To: Mike Zarnstorff
From: Larry Grisham
Subject: Utilization of PDX/PDX Beamlines for your Stellarator
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Introduction

Reusing the PDX beamlines for the new stellarator would offer some appealing advantages, but also some technical uncertainties, one of which is major. Jim Tsai at ORNL has previously taken a look at some of the changes and associated costs which would be incurred in converting these 300 msec systems into ones with several second beam capability. He did his study in the context of using the beams for NSTX, so the cost numbers may be a bit dated by now.

This memo will discuss the possible advantages of using the PDX beam systems, the issues and problems, and the options. The equivalent considerations for using the TFTR beamlines will be discussed in a separate memo.

I will not repeat Jim Tsai's discussion here, except to note that the general scope of what he proposed was to upgrade the cooling capabilities of the principal beam-impinged components (the ion dumps and the calorimeters) by replacing the inertial copper plate surfaces with swirl tubes, to change the dimensions of the neutralizer duct, to change the type of cathode used to supply primary electrons to the sources, and to make some changes to the power supplies. The estimated ORNL costs were roughly estimated as about 4.3 M$, with the estimate for costs at PPPL (by Henry Kugel) bringing this up to about 5.5 M$. Importantly, this figure apparently did not include any estimate for the cost of developing, building, and retrofitting new long pulse grids compatible with these sources and capable of operating at full beam power.

Advantages of using the PDX beams for a stellerator:

(1) They are designed for the relatively small entrance aperture on PDX, although their transmission factor is reltively poor. However, they are easier to fit into a PDX device than would be a larger footprint beam.

(2) The PDX grids are already gapped to run about the voltage (40 - 50 keV) which may turn out to be the optimum for a PDX-sized stellerator.

(3) The PDX ion sources and accelerators are reasonably well matched to their various supplies, since these supplies were originally designed with the purpose of driving ORNL cusp-duoPIGatron sources.

(4) The PDX beam lines and power supplies take up relatively small amounts of space compared to later systems.

(5) Each PDX beamline carries only one ion source. This allows more precise aiming of the beam, because there are none of the included angles which result from multiple sources on a beamline.

(6) The PDX beamlines and their power supplies are already in approximately the places they would need to be for a PDX-sized stellarator located at C-Site. This will save substantial moving costs.

(7) The PDX ion source plasmas are probably somewhat more atomic (increasing the fraction of power in the full energy beam components) than are the later LBL sources. This is, I think, due to the intense discharge region in the throat of the intermediate electrode; the discharge characteristics that occur in this part of a duoPIGatron are different than are found in bucket cusp sources, such as those used for TFTR.

<u>Problems and Issues with regard to the utilization of PDX sources and beamlines:</u>

Inertially cooled PDX grids

(1) The principal problem is that the present grid system is for the most part inertially cooled on the time scale of a beam pulse. These grids were designed for 300 millisecond pulses, with the possibility of extending the pulse length at some power level to 500 milliseconds. These grids are firmly tied down around their full circumference. Thus if they heat up, they cannot expand radially (perpendicular to the direction of beam extraction); they have to distort in the direction along the path of beam extraction. Because the three grids in a source will not, in general, see the same amount of power, they will distort by different amounts, resulting in non-uniform gaps between the grids. This results in mis-steering of the beamlets and, probably more importantly, worse divergence due to radial electric field strengths which are mismatched with the current density being extracted. This worse divergence and mis-alignment can in turn further increase the beam interception on the ground grid, and perhaps on the accel (middle) grid.

Depending upon operating conditions, ORNL measurements indicate a power loading to the ground grid (exit grid) of a PDX source ranging somewhere between 1% and 2% of the accelerated beam power. These are resonable values, which I would not expect to be much lower than this range for grids of this design. The plasma grid is also fairly heavily loaded according to their measurements. This is probably due in large part to loading from the plasma discharge. The arc power in the PDX sources ranges up to about 150 KW. The corresponding maximum for a TFTR ion source is 100 kW. ORNL gives the power loading onto the plasma grid as in the range of 1 - 2 % of the beam power. The middle grid, which should receive the least power in this arrangement, gets about 0.5% of the accelerated power.

For a total extracted power of 5 megawatts (50 kV x 100 A), a requirement that the grids be able to handle a 2% power load for five seconds means that the plasma and ground grids each need to be able to exhaust 100 kW of heat. Jim Tsai from ORNL told me that he thought that when one of these sources was run on their test stand in the late 1970's that each grid had a flow of 2 gpm with a pressure drop across the grid of 200 psi. Both he and Henry Kugel thought the pressure drop across the PDX grids was something like half of this, and that the water flow was no more than 1 gpm.

If, however, one assumes that the pressure could be fairly readily increased to 200 psi drop across the PDX grids, then the resulting 2 gpm seems much too low to adequately cool the grids for times long compared to the 300 milliseconds for which they were developed. This would give a water flow through a grid of 0.127 liter/sec, and a water temperature w rise of 191 degrees C in equilibrium. The lowest pressure end of each flow path would carry the hottest water, so somewhere along the flow path the water would presumably start boiling, giving very uneven cooling across the grid. This should be compared to a TFTR grid, which is handling a comparable or smaller power load, and has a water flow of 1.77 liters/sec. In the TFTR case, a 100 kW heat load gives rise to a water temperature rise of 13.7 degrees C along a rail which can undergo nearly force-free expansion into a bellows.

It is hard to imagine how the present PDX grids could be usable at anything like full power for 5 second pulses. At some lower power level they might survive, but it appears likely that level would be substantially lower than what is desired. Henry Kugel says that the present PDX sources operating at full power may be able to each inject 2 megawatts of deuterium if new cryopumps were designed and fabricated for the forward chamber of each beamline. If one reduced the injected power to 0.5 megawatts, then with a 200 psi drop across the grids, one might have steady state cooling (although still with a temperature difference of 35 - 50 degrees Centigrade along each cooling path). Since there are four beamlines, this would give a total power of two megawatts. Even at this reduced power level, grid temperature rise and differentials along the flow paths will lead to distortion because of the fixed perimeters of the grids. This will in turn increase the beam loading on the two downstream grids.

Electron Feed

(2) The present PDX sources use oxide-coated filaments as the cathodes. These are quite fragile, and are not thought by ORNL to be suitable for long pulses. In their NSTX upgrade assessment mentioned at the beginning of this memo, they proposed replacing them with an indirectly heated plasma-sprayed large area cathode which they developed in the early 1980's for their candidate for the TFTR long pulse source. I always found these cathodes appealing, and I think there is a

good chance that they would work in the PDX sources. I suspect that some redesign work might be required in either the cathodes or the backs of the PDX ion sources, and that this might entail some developmental work if the discharge characteristics change.

Arc Chamber Cooling

(3) I am not sure whether the present arc chamber cooling is adequate for 5 second pulses. If we actually proceeded with PDX sources, I would need to locate some information on this somewhere. I am also unsure how the 150 kW of arc power is split up between the various surfaces in the source.

Reionization Power Loading in Ducts

(4) The PDX beam ducts suffer excessive reionization losses from the beam due to a pressure which is higher than planned. These losses, which end up on the duct walls, run something like 10 - 14 %, and are likely to be somewhat focussed by the gradients in the fringe magnetic fields of the stellarator. The associated heat load may pose a problem with long pulses. The duct was designed to contain a cryocondensation pump, but this was abandoned early in PDX running due to problems with leaks in the internal feed lines running from the main beamline into the duct pump box. Building and successfully implementing a new cryopump would probably help this problem. A different, smaller divergence source would probably also reduce the reionization losses due to less stray beam desorbing gas from the duct walls.

Upgrading Cooling of Beamline Surfaces

(5) The PDX beamlines use inertially cooled copper (the attached water lines carry out the depositied heat between pulses, similar to the case with the grids). For longer pulses this would need to be replaced with actively cooled surfaces. This would entail replacing the ion dumps, beamline calorimeters, and perhaps some scrapers. ORNL suggested swirl tubes. Swirl tubes can have good heat transfer characteristics. On PLT, however, we had severe reliability problems with them, and had to replace them with inertial components. They also use several times more waterflow than hypervapotrons (the components used at JET), and the induced water temperature changes are small, making accurate power measurements more difficult than with hypervapotrons. Whether one uses one of these technologies, or one of the other variants of high heat transfer technologies available, upgrading the beamline component cooling is a tractable, although expensive, undertaking.

Changing the Neutralizer Cell

(6) ORNL would like to change the neutralizer cell so that it followed the contour of the beam and, more importantly, was as large at the entrance as the grid emitting array. This is likewise a tractable problem, and constitutes a relatively small fraction of the beamline upgrade costs.

Age of PDX/PLT Beam Power Supplies

(7) Henry Kugel and Dale Ashcroft felt that these very old power supplies would probably require replacements of some parts if they are to operate reliably for an extended period into the future. These costs are included in the upgrade estimate.

Some Options for Providing Neutral Beam Heating for a New Stellarator:

(1) Carry out the beamline upgrades, but retain the ion source grids as they are. One would then lengthen the beam pulse at some reduced power level until we run into problems. If the stellarator is fairly certain to need several second pulses with1.5 MW or more per beamline, then this appears to be a very high risk approach. MAST may be planning on trying such an approach, although communication has been too limited to be sure exactly what they expect to do. If they really did try this withinthe next year or two, then we might learn some lesson from it.

(2) Commission ORNL to adapt their 1985 entrant in the TFTR long pulse source competition to a PDX beamline and similarly constrained entrance aperture. This was the approach favored by Jim Tsai at ORNL when I talked with him. He told me he did not feel the present PDX grids were usable for long pulses (this is likewise my opinion). I was quite favorably impressed by their long pulse source in 1985. However, if we were going to have ORNL adapt this source to operate on a PDX-sized stellarator, we would have to understand why this approach would be better than the less expensive option of adapting our own TFTR long pulse souces. The optics of the ORNL source were alleged to have been better than for the LBL source, but it is not immediately clear that this should be the case. Adapting either source would probably require major changes to the PDX beamline involving replacing several of the major components (like the ion deflection magnets). Either source will probably have difficulty fitting its full power through a PDX duct.

(3) Adapt a commercially available ion source to the PDX beamlines. There is probably more than one possibility here. The JT--60U positive ion sources were designed for 10 second pulses, and routinely run this long. They normally run at 80-90 kV with delivered neutral power of 1.4 - 1.5 MW/source. They have also been run as a three grid system, rather than 4, at 40 kV. I think that in the 40 kV configuration their power is close to a factor of two less.

Kuriyama-san told me that they have three beamlines (six ion sources) which are no longer used because the beamlines are used to pump their divertor, and he suggested that these sources might be available for free if a collaboration could be worked out. He pointed out, however, that this was his idea, and he had not discussed it with anyone. If one had to buy these sources from a company they cost about 50 million yen each (about $390,000 at yesterday's exchange rate). It would be challenging fitting these sources into a PDX-sized machine, but less so than trying to fit a

TFTR-sized source from either LBL or ORNL. The biggest problem might be that the power at 40 - 50 keV might not be as much as wanted.

(4) <u>Commission the development of new long pulse grids to be mated to the PDX sources</u>. This is almost certainly a viable approach, but will require time, some technical risk unless the grids are tested either at the developer or in a test stand attached to a PDX beamline, and significant money (presumably a few million dollars on top of the 5.5 M$ of the ORNL estimate for the balance of the beamline and power supply upgrade).

(5) <u>Move one or two TFTR beamlines to C-site for injection into a PDX-sized or, preferably larger, stellarator.</u> The TFTR beamlines are already capable of operation at 80 kV for five seconds (4.5-5 MW/beamline). The sources are capable of much longer. With a modest upgrade to the ion dump, this limit could be extended several seconds further. With TPX-level upgrades, it could be extended to 1000 seconds or more, if this were ever desired. However, there are severe access problems in getting the beams into a PDX-sized machine if the present port sizes are retained. There are also other problems, such as the 8.4 degree included angle in the TFTR source array, which might be too wide for a PDX-sized stellarator. Moving the beamlines and some of their supplies, and adding the necessary cable and piping, would obviously be fairly expensive. Moreover, the beamlines would have to be decontaminated of tritium to some regulationally acceptable level. If a beam energy of only 40 - 50 keV is required, the grids can be regapped with probably acceptable effects upon the optics, but the neutral power will be reduced somewhat (the reduction will probably be less serious than a factor of two).

(6) <u>Locate the stellarator in the tokamak test cell and swing around two of the TFTR beamlines.</u> This would work nicely if the stellarator were located over the 14 ft hatch, although it would probably require opening up the large closed doorway for moving things in and out of the cell. Other than swinging around two bealines, very little repostioning of the neutral beam infrastructure would be required, and these beamlines could be run in conjunction with the NSTX beamline. They could also use the same liquid helium system. This should be substantially cheaper than taking them to C-site. The other considerations mentioned for option 5 apply here also if the stellarator is similar in size and port access to PDX. If a somewhat larger device were built, however, we could, one hopes, design in better beam access. If the path length through the plasma increased sufficiently, then we could operate the beams at 80 keV or more, allowing higher heating powers.

Note: Options 3, 5, and 6 will be discussed more fully in a subsequent memo.

<u>Rough Estimates of Costs for the Different Options</u>

The cost estimates for options 0,5,&6 arose in the course of discussions with Tim Stevenson, and the cost for option 1 was obtained from Henry Kugel based in part on cost estimates from ORNL. These costs are very rough estimates, intended only to give an idea of the relative cost of different options.

(0) The cost of simply restarting the PDX beam system without any upgrades is estimated to be about 500 k$ for necessary repairs. This would give full power capability (1.5 MW per beamline) for 300 msec, and at least half power capability (750 kW pwr beamline) for 500 msec.

(1) The cost for the PDX beamline upgrades recommended by ORNL and power supply improvements to give everything but the grids full power capability for 5 seconds is estimated to be 5.5 M$.

(2) The cost of adapting the Oak Ridge long pulse source to a PDX duct geometry and fabricating four sources is also very uncertain. However, this, coupled with necessary modifications to the beamline over and above the basic 5.5 M$, would probably result in an additional cost of 3 to 5 million dollars. This approach would probably cost somewhat more than option 4.

(3) JT-60 positive ion sources cost about $390,000 at current exchange rates, and we might be able to borrow 6 for free in a collaboration. Beamline or additional power supply modifications which might be required might run of the order of 1 M$ in addition to the basic 5.5 M$ for upgrading the beamline and supplies. However, further work needs to be done to properly assess what beamline modifications would be required with these sources.

(4) The costs of designing, testing, and fabricating new steady state capable grids for the PDX ion sources are not easy to estimate, but could easily be as much as three to five million dollars. These costs would be in addition to the basic 5.5 M$ cost of option 1. The development and testing would also add an extra year or two to the schedule. If we could collaborate with MAST on steady state grids, and have the testing done at Culham, then the cost to PPPL would presumably be somewhat reduced, as would the risk. Alternatively, if we simply subcontract the grid development and testing and the beamline upgrade to Culham, there should still be significant economies involved if they find that they need to do the same development for MAST. This should also reduce the development risk.

(5) The cost of implementing one TFTR beamline at C-site is estimated to be 14 M$. The estimate for two beamlines is 19 M$. These costs do not take into account the lack of a tritium venting stack system at C-site, which might further increase the costs. These costs assume that the liquid

helium is carried in dewars to C-site, but that the exhaust helium gas is piped back to D-site.

(6) The cost for reorienting one TFTR beamline to fire into a stellarator positioned over the 14 ft hatch in the D -site tokamak test cell is estimated to be 1.7 M$, and for two beamlines 3.4 M$. This includes decontamination costs which are, however, uncertain at this point. If the sources had to be regapped for lower voltage operation, this would invoke additional costs which have not been evaluated, but might amount to somewhere between one and a few hundred thousand dollars for new epoxy insulators. This option would have certain economies of scale for the beam group, since the beams for both NSTX and the stellarator could be controlled from the same area. Moreover, all of the liquid helium could be transported through the closed loop helium piping system. The net result should be that the costs of operating both NSTX and the stellarator at D-site should probably be less than the combined costs of operating NSTX at D-site and the stellarator at C site.