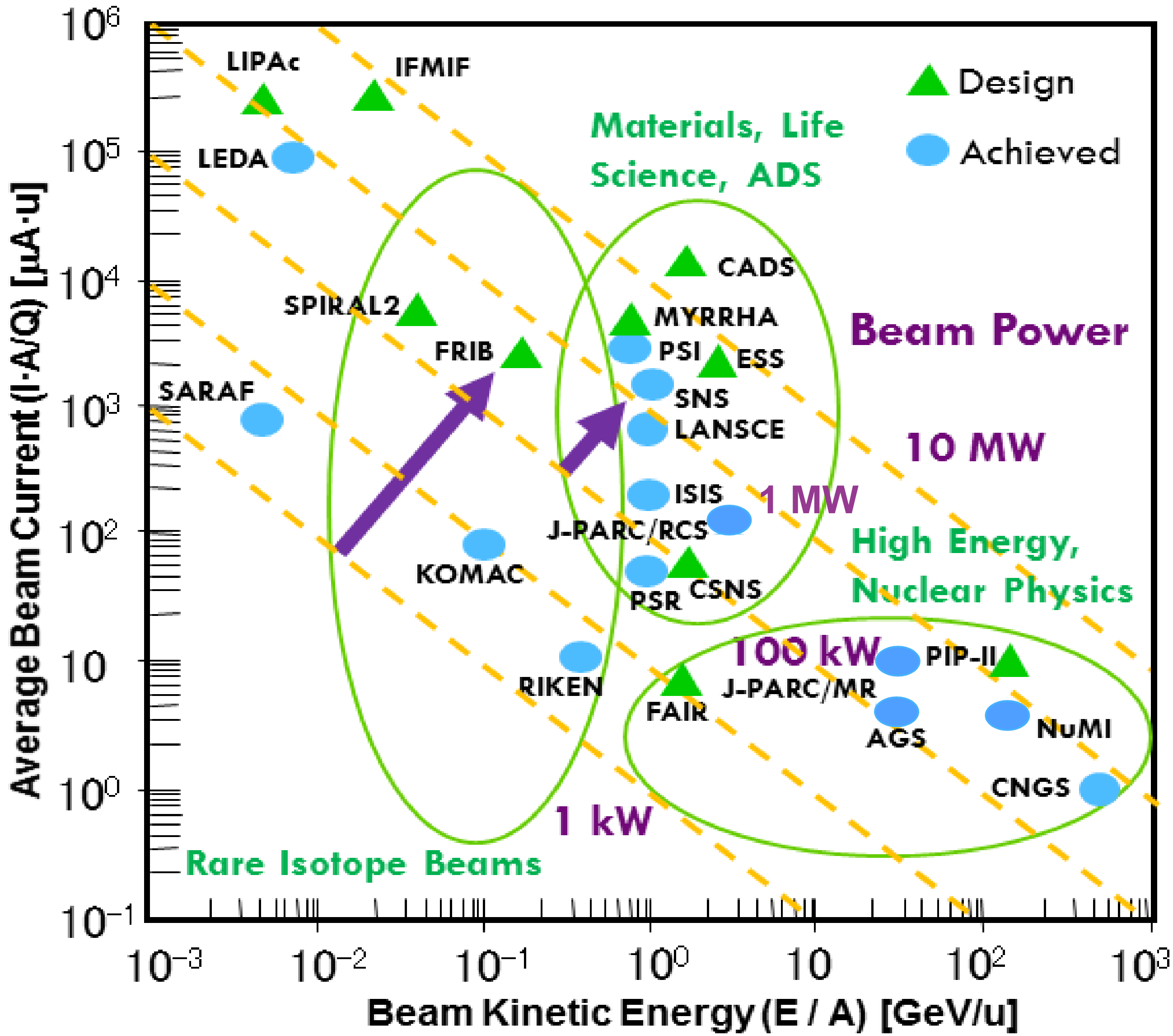
SRF2017
Lanzhou, China, July 21, 2017

Next Generation Neutrino Facility for Long Baseline Oscillation Experiment by Multi-MW Proton SC Accelerator

Tadashi Koseki

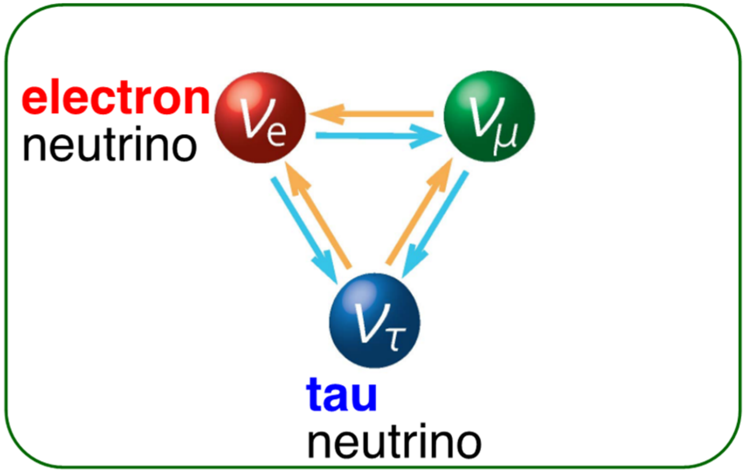
J-PARC center, KEK&JAEA

Hadron accelerators in the world



J. Wei / Y. Yamazaki

Neutrino Oscillation



$$s_{ij} = sin\theta_{ij}\ , \qquad c_{ij} = cos\theta_{ij}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}\, e^{-i\delta_\nu}\\ 0 & 1 & 0\\ -s_{13}\, e^{i\delta_\nu} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$\Delta m^2_{21} = m^2_2 - m^2_1\ , \Delta m^2_{32} = m^2_3 - m^2_2,\ \Delta m^2_{31} = m^2_3 - m^2_1$$

$$\Delta m^2_{21} + \Delta m^2_{32} - \Delta m^2_{31} = 0$$

Neutrino oscillation is characterized by six independent parameters, $\theta_{ij}, \delta_\nu\ , two\ of\ \Delta m^2_{ij}$

Neutrino Oscillation in Particle Physics

Observation of the neutrino oscillations:

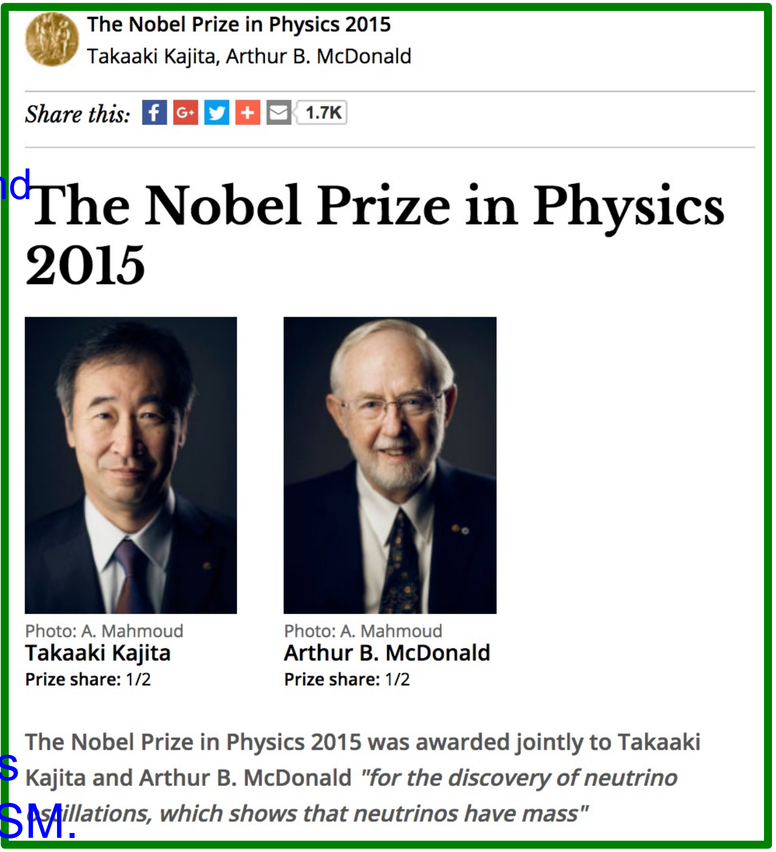
In 1998: Oscillation of atmospheric neutrinos (Δm_{32}^2, θ_{23})

→ confirmed by accelerator experiments.

In 2001: Oscillations of solar neutrinos (Δm_{21}^2, θ_{12})

→ confirmed by reactor experiments.

In 2011-2013: Oscillations with θ_{13} (Δm_{32}^2) by reactor and accelerator experiments



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/

Neutrino is still mysterious particle in particle physics

Non-zero mass is a hint of physics beyond the SM.

- extremely small mass with unknown reason.
- large mixing in contrast with the quark sector.

Is CP violated in the neutrino sector ?

- A possible explanation for matter dominated universe

Long baseline neutrino oscillation experiments

	Baseline (km)	Energy (GeV)	Mass (ton)	Starting year	#Events
* T2K	295	0.6	32k	2010~	37 ν_e, 4 $\overline{\nu}_e$
* NOvA	810	2	14k	2013~	33 ν_e
* OPERA	730	17	1.2k	2006~	5(+5) ν_τ
* ICARUS	730	17	0.6k	2010~	
MINOS(+)	730	2~10	5k	2005~	
* DUNE	1300	2~3	40k	2026~	O(1000) ν_e
* Hyper-K	295	~0.6	190k	2026~	O(1000) ν_e
ESSnuSB	360, 540	~0.3	500k	2030~	
T2HKK	295+1100	~1	190k+190k	TBA	O(1000) ν_e

T. Nakaya, "Neutrino Physics from Particle Beam and Decay Experiments", EPS conference on High Energy Physics, Venice, July 5-12, 2017.

$\nu_\mu \rightarrow \nu_e$ appearance and CPV

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Delta_{31}$$ Leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

$$\mp 8C_{13}^2 C_{23} S_{12} S_{13} S_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPV

$$+4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \frac{(\pm a)L}{4E_\nu}(1-2S_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$

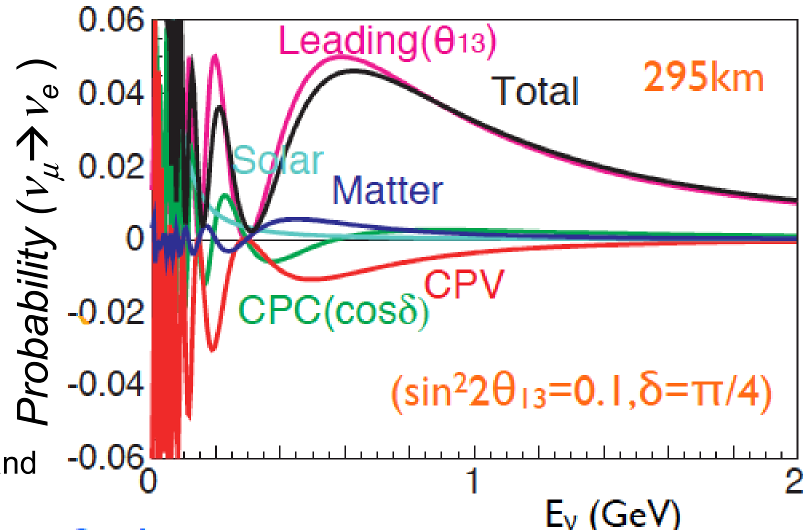
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{(\pm a)}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}$$ Matter effect

$$S_{ij} \equiv \sin\theta_{ij}, C_{ij} \equiv \cos\theta_{ij}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/E$$

Leading term

$$\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$



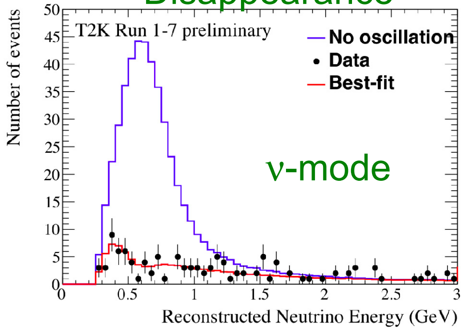
T. Nakaya, “Neutrino Physics from Particle Beam and Decay Experimentsin”, EPS-HEP 2017.

T2K and NOvA

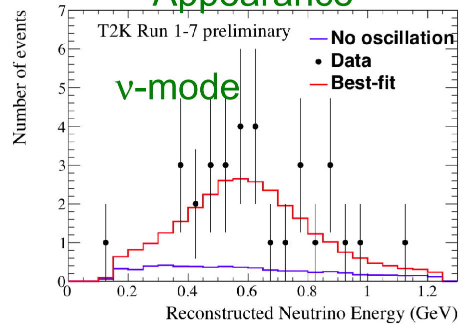
Paul Derwent,
in APS Meeting 2017

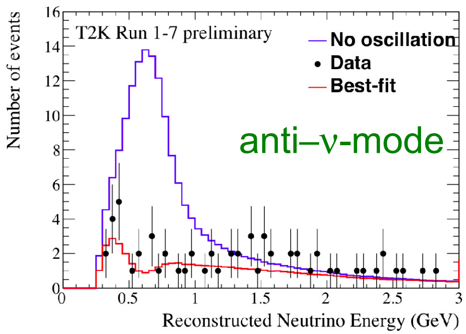
Recent T2K&NOvA results

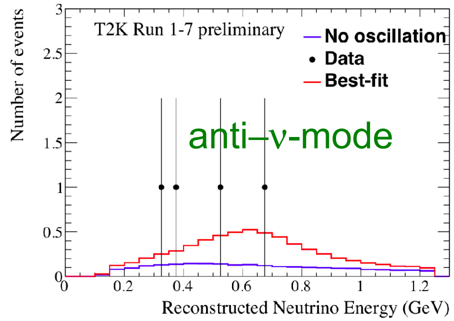
Disappearance



Appearance

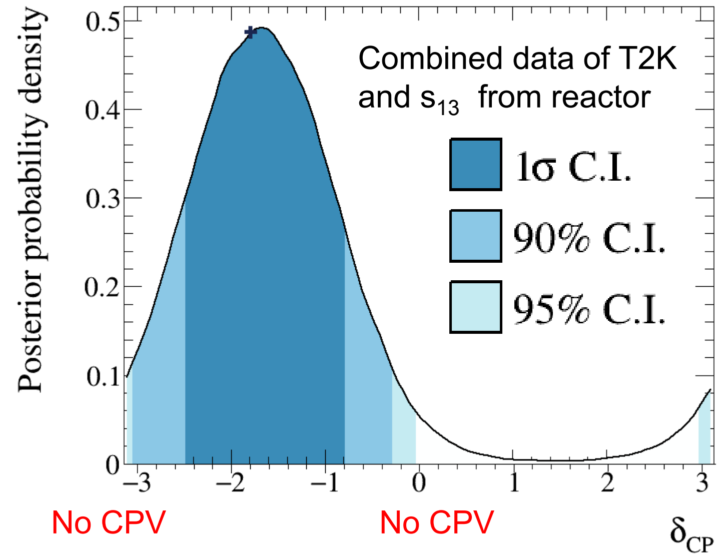


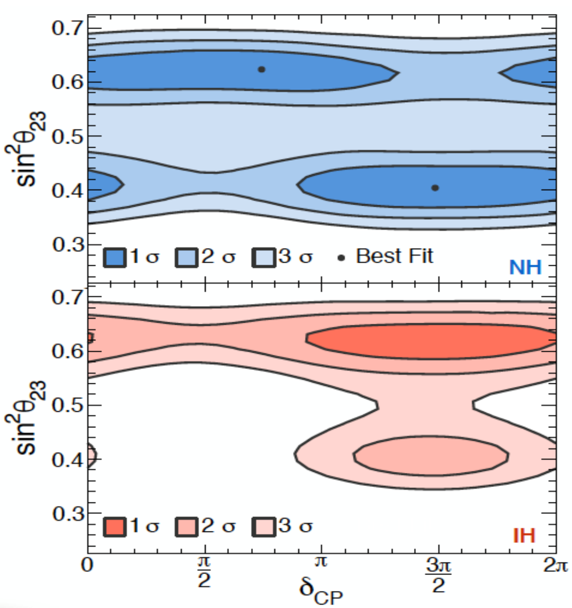




From presentations in ESP conf. HEP, 5-12, July, 2017.

Leila Haegel, "Latest neutrino oscillation results from T2K"

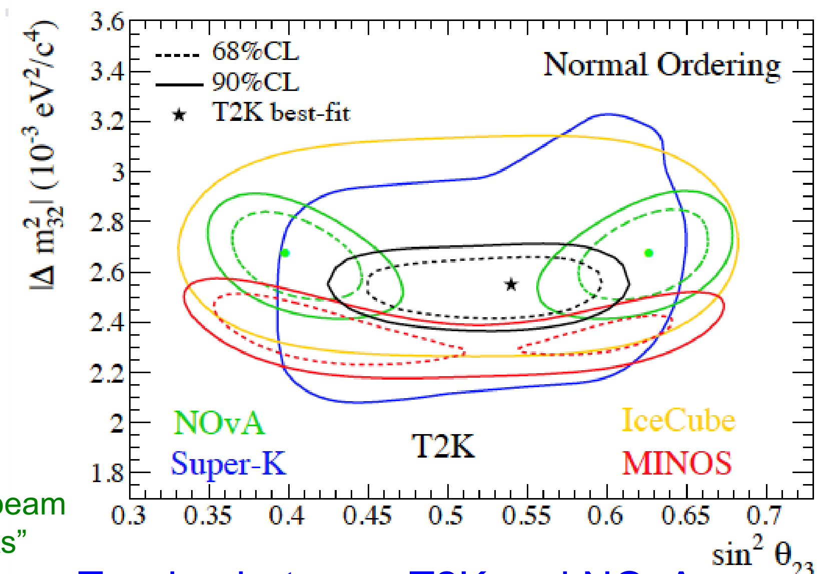




B. Zamorano, "Latest oscillation results from the NOvA experiment"

Best fit to NH:
$\delta CP = 1.49\pi$,
$\sin^2\theta_{23} = 0.40$

T. Nakaya, "Neutrino physics from particle beam and decay experiments"



Tension between T2K and NOvA

Recent T2K&NOvA results

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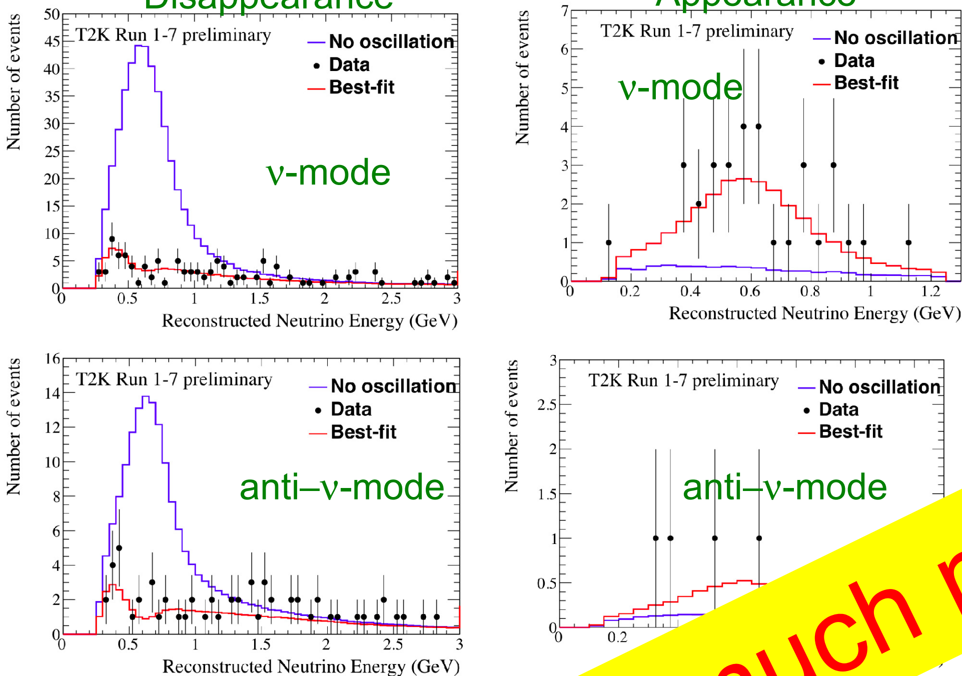
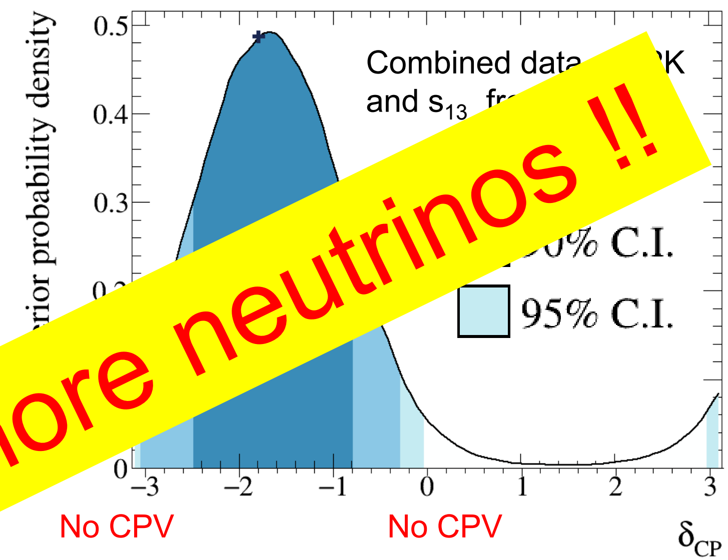
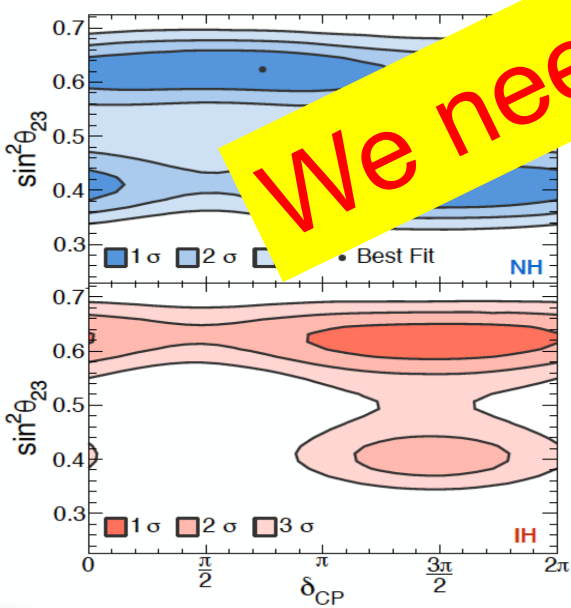




We need much more neutrinos !!



…, Latest …n results from … NOvA experiment”

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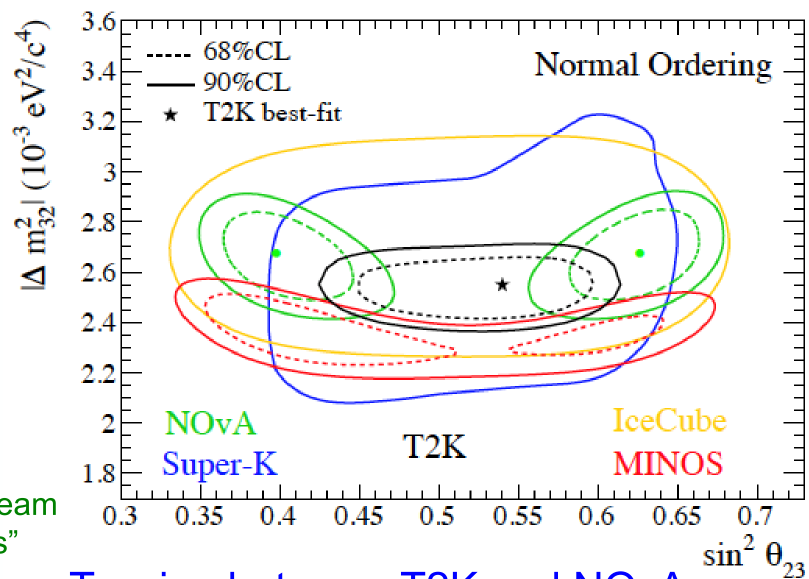
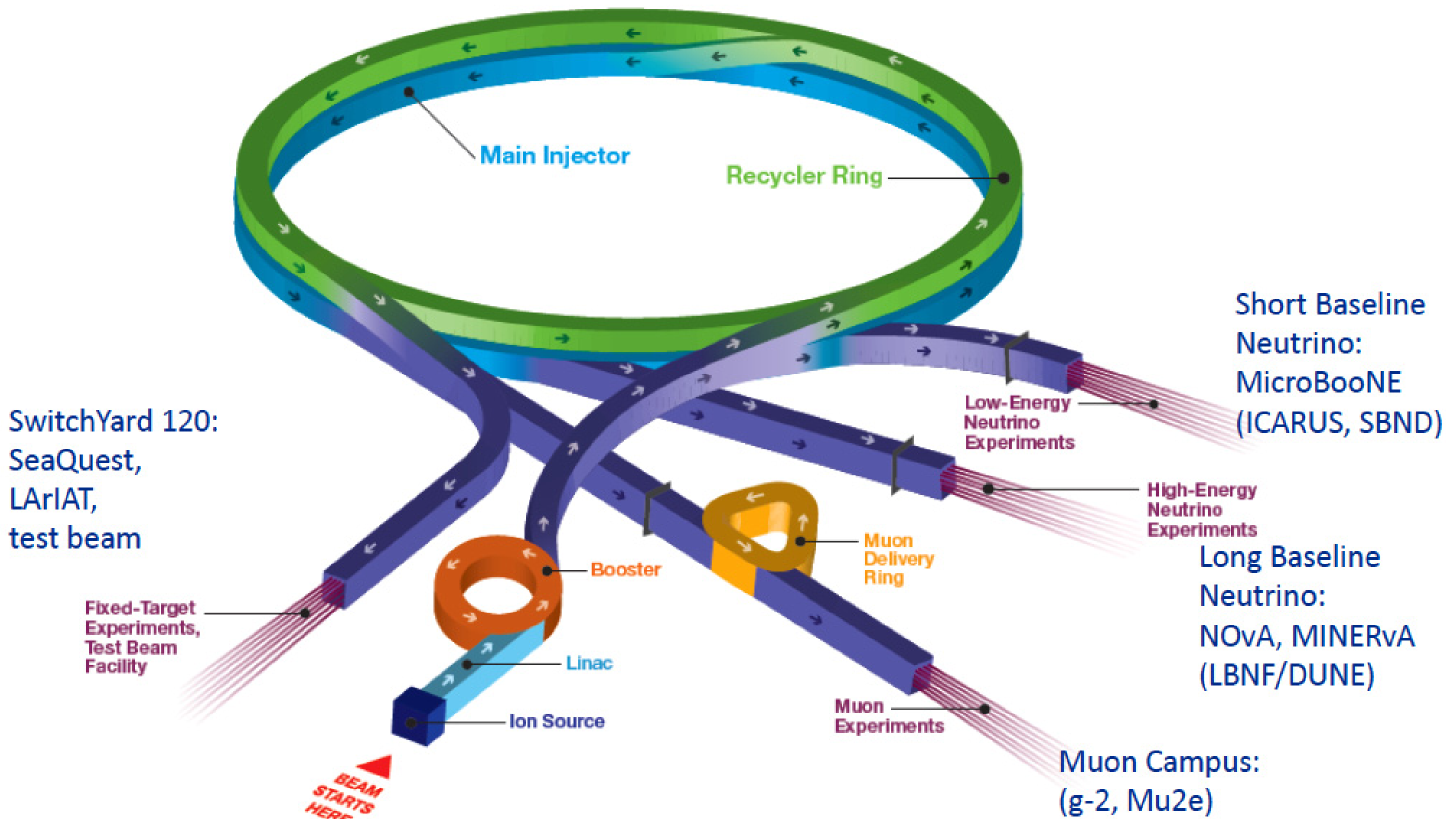


Tension between T2K and NOvA

Fermilab Accelerator Complex (enabled by PIP-I)

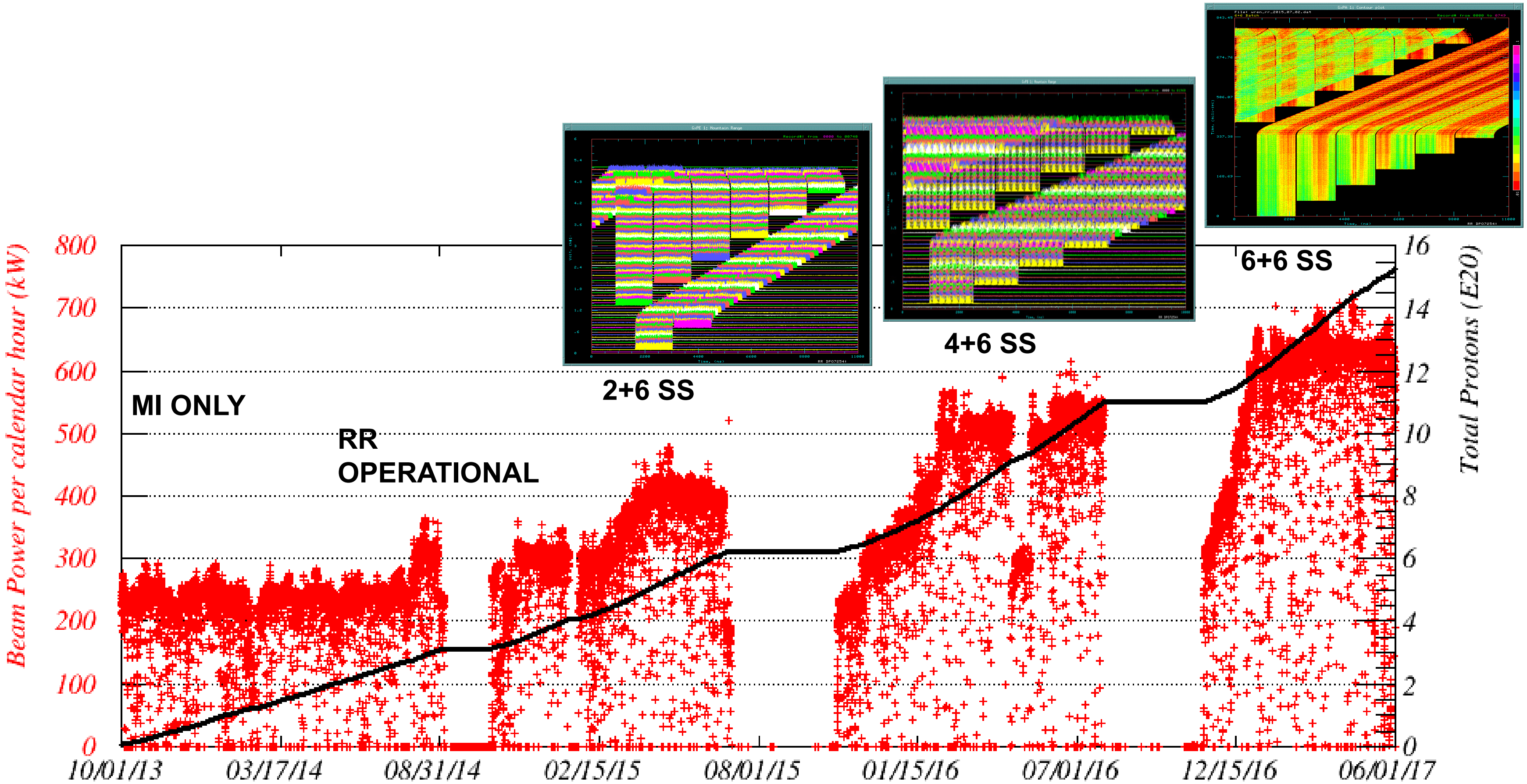
H$^-$ linac : Accelerates H$^-$ to 400 MeV
Booster : 400 MeV → 8 GeV at 15 Hz since June 2015 , h=84
Beam delivery to RR/Low energy neutrino experiments
Recycler Ring: a permanent magnet accumulator ring in the MI tunnel, h=588 (7*84)
6+6 booster batches are injected to RR using slip-stacking
Beam delivery to the MI and the Muon campus simultaneously.
Main Injector: 8 GeV →120 GeV at 1.33 s cycle time
Beam delivery to high energy neutrino experiments /SY120



Courtesy of S. Nagaitsev

MI Beam power and beam delivery to NuMI

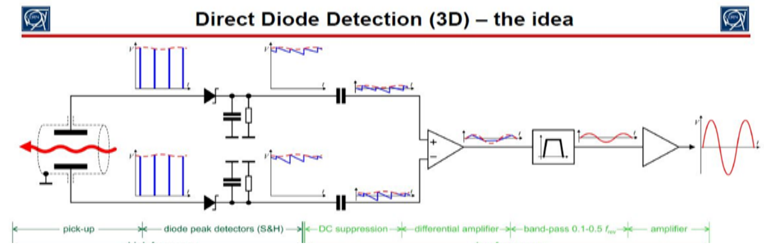
MI Beam Power and Beam Delivered since the shutdown of accelerator upgrade



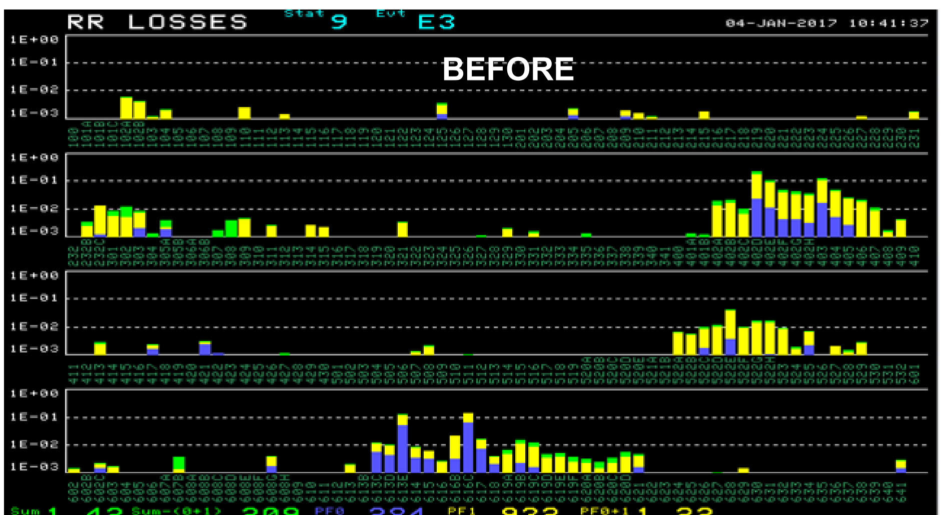
Beam power 700 kW, performance goal of PIP, has been achieved.

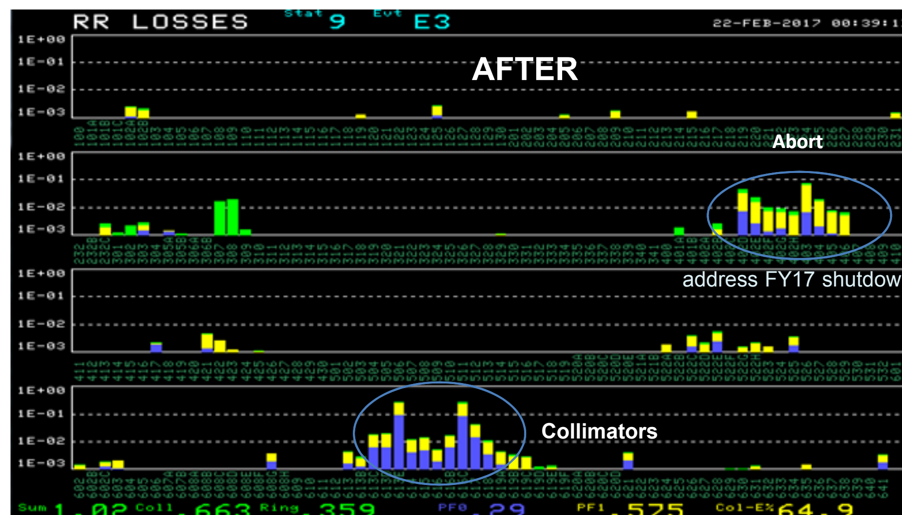
Accumulated ~1.6×10^{21} POT from 2013

Recycler collimators and new damper (reduce/control loss)



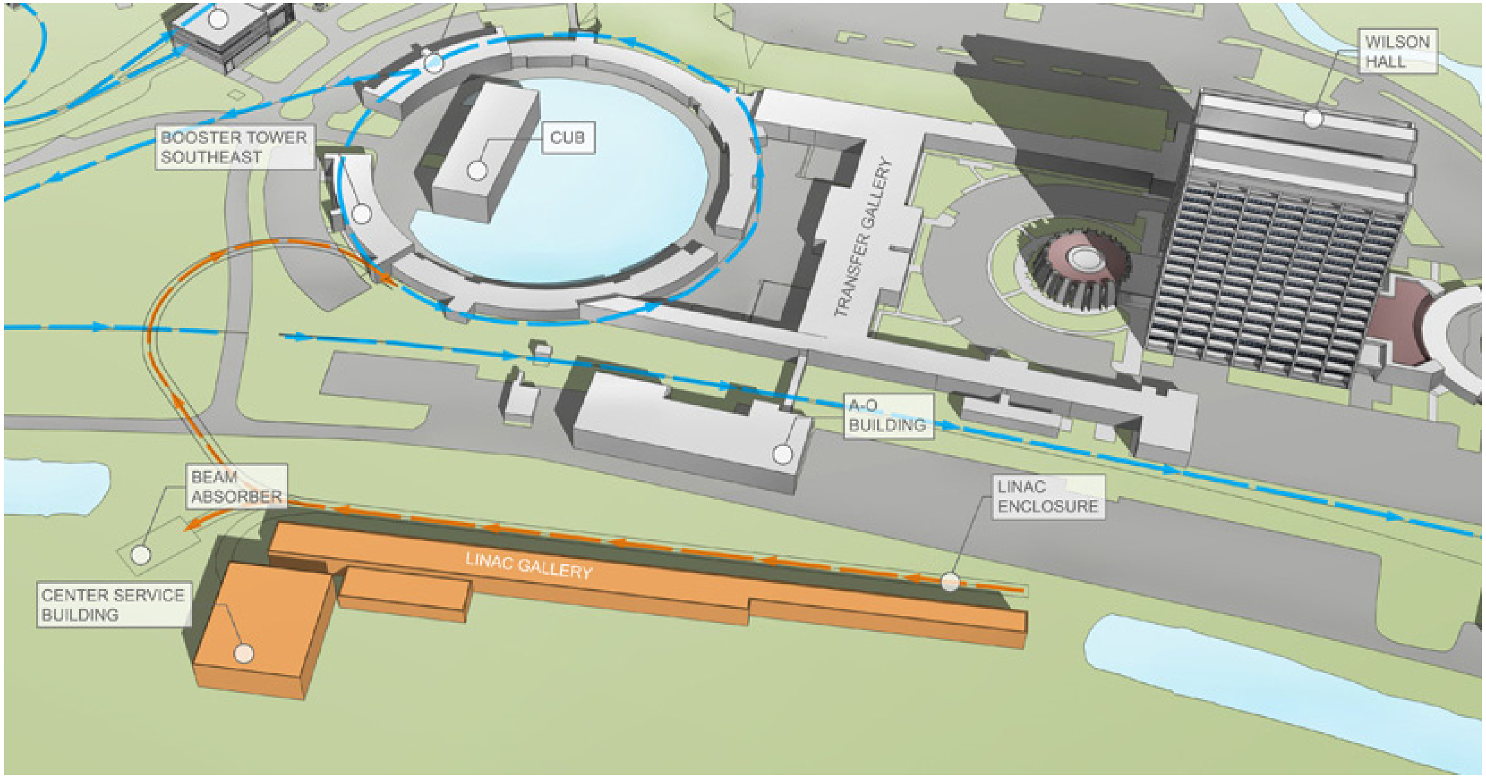
- Bunch-by-bunch damper didn't work when bunches overlapped during slip stacking
- Implemented diode frequency damper
- No longer need for high chromaticity during slip stacking
- Reduced losses from tune shift



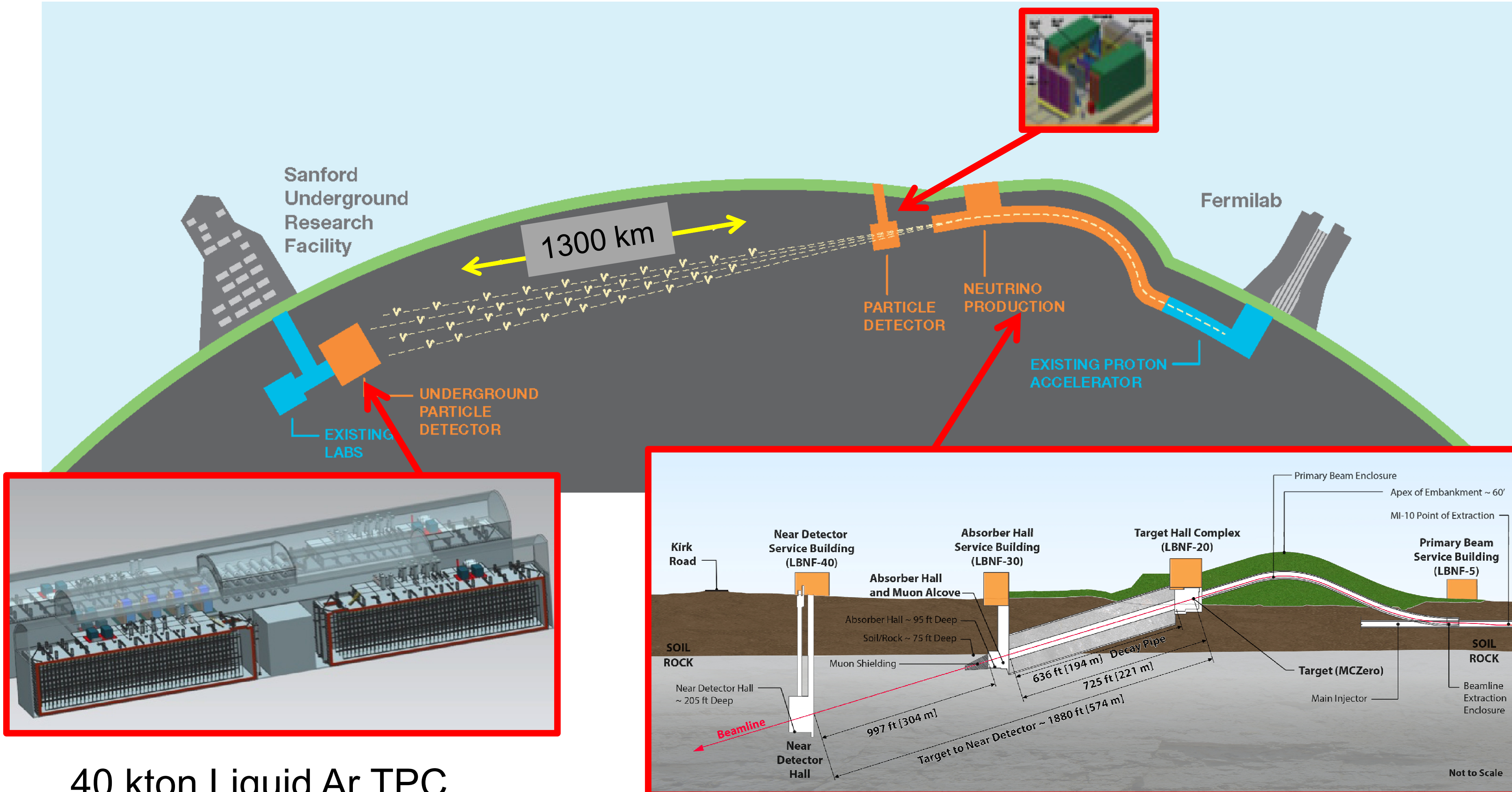


Beyond 700 kW: PIP-II

PIP-II project aims to provide >1 MW starting in 2025 (time of LBNF startup) with new 800-MeV cw-capable superconducting Linac to increase booster beam current.



PIP-II, LBNF and DUNE

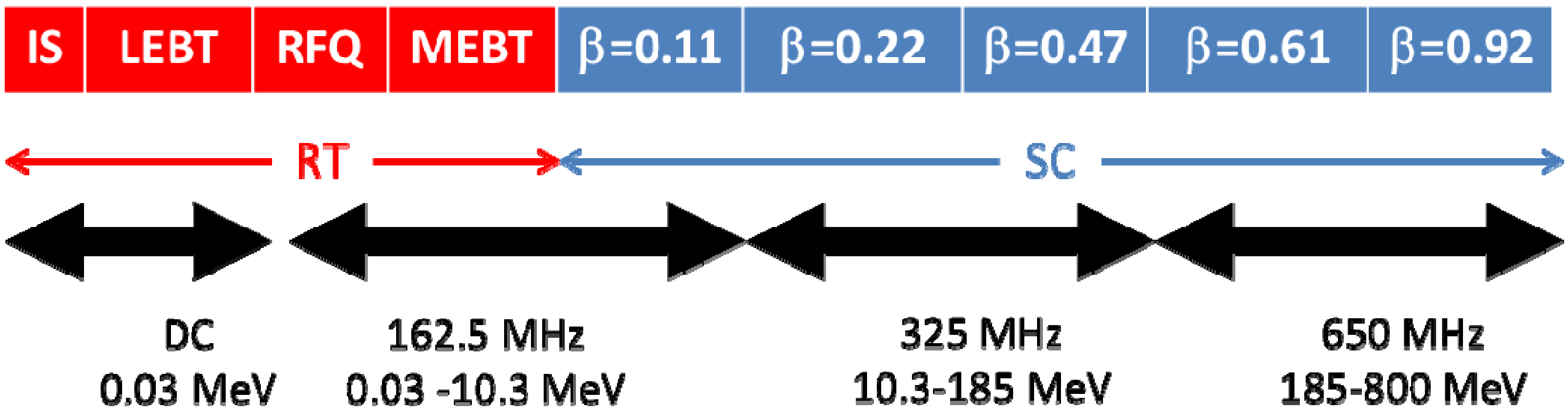


40 kton Liquid Ar TPC

- Observation of CP violation
- Precise measurement of CP phase
- Determination of mass hierarchy….

S. Nagaitsev

Scope/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

Courtesy of S. Nagaitsev

M. Kelly, “SRF Technologies for PIP-II and III”, this conference.

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	0.54	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	17	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	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{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

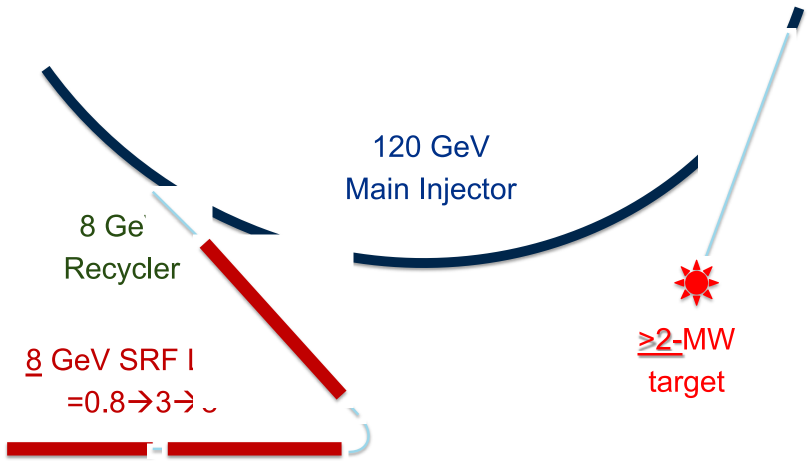
*NOvA operations at 120 GeV

Paul Derwent "PIP-III and Future Opportunities in the U.S. Neutrino Program" in APS Meeting 2017

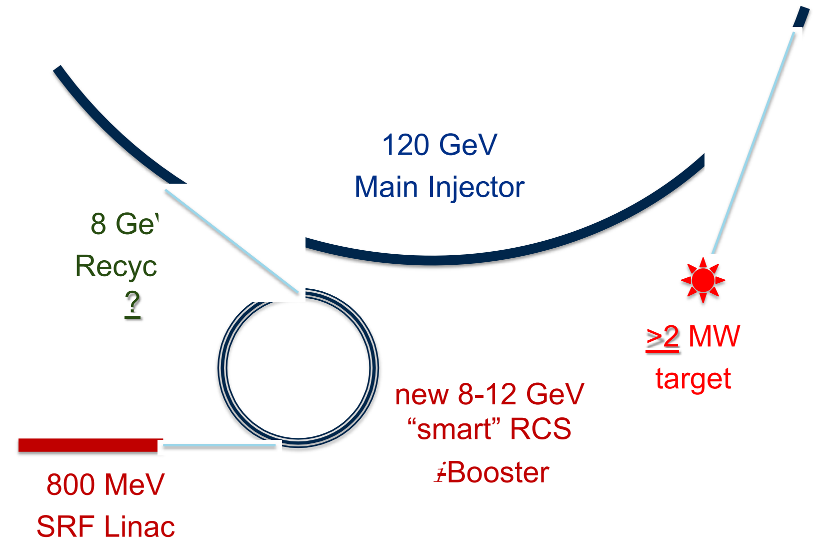
For the physics goal of DUNE, 40 kton with 1.2 MW is 20 years program.
→ More beam intensity

PIP-III

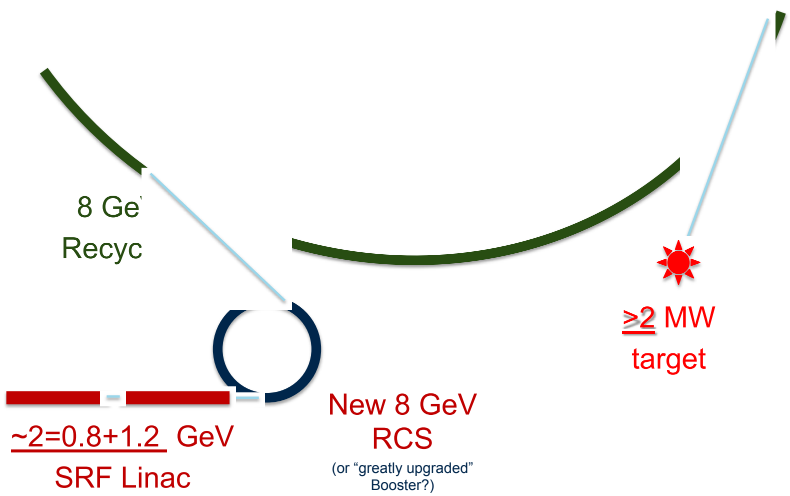
PIP-III "multi-MW" -Option A



PIP-III "multi-MW" -Option C



PIP-III "multi-MW" -Option B



Sergei Nagaitsev ,"High Power Proton Beams for Particle Physics ",
11th ICFA seminar on Future Perspective in High Energy Physics

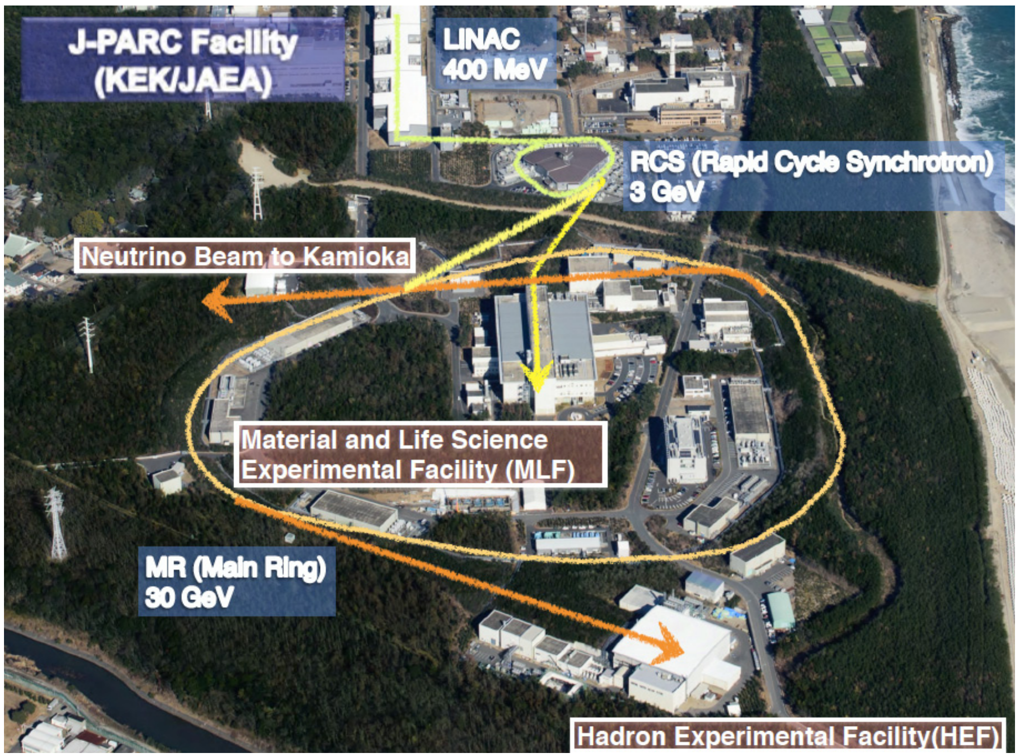
Comparison of Parameters

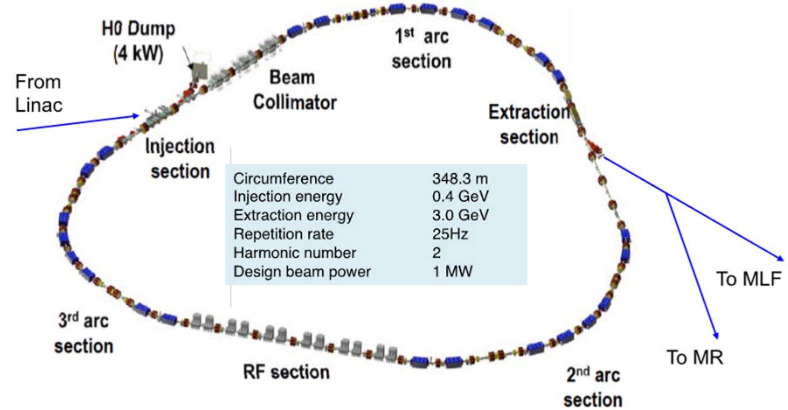
		PIP-II (Existing Booster)	New 8 GeV Linac	New 8 GeV RCS	units
MI/Recycler					
	Beam Energy	120	120	120	GeV
	Cycle Time	1.2	1.2	1.45	sec
	Protons per pulse	7.5E+13	1.6E+14	1.9E+14	ppp
	Beam Power	1.2	2.5	2.5	MW
Proton Source					
	Injection Energy (Kinetic)	0.8	0.8	0.8-2.0	GeV
	Extraction Energy (Kinetic)	8.0	8.0	8.0	GeV
	Protons per Pulse	6.4E+12	1.6E+14	3.2E+13	
	Beam Power to Recycler/MI	82	168	168	kW
	Beam Power to 8 GeV Program	82	3872	645	kW

~4x record Main Injector ppp

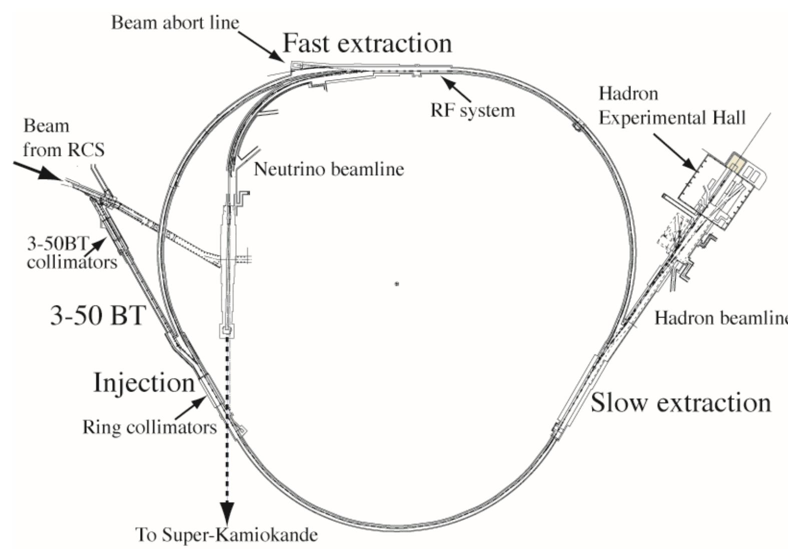
Paul Derwent, “PIP-III and Future Opportunities in the U.S. Neutrino Program” in APS Meeting 2017

J-PARC





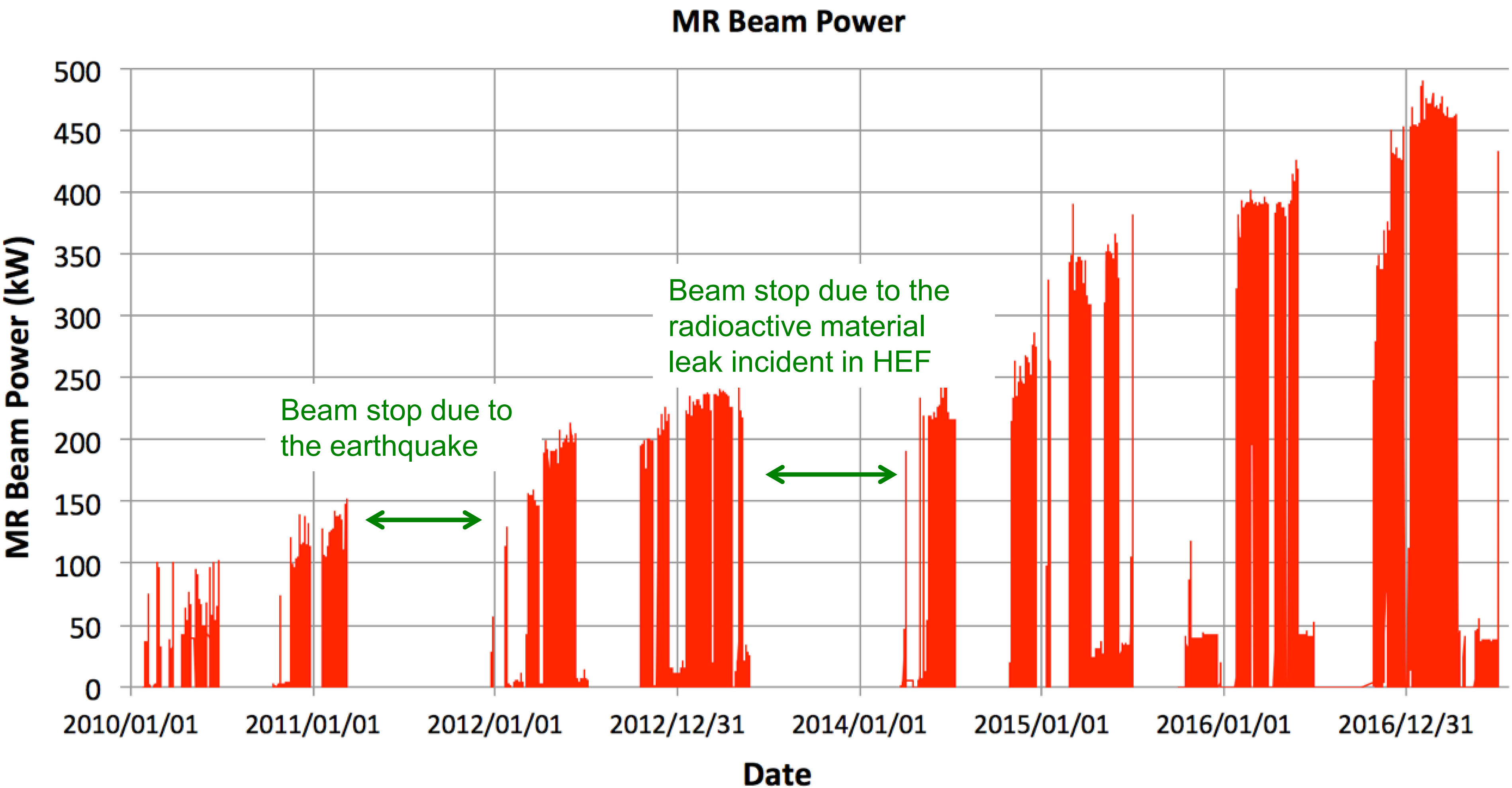
RCS is proton driver for neutron/muon production in MLF and booster for the MR.



- 400-MeV H- linac
- 3-GeV RCS with 25 Hz
- 30-GeV MR with cycle time of 2.48/5.52 sec

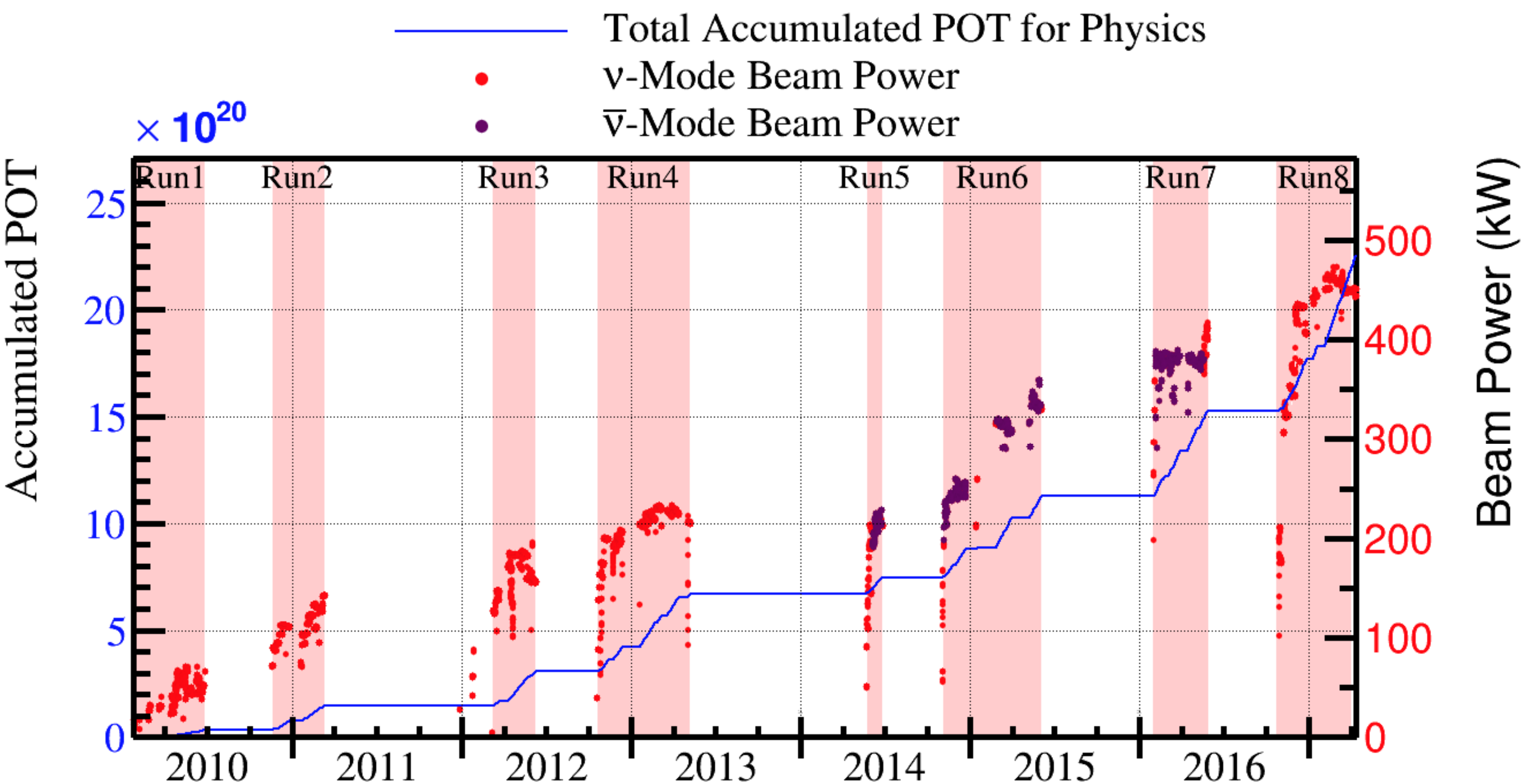
MR has a lattice of imaginary transition γ and two extraction modes (FX and SX).

History of MR beam power



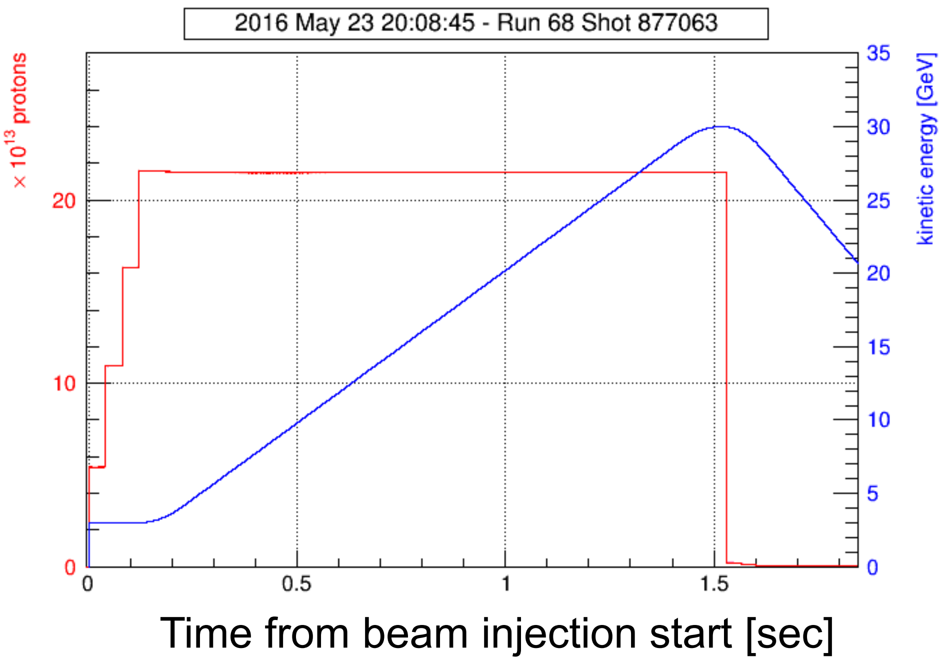
Achieved beam power:
Fast extraction ~ 470 kW (2.4 x10^{14} ppp) for users, 516 kW for demonstration.
Slow extraction ~ 44 kW (5.1 x10^{13} ppp) for users , 50 kW for demonstration.

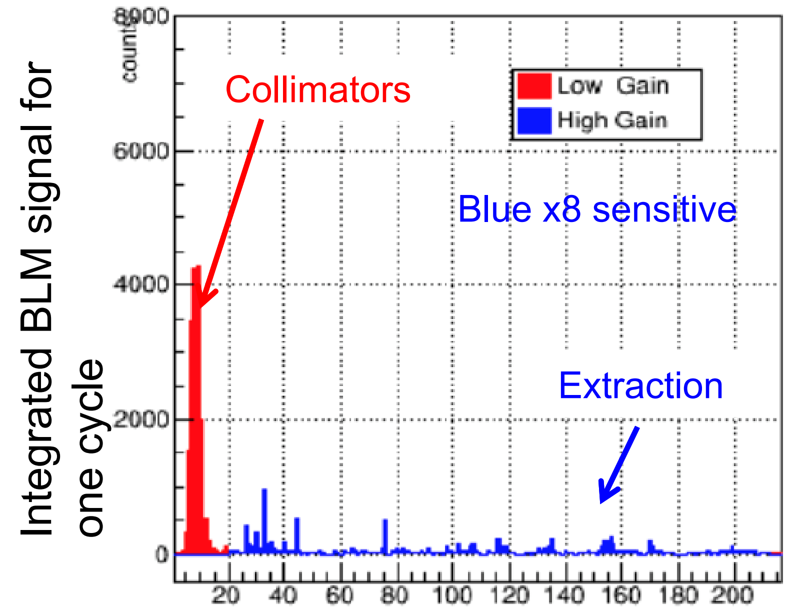
Beam power and POT of T2K

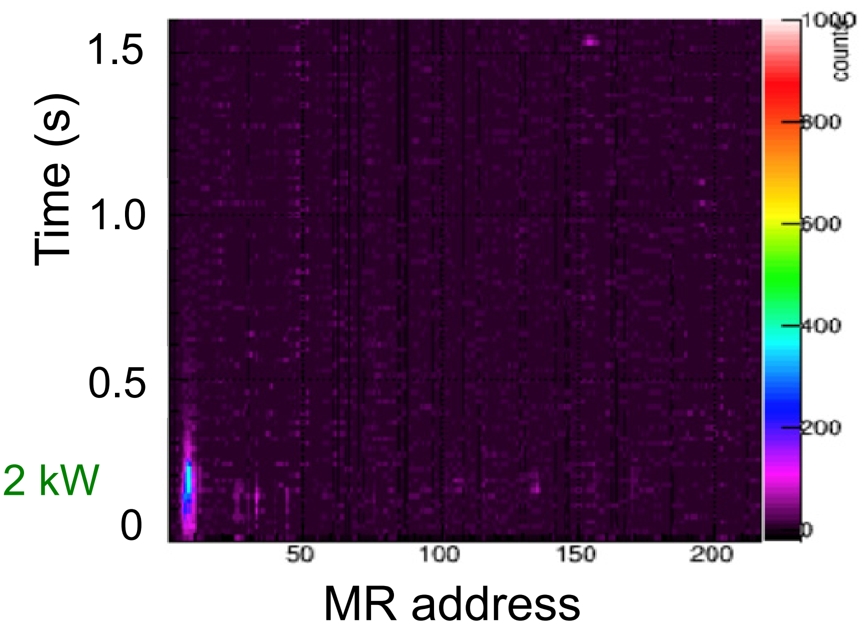


Accumulated from 2010: 2.25×10^{21} POT (29 % of approved)
Neutrino Beam : 1.49×10^{21} POT
Anti-Neutrino Beam : 0.76×10^{21} POT

Typical user operation of MR-FX



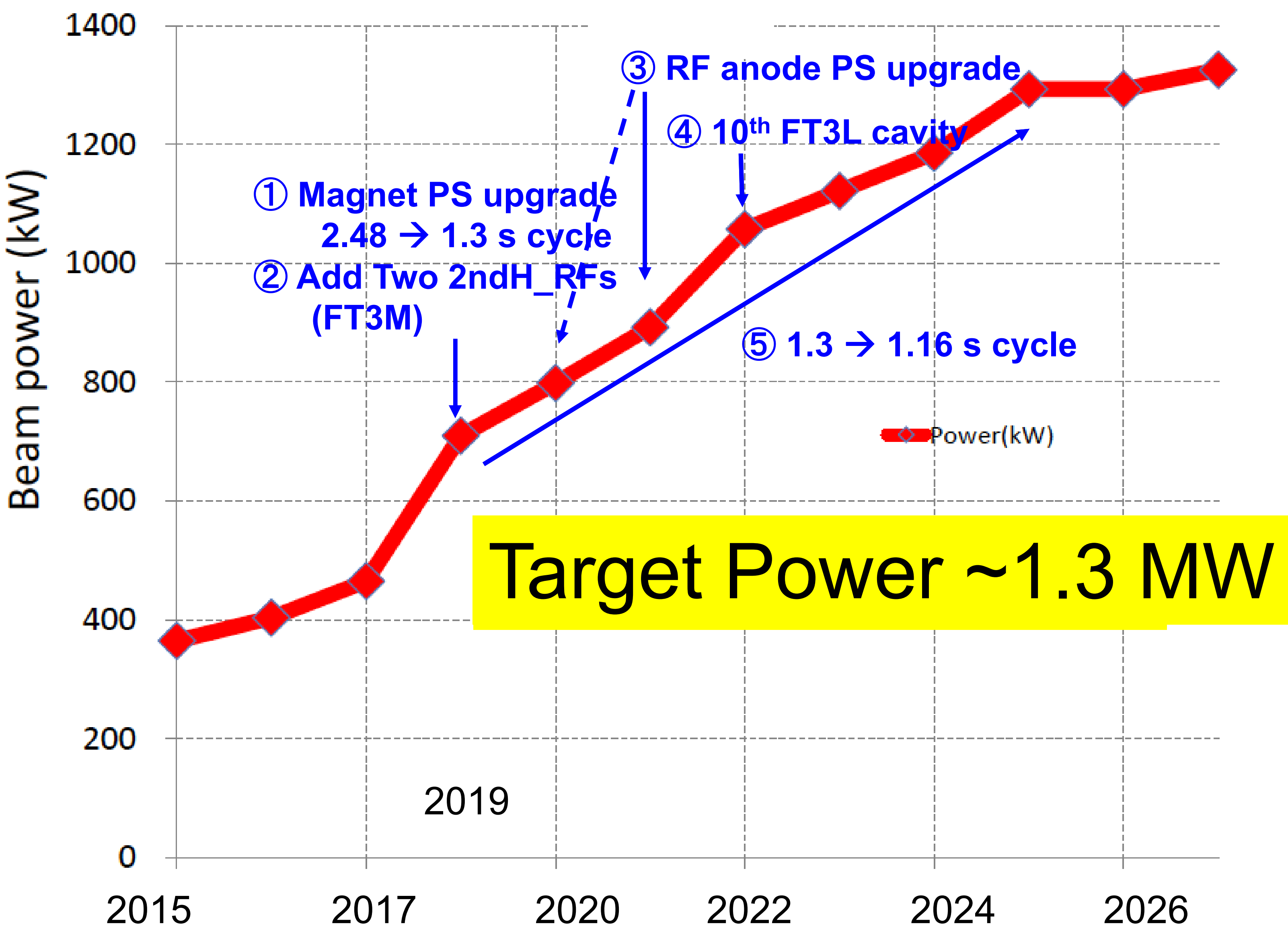




Power : 473 kW @ 2.48 sec
2.44e14 ppp
3.05e13 ppb

Loss at MR ~ 800 W < MR collimator limit of 2 kW .
Loss at 3-50BT <100 W < 3-50BT collimator limit of 2 kW

Mid-term plan of MR upgrade for FX



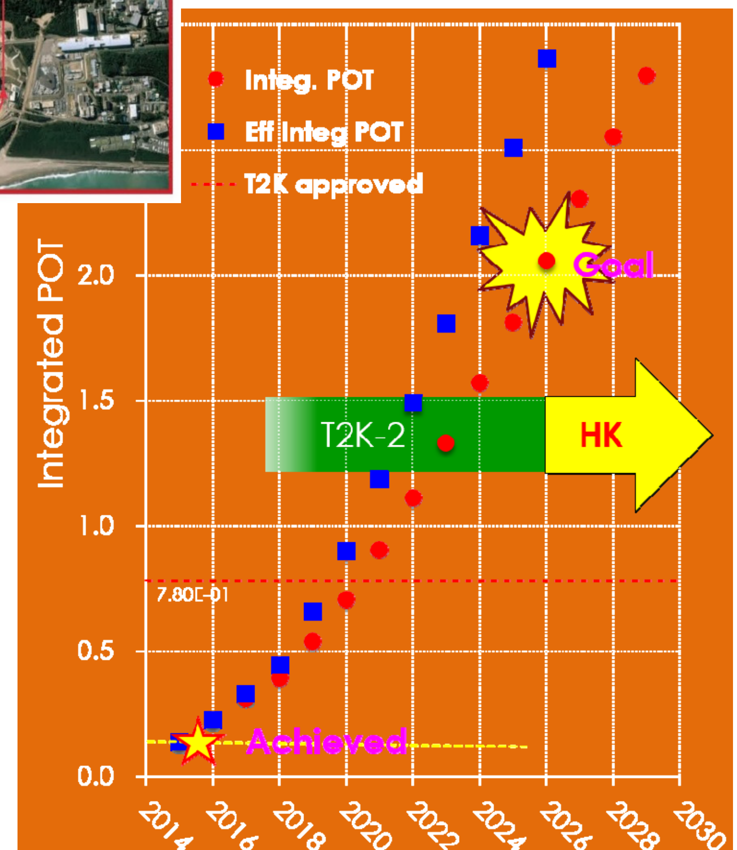
Hyper-Kamiokande (2026 -)

T. Kobayashi/T. Nakaya

Hyper-K:
190 kton Water Cerenkov detector
A new PMT has x2 better photon sensitivity

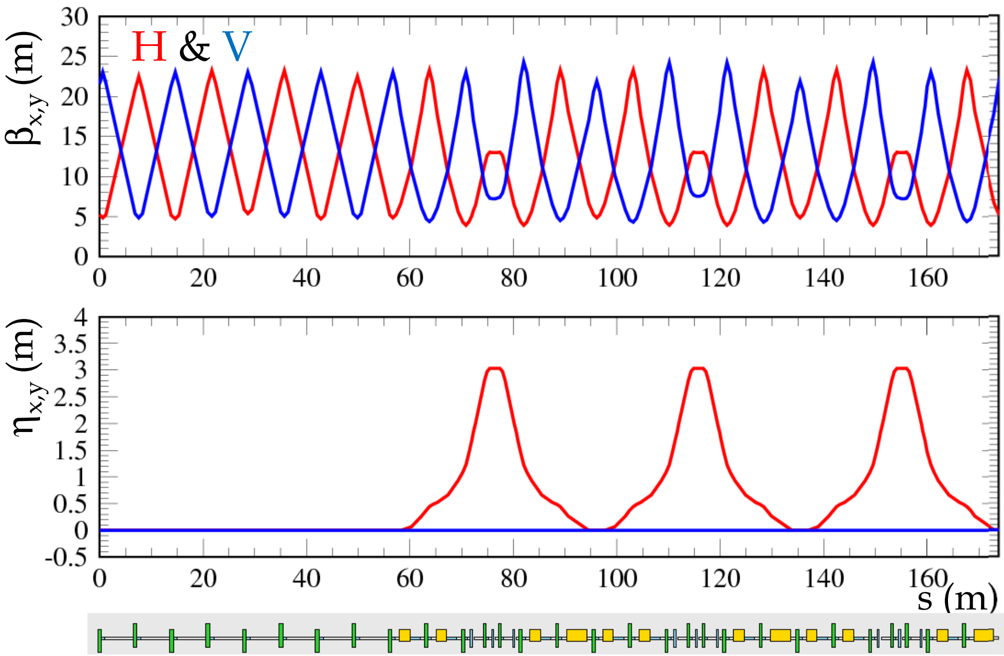
- Beam power : 1300 kW
- Distance : 295km
- Detector : HK (190 kt)
  - T2HKK: Idea of 2nd detector in Korea (~1000km) is under discussion.

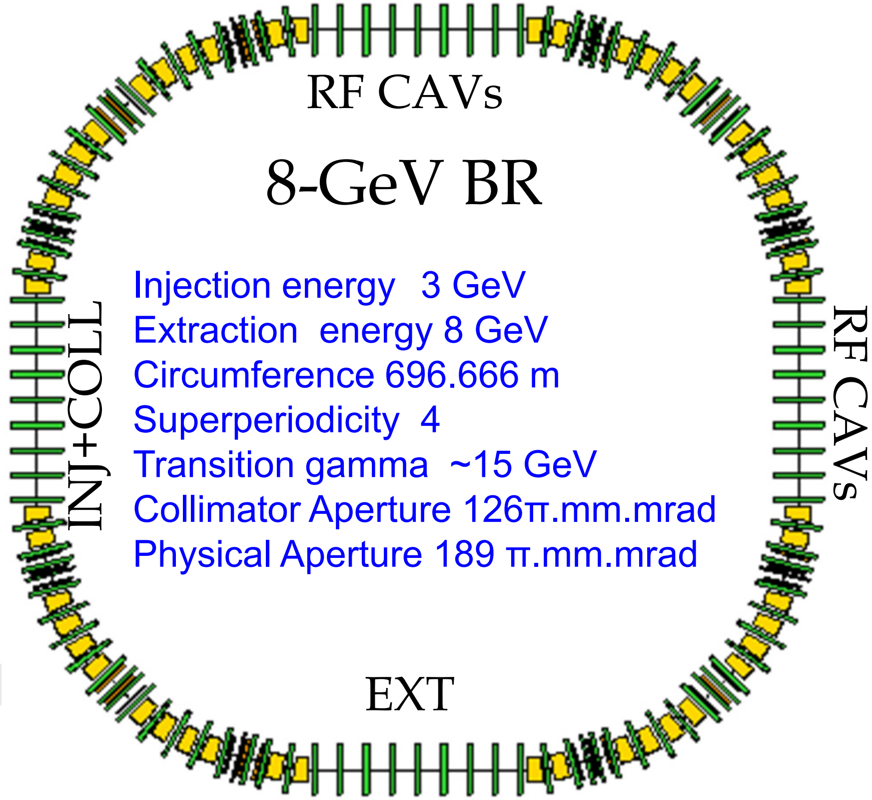
- Physics
  - Observation of CP violation
  - Precise measurement of CP phase
  - Discovery of proton decay
  - Determination of mass hierarchy…



J-PARC: The 8-GeV booster ring

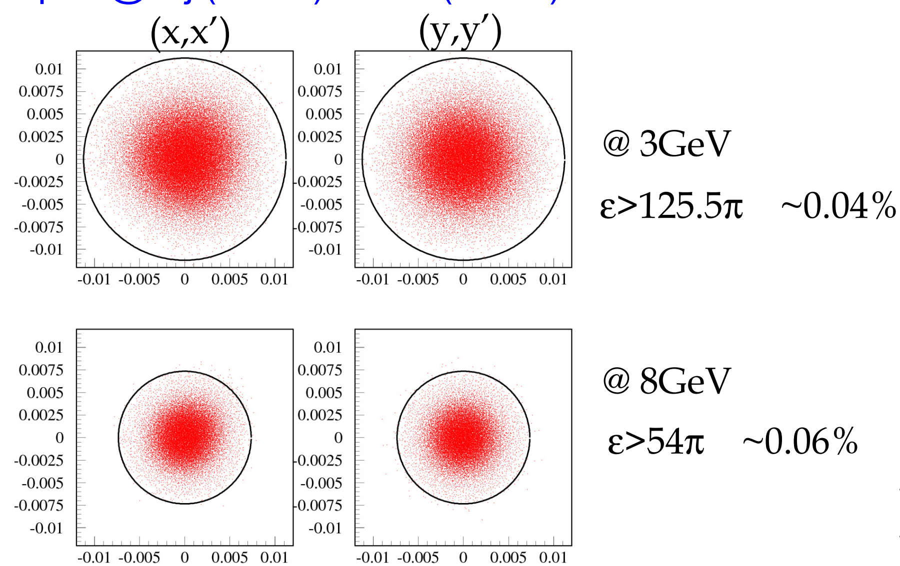
Beta & Dispersion for 1-superperiod

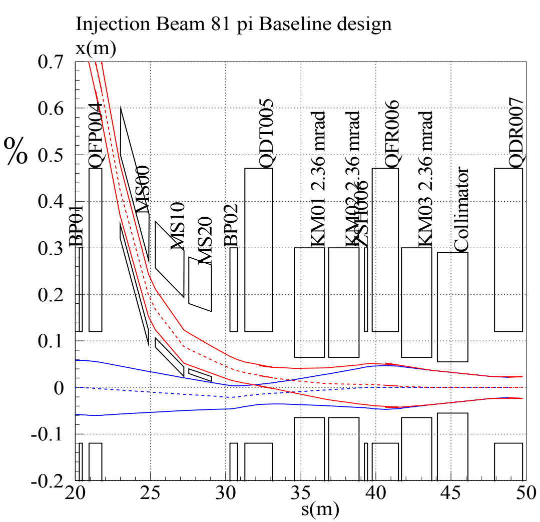




- Injection energy 3 GeV
- Extraction energy 8 GeV
- Circumference 696.666 m
- Superperiodicity 4
- Transition gamma ~15 GeV
- Collimator Aperture 126π.mm.mrad
- Physical Aperture 189 π.mm.mrad

Phase plot @ inj.(3GeV) & extr.(8GeV)





8 GeV injection in the MR using new septa&kickers

RCS : 1.6 MW
MR > 2.6 MW

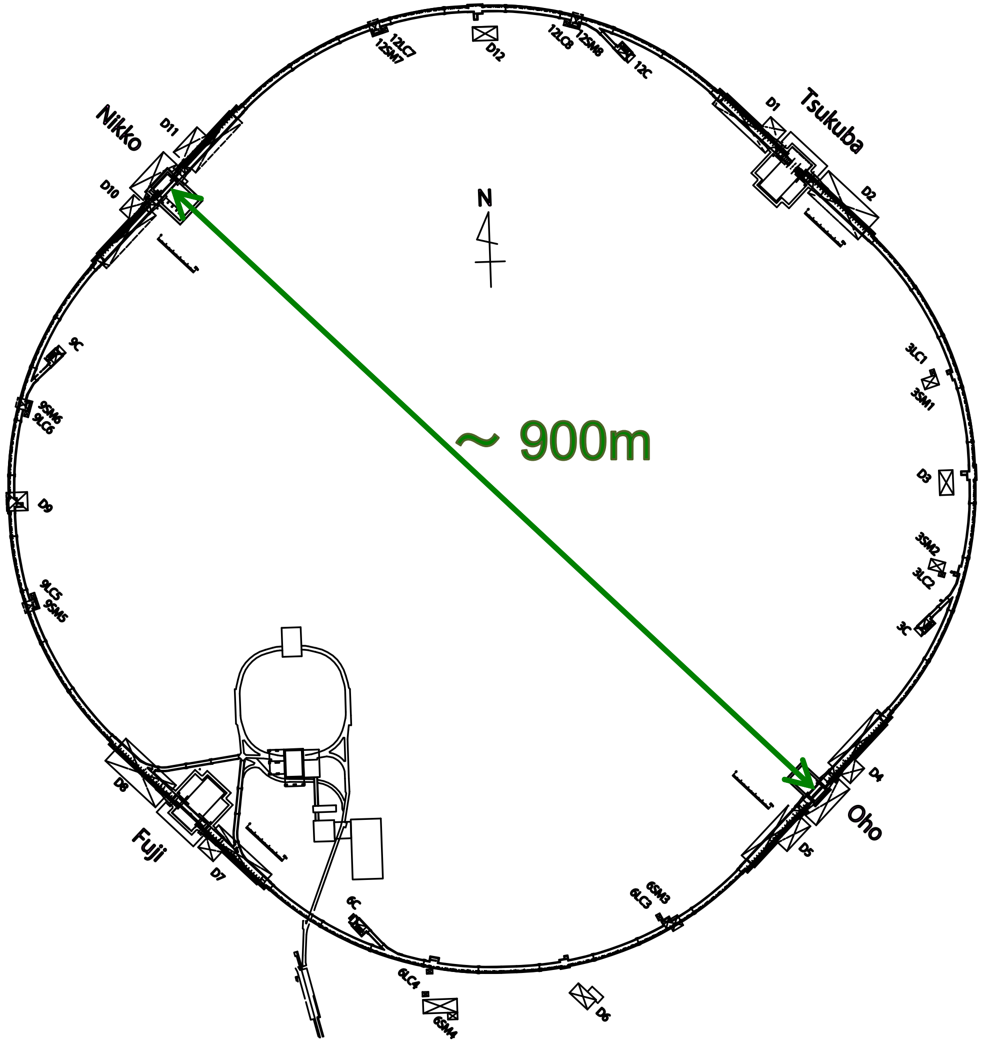
RCS : 2 MW
MR > 3.2 MW

Proton Driver in the KEKB Tunnel

- As the post-Super KEKB projects in KEK -

KEKB tunnel:

- fourfold symmetric configuration.
- Circumference: ~ 3 km
  - Straight section : beam acceleration
    200 m x 4 = 800 m
  - Arc section : beam transportation to
    the next straight section.
    550 m x 4 = 2200 m



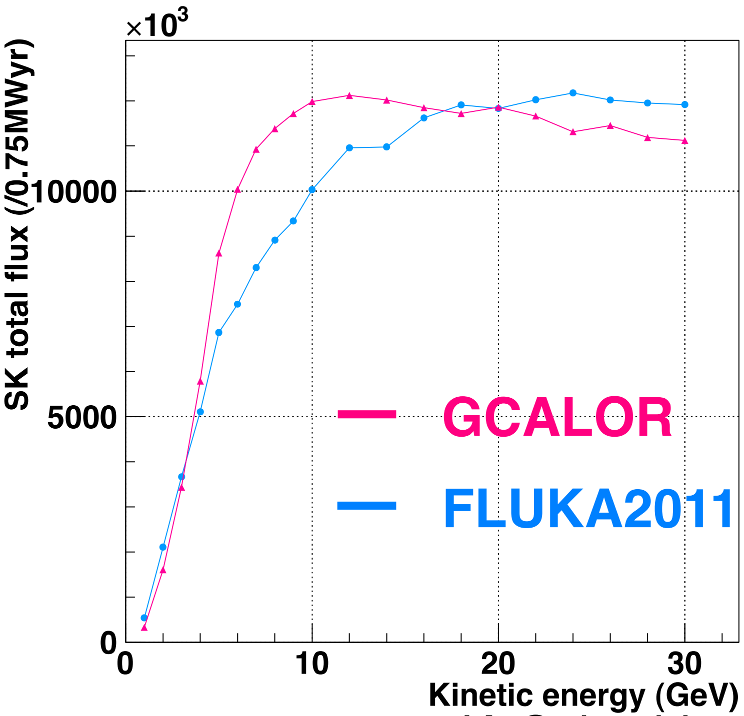
Subjects :

- Feasibility of 9 GeV proton linac in straight sections of 800 m.
  ⇒ High acceleration field is required.
  ⇒ SC accelerator is essential.
- Beam transport at Arc sections.

- In this scenario, the MR is operated exclusively for the SX users.

Beam Energy, Integrated n Flux

Neutrino flux normalized by beam energy



K. Sakashita

- Neutrino flux at Super Kamiokande as a function of proton energy.
- Hadron generation model.
  - GCALOR
  - FLUKA2011
- Off axis beam 2.5 deg.
- 3 Horn magnet scheme same as T2K.

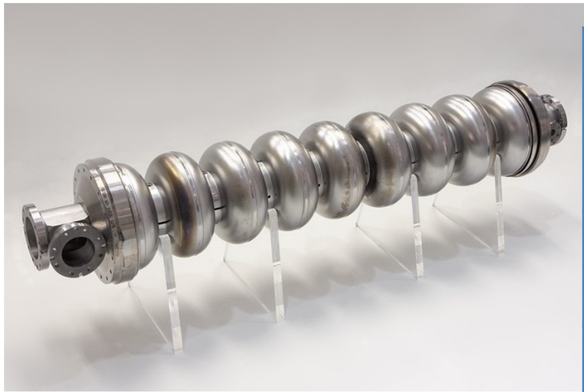
- At < 9 GeV, Neutrino flux per energy increases as beam energy to be high.
- Then, the flux almost saturates.

- 9 GeV proton accelerator
- Linac configuration for high duty
- With high duty magnetic horn

SC Cavity for 2nd to 4th Straight Sections

For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.

<u>ILC cavity</u>



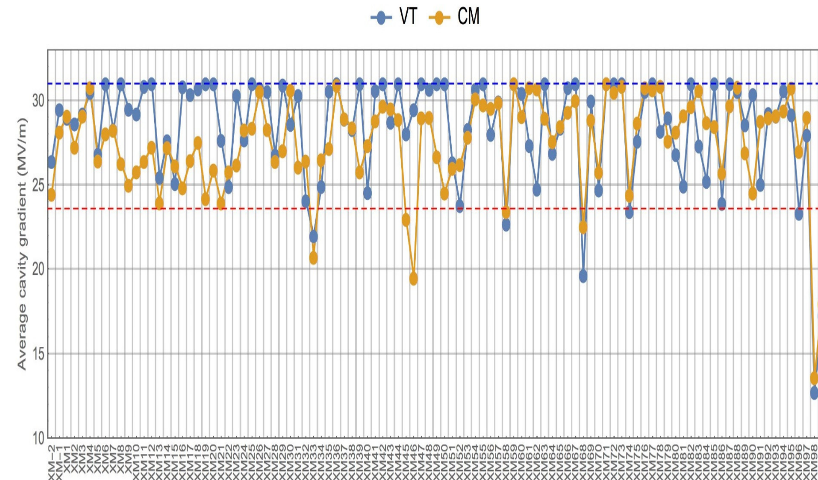
Shape	ellipse
RF frequency	1.3 GHz
# of cells per cavity	9
Quality factor	> 1 x 10^{10} @ 2K

<u>ILC cryomodule</u>

KEK has rich experience and know-how of ILC cavity and cryomodule fabrication.

Average gradient (E_0)

Cryomodule average gradient performance of EURO-XFEL (97 modules)



<u>Nick Walker et al, DESY LINAC16 Conference</u>

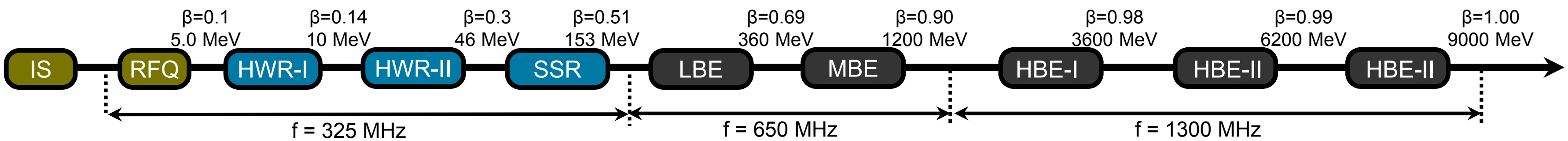
	N_{cavs}	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

With the expectation of further R&D, we set the E_0 to **30 MV/m**.

Present Design Parameters

T. Maruta and Gunn Tae Park

☐ Baseline layout



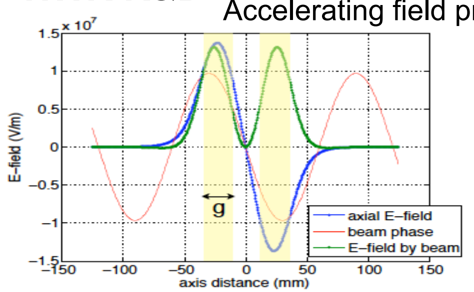
☐ Accelerating cavity parameter

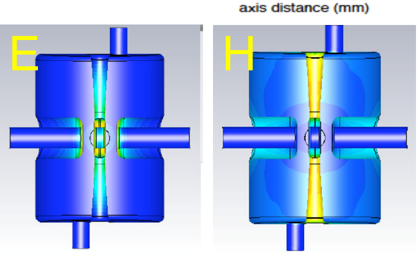
ILC cavities (HBE-I, HBE-II)

	RFQ	HWR-I	HWR-II	SSR	LBE	MBE	HBE-I	HBE-II
β_{opt}	0.01 – 0.10	0.13	0.21	0.38	0.62	0.73	0.93	1.0
V_{acc}	–	0.89 MV	3.7 MV	4.5 MV	11.9 MV	16.2 MV	30 MV	30 MV
E_{out}	–	10 MeV	46 MeV	153 MeV	360 MeV	1200 MeV	3600 MeV	9000 MeV
cavity no.	1	6	16	29	13	74	108	256
cm no.	–	1	2	6	5	25	27	32
cavity/cm	–	6	8	5	3	3	4	8

☐ HWR R&D

Accelerating field profile



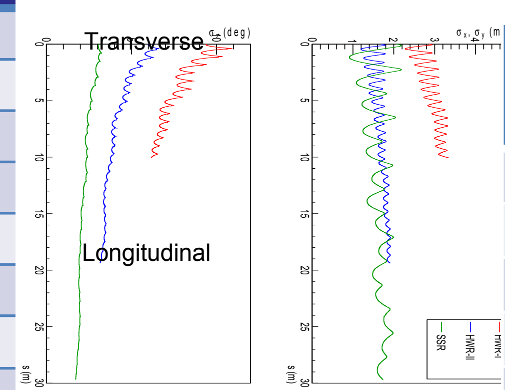


Field distribution

Figures of merit	Value
V_{acc}	0.66 MV
E_{acc}	5.5 MV/m
R/Q_0	237.7
G	53.8
Q_0	1.1E+09
P_{wall}	1.6 W
E_p/E_{acc}	6.3
B_p/E_{acc}	12.9 mT/(MV/m)

☐ Beam dynamics simulation

Beam envelope of HWR-I to SSR



	ϕ_s (deg)	Acc. gradient (MV/m)
HWR-I	-30	0.61
HWR-II	-30	1.9
SSR	-27	3.7
HBE-I	-24	10.9
HBE-II	-20	14.9

The proton driver in the KEKB Tunnel

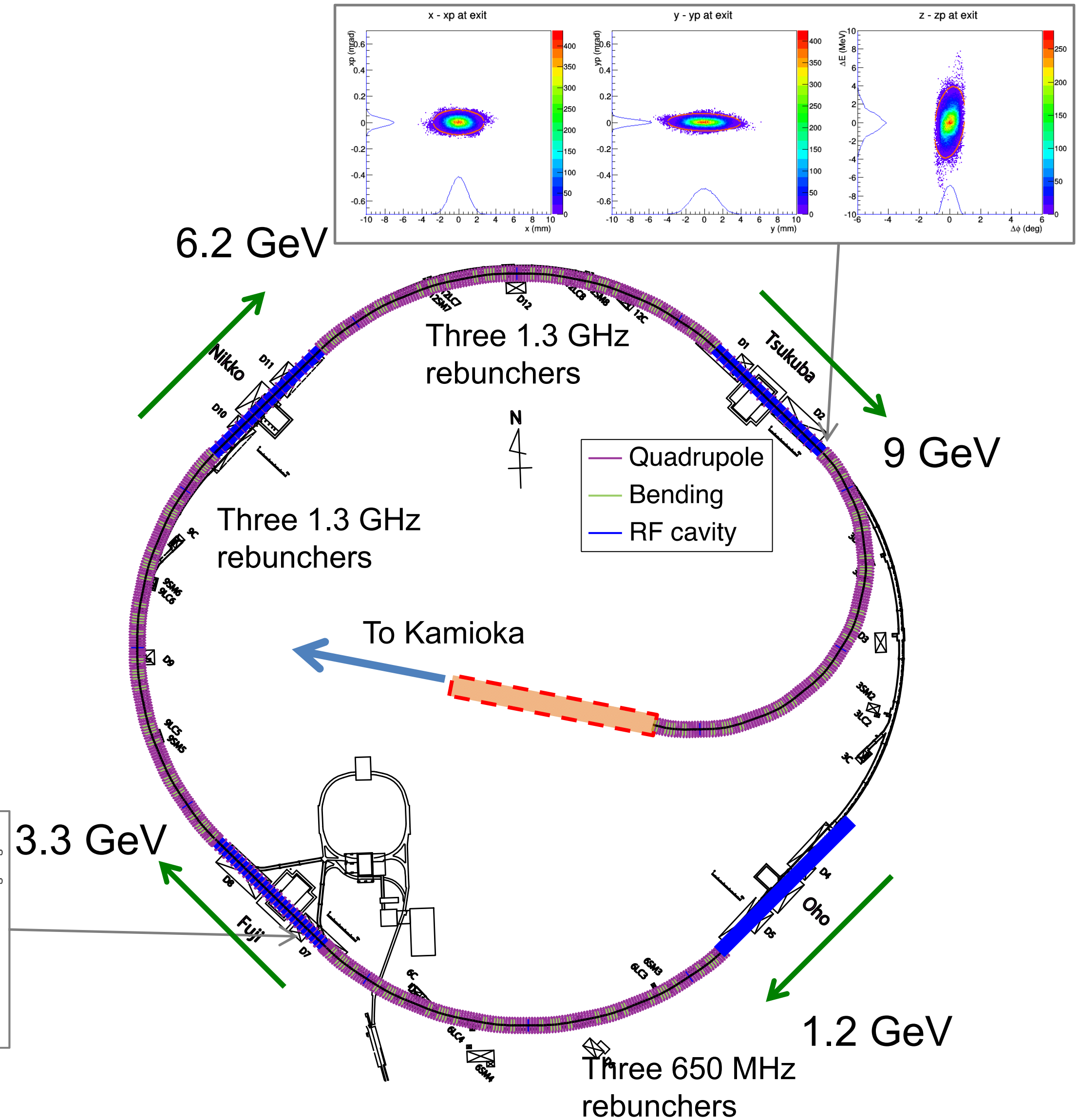
- Outline of acceleration :
    - 1.2 GeV in 1st straight.
    - 3.3 GeV in 2nd straight.
    - +2.9 GeV in 3rd and 4th straight.

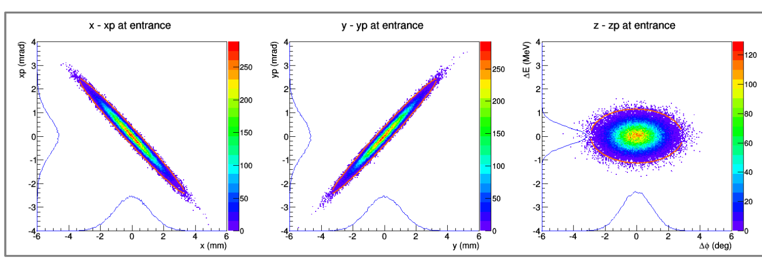
      3.3 + 2.9 x 2 = 9.0 GeV

- Peak current : 100 mA (pulse)
- Beam duty : 1 %

- Beam power :

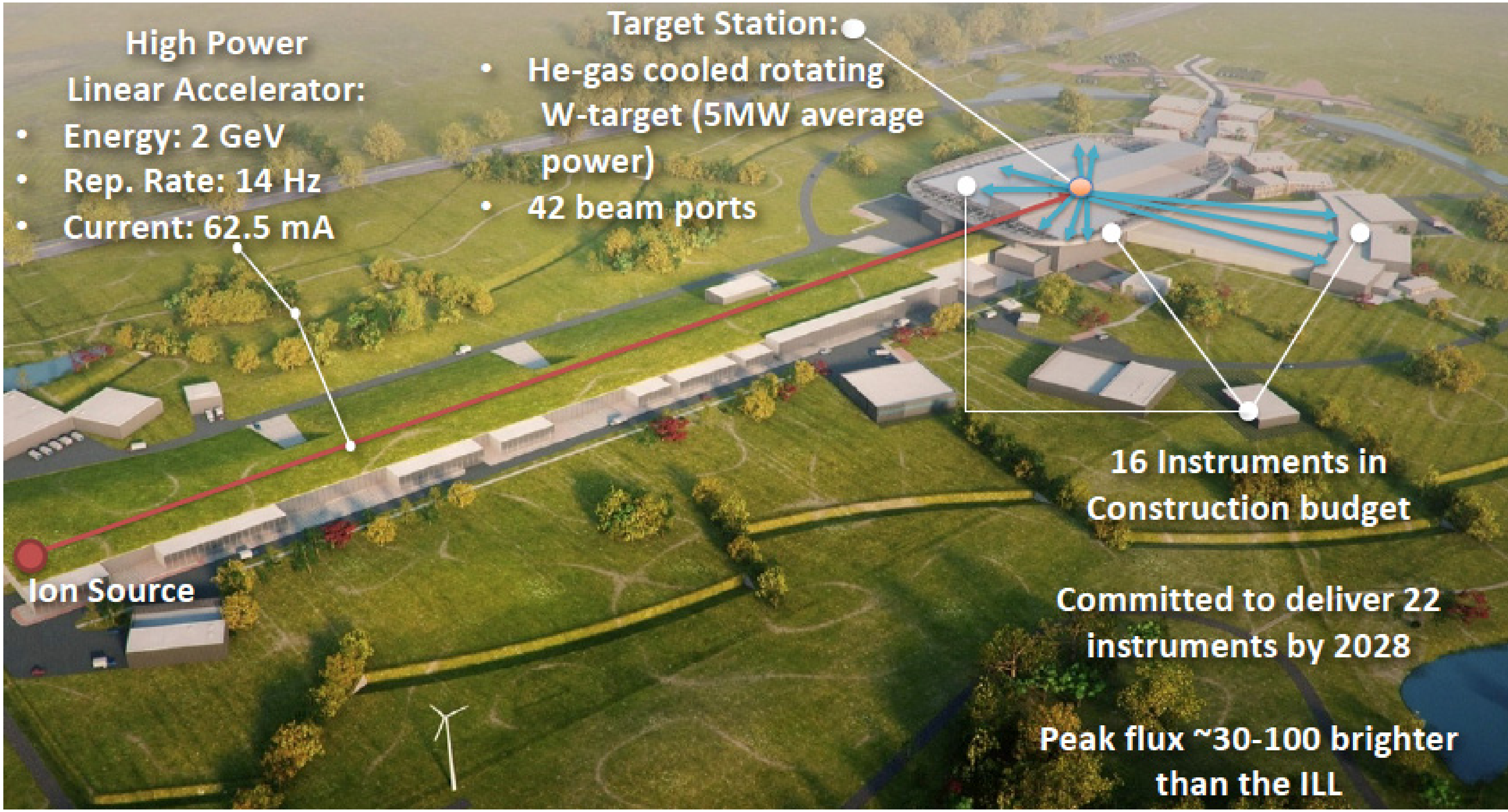
9000 MeV x 0.1 A x 1 % = **9 MW**





R&Ds : High duty horn, higher gradient SC cavity, high power target...

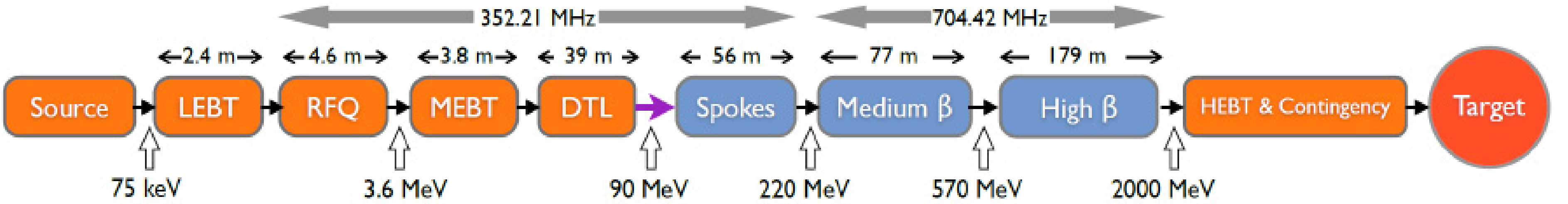
ESS(European Spallation Source)



Construction started in 2014.
First beam on target at 572 MeV in June 2019
Start user operation in 2023

Courtesy of H. Danared

ESS Linac



- Average beam power of 5 MW
- Peak beam power of 125 MW
- Acceleration to 2 GeV
- Peak proton beam current of 62.5 mA
- Pulse length of 2.86 ms at a rate of 14 Hz (4% duty factor)

96% of acceleration will be provided by superconducting cavities supplied by 150 high power RF sources (one per cavity)

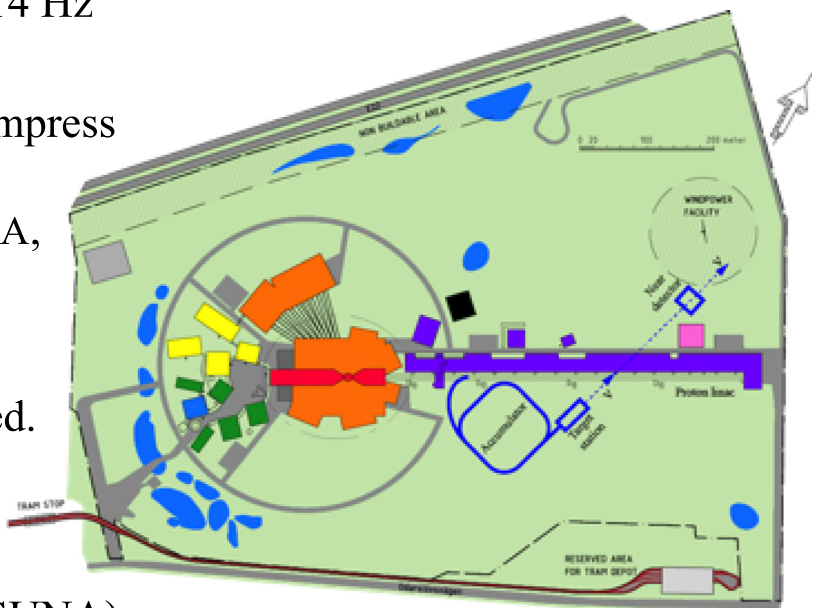
R. Garoby, "Progress on ESS Project Construction", IPAC2017

ESSνSB: Neutrino facility for CP violation discovery

Nikos Vassilopoulos, "ESSνSB: The ESS neutrino facility for CP violation discovery", Nufact2016

How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons),
  - space charge problems to be solved.
- ~300 MeV neutrinos.
- Target station (studied in EUROν).
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



ESSνSB: Neutrino facility for CP violation discovery

Nikos Vassilopoulos, “ESSvSB: The ESS neutrino facility for CP violation discovery”, Nufact2016

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Conclusion

During past decade, accelerator facilities for neutron/muon generation advanced the frontier of beam intensity and realized > 1 MW.

High energy accelerators for long baseline neutrino experiments are also frontier of beam intensity. They will reach beam intensity > 1 MW with high energy beams of 30 GeV / 120 GeV by the middle of 2020s or earlier.

The most intense beam in near future will be driven by SC proton linacs. The intensity frontiers, ESS, accelerators for ADS, PIP-III and the 9 GeV proton driver in KEK, adopt SC linacs to realize multi-MW beam intensity.

I believe that long baseline neutrino oscillation experiment is one of the most important and active fields in particle physics in the next two decades.
In the future neutrino facilities, SC linac will play an important role to realize the required beam intensity and make a great contribution to the neutrino physics.