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P-X as a Prototype for an Accelerator to Drive Several ADS-ATW Reactors or Environmentally Friendly Power Stations for National Goals and the Power Industry

Rolland P. Johnson

Muons, Inc. (http://www.muonsinc.com/)

Not so Hidden Agenda # 1

8-GeV protons not be a bottleneck at Fermilab

Personal perspective: 1975-1977 I was FNAL Booster Group Leader
Productive years with creative people who worked very hard:
Griffin and Ankenbrandt invented barrier buckets
Ankenbrandt invented slip stacking
Had 300 mA down linac designed for 80 mA (feed forward)
Installed first H- charge exchange injection system using Carbon foils
Discovered that Laslett tune shift was an essential limitation,
largely overcome with Linac upgrade from 200 to 400 MeV in ~1992,

But still more limitations were discovered !
(e.g. residual radioactivity).

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Not so Hidden agenda # 1 (continued)

8-GeV protons not be a bottleneck at Fermilab

Although we increased the beam power >3x beyond a "topped-out" machine, the 8-GeV Booster, in spite of being the world's most powerful machine for much of the past 40 years, has remained a limitation to Fermilab's ability to do physics.

Experiments were not even considered feasible or were limited because of proton economics, e.g. the Tevatron luminosity usually depended on the Booster proton intensity.

It is really hard to know what will be needed in the future. Best to provide a machine that will not be the bottleneck.

Not so Hidden agenda # 2

Proton power to produce muons for a collider

Present schemes to create cooled muon beams show great promise, but may be optimistic.

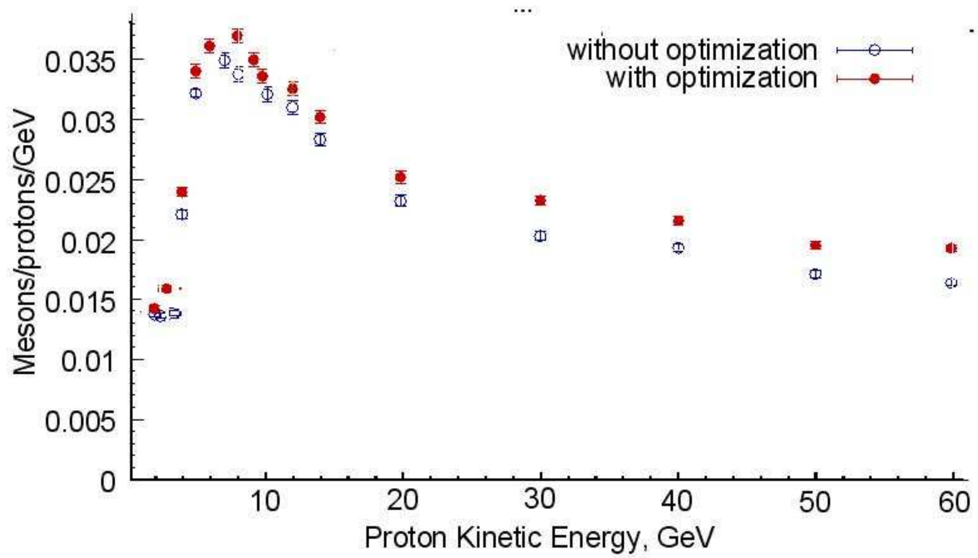
4 MW at 8 GeV is as far as people have dared to suggest, but it may not be enough, especially at the beginning. You would like to be able to do more than one experiment at a time! (e.g. NF and MC could each use 4 MW, mu2e at least 1 MW, etc. and there will be more)

8 GeV looks like the best place for muon production! And to get the required beam power, CW is needed.

Not so Hidden agenda # 2 (continued)

Proton power to produce muons for a collider (Mokhov via Palmer plot)

Pion production



- Production predicted by MARS with optimized target rad and length
- Peak is at 8 GeV
- Production down to 51% at 60 GeV

3

Not so Hidden Agenda # 3

Accelerator physicists need to save the world

The DOE, more than any other entity, has the most accelerator expertise in the world (e.g. HEP, BES, NP, NNSA)

A coherent plan to involve that expertise in a project with important national goals would be good for everybody. The synergy of accelerator research for ADS and fundamental physics seems compelling.

We tried to get ARPA-E interest earlier this year:

How to Fund a Muon Collider (by Solving Important Problems Along the Way)

Rolland Johnson
Muons, Inc.

“ask not what your country can do for you - ask what you can do for your country”

J. F. Kennedy, Jan 20, 1961

CONCEPT: SRF Linear Accelerators for Transformational Energy Technologies

Lead proponent: Muons, Inc. (http://muonsinc.com/)
Proposed partners: Fermi National Accelerator Laboratory (Fermilab), Thomas Jefferson National Accelerator Facility (JLab), and Oak Ridge National Laboratory (SNS)
Interest also from BNL, LBNL, PNNL

GOALS: accelerator-driven subcritical (ADS) nuclear power stations

- operating at 5 to 10 GW,
- in an inherently safe region below criticality,
- without generation of greenhouse gases,
- producing minimal nuclear waste,
- no byproducts that are useful to rogue nations or terrorists,
- incinerating waste from conventional nuclear reactors (ATW),
- efficiently using abundant thorium fuel,
- which does not need enrichment.

CONCEPT: SRF Linear Accelerators for Transformational Energy Technologies

First, the feasibility of the accelerator technology must be demonstrated.

Fermilab has already proposed a $1B to $1.5B 8-GeV super-conducting RF (SRF) linear accelerator called Project-X for particle physics at the intensity and energy frontiers.

Muons, Inc. proposes to work with its SBIR-STTR partners Fermilab, JLab, and SNS (also ANL, BNL, LBNL, and PNNL) to extend this linac design to become also a prototype for a practical accelerator for ADS reactors and to provide beams for reactor development.

The first major milestone of the project to be proposed here is to produce an enhanced or alternative design for the Project-X CD1 document that includes ADS and ATW development needs.

Concept paper is posted on Papers and Reports of Muons, Inc. web site.

Energy Independence, Climate Change, High-Tech National Goals

What does P-X have to do with ADS?

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Once above ~1 GeV, neutron yield is proportional to beam power (Peggs or Revol)

The first beta<1 part of the Linac is hardest:
Less gradient, lower frequency, lower efficiency, more parts, more complex, more expensive to operate and maintain, and the most difficult to make reliable . (See Solyak & Yakovlev)

beta=1 cavities easily add beam power, and can overcome certain kinds of failures.

Multiple beta<1 initial sections can inject into the more robust beta=1 part (see Pagani slide)

P-X can be the prototype for this ADS ATW machine to develop accelerator and reactor techniques and to test materials.

Let's try to get the US Government (for national environmental goals) and US Industry (for fun and profit) interested to support ADS R&D!

neutrons

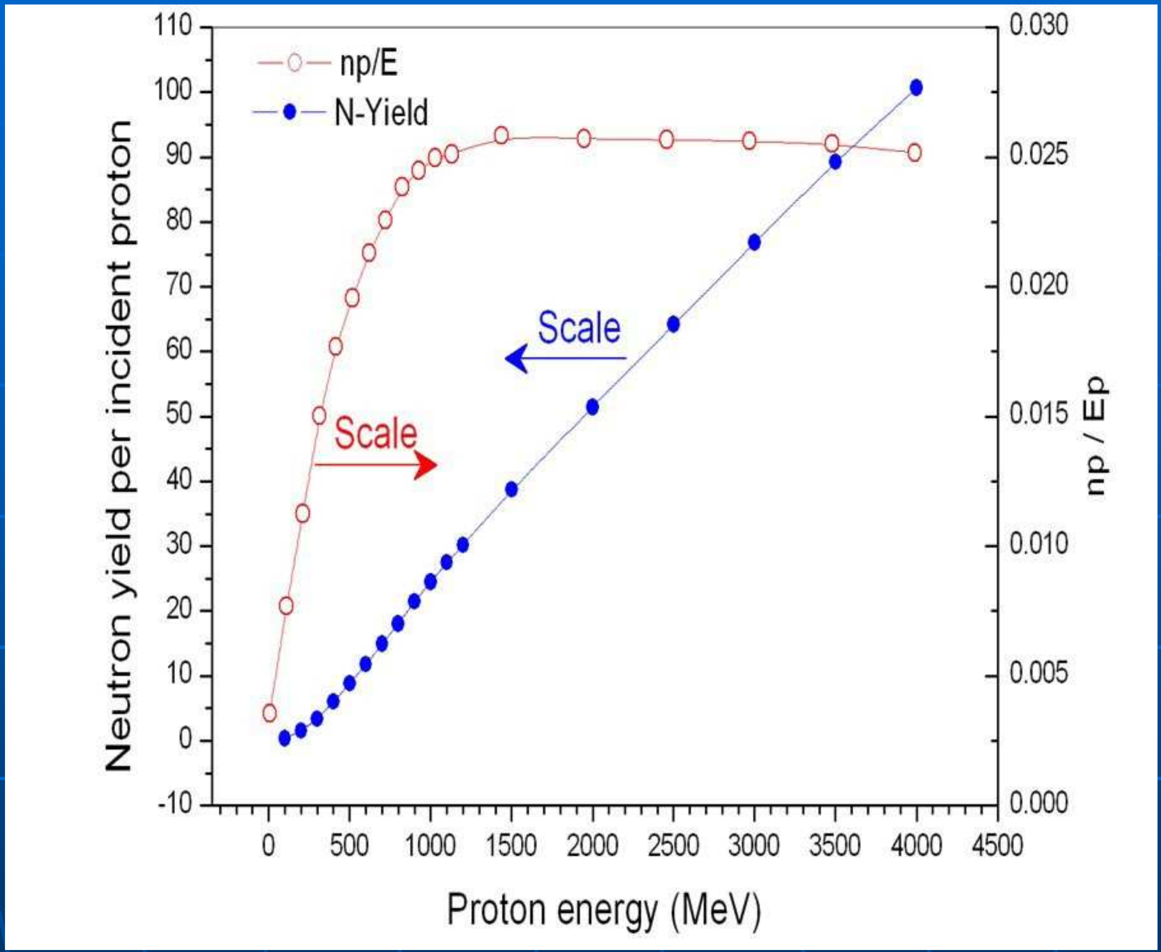
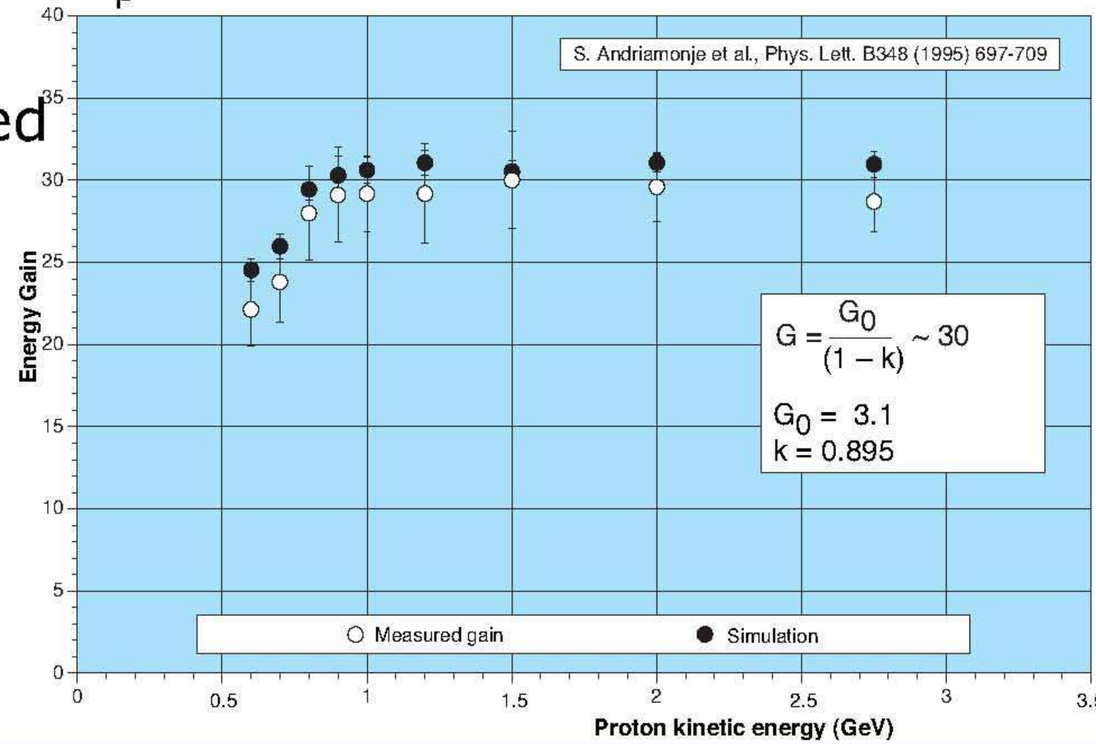


Figure 1: Neutron yield as a function of proton energy for one set of target and moderator conditions. Above about 1 GeV the useful neutron flux is ~proportional to beam power. (Peggs Erice lecture.)

Results from FEAT

- Optimum beam energy reached at 900 MeV, with slow decrease at higher energies (ionization vs nuclear cascade production): neutron yield scales with proton energy (E_p)
- Simulation validated from spallation to heat production



Revol talk

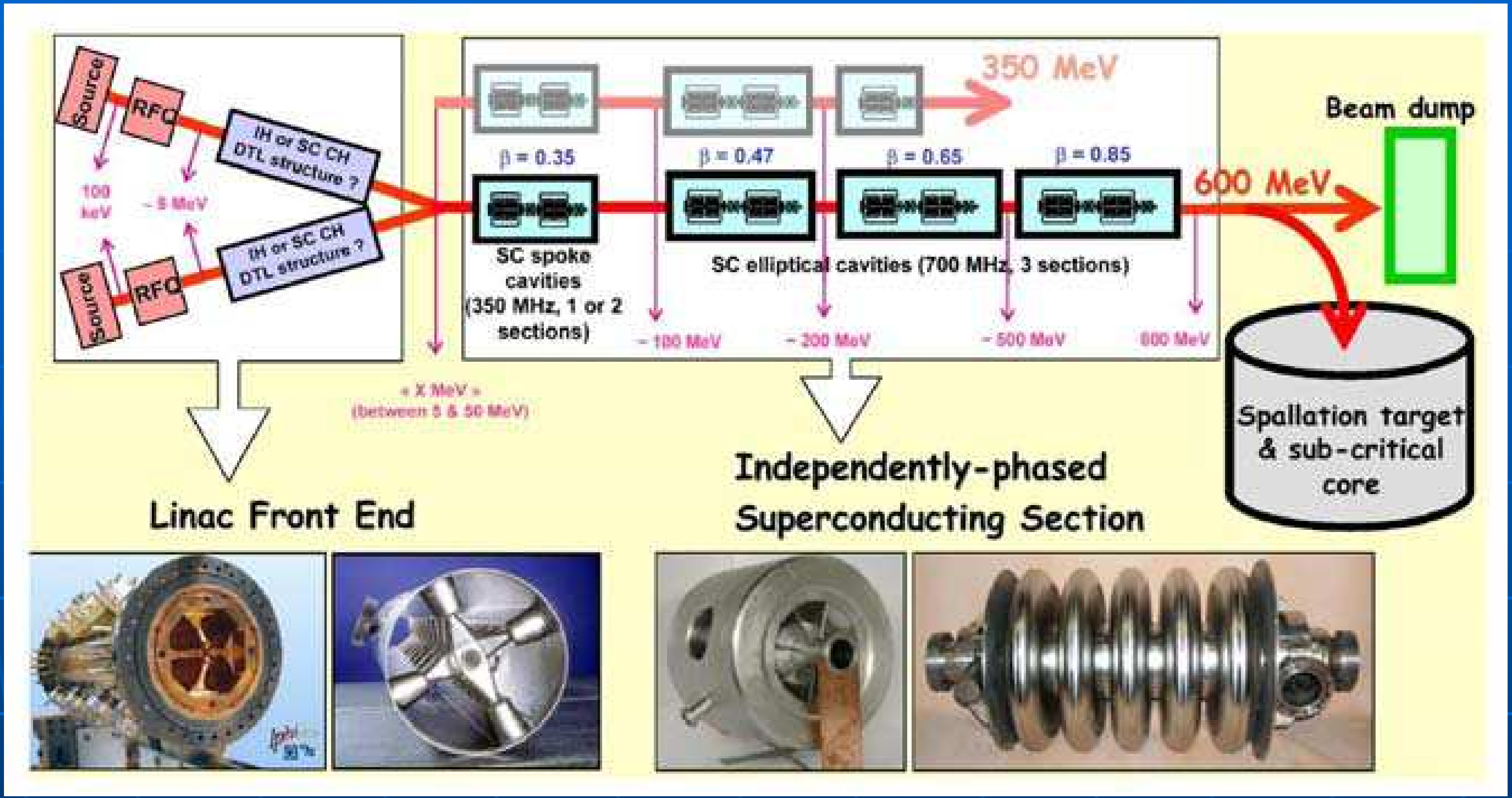


Figure 4: The reference accelerator scheme for the ETD/XT-ADS.

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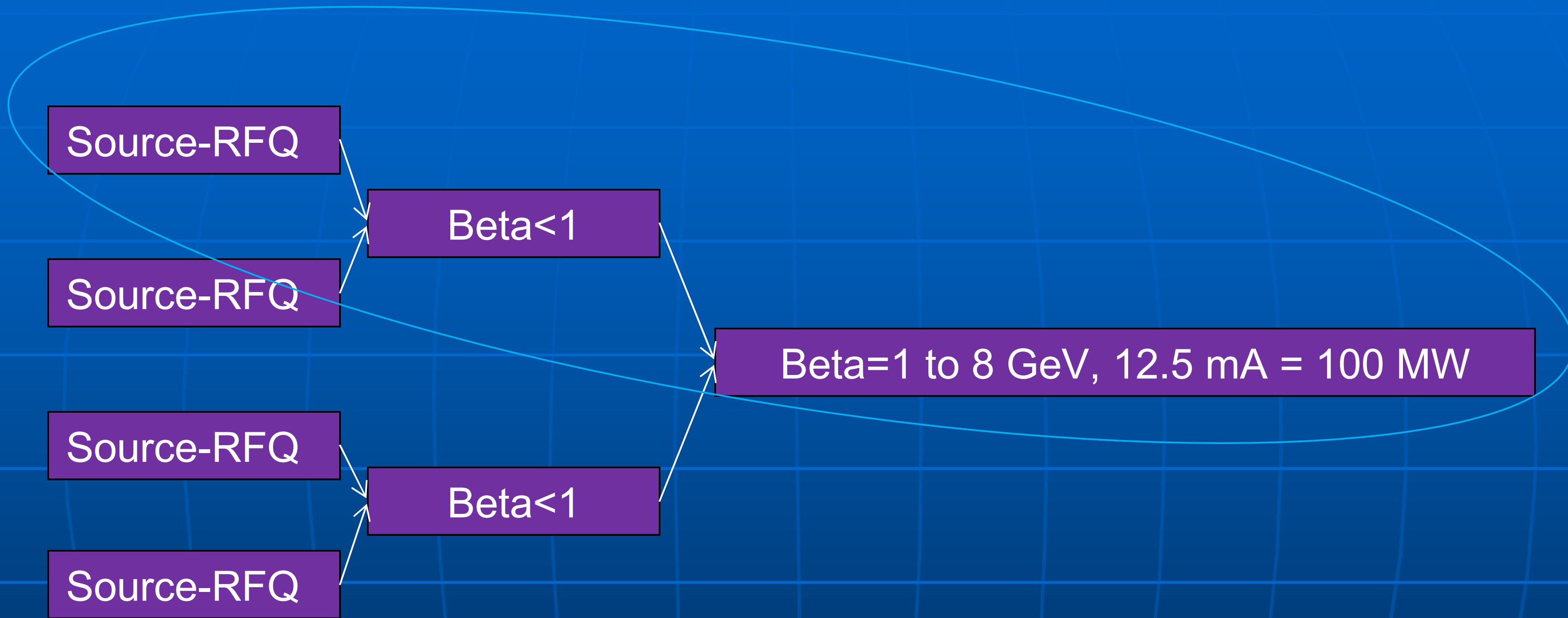
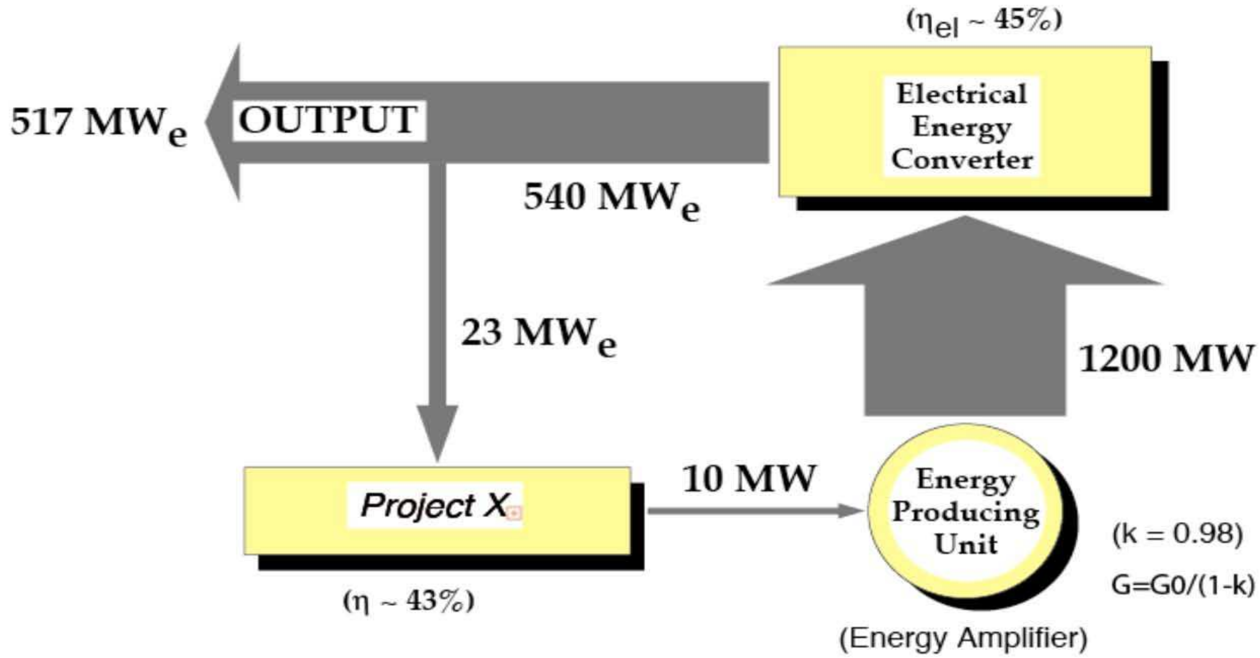
Son of P-X Conceptual Picture



Less reliable components are duplicated. Maybe even the beta=1 part, too.

Principle of energy flow

- Example of a 10 MW beam (Project X?); very close to the power of standard EA unit defined by C. Rubbia.



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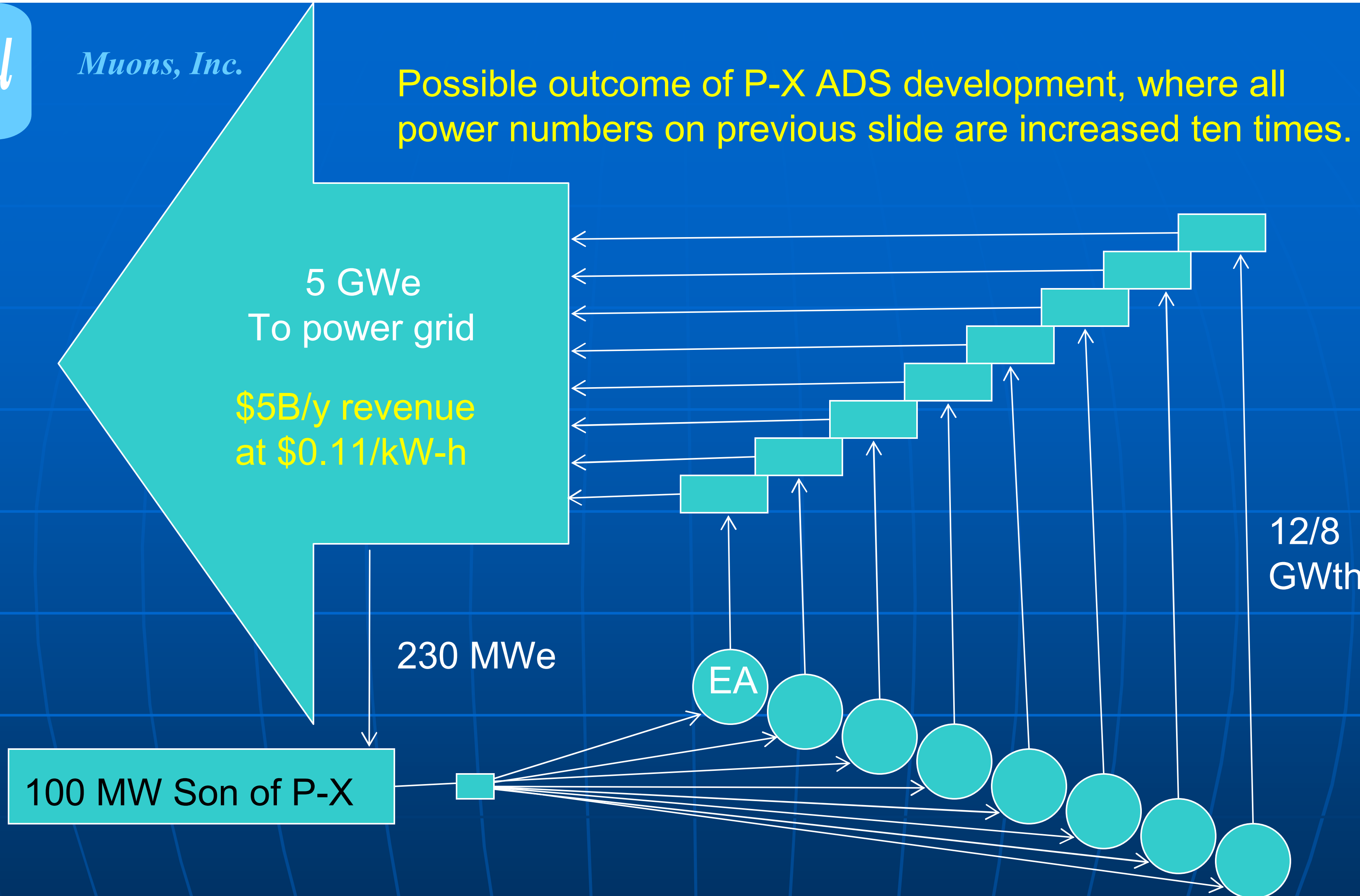
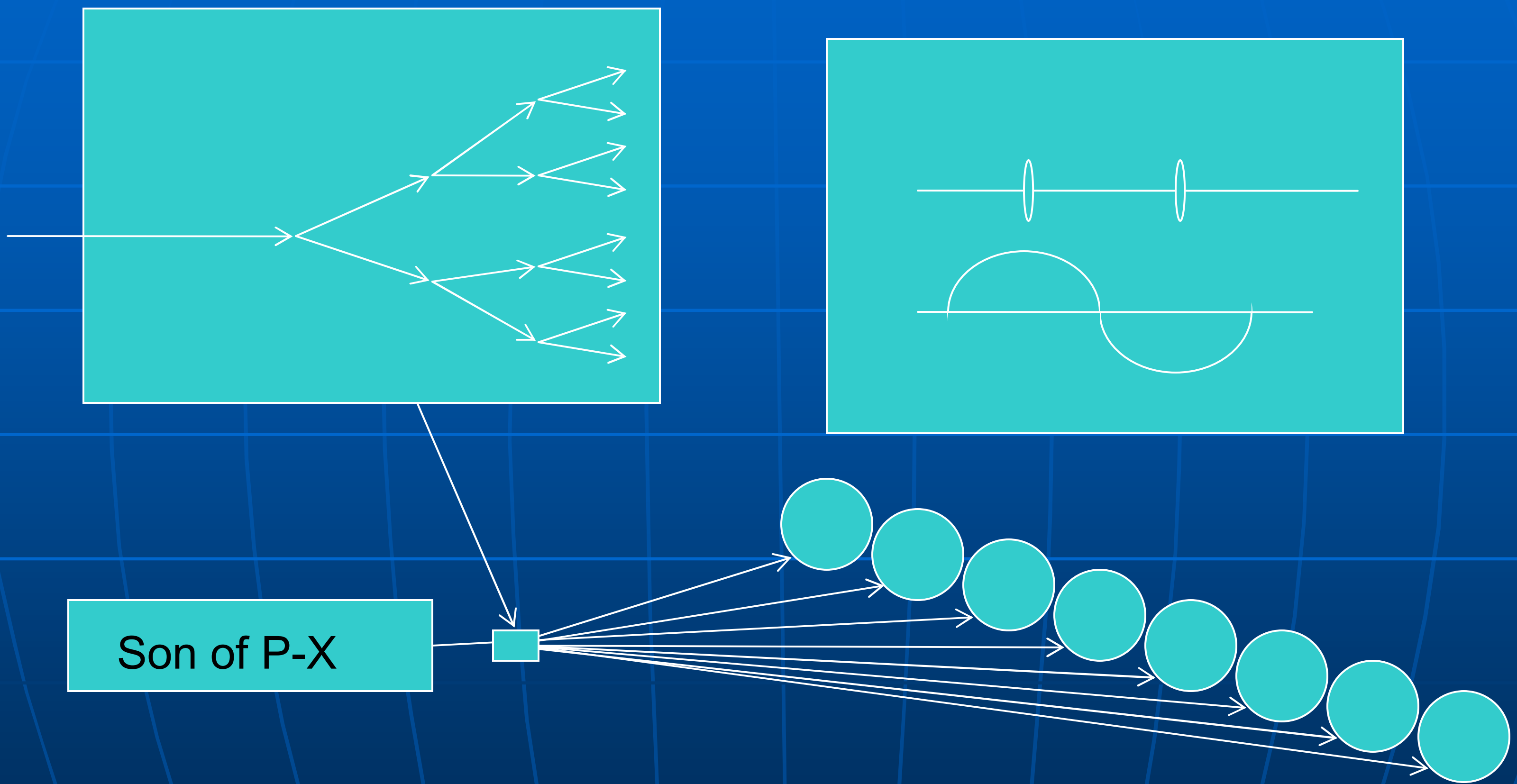
Possible outcome of P-X ADS development, where all power numbers on previous slide are increased ten times.



In a few years the grid should be lossless and this power station can be placed anywhere, e.g. in a geologically, environmentally, etc. acceptable location.

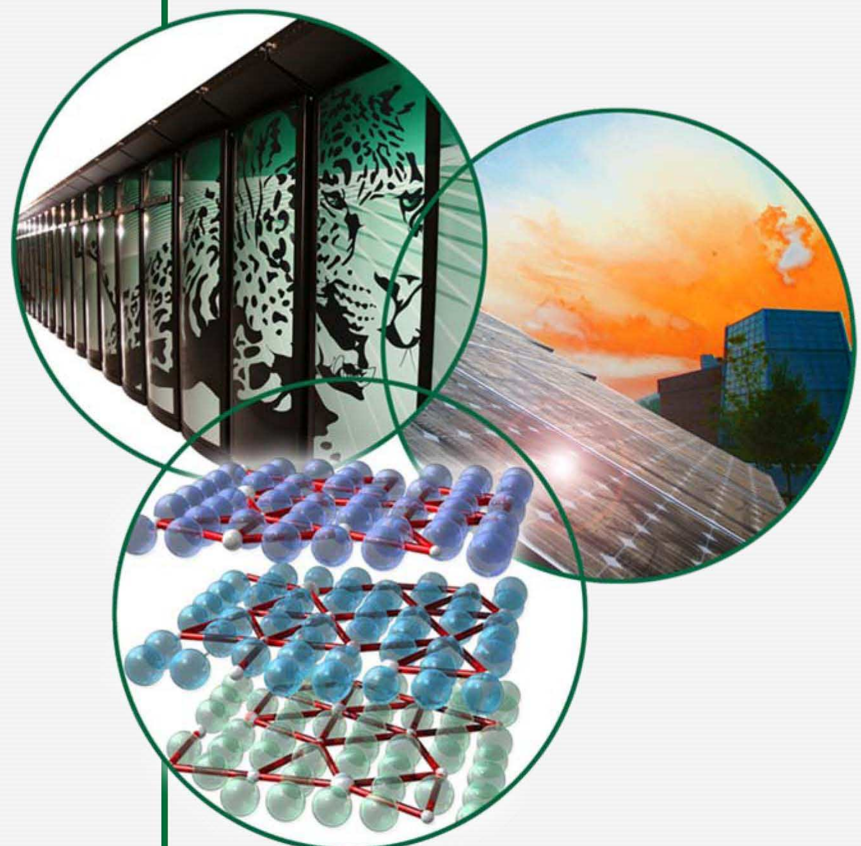
A beam splitter concept using transverse RF kicks



Intensity of each bunch is determined at the source

A Review and Preview of High-Current, High Power (Hadron) Accelerators

A few slides from ICIS09



Stuart Henderson

Director, Research Accelerator Division

Spallation Neutron Source
Oak Ridge National Laboratory, USA

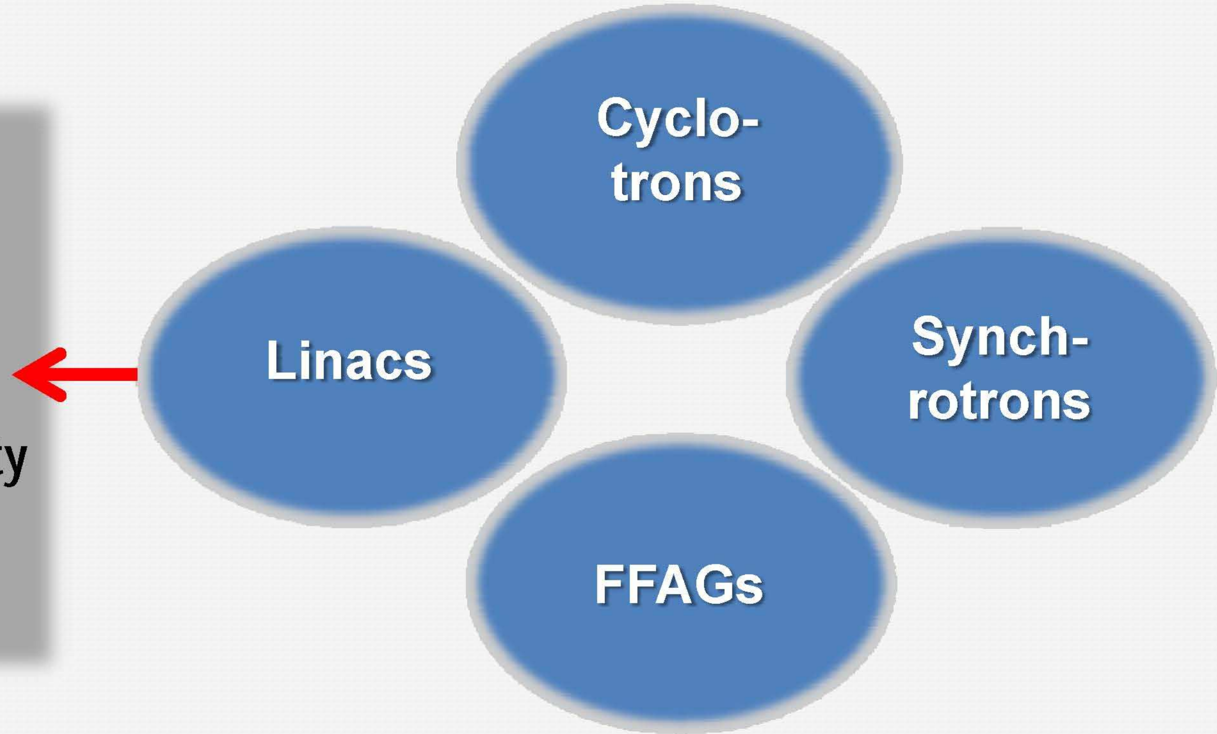
September 25, 2009

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

A Variety of High-Power Approaches

- Pros: good beam quality, low-loss, potential for very high-beam power
- Cons: Large RF plant, expensive, high availability is challenging; downstream ring may be required



High Power Beam Facilities

- Multipurpose facilities
  - LANSCE (US), J-PARC (Japan), PEFP (Korea)
- Spallation neutron sources
  - SNS (US), SINQ (Switzerland), ISIS (UK), ESS (Europe), CSNS (China)
- Radioactive Ion Beams, Nuclear Physics
  - RIKEN (Japan), TRIUMF (Canada), FRIB (US), EURISOL (Europe), FAIR (Germany), SPIRAL2 (France), SPES (Italy), SARAF (Israel)
- Particle Physics
  - NuMI (US), CNGS (CERN), Project-X (US), SPL (CERN), MC/NF (US&CERN)
- Materials Irradiation
  - IFMIF (EU&Japan)
- Accelerator Driven Systems
  - MYRRHA (Belgium), EUROTRANS (EU), TRASCO (Italy), ADS (China, Japan, Korea)

The Beam Power Landscape for Proton Accelerators

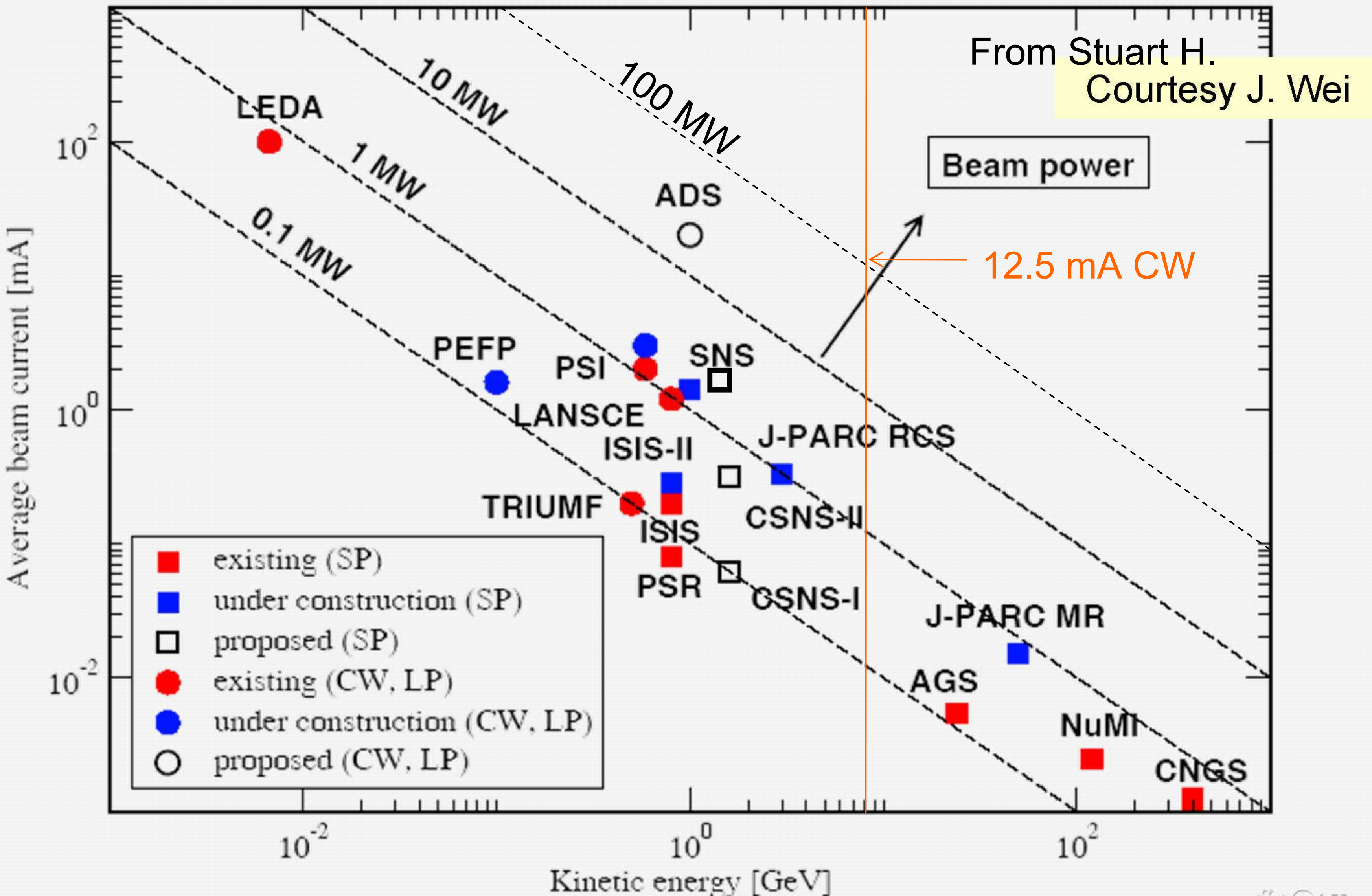


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Table 2: Parameters of the different ADS projects from updated Table 1 of Gulevich[31]. ICFA Newsletter

Project	Accelerator power (MW)	keff	Blanket power (MW)	Target	Fuel	Ref.
OMEGA	58 (1.5 GeV, 39 mA)	0.9	820	W	Np/5Pu/30Zr	[32]
JAERI-ADS (Japan 2004)	27 (1.5 GeV, 18 mA)	0.97	800	Pb-Bi	MA/Pu/ZrN	[33]
HYPER (Korea)	15 (1 GeV, 10-16 mA)	0.98	1000	Pb-Bi	MA/Pu	[34]
XADS Design A (Italy)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Pb-Bi	U/Pu/MOX	[35]
Design B (France)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Steel	U/Pu/MOX	[9]
Design C (Belgium)	1.75 (350 MeV, 5 mA)	0.95	50	Pb-Bi windowless	U/Pu/MOX	[36]
INR (Russia)	0.15 (500 MeV, 0.15-0.3 mA)	0.95-0.97	5	W	MA/MOX	[37]
NWB (Russia)	3 (380 MeV, 10 mA)	0.95-0.98	100	Pb-Bi	UO2/UN U/MA/Zr	[38]
CSMSR (Russia)	10 (1 GeV, 10 mA)	0.95	800 cascade scheme	Pb-Bi	Np/Pu/MA	[39]

Conventional Front End

- Ion Source, H- , DC, < 1mA
- LEBT, ~30-50 kV, short
- RFQ, 162MHz , < 2.2MeV, DC, warm
- MEBT, probably very short

"Low" Energy Linac

- Single Spoke, ~10MeV
- Double Spoke ~100MeV
- Triple Spoke ~400MeV
- Beta=0.81 ~1.2GeV
- Beta=1, ~2.xGeV
- FODO, quads

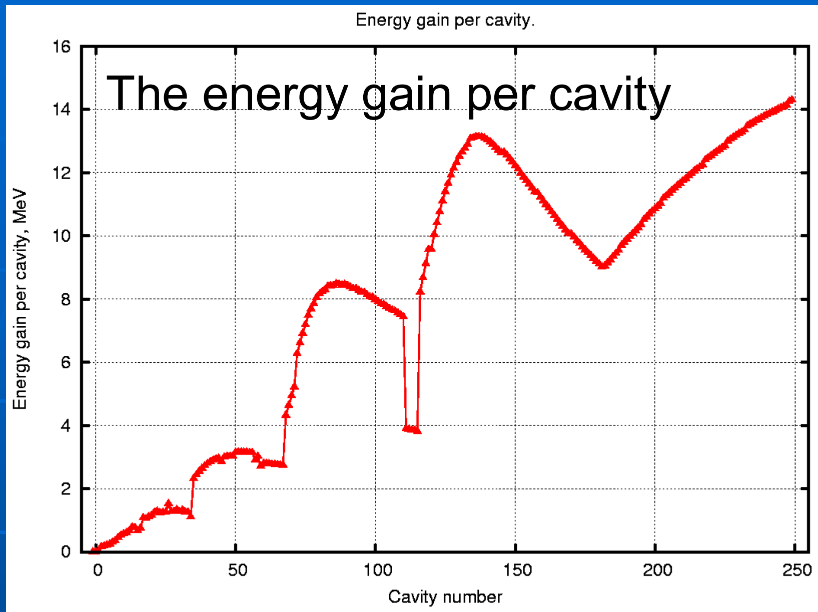
(Almost) Copy of ICD-2,

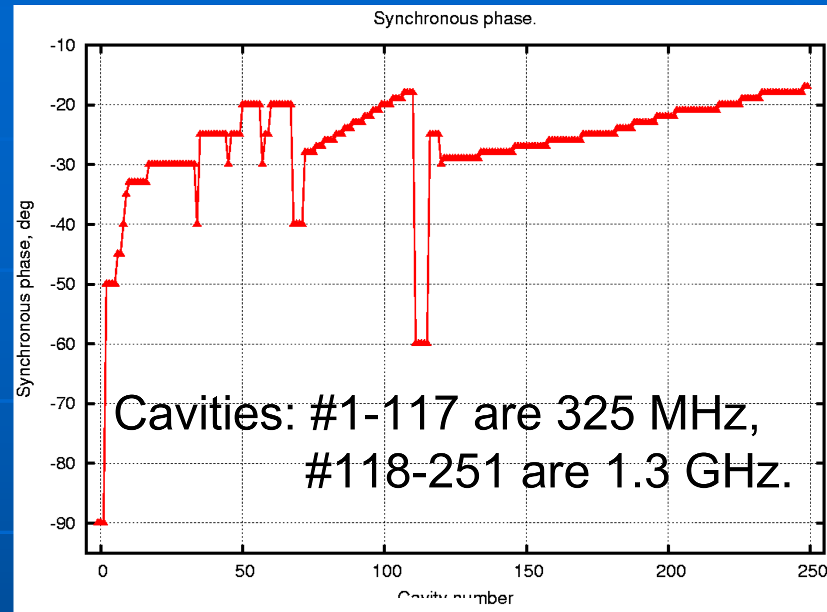
Nagaitsev, Solyak, Yakovlev, et al

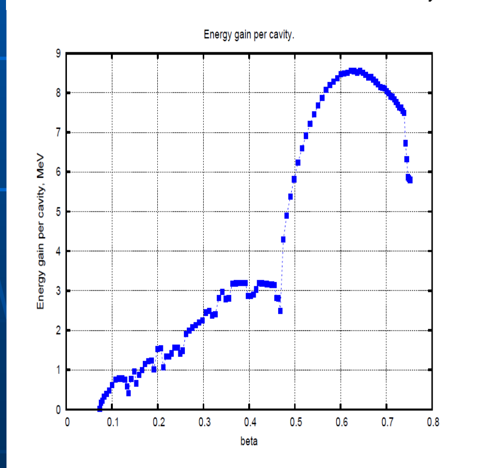
Copy of ICD-1, (Almost)

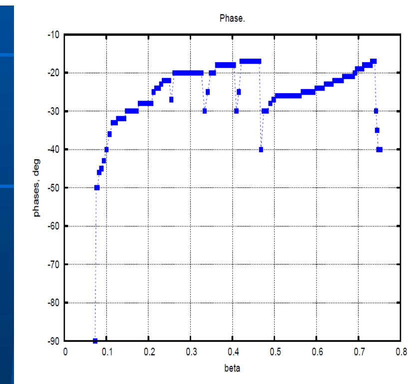
Ostroumov, et al

From Solyak and Yakovlev ICD-2 CW Linac Update









Blue: re-optimization of the 325 MHz linac (SSR0+SSR1+SSR2+TSR)

- 14 SRR0 (instead of 16)
- Increase gradient, optimum phases
- Better longitudinal/transverse dynamics

Cavity Parameters

325 MHz

cavity type	F [MHz]	$U_{acc, max}$ [MeV]	E_{max}, [MV/m]	B_{max} [mT]	R/Q, Ω	G, Ω	$Q_{0,2K}$ $\times 10^9$	$Q_{0,4K} \times 10^9$	$P_{max,2K}$ [W]	$P_{max,4K}$ [W]
SSR0	325	0.78	53	59.5	120	57	9.5	0.7	0.77	10.4
SSR1	325	1.53	34.4	50.8	242	84	14.0	1.0	0.94	13.2
SSR2	325	3.16	33	54	322	112	18.0	1.3	2.07	28.6
TSR	325	8.5	31.4	67	554	117	19.0	1.4	7.9	106.9

1.3 GHz

cavity type	F [MHz]	E_{acc} [MV/m]	L_{eff}, mm	E_{max} [MV/m]	B_{max} [mT]	R/Q Ω	G Ω	$Q_{0,2K}$ $\times 10^9$	$Q_{0,4K} \times 10^9$	P_{2K} [W]
11-cell, β=0.81	1300	14.4	1028	34	72	750	228	12.7	n/a	22.4
9-cell, ILC	1300	16.9	1038	34	72	1036	270	15.0	n/a	19.0

Technical Challenges: Front-End Systems

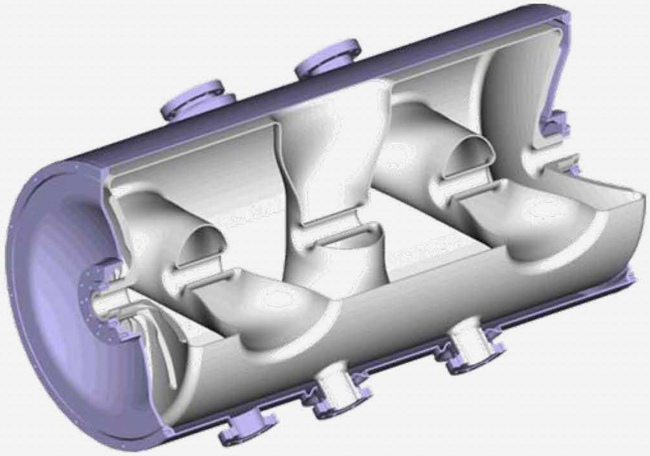
- Multi-MW sources place extreme demands on the linac injector
  - Requires development of high-brightness H- and proton sources capable of operating reliably at high average powers
  - Requires fast-risetime chopper systems (for short pulse)
  - Beam transport system designs which minimizes emittance and halo growth at low-and medium- energy
  - Several test-stands and test accelerators have been devoted to this topic: RAL FETS, SILHI at CEA/Saclay (IPHI, IFMIF) , SNS Test-Stand, LEDA

	1.4 MW SNS	3 MW SNS	5 MW Long-pulse
Ion Source current	42 mA H-	~80 mA H-	~130 H+
RFQ output current	38	59	112
RFQ output emittance	0.3	0.3	~0.3
Pulse length/rep-rate	1.0/60	1.0/60	2.0/17

Technical Challenges: Acceleration to High-Energy in a SC linac

- SC technology was successfully deployed for proton acceleration at the SNS
- Known advantages of a SC proton linac: high-gradients, large aperture, efficient power transfer, high stability due to constant temperature, low vacuum, tremendous flexibility when independently controlled
- RF Infrastructure is challenging: high-power, high-duty, multiple cavity control from a single source, control of cavity detuning effects

Single Spoke Resonator



ANL 345 MHz Triple Spoke Resonator

Challenges for Multi-MW Sources

- Producing high current beams, properly chopped
  - Front-end systems: very demanding beam current, duty-factor and emittance requirements, with associated fast chopping
- Accelerating high beam currents to high energy
  - SC linac performance: high-gradient, lorentz-force detuning, RF cavity phase/amplitude control for multiple cavities/klystron
  - Linac systems: high-duty factor, high-power RF systems and associated components
- Transporting high power beams while maintaining beamloss at a level where routine maintenance is possible (< 1 Watt/m)
  - Beamloss: requires beyond state-of-the-art computation, instrumentation and control
  - Rings: Injection, collective-effects, stripping foil lifetime
  - Machine Protection and beam/target interface…
- Converting high power proton beams to neutrons
  - Target Systems: mitigation of single-pulse damage

Experience at Existing Machines Lays the Groundwork for Multi-MW Facilities

What have we learned?

- 1 W/m beamloss in a MW-class pulsed accelerator is achievable
  - Space-charge limits in rings can be mitigated by phase-space painting
  - Collective phenomena at high intensity are calculable, and results are believable
  - Electron cloud effects can be mitigated
  - Linac emittance growth is calculable and can be minimized in practice
- Superconducting linac technology works in a proton beam context: high-quality beams are obtained together with flexibility given by independently-powered SC system
- High beam powers can be safely handled
- Liquid metal targets work at MW beam powers
- Rapid synchrotron acceleration rates can be achieved with new magnetic alloy core technology
- H- sources can provide low-emittance, high beam current at high duty factor

Trends in High-Power Hadron Accelerator Design

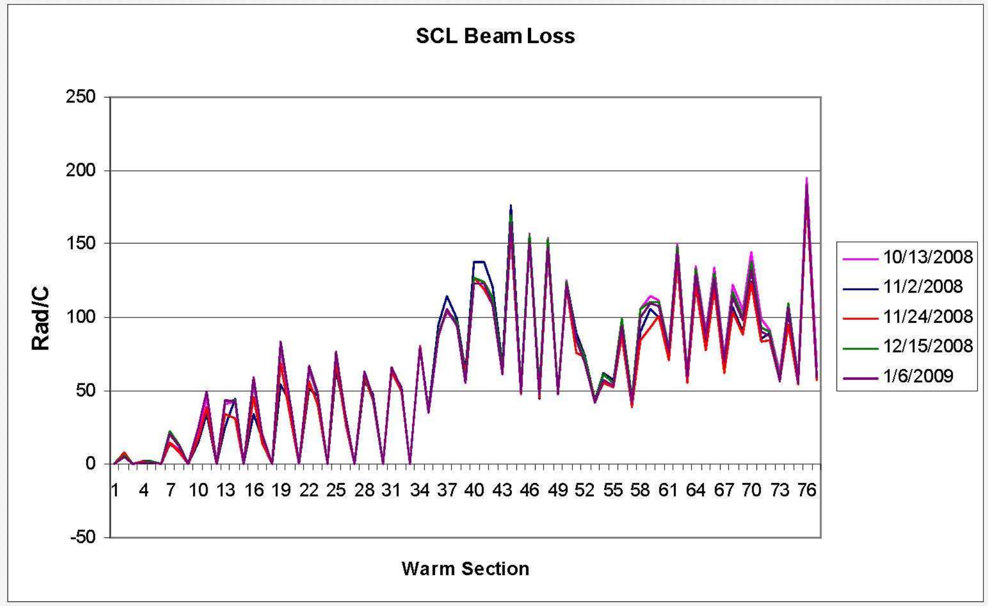
- **Front-ends**:
  - RFQs are the modern choice
  - Push toward CW beams in applications where the linac produces the primary beam
- **Linacs**:
  - Use of SC rather than NC structures
  - Extend NC/SC transition to lower and lower energies
- **Rings**:
  - Rapid-cycling, large aperture synchrotrons for high power
  - Incorporation of phase-space painting for multi-turn injection
  - Dedicated collimation systems
  - Mitigation of collective effects in design (electron-cloud)

Technical Challenge: Beamloss Design, Measurement and Control

- Multi-MW facilities need to predict, measure and control beam particle distributions at the part per million level to reach 1Watt/m beamloss requirements
- Prediction of beamloss is not to the point where an accelerator can be "engineered"
- Simulation capability is advanced, but incomplete knowledge of input distributions makes quantitative predictions at the ppm level impossible
- Our field needs to overcome the issue of incomplete accelerator input distributions (ion source/LEBT output distributions)
- Beam instrumentation tends to focus on beam-core parameters. Lost particles are those that have reached large amplitudes, many-sigma beyond the core.
- Control of beamloss that cannot be predicted or measured demands that flexibility be built into the accelerator design!

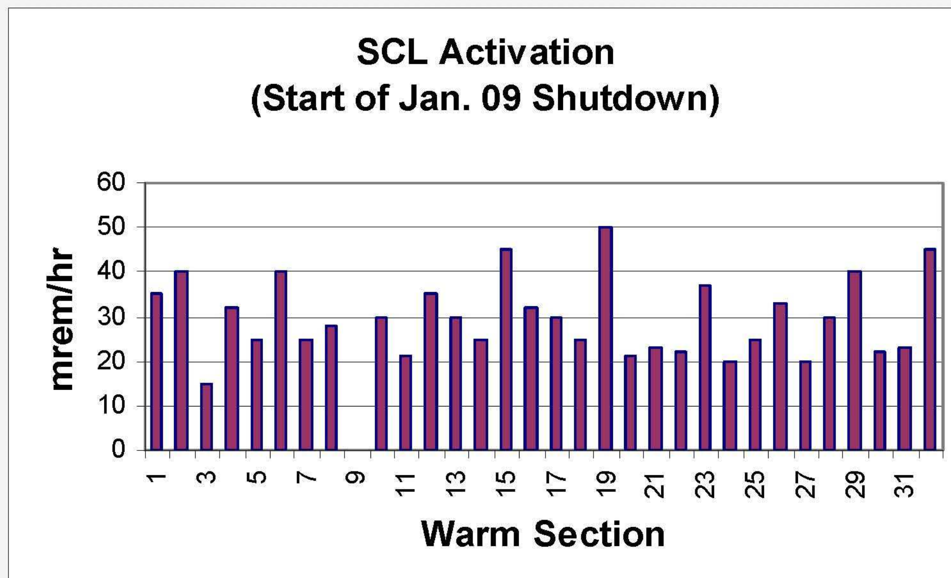
Example: Beamloss in the SNS Linac

- Simulation predicts no beamloss in SCL
- Measured prompt beam loss in the SCL
  - < 10^{-5} beam loss per cryomodule



- Measured residual activation throughout the SCL at 1 ft

Some beam is lost everywhere !



P-X and ADS

P-X can be the prototype for an ADS ATW machine to develop accelerator and reactor techniques and test materials (>>10 MW)

Since most P-X physics uses require accumulator and buncher rings, the linac design can be flexible. High current capability makes HEP easier.

Let's get the US Government (for national environmental goals) and US Industry (for fun and profit) interested to support ADS R&D using our unique accelerator expertise.

We imagine a Project-X which would supply the required power for ADS & ATW development and also replace the Fermilab Booster for the next 40 years of exciting fundamental science at the intensity and energy frontiers while addressing National Goals: Energy Independence, Climate Change, High-Tech Work Force.

An Intensity Frontier Machine to also feed an Energy Frontier Machine