Therapy & ThorEA, FFAG & RCS: Common Challenges

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With special thanks (and no further attribution) to:

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Therapy accelerators

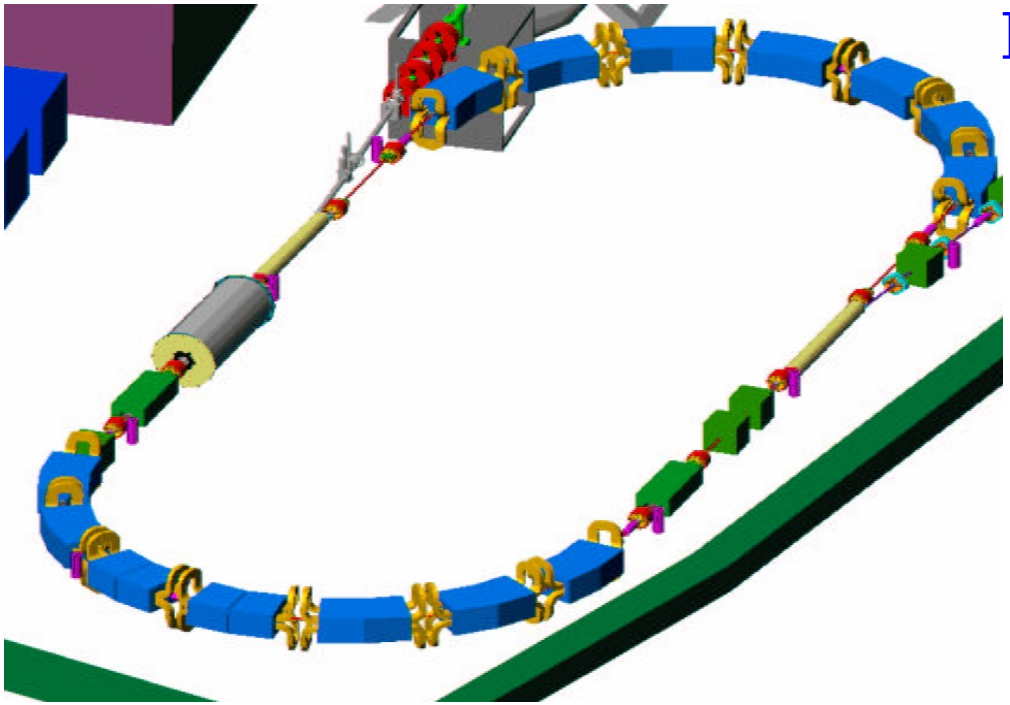
LOW power LOW energy

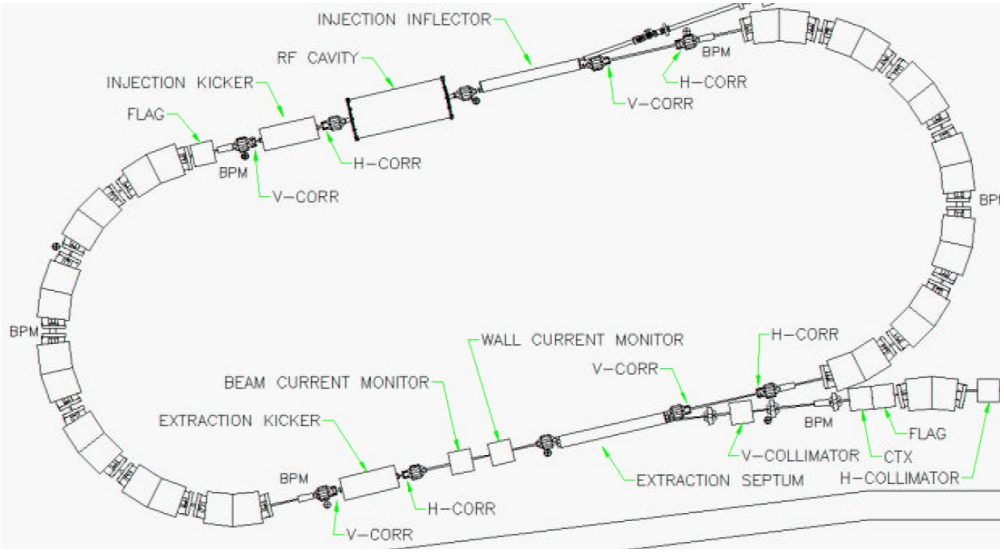
Swept frequency cyclotrons

1980's Design studies confirm $1/B^3$ scaling of SC cyclotrons, but leave synchrocyclotrons (swept RF frequency) out of reach.

ACCEL Superconducting COMET (below): 80 tons, 3 m dia.
250 MeV protons with markedly better extraction efficiency

Rapid Cycling Medical Synchrotron





Racetrack design

- 2 super-periods
- Strong focusing minimizes the beam size
- FODO/combined function mags with edge focusing
- 2x7.6m straight sections, zero dispersion, tune quads
- Working tunes: 3.38, 3.36

Compact footprint

- Circumference: 27.8 m
- Area: 37 sq m

Required rep rates?

What rates do current "point-and-shoot" slow extraction facilities deliver?

PSI 50 Hz (Med. Phys. 31 (11) Nov 2004)

- 20 to 4,500 ml per treatment volume
- 1 to 4 fields per plan
- 200 to 45,000 Bragg peaks per field
- 3,000 Bragg peaks per minute
- few seconds to 20 minutes per field

MDACC ~70 Hz (PTCOG 42, Al Smith, 2005)

- 10x10x10 cm tumor treated in 71 seconds
- 22 layers, 5,000 voxels

Clinical requirements

Easy to operate

– environment is very different from a national lab

Overall reliability of 95%

– accelerator reliability greater than 99%

Penetration depth

– 250 MeV protons penetrate 38 cm in water

– carbon equivalent is 410 MeV/u - 2.6 times the rigidity

Dose rate

– deliver daily dose of 2 Grays (J/kg) in 1 or 2 minutes

– 1 liter tumor needs (only) ~ 0.02 W very low power!

– need x10 or x100 with degraders & passive scattering

Thorium Energy Amplifiers

ThorEA!

Global interest

Global Energy

Iran Daily August 6, 2007

World's First Alternative Nuclear Reactor

India plans to start construction of the world's first advanced heavy water reactor (AHWR) using thorium as a fuel, which is less radioactive than uranium, enabling the country to ensure energy security, Asian Age reported Friday.

"We have the design and the technology to install a 300MW thorium-based reactor. It is going through the process of regulatory clearance. We will start work on it in the Eleventh Plan (2007-2012) period... and we hope to complete the work within seven years," the paper quoted Dr. Baldev Raj, director of the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, as saying.

He said that India is the only country in the world with adequate reserves of thorium to make building this type of reactor financially viable, RIA Novosti reported.

"As of today, no other country in the world is doing any research on thorium-based reactors as they do not have adequate thorium reserves," Dr. Raj said, adding that this would be a major technological achievement for the country as thorium-based reactors would see the completion of India's nuclear fuel cycle.

India is the only country in the world with adequate reserves of thorium to make this type of reactor financially viable.

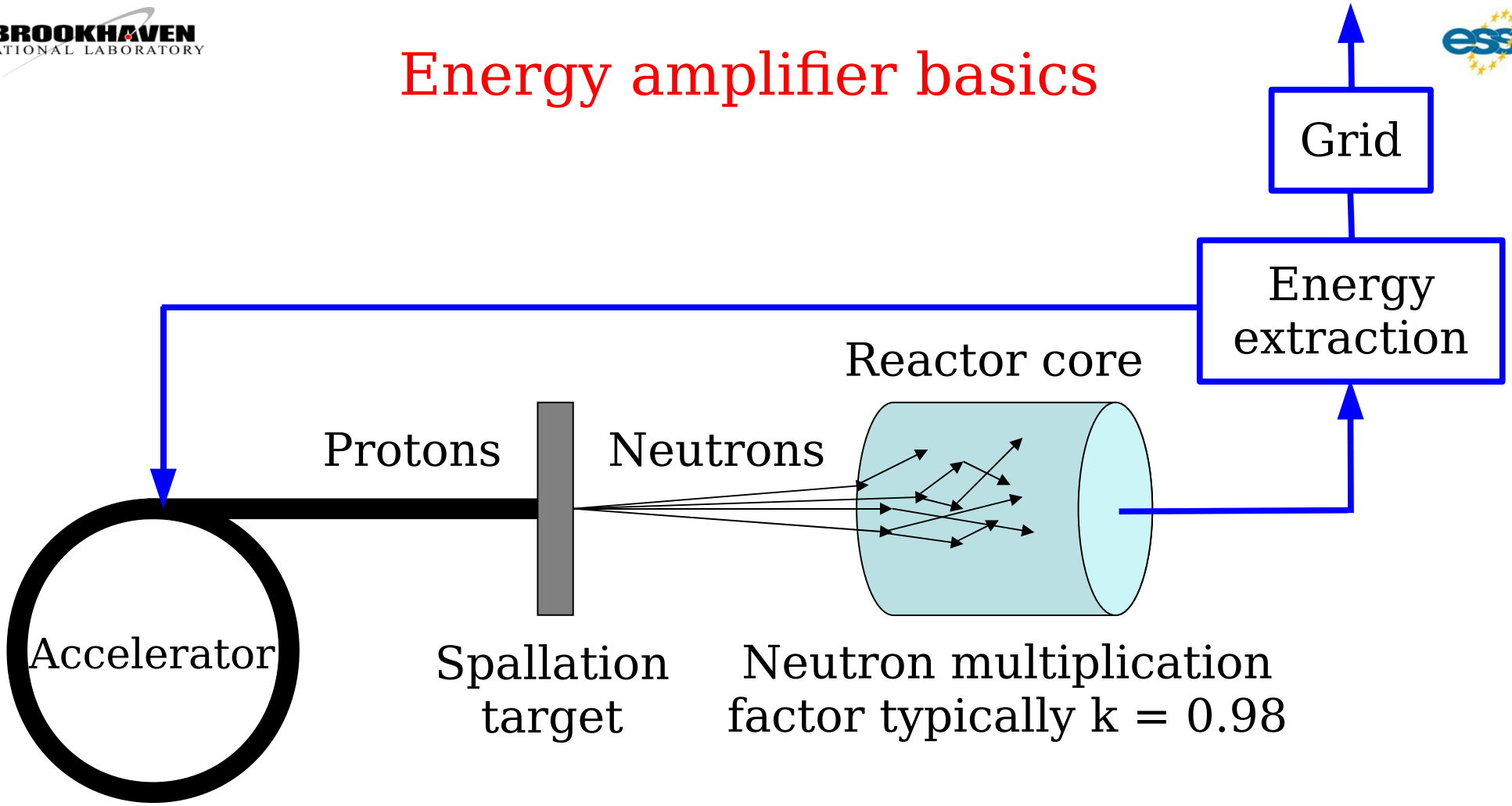
The first stage of India's nuclear program saw pressurized heavy water reactors which created plutonium. With its vast thorium resources along the Kerala and Tamil Nadu coasts, the country does not need to worry about its future fuel needs, Dr. Raj said.

Experts point out that with thorium producing radioactive waste that has a half life 10 to 10,000 times less than that produced by uranium or plutonium reactors, the chances of any hazards are fewer in thorium reactors.

According to Dr. Raj, work on the 500MW fast breeder reactor at Kalpakkam is progressing according to schedule.

"We are sure that the FBR will be commissioned by September 2010. It will start supplying power to the national grid by March 2011. We have almost finished the civil construction work. The reactor vault has been completed without any problems. The main vessel of the reactor, the safety vessel, core structure, control rod drives, fuel-handling mechanism are all in various stages of completion. From the end of September, we will start loading all components into the building," he said.

Energy amplifier basics



Protons injected into a target generate neutrons into a subcritical core which “burns”, creating heat & electricity.

Power generation ceases quickly when the beam stops

Inherent safety at the cost of ultra-high reliability!

Sustainable

Known Thorium reserves are more than sufficient for centuries of significant power production.

More will be found – Thorium has been of little interest.

World Thorium Resources	
Country	**Reserve Base (tons)**
Australia	340,000
India	300,000
USA	300,000
Norway	180,000
Canada	100,000
South Africa	39,000
Brazil	18,000
Other countries	100,000
World total	1,400,000

Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2008

India, Australia, Canada, U.S., Norway have lots.

Strong interest/activity in **Australia, China, EU, India, Norway-UK.**

Exploding global interest will soon include North America?

ThorEA

Thorium Energy Amplifiers (possibly) enable a method of nuclear power generation that avoids the problems of:

Critical accidents. Not possible (AND) turn beam off.

Long-lived waste. The modest amount of “true waste” has only to be stored for some 300 years, not millions.

Plutonium stockpiles. Transmutation of conventional reactor waste includes plutonium - “negative waste”.

Fuel inventory. Re-fueling only every 5 to 10 years enables easy central management & monitoring of many reactors.

Proliferation. The fuel mixture cannot be used for nuclear weapons – neither unburnt nor after the burn cycle.

ThorEA

The Thorium Energy Amplifier Association

ORGANISATION

ThorEA is constituted as a non-profit-making association, with a committee presently composed of the following members:

- Roger Barlow (Chair)
- Bob Cywinski (Deputy Chair)
- Geoff Parks (Secretary)
- William Nuttall (Treasurer)
- Hywel Owen (Webmaster)
- Steve Peggs (US Coordinator)

Other members of the association include:

- Kirk Atkinson
- John Back
- Jon Billowes
- Cristian Bungau
- Peter Butler
- David Cussans
- Yoel Giboudot
- Tim Greenshaw
- David Hamilton
- Paul Harrison
- Dave Ireland
- Ralf Kaiser
- Akram Khan
- Susan Kilcoyne
- Grant Kopec
- Mats Lindroos
- Neil Marks
- Morgan Murray
- Paul Norman
- Ken Peach
- Simon Pimblott
- Chris Prior
- David Reid
- Guenther Rosner
- Susan Smith
- Stephan Tzenov
- David Wark
- Peter Williams

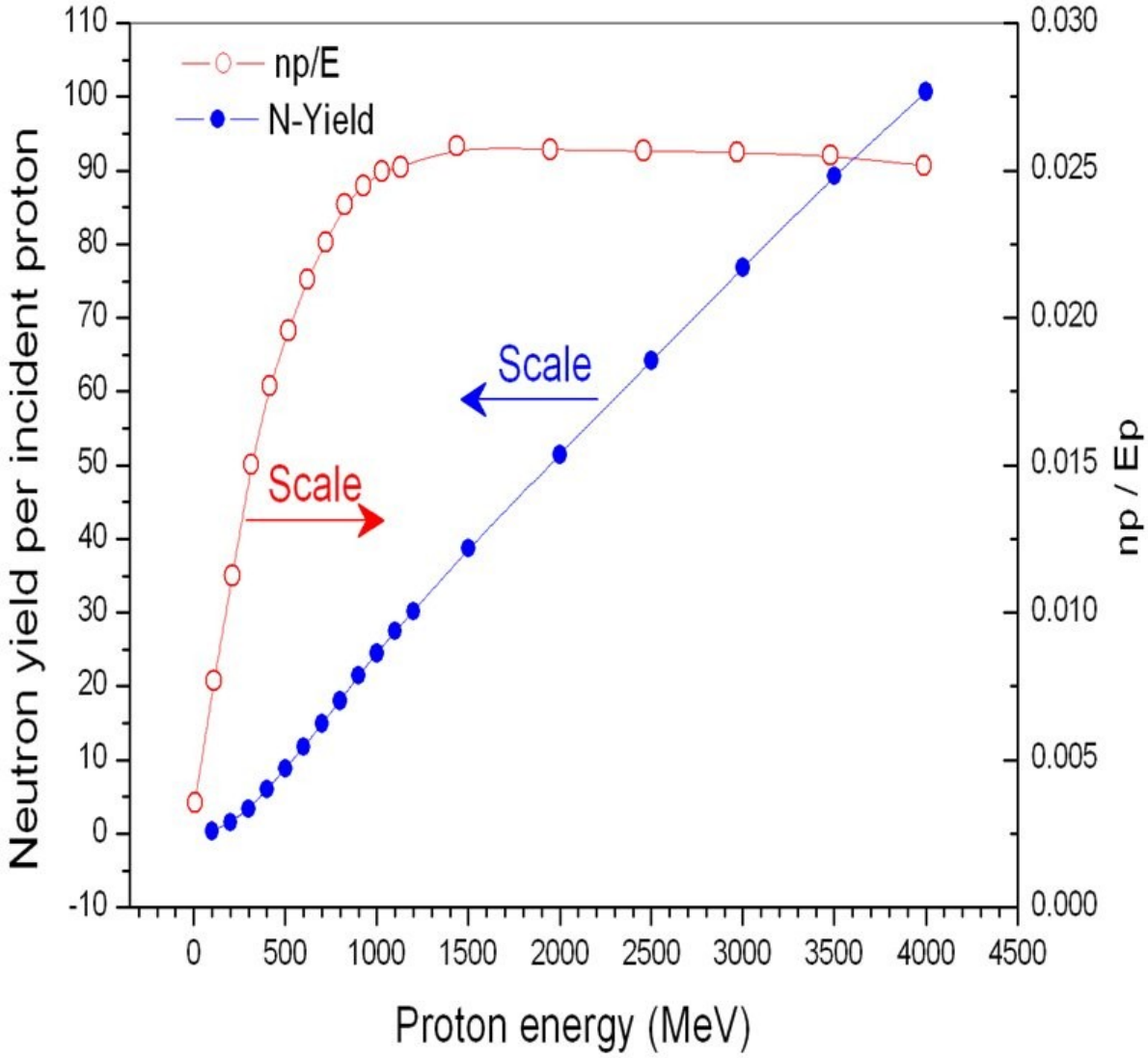
"The need to avert climate change through reducing our use of fossil fuels is now acknowledged to be of paramount importance. Nuclear power is a zero carbon energy source, but the Uranium-Plutonium fuel cycle in current use suffers from problems around safety, waste disposal, and weapons proliferation. Problems of public acceptance persist."

"Thorium-fueled subcritical reactors driven by accelerators (Thorium Energy Amplifiers) do not have the drawbacks of conventional nuclear power, and can provide safe, clean, carbon-free power that will satisfy the world's energy needs for tens of thousands of years without the danger of weapons proliferation, or the need to dispose of long-lived waste. Thorium EAs have the additional benefit that they can use the waste from other reactors as fuel."

ThorEA accelerators

HIGH power LOW energy

What beam energy?



Above ~1 GeV neutron flux is proportional to beam power

(Depends somewhat on the target & moderator design)

What beam power?

$$\text{Large system gain} \quad G \equiv \frac{P_{thermal}}{P_{beam}} \approx \frac{3}{1-k}$$

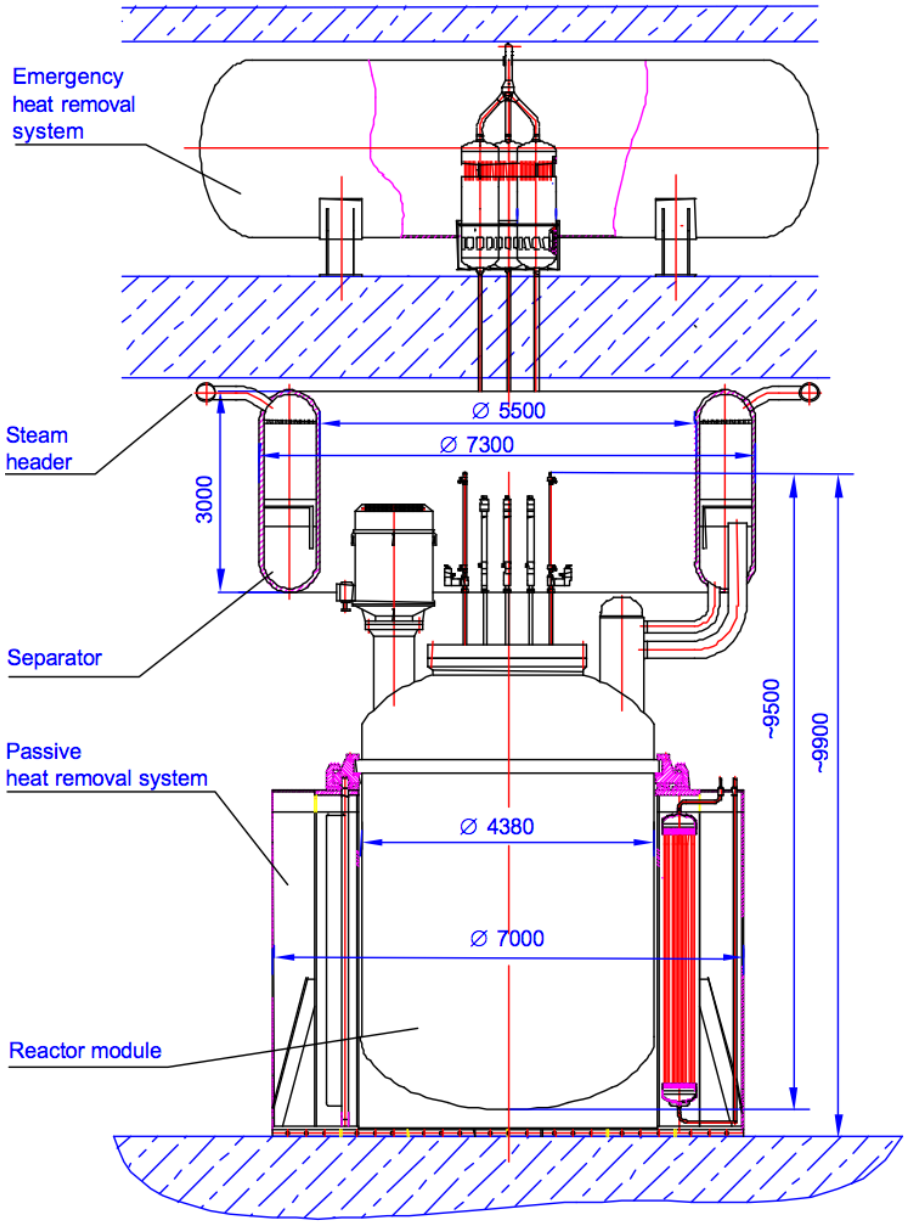
Full scale electricity plant needs (eg) 1 GW thermal

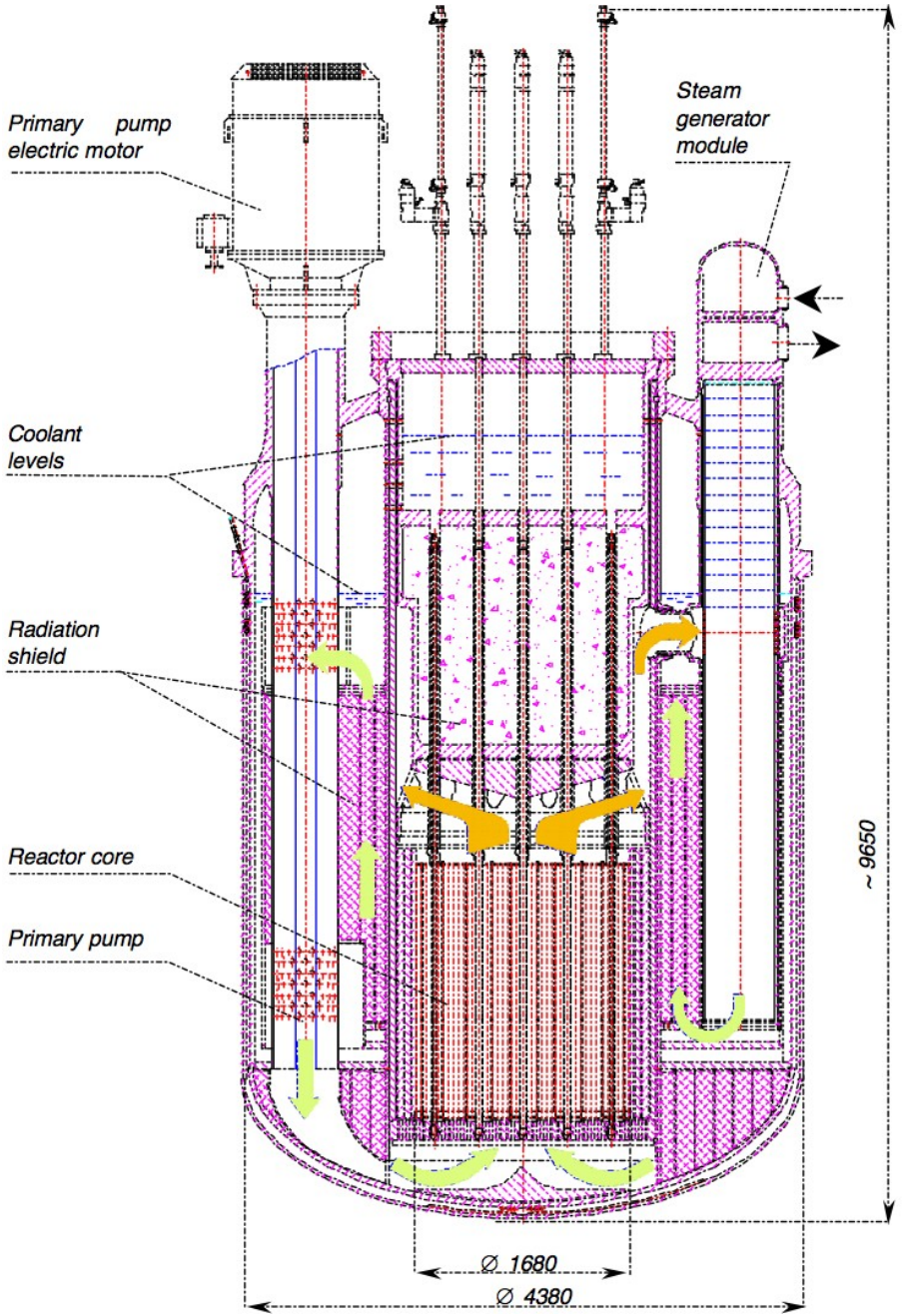
- if criticality factor k = 0.985, then gain G = 200
- required beam power = 5 MW

Medium scale demonstrator only needs (eg)

- k = 0.94, G = 50,
- thermal power = 10 MW, beam power = 200 kW

Demonstration – SBVR75 submarine reactor?





4 accelerator technologies

Some truths seem self-evident ..... ??

Technology	Machine	Energy [GeV]	Power [MW]	
SRF linac	SNS	1.0	0.9	achieved
	ESS	2.5	5.0	goal
Cyclotron	PSI	0.6	1.3	achieved
FFAG	KURRI	0.15	0.000001	achieved
RCS	ISIS	0.8	0.2	achieved
	CSNS	1.6	0.5	goal

SRF linac cost estimate > $1B or 1 B Euro !!

SNS reliability is 80% : multiply by availability!

FFAGs

KURRI

"Study neutron production"

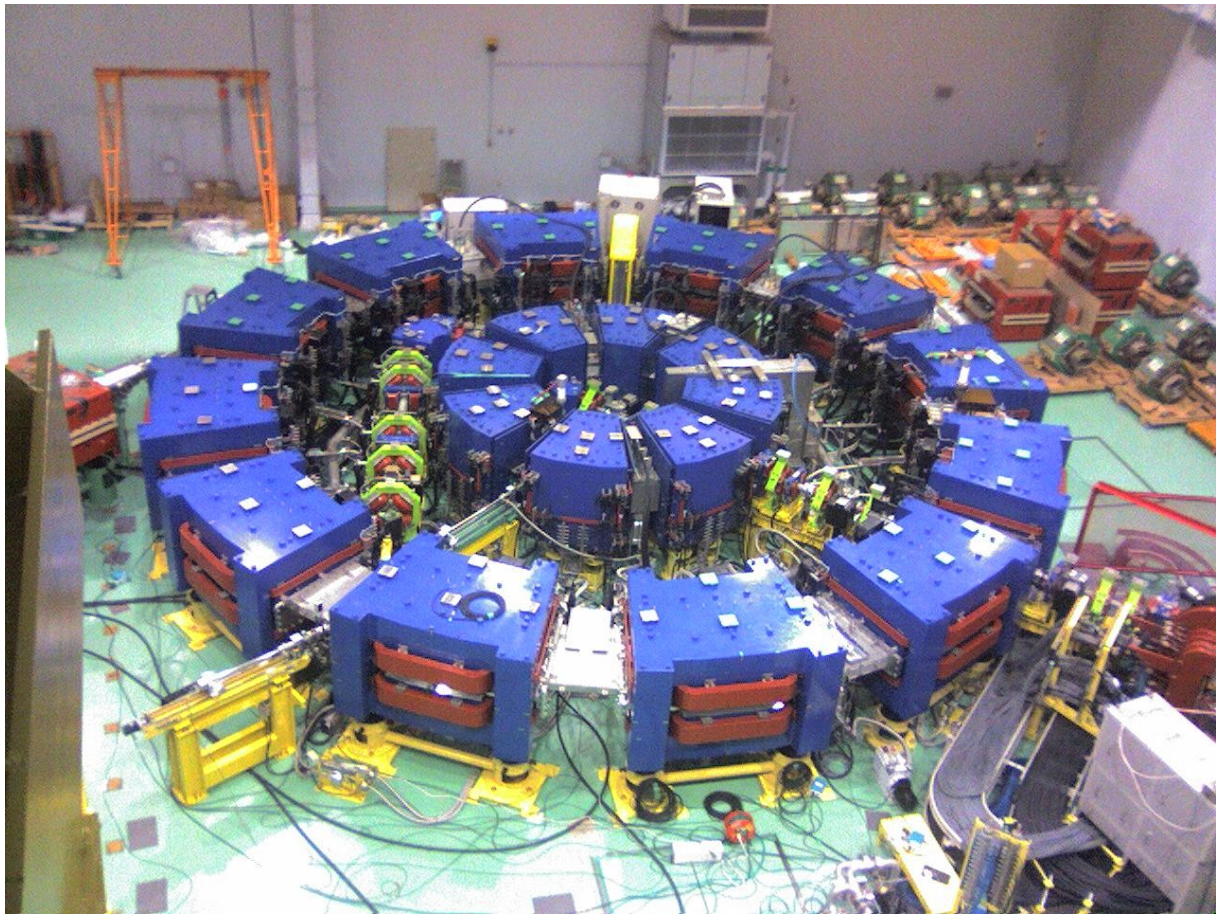
3 stage FFAG, 120Hz

- 0.1 – 2.5 MeV
- 2.5 – 20 MeV
- 20 – 150 MeV (?)

Current ~1 nA

Beam power ~0.15 W

Therapy?



EMMA & PAMELA

Synchrotron space charge

$$P_B = \left(\frac{2\pi}{r_0}\,\Delta Q_{L,max}\right) \cdot \frac{\epsilon_N}{F_B}\,(\beta\gamma^2)_{in} \cdot K_{out} \cdot f_{rep}$$

Laslett space charge tune shift parameter

Injection energy: maximize, eg DTL: ~200 MeV

Extraction energy: 1 GeV or more

Rep rate! Want ~kHz

Space charge limits injected intensity, output beam power

Rapid Cycling (RCS) technology has been with us for more than 40 years – before "real" control systems.

FNAL 15 Hz, Cornell 60 Hz, DESY 50 Hz, KEK 50 Hz, RAL 50 Hz, (transformers 50/60 Hz), ...

How to answer the critics?

Critics claim that accelerators:

- are not reliable enough
- don't have the performance at a reasonable cost

Very likely they are wrong.

- How to prove it without making extravagant promises?

What accelerator R&D?

What demonstration stages?

Common RF challenges:

Therapy OR Thorium

Fast RF challenges

FFAGs & RCSs face a similar need for fast RF with

~1 kHZ rep rates, especially (but not only) with
~1 GeV high power thorEA implementations:

~ 10 times more RF volts
~ 10 times faster df/dt

7 MeV to 250 MeV:	factor of 5.1 freq swing
100 MeV to 1 GeV:	factor of 2.0
200 MeV to 1 GeV:	factor of 1.5

FFAGs frequency swing somewhat ameliorated?

Voltage requirement

Energy gain ΔK [GeV]	Acceleration time ΔT [ms]	Circumference C [m]	Average speed $\langle\beta\rangle$	Minimum RF voltage $\langle V_0\rangle$ [kV]
0.25	8.3	30	0.5	6
0.25	1.0	60	0.5	100
1.0	1.0	100	0.5	667

700 kV solution not yet demonstrated … !

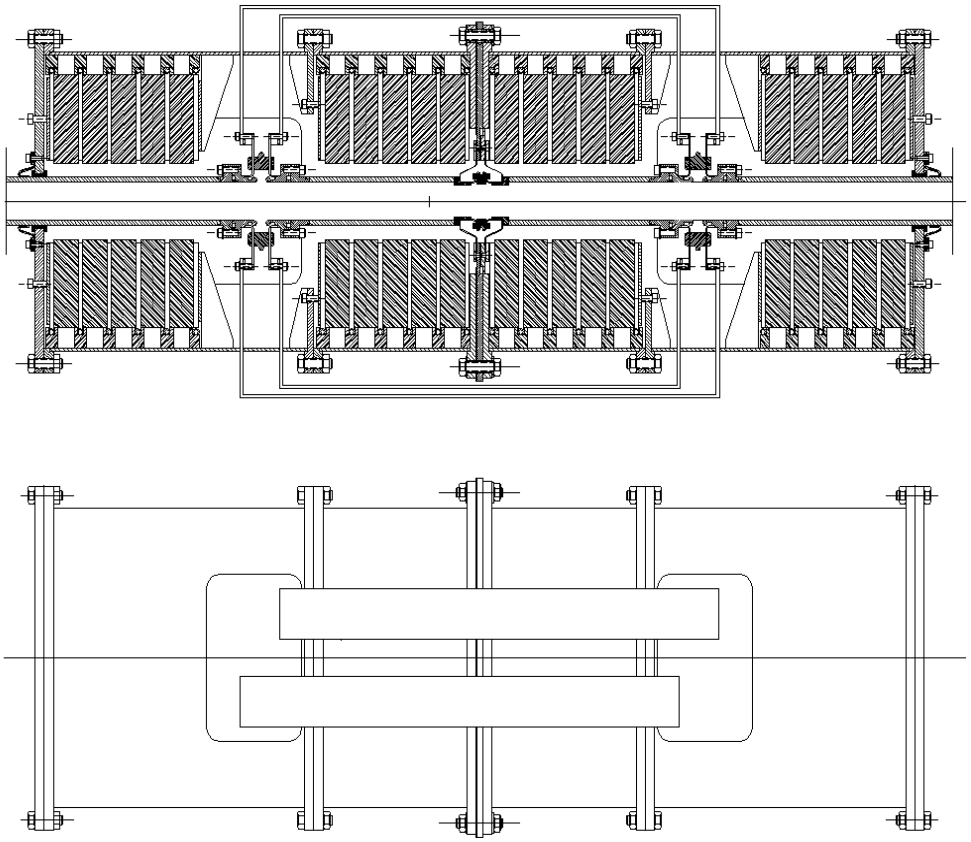
… but plausible given enough space(?)

Biased ferrite (RCMS)

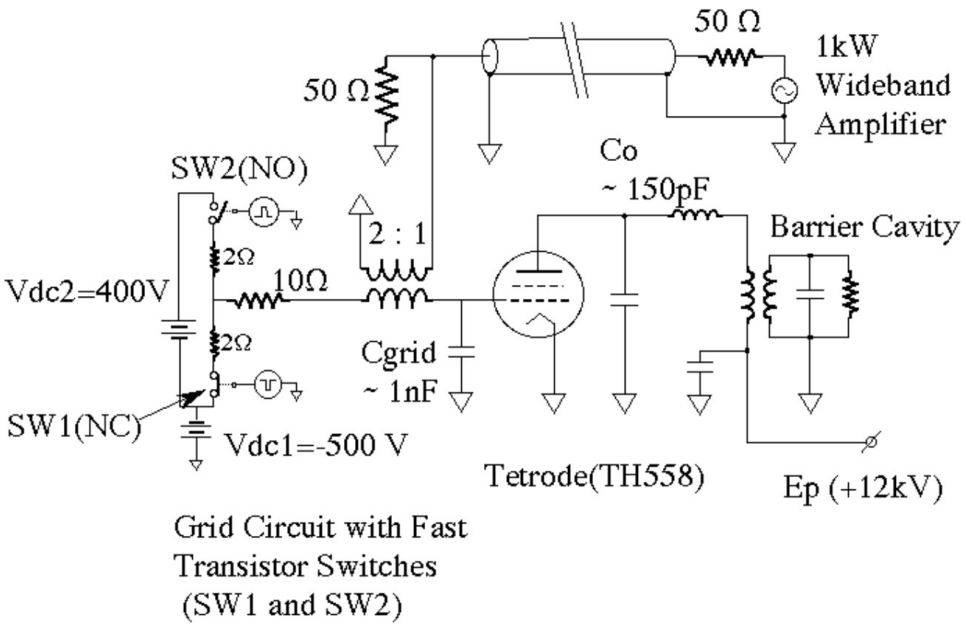
RCMS cavity design is ready for early prototyping

Ferrites procured and tested for large frequency swing
- 1.3-6.6 MHz
- 60 Hz is aggressive but feasible

60 Hz requires two cavities
- Expected voltage limit is about 6-7 kV/cavity



Barrier buckets (AGS)



Grid Circuit with Fast Transistor Switches (SW1 and SW2)

4MHz

Items	*Value*
Barrier Potential	*Total 80kV*
Number of Gaps/or Cells	*8*
Number of Cores	*Total 48*
Core (μ',μ")	*4B3* (490,4.9)*
Sizes of Core	*$\phi 500^{mm}$ x $\phi 200^{mm}$ x 28.1^{mm}*
Rsh	*Total 245 •*
Peak Power	*200kW*
Operation Duty	*8.9%*
Inductance per cell	*16μH*
Peak RF Current	*240A*
*Peak Power Density**	*2.6 W/cc*
Bmax at r=a	*26mT*

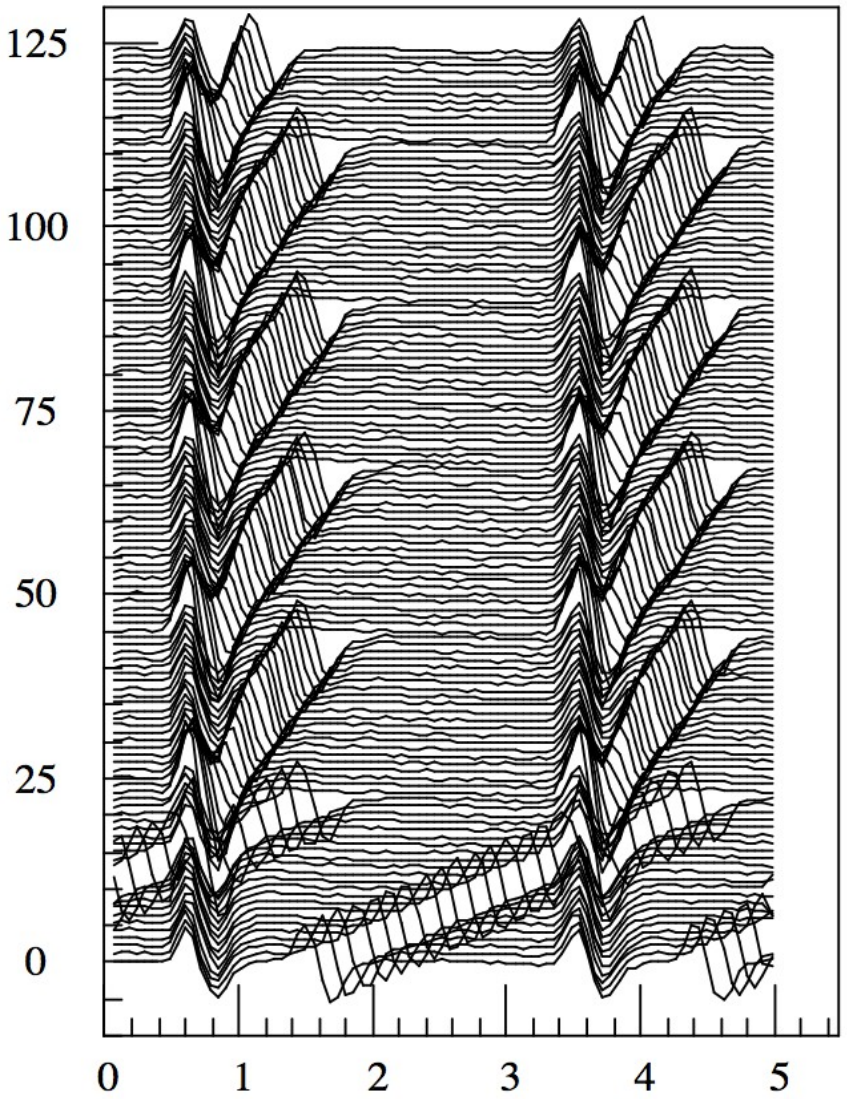


Figure 2: Mountain range display of the sum of the rf voltage from the two barrier cavities for 6 transfers. There are $6.0\text{ms} = 2048\text{ turns}$ between traces and the horizontal axis is in μs, (2.9μs per turn).

"Wave packet" (SPS)

Linnecar: "Our cavities are about 16 m long and can work in fixed frequency operation for a beta swing of about 10%."

"Reducing the length, and .... voltage (at the moment .... 2 MV), by a factor 10 should allow the beta or frequency swing to reach ~ 1.5."

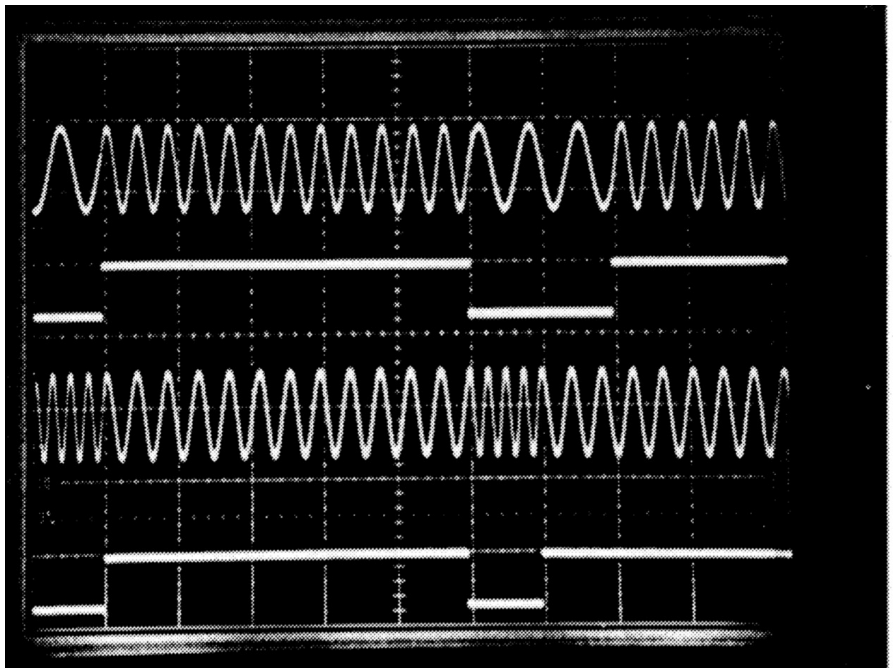


Illustration of periodic waveform with two frequency regions;
a) waveform when the average frequency is low;
b + d) beam pulse;
c) waveform when average frequency is higher.

"For a 1 GeV top kinetic energy [and] 200 MeV injection the swing is 1.54 and for 100 MeV it's 2.04."

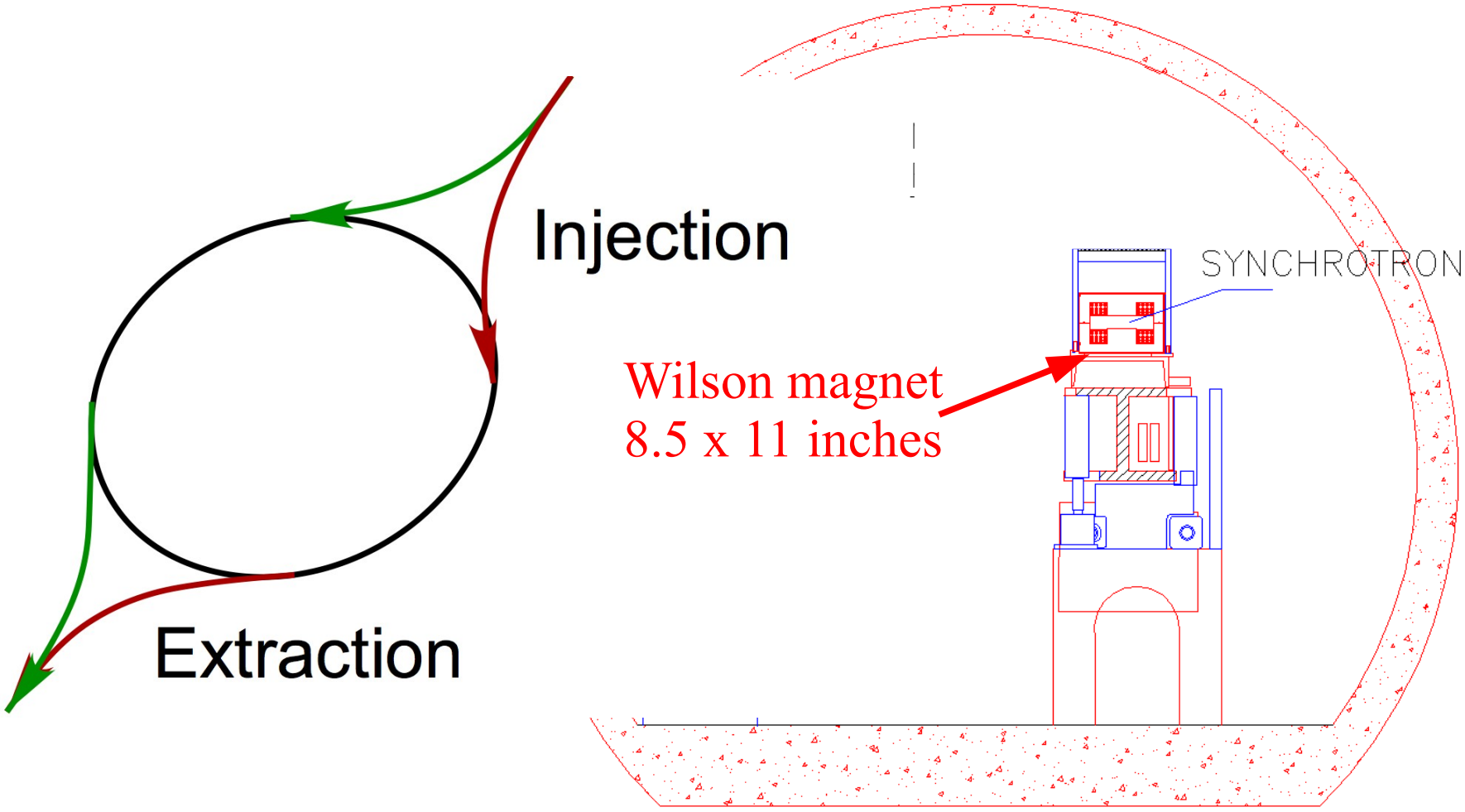
"So .... [wave packet] operation is not excluded!"

"Traditional ferrite tuners can also do this readily – but can they be persuaded to do it at 600 Hz?"

Very Rapid Cycling Synchrotrons

Bipolar injection + “Wilsons” magnet

Cornell synchrotron (60 Hz) & FNAL booster (15 Hz) use the same combined function magnet, with “no” beam pipe.



Bi-polar injection gives redundancy & doubles the frequency

Multiple redundancy

PS Booster: 1.4 GeV, ~1 Hz

1.6 kJ per cycle per ring!

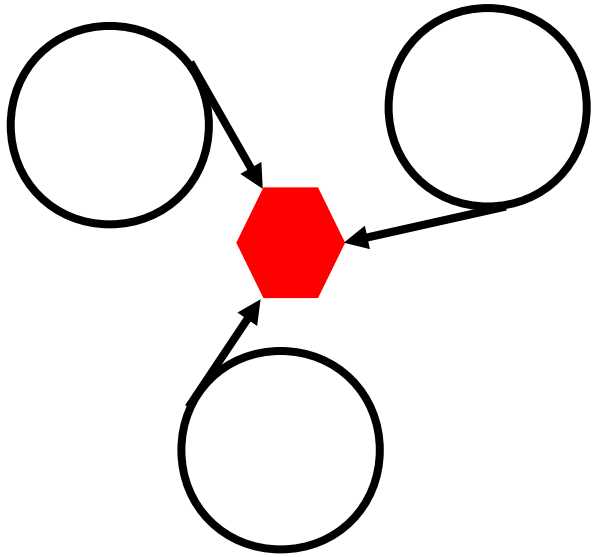
Factor of 4 in rep rate!?

Eg, use 3 or 4 accelerators per reactor core?

1st is down for maintenance, 2nd fails, 3rd & 4th keep on ...

Need inexpensive unit cost

Single points of failure?



Eddy currents

As well as RF, a VRCS also must worry about

1. eddy currents: beam pipe, magnet iron & copper
2. high voltages in driving magnets that fast.

Four 60 Hz "Wilson" magnet rings with bipolar injection and extraction take the rep rate up to

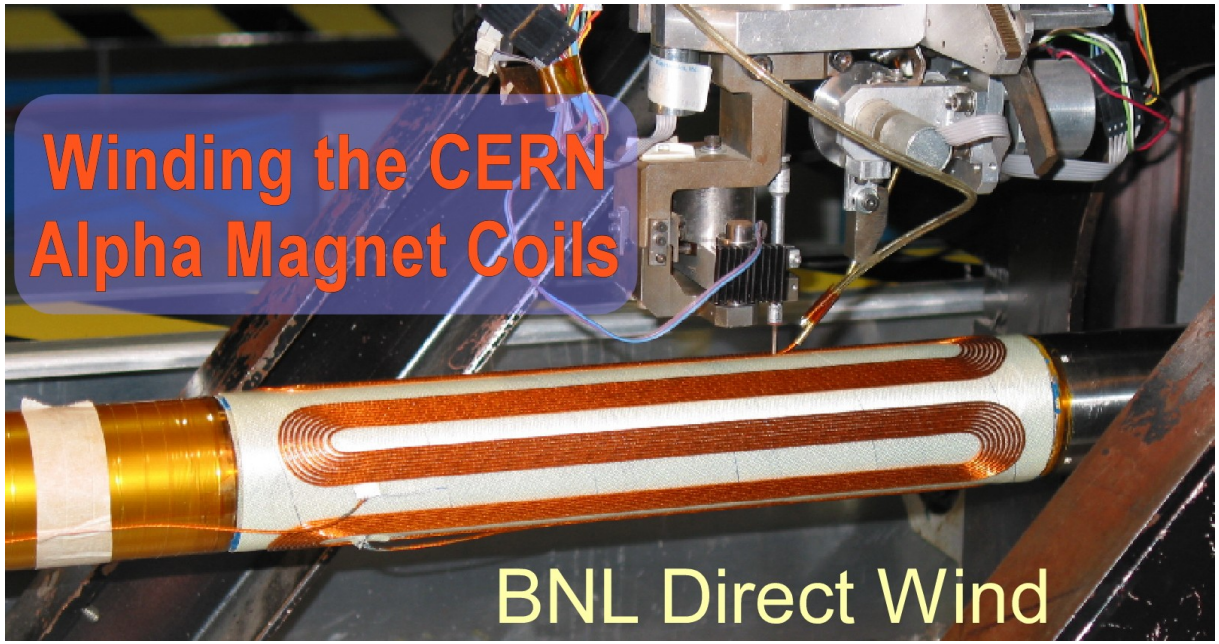
4 x 2 x 60 Hz = 480 Hz

Beyond 1 kHz: direct-wind iron-free bent active shielding SC combined function magnets?

Direct wind iron-free magnets

ALPHA octupole for anti-proton cooling experiment at CERN.

Very fast turn on (half-cycle?)!



ILC prototype IR quadrupole QD0, with concentric corrector layers.

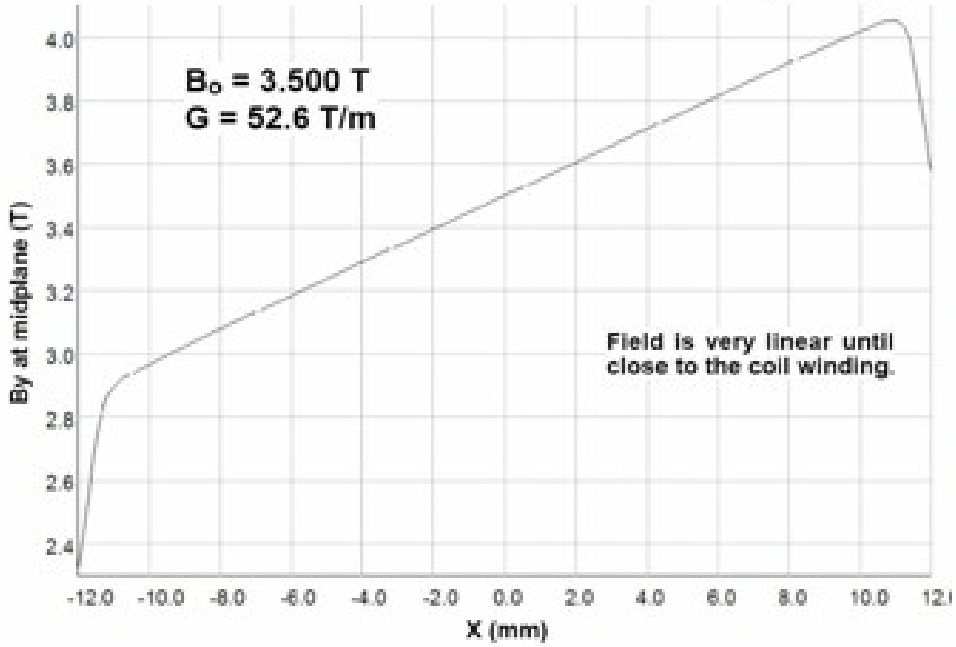
Combined Function 3.5 T direct wind magnet

for a Carbon gantry

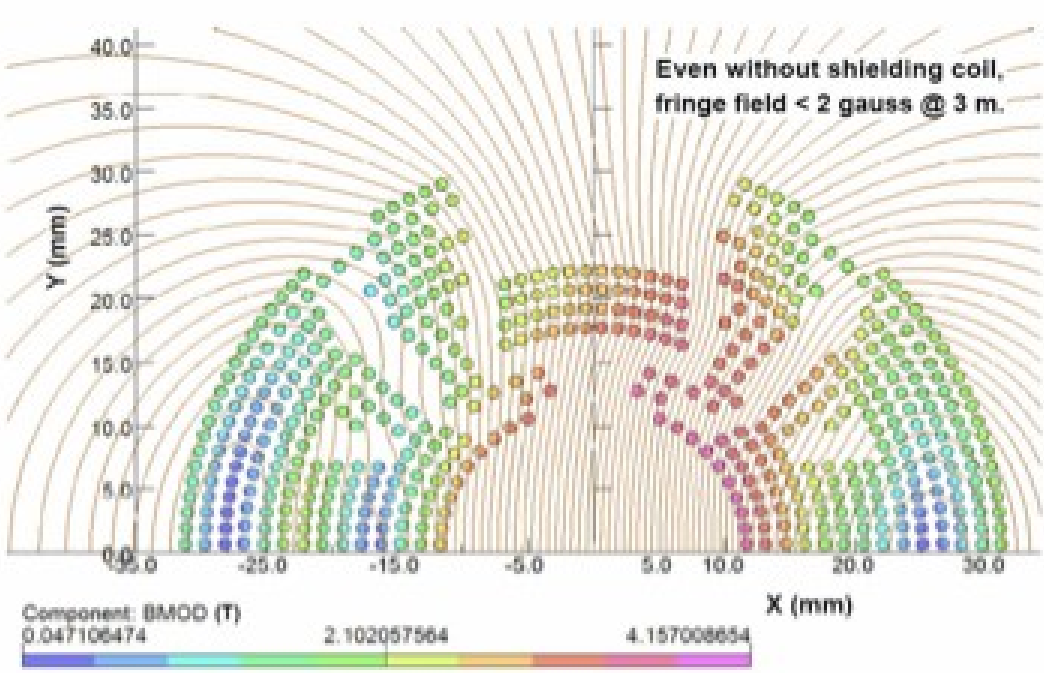
Table 1: Magnet properties

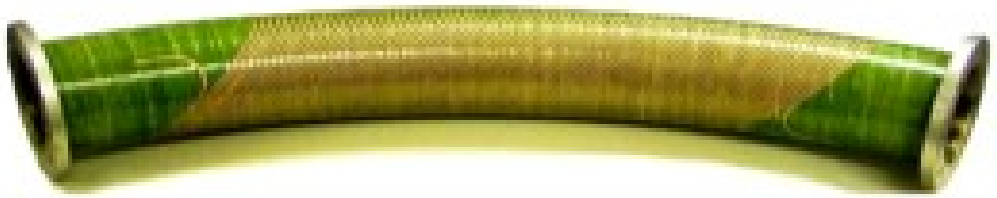
	L(m)	B(T)	G(T/m)	A_p(m)	B_{max}(T)
BD	0.40	3.7-4.3	-68.5	± .008	4.24
BF	0.40	1.00	71	± .010	1.8

Direct Wind Combined Function Gantry Magnet



Direct Wind Combined Function Gantry Magnet





Bent Combined Function Magnets

ENABLING
Bent, Twisted or Straight Magnets
Combined Function Magnets (dipole, quadrupole, sextupole...)
Bent Dipole - Fully Compensated Quadrupole
Compact Design
Highly Scalable in Size & Field Strength

HIGHEST QUALITY & RELIABILITY
"Perfect Fields" with Zero Systematic Errors
Uniform Field over a Large Percentage of Aperture
Unmatched Mechanical Coil Robustness
Simplified Coil Ends with High Field Quality
Conductor and Layer Stabilization
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MOST COMPACT & LOWEST COST
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What next?

Upcoming ThorEA events

May 4–6, Vienna: IAEA meeting, with reps from China & India.

Sept, Chicago area: FNAL & ANL joint workshop on ADS. Some involvement of the BNL non-proliferation folk?

Sept++, DC area: DoE Nuclear Engineering ThorEA workshop.

October, DC area: DoE Science workshop (2, phased). What does it mean, “OHEP is the steward of accelerator R&D"?

ThorEA stakeholders: DoE Science, DoE NE, NE departments, NE industry, National labs, Universities, AR+D, ...

DOE & ARPA-E

Chu ... plans to appoint a blue ribbon panel to develop a comprehensive plan to deal with nuclear waste ... DOE will begin a “vigorous research and development program” to determine how to reduce the proliferation risk associated with the recycling of nuclear waste. Chu [said that] "We are trying to ... restart the American nuclear industry again."

AIP Bulletin of Science Policy News, Number 50: April 29 2009

“ARPA-E applicants are required to submit a concept paper as the f rst step ... Only after notif cation from ARPA-E on the concept paper will the applicant be permitted to submit a full application.”

“Submission of concept papers begins May 12, 2009 [until] 2 June 2009.”

“... funding for the FFRDC [eg BNL, FNAL] portion of the work will not be included in the ARPA-E award, and instead will have to come through the “DOE f eld work proposal system.”

ThorEA (accelerator) stages

0) Develop a loosely co-ordinated global plan, in broad agreement with ThorEA (target/moderator/core) & therapy folk.

1) Early hardware prototyping without beam, eg fast RF & magnets

2) Low power acceleration, with minimum complexity.

3) Demonstrate & develop reliability. Increase power.

4) Medium power integrated tests (eg SBVR75)

5) Full power electricity production ....

Summary

ThorEA: more haste, less speed

Fusion promised too much too soon! Don't!

A prominent early failure would cause lasting harm

Aim low, succeed with ease, look good, move on!

Summary: Accelerator R&D

1) FFAGs &/or VRCSs may eventually provide excellent low and high power proton performance – power, reliability & availability at reasonable cost – for Therapy, ThorEA, HEP, ...

2) Fundamental accelerator R&D topics are fast magnets (eg VRCS) and fast RF (eg FFAG & VRCS).

3) Collaborate with ThorEA, first with zero or low power demonstrations, only then with medium power prototyping.

4) Leave GW electricity production until later.

5) Don't promise too much too soon!

There is only one boat!

Easily said:

No destructive war between competing designs

Share R&D on common challenges, eg RF