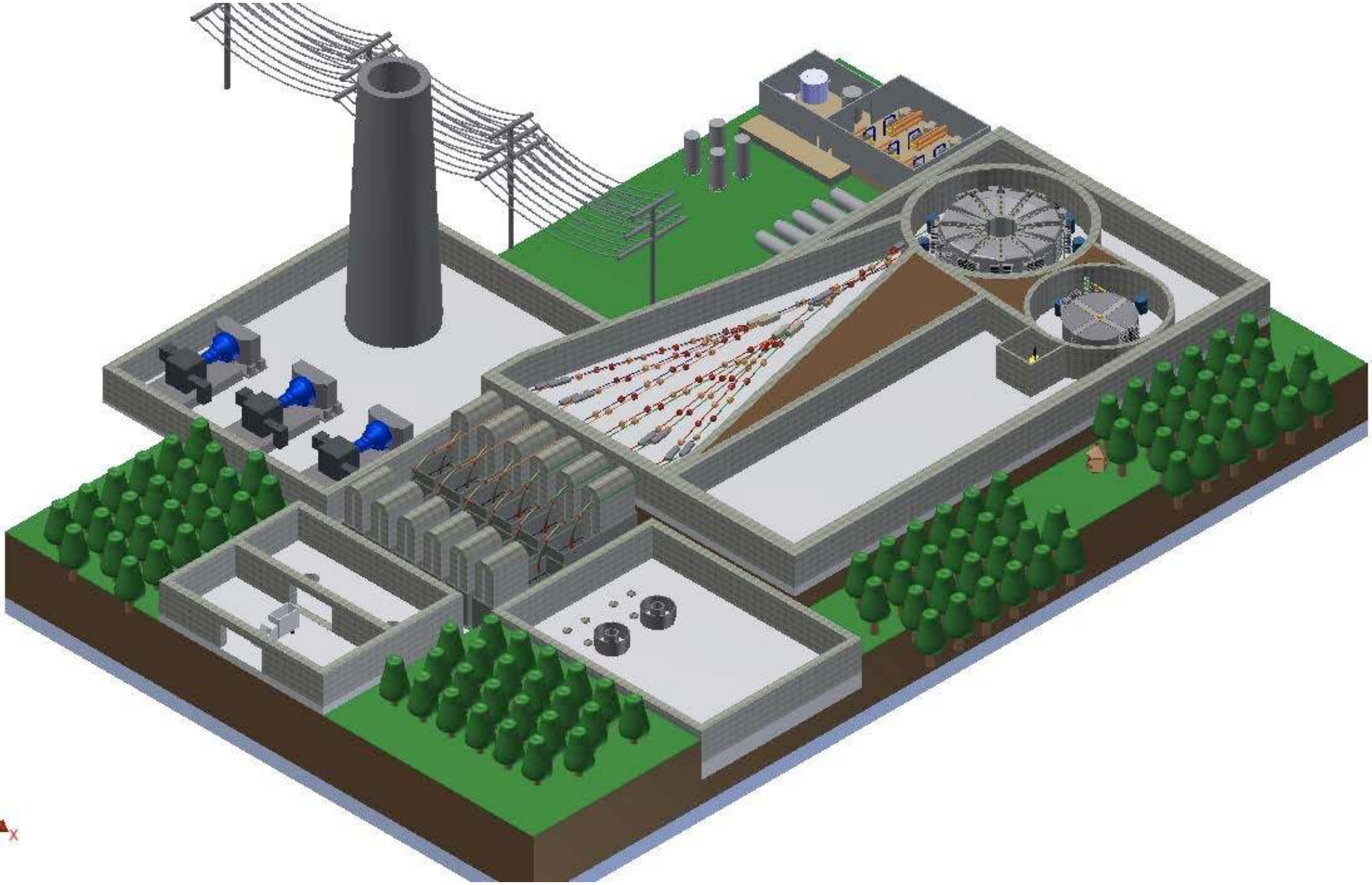
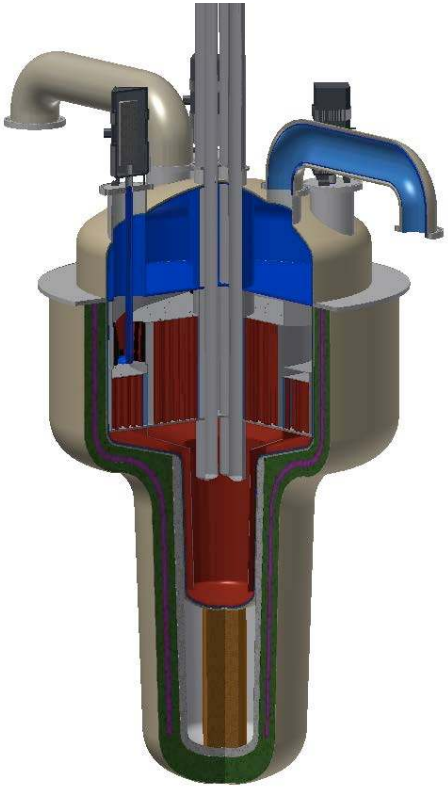
Accelerator-Driven subcritical fission in A Molten salt core: Closing the Nuclear Fuel Cycle for Green Nuclear Energy





Peter McIntyre, Texas A&M University

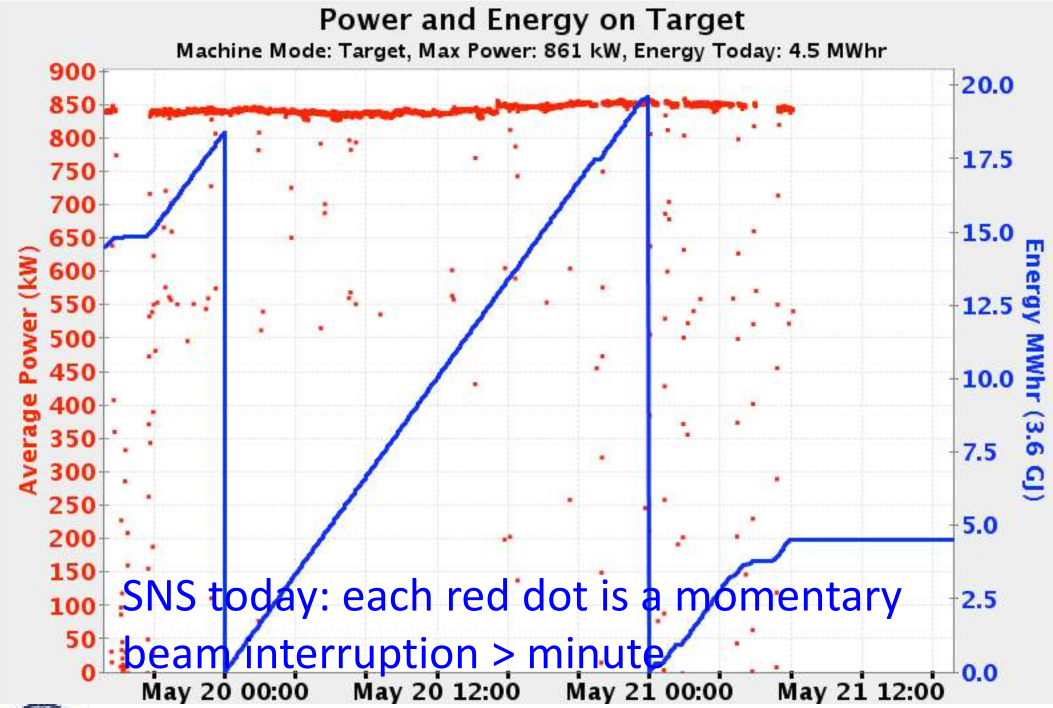
For the ADAM Collaboration

ADS Fission in a Molten Salt Core

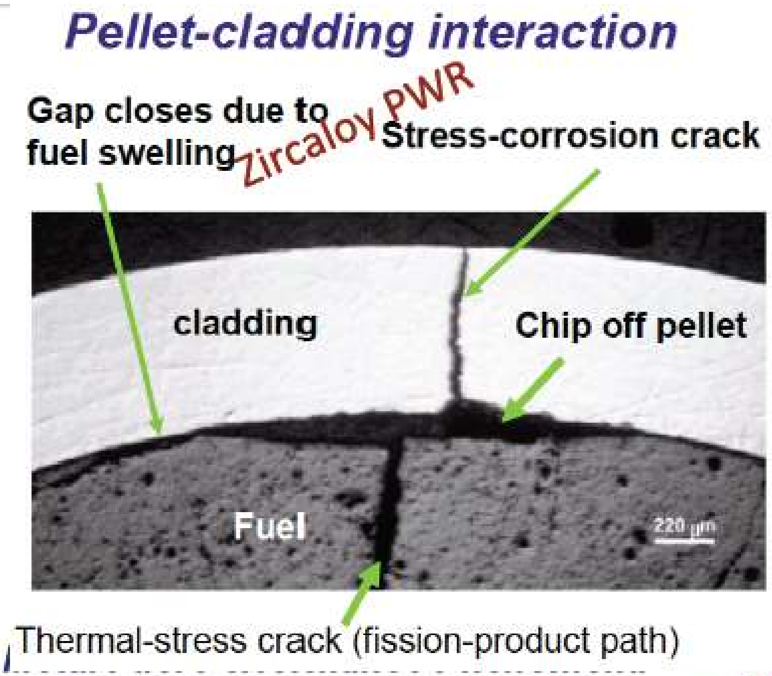
- Extract the minor actinides and long-lived fission products from spent fuel into molten salt
  - Pyroprocessing and electroseparation
  - Developed at ANL, INL, PRIDE
  - Never separate Pu from other TRU

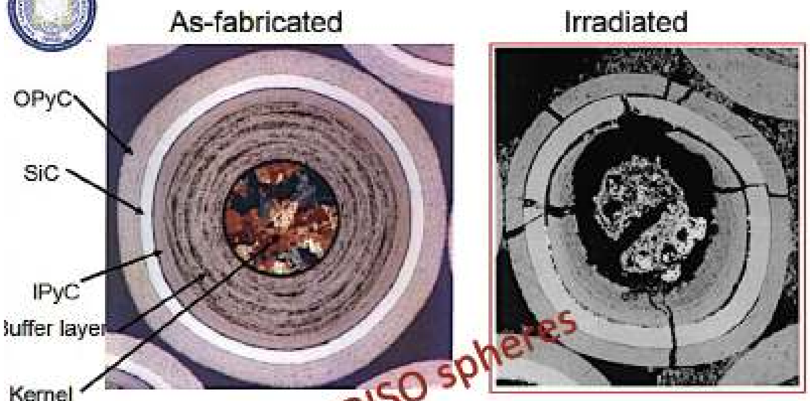
- Fast neutronics in a subcritical moletn salt core
  - Fastest neutron spectrum ever designed $\langle E_n \rangle = 1$ MeV
  - Burns all the transuranics together at the same rate
  - No thermal shock when drive beam is interrupted
  - Cannot go critical, cannot overtemp even if power fails

Molten salt fuel eliminates thermal shock



SNS today: each red dot is a momentary beam interruption > minute



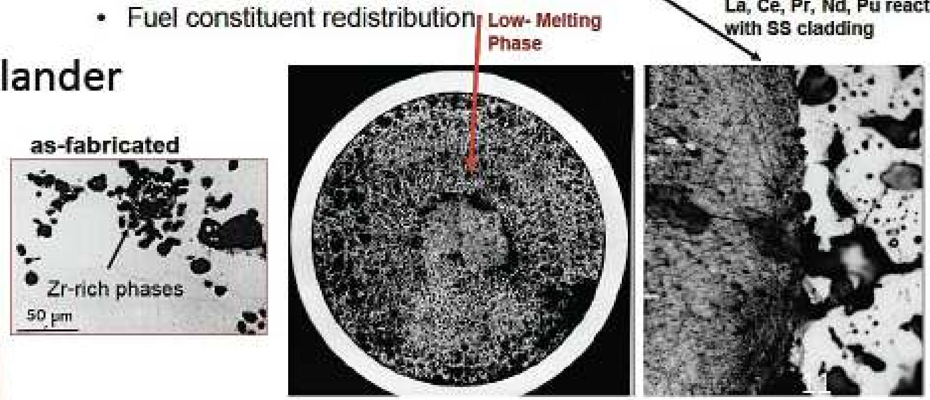


- Xe and Kr released from fuel kernel
- oxygen liberated from $(U,Pu)O_{2-x}$
- $2C + O_2 \rightarrow 2CO$ reaction of carbon in buffer layer

Probably failed by overpressure due to fission gases and CO

- Irradiation growth: ~ 3% at 14% burnup of metal atoms
- Fuel swelling and fuel-cladding mechanical interaction (FCMI)
- Gas release
- Fuel-cladding chemical interaction (FCCI)
- Fuel constituent redistribution

D. Olander



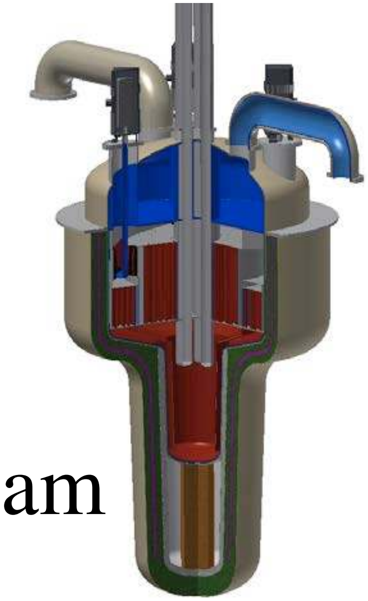
ADSMS

A molten salt core optimizes TRU-burning

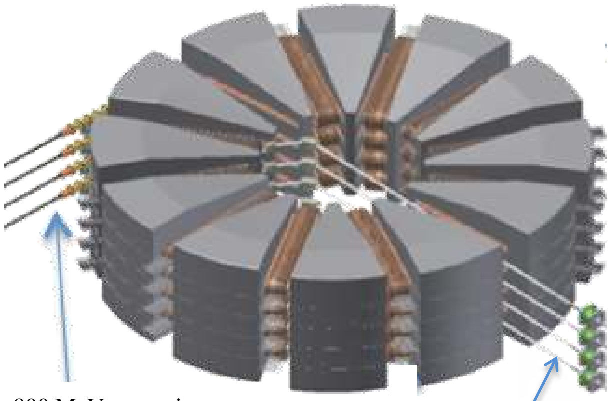
- The TRU contents can be extracted from UNF using pyroprocessing technology developed at ANL and INL.
- The molten salt serves as spallation target, moderator, and fissile inventory.

- The molten salt flow on the beam window makes delivery of a 2.7 MW proton beam realistic.
- The core is designed to provide passive cooling of decay heat in event that HX flow were lost.

- Molten salt core – simple to fuel, simple to recycle
  - Every 3 months add 90 kg of TRU to replace what was burned
  - Every 5 years, transfer fuel salt from core to remove fission products, then return to core
  - Fuel salt is 100% contained in 5 layers for 5 years of operation

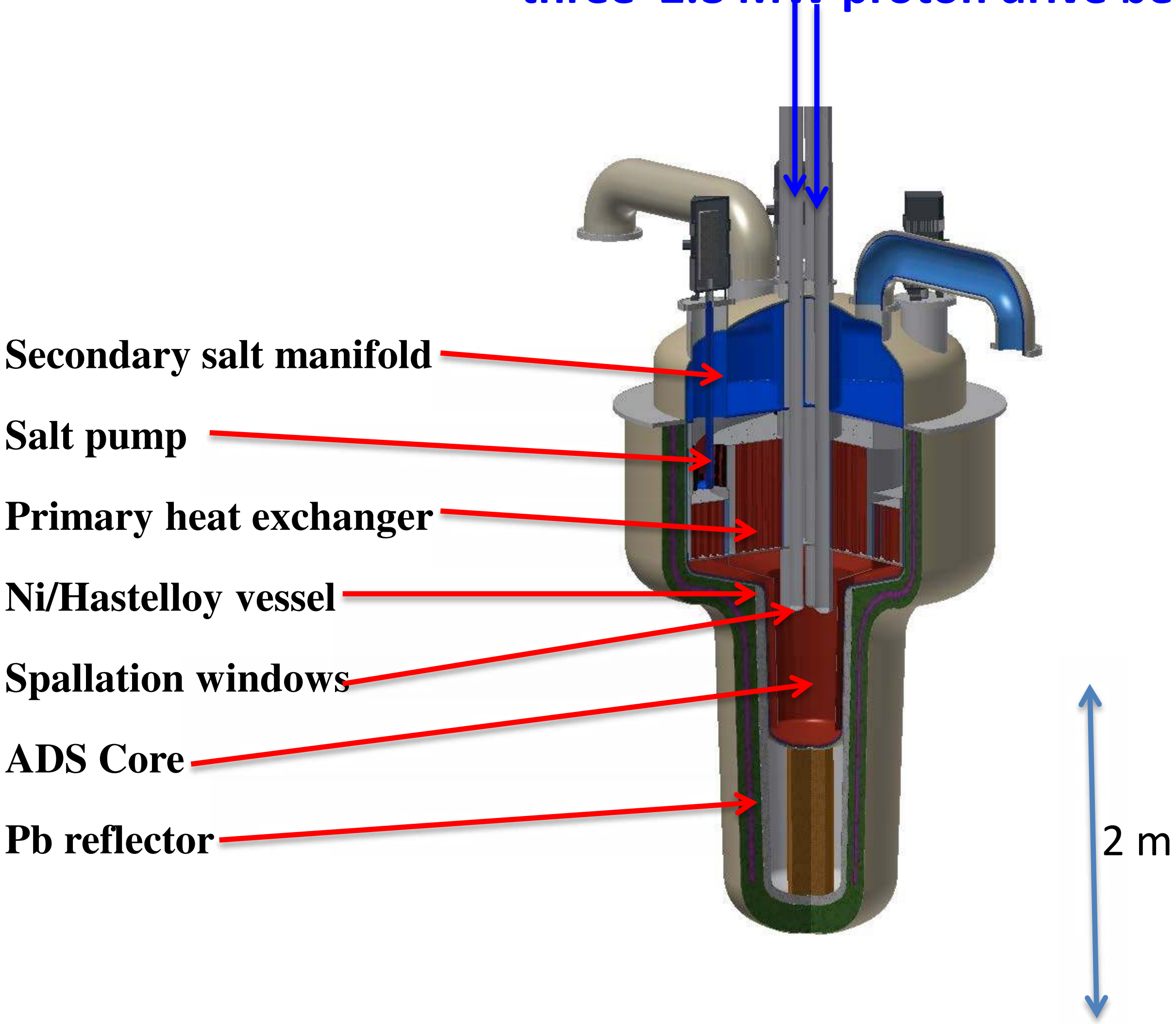


- Drive the subcritical core with proton beam
  - Stack of 3 cyclotrons
  - Drives 3 ADSMS cores
  - Modulate current 9➔12 mA for const P_t
  - **5:1 Energy Amplifier**



290 MW ADAM Core

three 2.8 MW proton drive beams



Molten salt fuel:

70 NaCl – 15 $TRUCl_3$ – 13 UCl_3

Fast fraction 20% E_n>1 MeV

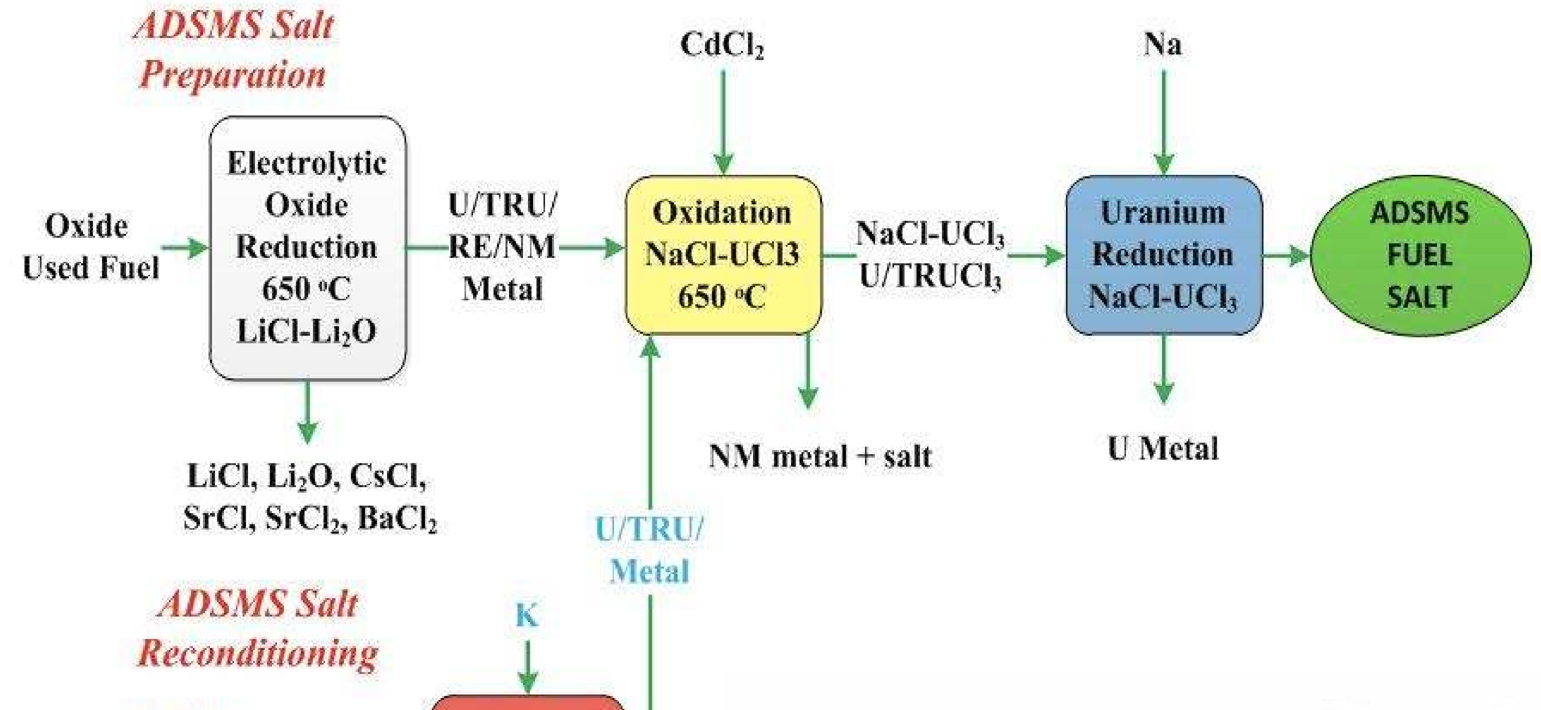
All fuel salt in one vessel

575 –675 C operating temp

The molten salt chemistry is important

- LiF-based salts were used in the original MSRE, and have been proposed for many designs of critical and subcritical molten salt cores.
- LiF has several problems for a TRU-burner:
  - The light elements moderate the neutron spectrum;
  - Multiple ionization states of TRU elements are metastable, including volatile species (analogs of UF_6).
  - LiF is corrosive, which presents a challenge for the lifetime of core vessel and HX components.
  - Loading the necessary mole% of TRU would push a F-based salt beyond the eutectic limit at reasonable operating temp – TRU salt could drop out of the mixture if the salt freezes.
- ***All of these issues are resolved by using $TRUCl_3$-NaCl.***

Extracting TRU from UNF fuel bundles



ADSMS Salt Preparation

Oxide Used Fuel → Electrolytic Oxide Reduction 650 °C LiCl-Li_2O

→ LiCl, Li_2O, CsCl, SrCl, $SrCl_2$, $BaCl_2$

U/TRU/RE/NM Metal → Oxidation NaCl-UCl3 650 °C (+ $CdCl_2$)

→ NM metal + salt

$NaCl-UCl_3$ U/$TRUCl_3$ → Uranium Reduction $NaCl-UCl_3$ (+ Na)

→ U Metal

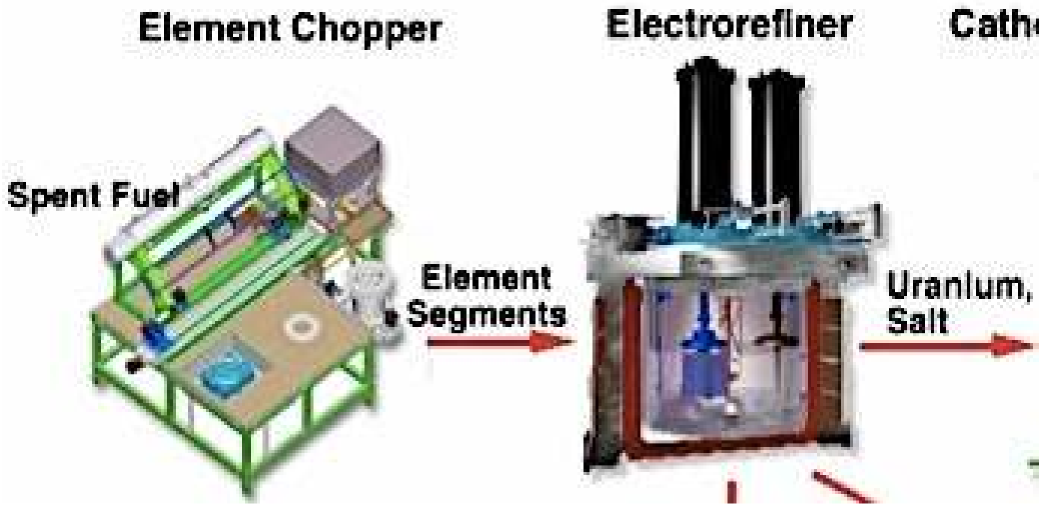
→ ADSMS FUEL SALT

ADSMS Salt Reconditioning

ADSMS Fuel Salt After 1 Year of Operation → Stage I Reduction 550 °C (+ K)

→ U/TRU/ Metal → Oxidation

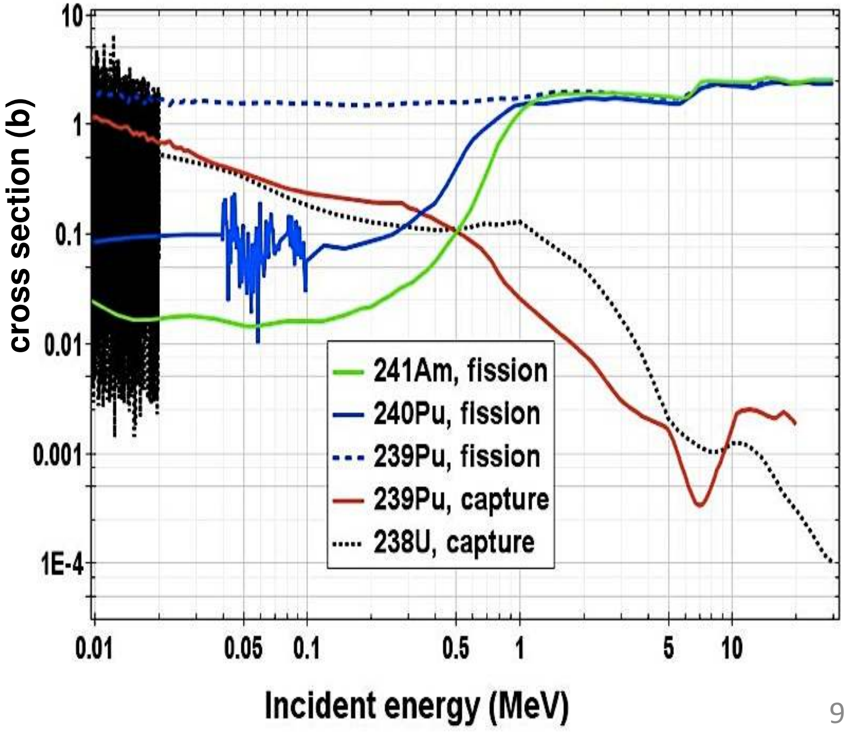
→ KCl-NaCl-$FPCl_x$



The PRIDE facility in ROK has developed to pilot-industrial scale

Neutronics for Isoburning

- One batch of UNF has a ton of ^{239}Pu
- Non-proliferation – keep Pu with intensely radioactive ingredients – TRU, FP
- *Strategy – we extract all the TRU elements together from UNF; we destroy them together*
- The fission cross-sections for Pu, TRU are equal for $E_n > 1$ MeV
- But for $E_n < 1$ MeV MA fissions 10 times less than ^{239}Pu



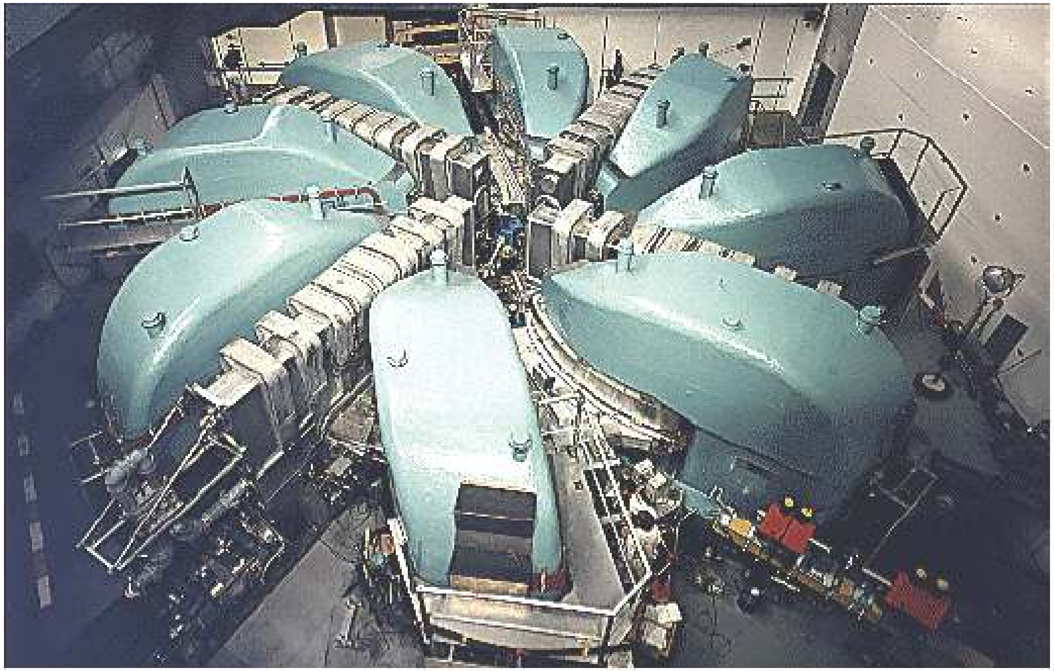
Choice of criticality k_{eff}

- We need to run the core subcritical
  - ^{239}Pu has 3x fewer delayed neutrons than ^{235}U
  - ^{241}Am has 5x fewer delayed neutrons than ^{235}U
  - ^{239}Pu fissions faster than ^{241}Am ➔ neutronics shifts
  - TRU-burning is a challenge for any critical core design.
- Suppose cooling is lost…
  - Passive heat pipes remove decay heat
  - The salt cannot freeze – k_{eff} has strong negative temp coeff.
- Design core to operate with $k_{eff} = 0.97$.
- Core cannot go critical under any of the many failure modes considered.
- But we need lots of proton drive…

Each 290 MW_t ADAM core requires 3 x 4 mA of 800 MeV proton drive beams, and destroys 130 kg/year of TRU.
Each GW_e nuclear plant produces 390 kg/year of TRU.
So how do we make 9 x 4 mA of 800 MeV protons?


The first cyclotron.

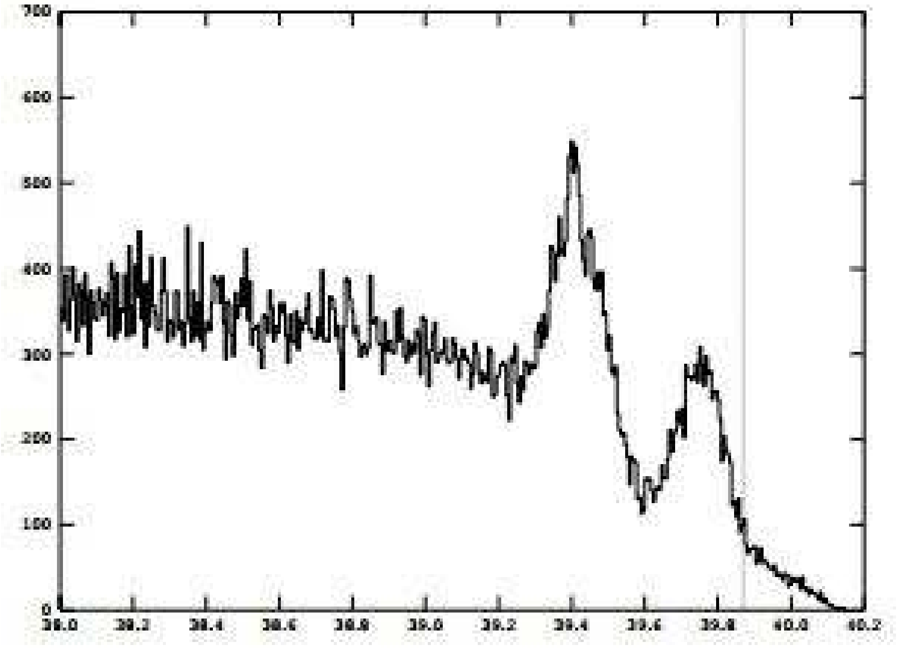
invented by Ernest Lawrence, 1930 at Berkeley



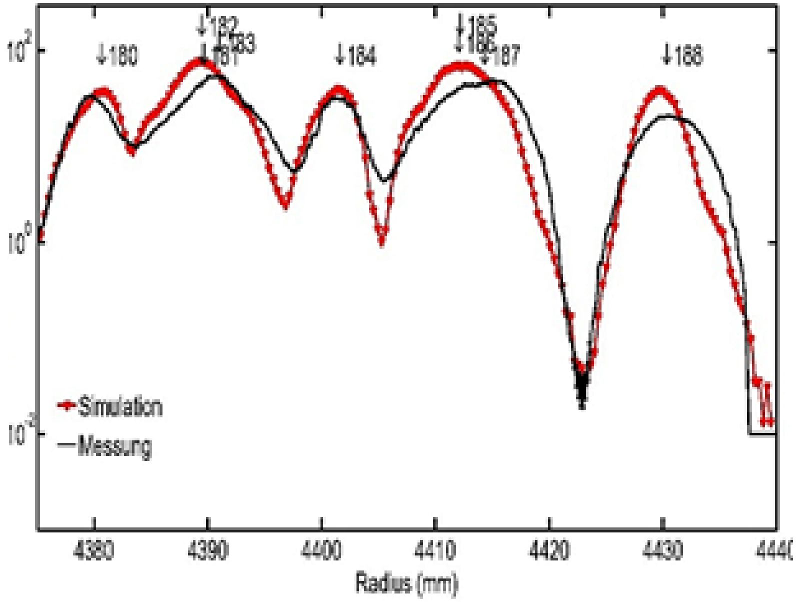
PSI operates the highest power accelerator in the world: 2.3 mA @ 590 MeV

The **cyclotron** is among the oldest of particle accelerators, and it still holds the world record for the highest beam power – 1.3 MW.
Even teenagers can build one:
http://www.youtube.com/watch?v=d7tKxqwfZoE&feature=autoplay&list=ULTLdlKDP76b4&index=1&playnext=1

Current limits in cyclotrons:
1) Overlapping bunches in successive orbits



http://www.nscl.msu.edu/~marti/publications/beamdynamics_ganil_98/beamdynamics_final.pdf



http://cas.web.cern.ch/cas/Bilbao-2011/Lectures/Seidel.pdf

Overlap of N bunches on successive orbits produces N x greater space charge tune shift,

non-linear effects at edges of overlap.

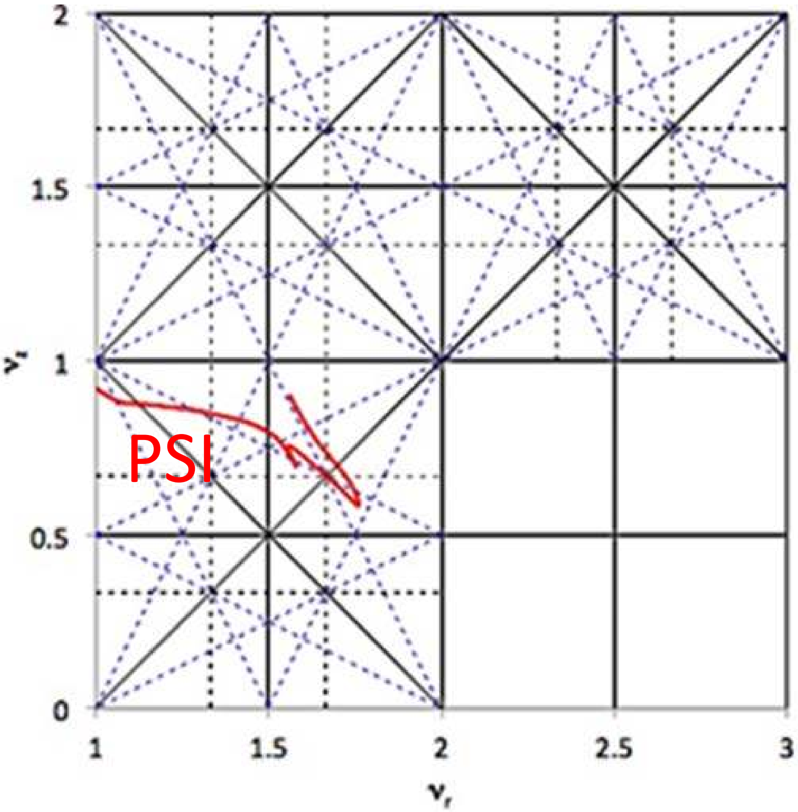
2) Weak focusing, Resonance crossing

Cyclotrons are intrinsically weak-focusing accelerators

- Rely upon fringe fields
- Low tune requires larger aperture
- Tune evolves during acceleration
- Crosses resonances

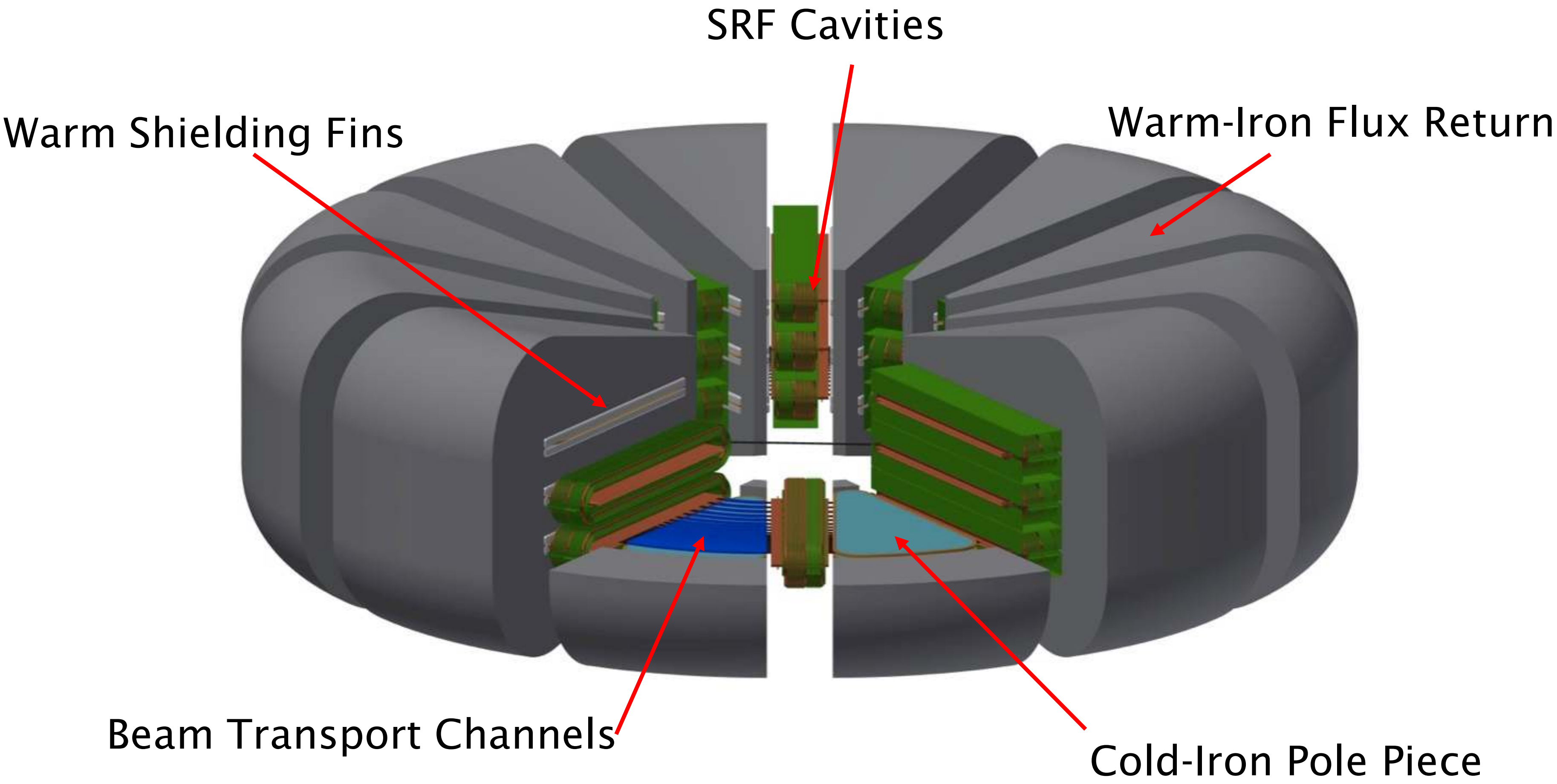
Scaling, Non-scaling FFAG utilize non-linear fields

- Rich spectrum of unstable fixed pts



Space charge shifts, broadens resonances, feeds synchro-betatron
Even if a low-charge bunch accelerates smoothly, a high-charge bunch may undergo breakup even during rapid acceleration

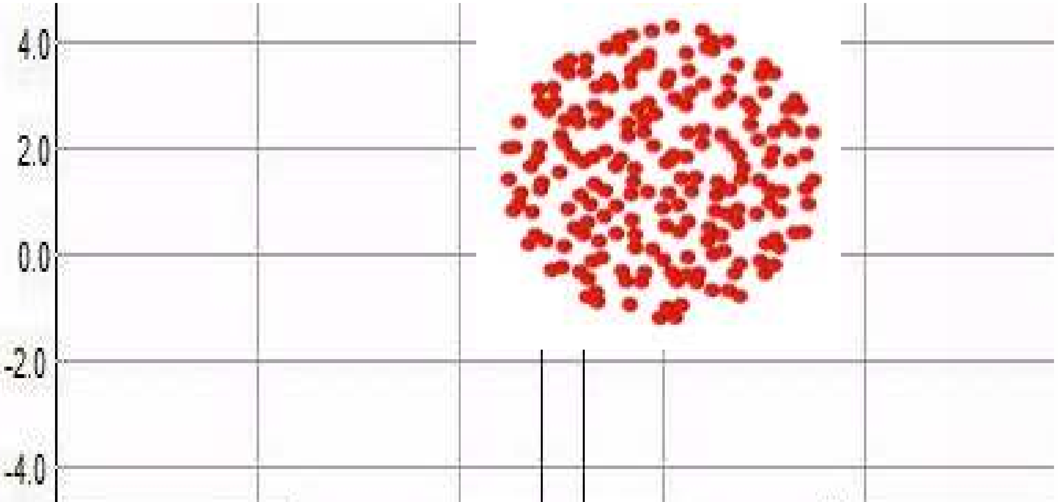
Hence the Strong-Focusing Cyclotron…

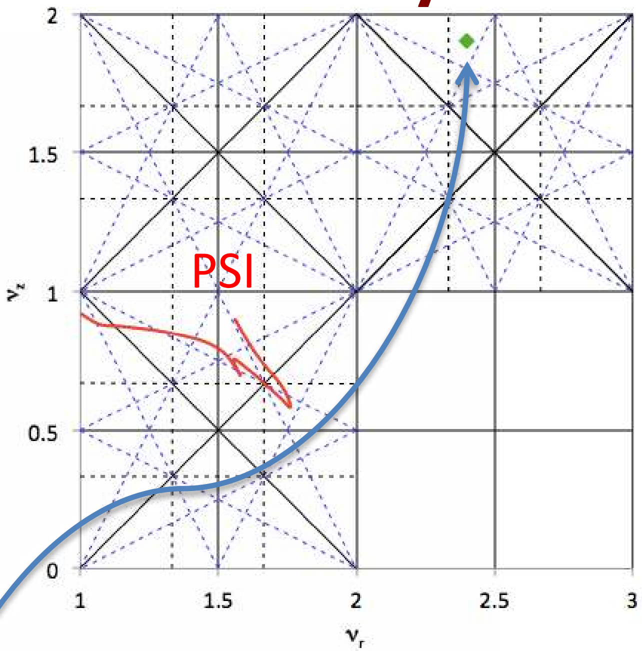


- SRF cavities provide 20 MeV/turn energy gain – fully separate orbits
- Sectors are simple radial wedges – optimum for integrating SRF
- Beam transport channels control betatron tunes, isochronicity

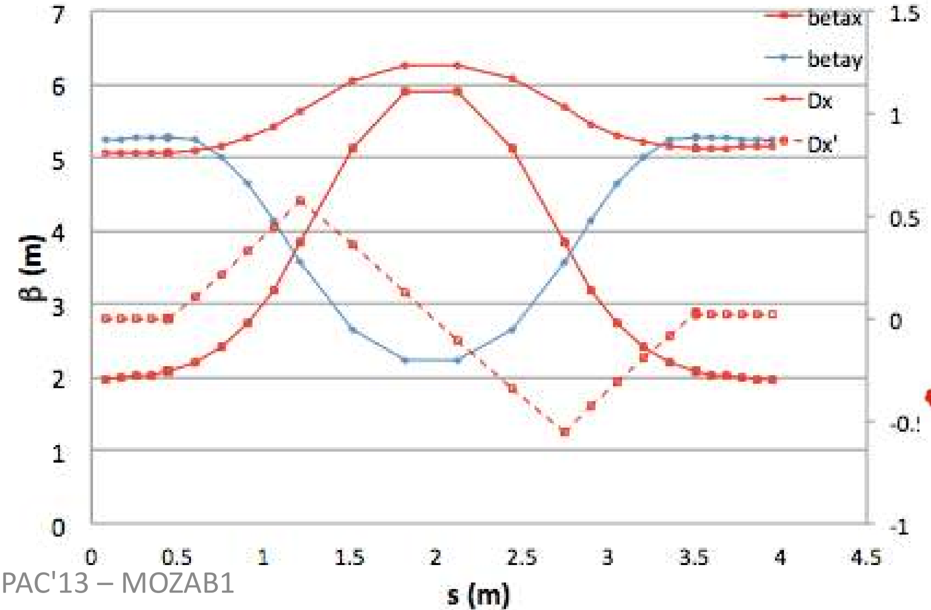
BTCs control tune, isochronicity

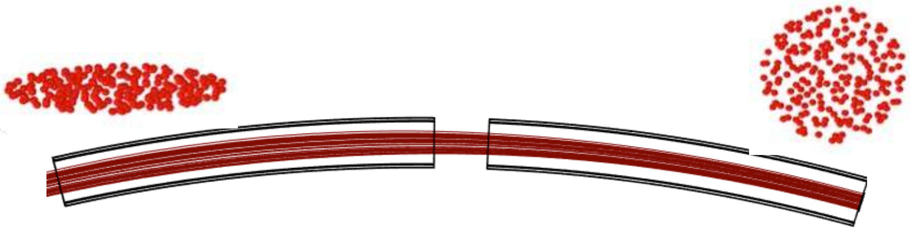
Uniform gradient in each channel: excellent linear dynamics





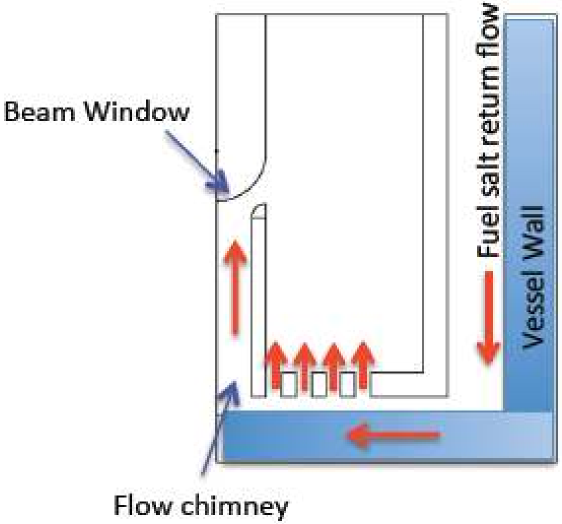
Select desired operating tune, use quad focusing to lock the tune for all energies

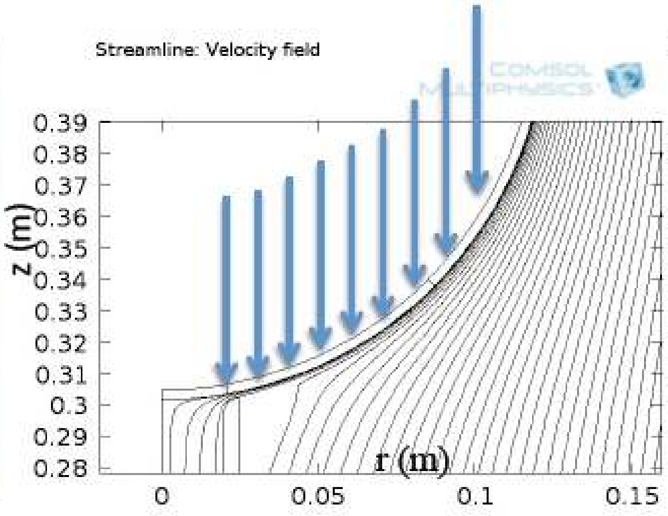


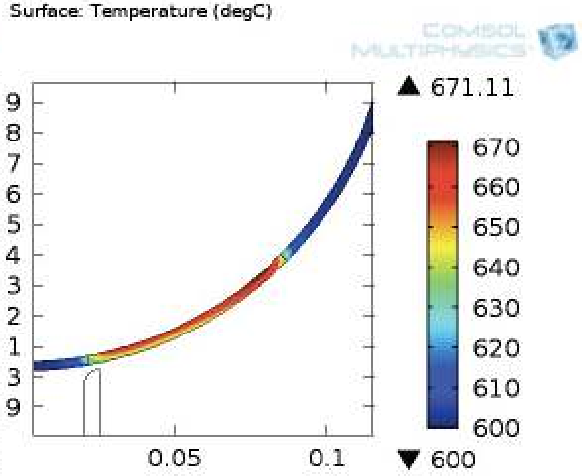


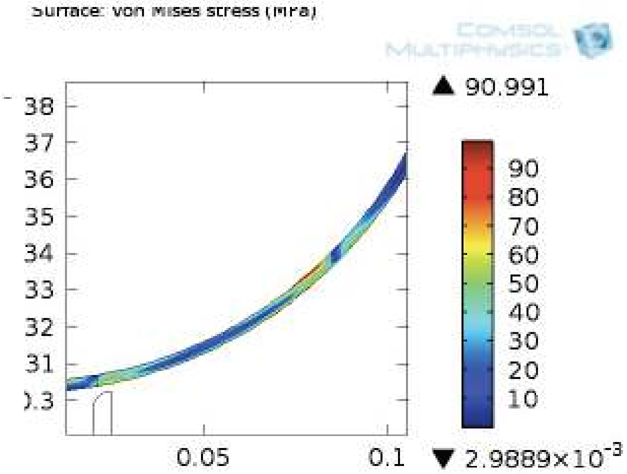
We inject 2.8 MW protons through a 3 mm-thick Hastelloy window

We direct a dedicated molten salt flow on the window in the HX circuit.









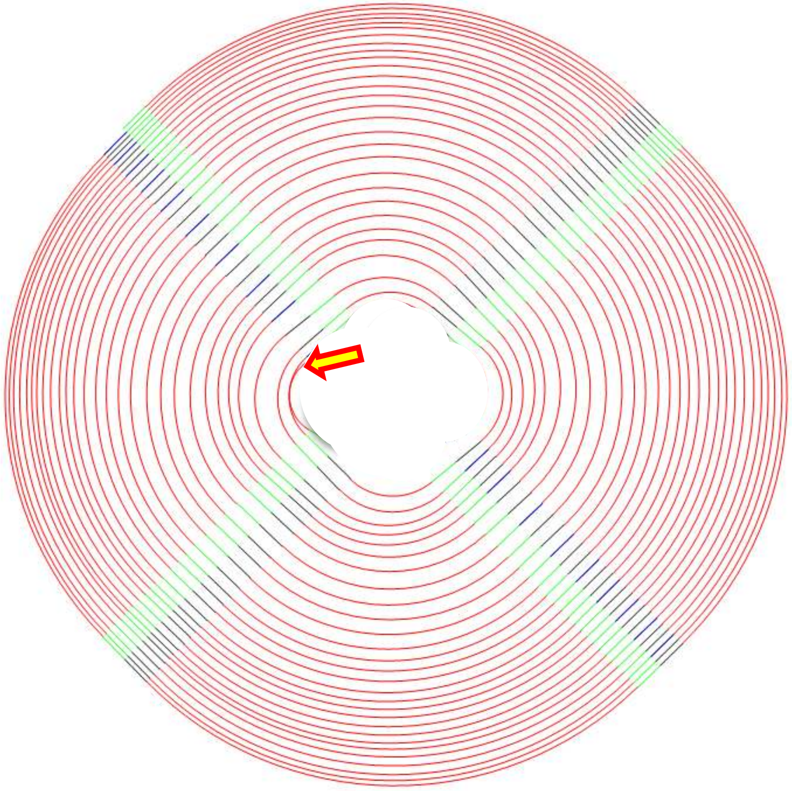
Protons pass through window, deposit most of their energy in molten salt.

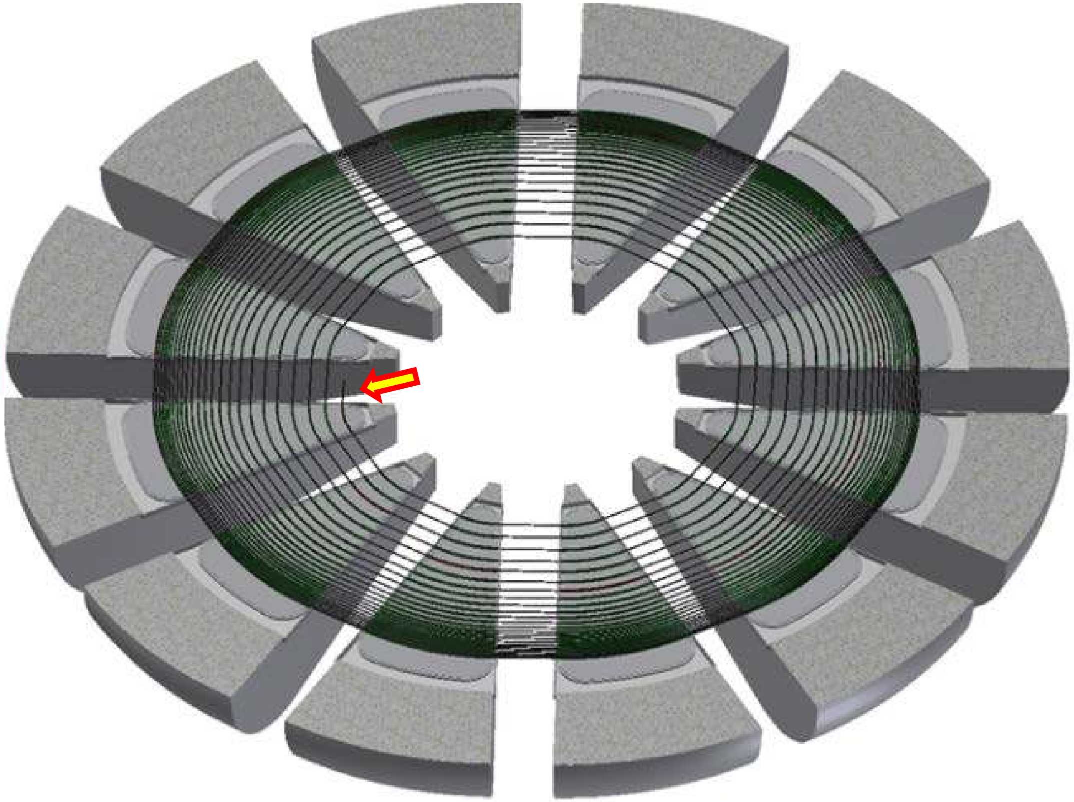
~22 kW is deposited in the 3 mm Hastelloy window.

Max temp gradient ~60 C, max von Mises stress ~60 MPa.

Should be fine, we will do experiments to verify.

Control all orbits: betatron tunes, isochronicity, position





TAMU100: 6.5→100 MeV

TAMU800: 100→800 MeV

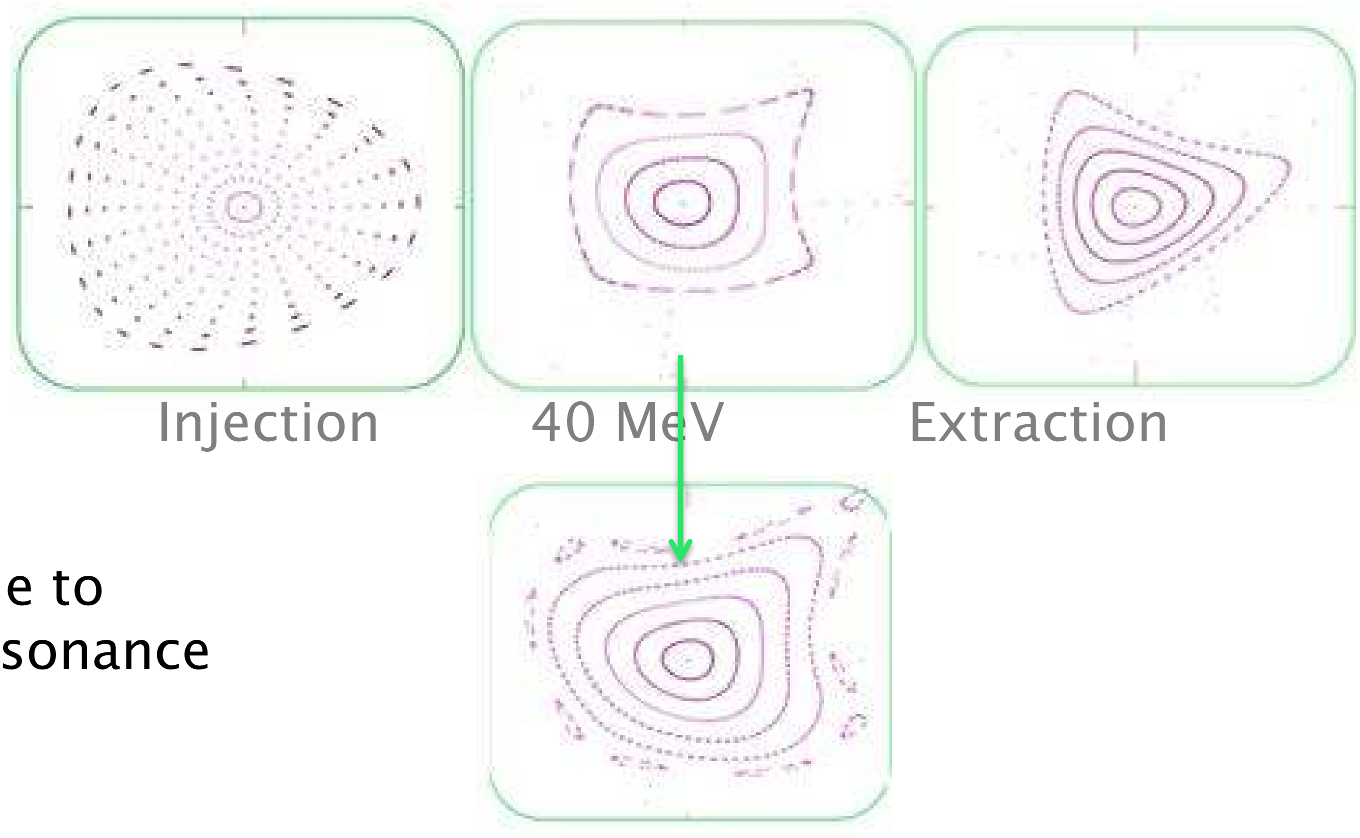
If any one of the 10 rf cavities malfunctions, increase gradient in the remaining 9 to maintain energy gain/turn, use trim dipoles in the beam transport channels to maintain equilibrium orbit unchanged. Works like a 'spiral linac'.

We have simulated spiral transmission line, including x/y coupling, synchrobetatron, space charge
Poincare Plots of 1-5 σ contours in TAMU100

3.5 mA beam

First lock tune to favorable operating point:

Now change the tune to excite a 7th order resonance



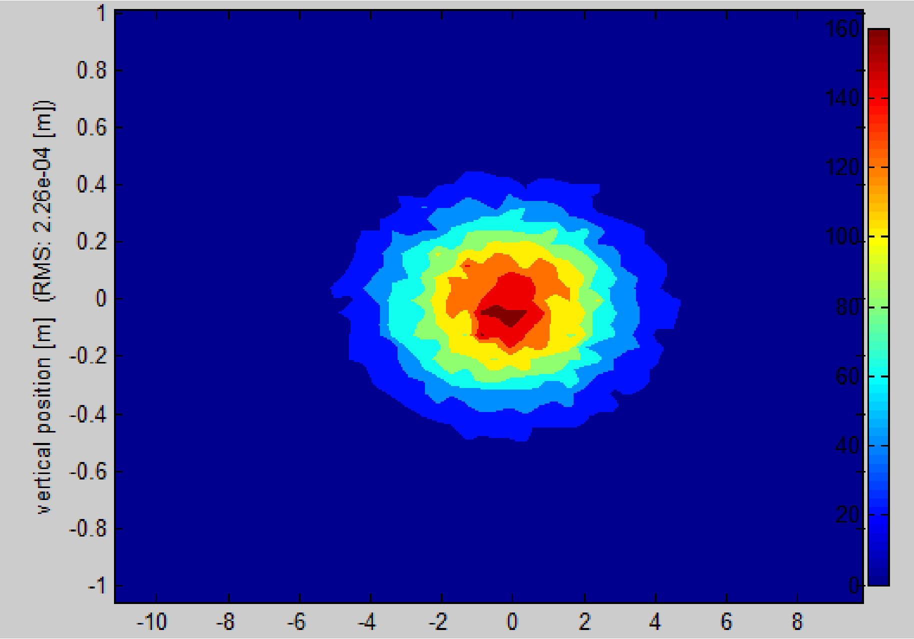
We are seeing the origins of the current limits in PSI from overlapping bunches, tune trajectory. Both are cured in the SFC.

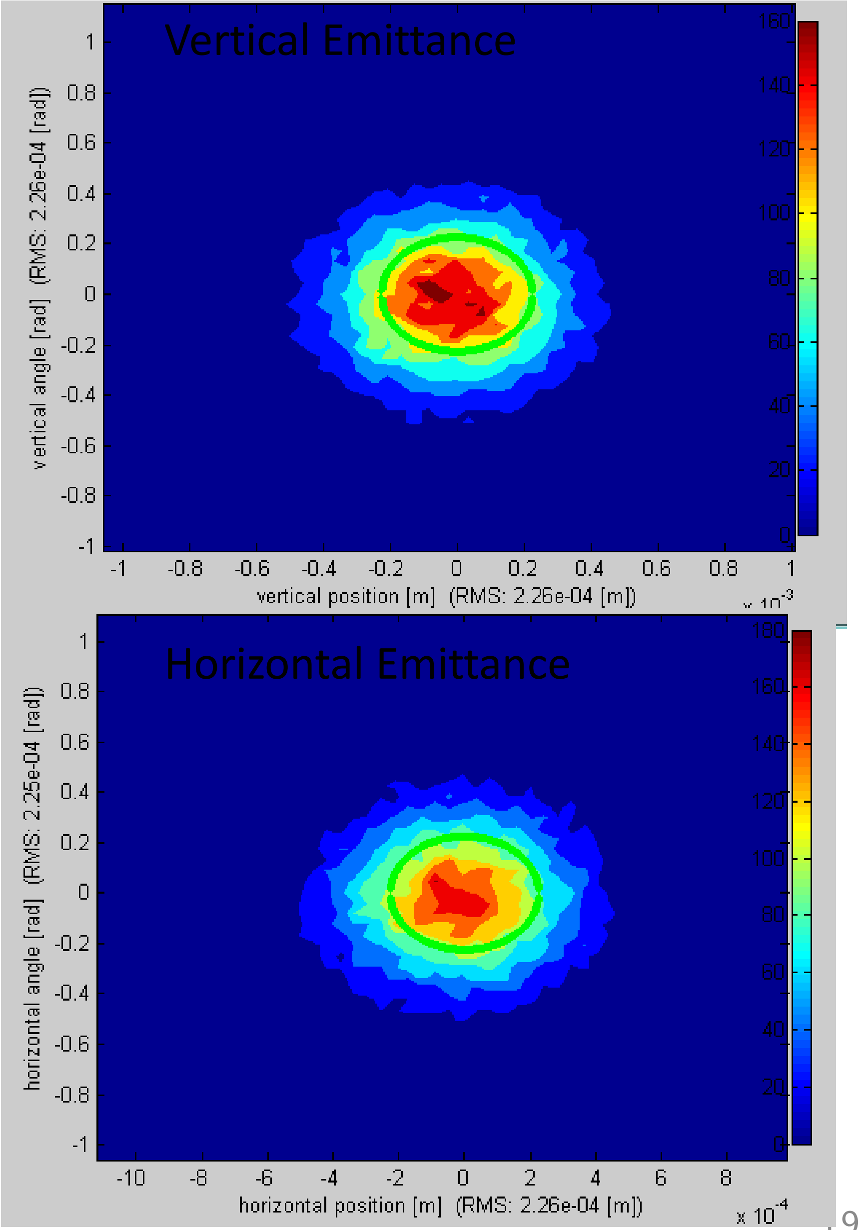
Next studies: beam loading of cavities, wake fields…

Transverse phase space of 10 mA bunch

First at injection:

x/y profile

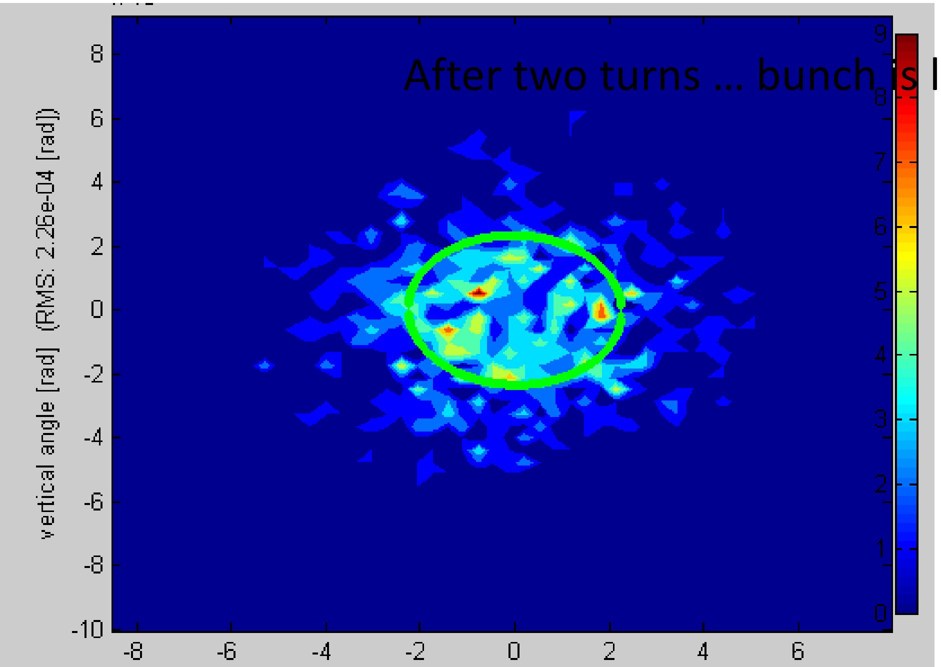




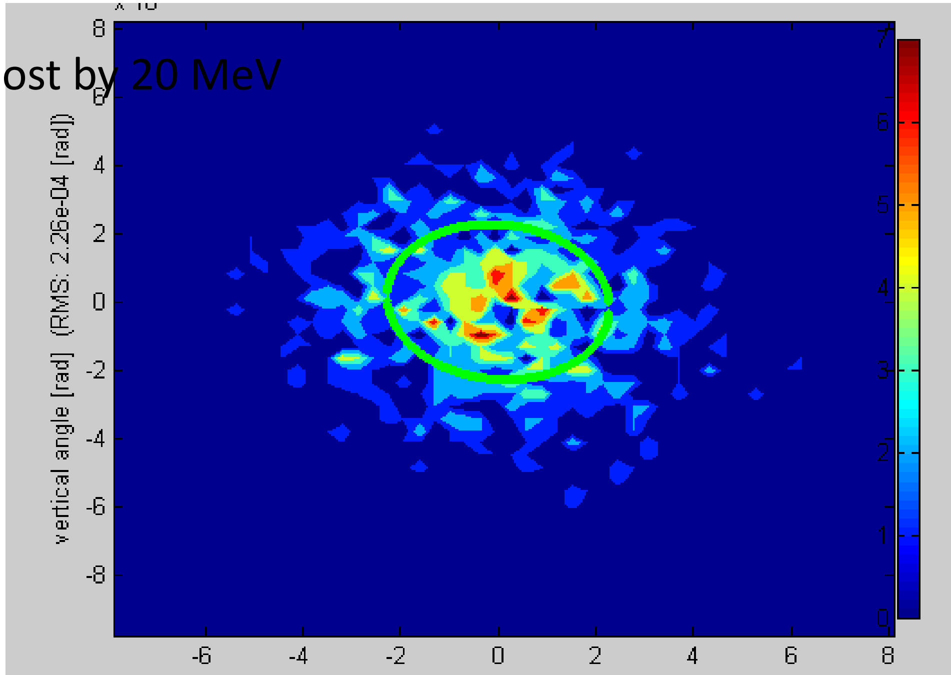
Now look at effects of synchrobetatron and space charge with 10 mA at extraction:

Move tunes near integer fraction resonances to observe growth of islands

After two turns … bunch is lost by 20 MeV



1/3 order integer effect



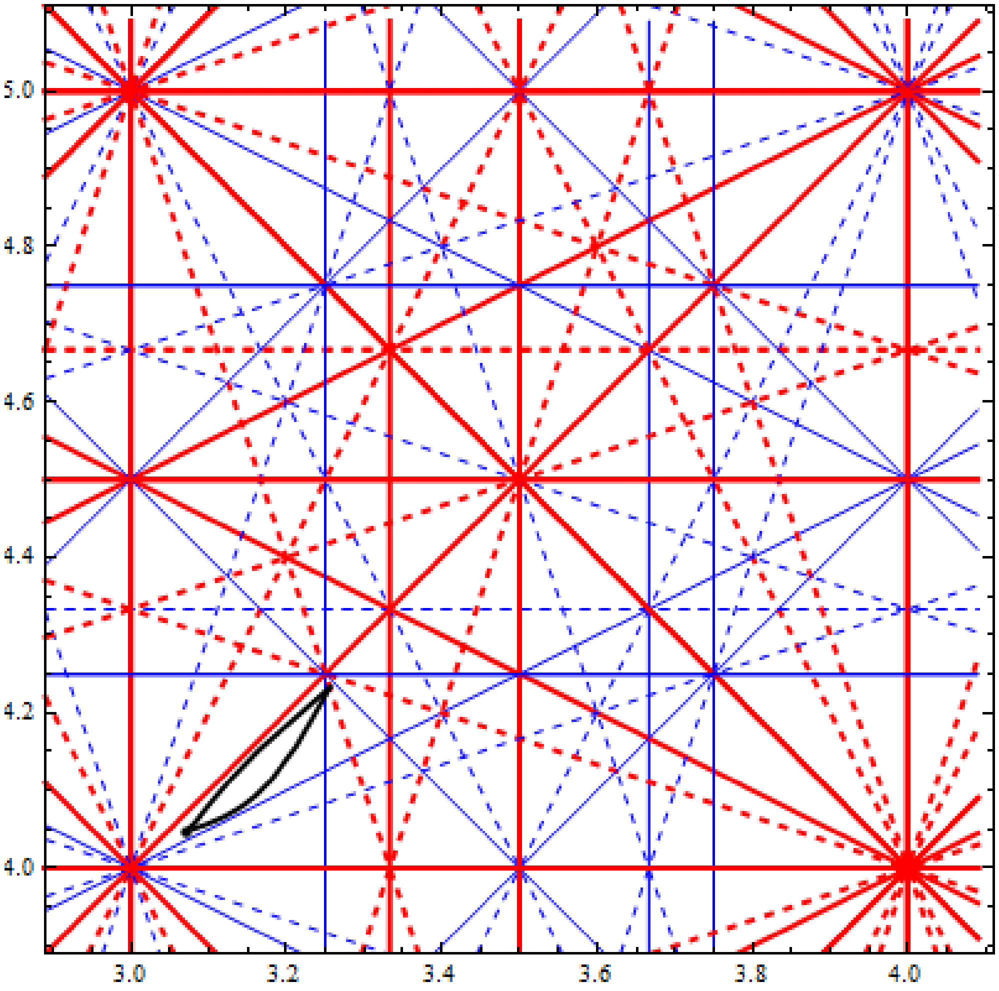
1/5 order integer effect

1/5-order islands stay clumped, 1/3-order islands are being driven. Likely driving term is edge fields of sectors (6-fold sector geometry). We are evaluating use of sextupoles at sector edges to suppress growth.

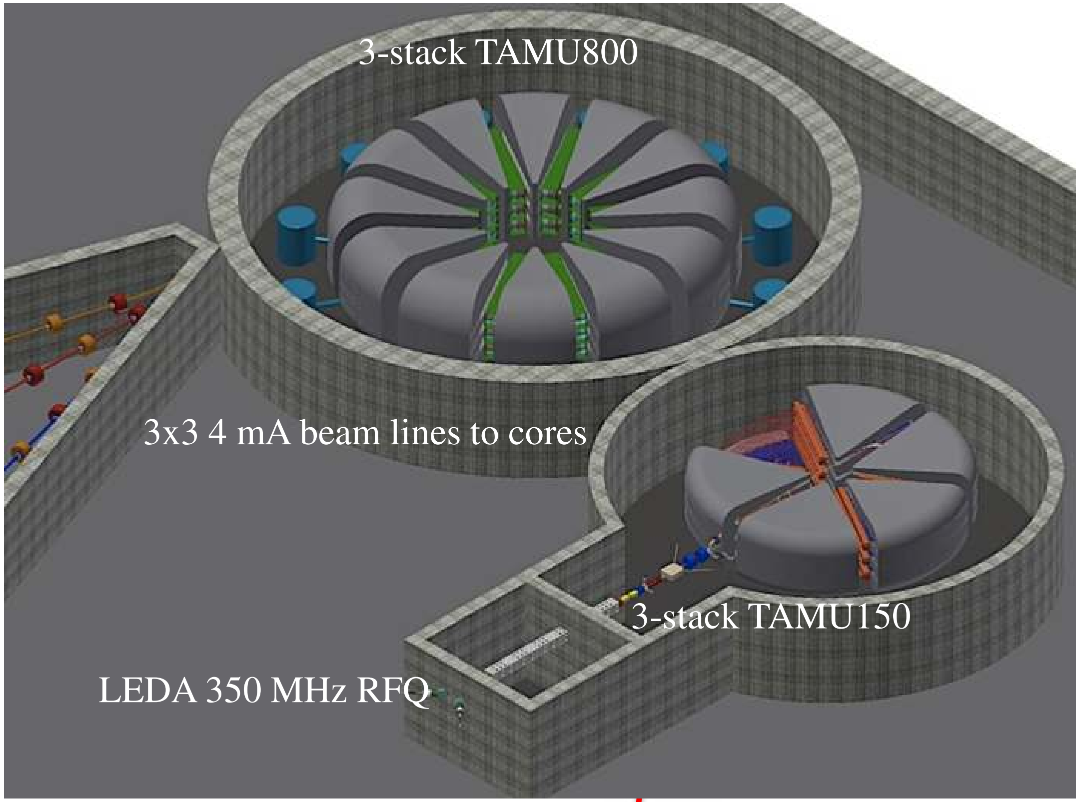
Now find tunes for all particles on the 5 s contour in a 10 mA beam accelerated to 800 MeV:

Since we can control tune using BTCs, we can place the operating point so that no significant resonance is crossed by any beam out to 5σ

We are exploring placement of 4 families of sextupole correctors after each sector; We expect that to enable us to push further in current…



To destroy TRU generated from a GW$_e$ power plant:



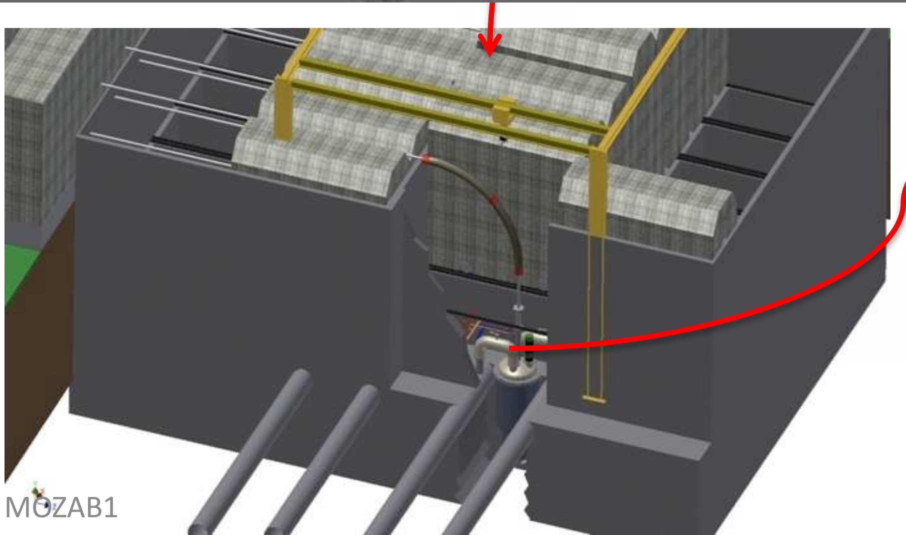
Each 800 MeV SFC

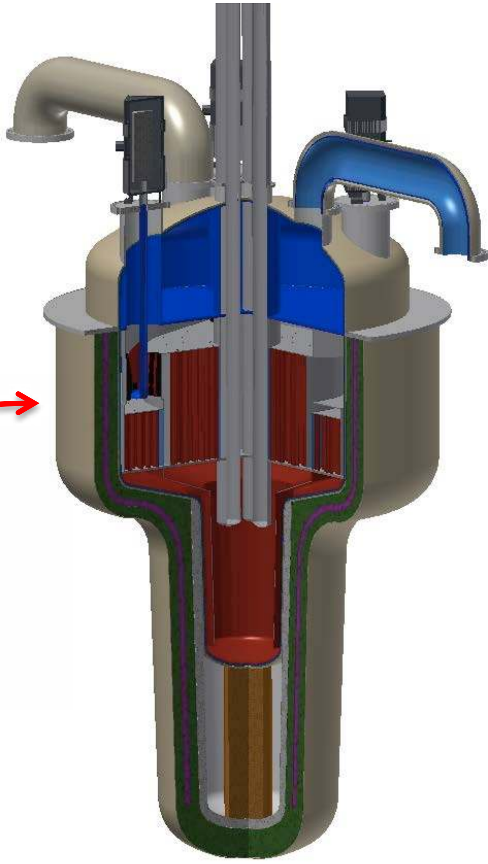
  12 mA current ➔3 beams

Total 30 MW CW:

  9 drive beams

  3 ADSMS cores

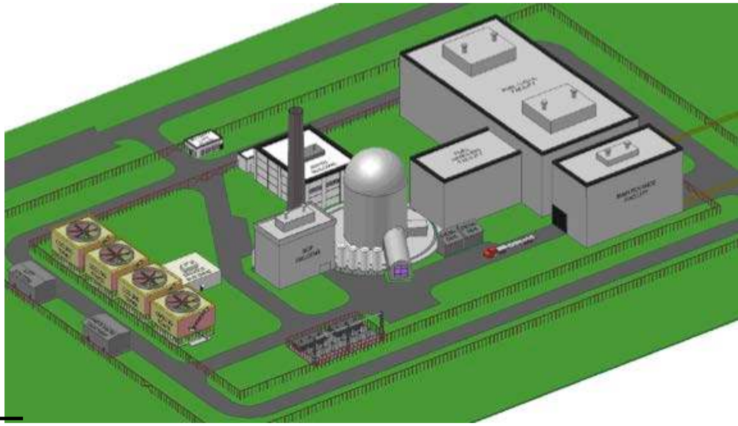




Compare performance for TRU-burning between ADAM and three flavors of critical fast reactors:

Critical reactors to burn TRU must operate with fast spectrum and non-H coolant/moderator:

Sodium-cooled fast reactor	SFR
High-temperature gas fast reactor	GFR
Lead-cooled fast reactor	LFR



System	**ADAM**	**SFR**	**GFR**	**LFR**	
Net TRU Destruction	0.84	0.74	0.76	0.75	g/MW$_t$-day
			21	180	GWd/tHM
dTRU/TRU	**0.056**	**0.086**	**0.049**	**0.048**	**/year**

RN Hill and TA Taiwo, PHYSOR-2006, ANS Topical Meeting, Vancouver, 9/2006.

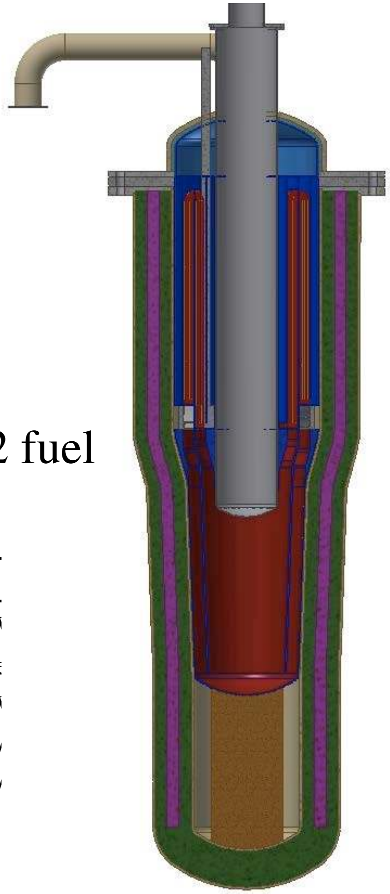
ADAM burns TRU as well as the best critical core yet designed, it operates with smallest TRU inventory, and it has no potentially disastrous failure modes.

Summary: ADAM is a safe, effective method for destroying the TRU in UNF

- One ADAM system destroys TRU at the same rate that it is made by one GW_e nuclear power plant.
- It also generates 280 MW_e of new electric power – an energy amplifier with a gain of 5.
- It is safe to operate – there are no failure modes that could produce disastrous consequences – *see next talk*.
- Estimated cost of one ADAM facility ~$1 billion, net cost of TRU destruction comparable to nuclear fuel fee.
- But how can we prove the ADAM technology at a cost <<$B?

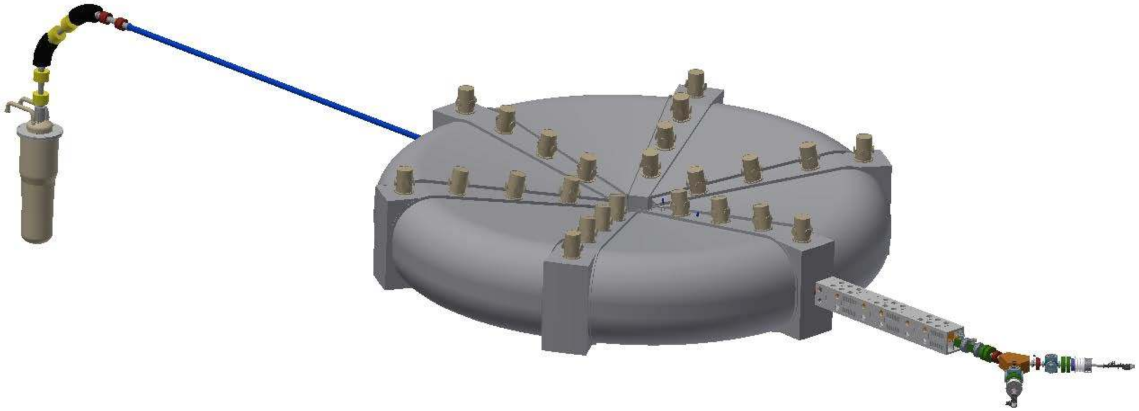
We can *miniaturize* ADAM yet preserve all elements of its performance

- Reduce core size 560 liters ➔ 60 liters
- Initial operation with lanthanide surrogate fuel – no actinides…
- The shift to actinide fuel:
  - Increase $TRUCl_3$ fraction in the fuel salt 15%➔ 60%
  - Criticality remains the same = 0.97
- Reduce proton drive beam energy 800 MeV ➔150 MeV
  - Spallation yield decreases 14 ➔ 1
- Test all ADAM technology under parameters of full system.
- Total TRU required = 220 kg - ~ amount recoverable from EBR2 fuel
- Estimated total project cost $100 million.

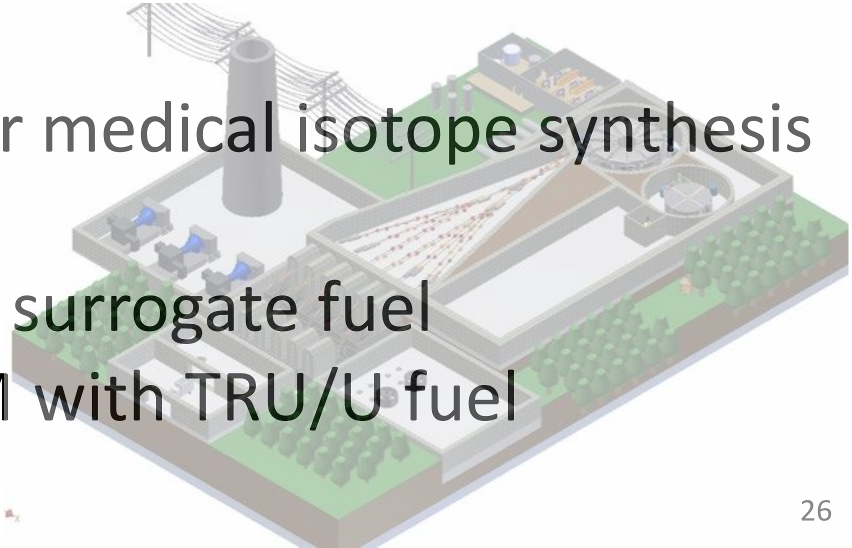


System		SFR	GFR	LFR	SABR		ADAM		
Thermal Power	**Q**	840	600	840	3000	290	5.46	16.38	M
ADS proton energy	E_p					800	150	150	Me
ADS beam power	P_p					8	0.5	1.5	M
Net TRU Destruction		0.74	0.76	0.75	1	0.84	1	1	kg
Core Power Density	**q**	300	103	77	73	207	64	192	W
Outlet temperature	T_{max}	510	850	560	650	665	695	695	C
Thermal Efficiency	h_{th}	38%	45%	43%		44%	44%	44%	
TRU Inventory	T	2250	3420	4078	36000	1733	220	220	kg
Fuel Volume Fraction		22%	10%	12%	15%	100%	100%	100%	
TRU Enrichment	T/U	44-56 %	57%	46-59%	100%	53%	100%	100%	TRU/HM
Fuel Burnup		177	221	180	249	129.5	9.1	22.8	GWd/THM
dTRU/TRU		8.6%	4.9%	4.8%	3.0%	5.6%	1.0%	2.5%	/year

Destroying transuranics is the gift we can give our future generations…



Our plans to make it all happen:



- 2014-2017 Build 70 MeV SFC for medical isotope synthesis
- 2017-2019 Build baby-ADAM
- 2020-2022 Commission with La surrogate fuel
- 2022 Operate baby-ADAM with TRU/U fuel

Thank You for Listening