High Intensity Frontier Proton Accelerators

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ICFA HB2014

Michigan State University

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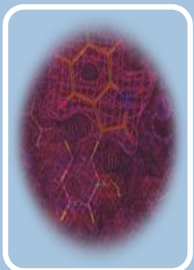
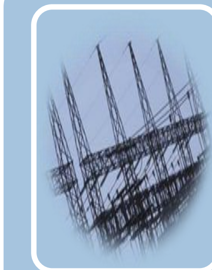
Applications of High-Intensity High-Power Proton Accelerators



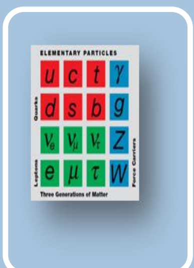
Materials Science

- Neutron Sources
- Muon Sources



Energy & Environment

- Materials Irradiation
- Accelerator Driven Systems

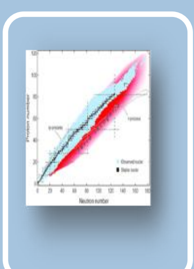


Particle Physics

- Proton Drivers for Intensity Frontier of HEP

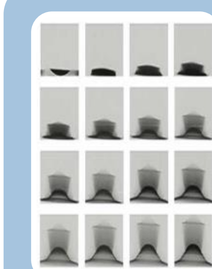
Health and Medicine

- Isotope production



Nuclear Physics

- High-power ISOL
- Neutron, nuclear EDMs



National Security

- Radiography Applications

…and shares technology with industrial applications

Applications of High-Intensity High-Power Proton Accelerators

Particle Physics

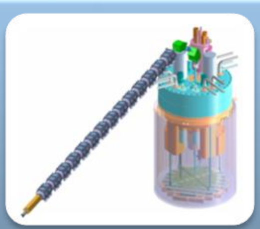
- Existing: FNAL NuMI (US), CNGS (CERN), J-PARC (Japan)
- Upgrades: FNAL Complex, J-PARC Complex
- Proposed: PIP-II (US)

Nuclear Physics

- Existing: RIKEN (Japan), TRIUMF (Canada),
- Under Construction or Upgrade: FRIB (US), FAIR (Germany), SPIRAL2 (France), SARAF (Israel), PEFP (Korea)
- Proposed: EURISOL (Europe), SPES (Italy)

Materials Science

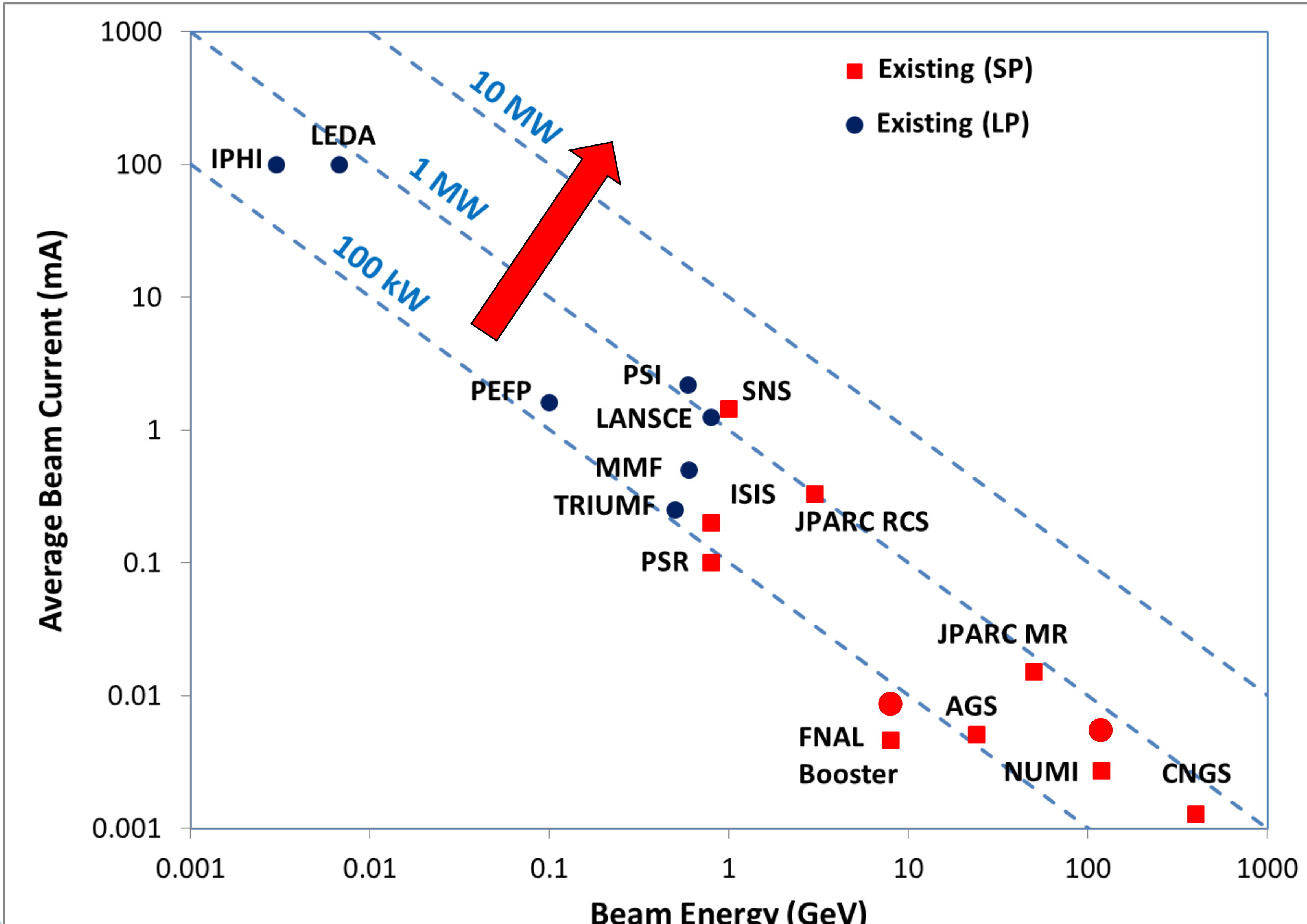
- Existing: SNS (US), SINQ (Switzerland), J-PARC (Japan), ISIS (UK), LANSCE (US)
- Under Construction or Upgrade: CSNS (China), ESS (Europe)
- Proposed: IFMIF (EU&Japan), India Spallation Source



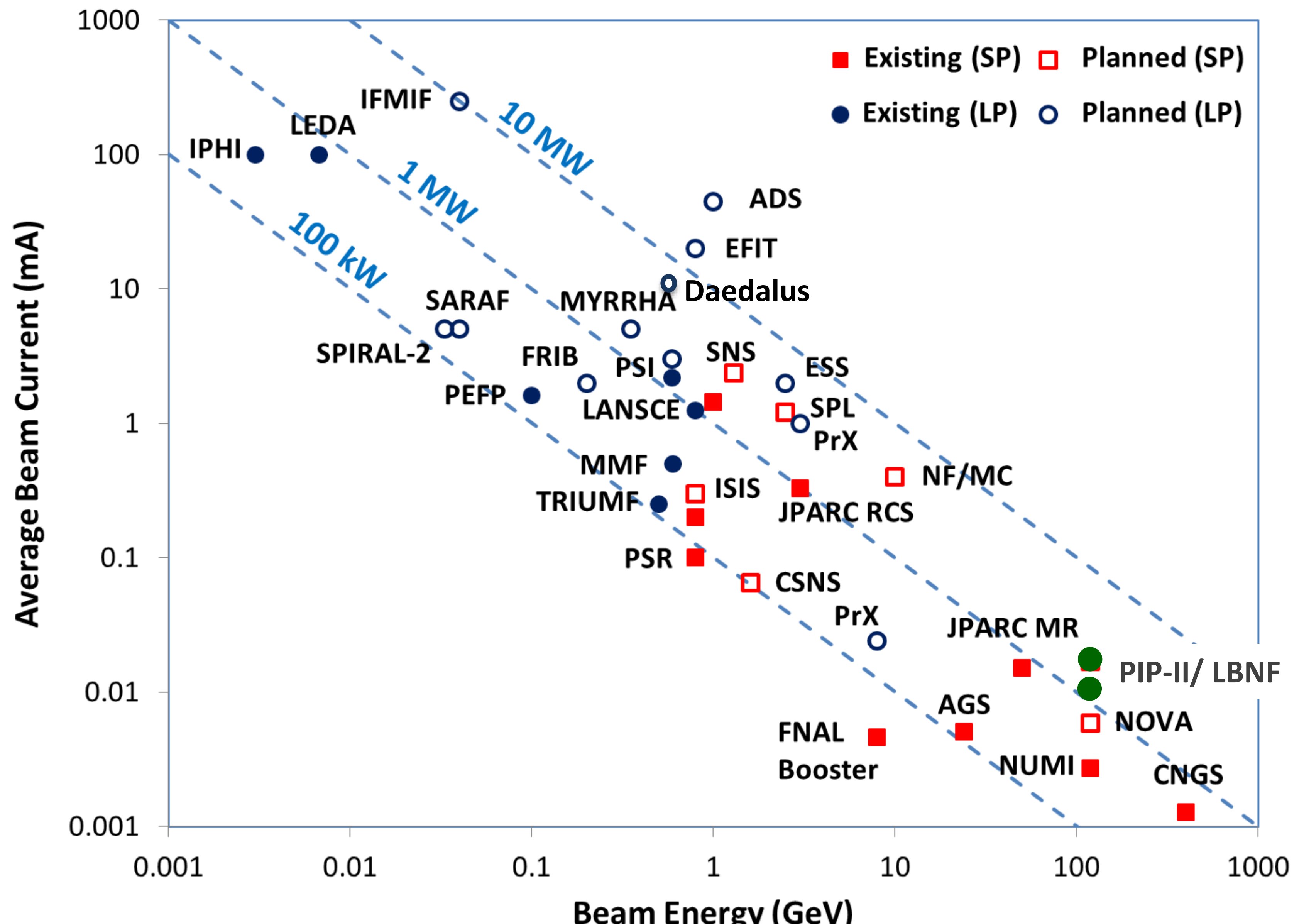
Applications

- Proposed: MYRRHA (Belgium), China ADS
- ADS R&D worldwide: India, Japan, Korea, UK, US

The Beam Power Landscape

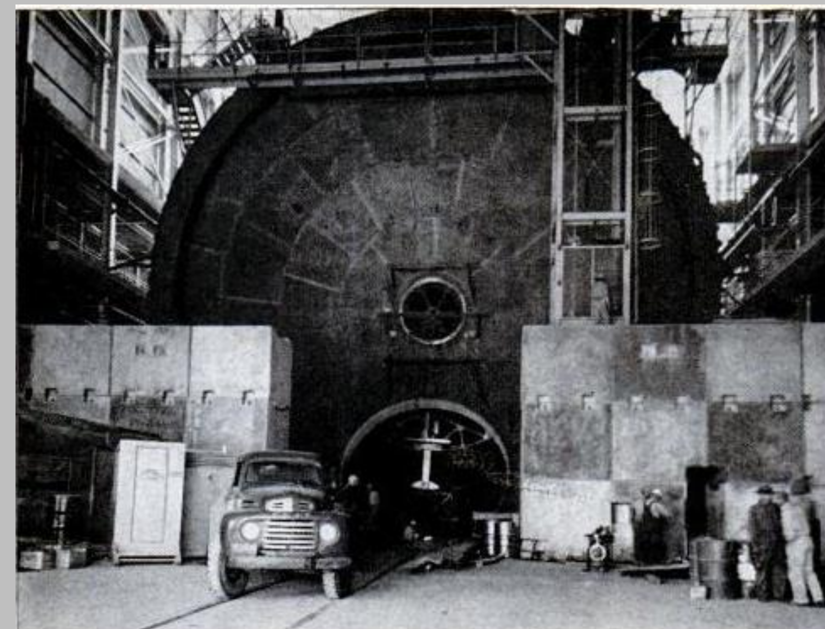


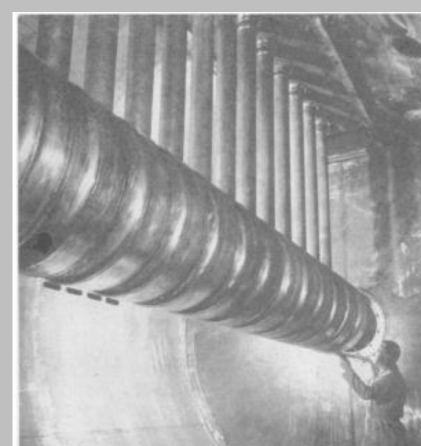
The Beam Power Landscape: Planned

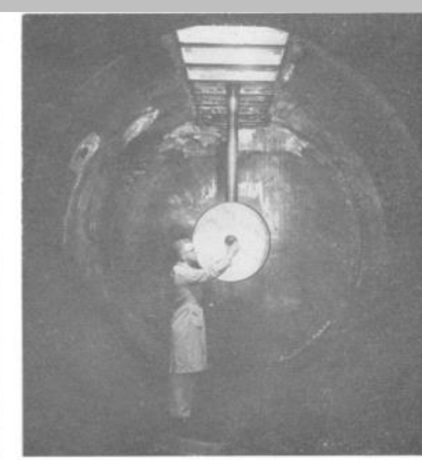


The Beginning: the Materials Testing Accelerator Program

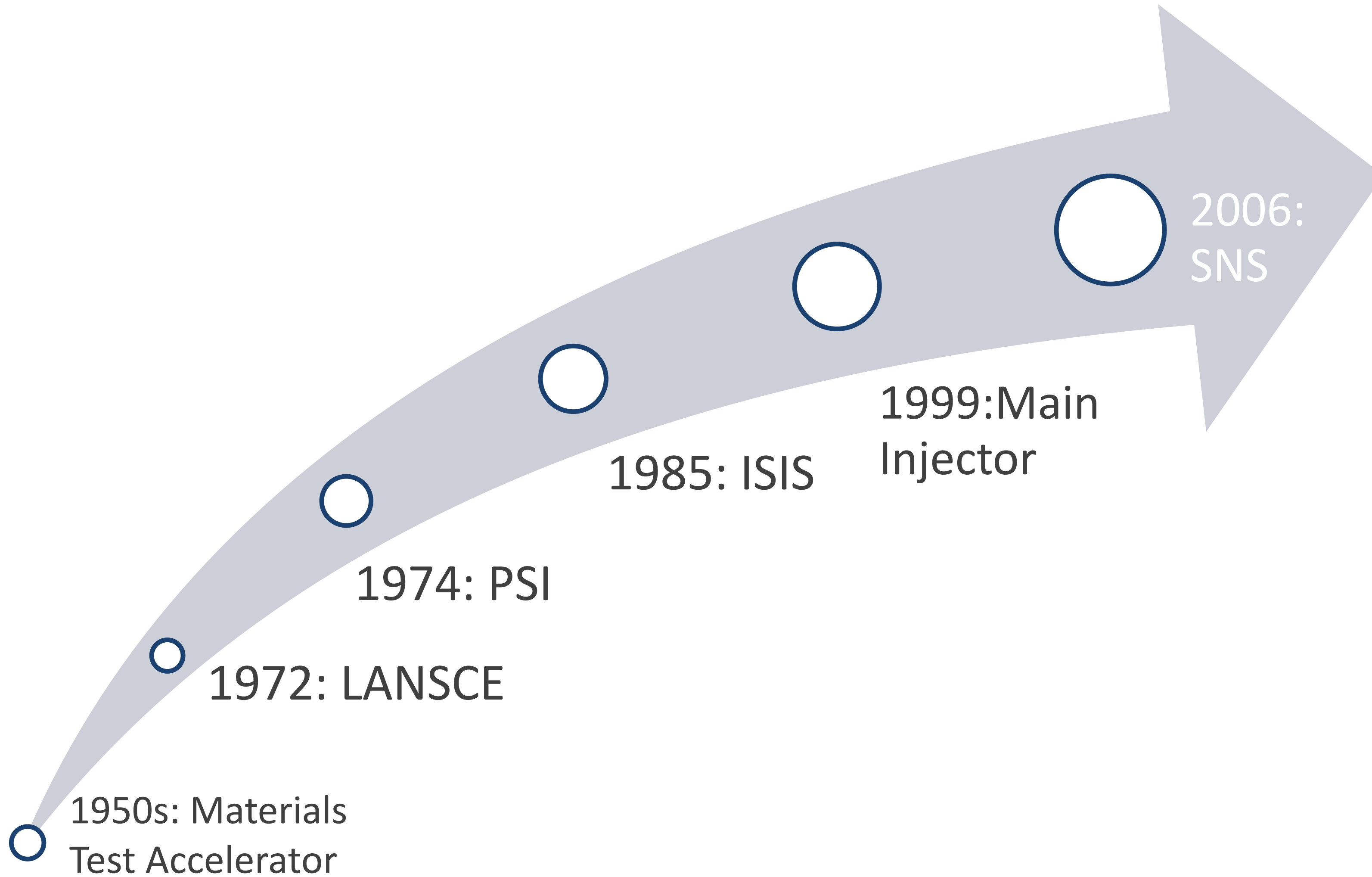
- MTA Program at UCRL (early 1950s) marks the birth of high-power hadron accelerator field
- Goal: Breed Pu-239, U-233 and H-3 with a 350 MeV, 0.25 Amp deuteron beam (Livdahl, Proc. LINAC81 p.5).
- The Mark I accelerator : 12 MHz drift-tube linac (60 ft. diameter!), eight 40 ton drift tubes, delivered ~50 mA at ~10 MeV (briefly)
- Two other accelerators built, based on 48.6 MHz (12 ft. dia.) DTLs. The A-48 produced 30mA, 7.5 MeV deuterons
- Numerous fundamental limits were encountered







High Power Proton Accelerators: Some History



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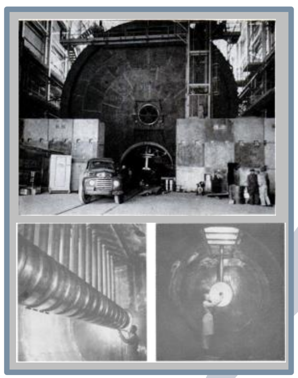
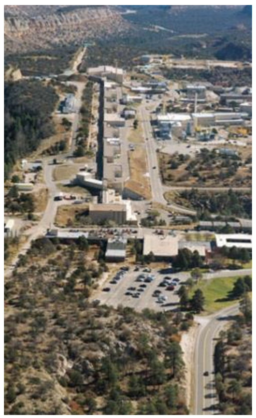
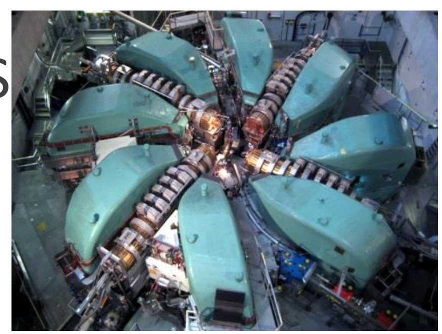




1950s: Materials Test Accelerator

1972: LANS

1974: PSI



1985: ISIS

1999:Main Injector

2006: SNS

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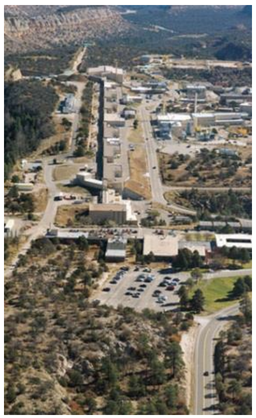

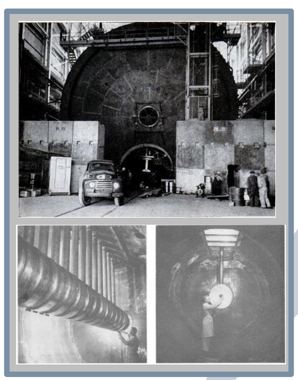

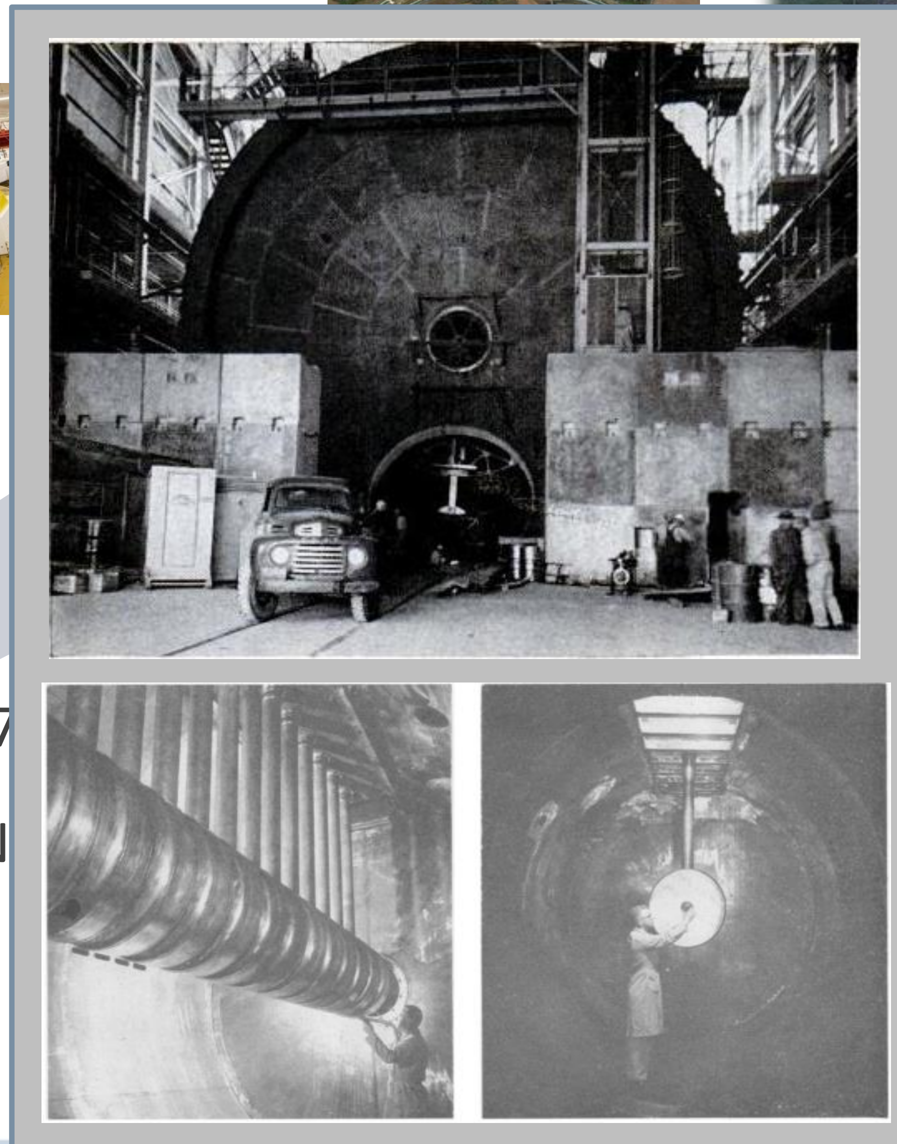

2006: SNS

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1972: LAN

1950s: Materials Test Accelerator

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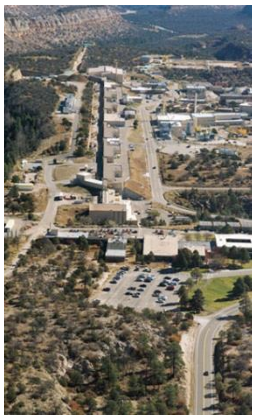

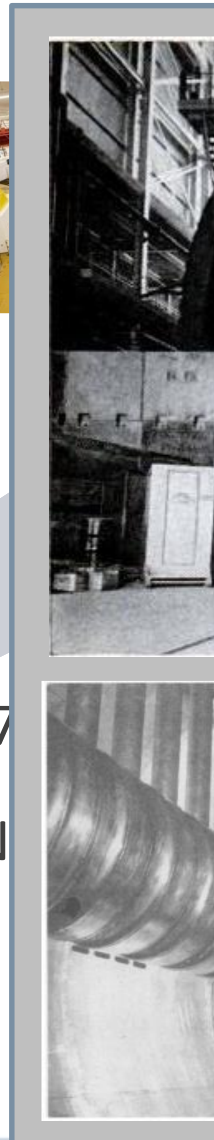

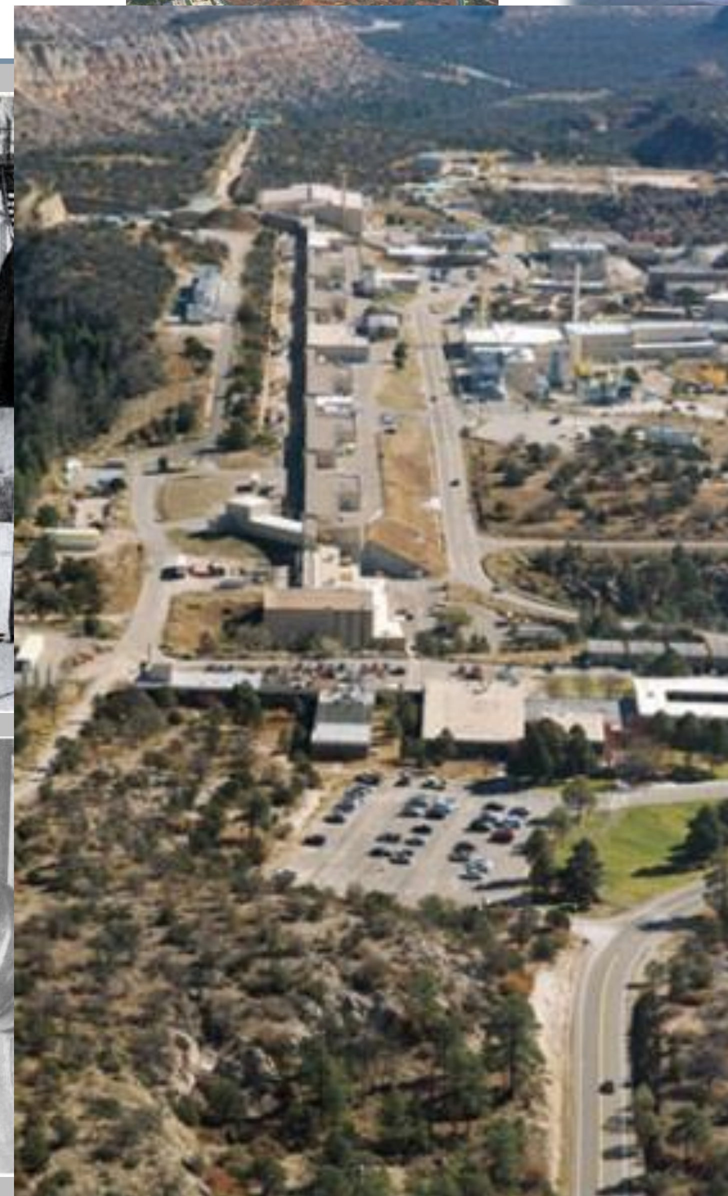

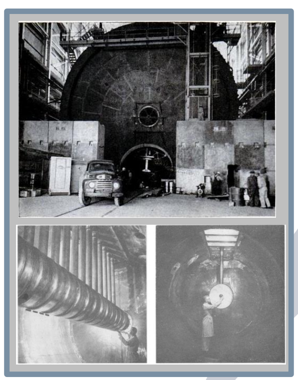

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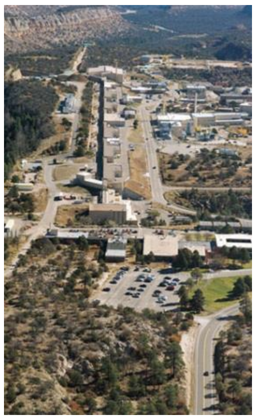

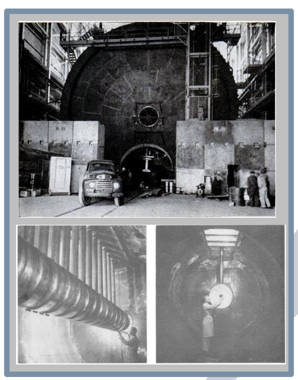

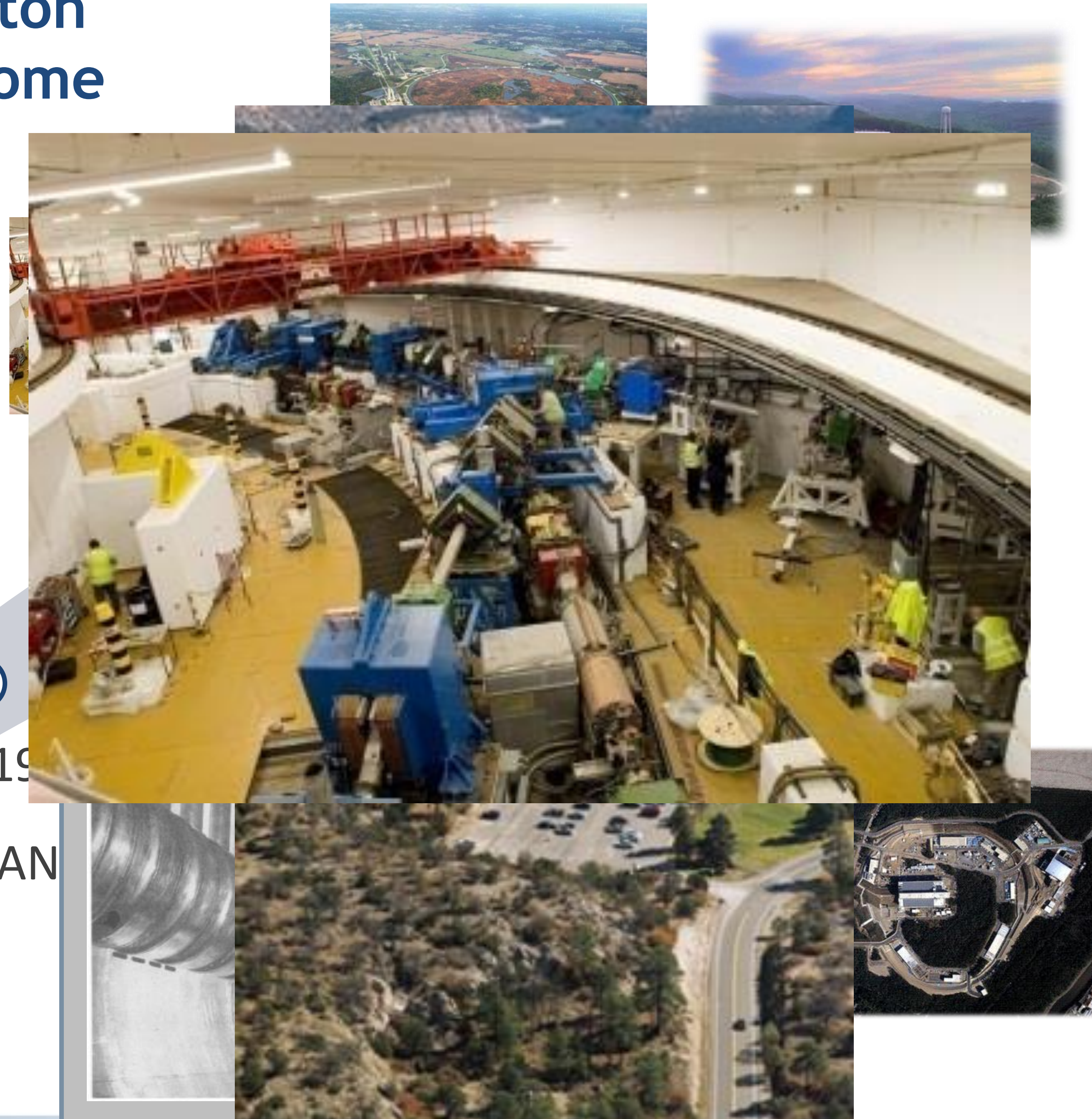

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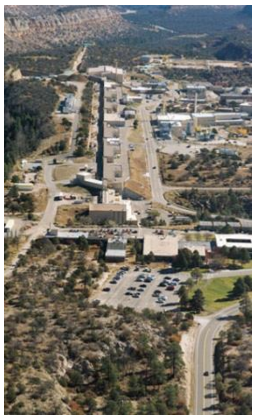

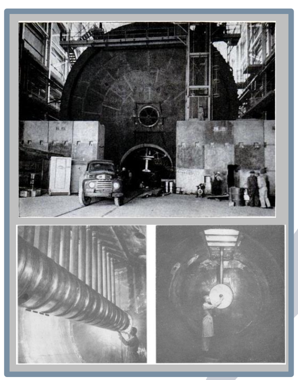

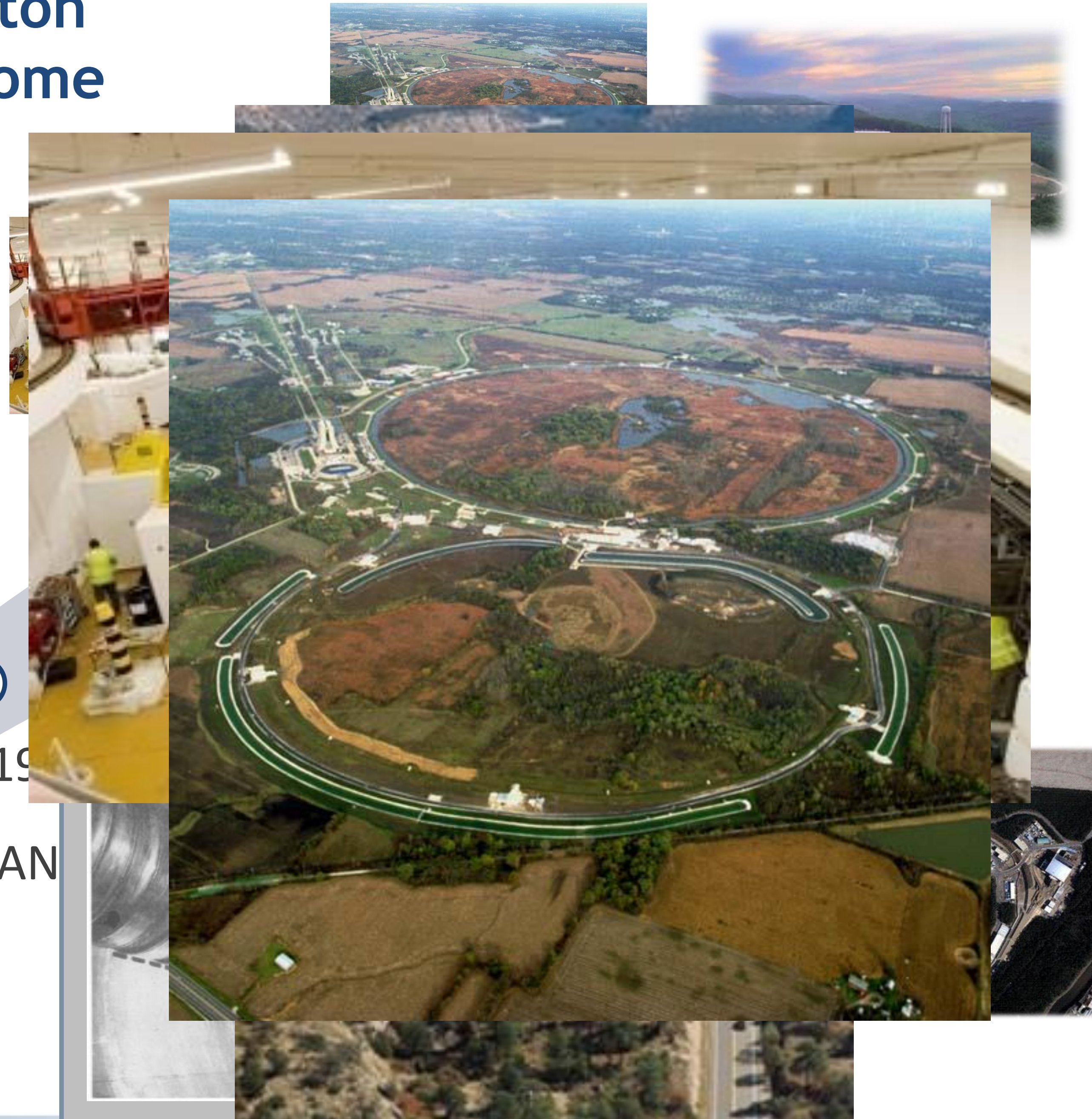

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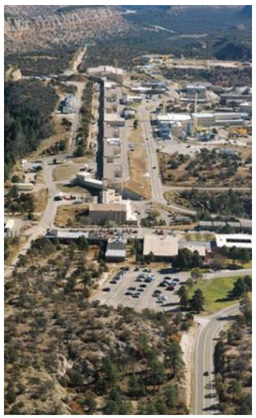

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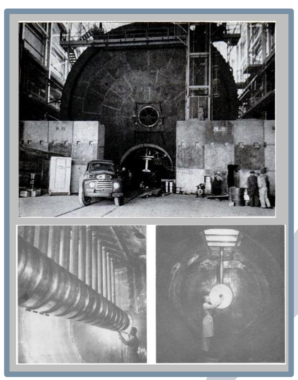
1972: LA



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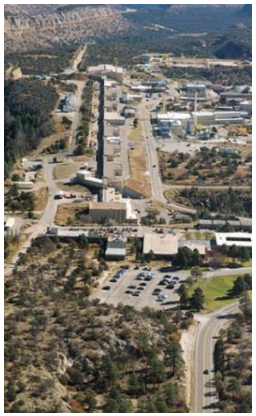

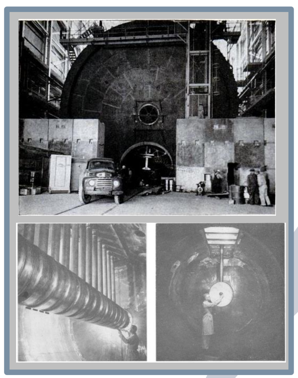

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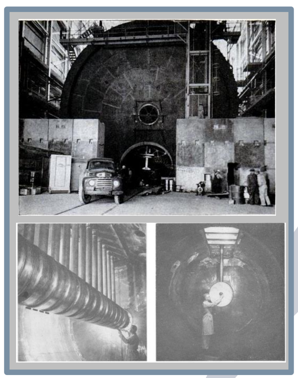

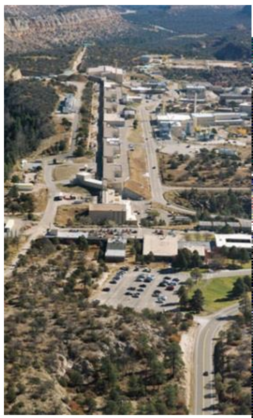

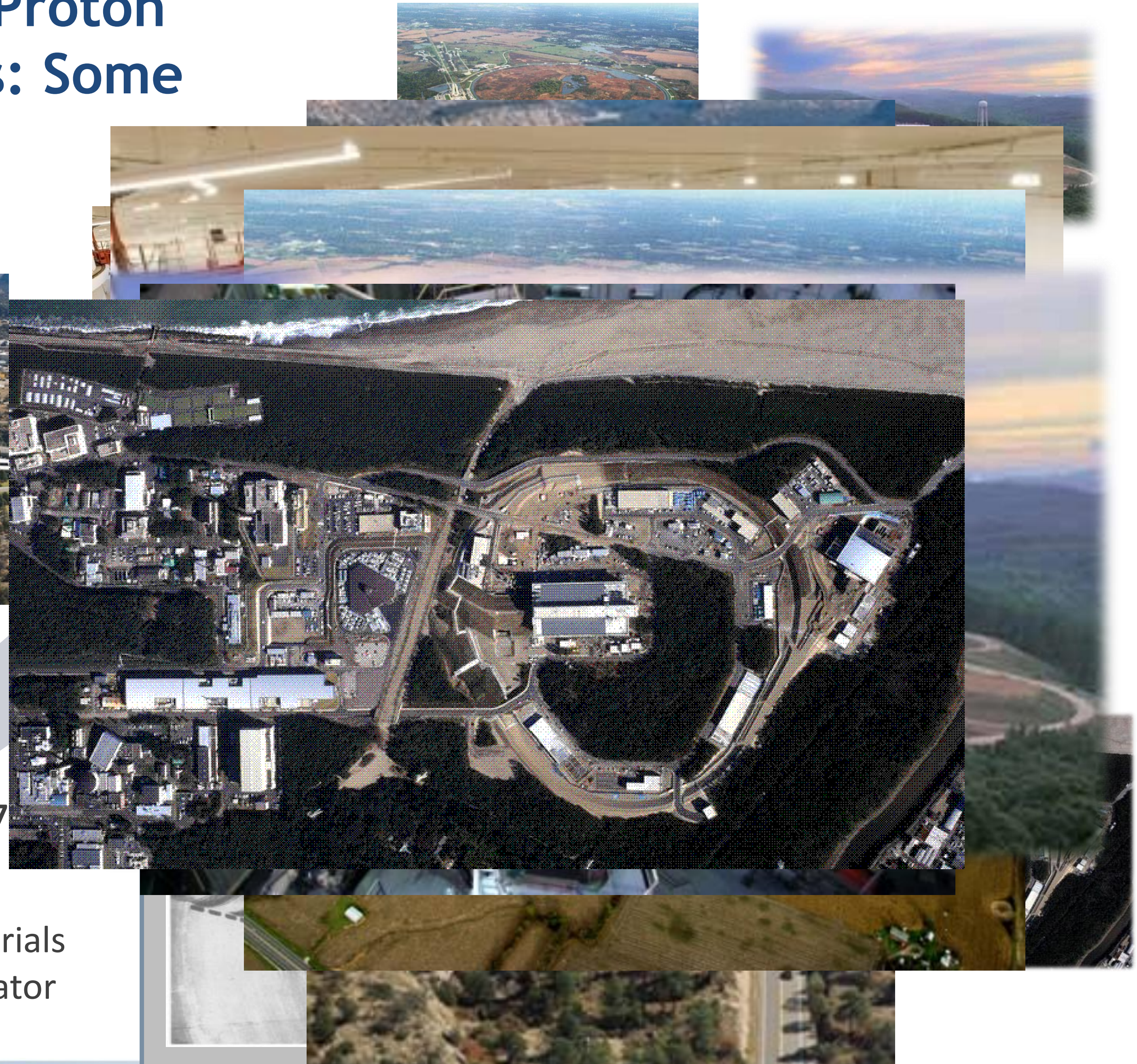

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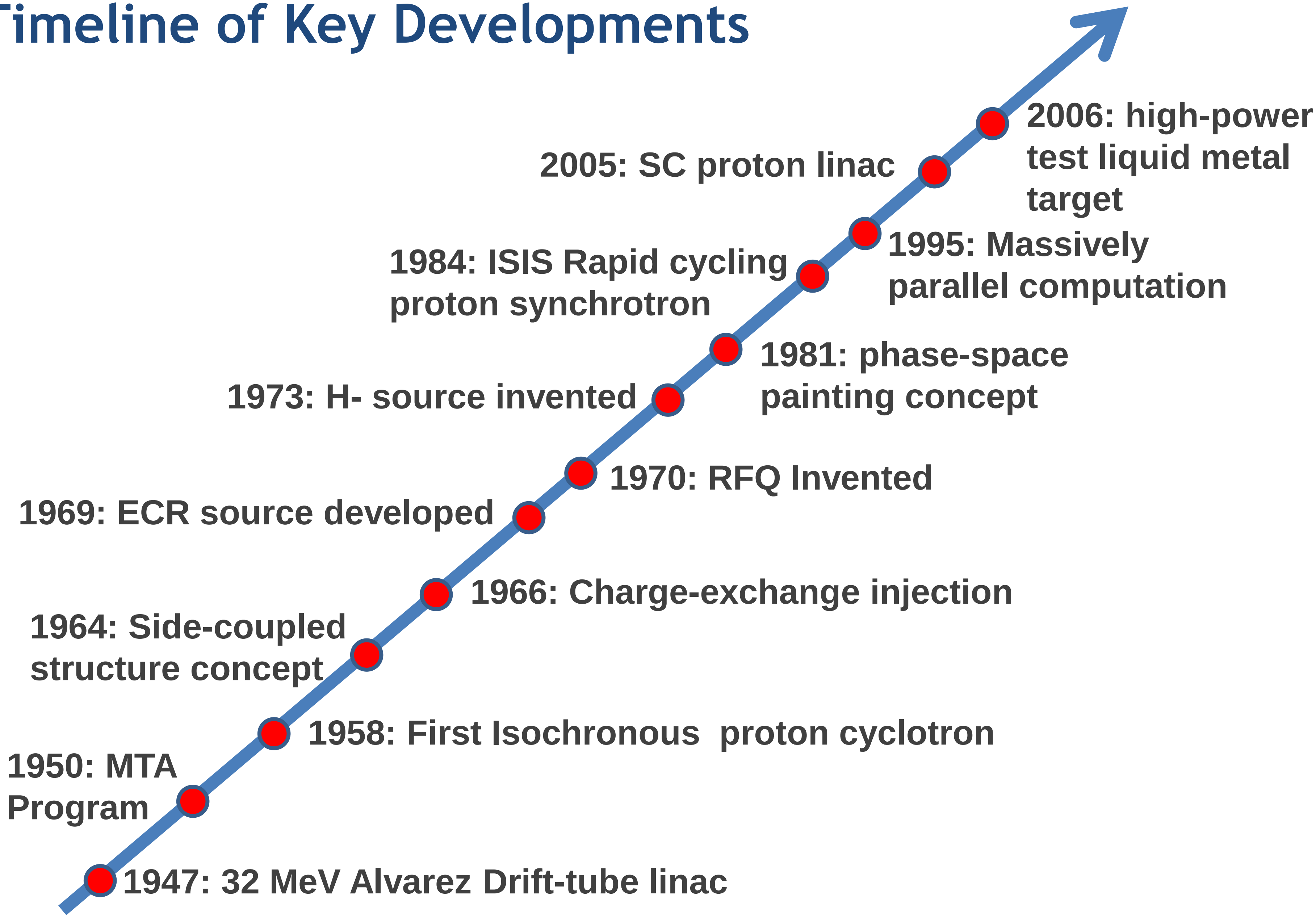
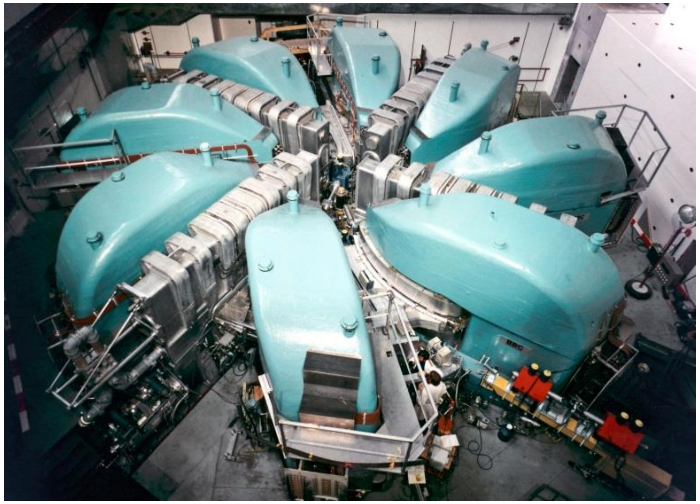
1950s: Materials Test Accelerator

Timeline of Key Developments



Accelerators Operating at the Frontier

Spallation Neutron Source ORNL: 1.4 MW, 1 GeV, short pulse

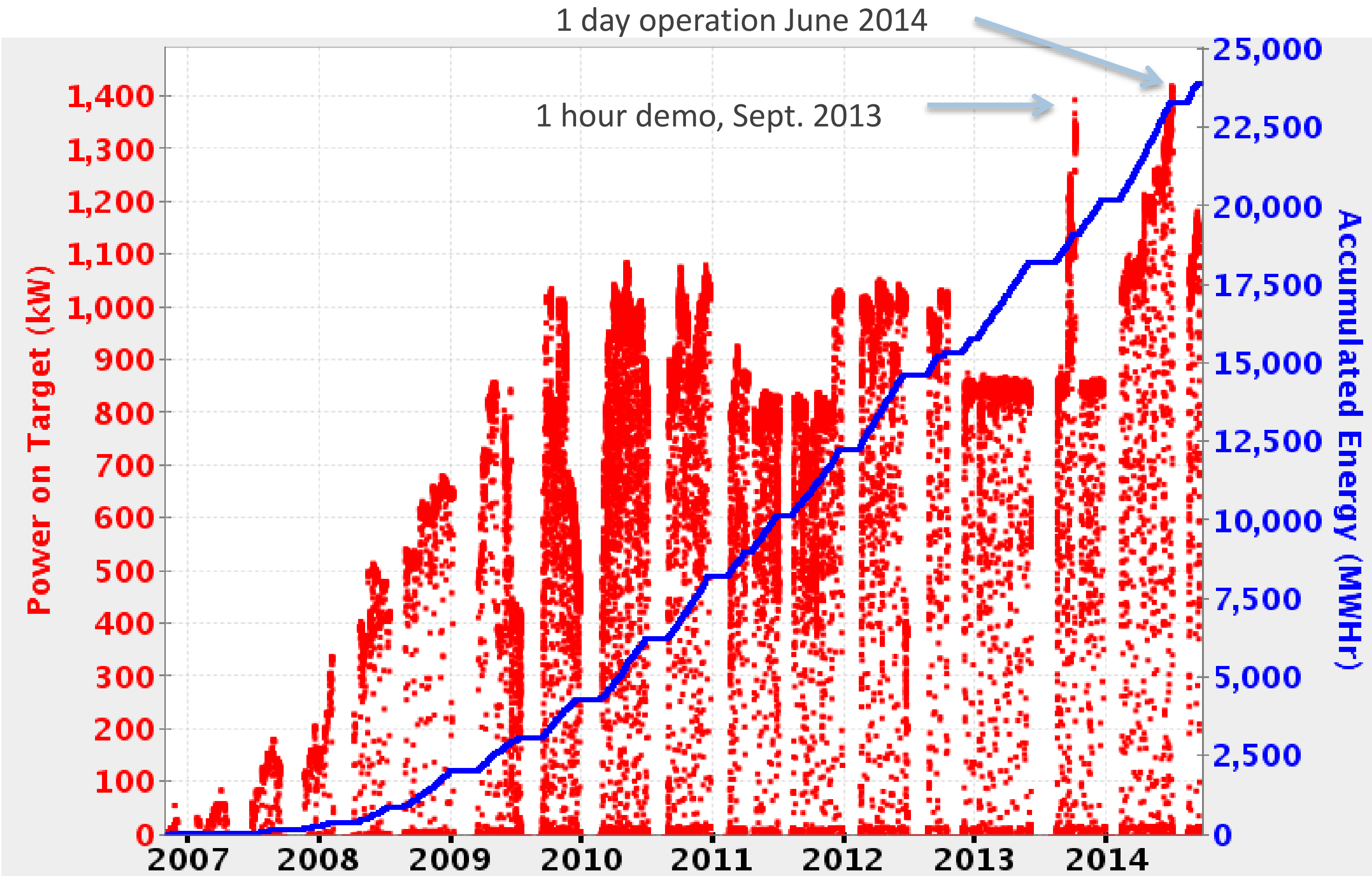


PSI Cyclotron: 1.4 MW, 600 MeV DC beam

Fermilab Main Injector: 700 kW design, 120 GeV

JPARC: 1 MW 3 GeV RCS and 750 kW 30 GeV Main Ring

1.4 MW Beam Operation at SNS



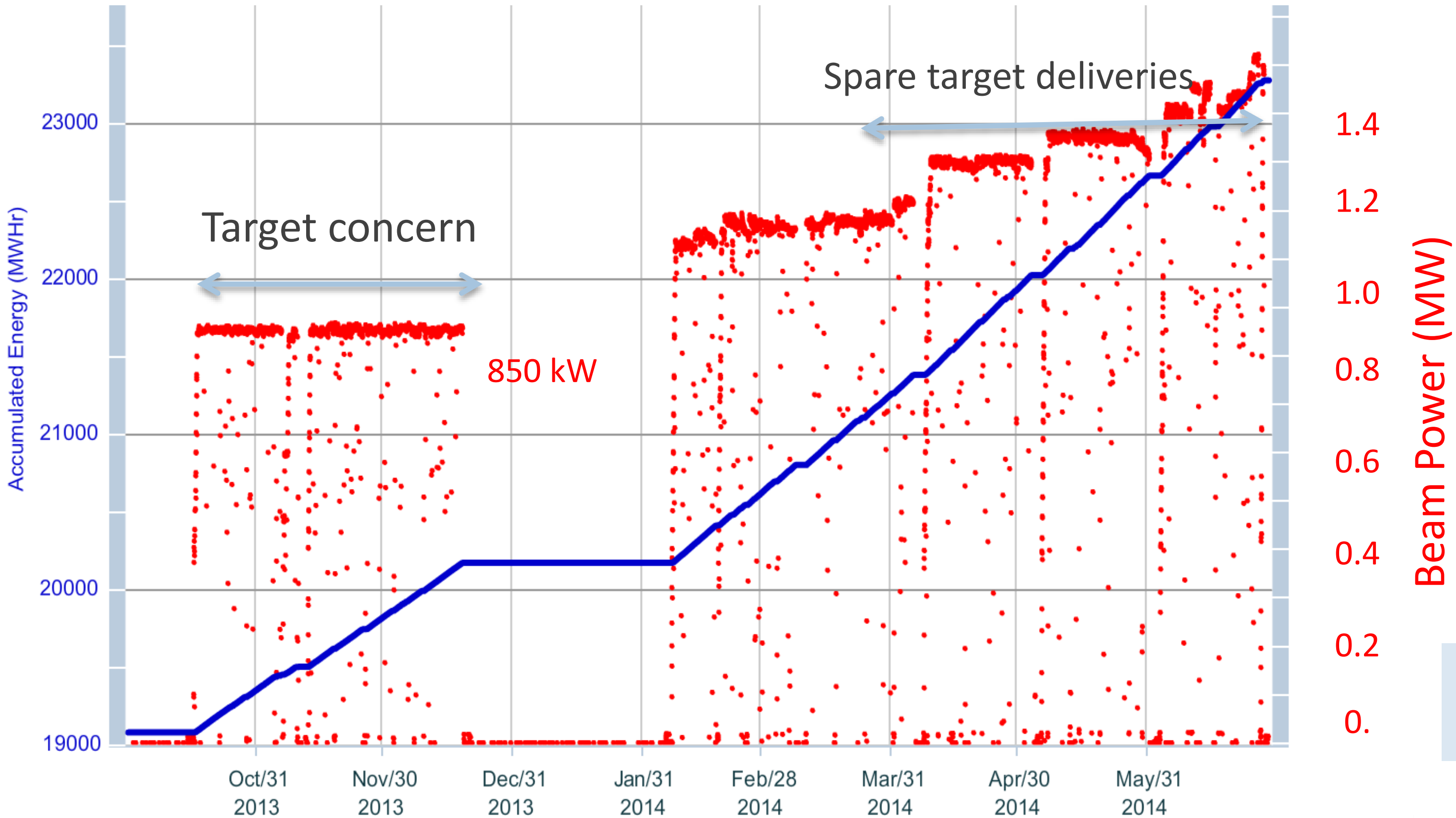
- First neutron production at 1.4 MW: June 29, 2014
  - Sustained power increase during the 2014 run, increasing power from ~ 1. MW to 1.4 MW

Courtesy J. Galambos

1.4 MW Operation: The Final Assault

- Power ramp-up approach:
  - Adiabatic
  - Most effective use of what works
- Plan is to operate at 1.3-1.4 MW

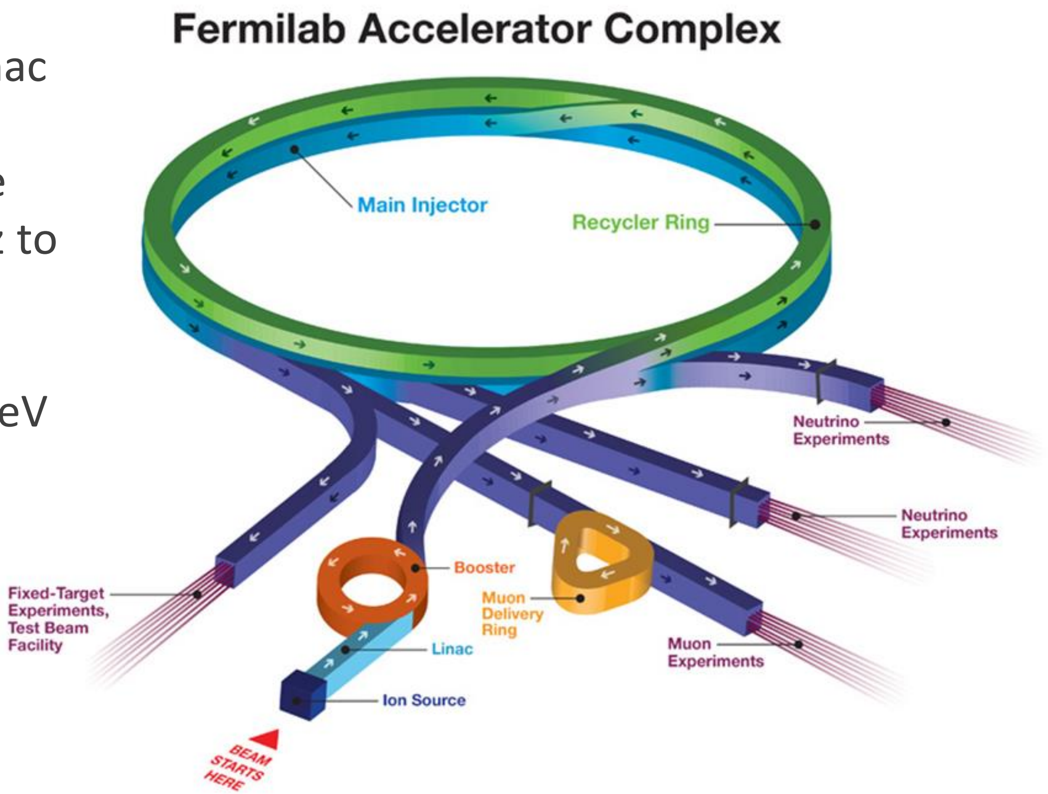
	1.4 MW Design	1.4 MW Operation (June 2014)
Energy (GeV)	1.0	0.94
Rep rate (Hz)	60	60
Macro-pulse length (ms)	1.0	0.97
RFQ output beam current (mA)	38	35
“un-chopped” fraction	0.68	0.78



Courtesy J. Galambos

The Fermilab Accelerator Complex Today

- A recently completed major upgrade to Fermilab's accelerator complex allows 700 kW operation from the Main Injector at 120 GeV
- Recycler 8 GeV permanent magnet accumulator ring was recently reconfigured for proton operation and slip-stacking accumulation
- Recycler commissioning has been ongoing and is now delivering beam in routine operation
- Major improvements to the linac and Booster (Proton Improvement Plan) to increase the repetition rate (from ~7 Hz to 15 Hz) will enable 700 kW operation from MI and simultaneous operation of 8 GeV program **(K. Seiya)**

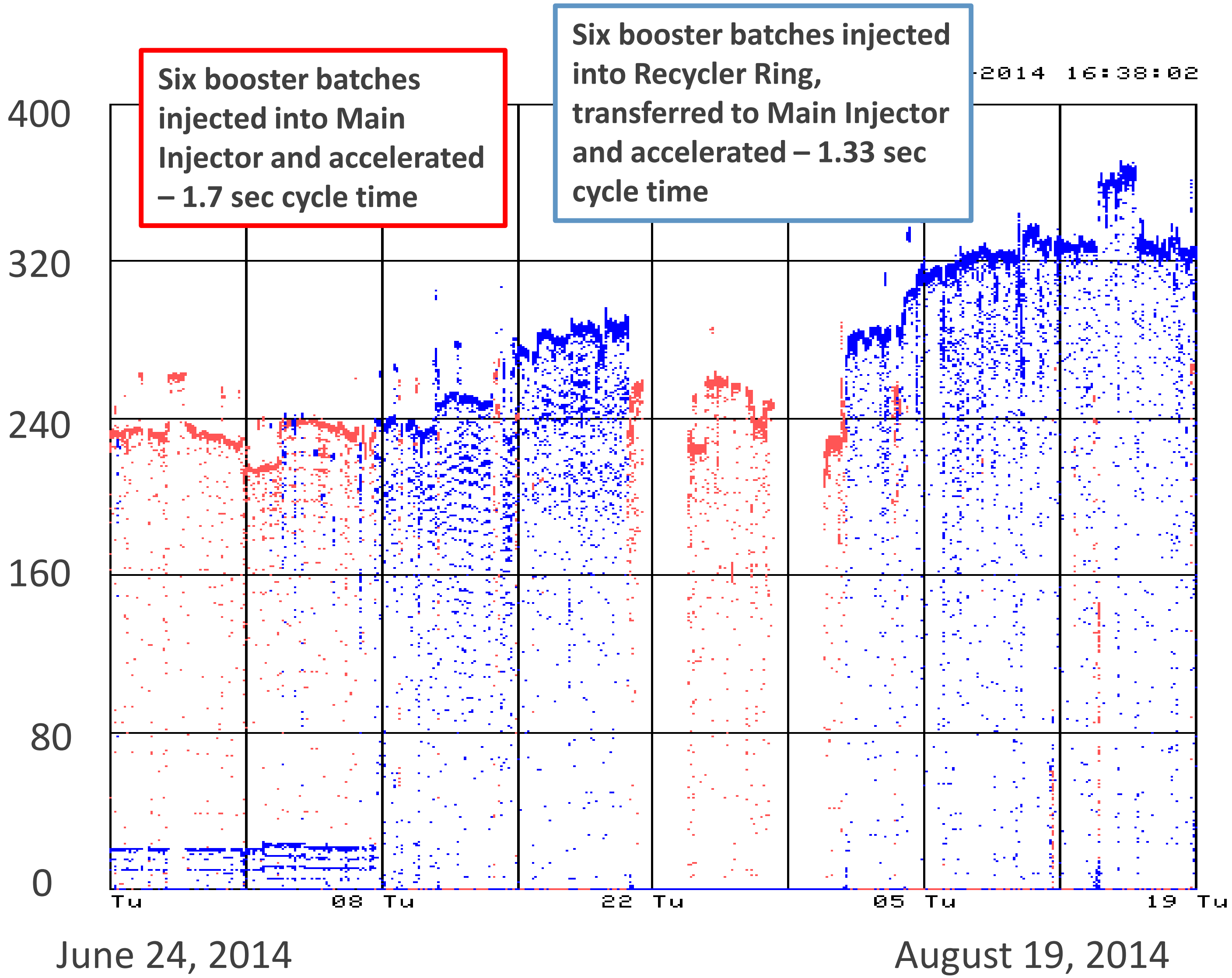


Main Injector Beam Power

FY15 Plans:

- Commission 2+6 operation, achieving 450 KW of beam power.
- Gradually increase the number of the slipped stacked batches.

Courtesy I. Kourbanis

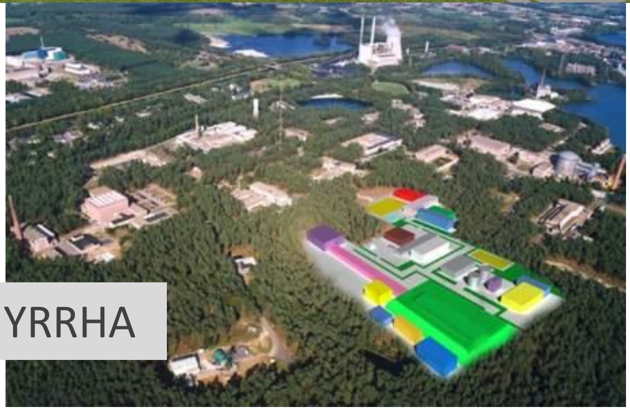


What's Next? Frontier proton accelerators in the next 10-15 years

- Spallation neutron sources
  - European Spallation Source (ESS) – 2 GeV, 5 MW **(M. Lindroos)**
  - SNS Second Target Station (with beam power upgrade) – 1.3 GeV, 2.8 MW
- Accelerator Driven Systems
  - MYRRHA, 600 MeV, 1.5-2.4 MW, Mol, Belgium
  - China ADS Program – Demo transmutation by early 2030s – 15 MW **(H. Zhao)**
- Intensity Frontier of Particle Physics
  - PIP-II Linac and > 1 MW beam power at 120 GeV
- Supported by R&D for SC linacs, synchrotrons, cyclotrons, FFAGs, …

ESS

SNS



MYRRHA

Intensity Frontier: Neutrino Sector

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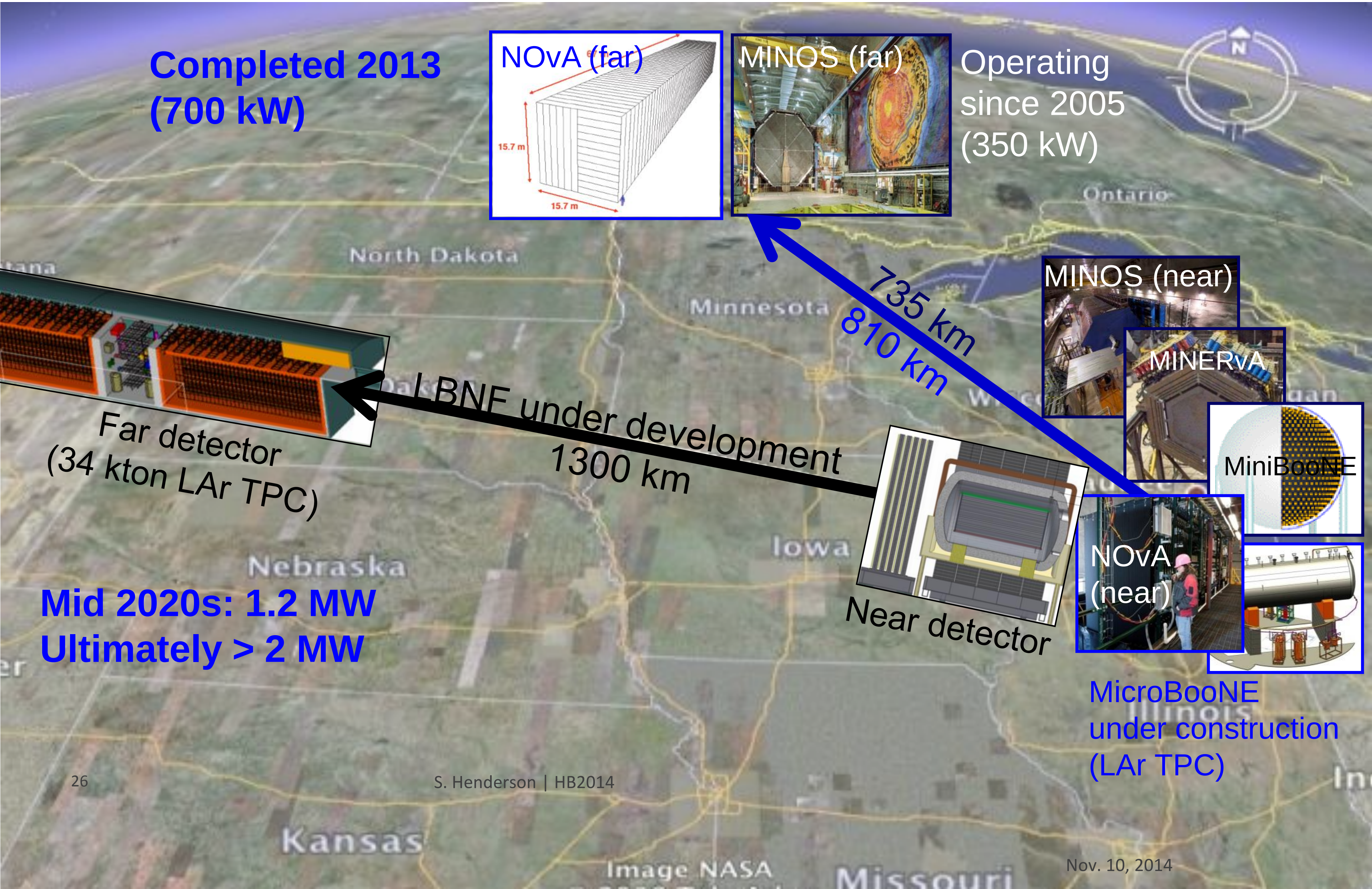
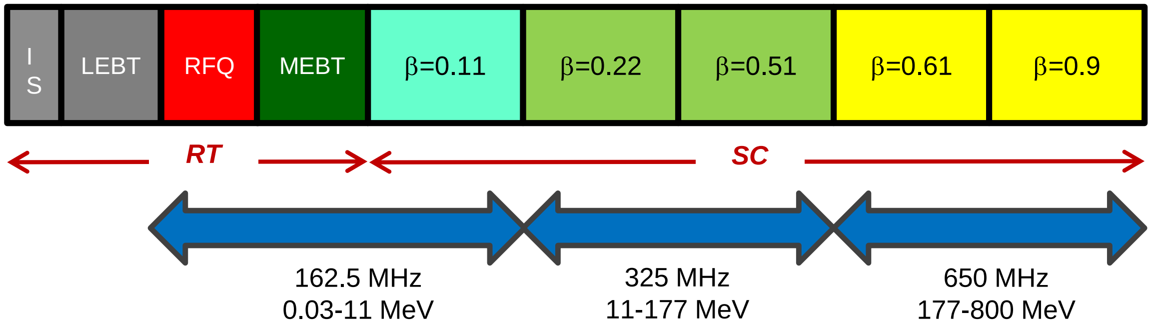
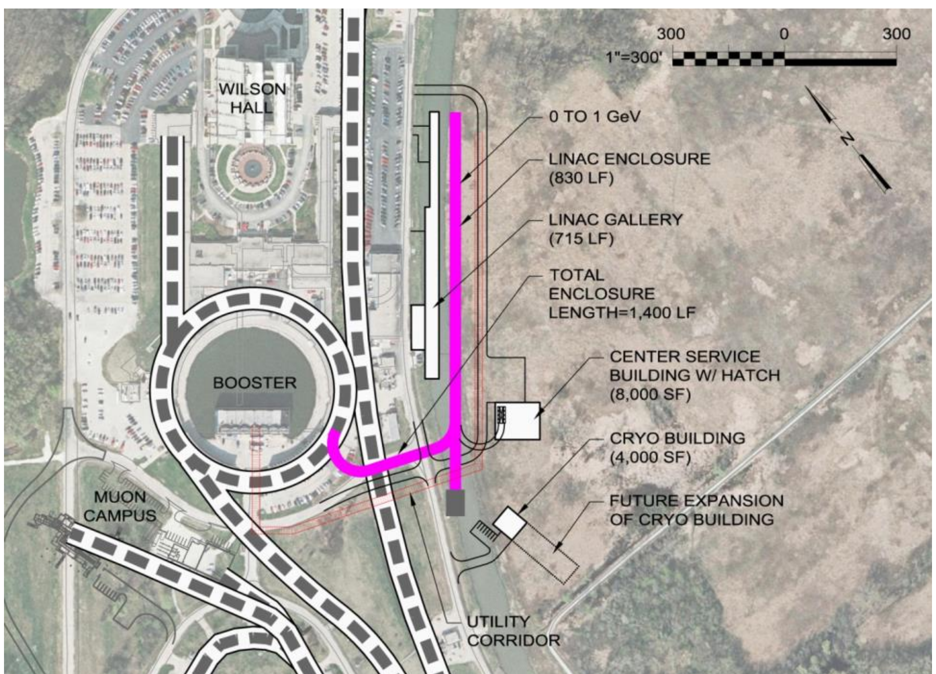


PIP-II Linac at Fermilab





Performance Parameter	PIP-II
Linac Beam Energy	800 MeV
Linac Beam Current	2 mA
Linac Beam Pulse Length	0.5 msec
Linac Beam Power to Booster	13 kW
Linac Beam Power Capability (@>10% Duty Factor)	~200 kW
Linac and Booster Pulse Repetition Rate	20 Hz
Booster Beam Power @ 8 GeV	160 kW
Beam Power to 8 GeV Program (max)	80 kW
Main Injector Protons per Pulse	7.5×10^{13}
Main Injector Cycle Time @ 120 GeV	1.2 sec
LBNF Beam Power @ 120 GeV	1.2* MW
LBNF Upgrade Potential @ 60-120 GeV	>2 MW

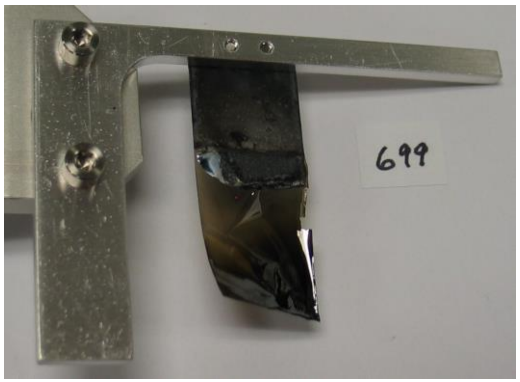
The Hard Limits in High Power Proton Accelerators

- Collective effects
  - Space charge, instabilities, electron-cloud effects
  - Halo dynamics: predict, measure halo population and dynamics at the level which is relevant for actual beam losses in self-consistent way: design to simulation to measurement validation
- Slow extraction of intense, high power beams
- Ability to package beams from pulsed linac to a few very high intensity bunches for proton drivers for neutrino factories/muon colliders (e.g. 4 MW at 8 GeV in 2 nsec long bunches at 15 Hz)
- Multi-turn charge-exchange injection via **stripping foils**
- Target systems
- Cost

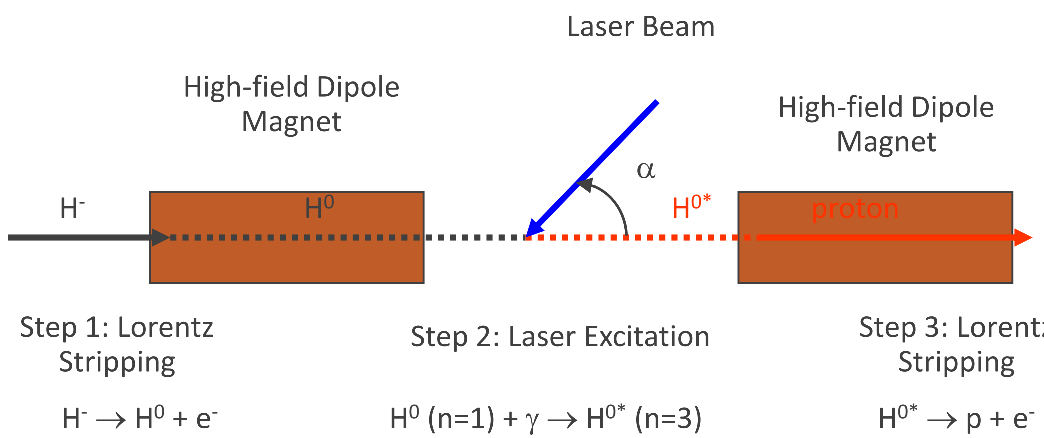
Charge-Exchange Injection and Stripping

- The conventional approach to accumulating high proton intensities in a ring is to use multi-turn charge-exchange injection of H- beams
- But it is very challenging:

Examples from SNS



- Novel Laser Stripping idea from Danilov et. al. has been demonstrated
- Scaling to realistic parameters is needed **(S. Cousineau)**



High Intensity Beam Dynamics

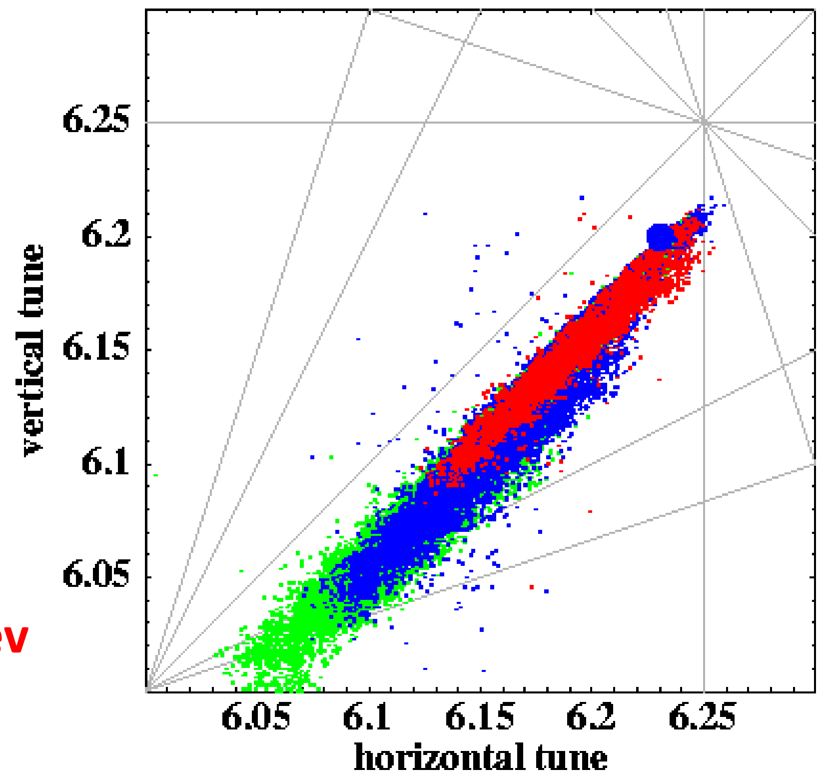
Typical design of a synchrotron or accumulator is limited in intensity due to

- space-charge at injection
- instabilities

A number of interesting ideas to overcome limitations require further development

- Creating self-consistent beam distributions (i.e. linear space-charge force) - Danilov
- Generating large Landau-damping of coherent instabilities via non-linear (but stable) betatron motion: IOTA and previous work – Danilov and **S. Nagaitsev**

Experimental insight is very important (UMER Ring) **(R. Kishek)**



Tune footprint vs. intensity in SNS accumulator ring

Extracting High Power Beams

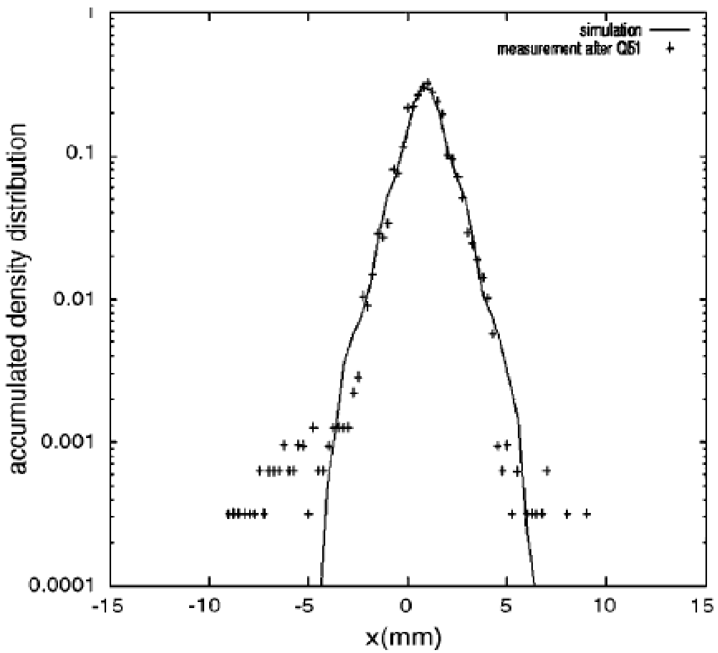
- Slow spills of high intensity beams are needed in particle physics, but beam loss limits intensity
- **Challenge for the community: are there novel ways to cleanly achieve slow spills of high intensity beams?**
- Resonant extraction, can it be extended to higher orders?
- Can crystals be used for high-power proton extraction?
- Novel approaches: Can electron beams be used to extract protons?

New ideas are needed!!!

Characterization and Understanding of High Intensity Beams and Underlying Dynamics

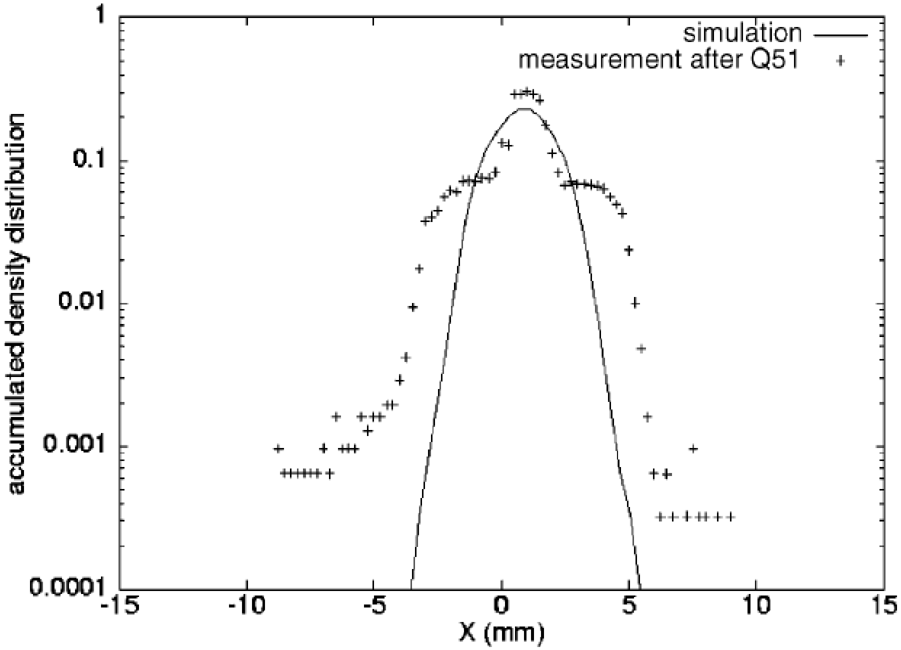
- Need to close the loop between prediction and measurement and simulation/propagation of halo that leads to beam loss

Matched Beam



Horizontal profile measured at end of channel compared with profile of beam simulation.

Mismatched Beam



Horizontal profile measured at end of channel compared with profile of beam simulation.

Simulations used particle distributions generated from beam evolution through LEBT and RFQ.

LEDA measurements and IMPACT code comparison: J. Qiang et. al., PRST-AB 5 (124201) 2002.

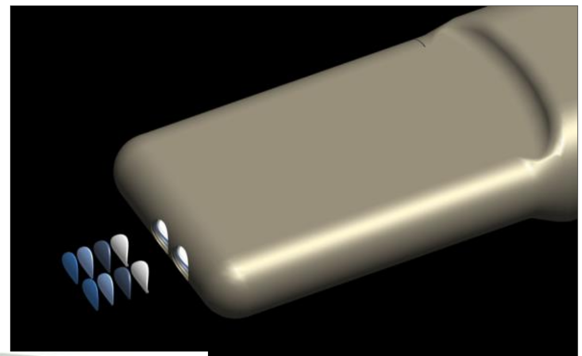
Mastering High Power Target Systems

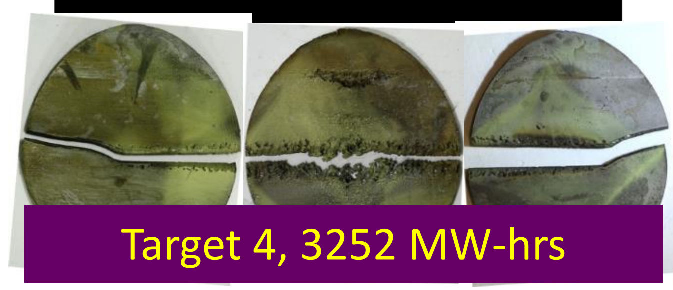
Liquid metal target systems required for many applications, in which beam power densities (MW/liter) are beyond the level at which solid materials can survive (or heat removal can be accomplished)

Pb-Bi Eutectic

MegaPIE experiment at PSI tested Pb-Bi Eutectic as a spallation target material [W. Wagner et. al., J. Nuc. Mat. 377 (2008) 12.

Closed loop Liquid Mercury

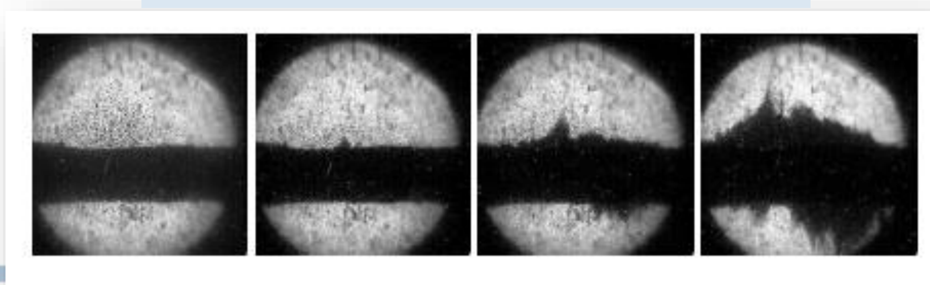




Cavitation induced erosion, scales as the 3rd - 4th power of intensity

Note recent SNS target issues NOT due to this mechanism

Free flowing Hg jet



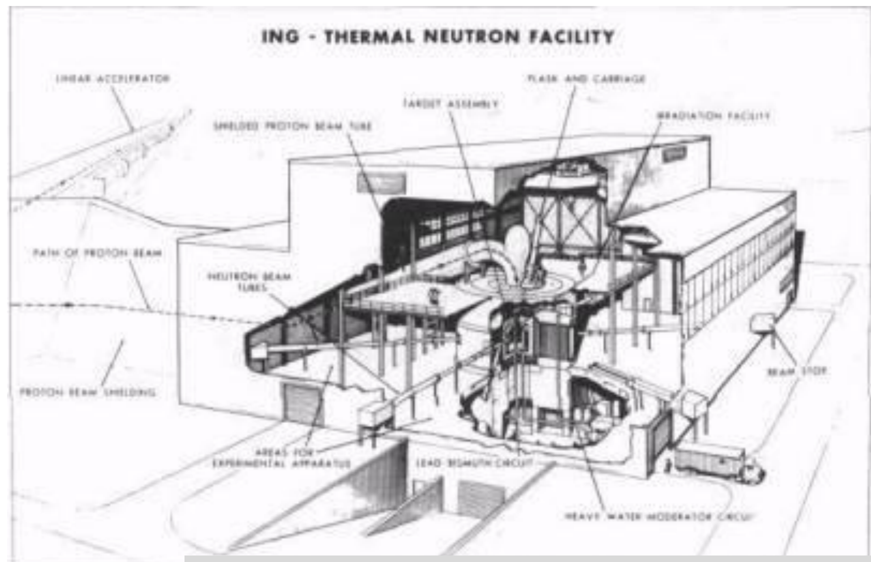
MERIT at CERN demonstrated free-flowing jet in 15T field for front-end of a neutrino factory/muon collider [H. Kirk et. al., Proc. EPAC 2008, p. 2886]. Dispersal/reformation time consistent with 8 MW beam parameters

Perspective

- I believe that the high power future in the near term will be driven by SC proton linacs operated CW
- Scaling from SNS linac suggests ~15 MW CW should be achievable.
- Interestingly, we just now closing in on the technology that was dreamt of in the 1950s and 1960s
- The question is, do governments have the ambition to make use of this technology to propel science forward?

MTA, authorized in 1950 for construction in Missouri ($500M) in weapons program

- 500 MeV, 320 mA = 160 MW on a NaK cooled Be primary target surrounded by a depleted Uranium target for neutron multiplication



Intense Neutron Generator:

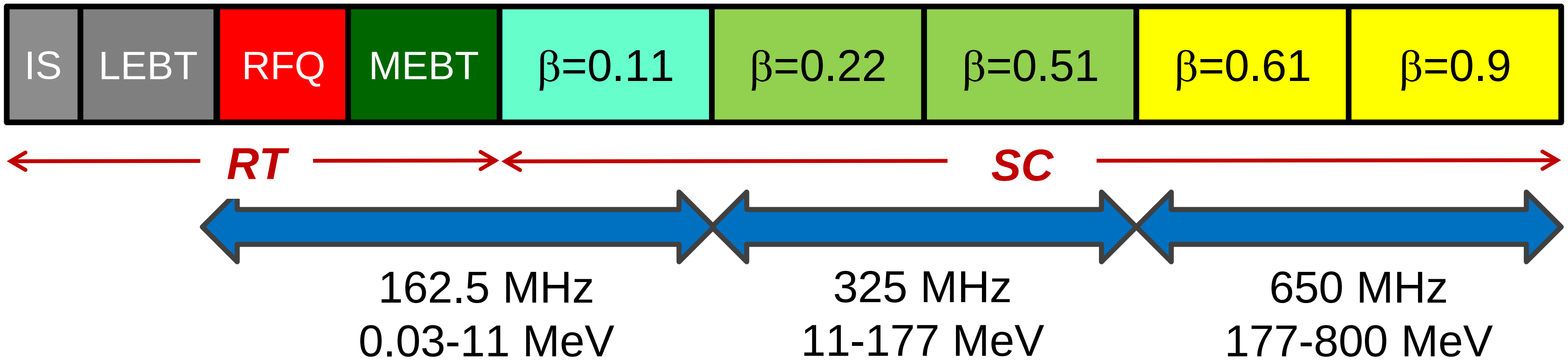
- Mid 1960s Chalk River Laboratory, Canada, cancelled in 1968
- Isotope production and neutron scattering
- 1 GeV proton, 65 mA CW = 65 MW
- Pb-Bi eutectic liquid target; Be multiplier and D20 moderator

PIP/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	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{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}	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
LBNF Beam Power @ 120 GeV	0.7	1.2*	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*LBNF beam power can be maintained to ~60 GeV, then scales with energy

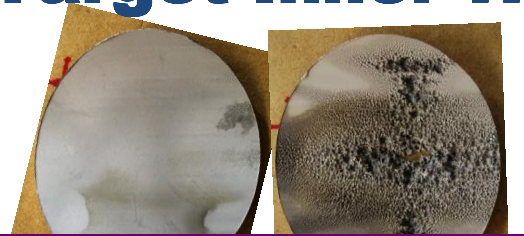
PIP-II Linac Technology Map



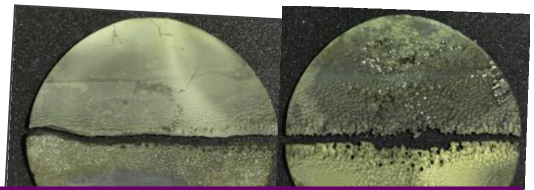
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

All components CW-capable

Target Inner Wall Cavitation Erosion

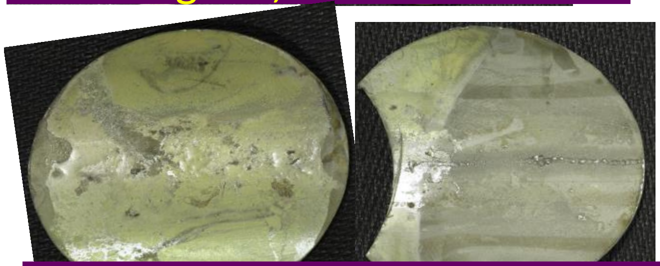


Target 1, 3055 MW-hrs, <P>=0.31 MW



Target 2, 3145 MW-hrs

Target 6, 617 MW-hr

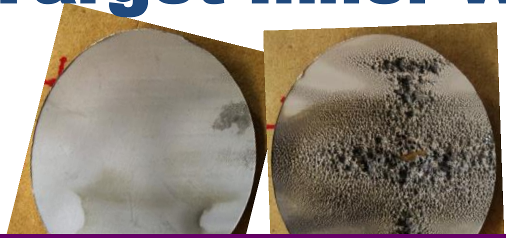


Target 7, 98 MW-hr

Target 8, 3750 MW-hr, <P>=0.85 MW

- Through-wall erosion damage along the horizontal centerline – occurs soon, but not much difference with increasing power, fluence

Target Inner Wall Cavitation Erosion



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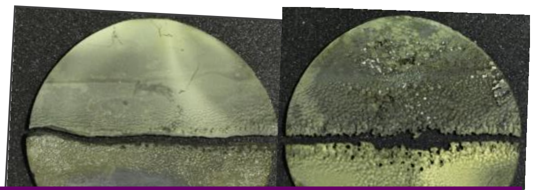

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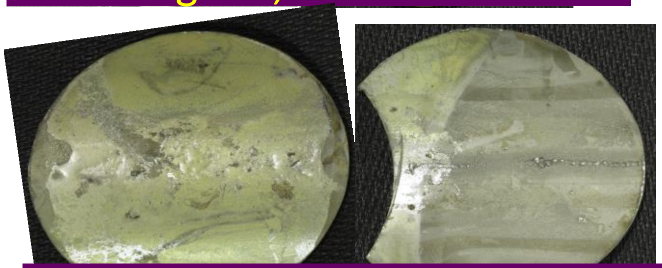
Target 3, 2791 MW-hrs

Target 6, 617 MW-hr



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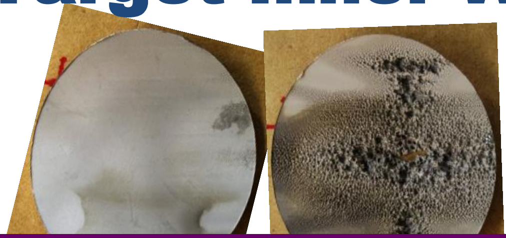

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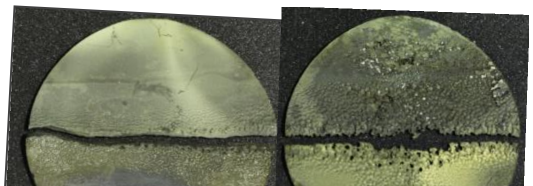

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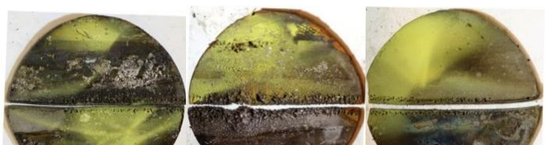
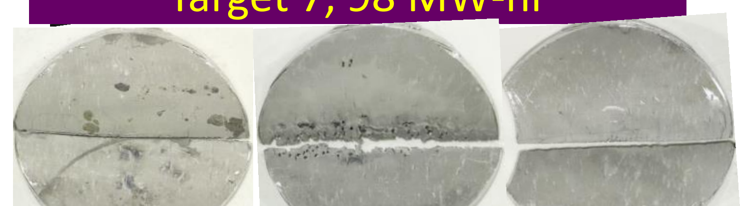


Target 3, 2791 MW-hrs

Target 5, 2362 MW-hrs

Target 6, 617 MW-hr

Target 7, 98 MW-hr



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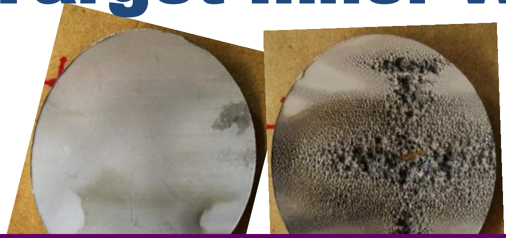

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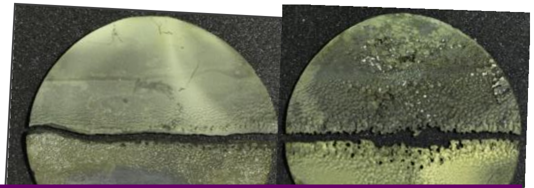

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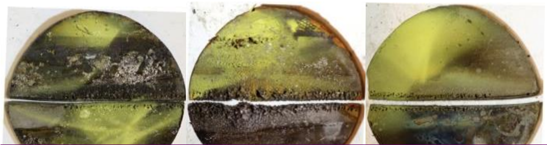

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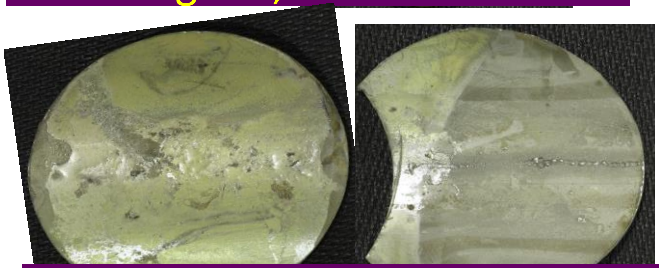

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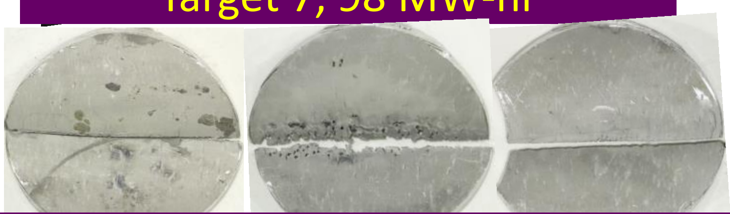

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