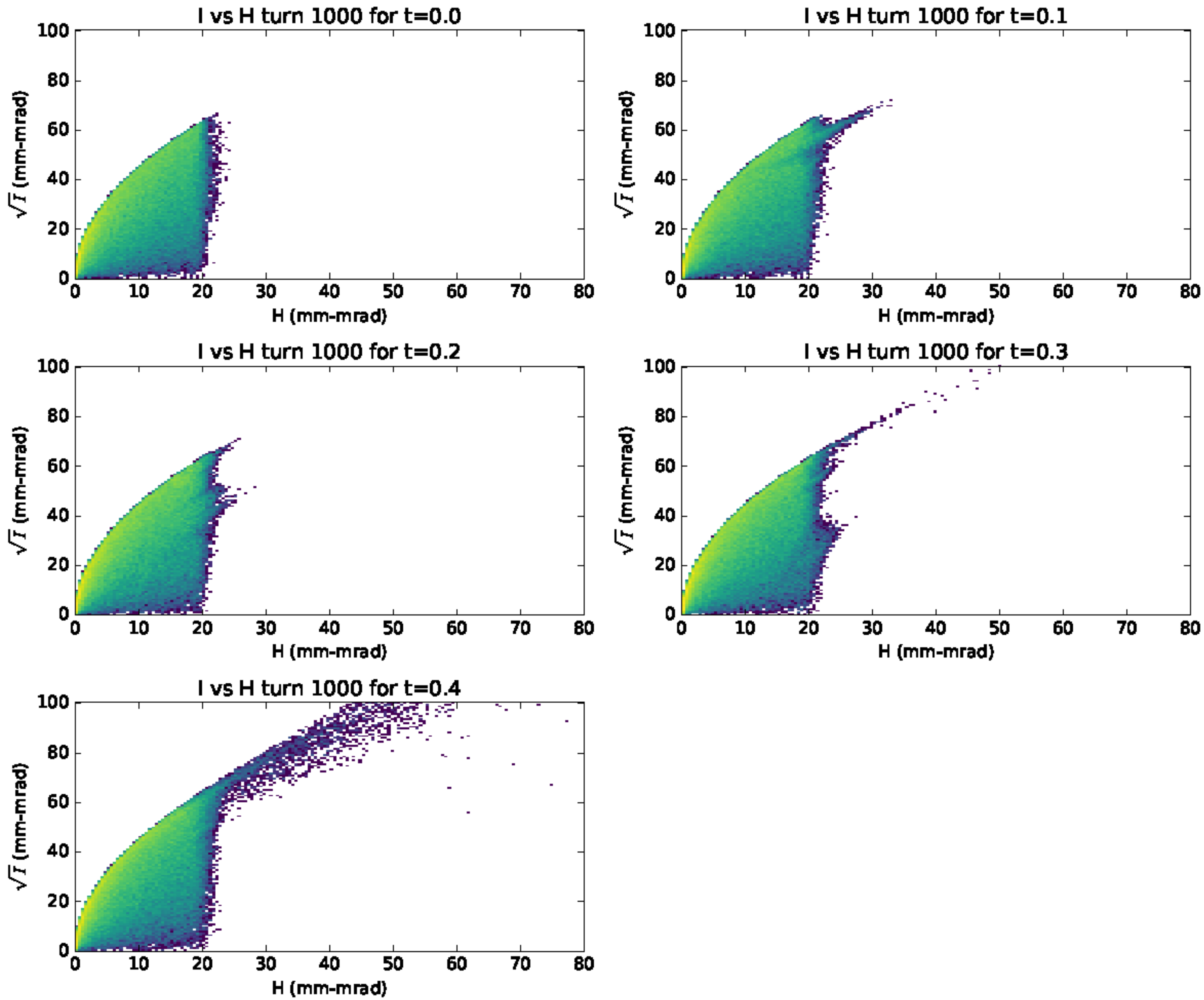
For a linear lattice, core mismatch oscillations quickly drive test-particles into the halo



For integrable nonlinear magnetic fields (D&N 2010), nonlinear decoherence suppresses halo formation



H-I 2D distribution after ~1000 turns (log scale)



Calculating the Diffusion Coefficient

$$\mathcal{M} = \exp\left(- :H_0(\mathbf{J}): C\right)$$

TRANSFER MAP a Lie Operator

$$\mathcal{H} = H_0(\mathbf{J}) + \mathcal{V}(\mathbf{J}, \psi; f)$$

Integrable Hamiltonian plus perturbation due to nonlinear space charge forces

$$\mathcal{V} = N\eta \int d\boldsymbol{\Omega}' \mathscr{G}(\mathbf{J}, \psi; \mathbf{J}', \psi') f(\mathbf{J}', \psi')$$

Green's function representation of the nonlinear space charge forces

Fundamental assumption: change in the invariant during a single turn (or a few turns) is a Markov process, which means there is no dependence on earlier states, which in turn implies strong phase space mixing.

$$f(\mathbf{J}, n+1) = \int f(\mathbf{J} - \delta\mathbf{J}, n) W(\mathbf{J} - \delta\mathbf{J}, n, \delta\mathbf{J})\ d\left(\delta\mathbf{J}\right)$$

W(J-dJ, n, dJ) is the probability that a trajectory with invariant value J-dJ at time 'n' will be kicked to

$$\mathbf{J} + \delta\mathbf{J} = \exp\left(- :\mathcal{H}(\mathbf{J}, \psi): C\right) \mathbf{J}$$

Analytical form may be possible in some limits. In general, numerics will be required.

Calculating the Diffusion Coefficient (cont'd)

Taylor series expansion of the Markov process equation yields a proto-diffusion equation:

Time derivative of f(J)

Dynamical friction (often vanishes)

Diffusion

$$f(\mathbf{J}, n+1) = f(\mathbf{J}, n) - \int d(\delta\mathbf{J})\delta\mathbf{J} \cdot \partial_{\mathbf{J}} (fW) + \frac{1}{2}\int d(\delta\mathbf{J})(\delta\mathbf{J} \cdot \partial_{\mathbf{J}})(\delta\mathbf{J} \cdot \partial_{\mathbf{J}})(fW) + \ldots$$

Phase-averaged form of the 1st-order kick in dJ (may have to be obtained numerically):

$$\langle \delta\mathbf{J} \rangle_{\boldsymbol{\psi}} = \sum_{\mathbf{n}} \mathbf{n} \frac{\mu^2 (2\pi)^d}{(2\pi\mathbf{n}\cdot\boldsymbol{\nu})^2} (\mathbf{n}\cdot\partial_{\mathbf{J}}) \left(\int d\mathbf{J}' d\mathbf{J}'' f(\mathbf{J}') f(\mathbf{J}'') g_{\mathbf{n},\mathbf{0}}(\mathbf{J},\mathbf{J}') g^*_{\mathbf{n},\mathbf{0}}(\mathbf{J},\mathbf{J}'') \right) \sin^2(\pi\mathbf{n}\cdot\boldsymbol{\nu})$$

Phase-averaged form of the 2nd-order kick in dJ (may have to be obtained numerically):

$$\langle \delta J_i \delta J_k \rangle_{\boldsymbol{\psi}} = \sum_{\mathbf{n}} \frac{\mu^2 (2\pi)^d}{(2\pi\mathbf{n}\cdot\boldsymbol{\nu})^2} n_i n_k \left(\int d\mathbf{J}' d\mathbf{J}'' f(\mathbf{J}') f(\mathbf{J}'') g_{\mathbf{n},\mathbf{0}}(\mathbf{J},\mathbf{J}') g^*_{\mathbf{n},\mathbf{0}}(\mathbf{J},\mathbf{J}'') \right) \sin^2(\pi\mathbf{n}\cdot\boldsymbol{\nu})$$

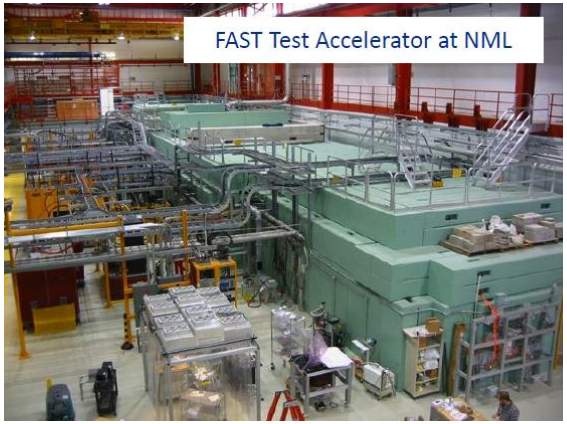
Fermilab Beam Test Facilities:

Accelerator Science Research and Development to enable:

(i) high intensity neutrino beam development

(ii) to develop a high-level understanding of experimental control of classical nonlinear dynamics and chaos and associated phase-space diffusion and particle loss; and

(iii) to perform unique "one-of-kind" experiments to control classical, semi-classical and quantum anharmonic oscillators and their phase-space.

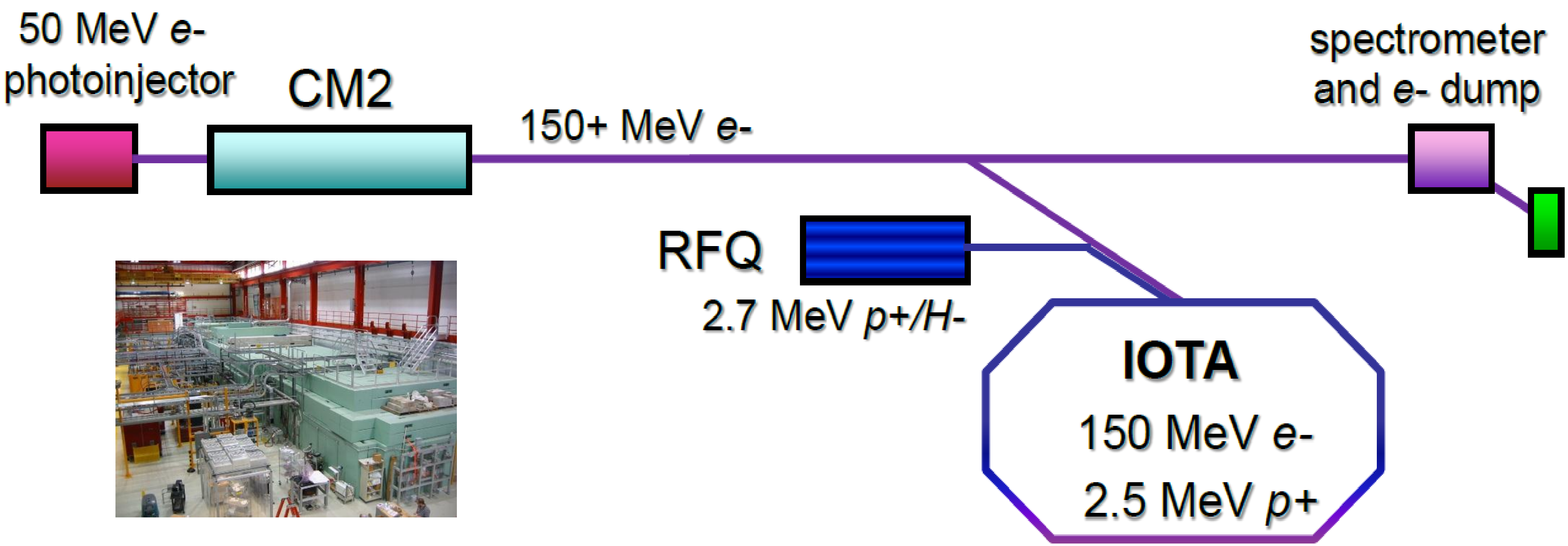


300 MeV e-
2-3 MeV/c p+/H-

I will focus this talk on FAST/IOTA Facility to facilitate development of <u>Intensity Frontier High Energy Particle</u> accelerators and enable fundamental accelerator science R&D

FAST/IOTA schematic

2.5 MeV p+ or 150 MeV e- / 40 m



IOTA under construction at Fermilab →

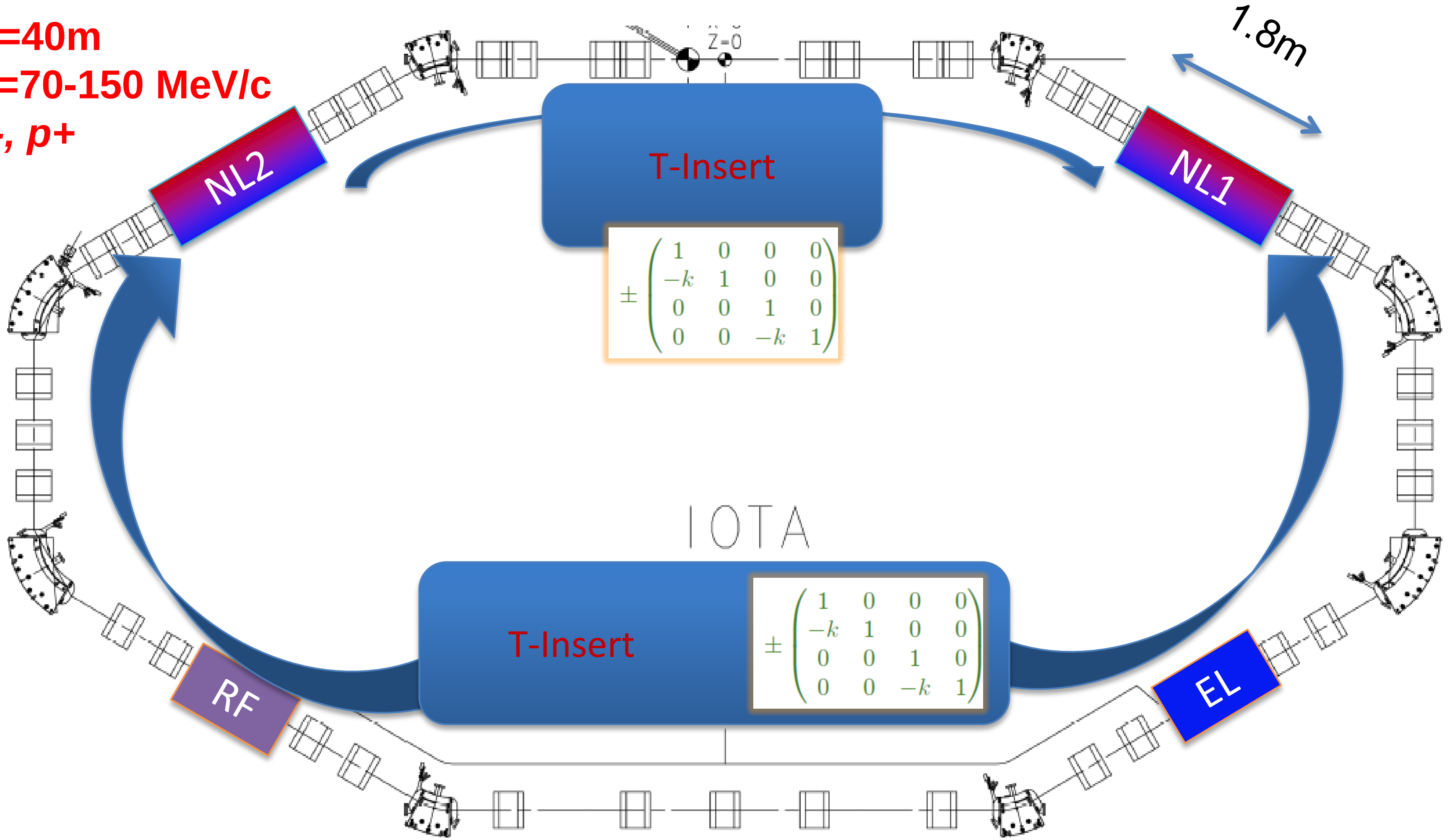
Excellent opportunity for PhD research in nonlinear dynamics!!!!

IOTA Parameters

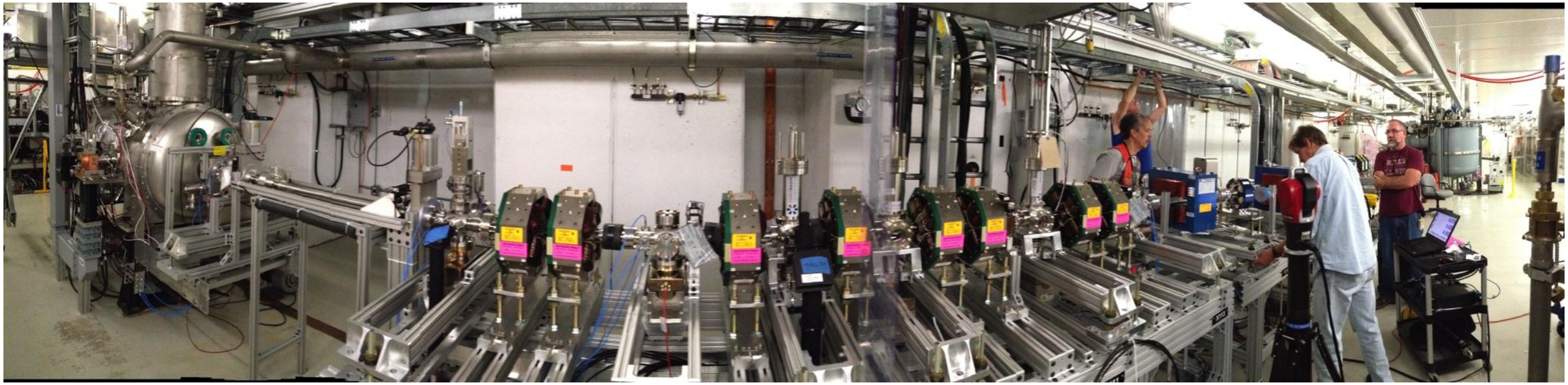
Nominal momentum	***e***$^-$**: 150 MeV/c** ***p+*****: 3 MeV/c**
Nominal intensity	e$^-$: 1×10^9, p+: 1×10^{11}
Circumference	**40 m**
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 ÷ 0.1
Betatron tune (integer)	3 ÷ 5
Natural chromaticity	-5 ÷ -10
Transverse emittance r.m.s.	*e*$^-$: 0.04 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$^-$: 12 cm, 1.4×10^{-4}

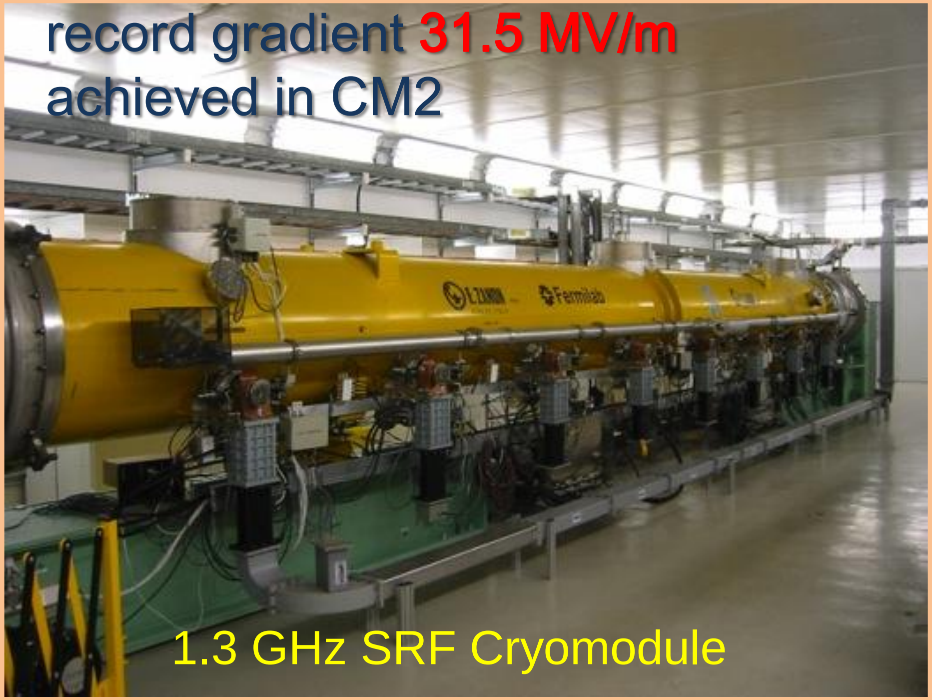
IOTA is designed flexibly to allow insertions of an E-lens, Two Nonlinear Lenses and a special Optical Cooling Bypass

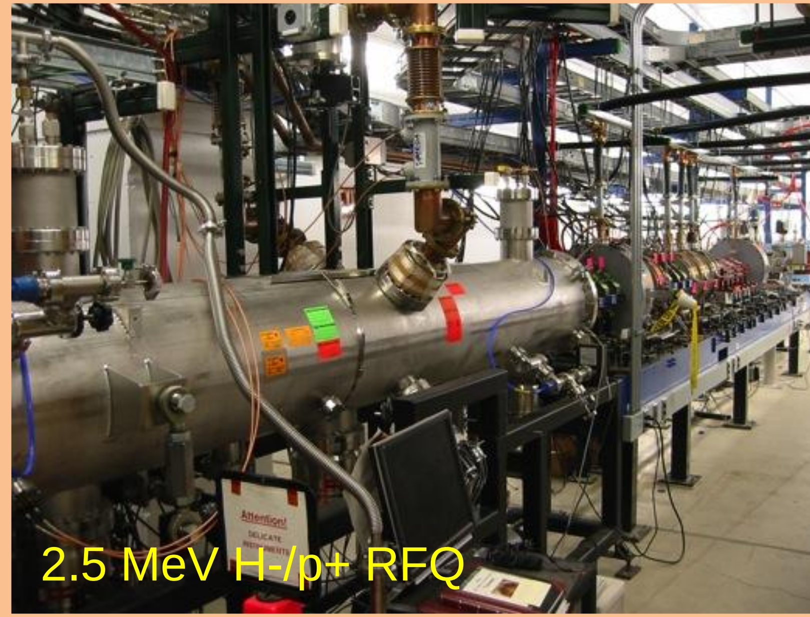
C=40m
P=70-150 MeV/c
e-, *p*+

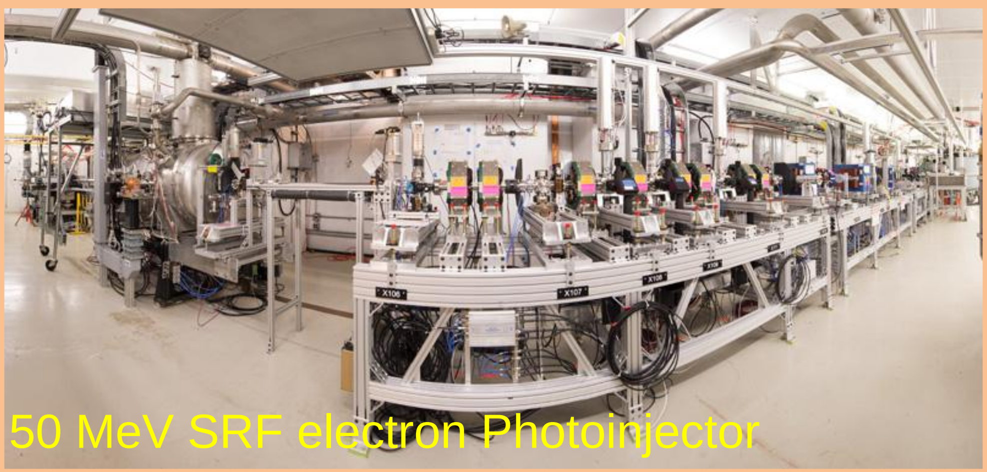


FAST Facility



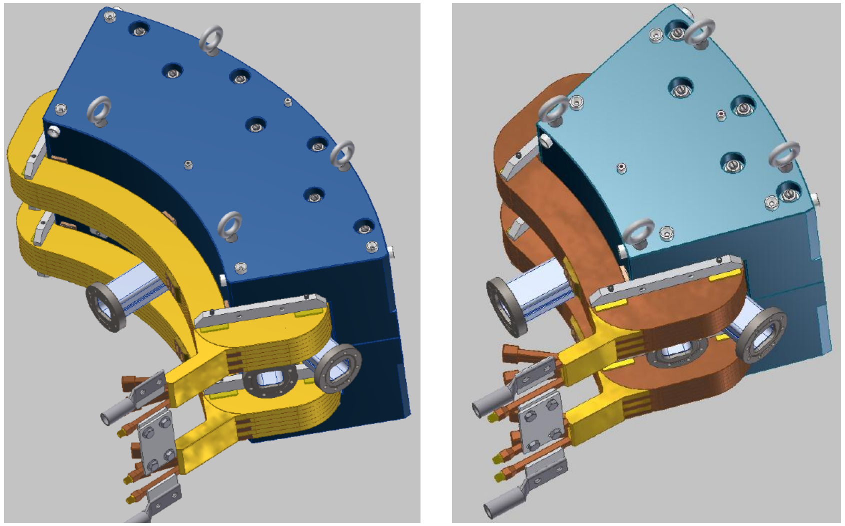

record gradient 31.5 MV/m
achieved in CM2
1.3 GHz SRF Cryomodule


2.5 MeV H-/p+ RFQ


50 MeV SRF electron Photoinjector


IOTA Ring Hall

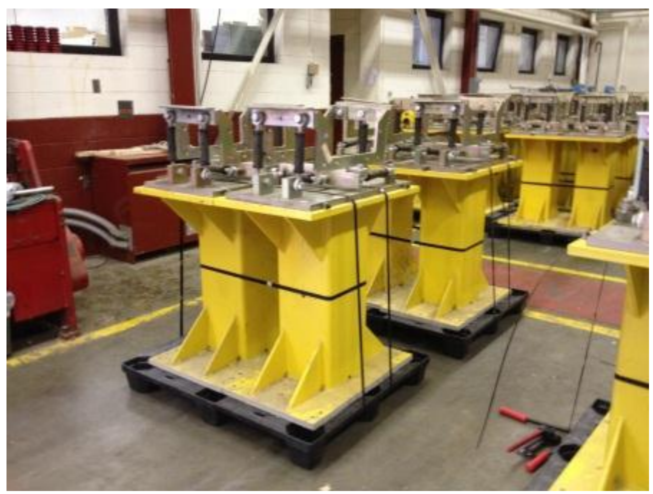
Ring Elements in Hand



Dipole magnets

32 quads from **JINR (Dubna)**

Vacuum chambers for dipoles



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

Also:
BPM bodies and electronics
Vacuum system
Dipole power supply
Quad supplies
Corrector power supplies

IOTA Ring: ~80% of All Components in Hand

32 IOTA ‘Dubna’ quadrupoles

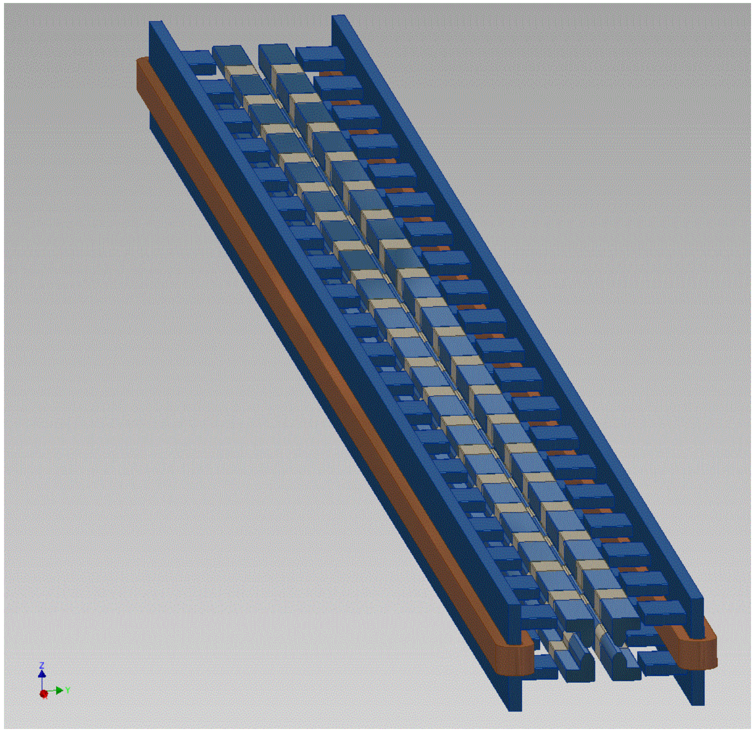
- being measured in TD

10 more being built

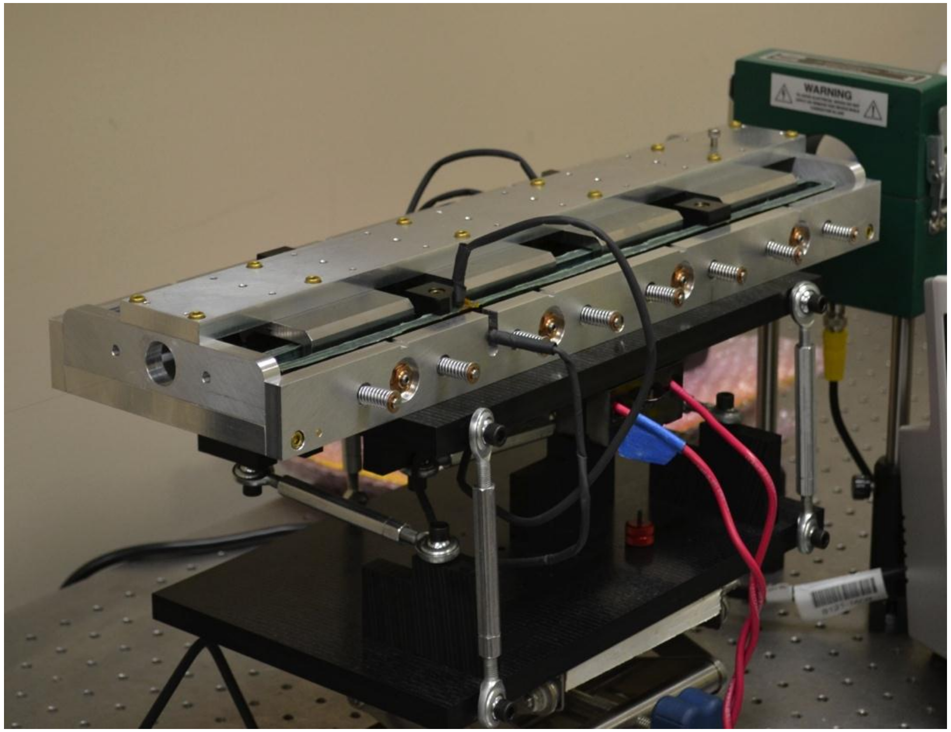
1st IOTA 30-deg. Dipole
9 more ready to ship (from China)

Nonlinear Magnet

- **Joint effort with RadiaBeam Technologies**

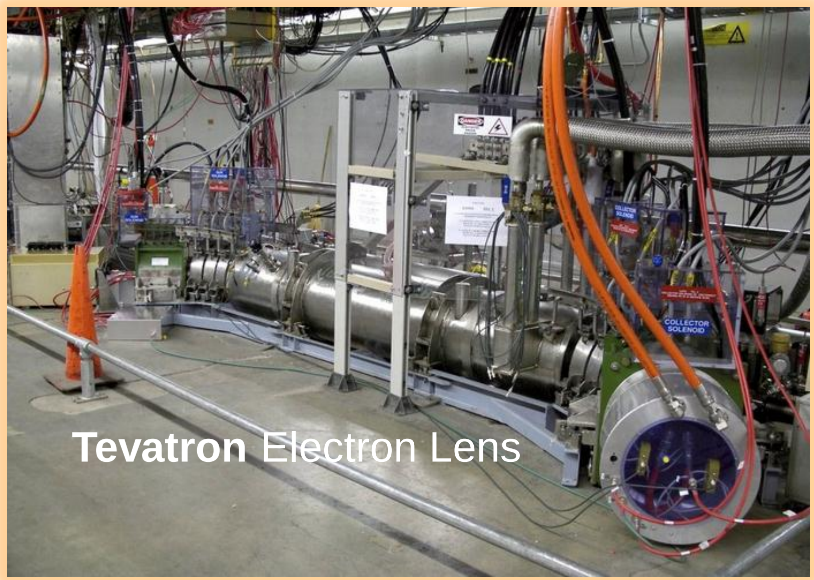


FNAL Concept: 2-m
long
nonlinear magnet



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

Electron Lenses



Tevatron Electron Lens

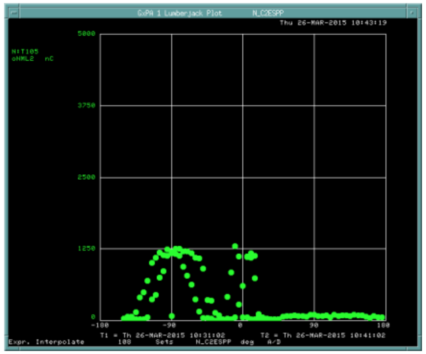
IOTA Construction and Research Timeline

	Electron Injector	Proton Injector	IOTA Ring
FY15	20 MeV *e*- commiss'd beam tests	Re-assembly began @MDB	50% IOTA parts ready
FY16	50 MeV *e*- commiss'd beam tests	50 keV *p+* commiss'd	IOTA parts 80+% ready
FY17	150-300 MeV *e*- beam commissioning/tests *	2.5 MeV *p+* commiss'd beam tests @ MDB	IOTA fully installed first beam ? *
FY18	*e*- injector for IOTA + other research	*p+* RFQ moved from MDB to FAST *	IOTA commiss'd with *e*- **Research starts (NL IO)**
FY19	*e*- injector for IOTA + other research	2.5 MeV *p+* commiss'd beam tests	**IOTA research with *e*-** IOTA commiss'd with *p+*
FY20	*e*- injector for IOTA + other research	*p+* injector for IOTA	**IOTA research with *p+*** *

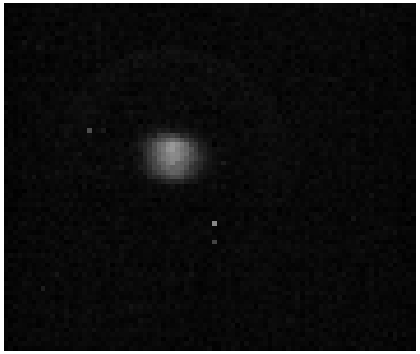
beam operations

First Electrons Through Photoinjector!

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



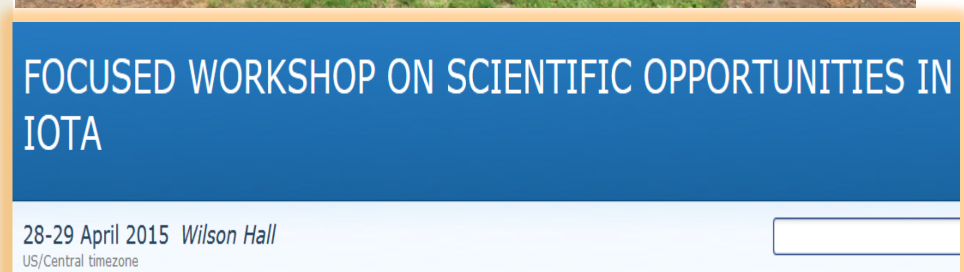
Initial CC2
Phase Scan



OTR Screen after
22.5° bend

Scientific IOTA Collaboration

- **22 Partners:**
  - ANL, Berkeley, BNL, BINP, CERN, Chicago, Colorado State, IAP Frankfurt, JINR, Kansas, LANL, LBNL, ORNL, Maryland, Michigan State, Northern Illinois, **Oxford,** RadiaBeam Technologies, RadiaSoft LLC, Tech-X, Tennessee, Vanderbilt
- **NIU-FNAL:** Joint R&D Cluster
- **3 PhD/MSci** graduated ’15
- **Chad Mitchell (LBNL)** – awarded DOE Early Career on IOTA (2016)
- Publications, wkshps, etc



First meeting since April 28-29 Workshop on IOTA

September 23, 2015

Accelerator Science Program in FAST/IOTA

Accelerator Science Program in FAST/ IOTA

- ***Laboratory, DOE and Community expectations: launching the first set of critical experiments by FY 18 – FY 19 time frame.***

- ***Scientific Output Expectations: first publications in journals no less reputable than Phys. Rev. Letters, Nature Physics, Science, Nature, ….***

- ***Lot of information and interest from April 28-29, 2015 IOTA workshop until now;***

- **GARD call for proposals from DOE → received more than half a dozen IOTA related proposals and has just funded a few starting this year.**

Science Program in FAST/ IOTA

3 High-impact Experiments in IOTA Ring

- **Space-Charge Compensation and Special Distributed Lenses and Induced Nonlinear Dynamics:**
  → *Electron lens, McMillan lens , etc. (funded through Fermilab)*

- **2-D and 3-D Nonlinear Resonances, Phase-space Kinetic Diffusion, Dynamic Arnold Diffusion and Hamiltonian Chaos**
  → *Proton beam diagnostics, instrumentation, measurements, mathematical and numerical modelling, collaboration with Paul Trap studies at Oxford/JAI (funded through DOE GARD at NIU)*

- **Single Electron Optical Stochastic Cooling in IOTA Ring**
  → *Need to have the undulators and photon detectors etc. in hand*
    → *possible collaboration with ANL*

Accelerator Science Program in FAST/ IOTA (cont'd)

2 High-impact Experiments in FAST Linac/Injector

- **Correlation of electron beam with 'radiators' in a chicane**
  → *Precursor to Optical Stochastic Cooling experiment in IOTA ring (driven by NIU)*

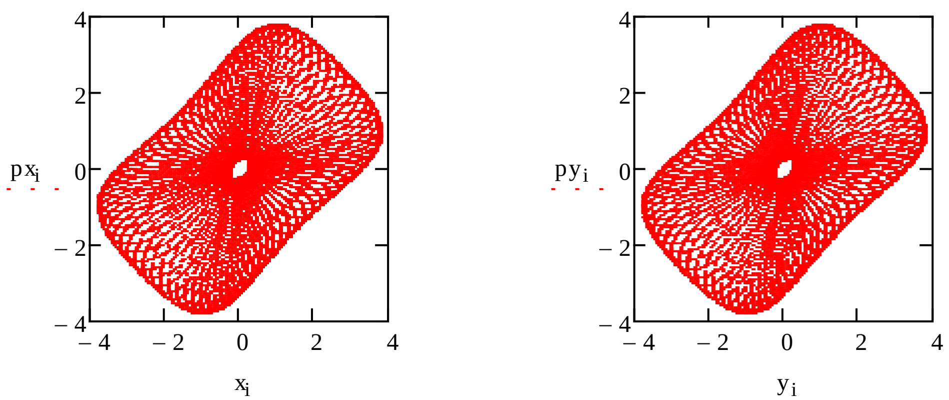
- **High Brightness Channelling X-ray radiation**
  → *Brightest x-ray source (driven by NIU)*

The list of IOTA Experiments Towards Post PIP-II

- E1-3: Integrable Optics (IO)
  - #1: IO with non-linear magnets, test with electrons
  - #2: IO with non-linear magnets, test with protons
  - #3: IO with e-lens(es), tests with protons
- E4-5: Space-Charge Compensation
  - #4: SCC with e-lens(es), test with protons
  - #5: SCC with e-columns, test with protons

E1: IO with NL magnets, test with e-

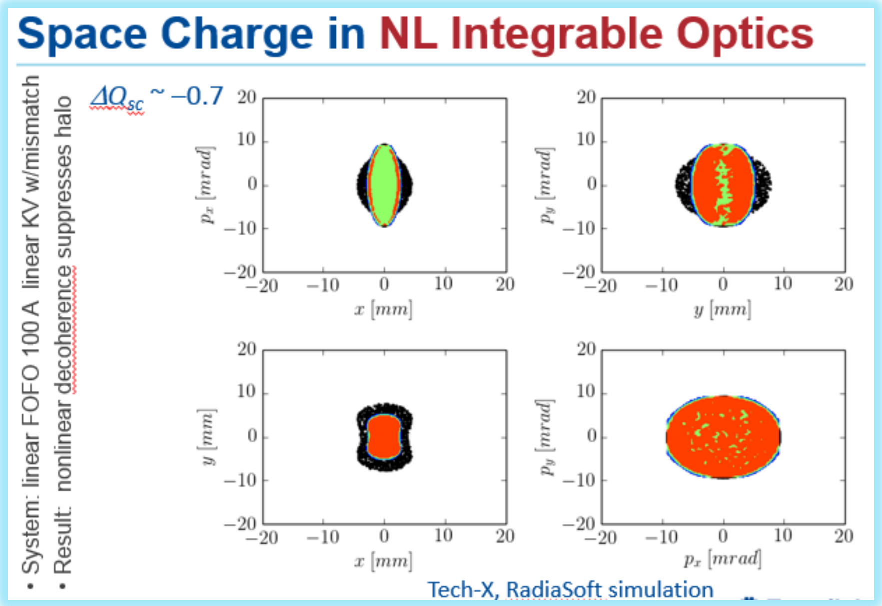
- Goals:
  - create integrable optics accelerator (system with add'l integrals of motion (transverse), Angular momentum and McMillan-type integral, quadratic in momentum)
    - "Reduced integrability" with octupoles
  - Confirm with pencil e- beam the IO dynamics



  - Confirm stability over tune spreads ~0.5/cell, can cross integer resonance

E2: IO with NL magnets, test with protons

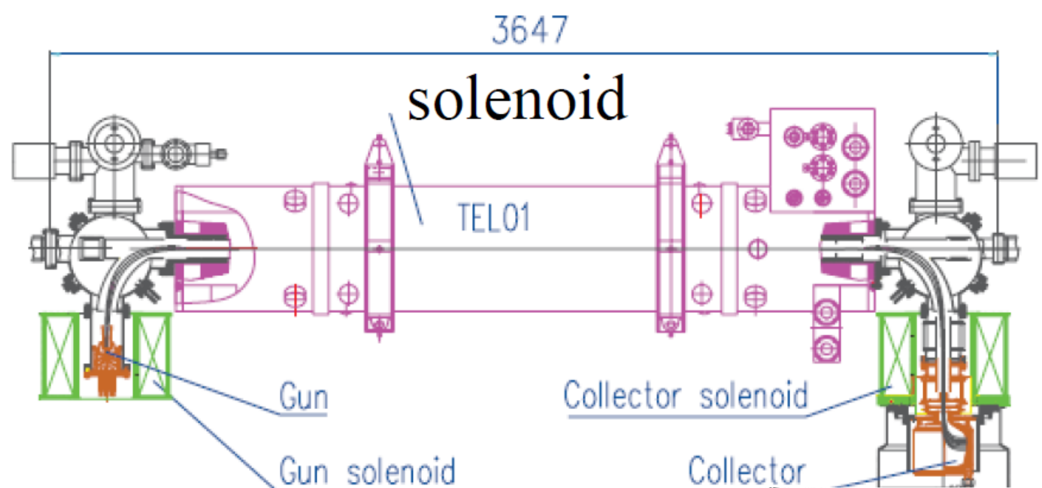
- **Goals:**
  - **to demonstrate nonlinear integrable optics** with protons with a large betatron frequency spread Δ*Q*>1 and stable particle motion **in a realistic accelerator design**
  - Expectations:
    - "No" space-charge losses
    - Acceptable stability to perturbations 3D
    - Stable coherent and incoherent dynamics



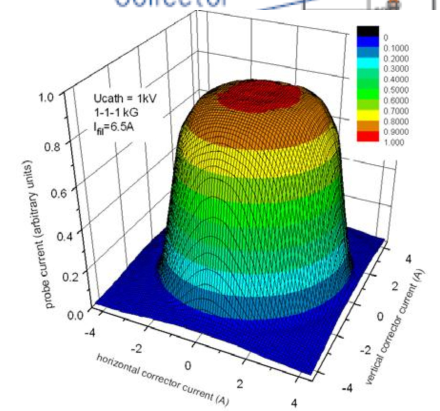
E3: IO with e-Lens, test with protons

- **Goals:**
  - **to demonstrate IO with non-Laplacian ELs** with protons with a large betatron frequency spread ΔQ>1 and stable particle motion **in a realistic accelerator design**

$$n(r) \propto \frac{I}{\left(ar^2+1\right)^2}$$

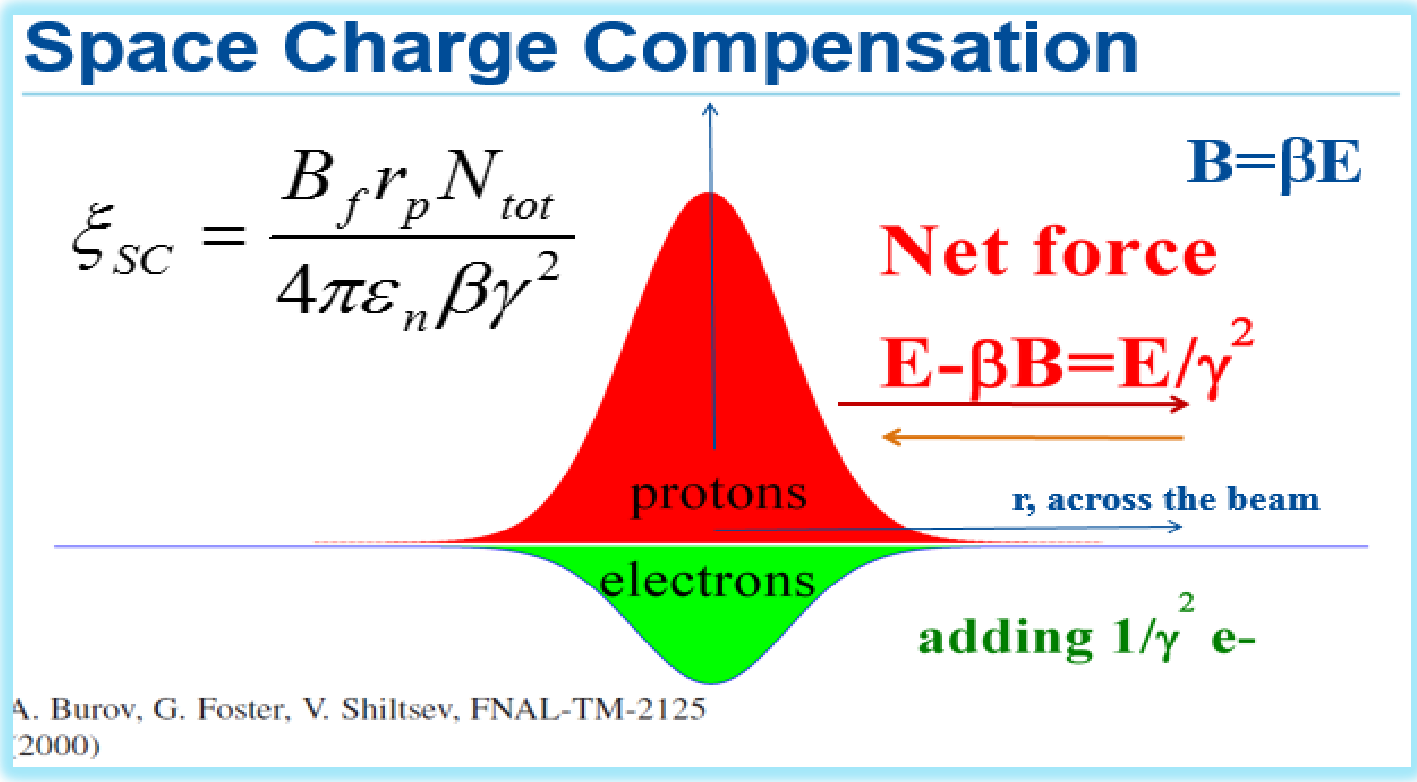


  - Expectations:
    - "No" space-charge losses with IO
    - Understand sensitivity to errors in *n(r)*
    - Stable coherent and incoherent dynamic



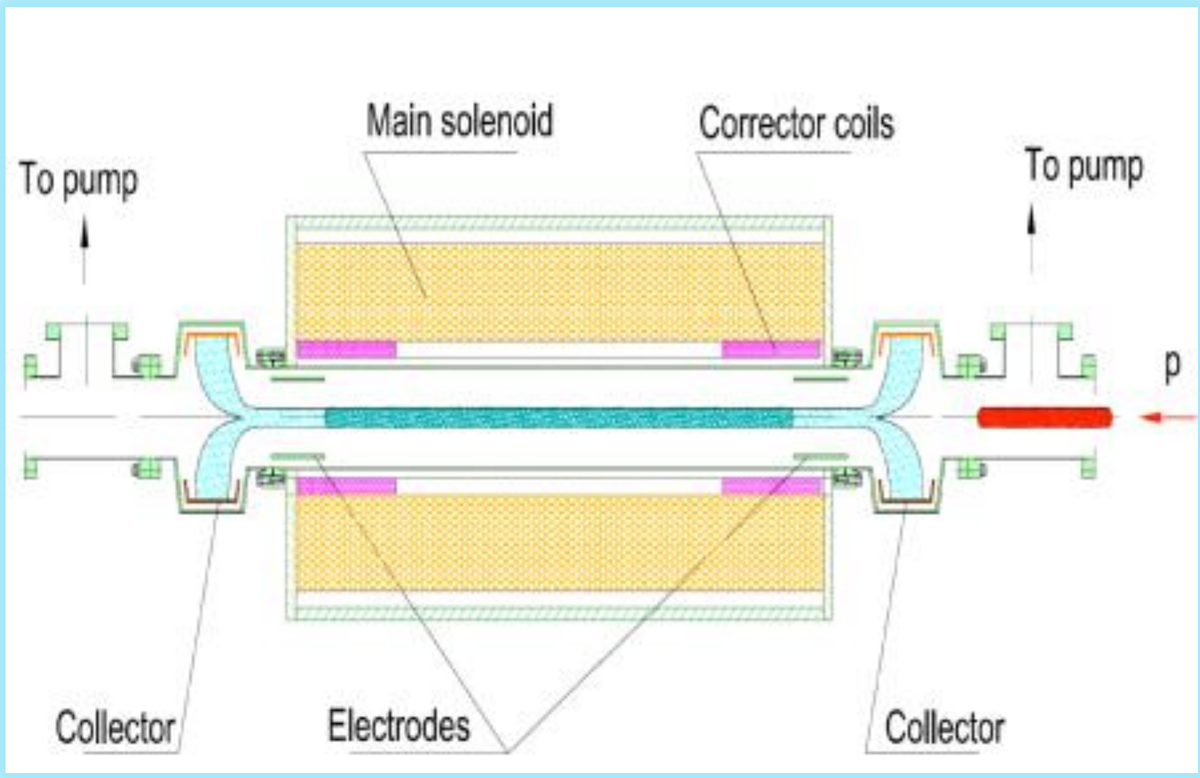
E4: SCC with e-Lens, test with p+

- **Goal:**
  - **to demonstrate SCC with Gaussian ELs** with protons with a large betatron frequency spread ΔQ>0.5 and stable particle motion **in a realistic accelerator design**



E5: SCC with e-Columns, test with *p+*

- **Goal:**
  - **to demonstrate SCC with electron columns** with protons with a large betatron frequency spread ΔQ>0.5 and stable particle motion **in a realistic accelerator design**



Students at IOTA/FAST

2015 Graduates

Sriharsha Panuganti

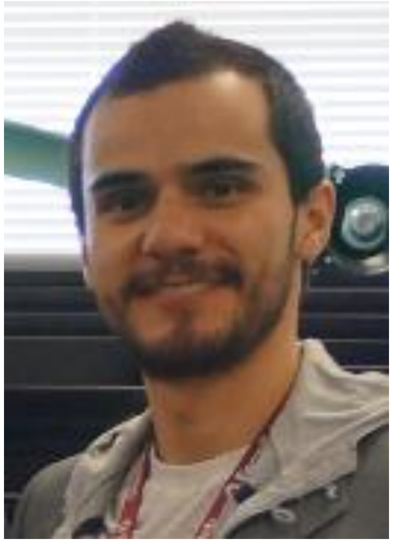
PhD

NIU

Frederic Lemery

PhD

NIU



David P. Lopez

MSci

Universidad de Guantajuato (Mexico)

2016 Inductees: Karie Badgley (PDRA, will also collaborate with JAI on IBEX) and Sebastian Suztowski (PhD student), both NIU

DOE Early Career Research Proposals

2016 Award

Chad Mitchell –

our collaborator from the Lawrence Berkeley National Laboratory, Berkeley, CA - selected by the Office of High Energy Physics for the Early Career Research Proposal award "*Compensation of Nonlinear Space Charge Effects for Intense Beams in Accelerator Lattices*"

Partners (to date)

- Fermilab
- NIU
- Univ. of Chicago
- Univ. of Maryland : Unique collaboration on simulating IOTA physics using UMER electron ring facility (Rami Kishek)
- Berkeley Lab : Theoretical formulation (Chad Mitchell)
- Univ. of Oxford : Unique collaboration on simulating IOTA physics using IBEX facility, a Paul Trap!! (Suzie Sheehy)
- Univ. of Hiroshima
- RadiaSoft : Simulations and Modelling (David Bruhwiler)
- RadiaBeam: Building special-purpose nonlinear magnets
- Tech-X: Particle-in-cell codes (John Cary)

Opportunities in PhD Research in Accelerator Science and Technology at Fermilab and Associated Collaborating Universities

(Northern Illinois University, Univ. of Chicago, University of Illinois at Urbana-Champaign, Illinois University of Technology at Chicago, Northwestern University, University of Maryland, etc.)

→ *University of Oxford a partner!!!*

1. Nonlinear Dynamics – Theory and Experiment
2. Experimental Implementation in IOTA
3. Experiments on Arnold Diffusion and Nonlinear Diffusion
4. Complementary "Paul Trap" studies in JAI-RAL IBEX facility
5. Demonstration of Optical Stochastic Cooling of Phase Space
6. Experiments on Quantum Optics with a Single Electron in IOTA

People's Fellowship, post-doctoral positions and joint university-lab faculty positions open for applications (see advert in Physics World, CERN Courier, etc.).

Thank you!!